SPECIAL ISSUE:

PHYSICAL REVIEW CENTENARY—FROM BASIC RESEARCH TO HIGH TECHNOLOGY

A century of fundamental physics research has appeared in the *Physical Review*. Such research is the seed corn of the technological harvest that sustains modern society.

Robert K. Adair and Ernest M. Henley

Edward Nichols and Ernest Merritt began the *Physical Review* at Cornell University in 1893. Any new journal incurs a financial risk; Cornell assumed that risk.

The first issue carried no editorial celebrating the birth of this first American journal devoted exclusively to physics, and we can presume that the editors considered it unnecessary to emphasize a purpose that was so universally understood: The journal would record efforts, especially by Americans, to understand the physical character of nature. Those efforts were both idealistic and pragmatic. The Silliman Lectures on Science, which had begun at Yale University ten years before, in 1883, were "designed to illustrate the presence and providence, the wisdom and goodness of God, as manifested in the natural and moral world. . . . The subjects would be selected from the domains of natural science." But if such an understanding of nature had a moral dimension—and even a religious dimension—we can be sure that in that American apogee of pragmatism, the editors of the journal and the authors of the papers they accepted had a sharp appreciation that an understanding of nature also generated important material advantages.

The time of the journal's founding is marked by the obituaries—with portraits—of eminent physicists who had died recently: John Tyndall and Heinrich Hertz are portrayed in the first volume, August Kundt and Hermann von Helmholtz in the second. Though many of the articles in the first two volumes are concerned with mensuration and subjects we might now file under applied physics, the first article (volume 1, page 1), by Ernest Nichols, is titled "The Transmission Spectra of Certain Substances in the Infra-red." The first sentence reads, "Within a few years the study of obscure radiation has been greatly advanced by systematic inquiry into the laws of dispersion of the infra-red rays." In another article in that volume Benjamin Snow, who moved to the University of Wisconsin after working in Germany, described his measurements of the infrared spectra of alkali metals.

Long before Niels Bohr, and with Johann Balmer's insights (published eight years before) of little help, Nichols and Snow were observing a part of nature that they did not understand deeply. But they proceeded with confidence that an understanding of the emanations of the atoms they studied would come and would be valuable. Abraham Pais[1] refers to Nichols's paper, among others, commenting, "These experimental developments are of fundamental importance for . . . the quantum theory, since they were crucial to the discovery of the blackbody radiation law."

In the first volume there were also infant steps in what would later be called rheology, condensed matter physics and statistical mechanics—though the *Journal of Physical Chemistry,* also founded at Cornell (but a few years later, in 1896), was to be the American journal of choice for the discussion of Josiah Willard Gibbs's work in statistical mechanics. Along with articles, the new *Physical Review* published "Minor Contributions" in 1-point-smaller type. Hence, "Brief Reports" and *Physical Review Letters* have antecedents. Book reviews appeared in a "New Books" section. Helmholtz's *Handbuch der Physiologischen Optik* and J. J. Thomson's *Recent Researches in Electricity and Magnetism* were reviewed in volume 1. In the "Notes" section the editors reported on an August 1893 meeting of the American Association for the Advancement of Science held in Madison, Wisconsin, where 19 papers were presented in the physics section, including one by Edward Morley on his interferometric work. According to the note, the meeting was not well attended as a consequence of the depressed economy.

Most of the papers in the first volume have a single author, two have three authors, and no paper in either of the first two volumes lists more. The total number of

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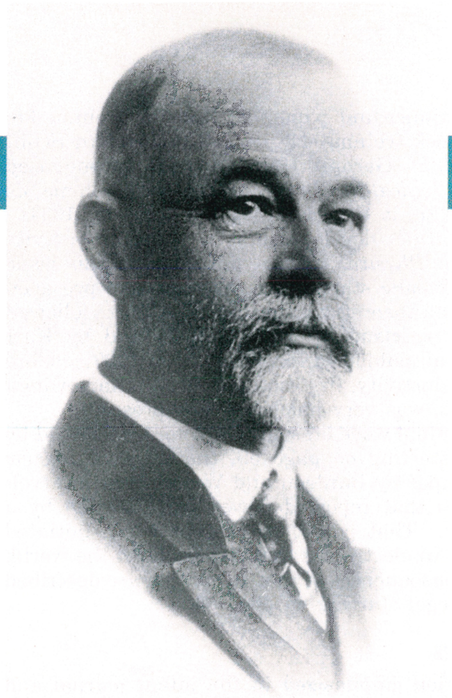


