NATIONAL ACADEMY OF SCIENCES

IRVING LANGMUIR

1881—1957

A Biographical Memoir by

C. GUY SUITS AND MILES J. MARTIN

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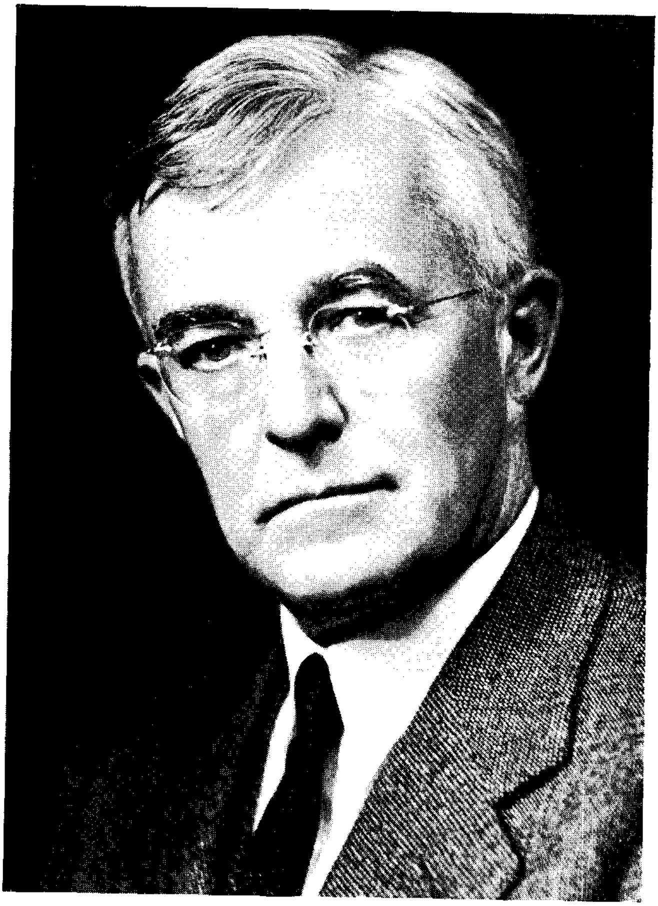

Irving Langmuir

IRVING LANGMUIR

January 31, 1881–August 16, 1957

BY C. GUY SUITS AND MILES J. MARTIN

FEW SCIENTISTS, in either university or industry, have made as many, and as significant, contributions to scientific progress as did Dr. Irving Langmuir, the 1932 Nobel Prize winner in chemistry. It was on July 19, 1909, that Langmuir joined the General Electric Research Laboratory in which he was to become, first, assistant director and then associate director and which was to be the scene of his greatest achievements.

One of Langmuir's first achievements was in the field of lighting. After Dr. William D. Coolidge, also of the Research Laboratory, developed the drawn tungsten-filament incandescent lamp, it fell to Langmuir to further develop an improved lamp—a gas-filled one instead of the vacuum type—and thereby make a great gain in lighting efficiency.

The gas-filled lamp soon began driving arc lamps from the street lights, greatly increasing the use of electric lighting by increasing efficiency. With the lower cost of lighting came a large increase in the amount of light used, so that electric utility revenues from lighting were soon higher than ever before. They continued to increase steadily as efficiency improved. Further improvements in incandescent lamps were to be made in various laboratories, but Coolidge's tungsten filament and Langmuir's gas filling remain today two basic elements of incandescent lamps.

Irving Langmuir, in the forty-one active years he was a versatile researcher in the General Electric laboratory, was distinguished for his epoch-making discoveries in science and also for the many very important practical applications that were made of his work. His scientific productivity was prodigious. He published about five scientific papers a year for the full period of his research career, and the resulting group of more than 200 papers* included a great diversity of topics, for example:

The Laws of Convection and Conduction of Heat in Gases (1912).

The Effect of Space Charge and Residual Gases or Thermionic Currents in High Vacuum (1913).

The Constitution and Fundamental Properties of Solids and Liquids (1916).

The Condensation Pump: An Improved Form of High-Vacuum Pump (1916).

The Arrangement of Electrons in Atoms and Molecules (1919).

Chemical Reactions on Surfaces (1921).

The Electron Emission from Thoriated Tungsten Filaments (1921).

Atomic Hydrogen Arc Welding (1926).

The Theory of Collectors in Gaseous Discharges (1926).

General Theory of the Plasma of an Arc (1929).

Oxygen Films on Tungsten (1931).

Surface Chemistry. Nobel Lecture (1933).

Built-Up Films of Proteins and Their Properties (1937).

Rates of Evaporation of Water through Compressed Monolayers on Water (1943).

Studies on the Effects Produced by Dry-Ice Seeding of Stratus Clouds (1948).

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* See the twelve volumes entitled *The Collected Works of Irving Langmuir,* Pergamon Press, Elmsford, N.Y. (1962).

ELECTRONICS INDUSTRY

Langmuir's study of thermionic phenomena produced effects that later became the heart of the electronics industry. His research gave the world the first high-vacuum electron tubes and the first high-emission electron tube cathodes.

Not only was the study of heat transfer in gases the scientific source of Langmuir's basic invention of the gas-filled lamp and atomic hydrogen welding but it also provided the technology for hydrogen-cooled turbines.

Langmuir made basic contributions to the understanding of gaseous discharge phenomena—he invented the word *plasma*—and his work on surface films, later protein films on water, provided an important new technique in biochemistry. He received the Nobel Prize in 1932. Later he devoted his time more to "science out-of-doors."

SCIENTIFIC WORK

Irving Langmuir's scientific career covered fifty years, starting in 1904 with his doctoral dissertation at Göttingen, "Ueber partielle Wiedervereinigung dissociierter Gase im Verlauf einer Abkühlung," and ending in 1955 with an unpublished report on "Widespread Control of Weather by Silver Iodide Seeding." In order to convey a feeling for the diversity of his work, Langmuir's published scientific work has been grouped into seven categories below, this grouping following rather closely that used by Langmuir himself in the Introduction to *Phenomena, Atoms, and Molecules,* a reprint* of some twenty of his papers selected by him in 1950. The dates associated with each category indicate when most of the relevant work was published, although it will be clear from the span of some of these dates that Langmuir's productive interest in certain areas continued

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* Philosophical Library, Inc., New York, N.Y. (1950).

throughout a large part of his active scientific life and even into retirement:

1906 to 1921	Chemical Reactions at High Temperatures and Low Pressures
1911 to 1936	Thermal Effects in Gases
1919 to 1921	Atomic Structure
1913 to 1937	Thermionic Emission and Surfaces in Vacuum
1916 to 1943	"Chemical Forces" in Solids, Liquids, and Surface Films
1923 to 1932	Electrical Discharges in Gases
1938 to 1955	Science Out-of-Doors

CHEMICAL REACTIONS AT HIGH TEMPERATURES AND LOW PRESSURES

When Langmuir commenced his doctoral work at Göttingen, Professor Walther Nernst suggested as a thesis subject the study of the formation of nitric oxide from air in the vicinity of a glowing Nernst filament. It was thought that the filament would act catalytically on the reaction between oxygen and nitrogen and that the final equilibrium would correspond to the temperature of the filament. This method of studying equilibria looked extremely attractive because of the simplicity of the apparatus involved, compared with the complexity of the equipment more generally used in such studies. This simple hypothesis proved not to be applicable to the interaction of nitrogen and oxygen in the vicinity of a glowing Nernst filament, and the thesis effort was shifted to studying other gaseous equilibria, such as the dissociation of carbon dioxide brought about by a glowing platinum filament, where the hypothesis was found to be valid.

