NATIONAL ACADEMY OF SCIENCES

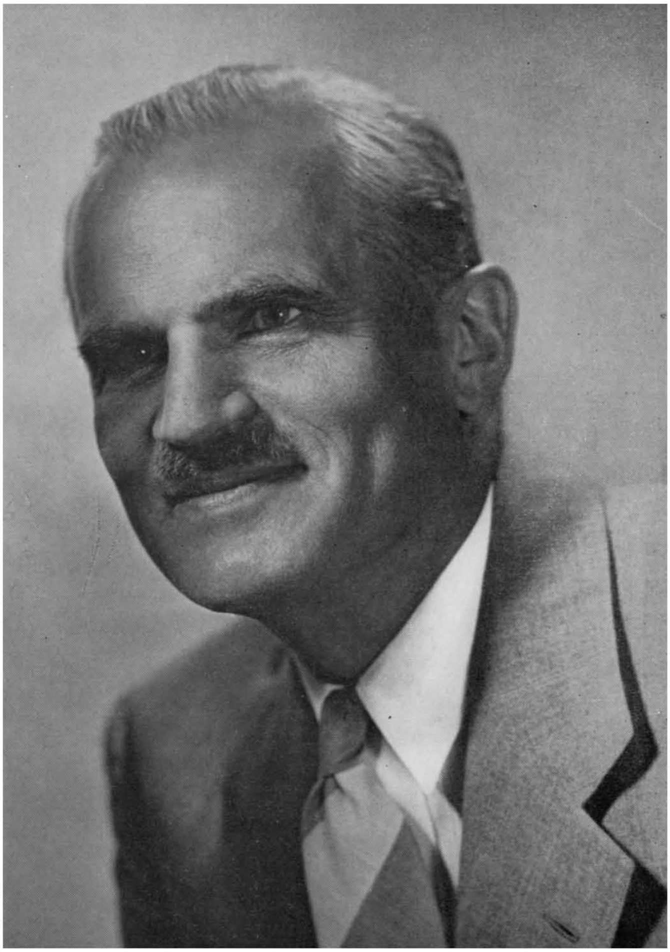
ARTHUR HOLLY COMPTON

1892—1962

A Biographical Memoir by

SAMUEL K. ALLISON

Biographical Memoir



Arthur H. Compton

ARTHUR HOLLY COMPTON

September 10, 1892–March 15, 1962

BY SAMUEL K. ALLISON

ARTHUR HOLLY COMPTON was born in Wooster, Ohio, September 10, 1892, to a family destined to become known for its distinguished educators. His father was an ordained Presbyterian minister and Professor of Philosophy at the College of Wooster; at the time of Arthur's birth he was dean of the College. He believed deeply in the old saying "scientia et religio ex uno fonte." Compton has said that his father considered it important to teach in a Christian college, for there one could best learn and teach truth in its wholeness as it affects the life of man.

Compton's mother came from a long line of Mennonites, a Protestant sect related on one hand to the Calvinists and on the other to the Quakers. Pacifism was a fundamental doctrine of this sect. A forebear of hers had fled from France to avoid military service and her father was a conscientious objector during the American Civil War. Upon leaving the restricted community of her youth, she became devoted to the success of the College of Wooster and to its ideals: service to mankind expressed in the fields of education and foreign missions. She twice received public recognition as a woman and mother. Western College for Women gave her an honorary degree in 1933 and in 1939 she was named "American mother of the year."

Arthur Compton was the youngest of three boys. His eldest brother, Karl, became a well-known scientist, president of the Massachusetts Institute of Technology, and a member of the National Academy of Sciences; he served the government and American science in ways too numerous to mention. The two brothers were close friends and Arthur spoke often of his admiration for Karl and of his dependence at certain moments upon his judgment. His brother Wilson taught briefly at Dartmouth and then spent twenty-five years in business, leaving to become president of Washington State College. The family tradition of teaching was in his blood. Their sister, Mary, married a missionary, C. Herbert Rice, who served the Presbyterian Board of Foreign Missions for forty years in India, becoming principal of Forman Christian College at Lahore.

In this close-knit, harmonious family which was so closely identified with the College of Wooster, Compton spent his school and college years. Scientific interests appeared early. He enjoyed mechanical toys, collected stones and butterflies, studied paleontology and, later, astronomy. He enjoyed school science and mathematics. Then and throughout his life he took pleasure in the outdoors and in physical activity, and became a competent all-around athlete. It was a family tradition and became part of his credo that a person should keep himself physically and mentally fit to serve at his highest efficiency.

Upon graduating from Wooster in 1913 he went to Princeton, where he received a master's degree in 1914 and a Ph.D. degree in 1916. In June 1916 he married Betty Charity McCloskey, herself a graduate of the College of Wooster and his classmate. It was a happy and successful marriage. In *Atomic Quest* Compton describes how necessary it was for him to talk over important problems with his wife, and when the matter of "clearance" came up for work on the atomic project he explained that Betty would have to be cleared too. As far as is known, she was the only nonscientific wife on the Manhattan Project to have the same clearance as her husband.

After a year of teaching physics at the University of Minnesota (1916-1917) Compton spent two years as research physicist for the Westinghouse Lamp Company in East Pittsburgh where he did original work on the sodium vapor lamp.

During part of this period he helped develop aircraft instruments for the Signal Corps. For Compton was not a pacifist in spite of his religious background and Mennonite mother. Although troubled by the warlike spirit of fellow students at Princeton when the *Lusitania* was sunk, he came to believe that a nation cannot by itself determine to remain at peace. It can be forced into a position where the defense of the right to freedom is the only honorable course. Compton could not accept the position that war is always wrong. He did not support the pacifist activities of some of his friends during the interwar years. As World War II approached he believed the United States should enter the struggle to prevent the Nazi powers from controlling the earth.

Arthur Compton's career as an investigator in basic physics essentially began with his appointment in 1919 as a Fellow of the National Research Council. He was the recipient of one of the first two such fellowships granted for study abroad. With this appointment he went to Rutherford's laboratory at Cambridge, England, and studied the scattering and absorption of gamma rays. Here he observed that the scattered radiation was more absorbable than the primary. This observation, which confirmed those of previous experimenters on gamma rays, led to his Nobel Prize discovery of what is now known as the Compton Effect. The steps toward this discovery and its impact on the physics of that time have recently been reviewed by Compton himself.[1]

[1] A. H. Compton, *American Journal of Physics*, 29 (1961): 817.

