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THE ELECTRON: ITS INTELLECTUAL AND SOCIAL SIGNIFICANCE[1]

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WITHIN the past five years, centenaries, bicentenaries and tercentenaries have been much in vogue. Every town or institution or event which has claim to distinction has sought the excuse of the calendar to remind the world of its claims to greatness. Thus we have recently celebrated the centenary of Faraday's discovery of the principles of electromagnetism and the bicentenary of Watt's invention of the steam engine—discoveries which have introduced the eras of electricity and of mechanical power. The city of Chicago has reminded us that the progress of mankind really began with the founding of that community, and has led us to spend millions of dollars to gain the impression that there is really some causal relationship between Chicago and world progress. In my part of the country, the city of Boston and its suburbs staged a succession of tercentenary celebrations, as proud of their past as Chicago is of its present. Greatest of all was last summer's tercentenary celebration of Harvard University, signalizing the firm basis of intellectual freedom and leadership which is the prime requisite for a free people in a democracy.

Encouraged by the success of the Chicago Century of Progress and the Harvard Tercentenary, I venture to feature my address as signalizing an anniversary of the discovery of the electron. To be sure, it is only one generation old, and a generation is a sufficiently vague unit of time for my purposes. Yet, in spite of its youth, it bids fair to rival Chicago in its contributions to economic progress, and Harvard University in its contributions to the understanding of this world in which we live. So I venture to assert that no institu-

[1] Address of the retiring president of the American Association for the Advancement of Science, Atlantic City, evening of December 28, 1936.

tion or community, which has used one of these milestones to take stock of its achievements and plot its future course, has stronger claims to intellectual significance and practical utility than I will to-night claim for the electron.

The history of science abounds with instances when a new concept or discovery has led to tremendous advances into vast new fields of knowledge and art whose very existence had hitherto been unsuspected. The discoveries of Galileo, Faraday and Pasteur are such instances. But, to my notion, no such instance has been so dramatic as the discovery of the electron, the tiniest thing in the universe, which within one generation has transformed a stagnant science of physics, a descriptive science of chemistry and a sterile science of astronomy into dynamically developing sciences fraught with intellectual adventure, interrelating interpretations and practical values.

I take particular pleasure in mentioning these practical values, for even the most unimaginative and short-sighted, hard-headed, "practical" business man is forced to admit the justification for the pure research —of no preconceived practical use whatsoever in the minds of those who led in its prosecution and of all degrees of success and significance—which has been directed at the electron. For out of this research have come the following things which all can understand and appreciate: a growing business in manufacture of electronic devices which now amounts to fifty million dollars a year in America alone; a total business of some hundreds of millions of dollars a year which is made possible by these electronic devices; innumerable aids to health, safety and convenience, and an immense advance in our knowledge of the universe in which we live.

In science, as in human affairs, great events do not occur without a background of development. The electron had an ancestry which can be traced back through the centuries. Its immediate progenitors were the electromagnetic theory of light, spectroscopy and the leakage of electricity through gases. First cousins were x-rays and radioactivity and quantum theory, for, out of a background of long investigation of bewildering and apparently unrelated phenomena, there burst upon the scientific world the x-ray in 1895, radioactivity in 1896 and the electron in 1897—all while investigators in the older fields of heat radiation and thermodynamics were finding those bothersome inconsistencies in these hitherto respectable subjects which led to that unexpected extension of Newtonian mechanics which we now call quantum mechanics. The concept of the electron, behaving according to the laws of quantum mechanics, is now the basis of most of our interpretation of all that falls under the good old name of natural philosophy.

That only the pioneers of the scientific world were prepared for these discoveries, however, is witnessed by the fact that a standard text-book of chemistry widely used in my student days in 1904 stated that, "Atoms are the indivisible constituents of molecules," and as late as 1911 a prominent physicist warned his colleagues not to be too hasty in accepting these newfangled ideas.

