Introduction

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The year 2025 marks the centennial of quantum mechanics, a theory that has revolutionized scientific thinking about matter, energy, causality, and information. That theory continues to amaze researchers and the general public not only because of its internal intricacies, such as entanglement and superposition, but also because of the phenomena it has helped reveal, such as the quantum Hall effect and Bose–Einstein condensation, and not least because of the technologies it has brought forward, from transistors and lasers to the putative building blocks for future quantum computers. These advances underlie the rationale for making the 2025 centennial the International Year of Quantum Science and Technologies (IYQ, 2025).

Over a Century of Quantum Physics

Although the birth of quantum mechanics is generally acknowledged as a major turning point in the development of modern physics, it is of course part of a larger story. Quantum mechanics – like any other theory – did not simply fall from the sky in 1925. It had taken roughly a quarter of a century of instrumental, experimental, and theoretical work seeking to understand phenomena at the smallest accessible scales to shape the ideas that, starting in 1925, were cast in coherent – albeit difficult to interpret – mathematical formulas. The quantum-mechanical formalism, in turn,

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proved to be a powerful theoretical basis for the growth of diverse and fruitful theoretical, experimental, and applied research programs.[1]

Interestingly, quantum mechanics is distinct from some of the other well-known and revolutionary theories in physics, such as Isaac Newton's mechanics and Albert Einstein's theory of relativity. These theories were mainly the result of strenuous efforts by single individuals, whose names remain attached to their work. By contrast, the formulation of quantum mechanics was a collective endeavor right from its beginning. It resulted not only from the development of theoretical physics as a professional specialization at the beginning of the twentieth century and the ongoing conversation between experimentalists and theorists, but also from the interplay between theoretical physicists from different schools. Such exchanges were facilitated by the emergence of centers of theoretical physics in various European countries in the early twentieth century. In the aftermath of World War I, interactions between these centers could and indeed did grow markedly (Seth, 2013; Schirrmacher, 2019; Kojevnikov, 2020).

Conventional and popular narratives of the quantum revolution tend to highlight a sequence of theoretical (and sometimes experimental) breakthroughs, each linked to one or two of the big names of physics history. In a typical version, the buildup begins in 1900 with Max Planck's proposal to mathematically quantize the energy to derive an empirically accurate formula for the entropy of thermal radiation. It is furthered in 1905 by Einstein's interpretation of the "light quanta" as physical entities (though this proposal would not be widely accepted for nearly two decades) and by his 1907 application of energy quantization to the specific heats of solids. The quantum hypothesis then gains additional buoyancy in 1913, when Niels Bohr successfully applies it to a solar-system model of the hydrogen atom. In the following decade, Arnold Sommerfeld, Bohr, and others extend and refine the quantum model of the atom. These studies raise a wealth of new questions about the behavior of electrons in heavier atoms, as well as questions about the interaction between such electrons and external electric and magnetic fields, and the underlying role of quantization. As theorists and experimentalists address the newest scientific questions, they pave the way toward the mathematically sophisticated and radical theory of quantum mechanics, which is successfully formulated in 1925–1926 by Werner Heisenberg, Max Born, Pascual Jordan, Paul Dirac, and (by a different route that passes through Louis de Broglie's ideas about matter waves) Erwin Schrödinger.

[1] It is impossible to do justice to the vast and multifaceted literature on the history of the quantum revolution. Among relevant and relatively recent works, we note Beller (1999), Darrigol (2002), Carson et al. (2011), Katzir et al. (2017), Schirrmacher (2019), Kojevnikov (2020), Duncan and Janssen (2019, 2023), and Freire (2022). A more general volume that places the development of quantum physics in the broader context of twentieth-century physics is Kragh (1999). A work that integrates quantum physics in an even broader perspective on the history of science in the twentieth century and beyond is Agar (2012). Other important works explore different facets and spotlight specific historical actors, events, and sites; they are too numerous to mention here. Helpful reviews of the historiography include Staley (2013), Badino (2016), and Joas and Hartz (2019).