The increased absorption indicated an increase of wavelength and, on the corpuscular theory of light, a decrease of momentum. At that time the relation between gamma ray wavelength and absorption coefficient was not sufficiently well known for Compton to estimate the wavelength shift at 90° more accurately than 0.03 A. The interpretation of the phenomenon was complicated by the knowledge that the gamma rays could excite fluorescent radiation in the scatterers, and that this would provide a component of longer wavelength by a classical process. The accuracy of the gamma ray experiments was not sufficiently high to enable Compton to announce a photonic interpretation with full confidence.

After his year at the Cavendish Laboratory, he accepted the Wayman Crow Professorship of Physics at Washington University, and at once set about extending his gamma ray scattering observations to the x-ray region, where analysis of the primary and scattered radiation by x-ray diffraction would give a result for the shift of considerably increased precision. He mounted a graphite block scatterer on the outer wall of a molybdenum target x-ray tube operating at approximately 30 kilovolts and 30 milliamperes, and used a system of defining slits such that no radiation direct from the target could impinge on his calcite crystal. The spectrum showed both a scattered molybdenum $K\alpha$ line at its original wavelength and a shifted line whose wavelength was increased by 0.024 A (within an accuracy of 3 percent) if the angle of scattering was 90°. Compton[2] solved the equations for conservation of energy and momentum as applied to the impact of a photon with a free electron and showed that the shift could thus be quantitatively explained. A few days after Compton's publication, a similar calculation was published independently by P. Debye.[3]

[2] A. H. Compton, *Physical Review,* 21 (1923): 484.
[3] P. Debye, *Physikalische Zeitschrift,* 24 (1923): 161.

Compton's discovery created a sensation among the physicists of that time. It was not generally foreseen that a dual wave-mechanical theory of electromagnetic radiation was possible, and it seemed that Compton's effect and his explanation of it indicated an exclusively corpuscular theory of light, although in observing it he had used diffraction from a crystal lattice, a phenomenon only explicable by the wave theory. And in 1924 Compton and Hagenow showed that the scattering of 130,000-volt x rays from elements up to sulfur was completely polarized, as predicted by the classical J. J. Thomson theory.

Professor William Duane of Harvard was foremost among those unwilling to accept the new idea, and at the Christmas meeting of the American Physical Society in 1923 a "debate" ("invited" papers had not yet been invented) was arranged between Compton and Duane on the validity of Compton's results and their interpretation. The matter was, however, clearly one to be decided by further experiments, including determination of the angular dependence of the shift and its dependence on the atomic number of the scatterer. In the absence of such evidence the "debate" was continued at the 1924 summer meeting of the British Association for the Advancement of Science, with Sir William Bragg presiding. Duane interpreted the shifted spectrum as "tertiary radiation," of the bremsstrahlung type, caused by the deceleration of photoelectrons ejected from the scatterer by the primary radiation. Actually the shift at 90°, from carbon, of the K x-rays of molybdenum could be quantitatively accounted for by the energy loss in the ejection of carbon K-electrons.

Evidence from other investigators began to accumulate, however, and supported Compton's interpretation. In Duane's own laboratory the experiments which at first seemed to support his "tertiary radiation" hypothesis, when repeated with greater accuracy, gave evidence for Compton's point of view, and in

1924, at a memorable meeting of the American Physical Society, Duane withdrew his objections and reported very good measurements of the change of wavelength as calculated from photon-free electron impact.

As a consequence of his interpretation, Compton had also predicted that the transfer of momentum from photons to individual electrons would produce a new type of electronic radiation as x rays moved through matter, namely the "recoil" electrons. It was also predicted that each scattered photon would be simultaneous with its recoil electron. The existence of the predicted recoil electrons was quickly detected by C. T. R. Wilson at the Cavendish Laboratory and by W. Bothe in Germany. Favorable evidence for the predicted simultaneity was obtained by Compton and Simon in 1925.

In 1927 the Nobel Prize for Physics was shared between A. H. Compton and C. T. R. Wilson, and in the same year Compton was elected to the National Academy of Sciences. He was then thirty-five years old.

In 1923 Compton moved to the University of Chicago, where he remained for twenty-two years, advancing to an appointment as Charles H. Swift Distinguished Service Professor in 1929. In the early 1920 period, the National Research Council had a Committee on X Rays and Radioactivity, of which Compton was first a prominent member and then chairman. Compton had used the Bulletin of the National Research Council for his first announcement of his experiment on the shift of x-ray wavelengths, and in the same year (1922) the Bulletin carried his announcement of the discovery of the total reflection of x rays. This work alone, if it had not been overshadowed by the work on scattering, would have established him in the first rank of experimental physicists. The earlier work of Stenström in Sweden had indicated that the index of refraction for x rays was less than unity; Compton realized that this meant total reflection from denser to lighter media if the interfacial glancing angle were small enough. He quickly selected monochromatic radiation with his crystal spectrometer and demonstrated that the beam was totally reflected from glass and silver mirrors, the effect disappearing if the glancing angle was more than a few minutes of arc. In the hands of subsequent experimenters this became an important method for measuring the refractive index.

The existence of this specular reflection indicated to Compton that, if the reflecting surface were ruled, grating spectra of x rays could be obtained at glancing angles less than the limit for total reflection. This was accomplished in 1925, with R. L. Doan, using a grating ruled on speculum metal, and showed clearly a diffraction maximum due to the molybdenum Kα radiation. In the hands of Compton and his student, J. A. Bearden, the technique was rapidly improved and quantitatively significant absolute measurements of x-ray wavelengths were obtained. When these were compared with the wavelengths as measured from crystalline diffraction, it appeared that the then accepted value of the electronic charge was slightly in error. Our present value of the charge of the electron is largely due to this development which Compton initiated.

