**Editorial**

   Nobel Prize winning discoveries in Nuclear Sciences have had a profound influence on the growth of science and technology in the last century and even shaped the path of human civilization. In a way the quest for unraveling the mystery of the atom and its constituents ultimately led to discovery of many phenomena which later proved to be the major milestones in the history of man kind. The discovery of Radioactivity by Henry Becquerel in 1896 initiated the intense research on understanding the structure of the atom which was led initially by E. Rutherford and Madam Curie and later by Niels Bohr. Of course Albert Einstein's revolutionary ideas of physics ($E=mc^2$, photoelectric effect and special theory of relativity) were to be understood and their implications realized much later than the actual discoveries. With the discovery of Ra and Po by Madam Curie and Pierre Curie intense alpha sources became available for bombarding the atom which was used by E. Rutherford to discover the nucleus.

   The third and fourth decade of $20^{th}$ century saw the maximum growth in the development of new ideas in science in general and nuclear science in particular. While George Hevesy and W.F.Libby and later Rosalin Yalow discovered many innovative ways to utilize the radioisotopes for peaceful purposes, Enrico Fermi, Irene Curie & F. Joliot and Otto Hahn & F Strassmann contributed in understanding the nuclear reactions induced by a new projectile (Neutron) discovered by James Chadwick in 1932. The discovery of artificial radioactivity by I. Curie and F. Joliot paved the way for production of a host of radioisotopes which later found applications in many fields such as medicine, industry, agriculture etc. The discovery of nuclear fission by O. Hahn and F. Strassmann culminated in harnessing the nuclear energy for producing electricity through sustenance of nuclear chain reaction which was demonstrated by E. Fermi for the first time at Chicago. Of course the discovery of nuclear fission also resulted in the birth of nuclear weapons, the consequences of which are felt even today. Their have been many discoveries in the later years of $20^{th}$ century, such as shell model by Mayer and Jenson, Mossbauer effect by R.L.Mossbauer, Quark model of nucleons by Murray Gellmann et al., and many others which led to the advancement of nuclear science. It may be difficult, if not impossible, to put together all the Nobel Prize winning discoveries in one compilation of this size. However a small effort has been made here in bringing out the salient features of the discoveries and the personal lives of the discoverers so that the young readers may draw the inspiration from their lives and works.

   We are thankful to all the authors of the articles who responded promptly to contribute towards the special bulletin which is being released to commemorate the Silver Jubilee of Indian Association of Nuclear chemists and Allied Scientists (IANCAS).

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## From the Secretary's Desk

*Today, science is wide spread in India. We have a large stock of highly trained scientists in all disciplines of science. Several of distinguished Science Academies in India and are well recognized that the biggest change in the scientific landscape of India occurred only after it gained independence. Yet the subject is not legitimately received beyond a level as too much of science is taught at a very young age and it is confined only to class rooms. Given the students an opportunity for learning the subject by practice, by imagination, by imitation and by observation from the nature and the society that enable them to have a propensity to become sensitive to the nature and responsible to the needs of the society. Perhaps one of the most valuable pedagogical tools for science teaching is to enable students to reflect on the important concepts using hands-on and minds-on processes. Every effort needs to include activities that can be carried out safely with materials commonly found in the student's everyday environment.*

*Science teaching is an art that requires a unique combination of knowledge and skills to engage students and foster their understanding. A lack of students desiring to study the sciences has recently been examined by several studies, and most of them reflect on the teaching strategies of most university professors. The biggest problem is that scientists and academics do nothing to change the perspectives that undergraduates come to college with.*

*New curriculum and standards need to be explored to show science as a process of building theories and models using evidence. Evidence lies in Nature. This is an important idea though not very new. Science needs to include in the curriculum the topics that concern the human, its very existence, the global warming, changing seasons, the raising levels of sea, depleting of fossil fuels and increasing demand of power, growing population, the factors that govern the sovereignty of the nation, threatening acts of terrorism and the mounting expenditure on defense. We should expand our instruction here to include observational methods, historical analysis and other "non-experimental methods."*

*IANCAS compliments the authors for their expertise in bringing the life sketch of those great people whose intriguing investigations shaped history and this bulletin is expected to ignite the young minds in a genuine pursuit of science.*

**G.A. Rama Rao**

# The Discovery of Atomic Nucleus

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*Sir E. Rutherford*

"It is well known that the  and the  particles suffer deflexions from their rectilinear paths by encounters with atoms of matter. This scattering is far more marked for the  than for the  particle on account of the much smaller momentum and energy of the former particle. There seems to be no doubt that such swiftly moving particles pass through the atoms in their path, and that the deflexions observed are due to the strong electric field traversed within the atomic system. It has generally been supposed that the scattering of a pencil of  or  rays in passing through a thin plate of matter is the result of a multitude of small scatterings by the atoms of matter traversed. The observations, however, of Geiger and Marsden[1] on the scattering of  rays indicate that some of the  particles, about 1 in 20,000 were turned through an average angle of 90 degrees in passing though a layer of gold-foil about 0.00004 cm. thick, which was equivalent in stopping-power of the  particle to 1.6 millimetres of air. Geiger [2] showed later that the most probable angle of deflexion for a pencil of  particles being deflected through 90 degrees is vanishingly small. In addition, it will be seen later that the distribution of the  particles for various angles of large deflexion does not follow the probability law to be expected if such large deflexion are made up of a large number of small deviations. It seems reasonable to suppose that the deflexion through a large angle is due to a single atomic encounter, for the chance of a second encounter of a kind to produce a large deflexion must in most cases be exceedingly small. A simple

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*calculation shows that the atom must be a seat of an intense electric field in order to produce such a large deflexion at a single encounter."*

This is the first paragraph of the epoch making 1911 paper [3] of Sir E. Rutherford in the journal "Philosophical Magazine". The last line of the excerpt heralded the existence of the atomic nucleus which was hitherto unknown. Rutherford later described the unexpected nature of this alpha scattering result in his lectures on the "Background to Modern Science" (1936) as: *"It was about as credible as if you had fired a 15-inch shell at a piece of tissue paper and it came back and hit you."*

Understanding the origin of the diversity of material world was the subject of great interest to human being since the early days of his existence. Dalton was the first person who attempted to stitch the information then available into his atomic theory. He conjectured that elements are made up of smallest, indivisible, discrete particles called atom which combine in simple ratio to form compounds. Mendaleef (1863) was the first chemist to bring about an order in the seemingly chaotic chemical properties of elements by putting them into periodic table showing that properties of elements repeat in a definite manner. The periodicity of chemical properties was associated with the atomic weight of elements. Discovery of electrons by Sir J.J. Thomson (1897) and protons in positive rays showed the existence of subatomic particles, but the exact composition and structure of atom was not known.

Discovery of radioactivity by Becquerel (1896) was not only a significant step towards understanding the behavior of atoms of heavy elements, but also a great boon for the study of the structure of atom since radioelements were the source of swift charged particles viz. alpha particle ($He^{++}$) and beta particle ($e^-$). Scattering of and particles by thin metallic foils were immediately undertaken to study the distribution of positive and negative charges within the atoms whose dimension was known to be of the order of $10^{-8}$ cm. The first line of the Rutherford's paper shows that the deflection of and particles by encounter with the atoms of matter was known well before the time of Rutherford's paper. In fact, based on these results,
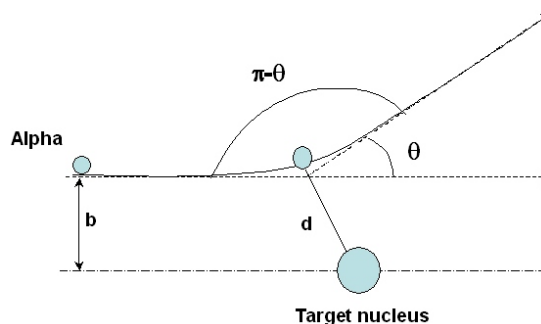


*Fig. 1   Picture of Rutherford scattering of an alpha particle by a target nucleus.*

Sir J.J. Thompson gave a picture of atom [4] as made up of N negatively charged electrons, and an equal quantity of +ve electricity uniformly distributed throughout a sphere. He explained the deflections as resulting from multiple scattering with atoms of the target element, each encounter with an atom producing a small deflection. The values of N for different elements were known. The observation of Geiger and Marsden [1] that 1 in about 20000 ά particles deflected through an angle of about $90^o$ in passing through a thin gold foil did not escape the attention of Sir E. Rutherford. He picked up the cue from here and went on to conjecture that the large deflections are due to a single encounter with a gold atom and the atom must be a seat of intense electric field in order to produce such a large deflection in single encounter. So he started with the assumption:

*"Consider an atom which contains a charge ±Ne at its centre surrounded by a sphere of electrification containing a charge -$^+$Ne supposed uniformly distributed throughout a sphere of radius R. e is the fundamental unit of charge, which in this paper is taken as 4.65 x $10^{-10}$ esu. We shall suppose that for distances less than $10^{-12}$ cm. the central charge and also the charge on the alpha particle may be supposed to be concentrated at a point. It will be shown that the main deductions from the theory are independent of whether the central charge is supposed to be positive or negative. For convenience, the sign will be assumed to be positive. The question of the stability of the atom proposed need not be considered at this stage, for this will obviously depend upon the minute structure of the atom, and on the motion of the constituent charged parts."*

These lines contain the essence of what is called "The Nuclear model of the Atom." The term "Nucleus" was coined by Rutherford in 1912.

The geometric picture of the alpha particle scattering by a nucleus is shown in the figure. The alpha particle having charge ze approaches the stationary target nucleus, considered to be a point charge Ze, at a lateral distance 'b'. As it approaches the target, it experiences a repulsive Coulomb potential due to nuclear charge and deviates from its rectilinear path and follow a hyperbolic orbit. Let 'd' be the closest distance of approach between the alpha particle and the nucleus. Let be the scattering angle, and ( - ) is the angle between the asymptotes of the hyperbola. Let v and $v_0$ be the initial velocity and the velocity at the closest distance of approach of the alpha particle. From the conservation of energy, one can write at the closest distance of approach,

$$\frac{1}{2}mv^2 = \frac{1}{2}mv_0^2 + \frac{1}{4\pi\epsilon_0}\frac{zZe^2}{d} \tag{1}$$

Dividing the left and right hand side by $\frac{1}{2}mv^2$ and rearranging,

$$\frac{v_0}{v} = 1 - \frac{d}{d_0} \tag{2}$$

Where $d_0$ is given by

$$d_0 = \frac{zZe^2}{4\pi\epsilon_0 E} \tag{3}$$

Where E is the initial kinetic energy of the alpha particle. Clearly $d_0$ is the closest distance of approach when $v_0$ is zero i.e. the distance between the alpha particle and the nucleus at head on collision so that the repulsive coulomb potential just counterbalances the kinetic energy of the particle. For such a collision trajectory, the value of 'b' will be zero. For higher values of b, there will be an angular momentum due to relative motion of the target and the projectile which will take away part of the kinetic energy of the projectile. As a result, lower coulomb potential is required to counterbalance the residual kinetic energy, so the closest distance of approach 'd' will increase and the deflection of the projectile from its path will decrease resulting in lower scattering angle. The relationship between 'b', 'd' and the scattering angle was derived as follows.

Angular momentum conservation gives,

$$mvb = mv_0 d \tag{4}$$

$$b = \frac{v_0}{v} d \tag{5}$$

$$b^2 = \left(\frac{v_0}{v}\right)^2 d^2 \tag{6}$$

Using equation 1,

$$b^2 = \left(1 - \frac{d}{d_0}\right)^2 d^2 \tag{7}$$

$$= d(d - d_0) \tag{8}$$

It can be shown that for a hyperbolic orbit

$$d = b \cot\frac{\theta}{2} \tag{9}$$

Eliminating d from equation 8 and 9 and substituting for ,

$$\cot\frac{\theta}{2} = \frac{2b}{d_0}$$

This equation gives the relation between scattering angle and 'b' called impact parameter of the collision. This shows that decreases as impact parameter for the collision increases. For head on collision, b=0 and = and alpha particle turn back. The following table from Rutherford's paper gives the values of for different values of ($b/d_0$):

| $b/d_0$ | |
|---------|------|
| 10 | 5.7 |
| 5 | 11.4 |
| 2 | 28 |
| 1 | 53 |
| 0.5 | 90 |
| 0.25 | 127 |
| 0.125 | 152 |

Having established a relation between the extent of deflection of alpha particle with closeness of collision, the next step was to derive the probability of single deflection through a given angle or angular distribution of the alpha particle. Referring to Fig. 1, it is seen that all the alpha particles that approach the nucleus within a annular region defined by circle of radius b and b+db will be scattered (due to coulomb force exerted by the target) through a conical region defined by the cones having half angle and +d . The probability of scattering per unit solid angle (differential scattering cross section) was classically known to be related to the scattering angle and the impact parameter of the collision by the formula:

$$\frac{d}{d} \quad \frac{1}{\sin} \frac{db}{d} \qquad (11)$$

Differentiating equation 4, Rutherford obtained the right hand side of equation 5:

$$\frac{d}{d} \quad \frac{d_0}{4}^2 \frac{1}{\sin^4 \frac{}{2}} \qquad (12)$$

Putting the value of $d_0$ from equation 2, one obtains the classical Rutherford scattering formula:

$$\frac{d}{d} \quad \frac{zZe^2}{16 \ _0 E}^2 \frac{1}{\sin^4 \frac{}{2}} \qquad (13)$$

Regarding the correctness of this formula, Rutherford concluded in his paper, *"The angular distribution of the particles scattered from a thin metal sheet affords one of the simplest methods of testing the general correctness of this theory of single scattering. This has been done recently for rays by Dr. Geiger, [2] who found that the distribution for particles deflected between 30° and 150° from a thin gold-foil was in substantial agreement with the theory."* In order to fit this formula to result of Geiger and Marsden, the charge of the gold nucleus (Ze, Ne in original paper) was assumed to be 100e which is quite closer to the actual charge of 79e.

Other than the alpha scattering experiment on gold, Geiger and Marsden also determined the relative number of alpha particles (z) diffusely reflected from thick layers of different metals, under similar conditions. The following Table, taken from the original paper of Rutherford, summarizes the results.

| Metal | Atomic weight (A) | z | $z/A^{3/2}$ |
|---|---|---|---|
| Lead | 207 | 62 | 208 |
| Gold | 197 | 67 | 242 |
| Platinum | 195 | 63 | 232 |
| Tin | 119 | 34 | 226 |
| Silver | 108 | 27 | 241 |
| Copper | 64 | 14.5 | 225 |
| Iron | 56 | 10.2 | 250 |
| Aluminium | 27 | 3.4 | 243 |
| | | | Average 233 |

Assuming that the central charge is proportional to atomic weight, the third column shows increase in back scattering of alpha particles with atomic weight, as expected from equation 13. These experiments were done with thick target. Bragg from his experiments on stopping power of alpha particles by different target elements showed that the stopping power of an atom for an alpha particle is proportional to the square root of its atomic weight. Equation 13 shows that the scattering at any given angle will increase with the square of the atomic number Z of the scattering element for a given energy E of the alpha particle. Assuming the proportionality between Z and atomic weight, the backscattering probability will be proportional to square of A. Thus taking into consideration of target thickness and the density of different elements, back scattering probability from a thick target element is expected to be proportional to $A^{3/2}$. Thus $z/A^{3/2}$ should be constant and the fourth column of the table shows fair agreement between theory and experiment showing the correctness of the Rutherford scattering formula.

Rutherford also proved that the data on scattering of rays of different velocities by various

metals by Crowther [5] was also consistent with his theory, thereby negating the theory of compound scattering by Sir J.J. Thomson and firmly established the concept of atomic nucleus. However the exact values of the charge of the atomic nucleus or atomic number of the elements were very soon obtained from Mosley's experiment (1913) [6] on the X-ray spectra of the elements. Rutherford was a collaborator of this work.. Based on Rutherford and Mosley's work, Bohr gave the quantum theory of hydrogen atom.

Finally at closest distance of approach in head on collision, taking the charge of alpha particle as 2, one can write:

$$E = \frac{1}{4\pi\epsilon_0} \frac{2Ze^2}{R} \qquad (14)$$

In the original alpha scattering experiment, 7.7 MeV ($1.2 \times 10^{-12}$ J) alpha particles from $^{210}$Po were used. Taking the value of Z=79 for gold and putting value of $1/4\pi\epsilon_0$ as $9.0 \times 10^9$ Nm$^2$/C$^2$ and C=$1.9 \times 10^{-19}$ Coulomb, the value of R can be calculated using equation 14 which turns out to be $30 \times 10^{-15}$ m. Nuclear dimension is thus expressed in unit of $10^{-15}$ m and called Fermi(F). The value of 30F is much higher than the actual value of about 7F because the experiment was done at alpha particle energy much below the Coulomb barrier at which the colliding nuclei actually touch each other. This requires alpha particle energy of about 25 MeV for gold which is easily obtained in a modern day charged particle accelerator. In fact, the Rutherford scattering formula is accurate and commonly used in accelerator experiments to normalize the flux of the beam falling on the target. Deviation of scattering from Rutherford's value is also used to obtain information of nuclear reaction radius.

**Biography (7)**

Ernest Rutherford was born on August 30, 1871, in Nelson, New Zealand. He received his early education in Government schools and at the age of 16 entered Nelson Collegiate School. He graduated in 1893 with a double first in Mathematics and Physical Science from Canterbury College, University of New Zealand, Wellington. In 1894, he joined Trinity College, Cambridge, as a research student at the Cavendish Laboratory under J.J Thomson who immediately recognised his talent.

In 1907 he become Langworthy Professor of Physics in the University of Manchester. A distinguished list of his collaboratos at Manchester is : Frederick Soddy, Otto Hahn, H. G. Moseley, G. de Hevesy, H. Geiger, E. Marsden and N. Bohr. In 1919 he succeeded Sir Joseph Thomson as Cavendish Professor of Physics at Cambridge. At Cavendish Laboratory, he inspired many future Nobel Prize winners: Chadwick, Blackett, Cockcroft and Walton. Other laureates who worked with him at the Cavendish are: G.P. Thomson, Appleton, Powel and Aston. He remained active and working to the very end of his life.

Rutherford was awarded the 1908 Nobel Prize for chemistry for his work with radioactive substances, and his study of the disintegration of elements. The topic of his noble lecture was: "The Chemical Nature of the Alpha Particles from Radioactive Substances." His research career encompassed both physics and chemistry, including research into magnetism, radioactivity, and inert gases; he discovered thoron, an isotope of radon, and also discovered the existance of atomic nucleus, his greatest contribution to physics. Rutherford was the first to transmute one element into another.

Rutherford was knighted in 1914; he was appointed to the Order of Merit in 1925, and in 1931 he was created First Baron Rutherford of Nelson, New Zealand, and Cambridge. He was elected Fellow of the Royal Society in 1903 and was its President from 1925 to 1930. Rutherford married Mary Newton, only daughter of Arthur and Mary de Renzy Newton, in 1900. Their only child, Eileen, married the physicist R.H. Fowler. Rutherford's chief recreations were golf and motoring. He died in Cambridge on October 19, 1937.

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# Marie and Pierre Curies and their Polonium and Radium

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*Lives of great men all remind us We can make our lives sublime,*
*And, departing, leave behind us Footprints on the sands of time.*
*Let us, then, be up and doing With a heart for any fate.*
*Still achieving, still pursuing Learn to labor and to wait.*
**From A Psalm of Life by H.W. Longfellow**

## Introduction

*Obedient daughter*
*Affectionate sister*
*Beloved wife*
*endearing soulmate*
*doting mother*
*accomplished scientist*
*and above all*
*perfect human being*

*Maria Sklodowska-Curie*
*(1867 - 1934)*

Prof. Glenn Seaborg, in his foreword to the third edition of the book "Source Book of Atomic Energy" by Dr. Samuel Glasstone observed: "When nuclear energy emerged suddenly from the shrouds of secrecy there was an overwhelming need for explanation and clarification before this new force could assume its role as a useful servant of man. How fortunate we were that a man of Samuel Glasstone's supreme attainments chose at that time to devote his career to filling this need!" These words are equally applicable to Marie Curie. When during the last decade of 19th and the first decade of 20th centuries, Mother Nature was willing to reveal Her secrets for the birth of a new scientific thought, there came on the scene Her illustrious progeny who rose to the challenge, dared to think differently and through their profound discoveries, firmly laid the foundations of a new science called Radiochemistry. That illustrious progeny include Roentgen, Becquerel, Pierre and Marie Curie and Rutherford.

Roentgen had discovered X rays, a momentous event that instantly revolutionized the field of physics and medicine. He was the first recipient of Nobel Prize for Physics.

Becquerel demonstrated that the radiation emitted by uranium shared certain characteristics with X-rays but, unlike X-rays, could be deflected by a magnetic field and therefore must consist of charged particles. Marie and Pierre Curies investigated extensively the phenomenon of radioactivity, which was discovered by Henri Becquerel. It was Marie who coined the term radioactivity. They rightly pointed that radioactivity is an "atomic phenomenon" and radioactivity offers one of the most sensitive measurements for detection

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of unstable nuclides. Becquerel and the Curies were awarded the 1903 Nobel Prize for physics.

After chemical extraction of uranium from the ore, Marie noted the residual material to be more "active" than the pure uranium. She concluded that the ore contained, in addition to uranium, new elements that were also radioactive. This led to the discoveries of the elements polonium and radium. But it took four more years of processing tons of ore under oppressive conditions to isolate enough of each element to determine its chemical properties, which resulted in Marie Curie receiving her second Nobel Prize in 1911 this time for Chemistry.

Rutherford's investigations into the disintegration of the elements, and the chemistry of radioactive substances are seminal. Particles named and characterized by him include the alpha particle, beta particle and proton. Rutherford received Nobel Prize for Chemistry in 1908. These are the four cornerstones on which the edifice of Radiochemistry is firmly anchored. Marie Curie opened up the science of radioactivity. She is best known as the discoverer of the radioactive elements polonium and radium and as the first person to win two Nobel prizes. For scientists and the public, her radium was a key to a basic change in our understanding of matter and energy. Her work not only influenced the development of fundamental science but also ushered in a new era in medical research and treatment. The story of the Curies' search is one of the most interesting and inspiring in all the history of science. Perseverance, dedication, and intelligence finally brought success and accolades.

**Marie Curie and her quest for Science**

It is very difficult and not justifiable also, to exclude the events in the life of Marie the person and of Marie a diligent student wanting to pursue career in Science. Marie finished first in her master's degree physics course in the summer of 1893 and second in maths the following year. Before completing the maths degree she was also commissioned by the Society for the Encouragement of National Industry to do a study, relating magnetic properties of different steels to their chemical composition. She needed to find a lab where she could do the work. The search for lab space led to a fateful introduction of Marie to Pierre Curie. Pierre

was also a pioneer in the study of magnetism. He discovered a basic relationship between magnetic properties and temperature. The temperature at which certain magnetic materials undergo a marked change in their magnetic properties is today called the Curie point after Pierre. He also invented a highly sensitive scientific balance, similarly named in his honor, and likewise extremely useful in Marie's later work. The meeting between Curie and Marie Sklodowska would change not only their individual lives but also the course of science. In a simple civil ceremony in July 1895, they became husband and wife. Instead of a bridal gown Marie wore a dark blue outfit, which for years after was a serviceable lab garment.

**Becquerel and Marie Curie's Doctorate Work**

She had chosen in 1897 to study what were then known as Becquerel rays for her doctoral thesis. In early 1896, only a few months after Roentgen's discovery, Henri Becquerel reported to the French Academy of Sciences that uranium compounds, even if they were kept in the dark, emitted rays that would fog a photographic plate. Despite Becquerel's intriguing finding, the scientific community did not pay much attention to weaker Becquerel rays or uranium rays. The ignored uranium rays appealed to Marie Curie. Since she would not have a long bibliography of published papers to read, she could begin experimental work on them immediately. The director of the Paris Municipal School of Industrial Physics and Chemistry, where Pierre was professor of physics, permitted her to use a crowded, damp storeroom there as a lab.

In 1897 Maria started her own investigations with Becquerel as her supervisor, on the new uranium ''radiations'' with her first task being the development of an accurate method of measurement which would enable the uranium radiations to be studied at length. She used a quadrant electrometer, piezoelectric quartz, and a flat condenser as an ionization chamber; the powdered substances being in the form of a thin layer on a metallic substrate placed inside the ionization chamber on one of its flat electrodes. This piezoelectrmeter was earlier invented by Pierre Curie along with his brother Jacques. The null method of measurement was used in which the saturated current in the ionization chamber was compensated for by the current

appearing in the piezoelectric quartz crystal. She confirmed Becquerel's observations that the radiation of uranium was very constant, varying neither with the temperature nor with the illumination. Moreover, all the compounds of uranium were active and the activity was in direct proportion to their uranium mass fraction. She went beyond Becquerel's work, however, in forming a crucial hypothesis: *the emission of rays by uranium compounds could be an atomic property of the element uranium independent of its chemical or physical state --something built into the very structure of its atoms.*

How the Curies went about their investigations has been beautifully presented by Marie herself:

*"First of all, I studied the radiation of the compounds of uranium. Instead of making these bodies act upon photographic plates, I preferred to determine the intensity of their radiation by measuring the conductivity of the air exposed to the action of the rays. To make this measurement, one can determine the speed with which the rays discharge an electroscope, and thus obtain data for a comparison. I found in this way that the radiation of uranium is very constant, varying neither with the temperature nor with the illumination. I likewise observed that all the compounds of uranium are active, and that they are more active the greater the proportion of this metal which they contain. Thus I reached the conviction that the emission of rays by the compounds of uranium is a property of the metal itself that it is an atomic property of the element uranium independent of its chemical or physical state. I then began to investigate the different known chemical elements, to determine whether there exist others, besides uranium, that are endowed with atomic radioactivity that is to say, all the compounds of which emit Becquerel rays.*

*It was easy for me to procure samples of all the ordinary substances the common metals and metalloids, oxides and salts. But as I desired to make a very thorough investigation, I had recourse to different chemists, who put at my disposal specimens in some cases the only ones in existence containing very rare elements. I thus was enabled to pass in review all the chemical elements and to examine them in the state of one or more of their compounds. I found but one element undoubtedly possessing*

*atomic radioactivity in measurable degree. This element is thorium. All the compounds of thorium are radioactive, and with about the same intensity as the similar compounds of uranium. As to the other substances, they showed no appreciable radioactivity under the conditions of the test.*

*I likewise measured the activity of a number of minerals; all of them that appear to be radioactive always contain uranium or thorium. But an unexpected fact was noted: certain minerals (pitchblende, chalcolite, autunite) had a greater activity than might be expected on the basis of their uranium or thorium content. Thus, certain pitchblendes containing 75% of uranium oxide are about four times as radioactive as this oxide. Chalcolite (crystallized phosphate of copper and uranium) is about twice as radioactive as uranium. This conflicted with views which held that no mineral should be more radioactive than metallic uranium. To explain this point I prepared synthetic chalcolite from pure products, and obtained crystals, whose activity was completely consistent with their uranium content; this activity is about half that of uranium.*

*This observation astonished me greatly. What explanation could there be for it? How could an ore, containing many substances which I had proved inactive, be more active than the active substances of which it was formed? The answer came to me immediately: The ore must contain a substance more radioactive than uranium and thorium, and this substance must necessarily be a chemical element as yet unknown; moreover, it can exist in the pitchblende only in small quantities, else it would not have escaped the many analyses of this ore; but, on the other hand, it must possess intense radioactivity, since, although present in small amount, it produces such remarkable effects. I tried to verify my hypothesis by treating pitchblende by the ordinary processes of chemical analysis, thinking it probable that the new substance would be concentrated in passing through certain stages of the process. I performed several experiments of this nature, and found that the ore could in fact be separated into portions some of which were much more radioactive than others.*

*To try to isolate the supposed new element was a great temptation. I did not know whether this*

*undertaking would be difficult. Of the new element I knew nothing except that it was radioactive. What were its chemical properties? In what quantity did it appear in pitchblende? I began the analysis of pitchblende by separating it into its constituent elements, which are very numerous. This task I undertook in conjunction with P. Curie. We expected that perhaps a few weeks would suffice to solve the problem. We did not suspect that we had begun a work which was to occupy years and which was brought to a successful issue only after considerable expenditure.*

*We readily proved that pitchblende contains very radioactive substances, and that there were at least three. That which accompanies the bismuth extracted from pitchblende we named Polonium; that which accompanies barium from the same source we named Radium; finally, M. Debierne gave the name of Actinium to a substance which is found in the rare earths obtained from the same ore.*

*Radium was to us from the beginning of our work a source of much satisfaction. Demarçay, who examined the spectrum of our radioactive barium, found in it new rays and confirmed us in our belief that we had indeed discovered a new element."*

(Radium and Radioactivity, Mme. Sklodowska Curie, Discoverer of Radium from Century Magazine (January 1904), pp. 461-466 and Marie Curie Nobel Lecture 1911).

Following Table gives the extent of ionization caused when different uranium containing materials were investigated by Marie Curie:

| Material | picoamps |
|---|---|
| Uranium | 24 |
| Black oxide of uranium | 27 |
| Hydrated uranic acid | 6 |
| Pitchblende from Johanngeorgenstadt | 83 |
| Pitchblende from Joachimstahl and from Pzibran | 67 |
| Natural chacolite | 52 |
| Artificial chacolite | 52 |

Marie's simple hypothesis of radioactivity being atomic property would prove revolutionary. It would ultimately contribute to a fundamental shift in scientific understanding. At the time scientists regarded the atom--a word meaning undivided or indivisible -- as the most elementary particle. Marie and Pierre Curie themselves were not convinced that radioactive energy came from within atoms. But her real achievement was to cut through the complicated and obscure observations with a crystal-clear analysis of the set of conclusions that, however unexpected, were logically possible.

**First Paper on the discovery of elements**

The paper announcing the discovery of radium was presented at the French Academy of Sciences in December 1898 by Henri Becquerel on behalf of Maria, Pierre, and their colleague G. Bemont. (P. Curie, M. Curie, and G. Bemont, ''Sur une nouvelle substance fortement radioactive, contenue dans la pechblende,'' C. R. Se´ances Acad. Sci. Paris 127, 1215–1217 (1898)). A few translated excerpts are:

*"Two of us have shown that by purely chemical procedures it is possible to extract from pitchblende a strongly radioactive substance. This substance is related to bismuth by its analytical properties. We have expressed the opinion that perhaps the pitchblende contained a new element, for which we have proposed the name of polonium.*

*The investigations which we are following at present are in agreement with the first results we obtained, but in the course of these investigations we have come upon a second, strongly radioactive substance, entirely different from the first in its chemical properties. Specifically, polonium is precipitated from acid solution by hydrogen sulfide; its salts are soluble in acids and water precipitates them from solution; polonium is completely precipitated by ammonia.*

*The new radioactive substance which we have just found has all the chemical appearance of nearly pure barium: it is not precipitated either by hydrogen sulfide or by ammonium sulfide, nor by ammonia; its sulfate is insoluble in water and in acids; its carbonate is insoluble in water; its chloride, very soluble in water, is insoluble in concentrated hydrochloric acid and in alcohol.*

*Finally this substance gives the easily recognized spectrum of barium.*

*We believe nevertheless that this substance, although constituted in its major part by barium, contains in addition a new element which gives it its radio-activity, and which, in addition, is closely related to barium in its chemical properties.*

*Here are the reasons which argue for this point of view:*

1. *Barium and its compounds are not ordinarily radioactive; and one of us has shown that radio-activity appears to be an atomic property, persisting in all the chemical and physical states of the material.*

2. *From this point of view, the radio-activity of our substance, not being due to barium, must be attributed to another element.*

3. *The first substances which we obtained had, in the form of a hydrated chloride, a radioactivity 60 times stronger than that of metallic uranium (the radioactive intensity being evaluated by the magnitude of the conductivity of the air in our parallel-plate apparatus). When these chlorides are dissolved in water and partially precipitated by alcohol, the part precipitated is much more active than the part remaining in solution. Basing a procedure on this, one can carry out a series of fractionations, making it possible to obtain chlorides which are more and more active. We have obtained in this manner chlorides having an activity 900 times greater than that of uranium. We have been stopped by lack of material; and, considering the progress of our operations it is to be predicted that the activity would still have increased if we had been able to continue. These facts can be explained by the presence of a radioactive element whose chloride would be less soluble in alcohol and water than that of barium.*

4. *M. Demarçay has consented to examine the spectrum of our substance with a kindness which we cannot acknowledge too much. The results of his examinations are given in a special Note at the end of ours. Demarçay has found one line in the spectrum which does not seem due to any known element. This line, hardly visible with the chloride 60 times more active than uranium, has become prominent with the chloride enriched by fractionation to an activity 900 times that of uranium. The intensity of this line increases, then, at the same time as the radioactivity; that, we think, is a very serious reason for attributing it to the radioactive part of our substance".*

The Curies had been told that their paper would not be accepted unless spectrometry confirmed the existence of this new element radium. Eugene Demarçay carried the spectrum analysis and his presentation ended with the conclusion; ''La pre´sence de la raie 3814,8 confirme l'existence, en petite quantite´, d'un nouvelle e´le´ment dans le chlorurede baryum de M. et Mme Curie.'' (E. Demarçay, ''Sur le spectre d'une substance radioactive,'' C. R. Se´- ances Acad. Sci. Paris 127, 1218 (1898.)) It is interesting to mention that the spectroscopy evidence of existence of radium could also be obtained even in 1997 on the contamination on some of Pierre's apparatus which is still retained in a display cabinet in the Physics Department at the Ecole Supe´rieure de Physique et de Chimie Industrielles.

