BIOGRAPHICAL MEMOIRS

Myriam P. Sarachik

August 8, 1933–October 7, 2021
Elected to the NAS, 1994

A Biographical Memoir by Greg Boebinger, Jonathan R. Friedman, Laura H. Greene, and Clare C. Yu

Figure 1 Myriam P. Sarachik. Courtesy of *Philip Sarachik*.

The world lost a great physicist, trailblazer, and dear friend to each of us when Myriam Sarachik passed away on October 7, 2021, at the age of eighty-eight. Her personal and scientific journeys were an inspiration to all who knew her. Throughout her remarkable career, she pushed the frontiers of condensed-matter physics while championing equity, integrity, and compassion in our scientific community. Her story includes escaping from Nazi prison camps and personal tragedy but also rising to the highest levels of scientific accomplishments and leadership; her resilience and perseverance remain an inspiration and a lasting example of courage and purpose. Her numerous awards include the 2023 National Medal of Science, the American Physical Society (APS) Medal for Exceptional Achievement, the 2005 APS Buckley Prize, the L'Oreal/UNESCO Prize for Women in Science, and election to the National Academy of Sciences (NAS) in 1994. Her exceptional public service included serving as president of the APS in 2003. Sarachik was also a long-time supporter of the Committee on Human Rights (CHR) of the NAS, National Academy of Engineering (NAE), and National Academy of Medicine (NAM). She advocated tirelessly in support of dozens of scientific colleagues subjected to serious human rights violations around the world—from China to Bahrain to Iran to Turkey. She also established—together with NAS members Vera Rubin and Maxine Singer—a Support Network for Iraqi Women Scientists, Engineers, and Health Professionals that was staffed by the CHR. The project strove to provide collegial support to Iraqi women scientists, engineers, and health professionals by "pairing" them with women members of the NAS, NAE, and NAM in similar fields. Myriam was also a longtime board member of the Committee of Concerned Scientists (CCS) and a member of the New York Academy of Sciences's Committee on Human Rights of Scientists and served as a member of APS's Committee for the International Freedom of Scientists (CIFS).

Born on August 8, 1933, in Antwerp, Belgium, into an Orthodox Jewish family, Myriam Morgenstein fled with her parents and two brothers in 1940 to escape the advancing Nazi army. While attempting to cross from Hendaye in occupied

France into Spain, the family was captured and sent to an internment camp in Mérignac, France, near Bordeaux. Through the intervention of the chief rabbi of Bordeaux, they were transferred to a forced residence camp—Camp de Leland—that housed families and was not enclosed by barbed wire.

Around her eighth birthday, the family arranged a daring escape, slipping out of the camp, traveling to Tours, and crossing into Vichy (unoccupied) France. After several weeks, her father succeeded in securing passage for the family by train to Spain, followed by a ship bound for the Dominican Republic. When the ship stopped in Havana, Cuba, her uncle boarded and informed them that he had arranged for the family to disembark there. They remained in Cuba for more than five years as refugees. In 1947, the family emigrated to New York City.

After graduating from the prestigious Bronx High School of Science in 1950, Sarachik enrolled in Barnard College. She took a physics class at affiliated Columbia University and found it an unexpected challenge, especially her first midterm. "It was the first and only thing I ever failed," she recalls.[1] Instead of being deterred by the subject, however, she became resolved to succeed in physics and finished the class with a B. She graduated from Barnard in 1954, and that same year married Philip Sarachik, who had been a fellow student with her in some of her Physics classes and would later become a professor of electrical engineering at New York University. They would have two children.

In 1960, Sarachik earned her Ph.D. in physics from Columbia University, working under Richard Garwin in the IBM Watson Scientific Computing Laboratory. She published the important observations from her thesis, "Measurement of magnetic field attenuation by thin superconducting lead films," in *Physical Review Letters* that same year.[2] Her experimental setup and measurements of the mutual inductance across varying thicknesses of superconducting Pb, down to 1.35 K, detected changes in the magnetic field attenuation as small as 0.5 percent.[3] These measurements showed that the temperature dependence of the superconducting penetration depth agreed with the functional form predicted by the Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity that was published just prior to Sarachik's thesis. Her work provided one of the first measurements of the energy gap in lead, 4.9 $k_B T_c$, remarkably close to the modern value of 4.38 $k_B T_c$, where T_c is the superconducting transition temperature.

