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BIOGRAPHICAL MEMOIR

OF

WILLIAM DUANE

1872-1935

BY

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William Duane was born in Philadelphia on Feb. 17, 1872, the son of Charles William Duane and Emma Cushman (Lincoln) Duane. He was a descendant in the fifth generation from Benjamin Franklin, the family line running as follows: Benjamin Franklin's daughter Sarah married Richard Bache, a native of England, who held important offices in the Colonial Government. They had seven children, of whom the fourth, Deborah, married William John Duane. William John Duane was the son of William Duane, who in his capacity as editor of the Philadelphia *Aurora* was influential in bringing on the War of 1812. William John Duane was Secretary of the Treasury of the United States under President Jackson, but resigned, or was dismissed from his office, for refusing to remove the government deposits from the United States Bank at the order of the President.

From Richard and Sarah Bache was also descended, in the second generation, Alexander Dallas Bache, Superintendent of the United States Coast Survey for many years, and one of the founders of the National Academy of Sciences.

William John Duane and Deborah had nine children, of whom the oldest, William, married Louisa Brooks. From this union there were two children, a son and a daughter. The son, the father of our William Duane, was the Rev. Charles William Duane, at one time rector of St. Andrew's church in West Philadelphia, and during a period of nearly fifty years rector of a series of parishes in Pennsylvania, New Jersey, and Massachusetts. Rev. Charles William Duane married Helen Frances Lincoln, a descendant of the Rev. Andrew Eliot of Boston, of whom President Eliot of Harvard was a great-great-nephew. By her he had a daughter who died in infancy, and a son, Russell Duane, at present a prominent practicing lawyer in Philadelphia. On the death of Helen Frances, Charles William Duane married her younger sister, Emma Cushman Lincoln,

by whom he had two daughters, one long since deceased, and the other Louise Duane, now Mrs. Bodine Wallace, and one son, our William Duane.

Duane was graduated from the University of Pennsylvania in 1892 as valedictorian of his class, with the A.B. degree. From Harvard he received the A.B. degree in 1893 and the A.M. in 1895. From 1893 to 1895 he served as Assistant in Physics at Harvard, and in 1895, in collaboration with Professor John Trowbridge, published a research on the velocity of electric waves on wires. As holder of the Tyndall Fellowship of Harvard University he studied from 1895 to 1897 at Göttingen and Berlin, receiving the Ph.D. degree from Berlin in 1897. Four papers on electrical topics were the result of this period. One of them, on thermo-electric circuits composed of electrolytes, was done under the direction of Nernst, and probably contained the material of his thesis, although no explicit statement appears to this effect. On his return to this country, he accepted a position as Professor of Physics at the University of Colorado, a position which he held from 1898 to 1907. During this period he married, in 1899, Caroline Elise Ravenel of Charleston, South Carolina, by whom he had four children, William, Arthur Ravenel (now deceased), John, and Magaretta. During the Colorado period eight papers were published. It is probable that the facilities for consistent research were not good at Colorado, and the titles of the papers would suggest that Duane had to content himself with rather miscellaneous outlets for his impulse for creative work.

The next period embraces the years from 1907 to 1913, when he was in residence in Paris, where, in the laboratory of Madame Curie at the Sorbonne, he carried out a number of researches on various aspects of radioactivity. Seventeen papers were the result of this period. Although none of them was in direct collaboration with Madame Curie, his contact with her was close. It is reported that when Madame Curie visited America some years later she replied, in response to the question as to what she wished most to see in the United States, "Niagara Falls, the Grand Canyon, and William Duane." His papers

from this period were mostly concerned with various properties of α rays from radioactive sources, and with accurate measurements of the heat generated by radioactive disintegration.

