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2. IRÈNE JOLIOT-CURIE, A NOBEL LAUREATE IN ARTIFICIAL RADIOACTIVITY

INTRODUCTION

This chapter provides a biographical profile of Irène Joliot-Curie, the daughter of Nobel laureates Marie and Pierre Curie, and details of her personal life and professional accomplishments. Growing up with internationally renowned parents, Irène led a life marked by both expectations and obligations. Irène, like her mother, chose to marry a scientist, Frédéric Joliot, with whom she would collaborate successfully (leading eventually to a joint Nobel Prize in Chemistry) and have two children, both of whom would become part of the next generation of scientists. Even with all of her successes, the difficulties of being a woman in the sciences affected Irène, as they had her mother. Denied memberships and honors given to men with equal successes, both Marie and Irène fought for their place, respectability and research opportunities.

IRÈNE'S EARLY LIFE

Marie and Pierre Curie had their first child, Irène, when Marie was starting her doctoral work on radioactivity. Marie and Pierre worked jointly on this research project—Marie focused on the chemistry-related aspects while Pierre concentrated on the physics. After Marie and Pierre had taken a strenuous bicycle ride in the country Marie went into labor one month early, and Irène was born on September 12, 1897. A few weeks later, Pierre's mother died. Marie and Pierre invited Pierre's father, Dr. Eugène Curie, to live with them at the edge of Paris in their small house with an attached garden. During this time, Marie was heavily involved in her doctoral research on the emissions from radioactivity of natural sources, so it was difficult to be both taking care of her infant daughter and conducting her research on newly identified radioelements. The presence of Eugène aided Marie as he could help take care of baby Irène (Curie, 1923). Still, Marie doted on her daughter's progress and recorded in a notebook her daughter's daily events.

Dr. Eugène Curie "loved her [Irène] tenderly and [his] own life was made brighter by her" (Curie, 1923, p. 179). He delighted in caring for his granddaughter until his death when Irène was 12 years old. He taught Irène, much like he taught his son Pierre, "to love nature, poetry, and radical politics" (McGrayne, 1998, p. 121). Later in life, Irène said, "My spirit had been formed in great part by my grandfather, Eugène, and my reactions to political or religious questions came from him more than from my mother" (McGrayne, 1998, p. 121).

M.-H. Chiu, P. J. Gilmer, & D. F. Treagust (Eds.), Celebrating the 100th Anniversary of Madame Marie Sklodowska Curie's Nobel Prize in Chemistry. 00–00.

When Irène was just six years old, her family life changed significantly. The radiochemical research conducted by her parents led to Marie and Pierre's shared Nobel Prize in Physics, together with Becquerel, in 1903. With this announcement they became well known, and family life was no longer so private. A year later, Irène's sister, Eve, was born. Then, however, in 1906, tragedy struck the family. Pierre was killed in an accident when he was hit by a horse-drawn carriage and died instantly. For many years, Marie did not even mention Pierre's name to her children. Irène became very close to her mother after Pierre's death and remained close for the rest of Marie's life.

For two and a half years after Pierre's death, Marie Curie and some of her academic colleagues formed a cooperative schooling arrangement for their children, ten in all, which included Irène. Eve was too young to be part of it. Marie Curie said that each of the colleagues took "charge of the teaching of a particular subject to all of the young people… With a small number of classes we yet succeeded in reuniting the scientific and literary elements of a desirable culture" (Curie, 1923, p. 195). Marie Curie and Paul Langevin taught the children physics while Jean Perrin taught them chemistry. Henriette Perrin taught French literature and history and took the children on visits to the Louvre. Isabel Chavannes, wife of a professor, taught them German and English. Henri Mouton taught natural science, and sculptor Jean Magrou taught drawing and modeling (Crossfield, 1997; Physicist of the week, 2011). Irène profited enormously from this type of education, especially because it included practical exercises.

With both of her daughters, Marie believed that physical education was critical for their development. In the summers, the daughters went to the French coast in Brittany to swim in the Atlantic Ocean and in the winters to ski areas for vigorous exercise. At home the children did gymnastics on a regular basis. Marie and her two daughters exercised and also relaxed by hiking and riding bicycles together.

IRÈNE'S TEENAGE YEARS

Dr. Eugène Curie, Irène's grandfather, died on February 25, 1910, after a yearlong illness. This was another trauma for Irène, especially after losing her father in 1906, and she worried that she would also lose her mother. Eugène was also not there to help her through another trauma in 1911 when the newspapers published reports that Marie Curie had an affair with Paul Langevin. Though Langevin was the one who was married, these reports were much more critical of Marie. She and her family were verbally antagonized and threatened by the general public.

Later that year, Marie Curie received word that she was to be the sole awardee of a second Nobel Prize. Because of the publicity surrounding the affair Marie had with Paul Langevin, the Nobel Committee even wrote Marie shortly afterward, advising that because of the affair, she perhaps ought not to accept the award. Marie adamantly refused this suggestion, writing a fiery letter back that the award had nothing to do with her personal life, only with her scientific discovery. In October 1911, now a hundred years ago this year (2011), she and 14-year old Irène traveled to Stockholm for Marie Curie to accept the Nobel Prize in Chemistry as the sole recipient for the discovery and isolation of polonium and radium. "Irène was dazzled. For the first time, she sensed her mother's fame and importance and her standing in the scientific community" (McGrayne, 1998, p. 124).

