NATIONAL ACADEMY OF SCIENCES

ROBERT ANDREWS MILLIKAN

1868—1953

A Biographical Memoir by

L. A. DU BRIDGE AND PAUL A. EPSTEIN

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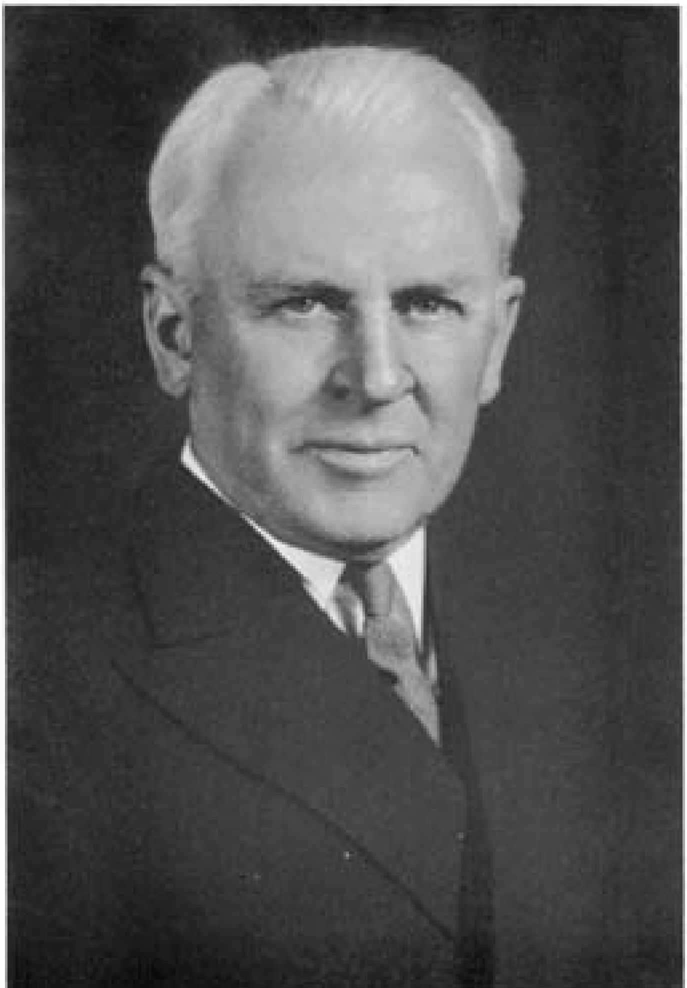

R. A. Millikan

ROBERT ANDREWS MILLIKAN

March 22, 1868–December 19, 1953

BY L. A. DU BRIDGE AND PAUL S. EPSTEIN

ROBERT ANDREWS MILLIKAN was without question one of America's greatest scientists. He was, at the height of his career, not only the nation's most renowned physicist but also a conspicuous educational leader and public citizen. To write his biography in a brief form is certain to do an injustice to one or more aspects of his career. But, fortunately for the authors of this memoir and for the world in general, Robert Millikan wrote his *Autobiography,* published in 1950 by Prentice-Hall, New York. In that important and fascinating book of 300 pages, he himself sets forth the story of his life—his schooling, his experiences as a teacher and research physicist, his building of Caltech, his work in two world wars, and last but not least, a generous introduction to his own philosophy of life and of science.

To the *Autobiography* the interested reader must be referred for a full account of these matters. It will be our intention here to devote primary attention to examining and evaluating his contributions to physics and to describing his leadership in building the modern California Institute of Technology.

BIOGRAPHICAL OUTLINE

Robert Millikan was born on March 22, 1868, in Morrison, Illinois, the son of a preacher, and grandson of one of the early settlers (1834) of the Mississippi River country of western Illinois. At the age of five his family moved to McGregor, Iowa, and two years later to Maquoketa, Iowa, where Robert went through high school and lived the life of an Iowa country boy, not unlike Mark Twain's Tom Sawyer.

He entered Oberlin College in 1886, and took trigonometry, analytic geometry, and Greek—"the subjects which interested me most" [1] —and a twelve-weeks' course in physics—"A complete loss." But, to his astonishment, he was asked to *teach* the physics course during his junior year. He prepared himself by working all the problems in the book that summer—and then making the students work them during the year. He became then, and remained all his life, a vigorous exponent of the problem method of teaching. The lecture method, he insisted, is "a stupid anachronism—a holdover from the pre-printing-press days."

He received his bachelor's degree from Oberlin in 1891 and a master's degree in 1893, and then went to study at Columbia as the sole graduate student in physics there. Michael Pupin—"the only teacher there with analytical training"—had a great influence on Millikan, in spite of the fact that Pupin—to Robert's horror—took no stock in the atomic theory of matter.

Following the receipt of his doctor's degree in 1895 Millikan decided on Pupin's insistence—"and since a satisfactory job did not appear"—to study in Germany. It was a fortunate time to be studying physics in Europe—Roentgen's discovery of X rays, for example, came in November of that year, and Becquerel's discovery of radioactivity only a few months later. Millikan frequently remarked on how fortunate he was to be born in 1868, just in time to study in Germany in the critical year 1895–96. (Others born in that year made less use of their good fortune!)

In 1896 Professor A. A. Michelson, with whom Millikan had studied at the University of Chicago during the summer of 1894,

[1] Quotations here and on the following pages, if not otherwise identified, are from the *Autobiography*.

offered him an assistantship in the Chicago department and Robert hastily terminated his sojourn in Europe to accept.

For the next twelve years at Chicago Millikan worked on a twelve-hour schedule—twelve hours *a day*—six hours teaching and writing textbooks and six hours in research. His major interest, born of necessity, was in teaching; and the text books which he and his colleagues then wrote were the foundation of most high school and college teaching of physics in the United States for the next quarter century. A descendant of one of them—by Millikan, Roller, and Watson—is in use to this day. Under Millikan's influence the physics teaching in this country "grew up"—and the spectacular development of American physics in the second quarter of the twentieth century was a direct consequence, though it was also assisted by Millikan in many other ways to be discussed later.

In 1902 Robert married Greta Blanchard and they spent their honeymoon in Europe. It was his third visit, since he had been sent by the University to the World's Fair in Paris in 1900 to set up an exhibit of some of Michelson's instruments. During all his early and later visits to Europe, Millikan made excellent use of his time and made friends of most of the leading physicists of that day. In fact, few American scientists have ever had such a host of personal and professional friends in all parts of the world. He remembered everyone he met, and corresponded extensively with many. His warm personality and wide range of interests made his friendship something to be highly valued by anyone.