**Magnificent Opus in Science**

In order to be certain of showing that it was a matter of new elements, the Curies would have to produce them in demonstrable amounts, determine their atomic weight and preferably isolate them. After their discovery of polonium and radium, the Curies decided on a division of labor: he concentrated on investigating the properties of radium, while she did chemical experiments with a view to preparing pure compounds. So it was Pierre (with a student) who noticed that a speck of radium spontaneously and perpetually emits heat--discovering what is now called nuclear energy. He was also, with collaborators, the first to report the decay of radioactive materials and the skin burns that radioactive substances can inflict.

Marie Curie's initial work was done with a 100-gram sample of pitchblende, which was soon exhausted. Pierre wrote to colleagues and mineral dealers in Europe, Britain and the U.S. in search of additional materials, and 500 grams of pitchblende

were provided without charge by the U.S. Geological Survey. The initial investigations had suggested, however, that the quantity of ore needed to isolate enough pure radium salts for study would be tons rather than grams. What followed was a saga of human tenacity, dogged detetmination, indomitable, uncompromising, pure and unadultrated scientific endeavour. There began the heroic epoch in their life that has become legendary. Through contacts with Eduard Seuss of the University of Vienna they obtained small samples of the St. Joachimsthal pitchblende ore and learned of the waste-dump residue. Through Seuss's intervention they were given 100 kilograms of the residue by the Austrian Government. Between 1898 and 1902 they bought with their own money about 11 metric tons of the residue for little more than the cost of transport. The shed became the first radium factory, with Marie the director and labor force all rolled into one person.

In Marie's extraction process radium was repeatedly converted from one salt into another in order to separate it from other components of the material. At St. Joachimsthal the ore had been treated with sodium carbonate and sulphuric acid to extract uranium, leaving the carbonate and sulphate salts of radium in the insoluble residues obtained by the Curies. The sulphates were transformed into carbonates by treating the residues with boiling sodium carbonate, and the carbonates were then transformed into soluble chlorides by treatment with hydrochloric acid. The solution was filtered to remove extraneous materials, then sulphuric acid was added, converting the radium into its sulphate form again, which precipitated. With the St. Joachimsthal residue one ton of ore yielded between 10 and 20 kilograms of the crude sulphates of radium, barium and calcium, which were from 30 to 60 times as radioactive as metallic uranium. Physically it was heavy work for Marie. She processed 20 kilos of raw material at a time. First of all she had to clear away pine needles and any perceptible debris, then she had to undertake the work of separation.

The crude sulphates were purified by a similar series of steps designed largely to remove calcium. The yield was about 8 kilograms of mixed barium and radium chlorides per ton of ore. It then remained to extract the small quantity of radium chloride in the solution from the much larger amount of barium chloride, The method called fractional crystallization, was again based on a difference in the solubility of the two salts. The solution in which the chlorides were dissolved was allowed to evaporate partially, so that crystals formed. Because barium chloride is more soluble than radium chloride the radium salt precipitated earlier, and so the crystals were richer in radium than the solution from which they formed. The crystals were then redissolved and the process was repeated, bringing a further enrichment. After a number of fractional crystallizations the least soluble was retained; the crystals were nearly pure radium chloride.

*"Yet it was in this miserable old shed that we passed the best and happiest years of our life, devoting our entire days to our work. Often I had to prepare our lunch in the shed, so as not to interrupt some particularly important operation. Sometimes I had to spend a whole day mixing a boiling mass with a heavy iron rod nearly as large as myself. I would be broken with fatigue at the day's end.*

*Other days, on the contrary, the work would be a most minute and delicate fractional crystallization, in the effort to concentrate the radium. I was then annoyed by the floating dust of iron and coal from which I could not protect my precious products. But I shall never be able to express the joy of the untroubled quietness of this atmosphere of research and the excitement of actual progress with the confident hope of still better results. The feeling of discouragement that sometimes came after some unsuccessful toil did not last long and gave way to renewed activity. We had happy moments devoted to a quiet discussion of our work, walking around our shed.*

One of our joys was to go into our workroom at night; we then perceived on all sides the feebly luminous silhouettes of the bottles or capsules containing our products. It was really a lovely sight and one always new to us. The glowing tubes looked like faint, fairy lights."

*--from Autobiographical Notes pp. 186-187.*

**Fruits of Labour**

It took Marie nearly four years to reduce eight tons of the St. Joachimsthal residue to crude sulphates. The reaction vessel was a hand-stirred iron cauldron, and the ventilation of the irritating smoke and fumes was provided solely by the winds of Paris. The purification and fractional crystallization stage was then begun. The atomic mass of radium was determined in the spring of 1902 from the first decigram of the element concentrated. *"I determined the atomic weight of this new element, finding it to be 225, while that of barium is 137"* (Mme. Curie, *Century Magazine*, 461 (1904)). She presented the findings of this work in her doctoral thesis on June 25, 1903. Of the three members of the examination committee, two were to receive the Nobel Prize a few years later: Prof. Gabriel Lippmann, her former teacher, in 1908 for physics for his method of reproducing colours photographically based on the phenomena of interference, and Prof. Henri Moissan, in 1906 for chemistry in recongnision of the great services rendered by him in his investigations and isolation of the element fluorine, and for adoption in the service of science of the electric furnace called after him. The committee expressed the opinion that the findings represented the greatest scientific contribution ever made in a doctoral thesis.

As more radium was isolated- Marie Curie's toil with the eight tons of residue would ultimately yield one gram of radium-its remarkable properties become evident. Radium was found to be luminous and produced phosphorescence in diamonds exposed to its rays. The rays also disintegrated paper and cotton fibres, caused skin burns and could destroy certain forms of cancerous growth.

The Curies were close to reaching one of the highest goals that a scientist of the time could hope to achieve--placing new elements in the Periodic Table. The series of experiments and observations by the Curies has been elegantly enunciated by Pierre Curie in his Nobel Lecture in 1905. (The Curies received the Nobel Prize for Physics in 1903 along with Becquerel but Pierre delivered his Nobel lecture in 1905).

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*The Nobel Prize in Physics 1903*

***Antoine Henri Becquerel, France, ½ of the prize:*** *"in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity"*

***Pierre Curie and Marie Curie, née Sklodowska, France, ¼ of the prize each:*** *"in recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel"*

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**Different Properties Exhibited by Radium**

*The properties of radium are extremely curious. This body emits with great intensity all of the different rays that are produced in a vacuum-tube. The radiation, measured by means of an electroscope, is at least a million times more powerful than that from an equal quantity of uranium. A charged electroscope placed at a distance of several meters can be discharged by a few centigrams of a radium salt. One can also discharge an electroscope through a screen of glass or lead five or six centimeters thick. Photographic plates placed in the vicinity of radium are also instantly affected if no screen intercepts the rays; with screens, the action is slower, but it still takes place through very thick ones if the exposure is sufficiently long. Radium can therefore be used in the production of radiographs.*

*The compounds of radium are spontaneously luminous. The chloride and bromide, freshly prepared and free from water, emit a light which resembles that of a glow-worm. This light diminishes rapidly in moist air; if the salt is in a sealed tube, it diminishes slowly by reason of the transformation of the white salt, which becomes colored, but the light never completely disappears. By redissolving the salt and drying it anew, its original luminosity is restored.*

*A glass vessel containing radium spontaneously charges itself with electricity. If the glass has a weak spot, for example, if it is scratched by a file, an electric spark is produced at that point, the vessel crumbles like a Leiden jar when overcharged, and the electric shock of the rupture is felt by the fingers holding the glass.*

*Radium possesses the remarkable property of liberating heat spontaneously and continuously. A solid salt of radium develops a quantity of heat such that for each gram of radium contained in the salt there is an emission of one hundred calories per hour. Expressed differently, radium can melt in an hour its weight in ice. When we reflect that radium acts in this manner continuously, we are amazed at the amount of heat produced, for it can be explained by no known chemical reaction. The radium remains apparently unchanged. If, then, we assume that it undergoes a transformation, we must therefore conclude that the change is extremely slow; in an hour it is impossible to detect a change by any known methods.*

(Radium and Radioactivity, Mme. Sklodowska Curie, Discoverer of Radium from Century Magazine (January 1904), pp. 461-466)

Pierre Curie in his Nobel lecture referred also to the following additional properties of radium:

*"Excitation of the phosphorescence of barium platinocyanide, willemite and kunzite. - Coloration of glass by the rays. - Thermoluminescence of fluorine and ultramarine after the action of radiation from radium on these substances. -Radiographs obtained with radium."*

**Predictions for the New Science**

The consequences of the experiments and the results obtained spurred the Curies to boldly predict some of the new directions the new science would take: (i) The electromagnetic nature of high energy particles emitted from radioactive substances, (ii) colossal quantities of energy hidden in the unstable elements, (iii) transmutation of elements, (iv) radium and polonium are forming from uranium, and (v) applications to geochronology. All of them have been proved subsequently.

France was less forthcoming than other countries when it came to honoring the Curies' work. In early June 1903 both Curies were invited to London as guests of the prestigious Royal Institution. Since custom ruled out women lecturers, Pierre alone described their work in his "Friday Evening Discourse." He was careful, however, to describe Marie's crucial role in their collaboration. The audience included representatives of England's

social elite and such major scientists as Lord Kelvin. Kelvin showed his respect by sitting next to Marie at the lecture and by hosting a luncheon in Pierre's honor the following day.

**Final Proof**

Interestingly Lord Kelvin disputed the claims of the Curies in a letter he wrote to the editor of *The London Times* of August 9, 1906. Lord Kelvin advanced a theory that radium was no element but rather a compound of lead and five helium atoms. Since the theory threatened the entire science of radioactivity, Marie began lab work to disprove it -- and more generally to put her discovery on such a firm basis that nobody could doubt it. Enlisting the aid of her old colleague Andrè Debierne, she eventually confirmed that radium was indeed an element. It was an effort of years to measure the atomic weight of radium beyond question and thus firmly locate the element in the Periodic Table. The measurements left nothing in doubt.

But Marie Curie was not content with radium isolation alone. *"Although radium has so far only been obtained in very small amounts, it is nevertheless true to say, in conclusion, that it is a perfectly defined and already well-studied chemical element. Unfortunately, the same cannot be stated for polonium, for which nevertheless considerable effort has already been spent. The stumbling block here is the fact that the proportion of polonium in the mineral is about 5,000 times smaller than that of radium."* She says in her Nobel lecture in 1911. As the half life is also only 138 days, polonium was decying over the period it was being separated. Ultimately after treating several tons of residues from uranium mineral,she was able to isolate a few milligrams of polonium about 50 times more active than an equal weight of pure radium. In the spectrum of the substance some new lines could be observed which appear attributable to polonium and of which the most important has the wavelength 4170.5 Å.

And now she delivered a final and decisive conclusion to demolish Lord Kelvin's "flyer" statement.

"….one of the most brilliant triumphs of the theory is the prediction that the gas helium, always present in radioactive minerals, can represent one of

the end-products of the evolution of radium, and that it is in the form of alpha rays that the helium atoms which are formed when radium atoms distintegrate are discharged. Now, the production of helium by radium has been proved by the experiments of Ramsay and Soddy, and it cannot now be contested that the perfectly defined chemical element, radium, gives rise to the formation of another equally defined element - helium…….. I must remark here that the bold interpretation of the relationship existing between radium and helium rests entirely upon the certitude that radium has the same claim to be a chemical element as have all the other known elements, and that there can be no question of regarding it to be a molecular combination of helium with another element. This shows how fundamental in these circumstances has been the work carried out to prove the chemical individuality of radium, and it can also be seen in what way the hypothesis of the atomic nature of radioactivity and the theory of radioactive transformations have led to the experimental discovery of a first clearly-established example of atomic transmutation. This is a fact the significance of which cannot escape anyone, and one which incontestably marks an epoch from the point of view of chemists."

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***The Nobel Prize in Chemistry 1911***

***Marie Curie, née Sklodowska, France:*** *"in recognition of her services to the advancement of chemistry by the discovery of the elements radium and polonium, by the isolation of radium and the study of the nature and compounds of this remarkable element"*

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### Other significant observations of Marie Curie

1. Verification of Avogadro number: Mme. Curie very ingeniusly deduced that by collecting helium generated as a result of decay of polonium into a known volume and measuring its mass one can calculate Avogadro number. She found the Avgadro number calculated this way was in good agreement with other values.

2. Other radioactive nuclides: She also showed that potassium and rubidium emit a very feeble radiation, similar to the beta radiation of uranium and radium.

3. **New measurement technique:** Perhaps the most original outcome of Mme.Curie's invetigations is the elegant way by which one can monitor minute quantities of radioactive substances. *"Very often material has been handled in which the presence of radium could not be detected by the balance, nor even by the spectroscope. And yet we have methods of measuring so perfect and so sensitive that we are able to know very exactly the small quantities of radium we are using. Radioactive analysis by electrometric methods allows us to calculate to within 1% a thousandth of a milligram of radium, and to detect the presence of $10^{-10}$ grams of radium diluted in a few grams of material. This method is the only one which could have led to the discovery of radium in view of the dilution of this substance in the ore. The sensitivity of the methods is still more striking in the case of radium emanation, which can be detected when the quantity present amounts, for example, to only $10^{-10}$ $mm^3$…… This means that we have here an entirely separate kind of chemistry for which the current tool we use is the electrometer, not the balance, and which we might well call the chemistry of the imponderable."*

### Awards and Honors

Marie received numerous awards and honors: 15 gold medals, 19 honorary degrees and two Nobel Prizes (Physics 1903 and Chemistry 1911). More than 20 Nations released postage stamps honoring her and Pierre Curie. More than 70 stamps have been released. India also honored her in 1968 by releasing a postage stamp. France came out with a 500 Franc bank note with Marie Curie's picture. A movie titled Madame Curie was also made in 1943 on Marie



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Curie. She secured the right to define an international standard for radium emissions. Such a standard was essential for an efficient radium industry and uniform medical applications. The measure she established was accepted by the international scientific community, which named it the Curie. She also received, jointly with her husband, the Davy Medal of the Royal Society in 1903 and, in 1921, President Harding of the United States, on behalf of the women of America, presented her with one gram of radium in recognition of her service to science. In 1909, Cresson medal was awarded by The Franklin Institute to Marie and her husband Pierre (posthumously), and was given in the field of chemistry for the discovery of radium. She also received Benjamin Franklin Medal in Physics and Willard Gibbs award. The scientific community honoured itself by naming one of the transuranium elements, (At. No.=96) after Marie Curie as Curium.

**For more information**

1. Selected Classic Papers from the History of Chemistry compiled by Carmen Giunta at Le Moyne College.

2. Radium and Radioactivity by Mme. Sklodowska Curie, Century Magazine, (January 1904), pp. 461-466.

3. The Nobel Laureates site has a wealth of information about the Nobel Prize won by the Curies.

4. Many International Journals published between 2002-2004 celebrating first Nobel Prize to the Curies in 1903.

5. Madame Curie by Eve Curie, Heinemann, London (The most poignant and best tribute a daughter could give to her mother).

# Development of Theoretical Physics by Albert Einstein

**Dr. S. Kailas**, *a graduate of Madras university joined Nuclear Physics Division, BARC in 1971. He obtained his Ph.D in 1977. His field of specialisation is Nuclear Physics. He has to his credit nearly 150 journal publications and 300 conference papers. He is a Fellow of Indian Academy of Sciences. He is keenly interested in Accelerator based Multidisciplinary research. Currently he is Associate Director, Physics group, BARC.*
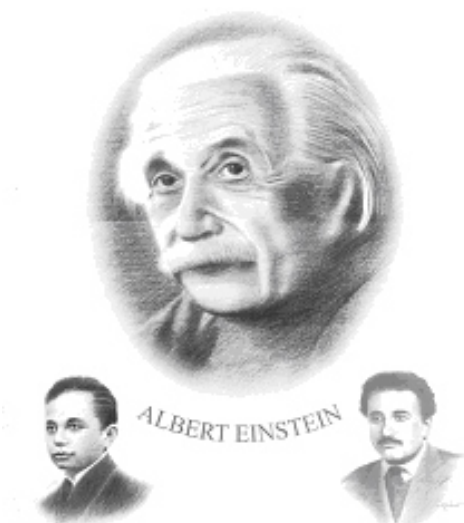
*"My Scientific work is motivated by an irresistible longing to understand the secrets of nature and by no other feelings. My love for justice and the striving to contribute towards the improvement of human conditions are quite independent from my scientific interests"* --- Albert Einstein

## Introduction

The year 2005 was celebrated as the International Year of Physics to commemorate the completion of a century after the publication of the landmark papers by Albert Einstein in the year 1905. According to many, the year 1905 can be considered as Einstein's miracle year when he published in quick succession, within the same year and in the same German journal Annalen der Physik, the three famous papers on Photoelectric Effect, Brownian Motion and Special theory of Relativity. These epoch making papers changed our concepts of space and time and our understanding of matter and radiation. Einstein was just 26 years old that time and he was awarded the prestigious Nobel Prize in Physics in the year 1921 for " his services to theoretical physics and especially for his discovery of the law of the Photoelectric Effect". Einstein being an artist and scientist at the same time, could innovate and create theories and connect apparently different things on a common framework. Even though Einstein achieved so much in such a short time, he was modest to the core as is evidenced by his saying: " One thing I have learned in a long life: that all our science, measured against reality, is primitive and childlike – and yet it is the most precious thing we have". The pioneering papers of Einstein on classical mechanics, quantum physics, mathematical physics, electromagnetism, relativity, thermodynamics and statistical physics paved the way for the development of theoretical physics in the $20^{th}$ century. Needless to say, the monumental theories of Einstein have brought about tremendous advancement in science and technology. In this article we will try to capture some of the highlights of his outstanding contributions to theoretical physics.

## *Einstein's contributions to the growth of Theoretical Physics*

Intellectual mastery of nature was the stated goal of physicists of the nineteenth and early twentieth centuries. By then the discipline of theoretical physics became a mature field and a

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specialty, distinct from mathematical and experimental physics. It was perhaps the golden period of physics in Germany. The leading ones were Weber, Minkowski, Helmhotz, Kirchhoff, Hertz, Planck, Boltzmann, Sommerfeld, Lorentz, Rontgen and Einstein to name a few. Einstein's curiosity driven research began when he was working at the Swiss patent office during the period 1902 to 1909. Most of his celebrated papers were written during that period. It is very astonishing that these papers were written in spare time and without the benefit of close contact with either the scientific literature or theoretician colleagues. At the start of his scientific work, Einstein realized the inadequacies of Newtonian mechanics and his special theory of relativity stemmed to reconcile the laws of mechanics with the laws of the electromagnetic field. He dealt with classical problems of statistical mechanics and problems in which they were merged with quantum theory: this led to an explanation of the Brownian movement of molecules. He investigated the thermal properties of light with a low radiation density and his observations laid the foundation of the photon theory of light. He provided the explanation of photoelectric effect. The year 1905 was very special in the life of Albert Einstein. It was in this year he earned his Ph.D from the university of Zurich on the topic " on a new determination of molecular dimensions". In the same year he published four more monumental papers, which revolutionized our conceptions of the physical world. In the first one (On a heuristic point of view concerning production and transformation of light – Annalen der Physik 17(1905) 132) he laid the foundation of quantum theory. In the second, (On the motion of small particles suspended in liquids at rest required by the molecular- kinetic theory of heat – Annalen der Physik 17 (1905) 549) he explained Brownian motion. In the third and the fourth, (On the electrodynamics of moving bodies - Annalen der Physik 17 (1905) 891; Does inertia of a body depend on its energy content? – Annalen der Physik 17 (1905) 639). He introduced what is now known as the special theory of relativity. In 1916, he published the general theory of relativity. In the following sections, some details are given on the above-mentioned three theme areas of Albert Einstein.

**Photoelectric Effect**

During the end of nineteenth century, when Einstein entered the scene the wave nature of electromagnetic radiation was firmly established by Maxwell and Lorentz through the electromagnetic theory. Numerous experiments on the interference, diffraction and scattering of light had confirmed its wave nature. Einstein's quantum hypothesis arose from an experimental puzzle and duality in physics theories. This consisted of the well-known distinction between the material atoms and the continuous ether. There were two schools of thought. Boltzamann and others conceived of gases as consisting of myriads of individual atoms while Maxwell and Lorentz envisioned electromagnetic processes as consisting of continuous waves. Einstein sought a unification of these viewpoints by removing the asymmetry in favor of a discontinuous quantum theory of light. Resolution of an experimental puzzle encouraged this approach. The puzzle concerned the so-called black body radiation, i.e. The electromagnetic radiation emerging from a small hole in a perfectly black box containing electromagnetic radiation at a high temperature. Max Planck at the turn of the 19th century was able to give a single mathematical formula for the observed distribution of the energy among the emitted wavelengths. The important path breaking assumption made by Planck to satisfy the mathematical formula was that the energy of the radiation does not act continuously as one would expect for waves, but exerts itself in equal discontinuous parcels, or quanta of energy. In essence Planck had discovered the quantum structure of electromagnetic radiation. Encouraged by his brief but successful application of statistical mechanics to radiation, Einstein attempted to resolve the duality of atoms and waves by demonstrating that part of Planck's formula can arise only from the hypothesis that electromagnetic radiation behaves as if it actually consists of individual quanta of energy. The continuous waves of Maxwell's equations could be considered only averages over myriads of tiny light quanta, essentially atoms of light. With his light quantum hypothesis Einstein could derive Planck's formula but also explain for the first time the Photoelectric effect – the ejection of energetic electrons from a metal when irradiated by light. Hertz discovered photoelectric effect in 1887.
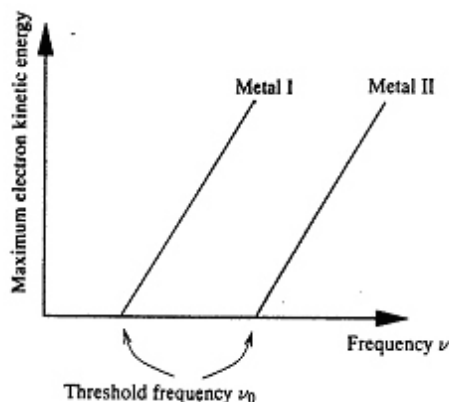
*Fig. 1    Photoelectric Effect. Dependence of the maximum kinetic energy of the photoelectrons on the frequency of the incident light as implied by the photoelectric equation.*

Following this, Lenard demonstrated that the electrons are indeed emitted as a result of radiation falling on metal surface. The most extraordinary effect was that the electron emission velocity was independent of the intensity of the radiation but found to increase with the frequency of the incident radiation (Fig.1). An associated phenomenon was the phosphorescence or luminescence. Here phosphorescence light is of lower frequency compared to that of the incident one. This is the famous Stoke's rule and Albert Einstein explained both this and the photoelectric effect using the quantum hypothesis propagated by Planck. Einstein came up with his masterpiece photoelectric equation, according to which $h\nu = \phi + E_e$ ($h\nu$ is the energy of the photon (light), $\phi$ is the work function of the metal for release of electron, $E_e$ is the maximum kinetic energy of the emitted electron). One can easily imagine the shock and disbelief of the community when Einstein made this bold theory according to which under certain circumstances light behaved not as continuous waves but as discontinuous individual particles. Even the title of Einstein's paper indicated his hesitance. That is why he titled his paper on this subject as "heuristic view ". Amongst others the famous Millikan was one of the scientists who carried out extensive investigations to validate Einstein's theory. Extending this argument

of photon having well defined energy, Einstein said that it should have momentum. Compton scattering of photons by free electrons - the Compton effect is an example of this. Similarly light photons can transfer energy to molecules of atoms and this formed the basis of Raman effect. Typical values, in eV, of $\phi$ for various metals are: Li -2.5, K-2.2, Na-2.3, Cs-1.9. According to the photoelectric equation, the maximum value of $\nu$ in the case of Li (i.e. $E_e = 0$) is $hc/\phi$ = (4.136 x 10$^{-15}$ eV.s) (2.998 x 10$^{+8}$ m/s) / 2.5 eV) = 497 nm.

**Brownian Motion**

At the turn of the 19th century, the school which believed in unifying physics on the formulation of mechanics was in a minority. The theoretical physicists thought of two alternatives: energetic and electromagnetic points of view. These arose due to the difficulties encountered by mechanics to understand features of heat and electromagnetism. Einstein was part of the history of scientists involved in the reformation of mechanics and electrodynamics in the wake of the above developments in heat and electromagnetism. According to the fundamental laws of dynamics of heat flow or thermodynamics, heat, energy and useful work are related to each other in thermal process. The law could be understood in terms of the motions and collisions of Newtonian atoms. However, the second law could not be understood this way. According to this, the flowing of heat in natural processes, (such as melting of ice cube) is always irreversible; that is heat will not naturally flow of its own accord in the opposite direction – the melted ice cube at room temperature will not refreeze by itself. How to account for this in mechanical terms? This behaviour was certainly not compatible with the Newtonian mechanics and the hypothesis that matter consists of atoms and heat is nothing but energy of motion of the atoms. If this is so then the reactions will be reversible. It was a puzzle that melting of ice (microscopic events) was irreversible. There was a debate going on to see which of the theories persisted the test of time. Mechanics required hypotheses about matter and invisible atoms in motion, but thermodynamics referred only to energy and its observed transformations in the everyday world. Because thermodynamic laws were closer to laboratory
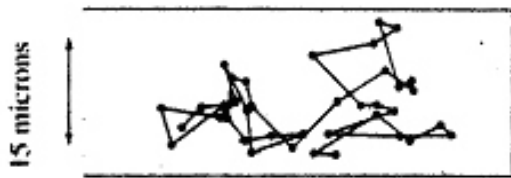
*Fig. 2 Brownian motion. Random motion exhibited by tiny particles due to collision with the liquid molecules.*

observations, Ostwald and his followers proclaimed the predominance of a new energetic worldview: energy and the laws of thermodynamics are the bases for understanding all processes within physical science and even beyond. Others, of course, held tightly to material atoms. They found support in the work of Maxwell, Clausius and Boltzmann, who managed to resolve the reversibility paradox in favour of atoms. The second law of thermodynamics says that most natural processes are irreversible, in contradiction to Newtonian mechanics of atoms. Boltzmann in particular resolved this contradiction by interpreting the second law as a new type of law: a statistical, not an absolute law. Since there are so many atoms or molecules, even in tiny ice cube, it is extremely unlikely – but not impossible for the myriads of molecules in a melted ice cube to return in a finite time from the disorder of a liquid to their original order, crystalline arrangement. The macroscopic properties of heat and material objects, such as irreversibility arise from the statistical behaviour of numerous mechanical atoms, behaviour to be described by a new statistical mechanics. Boltzmann and Gibbs provided the first accounts of how exactly the second law of thermodynamics arises from the statistical behaviour of myriads of randomly moving atoms. Einstein in parallel proposed an independent derivation of the second law in the course of developing his own statisitical mechanics based on atoms and mechanics. Einstein used mechanics, atoms and statistical arguments to achieve general molecular theory of heat confirming that both laws of thermodynamics are indeed fully explainable on mechanical grounds. For his Ph.D Einstein developed a statistical molecular theory of liquids. He applied this theory to obtain the solution to decade old puzzle of Brownian motion. Brown, a

Botanist had noticed tiny particles mixed in with the pollen exhibited incessant irregular swarming motion since called Brownian motion (Fig. 2). Einstein predicted that the random motions of molecules in a liquid impacting on larger suspended particles would result in irregular random motions of the particles, which could be directly observed under the microscope. The predicted motion corresponded precisely with the puzzling Brownian motion. From this motion Einstein accurately determined the dimensions of the hypothetical molecules. Modern day scientists can see the atoms through the STM. Einstein also obtained a connection between his statistical theory of heat and the behaviour of electromagnetic radiation. Let us discuss the random motion of the tiny particles in the liquid. The average value of the position of the particle due to this will be zero. ($\langle x \rangle = 0$). Similarly $\langle v \rangle = 0$. However, $\langle v^2 \rangle$ can be zero or positive. When the water is heated, the molecules of water start moving faster in different directions. The average kinetic energy rises. The temperature of water also rises. When the suspended particle is in thermal equilibrium with the water, its average kinetic energy is proportional to the temperature: $\frac{1}{2} m \langle v^2 \rangle = \frac{1}{2} kT$, where m is the mass of the suspended particle and T is the absolute temperature of the water. Using the ideas of statistical mechanics, Einstein derived the following result:

$$\langle x^2 \rangle = (kT / 3\pi\eta a) t$$

where $\eta$ is the viscosity of the liquid, a is the radius of the suspended particle and t is the elapsed time. Thus the mean squared displacement $\langle x^2 \rangle$ increases linearly with time, t. Further the Brownian motion will be damped in a larger viscous liquid and the bigger particle will have less of Brownian motion. To get an idea of the typical value, let us work out the displacement of suspended particle of size one micron ($10^{-6}$ m) in water at room temperature (300 K) The viscosity of water at this temperature is roughly $10^{-3}$ N.s/ $m^2$. Boltzmann constant k is 1.38x $10^{-23}$ N.m/K. The $\langle x^2 \rangle$ value works out to about 0.7 micron for one second. Moelcular dimesion is of the order of a few nm ($10^{-9}$ m). Perrin verified the prediction of Einstein. He obtained the value of k and a good value of Avogadro number. Einstein's explanation of the Brownian motion provided a strong evidence for the molecular theory of matter.

**Theory of Relativity**

Since the time of Galileo and Newton, physicists had known that laboratory measurements of mechanical processes could never show any difference between an apparatus at rest and an apparatus moving at constant speed in a straight line. This is called the principle of relativity. But according to the electromagnetic theory of Maxwell and refined by Lorentz, light should not obey this principle. Their electromagnetic theory predicted that measurements on the velocity of light would show the effects of motion. Yet no such effect was detected. Einstein was convinced that the principle of relativity must apply to all phenomena, mechanical or not. He tried to make this compatible with the electromagnetic theory by a novel analysis of space and time. This theory is called the special theory of relativity. Einstein was concerned about asymmetry in Maxwell's electrodynamics. The problem was that two descriptions of a phenomenon for which Einstein held there should be only one: the current induced in a conductor by a magnet depends only on their relative motion, yet by Maxwell – Lorentz theory the description of what happens depends on whether the magnet or the current moves. Einstein also was concerned about the failure to detect the ether. Hence he was convinced that there was nothing absolute either in mechanics but also in electrodynamics. He proposed the theory of relativity: the laws of nature are the same for all observers regardless of any uniform motion they may have with respect to one another. He also proposed that the velocity of light would be constant regardless of the motion of its source. Einstein analyzed the measurement of space and time, leading to the relativity of simultaneity of physical events and of lengths and time intervals. He deduced the equations of transformation of the coordinates and the time of observers in uniform relative motion in the x direction which are identical with the transformation equations Lorentz had arrived at by different reasoning: they preserve the form of Maxwell – Hertz equations of the electromagnetic field in empty space: $T = t - xv/c^2)$ and $X = (x - vt)$ . $Y = y$ and $Z = z$. Here $= 1/\sqrt{[1 \quad (v/c)^2]}$. x,y,z are the spatial coordinates and t is time in one reference system. X,Y,Z and T are the corresponding quantities in a system moving with velocity v with
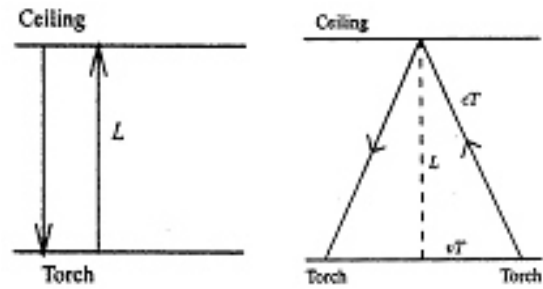


*Fig. 3   Theory of Relativity. L = distance to ceiling. t = time taken to reach the ceiling as measured by a person in the moving train. T = time taken to reach the ceiling as measured by a person at rest with respect to the moving train. v = velocity of the train.*

respect to the first. c is the velocity of light which is the same in any frame of reference. Laws of physics had to have the same form in any frame of reference. Suppose there is a person in a train moving with velocity v and he shines a torch ( Fig.3) vertically at the ceiling at a height L, then the time taken by light to ceiling is t. Hence L = ct. Now let us see what the person at rest will make of this: As the light is shone, the train is also moving forward. The observer will say during the time T, the light moved a distance of cT and reached the ceiling. During this time, the train covered a distance of vT forward. So the height of the ceiling to the observer will be $L^2 + (vT)^2 = (cT)^2$. Hence $T = t / \sqrt{(1 \quad v^2/c^2)}$ . This implies that the time T is larger than. i.e. the time appears dilated to an observer at rest with respect that measured by a person in a moving train. Extending this argument to the length measurement, it can be shown the actual length (L) of an object say rod in a moving frame with velocity v will appear to an observer at rest as $LL = L\sqrt{(1 \quad v^2/c^2)}$ . The length appears smaller to a person at rest with respect to the moving train. Suppose an object of length 250 m is travelling at a speed of 0.6 c, it will appear to be 200 m to an observer at rest with respect to the moving object. Length contraction and time dilation are both consequences of the fact that velocity of light is the same for all frames of reference. One can see the above relations reduce to Newtonian laws when v is very small compared to c. Einstein in a later paper

showed that a remarkable consequence of his special theory of relativity would be: if a body emits a certain amount of energy, then the mass of that body must decrease by a proportionate amount. According to him, the connection with the Maxwell equations demands that the mass is direct measure for the energy contained in bodies; The deep connection Einstein discovered between energy and mass is expressed in the equation $E = mc^2$. Here E represents energy, m represents mass and $c^2$ is a very large number, the square of the speed of light. In 1933, Irene and Joliot Curie took a photograph showing the conversion of energy into mass. The reverse process was also seen: the conversion of mass into energy. Cockroft and Walton broke apart an atom. The fragments had slightly less mass in the total than the original atom, but they flew apart with great energy.

