NATIONAL ACADEMY OF SCIENCES

LEONARD ISAAC SCHIFF

1915—1971

A Biographical Memoir by
F. BLOCH

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March 29, 1915–January 19, 1971

BY F. BLOCH

LEONARD SCHIFF was born in Fall River, Massachusetts. His father, Edward, descended from a Lithuanian family of rabbinical scholars, had come to the United States as a young boy. An early ancestor was an apothecary who took the name "Schiff," the old German word for a vessel used in his trade. His mother Mathilda (nee Brodsky), also of Lithuanian descent, was born in Brooklyn. She was an accomplished pianist and composer; her two sons and three daughters all began to receive musical education when they were still very young. She began to teach Leonard to play the piano when he was four years old, but two years later he took up the clarinet, an instrument that he loved and came to master remarkably well.

Leonard's school years were spent in Brooklyn after his family had moved there. This was a time of financial difficulties for Edward Schiff, who helped to alleviate them by free-lance writing. Leonard was a precocious child; therefore he was quickly advanced in school in order to remain sufficiently occupied with his classwork. Although by no means one-sided, his special interest and talent in mathematics soon became evident; he later belonged to a small group of volunteers who received additional instruction from their mathematics teacher after school hours. The knowledge thus acquired brought Leonard so far that he was well versed in calculus when he graduated from James Madison High School in June 1929.

Another family move brought Leonard to Columbus, where he entered Ohio State University at the age of fourteen. It was his desire to come closer to reality than he felt he could reach through pure mathematics that brought Leonard Schiff to the study of physics. The subject was taught at the School of Engineering, and he received the bachelor's degree (B.E., physics) in 1933. His first piece of research was done in the course of the next two years; it arose from close contact with L. H. Thomas, an outstanding member of the faculty and originator of the well-known Thomas factor in atomic physics. Leonard's investigation concerned the quantum theory of metallic reflection and analyzed the effect of surface properties. Published with Thomas as coauthor, it already shows the influence of Schiff's method, seen in much of his later work, of starting with fundamentals and proceeding systematically from there to the derivation of new results. He once told his younger brother Dan, also a physicist: "Physics is really simple—you only have to know the few basic facts whereupon everything else just follows."

After receiving the degree of master of science, Leonard left Columbus in 1935 to continue his graduate studies at the Massachusetts Institute of Technology. Although much younger than his classmates, he surpassed most of them in training and knowledge. He and some fellow students, including Marvin Chodorow, who became a lifelong friend, soon formed a group of close companions who gathered for hikes or similar occasions to talk about physics and other matters of shared interest. Clearly a hard worker, Leonard appeared self-assured while totally free of arrogance; and he was also blessed with a fine sense of humor.

From the beginning, Schiff enrolled in the advanced courses offered at MIT, and it did not take long before he was also engaged in research. A course on statistical problems that he took from Robley D. Evans led to their collaboration on the statistics of counters and to a joint publication in 1936. With Philip M. Morse and J. D. Fisk as coauthors, an earlier publication of the same year concerned an altogether different subject, the collision of protons and neutrons. It is significant because it marks the beginning of Schiff's association with Phil Morse, to whom he felt drawn by personality as well as by their shared inclination toward mathematical physics, meant in the more literal sense than in the old usage for the entire field of theoretical physics. An emphasis on mathematics can be noticed here in that the potential is chosen to allow a rigorous analytical solution of the Schrödinger equation. The work is also significant because it represents the start of Leonard's occupation with problems of collision, a phenomenon which he later investigated in its many different aspects so that it runs as a strong thread through his life's work. In immediate continuation, he included the deuteron as collision partner and treated the related capture and binding process of neutrons, which yielded four more papers in 1937 and, by further extension, led in June of that year to his Ph.D. thesis under the supervision of Morse, entitled "Theory of the Collision of Light Elements."

He worked during the rest of the summer as a research physicist for the General Electric Company, whereupon a fellowship from the National Research Council for 1937 and 1938 enabled him to join the group of young theorists at the University of California in Berkeley and the California Institute of Technology in Pasadena. It was the presence of J. R. Oppenheimer, then a joint professor at these institutions, that had brought them together and greatly influenced their activities. Oppenheimer's quick grasp in the course of a discussion was most impressive, but the ensuing comments were often quite mystifying. One can see how Leonard's generally positive attitude enabled him to reconcile this fact with his deep desire for clarity by quoting from a memorial talk that he gave in Berkeley after the death of Oppenheimer: "I think he enjoyed talking in riddles; certainly there was an enigmatic quality to the choice of his words. Students and colleagues spent much time wondering about just what he had meant and often ended up with a much deeper understanding of the subject than they would have attained otherwise."