Duane's experience with radioactivity coincided with rapidly increasing activity in the medical profession in various parts of the world in experimentation with the possibility of applying radium and X-rays in the treatment of various diseases, especially cancer. About the year 1913 the wave-like nature of X-rays had been established by the work of Laue and the Braggs, and the γ rays from radium were known to be essentially a penetrating X radiation. It was evident, therefore, that the adequate application of X-rays and radium to the treatment of cancer was, at least in its initial stages, a problem involving many physical aspects. It was natural that the newly founded Harvard Cancer Commission should seek the services of a man with competent training in radioactivity, which at that time meant almost inevitably some one trained in Europe. The Harvard Physics Department at the same time had a vacancy because of the retirement of Professor John Trowbridge, and was anxious to find a young man, with a new line of promising work for the future, and whose subject might possibly at the same time be such that he could carry on the use of Professor Trowbridge's 50,000 volt storage battery, an unique instrument, and one which later played an important part in many of Duane's precise measurements. Duane combined in a singularly fortunate degree the qualifications for these two positions, and in 1913 he accepted a joint appointment as Assistant Professor of Physics in Harvard University and as Research Fellow in Physics of the Cancer Commission. In 1917 he was promoted to Professor of Bio-Physics, a title of which he was very proud, esteeming it, with probable correctness, to be the first of its kind in America. Between 1928 and 1933 his official title with the Cancer Commission was "Member of the Cancer Commission," and from 1933 until his retirement, "Research Fellow in Physics" again. On his retirement in September, 1934, he became Professor of Bio-Physics Emeritus.

As would be expected, he divided his time between the Cancer Commission at the Huntington Hospital, and the Jefferson Physical Laboratory of Harvard University, and his salary was carried on the budget of both organizations.

Duane served as Councillor of the Société de Physique during the years 1920-23, as Chairman of the Division of Physical Sciences of the National Research Council 1922-23, as President of the Society for Cancer Research during 1923, as Vice-President of section B of the American Association for the Advancement of Science during 1927-28, delivering the address of the retiring Vice-President on "The General Radiation" at the Nashville meeting in December, 1928. He presented invited papers at the symposium held in New York in December, 1917, by the sections of chemistry and physics of the American Association for the Advancement of Science on the structure of matter, and at the symposium of the section of physics of the American Association for the Advancement of Science held at St. Louis in 1920 on phenomena in the ultra violet spectrum, including X-rays. He was one of the invited participants at the Volta Congress of Physicists at Lake Como in September, 1927, and an American representative at the International Conference of the Grand Council of the British Empire Cancer Commission in London in July, 1928, and at the Second International Congress of Radiology held at Stockholm, July 23-27, 1928.

In 1922 he received the John Scott Medal and Certificate, with a premium of \$800, from the Board of Directors of City Trusts of Philadelphia for his researches in radioactivity and X-rays. This award is made annually for scientific achievement in accordance with the terms of a bequest over a century ago by John Scott. The award the previous year had been made to Madame Curie. In 1923 he received the Leonard prize of the American Roentgen Ray Society for work done in 1922. This was a competitive prize, awarded for work presented anonymously to the judges. In 1923 he received the Comstock Prize of the National Academy of Sciences, a prize awarded

every five years for discovery or investigations in electricity, magnetism, or radiant energy.

He was awarded the honorary Sc.D. degree by the University of Pennsylvania in 1922 and by the University of Colorado in 1923.

He was a member of the National Academy of Sciences, the Philosophical Society, the American Academy of Arts and Sciences, the American Physical Society, the American Association for the Advancement of Science, Société de Physique, Radiological Society, Roentgen Ray Society, American Society for Cancer Research, Phi Beta Kappa, Sigma Xi, and of the Society of the Descendants of the Signers of the Declaration of Independence.

For many years before his death Duane was a sufferer from diabetes, which progressed with continually increasing intensity, making necessary the constant administration of insulin, and imposing continually increasingly severe restrictions on his activity. As early as 1927 his sight was so impaired that his scientific reading was seriously restricted, and from this time on much of his reading and writing had to be done through his secretary. In 1931 he suffered a paralytic shock, which totally incapacitated him for some months. From this he slowly recovered, and was able to resume productivity. His active work practically terminated in the fall of 1933, when he was given a year's leave of absence. In the fall of 1934 he retired with the title of Professor of Bio-Physics Emeritus. He spent the last months of his life at his home in Devon, Pennsylvania. Here he died on March 7, 1935, weakened by the continual progress of the diabetes, but the immediate cause of his death was a second paralytic stroke. In spite of the fact that toward the end his physical incapacity was almost complete, he continued his scientific work with mental alertness, enthusiasm and courage. In fact, his courage and uncomplaining cheerfulness during the whole course of his illness was an inspiration and a wonder to all who knew him.