The existence of electrons had been foreshadowed for a century by the facts of electrolysis which led Davy and Berzelius to conclude that chemical forces were electrical in nature, and Faraday to conclude that electrical charges exist only in multiples of some fundamental unit. For chemical acids and salts, dissolved in water, tend to split up into ions, *i.e.,* atoms or groups of atoms which move in an electric field in such directions as to indicate that they carry either positive or negative electric charges. Furthermore, it is found that the amounts of these ions which carry equal amounts of electricity are exactly proportional to the chemical combining weights of the ions. Faraday saw that this fact would be simply explained by assuming that every ion carries a charge proportional to its chemical valency, *i.e.,* the valency times a fundamental unit charge. But Faraday could not, from these facts, deduce the size of this unit of charge; he could only state the ratio of this charge to the mass of the chemical substance with which the charge was associated. Hydrogen, being the lightest of all ions, had of all known substances therefore the largest value of this ratio of charge to mass.

The first real evidence of particles of larger ratio of charge to mass than hydrogen ions came from the field of optics. Ever since Maxwell's equations of electromagnetism had predicted the existence of electromagnetic waves with the velocity of light, and Hertz, seventeen years later, had discovered them experimentally, physicists had felt sure that light must be caused by some sort of oscillations of electricity within atoms. But only the vaguest and most unsatisfactory speculations, such as whirling vortices or pulsating spheres of electricity, had been suggested.

In 1896, however, Zeeman tried the experiment of examining the spectrum of a light source placed in a strong magnetic field, and discovered that the spectrum lines thus became split into components of slightly differing wave-lengths, and that these components of the light showed characteristic types of polarization, depending on the direction in which the light emerged from the magnetic field. Almost at once, in January, 1897, Lorentz showed that this experiment proved that light is caused by the oscillation of electric charges, whose motions are affected by the magnetic field in the manner to explain Zeeman's experiments. This much was not unexpected, but what was startling was Lorentz's proof that the Zeeman effect could only have been produced by electrified particles whose ratio of charge to mass is nearly two thousand times larger than that of a hydrogen ion, and whose mass is therefore presumably nearly two thousand times lighter than hydrogen.

Almost at once this conclusion was confirmed in a more dramatic and understandable way by J. J. Thomson, the then youthful director of the Cavendish Laboratory. But let me first pick up this thread of the story a little farther back.

All through the eighteen-eighties and early eighteen-nineties a series of most striking and unexpected discoveries followed from investigations of electric arcs, sparks and especially the glowing discharges of electricity at high voltages through glass tubes containing various gases at pressures far below atmospheric pressure. The striking color effects, mysterious luminous streamers and entirely bizarre behavior of these discharges made them the most popular, yet most elusive subject of laboratory research of those days.

It was these phenomena which led Crookes to postulate the existence of a mysterious "fourth state of matter," different from the solid, liquid or gaseous states. (Of course we now know that Crookes's fourth state is simply the ionized state of matter.)

Once, while attempting to photograph the appearance of a discharge at very low gas pressure, Crookes was bothered by the fact that all the photographic plates in the room with his apparatus became fogged, as if light-struck in spite of their opaque wrapping. He avoided the trouble subsequently, however, by keeping his new supply of plates in another room until, one at a time, they were wanted for use. Thus he solved an experimental difficulty and missed making a great discovery.

At about the same time Roentgen, in Germany, was trying the same experiment, and he too was troubled by the fogging of his photographic plates. But, as the story goes, his laboratory assistant called his attention to the peculiar fact that these fogged plates, when developed, showed the image of a bunch of keys which had accidentally been lying on top of the box of plates while the electric discharge experiments were in operation. Roentgen immediately looked into this and discovered that the fogging was due to penetrating radiations produced in the discharge tube where the cathode rays struck the target or anode. Thus by accident were x-rays discovered, that type of accident not uncommon in science when an observant experimenter is at work.

