BIOGRAPHICAL MEMOIRS

Philip Warren Anderson

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Elected to the NAS, 1967

A Biographical Memoir by William F. Brinkman, Patrick A. Lee, and N. Phuan Ong

Philip Warren Anderson was one of the intellectual giants who shaped and nurtured the rapid growth of condensed-matter physics during the second half of the twentieth century. He made fundamental contributions to diverse subfields, including antiferromagnetism, superconductivity, localization, superfluidity in helium-3, spin glasses, quantum spin liquids, local moments in metals and the Kondo effect, poor-man's renormalization, and high temperature Cuprate superconductivity. Many of those concepts now carry his name. In addition, his insight on the fate of the expected soft mode in superconductors led to the Anderson-Higgs mechanism of how particles acquire mass despite their origin in spontaneously broken symmetry. He was a corecipient, along with Nevill Mott and John Van Vleck, of the 1977 Nobel Prize in Physics for "fundamental theoretical investigations of the electronic structure of magnetic and disordered systems."

Anderson was born on December 13, 1923, in Urbana, Illinois. His father, Harry, was a professor of plant pathology at the University of Illinois Urbana-Champaign, and his mother, Elsie (nee Osborne), took care of the family. He graduated from the University Laboratory High School on the University of Illinois campus and did his undergraduate studies at Harvard University on scholarship. In 1947, he married Joyce Gothwaite, which was the beginning of a lifelong partnership. Their only child, Susan, was born in 1948.

After a stint at the Naval Research Laboratory in Washington, D.C., during World War II, Anderson obtained his Ph.D. in 1949 from Harvard University, working under John Van Vleck. Not wanting a postdoctoral position because of the need to support his family, the only academic job offer he received was from Washington State College, which had no graduate physics program. Anderson was ready to accept this position when Van Vleck intervened and directly appealed to William Shockley at Bell Labs in New Jersey. Shockley offered him a position, and in 1949 Anderson joined a group of talented physicists at Bell Labs that included Conyers Herring, John Bardeen, William Shockley, Charles Kittel, and Bernd Matthias. Their strong influence on the company to invest in basic research had a great effect on the labs for the rest of the century. From 1967 to 1975, Anderson worked part time at Cambridge University and then joined the faculty of

Princeton University. In 1984, after retiring from Bell Labs, he started as a full-time professor and was named emeritus in 1996.

One of Anderson's most influential works is his 1958 prediction that sufficiently strong disorder can turn metals into insulators via a process now known as Anderson localization. Before his work, the common view was that electron waves are described by band theory and are extended throughout the material. Disorder would simply lead to scattering and a finite resistivity. Anderson showed that sufficiently strong disorder can cause the waves to be localized in space and stop conducting current altogether at zero temperature. The influence of this work goes beyond the solid-state setting and extends to optical and acoustic wave propagation in random media. Anderson would return to this subject in 1979 in an influential paper written with Elihu Abrahams, Donald Licciardello, and Tiruppattur V. Ramakrishnan. They set up a scaling description of localization that began a new revolution that has led to a rather complete understanding of the subject today.

In the 1950s and 1960s, Anderson elucidated how a combination of quantum mechanics and strong repulsion between electrons causes electron spins to form local moments; his insight laid the foundation of the modern theory of magnetism. He worked extensively on coupling between local magnetic moments and how it leads to ferromagnetism and anti-ferromagnetism. A unifying theme that emerged from this work is the concept of broken symmetry: a system's ground state can have less symmetry than what the basic interactions possess. Anderson would return repeatedly to this principle, and his influential textbook *Concepts in Solids* and its sequel, *Basic Notions in Condensed Matter Physics,* were built around this theme.

After John Bardeen, Leon Cooper, and J. Robert Schrieffer proposed their pairing theory of superconductivity in 1957, Anderson became a major contributor to the topic. He was the first to recognize the importance of the phase of the superconducting wavefunction and how it is quantum mechanically conjugate to the number of Cooper pairs. His lecture on the topic was inspirational to Brian Josephson, a student in his class at Cambridge, who went on to discover the Josephson effect and thereby garnered a Nobel Prize in 1973. Anderson immediately understood that a small magnetic field can destroy the effect and collaborated with John Rowell at Bell Laboratories to achieve the first experimental demonstration of the Josephson effect.

