NATIONAL ACADEMY OF SCIENCES

# GILBERT NEWTON LEWIS

*1875—1946*

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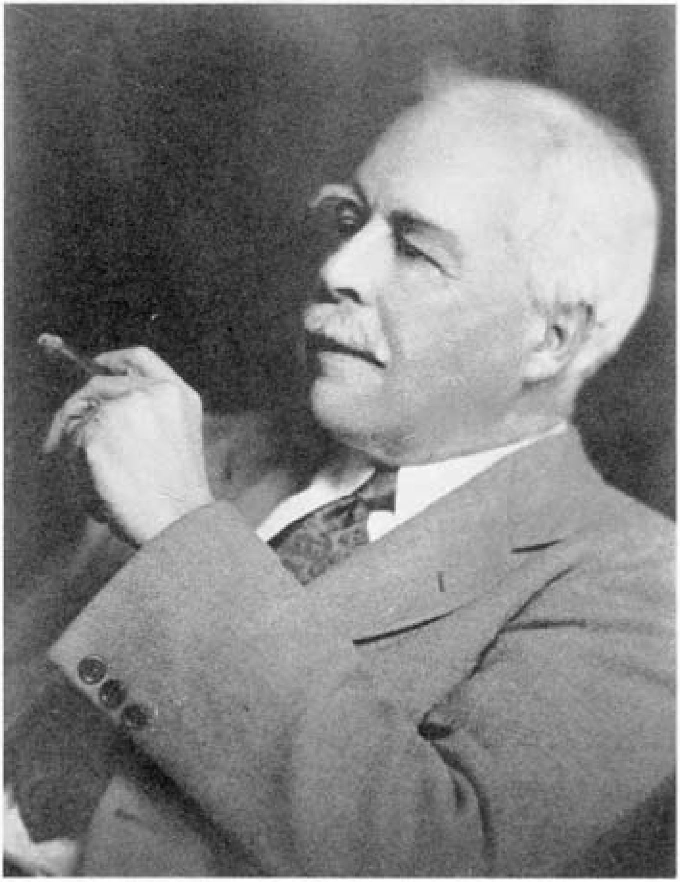
*A Biographical Memoir by*

JOEL H. HILDEBRAND



*Biographical Memoir*



Gilbert N. Lewis

# GILBERT NEWTON LEWIS*

*October 25, 1875—March 23, 1946*

BY JOEL H. HILDEBRAND

Gilbert Newton Lewis was born near Boston, Massachusetts, on October 25, 1875. At the age of nine he was taken by his parents to live in Lincoln, Nebraska. Here, for several years, he had little formal schooling, enjoying an advantage which he mentioned in his later years as having occurred frequently in the careers of the world's most distinguished men, that of having "escaped some of the ordinary processes of formal education." At the age of thirteen he was admitted to the preparatory school of the University of Nebraska. He graduated from this school into the University of Nebraska, where he remained to complete the sophomore year. In 1893 he transferred to Harvard College, and, after graduating in 1896, spent a year in teaching at Phillips Academy at Andover. He then returned to Harvard for graduate work and received the degree of Master of Arts in 1898 and Doctor of Philosophy in 1899. His thesis was entitled, "Some electrochemical and thermochemical relations of zinc and cadmium amalgams," and was published with Theodore William Richards as joint author.

After remaining one year at Harvard as instructor, he went abroad on a traveling fellowship and spent a semester at Leipzig with Ostwald and another at Göttingen with Nernst. He returned to Harvard as instructor for three years, following which he accepted the position of Superintendent of Weights and Measures in the Philippine Islands and Chemist in the Bureau of Science at Manila. It was char-

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acteristic of his indefatigable pursuit of pure science that he found sufficient facilities and time, even there, to study the decomposition of silver oxide as well as to publish a paper on "Hydration in solution."