This very early work is especially interesting as a foreshadowing of Langmuir's predilection for experiments requiring only simple apparatus but where understanding of the experimental results might involve new, bold concepts and extended theoretical analysis. In this case, the work led to an understanding of the unexpectedly much greater importance of thermal conduction, as compared with convection, in determining the heat loss from a filament through the first few tenths of a millimeter of gas surrounding it.

This thesis work was also important in orienting Langmuir's scientific interests in 1909 when, at Dr. Willis R. Whitney's invitation, he joined the Research Laboratory of the General Electric Company, which laboratory had been established only nine years before. Dr. Whitney suggested that Langmuir should spend a few days looking around to see what was going on, and the first entry in his laboratory notebook reads:

> July 19–July 21
>
> Spent these two days looking thru lab and seeing what work was being done.

Apparently "these two days" were sufficient to show Langmuir that the laboratory was intensely interested in problems connected with making good incandescent lamps out of the then-new ductile tungsten wire just introduced by Coolidge. The first experiments of his choice were concerned with preparing pure hydrogen and studying the effects of heating tungsten wire in it.

At that time, all incandescent lamps were vacuum lamps, and the general feeling was that, if the vacuum could be made better, the life of the lamp would be improved. Langmuir, on the other hand, had been impressed with how much better lamp-factory vacuum was than what had been available to him at the university, and, not knowing how to improve on this, he resolved to see what effects the opposite approach of adding various gases would have on the life of tungsten lamps. He was also impressed with the ready availability of tungsten wires capable of being heated electrically to very high temperatures. From this combination of good vacuum and high-temperature filaments grew his work on chemical reactions at high temperatures and low pressures. These studies included the discovery and detailed investigation of the formation of atomic hydrogen by contact of molecular hydrogen with a hot tungsten filament, a careful analysis of the effects of water vapor in incandescent lamps, and a systematic investigation of the mechanism of "cleanup" of oxygen, nitrogen, and other gases at low pressure by hot tungsten and molybdenum filaments.

THERMAL EFFECTS IN GASES

Langmuir had established that, apart from a special chain reaction with water vapor, the life of a tungsten vacuum lamp was insensitive to the residual gases usually present and was determined entirely by the evaporation of tungsten. This encouraged him to experiment with lamps containing much higher pressures of inert gases and to study heat losses from filaments under these conditions.

He found that the evaporation of tungsten in nitrogen at approximately atmospheric density is essentially a diffusion process and obeys laws similar to those of conduction or convection of heat from a wire; that is, for wires of small diameters, the actual amount of tungsten evaporated is almost independent of the size of the wire, an unfavorable result for the very small filaments used in most lamps. On the other hand, experiment showed that, for several reasons, life and efficiency were better for large filaments in nitrogen. This dilemma was resolved by coiling the small wire tightly into a helix of substantially larger diameter, a form of construction that led to widespread adoption of the gas-filled lamp.

The dissociation of hydrogen by a hot tungsten filament had been postulated by Langmuir to explain the sudden increase in heat loss from a filament in hydrogen at high temperatures. Estimates of the heat of dissociation were made, and some properties of atomic hydrogen were observed, such as its adsorption on a cold glass wall.

Several years later Langmuir's attention was attracted by R. W. Wood's* preparation of concentrated atomic hydrogen in an electric discharge tube and Wood's observations on the heating effects produced by the recombination of the atomic hydrogen on a variety of surfaces. This led Langmuir to the invention of the atomic hydrogen welding torch, in which large amounts of atomic hydrogen are produced by an arc between tungsten electrodes in hydrogen, and the atoms are allowed to recombine on the metal to be heated.

ATOMIC STRUCTURE

Some of Langmuir's most productive thinking was guided by consideration of the differences between what he called "physical forces" and "chemical forces." This thinking led to his concept of the adsorption process and also to his rather brief sortie into the field of atomic structure during 1919–1921.

The Bohr† theory was then well established by reason of its spectacular spectroscopic successes. Langmuir considered this to be a typical "physical force" theory based on forces acting according to simple laws between mathematical points separated by relatively large distances. The chemist, on the other hand, did not think of molecules as point centers of force, but rather as complex entities having structures which made the outward acting "chemical forces" at one part of the molecule quite different from those at another. Moreover, the "chemical forces" were usually of shorter range than the "physical forces." This thinking, together with G. N. Lewis's‡ theory of the "cubical atom" and a keen feeling for the complex chemical phenomena to be explained, led Langmuir to his "octet theory" of atomic structure, in which Bohr's centrally orbiting electrons were replaced by electrons distributed in regions throughout the

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* R. W. Wood, *Proc. Roy. Soc.*, 102, 1 (1922), and *Phil. Mag.*, 44, 538 (1922).
† N. Bohr, *Phil. Mag.*, 26, 1 (1913).
‡ G. N. Lewis, *J. Am. Chem. Soc.*, 38, 762 (1913).

atom, each electron being stationary in its region or describing a restricted orbit within the region.

With these concepts, and a limited number of postulates, Langmuir was able to correlate a tremendous variety of chemical phenomena. Further detailed calculations, however, led to the need for more assumptions, and it was not long until the advent of quantum-mechanical concepts of chemical bonds led him to transfer his efforts to other problems. Langmuir, while appreciating the great conceptual contributions made by quantum mechanics, was impressed by the tremendous mathematical difficulties of attempting to understand chemical properties in detail by this route. Because of this he apparently made a decision not to develop a working knowledge of these new tools for himself, but to continue his work where more classical methods were still fruitful.

THERMIONIC EMISSION AND SURFACES IN VACUUM

As a natural outgrowth of his earlier work on tungsten lamps, Langmuir entered the field of thermionic emission in 1913 to answer the specific question of why relatively large electron currents did not appear as shunt currents from the negative leg to the positive leg of a tungsten lamp with a hairpin filament. At that time the true origin of thermionic emission was still in doubt, and there were even suggestions that the thermionic electrons were by-products of a chemical reaction and, therefore, that the absence of the shunt current in lamps was due to the very high vacuum. Langmuir made experiments with lamps containing two separate hairpin filaments and soon arrived at the concept that the shunt currents were small because the charges on the electrons in the space between the legs of the filament shielded the negative leg from the acclerating field due to the positive leg.