In 1907 he proposed that if mass were equivalent to energy, then the principle of equivalences required that gravitational mass would interact with the apparent mass of electromagnetic radiation which included light. By 1911 he made preliminary predictions about how a ray of light from a distant star passing near the sun would appear to be attracted or bent slightly in the direction of the sun's mass. Again light radiated from the sun would interact with the sun's mass resulting in a slight change toward the infrared end of the suns'; optical spectrum. This theory of Einstein has to also account for the small but persistent anomaly in the perihelion motion of the planet mercury. In 1915 he published the general theory of relativity. Einstein's prediction about deflection of light could be confirmed during solar eclipse in 1919.

## Conclusion

Einstein could never accept quantum mechanics with its principle of indeterminacy. Even though he acknowledged that it was the most successful physical theory, he could not accept quantum mechanics as a complete theory. Albert Einstein had worked for many years to obtain a unified theory of gravitation and electromagnetism. By following the approach of his own general theory of relativity, he hoped to dig deeper than quantum mechanics. The search for an ultimate unified theory was to occupy much of his life towards the end of his chequered career. Albert Einstein died at the age of

76 leaving behind him the memory of a man who gazed upon the universe with the dissipation of a scientist and upon mankind with the compassion of a saint. In some sense, the papers of Einstein presented radically different ideas and brought about a change in our dealing with space and time as well as matter and radiation. "The hallmark qualities of Einstein are: His unflinching boldness; His open-mindedness in embracing ideas and concepts from apparently distant fields; though a theoretician by training, he was close to experiments". In the end, to quote Bertrand Russell: " Einstein was undisputedly one of the greatest men of our time. He had a high degree of simplicity, characteristic of the best men of science – a simplicity which comes of a single minded desire to know and understand things that are completely impersonal".

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# Niels Bohr- The man and his work

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**Niels (Henrik David) Bohr** was a Danish physicist who made fundamental contributions to understanding atomic structure and quantum mechanics. In terms of scientific brilliance Niels Bohr is right at the top, perhaps second only to Einstein among the galaxy of scientists of 20th century. He was born in Copenhagen on October 7, 1885. His father Christian Bohr was a Professor of Physiology at Copenhagen University, and his mother Ellen was the daughter of a prominent Jewish politician in Denmark. He and his younger brother Harald (the future Professor in Mathematics), grew up in an atmosphere most favourable to the development of their genius. His father was largely responsible for awakening his interest in physics while still at school. After matriculation in 1903, he joined Copenhagen University. He studied physics as his main subject but took mathematics, astronomy and chemistry as minor subjects. He was taught physics by Professor C. Christiansen, a profoundly original and highly endowed physicist. While studying for his Masters degree Bohr distinguished himself by winning a gold medal from the Royal Danish Academy of Sciences and Letters for his theoretical analysis of and precise experiments on oscillating fluid jets as a way of determining surface tension. This work, which he carried out in his father's laboratory, was published in the Transactions of the Royal Society, 1908. He got his Master's degree in Physics in 1909. In 1911 he received his doctorate for a thesis on the electron theory of metals. It was a thesis based on classical physics and as such necessarily failed to explain certain effects. Bohr wrote in this work:- "It does not seem possible at the present stage of the development of the electron theory to explain the

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magnetic properties of bodies from this theory." That stressed the difficulties for treating the behaviour of matter at the atomic level by principles of classical physics.

In the autumn of 1911 Bohr traveled to England on a study grant. He first worked at the Cavendish Laboratory, Cambridge to carry out experimental and theoretical studies under the guidance of Sir J.J. Thomson who had discovered the electron in 1897. Most physicists in the early years of the twentieth century were engrossed by the new and fascinating discovery of electron. Bohr was interested in exploring new ideas from the work of Max Planck or Albert Einstein for his work. However, Thomson did not show much interest in these new ideas. In the spring of 1912 Bohr went to Ernest Rutherford (a former student of Thomson's) in Manchester, where a strong team was busy exploring scientific ideas as a consequence of fundamental inquiries into the radioactive phenomena. At Manchester he carried out a theoretical piece of work on the absorption of alpha rays which was published in the Philosophical Magazine, 1913, and then began to study the structure of atoms on the basis of Rutherford's discovery of the atomic nucleus. He returned to Copenhagen in July 1912 and continued his studies on atomic structure for which he received the Nobel Prize in Physics in 1922. It is best to understand the scientific environment prevailing at the time of this epoch making discovery, as was done by Bohr himself in his Nobel lecture.

At that stage of the development of atomic theory, the existence of atoms had been proven. Mendeleev and Lothar Meyer had postulated that when elements are arranged in an order depending on their atomic weights, their physical and chemical properties show a pronounced periodicity. The ordinal number of the element in the periodic table was called the atomic number though this term was to acquire a fundamental definition at a later stage. The elements themselves were discovered by a number of techniques but the most powerful among these was the use of atomic spectra. The technique of measuring wavelengths of spectral lines had evolved to a very high precision and each element was shown to have characteristic atomic spectrum. Balmer, Rydberg and Ritz established wavelengths of a number of elemental spectra. Mention may be made here of the work of William Ramsay who discovered noble gases from argon to xenon between 1894 and 1898. He received the Nobel Prize in chemistry in 1904. He also discovered helium in the emanations of Radium in 1903.

The concept of the atomic nature of electricity had evolved since the discovery of the fundamental laws of electrolysis by Michal Faraday in 1834 and electrochemical theory by Berzelius. The electrolytic theory of dissociation discovered by Svante Arrhenius (Nobel Prize in Chemistry, 1903), put a firm seal on this concept. Faraday had also shown that every atom carries an electric charge as large as that of a hydrogen atom, or else a simple multiple of it corresponding to the chemical valence of the atom. On the basis of his measurements he estimated the atomic charge to be $3.4 \times 10^{-10}$ electrostatic units. Hittorf had discovered cathode rays in 1869 but it was only Heinrich Hertz's assistant Philipp Lenard who in 1893 could find a method for taking cathode rays out of the tube for experimental investigations, by using a thin aluminum window. He received Nobel Prize for physics in 1905. Lenard's technique led to a wide spread investigation on cathode rays and eventually to the discovery of electron by J.J. Thomson for which he received Nobel prize in physics in 1906.

Lenard's discovery was in fact the first link in the chain of discoveries related to atomic physics. Wilhelm Conrad Roentgen discovered X-rays in 1896 and received the first Nobel Prize in physics in 1901. This was soon followed by the discovery of radioactivity by Antoine Henri Becquerel and the study of this phenomenon by Marie Curie and Pierre Curie in 1898. The trio received the Nobel Prize in physics in 1903. Marie curie continued her work on radioactive substances and discovered highly radioactive elements radium and polonium. She received a second Nobel Prize in Chemistry for these discoveries in 1911. The discoveries of these elements were extremely important as radium and polonium provided high intensity of energetic alpha particles for studies on the constitution of the atom. In the first decade of the $20^{th}$ century, Ernest Rutherford was also carrying out investigations on disintegration of elements and the chemistry of radioactive substances. He received Nobel Prize in

Chemistry for this work in 1908. Rutherford and Frederick Soddy also proposed a disintegration theory in 1902 which described the transformation of elements following radioactive decay. Soddy's further work on this concept led to the discovery of isotopes in 1913. Soddy received Nobel Prize in Chemistry for this discovery in 1921.

While the experimental studies had led to the generation of a large body of scientific information the theoretical physicists were also presenting path breaking theories related to atomic physics. Maxwell's laws of electrodynamics, postulated in the first half of the nineteenth century, served as a gospel for all known electrical and magnetic phenomenon and had predicted the existence of electromagnetic waves later discovered by Hertz. Some of the observations, however, could not be explained by the electrodynamics theory. During 1900 Max Planck, in his studies on characteristics of heat radiation emitted by a black body, had postulated that the energy of a vibrating electron can not change continuously, but only in such a way that the energy of the system remained equal to a whole number of so called energy quanta. The magnitude of the quantum was found to be proportional to the frequency of oscillating particle. The proportionality factor had to be a universal constant since termed as Planck's constant ($\hbar$), similar to the velocity of light, charge and mass of an electron. Max Planck was awarded the Nobel Prize in Physics for his discovery in 1918. Planck's contribution stood isolated in natural sciences, but gained wider acceptance with the work of Einstein on specific heat of crystalline bodies. Einstein also emphasized that another consequence of Planck's theory i.e. radiant energy could only be emitted or absorbed by the oscillating particles in so called "quanta of radiation" the magnitude of which was equal to the Planck's constant multiplied by frequency. Einstein thus formulated the hypothesis of light quanta, according to which radiant energy, in contradiction to Maxwell's electromagnetic theory of light, would not be propagated as electromagnetic waves, but rather as concrete light atoms, each with energy equal to that of the quantum of radiation. This theory also led to Einstein's discovery of photoelectric effect which could not be explained by the classical theory. Einstein was awarded Nobel Prize in Physics for these two discoveries in 1921. However,

Einstein's theory could not explain the so called interference phenomenon readily explained by classical wave theory.

Coming back to the subject of atomic structure J.J. Thomson had made very important contributions to the subject by his ingenious attempts to develop ideas about atomic constitution on the basis of the electron theory. His investigations had already generated information regarding the number of electrons in an atom. He postulated that the atom was like a "plum pudding." That is, it has roughly the same consistency throughout, with negatively-charged electrons scattered about in it like raisins in a pudding. As part of an experiment with X-rays in 1909, Rutherford was shooting a beam of alpha particles (or alpha rays, emitted by the radioactive element radium) at a sheet of gold foil only 1/3000 of an inch thick, and tracing the particles' paths. Most of the particles went right through the foil, which would be expected if the atoms in the gold were like a plum pudding. But every now and then, a particle bounced back as though it had hit something solid. After tracing many particles and examining the patterns of scattered alpha particles, Rutherford deduced that the atom must have nearly all its mass, and positive charge, in a central nucleus about 10,000 times smaller than the atom itself. All of the negative charge was held in the electrons, which must orbit the dense nucleus. This model of atomic structure was proposed by Rutherford in 1911. Rutherford also measured the charge on the atomic nucleus.

In 1913 Rutherford and Mosley assigned atomic numbers to each element based on the nuclear charge, or the charge of electrons orbiting around it. In this picture of atomic structure one can at once see a striking resemblance to the planetary system, such as we have in our own solar system. It was, however, impossible on this basis to give a closer explanation of the spectra of the elements, or even of the general type of the laws holding with great exactness for the wavelengths of lines in these spectra, which had been established by Balmer, Rydberg, and Ritz. In 1912 Bohr joined Rutherford. He realized that Rutherford's model wasn't quite right. By all rules of classical physics an orbiting electrons should give off energy and eventually spiral down into the nucleus, making the atom collapse. Bohr turned to

Planck's quantum theory to explain the stability of most atoms and the sharp lines observed in elemental spectra. He found that the ratio of energy in electrons and the frequency of their revolution around the nucleus was equal to Planck's constant (the proportion of light's energy to its wave frequency, or approximately $6.626 \times 10^{-23}$). Bohr suggested the revolutionary idea that electrons "jump" between energy levels (orbits) in a quantum fashion, that is, without ever existing in an in-between state. Thus when an atom absorbs or gives off energy (as light or heat), the electron jumps to higher or lower orbits. In 1913 Bohr published three papers of fundamental importance on the theory of atomic structure. The first paper was on the hydrogen atom, the next two on the structure of atoms heavier than hydrogen. In 1922 he was awarded the Nobel Prize in physics for this work. His two main postulates are:

1. Among the conceivably possible states of motion in an atomic system there exist a number of so-called stationary states which, in spite of the fact that the motion of the particles in these states obeys the laws of classical mechanics to a considerable extent, possess a peculiar, mechanically unexplainable stability, of such a sort that every permanent change in the motion of the system must consist in a complete transition from one stationary state to another.

2. While in contradiction to the classical electromagnetic theory no radiation takes place from the atom in the stationary states themselves, a process of transition between two stationary states can be accompanied by the emission of electromagnetic radiation, which will have the same properties as that which would be sent out according to the classical theory from an electrified particle executing an harmonic vibration with constant frequency. This frequency has, however, no simple relation to the motion of the particles of the atom, but is given by the relation:

$$h = E' - E''$$

where h is Planck's constant, and E' and E" are the values of the energy of the atom in the two stationary states that form the initial and final state of the radiation process. Balmer, in interpreting the

relation between different spectral lines of hydrogen atom had postulated that the frequencies of the lines may be represented with great accuracy by means of the formula:

$$= K \left( 1/n''^2 - 1/n'^2 \right)$$

where K is a constant and n' and n" are two integers. In the spectrum we accordingly meet a single series of spectral terms of the form $K/n^2$, which decrease regularly with increasing term number n. In accordance with the postulates, Bohr assumed that each of the hydrogen lines is emitted by a transition between two states belonging to a series of stationary states of the hydrogen atom in which the numerical value of the atom's energy is equal to $hK/n^2$. On the basis of his theory Bohr calculated that the constant in the Balmer formula can be expressed by means of the relation:

$$K = 2 \ ^2e^4m/h^3$$

where e and m are respectively the charge and mass of the electron, while h is Planck's constant. Bohr thus arrived at a manifold of stationary states for which the major axis of the electron orbit takes on a series of discrete values proportional to the squares of the whole numbers. Bohr could accurately reproduce the frequencies of the transition processes that correspond to the red and green hydrogen lines, H and H the frequency of which is given by putting n" = 2 and n' = 3 and 4 respectively. Similarly the infrared line of Paschen series could be reproduced by putting n" = 3. Later the frequencies of the first three lines of the series of ultraviolet lines found by Lyman in 1914, could be explained by putting n'' = 1. The number 'n' was designated as the quantum number of the energy state. Thus the quantum-theory condition entering in the last postulate laid the foundation for the interpretation of the laws of series spectra. The presence of hyperfine structure in each of these lines led to the postulate that the energy is dependent upon 'n' the principle quantum number and 'k' the subordinate quantum number. Further theoretical work on this concept, involving quantum mechanics, led to the definition of four quantum numbers for each energy state.

Bohr's theory that electrons existed in set orbits around the nucleus was the key to explaining the periodic repetition of properties of the elements.

The shells in which electrons orbit have different quantum numbers and hold only certain numbers of electrons - the first shell holds no more than 2, the second shell up to 8, the third 18, the fourth 32. Atoms with less than the maximum number in their outer shells are less stable than those with "full" outer shells. Elements that have the same number of electrons in their outermost shells appear in the same column in the periodic table of elements and tend to have similar chemical properties.

In July 1913 Bohr was appointed as a docent in Copenhagen. However, it was not a situation which pleased him since he could not pursue the style of mathematical physics which he was developing. On 10 March 1914 he wrote to the Department of Educational Affairs regarding founding of a professorship in theoretical physics at the university and in addition to possibly entrusting him with that position. The Faculty of the University recommended him for a chair of theoretical physics but the Department of Educational Affairs decided to delay confirming the post. Of course in 1914 times were uncertain and Bohr realized that no quick decision was likely. He, therefore, was delighted to accept an offer by Rutherford to join his Manchester group as Schuster Reader. He expected to be in Manchester for a year, anticipating that his chair of theoretical physics in Copenhagen would be confirmed by then. The outbreak of World War I while he was on holiday in the Tyrol before traveling to Manchester made his journey extremely difficult, but he and his wife arrived in Manchester in October 1914 having sailed round the north of Scotland through severe storms on their way. Bohr was in Manchester longer than he expected since his chair was not confirmed until April 1916. However, it was a very productive and happy period and he returned back to Copenhagen as a professor in theoretical physics.

In 1917 Bohr was elected to the Royal Danish Academy of Sciencies and he began to plan for an Institute of Theoretical Physics in Copenhagen. This was created for him and, from its opening in 1921, he became its director, a position he held for the rest of his life. Through the early 1920s, Bohr concentrated his efforts on two interrelated sets of problems. He tried to develop a consistent quantum theory that would replace classical mechanics and electrodynamics at the atomic level and be adequate for treating all aspects of the atomic world. He also tried to explain the structure and properties of the atoms of all the chemical elements, particularly the regularities expressed in the periodic table and the complex patterns observed in the spectra emitted by atoms. In this period of uncertain foundations, tentative theories, and doubtful models, Bohr's work was often guided by his correspondence principle. According to this principle, every transition process between stationary states as given by the quantum postulate can be "coordinated" with a corresponding harmonic component (of a single frequency) in the motion of the electrons as described by classical mechanics. As Bohr put it in 1923, "notwithstanding the fundamental departure from the ideas of the classical theories of mechanics and electrodynamics involved in these postulates, it has been possible to trace a connection between the radiation emitted by the atom and the motion of the particles which exhibits a far-reaching analogy to that claimed by the classical ideas of the origin of radiation."s20 Indeed, in a suitable limit the frequencies calculated by the two very different methods would agree exactly. Gradually, a genuine quantum mechanics was created, the new synthesis that Bohr had been expecting. The new quantum mechanics required more than just a mathematical structure of calculating; it required a physical interpretation. Quantum mechanics may be said to have arrived in 1925 and two years later Heisenberg stated his uncertainty principle. This principle helped Bohr to improve his model for atomic structure. The uncertainty principle was hard even for scientists to accept at first. After struggling with it, however, Bohr developed complementarity theory. This stated that there was a dual nature to things — an electron was a wave and a particle, for example — but we could only perceive one side of that dual nature.

Bohr's activities in his Institute were since 1930 more and more directed to research on the constitution of the atomic nuclei, and of their transmutations and disintegrations. In 1936 he pointed out that in nuclear processes the smallness of the region in which interactions take place, as well as the strength of these interactions, justify the transition processes to be described more in a classical way than in the case of atoms. A liquid drop would, according to this view, give a very good

picture of the nucleus. This so-called *liquid droplet theory* permitted the understanding of the mechanism of nuclear fission, when the splitting of uranium was discovered by Hahn and Strassmann, in 1939, and formed the basis of important theoretical studies in this field (among others, by Frisch and Meitner). Similarly, his compound-nucleus model of the atom proved successful in explaining other types of nuclear reactions.

Bohr's institute in Copenhagen soon became an international centre for work on atomic physics and the quantum theory. Even during the early years of its existence, Bohr had a series of coworkers from many lands, including H.A. Kramers from The Netherlands, Georg Charles von Hevesy from Hungary, Oskar Klein from Sweden, Werner Heisenberg from Germany, and John Slater from the United States. Like Rutherford, Bohr took special interest in training a new generation of physicists. Bohr himself began to travel more widely, lecturing in many European countries and in Canada and the United States. After 1933 the institute also provided refuge for a good many scientists who had fled from Hitler's Germany. The annual conferences on nuclear physics as well as formal and informal visits of varied duration brought virtually everyone concerned with quantum physics to Copenhagen at one time or another. Many of Bohr's collaborators in those years have written lovingly about the extraordinary spirit of the institute, where young scientists from many countries worked together and played together in a lighthearted mood that concealed both their absolutely serious concern with physics and the darkening world outside.

After Hitler took power in Germany, Bohr was deeply concerned for his colleagues there, and offered a place for many escaping Jewish scientists to live and work. He later donated his gold Nobel medal to the Finnish war effort. In 1939 Bohr visited the United States with the news from Lise Meitner (who had escaped German-occupied Austria) that German scientists were working on splitting the atom. This spurred the United States to launch the Manhattan Project to develop the atomic bomb. Shortly after Bohr's return home, the German army occupied Denmark in 1940. Bohr, although he had been christened in the Christian Church, had Jewish origins on his mother's side and so his life became

exceedingly difficult. Three years later Bohr's family fled to Sweden in a fishing boat. Then Bohr and his son Aage left Sweden traveling in the empty bomb rack of a British military plane. They began to work on the project to make a nuclear fission bomb. After a few months they went with the British research team to Los Alamos in the United States where they continued work on atomic bomb at Los Alamos.

Bohr's concern about the terrifying prospects for humanity posed by such atomic weapons was evident as early as 1944, when he tried to persuade British Prime Minister Winston Churchill and U.S. president Franklin D. Roosevelt of the need for international cooperation in dealing with these problems. Although this appeal did not succeed, Bohr continued to argue for rational, peaceful policies, advocating an "open world" in a public letter to the United Nations in 1950. Bohr was convinced that free exchange of people and ideas was necessary to achieve control of nuclear weapons. He led in promoting such efforts as the First International Conference on the Peaceful Uses of Atomic Energy, held in Geneva (1955), and in helping to create the European Council for Nuclear Research (CERN). Among his many honours, Bohr received the first U.S. Atoms for Peace Award in 1957.

In 1912 Bohr married Margrethe Nørlund. They had six sons, of which two died young but other four had successful careers. He drew strength from his close personal ties with his coworkers and with his sons, his wife, and his brother. Profoundly international in spirit, Bohr was just as profoundly Danish, firmly rooted in his own culture. This was symbolized by his many public roles, particularly as president of the Royal Danish Academy from 1939 until his death in 1962. In 1948 Bohr's son Aage Bohr collaborated with Ben Mottelson and Leo James Rainwater for work on nuclear theory which led all three of them to receive the 1975 Nobel Prize in Physics, for research on the quantum mechanical description of nucleons orbiting inside an oscillating rotating droplet. He was appointed the Director of Bohr Institute for Theoretical Physics from 1963 to 1970.

In addition to his major contributions to theoretical physics, Niels Bohr was an excellent

administrator. The institute he headed is now named after him. He died at home on November 18, 1962, following a stroke. In 1994 a committee of IUPAC recommended that element 107 be named bohrium in memory of Niels Bohr.

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# Use of Isotopes as Tracers by George Hevesy

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## Introduction

*George Hevesy*

George Hevesy belongs to a galaxy of twentieth century's brilliant Hungarian Jewish Scientists that include Eugene Wigner, John von Neumann, Leo Szilard and Edward Teller. In 1944, Hevesy was awarded undivided Nobel Prize in Chemistry, for his work on the 'Use of Isotopes as Tracers in the Study of Chemical Processes', for the Year 1943,. At present the topic of the use of isotopic tracers is taught in undergraduate classes. The availability of the requisites such as the isotopic tracers and the radiation detectors viz. GM counter or photomultiplier tube coupled scintillation counter with associated electronic equipment, is almost taken for granted. Hardly any thought is given to their historical and technical developments.

George Hevesy was the pioneer in conceiving the use of isotopic tracers in the study of chemical processes. At the beginning of last century the phenomenon of natural radioactivity was explored by physicists as well as by chemists. Hevesy, then, working in Rutherford's laboratory, in Manchester, was met with an utter failure in his endeavour of a radiochemical separation. But his fertile imagination transformed the adversity into advantage which led to ultimate triumph and gave birth to radioindicator or radiotracer method which is one of the most sensitive methods of analysis. Hevesy's perception and his indefatigable efforts to try, to develop and ultimately to establish a method eventually resulted in one of the most important and widely used research tools in basic science, in medicine, biology and also in industry.

## Education

Hevesy was born in Budapest, Hungary, on $1^{st}$ August 1885 in an aristocratic wealthy family. He studied in the local school and entered the University of Budapest where he studied, mainly Physics and Mathematics, for a year. With an ambition of becoming a chemical engineer, he joined the Technical High School in Berlin. A few months later, however, he became ill with pneumonia and was advised to move to other place where the climate would be more suitable to his health. In general his health was somewhat delicate and continued to be so throughout his life. After about six months in Berlin, he left for Freiburg where the climate was agreeable to him. Though initially he intended to spend a term there, he remained in Freiburg to study physical chemistry. He had a life-long association with the University of Freiburg, first as a student and later as a Professor. In 1906 he began his doctoral work on interaction of metallic sodium with molten sodium hydroxide and obtained his Ph.D. in 1908.

For his post doctoral studies he went to Technical High School, Zurich to work with Richard Lorenz who was a great authority on molten salt

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chemistry. Later Lorenz left Zurich to join University of Frankfurt and he desired Hevesy to follow him. Prof. Willstatter (NL1915) who was the head of chemistry department advised Hevesy to remain in Zurich. Hevesy however neither remained in Zurich nor went with Lorenz to Frankfurt. He chose his own a third alternative and left for Karlsruhe to work under Haber, whose epochal work on catalytic synthesis of ammonia was to lead to the foundation fixation of atmospheric nitrogen.

Instead of the work in the catalytic synthesis, Haber assigned Hevesy to investigate whether or not emission of electrons occurs during the oxidation of molten zinc. Hevesy worked for about 3 months, but his efforts proved futile. Nobody in Haber's institute had experience in the field of the conduction of electricity in gasses which was crucial to achieve the desired objective. Hevesy suggested to Haber that he should go to England to learn the required technique and then return to his laboratory. Haber supported the suggestion. Hevesy decided to go to Rutherford at Manchester and not to J.J in Cambridge. An advice of Gustav Rumelin from Freiburg, who had studied under Rutherford in McGill University, Montreal, may at least partially have helped Hevesy to make his choice of Manchester.

**To Manchester**

Hevesy wrote to Rutherford to seek his permission to work in his laboratory and in June 1910, Rutherford accepted his request. At the beginning of January 1911, Hevesy left for Manchester to work under Rutherford. He entered the Physical Laboratory on $29^{th}$ January 1911. Probably providence helped Hevesy in his decision to go to Rutherford that eventually proved to be very fortunate for him as it proved to be of decisive importance for his scientific career.

Rutherford, the crowned king of radioactivity, was then at the height of his powers, a world authority on the science of radioactivity and had a team of exceptionally gifted young scientists, many of whom through their work, were to become world renowned [Moseley, Geiger, Bohr (joined in 1912) Marsden, Chadwick]. Hevesy was lucky to be in the right place, at the right time and among right colleagues. Hevesy and Bohr became life long friends and Bohr's Institute became a refuge for Hevesy whenever he was in need of. Hevesy spent about 3 years (1911-1914) in Rutherford's laboratory and was privileged to witness some of the greatest discoveries (The discovery of atomic nucleus and Moseley's work on X-ray spectroscopy) in Physics.

After undergoing the training in radioactivity, he was asked to determine the solubility of actinium emanation ($^{219}_{86}$Rn, $T_{1/2}$  4 sec.) which offered him an excellent opportunity in handling short lived activities. Hevesy became friend of Moseley and helped him to set up the first X-ray spectrograph.

Rutherford had received 100 Kg of $PbCl_2$ containing RaD as donation from Austrian Government which owned the Joachimsthal mine Radium work. As RaD is soft  -emitter ($E_{max}$= 61 keV) a strongly active source of RaD was needed to study it's properties and hence RaD had to be separated from large quantities of $PbCl_2$. One day, Hevesy met Rutherford in the basement of the laboratory where $PbCl_2$ was stored and he said to Hevesy, "If you are worth your salt, you separate RaD from all that nuisance of lead". Hevesy was enthusiastic about task assigned and felt confident that he would succeed in achieving the desired separation. For more than year he tried several separation methods with great effort, with occasional illusionary success but the separated activity was found to be RaE ($^{210}$Bi, $T_{1/2}$=5 days, the decay product of RaD). The net result of his endeavour was utter failure. But ruminating over his failure and frustration, he conceived: If RaD could not be separated from lead, it should be possible to add pure RaD of known activity to some lead compound to carry out chemical reactions with this 'Labelled lead' and follow the path of lead ions with the aid of radioactive measurements. Thus was born the concept of the use of radioindicator (radiotracer) in chemistry. Pure RaD ($^{210}$Pb, $T_{1/2}$=22.3 yrs.) can be obtained from tubes containing radium emanation ($^{222}$Rn) after its decay.

**Radiotracer use in Chemical Studies**

Hevesy knew that Vienna Institute for Radium Research had large quantities of radium and also of Ra-emanation. He visited Vienna where he found Paneth was working on RaD separation and had also

met with the same failure. He and Paneth decided to collaborate and first, at Hevesy's initiative, they began, the work on the determination of the solubility of sparingly soluble lead salts viz.PbS and $PbCrO_4$ using RaD indicator, in January 1913. 0.2 Ci of $^{226}$Rn in a closed flask was allowed to decay over distilled water to RaD and to the resulting solution of RaD, 10 mg of $PbCl_2$ in water was added. The weight of RaD was ~1 g and its activity ~$10^8$ dpm. $PbCrO_4$ was precipitated which was now labelled with RaD and was used for the measurement of its solubility in water. It must be noted that the measurement of radioactivity of RaD samples under assay was achieved using Gold Leaf Electroscope as now familiar G-M counter was not then available. This was the <u>First Application of Radiotracer to Chemistry</u>. Their historic paper begins as:

"The fourth decay product of radium emanation, RaD, shows as is well known, the chemical reactions of lead. If one mixes the RaD with lead or lead salts, the former can not be separated from the lead by any chemical or physical methods; and once the complete mixing of the two materials has taken place, the concentration ratio remains the same even for arbitrarily small amounts of lead that one removes from the solution. Since RaD as result of it's activity, can be detected in incomparably smaller amounts than lead, it can thus serve as a qualitative and quantitative proof of the presence of lead to which it is attached: <u>RaD becomes an indicator of lead</u>." When this pioneering work was done the development of the concept of isotopes was in a nascent stage. Soddy introduced the word isotope in a letter to 'Nature' dated 4th Dec. 1913 and thus the radioisotopic tracer then called as radioindicator was successfully used in chemistry before (~ 9 months) the birth of the word "Isotope". Hevesy and Paneth have defined the terms "indicator" as in problems of this kind in which the radioelement is not the object but the agent of investigation, we say that the radioelement serves as "Indicator". Today the term "radioindicator" is commonly used as "radiotracer" or "radioisotopic tracer".

In order to test whether his landlady, in Manchester, in spite of denial, was using the remains of the Sunday pie in meals served later in the week, Hevesy secretly added on Sunday some thorium active deposit in the pie and on the following Wednesday, using electroscope, showed to the landlady the presence of radioactivity in the food served. Hevesy did not consider this as the First Tracer application although it is sometimes quoted so.

In the next application of radiotracer, Hevesy and Paneth investigated the electrochemistry of bismuth (using RaE) and lead and showed that Nernst's law of the dependence of the electrode potential on the ionic concentration remains valid even at extremely low concentration. They isolated visible amounts of RaD from large number of old radon bulbs and measured the electrode potential of the deposited RaD which was found to be identical with that of lead.

The radiotracer technique was limited to the natural radioactive tracers then available, which are mainly isotopes of Bi (RaE) and Pb (RaD and ThB $^{212}$Pb, $T_{1/2}$=10.6hrs.). They, however, exploited these to a number of applications. In the self-diffusion studies which are possible only with radiotracers, ThB ($^{212}$Pb) was condensed on the surface of lead foil and thus labelled foil was counted for activity using ZnS scintillation counter [ activity results from the disintegration products of ThB, (ThC & ThC') which attain radiochemical equilibrium in a few hrs.]. When the foil is heated, say at $200^oC$ for a few hours, the diffusion of ThB atoms into lead foil takes place thereby reducing the -count rate. The counting of recoil particles accompanying particle emission, by ionization measurements, helped to measure even small diffusion. By this technique diffusion coefficients as small as $10^{-12}$ cm$^2$/day were measured.

A kinetic interchange between lead atoms of solid $PbCl_2$ and the lead ions of a surrounding saturated $PbCl_2$ solution was studied using ThB ($^{212}$Pb) labeled solid $PbCl_2$. It was found that ThB passed into the solution. The bulk rate of dissolution of $PbCl_2$ in pure water was much greater than the measured rate of exchange with a saturated $PbCl_2$ solution and this suggested that only the surface was concerned in the exchange. Similar studies by Paneth on the interchange between solid $PbSO_4$ and the labelled lead ions of the saturated $PbSO_4$ solution revealed that only the uppermost layer of the solid

PbSO$_4$ participated in an interchange process. When a metallic lead surface is surrounded with the labelled lead salt solution, many atomic layers of the surface of lead foils participated in the interchange.

