Charles P. Bean

1923–1996

BIOGRAPHICAL *Memoirs*

A Biographical Memoir by
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Gordon Bean,
and Ivar Giaever

NATIONAL ACADEMY OF SCIENCES

CHARLES PALMER **BEAN**

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By James D. Livingston, Gordon Bean, and Ivar Giaever

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Charles Palmer Bean was a physicist who did outstanding and influential research in a variety of fields, including magnetism, superconductivity, and biophysics. He worked at the General Electric (GE) Research and Development Center in Schenectady, New York, (GE's renowned laboratory) from 1951 to 1985 and at Rensselaer Polytechnic Institute (RPI) in Troy, New York, from 1978 until his death. The importance of Bean's early work at GE on magnetism and superconductivity prompted his election to the National Academy of Sciences in 1976 and to the American Academy of Arts and Sciences in 1977. The excellence of his teaching at RPI earned him the Klopsteg Memorial Award of the American Association of Physics Teachers in 1993. Having long worked for an industrial laboratory, he also held numerous patents (a partial list is provided at the end of this article).

Charlie was not only an outstanding scientist but also had a deep knowledge of the humanities, especially fine art, literature, and music. For example, he informed the Norwegian coauthor of this memoir (Giaever) that Edvard Munch's Madonna had sperm around its edges—and that since Munch's father was a medical doctor, he must have learned about their shape through using a microscope. Charlie loved the Sunday New York Times and claimed that he could tell what kind of people he was dealing with by what section of the newspaper they read first; he himself always started with the book reviews. He also told the Norwegian coauthor about *Sophie's World: A Novel About the History of Philosophy* (by Norwegian writer Jostein Gaarder) and amazed Giaever by knowing more than he did about other famous Norwegians, such as playwright Henrik Ibsen and composer Edvard Grieg.

Charlie was born in Buffalo, New York, in 1923 to Teresa (Palmer) and Barton Bean, the latter an attorney specializing in patent law. He had one brother, Barton, Jr.

Charlie's interest in science developed when his brother Barton would go to a general store and fetch little toy science kits and report that they just happened to cost the exact amount of Charlie's monthly allowance. Later, Charlie acquired a lifelong scar on his thigh after riding his bike home with a new bottle of acid for his chemistry set and crashing his bike. Throughout his life, he was a strong believer in the primacy of rational thought, but he often recalled the time he and his brother were on a bike expedition—planned to take several weeks—when one afternoon they simultaneously had an inexplicable feeling that something was wrong and headed home. They found out upon their return that their shared unease had coincided with the day of their father's death.

During World War II, Charlie served in the U.S. Army Air Corps in Colorado Springs, specializing in aerial photography. In 1947, he married Elizabeth ("Betty") Harriman, whom he had known since they attended dancing school together as children in Buffalo. Katherine, their first child, arrived in 1950, followed by Bruce, Margaret, Sarah, and Gordon. The children have fond memories of their father's love of better understanding the world around him, whether conducting experiments on the water in ponds and lakes or keeping a keen eye on the many trees around their house.

When Betty died of breast cancer in 1990 Charlie was devastated. But fortunately he soon met up with Jenny Overeynder, who was a good companion for him until he died of heart failure in 1996.

After graduating from the University of Buffalo in 1947 with a bachelor's degree in physics, Bean did graduate work in physics at the University of Illinois at Urbana/Champaign, from which he received his Ph.D. in 1952. His doctoral thesis (under advisor Robert J. Maurer) on electrical conductivity in sodium chloride crystals introduced him to the rapidly growing field of solid-state physics, an interest he carried with him to the General Electric Research and Development Center.

At GE, Bean became very interested in magnetism, and he developed a collaborative research style that led to many of his papers being coauthored. His first published paper, written with B. W. Roberts, appeared in 1954; it reported the observation of magnetic domains in MnBi by the Kerr effect, the rotation of plane-polarized light in reflection. The next five years saw a flood of his research papers in magnetism with numerous coauthors, including R. W. DeBlois, I. S. Jacobs, J. D. Livingston, W. H. Meiklejohn,

R. H. Pry, and D. S. Rodbell. His deep understanding of the basics of magnetism and of the latest research literature, together with his enthusiastic and supportive personality, helped him inspire and guide his many colleagues and assist them in analyzing their experimental results.

