WOMEN IN PHYSICS: PIONEERS WHO INSPIRE US

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Abstract — **The 5th International Day of Medical Physics (IDMP) on November 7, 2017, featured six women physicists, including Marie Skłodowska Curie, who pioneered the study of radioactivity. It was held in conjunction with her 150th birthday anniversary. The other five were Chien-Shiung Wu, Rosalyn Yalow, Maria Mayer, Harriet Brooks and Marie Curie's daughter, Irène Joliot-Curie. All of them had dedicated their lives to study physics, despite living in a time when the role of women were rarely recognized in higher-learning institutions, and poverty and conflicts were rife. They left a huge legacy of knowledge to many generations of scientists. Wu's discoveries had paved the way for other researchers to win the Nobel Prize. She was known for her research in beta decay and, through the 'Wu Experiment' in 1956, had discovered a contradiction in the law of parity conservation. Yalow won the Nobel Prize in Physiology and Medicine in 1977 for developing the radioimmunoassay technique. Mayer won the Prize in Physics (1963) for discovering the nuclear shell structure. Brooks, who studied under Ernest Rutherford (the father of nuclear physics), was credited with discovering the concept of atomic recoil. And Joliot-Curie won the Nobel Prize in Chemistry (1935) with her husband for their discovery of artificial radioactivity. In this article, we briefly describe the lives and achievements of each woman. Their fascinating stories serve as an inspiration for hardworking scientists, especially women, who have to rise against the odds.**

Keywords— **women, nuclear physics, physicists, history, Nobel Prize.**

I. INTRODUCTION

It is an honor to be awarded the Nobel Prize. It is a greater honor if you are among the 2% of women who had won any of the prizes in physics, chemistry, physiology or medicine, literature and peace.

In this review, we feature five women who have won the Nobel Prize, or played a critical role that provided someone else with the opportunity to win. However, this is far from their greatest achievement. More importantly, they fought against discrimination and prevailed. They stood up to their goals when society demanded they stay home.

They are all survivors. They are a group that faced a number of obstacles, from professional rejection to racial and religious discrimination, poverty, and war. Their passion for science, together with strong persevering spirit, had kept these brilliant women from giving up on their dreams.

The 5th International Day of Medical Physics (IDMP) was celebrated worldwide on November 7, 2017, marking the 150th birthday anniversary of Marie Skłodowska Curie [1]. The event was dedicated to the improvement of safety for women as patients, hospital personnel and researchers who are exposed to medical radiation.

Besides the well-known Marie Curie, five exceptional women, Chien-Shiung Wu, Rosalyn Yalow, Maria Mayer, Harriet Brooks and Irène Joliot-Curie were recognized for their outstanding roles in nuclear physics (Fig. 1).

We are proud to highlight the achievements of these illustrious women and, at the same time, we also remember their life struggles. Their remarkable breakthroughs and strong personalities can motivate, inspire and make us strive for excellence in scientific research.

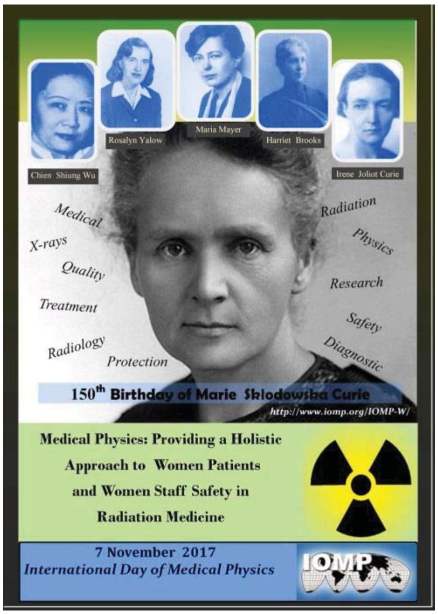

Fig. 1 The 5th International Day of Medical Physics poster produced by the Asia-Oceania Federation of Organizations for Medical Physics (IOMP Member) in November 7, 2017 [1].