**Isotope Dilution Analysis**

RaD was used in the measurement of lead in rock samples. In the method used, the rock sample is dissolved and lead present is electrolytically deposited as peroxide. But how to ascertain that total lead in the sample is recovered? For this, a known activity of RaD is added to rack sample solution and the usual electrodeposition procedure is carried out. Finally the activity of lead peroxide deposit is measured from which the % recovery of lead is calculated. It was found the recovery varies from ~50% to ~100% depending on the rock sample. This is the First Application of Isotope Dilution Analysis. Subsequently it was extended to Reverse Isotope Dilution Analysis.

**Intermolecular Exchange**

Hevesy in collaboration with E.Rona investigated the intermolecular exchange of atoms of the same kind. For this equimolecular quantities of ThB labelled Pb(NO$_3$)$_2$ and unlabelled PbCl$_2$ were dissolved together, a time was allowed for exchange, if any, and subsequently PbCl$_2$ was separated by crystallization. On measuring the activity of the separated PbCl$_2$ it was observed that half of the active atoms originally present in the Pb(NO$_3$)$_2$ had been transferred to PbCl$_2$. This is the direct and striking proof of correctness of the theory of electrolytic dissociation put forward by Arrhenius some 40 yrs. ago. In 1922 Hevesy met Arrhenius who was most pleased with this work. Similar experiment was carried using labelled PbCl$_2$ and tetraphenyl lead and it was found that the activity of separated PbCl$_2$ was almost the same as that of the original labeled PbCl$_2$. As lead atom is bonded directly to carbon atom in tetraphenyl lead, no exchange occurs.

**Use of Radiotracers in Life Science Studies**

Hevesy was working in Bohr's Institute in Copenhagen from 1920-1926. As mentioned earlier the most useful radiotracers then available were RaD ($^{210}$Pb), ThB ($^{212}$Pb) and RaE ($^{210}$Bi). These heavy elements were known to be toxic to living organism.

Hevesy in collaboration with the Department of Plant Physiology of the Agricultural College investigated the absorption and translocation of lead by plants. Bean seedlings roots were immersed in ~$10^{-5}$ M Pb(NO$_3$)$_2$ solution labelled with radiotracer ThB ($^{212}$Pb). After desired time seedlings removed, washed and various plant parts viz. root, fruit, stem and leaves dried and ignited. The resulting ash samples were analysed electroscopically. It was further shown that radiotracer taken up by the seedling was entirely replaceable by inactive lead by immersion in an inactive Pb(NO$_3$)$_2$ solution. This work led to an important conclusion that in the plants, lead remains in ionic and mobile form and not organically bound in the roots. This is the First Application of Radiotracer in the Life Science.

Bismuth salts were then used for the treatment of syphilis. The conditions of absorption, distribution and elimination of bismuth injected intramuscularly into rabbits using RaE labelled bismuth preparation was investigated. Similar experiments were carried out using RaD as radiotracer. This is the First Use of Radiotracers in the Study of Animal Metabolism. These studies on the use of radiotracers in Biology were carried out ten years after the recognition of importance of radiotracers in chemical studies in 1913.

**Professor at Freiburg**

Hevesy accepted Professor's post at Freiburg in 1926 and remained there till 1934. It was known that one of isotopes of potassium is radioactive but it was not identified. Hevesy, using the evaporation method to metallic potassium, separated potassium into light and heavy fractions. From the determination of At.wt.of these fractions and measurement of their activity, it was inferred that $^{41}$K is radioactive. This was, however, found to be erroneous. Hevesy's subsequent work established that radioactivity of potassium is due to $^{40}$K. Hevesy developed X-ray fluorescence method for the determination of elements in minerals rocks and meteorites. By X-ray fluorescence, Zr, Hf, Nb, Ta, Mo, w, Ti, Cr and RE were determined.

**Deuterium as Stable Isotope Tracer**

Hevesy and Moseley in the Manchester Physics Laboratory were discussing 1913, on

applications of Radioactive Indicators in April. Hevesy told that it would of interest to him to follow the path of tea through his body. Moseley, however, felt that his wish was ideal but impractical to achieve. Heavy hydrogen, deuterium, was discovered by Urey in 1932 and he succeeded in obtaining water enriched in $D_2O$. In 1923 Urey, as American-Scandinavian Foundation Fellow, had come to Bohr's Institute, where Hevesy was then working, to study with Bohr. Hevesy and Urey had developed friendly relations. Hevesy being a tracer-minded scientist immediately saw importance of deuterium as a tracer in biological applications. He requested to Urey to send some $D_2O$ enriched water and Urey generously sent him a few litres of water enriched in $D_2O$ (0.6%) (Deuterium is present in this water as HDO and not as $D_2O$). The interchange between the water molecules of a gold fish (placed in $D_2O$ enriched water) with those of surrounding water was studied. By taking (drinking) a known volume of water of known $D_2O$ content, allowing some time for uniform distribution of this water in the body and then producing some water, say from blood sample, Hevesy measured the total body water content which resulted to the dilution of $D_2O$ enriched water swallowed. The dilution was calculated from the measurements of density of water. (Not by Mass Spectrometric Analysis). The body water content was found 67% for lean persons. In another study Hevesy drank 2 litres of $D_2O$ enriched water and his collaborator Hofer carried out density determinations on water derived from urine samples taken at various times. They concluded that, 1) Within alf an hour some water taken, reports to urine. 2) Half life of water in the body is 9  1day and 3) the average life of water in the body is 13  1.5 days. This is the First Application of Stable Isotopic Tracers in Clinical Studies and the First Application of the device of Isotope Dilution in Life Sciences. After 1933 besides deuterium, concentrated $^{15}$N and $^{13}$C became available for tracer studies mainly due to the discoveries of Urey.

**Discovery of Hafnium**

In 1914 Hevesy and Moseley had planned to carry out a joint study of the X-ray spectrum of the elements with At.Nos.68 to72 but the World War-I broke out soon and both joined their respective armies who were fighting against each other. The most tragic death of Moseley in August 1915 by Turkish bullet prevented this joint work. Hevesy, however, was destined to discover by x-ray spectrum, the element 72.

Bohr in 1922 suggested a periodic system of elements where it was inferred that rare earth series would end with At No. 71 and thus the element with At.No.72 can not be a rare earth and would belong to titanium group. This was also suggested a couple of years earlier by C.R.Bury. Hevesy and Coster working in Bohr's Institute, searched for the element 72 in zirconium rich mineral samples obtained from the Mineralogy Museum. After chemical purification of the minerals, they studied their x-ray spectra and identified the element 72, which they named Hafnium, in all the materials studied. This brought immediate confirmation of Bohr's theory of Periodic Table. French chemist Urbain, however, had claimed to have discovered element 72, both by spectrometric and x-ray spectroscopic methods, which belonged to rare earth group which he named Celtium. The controversy about this discovery continued for several years. Hevesy was nominated for Nobel Prize in chemistry several times. The Nobel Committee avoided giving prize to potentially deserving scientists embroiled in priority disputes. The committee evaded nominations for both sides of the dispute though the work of Coster and Hevesy was undoubtedly correct.

Hevesy devised crystallization of double fluoride $[(NH_4)_2MF_6]$ for complete separation of Zr and Hf. This was the only method used before World War-II. In late 40's and early 50's, as zirconium was chosen as cladding for nuclear fuel in LWR, highly successful solvent extraction processes were developed for the separation of Zr from Hf. Hevesy's separation method based on double fluorides impressed greatly Welshbach, a Pioneer in the Industrial Application of Rare Earths through his invention of the incandescent gas mantle and pyrophoric mischmetal alloy. He was then the only person having highly purified samples of all the rare earth elements. He gave Hevesy, a small quantity of each of them and at Hevesy's random choice, when asked by Welshbach; he gave a larger quantity of Dysprosium which was to turn out a variable talisman to yet another important discovery.

**Neutron Activation Analysis**

Hevesy resigned from Freiburg in July 1934 and again came to Bohr's Institute in Copenhagen. Two important discoveries in that year were to prove most important for radiotracer applications. Curie-Joliots discovered artificial radioactivity and Fermi group showed that by neutron exposure, radioisotopes of different elements can be produced. Hevesy thought of a Fairyland where radioactive isotopes of all elements are available and this was soon to become a reality.

Hilde Levi and Hevesy found that by neutron irradiation some of the rare earth elements produced strong activities, dysprosium producing the strongest activity. By measuring the activity formed, they could detect traces of dysprosium present in the samples. This was the method, now, well known as Neutron Activation Analysis (NAA). In their historic paper entitled "The Action of Neutrons on the Rare Earth Elements" they wrote, "The usual chemical methods of analysis fail as is well known, for most of the rare earth elements and have to be replaced by spectroscopic, x-ray and magnetic methods. The latter methods can now be supplemented by the application of neutrons to analytical problems by making use of both of the artificial radioactivity and of the great absorbing power of some of the rare earth elements for slow neutrons.....We used the method of artificial radioactivity to determine the dysprosium content of yttrium preparations. The procedure: We mixed 0.1% ....1% etc. dysprosium with neodymium oxide, the latter being chosen because it is one of the cheapest rare earth elements having a low neutron absorption power as has yttrium and determined the intensity (of radioactivity) obtained. The yttrium sample to be investigated was then activated under exactly the same condition and a comparison of the dysprosium activities obtained gave 1% as the dysprosium content of the yttrium sample. ....This method of analysis..... gives a direct means of identification of the Nuclei involved; this distinguishes it from all other analytical methods, chemical, spectroscopic, X-ray and magnetic, which are based on the investigation of electronic properties of the atom in question". Their NAA work was carried using a very modest (Ra-Be) neutron source.

Hevesy's Italian friend Prof. Rolla, who had prepared a few kilogram quantities of $Gd_2O_3$, sent him samples of the same which Rolla wished that they be analysed for europium by x-ray fluorescence spectroscopy. But such a setup then was not available in their laboratory. The samples were, however, analysed by NAA and it was found that all samples contained europium; the purest sample contained 0.4% of europium.

NAA method exploits the nuclear property of the element investigated. Usually the radioactive indicator must be added to the element of the atoms of which are to be traced. It is however, also possible to produce the radioactive tracer in situ by bombarding the sample with a neutron stream. The crucial measurement of liberation of neutrons, in neutron induced splitting of uranium, was carried out by neutron activation method by Joliot's group using Dysprosium and the Fermi group using Rhodium. With high neutron flux available from nuclear reactors, NAA method has emerged as one of the excellent methods for trace analysis. It is widely applied presently in radiochemistry, chemical technology, studies of environmental contaminations, crime detection, geology and soil science analysis of art and archeological objects, oil refinery, agriculture, electronics etc.

**Phosphorus-32 as Tracer in Life Science**

The radioisotope $^{32}P$ was discovered by Fermi group. Hevesy immediately recognized the potential applicability of this isotope as a radiotracer in studies related to metabolic processes. $^{32}P$ was produced by bombarding carbon disulphide, with neutrons from Ra-Be or Rn-Be source for some weeks and resulting $^{32}P$ [$^{32}S(n,p)$ $^{32}P$] was extracted with dilute acid. (Radioactive properties of $^{32}P$ are very suitable for its use as a radiotracer, $T_{1/2} = 14$ days, $E_{max} \sim 1.71 MeV$ conveniently measured by G-M Counter). The radioactive tracer $^{32}P$ thus obtained per batch was about 1 Ci or less. The $^{32}P$-phosphate was placed on bits of bread to feed to a rat. G-M counter was used to assay the amount of $^{32}P$ found in various organs and excreta as a function of time. The most important observation was that there is rapid turnover of phosphorus atoms in bone and that the formation of bones is a dynamic process; the bone continuously taking up phosphorus atoms which are partly or

wholly lost again and are replaced by other phosphorus atoms. This is the First Biomedical Application of Artificially Produced Radiotracer.

During the Harvard University Tercentenary, in September 1936, August Krogh, (NL 1920) the well known Danish physiologist and enthusiastic supporter of Hevesy's work on tracer applications, gave a lecture on the use of deuterium and radioactive isotopes of light elements for studying fundamental physiological problems. Meghnad Saha, who attended this lecture, could foresee the potential of tracer applications to chemical and biological problems. G-M counter was used then for detecting radioactivity and Saha predicted that probably a day may soon be there when G-M counter would be used for biological investigations as frequently as a thermometer. G-M counter and photomultiplier coupled scintillation detectors, which were yet to be invented, are commonly used by those using radiotracers for the desired investigations.

It is interesting to note that C.V.Raman, then director of Indian Institute of Science, with approval of Institute's Council, offered temporary readership to Hevesy for a period of six months during 1934-35, on a fixed honorarium of Rs.15000/-, who, however, declined the offer. In 1950 Hevesy was made a member of the Indian Academy of Science.

1937 onwards strongly radioactive isotope samples produced by the cyclotron became available through the ingenuity and generosity of Ernest Lawrence. With the availability of reactor produced radioisotopes of most elements at reasonable cost and the required counting setup, the radiotracer technique has flourished and is now widely used. Isotopic tracers are used in all branches of biology in elucidation of a great variety of problems especially demonstrating the dynamicity of metabolic processes. The eminent physiologist A.V.Hill (NL1922) told Ernest Lawrence that he believed that the use of such tracer elements will some day be recorded in history as a technique of equal importance with the use of microscope.

**Honours and Prizes Galore**

Hevesy's publications, including articles, reviews and books, are about 400. Hevesy is the Father of Nuclear Medicine. He received more than dozen honorary degrees from various universities in different countries, of which that received, along with Rutherford, from Cape Town University, South Africa in 1929 he enjoyed most. The prizes he won include Nobel Prize, Cannizarro Prize, Faraday Medal, Niels Bohr Medal and the most Prestigious Royal Society's Copley Medal of which Hevesy was proud. Besides he won membership of a number of academies and learned societies including Royal Society and Royal Institution. A number of societies of Nuclear Medicine in different counties have instituted Hevesy Memorial Lecture.

On his 80th birthday several letters of greeting were presented to Hevesy. Lajtha has said, "What makes a great Scientist? I would say there are two things: His work and his personality; that work which opens a whole new horizon, that work which is giving truly basic new information, information which is truly important to a large number of scientists working in a truly wide variety of fields of science – that work is great. It is given to few to have the ability or good luck to hit on and execute a great piece of work– and to very few indeed to keep hitting on and executing great pieces of work. To strike gold once may be helped by luck but to keep on striking gold is no mere luck, it is that inexplicable capacity to see possibilities ahead which make a great creative worker. As to the personality, the spectrum is wide. There are scientists who are shy and uncommunicative, there are those who drive hard and build empires, there are people with chips on their shoulders, people who grow stiff with success, people who go prematurely old and dispirited. But, there are a few who never change and never grow old, those who maintain the deep sincere enthusiasm of youth, who retain a genuine humility even when met with all the success and honors of the world. To these few, success is sort of wonderment, and to some extent irrelevant, because their inner harmony cannot be touched by it. These are people who have compassion and deep understanding because they are sincere and want to understand. Their dignity comes from their harmony, their kindness from their understanding–these few are great human beings. One can meet with great creative workers but even giants can have feet of clay. One can meet great human beings, but they may not be exceptionally creative. Very seldom though can one meet a man

who is both: a great creative genius and a great human being… Such a man is Professor George de Hevesy."

It was by a strange coincidence that on the day of the 48th anniversary of his entering the Physics Department of Manchester University, Hevesy received the 'Atoms for Peace Award'. On the occasion of the presentation of the Award, Seaborg has succinctly summarized Hevesy's scientific accomplishments. He stated:"…Science is one part curiosity, that blessing of nature without which man could never have elevated himself above the animal level. Another part is a powerful potion –a mixture of adventure, challenge, and the unexpected − which cannot be resisted, once tasted. Finally one must add a liberal dash of satisfaction in achievement. The scientist's satisfaction may come in the form of his own personal triumph over nature, and in the realization that he has added to the pool of human knowledge, which in turn increases man's total achievement and liberates his mind from the constraints of ignorance. When, in addition, the fruits of the scientist's labours palliate the cruelties nature inflicts upon the body or otherwise provide techniques for the improvement of the general welfare, then the cup of the scientist's satisfaction overflows….few living scientists have partaken the joys of science to the extent that Professor de Hevesy has. He has known to the full the nagging spur of curiosity, the thrill of adventure and the unexpected, and the sweet joy of defeat turned into victory. And few men claim more the right to satisfaction in achievement – in the expansion of human knowledge and in the immeasurable and enduring benefits of his work for mankind. The Atoms for Peace Award would seem to have been designed especially to fit the life and the work of Professor George de Hevesy".

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# C.V. Raman (1888 –1970):The Man of Science

*Dr. (Ms) Romola D'Cunha joined the 9th batch of the Training School of Bhabha Atomic Research Centre after a brilliant academic career. She was awarded the first Homi Bhabha Prize for academic excellence in 1966 and joined the Spectroscopy Division of BARC as a Scientific officer. She received the Ph.D. degree in 1979 from Mumbai University for her studies on the Vibration Spectra of Molecules and was awarded a National Science Foundation (NSF) travel grant for Post-doctoral studies at Ohio State University (OSU). She was subsequently invited as visiting scientist to OSU for a period of three months each in 1988 and 1990. Dr. D'Cunha was also awarded the NSF Fellowship in 1995 for collaborative research at NASA Langley (Virginia, USA) and the National Institute of Standards and Technology (former NBS). In 2000 she was invited as Senior Scientist to Okayama University under the Japanese Society for the Promotion of Science (JSPS) programme. In her research career spanning 35 years she has published more than 100 papers in journals and conference proceedings. Her research interests included the Infrared and Raman studies of molecules of interest in material sciences, environmental pollution, planetary atmospheres and laser development programmes. She is the life member of several scientific associations (IPA, IWSA & ISEST). Since her retirement as the Head of IR & Raman spectroscopy Section of BARC, she has been active as a resource person in Refresher Courses for University lecturers and post-graduate students.*

*"There is only one solution to India's economic problems, and that is science, more science and still more science!" Sir C.V. Raman*

*Chandrasekara Venkata Raman, the only Indian to have won the Nobel Prize for contributions to science, made from within the country, was born on 8th November 1888 in a village near Tiruchirapalli. He was the second son of R.Chandrasekara Iyer and Parvathi Ammal and the younger brother of C. Subramanian Iyer.*

## The wonder Years

Raman was a brilliant student and a voracious reader although he lacked physical strength. He passed out of school at the tender age of eleven and entered Presidency College at the age of thirteen with a scholarship. He soon made a name for himself as the best student with a flair for English, Science and Physics in particular. Raman topped the B.A.

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exam with honours bagging all the prizes and was advised to go to England to prepare for the much coveted I.C.S. where usually only the Britishers made the grade. The Civil Surgeon of Madras who conducted the mandatory medical examination declared Raman unfit, "The only examination that Raman ever failed". In later years, Raman said he would ever be grateful to this man for obvious reasons! He enrolled for a degree in M.A. (Physics) and undertook original research in optics and acoustics. He published his first paper on the diffraction of light in Philosophical Magazine (London) while still in his teens, before passing his M.A. in January 1907. Inspite of his deep interest in science, due to lack of opportunities in the country (England was ruled out) he applied for a Government job in Financial Civil Services. He got married the same year to Lokasundari from Madurai and in mid 1907 proceeded to Calcutta to work as Assistant Accountant General. At a princely salary of Rs. 400/ and a marriage allowance of Rs 150/, this transition from science to Government service would have meant a life of obscurity for a man of Raman's calibre, but destiny had other designs for him. On his way to work each day by tram, his discerning eye noticed the building at 210 Bow Bazar Street with the board "Indian Association for the Cultivation of Science" (IACS) (founded by Professor Ashutosh Dey in 1876). He made enquiries at the Association and was given full freedom to carry out experiments. In the evenings after work and on all holidays Raman dropped in at the Association and engrossed himself in research. This marked the turning point in Raman's life as well as that of IACS. He set up a dedicated research team and carried out experiments in the field of optics and acoustics. He is said to have excelled in acoustics and sparkled in optics! (1). His initial studies were on sound, and the physics of stringed and other musical instruments (the tambura, veena, violin, tabla & even the piano). His paper reported from IACS was the first to be published from the Association in its thirty years of existence! He worked for ten years at the Association and published 27 papers in outstanding journals such as Nature (England) and Physical Reviews (USA). He frequently delivered popular lectures and regaled his audiences with his keen sense of humour and good command of English. He was awarded the Curzon research Prize in 1912 and Woodburn research Medal in 1913, while still in

Government service. The extraordinary genius of Raman and his enthusiasm to pursue scientific research attracted the attention of the Vice Chancellor of Calcutta University Prof. Ashutosh Mukherji who offered Raman the Chair of the first Palit Professor of Physics at Calcutta (Kolkata) University. Raman accepted the offer and gave up a lucrative Government job with attractive prospects for a university professorship at Calcutta University, which meant a huge pay cut from Rs 1100/ to Rs 600/ per month. To quote Sir Ashutosh Mukherji who was deeply touched by this gesture, "there is no lack of seekers of truth in the temple of knowledge!" Raman started experiments in Optics and supervised several Ph.D. students although he himself did not possess one, and in 1921 the University conferred on him an honorary doctorate. The same year he was persuaded to attend the University Congress at Oxford where he met the famous physicists of the time – Thompson, Bragg, Rutherford and others. He was easily recognized as the illustrious Indian scientist because of his trademark Madras turban.

**The Historic Voyage**

Raman's return trip was historic. On board the Narkunda, his attention was drawn to the deep blue colour of the Mediterranean, which he felt was molecular in origin and neither due to the reflection of the sky nor due to the dissolved impurities as was generally believed. He was some how convinced that the blue colour of the sea was related to the scattering by water molecules. On his return to India he rushed to his laboratory in Calcutta and he and his colleagues engrossed themselves in intense studies on the scattering of light by solids, gases and mainly liquids which ultimately culminated in the discovery of the Raman Effect. He verified his ideas with ingeniously devised experiments using sunlight as the source, liquids in a flask as sample and the human eye as the detector, with suitable optical filters to isolate a narrow band of wavelengths in the path of the incident as well as scattered light. Most of the scattered light was found to be at the same wavelength ( ) as that of the incident radiation, but his discerning eye noticed some weak features shifted to longer wavelengths (lower frequencies = c/ ) which were found to be dependent on the scattering species. He termed the weak features as a new "feeble radiation". This phenomenon was later

labeled as the Raman Effect by Pringsheim of Berlin. His primitive set up was later improved upon to include a mercury arc as the source, smaller amounts of samples in a bent tube (to recondense the evaporated sample) and a prism spectrograph (to disperse the scattered light) and a photographic plate for recording the spectra. Since Raman scattering is inherently weak, long exposures of several hours and even days were often required. The whole set up was enclosed in a box to prevent interference from stray light and it was often referred to as the "Black hole of Calcutta!". The results were confirmed by the study of more than 60 samples, mostly liquids. The liquids initially studied included carbon tetrachloride (an efficient scatterer), benzene, toluene and alcohol. When later Raman attended parties his friends coaxing him to drink would often joke and say "we know the Raman effect of alcohol, how about seeing the effect of alcohol on Raman?". In 1924 he became the fourth Indian only to be elected as the Fellow of the Royal Society (FRS) at the age of 36. When asked "what next", "the Nobel Prize of-course" he is reported to have quipped! Presumptious as these words may seem, they came from a man who was deeply committed to pursuing excellence in science and who was confident in achieving the best with the limited resources at his disposal. In later life when a young despondent colleague complained that while he had only a 10KW lamp, his contemporaries in England worked with a 100KW lamp, "put your 100KW brain to work" was reported to be Raman's advice!

**The Nobel Prize**

On February 28$^{th}$ at a press conference the discovery of the "new feeble radiation" was announced to the world. Raman was so confident of the importance of his discovery that in July 1930 he booked his passage to Stockholm by ship so as to be in time for the Nobel awards ceremony! In 1927 A.H. Compton received the Nobel Prize for Compton scattering of X-rays and in 1930 on December 10$^{th}$ C.V. Raman was awarded the Nobel Prize in Physics for Raman scattering. At the investiture ceremony it was the practice to raise the flag and play the national anthem of the country of the awardee when his or her name was announced. When Raman's turn came to receive the award, the Union Jack was unfurled and the British national anthem was played! The fierce nationalist that he was Raman's eyes turned misty at the thought that his beloved country was yet to attain independence from the British. "He looked like a prince from the Arabian Knights in his Indian dress and turban!" He was conferred the Knighthood by the British the same year, and acquired the title "Sir C.V. Raman".

In 1933 Raman left Calcutta with a heavy heart due to personal and professional problems to join the Institute of Science at Bangalore as its director. In addition to the studies on the Raman Effect, he created a school for research in colloids, ultrasonics, spectroscopy and the theory of solid state of matter. His other interests included the study of lattice vibrations in solids (diamonds, precious stones, shells and minerals) and unraveling nature's secrets. "He approached nature with childlike curiosity – he must touch, feel and play with sound waves and light waves often using nature as his laboratory" (1). He was passionately committed to science and neither power nor money could draw him away. Raman also founded the Indian Academy of Sciences of which he was the founder president. He initiated efforts to invite eminent scientists like Max Born and E. Schrodinger to provide training to young researchers to prevent "brain drain", but his efforts proved futile due to objections from vested interests. Raman gave up the directorship of the Institute under controversial circumstances but continued to work there as a professor till his retirement in 1948.

**The Raman Effect**

Unlike the earlier phenomenon of scattering of light explained by electromagnetic theory, the Raman Effect had to be tackled by quantum mechanics. The photons of the incident radiation interact with the various energy levels (vibrational, rotational and electronic) of the scattering species, exchanging energy with the system (inelastic scattering) leading to a shift in wavelength ( ) or frequency ( $=c/$ ) of the scattered radiation. Raman spectroscopy is thus concerned with the phenomenon of a change in frequency when light (usually in the visible region) is scattered by molecules. If the frequency of the incident light is $_0$ and that of a component of the scattered light is $_i$, then ( $_0$ $_i$) = is referred to as the Raman frequency (line) and the set of Raman frequencies

constitute the Raman spectrum of the scattering species. The lines observed at higher frequencies are called the anti Stokes lines (weaker) while the ones on the lower frequency side are called the Stokes lines (the molecule either looses or takes away energy from the incident photon respectively). The shifts observed in the scattered light are related to the vibrational modes of the scattering molecule.

A major portion of the light is scattered without a change in frequency (elastically) and is referred to as Rayleigh scattering The intensity of the scattered light follows the scattering law and varies as the fourth power of the frequency ($\nu^4$ or $1/\lambda^4$). The blue of the sky arises due to more efficient Rayleigh scattering in the blue region of sunlight by atmospheric molecules (due to its higher frequency or lower wavelength). $I_{ray} \propto I_0 \lambda^{-3}$ and $I_{ram} \propto I_{ray} \lambda^{-3}$, where $I_0$, $I_{ray}$ and $I_{ram}$ refer to the intensities of the incident light and the Rayleigh and Raman scattered light respectively. The vibration Raman spectra are most commonly reported in literature although the rotational Raman spectra of a few homopolar diatomic gases such as hydrogen, nitrogen and fluorine have also been studied.

For a vibrational mode to be active in the Raman it has to be accompanied by a change in polarisability (measure of the ease of distortion of its charge cloud) while in infrared absorption (IR) it needs to be accompanied by a change in dipole moment. For a molecule, with a center of inversion, group theory predicts that the modes that are active in the Raman will be inactive in the IR and vice versa. This is called the mutual exclusion principle which is very useful in determining the symmetry and the structure of molecules. The weak Raman scattering by water molecules makes it a favourable solvent (eg. for biological studies) unlike in the IR where it has strong absorption bands. Thus Infrared and Raman Spectroscopy are complementary techniques. With the discovery of the Raman Effect the whole range of vibration spectra ($10 - 4000 \text{ cm}^{-1}$) could be obtained with relative ease by using simple inexpensive instrumentation. Vibrational spectra are commonly represented in wave number units ($\text{cm}^{-1} = 1/\lambda = \nu/c$).

## Applications of Raman Spectroscopy

*"The universality of the phenomenon, the convenience of the experimental technique, and the simplicity of the spectra obtained enable the effect to be used as an experimental aid to the solution of a wide range of problems in physics and chemistry. Indeed, it may be said that it is this fact which constitutes the principal significance of this effect. The frequency differences determined from the spectra, the width and character of the lines appearing in them, and the intensity and state of polarization of the scattered radiations enable us to obtain an insight into the ultimate structure of the scattering substance".*

These words, taken verbatim from Sir C.V.Raman's Nobel lecture delivered at Stockoholm in 1930, seemed presumptious at the time they were made and were received with much skepticism due to the primitive type of equipment that was available for these studies at that time, and IR spectroscopy appeared to be the technique of choice. The wide range of applications of Raman spectroscopy (in pure and applied sciences) to problems in physics, chemistry, biology, biochemistry and medicine, including environmental sciences several decades later has now become a reality and bear testimony to Raman's prophetic words This "Raman Renaissance" can be largely attributed to significant advances in technology with the availability of laser excitation sources, spectrometers, ultra sensitive detectors, signal processors and computers for data handling. Raman spectra can now be obtained from minute quantities (<1 $\mu$g or 1 $\mu$l) of samples in almost any condition or environment.

The important parameters obtained from the Raman spectra are:

1. The frequency shifts from the excitation line which correspond to the positions ($\text{cm}^{-1}$) of the vibrational modes of the scattering molecule and therefore can be used in the identification and characterization of molecules.

2. Intensities and scattering cross sections measured at moderate levels of excitation are proportional to the concentration of the

scattering species and hence can be used for quantitative studies.

3. Depolarisation ratios (an experimentally measurable quantity) are useful in determining the symmetry of the vibrational modes and therefore the molecular structure.

4. The width and asymmetry of the Raman lines provide information on intermolecular interactions.

5. Pressure and temperature studies are useful in the study of phase transitions (in crystals, biopolymers, model membranes etc.)

The above mentioned parameters are also echoed concisely in the Nobel lecture delivered by Sir C.V. Raman and reveal his deep insight and perception.

Raman spectroscopy can be conveniently used for the characterisation, identification and structural determination (in favourable cases) of molecules. When H.W.Kroto, R.F.Curl and R.E. Smalley (2) announced the discovery of $C_{60}$ they made an intuitive guess and proposed that the molecule should have the structure of a football made up of 5 and 6 membered rings (with alternate single & double bonds between the carbon atoms). If the molecule indeed had this structure then Group theory predicts that it would belong to the Icosohedral point group ($I_h$), with four highly degenerate IR bands and ten Raman bands (two of them totally symmetric and therefore polarized). Moreover, such a highly symmetric structure ($I_h$), would have a center of inversion and therefore would be expected to obey the mutual exclusion principle. When methods to prepare larger quantities of the sample became available the IR and Raman spectra of $C_{60}$ were recorded and these facts were indeed borne out, thus confirming experimentally for the first time the structure of this exotic molecule. Structural deductions based on symmetry properties have also been possible in the study of compounds which exist in several molecular conformations or isomeric forms such as cis and trans isomers. The trans isomer with a center of inversion would be expected to obey the mutual exclusion principle. Determination among several possible crystal structures based on polarization measurements have also been reported. Homopolar molecules such as hydrogen, nitrogen, fluorine etc do not possess a permanent dipole moment and produce no change in the dipole moment during vibration and hence their pure rotational and vibrational spectra cannot be obtained through Microwave or IR spectroscopy. The rotational as well as vibrational Raman spectra of these molecules have been studied and provide information on the bond lengths and bond strengths (force constants).

An important application of Raman studies is in the characterisation of new materials. Raman in his quest for new materials of interest picked on diamond and its remarkable properties and it became a life long obsession with him, calling it the "Prince of solids". He borrowed gems and took precious stones on loan for study from rich friends and princes. There are reports of a large diamond (140 carats) that he borrowed from a Maharaja against a huge deposit and his student (the famous physicist Professor Bhagavantam) spent two sleepless nights while its spectra were being recorded for fear of it being stolen! He even bid at auctions at the diamond mines in M.P. and had a collection of 310 diamonds. There were reports of almost all his students being engaged at one time in the study of some aspect or the other of diamond!

