Marie Curie's Influence on Science and On Society*

by

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August 1985

With many thanks for your help — Trudy

In 1881, at the age of 14, Maria Sklodowska, the daughter of a rationalistic, yet in his relations to the Government cautiously submissive mathematics and physics teacher in Warsaw, declared herself an agnostic and decided to live from then on strictly according to the dictates of rationalism. Clearly, preceding events had provoked this step: her mother, the director of a small girls' boarding school who had borne five children of whom Maria was the youngest, had been a deeply religious woman. She had inspired little Maria by her example, even after she had contracted tuberculosis. She died at forty-two, when Maria was only nine years old,two years after her oldest daughter had died of typhus. The remaining family members, two daughters Bronia and Helena followed by a son named Jozef, formed a close-knit group: the children acquired from their father, Wladislaw, a great love for learning, especially of science. Maria had intense powers of concentration and a remarkable memory. When she was fifteen, she emerged from the Warsaw State School with a gold medal, as always the first in her class. However, her studies had left her in a severely fatigued state, and the family had to send her off to relatives in the south of Poland where she could relax and enjoy the intellectually undemanding entertainments offered in a rustic environment.

After many months, when she had recovered and returned to Warsaw at 16, she got acquainted with many of the young intellectuals who tried to overcome

*Talk given at Symposium held at the University of Wisconsin/Milwaukee on September 6, 1985 in honor of the fiftieth anniversary of the death of Marie Curie (Nov. 7, 1867 - July 4, 1934).

the depressing effects of the ever increasing Russian subjugation of Poland, either by acquiring more knowledge or by trying to bring about revolution. Maria chose the first path: she began to read voraciously the great 19th century literature, including works of Darwin and other scientists. However, academic studies leading to a degree were not possible for women in Poland. She therefore made an agreement with her oldest sister, Bronia, who wished to study in France, that she would earn money by tutoring and thus make it possible for Bronia to study at the Sorbonne until she, Maria, was able to come to Paris and in turn receive support from Bronia. She therefore tutored children of wealthy Polish families from 1885 to 1891. This gave her experience in developing study plans and acquiring authority. She even decided, for purely humanitarian reasons and without additional pay, to dedicate her weekends to the education of children of the peasants working on her employer's estate. Meanwhile, in her free time, she studied books on physics, sociology, anatomy, and physiology.

When Maria finally left for France at the age of 24, she had developed good study habits and acquired a great deal of general knowledge. In Paris she studied physics and mathematics at the Sorbonne, with a minimum of distractions, while also improving her French. Her professors emphasized the need for studying "pure" science without being interested in profiting from practical applications. Among these men were Louis Marcel Brillouin, Paul Painlevé, Gabriel Lippmann, and Paul Appell. In 1893 she passed the requirements for her physics degree with flying colors. She also acquired an excellent knowledge of chemistry, calculus and other branches of mathematics, and of laboratory methods. In 1895, she was still planning to return to Poland when Pierre Curie, a brilliant young professor of physics, eight years her senior, persuaded her to marry him. Pierre, already known for his studies of the electric and magnetic properties of crystals and their temperature dependence, had postponed the thought of marriage in order not to be distracted from scientific work. However, he felt that Marie was a woman of genius who would understand, and participate in, his strivings, and would share his deep love for Nature. Theirs was to be a very close, congenialrelation which led to epoch making scientific success. He was the son of Eugene Curie, a doctor with strongly anticlerical tendencies, and Pierre and Marie were married in the town hall of Sceaux near Paris where Pierre's parents lived. Fig. 1

In her first publication Marie Curie reported on the variation of the magnetic properties of tempered steels as a function of their chemical composition. This study, carried out thoroughly and professionally under the direction of Henri le Chatelier, a well known physical chemist and Professor at the School of Mines, made her aware of the role which the chemical environment plays in ferromagnetism.