II. CHIEN-SHIUNG WU

A. Rising against all odds

Chien-Shiung Wu, whose name means "*courageous hero"* [2], was born in Liuhe, a small town near Shanghai, China, on May 31, 1912 [3]. She is known for her remarkable work in nuclear physics in the United States.

As a young girl, there was very little opportunity for her and her peers to gain a formal education. Her father, Zong-Yi, however, was responsible for opening one of the earliest schools for girls in China. Along with his daughter, they would go door-to-door to recruit students from both rich and poor families, as there was no charge for attending the school [4]. Zong-Yi's goal was to eradicate illiteracy and prejudice against women by giving them a good education.

Chien-Shiung's father was her greatest inspiration to succeed, and he encouraged her to pursue an education beyond their hometown [3]. In 1923, at age 11, Chien-Shiung applied to join the teacher-training program at the Soochow Girl's High School, which provided graduates with a stable teaching job upon completion of their studies [4]. This was a prestigious and highly-competitive program, but Chien-Shiung proved her potential by emerging at 9th place out of 10,000 applicants in the school's matriculation examination [4].

Chien-Shiung graduated from high school in 1929 with the highest grades in her class. From 1930 to 1934, she studied for a degree in physics at the National Central University in Nanjing [4,5] before leaving for the United States in 1936.

She enrolled in the University of Michigan to pursue a PhD, but changed her mind after visiting the University of California in Berkeley (UC Berkeley) in a week [4]. While staying in California, she found the state to be more liberal, which led her to stay on in Berkeley. There, she met physicist Luke Chia-Liu Yuan, who showed her around the campus and introduced her to R. Birge, chairman of UC Berkeley's Physics Department. Birge immediately recognized her potential and offered a position to do a PhD [3,4].

After one year, she decided to apply for a scholarship, and that was the time she felt discriminated over her Asian lineage. Birge apparently awarded smaller stipends to her and Luke [4], which made them unhappy. Luke decided to finish his studies at the California Institute of Technology (Caltech), but Chien-Shiung stayed at UC Berkeley until she graduated in 1940 [4].

Fig. 2 Chien-Shiung Wu in Columbia University (1958). Courtesy of Smithsonian Institution Archives. Image #SIA2010-1511.

Chien-Shiung and Luke were married in May 1942. In the second half of that year, she decided to leave UC Berkeley because women were not offered teaching positions. This discriminatory practice was a norm then, even in the top 20 universities in the US. Chien-Shiung eventually taught at Smith College, a private, independent women's liberal arts college in Northampton, Massachusetts [4].

After that, she worked as a research assistant again before moving up to important positions at Ivy League universities, such as Princeton, Columbia, Harvard and Yale, when the role of women began to receive recognition [3,5,6] (Fig. 2).

When war erupted between China and Japan in 1937, Chien-Shiung lost all contact with her family until 1945, when Japan was defeated in World War 2 [4]. But the turmoil continued with the civil war between the Communists and Kuomintang, thus preventing her from returning to her home country to visit her family.

Chien-Shiung and Luke had started a family of their own and they found it safer to remain in the US. In 1949, when the Kuomintang lost the war, Chien-Shiung suddenly found herself stateless when her Republic of China passport was no longer valid. Fortunately, she managed to become a naturalized US citizen in 1954. When she finally returned to China in 1973, after 37 years of leaving home, she discovered that her parents and brother had died, and she had no chance of seeing them [4].

B. Scientific work

Chien-Shiung made significant contributions to the Manhattan Project, a US government research that notably led to the creation of the atomic bomb. Even though she was an Asian, she had the opportunity to play a crucial role in such important project [4,7].

Her involvement began as soon as she started pursuing her PhD at UC Berkeley. Just after getting her doctorate, she had the opportunity to establish a network with Enrico Fermi, who was famous for constructing the first US nuclear reactor [2].

As her capabilities became known, the theoretical physicist Robert Oppenheimer, known as the “father of the atomic bomb”, would invite Chien-Shiung to talk about the latest developments of her work in nuclear fission at UC Berkeley, where she was known as the “Chinese Marie Curie” [4].