Though she did travel to Sweden, to give her Nobel lecture and receive her award, the scandal devastated Marie. At the lecture itself, Marie was sick, in part because of the stresses of the scandal, but also because of the disappointment earlier in 1911 of not being elected to the Academy of Sciences of Paris, even though she had already become a Nobel laureate in physics in 1903. This trip and the emotional turmoil surrounding this time of Marie's life exhausted her so much that she went into seclusion for a year. She did not even see her children and instead had a governess care for them.

Meanwhile, Irène continued to excel in her studies. With her excellent education in the cooperative, Irène entered the independent school, the Collège Sévigné, in Paris in 1912, finishing her high school education in 1914. In that same year, Irène started her college education at the Sorbonne University, but preambles of the European war got in the way of her continued education.

Earlier in the summer of 1914, World War I started, and on August 1st, Germany declared war on France. During that summer Marie had two Polish maids supervise both Irène and Eve on the French coast in l'Arcouest with war on the horizon. Meanwhile Marie stayed at the Radium Institute in Paris as most of the men who worked there had been mobilized for war following the preambles to war starting with the assassination of Archduke Franz Ferdinand of Austria on June 28, 1914. During that time Marie Curie worried about losing her precious supply of radium and decided to transport it from Paris to Bordeaux. She did this herself by carrying the radium in a lead-lined suitcase on a train. After the trip, Marie wrote for Irène and Eve to return home to Paris, as occupation of the city did not seem imminent following the successful Battle of the Marne, which ended on September 12, 1914.

In the same year, when Irène was just 17 years of age, she started helping her mother teach surgeons and doctors in the battlefield how to use X-rays to find the bullets and shrapnel in the wounded soldiers, to aid in their extractions. With so much need for this type of service to the injured French soldiers, Marie Curie organized 20 radiologic cars, which were equipped with X-ray equipment. Irène and her mother trained other women to go into the battlefields to help the surgeons on site. Irène "did ambulance work between Furnes and Ypres, and also at Amiens, receiving, from the Chiefs of Service, testimonials of her work satisfactorily performed and, at the end of the war, a medal" (Curie, 1923, pp. 213-214). Irène reflected later about the experience, "My mother had no more doubts about me than she doubted herself" (McGrayne, 1998, p. 117). During this time Irène and Marie formed a true collaboration, much like that Marie experienced with her husband Pierre. About this collaboration, Irène said reflectively, years later, "'[I am] more like my father and, perhaps, this is one of the reasons we understood each other so well'" (Pflaum, 1989, p. 201).

Despite the war, during the bombardment of Paris by the Germans, Irène and Eve stayed in town with their mother. Irène continued with her undergraduate studies with the Faculty of Science at the Sorbonne University in October 1914.

Even while bringing X-ray equipment and know-how to the staff at an Anglo-Belgian hospital, a few kilometers from the battlefront, Irène studied for her baccalaureate examinations in physics and mathematics. After four years of war, French people and countryside were devastated. In 1918, when Irène was 21 years old, the armistice finally brought the war to an end.

IRÈNE'S START TO HER DOCTORAL RESEARCH IN THE RADIUM INSTITUTE

Marie Curie created the Radium Institute that opened in Paris in 1914, at the start of World War I. After the war, Irène worked side-by-side with her mother in the Radium Institute. The composition of the laboratory in which Marie had worked changed over the years. For instance from 1904 to 1914, ten of the 58 workers were women, mostly from countries other than France. In the two years after the war, the majority of the workers were women as many of the men had died in the war, with the percentage of women stabilizing at 30% years later (Boudia, 2011).

Irène was one of 47 women in all who worked in Marie Curie's laboratory (Boudia, 2011) between 1904 and 1934. There, Irène "simply studied science for the personal pleasure of understanding nature's beauty" (McGrayne, 1998, p. 126). She loved chemistry, including seeing a brightly colored precipitate or the glow of a radioelement. But her life was not only science. Irène and Eve moved back with their mother during this time in order to help her with the household chores. They also spent much time discussing poetry and music, as well as the laboratory work. Eve was particularly interested in music.

Marie had always encouraged athletic ability and intellectual development for her daughters. To her colleagues in the laboratory, though, these traits made Irène seem "intimidating and robust, both intellectually and physically. Her imperturbability and her knowledge of physics and math seemed well-nigh incredible for someone age[d] twenty-five" (McGrayne, 1998, p. 127). Her nickname in the laboratory was "Crown Princess," in part because others were jealous of her and recognized her privileged position with her mother as Director. In the laboratory, Irène was known for behaving more like a man in that she was short-tempered, direct, and sometimes brutally honest with colleagues, and did not take the time for niceties of conversation. Perhaps Irène's tough posture developed from the scandals and frustrations endured by her mother as Marie struggled for her place within the mostly male world of scientific research.