After ten years at Chicago, Millikan decided to "get busy on some more serious research." He was still only an assistant professor at a salary of less than $2,000, not counting a growing income from his books. He was not then satisfied with his achievements as a physicist, but his first "serious" experiment was a spectacular success indeed. He called it "My Oil Drop Venture (e)." In the next few years he developed the famous technique of the falling charged oil drop and used it to prove the atomicity of electric charge and also to measure accurately the value of the universal unit of charge, the electron.

No sooner had he finished most of this long series of experiments than he began another—technically more difficult and equally significant—which established the atomic or quantum nature of light by verifying Einstein's 1905 quantum theory of the photoelectric effect. For these two magnificent experiments—to which we shall return later—Millikan was awarded the Nobel Prize in Physics in 1923.

These and other research activities, plus his normal duties as a faculty member at Chicago, his growing participation in the affairs of the American Physical Society (he became president in 1916), and other extracurricular activities kept him busy until the United States entered the First World War.

In April, 1916, the National Academy of Sciences took steps to organize the National Research Council to assist the Government in mobilizing the nation's scientific resources for preparedness. Millikan was a member of the organizing committee, along with Edwin G. Conklin, Simon Flexner, Arthur A. Noyes, and George E. Hale (chairman). Later Hale, as permanent chairman of the Council, asked Millikan to serve as Executive Officer and Director of Research. He moved to Washington in February, 1917, and spent the remainder of the war there directing the mobilization of civilian scientists and their collaboration with the military agencies. Millikan's account of those years in his *Autobiography* constitutes a historic document.

The mobilization of civilian scientists—as scientists—for war was a new thing in 1917, and the difficulties were great. However, the new ideas developed in the New London laboratories on submarine detection were so important and affected such a critically serious problem that military respect for the scientist was greatly enhanced. The advances in chemical warfare were even more significant. Had there been a mechanism for continuing the scientific work on antisubmarine warfare effectively after 1918, the submarine menace in

1942 might not again, as in 1917, have been the instrument of bringing near disaster to the Allies.

An interesting sidelight on Millikan's experience in the First World War was the fact that he—the leading civilian scientist—was urged, and consented, to accept a commission in the Army Signal Corps—as a major!

After the armistice Millikan remained in Washington most of his time until October, 1919, assisting in the permanent establishment of the National Research Council and the planning of the new building to house the Council and the Academy following the gift in June, 1918, by the Carnegie Corporation of $5,000,000 for the purpose. Millikan personally raised a substantial share of a fund of $160,000 required for the purchase of the site for the building, this being a condition of the Carnegie gift.

In 1918, George E. Vincent, president of The Rockefeller Foundation, requested advice on the strengthening of American science. Millikan proposed the establishment of what were to become the National Research Council Fellowships. Millikan said later that this program was "the most effective agency in the scientific development of American life and civilization that has appeared . . . . in my lifetime." There are few who know the story of the rise of American science from almost nothing to full maturity in the twenty years following 1918 who could disagree. Millikan's objective was the *decentralization* of science and was contrary to a strongly supported proposal for a central national institute of science. He felt strongly that many universities throughout the country must become centers of research and that the National Research Council Fellows would be the "seed corn" of such a development. By 1940 a large share of the leading physicists and chemists of the country were former NRC Fellows and they were to be found in dozens of flourishing research centers from coast to coast. Millikan's foresight was fully justified.

In October, 1919, Millikan returned to Chicago fully expecting to carry on there with the many research programs he had undertaken and which he resumed after the wartime interruption. But the persuasiveness of two old friends with whom he had been in intimate association during the war—George E. Hale and A. A. Noyes—plus, as he frankly admitted, a handsome offer as to salary and research funds—brought him to the new and almost unknown Throop College of Technology in Pasadena, California. He insisted that the name be changed to the California Institute of Technology, and he arrived to take up his duties in late 1921.

He also frankly stated that his main objective in going to Pasadena was "to build an outstanding department of physics." As far as Hale and the other trustees were concerned, however, Millikan was "president"—even though he insisted that the administration be assigned to an "executive council" of which he was chairman.

At any rate, the next twenty years of his life—until the onset of the Second World War—were years of almost unbelievably intense activity. In 1921 Millikan was already fifty-three years old. At sixty-three he was at the peak of his efforts, and he did not retire until 1945, aged seventy-seven. During those years he pursued an energetic research program which made the Norman Bridge Laboratory one of the most famous physics centers in the world, and at the same time he built the California Institute from almost nothing to a position of financial stability and world preeminence. When he retired, his efforts had built an institution whose worth was $40,000,000 and his influence was still being exhibited through bequests and gifts that were still coming in in 1956.

But enormous though these achievements were, Millikan's efforts were by no means confined to Pasadena. He never lost interest in the National Academy of Sciences and the National Research Council, and he maintained active responsibilities until 1940. He was a public citizen in a wide variety of ways, ranging all the way from active participation in two "social-literary" clubs (the Twilight and the Sunset Clubs) of Southern California to the Committee on Intellectual Cooperation of the League of Nations. He traveled all over the earth, both on lecture tours and on cosmic-ray expeditions. He was elected to most of the scientific academies of the world and accumulated more honors and awards than any American scientist of his time.

During the Second World War Caltech was immersed in an enormous war research program—expending over 80 million dollars. Though he left the active direction to others, Millikan's administrative tasks were obviously very heavy, and he followed all the projects with meticulous interest.

After his retirement in 1945 he came daily to his office in the Norman Bridge Laboratory in Pasadena, read omnivorously, kept in close touch with research in many fields, and as late as 1947 led a cosmic-ray expedition, releasing high altitude balloons at a series of remote locations from Texas to Canada.

In early 1953, at the age of eighty-five, he began to fail physically, and he passed away on December 19, 1953, only a few weeks after the death of his wife Greta.

American science and education had changed markedly in the first half of the twentieth century, and Robert Millikan took a leading part in bringing the change to pass.