Founding editors of the *Physical Review,* Edward Nichols (far left) and Ernest Merritt. (Courtesy of Cornell University physics department.)

authors in the first three volumes of the *Physical Review* does not quite equal the number of coauthors of some single experimental particle physics papers published in *Physical Review Letters* today. Although there are no women authors in the first volume, three are listed in volume 2: Mary L. Crehore, Mary C. Noyes and Mary C. Spenser. Noyes was sole author of her paper "The Influence of Heat and Electric Current upon Young's Modulus for a Piano Wire."

Beginning in 1903 with volume 16, the Notes section listed the proceedings of the American Physical Society, formed in 1899, with a comment to the effect that the *Physical Review* would continue to publish these proceedings and that the *Bulletin of the American Physical Society* had been discontinued.

In 1912, after the publication of volume 35, APS, now 13 years old and mature, took over the *Physical Review,* beginning with volume 1 of the second series on 1 January 1913. As an APS journal, the *Physical Review* continued to publish papers on practical matters—some, such as the description by William Coolidge in 1913 (volume 2) of his x-ray tube, of immediate economic importance. But the early currents of American pragmatism did not suppress those queries into the fundamental character of nature that, over time, have proved to be more important economically as well as intellectually.

During the first decades of the *Physical Review,* the center of physics was firmly based in Europe, and the bulk of the seminal papers in quantum mechanics, relativity, the physics of the nucleus and elementary particles, atomic physics, condensed matter physics and much else are found in the important European journals. But the *Physical Review* was known early on as an important journal, if not the preeminent physics journal we know today.

Fundamentals of physics

The world we know and the technical command of nature we apply to that world would be vastly different without the deeply fundamental knowledge described in seminal papers in the first half-century of the *Physical Review.* Roots of all of the subjects covered in the eight articles in this issue of PHYSICS TODAY can be found in such papers—whose authors themselves could never have foreseen the ultimate consequences of their studies. These fundamental researches constituted the seed corn that has led to a scientific harvest of inestimable value today.

Robert Millikan published his "oil drop" measurement of the charge of the electron in 1911 (volume 32). In 1923 (volume 21) Arthur Compton's demonstration of the particle nature of the photon appeared, and in 1927 (volume 30) Clinton Davisson and Lester Germer showed the wave nature of electrons. In 1929 (volume 33) Edward Condon and Ronald Gurney published their description of quantum tunneling and the alpha decay of nuclei.

While of no clear economic importance, the remarkable debate on the fundamentals of quantum mechanics opened by the paper by Albert Einstein, Nathan Rosen and Boris Podolsky in 1935 (volume 47) and the response by Bohr (writing his name "Nils" on that paper) later that year (volume 48) represents an intellectual and philosophical landmark that continues to play a major role in our efforts to understand and define reality.

Atomic physics

The essays into the physics of the atom by Nichols and by Snow reported in the first volume of the *Physical Review* were the forerunners of many more reports of studies of atomic physics. This fundamental physics, conducted with little concern about economic consequences, underlies a substantial portion of our economy today.