Duane, at as early an age as four years, manifested a keen interest in mechanical matters which foreshadowed his later

physical interests. His most noticeable personal characteristic was the quietness and modesty of his manner. He never seemed excited or hurried, but was nevertheless certain of his own mind. In spite of his quietness, in committee meetings he managed in his own way to give weight to his opinions, which always were of an admirable sanity. His tastes were pronouncedly musical and he was a competent performer, not only on the piano, but on the organ. A favorite recreation was bridge whist with his friends at the Somerset Club in Boston.

Duane's contributions as a member of the Cancer Commission of Harvard University were most important in introducing clarity and precision into a subject which, when he took hold of it, had realized few of its own possibilities. Of his published papers, eight, presented mostly in medical journals, deal with technical matters pertaining to the application of radioactive materials and of X-rays in the treatment of cancer. Doubtless Duane's most important contribution in this field was in working out the technical details of the method of measuring X-ray dosage in terms of the ionization of air. Not only did he work out the details, but he was largely influential in securing, first its official adoption in this country, and then its international adoption at the Stockholm Congress in 1928. Further, the technical details of the method of collecting radon, purifying it and mounting it in "applicators" for transfer to the affected location in the patient were largely of Duane's devising. In the early years of his connection with the Cancer Commission, Duane personally made the radium applications to the patients, but later turned this phase of the work over to others.

There can be no question, however, but that Duane's chief claim to scientific eminence rests on his work done in the Jefferson Laboratory after 1914, much of it in collaboration with a number of pupils, candidates for the Ph.D. degree under his direction. Probably the most important single piece of work was done very early in his career at the Jefferson Laboratory. At the Washington meeting of the American Physical Society in April, 1915, Duane and Hunt announced the celebrated

“Duane-Hunt law.” This law states that there is a sharp upper limit to the X-ray frequencies emitted from a target stimulated by the impact of electrons, and that this frequency is given by the quantum connection, independently of the material of the target, $h\nu = eV$, where ν is the maximum frequency of the emitted radiation, and V the total difference of potential through which the exciting electrons have fallen. This discovery had been foreshadowed in the announcement by Duane at the Philadelphia meeting in December, 1914, that the effective wave length of the total X radiation (that is, roughly, its center of gravity) satisfies the quantum relation within a factor of less than 2. Of this law the *Handbuch der Experimental Physik* remarks, “The significance of the Duane-Hunt law for Roentgen spectroscopy cannot be overestimated.” It has been abundantly checked since then by other experimenters. Duane’s physical intuition convinced him that his law could be used inversely as a more accurate method of determining Planck’s h , or more strictly h/e , than any hitherto used, and in 1917 he determined with Blake as the most probable value of h , 6.555×10^{-27} , as contrasted with 6.41, the accepted value when he published his law. Important improvements in the technique of the ionization chamber were made in connection with these measurements. Finally, in 1921, he found with Palmer and Yeh the value $6.556 \pm 0.009 \times 10^{-27}$, as against the value 6.542 ± 0.008 , estimated by Birge in 1932 as the best mean from all sources. In February, 1936, Birge in reviewing the entire situation with respect to the fundamental physical constants states that of the six known methods of determining h/e , by far the most accurate is the method of determining the Duane-Hunt limit of the continuous spectrum.

In 1919, Duane and Shimizu, among others, were instrumental in establishing that there is no “J” radiation, of frequency greater than the K series, a subject about which there was considerable discussion at that time. Their method of attack was by absorption measurements on aluminum. Also in 1919, Duane and Shimizu first established that the total X-ray intensity produced by cathode rays of given intensity is propor-

tional to the ordinal number of the element composing the target, not to its atomic weight. The proof was given by observations of targets of iron, nickel, cobalt, and copper.

In 1920, Duane and Patterson found that the angles of reflected X-rays from crystals deviated by small amounts from what would be calculated by the simple Bragg reflection formula. The explanation was found in the partial penetration of the X-rays into the body of the crystal and a deviation from unity of the index of refraction of the crystal for X-rays. From their measurements they deduced a value for the index of refraction of the crystal for X-rays close to the value now accepted. This phenomenon had been previously observed qualitatively by Stenström, and the explanation suggested. Also in 1920, Duane and Patterson with the aid of improved apparatus of improved resolving power, split the β_1 line of molybdenum into two components.