Chien-Shiung is known for her parity conservation experiments in beta decay [3]. She worked in Columbia University after World War 2 to study Fermi’s theory on the subject [2].

In the 1950s, studies using particle accelerators became popular and scientists were discovering new subatomic particles. Tsung-dao Lee of Columbia University and Chen-ning Yang of Princeton University had proposed that the idea of parity conservation applied to electromagnetic and strong interactions did not apply to weak interactions. This was based on the discovery of the K-meson particle [2,4].

They needed help to prove their theory, and it was Chien-Shiung who conducted the experiment [8]. The results of her experiment eventually established parity conservation as a fundamental law of physics. It also significantly helped Lee and Yang to win the 1957 Nobel Prize in Physics.

Even though she did not win the coveted prize, Chien-Shiung continued her research until she retired in 1980. Her achievements were recognised through other prestigious awards and service in important positions. In 1974, for instance, she was named "Scientist of the Year" by *Industrial Research* [6]. In 1975, she became the first woman president of the American Physics Society and in 1978, she was the first Wolf Prize winner in physics [4].

Chien-Shiung Wu died in New York City on February 16, 1997, at age 84 [3]. Her achievements are a permanent inspiration for those striving to attain excellence in nuclear physics research, particularly Asian women.

Her namesake “*courageous hero*” truly describes someone with a brilliant mind, who has risen against all kinds of challenges to succeed in life.

Fig. 3 Chien-Shiung Wu in Columbia University (1963), where she worked as a professor. Courtesy of Smithsonian Institution Archives. Image #SIA2010-1507.

III. Rosalyn yalow

A. Hard worker who won't clock out

A woman with great determination and brilliant mind, Rosalyn Yalow made a name for herself by working up to one hundred hours a week (Fig. 4). She was born to Jewish parents in the tough neighborhood of The Bronx in New York City on July 19, 1921.

Neither her parents nor most of her neighbors had gone to high school. Her father was a local who dropped out after Eighth Grade to become a streetcar conductor before opening a one-man business. Her mother migrated to the US from Germany when she was a child, and had also quit school after Sixth Grade [9].

Nonetheless, they recognized the importance of a good education for their children. Rosalyn was very close to her father, and he encouraged her to pursue her dreams, regardless of her gender. When Rosalyn was 5 years old, she used to read a lot at the public library with her brother. In school, she was not afraid to question her teachers.

When she was 10 years old, she enrolled in a high school for girls. There, she developed an interest in medical science and earned the praise of her teachers for her excellent results [9].

Rosalyn graduated from high school in 1937 at age 15. Her mother wanted her to become a teacher, which was expected of Jewish girls in the 1930s [9,10], but she deeply wanted to attend medical school.

Unfortunately, not only was she not able to afford the tuition, medical schools then would not even accept Jewish men. As a Jewish woman, Rosalyn knew she her chances were next to nothing. So, she enrolled in Hunter College, a highly-competitive girls' college, but where tuition was free [9]. This gave her the opportunity to pursue a higher education and she chose to major in Physics.

When she graduated in 1941, she worked as a secretary at Columbia University before getting an offer to work as a teaching assistant at the University of Illinois at Urbana-Champaign, where she did her post-graduate study in nuclear physics [2,9].

At the onset of World War II, she became the first woman to be admitted into the university's engineering school since World War 1. The two World Wars, in fact, were the reason why women got to enroll in the University of Illinois in the first place -- the men had been called up to serve in the military, thus graduate schools had no choice but to admit women instead of closing their doors! [9]. Women were also not allowed to teach in the university until after the bombing of Pearl Harbor in December 11, 1941 [9].

While studying for her doctorate, Rosalyn met and married her fellow student Aaron Yalow in June 1943. After completing her doctorate in 1945, she got a job at the Bronx Veterans Administration Medical Center to study the use of radioisotopes in medicine, where she had to set up her laboratory in a janitor’s closet [9].

Fig. 4 Rosalyn S. Yalow at the Bronx Veterans Administration Hospital (1977). Photo by US Information Agency (USIA), via Wikimedia Commons.

