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RESEARCH ARTICLE OPEN ACCESS

THE FIVE WOMEN AWARDED THE NOBEL PRIZE IN PHYSICS UNTIL 2023

***Juan Núñez Valdés**

Investigador Honorario, Dpto. de Geometría y Topología, Facultad de Matemáticas, Universidad de Sevilla (Spain)

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****Corresponding Author: Silvio Moises Negri***

ABSTRACT

A This article shows the biographies of the four women, Maria Goeppert-Mayer, Donna Strickland, Andrea M. Ghez and Anne L'Huillier, who, in that order, followed, although many years later, in 1963, 2018, 2020 and 2023, respectively, the path that Marie Curie initially opened in 1903, when she was the first woman to be awarded the Nobel Prize in Physics. The objective is to reveal to society the lives and scientific works of these four women, giving special emphasis to the important achievements they have obtained, taking into account that, with some slight exception in the scientific world, the four ones are quite unknown by the rest of society in general.

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INTRODUCTION

The first Nobel Prize to be awarded in the category of Physics was awarded, in 1901, to the German scientist Wilhelm Conrad Röntgen "in recognition of the extraordinary services he has provided with the discovery of the extraordinary rays that later bear his name." Since then and until 2023 inclusive, this Prize in this modality has been awarded to 224 researchers, of which only 5 have been women (2.2%). It is important to note that for six years (1916, 1931, 1934, 1940-1942) this Prize was not awarded, on some occasions, because it was declared void and, on others, due to the situation of world war and the forced exile of several members of the committee. The only scientist to win the Nobel Prize in Physics twice was John Bardeen (in 1956 and 1972). Another 4 researchers also managed to be awarded the Nobel Prize on two different occasions, although they were in another modality or in two different modalities. Chronologically, in order of award, they were Marie Curie, who won it in Physics in 1903 and in Chemistry in 1911, Linus Pauling (Chemistry in 1954 and Nobel Peace Prize in 1962), Frederick Sanger (both in Chemistry, in 1958 and 1980) and Barry Sharpless (both in Chemistry, 2001 and 2022). Only five women have won the Nobel Prize in Physics so far: Marie Curie (1903), Maria Goeppert-Mayer (1963), Donna Strickland (2018), Andrea M. Ghez (2020) and Anne L'Huillier (2023). This makes Physics the category of the 6 of which the Nobel Prize consists that the fewest women have won. Of these 5 women, Marie Curie (Figure 1), whose life and scientific work are really well known by society in general, was awarded in 1903 the first Nobel Prize in Physics that was awarded to a woman, sharing it with her husband, Pierre Curie, and with the French physicist Henri Becquerel,who discovered radioactivity, "in recognition of the extraordinary services rendered in their joint investigations into the radiation phenomena discovered by Henri Becquerel." As an anecdote in this regard, it should be noted that, initially, the Swedish Academy intended to award only the two men and not give it to her, given her status as a woman. The mathematician Magnus GöstaMittag-Leffler, a member of the Academy, notified Pierre Curie of this situation and this last one threatened to reject the award if Marie's work was not also recognized. In response to this, the academics relented and included her in the nomination. Eight years later, she also won, this time alone, the Nobel Prize in Chemistry, in 1911 (García, 2020). However, after her and since 1903 no other woman was awarded the Nobel Prize in Physics until sixty years later, when Maria Goeppert-Mayer obtained it "for proposing the nuclear shell model of the atomic nucleus" in 1963 (shared with Eugene Paul Wigner and Johannes Hans Daniel Jensen). And she was followed, already in the current century, by Donna Strickland, in 2018, "for her revolutionary contributions in the field of laser physics, the use of optical tweezers and their application in biological systems" (shared with Gérard Mourou and Arthur Ashkin), Andrea M. Ghez, in 2020, "for the discovery of a supermassive compact object in the center of the galaxy" (a recognition shared with Reinhard Genzel and Roger Penrose) and Anne L'Huillier, in 2023 (together with Pierre Agostini and FerencKrausz), "for experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter."