In 1905 he returned to the United States to join the notable group of physical chemists gathered at the Massachusetts Institute of Technology by A. A. Noyes, men who powerfully stimulated the development of physical chemistry in the United States. The seven years which he spent in that laboratory were marked by that intense scientific activity, both experimental and theoretical, which continued throughout his whole career. The results appeared in over thirty papers, several of which are particularly notable as laying the foundations for the later distinguished superstructures now well known to physical chemists throughout the world. They included a series of precise determinations of the electrode potentials of elements, contributions which Lewis characterized in later years as high among those which had given him greatest satisfaction. It was during this period that he wrote his epoch-making papers, "Outlines of a new system of thermodynamic chemistry" (1907) and "The free energy of chemical substances," the nucleus from which grew a long series of papers on experimental determinations of free energies and, in 1923, his great work, written with the assistance of Merle Randall, *Thermodynamics and the Free Energy of Chemical Substances*. But his mind was not one that had to economize on effort by concentrating in only one or two directions, for during this same period, as a result of meeting Einstein, he became a prophet of and a contributor to the then unpopular theory of relativity, publishing papers on the subject with E. B. Wilson and later with E. C. Tolman.

By 1912 he had passed through the lower professorial grades and made such a reputation as to bring a call to become Dean of the College of Chemistry and Chairman of the Department of Chemistry at the University of California, an institution then rapidly rising under the able leadership of its president, Benjamin Ide Wheeler, to its present place among the most distinguished of American universities. Lewis accepted under wise stipulations, including new facilities for research and a complete departmental rejuvenation. He recruited a group of young men who, under his stimulating leadership established a center of intense scientific activity. All were named instructors or professors of *chemistry,* not of its subdivisions. No one was in a position to "reserve" a field or to pose as the authority therein. There were no divisions within the department in either organization or spirit. All met together to discuss chemistry, organic, inorganic, or physical, alike. The utmost freedom in discussion was the rule. The writer recalls one of the first research conferences which he attended when Lewis made a deliberately challenging statement, as he loved to do, taking a boyish delight in shocking conservative prejudice, whereupon a particularly brilliant graduate student interrupted with, "No, that isn't so!" I was aghast at his temerity—such a remark at certain institutions would have been dangerous; but Lewis turned to him with interest, saying, "No? Why not?" There followed a lively discussion, facts and logic alone determining the outcome. On another occasion, when a student criticized one of his assertions, Lewis remarked: "That is an impertinent remark but it is also pertinent."

The members of the department became like the Athenians who, according to the Apostle Paul, "spent their time in nothing else, but either to tell or to hear some new thing." Any one who thought he had a bright idea rushed to try it out on a colleague. Groups of two or more could be seen every day in offices, before blackboards or even in the corridors, arguing vehemently about these "brain storms." It is doubtful whether any paper ever emerged for publication that had not run the gauntlet of such criticism. The whole department thus became far greater than the sum of its individual members.

Lewis seemed to take as much satisfaction in the productivity of his young colleagues as in his own. He protected us from excessive teaching schedules. He sent new graduate students to talk with the members of the staff, and left them free to choose that particular problem which appealed most strongly. He accepted rather less than his share of research students, in striking contrast to the practice of certain other German-trained department heads who had imported the theory that all junior members of an "institute" should work for its chief.

One of his first moves was to turn almost the entire staff loose upon the problem of starting the freshman in the way he should go, by fostering a scientific habit of mind in every conceivable way. We met weekly to discuss the organization of the freshman course and the methods of presenting difficult topics. Although the lectures were given to five hundred students at a time in the large chemistry auditorium, with great attention to lighting, projection and realization of the full dramatic possibilities of the subject, the laboratory work and quizzing took place in sections of only twenty-five students, taught by a majority of the permanent staff with the help of numerous teaching assistants. The complaint that a freshman in a large university has no contact with professors has not applied in freshman chemistry at the University of California, for as many as eight full professors have in a single term taught freshman sections. The example thus set by senior professors has had a profound effect upon the apprentice teachers, making them take their teaching seriously and convincing them that talent for research is not demonstrated by indifferent teaching.