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Bean had a major influence on the development of the GE laboratory in the late 1950s and early '60s, at a time when industrial labs still engaged vigorously in basic research. He was one of the main reasons the lab became so prominent in the world, not only because of the excellence of his own research but also because of his positive effects on others. What he liked best was to work with other people, to prod and challenge his colleagues to do their very best. At that time, during a visit to Schenectady Sir Neville Mott of Cambridge University put it succinctly when asked to give his impression of the GE laboratory: "I am surprised," he said, "that a second-rate place can do so much first-rate work!" This was of course due to Charles Bean.

Magnetic materials are most commonly characterized by measurement of their magnetization—i.e., the average of the internal magnetic field produced by the atoms of the material, as a function of applied magnetic field. For permanent-magnet materials, commonly called hard magnets, the magnetization curve is not reversible; the magnetization from a given applied magnetic field depends on whether the field is increasing or decreasing. This "magnetic hysteresis" leads to a remanent (residual) magnetization after the applied field is removed, and a reverse magnetic field—termed the "coercivity"—must be applied in order to reduce the net magnetization to zero. The remanent magnetization and the coercivity are major factors defining the quality of a permanent magnet.

Much of Bean's early research focused on magnetic hysteresis and coercivity in small magnetic particles, and his three contributions that had the greatest long-term impact on the field of magnetism were those that introduced: (1) the "chain-of-spheres" model of magnetic reversal (with Jacobs); (2) exchange anisotropy (with Meiklejohn); and (3) superparamagnetism (with Jacobs and Livingston).

Chain-of-spheres. For some years, GE had been developing a commercial permanent-magnet material called Lodex, based on ferromagnetic particles fine enough that they consisted of only one magnetic domain—so-called single-domain particles. The Lodex process involved the electrodeposition of elongated iron-cobalt particles into a mercury cathode, but although the final product had promising magnetic properties it fell short of theoretical predictions. In particular, the coercivity was significantly lower than expected for elongated single-domain particles. Microscopic observations of the magnetic particles in Lodex showed that the diameter of the rodshaped particles varied along their length, so Jacobs and Bean (1955) modeled the particles as a chain of spheres rather than as a uniform rod. When a magnetized chain of spheres was exposed to a reverse magnetic field, they found that the magnetization reversed direction not by a coherent rotational process, as assumed in previous single-domain theory, but incoherently in a so-called "fanning" process—in which the magnetization of alternating spheres rotated in opposite directions. Jacobs and Bean's results explained many of the properties of Lodex, and in subsequent years the chain-of-spheres model of magnetic reversal was successfully applied by many researchers to a wide variety of fine-particle magnetic materials, including the chains of magnetite particles found in magnetotactic bacteria.

Exchange anisotropy (exchange bias). Curves of magnetization vs. applied magnetic field are usually symmetric with respect to field. However, fine cobalt particles electro-deposited into mercury were sometimes found to have asymmetric magnetization curves, with the coercivity different in one direction than in the opposite direction. Although cobalt itself is ferromagnetic—i.e., the spins of adjacent atoms are aligned in parallel—the particles were coated with a shell of cobalt oxide, which is an antiferromagnet (wherein spins of adjacent atoms are aligned anti-parallel). Meiklejohn and Bean (1956) were able to demonstrate that the asymmetric magnetization curves of the cobalt particles were associated with the antiferromagnetism of their oxide coatings—that there was a surface interaction between the ferromagnetic core and the antiferromagnetic shell. The quantummechanical force between spins of neighboring atoms is called the exchange force, and the researchers therefore called this asymmetry effect an "exchange anisotropy." The alternate term "exchange bias" later came to be associated with such asymmetric, or biased, magnetization curves, and it was critical to the development of magnetic recording heads that involved a ferromagnetic layer exchange-coupled to an antiferro-magnetic layer.