Interest in diamond and diamond like films has recently revived. Due to its hardness and inert properties, there have been attempts to produce diamond coatings on industrial tools, surgical scalpels (for bloodless surgery!) and pace makers (for heart patients). Various techniques such as hot filament chemical vapour deposition (HFCVD), Microwave CVD, high pressure CVD etc have been developed. The optimization of the process parameters such as, the temperature, pressure of the seed gas (eg. $CH_4$/Ar), choice of substrate etc can be carried out from the study of the Raman spectra of the films. A sharp peak at 1332 cm$^{-1}$ not only identifies a good quality diamond, but the width and asymmetry of the peak and the absence of the broad band - 1500 cm$^{-1}$ due to graphite (impurity) provide information on the quality of the film and in the control and optimization of the process parameters (3). The integrity of natural gem quality, colourless diamond, against gems treated by high temperature and pressure (to render them colourless) has been possible through distinctly different signatures observed apart from the 1332 cm$^{-1}$ diamond peak common to both. The Raman fingerprint of diamond

is also used by Gemological Institutes to distinguish real diamonds from fake ones and also to identify inclusions.

To Raman, science was the highest form of art! Raman spectroscopy has emerged as an ideal, in-situ, nondestructive technique, with high spatial resolution for the identification of pigments in medieval works of art, such as paintings, manuscripts and ceramics. Analysis of pigments in paintings is of major significance as it can lead to detailed characterization of the materials, and is therefore important for dating, authentication (detection of fakes), conservation and restoration of artwork (4). The Raman spectrum provides a unique molecular spectral fingerprint of each pigment and scores over other analytical techniques such as SEM, XRF, XRD and PIXE. Raman microscopy can address questions such as:

1. The pigments used by the artist, single pigment or mixes to achieve the desired shade and effect. The impressionist painters (eg. Claud Monet) used synthetic CdS as the yellow pigment (-1846). In the latter part of the 19th century Cadmium seleno sulphides were introduced to achieve various shades ranging from orange to maroon depending on the Se content.

2. Restoration of flawed medieval paintings can be carried out more faithfully when the actual compositions of the pigments, used in a localized area, are known. The flaw observed in the restoration of a 16th century icon was attributed to the use of Zinc White (ZnO; 1834A.D.) as compared to Lead White - $2PbCO_3$, $Pb(OH)_2$ (500 – 1500 B.C.) used in the original painting from their Raman signatures (5). Rutile – titanium (IV) oxide has been in use since 1947.

3. Conservation and care: study of the effects of heat, light, pollutants and degradation products are needed to protect national treasures. 13th century painters used vermillion (red pigment) which is naturally occurring cinnabar Hg(II)S (Raman band at 250 cm$^{-1}$) and is sensitive to moisture while synthetic read lead was introduced in later years (bands at 180 cm$^{-1}$ and 550 cm$^{-1}$ ).

4. Dating and authentication: Medieval artifacts used inorganic pigments such as minerals and organic pigments of natural origin (eg. Indigo from plants) while synthetic pigments were introduced in later years and the relevant information has been well documented. Detection of synthetic pigments against naturally occurring ones used in medieval paintings thus clearly help in "dating" and authentication of national treasures and is therefore helpful in museums and art galleries and in auction houses for judging the value of a painting (and distinguish fakes) (4,5).

In the development of environmentally friendly fuel cells, the presence of $NO^+$ ions in the solid electrolyte (due to contamination) can lead to performance deterioration. Its presence can be easily detected through its strong Raman peak at 2250 cm$^{-1}$. Using Raman LIDAR (Light Detection And Ranging) pollution measurements from automobile exhausts and industrial smoke plumes have been reported. Signatures of CO, $C_2H_2$, and other hydrocarbons have been detected.

The use of water (weak Raman scatterer) as a favourable solvent in Raman has led to extensive studies in biological systems. Investigations on naturally occurring model membranes and polymers related to more complex biopolymers have been carried out to identify characteristic features of the various components. The change in frequencies, relative intensities and bandwidths, with concentration, temperature, pH and ionic strengths are useful inputs in these investigations. Phase transitions, conformational changes (eg. photo isomerisation of the visual pigment Rhodospin), drug-protein interactions have also been reported and can be extremely useful in clinical trials.

Surface Enhanced Raman Scattering (SERS), a widely applicable tool in surface physics and chemistry was first reported in the context of an electrochemical cell. Organic molecules mainly those containing nitrogen atoms (such as pyridine, pyrrole, benzotriazole, proteins etc) when absorbed on silver or gold colloids (nanoparticles) are known to show enhancements of the order of $>10^4$ or more when compared to their normal spectra. This is seen to be accompanied by relative changes in intensities, bandwidths and frequency shifts of specific bands.

The data have been interpreted to provide information on the relative orientation of the molecules on the Ag/Au nanoparticles and has promising analytical applications (single molecule detection). SERS has opened up exciting opportunities in Life Sciences and provides ultra sensitive detection and characterization of biophysically and biomedically relevant molecules and related processes. SERS detection and identification of microorganisms, neurotransmitters, DNA and RNA fragments, and studies inside living cells have been reported (6). The technique has been used to monitor intracellular distribution of drugs in the cell and to study anti tumor drugs/nucleic acid complexes using colloidal gold nanoparticles. Assignment of the Raman features inside the cell nucleus and cytoplasm to chemical constituents such as DNA, RNA, phenylalanine and tyrosine are some of the interesting developments in this field. Ultrasensitive Raman spectra inside living cells open up possibilities for monitoring small chemical changes in the cell which could be precursors of larger morphological changes. These studies have opened up exciting opportunities for the diagnosis of diseases such as cancer at an early stage and in the pharmacological development of appropriate drugs (6).

The field of Raman spectroscopy is still vibrant with new frontiers opening up leading to newer and more challenging developments and applications, especially those related to higher order Raman effects from the use of high power lasers.

**The Twilight Years**

In 1939 the war broke out in Europe while Homi Bhabha was holidaying in India after his return from Cambridge, and in 1940 under persuasion from Raman joined the Institute of Science as Reader of Physics. This was a turning point in the life of Bhabha who went on to become the founding father of the Atomic Energy programme in India. The best tribute to Raman was indirectly paid by Homi Bhabha, when he resolved to continue in India after the war. Although they disagreed on issues, they both shared a common love for nature, a quest for aesthetics and enthusiasm for science. Raman even toyed with the idea of doing experiments in Nuclear physics but could not afford the cost of a tiny sample of radium!. He even advised

a young Vikram Sarabhai to look for Cosmic ray tracks in photographic emulsions, confident that it would lead to a Nobel Prize! Sarabhai's interests however lay elsewhere.

Two years prior to his retirement Raman began to plan and develop his own research institute, later named after him as the Raman Research Institute (RRI) with his own resources and funds raised through friends and philanthropists. All his life he was skeptical of approaching the government for funds and was critical of friends and colleagues who gave up scientific pursuits for lucrative government positions. He declined vice- presidentships of organisaions saying, "of what use is this ship?". Retirement to Raman was just a change of venue and he continued his scientific pursuits with equal vigour. During the first year at RRI there was no electricity and yet using sunlight and a few lenses he carried out beautiful optical experiments! Visitors still marvel at the beautiful garden with its layout that Raman had planned and supervised himself. He was close to nature and loved trees, flowers and above all his rose garden and often spent time in his garden to think, relax and draw inspiration.

Raman soon grew increasingly isolated and earned the displeasure of his colleagues and bigwigs for his caustic comments on public affairs, especially concerning wasteful expenditure on import of sophisticated equipment from abroad. He was an experimentalist and shied away from quantum theory and was criticized for not matching his observations with theoretical interpretations. He became a disillusioned man, avoided meeting people and became a recluse. Had the tremendous progress in Raman Spectroscopy and its fascinating range of applications taken place during his lifetime, Raman might have derived much comfort and happiness. Nevertheless, from his despondent mood Raman woke up to the happy world of children. In the youth he saw the future of a strong and resurgent India. He would take them round his garden, regaling them with interesting anecdotes and introducing them to the enchanting world of science. He started accepting invitations to give lectures in schools and would enthrall the students with his oratorical skills and fascination for science.

On Raman's 80th birthday (1968) he was felicitated at the Science Congress at Ahmedabad

and was asked by Dr. Vikram Sarabhai to dedicate the Community Science Centre to the youth. In his address aptly titled "Why is the sky blue ?", he urged his young audience, "… look up at the sky and ask why is the sky blue? You learn science by keeping your eyes and ears open. We see all kinds of miracles happening in nature – we take them for granted. The essence of the scientific spirit is to look beyond and realise what a wonderful world we live in!" Raman breathed his last on 21st November, 1970, and was cremated on the grounds of the Raman Research Institute. In keeping with his wishes, there were no religious ceremonies, no plaque nor monuments in his memory. A solitary tree at the site stands tall and majestic as a memorial to the man who loved nature, looked to it for inspiration, and in death chose to be reunited with nature. The tree was reported to have bloomed for the first time in 1986 –1987.

February 28th, the day of the discovery of the Raman Effect is celebrated in India as National Science Day - a fitting tribute to the man whose mission was to promote science in the country and whose vision was to look beyond and probe the very depths of nature. His legacy to the world is the Raman Effect and its applications.

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# Discovery of neutron by James Chadwick and its use in condensed matter research by Bertram N. Brockhouse and Clifford G. Shull

**Dr. S.L. Chaplot** *joined BARC (1974) through 18th Batch Training School and joined Nuclear Physics Division. Presently he is Head of Solid State Physics Division, BARC. His research involves the study of the structure and dynamics of various materials using neutron scattering and other experimental and theoretical techniques. He was the recipient of the DAE Homi Bhabha Award for Science and technology for 1994, a higher honour bestowed by DAE, Government of India. He was a Research Associate at University of Edinburgh (1979-81), a young Associate of the Indian Academy of Sciences (1985-90), recipient of the N.S. Satya Murthy Memorial Award of the Indian Physics Association (1989), the Alexander von Humbold Fellowship, Germany (1992) and the Material Research Society of India Medal (2002).*

## Summary

James Chadwick was awarded the Nobel Prize for Physics in 1935 for the discovery of the neutron. The 1994 Nobel Prize in Physics was awarded jointly to Bertram N. Brockhouse and Clifford G. Shull for pioneering contributions to the development of neutron scattering techniques for studies of condensed matter. The article will briefly discribe their contributions.

## Introduction

The existence of neutron is now taken for granted. However its discovery in 1932 was path breaking and occurred at nearly the end of a relatively brief era in early twentieth century when the face of Physics changed forever. We are all too familiar with the then unimaginable role that the neutron was to play in subsequent march of the mankind. Let us start with the Nobel Prize story of the discovery of the neutron. We shall follow it with another Noble Prize story of rather wide use of neutron in condensed matter research that is much less known than the greater role in nuclear fission.

## The Discovery of Neutron

Radioactive disintegration of atoms showed the presence of electron and proton with electrical charges. In 1930, Bothe and Beeker found a new radiation (called the radiation of Beryllium) on bombarding beryllium with alpha particles that was extremely penetrating up to several centimeters in brass without any significant loss of energy, but then causing disintegration of Beryllium atoms on hitting them.

Initially the new radiation was thought to be like gamma rays. On bombarding this new radiation to hydrogenous substances produced protons whose energies could be estimated from particle tracks in Wilson chambers. By extensive studies of energies on collisions, Chadwick showed that the new radiation could not be gamma rays.

Rutherford had suggested in 1920 the existence of neutron having the same mass as proton but without any charge. The neutron could not be detected in experiments involving electric or magnetic fields. Chadwick studied the exchange of energies on collision with nuclei and found the results consistent with his supposition that the new radiation may be neutrons. Chadwick further examined the exchange of mass upon the collisions between various nuclei and could estimate the mass of the neutron to be very close to that of proton. Chadwick also used his new method to determine

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more exact values of the atomic weight of a number of elements.

**Applications of Neutron in Condensed Matter Research**

Much later in 1994, Nobel Prize was awarded on utilization of neutrons in condensed matter research primarily as a technique. The prize was given to Shull and Brockhouse for development of neutron diffractions and neutron spectroscopy respectively. This recognition was probably prompted by many major and important contributions of neutrons in research and technology e.g. in study of crystal structure and dynamics of ceramic superconductors, the connection between ordered and non-ordered structure of polymers and their elastic properties (related to the Nobel Prize to de Gennes is 1991), structure of viruses, molecular dynamics at surfaces relevant to catalytic exhaust cleaning and diffusion in batteries. At present there are about 7000 users of neutron facilities, which include about 4000 in Europe alone.

Brockhouse and Shull developed the neutron techniques as early as 1940s and 1950s. Shull started working at the nuclear reactor at Oak Ridge in a new group lead by E. O. Wollan. He used the elastic scattering of neutrons that change direction without losing energy when they collide with atoms. The wavelengths of thermal neutrons are of a value close to typical distances between neighbouring atoms in a solid or a liquid. Therefore neutron diffraction is useful to study how atoms are arranged with relation to each other in a sample, i.e. the structure of the sample. Unlike with X-rays, it was easy to determine the positions of light elements such as hydrogen in metallic hydrides, or that of hydrogen, carbon and oxygen in organic substances. Since the magnetic spin of the neutron interacts with magnetic moments of electrons, neutron diffraction also shows how atomic dipoles are oriented in magnetic materials.

Brockhouse used the inelastic scattering of neutrons, which change both direction and energy when they collide with atoms. The energies of thermal neutrons are of similar value as that of thermal energies of atoms or molecules in solids and liquids. Therefore neutron spectroscopy gives information on the dynamics of atoms in the sample and is also used to study dynamics of magnetic

moments of atoms in samples. With his 3-axis spectrometer Brockhouse measured energies of phonons (atomic vibrations) and magnons (magnetic waves). He also studied how atomic structures in liquids change with time. Inelastic neutron scattering provided unique information about the details of atomic dynamics of various kinds, be it vibrations, diffusion or fluctuations of magnetic moments, or dynamics of interactions with electrons. It is said that Shull helped find "where atoms are" and Brockhouse helped answer "what atoms do".

From BARC, P. K. Iyengar, K. R. Rao, B. A. Dasanacharya and A. P. Roy worked with Brockhouse during 1950s and 1960s on many important problems of phonons in solids and liquids.

**The Nobel Prize in Physics 1935 "for the discovery of the neutron"**
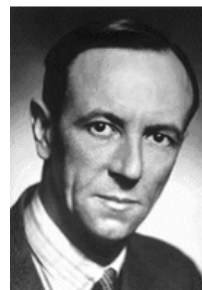


*James Chadwick, United Kingdom, Liverpool University, Liverpool, United Kingdom (b. October 20, 1891, d. July 24, 1974)*

Born in Cheshire, England. Obtained M.Sc. in 1913 working with Rutherford at Physical Laboratory at Manchester. Later moved to Berlin to work with Geiger. Returned in 1919 to Cambridge to again work with Rutherford on transmutation of various light elements by bombardment with alpha particles. Assistant Director of Research in the Cavendish Laboratory (1923). Lyon Jones Chair of Physics in the University of Liverpool (1935). Head of the British Mission attached to the Manhattan Project in USA (1943). Returned to Liverpool (1946). Master of Gonville and Caius College, Cambridge (1948-1959).
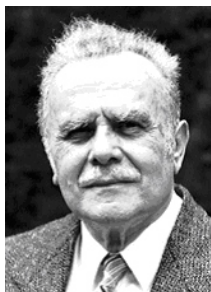
**The Nobel Prize in Physics 1994**

"for pioneering contributions to the development of neutron scattering techniques for studies of condensed matter",

"for the development of neutron spectroscopy",

"for the development of the neutron diffraction technique"



*Bertram Neville Brockhouse, Canada,*
*McMaster University, Hamilton, Ontario,*
*Canada,*
*(b. July 15, 1918, d. October 13, 2003)*

Born at Lethbridge, Alberta, Canada. Obtained M.A. in 1948 and Ph.D. in 1950 (Physics : Solid State) from University of Toronto. During 1950-1959 Betram was Research Officer at Chalk River Laboratory and he was seconded for 10 months to Brookhaven National Laboratory during 1953-54. He was Head, Neutron Physics Branch CRNL, (1960-1962) and Professor of Physics, McMaster University, Hamilton, Ontario, Canada (1962-1984). Sabbatical year (1970-71 - Guggenheim Fellowship - BNL, ORNL in USA, AERE Harwell, England). Retired in 1984.

Prof. Clifford Glenwood Shull born at Pittsburgh, Pennsylvania, USA. Obtained Ph.D in 1941 from New York University. Position at Beacon, NY with the research laboratory of The Texas Company (1941). He studied the icrostructure of catalysts using gas adsorption and x-ray diffraction and scattering as tools for haracterizing



*Clifford Glenwood Shull, USA*
*Massachusetts Institute of Technology (MIT),*
*Cambridge, MA, USA*
*(b. September 23, 1915, d. March 31, 2001)*

the physical structure. Moved to Clinton Laboratory (now Oak Ridge National Laboratory) in 1946. At Massachusetts Institute of Technology (1955-1986).

**Present Scene**

Neutron scattering as a technique for condensed matter research has grown exponentially worldwide over the last five decades. This applies to the development of instrumentation, as well as the quality and quantity of results. The applications span almost all the fields of science and technology. Presently a US $ 1.4 billion spallation neutron source is being built in US, and there are major expansion activities being undertaken elsewhere. Currently there are about 7000 users of neutron scattering worldwide, and about 700 of them attended the last International Conference on Neutron Scattering in 2005 in Australia.

In India, a National Facility for Neutron Beam Research is operated at BARC, Trombay, which is utilized by researchers from all over the country for research in physics, chemistry, materials science and biology and some engineering application.

**Reference**

www.nobelprize.org

# Enrico Fermi (1901-1954) and his contributions to Nuclear Science

**Dr. B.S.Tomar** obtained his M.Sc. Degree in chemistry from Garhwal University, Srinagar in 1979. He joined the 25th batch of the BARC Training School in 1981 and won the Homi Bhabha Prize for academic excellence. Subsequently he joined the Radiochemistry Division in 1982. He obtained his Ph.D. degree in Chemistry from Bombay University in 1990. His areas of research include Nuclear Chemistry in general and Nuclear Fission, Nuclear reactions, Perturbed Angular Correlation, Ion Beam Analysis and Speciation of actinides and fission products in particular. He is a Ph.D. guide of University of Mumbai and has a large number of publications in the international journals. He is a member of the IAEA expert panel on Radiation Detection and Measurement. Presently he is Head, Actinide Chemistry Section of Radiochemistry Division, BARC.

The Nobel Prize for Physics was awarded to Enrico Fermi in 1938 for his work on the artificial radioactivity produced by neutrons, and for nuclear reactions brought about by slow neutrons. The first paper on this subject "Radioattività indotta dal bombardamento di neutroni" was published by him in *Ricerca Scientifica*, 1934. All the work is collected in the following papers by himself and various collaborators: "Artificial radioactivity produced by neutron bombardment", *Proc. Roy. Soc.,* 1934 and 1935; "On the absorption and diffusion of slow neutrons", *Phys. Rev.*, 1936. The theoretical problems connected with the neutron are discussed by Fermi in the paper "Sul moto dei neutroni lenti", *Ricerca Scientfica*, 1936. However, Fermi made many more significant contributions in the field of science, namely, (i) discovery of Fermi's statistics, (ii) the beta decay theory and later (iii) the work related to the chain reaction which led to the making of the first nuclear reactor. The present article gives a glimpse of the life of Enrico Fermi along with the research work that enabled him to win the Nobel prize.

## Early days

Enrico Fermi was born on September 29, 1901 in a middle class family in Rome. His father, Alberto Fermi was a civil servant in Railways and his mother Ida de Gattis was the daughter of an Army officer and inculcated deep sense of discipline and culture in her three children, Maria, the eldest of all, Guilio the elder brother and Enrico. Enrico showed prodigious memory as evident from the way he would recite the poems from Ariosto'c Orlando Furioso, a heroic comic poem written around 1530. He showed great interest in mathematics from his childhood days. Fermi's were a close knit family and the loss of Guilio in 1915 gave a shock to the family which devastated Fermi's mother. Enrico's prodigious mind was very well read by Adolfo Amidei, a colleague of his father, who judging by Enrico's interest in mathematics, advised him to read (and lent) books on trigonometry (1914), algebra (1915), calculus (1916) and theoretical mechanics (1917). Adolfo was surprised by the speed with which Enrico finished reading the books and solved all the

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problems himself. However, Enrico's interest lay mainly in physics though to understand any phenomenon, he would use mathematical tools. It was on the advice of Adolfo that Enrico was sent for higher studies to University of Pisa and not University of Rome as the former had excellent library, it taught new subjects and he could study peacefully away from home which had a depressing atmosphere due to Guilio's death. Enrico had already learned German and French which helped him greatly in following the research papers published by European scientists.

## Higher education

During the four years (1918-1922) at Pisa, Fermi impressed his professors and friends by his brilliance and published many papers. His doctoral thesis was on X-ray diffraction by bent crystals. Fermi was self taught as he learned from books or discovered himself. After obtaining his doctoral degree from Pisa, Fermi returned to Rome. Those days getting a permanent position in university was very difficult as one had to win the competition. He met Professor Corbino, the director of physics laboratory at the University of Rome who was impressed by Fermi's research work. The Italian Ministry of education had one fellowship for postdoctoral study in natural sciences and Fermi competed for it. The committee that awarded the fellowship was composed of two physicists, two mathematicians, and one chemist and its conclusion was unanimous. in favour of Fermi. Fermi used the fellowship in 1923 to go to Gottingen at the institute of Max Born, which was witnessing the physics activity at its height. Born was professor of theoretical physics, James Franck was professor of experimental physics and around these two men was a group of young people who were destined to change physics. Many of the German theoretical students moved on an almost standard path: to Munich with Sommerfield, to Gottingen with Born, and to Copenhagen with Bohr. When Fermi arrived at Gottingen, he found there several brilliant contemporaries, among them Werner Heisenberg and Pascal Jordan, two of the brightest luminaries of theoretical physics. Unfortunately it seems Fermi did not become a member of that extraordinary group or interact with them, though he developed good equation with Born. One reason why Fermi

remained aloof may be that he was shy, proud and accustomed to solitude. Only in later years he became a good friend of Heisenberg and Pauli.

Fermi lost his mother in 1924 and father in 1927. He married to Laura Capon on July 19, 1928. They had two children, Nella born on Jan. 31, 1931 and Guilio born on Feb. 16, 1936. Laura Fermi gave a vivid account of the life of Enrico Fermi in her book "Atoms in Family", which is a masterpiece (2).

## Professor at Rome

When Fermi returned from Gottingen, he was asked to teach mathematics to chemists and biologists at the university of Rome, a job for a year, which was under Prof. Corbino' control. He read papers published in Z. Phys., wrote theoretical papers on the theory of atomic collisions, time dependent perturbation theory and its applications to transition from a state to a continuum and entropy of mono atomic perfect gas. At the end of 1924 Fermi took an interim post of an assistant at Florence. Finally he was appointed as professor at University of Rome in 1926, when he was twenty six years old. He took an important chair with lifetime tenure- a position that most professors reached only in their fifties. His first major contribution to physics was in 1926 when his paper on quantisation of the perfect mono atomic gas was published in Z.Phys. He used statistical mechanics to treat the radiation emitted by black body. Simultaneously Dirac also developed this theory and that how Fermi Dirac statistics was developed. The particles having half integral spin are today called as fermions after Fermi. He was striving hard to introduce modern physics in Italy and considered this one of the main objectives of his life. To achieve this goal he took several steps, which had important consequences. The steps were (i) to write articles on modern physics intended for a wide audience, including high school teachers. He delivered series of lectures along with Corbino, Rasetti and others to popularise the dew developments in physics at yearly meetings of Italian Society for the Advancement of Science and on other similar occasions. (ii) to write a text book devoted to atomic physics. The book titled "Introduzione alla fisica atomica" was published in 1928. (iii) to look for and train young physicists.

Fermi started setting up his laboratory for experimental physics and attracted young physicists. Notable among them were Franco Rasetti, Emileo Segre, Amaldi, Racah and Majorana. He developed a statistical method for determination of some atomic properties which is now known as Thomas Fermi statistical method. He took keen interest in all branches of physics, namely, classical physics, quantum mechanics, thermodynamics, spectroscopy and solid state physics. His paper on quantum theory of radiation in the Reviews of Modern Physics (1932) attracted the attention of leading scientists all over the world. At the same time Nazi movement in Germany brought many scientists to Rome: Hans Bethe, George Placzek, F.Bloch, Lother Nordheim, Fritz London, Edward Teller to name a few. All these scientists later went to USA.

**Neutron Research**

Soon after the discovery of neutron by James Chadwick (1932) and artificial radioactivity by Irene Curie and F. Joliot (1934), (the latter group used alpha particles as projectiles), Fermi began experiments with neutron as a projectile to study artificial radioactivity in almost all the elements. They used a Rn-Be neutron source having 800mCi Rn and a GM counter and observed artificial radioactivity being produced in almost al the targets. The group had experts, such as Rasetti for neutron source, Amaldi for detector electronics, Segre for target preparation, while Fermi planned and interpreted the results. In majority of the cases, they observed single radioactivity which they would analyse by fitting the half life. However, later, some of the targets showed multiple activities and hence the need was felt for radiochemical separations and that's how D'Agostino, who learned radiochemistry in the laboratory of Madam Curie in Paris, joined the group. They published ten papers on artificial radioactivity generated by neutron bombardment within a short span of time. In the words of Fermi,

*"A systematic investigation of the behaviour of the elements throughout the periodic table was carried out by myself, with the help of several collaborators, namely, Amaldi, D'Agostino, Pontecorvo, Rasetti and Segre. In most cases we performed also a chemical analysis, in order to identify the chemical element that was the carrier of the activity. For short living substances, such an analysis must be performed very quickly, in a time of the order of one minute. The results of this first survey of the radioactivities produced by neutrons can be summarized as follows: Out of the 63 elements investigated 37 showed an easily detectable activity; the percentage of the activable elements did not show any marked dependence on the atomic weight of the element. Chemical analysis and other considerations, mainly based on the4 distribution of the isotopes, permitted further to identify the following three types of nuclear reactions giving rise to artificial radioactivity:"*

(1) $\quad ^M_Z A \quad ^1_0 n \qquad ^{M\,3}_{Z\,2} A \quad ^4_2 He$

(2) $\quad ^M_Z A \quad ^1_0 n \qquad ^M_{Z\,1} A \quad ^1_1 H$

(3) $\quad ^M_Z A \quad ^1_0 n \; + \; ^{M+1}_Z A$

They identified three types of reactions, (n, ), (n,p) and (n, ). The first reaction was prominent among the heavier elements while the other two were found to be favoured by lighter elements. In the case of aluminium they observed all the three reactions,

$^{27}Al(n,\;)\;^{28}Al$ (2.3 min)

$^{27}Al(n,p)^{27}Mg$ (10 min)

$^{27}Al(n,\;)\;^{24}Na$ (15 hrs)
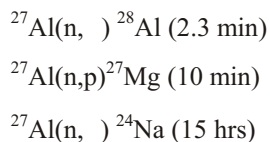
When they bombarded U and Th with neutrons the number of radioactive isotopes multiplied and attempts to look for elements 86-91 failed. The idea was to prepare element 93 but the dominant fission reaction giving large number of fission products denied them the discovery of element 93. It required the highly ingenuous radiochemical separations by Hahn and Strassmann to discover fission and that by McMillan and Abelson to discover element 93 in 1939. In fact when Fermi was delivering his Nobel lecture at Stockholm on Dec. 10, 1938, Hahn and Strassmann had already proved the formation of barium isotopes in neutron bombardment of uranium.

Another landmark contribution of Fermi was the discovery that neutron when slowed down by hydrogenous material, such as paraffin, became more reactive. The cross section for the slow neutrons being 100 times more than those directly

from the source. Fermi successfully explained the moderation of neutron energy by low Z elements and later studied the temperature dependence of neutron capture cross sections. He also qualitatively explained the anomalously high cross sections of Cd, B, etc., which were quantitatively explained by Bohr and Breit and Wigner.

**Nuclear Chain Reaction**

Fermi may perhaps be one of the youngest recipient of Nobel prize at the age of 37. However nuclear science was still to receive much more contribution form him. Fermi and his family left for Stockholm to receive the Nobel prize and from there they went straight to USA, where he joined Columbia University. They had to leave Italy because Nazi movement was gaining ground in Germany and its effect could be seen in Italy under Mussolini. Fermi's wife Laura was a Jew and hence they thought it right to move to USA. Shortly after Fermi landed in New York the news of the discovery of fission reached him, announced by Bohr on his visit to USA. The observation that more than one neutron are emitted in a fission process prompted the scientists to think of a chain reaction. Leo Szilard a Hungarian physicist residing in New York took keen interest in exploring the potential of a chain reaction to make a deadly nuclear weapon to defeat the Nazi forces which was further triggered by the attack on Pearl Harbor by Japanese forced in 1942.

The study of chain reaction was taken up independently by Von Halban, Joiliot and Kowrarski in France, by Fermi, Szilard and others in United States and by other groups in other countries. Szilard and Fermi worked closely during the subsequent years at University of Chicago and later at Los Alamos, where Fermi moved at the insistence of General Groves, in charge of Manhattan project. Fermi and his group successfully demonstrated the sustenance of the first nuclear chain reaction in the first nuclear pile made of graphite as a moderator and natural uranium as fuel. Most of the ideas were developed during the Columbia period. The use of graphite as a moderator rather than hydrogen, the most obvious material occurred independently to Pegram, Szilard, fermi and Placzek. Fermi invented the trick of counteracting the effect of resonance absorption by lumping the material. The effect of impurities was understood as well as the method of

measuring them by exponential experiments. Thus several crucial advances in reactor physics were accomplished during the first two years. Basic patents on the neutronic factor were granted after the end of war to Fermi and various collaborator. They assigned these patents to the government without compensation.

The discovery of nuclear fission and the potential of this process for making a bomb, attracted the attention of important American scientists –such as, A.H.Compton and E.O.Lawrence. Lawrence persuaded President Roosevelt to establish the office of scientific research and development (OSRD) in June 1941. Before the final decision to go full steam on making an atomic bomb, Compton visited Fermi at Columbia to gather first hand information on the feasibility of a nuclear bomb. Compton had a certain diffidence for a recently arrived emigre, but Fermi's technical explanations were clear and to the point. Compton was able to follow his calculations and later to reconstruct them in his mind. When the occasion arose he fully endorsed them. The site of the first nuclear pile was decided to be under the west stands of Stagg Field, the university of Chicago stadium, which was proposed by Fermi to Compton. Actual construction of the pile began in October under W.Zinn's and H.L.Anderson's immediate direction and Fermi's supervision. The weight of the uranium was approximately 6 tons. The pile went critical on December 2, 1942, with a power of less than 0.5W. In a few months the second pile was built at Argonne Laboratory which ultimately led to the large production piles built at Hanford, Washington by the Du Pont company.

The first batch of plutonium separated from the nuclear reactor was used in the Trinity test on July 15, 1945 at Alamogordo, Fermi watched the explosion from a distance of 14 km. Emileo Segre, who was with him gave an account of the ingenuous way in which Fermi deduced the energy liberated by the explosion.

*"After the sparkling light in the sky, Fermi got up and dropped small pieces of paper on the ground. He had prepared a simple experiment to measure the energy liberated by the explosion. The piece of paper would fall at his feat in the quite air but when the front of shock wave arrived (some seconds after the flash) the pieces of papers were displaced a few cm*

*in the direction of propagation of shock waves. From the distance of the source and the displacement of air due to shockwave he could calculate the energy of explosion. Is answer closely approximated that of the elaborate official measurement".*

**University of Chicago**

Fermi joined the university of Chicago as a professor in 1945 and when Atomic Energy Commission was established in 1946, he became a member of the General Advisory Committee chaired by Robert Oppenheimer with G.T.Seaborg, Rabi and others as members. Fermi was always looking forward to teach young students and even taught the famous C.N.Yung and T.D.Lee from China. He gave ideas of spin orbit interaction to Mayer, who along with Jensen received the Nobel prize for their discovery of nuclear shell model. He was very popular teacher among his students as he always made his lectures very lucid. He used to joke that complicated formalism was for the high priests. He would even give informal lectures to his students at evening hours and devoted almost all of his lunch hours to the graduate students.

On research front he carried out experiments on high energy physics, pion nucleon interactions using 170 inch 450 MeV synchrocyclotron built at Chicago in 1951. In 1949 Fermi went to Europe first time since his departure 10 years ago. He met many of his old friends and gave a series of lectures which were attended by post war generation of physicists. This shows his strong desire to contribute towards raising the standard of physics in his native country.

In the summer of 1954 Fermi fell ill. He was suffering from a serious stomach disease and an exploratory operation showed a malignant tumor that had metastasized. Enrico Fermi died on Nov. 29, 1954 in Chicago two months after his 53rd birth day.

**Awards and Honors**

(i) The US government honored Fermi by instituting Enrico fermi Award, which is a

Presidential award–one of the oldest and most prestigious science and technology awards given by the U.S. Government. It recognizes scientists of international stature for their lifetimes of exceptional achievement in the development, use, or production of energy (broadly defined to include the science and technology of nuclear, atomic, molecular, and particle interactions and effects).

(ii) Fermi National Accelerator Laboratory (FNAL) – A U.S. Department of Energy National Laboratory

(iii) The Enrico Fermi Institute – A component of the Physical Sciences Division at the University of Chicago.

