NATIONAL ACADEMY OF SCIENCES

WILLIAM DRAPER HARKINS

1873—1951

A Biographical Memoir by

ROBERT S. MULLIKEN

*Any opinions expressed in this memoir are those of the author(s)
and do not necessarily reflect the views of the
National Academy of Sciences.*

Biographical Memoir

Copyright 1975
NATIONAL ACADEMY OF SCIENCES
WASHINGTON D.C.

W. D. Harkins.

WILLIAM DRAPER HARKINS

December 28, 1873–March 7, 1951

BY ROBERT S. MULLIKEN

WILLIAM DRAPER HARKINS was a remarkable man. Although he was rather late in beginning his career as professor of physical chemistry, his success was outstanding. He was a leader in nuclear physics at a time when American physicists were paying no attention to nuclei. Besides this, his work in chemistry covers a broad range of physical chemistry, with especial emphasis on surface phenomena. He was a meticulous and resourceful experimenter, as well as an enterprising one, who did not hesitate to enter new fields and use new techniques. He participated broadly, not only in the development of pure science but also in its industrial applications.

Harkins was born December 28, 1873, the son of Nelson Goodrich Harkins and Sarah Eliza (Draper) Harkins, in Titusville, Pennsylvania, then the heart of the new, booming oil industry. At the age of seven, he invested his entire capital of $12 in an oil well that his father had drilled in the Bradford, Pennsylvania, fields. This investment returned his capital several times. Fortunately for science, the returns were not great enough to attract him permanently into oil production.

In 1892, at the age of nineteen, Harkins went to Escondido, California, near San Diego, to study Greek at the Escondido Seminary, a branch of the University of Southern California. The courses of study are described in the University of Southern

California Year-Book for 1891–1892, where Harkins is listed as a student. Apparently, the seminary (now the Escondido High School) served as a preparatory school for the university. Harkins attended the seminary for one year, but had to learn Greek elsewhere because it was discontinued the year he came; he enrolled in a general arts course. It seems that Harkins spent a few more years in Escondido, and made many friends, but there is no other information as to his activities while there.

Harkins entered Stanford University in 1896 at age twenty-three and received an A.B. in chemistry in 1900, at twenty-six. In 1898–1900, he was assistant, then instructor, in chemistry at Stanford. For the next twelve years, Harkins was professor and head of the Department of Chemistry of the University of Montana at Missoula, but he spent a considerable amount of time in postgraduate and postdoctoral work elsewhere. He did postgraduate work at the University of Chicago in 1901 and 1904, and at Stanford University, 1905–1906, culminating in a Ph.D. in chemistry from Stanford on June 10, 1908. He did research in Germany in 1909 and was at the Massachusetts Institute of Technology as research associate in 1909–1910. Harkins left Missoula in 1912 at age thirty-nine for an appointment at the University of Chicago, where he conducted further research the remaining thirty-nine years of his life.

In Missoula, Harkins took part in the life of the city and state: He was President of the Missoula City Board of Health from 1906 to 1912. He was chemist in charge of smelter investigations for the Anaconda Farmers Association (1902–1910), the Montana Copper Company of California (1904), and the U.S. Department of Justice (1910–1912). His first four scientific papers, published during the period 1907–1910, are devoted to arsenical poisoning of animals by smelter smoke, and related matters. In 1911 Harkins did some research for the Carnegie Institution of Washington. On June 9, 1904, he married Anna Louis Hathaway, who was head of the Department of English at the University of Montana. She had also been a graduate student at the University of Chicago.

At the University of Chicago, with the opportunity to conduct pure research and to work with graduate students, Harkins' advancement was rapid. He was first assistant professor of general chemistry (1912–1914), then associate professor (1914–1917), then professor of physical chemistry. In 1916–1917 he was a professorial lecturer at the Mellon Institute for Industrial Research, and he lectured at the University of Illinois (1918–1919). In 1935 he was appointed Andrew MacLeish Distinguished Service Professor at Chicago. He was George Fisher Baker Lecturer at Cornell University in 1936–1937. In 1939 he retired officially at Chicago, but continued research with undiminished vigor until his death in 1951.

During World War I, early in 1915, Harkins began work on explosives for the Allies. Later in the war, he did special work for the army and the Chemical Warfare Service. Throughout his career, while carrying on notable work in pure science, he also contributed to applied science: as a consulting chemist with the U.S. Bureau of Mines, 1920–1922; consulting engineer, U.S. Air Service, 1924–1927; and consulting chemist, Chemical Warfare Service from 1927, Libby–Owens–Ford Glass Company from 1929, Universal Oil Products Company, 1930–1951, and United States Rubber Company, 1939–1941. During World War II, he was a member of the National Defense Research Committee (1941–1945). Civically, he also participated as a member of the Chicago Commission on Ventilation (1916–1928).

Harkins was also active in the affairs of the American Chemical Society. He was editor of the section of General and Physical Chemistry of *Chemical Abstracts* (1939–1951), chairman of the Chicago Section (1915–1916), chairman of the Division of Physical and Inorganic Chemistry (1919–1920), and councillor-at-large for a time. He was the recipient of the Willard Gibbs

Gold Medal of the American Chemical Society on May 28, 1928, in recognition of his work in surface chemistry and on nuclear structure and isotopes. He was also a vice president (chemistry) of the American Association for the Advancement of Science. Harkins was elected a member of the National Academy of Sciences in 1921, and at the annual meetings in Washington in April he took a lively part in the discussions. He was also a member of the American Philosophical Society, to which he was elected in 1925.

In Chicago, Harkins always lived with his family near the university (at 5437 Ellis Avenue). He and his wife had two children, Henry Nelson Harkins and Alice Marion Harkins. Henry Harkins (born in Missoula in 1905) obtained B.S. and M.S. degrees in physical chemistry, a Ph.D. in medicine (1928), and an M.D. in 1931, all at Chicago. He went on to a distinguished career in surgery.* His M.S. thesis on surface tension of blood serum was completed under his father's direction in 1926. Marion Harkins won success as a concert singer. The members of the family were devout Episcopalians. The Harkins family had a summer home on Lake Michigan, at Lakeside, across the lake from Chicago. An active mountain climber in his youth in California and Montana, Harkins visited the Rockies annually for many years. At the time of his death, he had been paying daily visits to the hospital after Mrs. Harkins had suffered a stroke.

Harkins' contributions to pure science covered a wide spectrum in the field of physical chemistry, extending also into physics. When I came to Chicago as a graduate student in 1918, it was because I had read about Harkins' pioneering work toward the understanding of nuclear structure, a subject ignored at that time by American physicists. In fact, during the period 1913–1928, Harkins and his students were the only

---

* G. Egloff, "Fathers and Sons in Chemistry," *Chemical and Engineering News* 22(1944):804.

Americans engaged in work relating to the structure of the atomic nucleus.

A perusal of the bibliography of Harkins' papers gives a perspective of his scientific interests and of his graduate students and other collaborators. In 1915 the diversity of his interests is already evident. His most extensive work was in surface chemistry (115 papers) and in nuclear and atomic structure and isotope separation (nearly 80 papers).

On the occasion when he received the Willard Gibbs medal, Harkins gave an address that shows something of his personality and the beginnings of his activity in his major fields of research. Following is a quotation from the introductory part of his talk.

"As an undergraduate, research appealed to me as one of life's greatest adventures, and I was attracted both to the very large, in astronomy, and to the extremely minute, in chemistry and physics. While the study of the atom and of radioactivity, then a new subject, had an extreme fascination, there were two subjects of investigation in physical chemistry which seemed to me of such minor importance that I took a firm resolution never to be enticed into working on either of them.