An appointment as a research assistant after the expiration of Schiff's fellowship extended this first period in California by two more years. The intimate contact with other highly gifted members in the group, among them W. E. Lamb and R. Serber, contributed no less than Oppenheimer's stimulating influence to his productivity during that time. The collaboration with Lamb led to their joint paper on the electromagnetic properties of nuclei arising from the meson exchange between their constituents. This started his interest in the role of mesons, which he continued to pursue through a series of investigations in the 1950's. The scope of his activities was further enlarged, partly through work with H. Snyder and others, to encompass a variety of subjects as different as radiative capture of electrons, liquid helium, and the quadratic Zeeman effect, thus demonstrating anew Schiff's extraordinary versatility.

Those three years, spent mostly in Berkeley, brought him enrichments not only through his scientific work but also through new friendships, particularly with Bob and Charlotte Serber, Dale and Nelle Carson, Art Kipp, and Bill Steinhoff. He greatly enjoyed the evenings of chamber music in the home of Martin Kamen where he sometimes joined the fine players with his clarinet. Last and most important, it was in Berkeley that he met Frances Ballard, then a student of history, and found in her the ideal companion of his future life. They married in 1941 after Leonard's move to Philadelphia; complementing each other in many ways, they had in the course of time a daughter, Ellen, and a son, Lee.

The academic career of Leonard Schiff began in 1940 with an appointment as instructor at the University of Pennsylvania, followed at intervals of two years by promotion to assistant and associate professor. His exceptional gift for teaching immediately became evident; he impressed the students so much by his perfect clarity and his pedagogic skill that they regarded him as the best teacher at the University. Leonard was not the man, however, to earn such a reputation at the expense of his research. Continuing his interest in the properties of liquid helium, brought from Berkeley, he was able in his first year as instructor to publish several papers on the subject, aimed particularly at a better understanding of the phase transition to the superfluid state. He still found time to deal in two more papers with the performance of the electron microscope before his publications were brought nearly to a standstill until the end of the war.

Like that of most American physicists, Schiff's research during this interval became directed towards the war effort and the announcement of results was restricted by security regulations. In contrast to the specialization common at this time, he sometimes served simultaneously on many different projects, several of them arranged through Gaylord Harnwell, the chairman of the Physics Department at Pennsylvania. The first was initiated upon a request to develop a device for measuring the purity of helium in blimps. Leonard provided the analysis of the data, but he also assisted his coworker Robert Hofstadter, who had entered the University six months before him, in ably performing some of the glassblowing required for the apparatus. Neither of them could anticipate that they were later to be colleagues at Stanford, where the friendship, cemented at that time, would lead to a most fruitful interplay of their common concern about electron scattering at high energies.

Schiff later participated in a number of projects that dealt with various aspects of submarine warfare. In close personal contact with the successive directors—F. Seitz, A. W. Lawson, W. E. Stephens, and P. H. Miller—he was associated with a group formed to study the operation of the crystal detectors used in radar systems. Research in this group led Walter Meyerhof, his former student and a future colleague at Stanford, to the discovery of surface states and to a Ph.D. thesis on the subject. It is most remarkable that all the activities described above did not prevent Leonard from carrying on some teaching and from serving in Harnwell's absence as acting chairman of the Physics Department from the summer of 1942 to April 1945.

At that time he was granted a leave of absence to join the atomic bomb laboratory at Los Alamos, at Oppenheimer's request, and he was among those who witnessed in the Trinity Test at Alamogordo the first explosion of an atom bomb. Deeply impressed by this event and the subsequent destruction of Hiroshima and Nagasaki, he wrote a letter to the *Forum of the Review of Scientific Instruments* entitled "Atomic Energy and Physicists" shortly before leaving Los Alamos in January 1946. It warns with remarkable foresight that other nations would be able to make atomic bombs and that they could be made much more powerful than those used against Japan. The physicists were asked to use their special position not only to support international control of nuclear weapons, but also to make the public aware of the great benefits that atomic energy could bestow upon mankind.

After his return to Philadelphia, he again carried out the normal teaching and research activities during his remaining year-and-a-half at the University of Pennsylvania. He further used the partial removal of government restrictions to promptly publish, with his collaborators, some of the results previously reported only in classified documents.