Though the quantum revolution in physics (fueled by insights into atomic physics) was centered in Europe and reported for the most part in other journals, the *Physical Review* played a substantial role. The journal published significant papers by Erwin Schrödinger (volume 28, 1926), by Millikan and Ira S. Bowen (volume 24, 1924), by Henry Norris Russell (volume 29, 1927) and by John

S. Foster (volume 23, 1924). Important contributions by Samuel Goudsmit (volume 31, 1928), John C. Slater (volume 32, 1928) and Gregory Breit (volume 28, 1926) were followed by many others by these authors. Other famous names and important papers in atomic physics appear: Russell, A. G. Shenstone and Louis A. Turner (volume 33, 1929); Harold Urey, Ferdinand C. Brickwedde and G. M. Murphy (volume 40, 1932); Gilbert N. Lewis and Frank M. Spedding (volume 43, 1933); Otto Laporte and David Inglis (volume 35, 1930); Condon and George Shortley (volume 35, 1930); and Max von Laue (volume 37, 1931).

All of this work, as well as Nichols's paper in volume 1 and the early papers on quantum mechanics, provided a foundation for the development of lasers, described in this issue by Nicolaas Bloembergen beginning on page 28. Fiber optics, described in the article by Alastair Glass beginning on page 34, also owes much to these early atomic physics papers.

The *Physical Review* published papers on atomic physics by R. W. Wood (volume 38, 1931), Henry Margenau (volume 43, 1933), Rudolf M. Langer (volume 35, 1930), Walter V. Houston (volume 30, 1927), John H. Van Vleck and N. G. Whitelaw (volume 44, 1933), and Julian Mack, Laporte and R. J. Lang (volume 31, 1928). An early paper on molecular-beam work by I. I. Rabi and his collaborators Jerome Kellogg and Jerrold Zacharias appeared a little later (volume 46, 1934). Then in 1937 (volume 51) Rabi published the paper that Norman Ramsey and George Pake cite as the beginning of nuclear magnetic resonance in their articles starting on pages 40 and 46, respectively.

Condensed matter

The world today is not the same as the world viewed by Nichols and Merritt in 1893, and much of that difference follows from our increased knowledge of the properties of condensed matter. Though most important initial studies of condensed matter were printed in Europe, the *Physical Review* published a substantial set of important early papers in this area.

As early as 1924 (volume 23) Slater wrote on crystal structure energies; later he published, among other work, papers with John Kirkwood (volume 37, 1931) and William Shockley (volume 50, 1936). Other names foreshadowed the American explosion to come: Yakov Frenkel (volume 37, 1931), Margenau (volume 38, 1931), Eugene Wigner and Frederick Seitz (volume 43, 1933), Wigner and John Bardeen (volume 48, 1935), and Amelia Frank (volume 39, 1932), who married Wigner a few years later.

And there are important papers by Houston (volume 38, 1931), Van Vleck (volume 41, 1932) and Leonard Schiff (volume 47, 1935). Gerhard Herzfeld wrote on condensed matter in the *Physical Review* as early as 1930 (volume 35) and later with Maria Goeppert Mayer (volume 46, 1934).

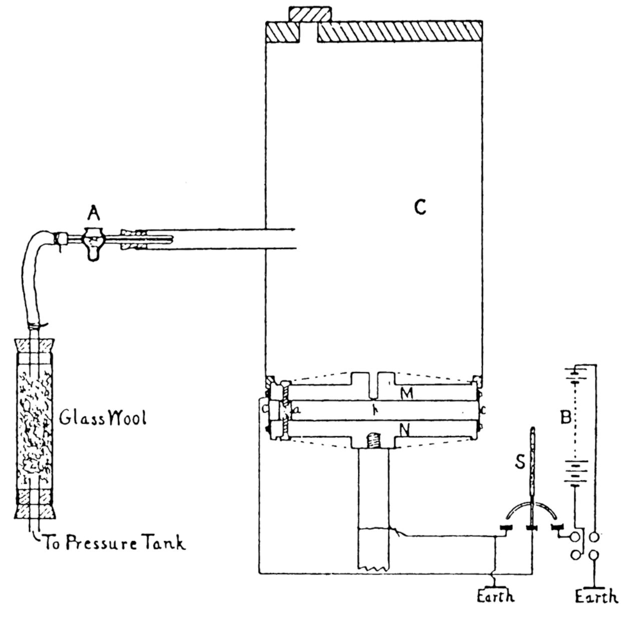
The important developments in superconductivity reported in the *Physical Review*, described in this issue by Theodore Geballe starting on page 53, were presaged by a significant theoretical surmise by Slater, followed by respectful criticisms by Fritz London and by Kurt Mendelssohn, all published in volume 51 of 1937. Before then superconductivity, first noted by Heike Kamerlingh Onnes in 1912, was very much a Dutch preserve.