Toward the end of the 19th century several prominent physicists had come to the conclusion that Maxwell's theory of electromagnetism had essentially completed the "edifice" of physics. However, three important new discoveries, made just before the close of the century, completely changed this picture: (1) The discovery of X rays by Wilhelm Röntgen in Würzburg in 1895, (2) the startling finding of penetrating radiations from the heaviest known element, uranium, by Antoine Henri Becquerel in Paris in 1896, and (3) the discovery of the electron by J.J. Thomson, the Cavendish Professor at Cambridge, in 1897. These three discoveries initiated the "atomic age". In addition to opening up an exciting new chapter in the history of Physics, Röntgen's discovery was almost immediately put to use for surgical diagnosis in locating bullets, observing broken bones, etc. However, it was especially the second discovery which proved on further study that the atom is not indivisible as implied by its name suggested by the ancient Greeks, but that it can undergo spontaneous, irreversible changes.

Meanwhile, on Sept. 12, 1897, Eugene Curie delivered Marie of a daughter who received the name Irene. Since his wife had died one month earlier, Eugene joined the young couple as a nursemaid, and a young woman was sent by Marie's family from Poland to take care of the household - the first of a long line of Polish housekeepers to work for Marie Curie. In spite of a difficult pregnancy she immediately concentrated on the search for a thesis problem. She decided to study the question of the origin of Becquerel's discovery, that a uranium compound covered by black cloth is capable of blackening a photographic plate. Where did the energy of this radiation come from?

At about the same time Ernest Rutherford, a young New Zealander who had joined J.J. Thomson in 1895 with a scholarship at the Cavendish Laboratory in Cambridge, got interested in this problem, as did some other scientists in Austria and Germany. Marie Curie set out to study the emitted ionizing radiation by means of the piezoelectric quartz electrometer developed by Pierre Curie. For her work she was allowed to use a small room in the School of Physics and Chemistry where Pierre was a Professor. Unfortunately the room was damp, which made it difficult to carry out delicate electrical measurements. First, she found that the intensity of the radiation depends only on the amount of uranium in a given compound, not on the chemical composition! From this she concluded that the phenomenon for which she coined the term radioactivity, is an atomic effect, independent of the binding inside the molecule. This was a most profound observation. She further studied all other known elements and reported on January 14, 1898 that thorium also emits such radiations. She had not been aware of the fact that the German Gerhardt C. Schmidt had already reported the same result on January 4. She found no other radioactivity emitted from known elements, and it was not until 1905 that J.J. Thomson reported that the much lighter elements rubidium and potassium are also weakly radioactive.

Marie Curie then proceeded to investigate two uranium minerals, pitchblende and chalcolite. Her electrometer showed that pitchblende was four times as active as uranium itself, and chalcolite twice as active. She concluded, with increasing excitement, that what she had discovered must be due to a new substance, or substances, not previously known. At this point, in the summer of 1898, Pierre Curie interrupted his work on crystals in order to join her in the search. They started out with the residue of pitchblende from which uranium had been separated, using chemical separation methods. This was the start of the science of radiochemistry! Careful analysis showed that an unknown activity could not at first be separated from the bismuth fraction, but by heating this fraction Pierre could separate the bismuth as a black powder in the hottest part of the tube; they found that the remainder had an activity several hundred times as high as that of uranium. Clearly, they had discovered a new element, which Marie named polonium in honor of her country of origin; they quickly published their findings at the end of June 1898. As we shall see, polonium was to play an important part in future nuclear research. In this paper the Curies for the first time used the word "radioactive" in print. It became the accepted term.