Like many female scientists of her generation, Sarachik faced significant opposition to her desire to pursue a career in physics.[4,5] "It was really difficult towards the beginning," she stated, "especially when I had a baby. Nobody would give me the time of day." Several people even actively encouraged her to leave the field. Some of these same people later agreed to help her by writing letters of support.

Thanks to Nobel laureate Polykarp Kusch, she obtained a postdoctoral research position in 1962 at Bell Labs in New Jersey, where she completed what she felt was her most significant work, albeit not well cited: Definitive experimental evidence of the origin of the Kondo effect. This had been in question since 1934 when Wander Johannes de Haas, Jan de Boer, and Gerard J. van den Berg measured the resistance of (not very pure) gold wires as a function of temperature and found that the resistance decreased as the temperature dropped, as expected. Below about 4 K, however, the resistance surprisingly increased with decreasing temperature.[6] This resistance minimum was subsequently observed in other metals and alloys, and the origin of this effect remained a matter of speculation until 1964, when Sarachik performed a beautiful series of careful and systematic measurements of the temperature dependence of the resistivity of transition-metal alloys containing iron impurities.[7]

It is well known that iron is magnetic. But an iron atom sitting in a metal does not always retain its magnetic moment; for example, an iron atom in aluminum is not magnetic. Myriam's experiments relied on this fact in a very clever way. She dissolved 1-percent iron impurities in molybdenum-niobium (Mo-Nb) samples. Whether or not the iron atoms in these alloys had a magnetic moment depended on the fraction of Mo that the alloy contained. When there was a large fraction of Mo, the iron atom was magnetic. But for alloy samples with smaller fractions of Mo, and hence higher fractions of Nb, the iron impurities were not magnetic. Thus, by studying samples with different proportions of Mo relative to Nb, she could effectively tune the magnetic moment of the iron impurities. She found that the resistivity minimum only occurred in samples where iron impurities had a magnetic moment. Thus, her experiments clearly demonstrated that the minimum in the resistivity was due to electron scattering from dilute magnetic impurities. Jun Kondo was independently working out the theory of this effect and that same year published his famous paper explaining what is now known as the "Kondo Effect," showing that the resistivity minimum comes from conduction-electron spin-flip scattering from the magnetic impurities.[8] In spin-flip scattering, a conduction electron scatters from the magnetic impurity and flips its spin by trading places with the opposite-spin electron at the impurity site. At low temperatures, spin-flip scattering from magnetic impurities dominates and, as Kondo showed, the resistivity increases as the temperature decreases.

Sarachik and Kondo published their respective papers less than two months apart. Sarachik had heard that Kondo was working on such a theory and contacted him, and their correspondence was clearly cited in both Sarachik's and Kondo's publications. As Kondo noted in a later publication[9]:

> The most convincing demonstration of the criterion is the observation made by Sarachik that the dilute alloys of Fe (one atomic percent) with the series of NbMo alloys as host metals show a marked resistance minimum in the range of concentration ratio, where the measurements of susceptibility revealed the existence of localized moments of Fe atoms and none where localized moments were not found.

Sarachik's work was crucial for this success. Although it became widely known that the minimum in the resistance is due to conduction electrons scattering from magnetic impurities, references to Myriam's classic work are almost entirely absent from the literature. One cannot help but think that this was due in large part to her gender. That said, although the number of citations for Sarachik's seminal, far-ranging work is embarrassingly small, the impact-to-citation-count ratio is astronomical!

Kondo's perturbation theory did not hold as the temperature continued to decrease: Does the resistance keep increasing to infinity? This was a very active field of inquiry in the late 1960s and early 1970s. Eventually, Philip W. Anderson, Gideon Yuval, and Donald R. Hamann showed that the ground state is a non-magnetic singlet formed from the impurity spin and the conduction electrons.[10] (So, the resistivity is finite at zero temperature.) Subsequently, Ken Wilson solved the Kondo problem to demonstrate the power of his renormalization group technique, for which he was awarded a Nobel Prize in 1982.[11] The Kondo problem remains a vibrant field as it arises in so many topics of current interest, including quantum dots and the many-body effects of strongly correlated electron systems, such as heavy-fermion Kondo lattices that often exhibit unconventional superconductivity whose underlying mechanisms still remain elusive.

In 1964, Sarachik became an assistant professor at the City College of New York (CCNY). Getting established there proved challenging for the first few years.[12] She recalled: "The potential barrier was enormous, but once I got over it, it was smooth sailing." Sarachik's early years at CCNY were devoted to studies of magnetic impurities in materials, still an important area of fundamental and applied research.