Leonard Schiff began the last and longest period in his academic life when he joined the Physics Department of Stanford University in the fall of 1947. Here, as elsewhere in the United States, the ways of physics had been greatly influenced by developments during the war, both in opening new avenues of research and through the generous support received from government agencies. At Stanford the principal new areas resulted from the vast improvements of radio and microwave techniques in the development of radar, now channelled into peace-time applications, the former used for the study of nuclear magnetism, the latter for the acceleration of electrons. Both developments were rooted in work done at Stanford before the war in a small department and with very modest means; now they were seen to have a much wider scope that pointed towards an extended period of promising future research.

While a great increase in staff did not seem to be indicated, it was recognized that the new era called for additional qualified members of the department. Edward Ginzton and his wife Artemas, a cousin of Frances Schiff, had known Leonard intimately for a long time. Upon Ginzton's suggestion, it was quickly agreed, both for reasons of personality and in view of Schiff's excellent record, that a position should be offered to him; it boded well for his future in the department that he accepted the offer of an associate professorship without much hesitation. To do justice to his great influence during nearly a quarter of a century at Stanford, the role of Schiff has to be considered in several different, yet not unconnected, aspects.

To begin with his part in affairs of the university, it was with the promotion to a full professorship, just a year after his arrival, that he succeeded Paul Kirkpatrick as executive head of the Physics Department. The following eighteen years, during which he remained in this position, were to give ample proof that a more fortunate choice could hardly have been made. Through strict adherence to democratic principles, Leonard gained the complete confidence of his colleagues and became their ideal spokesman in dealing with the administration of the University. The strengthening of the department by a number of excellent appointments and the move from inadequate quarters to a large new building with connected structures for administrative offices and auditoria were but two of the significant changes during the period of his chairmanship. Another major development resulted from the evergrowing scope and size of the department's research activities. While gratifying in many respects, the expected considerable expansion of certain activities caused problems since it called for special arrangements to allow their independent operation. This gave rise to the installation of applied physics as a separate department of the University and to the creation of the Stanford Linear Accelerator Center as a national laboratory; both events were accompanied by the transfer of some members of the department who became the core of a greatly enlarged staff. There followed a prolonged exchange of opinions about the relation of these new entities to the physics department with the strong involvement of the chairman until the issues had been sufficiently clarified and agreements were reached that worked to the greatest mutual benefit.

When Schiff decided in 1966 to give up the position as head of the department, he could look back with satisfaction to the achievements reached over his many years of unselfish devotion to the task that had been entrusted to him. Far from ending his services to the University, however, he continued for another three years as chairman of the Advisory Board, the highest position for the faculty at Stanford, and was elected as the first chairman of the newly formed senate during the University's turbulent year of 1968. In these as well as in a number of other functions, he never hesitated to give freely of his time and greatly contributed by his wisdom and judgment to the general welfare of the institution.

Coming now to his particular concern with education, Schiff realized the great importance of introductory courses for the development of a student and the experience required for their being taught well. He therefore saw to it that these classes were assigned to senior members of the faculty, setting a high standard by his own participation. The quality of his teaching came not only from an innate pedagogic ability but also from his having given a great deal of thought to the aims to be realized. He devoted much of an article about science in general education to clarifying the difference between pure science and technology and made a strong case for his conviction that the cultural rather than the utilitarian aspect of science should be the basis of scientific education. In a talk entitled "The Education of a Scientist," he warned against premature specialization and concentration on techniques—as advocated in the days of the Sputnik—arguing that a student of science will be best prepared for his future if he first acquires a broad knowledge. The talk ended with the following remark about the prospects of a scientist: "If he happens to become a university professor, perhaps his greatest ambition will be to develop a research student who will some day make a greater contribution to science than was within his own power"—a touching revelation of Schiff's personal feelings. In 1966, he received the Oersted Medal of the American Association of Physics Teachers for his "notable contribution to the teaching of physics" and Stanford's annual Dinkelspiel Award "for outstanding service to undergraduate education."

Schiff's widest influence as a teacher and scholar, however, has been achieved through his book, *Quantum Mechanics*. Although it deals with the very basis of modern physics, discovered twenty-five years earlier, there existed nothing comparable to this text before the first edition in 1949, and nothing like this volume was to appear for many years to come. Translated into many languages, among them Russian and Japanese, it is found today on most scientific bookshelves all over the world and has been instrumental in bringing up a whole generation of physicists. The second edition appeared in 1955 and the third in 1968, enriched each time to keep up with recent developments.