In 1950, she met and recruited Dr Solomon Berson, a resident physician at her workplace [2,10]. She was impressed by his strong personality and background, which was similar to hers -- he was the son of a Russian Jew who was rejected by 21 medical schools before being accepted by the University of New York [9].

Rosalyn gave up on working with other scientists to focus on her work with Dr Berson [11]. Together, they would form a strong working relationship in developing the radioimmunoassay (RIA) technique [2]. Their work relationship was a perfect match, and they shared the credits in every achievement.

B. Scientific work

Rosalyn and Dr Berson initially chose to study the mechanism of insulin in treating diabetes. They performed radioisotope tracing experiments with insulin injected into patients. It was in this work that they noticed the incompatibility of using pig and cattle insulin to treat humans, which was prevalent in the 1950s [2,10]. This was because the human immune system would produce antibodies to counter the animal insulin.

Nonetheless, their outstanding discovery was not related to the study of insulin, but to the method they developed to carry out their research.

They found a novel way to measure the level of hormones using antigen tagged with radioactive indicators. This so-called radioimmunoassay (RIA) technique [2,9] had revolutionized endocrinology research and the treatment of hormonal disorders, such as diabetes [9].

In addition, Rosalyn and Dr Berson discovered the difference between Type 1 and Type 2 diabetes, which was vital for doctors to identify before treating patients with insulin [2]. They expanded their research to measure the level of various biological substances in blood samples. They were generous and wanted to help people, and the techniques of their research had never been patented. [2,10].

The death of Dr Berson in 1972 from a heart attack had greatly affected Yalow. She became concerned that her work would lose credibility without Dr Berson's contribution. This led her to dedicate more effort in building her research by putting in hundreds of work hours a week, so much that she managed to produce 60 research papers in four years [2,10].

In 1977, she shared a Nobel Prize in Physiology or Medicine with Roger Guillemin and Andrew Schally. Unfortunately for Dr Berson, the Nobel Prize was not posthumously awarded. Rosalyn was the second woman to win the Prize in Physiology or Medicine after Gerty Cori [10]. She achieved an important position in medical research at a time when women suffered a discrimination of their abilities.

Rosalyn Yalow died on May 30, 2011, at age 89 in the same humble neighborhood where she was born. Her grit and determination had played a crucial role in her remarkable achievements. On overcoming the gender discrimination, she once said: "If I wasn't going to do it one way, I’d manage to do it another way." [2].

Fig. 5 Rosalyn S. Yalow, winner of a Nobel Prize in Physiology or Medicine, at The Bronx Veterans Administration Medical Center. Photo by US Department of Veterans Affairs[10].

IV. Maria Goeppert Mayer

A. Alchemy of excellence

Besides perseverance and hard work, the alchemy of a high-achieving person has two distinct virtues: a pioneering spirit and willingness to go the extra mile. These are the values of a woman named Maria Göppert-Mayer, who was born in Kattowitz, Germany, on June 28, 1906. She was the second female Nobel laureate in physics after Marie Curie [12,13].

Mayer grew up in Göttingen, Germany, where her family lived after her father, Dr Friedrich Goeppert, became a pediatrics professor at Georg-August Universität [14]. She was very close to her father, who strongly supported her quest to pursue a higher education instead of encouraging her to just "grow up as a woman" [14].

In 1914, when Maria was 8 years old, Franz Ferdinand, the archduke of Austria and heir to the Austro-Hungarian Empire was assassinated, sparking a chain of events that would plunge her country into World War I.

During the war, there was a shortage of food and Maria's father had to struggle to feed his family and his patients. After the war ended, Maria was a teenager and began to attend the all-girls' Hohere Tochterschule school, where she excelled in language and mathematics [9,15].

In 1921, she started attending the Frauenstudium private school, which prepared its students for university [9,15]. Her teachers doubted she would be able to enter a university, but she proved them wrong by earning a place at Goerg-August Universität (her father's workplace) in 1924 [15]. Initially Maria loved mathematics but her interest changed when she met Max Born, a famous theoretical physicist, who played a vital role in the development of quantum mechanics [15].

Born was a family friend, and he influenced Maria to take up physics [14] all the way till she finished her doctorate in 1930.