This hypothesis was at once submitted to theory and calculation, resulting in the Child–Langmuir* space-charge equation, according to which the electron current between electrodes of any shape in vacuum is proportional to the 3/2 power of the potential difference between the electrodes. This celebrated law was followed through in great detail for various electrode configurations, and corrections for the initial thermal velocities of the electrons were introduced. The 3/2 power law became an important issue in a hard-fought patent suit concerning electron discharges in very high vacuum, a major result of which, perhaps, was to illustrate the difficulty of patenting something that came so close to being a law of nature.

Thorium oxide is added to tungsten lamp filaments to improve their mechanical behavior at high temperatures, and it had been observed sporadically that abnormally high thermionic emission was obtained from some lamp filaments. When Langmuir undertook a systematic study of this problem, he soon showed that the abnormally high emission was definitely associated with the presence of thoria in the filament. He worked out in great detail the temperature treatment needed to obtain thoriated emission and the magnitude of the emission under various conditions. His theoretical study of the phenomenon showed that the enhanced emission could be explained in terms of the formation by diffusion of a single, more or less complete layer of thorium atoms on the surface of the filament. These rather detailed and involved concepts were obtained by interpretation of experiments with the simplest of vacuum tubes and current measurements with a portable microammeter.

It is interesting to observe that the interpretations of such simple experiments, in the hands of so great a master, at times cause corrections in detail. Langmuir interpreted the transient

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* C. D. Child, *Phys. Rev.*, 32, 492 (1911). Independent derivations of this equation were made by Langmuir for electrons and by Child for positive ions about two years earlier.

behavior of the surface film in formation as being due to a combination of the diffusion of the thorium atoms through the tungsten lattice plus a reasonable assumption of "induced evaporation" when a new thorium atom arrived under one already in the surface layer. It was not until considerably later that more complicated experiments by P. Clausing* showed that the thorium really diffused to the surface through the intercrystalline material and then spread over the surface from these lines of access in a two-dimensional diffusion. Yet, some thirty years later Clausing revealed that Langmuir's computations had been the correct ones after all.

Another extended series of thermionic studies, done in collaboration with K. H. Kingdon and J. B. Taylor, involved new phenomena observed when cesium is put into a vacuum tube containing a tungsten filament. At low filament temperatures, and particularly if the filament is first coated with a monatomic layer of oxygen, the cesium atoms are strongly adsorbed from the vapor onto the surface of the filament. Such a cesium–oxygen–tungsten surface is the most efficient thermionic emitter known, and high hopes were entertained at first for its application in radio tubes. However, the advent of conventional barium oxide cathodes heated from the alternating current supply replaced this possible application.

Another new phenomenon observed was that, at higher filament temperatures, cesium atoms (ionizing potential 3.9 volts) striking a tungsten filament are robbed of an electron by the filament (work function 4.5 volts) and come off as positive ions that may be collected at a negative electrode. Langmuir developed a theoretical interpretation of these phenomena in terms of his concepts of adsorbed films and the Saha equation. This equation gives the equilibrium concentrations of ions, electrons, and neutral atoms at a known temperature in a gas with known ionization potential and for this application must

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* P. Clausing, *Physica*, 7, 193 (1927).

be modified to include the electron-emitting capability of the hot filament, since this shifts the temperature equilibrium.

Langmuir had great hopes for the use of this controlled source of ionization for neutralizing electron space charge in power tubes, but experiment and, later, theory showed that only modest effects could be obtained. The principle of ionization at a hot surface found early application as a molecular beam detector and at present (1965) is being investigated as a source of ion propulsion for space vehicles.

All kinds of studies and processes requiring evacuated enclosures were aided tremendously by Langmuir's invention of the condensation pump. That pump was simple to construct, had very high speed, and, with the aid of refrigerants, produced an extremely high vacuum. It came rapidly into widespread use.

"CHEMICAL FORCES" IN SOLIDS, LIQUIDS, AND SURFACE FILMS

"Chemical forces" in solids, liquids, and surface films is the area of science to which about one quarter of Langmuir's publications are devoted and for which he received the Nobel Prize in Chemistry in 1932. His ideas on the short-range character of "chemical forces" led him to a new concept of adsorption, in which every molecule striking a surface remained in intimate contact with the surface for a short or long time and then evaporated. This adsorption contact was so intimate that it might be thought of as a chemical bond, and thus the concept of a firmly held, single layer of adsorbed atoms replaced the existing idea of a relatively thick adsorbed sheath extending some distance out from the surface with concentration decreasing with distance.

Langmuir made an early application of his ideas on surface films to the study of films on water surfaces, an area of science to which his attention had been drawn by the beautifully simple experimental techniques developed over the years by Miss

Pockels, Lord Raleigh, Devaux, and Marcelin.* Langmuir made a tremendous extension of this technique by the introduction of a surface balance method for measuring the spreading force of the films and showed that these films were truly monomolecular. In collaboration with Katharine B. Blodgett and Vincent J. Schaefer, he developed a whole series of techniques for working with surface films and used them to study gaseous, liquid, and solid films, including films of such complicated molecules as proteins.

Langmuir's ideas on adsorbed films were also applied to films on solids, leading to the Langmuir adsorption isotherm, which gives an expression for the fraction of the surface covered by the adsorbed layer in terms of ambient pressure and a temperature-dependent variable characterizing rates of condensation and evaporation at the surface. A theory was developed for the catalytic effect of an adsorbing surface which considered the chemical reaction as actually occurring in the adsorbed film and elucidated many features of such reactions which hitherto had been obscure. This theory became the basic approach to surface kinetics.

ELECTRIC DISCHARGE IN GASES

In 1914, mercury arc rectifiers were in common use, and Langmuir gradually became interested in some of the scientific problems of electric discharges in gases. He was impressed with the opportunities for electron tubes capable of controlling high power and endeavored to apply the newly understood phenomena of vacuum electron amplifier tubes to the much larger currents of gas tubes. Ernst F. W. Alexanderson pointed out in conversation that in alternating-current power circuits the important thing was to be able to control the initiation of the current in any part of the circuit and that, if this were done,

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* A. Marcelin, *Ann. Phys.*, 1, 19 (1914).

the circuit reversal of voltage could be used to extinguish the current at a later time in the cycle. Langmuir in 1914 came upon the idea of inserting a grid in a mercury arc device to control the starting of current to a main anode. The study of such devices was carried on in collaboration with A. W. Hull and others.

Langmuir's activity in the gas-discharge field developed rather slowly, but in 1923 he was analyzing the current–voltage characteristics of currents to probe electrodes placed in a mercury arc. He found that the current to a negatively charged plane collector was independent of voltage over a wide range and showed by gridding tests that the current was due to the arrival of positive ions rather than the emission of photoelectrons. The independence of voltage was explained in terms of a plane-parallel "positive ion space-charge sheath" in front of the plane electrode, whose thickness increased with voltage in accordance with the 3/2 power space-charge law, but whose outer surface was entered by an invariant stream of positive ions.