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By as early as 1968, however, science historian John Heilbron pointed out the nexus between social and scientific developments, writing, "The development of quantum physics was intimately linked to that of other branches of physical science, particularly statistical mechanics, the study of radioactivity, spectral analysis, and the theory of atomic structure. So, of course, it was connected somehow with the general cultural and social milieu in which it grew" (Heilbron, 1968, p. 90). Historians of physics have heeded the call. Since the 1970s, employing a rich methodological toolbox, historians have moved beyond the conventional story line by exploring the diversity of research streams, local contexts, and cultural, social, and institutional factors that fed into the canonical set of milestones and branched out from them. Nevertheless, as the philosopher and historian of science Massimiliano Badino noted, "Where HQP [history of quantum physics] lags shamefully behind other kinds of histories – and philosophy of science as well – is in the incorporation of geographical and gender perspectives. There has been a reassuring increase of studies on quantum physics in European and World peripheries, … but much work still needs to be done. Analogously, the narratives remain as male-dominated as the discipline as a whole" (Badino, 2016, p. 334).[2]

By pointing to the persistent underrepresentation of women in the field of physics, Badino rightly underscores that gendered narratives and gender participation in the discipline go hand in hand. Especially at the higher rungs of the career ladder and in gate-keeping positions, women are still severely underrepresented. At the top levels of professional recognition, imbalances are stark: of 226 Nobel laureates in physics, only five are women, and three of them – Donna Strickland, Andrea Ghez, and Anne L'Huillier – were awarded the prize only in the last seven years. Progress has unquestionably been made, but disparities persist despite several decades of studies, evidence-based recommendations, and equity-oriented policies.[3] The persistent gender gap is a complex issue, attributable to subtle dynamics of institutional, social, cultural, and individual factors. Current analyses, however, widely agree that deep-seated Western stereotypes attributing a masculine character to the hard sciences and associating a masculine identity with scientists play a large role in producing biases, professional segregation, and unfavorable conditions for the recruitment and

[2] A gender perspective should include all genders and not be limited to a focus on women. Focusing on women's contributions to science, however, does oftentimes bring up a broader consideration of gender. In this sense, the substantial subset of the literature on women in science that is dedicated to women in physics in the twentieth century, including biographies, biographical dictionaries, prosopographies, and gender analyses of research cultures, does offer a gender perspective on the field. An English-language sample of works specifically relevant to the history of women in quantum physics includes Kevles (1977, pp. 202–207), Traweek (1988), Schiebinger (1999), Rossiter (2002), Byers and Williams (2006), Götschel (2011), Rentetzi (2007), and Howes and Herzenberg (1999, 2015).

[3] The landscape of gender representation in science, technology, engineering, and mathematics (STEM) is complex and ever changing. There are significant regional and national differences, as well as differences between STEM disciplines and sub-disciplines, and between groups of different class, race, and ethnicity. In Western Europe, UK, US, Canada, and Australia, physics shares the problem of obdurate gender imbalances with other "hard" sciences, such as mathematics, engineering, computer science and technology, and (in a lesser measure) chemistry. Theoretical physics is one of the most male-dominated sub-specializations (Porter and Ivie, 2019; Nature Reviews, 2019; STEP UP, 2020; Roy et al., 2020; Schneegans et al., 2021).

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retention of women in these disciplines; see, for example, Hill et al. (2010), Sekuła et al. (2018), and Thébaud and Charles (2018). By spotlighting a handful of male "geniuses," conventional narratives of the quantum revolution somehow throw a longer shadow on women than on men. In part this is because the historical lens, polished by tales of heroic genius, at times tacitly reinforces the stubborn stereotypes that portray women as insufficiently interested in or not brilliant enough to excel in the field of physics. New historical narratives that complement the conventional all-male story line, by shining light on women's participation in the enterprise and the structural obstacles they faced, may therefore help to dismantle the tenacious gender stereotypes that stand in the way of diversity, equity, and inclusion.

The scientists who created quantum mechanics famously formed a youthful group. In his book, *The Copenhagen Network: The Birth of Quantum Mechanics from a Postdoctoral Perspective* (2020), Alexei Kojevnikov notes that: "Over 80 authors took part in that brainstorming effort: The majority of them were under 30 years of age and they authored almost 70% of all publications. Some were still working on their dissertations, but more commonly, they were recent PhDs, having obtained their degrees after 1920, and would have been considered postdoctoral students by today's standards" (Kojevnikov, 2020, p. 3). The young age of several of the most prominent contributors to quantum mechanics prompted bittersweet jokes at the time, and quantum mechanics itself was sometimes colloquially referred to as *Knabenphysik*, or "boys' physics" (Weyl, 1946, p. 216).[4] In the public imagination, therefore, the genesis of quantum mechanics is tied to the idea of a special innate ability, the "raw talent" of a select group of young men, who were united not only by many personal and social characteristics but also bound together and to their mentors (such as Bohr and Born) by homosocial relationships (or, more colloquially, a "boys' club" or a "boys' network"): collaboration, competition, friendship, and mentorship. Although quantum mechanics was not the creation of a solitary hero of science, the rhetoric of virile heroism is not absent from its narrative. The evocation of *Knabenphysik* reconciles two images that may otherwise seem mutually exclusive: that of the rebellious and creative "solitary genius," which dominated older narratives, and that of science as a collective enterprise. According to the *Knabenphysik* trope, quantum mechanics was created by an all-male team of scientific heroes.[5] Certainly, the *Knabenphysik* characterization did

