Introduction

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People tend to think that physicists are men. This book will help to bring a more gender-balanced perception of physicists. You will find here detailed descriptions of important, original contributions made by women in the century from 1876 to 1976. Many female physicists and mathematicians, historically excluded from participation in science, emerged in this time. It was a period in which there was great progress in science and in the liberation of women from centuries of repression. This book documents both aspects of recent history. Many of the contributors are distinguished scientists who have been actively engaged in the areas of physics about which they write. They describe with remarkable clarity and readability modern developments in fields as diverse as astrophysics, biomolecular structure, chaos theory, geophysics, nuclear physics, particle physics and surface physics. Each chapter provides detailed accounts of important discoveries made by a particular woman, places them in their historical context, gives references to the original papers for further reading, and suggestions, and provides a scientific biography. The discoveries are well established and fundamental to modern physics. It is not well known, however, that they were made by women.

There are only a few women in the history of physics in past centuries. They are upper-class women such as Emilie du Châtelet (1706–49), Laura Bassi (1711–78) and Mary Somerville (1780–1872), women who had a passion for physics and could study it. But, generally, most women in those centuries past had no opportunity to do this. With the proliferation of printing presses in the mid nineteenth century, and the opening of universities to women, this changed, and women took up the study of physics and mathematics.[1] Some were endowed with extraordinary talent and ability. This book is about forty such women. Some people have said that the examples of these women are daunting to the young who may be thinking of going into science. On the contrary, I have found them inspiring. For a number of years I taught a course at UCLA entitled "Women in Physics and Mathematics," which drew young men and women interested in science. The course was about the women who are the subjects of essays in this book. It was clear to us all that their intellects were far beyond those of ordinary people, but we didn't compare ourselves with them, rather their lives and accomplishments inspired us.

The essays here are generally presented in three sections; the first, and usually the longest, is a detailed exposition of major discoveries and their significance; the second is a brief biography focusing mainly on the subject's life in science; the third gives biographical details and references to original papers and suggested further reading. The authors were commissioned to write short essays of only about 3000 words. The chapters, therefore, are brief accounts of the work and lives of these women. They give references to longer appreciations, and biographies, where they exist. For example, several of the women, now deceased, were Fellows of the Royal Society (London) and Biographical Memoirs have been published in the RS yearly collection.

The women lived very full and diverse lives. Some married and had children and others never did. In the early days, it was far more difficult than it is now to reconcile a normal family life with a scientific career. For example, in 1906 the Dean of Barnard College of Columbia University obliged Harriet Brooks (Chapter 6) to resign her job teaching physics when she revealed that she planned to marry. The Dean said, "The College cannot afford to have women on the staff to whom the college work is secondary; the College is not willing to stamp with approval a woman to whom self-elected home duties can be secondary." And Harriet Brooks said, "I think it is a duty I owe to my profession and to my sex to show that a woman has a right to the practice of her profession and cannot be condemned to abandon it merely because she marries."[2] Some of the earliest physicists such as Marie Curie (Chapter 4) and Hertha Ayrton (Chapter 1) had both marriage and a scientific career, though Ayrton was refused election to The Royal Society (London) on grounds that she was a married woman.

These women emerged as scientists in a historical period in which opportunities for women to study and work were opening up in Europe and America. All were encumbered with serious gender discrimination in one form or another, which generally hindered their ability to get on with their work. This aspect of their lives is only briefly mentioned in essays here or left out altogether. This is mainly due to limitations of space. The authors' focus was on scientific achievement, rather than on barriers the women had to overcome to do their work. To compensate for this, at least in part, in this introduction I would like to augment chapters of this book with some examples of the egregious gender discrimination that are, or should be, part of the historical record.