MILLIKAN AS AN EDUCATOR

The supposed impossibility of being both a good research man and a good teacher was given a magnificent denial in the life of Robert Millikan. The first years of his career at Chicago were given over largely to teaching, and throughout his life his students were always close to his heart. He never forgot that the main purpose of a university was to educate young men and women. True, he also loved research for its own sake and for the new knowledge it revealed. But he loved it especially as an instrument of instruction. A major educational asset at Caltech, he insisted, was to be the atmosphere of research which was being built. He loved to take time out, day or night, for long, often rambling, but always enthralling discussions with his students. He was famous as a lecturer and often attracted thousands to the popular lectures on cosmic rays or atomic physics which he gave all over the country.

Every director of research who presides for a number of years over a large laboratory has the right to expect among his personal pupils one or two men of exceptional merit. But in Millikan's case, we find as his close associates, growing to manhood and fame in intimate collaboration with him, far more eminent physicists than can be accounted for by the law of averages. On the strength of this record, Robert Andrews Millikan must be classed as one of the most successful teachers in the history of science.

Physics had a great unity which was always dear to him. His experiments were related to everyone else's. He enjoyed every physics journal he read, for he saw in every paper a relation to work going on in his laboratory. And he conveyed this enthusiasm, these hidden relationships, to his students and colleagues.

His great contribution to American education was the building of the California Institute of Technology. There are many universities which have struggled for a hundred years to attain the excellence and prestige—and the funds—which Caltech achieved in less than twenty years. It is true that in the thirty years before 1921 Throop College had gone through its birth pangs, its growing pains, its days of penury. During that time it had acquired the respect of the community, a few able and devoted faculty members (including A. A. Noyes, chemist, and Royal Sorensen, electrical engineer) and a Board of Trustees containing some public-spirited citizens of outstanding ability—among them George Ellery Hale, the astronomer, and Henry M. Robinson, a wealthy Los Angeles business man. Southern California was an area of great promise—the time was ripe for a new educational experiment. Millikan was the man to guide it.

He had grown impatient with complex and cumbersome academic administration; he wanted to abolish departments and other artificial barriers to cooperation. He did.

He was imbued with the conviction that a great upsurge of science and technology in America was long overdue—and that some institutions should devote themselves single-mindedly to the task of educating the men who would lead that revolution. He dedicated himself to the task of creating such a place.

He was convinced that real research centers were not being built in American universities because research was still regarded as a junior partner to teaching—an activity to be carried on in a basement room on evenings and Sundays and without expense to the university. He was determined to found an institution where teaching and research went hand in hand, where a major assignment of resources to research would be achieved, where research would provide the creative atmosphere for stimulating teaching, and where young students would keep the freshness of the research spirit alive. These and other ideals became embodied in the new Caltech.

But, most of all, Millikan attracted to Caltech great men: R. C. Tolman (physics and chemistry), Paul S. Epstein (physics), Theodore von Karman (aerodynamics), Thomas Hunt Morgan (biology), Harry Bateman (mathematics), John Buwalda (geology), Chester Stock (paleontology), Beno Gutenberg (geophysics), Linus Pauling (chemistry), to mention but a few who were in residence there by 1930. In 1958, twenty-eight members of a total science faculty of 200 were members also of the National Academy of Sciences. Three were Nobel prize winners. In the year 1925 three future Nobel prize winners were students at Caltech, Carl D. Anderson, E. M. McMillan, and Linus Pauling. William Shockley, a fourth, arrived the following year.

The impact of Caltech upon the Southern California community was enormous. Millikan saw the need for electric power and began an important program in high-voltage engineering research—leading to the economical transmission of power from the Hoover Dam on the Colorado River to Los Angeles. He foresaw the growth of the aviation industry—and built a large wind tunnel, and initiated under Theodore von Karman a program of study of the *science* of aerodynamics. He took "earthquake" out of the category of forbidden words in California and established a first-class laboratory of seismology.

As Millikan bluntly stated it: "The California Institute of Technology has kept itself alive and has grown in plant and resources by the very simple technique of continuously seeking and finding ways in which it could serve in the first instance this Southern California community *with such efficiency as to convince its supporters* [italics his], whether they be philanthropic individuals, or business men, or the general public, that it is one of Southern California's greatest assets."

To serve the community through research projects and by providing educated leaders for science and industry—these remained the simple and unchanging goals. The Institute was kept small; no new projects were undertaken without adequate financing; temptations to multiply size and numbers, new schools, new divisions, new departments, were systematically avoided. Six academic divisions only were created by 1928, and six only exist today. In 1920 the freshman class was limited to 160; only in 1948 (after Millikan's retirement) was the limit raised to 180, its present level.

An insistence on a high content of basic science in the engineering curricula and a high content of basic studies in the humanities and social sciences was also a basic tenet of the Institute policy. These were not widely accepted principles in engineering schools in 1921. In 1955 they were laid down as essential qualities for engineering education by a Committee of the American Society for Engineering Education—and accepted and published by the Society. They were thirty-five years old at Caltech.

It is obviously difficult to describe Millikan's contributions as an educator without launching into a panegyric about Caltech. But few institutions in the nation are so completely the shadow of one man and, at the same time, stand out so conspicuously for their achievements. For thirty-five years Dr. Millikan was Mr. Caltech, and Caltech will always be his monument.

MILLIKAN AS A PHYSICIST[2]

The general characteristics of Millikan's approach to experimental research are worth noting. He began with a thorough study of the work of his predecessors, analyzing their methods with a view of discovering the weak points that could be improved upon. This enabled him to start work with an experimental setup eliminating some of the previous sources of error. Since the problems treated by Millikan were among the most difficult, an easy success in a single paper could not be expected. But even the first paper usually represented an advance over the preceding work; moreover, it gave him experience and a better understanding of the functioning of his instruments, thus enabling him to devise further improvements in his apparatus, to undertake with it a second piece of research, and to report the further progress in a second paper. He would always strive for a complete understanding of all the secondary processes taking place in his setup, often trying separate experiments to elucidate some obscure details. In this way, the very sources of error became subjects of research, leading to instructive results, and sometimes to significant discoveries. Thus, by slow degrees Millikan advanced to a complete mastery of every aspect of his problem and brought the investigation to a close, in the sense that he obtained final results which could not be improved upon with the experimental resources of the epoch.

All this required much time and hard work. Every subject of research developed into a whole program, often branching out into new subjects. Fortunately, Millikan did not have to accomplish everything singlehanded, but could delegate part of the work to his pupils. He always possessed, in a high degree, the ability for teamwork which springs from a friendly and sociable temperament. He delighted in paving the way for deserving younger men, who took their first scientific steps under his guidance, and he had much to

[2] This section is adapted from the article by Paul S. Epstein, "Robert Andrews Millikan as Physicist and Teacher," *Reviews of Modern Physics,* 20 (No. 1): 10–25.

offer them as the possessor of the vastest research experience and of the soundest experimental technique.