In an outline autobiography written in 1935 Compton has listed what he considers to have been his principal contributions to physics up to that time. In addition to the Compton Effect he mentions the study of the distribution of electrons in atoms by diffraction methods. In writing his first book on x rays (*X-Rays and Electrons,* Van Nostrand, 1926) Compton had worked out a method of calculating, from the intensities of diffraction in various orders, the linear density of diffracting material in a direction perpendicular to the set of crystal planes under investigation. The method was applied by Compton's associates, and produced elegant electron distribution curves; in the case of rock salt, these were easily identified as the electron clusters around sodium and chlorine nuclei. Similar and independent efforts were under way in England, in W. L. Bragg's laboratory. Later, in an even more impressive manner, Compton extended the method to the study of scattering from gases, where the sharp crystalline diffraction maxima do not exist and the coherent and incoherent components of the scattering can only be separated by an experimenter with a basic understanding of the complexities of the scattering process. Compton and his associates measured electron distributions in helium, neon, argon, and mercury atoms by this method, which is now being revived in the study of electric charge distribution in nuclei with ultra high energy x rays.

In his modest résumé of his contributions to physics, Compton fails to mention a fundamental contribution to the theory of ferromagnetism. By a very careful investigation of the intensity of x rays diffracted by magnetized and unmagnetized magnetite and silicon steel, Compton and his associate, the late J. C. Stearns, showed conclusively in 1930 that the magnetization of these substances could not be explained by tilting of the planes of electronic orbits in their atoms. As he correctly surmised, this left orientation of the electron spins as the ultimate source of the ferromagnetic behavior.

Along with his interests in academic physics Compton maintained some contact with industry. As a young man, beginning in 1917, he had worked for two years as a research engineer for the Westinghouse Lamp Company, and in 1926 he became a consulting physicist for the Lamp Department of the General Electric Company, spending about one day a month for many years discussing with the researchers their various projects, and lecturing to the general staff.[4] While he held the Eastman Visiting Professorship at Oxford in 1934-1935, the company asked him to report on research at the General Electric, Ltd., laboratory in Wembley, with which General Electric, U.S.A.,

[4] I thank Dr. Zay Jeffries for information concerning Compton's industrial connections.

had arranged to exchange information. In one of his letters he described a low wattage, gaseous discharge, fluorescent lamp which produced green light at attractive efficiencies. He provided enough detail to enable the Nela engineers to construct such a lamp, which they soon did. This was the beginning of a crash research and development program in General Electric Company which, after several years, resulted in the fluorescent lamp industry. Compton maintained an active interest in this whole program until commercial success was achieved. But, notwithstanding his substantial specific contributions to the science and technology incident to the electric lamp field, it is probable that his greatest value as a consultant was educational and inspirational.

About 1930 Compton's scientific interest began to shift from x rays to cosmic rays. In a happy combination with the extended travels he was making in this period he organized a world survey of cosmic ray intensities, in which he personally participated by carrying an ionization chamber as he journeyed. He soon was able to announce the discovery of a latitude effect, namely, that cosmic ray intensities are less near the equator than at the poles. Unknown to him such an effect had previously been discovered by a Dutch physicist, J. Clay, who had measured the intensity as a function of latitude on his travels from Holland to Java. But the effect remained buried in Clay's notebooks and obscure publications until Compton rediscovered it and independently realized its implication.

The other great name in cosmic rays at that time was R. A. Millikan, whose extensive observations had convinced him that the primary cosmic radiation, incident on the earth's outer atmosphere, was electromagnetic in nature. Compton realized that the probable explanation of his latitude effect was that at least a significant part of the primaries were charged particles, kept away from the earth's equatorial regions by the shielding effect of the earth's magnetic field, and a lively controversy over the nature of cosmic ray primaries arose. But the evidence of the latitude effect could not be refuted, and it is now accepted that charged particles play a predominant role in the influx from outer space.

The publishers of Compton's first book, *X-Rays and Electrons,* exerted great pressure on him to revise it for a second edition, and after many years of trying to find the necessary time, he asked his younger colleague, Samuel K. Allison, to collaborate with him in the effort. The result was essentially a new book, *X-Rays in Theory and Experiment* (Van Nostrand, 1935), which has remained the standard reference book on the subject for over thirty years.

In the latter part of the 1930s Compton spent less and less time working with his own hands in the laboratory. He became the leader of a very productive group of investigators in cosmic rays, which included, at various times, such men as Luis Alvarez, Pierre Auger, Gerhardt Herzog, W. P. Jesse, Marcel Schein, Volney Wilson, and E. O. Wollan, but his fame as a physicist and lecturer was spreading rapidly, and he was eagerly sought for as a guest professor by the world's universities. He enjoyed traveling, always accompanied by his wife, and he spent a considerable part of the time abroad, especially in India. It seemed more and more difficult for him to refuse any of the multitudinous requests he received for lecturing, both on scientific and on humanitarian topics. For there was an intense religious and idealistic side of his nature which coexisted, in a truly remarkable way, with his ability to reason in the rigorous and objective manner of physics. His early religious training, received from his mother and father, and reinforced by associations with his missionary relatives, had made a permanent impression. He was one of the few scientists of stature who could and would address religious groups, and was in constant demand in this capacity, as an outstanding example of the compatibility of science and religion. It is clear from his publications that from approximately 1939 on, his interest in philosophical and religious matters began to dominate over his purely scientific life. Before he could lay aside his active interest in science, however, a great ordeal was in store for him.

The story of Compton's involvement in the atomic bomb effort during the war has been written by himself, in his book *Atomic Quest.* In the summer of 1940 he had realized that a national effort to protect ourselves must be made, and at the same time he realized the importance of the recently discovered uranium fission. He asked Volney Wilson to study the uranium situation and report on what could be done at Chicago to realize a chain reaction. Wilson suggested that the properties of beryllium as a neutron moderator had not been sufficiently explored, and early in 1941 Compton obtained a grant from Washington to investigate neutron absorption and scattering in beryllium. Owing to shortage of material and rapid growth of the war effort, this project became overrun in the march of events.

On November 6, 1941, Compton, as chairman, presented the report of a National Academy committee organized to review the military prospects of atomic energy. This report, for which he was mainly responsible, was incisive and optimistic. It, as much as any other one item, precipitated the vast uranium project effort in the United States. Late in 1941 he gave up all other activities to direct the successful effort made at Chicago to initiate the chain reaction. After many reorganizations and changes of sponsorship he became Director of the Metallurgical Project of the Manhattan Engineer District. This project had responsibility for the production of plutonium, and diversified into installations at Palos Park (now the Argonne National Laboratory), Clinton, Tennessee, and Hanford, Washington. Compton devoted himself completely and exclusively to the great responsibilities of this appointment. He was not gifted as an administrator and this made the work even more difficult for him. However, he was outstanding in attracting and inspiring able scientists.