[4] Paul Ehrenfest, one of the mentors to the generation of theoretical physicists that came of age around 1925, felt overwhelmed by the storm of publications that heralded the new theory. In a letter to his brother Arthur, he wrote that he felt like an asthmatic dachshund chasing a tram full of young physicists (Ehrenfest to Arthur Ehrenfest, August 28, 1928; cited in Van der Heijden (2021, p. 290)).

[5] Kojevnikov attributes the subversive creativity of the quantum mechanics pioneers not (or not only) to their raw talent but to the dynamics of junior status in the academic hierarchies of the time, their professional insecurity, and their mobility in the historical context of the interwar period in Europe (Kojevnikov, 2020). The heroic overtones of the *Knabenphysik* trope still resonate in the genre of historical science popularizations, as illustrated by two recent bestsellers, Segrè (2007) and Rovelli (2022).

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not intend to refer to the gender of the protagonists, only to their age and independent spirit. *Knabenphysik*'s gender connotation has long gone unnoticed and unquestioned due to the prevailing stereotype that physicists would be men and scientific genius a masculine attribute.

Women in the History of Quantum Physics

The Women in the History of Quantum Physics (WiHQP) working group first convened in early 2021 in direct response to the challenge of broadening the gender perspective on the field. This international and interdisciplinary team of physicists, historians, philosophers, and writers, including renowned academics and early-career researchers, seeks to deconstruct the myth that women somehow lacked enthusiasm, talent, or character to participate in quantum developments. Our working group does so here by shedding light on the contributions of 16 women scientists. Through this new lens on quantum developments, we aim to reach beyond *Knabenphysik* and to add a new dimension to the prevailing narrative that suggests quantum physics resulted from the efforts of small group of brilliant men. Our working group seeks to ensure that women are discussed as part of the rich history of quantum physics, throughout the IYQ and beyond.

For this volume, the WiHQP working group has opted *not* to focus on the more well-known heroines of physics, Marie Skłodowska Curie, Lise Meitner, and Maria Goeppert Mayer. (For their stories, we refer interested readers to existing scholarship, including, e.g., Boudia (2001), Emling (2012), Goldsmith (2011), Sime (1996b), Wuensch (2013), and Masters (2017).) They have by now become legendary figures. But by perpetuating a mythology of uniqueness, these women also seem to have become inimitable by definition, as historian of gender Julie Des Jardins pointed out in *The Madame Curie Complex: The Hidden History of Women in Science* (Des Jardins, 2010). Moreover, their high visibility may – inadvertently – reinforce the common idea that fewer than a handful exceptional women made rare contributions to one of the most fruitful intellectual revolutions of the twentieth century. As a counterweight, our anthology purposefully highlights scientists who are less well known or have hitherto remained in the shadows. Far more women have contributed to the progress of quantum physics than just the celebrities. Shifting the focus to them rebalances the emphasis on the exceptional and helps to "show us more about everyday science and the opportunities open and closed to most women," as historian Margaret Rossiter points out (Rossiter, 2002, p. 59).[6] And as historian of science Ruth Lewin Sime mentions, in so doing, it further contributes "to an expanded, more

[6] See also Rossiter's trilogy, *Women Scientists in America* (Rossiter, 1982, 1995, 2012).

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nuanced understanding of social institutions, scientific practice, the personal lives of scientists, and science itself" (Sime, 1996a).