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Figure 1. Marie Curie. Source: (Web Image 1)

Although these last four women are relatively wellknown in the scientific world, although less so than Marie Curie, however, they are not so well known by society in general, despite the fact that their valuable contributions have contributed significantly to the development of current physics. Given, therefore, that the biography of Marie Curie is already sufficiently known and that, therefore, it is not necessary to elaborate on it further, this article presents the biographies of the only four other women awarded the Nobel Prize in Physics, emphasizing their most important scientific milestones and the importance of their discoveries, with the aim of highlighting their lives and scientific works, which have served to promote the remarkable development that physics has today. Do not forget that they, especially Maria Goeppert, had to challenge the usual customs of the society in which they lived, in which the still common gender inequalities meant that women, in general, were placed with many obstacles to their time to be able to practice their professions.

MATHERIALS & METHODS

The methodology followed in this research has been the usual one in this type of articles, that is, the search for information in all types of sources, both bibliographic and digital, fundamentally in primaries sources, on the women who are dealt with in the article, with the goal of completing those biographies on them already existing in the literature.

RESULTS

In the following subsections, and as main results of the article, we showthe biographies of the only four women, Maria Goeppert-Mayer, Donna Strickland, Andrea M. Ghez and Anne L'Huillier, who have been awarded the Nobel Prize in Physics after another woman, Marie Curie, obtained it for the first time.

MariaGoeppert-Mayer: herbiography: The second woman to receive the Nobel Prize in Physics, in 1963, Maria Goeppert-Mayer (née Maria Goeppert), 60 years after Marie Curie received it in 1903, was born in Katowice (a town that at that time was part of the province of Silesia of the German Empire) on June 28, 1906. Her father was Friedrich Goeppert, a university professor and member of a family that had an extensive academic tradition, which meant that she, from an early age, was surrounded and influenced by people with very high intellectual training, such as the scientists Enrico Fermi (known for the development of the first nuclear reactor and for his contributions to quantum theory, nuclear and particle physics and statistical mechanics), Werner Heisenberg (one of the researchers pioneers of quantum mechanics), Paul Dirac (who fundamentally contributed to the development of quantum mechanics and electrodynamics) and Wolfgang Pauli (also one of the founders of quantum mechanics and Nobel Prize winner in Physics in 1945).

When she was only 4 years old, in 1910, her family moved to Göttingen, when her father was appointed professor of pediatrics at the university of that city. After completing her first studies there and since there was no school specialized in teaching Mathematics in that city, which was what she liked, in 1921 she was forced to enter the Frauenstudium, a private school run by suffragettes, which prepared for the university entrance exam to the few girls who wanted to apply for admission. Unfortunately, however, the school closed its doors before she could complete the three-year program, cutting her formal preparation short. Even so, she decided to take the exam immediately and was admitted as a mathematics student in the spring of 1924 at the University of Göttingen. There, she had three future Nobel Prize winners as professors: Max Born (Physics modality, 1954), James Franck (Physics modality, Physics, 1925, shared with Gustav Hertz) and Adolf Otto Reinhold Windaus (Chemistry modality, 1928). More details of this Maria Goeppert's stage of studies can be seen in (Morrón, 2014). After graduating, Maria Goeppert obtained her doctorate in Physics at the same University of Göttingen in 1930, advised by Max Born, with a thesis in which she calculated the probability that an atom is capable of absorbing two photons simultaneously and exciting the atom as it would be a single photon with energy equal to the sum of the energy of both photons. Her completely novel theory was confirmed experimentally in the 1960s with the appearance of laser rays. Years later, Eugene Wigner described this thesis as a "masterpiece of clarity and concreteness" (Morrón, 2014).

In that same year, 1930, Maria Goeppert married Joseph Edward Mayer, an American who worked as James Franck's assistant. The couple moved to Baltimore, where he had a position as a professor at Johns Hopkins University. Their two children, Maria Ann and Peter Conrad, were born there. Maria Goeppert worked at that University between 1931 and 1939, and later she worked at Columbia University, between 1940 and 1946, and at Chicago University, because her husband was hired there. However, she was allowed to work as a researcher under the condition of not having the right to remuneration, due to the gender inequalities prevailing in the country at that time. Thus, she also worked practically her entire career, which she developed as an unpaid volunteer teacher and researcher, not obtaining a full-time paid position until she was 53 years old (Figure 2). However, that did not prevent her research activity from being very brilliant, eventually leading her to occupy a teaching position at Sarah Lawrence College (Pais, 2021).