This initial work with collecting electrodes or probes led to a most fruitful series of experiments in collaboration with H. M. Mottsmith, Jr., and Lewi Tonks. The current–voltage characteristics of probe electrodes of all sorts were studied experimentally and theoretically, the results being used to elucidate the mechanism and behavior of electric discharges in gases under a wide range of conditions. One of the most important concepts arising from this work was the interpretation of the volt–ampere characteristic of a probe collecting electrons in terms of a Maxwellian temperature distribution of the electrons. The temperatures found were very high, of the order of 15,000 K, and showed that the electrons were continually receiving energy from the drift gradient in the discharge and were far from being in temperature equilibrium with either the positive ions or the neutral gas. The ionization in the discharge could be explained quantitatively in terms of the ionization effectiveness of the electrons in the high energy Maxwellian tail.

Langmuir and Tonks also made a study of electrical oscillations in an ionized gas. Langmuir was so impressed with the implication of organization and structure in the ionized gas, evidenced by the capability of oscillation, that he adopted the word "plasma" to indicate the fundamental nature of a volume of ionized gas essentially free of space charge. At the same time he was much impressed with the instabilities and the energy-transfer capabilities of a plasma, properties which have come to the fore in recent studies of fusion plasmas.

SCIENCE OUT-OF-DOORS

Langmuir had a keen and continuing interest in the scientific basis of outdoor phenomena. One of the earlier examples of this was his explanation of the streaks or windrows of seaweed and bubbles which form on the ocean parallel to the direction of a moderate wind. He had noticed this phenomenon especially during an Atlantic crossing in August 1927, and he studied windrows for several years at Lake George, New York, where he had a summer cottage. By simple but carefully planned experiments, using such apparatus as oriented umbrellas and lamp-bulb floats, Langmuir was able to establish that the windrows were caused by wind-induced circulation of the surface water, the water on the surface flowing toward the windrows, downward under them, and up again at a point halfway between them.

An extended series of experiments with V. J. Schaefer was devoted to the production of particles of various desired sizes in atmospheric air, their behavior in filters, and the development of apparatus for generation of oil smokes for military use. The resulting smoke generator was of the order of one hundred times more effective than existing generators and was adoptd and used by the United States forces in World War II.

Another series of studies with Schaefer concerned the nucleation of ice crystals in supercooled clouds by seeding with particles of solid carbon dioxide; Schaefer showed that the low temperature is the important thing. This led to a great deal of outdoor experimentation related to possible modification of the weather by such processes. This was the last field of science in which Langmuir took an active part.

The diversity of Langmuir's scientific work shows his great breadth of interest and also indicates his characteristic approach —which was to seize on some unusual phenomenon or technique, exploit this until the returns showed signs of diminishing, and then pass on to something else.

Examples of this approach were his realization that the ready availability of tungsten filaments and good vacuum conditions in the General Electric Research Laboratory (in 1909) offered an excellent opportunity for the study of chemical reactions at high temperatures and low pressures; his attack on the random, anomalously high electron emission observed from tungsten filaments containing thoria; his appreciation of the possibilities of the surface tension trough for the study of surface film phenomena, coupled with the insight that his ideas on localized "chemical forces" gave him into the fundamentals of the problem; and his realization of the power of the probe-characteristic technique for studying the mechanism of electric discharge in gases.

Langmuir's brilliant insight into fruitful directions for applying his effort was coupled with the characteristic of being a tremendous worker. Although he was not by any means a slave to science, science was never far from his thoughts, whether in the laboratory, at home, traveling, or out-of-doors.

Perhaps the best demonstration of this work effort is given by Langmuir's notebooks. During his many active years in the laboratory, Langmuir filled fifty-four notebooks, of three hundred thirty pages each, with the details of his scientific work. These notebooks exhibit the vast foundation of data, theory, and numerical calculations on which the structure of Langmuir's published scientific work was erected. There was always a notebook with him, and he wrote in it at any time, even in a sleeping-car berth. His records were especially detailed regarding the genesis of ideas and must have been the delight (or the embarrassment?) of all patent lawyers who encountered them.

Langmuir combined his unusual scientific ability with a strong practical bent and was always on the lookout for applications of any idea or new piece of knowledge with which he came in contact. For example, he was keenly aware of the great opportunities for electron tubes capable of controlling power circuits, and his notebooks contain detailed schemes of using "trapped ions" and cesium thermions for neutralizing electron space charge. Both of these possibilities were later made obsolete by the development of controlled plasma tubes.

Langmuir made one hundred thirty-eight personal patent disclosures, of which sixty-three led to issued patents. Some of these were of great practical importance, such as the gas-filled incandescent lamp, high-vacuum electron tube principles, the condensation pump, the thoriated tungsten filament, atomic hydrogen welding, the grid-controlled arc, and the military smoke generator. Much of Langmuir's scientific work lay in areas in which there was little opportunity for patent protection, but whenever the opportunity existed, Langmuir was quick to recognize it.

Langmuir had well-developed abilities as an applied mathematician. His notebooks were filled with theoretical work related to his experimental investigations and with the results of extended computations made in testing the theories. Most of these computations were on the desk computer scale, since much of his work was done before the advent of large computers.

Most of Langmuir's scientific work was accomplished with the assistance of relatively few people. He never directed a large research team. In much of his earlier experimental work he was assisted by Samuel P. Sweetser, whose name appears in many publications. Sweetser prepared the experimental equipment and, with meticulous care, took volumes of characteristic curves for analysis by Langmuir. At one time, when the electron emission studies were very active, Langmuir's notebook gave a list of some eighty-two experiments that he was interested in having Sweetser do. With such a backlog of work it would seem that the direct experimental staff might have been expanded, but apparently Langmuir preferred not to do this.

This may have been partly because Langmuir was usually closely connected with experimental work being done by some of the younger scientists in the laboratory, many of whom, at any given time, could be found working on problems he had suggested. In addition to these activities, the notebooks are filled with suggestions for work made to many people inside and outside the laboratory who were not at all directly connected with Langmuir. In this way, without formal organization, his scientific influence touched a great many people.

Langmuir's personal characteristics may be described by such words as sincerity, intensity, vigor, intellectual integrity, breadth of interest, depth of approach. His speech was rapid, emphatic, and filled with the intensity of his interest in the ideas that he was trying to convey.

In spite of these hard-driving characteristics, Langmuir was always approachable and willing to give his best attention to any sensible problem brought to him. If he passed anyone in the hall without recognition, this was not a demonstration of aloofness, but rather of his complete absorption in the current scientific problem. If the problems of others demanded too much of his time, he could always retire to his study at home until his own current idea was satisfactorily advanced. Monday morning was frequently dedicated to an exposition of the scientific developments of the weekend to those who might be interested.