Three years after enrolling in Goerg-August in 1927, her father died, leaving Maria and her mother devastated [15]. Her family faced financial difficulties after his death, and her mother had to rent the rooms foreign students at her university to supplement their income [9,15].

Well, despite such hardship, she met her future husband Joseph Mayer, a researcher from California, the United States, who came to Göttingen to study quantum mechanics [15].

When Maria and Joseph got engaged, she considered quitting her career to become a housewife, but her husband convinced her to keep on working [9]. They got married in January 1930, and she finally earned her PhD a few months later [15].

Fig. 6 Maria Göppert-Mayer, 1963. Courtesy of: Smithsonian Institution Archives. Image #SIA 2008-1865.

Maria knew she would not be able to become a professor in Germany, as women were rarely accepted as faculty staff. Moreover, Germany was experiencing political upheaval with the rise of Adolf Hitler and Nazism, which eventually lead to World War II in 1939 [15].

Maria and her husband moved to the United States, where Joseph secured a position at the Johns Hopkins University. Maria had to work as an unpaid research assistant because she was not allowed to hold a position at the same university due to unreasonable nepotism rules [2,15].

Life became difficult for the Mayers when their children were born in 1933 and 1938. Maria was forced to spend more time at home, even though she missed working in her laboratory for free [9].

In 1938, just before World War II began, her husband lost his job at Johns Hopkins when anti-German sentiments began rising in the university, and Maria blamed herself for her husband's predicament [2,9,15]. But soon, another silver

1. Retrieved from: https://www.bronx.va.gov/BRONX/features/AtomicMedicineAndRosalynYalow.asp

lining appeared when Joseph was offered a position to teach chemistry at Columbia University.

Recognition came quite late in life for Maria as it was only at age 53 in 1960 that she gained her professorship at the University of California, San Diego, which was a full-time job with fair pay commensurate with her qualifications [2,14].

B. Scientific work

Mayer was known for developing the double-photon emission theory, which was the subject of her doctoral thesis. Her predictions were proven in 1960, with the development of experiments with lasers [15,16]. Her sound knowledge in mathematics had given her an edge to join the pioneering work on the structure of organic compounds in Johns Hopkins University [12,14].

One of Maria's greatest achievements was during World War II while working for the Manhattan Project. She gained her first paid job in 1941, when she was hired by Columbia University to teach mathematics [2,15].

A second job offer came right after from a clandestine research group working on what would later become the Substitute Alloy Materials (SAM) project, one of the most important parts of the Manhattan Project.

Maria's work under this group was to design an efficient way to separate uranium-235 from uranium-238 [15]. Although she felt uneasy working on a project that led to the development of the atomic bomb, she was happy to be respected as a scientist for the first time [15].

When the war was over, Maria was offered a position at the Institute for Nuclear Studies at the University of Chicago. She focused on isotopes research, studying why some isotopes were more stable than others [2,15].

Her knowledge in matrix manipulation eventually led her to win the Nobel Prize in 1963 for discovering the nuclear shell structure (Fig. 7) [13,14]. She acquired data that supported the assumption that neutrons and protons rotated at different orbits in an atom as first proposed by scientists in 1930 [2].

Before winning the Nobel Prize, she had a string of impressive achievements. She became a member of the National Academy of Science in the United States in 1956 and a corresponding member of the Akademie der Wissenschaften in Heidelberg, Germany [14].

Despite largely being considered as just the "wife of a scientist", she never gave up on her passion and work [17]. Maria Goeppert-Mayer died on Feb 20, 1972 in San Diego, California, after a heart attack the previous year caused her to fall into a coma.

An award was created in her name by the American Physical Society to honor young women physicists [18]. Today, her discoveries in double-photon absorption have been applied in dermatological diagnoses [14].

Fig. 7 Maria Goeppert-Mayer (1906–1972), walking in to the Nobel ceremony with King Gustaf Adolf. Courtesy of: Smithsonian Institution Archives. Image #SIA 2008-1866.