Following the kidnapping and murder of her younger daughter in 1970, Sarachik left research for nearly a decade. After she returned, she started work in the field in which she was to earn much of her reputation: the metal-insulator transition in semiconducting materials. At the prompting of a program officer from the National Science Foundation (NSF), she applied for and received a grant for a dilution refrigerator, which enabled her to study materials down to 0.02 K. Armed with this, a large-field magnet, some good samples, and eager students, Sarachik turned out a series of seminal papers elucidating the nature of the metal-insulator transition and the roles played by impurity concentration, magnetic field, temperature, and pressure on the physics that underlie the transition.[13–16]

Symmetry plays an essential role in all of physics, and the metal-insulator transition is no exception. The symmetry of a physical system near a phase transition determines the "universality class" for the transition—a powerful concept allowing seemingly disparate systems, such as liquid-gas mixtures and Ising ferromagnets, to be part of the same theoretical framework because their universality class is determined by parameters, such as the dimensionality, that are independent of the system's components.

For each universality class, there are theoretical predictions for the "critical behavior" or the quantitative way the transition is approached. In general, the zero-temperature electrical conductivity σ obeys

$$\sigma(T \rightarrow 0) \propto (t - t_c)^{\mu},$$

where μ is the critical exponent, t is a control parameter such as impurity concentration or uniaxial stress, and t_c is the parameter value at which the transition occurs.[17] In general, the universality class for the transition determines the value of μ, and so it is this quantity that must be determined with great experimental precision. It is determined by plotting the measured quantity as a function of temperature over a broad range and extrapolating to zero temperature.

Sarachik's group studied samples of boron-doped silicon for many boron concentrations as a function of temperature, uniaxial stress, and applied magnetic field. The group demonstrated that an applied magnetic field and uniaxial stress could actually change the universality class of a system. They found μ increased from ~0.65 at zero magnetic field to ~1.0 at 7.5 Tesla, as expected for the magnetic-field universality class.[18] When tuned using uniaxial stress they found $\mu \sim 1.6$, indicating that stress had changed the physics.[19]

Scaling is an important tool for understanding the physics of the metal-insulator transition. For example, according to the theory of electron-electron interactions, the magnetoconductance (the difference between the conductivity in a magnetic field and in zero field) should be of the form

$$\Delta\sigma(H,T) \equiv \sigma(H,T) - \sigma(0,T) = T^{1/2} F(H/T),$$

where $F(H/T)$ is a function that depends only on the ratio H/T.[20] This means that if $\Delta\sigma(H,T)/T^{1/2}$ is plotted against H/T, all of the data for all values of H and T should fall on a single curve. This is indeed what the Sarachik group found for the magnetoconductance of boron-doped silicon.[21] Because other mechanisms, such as disorder, violate this form of

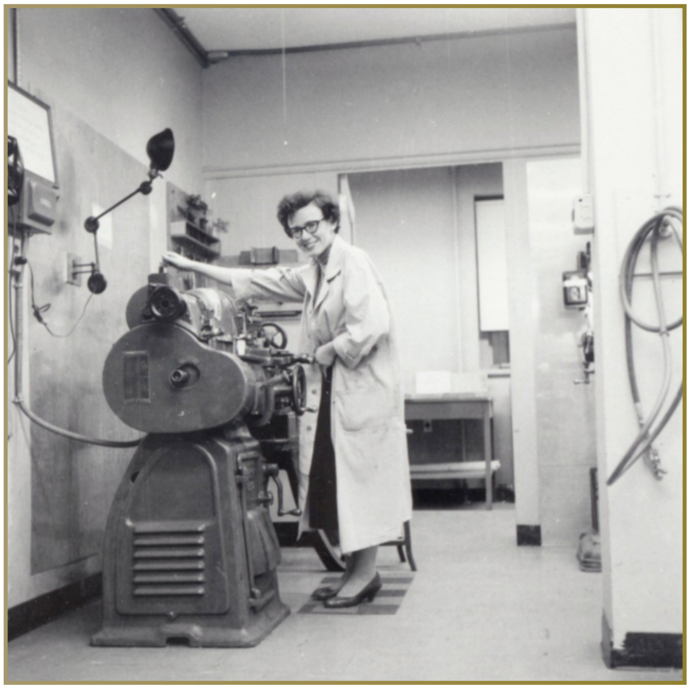

Figure 2 Myriam P. Sarachik at a lathe in 1956 when she was doing her PhD research. The photo was taking at the IBM Watson Laboratories on 115 St. in New York City near Columbia University. *Courtesy of Philip Sarachik.*

scaling, this result implies that electron-electron interactions cannot be ingnored near the transition.