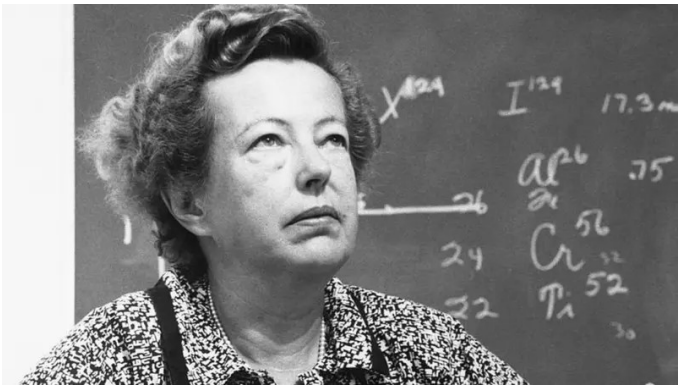

Figure 2. Maria Goeppert is 52 years old. Source: (Web Image 2)

He also collaborated, although as a more secondary line of research, in the Manhattan Project for the development of the atomic bomb in Los Alamos (New Mexico). As already noted, during the time that her husband was a professor at the University of Chicago, Maria Goeppert was a volunteer, non-paid associate professor of Physics. Near the end of that period, when the nearby Argonne National Laboratory was founded in 1946, she volunteered to work there part-time in the Theoretical Physics Division. During the time in which she worked in Chicago and Argonne she developed the mathematical calculation that demonstrated the nuclear shell model, work for which she would later be awarded the Nobel Prize in Physics in 1963, shared

with the two researchers, the German J Hans D. Jensen (1907-1973) and the Hungarian Eugene Paul Wigner (1902-1995). Independently of her, these two scientists were working on the same theory, and when she published her results Jensen asked her to agree to work together on it. In fact, he went to the United States to work with her. This work resulted in the joint publication of a book in 1950 entitled Elementary Theory of the Structure of Nuclear Shells. In 1963, the three researchers received the Nobel Prize in Physics, although she and Jensen were awarded "for proposing the nuclear shell model of the atomic nucleus", while Wigner was awarded "for his contribution to the theory of the atomic nucleus and of the elementary particles, especially for the discovery and application of the important principles of symmetry." In her acceptance speech Maria Goeppert-Mayer said: "Winning the award was half as exciting as doing the work." Also, when the Royal Swedish Academy of Sciences announced that she had won the Nobel Prize, a local San Diego newspaper led the news with the words "San Diego Mother Wins Nobel Prize." In 1960, Maria Goeppert-Mayer was appointed to a position as full-time professor of Physics at the University of California, San Diego, and the marriage moved to the neighboring town of La Jolla. Although she suffered a stroke shortly after arriving there, she continued teaching and researching for several years (Morrón, 2014).