IRÈNE AND EVE'S TOUR OF AMERICA WITH MARIE CURIE

In May of 1921, Irène interrupted her doctoral research, to go with Marie and Eve on a two-month tour of America organized by Marie (Missy) Mattingly Meloney, editor of the well-known New York women's magazine, *The Delineator*. The purpose of the tour was to gather funds from American women for the purchase of one gram of radium for the "Marie Curie Radium Fund," for her Radium Institute in Paris.

Years earlier, Marie and Pierre had purposefully decided not to patent the method to purify radium as they felt the discovery belonged to the public. Marie commented on this decision: "No detail was kept secret, and it is due to the information we gave in our publications that the industry of radium has been rapidly developed" (Curie, 1923, p. 226). One outcome of this decision though was the lack of financial support that the patent could have provided them— both personally and for the Radium Institute. Therefore, this trip to America would help Marie purchase the radium needed for new experiments.

On the trip through America, Marie received honorary degrees at a number of universities and attended receptions at the Museum of Natural History, the National Museum, and Carnegie Hall of New York, among others. The American Chemical Society had Marie present a lecture on the Discovery of Radium in Chicago at their annual meeting. Marie did not visit as many laboratories as she wanted because of her health; however, she did see the Bureau of Standards in Washington (now known as the National Institute of Standards and Technology), which is known for measurements. Employees of the Bureau packaged the radium supply for Marie to take back to France for her Radium Institute's research.

At times Marie was so exhausted from the travels and tension of meeting so many people that Irène occasionally gave the addresses on radium. In her best English, she spoke to the audiences and accepted honorary degrees for her mother. Marie received the gift, presented by U.S. President Warren G. Harding at the White House, from Americans for the supply of radium for her Parisian Radium Institute. The trip was not solely speeches, awards and meetings. The Curies also were able to visit many famous places across the American continent, from riding ponies down the Grand Canyon to a spectacular visit to Niagara Falls. Marie wrote of her daughters' trip: "my daughters enjoyed to a full extent the opportunities of their unexpected vacation and the pride in the recognition of their mother's work" (Curie, 1923, p. 255).

RETURN TO PARIS TO CONTINUE HER RESEARCH

After the trip to America, Irène returned to Paris to continue her doctoral research at the Radium Institute. At this time, in the 1920s, Irène was one of the few trained radiochemists in the world. Perhaps led by her mother's 1898 discovery of the element polonium, named after Marie's native country of Poland, Irène decided to study polonium for her doctoral studies. Polonium had the advantage that essentially only α–particles are given off in radioactive decay (actually one in 100,000 decays emits a γ-ray, International Atomic Energy Agency, 2011). Her major doctoral professor at the Sorbonne University was Paul Langevin, who had been supervised by her father Pierre, in his doctorate, and who had been one of Irène's teachers in the cooperative. Her doctoral studies focused on α-particles emitted from polonium during natural radioactive decay.

At Irène's doctoral defense in 1925, journalists filled the audience to see the daughter of Marie Curie. As Bensaude-Vincent (1996, p. 62) notes, they perceived her "to be a future star scientist and a potential Nobel Prize winner, even before she had done any work on her own. Irène, unlike Marie, never had to fight for recognition." Even across the ocean, the *New York Times* reported on her thesis defense.

Following in her parents' footsteps made Irène's life easier than other women of the day who were interested in pursuing science. However, she also lived in the shadow of her parents, particularly her mother. Irène stayed at the Radium Institute for the rest of her professional career after graduating with her doctorate, continuing her study of radioelements and radioactivity but also examining the structure of the atom. Shortly after defending her doctorate, upon the recommendation of Paul Langevin, her mother hired Frédéric Joliot at the Radium Institute. Initially, Irène was both his supervisor and teacher. Although Irène and Fred had opposite personalities, each had expertise that complemented the other, much like the way Marie and Pierre worked together in the laboratory and in life. Irène and Fred also had some things in common, like an interest in sports and leftish politics. "Fred's sociability softened and humanized Irène. Most important, they loved science and each deeply respected the other's abilities" (McGrayne, 1998, p. 129).

Fred Joliot said about Irène,

> I discovered in this girl, whom other people regarded somewhat as a block of ice, an extraordinary person, sensitive and poetic, who in many things gave the impression of being a living replica of what her father had been. I had read much about Pierre Curie. I had heard teachers who had known him talking about him and I rediscovered in his daughter the same purity, his good sense, his humility (McGrayne, 1998, pp. 129-130).

Irène and Fred married on October 9, 1926 when Irène was 29 years old and Fred was 27. Shortly after their marriage, they both changed their surname to Joliot-Curie, although they often published with their given names. They had two children, Hélène and Pierre, and Irène felt her life was complete with both research and children. "She was a feminist who defined her role as a woman in terms of both work and children. At home, she remained a traditional wife and mother" (McGrayne, 1998, p. 131). Publicly, Irène served on the National Committee of the Union of French Women (Comité National de l'Union des Femmes Françaises) and on the World Peace Council and promoted women's education. She may have been influenced by her trip to America with her mother when Marie raised funds for securing a supply of radium, as they visited two of the "seven-sisters" women's colleges, Vassar College and Smith College (Ham, 2002-03).