Irving Langmuir was born in Brooklyn, New York, on January 31, 1881, the son of Charles and Sadie Comings Langmuir. His mother was a descendant of the Lunt family, which came to this country on the *Mayflower*. His father, who was in the insurance business, came from a Scottish family.

After obtaining elementary education in public schools in Brooklyn, he traveled with his parents to Paris, where he studied for three years. He then returned to the United States, studied for a year at Chestnut Hill Academy, Philadelphia, then in Brooklyn at Pratt Institute, and at the School of Mines, Columbia University. In 1903 he was graduated from Columbia with a degree in metallurgical engineering.

"The metallurgical engineering course was strong in chemistry," he explained. "It had more physics than the chemical course, and more mathematics than the course in physics—and I wanted all three."

Again he visited Europe, this time to study at the University of Göttingen, in Germany, where he was awarded M.A. and Ph.D. degrees in 1906. From then until he joined the General Electric Company, in 1909, he taught chemistry at the Stevens Institute of Technology.

Dr. Langmuir and his wife, the former Marion Mersereau of South Orange, New Jersey, whom he married in 1912, made their home at 1176 Stratford Road, Schenectady, New York, with a son, Kenneth, and a daughter, Barbara.

He died August 16, 1957.

HONORS

Among scientific honors that were bestowed on Langmuir, the Nichols Medal, awarded by the New York Section of the American Chemical Society, was twice given to him, once in

1915 for his work on chemical reactions at low pressures and again in 1920 for his work on atomic structure.

In 1918 Langmuir was elected to the National Academy of Sciences and in the same year was awarded the Hughes Medal of the Royal Society of London for his researches in molecular physics.

In 1920, the American Academy of Arts and Sciences gave him the Rumford Medal for his thermionic researches and for his development of the gas-filled incandescent lamp.

In 1925, the Royal Academy of Lincei at Rome, Italy, bestowed on him the Cannizaro Prize. In 1928 he was the recipient of the Perkin Medal of the Society of Chemical Industry, and in 1930 he was awarded the Chandler Medal of Columbia University and the Willard Gibbs Medal of the Chicago Section of the American Chemical Society.

In 1932, Langmuir became the first American industrial chemist to be awarded the Nobel Prize, granted him for researches in surface chemistry. In the same year, *Popular Science Monthly* magazine awarded him its annual medal and honorarium of $10,000 for "an American who has done notable scientific work."

The Franklin Medal of the Franklin Institute and the Holly Medal of the American Society of Mechanical Engineers were given him in 1934, and the city of Philadelphia presented him the John Scott Award in 1937.

In 1940 he received a plaque as a "Modern Pioneer of Industry" from the National Association of Manufacturers, and in 1943 he became an honorary member of the British Institute of Metals.

In 1944, Langmuir became the fourth American to receive the coveted Faraday Medal of the British Institute of Electrical Engineers.

The Mascart Medal of the Société Française des Electriciens was presented to Langmuir in 1950.

He was a foreign member of the Royal Society of London and a Fellow of the American Physical Society. He had served as president of the American Chemical Society in 1929 and as president of the American Association for the Advancement of Science in 1941.

An honorary member of several societies, including the Chemical Society of London, Langmuir held honorary degrees from the following colleges and universities: Northwestern, Union, Edinburgh (Scotland), Columbia, Kenyon, Princeton, Lehigh, Harvard, Oxford, Johns Hopkins, Rutgers, Queens (Canada), and Stevens Institute of Technology.

Irving Langmuir spoke frequently of "the freedom that characterizes democracy and is necessary for making discoveries." His contributions to men everywhere should be measured both by the value of his scientific discoveries and by the extent of his efforts to maintain and enlarge the meaning of freedom. All of us who were honored to be his associates are sustained by the unparalleled legacy of knowledge and inspiration he has left to us and all the world.

BIBLIOGRAPHY *

KEY TO ABBREVIATIONS

Chem. Rev. = Chemical Reviews
Gen. Elec. Rev. = General Electric Review
Ind. Eng. Chem. = Industrial and Engineering Chemistry
J. Am. Chem. Soc. = Journal of the American Chemical Society
J. Chem. Phys. = Journal of Chemical Physics
J. Franklin Inst. = Journal of the Franklin Institute
Phys. Rev. = Physical Review
Proc. Am. Inst. Elec. Eng. = Proceedings of the American Institute of Electrical Engineers
Proc. Nat. Acad. Sci. = Proceedings of the National Academy of Sciences
Proc. Phys. Soc. (London) = Proceedings of the Physical Society of London
Proc. Roy. Soc. (London) = Proceedings of the Royal Society of London
Rev. Mod. Phys. = Reviews of Modern Physics
Trans. Am. Electrochem. Soc. = Transactions of the American Electrochemical Society
Trans. Faraday Soc. = Transactions of the Faraday Society
Z. Electrochem. = Zeitschrift für Electrochemie

1906

Ueber partielle Wiedervereinigung dissociierter Gase im Verlauf einer Abkühlung. Inaugural dissertation for doctor's degree. Göttingen.

The dissociation of water vapor and carbon dioxide at high temperatures. J. Am. Chem. Soc., 28:1357.

1908

The velocity of reactions in gases moving through heated vessels and the effect of convection and diffusion. J. Am. Chem. Soc., 30:1742.

1911

Thermal conduction and convection in gases at extremely high temperatures. Trans. Am. Electrochem. Soc., 20:225.

1912

Convection and conduction of heat in gases. Phys. Rev., 34:401; also in Proc. Am. Inst. Elec. Eng., 31:1011.

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* The twelve volumes entitled *The Collected Works of Irving Langmuir,* published by Pergamon Press in 1962, include several additional titles that were not included in this bibliography.

The dissociation of hydrogen into atoms. J. Am. Chem. Soc., 34:860.

A chemically active modification of hydrogen. J. Am. Chem. Soc., 34:1310.

1913

Chemical reactions at very low pressures. I. The clean-up of oxygen in a tungsten lamp. J. Am. Chem. Soc., 35:105.

Laws of heat transmission in electrical machinery. Proc. Am. Inst. Elec. Eng., 32:391.

Convection and radiation of heat. Trans. Am. Electrochem. Soc., 23:299.

With E. Q. Adams and G. S. Meikle. Flow of heat through furnace walls: The shape factor. Trans. Am. Electrochem. Soc., 24:53.

Chemical reactions at very low pressures. II. The chemical clean-up of nitrogen in a tungsten lamp. J. Am. Chem. Soc., 35:931.

A new vacuum gage of extreme sensitiveness. Phys. Rev., 1:337. (A)

The vapor pressure of metallic tungsten. Phys. Rev., 2:329.

The effect of space charge and residual gases on thermionic currents of high vacuum. Phys. Rev., 2:450.

Tungsten lamps of high efficiency. I. Blackening of tungsten lamps and methods of preventing it. Proc. Am. Inst. Elec. Eng., 32:1895.

With J. A. Orange. Tungsten lamps of high efficiency. II. Nitrogen-filled lamps. Proc. Am. Inst. Elec. Eng., 32:1915.