Superparamagnetism. Bean first introduced this term in a 1955 paper in which he analyzed the magnetization curves of three different types of ferromagnetic particles: (a) very small particles that are single-domain but equilibrate with an applied field from thermal vibrations; (b) single-domain particles that are too large to equilibrate and thus have permanent-magnet hysteretic behavior and coercivity; and (c) particles large enough to contain many magnetic domains. He termed the first type of particle "superparamagnetic" because the particle magnetization equilibrated with applied field from thermal vibrations like a paramagnet did, but while internally retaining long-range magnetic order and thus acting as a paramagnet with a very large magnetic moment. Because that magnetic moment was proportional to the volume of the particle, Jacobs and Bean (1955) then showed how superparamagnetic behavior allowed the use of magnetic measurements to measure particle size. A 1959 review paper summarized the theory and applications of superparamagnetism to a variety of materials, and it derived the temperature dependence of coercivity of fine particles. That paper remains the primary reference on this topic, cited by practitioners in many branches of magnetism, including magnetic recording, where superparamagnetism provides an upper limit to the density of recorded data.

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The second area of solid-state physics in which Bean made substantial and well-recognized contributions was high-field superconductivity. Building on his experience with the magnetization curves of ferromagnetic materials, he developed a model that became (and remains) the standard model—commonly called "the Bean Model"—for describing the distribution of magnetic fields and electric currents within high-field superconductors.

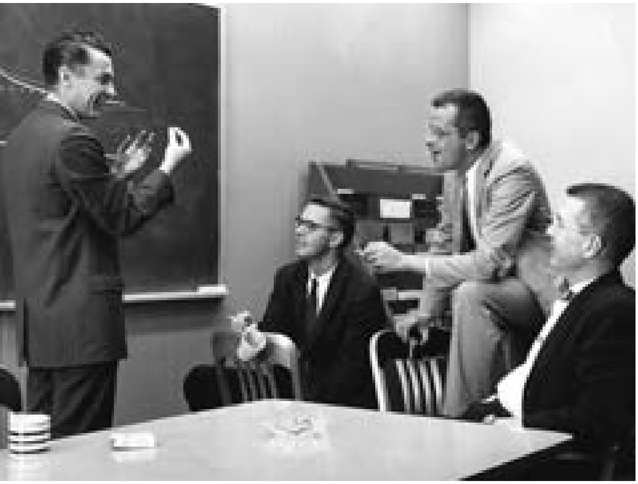
Superconductivity, the ability of some materials at low temperatures to carry electric current without resistance, was discovered in 1911. At first scientists thought that such materials could be used as electromagnet windings to produce high magnetic fields, but they soon discovered that the materials then known to be superconductors—pure metals such as lead and tin—lost that property in the presence of even moderate magnetic fields. Superconductivity appeared to be a delicate phenomenon that required the temperature to be below a critical temperature and the applied magnetic field to be below a critical field strength. For half a century, superconductivity remained a phenomenon of basic scientific interest to physicists but of little technological interest. That changed in 1961, when researchers from Bell Laboratories reported that a compound of niobium and tin was able to carry currents without resistance even in the presence of very high magnetic fields. Many research groups, including some at General Electric, rapidly initiated programs to understand and develop the exciting new materials.

At the time, there were two major models to explain how superconductivity in bulk materials could extend to high magnetic fields. It had been known for some time that very small particles of classical, or "Type I," superconductors had enhanced critical fields. As early as the 1930s, some researchers recognized that certain bulk superconducting alloys had higher critical fields than those of pure metals, and K. Mendelssohn in particular proposed that the microstructure of such alloys consisted of a fine network, or "sponge," of superconducting filaments. An alternate explanation of high-field superconductivity was offered in 1957 by A. A. Abrikosov, who proposed that the basic electronic properties of some superconductors, soon called "Type II" superconductors, were such that in the presence of an applied field the material would enter a "mixed state" in which the magnetic field spontaneously penetrates in the form of quantized flux lines.