Irène and Fred were a powerful collaborative team with her focusing more on the chemistry (although she had her doctorate in physics) and him concentrating more on the physics (although his doctoral degree was in chemistry). They were different in their thinking patterns as well. Irène processed ideas more slowly, with a more logical methodology, while Fred was quicker and often took a variety of positions in an argument. Both were experimentalists, however, and having less expertise in theory hurt them in their earlier joint studies, as they did not always see the implications of their research. Still, they enjoyed great success after a few early disappointments. Their collaboration resulted a very important discovery for radiochemistry—the discovery of artificial radioactivity.

JOINT RESEARCH OF IRÈNE AND FRÉDÉRIC JOLIOT-CURIE

In the early 1930s, the structure of the atom was understood to have a positively-charge nucleus, based on Rutherford's gold foil experiment.[1] However, the atom was not fully understood, as the neutron had not yet been discovered. Fred and Irène Joliot-Curie were competing with Lise Meitner from Berlin's Kaiser Wilhelm Institute, the New Zealander Ernest Rutherford from McGill University in Canada, and Niels Bohr from Copenhagen University in Denmark. All were hot on the trail of fully understanding the structure of the atom.

To keep up, Irène and Fred needed to increase their supply of polonium (atomic number 84). Polonium was a very dangerous element with which to work, but the two of them purified polonium by a method developed by Marie Curie to produce more of the element. They accomplished this purification using ampoules that originally held radium, with the chemical symbol, Ra. The radium undergoes radioactive decay to form radon, Rn, gas and an α-particle. The α-particle had been shown to be the helium nucleus, symbolized by ${}^{4}{}_{2}He$, with two positive charges (note subscript) and a mass of four (note superscript). This nuclear reaction, shown with the most stable radium isotope of mass 226, is as follows (written in the form used in Fred Joliot's Nobel lecture, 1935):

$$^{226}{}_{88}Ra = {}^{222}{}_{86}Rn + {}^{4}{}_{2}He$$

Note that the sum of masses (indicated by the superscripts) and the sum of the positive charges (indicated by the subscripts), respectively, are equal on both sides of the nuclear reaction 226 = 222 + 4, and 88 = 86 + 2. Then some of the radon undergoes further nuclear decay, to yield, polonium, Po, by this nuclear reaction, releasing another α-particle:

$$^{222}{}_{86}Rn = {}^{218}{}_{84}Po + {}^{4}{}_{2}He$$

When polonium undergoes radioactive decay, a particular isotope of the element lead, Pb, forms, with release of another α-particle:

$$^{218}{}_{84}Po = {}^{214}{}_{82}Pb + {}^{4}{}_{2}He$$

Therefore, here in a three series of three nuclear reactions, starting with radium, one radioelement decays into another, releasing an α-particle with each radioactive decay, finally ending with a particular isotope of lead.

Marie Curie had carefully collected these spent radium ampoules, obtained from physicians around the world (Weart, 1979). Irène and Fred used these samples to obtain highly purified polonium. With the world's best supply of highly purified polonium, they had ready access to this powerful tool of polonium-emitted α-

[1] Rutherford's gold foil experiment published in 1911 using α-particles bombarding gold foil showed that the nucleus of an atom contains all the positive charge and most of the mass in a very small volume relative to the size of the atom. The electrons that are negatively charged then must reside in the volume outside the nucleus.

particles in their hands. Using this polonium, with an abundant supply of high-energy α-particles, Irène and Fred could examine the structure of the atom.

In 1930, Irène read a paper by Walter Bothe and H. Becker in which they studied the bombardment of beryllium with α–particles from the nuclear disintegration of polonium. Bothe and Becker thought they had discovered a more penetrating form of radiation than γ–rays that was not deflected by a magnetic field. Irène and Fred repeated Bothe and Becker's study and found the same energetic radiation. They allowed this strange radiation to hit a thin piece of paraffin (which is rich in hydrogen atoms that bond to carbon atoms) and found very fast hydrogen nuclei were ejected from the paraffin. Unfortunately, Irène and Fred misunderstood their experiments. Since γ-rays do not have any mass, they could not have ejected the hydrogen nuclei that contain mass from the paraffin. In further experiments, Chadwick and Rutherford demonstrated that the radiation that the Joliot-Curie's mistakenly had thought to be γ-rays was actually neutrons. Consequently, Irène and Fred were incorrect in their inference of the type of radiation was emitted.

Chadwick and Rutherford published their explanation in 1932. Earlier, in 1920, Rutherford had predicted the existence of neutrons, so he was looking for evidence of them. The neutron is the uncharged subatomic particle of approximately the same mass as the proton and found within the nucleus. Chadwick alone received the Nobel Prize in Physics in 1935 for his discovery of the neutron (Nobelprize.org, 1935b). The discovery of the neutron opened further the fields of nuclear chemistry and nuclear physics, which ultimately led to the discovery of fission of uranium by slow-moving neutrons, with the concomitant release of enormous amounts of energy—the same process of fission used to make atomic bombs).