"These two fields of work were surface tension and solubility. To illustrate, let us consider surface tension. I did not realize that the importance of the study of surfaces and surface energy arises from the fact that the surface lies outside every body, particle or cell. To get inside from outside or outside from inside, the surface must be traversed.

"In 1909 I went to Germany to study with Fritz Haber, the chemist whose work on the synthesis of ammonia lengthened the World War by one or two years. On the first day of my stay in Karlsruhe, he invited me to lunch with him and his assistant at the leading hotel of the city.

"Haber insisted that as a visiting professor—I was then professor of chemistry at the University of Montana—only a problem of extreme importance should be given to me. He and his assistant rose, drank my health, and Haber said, 'He shall work on surface tension.' Unfortunately, or fortunately, I knew hardly enough German to object, and when much later I found that many of the world's greatest scientists had been interested in surface phenomena, I was thankful for this lack of knowledge."

The work revealed to Harkins the fascinating problems of surface chemistry and initiated his highly original work in that field. When he was able after his establishment in Chicago to resume that work, he began his investigation of the orientation of molecules in surfaces. He was one of the three (the others were W. G. Hardy and Irving Langmuir) who independently suggested the theory of orientation of molecules in surfaces. At Chicago in the winter quarter of 1913–1914, Harkins gave the earliest series of lectures on the theory of this subject. Thus began a long chain of steps, from improved experiments to improved theory to new experiments, which characterized Harkins' work in surface chemistry and related fields for forty years. The sequence was particularly fruitful because Harkins combined meticulous and ingenious experimental techniques with a knack for original interpretation of data. Now continuing the quotation from Harkins,

"After the completion of the experimental work, I returned to America in order to work on physical chemistry with A. A. Noyes and G. N. Lewis, both of whom have been awarded the Gibbs Medal. Here I met my second aversion, for A. A. Noyes stated that, under the grant from the Carnegie Institution which supported the work, it was expected that the general subject of research should be the theory of solutions, but the special subject solubility."

In the last year of his life, Harkins completed a book, published in 1952, *Physical Chemistry of Surface Films,* summarizing his work on the subject. The book contains an introduction by Thomas F. Young, a younger colleague and a great admirer of Harkins. This introduction contains a paragraph that comments interestingly on the fruits of Harkins' work at M.I.T.:

"During the brief period which Dr. Harkins spent at the Massachusetts Institute of Technology in 1909–10, Professor A. A. Noyes was greatly interested in theories of solutions, and inspired an outstanding group of young men to investigate the subject. A remarkable series of papers came from the laboratory describing work done by or under the direction of A. A. Noyes, G. N. Lewis, W. C. Bray, W. D. Harkins, and others. Of course Harkins did not know then how important that work on the thermodynamics of electrolytic solutions would be to his own later investigations of surface phenomena, especially his studies of adsorption. In 1911 he published three papers presenting his researches on solubility carried out at the Massachusetts Institute of Technology. In later years he contributed about ten more papers on ionic interactions. The work of A. A. Noyes and his group aided G. N. Lewis in his discovery of the ionic strength principle. The latter once remarked that the principle was obtained within a few hours after he had picked up notes of a conference held some ten years earlier with Harkins."

Continuing further with the quotation from Harkins' Gibbs Medal address, first about his work on surface chemistry, "Now the greatest of solubility rules is 'similia similibus solvuntur' or 'like dissolves like.' This rule suggested that the experiments on surface tension might have given results more in accord with the theory if more complicated molecules, such as those present in the muscles, had been used. It is advisable, however, in scientific work, to use as simple materials as will give the desired behavior, so substances like butyric acid were considered. . . . a molecule of this substance possesses the interesting characteristic that at one end it is like oil, and at the other like water.

"Thus we may place a thick layer of oil on water and add butyric acid. The water-like ends of the molecules should be soluble in water, and the oil-like ends in the oil, but only at the interface between the two can both ends of the molecule be satisfied at the same time. From this point of view the butyric acid should be very much more soluble at the interface than in either oil or water, which is true. Furthermore, at the interface there should be a certain structure, since the molecules of butyric acid should, in general, be oriented with oil-like ends toward the oil, and water-like ends toward the water. . . .

"A later careful search in the literature showed that Hardy, a noted English biologist, had just suggested (1912) that since a surface is extremely unsymmetrical with reference to the material on its two sides, the molecules in the surface should be oriented. Thus the theory of dissymmetry and that of solubility gave rise in two different minds to the same suggestion."

Especially in his later papers, Harkins deals extensively with emulsion polymerization, soap micelles, and other matters related to the formation of colloids. He also deals with adsorption and with the surfaces of solids and their interaction with liquids. Again, in the Gibbs Medal address, Harkins explains his interest in atomic nuclei as follows:

"In order to understand the action of surfaces, it appeared essential to learn as much as possible about the electrical structure of molecules and of atoms, so, in 1913, I began to study more intensively the current theories of atomic structure. In 1904, Nagaoka had suggested that an atom consists of a central sun or nucleus and a system of negative electrons as satellites. This theory was amplified by Rutherford, who showed that the positively charged atom nucleus appears to be extremely minute in comparison with the space occupied by the atom. For many years the phenomena of radioactivity had been extremely fascinating to me, and this was undoubtedly what caused my attention to be directed more specially to the nucleus, which determines the stability and even the existence of the atom as a whole."

A series of three papers by Harkins and his student E. D. Wilson in 1915 represents the first of a number of papers published over the years in which Harkins developed ideas on the structure of atomic nuclei. The papers distinguish carefully between chemical elements and atomic species. In general, an element is a mixture of atomic species (isotopes). In 1915 it was already clear that most of the lighter elements have atomic weights very close to a unit that is slightly (about 0.77 percent) less than the mass of the hydrogen atom. The 0.77 percent discrepancy was attributed by Harkins and Wilson (and also independently by Rutherford and others) to what they called a "packing effect," ascribed to a loss of mass predictable from Lorentz' electromagnetic theory if protons and electrons interact at sufficiently close range. They included a speculation that the conversion of hydrogen to helium might be a source of the energy for the sun and stars. Harkins' friend A. C. Lunn, professor of mathematical physics, made the calculations for him. As time went on, it became increasingly clear from mass spectroscopic evidence that those elements whose atomic weights differ from integral multiples of the basic unit are mixtures of isotopes.

Quoting G. N. Lewis [Phys. Rev. 46 (1934):897], "It was Harkins who first called attention to the striking connection between the atomic weights of the elements and their abundance, not only in the earth's crust, but [as a much better sample of the solar system], in the meteors." And it was he who first used these abundances as criteria for the relative stabilities of various atomic species. After E. Rutherford's proof of the nuclear atom, and until the experimental proof by J. Chadwick in 1932 of the independent existence of the neutron, it was generally believed that nuclei are built of protons (not so named at first) and electrons. Harkins noticed that the relative abundances, hence stabilities, of different atomic species are by far greater for nuclei containing an even number of protons and electrons; the next class, in terms of abundance, contains an odd number of protons and an even number of electrons. Two much rarer classes contain an even number of protons but an odd number of electrons, or odd numbers of both protons and electrons.

It was also apparent to Harkins that many of the lighter species (e.g., ^{12}C, ^{16}O, ^{20}Ne) could be thought of as built of α-particles; the α-particle itself, the helium nucleus, being a very stable composite, formed by close packing of four protons and two electrons, p_4e_2. The atomic weights of the α composites such as ^{12}C and ^{16}O showed little further packing effect. Harkins did not attempt to give a categorical answer to the question of whether such nuclei *consist of* (nearly unchanged) α-particles, or whether they merely could be *built from* α-particles. It was of course known that α-particles can have an independent existence.