It is research, however, that was always of primary importance to Leonard, whose well-organized system of working enabled him to remain highly productive in the pursuit of his investigations without neglecting other activities. The variety of topics he chose again reflects a wide range of interests, but two major groups stand out: the recurrent occupation with the theory of collisions and with general relativity.

The collision and scattering of particles was mentioned before to be of particular significance in the work of Schiff. His attention to the subject received a fresh stimulus through the development of the linear electron accelerator at Stanford. As early as 1949 he discussed in an extended report the type of information that could be obtained with the new accelerators, and he emphasized the utility of electron scattering as a probe of nuclear and nucleon structure. The important results of the experiments carried out by Hofstadter and his collaborators were to amply fulfill his expectations. In close contact with the progress of their work during the following years, he significantly contributed to the analysis of the data and investigated related problems concerning the treatment of scattering processes. He reviewed the research activities in high energy physics that bear on nuclear structure in 1955, and once more in 1968, under the title "Low Energy Physics from a High Energy Standpoint," aptly chosen to characterize a field in which he can be truly said to have been one of the founders.

Except for the application of Mach's principle to a problem of rotating charges, suggested in 1939 by Oppenheimer, Leonard's many contributions to general relativity were made almost entirely during the last decade of his life. The first of them was motivated by certain arguments in favor of the idea that the gravitational mass of antimatter might be negative. Schiff showed in a careful analysis that this is incompatible with the virtual presence of positrons in an atom, demanded by the formalism of quantum electrodynamics. A corresponding negative contribution to the gravitational mass would result in so large a difference from the inertial mass that it is ruled out by the high accuracy with which the equality of these two masses has been experimentally established.

The decision to base this conclusion on empirical evidence rather than to simply state it as a necessary consequence of general relativity characterizes the principal concern of Schiff's later work in that field. While fully aware of the depth and internal consistency of Einstein's theory, he felt that it was supported by a somewhat slender body of observations which, furthermore, had yielded most of the relevant data only within a considerable margin of error. The equality of inertial and gravitational mass being the most accurately confirmed basis of general relativity, he showed that it imposed powerful constraints on the coupling of gravitation to systems of interacting particles. In the same context he argued that this equality might suffice to establish Einstein's much more far-reaching principle of equivalence, the "Schiff conjecture," which has stimulated a great amount of research in that area.

Another important contribution to general relativity was his proposal of a new test, with results to be obtained by measuring the rate at which the axis of an orbiting gyroscope would change its direction with respect to the fixed stars. He calculated that for an orbit at 500 miles altitude it would amount to about seven seconds of arc per year, caused mainly by orbital motion, but with a correction of the order of one percent due to the Lense-Thirring effect of the earth's rotation upon the gravitational field. The development of the apparatus for this delicate measurement by Fairbank and his collaborators at Stanford is still in progress, and the performance of the test is awaited with great interest.

A close connection between experimental undertakings and Schiff's contributions to the theory manifested itself in many of his other investigations as well. As an example, he discussed the measurability of nuclear electric dipole moments when the possibility of such a measurement in Helium-3 was brought to his attention. Another example is his treatment of the gravitation-induced electric field near a metal, motivated by an experiment to observe the free fall of electrons in a hollow metallic cylinder. His willingness and ability to be of help to the experimentalists was greatly appreciated while at the same time providing him with a good deal of personal pleasure. "I like to solve problems" was one of his sayings, and it is not surprising that he had a special admiration for Rayleigh, a man whose work encompassed nearly all the physics of his time and whose biography he planned to write after retirement.

Beyond his prolific activities at Stanford, Schiff showed a great concern through his engagement in numerous problems concerning science at large. As a member of the council of the American Physical Society, in early 1956 he sent a memorandum to the director of the American Institute of Physics in which he advocated the establishment of a journal, tentatively to be named the *Journal of Mathematical Physics*. He reasoned that the ever increasing bulk of the *Physical Review* called for one or more new journals and delineated the scope of this particular one "to include any paper that applies established methods of mathematics or theoretical physics to a problem of physical interest, where the novelty lies in the mathematical procedure rather than in the physical understanding which is attained." His proposal initiated the actions that led to the start of the *Journal of Mathematical Physics* in 1960. Because of his prominent part in the preceding deliberations, he was asked to become the chairman of the editorial board; he declined but served as associate editor during the first two years of the *Journal.*

His services were further sought, and Schiff freely consented for extended periods to join the editorial staffs of the *Physical Review,* the *Reviews of Modern Physics,* and several other journals. He was a fellow or officer in many learned societies, including the American Academy of Arts and Sciences and the National Academy of Sciences, where he was chairman of the Physics Section at the time of his death.