In 1921, Duane, Palmer and Yeh, in the same paper already referred to, giving a more accurate value of h , found that there is no difference within one part in 2000 between the apparent limit of the spectrum for rays leaving the target at 90° and 45° , a fact which they expressed by saying that there is no Doppler effect of this magnitude.

During the years 1919-22 Duane and his pupils were especially active in making precision measurements of many characteristic X-ray radiations, from which they were able to establish the same sort of series relations that are known to be valid in the visible spectrum, and in measuring the X-ray absorption in various metals, for which they were able to establish definite formulas. In 1922, Duane established in collaboration with his son Arthur that the intensity of scattered X radiation goes rapidly to zero as the angle of incidence goes to zero, and in particular, the intensity of the radiation excited by 29.35 volt electrons is zero at all angles of scattering less than 9.7° . In 1922, Duane with Clark suggested an interesting modification in the Laue method of crystal analysis, in which the maximum frequency of each spot of the Laue pattern was measured independently by an ionization method.

In 1923, he made the interesting discovery that in some cases there is a certain extra radiation emitted from a crystal besides that to be expected by the Bragg law. This was correctly explained in terms of the excitation of the characteristic frequency of some of the atoms of the crystal by the analyzing X-rays. Also in 1923, Duane, by an interesting application of the more extreme form of quantum theory, obtained a very much simplified deduction of the Bragg law of reflection of X-rays from a crystal. The frequency entering into the quantum relation was found in the periodic repetition in space of the structure of the crystal, a novel and a fruitful point of view.

In 1924 and 25, Duane and several collaborators published a number of papers dealing with the recently discovered Compton effect, which consists in a shift in the wave length of X-rays scattered by impact on electrons. At first Duane was not able to verify the existence of the effect, but in its place found another effect, sometimes referred to in the literature of that time as the "Duane" effect. He thus became involved in a controversy with Compton which was later settled to the advantage of the latter, and not without some damage to Duane's reputation. It would seem that this episode has enough importance for the history of physics to justify recording it in a little more detail. What Duane found was a scattered radiation of altered wave length, but the alteration in wave length was not that demanded by Compton's formula, and furthermore it apparently exhibited a correlation with the scattering substance, instead of being independent of it. This led Duane to explain the scattering in terms of a "tertiary" effect. It was supposed that the incident X-rays liberated electrons by a photo-electric action, and these electrons, impinging on other atoms, in turn gave rise to X-radiation, which played the role of the scattered radiation. The loss of frequency by the scattered radiation was correlated with the loss of energy of the photo-electrons in the body of the scattering substance. Duane and Compton both made the most earnest efforts to find the reason for the lack of agreement. Compton visited Duane's laboratory, and with Duane's apparatus was able to get only

the same results as Duane. At the summer meeting of the British Association at Toronto in 1924 both Duane and Compton presented their own accounts, each so convincingly that the reporter of the meeting in *Nature* was led to remark, "At the time of the meeting each observer appeared to have almost overwhelming evidence in favor of his point of view, and had the audience had to listen to only one side—either side would have done equally well—it would probably have been convinced as to the accuracy and soundness of the views advanced." The explanation proved to involve a curious combination of experimental error and fortuitous coincidence. Duane's X-rays were probably not intense enough, the beam was too broad, there was too much scattered radiation from other parts of the apparatus, and in at least one case there was a spurious effect due to accidental impurity in the metal of the target. Once convinced of the true state of affairs, Duane was most generous in his admission of error, and the unreservedness of his announcement of his change of position at a meeting of the Physical Society must remain a pleasant memory to all who heard it. Later, Duane and Allison made one of the most accurate measurements of the Compton shift. At the same time, it would appear that even yet the subject is not completely cleared up. Duane and Allison found that the width of the line of characteristic molybdenum radiation scattered by lithium was too great to be accounted for by the Compton effect, and Compton has confirmed this observation. The explanation of this too great width appears not yet to have been given. At least one of Duane's collaborators, who was intimately associated with the work, is still convinced that the "tertiary" effect exists, and the necessity for a similar tertiary effect in million volt radiation has lately been recognized.