In a similar way, Harkins concluded that nuclei such as those of ^{19}F and ^{23}Na could be built from, or possibly consist of, α-particles plus a hypothetical υ-particle (p_3e_2). Harkins mentioned, but did not emphasize, the possibility of the independent existence of this and other particles (the helion, p_4e_4; p_2e; the μ particle, p_2e_2; and a particle pe). He mentioned that p_3e_2 and p_2e, since known, would be isotopes of hydrogen (the triton, and the deuteron). Rutherford entertained similar ideas, and independently (and earlier than Harkins) spoke of packing (of H to form He), but it was Harkins who made the major contributions on the stabilities of atomic species and the structure of nuclei. This work culminated in his "new periodic system" of atomic species expressed in a diagram of "isotopic number" versus atomic number. Here, if the structure of any nucleus is written as $(p_2e)Z\,(pe)_n$, n is the isotopic number if Z is the atomic number; n was later recognized as a neutron number.

It was first shown by Chadwick in 1932 that the grouping (pe) can exist as a free particle, the neutron. Rutherford in his Bakerian lecture in 1920 describes the properties of the neutron as a conceivable free particle. The idea that such a particle might exist kept Rutherford's laboratory "on the lookout" for it and doubtless thereby contributed to Chadwick's discovery. (A little later, it was realized that, in its formation from a proton and an electron, the neutron undergoes a much more radical change than simple association; for example, while the proton and the electron each have a spin $\frac{1}{2}$, so does the neutron. Its spin cannot be accounted for by the otherwise expected vector addition to give a spin 0 or 1.) Rutherford in his Bakerian lecture refers to Harkins' 1920 paper, "The Nuclei of Atoms and the New Periodic System," in which Harkins refers to the (pe) grouping. In 1921, in a paper communicated to *Philosophical Magazine* by Rutherford, Harkins first introduced the word *neutron* to describe this particle.* Harkins in an article in *Science* in 1946 said "that a neutron exists was assumed independently by Rutherford and Harkins in 1920."

Stimulated by work in Rutherford's laboratory, Harkins undertook work on the disintegration of nitrogen nuclei by the impingement of α-particles. Here he used C. T. R. Wilson's cloud chamber method to photograph the tracks of the α-particles and the disintegrating nuclei. Although apparently not the first or the most immediately successful in the use of this method, he and his students made valuable contributions. Later, after the neutron had been discovered, he did extensive work on the disintegration of nitrogen and other nuclei by

---

* N. Feather in "A History of Neutrons and Nuclei. I.," *Contemporary Physics* 1(1960):191, "A History of Neutrons and Nuclei. II.," *Contemporary Physics* 1(1960):257, and "Chadwick's Neutron," *Contemporary Physics* 15(1974):565 has reviewed the development of the neutron concept. As he points out, the *word* neutron was first used by W. Sutherland in 1899 and in 1903 by W. Nernst, but for different concepts than that of the current neutron. Feather refers to Harkins on pp. 260–61 of his earlier papers.

neutrons. In the course of this work, he developed ideas about the details of the mechanism leading to disintegration. He insisted that the neutron (or α-particle) is first captured and held very briefly in the form of a compound nucleus, which then disintegrates. For some years this formulation was frowned on by the theoretical physicists, but eventually it was seen that he was right.

In his later work, Harkins had some ideas about shell structure in nuclei. Harkins was a pioneer, but he was also quick to take up and implement new ideas originating elsewhere. Soon after Lawrence had invented the cyclotron, Harkins built one at the University of Chicago with the cooperation of his students. Planning began in 1935, and the cyclotron (larger than Lawrence's original) was in operation in 1936. Soon it also began to be used by physicists, Enrico Fermi in particular, for neutron-diffusion studies. With the advent of fission, and Harkins' official retirement in 1939, the cyclotron was turned over to the physics department, under S. K. Allison, a former student of Harkins and afterward a professor of physics. The Harkins cyclotron was used thereafter in the Manhattan Project at Chicago during the war. The papers in Harkins' bibliography make no mention of the cyclotron, except for a brief note in *Science* in 1936 by Moon and Harkins, which shows them as thinking about how to improve on Lawrence's cyclotron.

One activity not yet mentioned is Harkins' work on the separation of isotopes. Except for a partial separation of neon isotopes by F. W. Aston using a diffusion method, Harkins was the first to obtain such a separation. This he and his students accomplished in the case of chlorine, using the diffusion of HCl through clay pipe stems. Afterward there was work (not the first but by far the most extensive) on the partial separation of mercury isotopes.

In conclusion, I quote from T. F. Young's introduction to Harkins' book on surface chemistry, mentioned above. "It is of interest to note that many of Harkins' contributions [about one-third] were made after his formal academic retirement in 1939. His productivity, especially after 1940, was greatly enhanced by financial aid from industries and government agencies interested in catalysis, lubrication, the production of rubber, and other applications of surface chemistry. It was his own dominating curiosity, however, which was the principal cause of the productiveness which endured literally to the last day of his life."

BIBLIOGRAPHY

KEY TO ABBREVIATIONS

Chem. Rev. = Chemical Reviews
Colloid Symp. Monogr. = Colloid Symposium Monograph
Ind. Eng. Chem. = Industrial and Engineering Chemistry
J. Am. Chem. Soc. = Journal of the American Chemical Society
J. Biol. Chem. = Journal of Biological Chemistry
J. Chem. Phys. = Journal of Chemical Physics
J. Colloid Sci. = Journal of Colloid Science
J. Franklin Inst. = Journal of the Franklin Institute
J. Phys. Chem. = Journal of Physical Chemistry
J. Phys. Colloid Chem. = Journal of Physical and Colloid Chemistry
J. Polym. Sci. = Journal of Polymer Science
Philos. Mag. = Philosophical Magazine
Phys. Rev. = Physical Review
Proc. Natl. Acad. Sci. = Proceedings of the National Academy of Sciences
Publ. Am. Assoc. Adv. Sci. = Publications of the American Association for the Advancement of Science
Sci. Mon. = Scientific Monthly
Z. Phys. = Zeitschrift für Physik

1907

With R. E. Swain. Papers on smelter smoke. I. The determination of arsenic and other constituents of smelter smoke, with a study of the effect of high stacks and large condensing flues. J. Am. Chem. Soc., 29:970.

1908

With R. E. Swain. Papers on smelter smoke. II. Arsenic in vegetation exposed to smelter smoke. J. Am. Chem. Soc., 30:915.

With R. E. Swain. Papers on smelter smoke. III. The chronic arsenical poisoning of herbivorous animals. J. Am. Chem. Soc., 30:928.

1910

The Marsh test and excess potential: the quantitative determination of arsenic. J. Am. Chem. Soc., 32:518.

1911

The effect of salts upon the solubility of other salts. V. The solubility of unibivalent salts in solutions of salts of different types. J. Am. Chem. Soc., 33:1807.

With W. J. Winninghoff. The effect of salts upon the solubility of other salts. VI. The solubility of difficultly soluble unibivalent salts. J. Am. Chem. Soc., 33:1827.

The effect of salts upon the solubility of other salts. VII. Discussion of solubility relations of unibivalent salts. J. Am. Chem. Soc., 33:1836.

1915

With E. D. Wilson. Energy relations involved in the formation of complex atoms. Philos. Mag., 30:723.

With E. D. Wilson. The changes of mass and weight involved in the formation of complex atoms. J. Am. Chem. Soc., 37:1367.

With E. D. Wilson. The structure of complex atoms: the hydrogen–helium system. J. Am. Chem. Soc., 37:1383.