Irène and Fred also misinterpreted part of their data on the study of some lighter atomic nuclei that used a Wilson cloud chamber[2] in which charged particles could be monitored and recorded using photography. Although their experiments provided proof of the positron, which was predicted in theory by Paul Dirac in 1928, the Joliot-Curies failed to see the significance of the track of the movement of the particle in the Wilson cloud chamber. Soon after, Carl D. Anderson and Victor Hess in 1932 discovered the positron by studying cosmic rays interacting with a lead plate in the presence of a magnetic field (Nobelprize.org, 1936). Particles, which had the same mass as electrons, were emitted but they moved toward the negatively charged plate in the magnetic field; thus the particles had to be positively charged. Anderson received the Nobel Prize in Physics in 1936 for the discovery of the positron, and again Irène and Fred were disappointed that they had missed a great discovery.

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[2] The Wilson cloud chamber detects particles of ionizing radiation by providing an environment of supersaturated water vapor in which an α-particle or a β-particle causes the water to become ionized along its trajectory. The ions condense the water vapor in the chamber into droplets, so one can see the particle tracks, like those of airline contrails in the sky.

In their next experiment, Irène and Fred used their polonium source to bombard aluminum (atomic number 13) foil with α-particles, produced by polonium undergoing radioactive decay. First, they observed radioactive phosphorus (atomic number 15) plus a neutron. This isotope of phosphorus had never before been seen, as it is not the naturally occurring form of phosphorus but an artificially-made form generated through this nuclear reaction:

$$^{27}_{13}Al + ^{4}_{2}He = ^{30}_{15}P + ^{1}_{0}n$$

Many people at the Solvay Conference in 1934, including Lise Meitner, however, expressed reservations or doubts about the scientific accuracy of Irène and Fred's observation that neutrons were formed. The Joliot-Curies both felt discouraged by this reception, though they did get some private encouragement at this same conference from Niels Bohr and Wolfgang Pauli, two scientists who thought their observations were important.

Their observations this time turned out to be correct. The first nuclear reaction is as cited above, so the total mass 27 + 4 = 30 +1 and the total number of protons equals 13 + 2 = 15 + 0 (Joliot, 1935). Following this reaction was a subsequent nuclear reaction in which a positron, p, of mass zero and charge positive one, was ejected from the phosphorus isotope, leading to stable silicon (atomic number 14):

$$^{30}_{15}P = ^{30}_{14}Si + ^{0}_{1}p$$

As a positron is eliminated, a proton in phosphorus becomes a neutron, so the element changes from phosphorus with 15 protons to silicon with 14 protons, with constant mass of 30. Therefore, in the series of the two nuclear reactions, overall, aluminum converts to stable silicon, with release of a neutron in the first step and a positron in the second step. This is transmutation of elements, from one element, aluminum, to a radioactive and artificial isotope of phosphorus, to stable silicon. Even though Irène and Fred had not discovered either the neutron or the positron (both reported in 1932), they realized that the artificial radioactivity that they did discover in 1934 involved both the release of a neutron in the first step and of a positron in the second step. Therefore, these discoveries by others catalyzed their own discovery of artificial radioactivity.

They became more certain of their results when Fred removed the bombarded aluminum from the polonium source and could still detect the positrons being emitted. Irène developed a chemical test for the short-lived phosphorus radioisotope, artificially made, so they could verify their hypothesis. Fred said I felt "a child's joy. I began to run and jump a round in that vast basement… I thought of the consequences which might come from the discovery" (quoted in Quinn, 1995, p. 429). The Geiger counter showed that they had created an artificial radioelement, in this case, radioactive phosphorus, with a 3.5-minute half-life. They had created a radioactive element, a short-lived atom of phosphorus, from a naturally stable element, aluminum, by bombardment with helium nuclei with release of neutrons. Fred then showed the experiments to Marie Curie and Paul Langevin that evening, and all were jubilant.

> Afterward, Frédéric Joliot recalled that moment. 'I will never forget the expression of intense joy which overtook her [Marie] when Irène and I showed her the first 'artificially produced' radioactive element in a little glass

> tube. I can see her still taking this little tube of the radioelement, already quite weak, in her radium-damaged fingers. To verify what we were telling her, she brought the Geiger-Muller counter up close to it and she could hear the numerous clicks… This was without a doubt the last great satisfaction of her life.' (Quinn, 1995, p. 430)

"For a brief moment [Fred and Irène] had achieved the ancient alchemists' dream, transmutation—changing one chemical element, aluminum, into another, phosphorus, then into silicon" (Brian, 2005, p. 240).

This time Irène and Fred had been correct with the results that they had presented at the 1934 Solvay Conference. This work led to their joint Nobel Prize in Chemistry in 1935 for the discovery of artificial radioactivity induced by α-particles (Nobelprize.org, 1935a). Unfortunately, by this time, Marie Curie had passed away, so she did not know of the third Nobel Prize added in their family. Irène and Fred each gave an individual Nobel Prize lecture. Irène discussed the chemistry and Fred on the physics part of their discovery of artificial radioactivity. Irène in her Nobel Prize lecture (Joliot-Curie, 1935) gave credit to Rutherford for first reporting spontaneous transmutation of a radioactive element (Rutherford, 1919), thorium (atomic number of 90) to radium (atomic number of 88). Even though Irene was celebrated by the press when she received her doctorate in 1925, on the Joliot-Curie's joint Nobel Prize in Chemistry in 1935, Goldsmith (2005) notes, "Some things had not changed [since Marie Curie received her Nobel Prizes]. The press coverage almost universally attributed the prize to Frédéric's talent while Irène was relegated to an assistant's role" (p. 220). Pycior (1989) notes, "The Joliot-Curies' discovery was a fitting culmination of Marie Curie's life, in which science and family were the most important elements" (p. 213).