The WiHQP working group has also elected to use a broad definition of quantum physics, including the old quantum theory and the experiments that supported it, the birth of quantum mechanics and the philosophical enigmas associated with it, as well as quantum field theory and nuclear and particle physics, reaching beyond the traditional emphasis on leading centers of physics in Europe and the US. The table of contents of the resulting anthology is ordered chronologically in terms of key contributions to quantum science, starting with Williamina Fleming's (Chapter 1) discovery of spectroscopic lines that would prove crucial for validating Bohr's model, and ending with the present day, highlighting the activism for international scientific cooperation and the IYQ proposal by Mexican physicist Ana María Cetto (Chapter 16). The 16 narratives not only highlight women's contributions to quantum developments, but also illustrate how individual women scientists struggled with social conventions, scientific culture, and the – often unconscious or internalized – prejudices they confronted. Taken together, the chapters suggest several overarching mechanisms and possible explanations for why so many women scientists fell into obscurity. We offer these observations with the caveat that our contributors are not specifically trained as gender theory or women's studies scholars. This volume should nevertheless contribute to a broad and interdisciplinary conversation on the theme of inclusion.

We are acutely aware that our book does not present the full breadth of women's contributions to quantum physics. A much larger group of women scientists still remains hidden in the shadows. Too often, the missing voices are those of women of color, and women from countries and regions that are often lumped together under the umbrellas of "the peripheries" and "the global south." In some cases, despite intense and lengthy recruitment efforts, we could not secure authors for scientists we hoped to include; in other cases, the scarcity of historical sources – a problem that especially plagues the archival collections pertaining to women and to people of color – proved discouraging to potential authors before they had a chance to begin.[7] We find the missing voices deeply troubling, not only because the absence of stories and images of scientists from diverse genders and backgrounds erases their historical contributions, but also because their invisibility has a particularly negative impact on women and other underrepresented groups in the present day. We hope that this volume will not perpetuate long-standing omissions, but instead will stimulate and inspire further scholarship with an increasingly wide lens.

[7] We hesitate to include names for women scientists we were unable to feature, as mentioning some implies omitting many others. Willie Hobbes Moore, Purnima Sinha, Bibha Chowdhuri, and Shirley Ann Jackson are but a few examples.

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Emerging Themes

The chapters of this book encompass a diversity of time periods, contexts, and individual experiences. Each of them provides a detailed description and analysis of a scientist's unique trajectory in its specific context, to be appreciated in all its complexity and depth. In addition, we see several themes related to women's experiences in science emerging across the chronological timeline of the chapters. They notably include: isolation and invisibility; preconceptions about raw talent and the culture of competition; interrupted careers; hidden labor in science; intersectionality; and the role of collaborative couples.

Isolation and Invisibility

Women's erasure and omission from historical records may be one of the few constants of history. History of science is no different. In 1897, the French mathematician Alphonse Rebière published a volume about 650(!) women in the sciences who had previously been overlooked (Rebière, 1897). He was neither the first nor the last to do so (Boucard, 2020). Fifty years after Rebière, a US Department of Labor report titled *The Outlook for Women in Physics and Astronomy* bemoaned the "paucity of published information on women in science" despite the authors having consulted "more than 800 books, articles and pamphlets" (Zapoleon et al., 1948, p. 6-III). The Sources for History of Quantum Physics project, conducted before the emergence of the field of studies on gender and science, was no exception (Chapter 16). The general dearth of records about women remains a genuine obstacle, as several leading archives and archivists publicly acknowledge (Zanish-Belcher and Voss, 2017).

Women's erasure – documentary or otherwise – is difficult to remedy. The tendency to shape scientific discoveries into heroic tales has perhaps compounded the problem. As historian of science Naomi Oreskes points out, "Emphasizing activities that might be considered irresponsible if undertaken by a woman, the heroic ideology relegates women's work to the realm of the inconsequential. The marginalization of women in science is a predictable consequence of heroic rhetoric . . ." (Oreskes, 1996, p. 111). But it would be an oversimplification, as Oreskes also notes, to conclude that women have remained largely invisible in the historiography and popular narratives of quantum physics, exclusively *because* so few were able to attain the rank of "heroines of science." Instead, it is worth asking what results from "heroic ideology" with its concomitant impulse to neglect collaboration and collective effort.