Determination of the Electronic Charge e. The investigation of the electronic charge was started by Millikan in 1907 jointly with his student L. Begeman, with a view of improving the method of H. A. Wilson, which seemed to the authors to be the most promising. This method consisted in ionizing the air in a fog chamber and condensing on the ions a cloud by means of a sudden expansion. First, the rate of fall of the cloud under gravity alone was observed, then the rate of fall of a similar cloud when a vertical electric field was superposed upon gravity. Stokes' law of resistance made it possible to obtain the mass of the droplets constituting the cloud from the velocity of their descent under gravity. The additional knowledge of the velocity in the electric field gave information about the ratio of the electric to the gravitational forces and, ultimately, about the ionic charge.

Millikan saw in the Wilson experiments certain sources of error which he set out to correct, and he at once obtained more consistent results. His first value for the charge e was 4.03×10^{-10}e.s.u., compared to Wilson's value of 3.1×10^{-10}, a considerable improvement. But other sources of error at once appeared, and Millikan set out systematically to track them down. The temperature estimates were incorrect, and this led to the use of an erroneous value for the viscosity of air. The different parts of the cloud of droplets did not all fall with the same speed, for there were different size droplets and different charges. This led him to the very great step of observing individual drops. When he then substituted oil for water to reduce the rate at which the droplets evaporated, he laid the basis for a thoroughly comprehensive and highly precise experiment—one which he worked on patiently and brilliantly for ten years.

In the final form of the experiment a cloud of oil drops is produced by an atomizer, and it turns out that a large number of them carry electric charges. The drops are allowed to fall under gravity through a hole in a plate which constitutes the upper member of an accurately machined pair of plates between which an accurately measured electric field can be applied. A single droplet is selected for observation through a low-power microscope and its rate of fall under gravity is observed. If the viscosity of the air is known, the size and, hence, the weight of the drop is determined. The electric field is now applied in such a direction as to counteract gravity and a new rate of fall or rise is determined. If, for example, the electric field is adjusted to hold the droplet at rest, the upward force must equal the weight, and the charge is at once determined.

Occasionally the charge on a drop changes—and the frequency of change can be increased by irradiation with gamma rays. The change in charge causes a change in speed and the ratio of the old and new charges can be accurately determined. Millikan was thus able to establish beyond doubt that all charges and also the *changes* in charge were whole multiples of a least value, and the atomicity of electricity was confirmed. The attainment of a highly accurate value for this fundamental charge was, however, not so easy.

Already the first investigation with the oil-drop method showed that Stokes' formula was not accurate enough for determining the particle radii. However, the more accurate Stokes-Cunningham formula, which takes into account the dependence of the rate of fall on the mean free path, led to very consistent results and gave for the electron charge the slightly too high value of $e=4.891\times10^{-10}$e.s.u. The two final papers of the series were published in 1913 and 1917. They represent two complete and independent determinations of the electronic charge; although the method of the second investigation was the same, it was carried out with a new apparatus, and all the auxiliary constants were re-evaluated. The results were identical, namely, $(4.774\times0.009)\times10^{-10}$, in the first, and $(4.774\times0.004)\times10^{-10}$, in the second—a figure which essentially remained the standard value for over twenty years, though the new more accurate data for the velocity of light and the value of the absolute ohm brought it down to 4.770×10^{-10}.

These papers definitely settled the question of the uniqueness of the electronic charge which was until then open. Even today they are definitive for the oil-drop method in the close consistency and small spread of the individual determinations. Although the investigation has been repeated by several other authors, the accuracy of Millikan's relative results has never been equaled. With respect to the absolute result, a small uncertainty lay in Harrington's value of the coefficient of viscosity of air accepted by him. In the nineteen thirties the evidence of indirect determination of the electronic charge began to accumulate and to point to the conclusion that Harrington's value was slightly too low. Hence, redeterminations were undertaken in the Norman Bridge Laboratory and elsewhere (see below) which led to results clustering about $\eta_{23}=1830.0\times 10^{7}$. With this correction Millikan's determinations of 1913 and 1917 would give $e=4.799\times 10^{-10}$e.s.u., a value of the electronic charge which must be considered the most accurate directly obtainable by the oil-drop method. Millikan estimated its accuracy as ⅓ of 1 percent, owing, primarily, to the uncertainties in the determination of the viscosity of air.

Viscosity of Air and Stokes' Law. Millikan's interest in the viscosity of air grew out of the fact that an accurate knowledge of it was needed for the evaluation of his experiments on the electronic charge. The then available data were concerned not so much with the absolute value needed by Millikan as with its relative changes in dependence on temperature and pressure. Hence, he caused several determinations to be carried out under his supervision in his Chicago laboratory. The Poiseuille method of flow through capillary tubes was used by I. M. Rapp and E. Markwell, and the method of rotating cylinders by L. Gilchrist and E. L. Harrington. It was found that the second method was capable of a higher accuracy. Especially, as perfected by Millikan and Harrington in 1916, the rotating cylinder apparatus was superior to any that had been used before that time. (Their result was given above.)

In 1930 Millikan returned to the work with rotating cylinders for the purpose of determining the viscosity of organic vapors. Jointly with R. K. Day, he developed in the Norman Bridge Laboratory a modified apparatus which differed from Harrington's in that it could be used at high temperatures. This apparatus was used by Day to measure the viscosities of several substances in their dependence on pressure. R. K. Day worked with normal and isopentane and W. M. Bleakney with 2-pentene, trimethylethylene, and carbon tetrachloride. In all these cases the pressure coefficient was negative.

The circumstances which led to the reawakening of the interest in the absolute viscosity of air were mentioned above. After the importance of its redetermination was pointed out by K. Shiba in 1932, the work was undertaken independently by several investigators. As far as the rotating-cylinder method was concerned, the improvements were not primarily due to instrumental changes, because Houston worked with the identical apparatus built by Millikan and Day, while Kellström and Bearden used instruments of a very similar construction. The advances lay rather in a more thorough discussion of the sources of error and in more elaborate corrections for them. The results for η_{23} were as follows: Kellström $(1834.9 \pm 2.7) \times 10^{-7}$, Houston $(1829.2 \pm 4.5) \times 10^{-7}$, Rigden $(1830.34 \pm 0.6g) \times 10^{-7}$, Bearden $(1834.02 \pm 0.06) \times 10^{-7}$, and Banerjea and Plattanaik $(1833.3 \pm 2.2) \times 10^{-7}$, which are all above Harrington's, and led to the revised value of e as stated above.