Other important results date from the same period. In 1925, Duane and Allison checked with much greater precision the conclusion of M. de Broglie, reached in 1914, that the characteristic frequency of any substance is the same whether excited by electron bombardment or by incident X-rays. Duane and Allison also showed in 1925 that if K radiation appears

in the secondary spectrum of silver the exciting radiation must contain frequencies at least as high as those of the K radiation itself. In 1925, Duane resurrected an idea originally suggested by Bragg a number of years before, and showed how to get the electron distribution in a crystal from a Fourier analysis of the intensity of the reflected X-ray pattern, putting the method into a form conveniently suitable for calculation. The method was immediately applied to NaCl with interesting results by Havighurst, who was able to give a definite proof that all the 100 planes are equivalent, whereas the 111 planes alternate. The method of Fourier analysis has now come to play an indispensable part in the analysis of complicated crystals.

The end of the year 1925 marks an abrupt diminution in Duane's productivity. In 1926 he took his first sabbatical leave, being largely forced thereto by considerations of health. On his return he investigated the excitation of X-rays in a target consisting of mercury vapor, and was able to establish that the yield of X-rays in terms of the potential drop of the exciting cathode rays is not markedly different from that found in solid targets. At the New York meeting of the American Physical Society he presented, with Hudson, a study of the variation with direction of the intensity of radiation excited in mercury vapor, finding that the radiation emitted at an angle of 45° with the impinging electron stream is about twice as intense as that emitted at 135° a conclusion in agreement with that of other observers for emission from solids.

Duane's last three papers were published early in 1932. At that time he was constructing an improved photometer for the greater resolution of characteristic X-radiation, and determining new lines in the K series of various elements with the aid of the greater resolving power.

All these accomplishments, the enduring importance of which in the permanent achievements of the physics of X-rays is too obvious for further elaboration, were made under physical difficulties that would have stopped a less resolute and devoted man. Not only was there the handicap of his own physical

disabilities, but in the latter part of his life there was the sadness from his son's tragic death, a shock which seemed to overtax his elasticity and from which he recovered only slowly. His persistence of purpose and his winsomeness of spirit remain a cherished memory to those who knew him.

BIBLIOGRAPHY

1895

Velocity of Electric Waves on Wires. (With J. Trowbridge.) Amer. Journ. Sci., 49, p. 297.

1896

Ueber eine dämpfende Wirkung des magnetischen Feldes auf rotierende Isolatoren. Annalen der Physik, 58, p. 517.

1897

Ueber die dämpfende Wirkung des magnetischen Feldes auf rotierende Isolatoren. (With W. Stewart.) Annalen der Physik, 61, p. 436.

Ueber eine magnetische Methode metallisches Eisen nach zu weisen. Annalen der Physik, 62, p. 543.

1898

Ueber electrolytische Thermoketten. Annalen der Physik, 65, p. 374.

1900

An Electric Thermostat. (With C. A. Lory.) Amer. Journ. Sci., 9, p. 179, March.

1901

On the Velocity of Chemical Reactions. Amer. Journ. Sci., 11, p. 349, May.
The Absolute Measurement of Self-Inductance. Phys. Rev., 13, p. 250, October.

Note on Electrometers. Phys. Rev., 13, p. 369, December.

1902

On the Siphon. Science, 15, pp. 152-153.

On the Boundary Conditions of the Electric Field. Phys. Rev., 14, p. 149, March.

A Device for Synchronizing Motors. Elec. Rev. (New York), 40, p. 357, March 15.

1904

On the Differential Telephone. (With C. A. Lory.) Phys. Rev., 18, p. 275, April.

1905

Radioactivité:—Sur l'ionization produite entre les plateaux parallèles par l'émanation du radium. Comptes Rendus, 140, p. 786, March 20.

1906

Emission of Electricity from the Radium Products. *Science*, 24, p. 48, July 13.

1908

Radioactivité:—Le parcours des rayons α . *Comptes Rendus*, 146, p. 958, May 11.

Radioactivité:—Sur les rayons secondaires des rayons α . *Comptes Rendus*, 146, p. 1088, May 25.

On the Emission of Electricity from the Induced Activity of Radium. *Amer. Journ. Sci.*, 25, p. 1, July.