From the several months rest the Curies took after July 1898, one may guess that they needed to recover from the effects of radiation sickness; they took up the work again in November. This time they observed that an even stronger activity than that of polonium appeared in the barium fraction. However, soon they found that the activity was more soluble in sulphuric acid than barium sulphate. They decided to call the new element radium. A spectroscopist at their Institute, Demarçay, discovered a new spectral line in the tiny radium sample the Curies could provide. The results on radium, including its spectrum, were published in December 1898. Marie Curie realized that if a way could be found to separate a sizable amount of radium, say one gram, this would lead to most important consequences for science: (1) above all, it would convince the chemists that a new element has been discovered; (2) it would be possible to provide a standard radiation source, to be deposited at the Bureau of Weights and Measures in Paris; (3) it would greatly facilitate the study of radioactivity; (4) it could be used for medical purposes, e.g. to treat cancer and other diseases; (5) it would lead to industrial applications. She therefore set out on a truly Herculean task: In order to be able to separate weighable quantities of radium the Curies asked the owners of the Joachimsthal uranium mine in Bohemia, then part of the Austrian Empire, to provide them with eight tons of the pitchblende residue which had been dumped as valueless in the forest near the mine. These were provided for a small fee, and Marie Curie set to work under gruelling conditions, in an open shed of the school of physics and chemistry, to carry out the separation of radium from this enormous amount of material using 20 kg at a time; each time the separation of Ra from Ba was carried out by up to a thousand crystalline fractionations, in order to separate one gram of radium. However, in spite of the enormous hardship and the many frustrations connected with this work, she and Pierre received great joy from her progress. Finally, at the end of March 1902 Marie Curie had separated pure radium chloride, containing one gram of radium; she determined its atomic weight to be 225.93! (Later, in 1910, Marie Curie was able to produce one gram of radium metal.) Thus the atomic weight of radium was found to be intermediate between those of U (238) and Th (232) on one hand, and Bi (209) and Pb (207) on the other. The consequences of this success were even more startling than Marie had anticipated. However, the effort had taken its toll: The notebooks the Curies used in the three years following December 1897 for their important work on new radioelements are preserved but have not been decontaminated. Thus they are still dangerous to handle, more than 80 years later! As can be imagined,the Curies' health had suffered enormously during this period.

Ernest Rutherford was not skilled in the methods of chemical separation. He had approached the study of uranium radiation by using different thicknesses of Aℓ foils between the source and the electrometer. He found two different radiations: an easily absorbable but massive radiation which he called α rays, and a more penetrating radiation which could be deflected by electric or magnetic fields, called β rays; the latter turned out to consist of electrons. Finally, he found a third radiation, even more penetrating, which he called γ rays, for whose discovery the French scientist Paul Villard has also been credited. The γ rays consist of electromagnetic radiation, similar to X rays, which is electrically neutral and weightless. In 1899 Becquerel discovered that the Po solution he had received from Marie Curie emitted only α rays, but no β rays. In 1898 Rutherford had obtained the Professorship in Physics at McGill University in Montreal, where he continued his work. Marie Curie had carefully followed his progress. In March 1902 she proposed two alternative explanations for the origin of the apparently spontaneous radioactive emissions: (1) Absorption of an unknown radiation; and (2) tiny particles from the atomic interior thrown out as radiation. It was the second explanation which proved to be correct. Pierre Curie determined the heat produced by 1 g of Ra as ~ 100 cal/hr. This result turned out to be of great importance for the explanation of the development of the earth.

Early in 1901 Rutherford had been joined at McGill by a talented young chemist from Oxford, Frederick Soddy; with him he formed a team similar to that of Pierre and Marie Curie. In 1902 Rutherford made a basic discovery: he found that a substance separated from thorium which he called thorium X carried away all the activity emitted from thorium. The activity of thorium X, however, undergoes spontaneous disintegration. It decays exponentially and reaches half its original value in ~ 4 days, a time which is referred to as Fig.
half-life. At the same rate, the original activity of the thorium sample

returns. This behavior can be explained by assumming that if the number of atoms of a radioactive substance is N, of which (dN/dt) disintegrate at a given time t, then

$$\frac{dN}{dt} = -\lambda N, \quad \text{where } \frac{1}{\lambda} = \frac{T}{\log 2} = \frac{T}{0.693},$$

T being the half-life of the substance. By following the small decrease in radioactivity from this relation, Marie Curie calculated some years later the half-life of radium, which is now known to be 1600 ± 5 years.

On June 19, 1903, the Curies were awarded the prestigious Davy Medal at the Royal Society in London, where Pierre Curie was asked to give a demonstration lecture on their work on radioactivity. Meanwhile, Marie Curie had submitted her doctoral thesis on her observations on uranium and thorium, as well as her discovery of polonium and radium, and her separation of one gram of Radium in the form of radium chloride. On June 25, she gave her official report at the Sorbonne and received her Ph.D. degree. On the same day Ernest Rutherford happened to be visiting Paris and was included in the dinner party which her friends gave to honor her. He immediately took a liking to her because of her simple dress, dignified behavior, and knowledgeable discourse. He remarked to her and Pierre during the evening: "Radioactivity really and truly is a splendid subject to work on."