Donna Strickland: her biography: The third woman to be awarded the Nobel Prize in Physics is Donna Theo Strickland, born in Guelph, Canada, on May 27, 1959. Not much is known about her early years and early studies. She attended McMaster University from 1977 until 1981 and received the Bachelor of Engineering degree, with Honors in Engineering Physics, having shown during her studies a special interest in laser beams and light pulses. In the fall of 1981, just a few months after graduating, she entered the Ph.D. program in Optics at the University of Rochester. During her first year of study, she was a Fellow of the Institute of Optics. Since that time she has been a Fellow of the Laboratory for Laser Energetics, she was the recipient of a scholarship from the Natural Sciences and Engineering Research Council of Canada from 1981 to 1985 (BBC, 2018). After continuing her research in Rochester, she completed her doctorate in Optics in 1989, in that university. In her thesis, advised by Gérard A. Mourou (French physicist born in Albertville, in 1944), titled "Development of an ultra-bright laser and an application to multi-photon ionization", she represented the development of the pulse amplification technique, which allowed her to create the most intense laser light known up to that time (University of Rochester, undated). During the completion of that thesis, she and her director published a joint article, titled "Understanding amplified optical pulses," which was the seed of all the subsequent research that would allow them to earn the Nobel Prize in Physics. Since then, her career began to shine and she held different positions as a principal researcher, standing out for her contributions in the field of laser technology. Between 1988 and 1991 she was a research associate at the National Research Council of Canada, where she worked with Paul Corkum on research to produce short laser pulses. From 1991 to 1992 she worked in the laser research department of the Lawrence Livermore National Laboratory and in 1992 joined the technical team of the Advanced Technology Center for Opto-Electronic Materials at Princeton University (University of Waterloo, 2012). Particularly, her work, which was derived from her doctoral thesis project, focused on improving the flexibility of the human ocular lens to treat disorders such as presbyopia. The lasers developed by her have different medical applications, in addition to being extremely important in optical research. For example, ultra-short pulse lasers contribute to the manufacture of precise and compact medical devices, such as those used in eye surgeries to make extremely precise incisions. Thanks to her research, Donna Strickland (Figure 3) was admitted as a fellow in the American Optical Society in 2008, of which she became president and vice president in 2011 and 2013, respectively. She was also editor of the journal Optics Letters from 2004 to 2010 (University of Waterloo, 2012). In 2018, Donna Strickland won the highest award of her career, the Nobel Prize in Physics, which she shared with her thesis supervisor, Gérard Mourou, and with the American physicist Arthur Ashkin (1922-2020). The award was given to them "for their revolutionary contributions in the field of laser physics, the use of optical tweezers and their application in biological systems".

Source: (González, 2019)

Figure 3. Donna Strickland in 2017

The New York Times included this news in its pages with the following title: "For just the third time in 117 years, a woman wins the Noble Prize" and the subtitle: "Prof. Donna Strickland won the Nobel Prize in Physics for her work with lasers. "She is the first woman to receive the award in 55 years and the third woman to receive it in over acentury" (Fortin, 2018). More details about the obtaining of this prize can be found in an interview with her in December 2018, on the occasion of the awarding of the Prize, which can be seen in (The Nobel Prize, 2018). Other awards and distinctions that she has obtained throughout her brilliant scientific career are the following (OSA, undated)

- 1998: Alfred P. Sloan Research Award
- 1999: Premier's Research Excellence Award
- 2000: Cottrell Scholars Award from the Research Corporation
- 2008: Member of the American Optical Society8
- 2020: CSIC Gold Medal

Currently, Donna Strickland is an associate professor at the University of Waterloo since 1997, where she leads an ultrafast laser research group, whose main objective is to develop laser systems for research in the field of optics. Her most recent work focuses on developing new applications for ultrafast optical science at new wavelength ranges, such as the mid-infrared and ultraviolet. She is also working on the role of high-powered lasers in treating medical eye conditions, such as presbyopia. As already indicated, she is a member of the American Optical Society and also of the Royal Society of Canada (since 2019), of the National Academy of Sciences of the United States (since 2020), of the Royal Society of London (since 2020) and even from the Pontifical Academy of Sciences (since 2021). In fact, and with respect to the latter, it was Pope Francis who named her as such in August 2021, in recognition of her work (Boo, 2021).

Andrea M. Ghez:herbiography: Unlike what happened previously regarding the time elapsed between the awarding of the Nobel Prize in Physics to the second and the third woman who obtained it, 55 years, only 2 years separate the third from the fourth, the American Andrea M. Ghez, who achieved it in 2020. Although born in New York on June 16, 1965, Andrea Mia Ghez grew up from a very young age in Chicago, where her family had moved. Her parents had a very different origin, since her father, Gilbert Ghez, of Jewish heritage, was born in Rome, whereas her mother, Susanne, was from an Irish Catholic family from Massachusetts. As a child she wanted to be a dancer, but when she became very interested in The Apollo program Moon landings, she changed her desires and decided to become the