The extraordinary variety of Leonard's professional pursuits, indicated in the preceding account, and his careful attention to each of them might invoke the image of a man under constant severe pressure. Yet such was the wealth of his personality that he never lost his quiet and considerate way with others, nor was he forced to sacrifice the enjoyment of his family, the company of his friends, or his love of music and nature to devote himself to his equally beloved science. There was much that Leonard Schiff still had to give and wanted to give when a heart failure brought his life to a sudden end.

THE AUTHOR is greatly indebted to Marvin Chodorow, Robert Hofstadter, Walter Meyerhof, Robert Wagoner, Dirk Walecka, Frank Yang, and particularly Frances Schiff for much valuable information provided to him in the writing of this biography.

BIBLIOGRAPHY

1935

With L. H. Thomas. Quantum theory of metallic reflection. Phys. Rev., 47:860.

1936

Statistical analysis of counter data. Phys. Rev., 50:88.

With R. D. Evans. Statistical analysis of the counting rate meter. Rev. Sci. Instrum., 7:456.

With P. M. Morse and J. B. Fisk. Collision of neutron and proton. Phys. Rev., 50:748.

With J. B. Fisk and W. Shockley. On the binding of neutrons and protons. Phys. Rev., 50:1090.

1937

With P. M. Morse and J. B. Fisk. Collision of neutron and proton. II. Phys. Rev., 51:706.

Inelastic collision of deuteron and deuteron. Phys. Rev., 51:783.

Scattering of neutrons by deuterons. Phys. Rev., 52:149.

On the capture of thermal neutrons by deuterons. Phys. Rev., 52:242.

*Modern ideas concerning the nucleus of the atom. Gen. Electr. Rev., 40:504.

1938

With W. E. Lamb, Jr. On the electromagnetic properties of nuclear systems. Phys. Rev., 53:651.

With M. E. Nahmias. Sur l'absorption des rayons béta des radio-éléments. J. Phys. Radium, 9:140.

Excited state of He^3. Phys. Rev., 54:92.

On the paths of ions in the cyclotron. Phys. Rev., 54:1114.

1939

With H. Snyder. Theory of the quadratic Zeeman effect. Phys. Rev., 55:59.

A question in general relativity. Proc. Natl. Acad. Sci. USA, 25:391.

(The asterisk denotes publications that do not report original research.)

1940

With H. Snyder and J. Weinberg. On the existence of stationary states of the mesotron field. Phys. Rev., 57:315.
Scattering of light by liquid helium. Phys. Rev., 57:844.
Field theories for charged particles of arbitrary spin. Phys. Rev., 57:903.
With P. Morrison. Radiative K capture. Phys. Rev., 58:24.

1941

Theory of degenerate non-ideal gases. Phys. Rev., 59:751.
On the phase transition in liquid helium. Phys. Rev., 59:758.
Note on the structure of liquid helium. Phys. Rev., 59:839.
Degenerate non-ideal gases and liquid helium. Phys. Rev., 60:362.
With R. Hofstadter. Peak and null indicating circuit. Rev. Sci. Instrum. 12:448.
With L. Marton. Determination of object thickness in electron microscopy. J. Appl. Phys., 12:759.
*Statistical mechanics (book review). Rev. Sci. Instrum., 12:493.

1942

Ultimate resolving power of the electron microscope. Phys. Rev., 61:721.

1944

With P. H. Miller. A simple high impedance A.C. voltmeter. Am. J. Phys., 12:173.

1945

With P. H. Miller and W. E. Stephens. *Contributed points of view. Rev. Sci. Instrum., 16:58.

1946

Production of particle energies beyond 200 Mev. Rev. Sci. Instrum., 17:6.
Energy-angle distribution of betatron target radiation. Phys. Rev., 70:87.
*Atomic energy and physicists. Rev. Sci. Instrum., 17:88.
With E. C. Nelson. *What about energy in 1946? Look Magazine, 8 January:66.

*Statistical thermodynamics (book review). Rev. Sci. Instrum., 17:439.

With R. E. Marshak and E. C. Nelson. **Our Atomic World.* Albuquerque: University of New Mexico Press.

Thresholds for slow neutron induced reactions. Phys. Rev., 70:562.

Resonance fluorescence of nuclei. Phys. Rev., 70:761.

Discussion of the fluorine-proton resonances. Phys. Rev., 70:891.