Although metals seem ubiquitous in the everyday world, it has long been an accepted theoretical result that only insulators, that is, no metal, can exist in less than three dimensions. (In 1D and 2D, it was believed that the slightest amount of disorder would block the flow of electrons.) It was thus surprising when, in the early 1990s, Sergey Kravchenko and collaborators at the University of Oklahoma found evidence of a metallic state in a 2D system.[22] (Two-dimensional systems can be achieved when the electrons are forced to flow only very near the interface between two materials.) In 1995, at Myriam's invitation, Kravchenko joined the Sarachik research group and began trying to understand the nature of this unique system.

Sarachik's group conducted numerous studies of these two-dimensional metals in magnetic fields.[23–26] One major result was that the metallic state seems to be destroyed when a magnetic field was applied parallel to the plane in which the electrons are confined.[27] This implied that the conducting phase had something to do with the spin of the electrons. Electrons can react to a magnetic field in one of two ways. The field can cause the trajectory of the electrons to bend so that they tend to flow in circles that are perpendicular to the direction of the field, known as orbital coupling. The field can also influence the spin of the electrons, causing those with their spin pointing in the same direction as the field to have lower energy, whereas those whose spin points opposite to the field have higher energy. When the field is applied parallel to the two-dimensional plane of the electrons, orbital motion is prohibited because the electrons cannot flow in circles that leave the plane. Thus, the experimental results implied that the root of the unexpected metallic phase involved the electrons' spin. Experiments attempting to discern the precise physical mechanism by which the spins form the conducting state are still underway today.

Tunneling is a quantum-mechanical phenomenon. In most cases, a particle (such as an electron) travels between potential wells by passing through a region where it is classically forbidden because its energy is too small. Throughout most of the history of modern physics, it was thought that tunneling could only occur for small atomic or sub-atomic particles. Thus, a boulder stuck in the shallow valley between two mountain peaks does not spontaneously "tunnel" through one of the mountains and roll down the opposite side of the mountain, even though it would be energetically favorable to get to lower ground. If this same situation is reduced to the atomic scale, quantum mechanics allows a "boulder" the size of an electron or atom to actually tunnel through an insulating barrier.

In the 1980s it was suggested theoretically that under suitable circumstances some properties of macroscopic objects can themselves tunnel between sides of an energy barrier.[28,29] One such property is the magnetic moment of a small magnetic particle.[30–32] In this case, the phenomenon is not the result of the particle tunneling from one place to another, but rather the orientation of the magnetic moment from one direction to another.

Sarachik and collaborators (including author JRF) discovered the first unambiguous evidence for magnetization tunneling in a molecule-size magnet.[33] The molecule they studied has a magnetic moment about twenty times larger than that of a single electron. Because of the molecular structure, the magnetic moment finds it energetically favorable to point in one of two directions, called "up" and "down." The molecule has a series of quantized energy states in each direction. An applied magnetic field changes the energy of these states, and at certain values of field, an up state and a down state will become "resonant"—they have the same energy. The experimental mark of this phenomenon is that the measured probability for the magnetic moment to switch from up to down is much larger at the resonance fields than at other fields: Tunneling can be turned on and off by changing the magnetic field, providing evidence that the switching of the direction of the magnetic moment is caused by resonant tunneling and not by some other mechanism.

We have described Myriam's impressive achievements, but we would be remiss if we did not describe what she was like as a person. The challenges and tragedies in Myriam's life could have hardened her or made her bitter, but she was always warm, caring, and compassionate. She was a great friend to many; always ready to really listen and offer encouragement and wisdom. She will be greatly missed.

We end with a story that illustrates her no-nonsense approach. While chairing an NSF panel reviewing the National High Magnetic Field Laboratory (MagLab), she told its director, Greg Boebinger, one of the authors of this memoir, to jettison the detailed two-day agenda that he had prepared. Myriam designed her own plan, with each scientific direction being given fifteen minutes to present, followed by forty-five minutes of VERY informal, free-wheeling talk among all the participants; nothing needed to be polished, just convey the excitement! The science discussions were a success. They performed a valuable service for the MagLab and, in addition, they were thoroughly enjoyable.

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