(iv) Fermium, Element 100: The 100th element in the Periodic Table is named after Enrico Fermi.

(v) Several events were organized to mark the birth centenary of Fermi during the year 2001. US govt. released a commemorative stamp to mark the event.

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# Discovery of Artificial Radioactivity by I. Curie and F. Joliot

*Dr. N. Ramamoorthy, after graduating from the 15th Batch of BARC Training School, joined the Isotope Division, BARC in 1972. He obtained PhD in Chemistry (in 1988) from the University of Bombay based on his research work on technetium radiopharmaceuticals. His research interests include reactor and cyclotron produced radioisotopes, radiopharmaceutical sciences and radiation technology and for over 30 years, he has been an active contributor to the growth of radioisotope programmes in India. He served as Guest Scientist at the Nuclear Research Centre, Jülich, Germany for 14 months and as Visiting Assistant Professor in the University of Missouri-Columbia, USA for 3 months. Dr. Ramamoorthy has participated in a number of IAEA Projects as technical co-operation expert, faculty in training events and Chief Scientific Investigator in coordinated research projects (CRP). He held the positions of Head, Radiopharmaceuticals Division, BARC (May 1999 – July 2000), Associate Director, Isotope Group, BARC (Aug 2000 – Sep 2003) and Chief Executive of Board of Radiation and Isotope Technology (Aug 2000 – Sep 2003). Since October 2003, he is Director, Division of Physical and Chemical Sciences (NAPC) in the IAEA, Vienna, and is responsible for managing the Programmes on 'Nuclear Science' and on 'Radioisotope Production & Radiation Technology'. Dr. Ramamoorthy is a Founder Fellow of the Indian College of Nuclear Medicine, a Fellow of Maharashtra Academy of Sciences, and during 2000-01, he was the President of the Society of Nuclear Medicine of India. He has a large number of publications to his credit and is a co-author/editor of a book and 3 manuals. He has guided the research work of 3 students for M.Sc. Degree and 6 students for Ph.D. Degree of the University of Mumbai.*

## Preamble

The high standards of quality of life noticeable in many parts of the world, as well as the innumerable additional comforts available today to the society, would not have been a reality but for the epoch-making scientific and technological growth achieved over more than a century. Advances in nuclear sciences have a significant niche carved out among such growth, through considerable seminal contributions by legendary scientists right from the very early days. By bringing out this Special Bulletin, in order to commemorate its Silver Jubilee year of excellent performance, the Indian Association of Nuclear Chemists and Allied Scientists (IANCAS) is paying a befitting tribute to all those early pioneers in nuclear sciences in general and the Nobel Prize winners in particular. This article is devoted to one of the major discoveries of all times, described popularly as 'artificial radioactivity' (synthesis of radio-elements), and which has undoubtedly led to far reaching diverse applications in practically every branch of science and every walk of life. Since one cannot shed any new light on such a glowing subject, this article attempts to reflect flashes of glimpses to students and young researchers among the target audience to kindle their interest for their possible forays into basic and applied R&D in nuclear science.

## Introduction

*There are no such things as applied sciences, only applications of science. -* **Louis Pasteur**

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*We must not forget that when radium was discovered no one knew that it would prove useful in hospitals. The work was one of pure science. And this is a proof that scientific work must not be considered from the point of view of the direct usefulness of it. It must be done for itself, for the beauty of science, and then thee is always the chance that a scientific discovery may become like the radium a benefit for humanity. – Marie Curie (in her speech in May 1921)*

The discovery of X-rays by Wilhelm Conrad Roentgen in November 1895 and of radioactivity by Henri Becquerel in February 1896 opened up a vast avenue for a number of phenomenal discoveries to follow in the next decades and laid the foundation of the 'nuclear era'. Those were the times when a series of great scientific findings by several illustrious scientists was taking place unfailingly at short intervals. The tremendous endeavours and scientific spirit of Mme Marie Curie in the discovery of many radioactive substances are of direct relevance to this article, while at the same time, the many other major developments in the understanding of the atomic and nuclear structure and properties are no less important. This is because, while Mme Marie Curie is always remembered in connection with 'natural radioactive substances', the credit for discovering the phenomenon of and pathway to 'artificial radioactive substances' goes to her scientist daughter Irène Curie and her son-in-law, Frédéric Joliot, a talented physicist (Fig. 1).
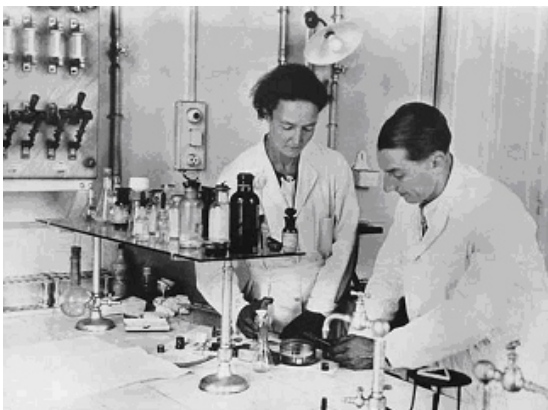


*Fig. 1*

## Discoverers' Life Profile

When Marie Curie and her husband Pierre Curie discovered Radium in 1898, they already had their daughter Irène as a toddler (born on September 12, 1897). Irène was not lucky enough to have the benefit of her father's care for long (as Pierre was killed by a truck in 1906; but only after receiving the Nobel Prize in physics jointly with Mme Marie Curie in 1903); but Irène was endowed with all the brilliance and genius of both her parents, as later history will show. Irène had a younger sister, Eve Denise Curie, who wrote the 1937 biography of their mother that inspired so many.

Marie Curie combined an active research career with motherhood and orchestrated the education of her daughters. It was clear that Irène was very intelligent and had exceptional talent in mathematics. She entered school at six, but not near the Curie home (as it was not considered suitable), but in a school near the Observatory offering a more challenging curriculum. Irène's talents and interest in mathematics becoming more apparent when she was ten, there was no appropriate school for her in all of Paris! Irène along with nine other children of prestigious scholars started studying at the teaching 'Cooperative' established by Marie Curie and her friends for their children. Apart from being under her mother's direct charge for her scientific education, Irène had the benefit of such teachers as Paul Langevin and Jean Perrin in the 'Cooperative'. It is perhaps because of this, there is one contention noticeable that Irène did not attend school until the age of twelve but studied at the 'Cooperative' apart from being educated by her mother! Irène acquired a great influence of liberal socialism from her grandfather, Eugene Curie, who was living with her family.

Irène received a Bachelor's degree in 1914 from Collège Sévigné and then studied at Sorbonne University during 1914 to 1920 and obtained the 'license' in physics and mathematics. During the period of the First World War, she also served as an army nurse and assisted her mother in installing mobile X-ray equipment for performing radiography of the wounded. In 1918, Irène took up a post of research assistant in her mother's Radium Institute in Paris to pursue research in classical

radioactivity. Her doctoral dissertation in 1925, submitted to Sorbonne University, was based on her studies of the fluctuations in the range of alpha rays of polonium by photographing the tracks formed in a Wilson cloud chamber.

Frédéric Joliot born in Paris on March 19, 1900 had his education from the Ecole de Physique et Chimie of the city of Paris. He became an assistant to Mme Marie Curie at the Radium Institute in 1925 (having visited her institute in December 1924 at the suggestion of his mentor, Prof. Paul Langevin), where Irène was already working. Irène taught him the techniques to work with radioactivity. He obtained his Doctor of Science degree in 1930 for his thesis on the electrochemistry of radio-elements, but before that in 1926 he married Irène Curie. Their marriage in a civil ceremony on October 29, 1926 led not just to a simply happy married life, but more importantly to invaluable scientific collaborations lasting several years from 1931 onwards - the most outstanding papers of their joint research being published between 1932 and 1934 - all the way to their being awarded the prestigious Nobel Prize in Chemistry in 1935 and beyond.

Mme Marie Curie was not destined to witness the continuing scientific glory in the family through the achievements of her daughter and son-in-law, as she died in July 1934. The 1935 Nobel Prize presentation speech by Prof. W. Palmaer, Chairman of the Nobel Committee for Chemistry of the Royal Swedish Academy of Sciences on December 10, 1935, contains detailed apt references to mother Mme Curie's work and the vital links, both in the family and the science they stood for. His speech begins with the words, *'On the 10$^{th}$ of December 1911, Marie Sklodowska, a Polish chemist of world-wide reputation, wife of Professor Pierre Curie, …………….'.*

Irène did some invaluable individual work in the years following the discovery of artificial radioactivity using her expert knowledge of radiochemistry, in analyzing the complex processes resulting from the bombarding of uranium with neutrons and came within a hair's breadth of discovering fission. Her paper on the findings of 'radioelement of period 3.5 hours formed from uranium bombarded by neutrons' published in *Comptes Rendus* (206: 906 and 1643) bears

testimony for this, as also cited by Prof. Chadwick in his obituary column for Irène (*Nature, 177, 964, 1956*). The later developments at the hands of Otto Hahn and Lise Mietner leading to the actual discovery of fission was thus traceable to this initial trigger from Irène!

Irène Curie was chosen Professor in 1937 at her University of Sorbonne. She continued working at the Radium Institute (Curie Institute) and became its Director in 1946. She held both these offices till her end in 1956. Irène is described to have been an autocrat in the laboratory with her demands for meticulousness of all the work done at the Institute. Irène is credited with three attributes in her functions, theoretician, experimentalist and superb administrator.

In 1935, Joliot became lecturer in the Paris Faculty of Science and in 1937, he was nominated Professor at the Collège de France. After being the Director of the Centre National de la Recherche Scientifique in 1945, he became the First High Commissioner for Atomic Energy in 1946. Irène Curie and Frédéric Joliot were the Directors of the French Atomic Energy Commission during 1946 to 1950. They both received several honours including the title, Officer of the Legion of Honour. Joliot was a Member of the French Academy of Science and of the Academy of Medicine, but Irène was never admitted to the French Academy of Science till her very end (all male status policy and denial meted out in much the same manner as to Marie Curie).

Frédéric Joliot and Irène Curie had a daughter (Hélène, born on September 17, 1927; became a physicist) and a son (Pierre, born on March 12, 1932; became a biochemist). In addition to all her scientific pursuits, Irène was also a loving mother like her own mother and took good care in bringing up her children till adulthood. Irène suffered from tuberculosis for many years and recovered to some extent after the II world war when antibiotics became available. Later, exactly following her mother's footsteps perhaps, Irène too succumbed to acute leukemia and died when she was just 59 years old (on March 17, 1956), an unfortunate consequence of inadequate realization of the radiation effects and need for protection measures in those days. Frédéric too passed away about two

*Fig. 2*



*Fig. 3*
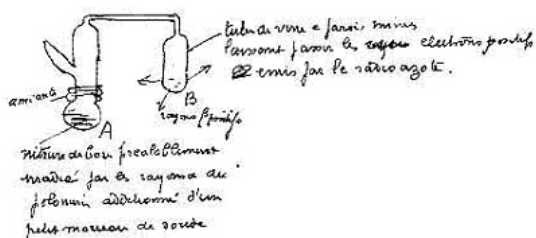
years later in 1958, when he too was just 58 years old, but only after devoting his two last years to the inauguration and development of a large centre for nuclear physics in Orsay, France, apart from holding the Chair of Nuclear Physics in Sorbonne, that he took over upon the death of Irène, who had held that Chair till 1956.

**Discovery Pathway**

Working in one of the new buildings of the Radium Institute in the same street as housing the old wooden building where her mother had done her pioneering work in the past, Irène and her brilliant husband Frédéric Joliot were trying to uncover the nature's secrets. During their bombardment studies using alpha particles on some elements, they were detecting radiations (They seemed to have been oblivious to the fact that they could have discovered neutrons; it was left to Prof. James Chadwick in England to discover neutrons, as described by Prof. Chadwick himself while writing an obituary column for Irène Curie in Nature in 1956. It is therefore a fine coincidence that Prof. Chadwick too was a recipient of the Nobel Prize in 1935 and in Physics!). Perhaps purely accidentally, the junior Curie – Joliot couple once noticed that the radiation was still there, even after stopping the bombardment with alphas from polonium! This then led to the identification of the source of radiation and the observation of time dependent reduction in intensity of radiation emission, all later attributable to the decay of a new radio-element, later christened as radiophosphorus
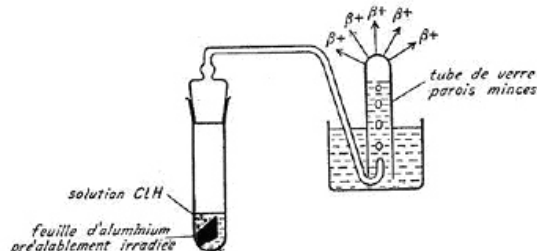
($^{30}P$ radioisotope, positron emitter) formed by the alpha induced nuclear reaction on aluminium.

$$^{27}Al + {}^{4}He \quad {}^{30}P + {}^{1}n$$

The same phenomenon was observed with boron too, with the radioactive element formed being $^{13}N$.

$$^{10}B + {}^{4}He \quad {}^{13}N + {}^{1}n$$

They used a reaction vessel like a small U-shaped tube and filled it with a compound of the target element to be bombarded (Fig. 2). The sample was bombarded with alphas from polonium which converted some of the nuclei of the element under study into nuclei of a second element, that is, phosphorus-30 from aluminium and nitrogen-13 from boron, with the resultant respective product, radiophosphorus and radionitrogen, emitting positrons. The decay by a new nuclear process of positron emission was thus found out by them. Through a clever step of separating the new radioelement formed, from the rest of the bombarded sample, and showing the radiation to be coming from the material removed – that is, $PH_3$ (phosgene) gas released upon acid (HCl) dissolution of the bombarded aluminium (Fig. 3) and ammonia released on treating the bombarded boron nitride with caustic soda (Fig. 2) - the proof of creating artificially produced radioactivity was unequivocally demonstrated by them. Magnesium was also subjected to similar experiments and shown to become radioactive due to radiosilicon ($^{27}Si$).

$$^{24}Mg + {}^{4}He \quad {}^{27}Si + {}^{1}n$$

*Fig. 4*

There lies the birth of 'artificial radioactivity'[1] published in Nature [Artificial production of a new kind of radio-element, *Nature* 133: 201 (1934)] and scantly a year thereafter in 1935, their achievements in nuclear and radiochemistry by way of 'synthesis of new radioactive elements', earned them the highest laurel of Nobel Prize (Fig. 4).

The reports of Irène Curie - Frédéric Joliot were noted by peers like Lord Rutherford, Director of Cavendish Labs, by beginning to confirm the experiments. Lord Rutherford said, "*It is remarkable that the life of the unstable atom produced is as long as it is. We do not know whether the atoms so far made artificially radioactive are typical or whether other unstable atoms which may be produced will have a longer or shorter life. The discovery of the Joliots shows how little we really know about radioactivity.*"

Mme Irène Joliot-Curie, the chemist, dealt with the discovery of the new type of radioactivity, that is, the positive beta decay (positron emission) in her Nobel Lecture on December 10, 1935, while the physicist Monsieur Joliot covered the chemical identification of the artificially created radioactive isotopes in his part of the Nobel Lecture. Their joint lecture begins with a warm reference to Irène's parents, *'It is a great honour and a great pleasure to us that the Swedish Academy of Sciences has*

*awarded us the Nobel Prize for our work on the synthesis of radio-elements, after having presented it to Pierre and Marie Curie in 1903, and to Marie Curie in 1911, for the discovery of radio-elements'.* Another quote of relevance from her part of the Nobel Lecture comes just after her describing the important consequences of the discovery of radio-elements in the knowledge of structure of matter, *'radioactivity remained a property exclusively associated with some thirty substances existing naturally. The artificial creation of radio-elements opens a new field to the science of radioactivity and so provides an extension of the work of Pierre and Marie Curie'.* She goes on to refer to Lord Rutherford's achievement of artificial transmutation as another forerunner for their discovery. In her own words, the description of their discovery reads as, *'we observed that aluminium and boron, when irradiated by alpha rays do not emit protons and neutrons alone, there is also an emission of positive electrons. .... We noticed a fundamental difference between that transmutation and all the others so far produced; all the reactions of nuclear chemistry induced were instantaneous phenomena, explosions. But the positive electrons produced by aluminium under the action of a source of alpha rays continue to be emitted for some time after removal of the source. The number of electrons emitted decreases by half in three minutes. Here, therefore, we have a true radioactivity which is made evident by the emission of positive electrons. We have shown that it is possible to create a radioactivity characterized by the emission of positive or negative electrons in boron and magnesium, by bombardment with alpha rays. These artificial radio-elements behave in all respects like the natural radio-elements'.* The interested readers are encouraged to dwell in nostalgic ecstasy by reading the full text of the lecture from web sites, the original in French or the translation in English.

**Important Scientific Impacts of the Discovery**

The possibility of having an infinite number of new synthetic radioelements, and that too of practically all elements known, was an instantaneous realization upon the discovery of Joliot and Curie.

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[1]The radioactivity phenomenon itself is a 'natural' process, while the way of inducing them in the elements studied was by using 'artificial' means and hence perhaps this terminology.

With the visionary predictions of good utility of the new radioelements for medical treatment already conceived and the very elegant (radio)tracer concept elucidated by Prof. George Hevesy in 1912-13 ('isotopic indicators' as it was called), the scope for using the synthesized radioelements was truly unfathomable. In a sense the concept of 'isotopic indicators' discovered by Prof. Hevesy assumed full significance only upon the revealing recognition of the unlimited possibility of synthesized radio-elements from the discovery of Joliot and Curie, a true synergy of findings later leading to an explosive growth of applications. It is pertinent to point out that Prof. Hevesy was later on only (1943) selected for the award of Nobel Prize in Chemistry.

An understanding of the requirements for bringing about any desired (nuclear) synthesis gave the impetus to studies of nuclear reactions as well as development and use of charged particle accelerators. The discovery of nuclear fission, in itself a source of a variety of radioelements, led to the development of sustained chain reaction and the nuclear reactor, which has since become the main source for most of the large-scale production of radioelements. The tremendous growth from seeking to prepare just several thousands of atoms of a new radioelement to the ability to obtain weighable quantities of a number of radioelements that ensued, could thus be viewed as an almost natural corollary from the discovery of Joliot and Curie!

Irène's work on nuclear reactions with uranium would surely merit an important place in the impact list (*Comptes Rendus* 206: 906 and 1643), for this later led to the discovery of nuclear fission, the firm foundation and the genesis of the entire field of nuclear science and technology and nuclear power - both energy production and military might.

The availability of and access to the new radioelements also opened up greater amount of investigations on nuclear characteristics and in turn on nuclear structure, decay features and decay theory. The filling up of the vacant slots in the periodic table, as for example that of element 43, the ubiquitous technetium in nuclear medicine field, is another impact attributable to the discovery under discussion.

The positron emission mode of radioactive decay, a feature found out in the discovery of Joliot and Curie, is naturally the origin of all the techniques and applications that are based on positron emitters and their properties, especially using the annihilation radiation arising when positron and electron interact and more so, the possibility of coincidence detection of the 511 keV annihilation photons coming out in nearly $180^o$ to each other. The utility of positron annihilation spectroscopy (PAS) in materials research and development of new materials, as well as the tomographic imaging in nuclear medicine in what is known as positron emission tomography (PET) are shining examples for any young talents and scientific minds to appreciate. The prospect of the latter method was in fact recognized much before the transmission computed tomography called CAT or CT came into existence. The much larger popularity and wide spread deployment of PET however followed much later on, as explained in the next Section.

The industrial practices did not lag behind in making sophisticated use of the positrons! Use of the more penetrating 511 keV annihilation photons, being more compatible with larger and denser industrial specimen, as also the merits of coincidence detection capability, propelled novel developments useful for several industries. A more recent development of the technique of single particle tracking after tagging with a positron emitter in studying industrial processes for optimising plants' functions and designs holds great promise for the future.

**Glimpses of Societal Benefits from the Discovery**

All the applications of radioisotopes available today, be it in biology, chemistry, medicine, analytical sciences, industries, environmental studies and involving either open sources of radiochemicals or sealed sources of radiation, are the most visible, tangible benefits attributable to the discovery of Joliot and Curie. The better understanding and knowledge contributed by the use of radioisotopes, right from photosynthesis phenomenon to fertilizer uptake by plants to flow rate of blood in humans to the relation of hormonal levels and disease states to industrial processes in closed and/or huge containers to molecular biology mechanisms etc, are undoubtedly the most

significant scientific values accrued as a consequence of their discovery.

The most important contributions from the discoveries of synthesis of radioactive substances by Joliot and Curie and of the tracer principle by Hevesy accrued to the medical field; this is in terms of rendering visibility to the interior body organs. Images of internal organs can be acquired after administering a suitable radiotracer (called radiopharmaceutical) and with the help of appropriate radiation mapping equipment. In the very early times, the radioisotope used was mainly iodine-131, though others were also tried out. The introduction of $^{99m}$Tc in the late 50s and early 60s ushered in a revolutionary change. For well over three decades now, $^{99m}$Tc is the reigning work-horse among all diagnostic isotopes in medicine – accounting for nearly 80% of nearly 25 million images done per year currently in nuclear medicine centres the world over. The advantages of the physical and chemical features of $^{99m}$Tc have largely contributed to this situation, taken along with the technology developments in instrumentation, namely, the gamma camera – computer paired system and the much later added tomographic system, single photon emission computed tomography (SPECT). These systems enable acquiring exquisite images of functional morphology of organs and metabolic pathways. SPECT is in fact a later spin-off, by analogy with PET concept and upon the advent of CAT/CT, and thus can be again credited in a way to positron emission decay discovered by Joliot and Curie!

The well-acknowledged immense values of PET available today are rooted in that discovery of the first artificially made positron emitter, $^{30}$P. The tracers of other more common biological elements of C, N, O (and an analogue F) can be availed from compact cyclotrons, while the merits of positron decay for higher quality tomographic imaging (PET) add yet another powerful dimension to their use. Fluorine-18 occupies an important role and especially one product, 2-fluoro deoxy glucose (FDG), called the 'molecule of the millennium', accounts for about 10% of all imaging done presently in nuclear medicine. The vast potential of PET imaging in unravelling the body functions and mechanisms e.g. in neurology, was immediately

recognised, while the switch over to its regular use, as a practical clinical methodology, evolved much later. It is a heartening piece of information to record here that the very same positron emitter $^{13}$N found out first by Joliot and Curie, and even the same chemical form of ammonia gas, was later keenly pursued and developed as a radiopharmaceutical for imaging myocardial blood flow (ammonium ions being a mimic of intracellular potassium ions) with PET (though only in limited use currently, due to other products in vogue; FDG-PET pair is still a major indicator for myocardial viability). The development of medically useful imaging procedures in cancer patients with FDG has in fact established the very important role of PET tracers in clinical nuclear medicine. This product along with some other $^{18}$F compounds, and probably a few $^{11}$C tracers, will be the mainstay for PET imaging, to complement $^{99m}$Tc in SPECT imaging, well into the distant future.

The very early recognition of the potential of radiation for treating diseases has also evolved into a mature medical modality over time. An important tool in management of cancer patients, along with chemotherapy and surgery, is radiation therapy using sealed sources of radiation, mostly of $^{60}$Co, $^{192}$Ir, $^{137}$Cs, $^{103}$Pd, $^{125}$I (and electrons and X-rays too, but the latter are from machine sources and not radioisotopes) - in some cases their use is the only mode of treatment too - as well as using radiopharmaceuticals of $^{131}$I, $^{90}$Y, $^{153}$Sm, $^{177}$Lu etc. The benefits to cancer patients, both curative and palliation, are immense and world-wide efforts to enhance the availability of and access to well-operated facilities as well as refining the treatment modes are being pursued.

Similarly, the applications in biology and life sciences are considerable and cover a vast spectrum, from hormone estimation in humans and veterinary samples to understanding mechanisms and processes in molecular biology and genetics. New knowledge on diseases acquired has in turn led to developing methods for early diagnosis of diseases or malfunctioning, as well as evolving better strategies for treatment. The important radioisotopes in this case are $^{32}$P, $^{33}$P, $^{35}$S, $^{14}$C and tritium.

Industrial growth is an important factor for economic development of nations and application of

radioisotopes, as tracers as well as sealed sources, has helped a number of investigations of industrial processes and practices and enabled tremendous savings of cost, time, energy and resulted in overall better productivity. The objective parametric-based process optimization, trouble-shooting to minimise downtimes, ability to more precisely locate spots of malfunctioning in large industrial systems, ascertaining flow patency/viability etc, have all become well-accepted procedures, often available from professional service providers. The radiotracers used are many, e.g. $^{82}$Br, $^{131}$I. The radiography based non-destructive testing and examination (NDT and NDE) using $^{192}$Ir, $^{75}$Se, $^{60}$Co, $^{137}$Cs sources, is a vast field in itself, for both certification of reliable function of industrial machinery as well as for quality assurance of products and facilities. Positron emitter based particle tracking technique is also envisaged to find increasing use in industrial process research and development in future.

Environmental studies and analytical sciences too derive good benefits from the use of radioisotopes and techniques based on them, among other nuclear techniques. Also, for basic and applied research in several of the above areas and allied sciences, one can make excellent use of several radioisotopes.

**Conclusion**

This article will not be complete without a warm, respectful reference to Prof. H.J. Arnikar's way of paying scientific homage to the famous couple Irène Curie and Frédéric Joliot, through his excellent organization of an International Symposium on Artificial Radioactivity (ISAR) in 1985 to commemorate in India the Golden Jubilee of their monumental discovery made in France. Thanks to Prof. Arnikar's close association with France in his academic life and his own brilliant knowledge of nuclear and radiochemistry, he conceived of this initiative as a major significant event to be held in his University town of Poona (now Pune). His efforts for mobilisation of adequate resources to hold a befitting function, brought him to the doors of DAE authorities. DAE/BARC being the official government machinery responsible for the entire field of nuclear programmes in India, the senior scientific fraternity of radiochemistry and radioisotopes in DAE and BARC not only offered to extend the resources needed by Prof. Arnikar, but also literally 'overwhelmingly' joined him in the conduct of this grand event! Most of the ISAR participants including the author recall nostalgically even today pleasant memories of that fine event. IANCAS was a fledgling at that time and joined the event with its own useful measure of contribution!

It is deemed appropriate to conclude this narration by citing Prof. E.O. Lawrence's remarks on the utility of artificial radioactivity while giving a speech, just some fourteen months after the discovery of artificial radioactivity. He said, "Now that radioactive forms of many of the elements can be manufactured in the laboratory, many new avenues of research are opened up. It is reasonable to expect that artificial radioactive substances will play a possibly more important role in the physical and biological sciences in the not distant future than the natural radioactive substances have in the past. Certainly extensive study of the artificial radioactive substances will lead to a greatly enlarged understanding of atomic structure. ------ There may result also many important biological applications. I hesitate to express views in this direction, but some of my medical colleagues think it quite possible that the discovery of artificial radioactivity will ultimately be of great importance to medicine. Opinions of this sort, of course, are highly speculative, and I leave it to you to estimate the advantages for radiation therapy and biological research, of radioactive substances having practically any desired chemical and physical properties". It is extremely heartening that not only all the foresight and visionary expectations have been proved a firm reality – in deed every attribute in the foregoing text - but also well exceeded in terms of the development of an enormously large number of products and techniques and delivery of tangible benefits to mankind. All scientific developments should eventually lead to, in one or more ways, impacting positively the society at large, and enhance the societal benefits. The recounting of the story of discovery of artificial radioactivity bears ample testimony in this regard and should hopefully exert a profound effect on at least some of the bright science students of the current generation. What more professional satisfaction to the scientific souls of Irène Curie and Frédéric Joliot could be there,

than the perennial, versatile utility of their invaluable scientific discovery!

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# The Discovery of Nuclear Fission

***Dr. S.B. Manohar***, *M.Sc. (Poona University, 1965) joined Radiochemistry Division, BARC through training school. He was heading the Division when superannuated in 2003. His area of expertise is in nuclear fission, nuclear reactions, nuclear spectroscopy and radiochemical separations. He has co-authored a book "Experiments in Radiochemistry" and he was the Ex-President of IANCAS. He continues to work for spreading the awareness of the subject of Radiochemistry by giving lectures and participates in IANCAS programmes in the schools and colleges.*

The discovery of nuclear fission in 1939 may be considered as the most outstanding discoveries of 20th century, which had far reaching consequences in the history of modern world. The Nobel prize for the discovery of nuclear fission was awarded to Prof. Otto Hahn in 1944, though the contribution from Lise Meitner, Hahn's colleague for 30 years and F.Strassmann, who was associated with the final radiochemical separations can not be ignored.

The discovery of nuclear fission was not an accident, although Hahn and Strassmann were indeed surprised by their unexpected results. After the discovery of neutron by Chadwick (1932) and the discovery of artificial radioactivity by Joliot-Curies (1934) a new research area opened up. In the quest of producing artificial radioactivity and new elements by Enrico Fermi's group systematically bombarded all known elements with neutrons. The absorption of neutron produces an isotope which is neutron rich and which, by ⁻ decay, transforms to next higher element. In an irradiation of uranium by slow neutrons Fermi and his coworkers discovered that they had produced four different radioisotopes as identified with their different half-life periods. Since there were only three known isotopes of uranium at that time, the fourth was claimed to be element 93. Fermi was awarded the Nobel Prize in 1938.

The main research groups working in this field were in UK, USA and Europe, of which prominent were that of Fermi, Hahn & Strassmann, Irene Curie & Paul Savitch. The four activities and their half life periods of 1 min, 14 min, 86 min, and 2.5 hrs were confirmed by all of them; besides these a long half life activity of 250-330 hrs and few others were also observed. Absorption of a neutron by uranium leads to formation of $^{239}$U which on subsequent four ⁻ decays can in principle explain the formation of elements 93-96. However the activities which were formed had chemical properties far different from those expected of elements beyond uranium. Furthermore existence of two or more isomers of isotopes of uranium or element 93 with such long half life period was also not easily acceptable. Some of these activities formed in neutron irradiation of uranium were getting separated with Ba led to a belief that they are isotopes of Ra which was known to follow chemistry of Ba. All these doubts led to intense research activity involving chemical separation followed by measurement of half life periods. These four isotopes of Ra decay to isotopes next higher element Ac which in turn decays to isotopes of Th. The four decay schemes proposed by Hahn, Meitner and Strassmann in (1938) were as follows;

Ra I $\xrightarrow{\text{1 mts}}$ AcI $\xrightarrow{\text{30 mts}}$ Th I

Ra II $\xrightarrow{\text{14 mts}}$ AcII $\xrightarrow{\text{2.5 hrs}}$ Th II

Ra III $\xrightarrow{\text{86 mts}}$ AcIII $\xrightarrow{\text{days}}$ Th III

Ra I V $\xrightarrow{\text{~300 hrs}}$ AcI V $\xrightarrow{\text{40 hrs}}$ Th IV

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Beside these, there were other radioactive elements which were found to be not getting separated with Ba and were ascribed to isotopes of Bi, Pb, Po & eka cesium (Fr) and to elements beyond uranium. *(It is to be remembered here that the hypothesis of actinides was not known at that time and elements beyond uranium were expected to fallow the chemistry of groups IV, to VIII).*

Hahn wrote to Meitner in December 1938 describing the "strange results", he and Strassmann had found. Meitner was equally baffled at first, but had great faith in the ability of her friend Hahn as a chemist. Later that month her nephew Otto Frisch visited her in Sweden. Even after proposing the above scheme of three / four isotopes / isomers of Ra to be formed from irradiation of uranium with slow neutrons it was difficult to accept and understand from the view point of energies involved in such reactions. Prof. Lise Meitner, a leading nuclear physicist and close associate of Hahn for more than 30 years, persuaded him to carry out detail investigations, though they were now separated due to Nazi regime. Hahn and Strassmann were also associated in the discovery of Ac in 1917 and were familiar with chemistry of both Ra and Ac. Mean while F.Joliot, I.Curie & P.Savitch had found activities of new isotopes of Ac in samples of Th irradiated with neutrons supporting the above schemes of decays.

Thus the stage had reached for the final important step of chemical separations by Hahn and Strassmann. In order to prove beyond doubt that the isotopes of Ra which were getting separated with Ba were indeed the isotopes of Ra, they decided to use Ra tracer in the chemical separations steps. They studied the fractional crystallization of Ba compounds such as chloride, nitrate, bromide and chromate in presence of Ra tracer and found that chromate of Ba carries very littlie to nil activity of Ra tracer and used this to separate the so called Ra activities from irradiated uranium solutions. To their surprise the activities were getting concentrated in Ba chromate ppt while Ra tracer was left in supernatant thus conclusively proving that the activities were that of isotopes of Ba and not that of Ra. Finally they used the Ac tracer to investigate the existence of Ac isotopes which were getting separated with La carrier in lanthanum oxalate precipitation step. They found that all the tracer activity of Ac was left in the supernatant and the activities formed in irradiation of uranium remain with lanthanum fraction. This actually was very conclusive proof that uranium nucleus was getting split by absorption of slow neutron, but it was so surprising and so difficult to understand the possibility of such a reaction.