1909

Ueber den Wirkungsbereich der α -Strahlen. *Annalen der Physik*, 28, p. 443.

Radioactivité:—Le dégagement de chaleur des corps radioactifs. *Comptes Rendus*, June 1.

Radioactivité:—La chaleur de polonium. *Comptes Rendus*, June 21.

1910

Radioactivité:—Sur les mesures quantitative de l'émanation du radium. (With A. Laborde.) *Comptes Rendus*, 150, p. 1421, May 30.

Sur une méthode photographique d'enregistrement des particules α . *Le Radium*, July.

Radioactivité:—Sur le dégagement de chaleur dans un mélange de radium et d'un sel phosphorescent. *Comptes Rendus*, August 1.

Radioactivité:—Sur l'énergie des rayons du radium. *Comptes Rendus*, August 16.

1911

On the Heat Generated by Radio-Active Substances. *Amer. Journ. Sci.*, 31, April.

Physique:—Sur la masse des ions gazeux. *Comptes Rendus*, 153, p. 336, July 31.

1912

Radioactivité:—Sur les charges électrique transportées par les rayons α et β . (With Jean Danysz.) *Comptes Rendus*, September 2.

The Effect of a Magnetic Field on Ionization Currents. *Le Radium*, 9, p. 342, October.

1913

The effect of a Magnetic Field on Ionization Currents. *Amer. Journ. Sci.*, 35, p. 206, February.

Radioactivité:—Décomposition de l'eau par les rayons α . (With Otton Scheuer.) *Comptes Rendus*, February 10.

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1915

- On the Extraction and Purification of Radium Emanation. *Phys. Rev.*, 5, no. 4, April.
Notes on the Atomic Nuclei. *Phys. Rev.*, 5, no. 4, April.
On X-Ray Wave-Lengths. (With Franklin L. Hunt.) *Phys. Rev.*, 6, no. 2, August.

1916

- Planck's Radiation Formula Deduced from Hypotheses suggested by X-Ray Phenomena. *Phys. Rev.*, 7, no. 1, January.
Radium in the Treatment of Cancer. Paper presented before the Second Pan-American Scientific Congress, Washington, D. C., December 27, 1915 to January 8, 1916.
A Chemically Active Modification of Hydrogen Produced by Alpha-Rays. (Abstract) (With G. L. Wendt.) *Phys. Rev.*, 7, no. 6, June.

1917

- A Reactive Modification of Hydrogen Produced by Alpha-Radiation. (With G. L. Wendt.) *Phys. Rev.*, 10, no. 2, August.
Radiation and Matter. *Science*, 46, p. 1189, October.
The Value of "h" as Determined by Means of X-Rays. (With F. C. Blake.) *Phys. Rev.*, 10, no. 6, December.
The Critical Absorption of some of the Chemical Elements for High-Frequency X-Rays. (With F. C. Blake.) *Phys. Rev.*, 10, no. 6, December.
Methods of Preparing and Using Radioactive Substances in the Treatment of Malignant Disease and of Estimating Dosage. *Boston Med. and Surg. Journ.*, 177, December 6.

1918

- On the Relation between the K X-Ray Series and the Atomic Numbers of the Chemical Elements. (With Kang-Fuh Hu.) *Phys. Rev.*, 11, no. 6, June.

1919

- Are the Frequencies in the K Series of X-Rays the Highest Frequencies Characteristic of Chemical Elements? (With Takeo Shimizu.) *Phys. Rev.*, 13, no. 4, April.
On the X-Ray Absorption Wave-Lengths of Lead Isotopes. (With Takeo Shimizu.) *Proc. Nat. Acad. Sci.*, 5, p. 198, June.
On the Relation between the K Series and the L Series of X-Rays. (With Takeo Shimizu.) *Phys. Rev.*, 14, no. 1, July.
On the Critical Absorption and Characteristic Emission X-ray Frequencies. (With Kang-Fuh Hu.) *Phys. Rev.*, 14, no. 4, October.

On the Spectrum of X-Rays from an Aluminium Target. (With Takeo Shimizu.) *Phys. Rev.*, 14, no. 5, November.

On the X-Ray Absorption Frequencies Characteristic of the Chemical Elements. (With Takeo Shimizu.) *Phys. Rev.*, 14, no. 6, December.