V. Harriet Brooks

A. Facing a woman's dilemma

Harriet Brooks, born on July 2, 1876, in Ontario, Canada, was one of the pioneer women in nuclear physics research. She was extremely talented and had worked with great physicists of her time, such as Ernest Rutherford, Marie Curie and J.J. Thomson [19].

Harriet was the third child in a family of nine siblings. Her father, George, worked as a travelling salesman in a flour company, where he constantly struggled to feed his large family. Due to this hard situation, only Harriet and her youngest sister were able to continue their studies after high school [19]. She completed her education at the Seaforth Collegiate Institute in Seaforth, Ontario [19].

When her family finally settled in Montreal in 1894, her mother encouraged her and her sisters to keep pursuing their education. She enrolled in McGill University in the same year [20]. She was an outstanding student and supported herself by winning scholarships and awards every year. Those prizes helped to fund her university education [19].

During the first two years at university, she studied mathematics and language. The last two years were almost entirely dedicated to physics. She obtained her BA with first-class honors in mathematics and natural philosophy in 1898 [19,20]. She was also awarded a teaching diploma, which was given to women graduates to encourage them to become schoolteachers.

Harriet had the opportunity to work with distinguished scientists in her field. Right after completing her degree, she had the honor of being hired by Rutherford, known as the father of nuclear physics, as his first graduate student researcher [19].

Besides the Cavendish Laboratory in Cambridge University, Rutherford had just established another laboratory at McGill University to conduct his research [20], where Harriet worked on her master. Her research was related to electricity and she graduated under Rutherford's supervision in 1901 [19].

She created history by becoming the first woman to be awarded a master's degree by McGill University. During her studies, she taught mathematics at the Royal Victoria College, which was a higher-learning institution for women at McGill [19,20].

In 1901, she was offered a position that enabled her to study for a PhD at Bryn Mawr College in the United States. In her first year, she won an important scholarship to spend a year in Europe. Harriet contacted her mentor Rutherford to share the good news, but she had a rather low self-esteem, and she believed that she did not deserve such award [19]. Her family had objected to her traveling alone and she was also concerned whether the money was enough. Rutherford, however, arranged for her to come to the University of Cambridge to work under J.J. Thompson, the British physicist who discovered the electron [19,21].

At Rutherford's Cavendish laboratory, she joined a study on radioactivity and, after a year in England, she did not return to Bryn Mawr to finish her PhD, but instead, joined Royal Victoria College as a tutor.

Fig. 8 Graduation picture of Harriet Brooks (1898). Photo by Wm. Notman & Son. Courtesy of the McCord Museum of Canadian History, Montreal[11].

In 1904, Harriet became a tutor at Barnard College, a women's college that was affiliated to the University of Columbia in New York City [19]. She got engaged to physics professor Bergen Davis in 1906 and unfortunately, being a common practice at that time, was asked by her dean to resign.

2. Retrieved from: http://collections.musee-mccord.qc.ca/en/collection/artifacts/II-123880/

As a strong woman who regretted the move as a waste of talent, she wrote to her dean, saying: "I think it is a duty I owe to my profession and to my sex to show that a woman has a right to practice her profession, and cannot be condemned to abandon it merely because she marries." [19,21,22]. She would break up her engagement anyway and would keep working at Barnard College for a while. A month later, she resigned her position [19].

Later in 1906, she traveled to Paris to become an independent researcher at Marie Curie's Laboratorie Curie. Marie Curie invited her to stay for the year, but she decided to apply for a position at the University of Manchester in England [19]. She was still waiting for a response when she decided to marry Frank Pitcher and stop doing research. Some years after the marriage, the couple had three children [19]. Harriet never continued her work in science.

B. Scientific work

Harriet was the first woman to graduate with a master's degree from the renowned McGill University, and was involved in some of the most important discoveries in the early days of radioactivity research [19,21].

Right after finishing her master's project, she was involved in an important discovery. Rutherford gave her the task to study the radioactive decay of thorium. It was observed that the radiation could be carried by air and it was not clear whether it was a gas, vapor or solid particles.

Harriet demonstrated that the radiation originated from a gas – now known as radon. This discovery eventually led Rutherford and Frederick Soddy to realize that one element could transmute to another [19–21].