In the same year, 1903, Becquerel and Pierre and Marie Curie were informed by the Nobel Committee in Stockholm that they were to share the Nobel Prize for Physics. However, only Becquerel was able to go to Stockholm; Marie, who had been pregnant, had suffered a miscarriage in August of that year, and Pierre too was not well enough to undertake the trip. In December 1904, Marie Curie gave birth to their second daughter, Eve. She was a very affectionate, musically gifted child who in the late 1930's was to write a biography of her famous mother. It was not until June 1905 that Pierre and

Marie Curie were able to attend the ceremony in Stockholm where Pierre delivered the address. He ended his lecture with some philosophical considerations concerning the impact the new discoveries might have on mankind: "It might even be thought that radium could become very dangerous in criminal hands, and here the question can be raised whether mankind benefits from knowing the secret of Nature, whether it is ready to profit from it or whether this knowledge will not be harmful for it. The example of the discoveries of Nobel is characteristic, as powerful explosives have enabled man to do wonderful work. They are also a terrible means of destruction in the hands of great criminals who lead the people towards war. I am one of those who believe with Nobel that mankind will derive more good than harm from the new discoveries."

The Curie's work had led to unexpected new insights into atomic structure, but it had also opened up a number of puzzling problems:

1) Ra was shown to be intermediate in mass between thorium and bismuth, but a large number of elements were still missing. How can they be discovered, and what is the place of polonium?
2) How is the nature of α and β emissions related to these missing elements?
3) What is the significance of these emissions for the structure of the atom?

The work of Rutherford and Soddy in 1902 on the radiations from uranium and thorium led to an exciting result: radioactivity leads to a transmutation of elements. Altogether three "decay chains" were put in evidence. Rutherford was first shocked by the idea of transmutation proposed by Soddy. This idea had been believed in by the alchemists who claimed to be able to transmute mercury into gold and who were now thought of as charlatans. Nevertheless, this idea described best what was found: a sequence of elements following each other until the last, which turned out to have the chemical properties of lead. Fi

Much later, in 1913-14, three scientists, Soddy, Russel, and Fajans, independently arrived at the radioactive displacement law. Already in 1903 Ramsay and Soddy had established that α rays consist of ions of helium. The displacement law states that by emission of an alpha-particle an atom moves two places down in the periodic table, whereas an atom which decays by emission of a beta-particle, known to be an electron, moves one place up in the periodic table. In the same year it was clearly recognized by Soddy that there are some activities in the decay chains which cannot be separated from each other chemically, although they are known to have different atomic masses. He was forced to arrive at the concept of isotopes, i.e. nuclear species with the same charge but different masses.

Until 1911 physicists thought of the atom as a sphere $\sim 10^{-8}$ cm in diameter filled with positive and negative charge. However, in 1909 Rutherford's associates, Geiger and Marsden, scattered alpha particles from certain heavy atoms and found that a very small fraction were backscattered. This brought Rutherford, after careful analysis, in 1911 to the conclusion that the atom has a nucleus with a density $\sim 10^{13}$ times as high as that of the atomic electrons. This observation led Niels Bohr two years later to the introduction of the quantum theory of the atom, which explains why the electrons revolving around this dense nucleus occupy orbits of well defined energies. In 1920 Rutherford, in a famous Bakerian lecture, speculated that the atomic nucleus, instead of being made up of positively charged protons and negatively charged electrons, contains in addition to the protons neutral particles, which he called neutrons, of approximately the same mass as that of protons. It was, however, not until 1932 that his associate Chadwick actually discovered neutrons by disintegrating beryllium by polonium alphas. The laws of the conservation of energy and momentum clearly showed that the emitted particle is not a massless γ ray, as two groups of physicists had believed, but must be a neutron. This discovery leads to a clear understanding of the decay-chains and of the places of radium (Z = 88) and polonium (Z = 84), the radio elements which the Curies had discovered. It also shows the places of the heretofore missing elements which had been discovered in radioactive decay, namely Radon (Rn), Z = 86, discovered by the Curies, Actinium (Ac), Z = 89 discovered by Debierne and Giesel, and protactimium (Pa), Z = 91, i.e. between thorium and uranium, found in 1918 by Lise Meitner and Otto Hahn, and finally francium, Z = 87, discovered by Marguerite Perey, an associate of Mme. Curie, in 1939, after Marie Curie's death. Fig.