Of the seminal work on semiconductors, described by Alan Fowler starting on page 59, the *Physical Review* printed the paper by Bardeen and Walter Brattain (volume 74, 1948) that reported power amplification by a semiconductor. That paper, with other work, initiated the revolution in electronics that has changed the world. Some of the consequences of that revolution are described by Richard Siegel starting on page 64.

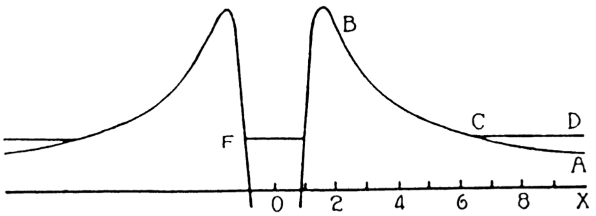
Accelerators

The mensuration emphasized in the infant journal and the instrumentation that allowed that mensuration seemed to strike a particularly American chord. The maturation of American physics that occurred about 1930 was perhaps most evident in the development of particle accelerators, which after Rolf Wideroe, and John Cockcroft and Ernest Walton, became almost exclusively an American preserve. Merle Tuve, working with Breit, Lawrence Hafstad and Odd Dahl, was only a little behind Cockcroft and Walton in accelerating particles that would penetrate nuclei. Tuve and his coworkers reported their use of a spark-gap Tesla-coil voltage generator and a multiple-electrode accelerator tube for that purpose in volumes 35 and 36 (1930) of the *Physical Review.*

About the same time, Ernest Lawrence, who grew up across the street from Tuve in Canton, South Dakota,



Oil-drop measurement of the charge of the electron by Robert Millikan, reported in the *Physical Review* in 1911, is one of the classic 20th-century experiments. (From *Phys. Rev.* **32**, 349, 1911.)



Quantum mechanical tunneling model of radioactive decay by Ronald Gurney and Edward Condon. The horizontal line is the measured energy of the alpha particle emitted by uranium. Curve B is a model of the potential felt by the alpha particle in the presence of the rest of the uranium nucleus. (From *Phys. Rev.* **33**, 127, 1929.)

picked up Wideroe's resonance acceleration idea and, with his graduate student M. Stanley Livingston, built the cyclotron. They reported preliminary results in the *Physical Review* (volume 37, 1931). With another graduate student, David H. Sloane, Lawrence described a successful linear resonance accelerator in the next volume of the journal (volume 38, 1931).

The same volume included Robert Van de Graaff's work using electrostatic generation to achieve high voltages, and in 1935 (volume 48) an article by Tuve, Hafstad and Dahl described the first electrostatic (Van de Graaff) generator to accelerate particles. A little later (volume 53, 1938) the journal published papers by Raymond Herb and others describing the pressurized electrostatic generators Herb built, which were so important in nuclear physics research in the 1940s.

In 1940 (volume 58) the *Physical Review* published Donald Kerst's description of the betatron. One year later (volume 60) the journal carried an analysis by Kerst and Robert Serber of betatron orbit stability.

In 1945 (volume 68) Lawrence's brother-in-law Edwin McMillan (he and Lawrence were married to sisters from New Haven, Connecticut) described the phase stability that led to the electron synchrotron. Much the same principles were applied in the designs of relativistic cyclotrons (the synchrocyclotrons) first developed at Berkeley and of proton synchrotrons. "Strong focusing," described by Ernest Courant, Livingston and Hartland Snyder in 1952 (volume 88), revolutionized proton synchrotrons and improved all heavy-particle accelerators.