While on the subject of accidents, I might digress to tell of another accident which did not happen, also in connection with x-rays. For more than fifteen years after their discovery, disputes raged as to whether x-rays were radiations, like light but of very short wave-length, or electrically neutral particles of small mass and high speed. It was evident that they were not electrically charged, since their paths were unaffected by electric or magnetic fields. The leading advocate of the neutral particle theory was W. H. Bragg. In 1912, at Princeton, O. W. Richardson tried an experiment to see if x-rays could be refracted by a prism. A positive result would support the wave theory of x-rays. People had tried this with x-rays through glass prisms without success, but Richardson had a hunch that an iron prism might be more effective. So he passed x-rays for hours and days through the tapering edge of a Gillette safety razor blade, but without finding any refraction. If he had happened to try the edge of a crystal instead of the edge of the razor blade, he would undoubtedly have discovered the peculiar diffraction of x-rays in passing through crystals, discovered a couple of years later by Laue, Friederich and Knipping and developed by father and son, W. H. and W. L. Bragg, and which proved both the wave nature of x-rays and the atomic lattice structure of crystals. If Roentgen's discovery of x-rays was an accident, then I suppose Richardson's failure to discover diffraction of x-rays was a negative accident. I often wonder how many important negative accidents slip past us week by week!

But to get back on the subject of the electron, it was the cathode rays, which produce the x-rays, which finally turned out to be electrons traveling at high speeds. These cathode rays had been observed to shoot out in straight lines from the surfaces of cathodes in rarefied gases through which electric currents were forced by high voltage. Objects which they struck became luminous with fluorescent light, and objects in their paths cast shadows. But their true nature was disclosed when a magnet was placed near the discharge tube, for then their paths were curved in a direction showing that cathode rays were negatively charged.

By measuring this curvature produced by a magnetic field of known strength, and making a pretty sure assumption that the kinetic energy of these rays was determined by the voltage applied to the tube, J. J. Thomson in 1897 first showed that cathode rays are negatively charged particles with a ratio of charge to mass nearly two thousand times that of hydrogen. He furthermore showed that these particles are of the same type, as regards ratio of charge to mass, from whatever gas or cathode material they are produced. He therefore announced these particles, which he called "corpuscles," to be universal constituents of all substances. Thus was the electron discovered.

Quick and fast came experiments of ingenious design to study the electrons more accurately. They were pulled this way and that by electric and magnetic fields. They were caught in miniature metal fly traps, called Faraday cages, to measure their charge and kinetic energy. They were detected in their paths electrically, or by photographic plates or by fluorescence. Continually refined from that day to this, we now know that an electron has a ratio of charge to mass which is about 1,842 times the similar ratio for a hydrogen atomic ion.

But it was very desirable to know separately the charge and the mass of an electron, and not just the ratio between these quantities. So an even more interesting lot of experiments has been carried on to measure the electron's charge. One of the papers on this week's program of the American Physical Society gives the latest results of such measurements. But they were begun back in about 1900 by J. J. Thomson and his colleagues, Townsend, H. A. Wilson and C. T. R. Wilson. I think a brief résumé of attempts to measure the electron's charge will throw an interesting sidelight on the versatility of scientific attack on a difficult problem.

The first attempts were by Townsend by measurements on the motion and electrification of fog produced when electrolytic gas was bubbled into a region of air which was slightly supersaturated with water vapor, but too many uncertainties were involved to make this work convincing. The first accepted results were by J. J. Thomson, who, after an earlier attempt, employed a technique of producing fog under controlled conditions, developed by his colleague, C. T. R. Wilson, and whose method was refined further by his pupil, H. A. Wilson.

It has long been known that water droplets of fog do not form in air which is somewhat supersaturated with water vapor unless there are nuclei, like specks of dust, on which the moisture can condense. Later Townsend found that fog will also condense on ions, and more readily on negative than on positive ions. C. T. R. Wilson designed an apparatus in which dust-free air could be supersaturated with moisture sufficiently to permit condensation of fog droplets on negative but not on positive ions, which were produced by some convenient ionizing agent. So a fog was formed, in which each droplet of water was condensed on a negative ion. Thomson employed this apparatus in the following manner.