1947

With B. Goodman and A. W. Lawson. Thermal ionization of impurity levels in semi-conductors. Phys. Rev., 71:191.

With A. W. Lawson and P. H. Miller, Jr. A device for plotting rays in a stratified medium. Rev. Sci. Instrum., 18:117.

With K. S. M. Davidson. Turning and course-keeping qualities. Trans. Soc. Naval Arch. Mar. Eng., 54:152. (Partially reprinted, The Shipbuilder and Marine Engine-Builder, 54:274.)

With H. Feshbach. Thresholds for creation of particles. Phys. Rev., 72:254.

1948

Photo-effects in middle-weight nuclei. Phys. Rev., 73:1311.

1949

With M. Gimprich. Automatic steering of ships by proportional control. Trans. Soc. Naval Arch. Mar. Eng., 57:94. (Abstracted Pac. Mar. Rev. (May):71.)

Radiation accompanying meson creation. Phys. Rev., 76:89. (Abstracted, Phys. Today (August):34.)

Spontaneous decay rate of heavy mesons. Phys. Rev., 76:303.

With D. L. Weisman. Spontaneous decay rate of heavy mesons. II. Phys. Rev., 76:1266.

*Introduction to statistical mechanics (book review). Rev. Sci. Instrum., 20:687.

1950

*Stanford Meeting of the American Physical Society. Phys. Today (April):30.

*Introduction to theoretical physics. Science, 111:413.

Deuteron photo-effect at high energies. Phys. Rev., 78:733.

**Quantum Mechanics.* New York: McGraw-Hill.

*Quantum mechanics. In: *Collier's Encyclopedia.* New York: Collier.
With R. F. Post. Statistical limitations on the resolving time of scintillation counters. Phys. Rev., 80:1113.

1951

*Thinking in quantum terms. Phys. Today (June):4.
Energy-angle distribution of thin target Bremsstrahlung. Phys. Rev., 83:252.
**Meccanica Quantistica*, trans. L. Radicati di Brozolo. Turin: Edizioni Scientifiche Einaudi.
*Reports on progress in physics (book review). Science, 114:370.
Nonlinear meson theory of nuclear forces. I. Neutral scalar mesons with point-contact repulsion. Phys. Rev., 84:1.
Nonlinear meson theory of nuclear forces. II. Nonlinearity in the meson-nucleon coupling. Phys. Rev., 84:10.

1952

Neutral V-particle decay and the negative proton. Phys. Rev., 85:374.
*Nonlinear physics. Phys. Today (June):5.
Nonlinear meson theory of nuclear forces. III. Quantization of the neutral scalar case with nonlinear coupling. Phys. Rev., 86:856.
Radiative correction to the angular distribution of nuclear recoils from electron scattering. Phys. Rev., 87:750.
Quantum effects in the radiation from accelerated relativistic electrons. Am. J. Phys., 20:474.

1953

With E. L. Chu. *Recent progress in accelerators. Annu. Rev. Nucl. Sci., 2:79.
With H. Motz. Cerenkov radiation in a dispersive medium. Am. J. Phys., 21:258.
Lattice-space quantization of a nonlinear field theory. Phys. Rev., 92:766. (Preliminary report, Proc. Int. Conf. Theor. Phys., pp. 226–32.)
Interpretation of electron scattering experiments. Phys. Rev., 92:988. (Preliminary report, Proc. Int. Conf. Theor. Phys., pp. 327–33.)

1954

On an expression for the total cross section. Prog. Theor. Phys., 11:288.

*Nuclear theory (book review). Phys. Today (June):24.

*Atomic structure. In: *Modern Physics for the Engineer.* New York: McGraw-Hill.

Nuclear multipole transitions in inelastic electron scattering. Phys. Rev., 96:765.

Paper representations of the noncubic crystal classes. Am. J. Phys., 22:621.

1955

*Quantum mechanics. In: *Fundamental Formulas of Physics.* New York: Prentice-Hall.

**Quantum Mechanics* (second edition). New York: McGraw-Hill.

With M. Chodorow, et al. Stanford high-energy linear electron accelerator. Rev. Sci. Instrum., 26:134.

Nuclear dispersion contribution to high-energy electron scattering. Phys. Rev., 98:756.

Electric monopole transitions in C^{12} and O^{16}. Phys. Rev., 98:1281.

*Low-energy physics from a high-energy standpoint. Science, 121:881.

1956

Remarks at the URSI Symposium on Electromagnetic Wave Theory. IRE Trans. on Antennas and Propagation, vol. AP-4, no. 3 (July), pp. 541–42, 576–77.