Bean (1962) first developed his model of the magnetization of high-field superconductors based on the "Mendelssohn Sponge," assuming that (1) the microstructure of superconducting filaments at any point in the sample was capable of sustaining lossless macroscopic supercurrents up to a critical current density; and (2) that critical current density, through Ampère's Law, would control the gradient of magnetic field as it penetrated the sponge. This led to a magnetization curve that was hysteretic, like that of a permanent magnet, but also to a curve that depended on sample size—a prediction that he confirmed with experimental measurements (by colleague M. V. Doyle) on bulk samples of niobiumtin. Bean's model was based on the supposition that the macroscopic internal supercurrent density at any point within the sample had only three possible values—zero, the critical current in one direction, or the critical current in the opposite direction. In an increasing field the internal current would flow in one direction, thereby limiting field penetration, but in a decreasing field the current would flow in the opposite direction, thus limiting field expulsion and yielding magnetic hysteresis. With this model, the magnetic and electrical properties of high-field superconductors could be understood in terms of one parameter—the critical current density.

Bean followed his initial paper with a lengthier exposition—entitled "Magnetization of high-field superconductors" (1964)—of his model. By this time, there was growing experimental evidence that Abrikosov's model of Type II superconductors provided the correct explanation of the basic properties of niobium-tin and most other high-field superconductors–with the added proviso that microstructure, by interfering with the flow of flux lines within the materials, created a "flux pinning" that led to magnetic hysteresis. Bean noted that his phenomenological model of magnetization still applied in this case, with his basic concept—the internal critical current density, now a consequence of the gradient of flux lines in the "mixed state" of a Type II superconductor—controlled by the strength of flux pinning. He supported his detailed calculations with magnetic-hysteresis measurements both of vanadiumgallium (a Type II superconductor) and of a model filamentary superconductor produced by inserting lead into a network of holes etched into Vycor glass.

The next few years saw much experimental verification, at General Electric and many other laboratories, of the Bean Model of high-field superconductors. Working with GE colleagues, Bean considered the "adiabatic critical state" (1968) and thermal effects to explain the phenomenon of "flux jumping," which often limited superconducting properties, and the researchers demonstrated the increase in critical currents produced in niobium-tin and related materials by radiation. Bean also applied his critical-state model to the case of rotating magnetic fields (1970). When experimental results indicated that the specimen surface itself could obstruct the entry and exit of flux lines into and out of a superconductor, he used the concept of an image flux line to develop a quantitative "surface barrier" theory that found wide application (1964). The field of superconductivity became energized again in 1987 by the discovery of oxide superconductors with high critical temperatures. Experimenters then found that the Bean Model applied equally well to these new materials, as did his model of a surface barrier to flux-line motion. By then Bean had left GE, but he did return briefly to the field with H. Jiang (1994) and study the AC properties of yttrium-barium-copper oxide, the classic high-temperature superconductor.



Left to right: Ivar Giaever, Walter Harrison, Charles Bean, and John Fisher at the General Electric Research Laboratory, circa 1970.
(Photo by General Electric Research Laboratory, courtesy AIP Emilio Segre Visual Archives.)

The Bean Model remains important to this day; in fact, an international workshop devoted to the model was held in Barcelona in 2012. Quoting directly from the introduction to the workshop:

> *Fifty years ago, Charles Bean provided the superconducting community with a model efficient enough to allow computing in an understandable way the response of a superconductor to external magnetic fields and currents flowing through the superconducting parts: the so called critical-state approach. The technical and scientific community could develop from that moment analytical and numerical approaches that could solve the electrical current distribution and the magnetization hysteretic behavior in most geometries and field distributions. Forces, energy concerns [such] as losses, or remanence could be solved in an equilibrium state or in a sequence of equilibrium states.*

Charlie recognized very well that his model was great science, but he himself remained modest. At another conference a young scientist asked him if he was related to the person who had developed the Bean Model. Without missing a beat, Charlie joked: "Yes, he was my father," since it was so long ago.