Many of the women in this book worked unpaid or in poorly paid positions. An outstanding example of an unpaid worker who made important discoveries is Marietta Blau (Chapter 10). She worked from 1923 to 1938 in the Institut für Radiumforschung in the University of Vienna. She had a place to work in the lab and some support for equipment, but no salary. As a Jew and a woman, her applications for paid positions were rejected. In his classic *Atomic Physics* text Max Born wrote, "A great advance was made by two Viennese ladies, Misses Blau and Wambacher, who discovered a photographic method of recording tracks of particles."[3] He explained that "the grains of a photographic emulsion are sensitive not only to light but also to fast particles; if a plate exposed to a beam of particles is developed and fixed the tracks are seen under the microscope as chains of black spots. Their quality depends very much on the size of the grains, and special emulsions with very small and dense grains have been developed." Much more about this and its significance for nuclear, cosmic ray and particle physics is given in Leopold Halpern and Maurice Shapiro's essay. Blau fled Nazi persecution when Germany occupied Austria in 1938. Shortly thereafter her methods were adopted by C. F. Powell in Bristol. (See endnote 2.) He subsequently improved them and won the

1950 Nobel Prize in Physics "for his development of the photographic method of studying nuclear processes and his discoveries regarding mesons made with this method." He is justly famous for his contributions, but adequate credit to Blau for her pioneering work is lacking. She was known and highly respected in Europe before World War II but, as Leopold Halpern and Maurice Shapiro recount in their chapter, did not receive appropriate recognition and employment after the war.

Another remarkable experimentalist is Agnes Pockels. Her early work was unpaid and, as Gary Williams explains in Chapter 3, laid the foundation for modern quantitative studies of liquid surfaces and films. She learned physics from her brother's texts, but was herself denied a university education. Apparently, her family felt it would be inappropriate for her to attend the university with her brother. For some twenty years, she pursued an experimental program in her kitchen with apparatus she devised and built herself. When she read that Lord Rayleigh was doing some of the same experiments, she wrote him a letter describing her work and her results. He published her letter in the March 12, 1891 issue of *Nature*, introducing it with the following comments: "I shall be obliged if you can find space for the accompanying translation of an interesting letter which I have received from a German lady, who with very homely appliances has arrived at valuable results respecting the behaviour of contaminated water surfaces. The earlier part of Miss Pockels' letter covers nearly the same ground as some of my own recent work, and in the main harmonizes with it. The later sections seem to me very suggestive, raising, if they do not fully answer, many important questions. I hope soon to find opportunity for repeating some of Miss Pockels' experiments." As Gary Williams writes, her work laid foundations for the work of Irving Langmuir, who was awarded a Nobel Prize in 1932 "for his discoveries and investigations in surface chemistry." It also underlies the important results on surface films achieved by his co-worker Katharine Blodgett (Chapter 13).

Although the discoveries described in these chapters underlie many well-established and fundamental elements of modern physics, most of the women are not well known. One reason for this is that references to their publications in scientific journals are not cited as frequently as one might expect. This is due to operation of the Matthew Principle, named by the sociologist R. K. Merton.[4] He found that highly acclaimed scientists' papers are by far the most frequently cited in scientific journals. Historically, females were not highly acclaimed and often remain unmentioned. One outstanding example of the Matthew Principle are references in the literature to the discovery of the period-luminosity relation of Cepheid variable stars. As is explained by Jean Turner in Chapter 5, this discovery enabled the first measurements of intergalactic distances. It was made by Henrietta Leavitt. Her discovery is reported in the *Harvard College Observatory Circular*, March 3, 1912. However, the report was published under the name of Edward C. Pickering, Director of the Harvard College Observatory.[5] The first sentence of the circular reads, "The following statement regarding the periods of 25 variable stars in the Small Magellanic Cloud has been prepared by Miss Leavitt." The remaining content is Leavitt's extensive, detailed presentation of her data and analysis. For decades, and probably even now, references to the discovery cite Pickering.

Several other very important discoveries are described here: for example nuclear fission (Lise Meitner, Chapter 7), the solid inner core of the earth (Inge Lehmann, Chapter 9) and the spatial structure of biomolecules (Dorothy Hodgkin, Chapter 22). Historically, the discovery of nuclear fission may be of prime importance. Often only Nobel laureate Otto Hahn is credited with this discovery. The relatively infrequent reference to Lise Meitner in this connection is another example of the Matthew Principle. As Ruth Sime writes in Chapter 7, this discovery was made by Hahn, Fritz Strassmann and Meitner. The work was begun and carried out in Meitner's laboratory in Berlin. Meitner, a Jewish woman, had had to flee Nazi persecution in 1938.[6] The discovery was announced by Hahn and Strassmann in 1939.[7] It is now generally acknowledged that physicist Meitner played a crucial role, and many contend that it was a mistake for the Nobel Committee to award the Prize to Hahn rather than to Hahn, Meitner and Strassmann.