Her next remarkable discovery, in between 1903 and 1904, was the atomic recoil phenomenon. She observed that a non-radioactive utensil could itself become radioactive simply by being in contact with a radioactive material [19–21]. When a particle is released from the nucleus of an atom, the nucleus recoils at the opposite direction [20].

This discovery would particularly have great influence on the work of Lise Meitner, an Austrian female nuclear physicist who, together with Otto Hahn and his team, discovered the concept of nuclear fission in 1939 [19,21,22]. In fact, Hahn and Meitner had re-observed this phenomenon four years later, and claimed to be the ones that discovered it. But Rutherford wrote to them, stating that this discovery had been made by Harriet. Later, Hahn agreed with Rutherford and wrote in his autobiography that "Brooks may have been the first researcher to have observed the phenomenon of radioactive recoil" [19].

Finally, her dedication to radioactive decay demonstrated that radiation is sequentially released when uranium and thorium decay. This was the first step that would build the concept of radioactive decay sequences. In addition, it was the main topic of Rutherford's 1904 Bakerian Lecture at the Royal Society of London, in which he discussed the successive decays of heavy radioactive elements.

Rutherford took the effort to credit Harriet for her contributions in his team [20]. He had always been her loyal co-worker and friend, who would never let the world forget the great achievements of Harriet.

Although she left physics research when she got married, her contributions were honored and recognized. In 1907, she enrolled in the Women's Canadian Club: from 1909 to 1912, she became an honorary secretary of the club and in 1923, she became the president [20]. In 2016, a new building at the Canadian Nuclear Laboratories was named after Harriet [23].

Harriet Brooks died in Montreal, Canada, on April 17, 1933, at age 56, possibly due to the effects of her exposure to radiation in her work [20]. She was an outstanding woman not only because of her research, but also for her strength. It is important to remember that the dilemma faced by Harriet in 1906, when choosing between a career or to start a family, is still a big dilemma among women after more than one hundred years.

VI. Irène Joliot-Curie

A. A legacy of her own

Born in Paris on September 12, 1897, Irène Joliot-Curie was the eldest daughter of the famous radioactive research couple Pierre and Marie Curie. Like her parents, who won the Nobel Prize in physics (1903) and chemistry (1911), Irène became a remarkable scientist and went on to win her own prize in chemistry in 1935 [24]. Until Irène got married in 1926, Marie's and Irène's lives were so tight that it was impossible to write about one without mentioning the other.

Irène was born one month premature [25], believed to be a consequence of Marie's exposure to radioactive materials. During Marie's time, the hazards of radioactive materials were not known, and she suffered illnesses during her pregnancy with Irène because of her exposure to radiation in her work [26]. As a child, it is also likely that Irène was exposed to radiation because of her parents' work, thus she was constantly in poor health [25]. She was only 6 years old when her parents won the Nobel Prize [9].

Irène had a very exclusive education. Marie strongly disapproved the rigid educational system in France. This provided Irène with the privilege to attend a private cooperative school organized by her mother and other eminent French scholars for 2½ years [25].

In the cooperative school, Marie taught physics and impressed Irène with her strictness and dedication to education [25]. During the last two years of high school, Irène attended a private all-girls' school. She furthered her studies at the Sorbonne (University of Paris) in 1914, just before the outbreak of World War 1 [25].

Only a little is known about Irène's relationship with her father, as he was killed in a car accident in 1906. Irène was not told what happened until after the funeral [25]. On the other hand, in 1910, the death of her grandfather affected her more, and she desperately needed her mother's attention. Marie, however, was also suffering from depression, poor health, and stress, which kept her apart from her children [25].

In 1911, Marie was awarded her second Nobel Prize, and Irène had begun to understand the importance of her mother's role in the scientific community [9].

Her studies at the Sorbonne were interrupted with the outbreak of World War 1. Irène, then, joined her mother to work as a nurse radiographer. Marie was a patriot and used the money from her second Nobel Prize to buy war bonds to support the French army. In the hospital where they worked, they used their knowledge to operate crude X-ray machines, which helped to locate bullets and shrapnel in the wounds of injured soldiers. Their work had saved the lives of many during the war [9,25].