As the project developed with an incredible rate of escalation, the strain on Compton became terrific. He was buffeted unmercifully by the internal frictions in the project, by the difficulties in splitting off men for the work in Tennessee, by distrust between the pure scientists and the industrial engineers, and by the great decisions regarding the role of heavy water and the relative efficacy of liquid versus gaseous cooling, to name but a few. All this, plus a gnawing doubt as to the morality of the whole effort, which, if successful, could very well mean a horrible death to thousands of civilians in the enemy countries. At this time he asked his friend Dr. Zay Jeffries, of the General Electric Company, to come frequently to Chicago and be his confidential adviser. This was a wise move, as the long experience and stability of Jeffries helped Compton through some difficult crises.

Compton must be given credit for arranging with the Mallinckrodt Chemical Works of St. Louis for the purification of uranium by ether extraction of an aqueous solution of uranyl nitrate. This process produces, in one step, sufficiently pure uranium to support the chain reaction in graphite, but the dangers of using ether on a large scale made many chemical companies unwilling to undertake the work. Compton's eloquence and earnestness won over Mallinckrodt, which had had some previous experience with ether for anesthesia, and in one stroke he solved the uranium purity problem.

A most agonizing moment arrived for him when the then Secretary of War requested his personal advice as to whether the atomic bomb should be used in an attack on a Japanese city. His decision to advocate the use of the bomb must have been a difficult one in view of his pacifist Mennonite ancestors and his intense religious indoctrination from his parents and missionary relatives, who had been against the use of violence.

After the capitulation of Japan[5] the group at Chicago who had worked under Compton heard that a ceremony had been arranged at which Chancellor Robert Hutchins would receive from General L. R. Groves a plaque and a scroll honoring the University of Chicago for its part in the effort, with no special mention of Compton. With the proposed ceremony only thirty-six hours away, they decided to have their own ceremony, and in addition insisted that Compton join with Chancellor Hutchins in receiving the award. After the main ceremony Compton was invited to a reception room in the Metallurgical Laboratory, where Dr. Farrington Daniels presented him with a plaque donated by the group and fabricated in the project shop. The sincere tribute, from his own men, impressed Compton much more than did the official government award. Later he personally was awarded the United States Government Medal for Merit.

The end of the war brought Compton's resignation as Charles H. Swift Distinguished Service Professor of Physics at Chicago and his acceptance of the chancellorship of Washington University at St. Louis, where his famous experiment on the Compton Effect had been performed twenty-four years previously. His administrative position meant that his career as a research physicist was ended, as also was my close association with him.

In 1954 he resigned the chancellorship to become Distinguished Service Professor of Natural Philosophy at Washington University. He devoted himself to teaching, to public lectures on the impact of science on society and the morality of science, and to writing his book *Atomic Quest; a Personal Narrative*.[6]

He resigned from his post at Washington University in

[5] I am indebted to Dr. Ralph Lapp for information about this incident

[6] New York, Oxford University Press, 1956.

1961, announcing plans of becoming professor-at-large. He intended to divide his time among Washington University, the University of California at Berkeley, and the College of Wooster.

Death came to him on March 15, 1962, at Berkeley, California, from a cerebral hemorrhage. His wife and his sons survive him. Arthur Alan Compton is a foreign service officer and John Joseph Compton is Professor of Philosophy at Vanderbilt University.

Compton was an extraordinarily gifted human being. He was vigorous, athletic, and handsome, and an earnest and convincing speaker. His insight into physics was clear and almost always correct, without the aid of advanced mathematical techniques. His activities outside of his profession were numerous. He was general chairman of the Laymen's Missionary Movement from 1934 to 1948, and participated in the small groups which organized the Freedom House Bookshelf for the purpose of distributing American books to Asian, African, and Latin American leaders. He was very active in the National Conference of Christians and Jews, and gave great thought to the philosophical significance of science.

The appended list of the honors conferred upon him shows that they are far too many for individual comment. Probably the one he appreciated most was the degree of Doctor of Science awarded him in 1927 by the College of Wooster, in the town where he had been born and lived as a child and young man, and where his father, Elias Compton had been Dean and Professor of Philosophy.

His place is secure as one of the great American physicists of the twentieth century.

HONORS AND DISTINCTIONS

SPECIAL POSITIONS, VISITING LECTURESHIPS, ETC.

Civilian Associate, U. S. Signal Corps, developing airplane instruments, 1917-1918

Consultant, General Electric Co., 1926-1945

John Simon Guggenheim Fellow, 1926-1927

Lecturer, Punjab University, Lahore, India, 1926-1927

Terry Lectures, Yale University, 1931

Elliott Lectures, Western Theological Seminary, 1931

Director, World Survey of Cosmic Rays, 1931-1934

Research Associate, Carnegie Institution, Cosmic Ray Research, 1931-1941

C. R. B. Foundation Lectures, Brussels, 1934

George Eastman Visiting Professor, Oxford University, 1934-1935

Fellow, Balliol College, 1934-1935

Loud Lectures, University of Michigan, 1935

McNair Lectures, University of North Carolina, 1939

Lowell Lectures, Boston, 1939

Walker-Ames Visiting Professor, University of Washington, 1940

First Garvin Lecture, Lancaster, Pa., 1940

Director, University of Chicago South American Cosmic Ray Expeditions, 1941

Lectures, Jewish Theological Seminary, 1949

Forbes-Hawkes Lectures, University of Miami, 1949

First DeGolyer Lecture, University of Oklahoma, 1953

Hill Foundation Lectures, St. Olaf College, Minnesota, 1955

Montgomery Lectures, University of Nebraska, 1955

Distinguished Visiting Professor, Michigan State University, 1956

Charles Schwab Memorial Lecture, American Iron and Steel Institute, 1956

PROFESSIONAL SOCIETIES AND OTHER MEMBERSHIPS

Honorary member, American Academy of Arts and Sciences, 1928

American Association for Advancement of Science (Vice President, 1927; President, 1942; Vice President, 1951)

