



True Genius: The Life and Science of John Bardeen

by Lillian Hoddeson and Vicki Daitch

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Reviewed by Howard Huff

John Bardeen was among the earliest group of American physicists, in the early to mid-1930s, who received their introduction to the new quantum mechanics and their PhD training in America, in contradistinction to the 1920s when Robert Oppenheimer, John Slater, and Isidor Rabi, for example, went to Europe for their training in quantum mechanics. Bardeen's research during the 1930s (Princeton for the PhD and Harvard for post-graduate work) was critical for his Nobel Prizes, the only person to receive two Nobel prizes in physics. The first Nobel was in 1956 for the invention of the transistor (with Walter Brattain and William Shockley) and the second in 1972 (with Leon Cooper and J. Robert Schrieffer) for his description of the fifty-year riddle of superconductivity (*i.e.*, the persistence of an electric current in the absence of an electric field). The authors share with readers a number of golden nuggets about Bardeen. The bibliography is especially rich and useful, while the notes and references to the interviews are exemplary, as expected from the senior author's previous legendary historical studies.^{1,2}

The authors interestingly note that students of current or future Nobel prize winners often tend to achieve Nobel prizes themselves, emulating a style, tactics, a methodology to enhance success. Indeed, both Bardeen's undergraduate teacher in quantum mechanics, John Van Vleck, and Eugene Wigner (Bardeen's PhD advisor at Princeton) received a Nobel Prize in physics. In Wigner's case, the emphasis was to reduce the problem to "the simplest possible case so you can understand that before you go on to something more complicated." While other pre-eminent scientists had a similar approach, Bardeen was regarded as especially tenacious in pursuing this mantra, and exploring complementary approaches if the first approach proved unfruitful, as noted by his Nobel colleague Philip Anderson. Van Vleck, who had transferred from the University of Minnesota to Harvard, was instrumental in facilitating Bardeen's acceptance as a Junior Fellow, even before he had received the PhD, reflecting both Bardeen's credentials and the influence of Van Vleck. Additional Nobel Prize teachers from whom Bardeen "learned a great deal from important leaders of modern physics" included Paul Dirac, Percy Bridgeman, and Peter Debye.

Bardeen's PhD research at Princeton considered the energy required to remove an electron from the surface of a metal into a vacuum, of immense importance at the time for the field of

vacuum tubes. Bardeen examined the influence of the exchange and correlation potential in reducing the free-electron spillover into the vacuum at the surface (leaving an equal, spatially fixed positive charge due to the positively charged ionic cores in the metal) and the resultant decrease in the surface dipole moment, a formidable problem that included elements of what later became known as many-body phenomena. Conyers Herring, a colleague of Bardeen at Princeton as well as later at Bell Telephone Laboratories (BTL) and Emeritus Professor of Physics at Stanford, has noted Bardeen's theory as valid to this day.³ This was the beginning of the burgeoning of the utilization of quantum mechanics to real problems in solid-state physics (today referred to as condensed matter physics)¹, although elements had already begun in Germany in the late 1920s.

Bardeen pursued a number of topics in many-body theory that had piqued his interest at Princeton during his post-doctoral research at Harvard in the late 1930s. These areas included superconductivity, discovered in 1911 by Kammerlingh Onnes, which the brothers Fritz and Heinz London had hypothesized in 1933 as originating from the existence of an energy gap tending to zero as superconductivity approached zero, with increasing temperature or increasing magnetic field. The superconductivity enigma and the implications of an energy gap in the excitation spectrum was pursued by Bardeen, on and off, for the next fifty years. Although Bardeen, with Cooper and Schrieffer, resolved the problem in 1957, Bardeen continued pursuing additional aspects of the phenomenon throughout his later years.

After briefly serving on the academic faculty at the University of Minnesota subsequent to Harvard, Bardeen joined the Naval Ordnance Laboratory (NOL) in the fall of 1940 in view of the upcoming war clouds. He eventually supervised 93 personnel in acoustics, magnetics, graphical analysis and detection units, building on his previous industrial geophysics experience at the Gulf Research Laboratories in Pittsburgh, between his undergraduate and masters years at the University of Wisconsin and subsequent PhD studies at Princeton. Although this may not have been the most exciting time of Bardeen's career, his team's achievements were significant and recognized with his being awarded the Meritorious Civilian Service Award as a result.