With E. D. Wilson. Recent work on the structure of the atom. J. Am. Chem. Soc., 37:1396.

With E. D. Wilson. The structure of complex atoms and the changes of mass and weight involved in their formation. Proc. Natl. Acad. Sci., 1:276.

With G. L. Clark. Binary and ternary systems of the nitrates of the alkali and alkaline earth metals. J. Am. Chem. Soc., 37:1816.

With E. C. Humphery. The surface tension at the interface between two liquids. Proc. Natl. Acad. Sci., 1:585.

1916

The abundance of the elements in relation to the hydrogen–helium structure of atoms. Proc. Natl. Acad. Sci., 2:216.

With R. E. Hall. The periodic system and the properties of the elements. J. Am. Chem. Soc., 38:169.

With E. C. Humphery. The drop weight method for the determination of surface tension. J. Am. Chem. Soc., 38:228.

With E. C. Humphery. Apparatus for the determination of the surface tension at the interface between two liquids. J. Am. Chem. Soc., 38:236.

With E. C. Humphery. The surface tension at the interface between two liquids and the effect of acids, salts and bases upon the interfacial tension. J. Am. Chem. Soc., 38:242.

With F. E. Brown. A simple apparatus for the accurate and easy determination of surface tension, with a metal thermoregulator for the quick adjustment of temperature. J. Am. Chem. Soc., 38:246.

With R. E. Hall and W. A. Roberts. Studies on the cobaltammines. I. Various ionization types as determined by the freezing-point lowering in aqueous solution, together with conductance measurements. J. Am. Chem. Soc., 38:2643.

With R. E. Hall. The free energy of dilution and the freezing-point lowerings in solutions of some salts of various types of ionization, and of salt mixtures. J. Am. Chem. Soc., 38:2658.

With W. A. Roberts. The freezing-point lowerings in aqueous solutions of salts and mixtures of salts and of a salt with a non-electrolyte. J. Am. Chem. Soc., 38:2676.

With W. T. Pearce. Ionization and solubility relations of salts of higher types. IV. Intermediate ions in solutions of unibivalent salts, and of lanthanum iodate, a triunivalent salt. J. Am. Chem. Soc., 38:2679.

With H. M. Paine. The effect of salts upon the solubility of other salts. VIIIa. The solubility relations of a very soluble biunivalent salt. J. Am. Chem. Soc., 38:2709.

With R. E. Hall. Das periodische System und die Eigenschaften der Elemente. Zeitschrift für anorganische und allgemeine Chemie, 97:175.

With R. E. Hall and W. A. Roberts. The cobaltammines. Proc. Natl. Acad. Sci., 2:598.

1917

With F. E. Brown and E. C. H. Davies. The structure of the surfaces of liquids, and solubility as related to the work done by the attraction of two liquid surfaces as they approach each other. J. Am. Chem. Soc., 39:354.

With E. C. H. Davies and G. L. Clark. The orientation of molecules in the surfaces of liquids, the energy relations at surfaces, solubility, adsorption, emulsification, molecular association, and the effect of acids and bases on interfacial tension. J. Am. Chem. Soc., 39:541.

The evolution of the elements and the stability of complex atoms. J. Am. Chem. Soc., 39:856.

The structure of atoms, and the evolution of the elements as related to the composition of the nuclei of atoms. Science, 46:419.

With L. Aronberg. The spectra of isotopes and the vibration of electrons in the atom. Proc. Natl. Acad. Sci., 3:710.

1919

An electromagnetic hypothesis of the kinetics of heterogeneous equilibrium, and of the structure of liquids. Proc. Natl. Acad. Sci., 5:152.

The building of atoms and the new periodic system. Science, 50:577.

The change of molecular kinetic energy into molecular potential energy: the entropy principle and molecular association. Proc. Natl. Acad. Sci., 5:539.

Cohesion, internal pressure, adhesion, tensile strength, tensile energy, negative surface energy, and molecular attraction. Proc. Natl. Acad. Sci., 5:562.

The adhesion between mercury, water and organic substances, and the fundamental principles of flotation. Proc. Natl. Acad. Sci., 5:569.

With F. E. Brown. The determination of surface tension (free surface energy), and the weight of falling drops: the surface tension of water and benzene by the capillary height method. J. Am. Chem. Soc., 41:499.

With H. H. King. An electromagnetic hypothesis of the kinetics of heterogeneous equilibrium, and the structure of liquids and cohesion. J. Am. Chem. Soc., 41:970.

With H. M. Paine. Intermediate and complex ions. V. The solubility product and activity of the ions in bi-bivalent salts. J. Am. Chem. Soc., 41:1155.

With D. T. Ewing. The effects of acids and bases on the surface energy relations of beta,beta-dichloroethylsulfide ("mustard gas"). J. Am. Chem. Soc., 41:1977.

1920

The nuclei of atoms and the new periodic system. Phys. Rev., 15:73.

With D. T. Ewing. An apparent high pressure due to adsorption, the heat of adsorption, and the density of gasmask charcoals. Proc. Natl. Acad. Sci., 6:49.

The ionization of strong electrolytes. Proc. Natl. Acad. Sci., 6:601.

The separation of the element chlorine into chlorine and metachlorine. Science, 51:289.

With G. L. Clark and L. E. Roberts. The orientation of molecules in surfaces, surface energy, adsorption and surface catalysis. V. The adhesional work between organic liquids and water. J. Am. Chem. Soc., 42:700.

With L. Aronberg. A force, apparently due to mass, acting on an electron, and the non-identity of isotopes in spectra and other properties. J. Am. Chem. Soc., 42:1328.

The stability of atoms as related to the positive and negative electrons in their nuclei, and the hydrogen, helium, H_3, H_2 theory of atomic structure. J. Am. Chem. Soc., 42:1956.

With G. L. Clark and A. J. Quick. The properties of subsidiary valence groups. I. The molecular volume relationships of the hydrates and ammines of some cobalt compounds. II. Subsidiary group mobility as studied by the heat of decomposition of some cobaltammines. J. Am. Chem. Soc., 42:2483.

With E. H. Grafton. Surface tension and molecular attraction: on the adhesional work between mercury and organic liquids. J. Am. Chem. Soc., 42:2534.

With W. W. Ewing. The surface energy of mercury and the energy relations at the interface between mercury and other liquids. J. Am. Chem. Soc., 42:2539.

1921

With V. C. Cheng. The orientation of molecules in surfaces: cohesion, adhesion, tensile strength, tensile energy, negative surface energy, interfacial tension and molecular attraction. J. Am. Chem. Soc., 43:35.

Natural systems for the classification of isotopes and the atomic weights of pure atomic species as related to nuclear stability. J. Am. Chem. Soc., 43:1038.

With D. T. Ewing. A high pressure due to adsorption and the density and volume relations of charcoal. J. Am. Chem. Soc., 43:1787.

The constitution and stability of atomic nuclei. (A contribution to the subject of inorganic evolution.) Philos. Mag., 42:305.

The separation of the elements chlorine and mercury into isotopes. Science, 54:359.

With A. Hayes. The separation of the element chlorine into isotopes (isotopic elements). J. Am. Chem. Soc., 43:1803.

1922

The stability of atomic nuclei, the separation of isotopes, and the whole number rule I. J. Franklin Inst., 194:165.

The stability of atomic nuclei, the separation of isotopes, and the whole number rule II. J. Franklin Inst., 194:329.

The stability of atomic nuclei, the separation of isotopes, and the whole number rule III. J. Franklin Inst., 194:521.

The stability of atomic nuclei, the separation of isotopes, and the whole number rule IV. J. Franklin Inst., 194:645.