first female astronaut in history. Her mother supported her without reservation, to the point of buying her a telescope. At the University of Chicago Lab. School, she initially tried to specialize in mathematics, but later switched to physics, although she came to take her chemistry teacher as a model (Lee, 2020). Andrea Ghez received a BS in physics from the Massachusetts Institute of Technology in 1987. At that time, she was a member of the fraternity of St. Anthony Hall. Later, in 1992, she received a PhD under the guidance of Gerry Neugebauer at the California Institute of Technology in 1992.Her thesis was titled; "The Multiplicity of T Tauri Stars in the Star Forming Regions Taurus-Auriga and Ophiucus-Scorpius: A 2.2 µm Speckle Imaging Survey."In it, she detected the remarkably stormy conditions in a hot plasma that was pulled toward the black hole that resides at the center of the Milky Way, 26,000 light-years away.This detection of hot plasma is the first at an infrared wavelength, where most of the energy from the disturbed plasma is emitted, and was made using the Keck II.6 Telescope

In addition to being elected to the National Academy of Sciences in 2004, and to the American Academy of Arts and Sciences, Andrea Ghez has received many awards and honors throughout her academic career. Among them, the following can be mentioned: the Gold Shield Alumnae of UCLA, the Amelia Earhart Award, the Maria Goeppert-Mayer Award,the Annie J. Cannon Award, the Packard Award, the Newton Lacy Pierce Award,the Sackler Prize, the Gold Shield for Academic Excellence,the Crafoord Prize and the Bakerian Reading Medal And apart from these mentions, in 2004, Discover magazine included her in the list of the twenty most significant scientists in the United States. She has also collaborated on a notable list of media outlets and documentaries produced by The Learning Channel, BBC and The History Channel. In 2006 she appeared in the American popular science series Nova. As a result of her research, Andrea Ghez (Figure 4) received the Nobel Prize in Physics in October 2020 "for the discovery of a supermassive compact object in the center of the galaxy".

Figure 4. Andrea Ghez. Source: (Web Image 4)

She shared that prize with the German astrophysicist Reinhard Genzel Bad, born in 1952, who was awarded "for the discovery of a compact supermassive object in the center of our galaxy" and with the British mathematical physicist and professor emeritus of Mathematics at the University of Oxford Roger Penrose, born in 1931, who received it "for the discovery that the formation of black holes is a robust prediction of the general theory of relativity. With this, Andrea Ghez became the fourth woman to obtain this award. Andrea Ghez is currently a professor in the Department of Physics and Astronomy at the University of California, Los Angeles, where she continues her research, which involves the use of high spatial resolution imaging techniques to study the regions of star formation and the supermassive black hole at the center of the Milky Way known as Sagittarius A*. These investigations have opened new paths in the study of compact and supermassive objects, and the result of them are the numerous publications she has both in the prestigious scientific journal Nature and in other scientific journals of great impact in astronomy. Y desde el punto de vista personal, ella está muy interesada en ayudar a las mujeres a progresar en el mundo científico. Al respecto, afirma que

Regarding her personal life, she is very interested in helping women advance in the scientific world. In this regard, she states that

> For me, it has always been very important to encourage young women into the sciences, so for me it is an opportunity and a responsibility to encourage the next generation of scientists who are passionate about this type of work.

She is very fond of swimming, a practice she does at the Masters Swimming Club, with the aim of relaxing from the effort her scientific work entails. More information about her can be seen at (Web 1).

AnneL'huillier: herbiography: The fifth and last woman so far awarded the Nobel Prize in Physics is the French physicist Anne Geneviève L'Huillier, currently professor of Atomic Physics at Lund University, in Sweden. There is not much information about her childhood and early studies in the literature. It is known that Anne L'Huillier was born in Paris, on August 16, 1958 (The Nobel Prize in Physics, 2023). With reference to her university studies, Anne L'Huillier obtained a Master of Science in theoretical physics and mathematics, but her doctorate, which she completed at the Commissariat à l'énergieatomique et aux énergies alternatives (CEA), at the Saclay headquarters, in Paris, dealt with experimental physics. Her thesis dealt with multiple ionization in high intensity laser fields. During her time as a postdoctoral student, she carried out research stays at the Chalmers Institute of Technology in Gothenburg, Sweden, and at the University of Southern California in Los Angeles, in the United States. After them, she returned again to the CEA of Paris-Saclay, where she already obtained a permanent position as a researcher since 1986. Regarding he research, she deals with experimental and theoretical aspects of high harmonic generation in gases, corresponding to extremely short light pulses in the ultraviolet spectral range, lasting tens or hundreds of attoseconds (an attosecond is a unit of time in the International System of Units equal to 10−18 of a second). In 1987, she first observed that gases like argon would react to a laser by becoming excited and emitting additional radiation or overtones, at various multiples of the frequency of laser (Wood, 2023).