On the X-Ray Absorption Frequencies Characteristic of the Chemical Elements. (With Kang-Fuh Hu.) *Phys. Rev.*, 14, no. 6, December.

The Relation between the Intensity of the General X-Radiation and the Atomic Number of the Anti-Cathode. (With Takeo Shimizu.) *Phys. Rev.*, 14, no. 6, December.

1920

On the K Series of X-Rays. (With Wilhelm Stenström.) *Proc. Nat. Acad. Sci.*, 6, August.

Characteristic Absorption of X-Rays: L Series. (With R. A. Patterson.) *Proc. Nat. Acad. Sci.*, 6, September.

On the Relative Positions and Intensities of Lines in X-Ray Spectra. (With R. A. Patterson.) *Proc. Nat. Acad. Sci.*, 6, September.

The Absorption of X-Rays by Chemical Elements of High Atomic Numbers. (With Hugo Fricke and Wilhelm Stenström.) *Proc. Nat. Acad. Sci.*, 6, October.

Data Relating to X-Ray Spectra. *Bull. Nat. Res. Council*, 1, November.

On the X-Ray Spectra of Tungsten. (With R. A. Patterson.) *Phys. Rev.*, 16, no. 6, December.

1921

A Remeasurement of the Radiation Constant, "h," by Means of X-Rays. (With H. H. Palmer and Chi-Sun Yeh.) *Journ. Optical Soc. Amer.*, 5, no. 3, May.

A Remeasurement of the Radiation Constant, "h," by Means of X-Rays. (With H. H. Palmer and Chi-Sun Yeh.) *Proc. Nat. Acad. Sci.*, 7, August.

On the Calculation of the X-Ray Absorption Frequencies of the Chemical Elements. *Proc. Nat. Acad. Sci.*, 7, September.

On the Calculation of the X-Ray Absorption Frequencies of the Chemical Elements. (Second Note.) *Proc. Nat. Acad. Sci.*, 7, September.

1922

Absorption of Short X-Rays by Aluminium and Copper. (With K. C. Mazumder.) *Proc. Nat. Acad. Sci.*, 8, March.

X-Ray Spectra Produced under Various Experimental Conditions. *Journ. Radiology*, March.

Roentgen Rays of Short Wave-Lengths and their Measurement. *Amer. Journ. Roentgenology*, 9, no. 3, March.

The Radio-Active Point of View. *Proc. Amer. Philosophical Soc.*, 61, no. 4.

- Note on X-Ray Spectra. (With R. A. Patterson.) Proc. Nat. Acad. Sci., 8, May.
- A New Method of Using X-Rays in Crystal Analysis. (With George L. Clark.) Proc. Nat. Acad. Sci., 8, May.
- The Production of Penetrating X-Rays. Amer. Journ. Roentgenology, 9, July.
- Experiments on the Wavelengths of Scattered X-Rays. Phys. Rev., 3, September.

1923

- The Reflection by a Crystal of X-Rays Characteristic of Chemical Elements in it. (With George L. Clark.) Proc. Nat. Acad. Sci., 9, April.
- On the Abnormal Reflection of X-Rays by Crystals. (With George L. Clark.) Proc. Nat. Acad. Sci., 9, April.
- The Transfer in Quanta of Radiation Momentum to Matter. Proc. Nat. Acad. Sci., 9, May.
- Measurement of Dosage by Means of Ionization Chambers. Amer. Journ. Roentgenology and Radium Therapy, 10, no. 5, May.
- A New Method of Crystal Analysis and the Reflection of Characteristic X-Rays. (With George L. Clark.) Journ. Optical Soc. Amer., 7, no. 6, June.
- The Abnormal Reflection of X-Rays by Crystals. (With George L. Clark.) Science, 58, p. 1507, November.
- The Wave-Lengths of Secondary X-Rays. (With George L. Clark.) Proc. Nat. Acad. Sci., 9, December.
- The Wave-Lengths of Secondary X-Rays (Second Note). (With George L. Clark.) Proc. Nat. Acad. Sci., 9, December.
- Ionization Methods of Measuring X-Ray Dosage. Amer. Journ. Roentgenology and Radium Therapy, 10, no. 12, December.