In principle, phase fluctuations lead to a collective mode of gapless excitations, an example of Goldstone's theorem; such excitations are observed in neutral superfluids but not in superconductors. Anderson realized that the coupling of Cooper pairs to the electromagnetic field boosts the mode to a finite frequency, at which point it merges with the plasma mode. Anderson learned that particle theorists were faced with a roadblock in the unified field theories being developed at the time. The theory was based on broken symmetry and was plagued by unwanted massless Goldstone particles. In 1963, he wrote a paper addressed to the particle physics community proposing that the same mechanism he discovered for superconductors could resolve this problem. A year later, Peter Higgs and others completed the program by working out the fully relativistic theory. Higgs fully credited Anderson, as he wrote in his Nobel lecture, "The Goldstone massless mode became the longitudinal polarization of a massive spin-1 'photon,' just as Anderson had suggested." The Anderson–Higgs mechanism is now a cornerstone of both particle and condensed-matter physics.

In the 1960s, Anderson returned to magnetism and focused on the question of how local moments form in a metal. In an influential 1964 paper, Jun Kondo discovered that if the local moments are formed from dilute impurities, the scattering of the conduction electrons from them give rise to an additional resistivity that rises with decreasing temperatures, thereby explaining the long-standing problem of resistivity minimum observed in many metals. Kondo's solution was perturbative, and the resistivity rise was logarithmically divergent at low temperatures. This raised the question of what the ultimate fate of the local moment is, a question known as the Kondo problem, which attracted the attention of condensed matter theorists in the 1960s. The taming of logarithmic divergence shared many commonalities with the problem of critical phenomena in statistical physics, and insightful ideas of scaling were being developed by Leo Kadanoff and Michael Fisher at that time. Anderson wrote a series of influential papers, culminating in a paper written with Gideon Yuval and Donald Hamann, which gave the essential solution to the problem. They cast the problem into a statistical physics problem and showed that by progressively integrating out the high energy/short distance degrees of freedom, the local moment formed from the magnetic impurity is gradually screened to behave like the non-magnetic ones, with the spin fluctuating quantum mechanically between up and down, even at zero temperature. Soon after this, Anderson wrote a paper with the alluring title, "A poor man's derivation of scaling laws for the Kondo problem," which gave a simplified and physically transparent way of deriving the same result in the characteristic Anderson style. This paper may be considered the first use of renormalization group in a quantum mechanical setting and has been highly influential. The full exposition of the renormalization group concept with application to critical phenomena and to the Kondo problem would come from Kenneth Wilson in a parallel and independent development.

A year after the 1986 discovery of high-temperature superconductivity in cuprates, Anderson published an enormously influential paper in *Science* pointing out that the key physics is the introduction of charge carriers ("holes") into the insulating state that arises from strong electron-electron repulsion. He recalled a 1973 paper that introduced the notion of quantum spin liquids, in which magnetic moments fail to achieve long-range order because of quantum fluctuation and instead form a state that he dubbed a "resonating valence bond" (RVB). He proposed that in a cuprate, when holes are introduced into that state it becomes a superconductor. Those revolutionary ideas met stiff resistance from the community. Although the specific mechanism he proposed for superconductivity remains controversial, many of the ideas he introduced in the 1987 paper, including the notion that superconductivity is a favorable ground state in a strongly repulsive system, have gained wide acceptance. The RVB state is the archetypal example of a quantum spin liquid, currently a vigorous area of research.

Anderson also suggested that the excitations of a quantum spin liquid behave as electrons that have lost their charge but retain their spin. That early example of "fractionalization" has found support both in exactly soluble models and in real materials. Time will tell, but Anderson's spin-liquid work may well be remembered as his most profound and prescient.