Let us now return to the Curies. After the announcement of having been awarded the Nobel Prize in 1903 they were subjected to an enormous amount of attention from the press, constant requests for interviews, letters of inquiries of all kinds, and requests from photographers and journalists. They also received a proposal from America to give a series of lectures there. All this interfered with their work and their peace of mind. There were, however, also some favorable consequences of their fame. In 1900 Pierre Curie had obtained a Professorship at the Sorbonne with adequate facilities for research. Marie became Laboratory Chief, and for the first time in her career, received a salary! She also received a part-time post teaching physics at a girl's normal school at Sevres. Pierre Curie in 1902 had been asked to campaign for membership in the Academie des Sciences. With great reluctance he had done so, but without success. When he was encouraged again to campaign in 1905 he did, again reluctantly, but this time successfully. Marie in the same year started to teach at Sevres again, two days a week, where she introduced for the first time a laboratory course for the women students, and also improved the theoretical instruction. She enjoyed having the intelligent Paul Langevin, a previous student of Pierre's, as a colleague there.

During the early days of 1906 the Curies realized that the discovery of radium was to play an even greater role in industry, medicine, and possibly warfare than they had anticipated, but they refused to take any patents which would have provided them with funds for their work. Pierre's health had suffered severely because of his many new responsibilities as well as the radiation effects. Besides, he longed to return to his work on the physical properties of crystals. A cruel fate prevented him from carrying out his plans: on April 19, 1906, in the Rue Dauphine in Paris, he was run over by a horse-drawn carriage and killed instantly. The letters from the small group of outstanding scientist friends which Marie Curie included in her very moving, beautiful biography of Pierre, published in 1923, testify to his luminous spirit, his integrity, and above all, to his unique scientific insights.

After Pierre's death Marie was given his Professorship at the Sorbonne, where she stoically continued Pierre's lecture course, starting on Nov 5, 1906. From then on, besides lovingly bringing up her two daughters and attempting to provide them with the best education possible, her first move was directed toward safeguarding the gram of radium which she had separated. For this purpose, as her friends among her colleagues advised, she had the Dean certify that she was the owner of the precious material. She was determined to continue on her own the work on which she had set out in collaboration with Pierre. The exploration of radioactivity had opened up many new avenues of research and a plethora of new phenomena to be investigated, for which new methods of production and measurement had to be developed. She counted on the help of some of her colleagues and on the bright young scientists who attended her lectures. Andrew Carnegie provided $50,000 for the continuation of her studies and she started out to have an Institute built and equipped. In fall 1911 she was informed that she was to receive the Chemistry

Nobel Prize for the discovery and separation of Po and Ra. She took her sister Bronia and her daughter Irene along to Stockholm. In 1913 while attending the British Association Meeting in Birmingham, as she had promised to Rutherford, she received an honorary doctorate from the University. In an interview there she emphasized the amazing contributions of Ernest Rutherford to the knowledge of radioactivity, at the same time modestly trying to evade questions about her own work.

Just when the building of her new institute was completed, the first world war started; scientists, including her associates, were drafted either for military service or to try to solve war related problems. Marie Curie, driven by patriotism and having come to the conclusion that the war would be a long one, decided to organize a radiological service for army hospitals. On her request automobiles were contributed by wealthy women, and these she equipped with portable x-ray tubes plus dynamos or induction coils. Besides some physicist colleagues she recruited her 16-year old daughter Irene to participate in the service, whose main goal was to locate bullets in wounded soldiers to guide surgeons in their work. Soon more operators were needed, and Marie Curie persuaded 150 young women from all walks of life to volunteer. She devised a two month course, given in her now empty new radium institute. It consisted of all-day classes in elementary mathematics, physics and anatomy, involving everything from theory to practice. Only good students were recruited for the service.