Approximation method for high-energy potential scattering. Phys. Rev., 103:443.

Approximation method for short wavelength or high-energy scattering. Phys. Rev., 104:1481.

1957

Optical analog of quantum-mechanical barrier penetration. Am. J. Phys., 25:207.

Effect of proton correlations on the scattering of high-energy electrons from nuclei. Nuovo Cimento, 5:1223.

With D. S. Saxon. Theory of high-energy potential scattering. Nuovo Cimento, 6:614.

Note on the elastic scattering of high-energy particles. Nucl. Phys., 4:632.

*A Não-Conservação da Paridade nos Interacções Fracas. Seara Nova, 36:205.

1958

*Quantum Mechanics (Japanese translation), part I, 1957; part II, 1958. Kyoto: Yoshioka Shoten.

*Statement before the Subcommittee on Research and Development of the Joint Committee on Atomic Energy, February 13, 1958, pp. 662–79. Washington, D.C.: Government Printing Office.

Electromagnetic structure of the neutron. Rev. Mod. Phys., 30:462.

1959

*Quantum Mechanics (Russian translation). Moscow: Government Publishing House for Foreign Literature.

Sign of the gravitational mass of a positron. Phys. Rev. Lett., 1:254.

Gravitational properties of antimatter. Proc. Natl. Acad. Sci. USA, 45:69.

1960

Possible new experimental test of general relativity theory. Phys. Rev. Lett., 4:215.

Interference effects in high energy bremsstrahlung from crystals. Phys. Rev., 117:1394.

On experimental tests of the general theory of relativity. Am. J. Phys., 28:340.

Motion of a gyroscope according to Einstein's theory of gravitation. Proc. Natl. Acad. Sci. USA, 46:871.

Equivalence principle "paradox" in the motion of a gyroscope. Nuovo Cimento, 17:124.

Note on the calculation of deuteron production in high-energy events. CERN Report 60-32, August 23.

Nucleon structure and electromagnetic interaction—theory. In: *Ninth International Annual Conference on High Energy Physics, Kiev, July 15–25, 1959*, vol. I, pp. 410–35. Moscow: Academy of Science USSR.

1961

*Report on the NASA Conference on experimental tests of theories of relativity. Phys. Today, 14 (11):42–44, 46, 48.

*Science in education. Stanford Rev., 63 (2):12–17.

1962

Particle theory approach to the two-pion and three-pion systems. Phys. Rev., 125:777–81.

Scattering of waves and particles by inhomogeneous regions. J. Opt. Soc. Am., 52:140–44.

*The humanities and the sciences. Stanford Today, 14(7).

Quantization of a self-coupled Boson field. In: *Proceedings of the 1962 International Conference on High Energy Physics at CERN, Geneva,* pp. 690–92.

1964

Proposed gyroscope experiment to test general relativity theory. (Presented at the International Conference on Relativity and Gravitation, Warsaw, July 1962.) In: *Proceedings on Theory of Gravitation*, pp. 71–77. Paris: Gauthier-Villars.

General relativity: Theory and experiment. J. Soc. Ind. Appl. Math., 10:795–801.

The experimental basis of general relativity. (Presented before the Physical Society of Japan, February 4, 1963, Tokyo, Japan.) Japanese translation, Buturi (August).

Application of the variation method to field quantization. Phys. Rev., 130:458–64.

Investigation of time reversal invariance through measurement of a nuclear electric dipole moment. Presented at the Conference on the Nature of Time, Cornell University, May 1963.

With H. Collard, R. Hofstadter, A. Johansson, and M. R. Yearian. An analysis of tritium and helium-3 form factors. (Presented at the 1963 International Conference on Nucleon Structure.) In: *The Proceedings of the Conference on Nucleon Structure,* pp. 385–86.

Measurability of nuclear electric dipole moments. Phys. Rev., 132:2194–2200.

**Nucleon Structure,* coeditor with R. Hofstadter. Stanford: Stanford University Press.

Theory of the electromagnetic form factors of H^3 and He^3. Phys. Rev., 133:B802–B812.

With N. T. Meister and T. K. Radha. Slow neutron-deuteron capture and the structure of H^3 and He^3. Phys. Rev. Lett., 12:509–11.

Observational basis of Mach's principle. Rev. Mod. Phys., 36:510–11.

Observational basis of Mach's principle. Ann. Univ. Sci. Budap., Rolando Eötvös Nominatae.