Lewis's own classroom teaching was limited to presiding at the weekly "research conference" attended by all staff members and graduate students of the department, but there his influence was impressive, upon staff and students alike. It was a rare presentation that did not elicit some stimulating question or comment from his far-ranging knowledge and interest. To-day there hangs on the wall of the seminar room, near the chair in which he sat, the portrait reproduced herewith, showing him in his characteristic pose and with his ever-present cigar.

The remainder of the undergraduate curriculum in chemistry was limited, under his leadership, to a small number of basic courses, with great freedom of election during the junior and senior years.

The contrast in this respect with certain other departments of the university has been so great as to suggest to the writer an empirical academic law to the effect that the number of courses taught by a department varies inversely with the eminence of its faculty and with the advancement of knowledge in the field.

The methods adopted for graduate instruction were such as to emphasize research. In place of lectures repeating material already available in book form, there were seminars on topics in process of development. A notable illustration is furnished by a seminar on valence offered by Lewis himself which culminated in the publication in 1923 of his influential book, *Valence and the structure of atoms and molecules.* The foreword to the book contains his own generous testimony to the cooperative nature of practically all the output of the laboratory, which, under his influence, has prevailed over the years against all the temptations of selfishness and jealousy. "To my colleagues and students of the University of California, without whose help this book would not have been written. In our many years of discussion of the problems of atomic and molecular structure, some of the ideas here presented have sprung from the group rather than from an individual; so that in a sense I am acting only as editor for this group."

In conducting the affairs of the Department of Chemistry, the business unit, as well as of the College of Chemistry, the curricular unit, Lewis showed himself to be one of the all too rare leaders who are able to influence the members of their organizations by natural gifts of reason and persuasion and do not need to invoke the artificial aids of authority and position. Despite a minimum of formal parliamentary procedure, whose tricks, as all know, may be used to thwart true democracy, there was always the fullest consultation with interested members of the department before important steps were taken. The result was a high degree of co-operation and loyalty.

The influence of Lewis was exerted upon the university as well as upon his own department. He came to it in the period during which the university was growing from adolescence to maturity, which was naturally a period of "Sturm und Drang." From this has emerged a great university almost unique in the extent to which its faculty shares in determining policies. A staff writer in *Fortune* magazine has referred to its Academic Senate as "undoubtedly the most self-determined faculty group in the country, and certainly the most conspicuous contribution of the University to educational administration." Lewis was outstanding during these years among the men who had the dignity, the insistence, and the sense of responsibility which made the building of a great institution the common, devoted enterprise of its administration and faculty.

His work at California was interrupted by World War I. In December of 1917 he was commissioned a Major in the Gas Service, later the Chemical Warfare Service, and in January, 1918, went to France. He began as Director of the Chemical Warfare Service Laboratory in Paris but, having been sent to the front as an observer during the great German offensive in March, he made, upon his return, such a penetrating report to the Chief, General Amos A. Fries, that the latter made him Chief of the Defense Division of the Chemical Warfare Service. In this capacity he organized the American Expeditionary Force Gas Defense School and established it near the A.E.F. Headquarters at Chaumont, at Hanlon Field, the Experimental Field of the service. Before long, the school was training as many as two hundred gas officers a week for the American Army, and as a result, gas casualties, which early in 1918, had constituted the majority of all casualties, soon dropped to a very small percentage of the total. The Distinguished Service Medal, awarded to him in 1922, was accompanied by the following citation: "By his unusual energy, marked ability, and high technical attainments he rendered extremely valuable service by securing first-hand data on the uses and effects of gas and submitting reports of such value that they became fundamentals upon which the gas-warfare policies of the American Expeditionary Forces were thereafter largely based. Later, as chief of the defense division, Chemical Warfare Service, he obtained a high state of efficiency in the protection of our officers and soldiers against enemy gas and furthered the successes of American arms by securing a better and more effective use of gas, especially mustard gas, against the enemy, thereby rendering services of great value to our Government."

He returned to Washington shortly before the end of the war, where he was promoted to the rank of Lieutenant Colonel and made Chief of the Training Division of the Chemical Warfare Service. He was awarded also the Cross of the Legion of Honor.