Finally, in November 1918, the fighting came to an end; and to Marie Curie's great joy, Poland was reunited. She immediately attempted to equip her new Institute, but the war had dried up the sources of support. At this point a young American journalist, Marie Mattingley Meloney, the editor of the magazine The Delineator who wanted to interview Marie Curie in connection with the American war relief effort, became so impressed by her disinterested love for science that she organized for her amd her daughters a tour through the United States to raise funds for her future scientific work. The women of America were persuaded to contribute the money for the purchase of one gram of radium, which President Warren Harding presented to her. She also was invited to visit a number of scientific laboratories of universities and industry.

A second such trip was organized in 1928, when President Hoover invited her to stay at the White House. During her visit to laboratories, she found that enormous progress had been made since 1920, far overshadowing the development at European laboratories. Again she returned home with very generous financial support. By then she had gathered an intelligent, international group around her, which devised impressive new methods of alpha and beta spectroscopy. It was Marie Curie who carried out the chemical separations for the most important experiments, e.g. for Salomon Rosenblum's remarkable studies of α-fine structure. She also continued giving her lectures at the Sorbonne and participated in a number of important international commissions, especially the prestigious Commission on Isotopes. Later, Marguerite Perey was to serve on this commission.

Her daughter Irene, who had been trained by her mother, had become an outstanding chemist. In 1926 Irene married Frederic Joliot, who had been a student of Pierre Curie's associate Paul Langevin and was an extraordinarily gifted physicist. Early in 1934 the young couple discovered the production of artificial radioactivity by bombarding aluminum and other light elements with alphas from a very intense polonium source provided by Marie Curie; a feat for which they received the Nobel Prize in 1935. Marie Curie, who had been delighted by this astounding discovery, and earlier by the birth of the couple's daughter Helene in 1927, was not to live to attend the award ceremony. Nursed by her faithful daughter Eve, she died of pernicious anemia in July 1934.

Marie Curie was no feminist. As we have seen she accepted the most dismal working conditions without ever complaining in order to follow her passion for scientific investigation, for which she set her own goals. She strove for the greatest possible accuracy, and expected the same from her associates. The conclusions from her work were lucidly expressed in her publications and her speeches. In addition to her scientific goals, she was motivated by strong humanitarian impulses, as we have learned from her dedication to the treatment of wounded soldiers during the first world war, and her eagerness to develop the use of radium for medical purposes. The radium industry of France and the U.S. owes her a great debt for having provided it, without cost, with the ingenious separation methods which she had developed.

Marie Curie's example has shown that a woman with a passion for scientific investigation can have a successful family life, raise children, and yet make first-rate contributions to science. It has had an extraordinary effect on women physicists all over the world, especially in western Europe and some of the eastern European countries, and also on the governments which have provided them with jobs. These women have largely adopted Marie Curie's style; they are extremely knowledgeable, are accustomed to very hard work and to the shouldering of administrative responsbilities. Their contributions at the Laboratories of Saclay and of Orsay are particularly impressive. Marie Curie's granddaughter, Helene Langevin, has worked for many years at Orsay, the Laboratory which was founded in 1957 by her father Frederic Joliot and Salomon Rosenblum. Many of the women physicists proudly display Marie Curie's portrait on their office wall. Thus her spirit lives on with undiminished force.