Irène and Fred's discovery of artificial radioactivity was an important discovery for subsequent research in medicine, chemistry and biology. Irène's daughter, Hélène Langevin-Joliot, a nuclear physicist, and Radvanyi (2006) says that Irène and Fred's discovery "suggested that the natural radio-elements were only the rare survivors of the very numerous radio-elements, which must have been formed at the beginning of the Earth's history" (p. 139). The ones with shorter half-lives were long since gone.

With this discovery, it became possible to make artificial isotopes that could be used to follow chemical and biochemical reactions. This procedure allowed scientists to understand the sequential steps of complicated series of reactions, using tracer amounts of the artificially made radioisotopes. In 1935, G. Hevesy and O. Chiewitz in Copenhagen "used radioactive phosphorus-32 to study the metabolism of phosphorus in rats" (Langevin-Joliot & Radvanyi, 2006, p. 140). Also Rosalyn Yalow's use of radioisotopic tracers to develop the radioimmunoassay, recognized with the 1977 Nobel Prize in Physiology or Medicine, was possible because of Irène and Fred's research on artificial radioactivity (Nobelprize.org, 1977).

The usefulness of the Joliot-Curies' discovery continues to this day. As a more personal example, Gilmer, the author of this chapter, once used ^{35}S-labeled amino acid methionine to follow membrane-bound proteins that coursed through the endoplasmic reticulum to the Golgi, and out to the cell surface of tumor cells from mice, using intact ^{35}S-cell-labeling (Gilmer, 1982). She purchased the ^{35}S-labeled methionine, sold industrially, but probably made by a process similar to one described in an experiment with yeast (Gajendiran, Jayachandran, Rao, Unny & Thyagarajan, 1994). Gajendiran et al. (1994) used ^{35}S-labeled sulfate obtained from a nuclear reaction, much like that discovered by Irène and Fred. Therefore, without the use of artificial radioactivity in Gilmer's experiment, the movement of membrane-bound molecules through various internal membranes to the plasma membrane could not have been followed. Indeed, much of the current understanding of biochemistry was determined using artificial radiotracers, discovered originally by Irène and Fred.

During the time of their discovery of artificial radioactivity and just before being awarded the Nobel Prize, as previously mentioned Marie Curie passed away on 4 July 1934. Her passing generated press and publicity—including Hollywood screenwriters who "believed that elements of her story would appeal to Americans during the anxious years of the Depression and World War II" (Des Jardins, 2010, pp. 200-201). Both Irène and her sister, Eve, were frustrated at the posthumous stories about their mother and tried to silence them. Although Irène's first impulse was to destroy all personal papers and letters of Marie, "Eve knew that unofficial accounts would be written anyway. She took control by writing a definitive biography and entering into an agreement with Universal Studies to make her [Marie's] work the basis of a screenplay" (Des Jardins, 2010, p. 201). MGM ended up releasing the movie, *Madame Curie*, in 1943, staring Greer Garson and Walter Pidgeon (Madame Curie (film), 1943).[3] Eve Curie's titled her book, *Madame Curie: A Biography by Eve Curie* (1937).

IRÈNE'S POLITICAL CAREER

After receiving the Nobel Prize in 1935, Irène and Fred decided to work separately. Fred was offered the position of director of research at the Caisse Nationale de la Recherche Scientifique. He became involved in transforming the old Ampère plant at Ivry into the Atomic Synthesis Laboratory, where they synthesized artificial radioelements. Meanwhile, Irène continued her research at the Institute, became a professor at the University of Paris, Sorbonne from 1932-1956, and became the research director at the Radium Institute in 1946. Fred also became the chair in nuclear physics and chemistry at the College de France. With these new positions, they basically "controlled every piece of serious nuclear work in France" (Crossfield, 1997, p. 115).

Irène's newfound fame as a Nobel laureate also propelled her into politics although she remained the scientific director of the Radium Institute until her death in 1956. She was part of the anti-Fascist coalition called the Popular Front in

[3] As a child, the author of this chapter saw this movie, *Madame Curie,* and after reading Eve Curie's biography of her mother, *Madame Curie: A Biography by Eve Curie* (Curie, 1937), she wanted to become a chemist and did so.

France in 1936. She also became one of the first cabinet ministers as an under secretary of state for scientific research. McGrayne (1998) explains,

> She took the job, calling it 'a sacrifice for the feminist cause in France.' She wanted to advance 'the most precious right of women…to exercise under the same conditions as men the professions for which they're qualified by education and experience' (p. 137).

It was ironic, however, that even though she was a cabinet minister, she was not permitted to vote, as women did not get that right in France until 1945. After three months, she resigned her cabinet position by prearrangement and turned over the job to Jean Perrin,[4] a 1926 Nobel laureate in Physics, her chemistry teacher in the cooperative school Irène had as an adolescent, and a good friend of the Curie family. She had quickly discovered that she did not have the patience or the diplomacy for politics. Around the same time, Irène began suffering from poor health.