With J. A. Orange. Tungsten lamps of high efficiency. Gen. Elec. Rev., 16:956.

1914

Note on the heat of formation of hydrogen from hydrogen atoms. Philosophical Magazine, 27:188.

The flicker of incandescent lamps on alternating current circuits and stroboscopic effects. Gen. Elec. Rev., 17:294.

Thermionenströme in hohen Vakuum. II. Die Elektronenemission seitens des Wolframs und die Wirkung von Gasresten. Physikalische Zeitschrift, 15:516.

With G. M. J. Mackay. Die Dissoziation des Wasserstoffs in atome. I. Experimentelles. Z. Electrochem., 20:498.

With G. M. J. Mackay. The vapor pressure of the metals platinum and molybdenum. Phys. Rev., 4:377.

With G. M. J. Mackay. The dissociation of hydrogen into atoms. J. Am. Chem. Soc., 36:1708.

1915

The dissociation of hydrogen into atoms. II. Calculation of the degree of dissociation and the heat of formation. J. Am. Chem. Soc., 37:417; also in Z. Electrochem., 23:217 (1917).

A theory of adsorption. Phys. Rev., 6:79. (A)

The melting point of tungsten. Phys. Rev., 6:138.

Chemical reactions at low pressures. J. Am. Chem. Soc., 37:1139.

The pure electron discharge and its applications in radio telegraphy and telephony. Gen. Elec. Rev., 18:327; also in Proceedings of the Institute of Radio Engineers, 3:261.

1916

Heat conductivity of tungsten at high temperatures. Phys. Rev., 7:151. (A)

Radiation from tungsten filaments and the mechanical equivalent of light. Phys. Rev., 7:152. (A)

The characteristics of tungsten filaments as functions of temperature. Phys. Rev., 7:302.

The relation between contact potentials and electrochemical action. Trans. Am. Electrochem. Soc., 29:125.

Dissociation of hydrogen into atoms. III. J. Am. Chem. Soc., 38:1145.

A high vacuum mercury vapor pump of extreme speed. Phys. Rev., 8:48.

The evaporation, condensation, and reflection of molecules and the mechanism of adsorption. Phys. Rev., 8:149.

The constitution and fundamental properties of solids and liquids. J. Am. Chem. Soc., 38:2221.

The constitution of liquids with especial reference to surface tension phenomena. Metallurgical and Chemical Engineering, 15:468.

The condensation pump: An improved form of high vacuum pump. Gen. Elec. Rev., 19:1060; also in J. Franklin Inst., 182:719.

1917

The condensation and evaporation of gas molecules. Proc. Nat. Acad. Sci., 3:141.

The shapes of group molecules forming the surfaces of liquids. Proc. Nat. Acad. Sci., 3:251.

The constitution and fundamental properties of solids and liquids. II. Liquids. J. Am. Chem. Soc., 39:1848.

1918

The adsorption of gases on plane surfaces of glass, mica, and platinum. J. Am. Chem. Soc., 40:1361.

The evaporation of small spheres. Phys. Rev., 12:368.

1919

Chemical reactions at low pressures. IV. The clean-up of nitrogen by a heated molybdenum filament. J. Am. Chem. Soc., 41:167.

The arrangement of electrons in atoms and molecules. J. Franklin Inst., 187:359; also in Gen. Elec. Rev., 22:505; J. Am. Chem. Soc., 41:868.

The properties of the electron as derived from the chemical properties of the elements. Phys. Rev., 13:300.

Isomorphism, isosterism, and covalence. J. Am. Chem. Soc., 41: 1543.

The structure of atoms and the octet theory of valence. Proc. Nat. Acad. Sci., 5:252.

1920

The mechanism of the surface phenomena of flotation. Trans. Faraday Soc., 15:62; also in Gen. Elec. Rev., 24:1025 (1921).

The octet theory of valence and its applications with special reference to organic nitrogen compounds. J. Am. Chem. Soc., 42:274.

The structure of atoms and its bearing on chemical valence. Journal of Industrial and Engineering Chemistry, 12:386.

The charge on the electron and the value of Planck's constant *h*. J. Franklin Inst., 189:603.

Theories of atomic structure. Nature, 105:261.

The structure of the helium atom. Science, 51:605; also in Phys. Rev., 17:339 (1921).

The structures of the hydrogen molecule and the hydrogen ion. Science, 52:433.

Fundamental phenomena in electron tubes having tungsten cathodes. Gen. Elec. Rev., 23:503.

Radiation as a factor in chemical action. J. Am. Chem. Soc., 42:2190.

1921

With Guy Bartlett. The crystal structure of the ammonium halides above and below the transition temperatures. J. Am. Chem. Soc., 43:84.

The structure of the static atom. Science, 53:290.

The structure of the static atom. Phys. Rev., 18:104. (A)

Future developments of theoretical chemistry. Chemical and Metallurgical Engineering, 24:533.

Types of valence. Science, 54:59.

Chemical reactions on surfaces. Trans. Faraday Soc., 17:607; also in Gen. Elec. Rev., 25:445 (1922).

1922

The mechanism of the catalytic action of platinum in the reactions $2CO + O_2 = 2CO_2$ and $2H_2 + O_2 = 2H_2O$. Trans. Faraday Soc., 17:621.

With H. Mott-Smith. Radial flow in rotating liquids. Phys. Rev., 20:95. (A)

The electron emission from thoriated tungsten filaments. Phys. Rev., 20:107. (A)

With K. H. Kingdon. The removal of thorium from the surface of a thoriated tungsten filament by bombardment with positive ions. Phys. Rev., 20:108.

With S. Dushman. The diffusion coefficient in solids and its temperature coefficient. Phys. Rev., 20:113.

Use of high-power vacuum tubes. Electrical World, 80:881.

1923

With E. H. Kingdon. Thermionic effects caused by alkali vapors in vacuum tubes. Science, 57:58.

The effect of space charge and initial velocities on the potential distribution and thermionic current between parallel plane electrodes. Phys. Rev., 21:419.

Positive ion currents from the positive column of mercury arcs. Science, 58:290.

With K. H. Kingdon. Removal of thorium by positive bombardment. Phys. Rev., 22:148.

With K. B. Blodgett. Currents limited by space charge between coaxial cylinders. Phys. Rev., 22:347.

The electron emission from thoriated tungsten filaments. Phys. Rev., 22:357.

A new photo-electric effect reflection of electrons induced by light. Science, 58:398.

The pressure effect and other phenomena in gaseous discharges. J. Franklin Inst., 196:751.

The mechanism of the positive column of the mercury arc. Phys. Rev., 23:109. (A)

With K. H. Kingdon. Electron emission from caesium-covered filaments. Phys. Rev., 23:112. (A)

Reflection of electrons caused by light. Phys. Rev., 23:112. (A)

Positive ion currents in the positive column of the mercury arc. Gen. Elec. Rev., 26:731.