Another crucial question is why women scientists have less frequently been found in the highest ranks of academia. Here, too, it helps to shift our gaze from the

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individual to the broader structure of the institution. Too often, a scientist found herself the sole woman in a laboratory or lecture room and was not readily admitted to the old (or young) boys' networks. For instance, Jo van Leeuwen (Chapter 2) was always a bit of an outsider among the young theoretical physicists in Leiden. Her supervisor, Hendrik Antoon Lorentz, had retired from the university and lived out of town. His successor, Paul Ehrenfest, gathered a circle of promising students, but Van Leeuwen was not truly part of this close-knit group, who would visit Ehrenfest at home, attend colloquia in the study of Ehrenfest's large house, and help Tatiana Ehrenfest-Afanassjewa in the garden. Moreover, although Van Leeuwen had been part of a small wave of women who enrolled in Leiden University to study physics, she went on to become the only woman in her department when she landed a position at Delft Technical University. She would remain in that solitary situation for the rest of her career.

The solitary and subordinate position of women scientists often had the effect of making them dependent on goodwill from select mentors who dared to break with conventions that otherwise interfered with women's full participation. Too often, such goodwill and support were partial and incomplete. When Jane Dewey (Chapter 5), for example, carried out an experiment on the Stark effect in helium while on a fellowship at Bohr's institute in 1926, Bohr prioritized the publication of the parallel experimental results of another visitor, J. Stuart Foster, with whom he had a relation of friendship and informal mentorship. At Princeton, where Dewey later landed as the first female postdoc thanks to the support of William Francis Magie, she was nicknamed "Magie's Folly" by colleagues who saw no room for women in physics (see also Kevles (1977), p. 207). Foster, in the meantime, befriended and collaborated with Heisenberg, who later would effusively recall Foster's work on the Stark effect in his written and oral memoirs about the birth of quantum mechanics. Heisenberg completely ignored Dewey's parallel work, a further illustration of how isolation (from the boys' networks) and invisibility (through blind spots of bias and prejudice) can combine to push women toward the margins. Even Foster's PhD student, Laura Chalk (Chapter 6), who actually produced the initial data validating the first new prediction of quantum mechanics while measuring the Stark effect in hydrogen, was left out of Heisenberg's narrative.

Whereas Heisenberg and Foster, as well as many other male scientists, celebrated one another's work with reciprocal gestures that were a steady element of their social and professional networks, Chalk, Dewey, and Van Leeuwen were kept out of these networks by gender norms, and worked in the absence of female colleagues who would propagate and advertise their work. Women scientists persisted in often isolated and dependent positions, rendering it nearly impossible to reach out to one another to obtain career advice from *girls'* networks until much

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later in the twentieth century (Rentetzi and Kohlstedt, 2009). A prime example of someone who has made a distinct commitment to improving networking opportunities for women is the Mexican quantum physicist Ana María Cetto (Chapter 16), who sees scientific collaboration as one of the pillars of international diplomacy. When, in 1989, the Third World Organization for Women in Science (TWOWS, now the Organization for Women in Science for the Developing World, OWSD) was established, Cetto became one of its inaugural vice presidents, making the elimination of gender bias in science one of her priorities.

Throughout history there also have been men who successfully supported women in physics research. Still, the gender-normative exclusion of women from male socio-professional circles had an overpowering dual impact. First, it disadvantaged women in scientific productivity and career advancement. Second, it contributed to *invisibilizing* women in scientific narratives, especially when those narratives were cast under the guise of virile heroism. In the male-dominated world of twentieth-century physics, what biophysicist Ellen Weaver wrote about female scientists who, like her, participated in the Manhattan Project, was especially poignant:

> When I read the personal reminiscences of the men who were pioneers in the nuclear field, I am struck by the importance they attach to their friends and colleagues, and to the intense interaction often present among them, which could lead to important insights in both the theory and practice of science. And I am a little jealous. In general, women did not participate in that exchange of ideas (Weaver, 1999, p. viii).

Raw Talent Preconception and Culture of Competition

A recent psychological analysis highlights that even today, after half a century of equality policies and efforts to eliminate gender gaps in academia, "women are stereotyped to possess less [raw intellectual talent] than men" (Meyer et al., 2015, p. 1). Noting that these stereotypes impact the fields' gatekeepers as well as other participants, Meyer et al. find that the disciplines with the widest and most persistent gender gaps – such as physics and mathematics – are often those in which success is mainly attributed to brilliance and raw talent rather than collaborative, diligent, and persistent work. According to these social scientists, one key mechanism through which this underrepresentation is produced is the existence in such fields of "masculinity-contest cultures," organizational environments in which ruthless competition discourages women's participation. For Vial et al., women express less interest and a lesser sense of belonging in fields of study and professions whose image emphasizes brilliance and competitiveness (Vial et al., 2022).