Inge Lehmann's discovery of the hard inner core of the earth was certainly important. Before Lehmann announced her discovery, people believed there was simply the molten iron/nickel core. In 1935, well before high-speed computers were available, Lehmann analyzed observational data on seismic waves generated by deep focus earthquakes, and found that there was a hard inner core. Bruce Bolt gives a very clear account of this in Chapter 9. Lehmann published this discovery in a paper that may have the shortest title of any in scientific literature.[8] She was Denmark's only seismologist for 20 years. In modern times most discoveries in physics are made collaboratively. However, historically, an unusually large fraction of female physicists worked alone. Many had been obliged to do so as a result of various forms of gender discrimination. Furthermore, funding for assistants, students and/or young colleagues was difficult, if not impossible, to obtain. Lehmann's nephew Niels Groes remembers, "It was not easy for a woman to make her way into the mathematical and scientific establishment in the first half of the twentieth century. As she said, 'You should know how many incompetent men I had to compete with – in vain.'" (See endnote 2.)

One sees from the essays in this book that, as soon as the restrictions barring women from studying and working in institutions of higher learning began to be breached, female scientists of the highest caliber appear. An outstanding example is one of the greatest mathematicians of the twentieth century, Emmy Noether (Chapter 8). She is universally credited with the development of modern abstract algebra. She was one of the first two women admitted as students to the University of Erlangen. They enrolled in 1904. Margaret Maltby (Chapter 2) was the first woman to receive a doctorate in physics from the University of Göttingen, awarded in 1895. No doubt she was a good physicist, but she had to abandon research for teaching. In those days, paid positions for a female physicist to do research were, as far as I know, non-existent. Maltby took a job teaching physics in Barnard

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More information

College, Columbia University's adjunct college for women. She had a long and distinguished career as a teacher and mentor to many young women. The fact that so many gifted and talented female scientists emerged in the early days indicates that many more were there also studying and wishing to pursue scientific careers. Opportunities to do so, however, were few and far between.[9]

Marie Curie (Chapter 4) is perhaps the most famous woman in the book. Her fame is in part due to the widespread publicity she encouraged in the interest of obtaining funding for her laboratory.[10] The success of this effort, particularly in the United States, enabled her to bring into her lab and support many male and female physicists. However, it seems to me that her fame today tends to be misplaced, because it rests more on the fact that she was a female physicist rather than on her brilliant insights and amazing experimental achievements. She was a very gifted physicist, as is apparent from her early studies of radioactivity which she initiated for her doctoral research. From these, she obtained and published important confirmation of the then still controversial idea that atoms are fundamental constituents of matter. Shortly thereafter her husband, Pierre, left his lab to join her in further studies. Together they laid the foundations of nuclear physics, as Abraham Pais beautifully describes in Chapter 4. People, in my view inaccurately, often describe her role in this collaboration as secondary. Her husband insisted this was not the case, refusing to accept the Nobel Prize the committee wished to bestow on him and Henri Becquerel if she were not also a recipient. Pierre died suddenly in 1906, only eight years after their collaboration began. Grief stricken, she spoke for years afterward of the importance of Pierre in her work. For example, on the occasion of her second Nobel Prize,[11] she says many of the discoveries for which she was given the award were made "by Pierre Curie in collaboration with me . . . The chemical work aimed at isolating radium in the state of the pure salt . . . was carried out by me, but it is intimately connected with our common work . . . I thus feel that . . . the award of this high distinction to me is motivated by this common work and thus pays homage to the memory of Pierre Curie." Many who knew her had the highest regard for her scientific acumen and ability. Indeed Rudolf E. Peierls[12] tells of meeting her at the 1933 Solvay Conference: "The subject was the atomic nucleus . . . I was very impressed with her poise and command of physics. She was then 66 years old yet she was absolutely up to date on all technical details, and often corrected her daughter Irène and her son-in-law Frédéric Joliot on points of fact." Irène and Frédéric Joliot-Curie were also Nobel laureates.[13] Aside from Marie and Irène Curie, three more of the women in this book are Nobel laureates – Maria Goeppert Mayer (Chapter 18), Dorothy Crowfoot Hodgkin (Chapter 22) and Rosalyn Yalow (Chapter 27). And there are several more women whose scientific achievements, it is thought, should also have been so honored. Some of them are Lise Meitner (Chapter 7), Marietta Blau (Chapter 10) and Chien-Shiung Wu (Chapter 24).