The stability of atomic nuclei, the separation of isotopes, and the whole number rule V. J. Franklin Inst., 194:783.

With S. L. Madorsky. A graphical study of the stability relations of atom nuclei. Phys. Rev., 29:135.

With R. S. Mulliken. The separation of isotopes. Theory of resolution of isotopic mixtures by diffusion and similar processes. Experimental separation of mercury by evaporation in a vacuum. J. Am. Chem. Soc., 44:37.

With L. E. Roberts. Vaporization in steps as related to surface formation. J. Am. Chem. Soc., 44:653.

With A. Feldman. Films: the spreading of liquids and the spreading coefficient. J. Am. Chem. Soc., 44:2665.

1923

The stability of atomic nuclei, the separation of isotopes, and the whole number rule VI. J. Franklin Inst., 195:67.

The stability of atomic nuclei, the separation of isotopes, and the whole number rule: supplementary note. J. Franklin Inst., 195: 553.

With S. L. Madorsky. The separation of mercury into isotopes in a large apparatus. J. Am. Chem. Soc., 45:591.

Isotopes, a new relation concerning the periodic system of the atomic species. J. Am. Chem. Soc., 45:1426.

With R. W. Ryan. A method for photographing the disintegration of an atom, and a new type of rays. J. Am. Chem. Soc., 45:2095.

With S. J. Bircher. The effect of pressure on overvoltage. J. Am. Chem. Soc., 45:2890.

1924

With T. H. Liggett. The discovery and separation of the isotopes of chlorine and the whole number rule. J. Phys. Chem., 28:74.

With S. K. Allison. The absence of helium from gases left after the passage of electrical discharges. I. Between fine wires in a vacuum. II. Through hydrogen. III. Through mercury vapor. J. Am. Chem. Soc., 46:814.

With L. J. Bircher and G. Dietrichson. Two types of overvoltage and the temperature effect. J. Am. Chem. Soc., 46:2622.

1925

With E. H. Grafton. Monomolecular films on water: the oriented adsorption of derivatives of benzene. J. Am. Chem. Soc., 47:1329.

With N. Beeman. The oriented wedge theory of emulsions. Proc. Natl. Acad. Sci., 11:631.

With J. W. Morgan. Polymolecular and monomolecular films. Proc. Natl. Acad. Sci., 11:637.

With H. M. McLaughlin. Monomolecular films between liquids: butyric acid between water and hexane, and acetic acid between water and benzene. J. Am. Chem. Soc., 47:1610.

With G. L. Clark. The effect of sodium hydroxide upon the surface tension of a solution of sodium nonylate. J. Am. Chem. Soc., 47:1854.

With H. M. McLaughlin. The structure of films of water on salt solutions. I. Surface tension and adsorption for aqueous solutions of sodium chloride. J. Am. Chem. Soc., 47:2083.

With H. S. Adams. Overvoltage as a function of current density and the effects of time, temperature, stirring, pressure, nature of surface, and of superimposed alternating current. J. Phys. Chem., 29:205.

1926

Surface energy and surface tension. In: *Colloid Chemistry,* ed. by J. Alexander, vol. I, pp. 192–264. New York: Chemical Catalog Co.

The drop-weight method for the determination of surface tension and the weight of the ideal drop. Nature, 117:690.

Application of the drop-weight method to the determination of the surface tension of colloidal solutions. Nature, 118:732.

With F. A. Jenkins. The separation of the element chlorine into isotopes. The light fraction. J. Am. Chem. Soc., 48:58.

With H. Zollman. Interfacial tension and emulsification. J. Am. Chem. Soc., 48:69.

With E. C. Gilbert. The structure of films of water on salt solutions. II. The surface tension of calcium chloride solutions at 25°. J. Am. Chem. Soc., 48:604.

With S. B. Stone. The isotopic composition and atomic weight of chlorine from meteorites and from minerals of non-marine origin. J. Am. Chem. Soc., 48:938.

With H. A. Shadduck. The synthesis and disintegration of atoms as revealed by the photography of Wilson cloud tracks. Proc. Natl. Acad. Sci., 12:707.

With T. F. Young and L. H. Cheng. The ring method for the determination of surface tension. Science, 64:333.

1927

The stability of emulsions, monomolecular and polymolecular films, thickness of the water film on salt solutions, and the spreading of liquids. Colloid Symp. Monogr. V, pp. 19–48. New York: Chemical Catalog Co.

1928

Electrical relations at surfaces, the spreading of liquids, the thickness of surface films, and the drop weight and ring methods for the determination of surface tension. Colloid Symp. Monogr. VI, pp. 17–40. New York: Chemical Catalog Co.

Surface energy and the orientation of molecules in surfaces as revealed by surface energy relations. Zeitschrift für physikalische Chemie, A139:647.

Die Atomsynthese, die sich in Begleitung von Atomspaltung (Atomzertrümmerung) kundgibt, und die Theorie vom Aufbau der Atome aus Wasserstoff und Helium. Z. Phys., 50:97.

The synthesis of atoms, the whole number rule, and the periodic system of the atomic species. Chem. Rev., 5:371.

With C. E. Broeker. Die erste Trennung der Chlor Isotopen. Z. Phys., 50:537.

With B. Mortimer. The separation of isotopes and a further separation of mercury by evaporative-diffusion. Philos. Mag., 6:601.

With W. B. Kay. An attempt to add an electron to the nucleus of an atom. Phys. Rev., 31:940.

1929

Surface structure and atom building. (Seventeenth Willard Gibbs Gold Medal address) Science, 70:433.

With N. Beeman. Emulsions: stability, area per molecule in the interfacial film, distribution of sizes and the oriented wedge theory. J. Am. Chem. Soc., 51:1674.

With H. N. Harkins. The surface tension of blood serum, and the determination of the surface tension of biological fluids. Journal of Clinical Investigation, 7:263.

1930

Atomic stability as related to nuclear spin. Phys. Rev., 35:434.

With H. F. Jordan. A method for the determination of surface and interfacial tension from the maximum pull on a ring. J. Am. Chem. Soc., 52:1751.

With D. M. Gans. The drop weight method for the determination of surface tension. The effect of an inclination of the tip upon the drop weight. J. Am. Chem. Soc., 52:2287.

With D. M. Gans. The surface tension of aqueous solutions of paratoluidine. J. Am. Chem. Soc., 52:2289.

With D. M. Gans. The spectroscopic determination of the decomposition products of organic compounds. Benzene in the electrodeless discharge. J. Am. Chem. Soc., 52:2578.

With H. E. Bowers. A continuous (or band) fluorescence emission spectrum which accompanies a change of color. J. Am. Chem. Soc., 52:4170.

With D. M. Gans. A spectroscopic study of the decomposition and synthesis of organic compounds by electrical discharges. I. The electrodeless discharge. J. Am. Chem. Soc., 52:5165.

With A. E. Schuh. The frequency of occurrence of the disintegrative-synthesis of oxygen 17 from nitrogen 14 and helium. Phys. Rev., 35:809.

With R. Dahlstrom. Wetting of pigments and other powders. Ind. Eng. Chem., 22:897.

1931

The principle of continuity and regularity of series of atom nuclei (atomic species). Phys. Rev., 37:1180.

With D. M. Gans. The masses of O^{17}. Phys. Rev., 37:1671.

Periodic system of atomic nuclei and the principle of regularity and continuity of series. Phys. Rev., 38:1270.

Periodic system of atomic nuclei and the principle of regularity and continuity of series: a correction. Phys. Rev., 38:1792.