We have already mentioned that the ordinary form of Stokes' law proved to be insufficiently accurate for the purposes of the oil-drop method. This law connects the force X acting on a spherical particle with its velocity v of motion, its radius a, and the viscosity of the gas in which it falls as follows: $X = 6\pi\eta av$. Millikan found that he had to use a more accurate formula, taking into consideration the mean free path l of the gas, namely, $X = 6\pi\eta av\ (1 + Al/a)^{-1}$, where A is a numerical coefficient. This expression is usually called the Stokes-Cunningham law, although its derivation by Cunningham was spurious. On the other hand, Millikan correctly interpreted it from the very start as the result of "slipping" or "sliding friction" at the surface of the moving particle.

A technique was developed by Millikan for changing the pressure of the gas (and consequently the mean free path l) while keeping a particle in the field of observation. Thus, the oil-drop method offered a convenient means of testing the Stokes-Cunningham formula and of measuring the coefficient A. The most extensive series of measurements referred to oil droplets in air and covered the enormous range from $1/a=0.05$ to $1/a=134$. It was found that the Stokes-Cunningham law holds accurately up to $1/a=0.5$, giving an experimental value of the constant $A=0.842$.

Photoelectric Effect and Planck's Constant. The phenomena of photoelectricity were partially elucidated by the work of P. Lenard, who showed that short-wave light falling on metal makes it emit electrons. The loss of negative charge causes the metal to assume a positive potential which increases to the point where it is sufficient to make the electrons return and thus prevent the escape of even the fastest of them. There was thus a limiting upper velocity of escape and this depended on the frequency of the light. This phenomenon completely defied any explanation on classical lines and remained mysterious until Einstein introduced in 1905 the assumption of the photon constitution of light. The conception of the photon easily explained the effect and immediately led to Einstein's famous photoelectric equation, $V=(h/e)\nu+V_0$, connecting the limiting potential V with the frequency ν of the incident light and with the fundamental constants h and e; the potential V_0 is the contact-electromotive force of the same metal when it is not illuminated.

It is true that most physicists of the time were not willing to accept this explanation, since they regarded the existence of photons as even more of a mystery than the photoelectric effect itself. But just because of the highly controversial character of Einstein's law, its experimental test was attempted by a number of independent investigators. The problem proved, however, to be technically extremely difficult. In 1913 Pohl and Pringsheim published a careful critical review of the numerous investigations and found them all inconclusive, and a similar opinion was expressed in the following year by J. J. Thomson. The prevailing degree of uncertainty may be inferred from the fact that such a sound experimenter as C. Ramsauer came in 1914 to the conclusion that the photoelectrons have no limiting velocity at all, but are liberated with a Gaussian velocity distribution.

Millikan's ultimate success was due not only to great experimental skill but in equal measure to long experience acquired by persistent work in this sphere of phenomena. His first publications of photoelectricity were made jointly with G. Winchester and appeared as early as 1907. The purpose was to investigate whether the photoelectric current and the limiting potential depend on the temperature of the emitting metal. Such a dependence was not found—as we know today—because of the degenerate state of metal electrons. Other photoelectric work belonged to the years 1909 and 1912. All these investigations taught Millikan the importance of using very clean metal surfaces and the danger of using sparks as the source of short-wave light, since the spark discharges are liable to falsify the measured potentials by inducing in the apparatus electric oscillations. Indeed, this source of error temporarily led him astray until he corrected for it in 1913.

It does not seem that in the early period of his photoelectric work Millikan was familiar with Einstein's equation. However, when he became aware of it and directed his efforts towards testing it, his progress was rapid. The test of Einstein's equation involves the following measurements:

1. It is necessary to determine the photo-potential V. For this purpose a retarding potential is applied which stops only part of the electrons, and the current carried by the escaping electrons is measured. As the retarding potential is gradually increased, the current becomes smaller. Plotting the current against the potential, it is possible to determine by graphic extrapolation the point at which the current vanishes altogether, corresponding to the photo-potential V. The whole curve is determined point by point while the metal is illuminated with light of the constant frequency ν.

2. After the photo-potential V has been measured for a number of different frequencies, ν, it is possible to plot V against ν. According to Einstein's relation the dependence must be rectilinear: the slope of the straight line must be (h/e) and its intercept must be V_0, corresponding to the condition $V=(h/e)\nu_0+V_0=0$, whence $V_0=-(h/e)\nu_0$. As we have mentioned above, Einstein's theory implies that V_0 is the contact-electromotive force (c.e.f.) of the non-illuminated metal. The second measurement which is necessary to test the formula is therefore the determination of the c.e.f. of the same metal surface. This determination was accomplished electrometrically. To carry out these operations on several metallic surfaces required a very elaborate piece of apparatus, in Millikan's own words: "As new operations have been called for, the tubes have by degrees become more and more complicated until it has become not inappropriate to describe the . . . experimental arrangement as a machine shop in vacuo."

The reason for Millikan's success where his predecessors failed lay in carefully choosing the conditions so as to minimize all the sources of error, of which the main were as follows: 1. The range of frequencies over which Einstein's formula had been tested in the previous work was too narrow. To extend the range Millikan used alkali metals which are photosensitive up to about $\lambda=6000$A. 2. The reference bodies with respect to which the photo-potential was measured were also photosensitive, complicating the conditions by their own photo-emission due to reflected light. Millikan used as his reference body a Faraday cage of well oxidized copper netting. The photosensitivity of this material extends only to $\lambda=2688$A. 3. For retarding potentials approaching the photo-potential the photo-currents became so weak that their measurement could not be made very accurately. It was found that the photo-current was many times stronger when the emitting surfaces were fresh. Hence the alkali metals were inserted into the tubes in the form of thick cylindric blocks. The "vacuum workshop" contained a rotating knife blade by means of which a thin layer of metal could be shaved off the plane surface of the block. 4. Very troublesome were traces of stray light of higher frequency than ν. Their contribution to the photo-current became important when this current was very small, falsifying the apparent point where electronic current approaches zero. To meet this source of error, the illumination was produced by a high pressure mercury-quartz lamp monochromized with a quartz monochromator, and the effect of stray light was further reduced with the help of proper light filters.