With the war winding down, it became obvious to Mervin Kelly, BTL's research director, that the interdisciplinary teams that contributed to the development of radar at the Massachusetts Institute of Technology's Radiation Laboratory in conjunction with BTL and Western Electric, and the atomic bomb at Los Alamos (the Manhattan project), might be usefully emulated to solve the most perplexing technology issues fac-

ing BTL's parent company, American Telephone & Telegraph (AT&T). Bardeen joined Bell Laboratories in October 1945. He was assigned to Shockley's semiconductor team in the solid-state physics group, which included Walter Brattain, an experimental physicist (an old bridge playing partner of Bardeen's from his Princeton days); Robert Gibney, a physical chemist; physicist Gerald Pearson; and Hilbert "Bert" Moore, an electronics expert. Their goal was the replacement of the vacuum tube amplifier and the electromechanical relay type devices, utilized in the Bell System, by a solid-state amplifier and switch, respectively. Although the focus was the scientific comprehension of the relevant phenomenon, the mission-oriented goal was clearly acknowledged.

Shockley's approach was to electrostatically modulate the conductivity of a semiconductor by the field effect; initial experimental results, however, were disappointingly small. Bardeen verified the correctness of Shockley's calculations and subsequently addressed the source of the discrepancy, resolving the issue in March 1946 by his introduction of the concept of surface states (theoretically anticipated in the late 1930s by Tamm and Shockley). The surface states arose as a result of the termination of the bulk material at the surface as well as extrinsic adsorbed chemical species on the material's surface. Bardeen's analysis not only explained the lack of a significant electrostatically induced conductivity modulation at the material's surface—due to the trapping of a significant fraction of the electrons induced by the applied electric field—but a host of additional experimental observations that had accumulated between the late 1930s and mid 1940s.² The authors then describe the technical forest that Bardeen and Brattain encountered during the next year or so until they developed the methodology for negating the surface states (building on a suggestion by Gibney on November 17, 1947) and within one month (December 16, 1947) they had achieved their mission—a solid-state amplifier. This device was called the point-contact semiconductor amplifier, based on Bardeen and Brattain's discovery of transistor action; that is, the observation of a significantly enhanced (amplified and modulated) output voltage due to a variable source current, which resulted in their being awarded a patent in 1951. The device operated as a result of the electrical introduction of minority-carriers—holes in this case—which previously could only be introduced by thermal energy or sufficiently energetic photons. Perhaps the most endearing description of Bardeen and Brattain's working relationship by the authors is noted as "Bardeen loved to peer over Brattain's shoulder and watch him prepare his experiments. Sometimes Bardeen would offer Brattain a hand in routine tasks, such as recording measurements or holding a piece of apparatus in place while Brattain soldered it." Indeed, Bardeen's handwriting of experimental data in Brattain's notebook has been previously described.²

Shockley was not a co-patent holder on the transistor device and transistor action; however, inasmuch as his contribution, the field-effect principle, had in effect already been patented a decade earlier by Lilienfeld and, moreover, was a majority carrier device structure. Shockley was extremely disappointed, to say the least and was spurred to his own "magic month" (December 23, 1947-January 23, 1948), identifying the injection concept (January 23, 1948) and the bipolar junction (bulk) transistor, for which he received a patent in 1951. Interestingly, Shockley's injection patent was awarded before either of the transistor patents. Nevertheless, all three men made seminal contributions, resulting in their joint Nobel Prize in physics in 1956. The competitiveness that had ensued in early 1948, however, distinctly soured a previous collegial relationship, which

was already becoming frayed in December 1947. Bardeen re-initiated his studies in superconductivity at BTL and shortly thereafter continued these studies by joining his colleague Fred Seitz—author of the seminal 1940 textbook *Physics of Solids*—in the Physics Department of the University of Illinois at Champaign-Urbana, which in short order became the premier physics department in America.