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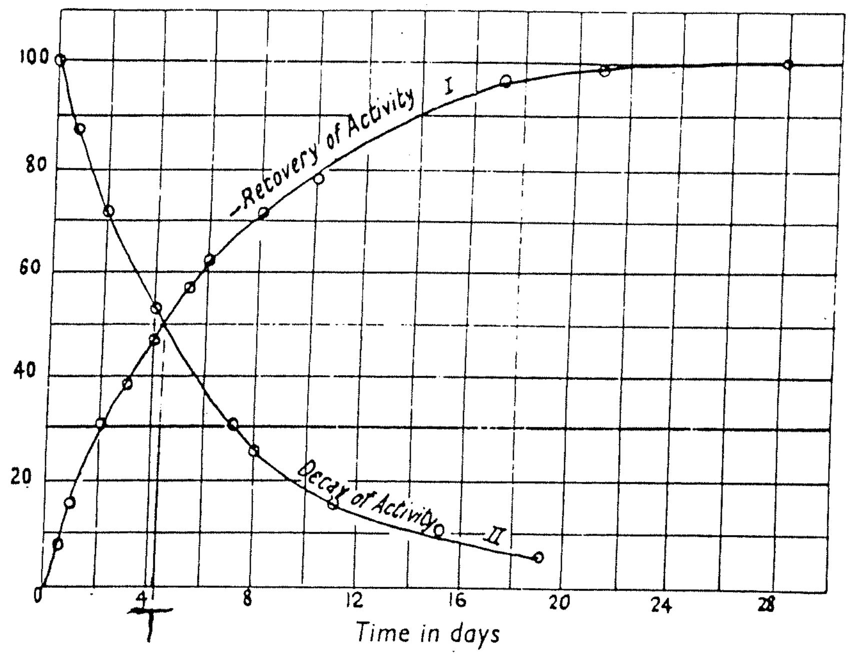
Pierre and Marie Curie in 1895

Fig. 1 Pierre and Marie Curie Curie in the year of their wedding. Bibliography (2).

RADIOACTIVE DECAY AND RECOVERY



Rate of transformation:

$$-\frac{dN}{dt} = \lambda N$$

By integration $$N(t) = N_0 e^{-\lambda t}$$

Half-life: $$T = \log 2 \times \frac{1}{\lambda} = \frac{0.693}{\lambda}$$

$$T(U) = 4.4 \times 10^9 \text{ Y}$$

$$T(Ra) = 1600 \text{ Y}$$

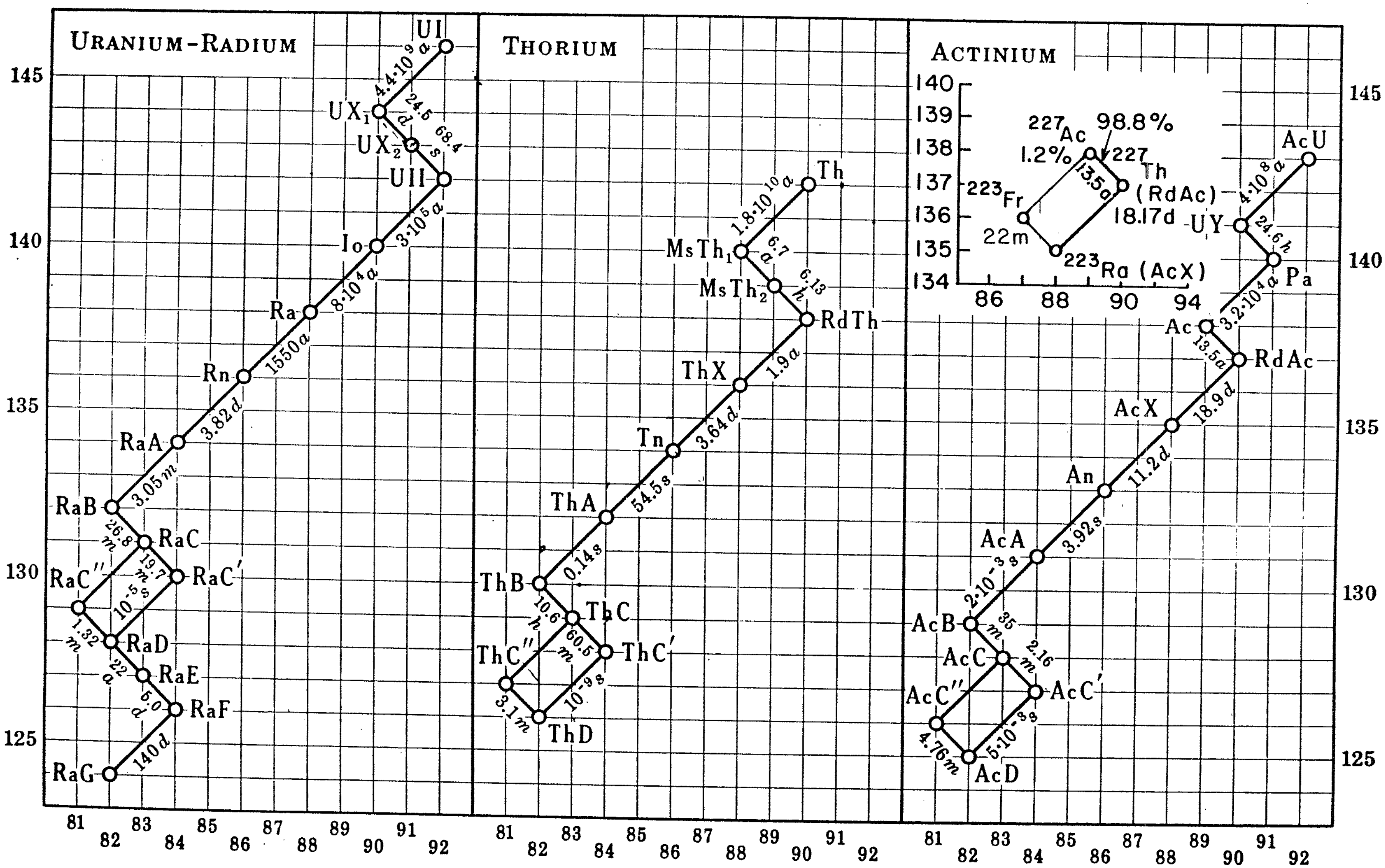
$$\frac{\lambda(Ra)}{\lambda(U)} = \frac{T(U)}{T(Ra)} = 2.75 \times 10^6;$$