The results of these investigations were published in part in Millikan's own papers, in part in those of his pupils. They amounted to a complete confirmation of Einstein's equation in all its details: 1. The dependence of V on ν is rectilinear, since no experimental point was above or below the straight line by more than 1 percent. 2. The slope of the line is equal to h/e; indeed, the experimental slopes found by Millikan were 1.376×10^{-17} for sodium, and 1.379×10^{-17} for lithium, while the best modern value is considered to be 1.3793×10^{-17}. 3. The intercept V_0 of the photoelectric straight line agreed with the electrostatically measured c.e.f. to better than 0.5 percent. These beautiful results established beyond any shadow of doubt the role which Planck's quantum of action h plays in the photoelectric effect. Besides, they represented at the time the most accurate numerical determination of that fundamental constant.

Extreme Ultraviolet Spectrum. Investigating the potentials of sparks between metallic electrodes, Millikan made, as early as 1905, the observation that the spark discharge of a large condenser could be maintained in the highest vacuum if the potential difference were sufficiently large. It occurred to him that these "hot sparks" provided a means of investigating the ultraviolet light which, in all likelihood, they were emitting. Indeed, the previous endeavors of extending the knowledge of the short ultraviolet spectrum had been limited by its extreme absorbability. But the use of a hot spark and of a concave reflection grating permitted completely eliminating all absorption by placing in a vacuum spectrograph the whole path of the rays, from their origin to the recording photographic plate. The first results obtained with a vacuum spectrograph of this type were described by Millikan and Sawyer in 1918. The only part of this early instrument which needed improvement was the grating; through the comparison of several gratings it was found that the best result was given by gratings ruled by "the easy touch method" in which the reflecting strips were parts of the original speculum metal surface and which threw most of the diffracted radiation into the first-order spectrum. With this modification the spectrograph afforded at once a very considerable extension of the measurable ultraviolet spectrum; the region up to the line $\lambda=209A$ of nickel was explored right away, and up to $\lambda=136.6A$ of aluminum in the next following paper. All the later work on the extreme ultraviolet was done jointly with I. S. Bowen. It consisted in photographing, measuring, and completely analyzing, as to their spectroscopic terms, the spectra of numerous elements. Not only neutral atoms of the light elements emit lines in this region, but also singly or multiply ionized atoms of somewhat heavier elements. Indeed, some of the analyzed spectra were produced by atoms stripped of as many as six (S, Cl) or even seven (Cl) of their electrons.

The joint work of Millikan and Bowen opened for spectroscopy a new and fruitful region whose exploration came exactly at the right time. By supplying valuable material it influenced and helped the development of theoretical spectroscopy which at this very period was rapidly advancing towards establishing the so-called Russel-Pauli-Heisenberg-Hund rules. The number of publications by Millikan and Bowen is so large that we must restrict ourselves to a brief outline of their significance:

1. Extending the ultraviolet measurements down to $\lambda=136.6A$ helped to close the last unexplored gap in the spectrum of electromagnetic frequencies, because very soon F. Holweck succeeded in reaching the same wave-length region from the side of the X rays.

2. More important still, Millikan and Bowen established the essential unity of the optical and the X-ray spectra. In his presidential address of the year 1917 before the American Physical Society, Mil-

likan had already pointed out the close analogy which the X-ray spectra (Mosely's formula) bear to the hydrogen spectrum (Balmer's formula) and stressed the importance of studying the extreme ultraviolet spectra of the light elements. Carrying out this program, Millikan and Bowen showed that the s, p_2, p_1 terms of optical series are, respectively, identical with the L_{I}, L_{II}, L_{III} X-ray levels.

3. The spectroscopic terms of the ultraviolet regions, like those of the visible and the X-ray spectra, were classified in terms of four quantum numbers, of which three belonged to the translational degrees of freedom of an electron, while the fourth was interpreted as residing in the atomic core. Such an interpretation involved, however, great difficulties from the point of view of the atomic model, which were forcibly stated by Bowen and Millikan in 1924 in reviewing the material they had accumulated. Precisely these difficulties caused Uhlenbeck and Goudsmit in 1925 to introduce the concept of the electron spin in order to explain the presence of the fourth quantum number mentioned above.

4. The combination of two ultraviolet spectroscopic terms occasionally gives a line in the visible spectrum. Some of these possible radiations have been identified by Bowen with unexplained lines from stellar sources and from the terrestrial atmosphere. In particular, Bowen succeeded in elucidating a series of lines observed in nebular spectra and heretofore ascribed to the hypothetical element "nebulium." He showed beyond doubt that they are due to nitrogen and oxygen by explaining the reasons why a line, which is "forbidden" and absent in terrestrial sources, may occur with considerable intensity under the conditions prevailing in a nebula. While Millikan has no direct share in these important discoveries, which are entirely due to Bowen, yet they grew out of a line of research initiated by Millikan.

Cold Emission of Metals. The phenomenon of negatively charged cold metallic surfaces giving off an electric current, when the potential gradient at their surface is very large, was first investigated by R. F. Earhart in 1901. Millikan became interested in this problem in his early Chicago days, and it was studied in his laboratory by G. M. Hobbs in 1905. In the following years, however, his time was fully occupied with work on the electronic charge and on the photo-effect, so that he was able to return to the questions of cold emission only in the nineteen twenties. After some preliminary exploration, a thorough study was completed by Millikan and Carl F. Eyring in 1926, working with very thin tungsten wires in an extreme vacuum. They introduced for the phenomenon the term *field current* and arrived at the following conclusions: 1. Although the emission characteristics of a wire depended on its previous heat treatment, a very strong field current brought the wire into a steady state. In this state the field currents were reproducible as long as they were weaker than the field current that had been used for conditioning. 2. These field currents set in at a certain minimum potential gradient which had the order of magnitude of a few hundred thousand volts per cm. 3. The minimum potential gradients as well as the field current were entirely independent of temperature in the interval from 300° to 1000° abs. 4. The field current I seemed to be a function only of the potential gradient F at the point of emission and not to depend on the total potential difference applied to the wire. It had been claimed by other authors that log I plotted against $F^{\frac{1}{2}}$ gave a straight line; this was definitely untrue for the data found by Millikan and Eyring.