Anticipating Lev Landau's theory of Fermi liquids, and well aware of Richard Feynman's investigations into the superconductivity enigma "using all sorts of complicated field theory," Bardeen knew the race was on. Leon Cooper introduced the concept of electron pairing and J. Robert Schrieffer identified the wave function that described the electron coherence. Bardeen macroscopically pulled the various threads together, assigning Cooper, Schrieffer, and himself explicit responsibilities to ensure the coherence of the approach with the host of experimental data, which nevertheless required "an intuitive leap." The theory accounted for the experimental data (*i.e.*, the Meissner effect and related electromagnetic properties, the isotope effect, the kT energy being less than the electron-phonon-electron coupling energy and related thermodynamic phenomena, etc). Their theory (now referred to as the BCS theory) was submitted on February 15, 1957 in a letter to Physical Review and presented in two post deadline papers at the March 1957 meeting of the American Physical Society in Philadelphia, by Cooper (Schrieffer, having received word too late to attend the meeting and deliver one of the papers, was writing up his thesis in New Hampshire). Bardeen preferred his younger colleagues to present the results, "even to the extent beyond that which is due and also pushing young people as fast as they can to become professionals, and treating them as professional, and making them rely on themselves," Schrieffer noted in a description of the events. This comment is just one of the many gems distributed throughout the book, which en masse present a picture of Bardeen as a truly self-confident man in his knowledge and accomplishments. The experimentalists were delighted with the BCS theory while many theorists were rather reticent and skeptical in their acceptance, having also worked assiduously on the problem and requiring more definitive evidence. The presumed "scientific" attitude of scientists is clearly described as a most human endeavor, contrary to other books, which often characterize scientists as otherworldly. Nevertheless, the BCS theory was recognized with Bardeen, Cooper, and Schrieffer being awarded the 1972 Nobel Prize in physics for solving the riddle of superconductivity, which was now realized to be a macroscopic quantum effect. The theory was later recognized as "among the 'big ideas' of physics, a theory applicable to problems in many areas of physics," such as superfluidity of nuclear matter and superfluid pairing of matter inside neutron stars.

The authors detail how Bardeen stimulated interest in the Nobel Prize in physics being awarded for the BCS theory, as he was especially desirous of his colleagues' recognition for their contribution; it would be a tremendous endeavor because no physicist had previously been awarded two Nobel prizes in physics. By proposing Nobel prizes for subsequent exceptional work by other—Leo Esaki for interband tunneling in p-n junction semiconductors, Ivar Giaever for tunneling through a thin oxide layer, and Brian Josephson for supercurrent flow through a tunneling junction—Bardeen successfully established the necessity of the BCS Nobel Prize in physics (and the subsequent 1973 Nobel Prize in physics shared by Esaki, Giaever, and Josephson). Charles Slichter observed that, "John was a very politically savvy person." Although Cooper noted upon his arrival at Champaign-Urbana that he "didn't like the geogra-

phy" of this "corn-field place," he soon discovered the wonderful physics environment, and the charm and camaraderie of the physics department.

So what does one do after two Nobels in physics? Bardeen certainly had no intention to pontificate, as numerous other Nobel winners were prone to do, although he did "meet the social obligations that arose from his scientific stature," including service on a number of presidential scientific commissions. Perhaps more significant was the expression "John will know" when knotty conundrums arose. Of course, there were errors, such as in the Brian Josephson case as to whether paired tunneling would occur through an insulating barrier, which the authors straightforwardly discuss and on which Bardeen eventually recanted his opposition. Interestingly, and perhaps not surprisingly, was Bardeen's reaction to invite Josephson to Illinois to further work out his theory, which resulted in Josephson writing his "now-famous paper on the second-order phase transition to the superfluid state." Additionally, Bardeen also charged ahead into clarifying charge density waves (CDW) in the 1980s. Although initial successes became tempered by alternative approaches, explanations and some acrimonious exchanges, it is clear that doing physics was Bardeen's great passion to the end of his days.

Or almost. What was most sad, from this reviewer's viewpoint, was the passing of John's enchanting wife Jane; their relationship simply was quite deep. On a more personal note, a cousin of this reviewer was a Bardeen PhD student in the late fifties, at the same time when the reviewer declined to attend

the University of Illinois' College of Engineering, often to his dismay in retrospect. So, while I have spent a weekend in the late 1960s with Brattain—certainly a garrulous individual—and a two hour one-on-one discussion in the mid 1980s with Shockley—a most brutally frank person—perhaps I can take the liberty of associating myself spiritually with Bardeen. Although Bardeen was reticent compared to, say, Feynman, he certainly was not a timid or non-competitive person, as amply described by the authors in Bardeen's sports endeavors, whether as a young man or later in golf, as well as in physics. Perhaps Nick Holonyak, Bardeen's colleague for forty years, as graduate student, professor, and the first (and current) holder of the John Bardeen Chair Professor of Electrical and Computer Engineering and Physics at the University of Illinois at Champaign-Urbana, best summed up the essence of his mentor, "John Bardeen knew he was John Bardeen!" ■

1. L. Hoddeson, E. Braun, J. Teichmann, and S. Weart, *Out of The Crystal Maze: Chapters from the History of Solid-State Physics*, Oxford University Press (1992).
2. M. Riordan and L. Hoddeson, *Crystal Fire: The Birth of The Information Age*, W. W. Norton & Company (1997).
3. C. Herring, *Phys. Today*, April 26-33 (1992).

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