Years earlier, Irène had contracted tuberculosis when she was pregnant with her first child, Hélène, in 1927. Despite this, Irène had a second child, her son Pierre, even though the doctors told her it would not to be wise to get pregnant again. By the late 1930s her tuberculosis worsened, and even weeks or months away in the Alps for a cure did not always restore her energy. She had been weakened by exposure to the high-energy radiation from X-rays during World War I while working with her mother. Later her immune system was further weakened by her work with radioelements, especially with polonium, and hindered her fighting the tuberculosis.

ONE MORE CHANCE AT A SECOND NOBEL PRIZE

Even with her health in decline, Irène had one more chance at a second Nobel Prize. She had begun conducting research with Pavel Savitch on uranium (atomic number 92). During the experiment, they thought they saw release of a neutron and a new radioisotope with a half-life of 3.5 hours that had properties similar to lanthanum (atomic number 57). However, two competitors from Germany, Otto Hahn and Lise Meitner, thought this was not correct. Hahn even belittled Irène's published research to Fred at a conference they both attended, perhaps trying to discourage her from continuing research on the subject. Irène and Savitch repeated their own experiment and saw the same result, so they republished their research. "They were within a hair's breadth of discovering nuclear fission, but did not rule out the possibility that it could be some unknown transuranium isotope, with $Z > 92$" (Vujic, 2009), meaning that an isotope of some new element larger in atomic number than uranium's of 92 had formed.

Meanwhile Hahn and F. Strassman repeated the Curie-Savitch experiment and observed some lanthanum, but they also saw barium (atomic number 56). Both of

[4] Jean Perrin is considered the founder of the Centre National de la Recherché Scientifique (CNRS), the French National Science Foundation.

these elements have a smaller atomic number than uranium. They published their results in January 1939. Scientists had expected to see an increase in the atomic number when bombarding with a neutron (as they saw with lighter elements), so this decrease in atomic number in the product was a great surprise.

Lise Meitner stayed in Germany until 1938, but with her Austrian passport and with the annexation of Austria by Germany, she essentially became a German national. Her professional associates and friends, because she was Jewish helped to smuggle Meitner out of Germany, initially into Holland, then to Denmark briefly, and finally to Sweden to be part of the newly founded nuclear institute at the University of Lund (Sime, 1996). This was an extremely difficult and stressful time for Meitner, and she wrote to the professional friend, Dirk Coster, who had helped her the most with her escape, "One dare not look back…one cannot look forward" (quoted in Sime, 1996, p. 209).

Once in Sweden Meitner was in almost daily contact with Hahn through letters. Meitner is the one who told Hahn that he had made the uranium atom undergo nuclear fission, a breaking apart of the element. Some mass is lost in this type of nuclear reaction, resulting in great releases of energy, much more than chemical reactions. Two authors, Meitner and her nephew, Otto Frisch, with whom she had worked with Otto Hahn at the Wilhelm Kaiser Institute for Chemistry in Berlin and who then was a refugee in Copenhagen, published a one-page note in *Nature* on February 11, 1939 entitled, "Disintegration of uranium by neutrons; A new type of nuclear reaction." Goldsmith (2005) wrote, "It was clear that Meitner had succeeded while others failed in solving the mystery of nuclear fission" (p. 225).

However, Lise Meitner was not included in the 1944 Nobel Prize in Chemistry, with the sole recipient being Otto Hahn for their discovery of fission of heavy nuclei. In Germany, many scientists celebrated the news of Hahn's award, but "Lise's friends were furious. They viewed her exclusion as neither omission nor oversight but deliberate person rejection" (Sime, 1996, p. 326). Meitner in a letter she wrote on November 20, 1945 to Birgit Aminoff, a scientist herself and wife of a member of the Nobel Foundation, said that she felt, "[Otto] Frisch and I contributed something not insignificant to the clarification of the process of uranium fission—how it originates and that it produces so much energy, and that was something very remote from Hahn" (quoted in Sime, 1996, p. 327). Interestingly, "after the war [World War II] the Nobel chemistry committee voted to reconsider the 1944 award to Hahn—an unprecedented move, and evidence that the original decision was flawed" (Sime, 1996, p. 327).

Interestingly, in a private letter to Hahn in 1938 (which University of California, Berkeley, nuclear engineering professor Jasmina Vujic published) Meitner wrote on Irène and Savitch's research, published in *Comptes Rendus*:

> In one of their C[omptes] R[endus] articles they emphasized strongly that their 3.5 h substance had very remarkable chemical properties and emphasized the similarity to lanthanum. The fact that they tried to place it among the transuranes doesn't change their experimental findings. And these findings led you to begin your experiments. And again you have not stated that quite clearly. One must not take people's words so literally. Curie

> obviously saw that something remarkable was going on, even if she did not think of fission. In November [1938] [George de] Hevesy heard her say in a lecture that entire periodic system arises from U + n bombardment. (Vujic, 2009)

The letter shows that Meitner thought that Hahn should have cited Irène and Savitch's research. He did not, however, and Irène received only the one Nobel Prize, the one that she shared with her husband, Fred.