American Association of Scientific Workers, 1938-1941 (President, 1939-1940)
American Optical Society, Councillor, 1929-1932
American Philosophical Society, 1927 (Vice President, 1948-1951)
American Physical Society (President, 1934)
National Academy of Sciences, 1927
Western Society of Engineers, 1930
New York Academy of Sciences, 1947
Academy of Sciences of Lisbon, 1953
Akademie der Wissenschaften in Wien, 1935
Association des Ingénieurs-Docteurs de France, 1949
Bavarian Academy of Sciences, 1932
Brazilian Academy of Sciences, 1941
Cambridge Philosophical Society, 1955
Chemical Society of Peru, 1941
Chinese Physical Society, 1943
Deutsche Akademie der Naturforscher
Indian Academy of Sciences
National Academy of Exact Sciences of Lima, 1941
National Academy of Peiping, 1948
Honorary member of the National Academy of Sciences of India, 1955
Norwegian Academy of Science, 1946
Société Philomathique de Paris, 1938
Prussian Academy of Sciences, Berlin, 1932
Reale Accademia dei Lincei, Rome, 1925
Royal Akademie, Amsterdam, 1938
Royal German Academy of Sciences, 1934
Royal Irish Academy, 1949
Royal Society of Canada, 1946
Royal Society of Sciences, Uppsala, 1938
Royal Society of New Zealand
Swedish Academy of Sciences

Phi Beta Kappa
Sigma Xi
Kappa Delta Pi
Gamma Alpha
Pi Kappa Pi

Alpha Tau Omega, Board of Governors ATO Foundation Fund, 1955-1956

Honorary member, Rotary Club of St. Louis, St. Louis Chamber of Commerce

HONORS

Sc.D., Wooster, 1927; Ohio State, 1929; Yale, 1929; Princeton, 1934; Brown, 1935; Harvard, 1936; University of St. Augustine (of Arequipa), 1941; Punjab University, Lahore, 1949; Capital University, 1949; Aligarh University, 1950; University of Chicago, 1952; Coe College, 1953; Brandeis University, 1957; Lake Forest College, 1957

LL.D., Washington University, 1928; University of California, 1930; Lehigh University, 1946; Texas Christian University, 1949; Baylor University, 1951; Westminster College, 1952; Michigan State University, 1956

L.H.D., University of Tampa, 1941

Litt.D., Jewish Theological Society of America, 1942

Doctorate, University of San Marcos, Lima, 1941

M.A., Oxford, 1934

Rumford Gold Medal of American Academy of Arts and Sciences, 1927

Nobel Prize for Physics, Swedish Academy of Sciences, 1927

Gold Medal, Radiological Society of North America, 1928

Matteucci Gold Medal, Italian Academy of Arts and Sciences, 1933

Hughes Medal of Royal Society of London, 1940

Franklin Gold Medal of Franklin Institute, 1940

Annual award, Jewish Education Committee, 1943

Washington Award, Western Society of Engineers, 1945

Franklin Medal of American Philosophical Society, 1945

U. S. Government Medal for Merit, 1946

St. Louis Award, 1946

Officer of the Legion of Honor of the French Republic, 1947

Grande Médaille, Association des Ingénieurs-Docteurs de France, 1947

Gold Medal of Academie Française with palm by French Government, with honorary titles of Officer of Academy, Officer of Public Instruction of French Government, 1947

Chevalier and Campagnon Honoraire de la Croix de Lorraine and de la Resistance, 1951; palms added, 1952

Northwestern University Centennial Award, 1951

Freedoms Foundation Award, 1952

Popular Mechanics Hall of Fame, 1952

Order "Pour la Merite," Federal Republic of Germany, 1955

Theodore Roosevelt Award, 1955

Röntgen-Plakette of Röntgen-Museums, Remscheid-Lennep, Germany, 1957

BIBLIOGRAPHY

KEY TO ABBREVIATIONS

Am. J. Phys. = American Journal of Physics
Carnegie Inst. Wash. Year Book = Carnegie Institution of Washington Year Book
J. Franklin Inst. = Journal of the Franklin Institute
J. Opt. Soc. Am. = Journal of the Optical Society of America
J. Opt. Soc. Am. and Rev. Sci. Instr. = Journal of the Optical Society of America and Review of Scientific Instruments
Phil. Mag. = Philosophical Magazine
Phys. Rev. = Physical Review
Proc. Am. Phil. Soc. = Proceedings of the American Philosophical Society
Proc. Nat. Acad. Sci. = Proceedings of the National Academy of Sciences
Rev. Sci. Instr. = Review of Scientific Instruments
Revs. Mod. Phys. = Reviews of Modern Physics
Sci. Am. = Scientific American
Sci. Monthly = Scientific Monthly

1909

A criticism of Mr. C. W. Williams' article, "Concerning Aeroplanes." Fly, 1:13.

Comparison of Wright and Voisin aeroplanes (letter). Sci. Am., 100:135.

Striving for the perfect aeroplane. Aeronautics, 5(2):58 ff.

1911

Aeroplane stability. Sci. Am. Suppl., 72:100-2.

1913

A laboratory method of demonstrating the earth's rotation. Science, 37:803-6.

1914

New light on the structure of matter. Sci. Am. Suppl., 78:4-6.

1915

A determination of latitude, azimuth, and the length of the day independent of astronomical observations. Phys. Rev., 5:109-17; reprinted in Popular Astronomy, 23:199-207.

Watching the earth revolve. Sci. Am. Suppl., 79:196-97.

An agglomeration theory of the variation of the specific heat of solids with temperature (abstract). Phys. Rev., 5:338-39.

What is matter made of? Sci. Am., 112:451-52.

With W. H. Bragg. The distribution of the electrons in atoms (letter). Nature, 95:343-44.

The variation of the specific heat of solids with temperature. Phys. Rev., 6:377-89.

1916

A physical study of the thermal conductivity of solids. Phys. Rev., 7:341-48.

On the location of the thermal energy of solids. Phys. Rev., 7: 349-54.

The X-ray spectrum of tungsten (abstract). Phys. Rev., 7:498-99.

A recording X-ray spectrometer, and the high frequency spectrum of tungsten. Phys. Rev., 7:646-59.