With R. W. Wampler. The activity coefficients and the adsorption of organic solutes. I. Normal butyl alcohol in aqueous solution by the freezing point method. J. Am. Chem. Soc., 53:850.

A relation concerning atomic nuclei. J. Am. Chem. Soc., 53:2009.

With H. E. Bowers. Raman effect and the carbon–halogen bond. Phys. Rev., 38:1845.

With H. E. Bowers. The carbon–halogen bond as related to Raman spectra. J. Am. Chem. Soc., 53:2425.

With D. M. Gans. An adsorption method for the determination of the area of a powder. J. Am. Chem. Soc., 53:2804.

With D. M. Gans. The direct measurement of the adsorption of soluble substances by the bubble method. J. Phys. Chem., 35:722.

1932

The hydrogen nucleus of mass 2 (isohydrogen nucleus p_2e) as a unit in atom building. J. Am. Chem. Soc., 54:1256.

With R. R. Haun. The Raman spectrum of germanium tetrachloride. J. Am. Chem. Soc., 54:3917.

With R. R. Haun. The vibration of atoms at the end of organic molecules: Raman effect and the carbon–chlorine bond. J. Am. Chem. Soc., 54:3920.

With D. M. Gans. Monomolecular films. The solid–liquid interface and the sedimentation and flocculation of powders in liquids. J. Phys. Chem., 36:86.

With L. W. Ryan and D. M. Gans. Flocculation, dispersion, and settling of pigments in relation to adsorption. Ind. Eng. Chem., 24:1288.

With E. K. Fischer. Monomolecular films. The liquid–liquid interface and the stability of emulsions. J. Phys. Chem., 36:98.

1933

The neutron, the atomic nucleus and mass defects. J. Am. Chem. Soc., 55:855.

The new kind of matter: element zero or neutron. Sci. Mon., 36: 546.

With D. M. Gans and H. W. Newson. Atomic disintegration by a relatively slow neutron. Phys. Rev., 43:208.

With D. M. Gans and H. W. Newson. A neutron of high velocity, and energy relations for nuclear disintegration by non-capture. Phys. Rev., 43:307.

Emission of gamma rays by nuclei excited by neutrons, and nuclear energy levels. Phys. Rev., 43:362.

The neutron, atom building and a nuclear exclusion principle. Proc. Natl. Acad. Sci., 19:307.

With C. Doede. An apparatus for the separation of isohydrogen (deuterium) oxide by electrolysis. J. Am. Chem. Soc., 55:4330.

With D. M. Gans and H. W. Newson. Disintegration of neon nuclei by fast neutrons. Phys. Rev., 44:236.

With D. M. Gans and H. W. Newson. Failure to detect the radioactivity of beryllium with the Wilson cloud chamber. Phys. Rev., 44:310.

With D. M. Gans and H. W. Newson. The disintegration of the nuclei of nitrogen and other light atoms by neutrons. I. Phys. Rev., 44:529.

With D. M. Gans and H. W. Newson. Disintegration of fluorine nuclei by neutrons and the probable formation of a new isotope of nitrogen (N^{16}). Phys. Rev., 44:945.

With J. M. Jackson. A spectroscopic study of the decomposition and synthesis of organic compounds by electrical discharges: electrodeless and glow discharges. J. Chem. Phys., 1:37.

With E. K. Fischer. Contact potentials and the effects of unimolecular films on surface potentials. I. Films of acids and alcohols. J. Chem. Phys., 1:852.

1934

Free radicals in electrical discharges. Transactions of the Faraday Society, 30:221.

Nomenclature for the isotopes of hydrogen (proto- and deuto-hydrogen) and their compounds. Science, 79:138.

With D. M. Gans. Atomic disintegration by "non-capture." Nature, 133:794.

With D. M. Gans. Inelastic collisions with changes of mass and the problem of nuclear disintegration with capture or non-capture of a neutron, or another nuclear projectile. Phys. Rev., 46:397.

With D. M. Gans. Artificial radioactivity and the conversion of kinetic into gamma ray energy associated with nuclear disintegration by neutrons. Phys. Rev., 46:827.

With D. M. Gans. The emission of gamma rays in nuclear reactions. J. Am. Chem. Soc., 56:2786.

With D. M. Gans. The mass of the neutron. Nature, 134:968.

With F. E. Kredel and H. N. Harkins. Toxicity of heavy water. Proceedings of the Society for Experimental Biology and Medicine, 32:5.

1935

With D. M. Gans and H. W. Newson. The disintegration of the nuclei of light atoms by neutrons. Phys. Rev., 47:52.

With H. E. Ries, Jr., and E. F. Carman. Surface pressures and potentials of long molecules: polymers of omega-hydroxy decanoic acid. J. Am. Chem. Soc., 57:776.

With E. F. Carman and H. E. Ries, Jr. Monomolecular films of molecules which lie flat on the surface of water. I. Surface pressures and potentials of films of long molecules: polymers of omega-hydroxy decanoic acid. J. Chem. Phys., 3:692.

With H. E. Ries, Jr., and E. F. Carman. Surface potentials and force-area relations of monomolecular films. II. *d*-Pimaric and tetrahydro-*d*-pimaric acids. J. Am. Chem. Soc., 57:2224.

1936

Some relations of carbon and its compounds. Journal of Organic Chemistry, 1:52.

With R. J. Moon. The production of high velocity ions for the disintegration of atomic nuclei. Science, 82:244.

Nuclear chemistry, the neutron and artificial radioactivity. Science, 83:533.

With M. D. Kamen, H. W. Newson, and D. M. Gans. Neutron–proton interaction: the scattering of neutrons by protons. Phys. Rev., 50:980.

With H. E. Ries, Jr. and E. F. Carman. The rearrangement of molecules in monomolecular films: polycyclic compounds of the five ring series. J. Chem. Phys., 4:228.

With E. F. Carman and H. E. Ries, Jr. The rearrangement of molecules in plastic monomolecular films: pressure–area and potential relations for polycyclic compounds of the five ring series. J. Am. Chem. Soc., 58:1377.

With R. J. Myers. Polymolecular films. J. Am. Chem. Soc., 58:1817.

With R. J. Myers. Hydrogen ion concentration and the behavior and measurement of monomolecular and polymolecular films on water. J. Chem. Phys., 4: 716.

With R. J. Moon. An electronic analysis of some surfaces by means of slow electrons. J. Phys. Chem., 40:941.

With R. J. Myers. Polymolecular films: mixed films with two or more components. I. Fatty acids and non-polar substances. J. Phys. Chem., 40:959.

With R. T. Florence and R. J. Myers. Contact potentials of reversible soluble films of lauric acid. Nature, 138:405.

1937

The intermediate nucleus in the disintegrative-synthesis of atomic nuclei: disintegration in steps. Proc. Natl. Acad. Sci., 23:120.

The intermediate nucleus and atomic disintegration in steps. Phys. Rev., 51:52.

The nuclear exclusion principle and the neutron–proton pattern. Phys. Rev., 52:39.

Linear or edge energy and tension as related to the energy of surface formation and of vaporization. J. Chem. Phys., 5:135.

With R. J. Myers. Effects of traces of metallic ions on films at interfaces and on the surface of water. Nature, 139:367.

With R. J. Myers. Viscosity of monomolecular films. Nature, 140: 465.

With F. M. Fowkes and R. J. Myers. Ultramicroscopic examination of mixed films. J. Am. Chem. Soc., 59:593.

With T. F. Anderson. I. A simple accurate film balance of the vertical type for biological and chemical work, and a theoretical and experimental comparison with the horizontal type. II. Tight packing of a monolayer by ions. J. Am. Chem. Soc., 59:2189.