Lucy Mensing (Chapter 4), a forgotten pioneer of quantum mechanics who obtained her doctorate in 1925 in Hamburg with Wilhelm Lenz and Wolfgang

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Pauli and was a postdoctoral scholar in Göttingen during the key years of the birth of quantum mechanics, may be a prominent example of this effect. In 1928, she indeed left physics ostensibly to marry and start a family, but also likely as a result of the fiercely competitive (and destructive) climate of the physics research environment she had experienced during her subsequent appointment in Tübingen.

A bit more speculatively, one can also wonder if Katharine Way's (Chapter 8) choice of a backstage role as creator and curator of the foundational Nuclear Data Project reflected a desire to remain involved in nuclear physics while keeping clear of the fierce competition in the field. Way's dissertation (with John A. Wheeler, on the instability of a rotating heavy atomic nucleus) and subsequent roles in the construction of the first nuclear reactors for the Manhattan Project could certainly have served as stepping stones for an altogether different, and perhaps more prominent, career in theoretical physics, had she chosen to pursue it.

Cetto (Chapter 16) has critiqued the culture of competition that she encountered as a graduate student at Harvard University. As Mar Rivera Colomer explains in that chapter, Cetto described the setting at Harvard as "characterized by competition and a notable absence of solidarity." In contrast, she found the Mexican scientific field to be "more open, flexible, and accommodating," which she tentatively attributed to it having a "relatively lower maturity level in scientific production."

Interrupted Careers

Gender norms, stereotypes, and biases, and the related social pressure to conform to such norms can help explain some of the interrupted careers of women in twentieth-century physics. As early as 1965, the American sociologist Alice Rossi pondered, "Women in science: why so few?" (Rossi, 1965). Her answer – along with that of many others – focused on the different social roles played by men and women, including the priority that society placed (and often still places) on women committing to marriage and motherhood. These factors certainly have presented barriers to women's full participation in scientific research as well as in academic and professional life, but they are not the only considerations. The concept of the *leaky pipeline* aims to shine light on how structural flaws in workplaces, and in broader society, disproportionately place the burden upon women to balance personal and professional responsibilities, and how those same structural flaws simultaneously blame women for exiting the professional realm. The leaky pipeline metaphor can help point out where fields like physics suffer from a loss of available talent. That metaphor, however, is not without limitations. While it conveys losses from the perspective of the talent pool for scientific research it also raises what are perhaps inappropriate concerns about the balance between educational investments and professional output. In so doing, it risks minimizing valuable contributions to social

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progress that many women have made in other capacities after they leave the scientific pipeline.

Without a doubt, the stories of several women in the present volume illustrate how difficult it was to reconcile a career in physics with the gender normative roles of wife, caregiver, and mother. But many also point out that even in cases where systemic, political, or personal obstacles prompted women to leave quantum physics entirely, it was not uncommon for those same women to subsequently make major contributions in other fields. After the fall of the Nazi regime, Grete Hermann (Chapter 11) left the philosophy of quantum mechanics to pursue political and educational reform in West Germany. When faced with institutional obstacles at Southern Illinois University, Maria Lluïsa Canut (Chapter 15) turned her attention from quantum physics to ethical and societal issues, in her case second-wave feminism in the US. Frieda Friedman Salzman (Chapter 14) would valiantly fight against gender discrimination after anti-nepotism policies deprived her of a secure faculty role at the University of Massachusetts Boston. Elizabeth Monroe Boggs (Chapter 7), who trained as a computational quantum chemist at the University of Cambridge and later worked on the Manhattan Project, left the scientific workforce after giving birth to a child with disabilities, and pivoted to a remarkable life of public advocacy.

Some career interruptions, however, were altogether unavoidable. A particularly dramatic one affected Sonja Ashauer (Chapter 9), the first Brazilian woman to obtain a doctorate in physics. She died of bronchopneumonia at the age of 25, six months after defending her thesis on the nonphysical consequences of the equation for the point electron in quantum theory at the University of Cambridge. She was one of Paul Dirac's few doctoral students, and the only woman he mentored.

Perhaps also for reasons of ill health, Carolyn Parker withdrew suddenly from her PhD program in 1954 and then again 1955. Little more than a decade later, she passed away at the young age of 49. Archival silences, however, make it difficult to determine whether these interruptions in Parker's later career were related to illness or to other hardship.