After the war, Irène returned to Paris to work as her mother's assistant at the Radium Institute and gained her doctorate in 1925 [24,25]. It was also at the Radium Institute that she met her fiancé, Frederic Joliot.

They were married in 1926 and had two children. Irène perfectly assumed her role both as a researcher and as a mother. Just like her parents, Irène and Frederic worked as a husband and wife team, focusing their research on the atomic nuclei structure.

MME CURIE AND HER DAUGHTER IRÈNE, 1925

Fig. 9 Portrait of Marie Curie and her daughter, Irène. Courtesy of: Wellcome Collection[12].

On July 4, 1934, Marie died without the chance to see her daughter win the Nobel Prize a year later [25].

Irène's legacy goes far beyond her accomplishments in chemistry. She was also an activist who joined a number of organizations for the advancement of women's rights. She encouraged women to earn money to support themselves during a time when fascism was widespread and demanded women to stay at home [25]. In 1936, she joined politics

3. Retrieved from: https://wellcomecollection.org/works/nbpjwgzw

and during World War II, she was threatened with arrest by the German soldiers [25].

Moreover, she was diagnosed with tuberculosis and was forced to stay in Switzerland. Near the end of the war in 1944, her two children joined her to live in the Swiss Alps. After the war, she went to the United States and then, back to France where she stayed until her death [25,26].

B. Scientific achievements

Irène completed her PhD in 1925. Her doctoral thesis was on alpha particles emitted by radioactive polonium during its disintegration. In particular, she focused on how alpha particles decelerate while moving through matter [9].

Polonium was discovered by her parents in 1898 and was extremely useful. Irène's expertise in dealing with this element was exclusive, and the Radium Institute, where she worked, was one of the most important radioactivity centers of the world [9]. Her dissertation defense made it to international news, and it was even reported by the *New York Times* [2].

While working with Frederic Joliot, they produced the world's largest supply of polonium [9]. Such work turned them into radiochemistry specialists, but it was very dangerous due to the high toxicity of the element they produced [9].

In the early 1930s, the whole world started paying attention on French research because of the scientific contributions by Irène and Frederic. They were on par with renowned nuclear physicists, such as Rutherford, Lise Meitner, and Niels Bohr [9]. The most important discovery made by Irène and Frederic was in 1934 and allowed them to win the Nobel Prize in Chemistry in 1935.

In their experiment, they placed their polonium next to an aluminum foil. They were expecting hydrogen nuclei to emerge, but neutrons and positrons appeared instead. A Geiger counter confirmed that the aluminum foil had itself become radioactive, which means that Irène and Frederic were the first scientists to artificially produce a radioactive element [2,9,25].

The discoveries by Irène and Frederic in artificial radioactivity had an enormous impact, not only allowing them to win the Nobel Prize in Chemistry, but also opening the practical applications of radiochemistry in medicine [27].

Irène's contribution to science was recognized a number of times. She was appointed the undersecretary of state for Scientific Research in 1936 by the French government, she was a member of a number of academies and scientific societies, and she was conferred honorary doctorates by several universities [24].

Irène passed away on March 17, 1956, at age 58 from leukaemia, probably because of exposure to radioactivity in her work [27]. Just like her mother, she is certainly a great inspiration to women, who are encouraged and influenced by her achievements in science and politics.

Fig. 10 Irène Curie, 1921. Courtesy of: Smithsonian Institution Archives. Image #SIA 2008-4488.

VII. Conclusion

The account of the six women described here inspires us today with their academic contributions, personal struggles and positive attitude. The world has changed in modern times, and it is important to cast aside all forms of discrimination to encourage young women to pursue a career in science. While the majority of women do not have to give up their careers anymore just because they got married, or be shunned from scholarships because men feared their abilities, they still face hurdles in other aspects that hinder them from contributing to society.

The physicists highlighted here role models for young women to persevere when facing their own challenges, before they, too, can rise up to achieve important contributions that shape the future of science, society and the world.

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