Once Fred was elected to the Academy of Science in 1943, Irène applied but was never elected, even though she had her name considered more than once. In the end, neither Irène nor her mother was ever elected to the French Academy of Science. Though both mother and daughter enjoyed great successes within the fields of chemistry and physics, they both found doors open to men with lesser credentials shut when they attempted entry. Finally, in 1962, one of Marie Curie's original research assistants, Marguerite Perey, discoverer of the radioactive element francium, was the first woman ever elected to the French Academy of Sciences (Bibliopolis, 1998-2011).

Irène received other awards, including the Matteucci Medal from the Italian Society for Sciences in 1932, Henri Wilde Prize in France in 1933, Marquet Prize from the Academy of Sciences in Paris in 1934, and the Bernard Gold Medal at Columbia University in New York City in 1940 (Callahan, 1997). She was elected an officer of the Legion of Honor in 1939.

Irène's health continued to decline but like her mother, she continued her research as much as she could. During World War II, Fred was part of the Resistance movement and had to go underground. His absence left Irène to do her best in taking care of their two children. After Hélène finished her baccalaureate examinations, she, her mother and brother, Pierre, secretly left France and hiked through the mountains into Switzerland on June 6, 1944. That day happened to be D-day, the day the Allied troops landed on the heavily guarded French coastline to fight the German army. The German guards were likely preoccupied and were not as engaged in looking for those fleeing France at that time.

In 1946, Fred became head of the French Atomic Energy Commission and helped France develop its first controlled nuclear reactor, which became active in 1948. Fred envisioned that France would only develop nuclear energy for peaceful purposes but after the end of World War II, the US and France wanted to develop the hydrogen bomb (McGrayne, 1998). During this period, Fred was the co-founder of the World Peace Council and was forced out of his scientific position due to his peace and socialist activism.

Antibiotics were developed during World War II. After the war, Missy Meloney, the woman who had brought Marie Curie to the US twice to raise funds from American women to purchase radium, sent the antibiotic streptomycin to Irène. This treatment cured her tuberculosis.[5] With improved health, Irène

[5] When antibiotics were first discovered, they could cure tuberculosis, but with time, bacterial resistance to antibiotics developed, so penicillin and streptomycin were no longer so effective.

participated in international meetings for bans on atomic weapons, on peace, and for women's rights. However, due their communist political leanings Irène and Fred lost favor especially in the US because of the McCarthyism era with its anti-Communist hysteria. Also on her third trip to the US in 1948 she was interned on Ellis Island for one night until the French embassy intervened on her behalf (Irène Joliot-Curie, n.d.). Travel to international conferences became much more difficult for both of them. For instance, in 1951 when Irène planned to attend a physics conference in Stockholm, the hotels would not give her a room (McGrayne, 1998). The American Chemical Society would not even offer Irène a membership (McGrayne, 1998). In 1956, Irène's health took a nosedive with the start of leukemia, and she died on March 17, 1956, at age of 58. Fred too was sick with radiation-induced hepatitis, and he died two years later. The French government gave both national funerals.

AFTERWORD

The Sorbonne University has commemorated Irène by inaugurating the Irène Joliot-Curie Prize, awarded annually to a "Woman Scientist of the Year." The winner of the 2010 Irène Joliot-Curie prize was Alessandra Carbone (Fondation d'Entreprise, 2010). This same foundation also offers the Young Woman Scientist Prize and the Corporate Woman Scientist Prize.

To date, the Nobel Committee has awarded a total of four Nobel Prizes in which five members of Curie family have been recognized (with Marie honored twice):

- Nobel Prize in Physics in 1903 (to Pierre Curie and Marie Curie, and jointly to Antoine Henri Becquerel)
- Nobel Prize in Chemistry in 1911 (to Marie Curie),
- Nobel Prize in Chemistry in 1935 (to Frédéric Joliot and Irène Joliot-Curie)
- Nobel Peace Prize in 1965 (to Henry Richardson Labouisse, Jr., Eve Curie's husband, on behalf of the United Nations UNICEF's efforts towards world peace) (The Nobel Prize in Peace, Acceptance speech, 1965).

An examination of Irène's biography demonstrates that because of her family's achievements, she gained fame before she could prove her own scientific worth. However, even after she had demonstrated her own scientific abilities, she lived and continued to live as a quasi-partner with considerable responsibility, with Marie until Marie's death in 1934, relying considerably on her. In 1946, she became the Director of the Radium Institute in Paris, which Marie had founded in 1914. Like her mother, Irène was often denied honors, likely because of her gender, even as her achievements surpassed many of her male counterparts who received such awards. This was the reality many women scientists faced during the 20th century. Irène benefited from being the daughter of a Nobel laureate and director of the Radium Institute, and thus was able to show what a woman, given a chance to conduct research, could do for scientific progress.

This chapter also describes the personal story of Irène, a woman driven by the expectations of greatness with two Nobel laureates as her parents, with her family name of Curie, and by her love for learning and for understanding the world through science.

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KEYWORDS

Academy of Science
Affair, adulterous
α-particle
Aluminum
Atom, structure of the
College Sevigne
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