Hidden Variables

In 1989, the historian of science Steven Shapin described how the experiments of the famous seventeenth-century chemist and natural philosopher Robert Boyle were in fact conducted by the invisible hands of a fleet of (male) operators and assistants. Shapin's paper, "The invisible technician," makes it clear that others designed and built instruments, collected data, and sometimes even drafted the publications, rather than Boyle himself. "The predominant biases in the Western academic world," Shapin wrote, "have traditionally portrayed science as

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a traditional and wholly rational enterprise carried out by reflective individual thinkers." It led him to conclude that: "People who are really present but invisible are those whose roles are considered to be unimportant" (Shapin, 1989, p. 563). This observation is not only true for technicians, but also for lower-rank physicists more generally. Rather than standing on the shoulders of giants, the scientists who have achieved celebrity status often stood on the backs of a great number of "hidden figures," both men and women (Star, 1991; Shapin, 1989, 1994; Bangham et al., 2022; Shetterly, 2016). In this sense, the low-visibility work of many women physicists becomes hard to distinguish from that of the majority of (male) physicists in subordinate positions or behind-the-scenes roles. For women, however, the issue is exacerbated by the larger proportion of them remaining at the lower ranks of professional hierarchies.

Williamina Fleming (Chapter 1) is a salient example of such erasure. She was one of the women *computers* hired on grossly unequal terms compared with men who were employed by the Harvard College Observatory. Later, as the curator of the Astronomical Photographic Glass Plate Collection, she discovered a peculiar pattern of spectroscopic lines. Her discovery, which later played a singular role on the path to quantum mechanics by serving as proving ground for Bohr's model of the atom, nevertheless became known as the "Pickering series" after the observatory director, Edward Charles Pickering.

Similarly, Hertha Sponer (Chapter 3), who ran James Franck's spectroscopy laboratory in Göttingen in the 1910s, designed and executed ground-breaking experimental work that applied quantization rules to molecular spectroscopy, for which Franck received significant credit. During her year-long Rockefeller Fellowship at the University of California, Berkeley, she also worked with prominent American spectrographer Raymond Birge; Sponer taught the group, including Edward Condon, how to apply quantization methods to radiation. She convinced Birge to jump on the quantum physics bandwagon early, and it paved the way for Condon's famous achievement (albeit without Sponer): the Franck–Condon principle. Meanwhile, Sponer's name slipped quietly from public and scientific consciousness.

Way (Chapter 8), as mentioned above, was the leading force behind the Nuclear Data Project, which quickly became an indispensable reference for the experimental, theoretical, engineering, and even biomedical communities as well as an opportunity to establish common standards among them. For Way's backstage work, Wheeler and others nominated her for the 1978 APS Tom W. Bonner Prize in Nuclear Physics. But, despite the strong supporting party, the prize was not awarded to her, neither that year nor later.

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Intersectionality

For Chien-Shiung Wu (Chapter 10) underrepresentation was manifold. She immigrated to the US from China and became one of relatively few women who studied physics *and* who had a successful career in experimental research. Still, she was described as "a decorative addition to any laboratory" and compared to a "lotus" as a young woman. Later, colleagues referred to Wu with derogatory ethnic stereotypes, even at the peak of her career. She conducted groundbreaking experiments that did not receive the recognition they deserved. Despite her pivotal role, Wu was passed over for the 1957 Nobel Prize that celebrated the "penetrating investigation of the so-called parity laws," and many years later, when "experiments with entangled photons" led to the 2022 Nobel Prize, her 1949 experiments in this field also seemed to have been glossed over.

Carolyn Parker's (Chapter 13) life and her physics career took shape in the midst of racial oppression in the Jim Crow South and in the grip of enduring northern US racism. Her story illustrates the intersectional barriers that a young Black woman aspiring to a nontraditional field encountered in the mid-century US. The intricate patchwork of traditional archival and Black counter-archival sources supporting this chapter also shows how scholars of Black history often must contend with silences and gaps in historical records (Hartman, 2008). The work notably reveals how circumstances forced Parker to detour at seemingly every step along the way. Between obtaining her degree in physics from Fisk University in 1938, contributing to applied research for the US military during World War II, and then obtaining a master's degree in physics at MIT in 1953, she also taught mathematics and physics in segregated high schools and in historically Black colleges and universities – detours which were arguably beneficial to the broader Black community, while perhaps also slowing her scientific trajectory.