1917

The intensity of X-ray reflection, and the distribution of the electrons in atoms. Phys. Rev., 9:29-57. (Ph.D. Thesis, Princeton University.)

The reflection coefficient of monochromatic X-rays from rock salt and calcite (abstract). Phys. Rev., 10:95-96.

With Oswald Rognley. The nature of the ultimate magnetic particle. Science, 46:415-18.

1918

The size and shape of the electron. Journal of the Washington Academy of Sciences, 8:1-11.

With Oswald Rognley. The nature of the ultimate magnetic particle (abstract). Phys. Rev., 11:132-34.

The size and shape of the electron (abstract). Phys. Rev., 11:330.

The non-molecular structure of solids. J. Franklin Inst., 185:745-74.

Note on the grating space of calcite and the X-ray spectrum of gallium. Phys. Rev., 11:430-32.

1919

With K. T. Compton. An addition to the theory of the quadrant electrometer (abstract). Phys. Rev., 13:288.

The law of absorption of high frequency radiation (abstract). Phys. Rev., 13:296.

The size and shape of the electron. I. The scattering of high frequency radiation. Phys. Rev., 14:20-43.

With K. T. Compton. A sensitive modification of the quadrant electrometer: its theory and use. Phys. Rev., 14:85-98.

The size and shape of the electron. II. The absorption of high frequency radiation. Phys. Rev., 14:247-59.

With E. Rutherford. Radio-activity and gravitation (letter). Nature, 104:412.

1920

A photoelectric photometer. Transactions of the American Illuminating Engineering Society, 15:28-33.

The elementary particle of positive electricity (letter). Nature, 106:828.

With C. C. Van Voorhis. Cathode fall in neon. Phys. Rev., 15:492-97.

Radioactivity and the gravitational field. Phil. Mag., 39:659-62.

With Oswald Rognley. Is the atom the ultimate magnetic particle? Phys. Rev., 16:464-76.

1921

The absorption of gamma rays by magnetized iron. Phys. Rev., 17:38-41.

Classical electrodynamics and the dissipation of X-ray energy. Washington University Studies, 8:93-129.

Possible magnetic polarity of free electrons. Phil. Mag., 41:279-81.
The degradation of gamma-ray energy. Phil. Mag., 41:749-69.
The wave-length of hard gamma rays. Phil. Mag., 41:770-77.
The magnetic electron. J. Franklin Inst., 192:145-55.
Secondary high frequency radiation. Phys. Rev., 18:96-97.
With C. F. Hagenow. The polarization of secondary X-rays (abstract). Phys. Rev., 18:97-98.
The width of X-ray spectrum lines (abstract). Phys. Rev., 18:322.
A possible origin of the defect of the combination principle in X-rays (abstract). Phys. Rev., 18:336-38.
The softening of secondary X-rays (letter). Nature, 108:366-67.

1922

The width of X-ray spectrum lines. Phys. Rev., 19:68-72.
The spectrum of secondary X-rays (abstract). Phys. Rev., 19:267-68.
With Newell L. Freeman. The intensity of X-ray reflection from powdered crystals (letter). Nature, 110:38.
Total reflection of X-rays from glass and silver (abstract). Phys. Rev., 20:84.
Secondary radiations produced by X-rays, and some of their applications to physical problems. Bulletin of the National Research Council No. 20, Vol. 4, Part 2, 56 pp.
Radiation a form of matter (letter). Science, 56:716-17.

1923

A quantum theory of the scattering of X-rays by light elements (abstract). Phys. Rev., 21:207.
With C. C. Van Voorhis. Luminous efficiency of gases excited by electric discharge (abstract). Phys. Rev., 21:210.
A quantum theory of the scattering of X-rays by light elements. Phys. Rev., 21:483-502.
Wave-length measurements of scattered X-rays (abstract). Phys. Rev., 21:715.
The total reflection of X-rays. Phil. Mag., 45:1121-31.
Recoil of electrons from scattered X-rays (letter). Nature, 112:435.
Absorption measurements of the change of wave-length accompanying the scattering of X-rays. Phil. Mag., 46:897-911.

The spectrum of scattered X-rays. Phys. Rev., 22:409-13.

The quantum integral and diffraction by a crystal. Proc. Nat. Acad. Sci., 9:359-62.

1924

A quantum theory of uniform rectilinear motion (abstract). Phys. Rev., 23:118.

Scattering of X-ray quanta and the J phenomena (letter). Nature, 113:160-61.

With C. F. Hagenow. A measurement of the polarization of secondary X-rays. J. Opt. Soc. Am. and Rev. Sci. Instr., 8:487-91.

With J. C. Hubbard. The recoil of electrons from scattered X-rays. Phys. Rev., 23:439-49.

A general quantum theory of the wave-length of scattered X-rays (abstract). Phys. Rev., 23:763.

With Y. H. Woo. The wave-length of Mo $K\alpha$ rays scattered by light elements (abstract). Phys. Rev., 23:763.

With Y. H. Woo. The wave-length of molybdenum $K\alpha$ rays when scattered by light elements. Proc. Nat. Acad. Sci., 10:271-73.

The scattering of X-rays. J. Franklin Inst., 198:57-72.

A general quantum theory of the wave-length of scattered X-rays. Phys. Rev., 24:168-76.

The scattering of X-rays. Radiology, 3:479-85.

1925

With A. W. Simon. Measurements of the beta-rays excited by hard X-rays (abstract). Phys. Rev., 25:107.

With J. A. Bearden and Y. H. Woo. Tests of the effects of an enclosing box on the spectrum of scattered X-rays (abstract). Phys. Rev., 25:236.

With J. A. Bearden. The effect of a surrounding box on the spectrum of scattered X-rays. Proc. Nat. Acad. Sci., 11:117-19.

With Alfred W. Simon. Measurements of β-rays associated with scattered X-rays. Phys. Rev., 25:306-13.

With O. K. DeFoe. The density of rock salt and calcite. Phys. Rev., 25:618-20.

With H. N. Beets and O. K. DeFoe. The grating space of calcite and rock salt. Phys. Rev., 25:625-29.

On the mechanism of X-ray scattering. Proc. Nat. Acad. Sci., 11: 303-6.

With Alfred W. Simon. Directed quanta of scattered X-rays. Phys. Rev., 26:289-99.