*At this stage it is interesting to know the conflict of thoughts in Hahn`s mind. In his own words, "We made precipitations, Strassmann and myself where we could be absolutely sure that there could be nothing else but either radium or barium. But physicists did not suppose a heavy element like uranium could be transformed into a light element like barium. You might be able to knock off four protons from the nucleus of uranium atom and create a radium atom, but to get from uranium to barium, the neutron would have to chip off hundreds of particles!. That seemed flatly impossible, and barium was out of question….."*

The experiments for this work were finished by 22nd of Dec1938 and Hahn wanted to publish it as soon as possible. So the manuscript was written in a hurry and was rushed to the editor on 26th, who obliged them by replacing another article which was in the queue by this paper titled as; "Concerning the existence of alkaline earth metals resulting from neutron irradiation of Uranium" by O Hahn and F.Strassmann , Naturwissenschaften vol. 27 p11. In this paper of 10th Jan 1939, they confirmed the formation of Ba in the neutron irradiation but added fallowing two paragraphs rather shyly at the end of their paper.

*"The Transuranic group of elements are chemically related but not identical to their lower homologues Rh , Os, Ir & Pt. Experiments have not been made yet to see if they might be chemically identical with even lower homologues, Tc, Ru, Rh, and Pd after all one could not even consider this as a possibility earlier. The sum of barium + technetium 138 + 101 gives 239!!. As chemists we really ought to revise the decay scheme given above and insert symbols Ba, La, and Ce in places of Ra, Ac and Th. However as "nuclear chemists" working very close to the field of physics, we cannot bring ourselves yet to take a drastic step which goes against all previous experience in nuclear physics. There could perhaps*

*be a series of unusual coincidence which has given us false indications. It is intended to carry out further tracer experiments with new radioactive decay products."*

After the publication of this paper they continued to carry out chemical separations of samples of irradiated uranium and thorium samples and conclusively found the existence of lanthanum as probable decay product of barium isotope and also existence of other decay chains involving strontium and yttrium and also that involving one of the noble gas as a reaction product. This led to their famous discovery paper in which they used the term "Nuclear Fission" for the first time, which they say that they barrowed from a biologist finding the similarity with the division of a cell. The second paper, published on 10th feb.,1939 was titled as. *"Verification of the creation of Barium isotopes from uranium and thorium by neutron irradiation: Identification of additional radioactive Fission Fragments from Uranium Fission" O. Hahn and F.Strassmann, Naturwissenschafte Vol 27 p89-95 (10 Feb 1939).*

The summary of this paper as given by them is,

1. The creation of Ba isotopes from uranium was conclusively demonstrated.

2. Formation of Ba isotopes for thorium was also established.

3. Some suggestions have been made regarding the atomic weights of barium isotopes.

4. Evidently some isotopes of barium produced from uranium and thorium are identical.

5. It is our belief that the "transuranic elements" still retain their placement.

6. A second group of fission fragments, Strontium (element 38) and Yttrium (element 39) was determined.

7. By an appropriate experimental arrangement, the formation of a noble gas was established; which in turn decays into alkali metal. it has not been yet possible to state whether it is xenon-cesium or krypton-rubidium

In a rather short time it has been possible to identify numerous new reaction products described above – with considerable certainty, - only because of the previous experience they had gathered, in association with L. Meitner; from the systematic study of uranium and thorium reaction products. One interesting question remains, why was the discovery of nuclear fission delayed by almost four years? The first results of the so called transuranic elements were published in 1934, and at that time Ida Noddack, a German chemist had argued that one should rule out the possibility of all other elements before talking of transuranics!. The discovery was so important and astonishing that almost one hundred papers were published in just one year after its discovery. As mentioned earlier Hahn and Meitner had worked together for more than 30 years and Hahn had written her a letter on 19th Dec 1938 itself in which he wrote

*"there is something very strange with our "Radium Isotopes" that we are telling to you only. Our radium isotopes behave like barium!!. Two days latter he wrote, we can not keep silent about our results even though they may be physically absurd."*

After reading these letters Meitner was equally baffled, latter that month, shortly before Christmas, her nephew Otto Fisch visited her in Sweden, who was a physicist working at Niels Bohr`s institute for theoretical Physics in Denmark. Frisch recounts his visit in following words.

*"When I came to Sweden she was brooding over the letter by Hahn and was saying Barium I do not believe it, there is some mistake. You could not chip a hundred particles of a nucleus in a one blow, It is fantastic, it is impossible!! a single neutron could do that? We walked up and down in the snow and gradually we came to the idea that perhaps one should think of nucleus being cleaved in half as with a chisel but rather that perhaps there was something in Behr's idea the nucleus was like a liquid drop."*

At this stage they understood what had happened in Hahn and Strassmann`s experiment. The neutron which they had shot into the uranium had been captured by the uranium nucleus. But then the nucleus changed the shapes, vibrated and finally came apart. Now, if that happened to a nucleus a lot of energy would be released.

## Early research in Nuclear Fission

As stated earlier within one year of the discovery itself more than 100 papers and two review articles were published on this topic. The scope of article is not to review them but it is essential to add here two of the land mark papers in this area of research. The very first among them was by Lise Meitner and O.H.Frisch published in the same week as that of the paper of Hahn. The paper was titled as "Disintegration of Uranium By Neutrons: a New Type of Reaction" Nature 143, 239-240 (Feb 11, 1939). Some important portions from this article are as follows.

*At first sight the result (of formation of lighter elements in uranium irradiation) seems very hard to understand. The formation of elements much below uranium has been considered before, but was always rejected for physical reasons, so long as the chemical evidence was not entirely clear cut. The emission of a cluster of charged particles may be regarded as excluded by the small penetrability of the "Coulomb barrier", indicated by Gamov`s theory of alpha decay. On the basis of present ideas about the behavior of heavy nuclei, a different and essentially classical picture of these disintegration processes suggest itself. On account of their closed packing and strong exchange force, the particles in a heavy nucleus would be expected to move in a collective way which has some resemblance to the movement of a liquid drop. If the movement is made sufficiently violent by adding energy, such a drop may divide itself into two smaller drops. In the discussion of the energies involved in the deformation of nuclei, the concept of surface tension has been used and its value decreases with increasing nuclear charge and may become zero for atomic numbers of the order of 100. It seems therefore possible that the uranium nucleus has only a small stability of form, and may, after neutron capture, divide itself into two nuclei of roughly equal size. These two nuclei will repel each other and should gain a total kinetic energy of the order of 200 MeV. This amount of energy is expected to be available from difference in packing fraction between uranium and the elements in the middle of periodic table.*

The second paper which forms the basis of the understanding of fission phenomenon itself was in the form of letter to editor of journal Nature and was published on 25th Feb. 1939, written by N.Bohr. He writes… *The letter to nature by L.Meitner and Frisch: these authors propose an interpretation of the remarkable findings of Hahn & Strassmann as an indication of a new type of disintegration of heavy nuclei, consisting of fission of the nucleus in two parts. According to these ideas, any nuclear reaction initiated by collisions or radiation excitation involves formation of a compound nucleus in which the excitation energy is distributed among the various degrees of freedom in a way resembling the thermal excitation in a solid or liquid body. The relative probabilities of the different possible courses of the reaction will therefore depend on the facility with which the energy is either released as radiation or converted into a form suitable for disintegration of the compound nucleus. The course of disintegration of a nucleus may thus said to result from a fluctuation in the statistical distribution of the energy between the various degrees of freedom of the system, the probability of occurrence of which will be entirely governed by the amount of energy to be concentrated on the particular type of motion considered and the excitation energy. We may therefore conclude that for the heaviest nuclei the excitation energy sufficient for the fission is of the same order of magnitudes as the energy necessary for the escape of a single nuclear particle. These considerations find their straightforward explanation in the fact, stressed by Meitner & Frisch, that the mutual repulsion between the electric charges in a nucleus will, for highly charged nuclei, counteract to the large extent the effect of the short range attractive force.*

Within two months a detail theory of nuclear fission was published in Phys. Rev by Bohr and Wheeler, which even today stands as the basic foundation of this interesting nuclear reaction. By the time the above letter was sent, Frisch had experimentally measured the kinetic energies of fission fragments using ionization chamber, and by the time the first theoretical paper of Bohr and Wheeler was published about thirty different fission product decay chains were identified.

I have tried to give a brief summary of the scientific activity at the time of the discovery which changed the modern world to a very large extent.

*Otto Hahn*



*Fritz Strassmann*



*L Meitner and O.Hahn in Radiochemistry laboratory*

### A Brief Biography of Otto Hahn (1879-1968)

Otto Hahn was born in Frankfurt am Main in March 1879. He studied chemistry at Marburg and Munich and received his PhD in 1901, submitting a thesis on organic chemistry. Hahn worked initially at the chemical institute at Marburg, then moved to University college of London in 1904, on to the Physical Institute of McGill University in Montréal in 1905, and then to the chemical Institute of the University of Berlin in 1906.

At the end of 1907, Lise Meitner came to Berlin from Vienna, and the two began more than 30 years of collaboration. Their joint work embraced investigations on beta-rays and the use of radioactive recoil to obtain new products. Between 1914-1918 Hahn served in World War I, but he resumed his research with Prof. Meitner in 1918, and discovered protoactinum. His most spectacular discovery came at the end of 1938 when, while working with Strassmann, Hahn discovered the fission of uranium.

This discovery earned him the Nobel Prize in Chemistry in 1944 and led directly to the development of atomic bomb. Hahn was scientific member of the Kaiser Wilhelm Institute for Chemistry since 1912 and was the director of the institute when he was taken into Allied custody fallowing World War II. Hahn, Meitner, and Strassmann were not engaged in nuclear weapons research during World War II. At the end of the war Hahn was astonished to hear that he had won the Nobel Prize for chemistry in 1944 and that nuclear bombs had been developed from his basic discovery. Later, as director of the Max-Planck-Gesellschaft (the postwar successor to the Kaiser Wilhelm Gesellschaft), he spoke vigorously against the misuse of atomic energy. Meitner—who many thought should have received the Nobel Prize with Hahn—continued to do nuclear research in Sweden and then England. Strassmann nurtured the study of nuclear chemistry in Mainz, Germany.

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# Glenn Theodore Seaborg

*Dr. V.K. Manchanda, a graduate from Delhi University, joined the Radiochemistry Division, BARC in 1969 through training school. He was awarded Ph.D. by Bombay University in 1975 and carried out Post-Doctoral work at UTEP, Texas, USA as a Fulbright Scholar (1985-87). His research interests include; Thermodynamics and kinetics of complexes of macrocyclic ligands with lanthanides and actinides, Physico-chemical studies on lanthanide / actinide chelates, Design and synthesis of novel extractants of actinides relevant in the back end of the fuel cycle and Chemical quality control of Pu based fuels. He has guided 15 Ph.D. scholars and has 150 International Journal Publications. He is the founder-Convener of Indian Association of Separation Scientists and Technologists (INSAT) and is President of IANCAS. He is a member of Advisory Board of an International Journal "Radiochimica Acta". He currently heads the Radiochemistry Division, BARC.*

*Dr. P.N. Pathak joined Radiochemistry Division in 1995 after comleting 38th Batch Chemistry Training course. He has contributed towards the basic studies dealing with reprocessing of thorium-based fuels using branched dialkyl amides and the use of macrocyclic ligands for $^{90}Sr/^{90}Y$ separation. He had worked as a post doctoral research fellow in Prof. G.R. Choppin's laboratory at the Florida State University, Tallahssee, Florida, USA. He is a recipient of Tarun Dutta Memorial Award by Indian Association of Nuclear Chemists and Allied Scientists (IANCAS). Dr. Pathak's has published 45 papers in leading International Journals and 90 papers in National / International Conferences*

## Introduction

Scientific advisor to 10 U.S. presidents, co-discoverer of 10 elements and the youngest Nobel Laurate, that was Glenn Theodore Seaborg, who is also credited with the discovery of Plutonium, an element which has changed the course of history since second world war. His codiscoveries include many isotopes, which have practical applications in research, medicine, and industry. He was awarded 50 honorary degrees for his contributions to science education and community service. From 1961 to 1971, he served chairman of the United States Atomic Energy Commission. Subsequently, he was university professor of chemistry at the University of California, Berkeley, associate director at large of the Lawrence Berkeley Laboratory, and chairman of the Lawrence Hall of Science. During these years, he was actively involved with research on new isotopes and new elements at the upper end of the periodic table. He also had the rare distinction of being the only scientist where an element was named after him in his lifetime. On March 13, 1994, the discoverers of element 106 recommended that element 106 be named Seaborgium, with the chemical symbol Sg, in his honor, which was accepted by IUPAC, in 1997.

## Childhood, Education and Marriage: 1912-1942

Glenn Theodore Seaborg was born in a Swedish ancestry in Ishpeming, Michigan, to Herman Theodore Seaborg and Selma Olivia Eriksson (changed to Erickson) on April 19, 1912. His only sibling, Jeanette, was born two years later. Since Glenn's parents were of Swedish origin, he learned to speak and understand Swedish before English. He started kindergarten in the High Street School in Ishpeming in September 1917 and continued there through the first three grades. Glenn was nicknamed "Lanky" because he was much taller than his classmates. Glenn never forgot his roots in

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*Glenn Theodore Seaborg*
*(April 19, 1992 - February 25, 1999)*

Ishpeming and was always very proud of his Swedish ancestry.

When Glenn was 10 years old, his family moved to Home Gardens, near Los Angeles, California. This move to California was made primarily because his mother wanted to broaden her childrens' horizons beyond the limited opportunities available in Ishpeming. Unlike in Ishpeming, where his father had guaranteed employment for life as a machinist in the iron works, in California his father never found permanent employment in his trade, and the family finances were in rather poor condition. Glenn started earning money, in his teens, by mowing lawns, and performing other odd jobs. He attended high school in the Los Angeles suburb of Watts and developed a special interest in chemistry and physics, which he attributed to his inspiring high school chemistry and physics teacher, Dwight Logan Reid. He graduated as valedictorian of his class in 1929. At first, he obtained work in a warehouse as a stevedore, but then found summer employment as a night laboratory assistant in the Firestone Tire and Rubber Co. to earn money for his freshman year at the University of California at Los Angeles (UCLA). UCLA was a tuition free public university and his earnings made it just barely possible for him to enter college in the depression year of 1929 because he could live at home and commute with friends some 20 miles to UCLA. He continued to work at a variety of odd jobs, but after getting a 99% in the Quantitative Analysis examination in the Fall of 1930, he was hired to help in the labs and stockroom for 6 hours a week at 50 cents an hour. Then he was awarded a $150 scholarship for 1931-1932, a handsome sum in those depression days. He decided to major in chemistry rather than physics because he felt it would provide him with better career opportunities if he was unable to find a position as a university teacher. During his last year, he became particularly interested in the exciting new developments in nuclear physics and chemistry. After receiving his degree in chemistry in 1933, he stayed on for the fifth year (1933-34) to take a number of courses in physics, which had just that year been started at the graduate (master's degree) level.

### At University of California, Berkley (UCB)

Since UCLA had not instituted the graduate work in the Department of Chemistry, he moved to Berkeley to pursue graduate work in chemistry. There he met the great Prof. Gilbert Newton Lewis, dean of the college of chemistry, and the rising young nuclear physicist Ernest Orlando Lawrence, who invented the cyclotron in the early 1930s, for which he received the Nobel Prize in physics in 1939. Seaborg took formal courses in chemistry from many eminent professors at UCB and earned his Ph.D. in chemistry in the spring of 1937 with a thesis on the *"Inelastic Scattering of Fast Neutrons".* He was asked by Prof. Lewis to stay on at Berkeley to serve as his personal research assistant. Glenn regarded Lewis as one of the scientific geniuses of his time and as a great teacher; they published several papers together. In 1939, he became an instructor at Berkeley and in 1941 he was promoted to assistant professor. During this period, he started collaborating with the physicist J. J. Livingood who had discovered several dozen new isotopes. Many of these, including iodine-131, are widely used in nuclear medicine procedures. In 1938, he and Emilio Segré discovered $^{99m}$Tc, still the most widely used radioisotope for nuclear diagnostics. These experiences as a *"Radioisotope Hunter"* led eventually to the exploration of the transuranium elements, which became Glenn's life-long research interest.

### Nuclear Transmutation/Fission: Neptunium Discovery

Even during his graduate years, Glenn closely followed the developments from Enrico Fermi's

group in Italy, which was bombarding uranium with neutrons and producing what they thought were transuranium elements, and the research of Otto Hahn, Lise Meitner, and Fritz Strassmann in Berlin on these so-called transuranium elements. These results were widely discussed at Berkeley at the weekly nuclear seminars and physics journal club meetings. In January 1939 the exciting news of the discovery of nuclear fission by the Berlin Group came to Berkeley by word of mouth. Edwin M. McMillan and Philip H. Abelson then set out to study the fission process by bombarding uranium with neutrons (produced by the bombardment of 8-16 MeV deuterons on a beryllium target) at Berkeley's new 60-inch cyclotron. Quite unexpectedly, they produced and identified the first "*real*" transuranium element, which they chemically separated and identified as element 93, for which they proposed the name *Neptunium*.

### Plutonium Discovery

Soon after the discovery of neptunium in the spring of 1940 at the University of California, Berkeley, by Edwin M. McMillan and Phillip H. Abelson, the search for the next transuranium element was underway. McMillan was working on the synthesis of next heavier transuranium element (atomic number 94), but received a call for wartime research at the Massachusetts Institute of Technology. With McMillan's concurrence, Glenn continued this search and led a team consisting of fellow instructor Joseph W. Kennedy and his first graduate student, Arthur C. Wahl, in performing the first chemical separation and positive identification of plutonium in February 1941. It was produced as the isotope $^{238}$Pu in deuteron bombardments of $^{238}$U. Soon after, the new isotope $^{239}$Pu was produced and was found to be highly fissionable. Because of potential military applications in nuclear weapons during World War II, these results were voluntarily withheld from publication until 1946.

These discoveries led to the U.S. decision to undertake a crash program to develop nuclear reactors for plutonium production to be used in the U.S. Atomic Bomb project. In April 1942, Glenn took a leave of absence from Berkeley to go to the University of Chicago Metallurgical Laboratory to direct the work on the chemical extraction and purification of plutonium produced in the reactors.

### The Plutonium Project and Marriage

In March 1942, when it was clear to Glenn that he is moving to Chicago to work on the plutonium project, he proposed to Helen Lucille Griggs (then E. O. Lawrence's secretary). The understanding was that he would soon come back to Berkeley and they would be married. In June 1942, he did return from Chicago to Berkeley and took Helen to visit his parents at Home Gardens, now a part of South Gate, near Los Angeles, California. During their return journey, he then persuaded Helen to marry en route. They disembarked from the train at Caliente, Nevada, and married at Pioche, Nevada, on June 6, 1942. Helen and Glenn's marriage was to last for more than 56 years and Seaborg often fondly referred to Helen as "his best discovery".

They had six children: Peter Glenn, who died in 1997, Lynne Annette Seaborg (Mrs. William B. Cobb), David Michael, Stephen Keith, John Eric, and Dianne Karole, all of whom survived. Helen was his constant companion and advisor and accompanied him on most of his trips, faithfully attending the scientific and other symposia in which he was involved. Personally, he was most gratified to have her support in the audience when he spoke at some of the meetings.

### Separation of Plutonium and Discovery of Elements (95-102): 1942-1961

The Metallurgical Laboratory Chemistry Group, headed by Seaborg, was responsible for devising plant processes for chemical purification of plutonium for the World War II Manhattan Project to develop an atomic bomb. The plant procedures, which were developed and later used in the manufacture of kilograms quantities of plutonium at Clinton, Tennessee, and Hanford, Washington, were devised on the basis of experiments with milligram (or less quantity) of plutonium. It represented a remarkable scale-up of more than six orders of magnitude, causing much initial skepticism about the success of the project. By 1944, the process chemistry of plutonium was established on an industrial scale.

### The Actinide Concept

A few attempts of Seaborg and his co-workers to produce and identify the next transuranium elements beyond Pu (Z = 94) were unsuccessful until he came up with the *Actinide Concept* based on electronic structure. A new periodic table incorporating this concept was published in *Chemical & Engineering News* in 1945. It was viewed as a "wild" hypothesis because at that time it was commonly believed that thorium, protactinium, uranium, neptunium, plutonium, and the following elements should be placed as the heaviest members of groups 4 through 10. But Seaborg postulated that the heavier actinides, like their lanthanide counterparts, would be extremely difficult to oxidize beyond the trivalent oxidation state. Therefore, he made a strong case for the positioning of separate 14 elements heavier than actinium (atomic number 89) in the periodic table of elements as a 5f transition series under the lanthanide 4f transition series. This concept was verified when chemical separations based on separating elements 95 and 96 as trivalent homologues of the lanthanides were successfully used in 1944 to separate and identify these new elements, subsequently named *Americium and Curium*.

### Nobel Prize: Post World War II Period

Glenn Seaborg returned to Berkeley from Chicago in May 1946 as full professor of chemistry, along with his associates, like Isadore Perlman, Burris B. Cunningham, Stanley G. Thompson, and Albert Ghiorso. In the following years up to 1958, Seaborg and co-workers, (including many graduate students and postdoctoral fellows), went on to synthesize and identify the next six transuranium elements with atomic numbers 97 through 102. The first of these, Berkelium (97) and Californium (98), were produced at the Berkeley 60-inch cyclotron in 1949-50. Shortly thereafter, in 1951, Seaborg and McMillan shared the Nobel Prize in chemistry for their research on the transuranium elements.

Elements 99 and 100 were most unexpectedly produced in the debris from the first thermonuclear device, which was designed and tested by the Los Alamos Scientific Laboratory on Eniwetok Atoll in the South Pacific on November 1, 1952. Its huge yield of some 10 megatons created such an instantaneous high neutron flux that at least 17 neutrons were captured by the $^{238}$U in the device. Seaborg's group at Berkeley was the first to separate and obtain evidence for these new elements, working together with scientists from Argonne National Laboratory and Los Alamos to confirm these results. The group proposed the names *Einsteinium* and *Fermium* for these elements in honor of the great scientists Albert Einstein and Enrico Fermi.

### Single Atom Chemistry

Mendelevium ($^{101}$Md), the ninth transuranium element to be discovered, was first identified by Albert Ghiorso, Bernard G. Harvey, Gregory R. Choppin, Stanley G. Thompson, and Seaborg in early 1955 as a result of the bombardment of about $10^9$ atoms of the isotope $^{253}$Es (20-day half-life) with helium ions in the Berkeley 60-in. Cyclotron. The isotope produced was $^{256}$Md, which decayed with a short half-life (approximately 1 h) by electron capture to $^{256}$Fm, which in turn decayed predominately by spontaneous fission with a half-life of 2.6 h. This first identification was notable in that only a few atoms per experiment were produced. The definitive experiments were performed in a memorable all night session, February 18, 1955, with chemical identification by the ion exchange adsorption elution technique. A total of five spontaneous fission counts were observed in the element 101 portion, and a total of eight spontaneous fission events were also observed in the element 100 position. This element was the first to be discovered on a *one-atom-at-a-time* basis, and the techniques developed served as a prototype for the discovery of subsequent elements.

Seaborg and co-workers produced Nobelium (102) in 1958 using the heavy ion linear accelerator at the Berkeley Radiation Laboratory. According to the actinide hypothesis, it was expected that nobelium should have a relatively stable 2+ state by analogy with ytterbium, which can be reduced from 3+ to 2+ with strong reducing agents. However, it was found that not only is the 2+ state of nobelium achievable, it is the most stable oxidation state of nobelium in aqueous solution. In addition to the discovery of transuranium elements, Seaborg and his colleagues were responsible for the identification

of more than 100 isotopes of elements spread throughout the Periodic Table.

During the period 1946-58, Seaborg served as director of the Nuclear Chemistry Division and in 1954 became an associate director of the Berkeley Radiation Laboratory. In addition to their pioneering work on the production and chemical properties of the transuranium elements, the division discovered dozens of new isotopes and furnished much of the data on alpha-particle radioactivity and nuclear energy levels needed for the evolution of modern theories of nuclear structure.

### Public Services & Other Responsibilities

Seaborg served in the first General Advisory Committee to the Atomic Energy Committee from 1947 to 1950. Consistent with his immense interest in athletics, he accepted Chancellor Clark Kerr's invitation to serve as Berkeley's faculty athletic representative from 1953 to 1958 and played a leading role in organizing the Athletic Association of Western Universities. When Kerr became president of the University of California in 1958, Seaborg was asked to serve as chancellor, which he did until 1961 when President-elect John F. Kennedy asked him to come to Washington, D.C., to chair the U.S. Atomic Energy Commission.

### The Washington, D.C. Years: 1961-1971

### Chairman, The U.S. Atomic Energy Commission

Seaborg was granted the leave of absence from the University of California to take up the responsibilities as the chairman of the U.S. Atomic Energy Commission (AEC). His tenure from 1961 to 1971 was longer than any other chairman's and spanned the presidencies of John F. Kennedy, Lyndon B. Johnson, and Richard M. Nixon. Seaborg negotiated for the limited nuclear test ban treaty, which prohibited the testing of nuclear devices in the atmosphere or under the sea. This treaty was approved by the U.S. Senate in 1963. Seaborg was a strong supporter of the use of nuclear energy for power generation and led delegations to several countries, including the Soviet Union, for the promotion of peaceful uses of atomic energy.

Even as Chairman, USAEC, he continued his interest in transuranium element research and the

National Transplutonium Production Program was established at the High Flux Isotope Reactor, which was commissioned at the Oak Ridge National Laboratory in the mid-1960s. These facilities were used for the production of rare heavy-element isotopes used in the synthesis of new heavy elements and in heat sources for space exploration. Other radioactive isotopes for applications in biology, nuclear medicine, and industry were also produced. As AEC chairman, due to his strong support, the basic research programs in the physical sciences, biology, and medicine nearly doubled. He also felt the need of the improvement of teaching in science and mathematics to attract young people to careers in science.

### Return To Berkeley: 1971-99

Seaborg returned to Berkeley in 1971 as University Professor of Chemistry. He continued to teach until 1979. He supervised the Ph.D. research of more than 65 students. In 1982, he became the first director of the Lawrence Hall of Science, which he founded. He served as associate director at large of the Lawrence Berkeley National Laboratory until his death in 1999. He was active in many international organizations for fostering the application of chemistry to world economic, social, and scientific needs. Seaborg maintained and even escalated his interest in better education in science and mathematics at all levels and served on many federal and state committees. President Reagan appointed him to be a member of the Commission on Excellence in Education (NCEE). Seaborg presented the report *"A Nation at Risk"* in April 1983. In 1989, Seaborg and the then Secretary of Energy James Watkins hosted a Mathematics/Science Action Conference at the Lawrence Hall of Science that again called for a revitalization of science education in the U. S. In 1989, Seaborg was asked to brief President George A. Bush on the *"cold fusion"* phenomenon.

### Other Interests

Seaborg was a keen student of history and kept a Journal since he was eight years old. After his return to Berkeley from Washington in 1971, he made a concerted effort to put them into a book form, which occupied him and several others for several years. His Journals also formed the basis for

monographs on his years as chancellor at Berkeley, as chairman of the AEC, and on several other fronts. On the rare occasions that he did not remember something that was asked, he would look it up in his Journals. He had a fabulous memory and was able to synthesize and apply to the situation at hand. One might almost say in the parlance of his time that he was a *"parallel processor"*!

In 1990 he decided that a symposium must be held to commemorate the fiftieth anniversary of the first chemical separation and proof of the discovery of plutonium on February 23, 1941. In this meeting, the announcement of the initial establishment of the Glenn T. Seaborg Institute for Trans-actinium Science at Lawrence Livermore National Laboratory was made by its former director and Seaborg Ph.D. student (in 1951) Roger Batzel. The institute is devoted to the study of the transactinium elements with special emphasis on the education and training of future generations of scientists in heavy-element research. Seaborg's legacy as a Citizen-Scholar was also commemorated by establishing the Glenn T. Seaborg Centre and the new Seaborg Science Complex, in 1998, for teaching and learning science and mathematics at Northern Michigan University in the Upper Peninsula, not far from his birthplace in Ishpeming.

Seaborg loved to hike, and he and his wife, Helen, laid out an interconnected network of 12-mile trails in the East Bay Hills above Berkeley extending to the California-Nevada border that forms a link in a cross-country trek of the American Hiking Society. He was also a strong supporter of the Berkeley athletic program. Football was his favorite spectator sport and he liked to point out that during his tenure as chancellor the Berkeley football team went to the Rose Bowl!

### Seaborgium: Element 106

Element 106, which was reported in 1974 was named "Seaborgium" in honor of Nobel Laureate Glenn T. Seaborg. The name Seaborgium, with its chemical symbol of "Sg," was announced at the 207th national meeting of the American Chemical Society in San Diego. The announcement was made by Kenneth Hulet, retired chemist from Lawrence Livermore National Laboratory (LLNL) and one of the co-discoverers of seaborgium. This name was officially approved by the International Union of Pure and Applied Chemistry in 1997. It was the first time an element has been named for a living person. Seaborg, the co-discoverer of plutonium and nine other transuranium elements remarked, *"This is the greatest honor ever bestowed upon me-even better, I think, than winning the Nobel Prize. Future students of chemistry, while learning about the periodic table, may have reason to ask why the element was named after me, and thereby learn more about my work."*

### Achievements & Honours

It is a daunting assignment to make an attempt on enumerating the major achievements of Seaborg, which culminated in Nobel Prize in chemistry in 1951. He held more than 40 patents, authored more than 500 scientific articles and numerous books, including his journals, which he faithfully kept throughout his career. These formed the basis for a number of books, including an autobiography published in 1998 entitled *A Chemist in the White House: From the Manhattan Project to the End of the Cold War*. One of his last accolades was being voted one of the top 75 distinguished contributors to the chemical enterprise over the last 75 years by the readers of Chemical & Engineering News. It was this award that he accepted at a huge ceremony and reception at the August 1998 American Chemical Society meeting in Boston the evening before he suffered a stroke. He died on February 25, 1999. He was 86. Seaborg's death came while he was convalescing at home in Lafayette, near Berkeley. A few of the several awards bestowed on Seaborg are listed below:

### Awards

1.  1947: Named as one of America's 10 outstanding young men by the U.S. Junior Chamber of Commerce;

2.  1947: Recipient of the American Chemical Society's Award in Pure Chemistry;

3.  1948: John Ericsson Gold Medal by the American Society of Swedish Engineers;

4.  1948: Nichols Medal of the New York Section of the American Chemical Society;

5.  1951: *Nobel Prize in Chemistry*;

6. 1953: John Scott Award and Medal of the City of Philadelphia;

7. 1957: Perkin Medal of the American Section of the Society of Chemical Industry;

8. 1959: Atomic Energy Commission's Enrico Fermi Award ;

9. 1962: Swedish American of the Year by Vasa Order of America, Stockholm;

10. 1963: Franklin Medal of the Franklin Institute, Philadelphia;

11. 1971: Nuclear Pioneer Award of the Society of Nuclear Medicine;

12. 1973: Order of the Legion of Honor of the Republic of France, Decoration;

13. 1979: Priestley Medal;

14. 1984: Swedish Council of America's Great Swedish Heritage Award;

15. 1986: University of California's Clark Kerr Medal;

16. 1988: National Science Board's Vannevar Bush Award;

17. 1991: Presidential National Medal of Science.

**Bibliography of Glenn T. Seaborg**

The Nobel prize winning chemist, G.T. Seaborb ranks among the most prolific authors in scientific history. With some 50 books, 500 scientific journal articles, hundreds of published speeches and a lifelong daily journal, a massive volume of written material written by Seaborg is available. Seaborg frequently collaborated with other scientists, co-authors and staff members to achieve the productivity for which he was so well-known. Although most of his writings were in the field of nuclear chemistry, history of science, science education and public science policy, he has also collaborated on works in sports and collegiate history. The partial list of books and other major publications by Glenn T. Seaborg can be retrieved from "http://en.wikipedia.org/wiki/Bibliography of Glenn T. Seaborg".

**Concluding Remarks**

As an educator he inspired thousands of students to become interested in chemistry and its applications, and as a public speaker he helped develop an awareness of the impact of science on daily life and the importance of non-proliferation of nuclear weapons. It would be befitting to conclude about the accomplishments of the Science Giant Glenn Seaborg with an excerpt from the statement he delivered upon being appointed Chancellor of the University of California, Berkeley in 1958.