Collaborative Couples

For women in this volume, participation in research as part of a collaborative scientific couple emerges as a two-sided coin. In the foreword to the anthology *For Better or For Worse? Collaborative Couples in the Sciences*, science historian Sally Gregory Kohlstedt remarked that "Viewed collectively, the results seem to be most consistently 'better,' [for women working in collaborative couples] especially if one of the measures is the science produced" (Lykknes et al., 2012, p. viii).[8] Marital and scientific partnership likely opened doors for women, making research opportunities more readily available than would otherwise have been possible; couplehood facilitated women's collaboration when they worked in partnership

[8] See also Pycior et al. (1996).

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with a supportive spouse. At the same time, anti-nepotism policies often blocked married women who wished to continue their scientific and academic careers.

Being part of a collaborative couple certainly was a double-edged sword for Maria Lluïsa Canut (Chapter 15). She built her career in the hostile environment of Francoist Spain, where gendered societal roles were promoted through segregated boys' and girls' education and curricular differences. In doing so, Canut, from an elite family in Menorca, worked in tandem with her husband and collaborator José Luis Amorós. He initially acted as a supportive mentor because he held higher positions. Eventually, however, he would overshadow her. The same fate befell Cetto (Chapter 16), who then diversified her interests, partly as a strategy to uphold her own scientific identity.

Freda Friedman Salzman (Chapter 14) and George Salzman had always striven to stay together despite the "two-body problem" that often plagues scientific couples looking jointly for a new position. After they both obtained a professorship at the Boston campus of the University of Massachusetts, it was Friedman Salzman, and not her husband, who faced (and fought) the threat of exclusion under anti-nepotism policies – policies that disproportionately impacted university women.

Finally, the narrative of the Portuguese Lídia Salgueiro (Chapter 12) and her partner and collaborator José Francisco Gomes Ferreira illustrates how gendered perceptions of the outside world influence gender roles within the laboratory. The two supported one another when forced to reinvent their research agenda in response to national political pressures. Salguiero was a behind-the-scenes researcher, whose scientific guidance and relevance was core to the group, but in contrast to Gomes Ferreira she seemed almost invisible to the outside world. The couple thus enacted the expected gendered roles of female self-effacement and male visibility, a mechanism that seems even more subtle than the tendency of the outside world to attribute a woman's work to a male colleague, the so-called Matilda effect (Rossiter, 1993).[9]

All things being equal, in these chapters it is thus women's visibility that suffers.

Epilogue

In 1906, when Van Leeuwen began to study physics in Leiden and 10 years after Fleming measured her peculiar pattern of spectroscopic lines, the Indian political activist, poet, and feminist Sarojini Naidu discussed the education of women in a speech to the Indian National Congress. "In the matter of education you cannot

[9] Margaret Rossiter named the effect in 1993 in commemoration of suffragist Matilda Joslyn Gage, who in an 1893 essay protested against the idea that a "woman . . . possesses no inventive or mechanical genius."

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say *thus far and no further*," she said. "Neither can you say to the winds of Heaven 'Blow not where ye list,' nor forbid waves to cross their boundaries, nor yet the human soul to soar beyond the bounds of arbitrary limitations" (Sarojini, 1906).

Yet, obstacles like the ones outlined above would continue to hinder women socially and institutionally throughout the twentieth century, raising questions about how substantial women's influence on quantum developments otherwise might have been. Questions of this type are not new. As early as 1738 French scientist Marquise Émilie du Châtelet wrote (du Châtelet, 1735, par. 24)[10]:

> Were I king, I would like to try this physical experiment. I would redress an abuse which cuts back, as it were, one half of humankind. I would have women participate in all human rights, especially those of the mind.

The result of such an experiment is obviously unknowable. But by shining a bright light on women in the history of quantum physics on the occasion of the IYQ, we hope that this volume contributes toward redressing the field's unbalanced history, and that it can be a sure step toward achieving a more inclusive world of physics, of science, and beyond, within our lifetime.

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[10] "Pour moy j'avoüe que si j'etois roy, je voudrois faire cette experience de physique. Je reformerois un abus qui retranche, pour ainsi dire[,] la moitié du genre humain. Je ferois participer les femmes à tous les droits de l'humanité, et sur tout à ceux de l'esprit."

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