Returning to the University of California, he began working, with the assistance of Merle Randall, upon his great treatise on thermodynamics, referred to above. This was published in 1923. It represented the fruition of work begun in 1899 and presented in a series of sixty papers.

It had long been the aim of chemists to possess tables of chemical affinity which would make it possible to predict the direction of any chemical reaction. The extensive determinations of heats of reaction made during the latter half of the last century had this aim largely in view. It was thought at one time that the heat of a reaction could be taken as the measure of chemical affinity, and consequently that the heats of formation of the substances involved could serve for the prediction of the direction of a reaction. The development of thermodynamics showed, however, that the correct measure of chemical affinity is not heat but "free energy." Lewis had set for himself many years ago the task of preparing tables of free energy. The accomplishment of this task involved, first, the critical examination, and in many cases the recalculation, of a wide range of chemical data. However, since the data at hand were not obtained with any such systematic aim in view as that proposed by Lewis, it became necessary for him and his coworkers to measure many chemical equilibria, and to study the electromotive force of many cells. The task involved, further, the application of thermodynamics to solutions, a field in which, before his work, comparatively little progress had been made.

The book summarized the work of twenty-five years. It contained the free energies of 143 important substances, making possible the calculation of chemical equilibria for many hundreds of reactions. The importance of these data is illustrated by the following remark of a reviewer: "If this book can further the use of those [free energy] values and can create a demand for more data, it will have added more to the development of civilization and the increase of human comfort than any other chemical treatise in all history."

In addition to these exceedingly important data, the book contains a large number of original and important applications of thermodynamics to chemical problems. In the words of another reviewer, published in *Nature:* "For many years back the published researches of G. N. Lewis and his collaborators have occupied a prominent place in the branch of science dealing with the application of thermodynamics to the solution of chemical problems. The book now under review, of which he and his coworker, Merle Randall, are joint authors, collects and summarizes these researches and places them in position in the general framework of thermodynamics. For this alone all interested in matters pertaining to physicochemical theory would owe them thanks, but the debt is increased by the fact that no better account of modern chemical thermodynamics than appears in this book can be placed in the hands of advanced students."

Lewis developed a variety of special methods, chemical, algebraic, arithmetical, and graphical, for the treatment of thermodynamic data. These methods did much to rescue thermodynamics from a barren position in treatises on theoretical physics, and to place it as a working tool of extraordinary potency in the hands of the chemist, who had been, up to that time, far too ignorant of its vital importance.

Lewis's first paper pertaining to thermodynamics was a joint paper with T. W. Richards, entitled "Some Electrochemical and Thermochemical Relations of Zinc and Cadmium Amalgams," embodying the results of his doctor's thesis. This was followed the next year by a most important paper in which he investigated the integration constant of the free energy equation. In 1906 he definitely established by equilibrium measurements the value of the oxygen electrode, and showed that direct measurements of the potential did not give the equilibrium value. This was the beginning of the long series of experimental and theoretical investigations to bring the various physico-chemical methods into agreement. The most important theoretical paper during this period was the "Outline of a New System of Thermodynamic Chemistry." He then began a determination of the electrode potentials of a number of elements, including lithium, sodium, potassium, rubidium, chlorine, bromine, iodine, oxygen, mercury, silver, thallium, lead, and iron. All these measurements were carried out with a precision far beyond that of the previous investigators. The ingenuity shown in obtaining the values for the alkali metal electrodes is worthy of particular mention. In 1912, Lewis laid the foundations for the exact treatment of aqueous solutions with the calculation of the activities of the ions of strong electrolytes.

With Burrows, 1912, he reversibly synthesized urea. It is noteworthy that the first typically organic substance to be synthesized from inorganic materials was likewise the first to be reversibly synthesized from the elements. In 1917, with Gibson, he began his investigation into the scope of the third law of thermodynamics, a return to the problem discussed in his doctor's thesis. In 1921, with Randall, he laid the basis for the treatment of concentrated solutions, and freed chemists from the necessity of limiting their work to dilute solutions. In the same year, in the paper "Activity Coefficient of Strong Electrolytes," again with Randall, he treated comprehensively the various methods of measuring the colligative properties of solutions. This paper also enunciated the important principle of the ionic strength, which has since been developed theoretically by Debye and Hückel.