With A. R. Brosi. The abundance ratio of the isotopes in natural or isotopically separated carbon. Phys. Rev., 52:472.

With R. J. Myers. The viscosity (or fluidity) of liquid or plastic monomolecular films. J. Chem. Phys., 5:601.

With E. S. Fetcher, Jr., and R. S. Lillie. A method for the investigation of electrostenolysis. Journal of General Physiology, 20: 671.

With F. A. Long and G. C. Nutting. The surface tension of aqueous soap solutions as a function of hydrogen ion (pH) and salt concentration. I. Sodium laurate and sodium nonylate. J. Am. Chem. Soc., 59:2197.

1938

With J. G. Kirkwood. The viscosity of monolayers: theory of the surface slit viscosimeter. J. Chem. Phys., 6:53.

With R. W. Mattoon. The contact potential of solid films formed by evaporation and by solidification and of built-up multilayers on metals. Phys. Rev., 53:911.

With T. F. Anderson. Protein monolayers: films of oxidized cytochrome C. J. Biol. Chem., 125:369.

With R. T. Florence. Effect of space isomerism on the squeezing out of an unsaturated compound from a mixed monolayer on an aqueous sub-solution. Nature, 142:913.

With R. T. Florence. Molecular interaction in mixed monolayers on aqueous subsolutions. I. Mixtures of alcohols, acids and amines. J. Chem. Phys., 6:847.

With F. M. Fowkes. Pressure–area relations of monolayers at the solid–liquid interface. J. Am. Chem. Soc., 60:1511.

With L. Fourt. Surface viscosity of long-chain alcohol monolayers. J. Phys. Chem., 42:897.

With R. T. Florence. Molecular interaction in mixed monolayers. II. Unstable mixtures with unsaturated acids. J. Chem. Phys., 6:856.

1939

With R. W. Mattoon. Film potentials of stearate multilayers and other dielectrics on metal surfaces. J. Chem. Phys., 7:186.

With G. E. Boyd. Viscosity of two-dimensional systems: effect of pressure and temperature, and the detection of phase transitions in monolayers. J. Chem. Phys., 7:203.

With G. C. Nutting. Pressure–area relations of fatty acid and alcohol monolayers. J. Am. Chem. Soc., 61: 1180.

With E. Boyd. Molecular interaction in monolayers: viscosity of two-dimensional liquids and plastic solids. V. Long chain fatty acids. J. Am. Chem. Soc., 61:1188.

With G. C. Nutting. Energy relations in transformations from three to two-dimensional systems. I. The latent heat and entropy of spreading of myristic and pentadecylic acids. J. Am. Chem. Soc., 61:1702.

With G. Groetzinger. A new method for the investigation of the electrical properties of multilayers. J. Chem. Phys., 7:204.

With W. D. Harkins. Some aspects of surface chemistry fundamental to biology. Publ. 7, Am. Assoc. Adv. Sci., p. 19.

With G. C. Nutting. The pressure–area and pressure–temperature relations of expanded monolayers of myristic and pentadecylic acids. J. Am. Chem. Soc., 61:2040.

1940

With L. Fourt and P. C. Fourt. Immunochemistry of catalase. II. Activity in multilayers. J. Biol. Chem., 132:111.

With T. F. Young and E. Boyd. The thermodynamics of films: energy and entropy of extension and spreading of insoluble monolayers. J. Chem. Phys., 8:954.

With L. B. Borst. Search for a neutron–deuteron reaction. Phys. Rev., 57:659.

With G. C. Nutting and F. A. Long. The change with time of the surface tension of solutions of sodium cetyl sulfate and sodium lauryl sulfate. J. Am. Chem. Soc., 62:1496.

With G. C. Nutting. The viscosity of monolayers: a test of the canal viscosimeter. J. Am. Chem. Soc., 62:3155.

With F. M. Fowkes. The state of monolayers adsorbed at the interface solid–aqueous solution. J. Am. Chem. Soc., 62:3377.

1941

Surface chemistry. Nature, 148:743.

A general thermodynamic theory of the spreading of liquids to form duplex films and of liquids or solids to form monolayers. J. Chem. Phys., 9:552.

Surface films of fatty acids, alcohols and esters. Chem. Rev., 29:385.

With E. Boyd. The states of monolayers. J. Phys. Chem., 45:20.

1942

Energy relations of the surfaces of solids. I. Surface energy of the diamond. J. Chem. Phys., 10:268.

With L. E. Copeland. A superliquid in two dimensions and a first-order change in a condensed monolayer. I. Energy, compressibility, and order of phase transformations. J. Chem. Phys., 10: 272.

With H. K. Livingston. Energy relations of the surfaces of solids. II. Spreading pressure as related to the work of adhesion between a solid and a liquid. J. Chem. Phys., 10:342.

With G. E. Boyd. The energy of immersion of crystalline powders in water and organic liquids. J. Am. Chem. Soc., 64:1190.

With G. E. Boyd. The binding energy between a crystalline solid and a liquid: the energy of adhesion and immersion. Energy of immersion of crystalline powders. II. J. Am. Chem. Soc., 64:1195.

With G. E. Boyd. The film balance as an analytical tool for biological and food research. Ind. Eng. Chem., 14:496.

With L. E. Copeland and G. E. Boyd. A superliquid in two dimensions and a first-order change in a condensed monolayer. II.

Abnormal viscosity relations of alcohol monolayers in condensed liquid phases. J. Chem. Phys., 10:357.

With L. E. Copeland. The pressure–area–temperature and energy relations of monolayers of octadecanitrile. J. Am. Chem. Soc., 64:1600.

1943

Intermolecular forces and two-dimensional systems. Publ. 21, Am. Assoc. Adv. Sci., p. 40.

With G. Jura. A new adsorption isotherm which is valid over a very wide range of pressure. J. Chem. Phys., 11:430.

With G. Jura. An absolute method for the determination of the area of a fine crystalline powder. J. Chem. Phys., 11:430.

With G. Jura. An adsorption method for the determination of the area of a solid without the assumption of a molecular area, and the area occupied by nitrogen molecules on the surfaces of solids. J. Chem. Phys., 11:431.

With G. Jura. The extension of the attractive energy of a solid into an adjacent liquid or film and the decrease of energy with distance. J. Chem. Phys., 11:560.

With G. Jura. The relationship between the energy of adsorption of a vapor on a solid and of immersion of the solid in a liquid. J. Chem. Phys., 11:561.

1944

The surfaces of solids and liquids and the films that form upon them. I. Liquids. In: *Colloid Chemistry,* ed. by J. Alexander. New York: Reinhold Publishing Corporation.

With G. Jura. The surfaces of solids and liquids and the films that form upon them. II. Solids and adsorption at the surfaces of solids or liquids. In: *Colloid Chemistry,* ed. by J. Alexander, vol. VI. New York: Reinhold Publishing Corporation.

With G. Jura. The decrease of free surface energy as a basis for the development of equations for adsorption isotherms; and the existence of two condensed phases in films on solids. J. Chem. Phys., 12:112.

With G. Jura. Surfaces of solids. X. Extension of the attractive energy of a solid into an adjacent liquid or film, the decrease of energy with distance, and the thickness of films. J. Am. Chem. Soc., 66:919.

With G. Jura. Surfaces of solids. XI. Determination of the decrease of free surface energy of a solid by an adsorbed film. J. Am. Chem. Soc., 66:1356.

With G. Jura. Surfaces of solids. XII. An absolute method for the determination of the area of a finely divided crystalline solid. J. Am. Chem. Soc., 66:1362.