1924

A simple method for quantitative studies of ionization phenomena in gases. Science, 59:380.

With K. B. Blodgett. Currents limited by space charge between concentric spheres. Phys. Rev., 23:49.

With H. Mott-Smith. Studies of electric discharges in gases at low pressures. Gen. Elec. Rev., 27:449.

A new type of electric discharge: The streamer discharge. Science, 60:392.

1925

With K. H. Kingdon. Thermionic effects caused by vapours of alkali metals. Proc. Roy. Soc. (London), 107A:61.

Scattering of electrons in ionized gases. Phys. Rev., 26:585.

The distribution and orientation of molecules. Colloid Symposium Monograph, 3:48.

Flames of atomic hydrogen. Science, 62:463; also in Gen. Elec. Rev., 29:153 (1926); Ind. Eng. Chem., 19:667 (1927).

1926

With R. A. Weinman. Atomic hydrogen arc welding. Gen. Elec. Rev., 29:160.

The effects of molecular dissymmetry on properties of matter. Colloid Chemistry, 1:525.

With L. Tonks and H. Mott-Smith. The flow of ions through a small orifice in a charged plate. Phys. Rev., 28:104.

With H. Mott-Smith. The theory of collectors in gaseous discharges. Rev., 29:160.

1927

With L. Tonks. On the surface heat of charging. Phys. Rev., 29:524.

With H. A. Jones. The characteristics of tungsten filaments as functions of temperature. Gen. Elec. Rev., 30:408.

With G. M. J. Mackay and H. A. Jones. The rates of evaporation and the vapor pressures of tungsten, molybdenum, platinum, nickel, iron, copper, and silver. Phys. Rev., 30:201.

With D. B. Langmuir. The effect of monomolecular films on the evaporation of ether solutions. Journal of Physical Chemistry, 31:1719.

Über elektrische Entladungen in Gasen bei niedrigen Drucken. Zeitschrift für Physik, 46:271.

1928

Electric discharges in gases at low pressures. In: *Congresso Internazionale dei Fisici,* Vol. I, p. 129. Como, Pavia, and Rome, September 1927. Bologna, Nicola Zanichelli. English translation.

Atomic hydrogen as an aid to industrial research. Science, 67:201; also in Ind. Eng. Chem., 20:332.

Die Entstehungsgeschichte der gasgefüllten Glühlampe. Naturwissenschaften, 16:1019.

With H. A. Jones. Collisions between electrons and gas molecules. Phys. Rev., 31:357.

Oscillations in ionized gases. Proc. Nat. Acad. Sci., 14:627.

1929

With L. Tonks. Oscillations in ionized gases. Phys. Rev., 33:195.

With A. W. Hull. Control of an arc discharge by means of a grid. Proc. Nat. Acad. Sci., 15:218.

The interaction of electron and positive ion space charges in cathode sheaths. Phys. Rev., 33:954.

With K. H. Kingdon. Contact potential measurements with adsorbed films. Phys. Rev., 34:129.

With L. Tonks. General theory of the plasma of an arc. Phys. Rev., 34:876.

Forces near the surfaces of molecules. Chem. Rev., 6:451.

1930

With S. MacLane and K. B. Blodgett. Effect of end losses on the characteristics of filaments of tungsten and other materials. Phys. Rev., 35:478.

Electrochemical interactions of tungsten, thorium, caesium, and oxygen. Ind. Eng. Chem., 22:390.

With K. T. Compton. Electrical discharges in gases. I. Survey of fundamental processes. Rev. Mod. Phys., 2:123

With C. G. Found. Metastable atoms and electrons produced by resonance radiation in neon. Phys. Rev., 36:604.

1931

With D. S. Villars. Oxygen films on tungsten. I. A study of stability by means of electron emission in presence of cesium vapor. J. Am. Chem. Soc., 53:486.

The alleged production of adsorbed films on tungsten by active nitrogen. Phys. Rev., 37:1006.

Experiments with oil on water. Journal of Chemical Education, 8:850.

With K. T. Compton. Electrical discharges in gases. II. Fundamental phenomena in electrical discharges. Rev. Mod. Phys., 3:191.

Diffusion of electrons back to an emitting electrode in a gas. Phys. Rev., 38:1656.

With K. J. Sixtus. Regions of reversed magnetization in strained wires. Phys. Rev., 38:2072.

With W. F. Westendorp. A study of light signals in aviation and

navigation. Physics, 1:273; also in Aeronautical Engineering, 4:151 (1932).

1932

With C. G. Found. Study of a neon discharge by use of collectors. Phys. Rev., 39:237.

Cesium films on tungsten. J. Am. Chem. Soc., 54:1252.

With K. B. Blodgett. Accommodation coefficient of hydrogen: A sensitive detector of surface films. Phys. Rev., 40:78.

With J. B. Taylor. The mobility of caesium atoms adsorbed on Tungsten. Phys. Rev., 40:463.

Vapor pressures, evaporation, condensation, and adsorption. J. Am. Chem. Soc., 54:2798.

Décharges électriques dans les gaz aux basses pressions. Congrès International d'Electricité, Paris, 1re Section, Rapport No. 7.

Electric discharges in gases at low pressures. J. Franklin Inst., 214:275.

With K. B. Blodgett. A film which adsorbs atomic H and does not adsorb H_2. J. Am. Chem. Soc., 54:3781.

1933

An extension of the phase rule for adsorption under equilibrium and non-equilibrium conditions. J. Chem. Phys., 1:3.

The nature of adsorbed films of caesium on tungsten. I. The space charge sheath and the image force. Phys. Rev., 43:224.

With J. B. Taylor. The evaporation of atoms, ions, and electrons from caesium films on tungsten. Phys. Rev., 44:423.

Surface Chemistry. Nobel Lecture presented in Stockholm on December 14, 1932. Kungl. Boktryckeriet. Stockholm, P. A. Norstedt & Söner.

Surface chemistry. Chem. Rev., 13:147; also in Gen. Elec. Rev., 38:402 (1935).

Oil lenses on water and the nature of monomolecular expanded films. J. Chem. Phys., 1:756.

1934

Thoriated tungsten filaments. J. Franklin Inst., 217:543.

Mechanical properties of monomolecular films. J. Franklin Inst., 218:143. (Franklin Medal Speech on May 16, 1934)

With K. B. Blodgett. The design of tungsten springs to hold tungsten filaments taut. Review of Scientific Instruments, 5:321.

Fundamental industrial research. The Denki-Gakkwai, Iwadare Foundation, Lecture I, Japan.

Surface chemistry. The Denki-Gakkwai, Iwadare Foundation, Lecture II, Japan.

Electric discharges in vacuum and in gases at low pressures. The Denki-Gakkwai, Iwadare Foundation, Lecture III, Japan.

1935

Fundamental industrial research. Gen. Elec. Rev., 38:324.

Electric discharges in vacuum and in gases at low pressures. Gen. Elec. Rev., 38:452.