No less important than the contributions of Lewis to thermodynamics have been his theories of valence. His first contribution upon this subject, entitled "The Atom and the Molecule," appeared in 1916 in the *Journal of the American Chemical Society,* almost simultaneously with the paper by Kossel in the *Annalen der Physik*, which dealt with the same general subject. Later publications by Lewis appeared in the *Proceedings of the National Academy of Sciences*, and in the *Transactions of the Faraday Society*. His most extensive treatment of the topic appeared in 1923 in a volume entitled *Valence and the structure of atoms and molecules*, published as a monograph of the American Chemical Society. In these publications he elaborated, as did Kossel, the ideas of Abegg regarding the significance of an outer octet of electrons of an atom, but he went further than Kossel in calling attention to evidence indicating the pairing of electrons, and explained nonpolar chemical bonds. The organic and inorganic views regarding the chemical bond, which had, prior to this time, little in common, were reconciled by this concept. He further harmonized with electron structure the empirical generalizations of Werner concerning valence and coordination number. He called attention to the atoms of "variable kernel," later recognized from spectroscopic studies. He pointed out the peculiar properties of molecules having an odd number of electrons and drew attention to relations between magnetic properties and electron structure.

These theories have had a wide influence upon chemical thought. One may mention, especially, their fruitful application in a series of papers by Langmuir, in the *Journal of the American Chemical Society*. Langmuir had previously stated that "the theory of valence recently advanced by G. N. Lewis seems to offer by far the most satisfactory picture of the mechanism of chemical combination that has yet been suggested." Chemical literature abounds in references to this work of Lewis. For some time his views upon the nature of the chemical bond, particularly the paired electron bond, were not popular among physicists, because they bore no very close relationship to the Bohr atom, but the advent of the new quantum mechanics yielded a striking confirmation of this type of bond, and gained a new appreciation of the significance of the views of Lewis. Pauling stated that "the application of the quantum mechanics to the interaction of more complicated atoms, and to the nonpolar chemical bond, in general, is now being made. . . . It is worthy of mention that qualitative conclusions have been drawn which are completely equivalent to G. N. Lewis's theory of the shared electron pair."

Certain additional lines of research by Lewis deserve mention. In 1933, he devoted great energy to the isolation of deuterium, which had just been discovered by H. C. Urey, who received his doctoral degree in the Berkeley department. With the assistance of a number of young collaborators, he determined by ingenious micromethods a number of the properties of the element itself, of "heavy water," and of other deuterium compounds, and he supplied E. O. Lawrence and other physicists with the deuterium oxide with which most of the first determinations of the physical properties of deuterium were made. A visiting scientist asked him one day what he was doing with a piece of apparatus provided with a long cellophane osmotic tube; he replied with one of those flashes of ready wit for which he was renowned among his friends, "I am trying to make heavy water with an artificial bladder."

In his *Valence,* in 1923, Lewis had outlined the several possible definitions of acid base systems, adding his own, the most general definition of all, that "a basic substance is one which has a lone pair of electrons which may be used to complete the stable group of another atom, and that an acid substance is one which can employ a lone pair from another molecule in completing the stable group of one of its own atoms. In other words, the basic substance furnishes a pair of electrons for a chemical bond, the acid substance accepts such a pair." This definition not only divorced the concept of a base from the properties of hydroxyl ion, as did the Lowry-Brönsted definition later, but also freed the notion of acid from the limitation that it must be able to "donate" a proton. The Lewis point of view was largely overlooked during the 1930s in the wave of enthusiasm for the proton-donor-acceptor theory as the "modern" and "correct" one, to be taught as such, even in elementary courses. Lewis returned to this question in a paper published in 1938 in the *Journal of the Franklin Institute,* entitled, "Acids and bases." In it he wrote, "The recognition of Brönsted and his school of such ions as the halide ions and acetate ion as true bases, together with the development of the concept of organic bases, tends to make the present recognized list of bases identical with my own. On the other hand, any similar valuable and instructive extension of the idea of acids has been prevented by what I am tempted to call the modern cult of the proton. To restrict the group of acids to those substances which contain hydrogen interferes as seriously with the systematic understanding of chemistry as would the restriction of the term oxidizing agent to substances containing oxygen."