With R. L. Doan. X-ray spectra from a ruled reflection grating. Proc. Nat. Acad. Sci., 11:598-601.

Light waves or light bullets? Sci. Am., 133:246-47.

1926

With R. L. Doan. Diffraction of X-rays by a ruled metallic grating (abstract). Phys. Rev., 27:105-6.

Electron distribution in sodium chloride (abstract). Phys. Rev., 27:510-11.

1927

Röntgenstrahlem als Teilgebiet d. Optik. Zeitschrift für technische Physik, 12: 530-37.

1928

On the interaction between radiation and electrons. Phys. Rev., 31:59-65; also in *Atti del Congresso Internazionale dei Fisici,* September, 1927, Vol. I, pp. 161-70.

With K. N. Mathur and H. R. Sarna. An attempt to detect a unidirectional effect of X-rays (abstract). Phys. Rev., 31:159.

Some experimental difficulties with the electromagnetic theory of radiation. J. Franklin Inst., 205:155-78.

X-rays as a branch of optics. J. Opt. Soc. Am. and Rev. Sci. Instr., 16:71-87; also published in *Les Prix Nobel en 1927* (Les Conférences Nobel, Stockholm, P. A. Norstedt & Fils, 1928). Nobel Lecture, December 12, 1927.

The spectrum and state of polarization of fluorescent X-rays. Proc. Nat. Acad. Sci., 14:549-53.

1929

What is light? Sigma Xi Quarterly, 17:14-34; reprinted in Sci. Monthly, 28:289-303; Proceedings of the Ohio State Education Conference, 35:401-20 (with alterations); Smithsonian Rep. for 1929, Publ. No. 3038 (1930), pp. 215-28; Journal of Chemical Education, 7:2769-87.

With K. N. Mathur and H. R. Sarna. An attempt to detect a unidirectional effect of X-rays. Indian Journal of Physics, 3(4):463-66.

The corpuscular properties of light. Phys. Rev. Suppl., 1:74-89; also published in *Electrons et Photons.* (report 5ᵉ Conseil de Physique, Institut Solvay, Brussels, 1927), Ch. 2, "Discordances entre l'expérience et la Théorie Electromagnetique du Rayonnement." (Paris, Gautier-Villars, 1928), pp. 55-104.

A new wave-length standard for X-rays. J. Franklin Inst., 208:605-16.

The efficiency of production of fluorescent X-rays. Phil. Mag., 8:961-77.

What things are made of. Sci. Am., 140:110-13, 234-36.

Compton effect. In: *Encyclopaedia Britannica,* 14th ed., through 1958.

Korpuskulare Eigensch. d. Lichtes. Die Naturwissenschaften, 17: 507-15.

1930

The efficiency of X-ray fluorescence (abstract). Phys. Rev., 35: 127-28.

Determination of electron distributions from measurements of scattered X-rays. Phys. Rev., 35:925-38.

Scattering of X-rays and the distribution of electrons in helium (abstract). Phys. Rev., 35:1427.

Are planets rare? Science, 72:219.

Looking inside the atom: X-ray scattering and the structure of atoms. Technology Review, 33:19-21, 50, 52.

1931

Electron distribution in argon, and the existence of zero point energy (abstract). Phys. Rev., 37:104.

The optics of X-rays. J. Opt. Soc. Am., 21:75-89.

Precision wavelength measurement with the double crystal X-ray spectrometer (abstract). Phys. Rev., 37:1694.

A precision X-ray spectrometer and the wave length of Mo K_{α_1}. Rev. Sci. Instr., 2:365-76.

The uncertainty principle and free will. Science, 74:172.

Assault on atoms. Proc. Am. Phil. Soc., 70:215-29; reprinted in Smithsonian Rep. for 1931, Publ. No. 3150 (1932), pp. 287-96.

With R. D. Bennett and J. C. Stearns. Ionization as a function of pressure and temperature (letter). Phys. Rev., 38:1565-66.

With R. D. Bennett and J. C. Stearns. The constancy of cosmic rays (letter). Phys. Rev., 38:1566.

1932

Comparison of cosmic rays in the Alps and in the Rockies (abstract). Phys. Rev., 39:190.

With R. D. Bennett and J. C. Stearns. Ionization by penetrating radiation as a function of pressure and temperature. Phys. Rev., 39:873-82.

Variation of the cosmic rays with latitude (letter). Phys. Rev., 41: 111-13.

With R. D. Bennett and J. C. Stearns. Diurnal variation of cosmic rays. Phys. Rev., 41:119-26.

With John J. Hopfield. Use of argon in the ionization method of measuring cosmic rays (letter). Phys. Rev., 41:539.

Progress of cosmic-ray survey (letter). Phys. Rev., 41:681-82.

Studies of cosmic rays. Carnegie Inst. Wash. Year Book No. 31, 1931-1932, pp. 331-33.

Sea level intensity of cosmic rays in certain localities from 46° S. to 68° N. latitude (abstract). Phys. Rev., 42:904.

1933

A geographic study of cosmic rays. Sci. Monthly, 36:75-87.

Some evidence regarding the nature of cosmic rays (abstract). Phys. Rev., 43:382.

A geographic study of cosmic rays. Phys. Rev., 43:387-403.

Nature of cosmic rays. Chapter 24 in: *The Science of Radiology*, ed. by O. Glasser, pp. 398-411. Springfield, Illinois, Charles C. Thomas, Publishers. Reprinted in part from Phys. Rev., 43:387-403; Sci. Monthly, 36:75-87.

With Luis Alvarez. A positively charged component of cosmic rays (letter). Phys. Rev., 43:835-36.

The significance of recent measurements of cosmic rays. Science, 77:480-82.

Nature of cosmic rays. Nature, 131:713-15.

The secret message of the cosmic ray. Sci. Am., 149:5-7.

With J. J. Hopfield. An improved cosmic-ray meter. Rev. Sci. Instr., 4:491-95.

Studies of cosmic rays. Carnegie Inst. Wash. Year Book No. 32, 1932-1933, pp. 334-39.

Progress of world-survey of cosmic rays. Transactions of the American Geophysical Union, 14th Annual Meeting, pp. 154-58.