1924

- On Tertiary X-Radiation, etc. (With George L. Clark.) Proc. Nat. Acad. Sci., 10, January.
- Further Experiments upon the Reflection by a Crystal of its Characteristic X-Radiation. (With George L. Clark.) Proc. Nat. Acad. Sci., 10, January.
- On Secondary and Tertiary X-Rays from Germanium, etc. (With George L. Clark.) Proc. Nat. Acad. Sci., 10, March.
- The Secondary and Tertiary Rays from Chemical Elements of Small Atomic Number Due to Primary X-Rays from a Molybdenum Target. (With George L. Clark and W. W. Stiffler.) Proc. Nat. Acad. Sci., 10, April.

- On the Theory of the Tertiary Radiation Produced by Impacts of Photo-Electrons. (With George L. Clark.) Proc. Nat. Acad. Sci., 10, May.
- Absorption Measurements of Certain Changes in the Average Wave-Length of Tertiary X-Rays. (With S. K. Allison.) Proc. Nat. Acad. Sci., 10, May.
- Standard=ionisationskammer für Messungen der Röntgenstrahlendosis. (With Egon Lorenz.) Fortschritte auf dem Gebiete der Röntgenstrahlen, Band XXXVII, Heft 5.
- The Reflection of Characteristic Bromine X-Radiation by a Crystal of Potassium Bromide. (With S. K. Allison.) Proc. Nat. Acad. Sci., 10, July.
- The Influence on Secondary X-Ray Spectra of Placing the Tube and Radiator in a Box. (With S. K. Allison and George L. Clark.) Proc. Nat. Acad. Sci., 10, September.
- The Influence on Secondary X-Ray Spectra of Placing the Tube and Radiator in a Box. (With Alice H. Armstrong and W. W. Stiffler.) Proc. Nat. Acad. Sci., 10, September.

1925

- On Scattered Radiation Due to X-Rays from Molybdenum and Tungsten Targets. (With S. K. Allison.) Proc. Nat. Acad. Sci., 11, January.
- Note on the Quantum Theory of the Reflection of X-Rays. Proc. Nat. Acad. Sci., 11, March.
- The Relative Intensities of Fluorescent and Scattered X-Rays. (With George L. Clark.) Proc. Nat. Acad. Sci., 11, March.
- The Reflection of X-Rays by Alkali Halide Crystals. (With Alice H. Armstrong and R. J. Havighurst.) Proc. Nat. Acad. Sci., 11, April.
- An Experimental Determination of the Critical Excitation Frequency for the Production of Fluorescent X-Radiation. (With S. K. Allison.) Proc. Nat. Acad. Sci., 11, August.
- The Calculation of the X-Ray Diffracting Power at Points in a Crystal. Proc. Nat. Acad. Sci., 11, August.
- Experiments on the Wave-Lengths of Scattered X-Rays. (With S. K. Allison.) Phys. Rev., 26, No. 3, September.

1926

- On the Reflection by a Crystal of its Own Characteristic Radiation. Proc. Nat. Acad. Sci., 12, March.

1927

- The Character of the General, or Continuous Spectrum Radiation. Proc. Nat. Acad. Sci., 13, September.

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The Character of the General Radiation. Estratto Degli Atti Del Congresso Internazionale dei Fisici. September.

The General Radiation. *Science*, 66, December.

1928

The Standard Ionization Chamber for Roentgen Ray Dosage Measurements. (With Egon Lorenz.) *Amer. Journ. Roentgenology and Radium Therapy*, 19, no. 5, May.

The General X-Radiation from Mercury Vapor. *Proc. Nat. Acad. Sci.*, 14, June.

The Measurement of Effective Wavelengths. (With J. C. Hudson and Helen N. Sterling.) *Amer. Journ. Roentgenology and Radium Therapy*, 20, September.

1929

On the Polarization of X-Radiation. *Proc. Nat. Acad. Sci.*, 15, November.

1932

New Lines in the K Series of X-Rays. *Proc. Nat. Acad. Sci.*, 18, January.

The Mass of the Electron. *Proc. Nat. Acad. Sci.*, 18, April.

An Instrument for the Photomentering of the New X-Ray Lines. *Proc. Nat. Acad. Sci.*, 18, April.