It has been my good fortune to have been able to work closely with some of the women in this book. When I was a graduate student in the University of Chicago, Maria Goeppert Mayer was on my Ph.D. committee. Though she was a world-renowned, highly respected theoretical physicist, author of many important papers in the literature, she was unpaid. She had a special appointment as "Volunteer Professor." Her husband, Joe, was Professor of Chemistry, and because of a nepotism rule she was denied a regular faculty appointment. She was finally offered an ordinary, paid professorship only a few years before she was awarded a Nobel Prize for Physics. Later, I met her in San Diego, where she was Professor in the University of California. In a brief conversation about her having worked for so long unpaid, she revealed, "I almost became bitter." Maria Mayer's 1948 discoveries of the magic numbers and nuclear shell model, are regarded by those who know them well as truly astonishing. Knowledgeable people were not surprised that a theoretical physicist with her acumen and insight might have made these discoveries. S. A. Moszkowski, author of Chapter 18, was a Ph.D. student of Mayer. When asked if he thought she was a genius, he said yes. When asked what kind of genius – a distinction the mathematician Mark Kac made between the ordinary kind whose results we might also achieve given enough energy, time and hard work, and the magician whose creative gifts go beyond that – Moszkowski replied she was a magician. She was legendary as one of the stars in the University of Chicago physics faculty.

One of the stars in the constellation of great scientists of our time, and all time, is Dorothy Crowfoot Hodgkin (Chapter 22). Among the great achievements for which she will always be remembered are her discoveries of the structure of penicillin, of the antipernicious anaemia factor, vitamin B_{12}, and of the diabetic hormone insulin. Her work was foundational for modern structural chemistry, molecular biology and genetics. I had the good fortune to work alongside her when I was elected to the Governing Body of Somerville College, Oxford, in 1967 as Official Fellow and Tutor in Physics. Dorothy, as she was universally called by her friends, associates, students and co-workers, was Professorial Fellow and Wolfson Research Professor. She regularly attended Governing Body meetings when she was in Oxford though she was no longer teaching undergraduates. Part of the work of the Governing Body was to elect fellows and tutors, and this necessitated rejections of some applicants. Dorothy never had a negative word to say about anyone. She shared her wisdom, remarkably, without ever denigrating anyone. She had an inner beauty of spirit that seemed to make all in her presence better than they might otherwise be. Anne Sayre described Dorothy very well for those of us who knew her when she wrote that:

> Few were her equal in generosity of spirit, breadth of mind, cultivated humaneness, or gift for giving. She should be remembered not only for a lifetime's succession of brilliantly achieved structures. While those who knew her, experienced her quiet and modest and extremely powerful influence, learned from her more than the positioning of atoms in the three-dimensional molecule, she will be remembered not only with respect, and reverence, and gratitude, but more than anything else, with love.

In Chapter 22, Jenny Glusker describes with clarity the progression of Dorothy's scientific work: her determinations of the three-dimensional structures of biochemically important molecules for which the chemical formula was uncertain or unknown, namely cholesterol, penicillin and vitamin B_{12}. It is a wonderful chapter, close study of which rewards the reader with an understanding of the scientific advances Dorothy achieved. Great respect is also due Dorothy for her courage and selflessness when one realizes that during most of her life she was afflicted with crippling rheumatoid arthritis. Since its onset at age twenty-eight, she must have suffered severe pain. However, those of us who knew her were unaware of this. Though the crippling effect of the arthritis was apparent, one's awareness of it was quickly overcome by the beauty of her spirit and intellect. The great British sculptor, Henry Moore, was asked to draw a portrait of Dorothy, and he chose to make the drawing of her hands, shown here.

FIGURE 1 A portrait of Dorothy Crowfoot Hodgkin's hands, by Henry Moore. From the Art Gallery of Ontario.

Among the many awards Dorothy Crowfoot Hodgkin received was a Nobel Prize "for her determinations . . . of the structures of important biological substances." She was the third woman to receive a Nobel Prize after Marie Curie who received two in 1903 and 1911,