The $F^{\frac{1}{2}}$ law follows from the classical theory on the assumption that the field current is in its essence nothing but a thermionic current modified by the presence of a very strong electric field. Thus, the observations (4) of Millikan and Eyring set the cold emission apart from the thermionic emission as an independent phenomenon and their result (3) pointed in the same direction. Further work by Millikan and co-workers established that the field currents I are, indeed, quite independent of the potential difference and (within the stated limits) of the temperature and are a function of the potential gradient F only, being accurately represented by an empirical formula due to Charles C. Lauritsen, $I = I_0 \exp(-b/F)$, where I_0 and b are constant.

Millikan's uncanny ability for choosing the most timely problems asserted itself also with respect to the work on cold emission. Its theoretical explanation given in 1928 independently by J. R. Oppenheimer and by R. H. Fowler and co-workers showed it to be due to the quantum-mechanical phenomenon of electrons leaking through a potential barrier. It was the first example of a previously unknown mechanism which has since received important applications in the theories of atomic and of nuclear structure. As given by Fowler and Nordheim, the theoretical law of field currents is $I = CF^2 \exp(-b/F)$, which is experimentally indistinguishable from Lauritsen's formula.

Cosmic Rays. The first reports about a penetrating radiation in the atmosphere were read before the Washington, D. C., meeting of the American Physical Society (December 31, 1902) by two independent teams of investigators: E. Rutherford and H. L. Cooke, of Montreal, and J. C. McLennan and E. F. Burton, of Toronto. At first it was believed that the origin of the penetrating radioactive rays lay in the top layers of the solid earth. However, in the years 1909 to 1911 the Swiss meteorologist, A. Gockel, took an ionization chamber (with 2-mm. brass walls) on several balloon ascents and found that the intensity of the penetrating radiation did not materially decrease up to heights 2.8 km. This result was confirmed and extended by V. Hess and W. Kolhörster, who made numerous balloon ascents up to heights of 5 km. and 9 km. respectively. With rising elevation the atmospheric ionization first decreased, reaching a minimum at about 700 m. From then on it increased, first slowly, then more rapidly. This pointed to a component of the penetrating radiation coming downward from high altitudes, possibly from outside the terrestrial atmosphere, whence the name "cosmic rays." Though this result was in principle well-established by 1915, the quantitative side of the measurements was by no means accurate. Indeed, estimates of the coefficient of absorption of the downward radiation, made on the basis of Kolhörster's data, lay in the vicinity of $\mu=0.57\times10^{-2}$ cm^{-1} of water, a value which later proved to be greatly in error.

Millikan became actively interested in cosmic rays, following his removal to Pasadena, when he conceived the idea of sending self-recording instruments high up into the atmosphere with the help of sounding balloons. The first recording electroscopes and barometers were constructed by him jointly with I. S. Bowen, and in the spring of 1922 sent up to heights of 15.5 km. The same year he caused his student, R. M. Otis, to make cosmic-ray measurements on Mt. Whitney (4,130 m.), and the following summer he went with Otis to the top of Pike's Peak (4,300 m.) for an elaborate series of measurements. Although this early work did not compare in accuracy with his later standards, yet it proved conclusively that the coefficient of absorption derived from Kolhörster's data was far too high. This discrepancy disappeared when Kolhörster, after measuring cosmic-ray intensities in ice caves of the Jungfrau glacier, scaled down his absorption coefficient to less than one-half, namely, to $\mu=0.25\times10^{-2}$ cm^{-1} of water. Thus it became evident that the cosmic rays are many times more penetrating than any known radioactive rays, a fact which clearly demonstrated the importance of their further investigation. While heretofore cosmic rays had been studied only by meteorologists and specialists in radioactivity, Millikan recognized in them a subject capable of yielding information of wider importance for the whole of physics.

From then on Millikan brought to bear on this problem the whole of his vast experience as an experimental physicist. His next piece of work was carried out jointly with G. H. Cameron, and consisted in sinking electroscopes to various depths of mountain lakes and in measuring the cosmic-ray intensity as a function of depth. Chosen were Muir Lake (3,540 m.), near the top of Mt. Whitney, and Lake Arrowhead (1,530 m.) in Southern California; the greatest depth to which the instruments were lowered was 27 m. The very neat absorption curves which their measurements yielded justify the statement that it marked the beginning of modern accuracy in cosmic-ray work. Two important results were inferred from the analysis of these curves: 1. It was concluded that all the penetrating radiation came from above the upper lake and, within the precision of the analysis, no part of it had its origin in the air between the levels of the two lakes. 2. The radiation was found to have a band structure consisting of harder and softer components whose coefficients of absorption ranged from $\mu=0.30$ to $\mu=0.18$. Later, as the measurements were extended to higher elevations and to greater depths in water, new, softer, and harder components were found, results which were confirmed by other observers. Millikan realized fairly early that the radiation measured in the atmosphere is not necessarily the primary radiation coming from outside but may consist of secondary and tertiary rays. Hence it is not safe to make inferences about the nature of the primary cosmic radiation from the band structure observed in one single geographical location.

The subsequent cosmic-ray work of Millikan and his collaborators was far too comprehensive to be surveyed paper by paper. We shall restrict ourselves to enumerating its most significant features:

1. For many years the electroscopes developed by Millikan and his school were more accurate than those employed by other workers. Marked improvement in accuracy was achieved by the use of high pressure ionization chambers, with 8 atmos. pressure of air in 1928 and 30 atmos. in 1931. (Subsequently the air was replaced by argon.) Two years later H. V. Neher developed his self-recording instrument with a very sensitive, temperature-independent, and vibration-free quartz system which even today satisfies all requirements of precision.

2. Because of the superior accuracy of his measurements, Millikan was able to disprove claims put forward, at different times, by other observers with respect to large daily variations of cosmic-ray intensity in dependence on the positions of the sun and of the stars. His school contended from 1923 on that the diurnal variations are either very small or nonexistent.

3. For the same reason Millikan and co-workers obtained, comparatively early, good curves of cosmic-ray intensities at high elevations in the atmosphere. Airplane flights yielded accurate results from 1933 on; sounding balloons, whose data were at first less reproducible, gradually also became highly reliable. It was found that the intensity rises with altitude to a certain height, then reaches a maximum and declines. Inasmuch as the response of the ionization chamber stands in a simple relation to the energy of the radiation, it is possible to derive from an intensity curve the total energy penetrating from outside into the atmosphere in the form of cosmic rays. Thus Millikan's energy determinations are independent of any hypothesis about the nature or mechanism of the radiation phenomena.