He then proceeded to give a number of instances of essentially acid-base reactions, including typical changes in the colors of indicators, where no proton transfer could possibly be involved, as where such bases as pyridine or triethylamine react with such acids as $SO_2$, $BCl_3$, or $SnCl_4$ in solvents such as dioxane or $CCl_4$. These experiments have helped to bring the enthusiasts for the proton theory down to earth, and to make clear that any such system represents merely convenience to the particular purpose at hand, not an ultimate truth. The fact that the organic chemist finds the proton-donor-acceptor system appropriate for most of his studies should not be used to set up a system of instruction in chemistry which would deny the right of, say, the geochemist to speak of acidic and basic oxides, lavas, or rocks.

Lewis had always taken great interest in color. Indeed, he used it in 1920 as the subject of his Faculty Research Lecture, an honor annually bestowed by the Academic Senate of the University upon one of its members. During his later years he returned to a study of color and fluorescence in relation to structure, publishing with his collaborators a series of eighteen papers. In this work, as always before, he exhibited his wide grasp of organic chemistry, a fact insufficiently appreciated by those who have thought of him primarily as a physical chemist.

Few men in their sixties have the imagination to branch out in new directions. It was characteristic of Lewis that most of the above new work was done after the age of sixty-five, at which time, according to

University rules, he laid down his administrative functions while continuing as a professor till the age of retirement at seventy. But Lewis, not content with occupying his mind with fluorescence and phosphorescence, was also then reading extensively for recreation in the field of American pre-history and, in 1945, read to the Chit-Chat Club of San Francisco a daring paper upon the subject. Another paper on "The Thermodynamics of Glaciation" appeared posthumously in *Science*. The mental activity that caused him to range from time to time beyond the bounds of his main field of research had been exhibited earlier in two articles on price stabilization, "Europas Skudder och Mynfoten" (*Finsk Tidskrift,* 1924), and "A plan for stabilizing prices" (*The Economic Journal,* 1925).

His wide interests, together with his sparkling sense of humor, made him one of the most stimulating and charming of companions and conversationalists. He loved good company and always made it better by joining it. He was very sensitive to humbug or pretense. He shunned the crowd and squirmed under personal praise. A number of his friends and former students, desiring to honor him by a dinner, knowing his tastes, avoided the set laudatory speeches under which a lesser man would have beamed, and simply had a good time together.

Lewis was not at ease in speaking in public and rarely accepted invitations to deliver any but a scientific address. When sufficiently aroused, however, he could be effective in debate, and few cared to cross swords with him in arguments in the Academic Senate. It was with the pen that he chiefly showed his skill. Those who have followed his writings have often been arrested by passages of high quality. The preface to *Thermodynamics* contains the following sample: "There are ancient cathedrals which, apart from their consecrated purpose, inspire solemnity and awe. Even the curious visitor speaks of serious things, with hushed voice, and as each whisper reverberates through the vaulted nave, the returning echo seems to bear a message of mystery. The labor of generations of architects and artisans has been forgotten, the scaffolding erected for their toil has long since been removed, their mistakes have been erased, or have become hidden by the dust of centuries. Seeing only the perfection of the completed whole, we are impressed as by some superhuman agency. But sometimes we enter such an edifice that is still partly under construction; then the sound of hammers, the reek of tobacco, the trivial jests bandied from workman to workman, enable us to realize that these great structures are but the result of giving to ordinary human effort a direction and purpose." Again, "Science has its cathedrals, built by the efforts of a few architects and of many workers."