Fig.2 Graph taken from (3), p. 159.

THE URANIUM-RADIUM SERIES

Radioelement	Symbol	Radiation	Half-life
Uranium I	U^{238}	α	4.507×10^9 yr
↓ α			
Uranium X_1	Th^{234}	β	24.1 day
↓ β			
Uranium X_2	Pa^{234}	β	1.175 min
93.87% β ↓ ; I.T. 0.13%			
Uranium Z	Pa^{234}	β	6.7 hr
Uranium II	U^{234}	α	2.48×10^5 yr
↓ α			
Ionium	Th^{230}	α	7.52×10^4 yr
↓ α			
Radium	Ra^{226}	α	1622 yr
↓ α			
Radon	Em^{222}	α	3.825 day
↓ α			
Radium A	Po^{218}	α and β	3.05 min
99.98% α ↓ ; 0.02%			
Radium B	Pb^{214}	β	26.8 min
Astatine^{218}	At^{218}	α	2 sec
β ↓ ; α			
Radium C	Bi^{214}	β and α	19.7 min
99.96% β ↓ ; 0.04% α			
Radium C′	Po^{214}	α	1.58×10^{-4} sec
Radium C″	Tl^{210}	β	1.32 min
α ↓ ; β			
Radium D	Pb^{210}	β	19.4 yr
↓ β			
Radium E	Bi^{210}	β and α	5.02 day
~100% β ↓ ; ~10^{-5}% α ; α 1.8×10^{-6}%			
Mercury^{206}	Hg^{206}	β	8.6 min
Radium F	Po^{210}	α	138.4 day
α ↓ ; β^-			
Thallium^{206}	Tl^{206}	β	4.19 min
↓ β			
Radium G	Pb^{206}	stable	

Fig. 3 Earl K. Hyde, Isadore Perlman, Glenn T. Seaborg, The nuclear properties of the heavy elements, Vol. 2, Prentice Hall, Inc, N.J., 1964.



The Three Radioactive Series in a Proton-Neutron Scheme. In this scheme, by an α-transformation, the element is shifted two places toward the left and two places down; by a β-transformation, one place toward the right and one place down. For the half-life period $T = 0.693\tau$, the following abbreviations are used: s = seconds, m = minutes, h = hours, d = days, a = years.

Fig. 4. (7), p. 39. The information on ^{233}Fr discovered by Marguerite Perey in 1939, is taken from Hyde, Perlman, and Seaborg, Vol. 2, p. 525. It is seen that only a weak α branch of 1.2% leads from the decay of ^{227}Ac to this 22 m isotope.