Relatively early in his career, Bean expanded his scientific interests beyond magnetism and superconductivity. He also studied biophysics, and he encouraged colleagues to consider the field as well. In an invited talk to the American Physical Society on how to change from physics to biology, one of his recommendations was straightforward: "Start to eat lunch with biologists." In 1960 Bean managed to convince the now-renowned biophysicist Carl Woese to join the General Electric Research and Development Center in Schenectady, where he stayed for three years before joining the University of Illinois in 1970. And Charlie took his own advice and ate with Carl every day.

Bean was elected the first Coolidge Fellow at the GE laboratory. The Coolidge Fellowship program was a way to recognize the company's most valuable scientists, and its main advantage was that the recipient could go on sabbatical leave to any another institution with full pay. Charlie decided to go to Rockefeller University, where he stayed (not full time) from 1973 to 1978. There he was exposed to neurophysiology, and he eventually wrote a theory of stimulation of myelinated fibers that was published in the *British Journal of Physiology* (1974).

At about this time Bean had started to spend his summers in Woods Hole, MA, which he enjoyed enormously, both for its outdoor activities and its laboratories. When asked why, he said, "I like to be at a place where the library is open 24 hours a day." Here he became interested in sea urchin sperm, and he invented a clever method to determine the average velocity and length they can swim. He did this by having a dilute concentration of sperm in a solution above a clean gold surface, and each time a sperm hit the gold it stuck.

Very soon Bean's research papers began to be published in biophysics journals rather than physics journals. He first became interested in membranes, for example, and wrote a long treatise for the U.S. Department of the Interior on reverse osmosis (1969). Taking advantage of GE's Nuclepore membranes, he developed, together with Ralph DeBlois, a virus counter—a variant of the famous Coulter counter (1970). Later he developed a seminal theory of neutral porous membranes (1972). On the basis of this paper he was offered a professorship, which tempted him, though eventually he turned it down.

Bean took early retirement from GE in 1985 to become an Institute Professor at Rensselaer Polytechnic Institute, where he had been an adjunct professor since 1978. Because he was born in 1923, however, he was part of the last group of faculty who had to retire because of age. Officially he retired from RPI in 1993, but of course he kept on working. Bean was a born professor and loved teaching. While at GE he had often taught courses for the staff in subjects he was especially interested in, which benefited his colleagues. At Rensselaer he focused on undergraduate teaching.

Bean taught mostly undergraduate courses, such as introductory physics. But he took great pride in a course he called "Light and Color in the Open Air," based on a book with a similar name by M. Minnaert. He also exposed many undergraduates to real laboratory research. These efforts resulted in a series of simple papers in *The Physics Teacher* with titles such "The quicker-picker-upper," which measured the absorbency of paper towels (1990, 1991).

Bean also continued more serious research while at RPI. For example, being a good friend of French biophysicist P. G. de Gennes, through him Bean became fascinated by electrophoresis—in particular the way a strand of DNA twists through a gel, like a snake through grass. He analyzed and modeled the process, and in 1987 wrote a paper on the subject with H. Hervet.

Bean spent much of his later time looking for the elusive magnetic bacteria, which were rediscovered by R. P. Blakemore at Woods Hole in 1975 (they had been seen in 1963 in Italy by Salvatore Bellini but thereafter largely forgotten). The reason why these bacteria are guided by a magnetic field is that they have small internal magnets corresponding to the chain-of-spheres model. Bean developed simple equipment that enabled him to seek such magnetotactic bacteria virtually everywhere. He thought he had found some in a pothole right outside RPI, but before verifying and publishing his findings Bean died of heart failure.

Like most renowned scientists, Bean also held several part-time positions. For example, he was a consultant to U.S. Department of State from 1957 to 1958. Given his longtime interest in astronomy, he also served as a president of the Dudley Observatory from 1983 to 1990.

Wherever he was and in whatever he did, Charlie was greatly respected and an inspiration to his colleagues. Here is how Ivar Giaever (co-recipient of the 1973 Nobel Prize in Physics) has put it:

> *My career would never have happened if I had not been so fortunate [as] to have Charlie as a friend. Because of the Nobel Prize, I have been fortunate to be able to interact with many of the most outstanding scientists in the world, and I can truly say that Dr. Charles P. Bean measures up to the very best.*

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