Mechanical properties of matter. Mechanical Engineering, 57:486.

With J. B. Taylor. Radiation and adsorption of energy by tungsten filaments at low temperatures. Journal of the Optical Society of America, 25:321.

With K. B. Blodgett. Über einige neue Methoden zur Untersuchung von monomolekularen Filmen. Kolloid Zeitschrift, 73:257.

1936

With V. J. Schaefer. Composition of fatty acid films on water containing calcium or barium salts. J. Am. Chem. Soc., 58:284.

With J. B. Taylor. The heat conductivity of tungsten and the cooling effects of leads upon filaments at low temperatures. Phys. Rev., 50:68.

With A. Forbes. Airplane tracks in the surface of stratus clouds. Journal of the Aeronautical Sciences, 3:385.

Two-dimensional gases, liquids and solids. Science, 84:379.

1937

With V. J. Schaefer and D. M. Wrinch. Built-up films of proteins and their properties. Science, 85:76.

With J. B. Taylor. Vapor pressure of caesium by the positive ion method. Phys. Rev., 51:753.

With K. B. Blodgett. Built-up films of barium stearate and their optical properties. Phys. Rev., 51:964.

With V. J. Schaefer. Optical measurement of the thickness of a film absorbed from a solution. J. Am. Chem. Soc., 59:1406.

With V. J. Schaefer and H. Sobotka. Multilayers of sterols and the adsorption of digitonin by deposited monolayers. J. Am. Chem. Soc., 59:1751.

With V. J. Schaefer. Improved methods of conditioning surfaces for adsorption. J. Am. Chem. Soc., 59:1762.

With V. J. Schaefer. Monolayers and multilayers of chlorophyll. J. Am. Chem. Soc., 59:2075.

With V. J. Schaefer. The effect of dissolved salts on insoluble monolayers. J. Am. Chem. Soc., 59:2400.

Air traffic regulations as applied to private aviation. Sportsman Pilot, 18:8.

1938

Surface motion of water induced by wind. Science, 87:119.

Surface electrification due to the recession of aqueous solutions from hydrophobic surfaces. J. Am. Chem. Soc., 60:1190.

With D. F. Waugh. The adsorption of proteins at oil-water interfaces and artificial protein-lipoid membranes. Journal of General Physiology, 21:745.

With V. J. Schaefer. Activities of urease and pepsin monolayers. J. Am. Chem. Soc., 60:1351.

The speed of the deer fly. Science, 87:233.

Overturning and anchoring of monolayers. Science, 87:493.

With F. J. Norton. Effect of x-rays on surface potentials of multilayers. J. Am. Chem. Soc., 60:1513.

With D. M. Wrinch. The structure of the insulin molecule. J. Am. Chem. Soc., 60:2247.

With V. J. Schaefer. Salted-out protein films. J. Am. Chem. Soc., 60:2803.

With D. M. Wrinch. Vector maps and crystal analysis. Nature, 142:581.

Repulsive forces between charged surfaces in water and the cause of the Jones-Ray effect. Science, 88:430.

The role of attractive and repulsive forces in the formation of tactoids, thixotropic gels, protein crystals, and coacervates. J. Chem. Phys., 6:873.

Protein monolayers. Cold Spring Harbor Symposia on Quantitative Biology, 6:171.

The properties and structure of protein films. Proceedings of the Royal Institution, 30:483.

1939

With D. M. Wrinch. Nature of the cyclol bond. Nature, 143:49.

Molecular layers. Pilgrim Trust Lecture. Proc. Roy. Soc. (London), 170A:1.

Simple Experiments in Science. In: *Excursion in Science,* ed. by Neil G. Reynolds and Ellis L. Manning. New York, McGraw-Hill Book Co., Inc.

With V. J. Schaefer. Properties and structure of protein monolayers. Chem. Rev., 24:181.

The structure of proteins. Proc. Phys. Soc. (London), 51:592.

With D. M. Wrinch. A note on the structure of insulin. Proc. Phys. Soc. (London), 51:613.

Structure of proteins. Nature, 143:280. (L)

1940

Monolayers on solids. Seventeenth Faraday Lecture. J. Chem. Soc., London, p. 511.

With D. F. Waugh. Pressure-soluble and pressure-displaceable components of monolayers of native and denatured proteins. J. Am. Chem. Soc., 62:2771.

1943

With V. J. Schaefer. Rates of evaporation of water through compressed monolayers on water. J. Franklin Inst., 235:119.

1948

Weather under control. Fortune, 37:106.

The production of rain by a chain reaction in cumulus clouds at temperatures above freezing. Journal of Meteorology, 5:175.

The growth of particles in smokes and clouds and the production of snow from supercooled clouds. Proceedings of the American Philosophical Society, 92:167.

Summary of results thus far obtained in artificial nucleation of clouds. Research Laboratory Report No. RL-140. In: *The Collected Works of Irving Langmuir,* Vol. 11, pp. 3–18. New York, Pergamon Press, Inc.

Studies of the effects produced by dry ice seeding of stratus clouds. Research Laboratory Report No. RL-140. In: *The Collected*

Works of Irving Langmuir, Vol. 11, pp. 74–100. New York, Pergamon Press, Inc.

1950

Progress in cloud modification by Project Cirrus. Research Laboratory Report No. RL-357. In: *The Collected Works of Irving Langmuir,* Vol. 11, pp. 101–19. New York, Pergamon Press, Inc.

Cause and effect versus probability in shower production. Research Laboratory Report No. RL-366. In: *The Collected Works of Irving Langmuir,* Vol. 11, pp. 120–23. New York, Pergamon Press, Inc.

With C. A. Woodman. A gamma pattern seeding of stratus clouds, Flight 52, and a race track pattern seeding of stratus clouds, Flight 53. Research Laboratory Report No. RL-363. In: *The Collected Works of Irving Langmuir,* Vol. 11, pp. 124–44. New York, Pergamon Press, Inc.

Results of the seeding of cumulus clouds in New Mexico. Research Laboratory Report No. RL-364. In: *The Collected Works of Irving Langmuir,* Vol. 11, pp. 145–62. New York, Pergamon Press, Inc.

Studies of tropical clouds. Research Laboratory Report No. RL-365. In: *The Collected Works of Irving Langmuir,* Vol. 11, pp. 163–77. New York, Pergamon Press, Inc.

Control of precipitation from cumulus clouds by various seeding techniques. Science, 112:35.

A seven-day periodicity in weather in United States during April, 1950. Bulletin of the American Meteorological Society, 31:386.

1951

Cloud seeding by means of dry ice, silver iodide, and sodium chloride. Transactions of the New York Academy of Sciences, 14:40.

1953

Analysis of the effects of periodic seeding of the atmosphere with silver iodide. Final Report of Project Cirrus, Part II. Research Laboratory Report No. RL-785. In: *The Collected Works of Irving Langmuir,* Vol. 11, pp. 181–457. New York, Pergamon Press, Inc.