*"There is a beauty in discovery. There is mathematics in music, a kinship of science and poetry in the description of nature, and exquisite form in a molecule. Attempts to place different disciplines in different camps are revealed as artificial in the face of the unity of knowledge. All literate men are sustained by the philosopher, the historian, the political analyst, the economist, the scientist, the poet, the artisan and the musician."*
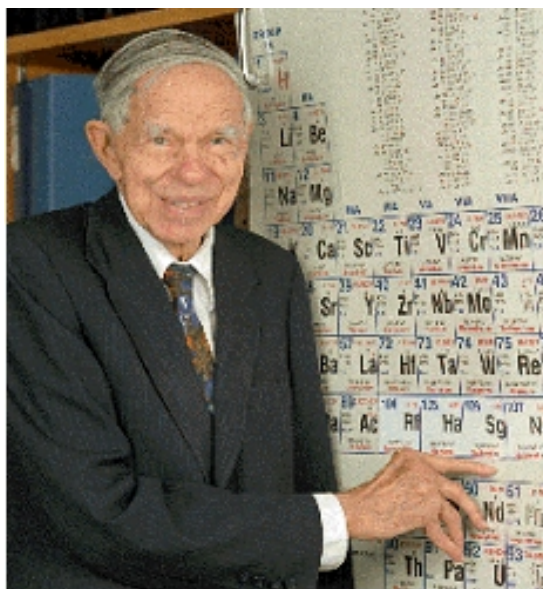


*Photo #1Glenn Seaborg points out Seaborgium on the periodic table*

Photo #2  In April 1992, Glenn Seaborg and his wife, Helen, celebrated his 80$^{th}$ birthday at Lawrence Hall of Science. The Time magazine cover behind them depicts Seaborg as chair of the Atomic Energy Commission, a position he held for a decade beginning in 1961.



Photo #3 The codiscoverers of element 106, seaborgium (Sg) at the Heavy Ion Linear Accelerator building of the Lawrence Berkeley Laboratory at the time of discovery in 1974. From left to right: Matti Numia, Jose R. Alonso, Albert Ghiorso, E. Kenneth Hulet, Carol T. Alonso, Ronald W. Lougheed, Glenn T. Seaborg, and J. Michael Nitschke
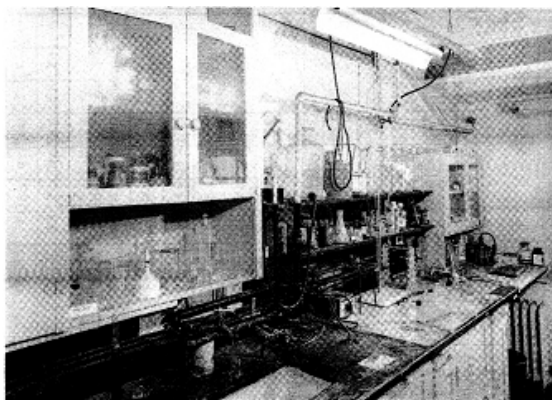


Photo #4Room 307 Gilman Hall at the University of California, Berkeley. This photograph was taken on February 21, 1966, when the room was still much the same as it was at the time of first chemical identification of plutonium

# Rosalyn Sussman Yalow

*Dr. Mrs. Meera Venkatesh joined the Radiopharmaceuticals Division, BARC through training school (1976). She has been engaged in the research and development of Radiopharmaceuticals and radiometric assays since then. Dr. Meera obtained her doctorate degree from the Bombay University in 1986 for her work in the field of Radioimmunoassays. She did her post-doctoral fellowship at the University of Missouri, USA during 1992-94 in the field of therapeutic radiopharmaceuticals and later in 1999 served as a visiting professor at the same University. Currently, Dr. Meera is heading the Radiopharmaceuticals Division, BARC and concurrently serves in the capacity of General Manager of Quality Control at the Board of Radiation and Isotope Technology. Dr. Meera has published over 75 papers in International and National Journals and presented ~85 papers in Conferences and Symposia. She has served as an expert in the field of Radiopharmaceuticals and Radiometric assays several times for the International Atomic Energy Agency (IAEA).*

*Rosalyn Sussman Yalow*

The name of Rosalyn Sussman Yalow, is immediately associated with the technique of "Radioimmunoassay" which she jointly developed with Dr Berson and for which she was awarded the Nobel Prize in Physiology and Medicine in 1977. The simple yet wonderful technique of "Radioimmunoassay" revolutionized the whole world of endocrinology, pathology and in fact the whole of medical diagnosis. Her journey through the scientific career is interesting and filled with exciting happenings. But, Dr Rosalyn Yalow had several other attributes too, that were commendable and worth emulating.

Rosalyn Sussman was born on July 19, 1921 in the Bronx, New York, USA. Her mother, Clara Zipper, was brought to America from Germany at the age of four and father, Simon Sussman, was born on the Lower East Side of New York, the Melting Pot for Eastern European immigrants. Rosalyn's scientific success was self-made, as both her parents had very little education, with her mother having finished sixth grade and father eighth grade. But her parents valued learning and were keen to help their children attain higher education. Dr Yalow mentions that her parents had acquired knowledge and were well read, although they did not have the degrees. She recalls that her father was a regular reader of New York Times and kept a very neat account book with extremely good handwriting. Her mother was an avid reader who read all the books that were brought into the house by her children. In their locality of Jewish immigrants, every child was keen on reading at a very young age so that they could enroll in a public library and get books issued. Rosalyn was able to read by the time she was five and marching to the library in the vicinity with her elder brother was her regular routine. Rosalyn was a very intelligent and adamant child. She was bold and did

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not hesitate to fight for a cause that she felt was right. These traits were seen right from the beginning. When she was in the first grade, she was beaten by a teacher who had earlier beaten her brother also. While her brother had cried submissively, Rosalyn struck back and marched to the Principal's office to protest. She had waited for five years to avenge the injustice meted to her brother. This was unheard of in the history of Jewish students. Rosalyn's parents were strong supporters of her and bemused by this incident, they staged a triumphant show in the local park. A photograph of the young five year old Rosalyn donning the boxing gloves of a man is a memory of that incident, cherished by the Noble Laureate. She feels that the aggressive attitude was responsible for her entry into Physics! "That's the attitude that made it possible for me to go into physics", she says. She was independent and stubborn, says her mother. Her parents let Rosalyn do what she wanted and encouraged her in her quest. Her father never distinguished her as a girl and never felt that girls were less important than the boys. This support of her father brought Rosalyn very close to him.

As a child, Rosalyn Sussman was always way ahead of other children in academics. She could finish the course work of three year duration in two years and thus be the youngest in the class. She had keen interest in mathematics in the elementary school, but was drawn towards chemistry in the high school owing to a good teacher. When she graduated from high school in 1937, her parents advised her to become an elementary school teacher, as was the practice with bright Jewish girls then. Rosalyn desperately wanted to pursue a career in medicine. But medicine and law were the forte of boys in those days. Admission into a medical college for a girl was very difficult and being a Jew made it impossible. The tuition fees were also beyond the affordability of Rosalyn's family. But her excellent grades won her admission to the Hunter College, the highly competitive women's college. There, she was drawn to physics and completed her B.A in Physics in 1941. Physics and in particular nuclear physics was the most exciting field in the world in the late thirties, says Rosalyn. Her interest in nuclear physics was reinforced by the biography of Marie Curie by her daughter Eva Curie in 1938. She read the book several times, as did other women scientists. The

Hollywood film on Marie Curie five years later enthralled Rosalyn. For her, Madame Curie's story had a special meaning. "For me the most important part of the book was that, in spite of early rejection, she succeeded. It was in common with my background" says, Yalow. Rosalyn had the highest admiration for Marie Curie. In 1939, fission was discovered by Lise Meitner, Otto Hahn and Fritz Strassmann. When Enrico Fermi gave a colloquium on nuclear fission at the Columbia University, Yalow was desperate to attend the lecture as were all physicists in New York. She hung from the rafters in the top rows of the lecture hall and listened to Fermi. Such was her dedication and perseverance.

Although Rosalyn was enthusiastic about a career in physics, she realized that it was unlikely that good graduate schools would admit and offer financial support to a woman interested in science, much less a Jewish woman. At Hunter's, she had faced discrimination by a few "old maid" women professors, who did not believe that a scientist could combine scientific career with a married life. Purdue University, in response to her application, said that "She is from New York. She is Jewish. She's a woman. If you can guarantee a job afterward, we'll give her an assistantship". With no such job guarantee, Rosalyn could not get into the Purdue University Grad School. Rosalyn has lost opportunities because of the discrimination against her as she was a Jew and a woman. But, instead of being bogged down, it made her stronger and fight back with the grit. On discrimination she says "**Personally, I have not been terribly bothered by it. I have understood that it exists and it's just one other thing you have to take into account in what you are doing. I have long felt that the trouble with discrimination is not discrimination per se, but rather that the people who are discriminated against think of themselves as second-class**".

In 1941, after graduating from Hunter College with honours in Physics and Chemistry, she was forced to take work as a secretary to a Columbia University biochemist. Rosalyn Sussman took a course in secretarial school, as this allowed her to take some science courses at the Columbia University. But, soon World War II was to begin and the colleges were bereft of their male students. This was a blessing for Rosalyn as Graduate schools were

offering teaching assistantships to women, and she too got an offer from the University of Illinois, the most prestigious university she had applied to. Her secretary course came to an abrupt end and she went off to Champaign-Urbana, in the fall of 1941. She was the first engineering student permitted in the Univ. of Illinois since 1917, which was during the first World War. No matter why she was admitted to Illinois, her academic performance once she was there was outstanding.

In 1943, she married a fellow student Aaron Yalow, who was a rabbi's son from Syracuse and another aspiring nuclear physicist. Aaron Yalow was an extremely understanding and supportive life partner. He encouraged her in her pursuits and was an understanding spouse. Rosalyn was a conscientious wife who used to even cook in advance when she went on tour. Both Rosalyn and Aaron did their Ph. D. research under the guidance of Prof. Maurice Goldhaber, who went on to become the director of Brookhaven National Laboratory. During her graduate training in Illinois under the renowned nuclear physicist Maurice Goldhaber, Rosalyn became proficient in the construction and use of apparatus for the measurement of radioactive substances, a skill that proved critical in her later research. She received her Ph.D. in nuclear physics in 1945. On being asked 'who was the better physicist among the two of them', Rosalyn replied that her aggressiveness made her better at times! She quotes the example of their examination by the Illinois' Department Chairman, who disliked both of them. He had asked Aaron to solve a problem in twelve different ways, and Aaron did so. When he tried the same ruse with Rosalyn, she retorted back saying that "Goldhaber and Nye have taught me this way. If there is anything wrong, you better talk to them about it" and the Chairman walked off from the examination.

Soon after receiving their Ph.D., both Aaron and Rosalyn Yalow returned to New York and looked for teaching jobs in universities. Unable to find a position to teach nuclear physics, she accepted a position as an engineer at the Federal Telecommunications Laboratory. But when the lab closed a year later, she took up a full-time teaching position at Hunter College in 1946. Hunter had no research facilities and she was getting nowhere in

nuclear physics. High energy physics was too big for her. At this juncture, Aaron suggested the field of medical physics and the use of radioisotopes . He introduced her to Dr. Gioacchino Failla, the dean of American Medical Physicists, who was instrumental in her entry into the Veterans Affairs (VA) Medical Centre in the Bronx, New York, in 1947 to set up a radioisotope service laboratory. VA had decided to establish Radioisotope Services in several of its hospitals nationwide, since it considered radioisotopes to be a cheap alternative to radium for cancer treatment. But Rosalyn had far more plans, having read the book by the 1943 Nobel Prize winner George Hevesy, on how radioisotopes could be used as tracers in chemical and biological sciences. Hevesy's book had tremendous impact on the young Rosalyn's mind. While most of us who read the books written by great personalities or their biographies are in awe of these gifted fellow human beings, Rosalyn went one step ahead and strived hard to reach the same heights as her heroes! Along with Hevesy, Marie & Pierre Curie, Henry Becquerel, Irene & Frederick Joliot-Curie were her idols and she considered them as the progenitors of her illustrious career.

While still on the faculty at Hunter as full time teacher, she became a consultant in nuclear physics at the Veterans Administration (VA) Hospital in the Bronx, and set up a radioisotope lab by turning a janitor's closet into the lab! Her strong willed nature and the "never say die" attitude infused the capability in her to make wonderful things out of ordinary day-to-day items! This radioisotope lab which was among the first few in the United States, swung into operation soon after and started several research projects with the hospital physicians, such as Bernard Roswit, chief of radiotherapy services. Her engineering training and skill helped her to design and build her own instruments as they were not available commercially. Within two years she had eight original publications to her credit. Working at VA was not an easy task for Yalow as she was a female Ph.D. in a hospital dominated by male physicians, in a place where scientific research is not the main stream activity. The tough path ahead perhaps made Yalow a very aggressive and assertive person. She was not scared of the "outsider" status. Her experience in Illinois had taught her to stand tall and realize her own potential to excel in whatever

she undertook. She was very well organized and worked towards her goals with full concentration and efforts. In the early years she did face the hints of discrimination at the VA and was "mad as the devil" when faced with such situations. One of her students recalls that "the only way she could make her point was to be very precise, definitive and assertive; otherwise nobody would have listened to her. Sometimes people see her brusque side. But, to be noticed in the world of science, she had to be that way. She was an outsider in everyway. She was working in a new field of physics and she didn't have the right credentials in medicine. So she had to let them know that she was for real". Yalow believed and still believes that "women, even now, must exert more effort than men for the same degree of success". However, realizing the good work done by Yalow, the VA authorities supported her. In 1950, Yalow left Hunter and accepted a full-time position with the VA, to be a full time medical physicist with the physicians. But she continued to teach one more course just for another semester only because she had spotted an extremely talented young student, Mildred Spiewak Dresselhaus. Mildred, the first student to taken under the wings of Yalow, went on to become a professor at MIT, a member of the National Academy of Engineering and National Academy of Sciences, and President of the American Physical Society. Yalow was a teacher who took her students to great heights. Mentoring students came very naturally to her. Her motherly attitude towards her students, protective nature, inspirational guiding capabilities, no-nonsense attitude and tough mentoring turned many of her students into protégés.

Soon after, she recognized the inter-disciplinary nature of the subject of medical physics and looked for a collaborator with complimentary abilities. Then she met Solomon Berson, a young talented resident physician in internal medicine. Berson was a brilliant personality who apart from his subject, namely physiology/biology, excelled in several skills such as playing violin, chess, art, writing and philosophy. His intense charming personality and the common bond of Jewish origin bonded Yalow and Berson strongly and their collaboration lasted for 22 years thereafter, until Berson's untimely death in 1972. Berson provided the biological insights, physiology, anatomy and clinical medicine, while Yalow provided physics, maths, chemistry and engineering. The passion to learn was so intense in Yalow that soon, she knew more physiology than most leading physiologists and became one of the few non-physician members of the prestigious Association of American Physicians. Rosalyn's deep desire to become a medical professional would perhaps have been fulfilled to some extent with this honour.

Dr Yalow and Dr Berson were a perfect team with complimentary attributes and expertise. The understanding between them was so complete that each could gauge what was in the others mind and needed to talk very less – and most of the times in cryptic short sentences! Although Dr Berson used to dominate everyone around, he was an equal partner with Yalow. They shared the credits equally, by each one being the first author of the publications alternately! However, it was Berson who shone in public and did most of the talking and writing. Yalow, Berson and their students were like a family who shared all the results, secrets and kept a close knit relation among each other. Yalow and Berson protected their wards from attacks from other colleagues. Yalow had the blend of professionalism and the affection making her a great scientist as well as a great mentor!

The joint investigations between Berson and Yalow began with an attempt to use radioisotopes to obtain more accurate estimates of blood volume, but their first major contribution was a study of how the thyroid gland and kidneys remove iodine from the blood. They developed a method of discerning the quantity of blood cleared of iodine by the thyroid gland per unit of time. Using radioisotopes, Yalow and Berson could readily ascertain clearance rates in a 35-min sitting, providing a quick determination of thyroid activity. Expanding these measuring techniques to the study of globins and other serum proteins, Yalow and Berson were determined to apply their methods to one of the most important classes of small peptides: hormones. According to Yalow, they chose insulin as a subject of research because it was the hormone most readily available in a purified form and was easier to work with in the laboratory than other hormones. But Yalow had a familial reason to be interested in insulin, as her husband, Aaron, was diabetic. Among the endocrine

gland disorders, diabetes affects the greatest number of people, making insulin uniquely important, as without its ability to lower blood sugar, death is inevitable.

Both Yalow and Berson were workaholics. Yalow noted once " **I'm a morning person. When I am stewing about something I'm working on in the laboratory, I'll wake up to two or three in the morning and by daybreak everything will fall into place and I know the experiment that has to be done the next day.**" Yalow worked through fevers, colds and several years of anemia. She typed her children's school papers, cooked in between her work at the lab, stayed up until late night with chemical assays and returned to work at 8 am next morning! She said that "**the excitement of learning separates youth from old age. As long as you're learning you're not old.**" Such dogged dedication sure deserves to be rewarded with a Nobel prize! Her eagerness to learn new things was something amazing and defied her age. Further, Yalow used to take care of the lab animals such as rabbits, mice and guinea pigs during the holidays and vacations. Such dedication and willingness to do far more than what one is paid for is rare to find and such qualities are vanishing with time!

Radioimmunoassay came into being not by directed design but more as a fall out from their investigations from an unrelated study by Dr.I.Arthur Mirsky who hypothesized that maturity-onset diabetes might not be due to deficiency of insulin secretion but rather to abnormally rapid degradation of insulin. To test this hypothesis they studied the metabolism of $^{131}$I labeled insulin following intravenous administration to non diabetic and diabetic subjects. They observed that radioactive insulin disappeared more slowly from the plasma of patients who had received insulin, either for the treatment of diabetes or as shock therapy for scizophernia, than from the plasma of subjects never treated with insulin. They suspected that the retarded rate of insulin disappearance was due to binding of labeled insulin to antibodies that had developed in response to administration of exogenous insulin. At that time classic immunologic techniques were not adequate for the detection of antibodies so they introduced radioisotopic methods of high sensitivity for

detection of soluble antigen-antibody complexes. With techniques such as electrophoresis and variety of similar systems they were able to demonstrate the ubiquitous presence of insulin binding antibodies in insulin treated subjects. This concept however, was not acceptable to the immunologists of the mid 1950's. The original paper describing these findings was rejected by the prestigious journal **Science** and the **Journal of clinical Investigation** refused to publish the article until the phrase "insulin antibody" was removed from the title. A compromise with the editors eventually resulted in acceptance of the paper after they omitted "insulin antibody" from the title and documented their conclusion that the binding globulin was indeed an antibody according to it's definition in immunology. Dr Yalow harbored bitter feelings even after decades of this incidence. Although other investigators had also observed that people who had been treated with insulin process the hormone slower than the others, it was only the Berson-Yalow team who could interpret the reason correctly and go further to invent a new methodology to measure the hormone itself! They were indefatigable! In Yalow's words, "it isn't by accident that you interpret the observation correctly; that's creativity. I still think discovery is the most exciting thing in the world."

Even though their technique detected and measured the antibodies to a hormone, Yalow & Berson realized that a complementary technique would measure the hormone itself. Yalow says "**once you saw it one way, you saw it the other way.**" This use of radioisotopic techniques for studying the primary reaction of antigen with antibody and analyzing soluble complexes initiated a revolution in theoretical immunology and it was appreciated that small peptides are antigenic and equilibrium constants for the antigen antibody reaction can be as great as $10^{14}$ liters per mole.
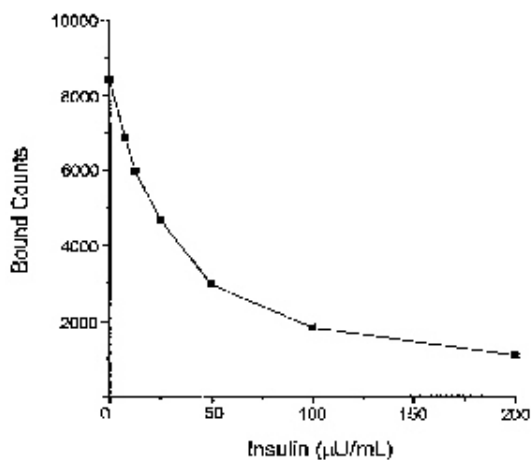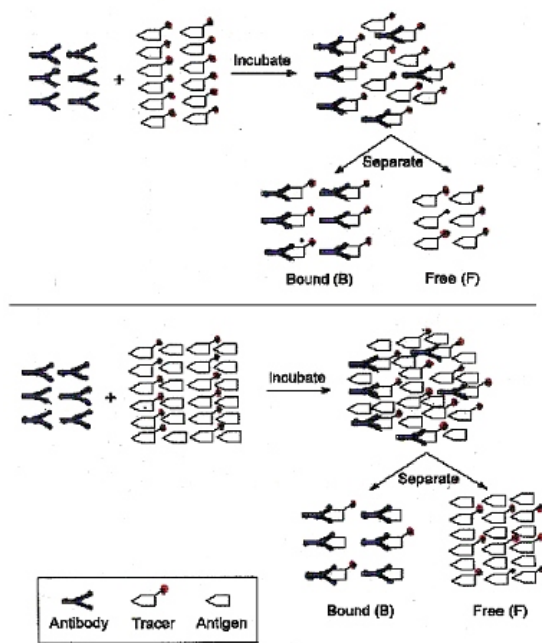
Yalow and Berson called their method "Radioimmunoassay" (RIA) as radiolabeled molecule was used to measure the hormone using its reaction with antibodies produced by the immune system. RIA was the first technique to use radioisotopic techniques for the study of the primary reaction of antigen with antibody. The principle of RIA is given in the inset and has been earlier covered in detail in one of the IANCAS bulletin (ref). They

reported that binding of labeled insulin to a fixed concentration of antibody is a quantitative function of the amount of insulin present. This observation provided the basis for the radioimmunoassay of plasma insulin. Though RIAs are performed by automated systems these days, Yalow and Berson worked tirelessly for several years, analyzing varied types of samples by RIA and processing the data. They worked day and night with no technicians to help them! The dedication and conviction can be seen in the manner in which they worked, and there is this lesson to be learned: "to be self reliant and self sufficient if one wants to succeed".

Yalow and Berson published the idea of radioimmunoassay in 1956 and worked for the next three years to convert the idea into a practical modality. Species specificity of the available antisera were required to translate the theoretical concepts of radioimmunoassay into experiments that led first to the measurement of plasma insulin in rabbits following exogenous insulin administration and finally in 1959 to the measurement of insulin in unextracted human plasma. This was not easy and the medical fraternity was full of skepticism. But Yalow and Berson, born fighters, fought it through by training scientists to use RIA. The latter half of

1960's saw an explosion in the field of RIAs and the two giants were convinced that their questioning and forcing every fact to defend itself had paid off! It did not just pay off ordinarily– but paid off brilliantly with the Nobel Prize Award!

The technique of RIA had several remarkable advantages; the high sensitivity in the range of one billionth of a gram was unheard of and unbelievable! The test is in-vitro, meaning "in test tubes" thereby causing minimal botheration to the patient. The volumes needed to perform the test were also far lesser than the other tests routinely used in those days. RIAs could be developed for nearly every hormone and biologically important molecule, facilitating analysis of a battery of hormones at one place simultaneously. With advent of RIAs the world of endocrinology was also revolutionized. It was diabetes in the beginning followed by all of modern endocrinology, with Berson and Yalow boldly and quickly moving from one area to another. The confidence built upon by analysis of tens of thousands of samples instilled the bold self-confidence in them. Yalow mentions that "**Only if we can detect and measure can we begin really to understand and herein lies the major contributions of RIA as a probe for insight into the function and perturbations of the fine structure of biologic systems**".

The patients affected by numerous kinds of hormonal disorders, (such as thyroid function, growth and fertility disorders), could now be diagnosed properly and logically and more importantly treated in the right way. The credit for reducing the number of cretins resulting from hypothyroidism in babies drastically to near zero in the developed countries, is solely due to the RIA technique. A new area "neuro-endocrinology" emerged from the studies on hormonal levels using RIAs. By 1970, assays for viral antigens such as Hepatitis B-antigen had been developed, which was the cause for elimination of transfusion induced hepatitis in the whole of North America! They could predict the biosynthesis of ACTH hormone based on their studies, which was later proven to be correct. Currently many other fields such as oncology, drug abuse and environment also benefit from RIAs and similar techniques.

The commercial possibilities for RIA were enormous, but while Yalow and Berson recognized this, they refused to patent the method, like the Curies. Instead, they made every effort to get RIA into common use, putting its value to humanity ahead of their own financial interests. Yalow asserted, **"We never thought of patenting RIA . . . . patents are about keeping things away from people for the purpose of making money. We wanted others to be able to use RIA."** Yalow also wondered **"What would we have done with the money except pour it into our research? If I had five million dollars a year for research, it would be necessary for me to supervise 100 scientists. It would be impossible for me to talk to each of them every day. I'm psychologically adjusted to 'mom and pop' science"**. The seemingly inextricable connection between money and medicine was never a primary concern to Yalow. Indeed, Yalow and Berson performed all their work without ever receiving a research grant! *This stands in sharp contrast to much contemporary medical research, which is corporate-sponsored and profit-oriented in the quest for intellectual property.*

The RIA diagnostic process was, and continues to be, used by researchers in myriad ways. Investigators use it to screen blood for hepatitis virus in blood banks, determine effective dosage levels of drugs and antibiotics, detect foreign substances in the blood, treat growth hormone related disorders in children, and test and correct hormone levels in infertile couples. RIA is remarkably sensitive. It measures incredibly low concentrations of many substances. Adaptations of the RIA principle are also possible. Nonradioactive labels, such as enzymes and fluorescent markers are used in place of radioisotopes. Owing to its almost limitless applicability, the RIA concept has spawned innumerable innovations in basic research and practical applications. RIA principle is not only limited to immune system but can be extended to other systems in which in place of the specific antibody there is a specific binding substance. This might be a specific binding protein in plasma, a specific enzyme or a tissue receptor site. Apart from it's application in medicine, since the recent past, RIA is being used for a number of non-clinical applications like measurement of toxins in food , hormone levels in animals and even for forensic

analysis. As someone said, **"The first telescope opened the heavens; the first microscopes opened the world of the microbes; radioisotopic methodology, as exemplified by RIA, has shown the potential for opening new vistas in science and medicine."**

During her busy career, Yalow raised two children, Benjamin, who was born in 1952 and Elanna in 1954. She took just a few days off when the children were born and juggled the office and home duties efficiently, aided by the household help and the ever supportive mother. In 1968, to Yalow's dismay Berson left to become chairman of the department of medicine at the Mount Sinai School of Medicine in New York, Rosalyn Yalow became the acting chief of the Radioisotope Service at the Bronx VA. But, both of them knew the enormous impact of RIA that they had developed and knew that they would one day with the 'Big One' – the Nobel prize. She assumed leadership of the RIA reference laboratory in 1969 and was the head of the nuclear medicine service from 1970 to 1980. Berson died and untimely death in 1972 due to a heart attack, and although Yalow was grief-stricken, she pulled herself up and held the group together from collapsing. Many said that her career was over without Berson and that she could not win Nobel Prize without him. But, Yalow decided to prove herself all over again. She continued to work 100 hours a week instead of 80 hours she did earlier and named her laboratory "Solomon A Berson Resaerch Laboratory". She took over Berson's writing and speaking engagements and the lab published 60 articles between 1972 and 1976. She along with the young Eugene Strauss, a researcher from Dr Berson's lab, did some good pieces of work. They had shown that the human antibodies can differentiate between insulin from various animal species despite being nearly identical. They also proved that cholecystokinen, a gastrointestinal hormone was also playing the role of a neurotransmitter in human body. Yalow won a dozen medical awards, and around 35 awards in all starting from 1960's. Yalow waited patiently with anticipation every year in October for the announcement of the Nobel Prize. The power of RIA technique was growing with every passing year and the Nobel Committee was reportedly under pressure to give her the prize. She was elected to the prestigious National Academy of Sciences in 1975, and in the next year became the first woman to be awarded the 10,000 $ Albert Lasker Prize for Basic Medical Research. Although extremely prestigious in its own right, the Lasker Prize is generally considered a precursor to the Nobel Prize in Physiology or Medicine. And true to form, at 6:45 h on 13th October, 1977, Yalow received call informing her that she has won the Nobel Prize in Medicine and Physiology, for her work on RIA. She shared the 145,000 $ prize with Dr. Roger C. Guillemin and Dr. Andrew V. Schally. Her only regret was that Berson was not alive to share it with her. She went to Stockholm with her husband Aaron, daughter Elanna and her newly wed husband and three students. During the ritual of escorting the Nobel Prize winner from the banquet table to the podium, the Swedish student was confused between the two Dr. Yalow's and assumed that Aaron was the prize winner. Realising the confusion, Rosalyn Yalow stood up from her chair and marched towards the podium unescorted, while the student haplessly accompanied in the opposite side of the table! She was always watchful and never bothered about trivialities. When asked what she would do with the Nobel prize money, she said that she had everything one would want and was very content. She felt that the excitement in scientific research cannot be matched by the rewards from any hobby or other professions. When her Nobel Lecture was reprinted in **Science**, in 1978, she also reproduced a portion of the letter from Journal of Clinical Investigation, rejecting her report on insulin antibodies 22 years ago, to settle the scores!

After she received the Nobel Prize, she shot to fame. She was flooded with invitations from many international institutes, which she accepted and spread the merits of RIA. She visited India in 1977, soon after she received the Nobel Prize and addressed the scientists of Bhabha Atomic Research Centre" in an overflowing auditorium with more than 1000 captivated listeners! It was at this time that she mentioned about possibility of developing RIAs for diagnosis of infectious diseases and offered a fellowship to the young physician from BARC, Dr (Mrs). Aban Samuel, in this area, who later propagated RIA in various areas and introduced RIA methods for patient service in BARC.

Dr Yalow hosted a five part television series about her heroine Marie Curie. She has received 47 honorary degrees from various universities and in 1988 she received the National Medal of Science, the highest science award in USA. Society of Nuclear Medicine established "SNM Berson Yalow award" in 1977, for all research that made use of the indicator dilution method in neurology, oncology, cardiology, radiopharmaceuticals and radioassay.

After working for 44 years, Yalow retired from the VA hospital in 1991. Apparently she was not pleased with the regulatory requirements and felt that her working environment was better in the old days. After retirement she became a science activist lecturing about things that appeal to her. One theme that she strongly dwells on and speaks against is the Public's unwarranted fear of small amounts of radiation. She says "people tend to confuse nuclear medicine with nuclear reactors and bombs. Radiation from a nuclear plant is less than the amount of radiation from a coal plant." She also used to propagate that nuclear power was the way to become energy self sufficient.



While working full time at VA, Dr Yalow also held professorships for several years at Albert Einstein College of Medicine in Yeshiva University, Montefiore Hospital & Medical Centre and Mount Sinai School of Medicine. Her achievements in medical research are impressive by themselves, yet considering the barriers to women in science, her success is particularly inspiring. Only the second woman to receive a Nobel Prize in Physiology or Medicine, Rosalyn Yalow overcame institutional prejudice and demonstrated that women's accomplishments are limited not by any innate deficiencies, but only by the social and cultural restrictions imposed on them.

Dr. Rosalyn Yalow is the guide for young women in achieving position and recognition in life. She has demonstrated through her life that it is possible for a woman to be an outstanding professional as well as having a good family in their lifetime. Yalow believed strongly in equal access and equal opportunity for women. But she was against women-only awards. The "Ladies Home Journal" wanted her to receive a special woman's award. She politely refused the offer, which she considered to be as a "ghetto" citation given to her because she was a brilliant woman, not a brilliant scientist. Similarly, she also turned down the Federal Women's Award. Yalow's achievements are not only essential to the story of modern medical research, they also help provide a broader understanding of the role of women in science. Addressing women she said **"We must believe in ourselves or no one else will believe in us; we must match our aspirations with the competence, courage and determination to succeed. We must feel a personal responsibility to ease the path for those who come after us. The world cannot afford the loss of the talents of half its people if we are to solve the many problems that beset us."**

Rosalyn Yalow stands out as a beacon owing to her dedicated scientific research, assertive and highly motivated outlook. Discrimination made her stronger and brought out her capability and made her shine above all others who discriminated against her!

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1. "Radioimmunoassay: A Probe for the Fine Structure of Biological Systems", Science 200: 1236 (1978) — **Nobel Prize Lecture.**

2. S.A. Berson, R.S. Yalow, A. Bauman, M.A. Rothschild, and K. Newerly, "Insulin-I131 Matabolism in Human Subjects: Demonstration of Insulin Binding Globulin in the Circulation of Insulin-Treated Subjects" J. Clin. Invest. 35(1956): 170-190

3. Peptide hormones. Yalow and Berson; New York; American Elsevier, 1973

4. Methods in Radioimmunoassay of peptide hormones. New York; American Elsevier,1976

5. Basic Research and Clinical Medicine.New York; Mc Graw Hill, 1981(with others). Radioimmunoassay.New York; Van Nostrand –Reinhold 1984.

6.. "Immunoassay of Protein Hormones," in The Hormones: Physiology, Chemistry, and Applications, v. 4, 557-630 (G. Pincus et al, eds. Academic Press, 1964).

# Photographs