In 1991, the group formed by Kenneth Schafer, Kenneth Kulanderand herself presented numerical simulations of the time-dependent Schrödinger equation,with the objective of knowing the generation of high-order harmonicsand three years later, MaciejLewenstein, Paul Corkumandand herself already showed a full quantum theory of high harmonic generation (Wood, 2023). In 1992, she participated in an experiment at Lund University, where she is currently working, where one of the first titanium-sapphire solid-state laser systems for femtosecond pulses in Europe had been installed. Two years later, she moved to that university, first as a lecturer in 1995 and later as a professor in 1997. The decade of the 1910s of this century and the years of the 20s have turned out to be very brilliant in terms of the awards and distinctions that, thanks to her research work, she has achieved. Among them, the following can be mentioned: In 2003, she was awarded the Julius Springer Prize. She is a Member of the Swedish Academy of Sciences since 2004. She was part of the Nobel Committee for Physics between 2007 and 2015, and was awarded the French Legion of Honor in 2011. That year, 2011, she received the L'Oréal-UNESCO Prize for Women in Science for her work on the development of an extremely fast photographic camera that can record the movements of electrons in an attosecond. The following year, she was elected Member of the Royal Swedish Academy of Engineering Sciences, and in 2013 she was awarded the Blaise Pascal Decoration of the European Academy of Sciences in physics and the Zeiss Research Award. However, the two most important awards that she has obtained throughout her career have taken place since 2022. That year, apart from receiving the French Legion of Honor, the first of them was the Wolf Prize in Physics, which was awarded in 2022

for "pioneering contributions to ultrafast laser science and attosecond physics", jointly with Hungarian physicist FerencKrausz (born in 1962, who works in attosecond science) and Canadian physicist Paul Corkum (born in 1943, a reputed specialist in the same subject) (Wolf Foundation, 2022). And already, in October 2023, she was awarded her most important award, the Nobel Prize in Physics (Figure 5), jointly with FerencKrausz and Pierre Agostini (born in 1941, a French experimental physicist and currently Emeritus professor at the Ohio State University in the United States), "for experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter" (Davis, 2023).

Source: Wolf Foundation, 2022

Figure 5: Anne L'Huillier

CONCLUSION

It is immediate to deduce from the research carried out that the 5 women cited in this article, Marie Curie, Maria Goeppert-Mayer, Donna Strickland, Andrea M. Ghez and Anne L'Huillier deserve to be considered a reference or model to follow for women who wish to dedicate themselves to science, not only for having been awarded the Nobel Prize in Physics, the highest recognition that a researcher can obtain in the field of this discipline, and for the other numerous awards and distinctions also received throughout their brilliant scientific careers, but also, and above all, for the legacy that they have left to science in the form of their discoveries, which have allowed progress and advancement, in this case of Physics, towards limits totally unsuspected before their contributions. They can also be considered as examples of women who have fought against gender inequalities, not yet completely overcome even in the most developed countries, and managed to overcome all established barriers, which has served to pave the way for other women who want to dedicate their lives to science. Remember, in this regard, one of her responses to an exclusive interview that was recently conducted with her (European Research, 2024)

> I think that my career has been influenced by the fact that I am a woman. As a woman, you are in a field which is predominated by men, and of course, you are more visible. Maybe you get more invitations to conferences, for example, and benefit from programs for women. The only thing I can say is that it has probably been a different career, with both positive and negative aspects.

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Web Image 2: Maria Goeppert-Mayer. https://www.bbc.com/mundo/noticias-56286955)

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