With R. J. Oakes, T. K. Radha, N. T. Meister, B. F. Gibson, B. P. Carter, and T. A. Griffy. Electromagnetic form factors of H^3 and He^3. In: *Proceedings of the International Conference on High Energy Physics, August 1964* (Dubna, USSR, 1964), vol. 1, pp. 983–84.

1965

Theoretical aspects of the space relativity-gyroscope experiment. In: *Invited Lecture Series of the Space Technology Laboratories*, vol. 2, pp. 47–50.

*Gravitation and relativity. Trans. Am. Geophys. Union, 45:3.

With B. F. Gibson. P and D state contributions to the charge form factors of H^3 and He^3. Phys. Rev., 138:B26–32.

Structure of the three-nucleon system. In: *Proceedings of the Third Nordic-Dutch Accelerator Symposium, Hanko, Finland, August 16–23, 1964* (Helsinki, 1964), pp. 163–69.

Classical examples of space inversion and time reversal. Physics, 1:209–13.

*The future role of high energy physics in interaction with other parts of physics. In: *Nature of Matter*, pp. 64–65. Brookhaven National Laboratory.

On the electromagnetic structure of the Yukawa meson. Prog. Theor. Phys. (Suppl.):400–405.

With R. Hofstadter. *Felix Bloch—A brief professional biography. Phys. Today (December):42–43.

1966

*Matrix mechanics. In: *Encyclopedia of Physics*, pp. 412–15. New York: Reinhold Publishing.

With D. K. Ross. Analysis of the proposed planetary radar reflection experiment. Phys. Rev., 141:1215–18.

*Some thoughts on classroom teaching. Am. J. Phys., 34:454. Also in: The Physics Teacher, 4:233.

Lateral boundary mixing in a simple model of ocean convection. Deep-Sea Res., 13:621–26.

Nonrelativistic quark model. Phys. Rev. Lett., 17:612–13.

Quarks and magnetic poles. Phys. Rev. Lett., 17:714–16.

With M. V. Barnhill. Gravitation-induced electric field near a metal. Phys. Rev., 151:1017–1067.

1967

With T. A. Griffy. *Electromagnetic form factors. In: *High Energy Physics*, pp. 341–90. New York: Academic Press.

*Electron scattering. In: *Cargèse Lectures in Theoretical Physics, High Energy Electromagnetic Interactions and Field Theory*, pp. 1–39. New York: Gordon & Breach.

Comparison of theory and observation in general relativity. In: *Relativity Theory and Astrophysics. 1. Relativity and Cosmology*, pp. 105–16. Providence, R.I.: American Mathematical Society.

*Gravitation and relativity. In: *Journeys in Science*, pp. 148–66. Albuquerque: University of New Mexico Press.

*How perceptive is hindsight? Science, 155:397.

*J. R. Oppenheimer—scientist, public servant. Phys. Today (April): 110–11.

Symmetries of Keplerian and harmonic ellipses and their quantum implications. Am. J. Phys., 35:670.

On the electromagnetic structure of the Yukawa meson. II. Prog. Theor. Phys., 37:635–36.

Quarks and magnetic poles. Phys. Rev., 160: 1257–62.

*Gravitation and relativity. In: *Journeys in Science*, ed. David L. Arm, pp. 148–66. Albuquerque: University of New Mexico Press.

1968

*Low-energy physics from a high-energy standpoint. II. Science, 161:969–73.

High-energy scattering at moderately large angles. Phys. Rev., 176:1390–94.

Some experiments on gravitation. Report presented at the 5th Int'l. Conf. on Gravitation and the Theory of Relativity, Tbilisi, U.S.S.R., September 1968.

Quantum Mechanics, 3d ed., xvii + 544 pp. New York: McGraw-Hill.

1969

Newton, Einstein, and gravitation. In: *Great Men of Physics: The Humanistic Element in Scientific Work,* University of California Letters and Science Extension Series, pp. 55–74. Los Angeles: Tinnon-Brown.

With C. W. F. Everitt and W. M. Fairbank. Theoretical background and present status of the Stanford relativity-gyroscope experiment. Presented at the ESRO Colloquium on Significance of Space Research for Fundamental Physics, Interlaken, Switzerland, September 4, 1969.

Nongeodesic motion. In: *In Honor of Philip M. Morse,* ed. H. Feshbach and K. U. Ingard, pp. 164–69. Cambridge: MIT Press.

1970

Quark selection principle. Phys. Lett., 31B:79–81.

Gravitation-induced electric field near a metal. II. Phys. Rev. B, 1:4649–54.