Many honors came to him. He received honorary degrees from the Universities of Chicago, Liverpool, Madrid, Pennsylvania, and Wisconsin. He was elected to honorary membership in the Royal Institution of Great Britain, the Chemical Society of London, the Indian Academy of Sciences, the Swedish Academy, the Danish Academy, the Royal Society, and the Franklin Institute of Pennsylvania. He was awarded the Nichols, Gibbs, Davy, Arrhenius, Richards, and Society of Arts and Sciences Medals. He was Silliman Lecturer at Yale in 1925, choosing as his topic "The Anatomy of Science," and doing his best to shock scientific prejudices in several fields.

Lewis was elected to the National Academy of Sciences in 1913, a year after going to the University of California. He served for a term as chairman of the section on chemistry. In 1934 he resigned from the Academy in disagreement with what he regarded as undue domination of its affairs by certain persons.

The end came suddenly on March 23, 1946, and, appropriately, in the laboratory while continuing his experiments on fluorescence. He is survived by his widow, Mary Sheldon Lewis, to whom he was married in 1912, and by his two sons, Richard Newton and Edward Sheldon, both chemists, and his daughter, Margery Selby.

The following paragraphs from a memorial resolution presented to the Academic Senate of the University of California by G. E. Gibson present a worthy summary of a distinguished career:

"The half century which terminated with the death of Gilbert Newton Lewis will always be regarded as one of the most brilliant in the history of scientific discovery, and his name ranks among the highest in the roster of those that made it great. The electron theory of chemical valence, the advance of chemical thermodynamics, the separation of isotopes which made possible the use of the deuteron in the artificial transmutation of the elements, the unravelling of the complex phenomena of the adsorption, fluorescence and phosphorescence of the organic dyes are among the achievements which will ever be associated with his name.

"The methods he chose were always simple and to the point. He was impatient of unnecessary elaboration, and like Sir Humphrey Davy, who was one of his heroes, loved to make important discoveries with a few test-tubes and simple chemicals. When the point at issue seemed to him sufficiently important, he would not hesitate to employ apparatus requiring skill and delicacy of manipulation, as in the beautiful but difficult experiment by which he and Calvin demonstrated the paramagnetism of the phosphorescent triplet state.

"He was ever conscious of the necessity for economy of time in research and out of the wealth of his ideas was careful to select those that would lead swiftly to the goal.

"As a man he was a great soul whose inspiration will never be forgotten by those who knew and loved him. He was one of those rare scientists, like J. J. Thomson and Rutherford, who are also great teachers and leaders of a school, so that their influence is multiplied by the many they have inspired.

"His brain was still fertile of ideas and his faculties all but unimpaired until the very end, when he died suddenly of heart failure, in harness as he would have wished it, in the act of performing his last experiment."

## KEY TO ABBREVIATIONS

Ann. Naturphil. = Annalen der Naturphilosophie
Bull. Gov. Lab. Manila., P. I. = Philippine Islands Bureau of Government Laboratories Publications
Chem. Met. Eng. = Chemical and Metallurgical Engineering
Chem. Rev. = Chemical Reviews
Contrib. Jefferson Phys. Lab. = Contributions, Jefferson Physical Laboratory
Econ. J. = The Economic Journal
Jb. Radioakt. = Jahrbuch der Radioaktivität und Elektronik
J. Amer. Chem. Soc. = Journal of the American Chemical Society
J. Franklin Inst. = Journal of the Franklin Institute
J. Chem. Phys. = Journal of Chemical Physics
Philippine J. Sci. = Philippine Journal of Science
Phil. Mag. = Philosophical Magazine
Phys. Rev. = Physical Review
Proc. Amer. Acad. = Proceedings of the American Academy
Proc. Nat. Acad. Sci. = Proceedings of the National Academy of Sciences
Publ. Astron. Soc. Pacific = Publications, Astronomical Society of the Pacific
Sch. Sci. Math. = School Science and Mathematics
Technol. Quart. = Technology Quarterly
Trans. Faraday Soc. = Transactions of the Faraday Society
Z. anorg. Chemie = Zeitschrift fur anorganische Chemie
Z. Elektrochem. = Zeitschrift fur Elektrochemie
Z. phys. Chem. = Zeitschrift fur physikalische Chemie

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