Anderson had a long-standing fascination with systems far from equilibrium and glassy behavior. Instead of structural glass, he focused on the relatively simpler system of spin glass, in which case local magnetic moments with random signs of interaction can end up in a glassy state. With Sam Edwards, he made the first formulation of what played the role of an order parameter for spin-glass in 1975, which opened up a floodgate of activities. The picture of a complex energy landscape with multiple minima had a profound influence on the development of neural network research and neuroscience, notably in the hands of his friend John Hopfield. Anderson himself got involved in the development of the emerging field of the science of complexity. He was one of the founding members of the Santa Fe Institute and spent some time exploring complexity issues with economists and biologists.

As described by his biographer, Andrew Zangwill, in the book *A Mind Over Matter: Philip Anderson and the Physics of the Very Many,* in the 1950s and 1960s the predominant view among elite physics departments in the country was that fundamental research was the domain of particle physics. Solid-state physics was viewed as applied research rather than as addressing fundamental questions towards the understanding of Nature. More than anyone else, Anderson was instrumental in changing that worldview. In a 1972 article entitled "More is different," Anderson attacked the reductionist view and emphasized that each layer of nature is as worthy of fundamental investigation as the most microscopic ones. The knowledge of quarks and gluons cannot anticipate, much less help explain, the rich variety of fascinating complex behavior in macroscopic systems, such as superconductivity, chaos, and a host of other complex behaviors. This point of view was summarized by the notion of emergence, which Anderson made concrete with his example of broken symmetry. That view has deeply influenced condensed-matter physics, physics as a discipline, and, according to Zangwill, broader areas such as philosophy and the history of science. This conflict between "Big Science" and "More is different" was on public display when Anderson emerged as the face of the opposition to the continuation of funding and construction of the Superconducting Super Collider. The back-to-back testimonies with Steve Weinberg in front of Congress in 1993 laid out these contrasting views most vividly. Whether these testimonies played a pivotal role in the cancellation of the project may never be known, as the project was under duress on many fronts, but the lack of unity within the physics community was certainly not helpful. This episode clearly demonstrated that Anderson was someone who would stand up for his principles and beliefs, even if it meant losing some friends in the process.

Indeed, Anderson was a self-described "thoughtful curmudgeon," the subtitle of his collection of essays "More and Different, Notes from a Thoughtful Curmudgeon." He held strong opinions and did not hesitate to make them known. He did not sugar-coat his objections, even if certain individuals might end up being offended. This side of him came to the fore in the era of high-temperature superconductivity, and many faulted him for contributing to the combative atmosphere surrounding the theoretical side of the field. Perhaps Anderson was frustrated that the insights that seemed so obvious to him did not immediately gain acceptance. In later years, Anderson was open in admitting that some of the more detailed ideas he pushed turned out to be incorrect, but the general framework he set up—that strong correlation resulting from repulsion between electrons can lead to pairing—has gained acceptance over time.

To those who were privileged to be counted among his friends, and there are many, Anderson was at heart compassionate and amazingly loyal to friends and colleagues. Former students who had hit a rough patch often moved back to Princeton to work with him until they regained their footing. After he learned that a collaborator had suffered a stroke, Anderson flew to stay with him for a week. For many years, he and Joyce hosted parties at their home in Princeton and welcomed visitors to their cottage in Cornwall. He and Joyce enjoy taking long walks with visitors. To their amusement, they took great pleasure in belting out old songs, especially those by Tom Lehrer (a friend from college). Both held strong anti-establishment convictions. Sadly, Joyce suffered a serious stroke in 2009, became bedridden, and lost some of her cognitive functions. Anderson would visit with her every day and read to her, giving her a great deal of comfort. He would spend his last years caring for her, with a devotion that was moving to behold. Anderson died on March 29, 2020, in Princeton, New Jersey. Joyce survived him for several months, and he was survived by their daughter, Susan.

In addition to the Nobel Prize, Anderson was awarded the American Physical Society's Oliver E. Buckley Prize in 1964 and the National Medal of Science in 1982. He had a lifelong interest in the game of Go dating from a yearlong visit to Japan in 1953–54, and he attained the rank of first-dan master. In 2007, the Nihon Ki-in, Japan's association for Go, gave him a lifetime achievement award.

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