1934

Scientific work in the "Century of Progress" stratosphere balloon. Proc. Nat. Acad. Sci., 20:79-81.

With J. M. Benade and P. G. Ledig. Further geographic studies of cosmic rays (abstract). Phys. Rev., 45:294-95.

With R. J. Stephenson. Cosmic-ray ionization at high altitudes. Phys. Rev., 45:441-50.

With R. J. Stephenson. Cosmic-ray ionization in a heavy walled chamber at high altitudes (abstract). Phys. Rev., 45:564.

Interpretation of data from world cosmic ray survey (abstract). Science, 79:378.

With E. O. Wollan. "Appearance" of atoms as observed with X-rays (abstract). Science, 79:379.

With E. O. Wollan, R. D. Bennett, and A. W. Simon. Precision recording cosmic-ray meter (abstract). Phys. Rev., 45:758.

With E. O. Wollan. The appearance of atoms as determined by X-ray scattering. J. Opt. Soc. Am., 24:229-33.

With H. A. Bethe. Composition of cosmic rays (letter). Nature, 134:734-36.

Studies of cosmic rays. Carnegie Inst. Wash. Year Book No. 33, 1933-1934, pp. 316-21.

Magnitude of cosmic ray bursts (letter). Nature, 134:1006.

With E. O. Wollan and R. D. Bennett. A precision recording cosmic-ray meter. Rev. Sci. Instr., 5:415-22.

1935

Incoherent scattering and the concept of discrete electrons (abstract). Phys. Rev., 47:203.

Incoherent scattering and the concept of discrete electrons. Phys. Rev., 47:367-70.

The composition of cosmic rays. Proc. Am. Phil. Soc., 75:251-74.
Cosmic rays. Nature, 135:695-98.
With Ivan A. Getting. An apparent effect of galactic rotation on the intensity of cosmic rays. Phys. Rev., 47:817-21.
An attempt to analyze cosmic rays. Proceedings of the Physical Society of London, 47:747-73.
Studies of cosmic rays. Carnegie Inst. Wash. Year Book No. 34, 1934-1935, pp. 336-40.
With Ralph D. Bennett. A study of cosmic-ray bursts at different altitudes. Papers and discussions of the International Conference on Physics, London, 1934. In: Volume I of *Nuclear Physics,* p. 225. London, The Physical Society.

1936

Recent developments in cosmic rays. Rev. Sci. Instr., 7:71-81.
Scattering of X-rays by a spinning electron. Phys. Rev., 50:878-81.
Studies of cosmic rays. Carnegie Inst. Wash. Year Book No. 35, 1935-1936, pp. 343-46.
Cosmic rays as electrical particles. Phys. Rev., 50:1119-30.

1937

An energy distribution analysis of primary cosmic rays (abstract). Phys. Rev., 51:59.
Effect of galactic rotation on cosmic rays (abstract). Science, 85: 25.
With R. N. Turner. Variations of cosmic rays with latitude on the Pacific Ocean (abstract). Phys. Rev., 51:1005.
With P. Y. Chou. On the origin of cosmic rays (letter). Phys. Rev., 51:1104.
With R. N. Turner. Cosmic rays on the Pacific Ocean. Phys. Rev., 52:799-814.
Studies of cosmic rays. Carnegie Inst. Wash. Year Book No. 36, 1936-1937, pp. 356-58.

1938

An alternative interpretation of Jauncey's "heavy electron" spectra (letter). Phys. Rev., 53:431.

1939

With P. S. Gill. Significance of sidereal time variations of cosmic rays (abstract). Phys. Rev., 55:233.
With M. Schein and P. S. Gill. Cosmic ray intensity and the thermal expansion of the atmosphere (abstract). Science, 89: 398.
Time variations of cosmic rays. J. Franklin Inst., 227:607-22.
With P. S. Gill. Cosmic rays on the Pacific Ocean. Revs. Mod. Phys., 11(3):136.
With A. T. Monk. Recurrence phenomena in cosmic-ray intensity. Revs. Mod. Phys., 11(3):173-79.
Chicago cosmic ray symposium. Sci. Monthly, 49:280-84.

1940

What we have learned from scattered X-rays. J. Franklin Inst., 230:149-57.
Physical differences between types of penetrating radiation. American Journal of Roentgenology and Radium Therapy, 44(2): 270-75.
Effect of an eclipse on cosmic rays (letter). Phys. Rev., 58:841.
Report on cosmic-ray research at the University of Chicago. Carnegie Inst. Wash. Year Book No. 39, 1939-1940, pp. 116-21.
Studies of cosmic rays at high altitudes. Year Book of the American Philosophical Society, 1940, pp. 147-49. (Report as recipient of Grant No. 427 from the Penrose Fund.)

1941

With A. T. Monk. Recurrence pulses in cosmic-ray intensity (abstract). Phys. Rev., 59:112.
With M. Schein. Protons as primary cosmic rays (abstract). Science, 93:436.
Recent studies of cosmic rays at high altitudes (abstract). Science, 93:462.
Physical differences between types of penetrating radiation (abstract). Radiography, 7:69-73.
Report on cosmic-ray research at the University of Chicago. Carnegie Inst. Wash. Year Book No. 40, 1940-1941, pp. 121-26.

1942

Report of cosmic-ray research at the University of Chicago. Carnegie Inst. Wash. Year Book No. 41, 1941-1942, pp. 90-94.

1943

On the fluctuations of cosmic rays. Symposium on Cosmic Rays, Academia Brasileira de Ciencias, pp. 59-66.

1945

Modern physics and the discovery of X-rays. Radiology, 45(5): 534-38.

1946

The scattering of X-ray photons. Am. J. Phys., 14:80-84.

1956

The world of science in the late eighteenth century and today. Proc. Am. Phil. Soc., 100(4):296-303.

1961

The scattering of X-rays as particles. Am. J. Phys., 29:817-20.

BOOKS

X-Rays and Electrons; an Outline of Recent X-Ray Theory. New York, D. Van Nostrand Company, Inc., 1926. xv + 403 pp. (2d printing, 1928.)

With S. K. Allison. *X-Rays in Theory and Experiment*. New York, D. Van Nostrand Company, Inc., 1935. xiv + 828 pp.

Atomic Quest; a Personal Narrative. New York, Oxford University Press, 1956. ix + 370 pp.