With G. Jura. Surfaces of solids. XIII. A vapor adsorption method for the determination of the area of a solid without the assumption of a molecular area, and the areas occupied by nitrogen and other molecules on the surface of a solid. J. Am. Chem. Soc., 66: 1366.

With G. Jura. Equations for the pressure–area relations (isotherms) of liquid expanded and intermediate monolayers on water. J. Chem. Phys., 12:113.

With G. Jura. The existence of expanded and intermediate phases in films on solids. J. Chem. Phys., 12:114.

1945

Determination of surface and interfacial tension. In: *Physical Methods of Organic Chemistry,* ed. by A. Weissberger, vol. I. New York: Interscience Publishers, Inc.

Determination of properties of monolayers and duplex films. In: *Physical Methods of Organic Chemistry,* ed. by A. Weissberger, vol. I. New York: Interscience Publishers, Inc.

Surfaces of solids in science and industry. Science, 102:263.

A general theory of the reaction loci in emulsion polymerization. J. Chem. Phys., 13:381.

With G. Jura, E. H. Loeser, and P. R. Basford. A first order change which involves the vaporization in two dimensions of *n*-heptane on the surface of silver. J. Chem. Phys., 13:535.

1946

The neutron, the intermediate or compound nucleus, and the atomic bomb. Science, 103:289.

A general theory of the reaction loci in emulsion polymerization. II. J. Chem. Phys., 14:47.

With R. W. Mattoon and M. L. Corrin. Structure of soap micelles indicated by x rays and the theory of molecular orientation. I. Aqueous solutions. J. Am. Chem. Soc., 68:220.

With R. W. Mattoon and M. L. Corrin. Structure of soap micelles as indicated by x rays and interpreted by the theory of molecular orientation. II. The solubilization of hydrocarbons and other oils in aqueous soap solutions. J. Colloid Sci., 1:105.

With G. Jura and E. H. Loeser. Surfaces of solids. XVI. Adsorbed films of water and normal heptane on the surface of graphite. J. Am. Chem. Soc., 68:554.

With G. Jura. The contact angle between water and a monolayer of egg albumin on glass as a function of film pressure. J. Colloid Sci., 1:137.

With G. Jura. Surfaces of solids. XIV. A unitary thermodynamic theory of the adsorption of vapors on solids and of insoluble films on liquid subphases. J. Am. Chem. Soc., 68:1941.

With G. Jura, E. H. Loeser, and P. R. Basford. Surfaces of solids. XV. First-order phase changes of adsorbed films on the surfaces of solids; the film of *n*-heptane on ferric oxide. J. Chem. Phys., 14:117.

With R. S. Stearns. Loci of emulsion polymerization: the diffusion of organic molecules from emulsion droplets through an aqueous phase into soap micelles. J. Chem. Phys., 14:214.

With R. S. Stearns. Loci of emulsion polymerization: diffusion of organic molecules from emulsion droplets through an aqueous phase into polymer latex particles. J. Chem. Phys., 14:215.

With M. L. Corrin and H. B. Klevens. The critical concentration for the formation of micelles as indicated by the absorption spectrum of a cyanine dye. J. Chem. Phys., 14:216.

With G. Jura and E. H. Loeser. Surfaces of solids. XVII. A first- and second-order phase change in the adsorbed film of *n*-heptane on graphite. J. Chem. Phys., 14:344.

With M. L. Corrin and H. B. Klevens. The determination of critical concentrations for the formation of soap micelles by the spectral behavior of pinacyanol chloride. J. Chem. Phys., 14:480.

With M. L. Corrin. The effect of solvents on the critical concentration for micelle formation of cationic soaps. J. Chem. Phys., 14:640.

With M. L. Corrin. Determination of critical concentrations for micelle formation in solutions of cationic soaps by changes in the color and fluorescence of dyes. J. Chem. Phys., 14:641.

With M. L. Corrin. Critical concentrations for micelle formation in mixtures of anionic soaps. J. Colloid Sci., 1:469.

1947

With M. L. Corrin. Determination of the critical concentration for micelle formation in solutions of colloidal electrolytes by the spectral change of a dye. J. Am. Chem. Soc., 69:679.

With M. L. Corrin. The effect of salts on the critical concentration for the formation of micelles in colloidal electrolytes. J. Am. Chem. Soc., 69:683.

A general theory of the mechanism of emulsion polymerization. J. Am. Chem. Soc., 69:1428.

With R. W. Mattoon and R. S. Stearns. Structure for soap micelles as indicated by a previously unrecognized x-ray diffraction band. J. Chem. Phys., 15:209.

With R. S. Stearns, H. Oppenheimer and E. Simon. Solubilization by solutions of long-chain colloidal electrolytes. J. Chem. Phys., 15:496.

With R. W. Mattoon and R. Mittelmann. A new type of micelle: soap with alcohol, amine or other polar–nonpolar molecules. J. Chem. Phys., 15:763.

1948

A cylindrical model for the small soap micelle. J. Chem. Phys., 16: 156.

With R. W. Mattoon and R. S. Stearns. Structure of micelles of colloidal electrolytes. III. A new long-spacing x-ray band, and the relations of other bands. J. Chem. Phys., 16:644.

With H. Oppenheimer. A new type of micelle; solubility by film penetration. J. Chem. Phys., 16:1000.

With P. R. Basford and G. Jura. Surfaces of solids. XVIII. The heats of immersion and desorption of water from graphite at 25°. J. Am. Chem. Soc., 70:1444.

1949

With M. Popelka, Jr. The existence of stable nuclei as related to the principle of regularity and continuity of series and the ends of nuclear shells. Phys. Rev., 76:989.

The effect of nuclear shells upon the pattern of the atomic species. Phys. Rev., 76:1538.

With H. Oppenheimer. Solubilization of polar–nonpolar sub-

stances in solutions of long chain electrolytes. J. Am. Chem. Soc., 71:808.

With R. Mittelmann. X-ray investigations of the structure of colloidal electrolytes. IV. A new type of micelle formed by film penetration. J. Colloid Sci., 4:367.

With R. Mittelmann and M. L. Corrin. Types of solubilization in solutions of long-chain colloidal electrolytes. J. Phys. Colloid Chem., 53:1350.

With M. L. Corrin, E. L. Lind, and A. Roginsky. Adsorption of long-chain electrolytes from aqueous solution on graphite of known area and on polystyrene. J. Colloid Sci., 4:485.

1950

The intermediate-compound nucleus in nuclear reactions. In: *Colloid Chemistry,* ed. by J. Alexander, vol. VII. New York: Reinhold Publishing Corporation.

Equivalence of protons and neutrons in nuclei. Phys. Rev., 78:634.

Special and magic numbers as factors in nuclear stability and abundance. Phys. Rev., 79:724.

With S. H. Herzfeld, A. Roginsky, and M. L. Corrin. Monomer–polymer ratio in emulsion polymerization of styrene. J. Polym. Sci., 5:207.

General theory of emulsion polymerization. II. J. Polym. Sci., 5:217.

Soap solutions: salt, alcohol, micelles, rubber. Sci. Mon., 70:220.

With E. H. Loeser. Surfaces of solids. XIX. Molecular interaction between metals and hydrocarbons. J. Chem. Phys., 18:556.

With E. H. Loeser. Surfaces of solids. XXI. Areas of nonporous solids from adsorption isotherms of *n*-heptane or *n*-hexane. J. Am. Chem Soc., 72:3427.

With S. H. Herzfeld and M. L. Corrin. The effect of alcohols and of alcohols and salts on the critical micelle concentration of dodecylammonium chloride. J. Phys. Colloid Chem., 54:271.

1952

Physical Chemistry of Surface Films. New York: Reinhold Publishing Corporation. xvi +413 pp.