Aside from providing information on the structure of elementary particles and nuclei, accelerators play an essential role today in other areas of science and in medicine. Synchrotron light from electron synchrotrons is used in materials research, in the manufacture of microelectronics and in studies of the structure of proteins and other biologically interesting macromolecules. Other accelerators are used in the production of isotopes, largely employed in medicine, and as subtle surgical tools, as discussed by Henry G. Blosser starting on page 70.

Nuclei and particles

The early work in nuclear physics, largely devoted to the understanding and exploitation of natural radioactivity, was led by Maria Sklodowska Curie in Paris and Ernest Rutherford in Cambridge. The later American dominance in accelerator design led to an accompanying dominance in nuclear physics in the 1930s, and much of the work was reported in the *Physical Review*. Again, the flow of names, familiar 60 years later, tells of the breadth and depth of scholarship reported in the journal. We have Breit (volume 42, 1932), Kenneth Bainbridge (volume 42, 1932), Goudsmit (volume 43, 1933), Enrico Fermi and George Uhlenbeck (volume 44, 1933), and Fermi and Eduardo Amaldi (volume 50, 1936). Carl Anderson described his discovery of the positron in 1933 (volume 43) and, with Seth Neddermeyer, the meson (now muon) in 1936 (volume 50). There are also papers by J. Robert Oppenheimer and M. S. Plesset (volume 44, 1933); Lewis, Livingston and Lawrence (volume 44, 1933); John Dunning, George Pegram, G. A. Fink and Dana Mitchell (volume 48, 1935); Franco Rasetti, Emilio Segrè, Fink, Dunning and Pegram (volume 49, 1936); and Hafstad, Norman Heydenberg and Tuve (volume 49, 1936).

Beginning in the mid-1930s, as the center of nuclear physics research moved to the United States along with immigrant scientists, the *Physical Review* published theoretical papers by Hans Bethe (volume 47, 1935) and by Emil Konopinski and Uhlenbeck on beta decay (volume 48, 1935). The Breit–Wigner formula appeared in 1936 (volume 49). Along with theory, there were important experimental papers by H. Richard Crane, L. A. Delsasso, William Fowler and Charles Lauritsen (volume 48, 1935); Thomas Bonner and W. M. Brubaker (volume 47, 1935); and Lawrence, McMillan and Edward Thornton (volume 48, 1935).

The seemingly esoteric knowledge of the properties of nuclei has changed our world, and many of the roots of that change can be found in papers published by the *Physical Review* a long time ago. Neutron beams from nuclear reactors play an important role in materials research and biophysics; nuclear power reactors account for about 15% of electrical power in the US, with no commensurate loading of the atmosphere with carbon dioxide; isotopes are important in medicine; and the magnetic moments of nuclei, studied early by Otto Stern (volume 45, 1934) and Rabi (volume 51, 1937), are exploited in nuclear magnetic resonance imaging.

Seed corn

A very large part of the enormous number of pieces of information that fit together to make up the science that defines our civilization are found in the *Physical Review* that Nichols and Merritt founded 100 years ago. Most of those pieces, including many that were found to lie near the center of important patterns, were extracted from an indifferent nature by men and women who sought no immediate material advantage but who labored because they believed that it was important to understand nature. That work by our forebears on fundamental physics with no practical goal in sight was the seed corn of the scientific harvest that we are now reaping. The eight articles of this special issue describe some of the seed corn and the subsequent harvest.

The critical importance of seed corn was known to all primitive agrarian societies. No matter how hard the winter, the tribe did not eat the seed corn—though some might starve. To consume the seed corn was to destroy the future. Today many of us worry that our tribe is ignoring the primary importance of basic research. Though times be hard, if we proceed, as our predecessors did, to sow the seed corn of research with no goal except the understanding of nature, we will ensure the harvest that will sustain our grandchildren.

Reference

1. A. Pais, *Subtle Is the Lord: The Science and Life of Albert Einstein,* Oxford U. P., New York (1982). ■