4. After the geomagnetic effect had been discovered by J. Clay and co-workers, Millikan and Neher found that it was more strongly marked at high altitudes. On the one hand, it was possible to calculate the velocity of the primaries eliminated by the geomagnetic effect between two locations of different latitudes. On the other hand, the comparison of the atmospheric cosmic-ray-intensity curves for these two locations yielded the coefficients of absorption of the radiation components weakened or removed in passing from the first location to the second. The results showed that the primitive view of cosmic-ray absorption as entirely caused by ionization was quite untenable. Since the existence of the maximum in the curves, mentioned under (3), pointed in the same direction (as also the existence of some unusually penetrating cosmic-ray corpuscles, ascertained by other observers with Geiger counters), these data formed a strong incentive for the development of modern theories of the stopping of fast particles.

5. In 1929 D. Skobelzyn presented strong evidence that some fog tracks he had observed in a Wilson expansion chamber were caused by cosmic rays. Sensing with his characteristic intuition the opening of a new research province, Millikan realized at once that here was a new and promising approach to the problems of the nature of cosmic rays and of the mechanism of their absorption. He con-

structed in 1931, jointly with Carl D. Anderson, a large vertical expansion chamber in a homogeneous magnetic field of 20,000 gauss. Even the early photographs showed the presence of electrons with kinetic energies of over 10^9 electron volts. It is common knowledge how in Anderson's hands (seconded by S. H. Neddermeyer) this method led to the discovery of the positron and the meson and how it continues to yield insight into atomic phenomena of fundamental importance in nuclear physics.

6. In 1942 Millikan, in collaboration with Professors H. V. Neher and W. H. Pickering, engaged in a refined analysis of the primary cosmic-rays spectrum by means of studying the geomagnetic effect. As a result of extensive investigations it was concluded that the energy spectrum of the primaries possesses a band structure. To explain both the origin of cosmic rays and the existence of the bands, Millikan proposed the theory of annihilation of atoms in the interstellar space. He suggested that atoms get annihilated in a single elementary process, converting their whole intrinsic energy into the kinetic energy of a positive-negative particle pair created in the process. This theory of atom annihilation was later disproved, but its value as a working hypothesis could not be denied.

In any case, the pioneering work of Millikan and his colleagues in the Norman Bridge Laboratory opened up the field and led dozens of other laboratories all over the world to initiate studies in this field. From these studies emerged the modern concept of the primary cosmic rays as consisting largely of very high energy atomic nuclei plunging into our atmosphere from outer space, causing cataclysmic nuclear disruptions as they collide with atoms in the earth's atmosphere. From these events emerge gamma rays, electrons, positrons, neutrons, protons, mesons of various kinds, and the whole range of "strange particles" which were constituting such a puzzle to the theoretical physicists in 1958. And in 1958 Millikan's successors in the Norman Bridge Laboratory were still taking a leading part in slowly unraveling the mysteries.

Millikan's scientific activities covered many more subjects than the ones outlined above. In his biography in *American Men of Science* he listed twenty-one research subjects in which he had worked. He might have listed many more in which he guided and counseled his students and colleagues in the fields of X rays, thermionic emission, physics of solids, nuclear physics and others. In all these fields of physics he displayed that uncanny intuition for picking the most basic and most timely problems. He could hardly have foreseen in 1925 that the study of cosmic rays would yield results of such surpassing importance in the field of nuclear physics. So unpromising indeed did it appear that he and his associates had the field almost to themselves for several years until its great importance had become evident. He himself was the first to admit—even to proclaim—that Lady Luck often smiled on him and his work. But it was Millikan himself who could capitalize on the slightest smile and turn it into a major advance in science.

CONCLUSION

There is no use denying that Millikan had stormy days in his varied activities. His many vigorous debates on the nature and origin of cosmic rays were major events in the world of science in the 1930s. His determination to elevate the prestige of Caltech as rapidly as possible led to his being dubbed one of the great publicity agents in the field of education. He often differed vigorously with his colleagues on matters of politics, philosophy, and religion. His administrative methods were hardly conventional, often confusing, yet his strong personal leadership always pulled things back into shape.

A long associate of his has said, "The secret of his success lay to a large extent in the simple virtues instilled in his upbringing. He had a single minded devotion to all that he was doing, and he put his work above his personal desires and aspirations. His combination of native good sense and intellectual honesty led him far both in science and in public life. In spite of his success and high public position, he always remained a simple man of true humility. He was not always, technically speaking, a 'good administrator,' but even this worked to the advantage of Caltech: he never lost sight of the ultimate aims; he was the rare administrator for whom the interests of science came first.

"But, above all, he was a man with a warm heart, a kind benevolent man always eager to be helpful, even at the cost of trouble and inconvenience."

In short, he combined a rare insight into science with a rare understanding of human beings.

KEY TO ABBREVIATIONS

Ann. Phys. = Annalen der Physik
Ann. Phys. Chem. = Annals of Physical Chemistry
Astrophys. J. = Astrophysical Journal
Deut. Phys. Gesell. Verhandl. = Deutsche Physikalische Gesellschaft Verhandlungen
Ind. Eng. Chem. = Industrial and Engineering Chemistry
Int. Cong. Arts Sci. = International Congress of Arts and Sciences
J. Am. Med. Assoc. = Journal of the American Medical Association
J. Chem. Ind. = Journal of Chemical Industry
J. Franklin Inst. = Journal of the Franklin Institute
Phil. Mag. = Philosophical Magazine
Phys. Rev. = Physical Review
Phys. Zeits. = Physikalische Zeitschrift
Pop. Sci. Mo. = Popular Science Monthly
Proc. Am. Phil. Soc. = Proceedings of the American Philosophical Society
Proc. Inst. Radio Eng. = Proceedings of the Institute of Radio Engineers
Proc. Nat. Acad. Sci. = Proceedings of the National Academy of Sciences
Pub. Astro. Soc. Pacific = Publications of the Astronomical Society of the Pacific
Rev. Modern Phys. = Reviews of Modern Physics
Sci. Mo. = Scientific Monthly
Trans. Am. Electrochem. Soc. = Transactions of the American Electrochemical Society
Trans. Chem. Soc. = Transactions of the Chemical Society (London)

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