Of course this fog gradually settled downward under the pull of gravity—slowly because the drops were small compared with the viscous resistance of the air through which they fell. It was like the slow settling of dust onto the furniture and floor of a room. But the theory of the rate at which spheres move when a force drives them through a viscous medium was already well known, due to Stokes's law. From this law, measurement of the rate of fall of the fog in centimeters per second as measured by a little telescope focused on the top edge of the fog, combined with knowledge of the force of gravity and the viscosity of air, enabled Thomson to calculate the size of the individual fog droplets. Dividing the total amount of water in the fog by the amount in one drop gave him the total number of fog droplets, and therefore the total number of negative ions. H. A. Wilson added the refinement of superposing an electric field on the gravitational field which pulled the drops through the air.

Then, as the fog settled to the bottom of the apparatus, it deposited its electric charge, which, altogether, was large enough to be measured with an electrometer. So, dividing this total charge by the number of ions composing it gave, as the charge of one ion, $3.4(10)^{-10}$ electrostatic units. This was the first real measurement of the charge of an electron, and was the value quoted in the tables of physical constants when I became a graduate student in 1910.

But about that time Millikan, who has always had a flair for picking strategically important subjects to which to devote his investigative talents, undertook with his students a revaluation of the electronic charge. Sources of error in the fog method were well recognized: fog droplets were not all the same size, though measurements could only be made on those smallest ones which fell most slowly; also droplets did not remain of constant size, smaller ones tending to evaporate and larger ones to grow; also there were unavoidable convection currents in the air which modified the rate of fall of the fog; and some droplets might contain more than one ion.

Millikan cleverly avoided or minimized these difficulties by using only a single droplet of some relatively non-volatile liquid like oil or mercury. By ionizing the surrounding air in an electric field he could put various electric charges on the drop. Illuminating it by a powerful light and viewing it like a star through a measuring telescope, he could measure its rate of fall under gravity and its rate of rise when pulled upward against gravity by an electric field, and keep repeating these observations for hours. These measurements were so precise that, to keep pace with them, he had to measure the viscosity of air with hitherto unequalled accuracy. When all this was done he had proved conclusively that all electric charges are integral multiples of a fundamental unit charge, the electron, whose value he set as $4.774(10)^{-10}$ electrostatic units, about 40 per cent. larger than the earlier estimates and believed by Millikan to be correct within one part in a thousand.

Within the past half dozen years, however, doubt has been thrown on the estimated accuracy of this value from quite a different direction, in work with x-rays. Originally x-ray diffraction experiments in crystals proved the geometric arrangement of atoms in the crystals, but did not establish the scale of distances between atoms or the x-ray wave-length. These distances, once the arrangement of atoms was known, were calculated from absolute values of the weights of the atoms, which in turn were derived from electrochemical equivalents and the value of the electronic charge. Thus x-ray wave-lengths, masses of atoms and distances between atoms in crystals all had values dependent on knowledge of the charge of the electron.

Recently, however, A. H. Compton, Beardon and others have succeeded in making measurements of x-ray wave-lengths by diffracting x-rays from a grating ruled with 15,000 to 30,000 parallel fine lines to the inch, and operating near the angle of grazing incidence. These measurements involve only knowledge of the number of lines per inch on the grating, and the angles of incidence and diffraction of the x-rays—both depending only on measurements of length and capable of high precision. X-ray wave-lengths thus measured were a little different from the earlier accepted values, and this cast doubt on the accuracy of the electron charge value which had been used in the earlier x-ray estimates. The difference was not large, only one part in two hundred, but it meant either that experiments had not been as accurate as believed or that there was some unrecognized complicating factor.

So Millikan's work has been repeated in various laboratories with refinements, such as the use of a remarkably non-volatile oil for the drop. But the chief error was found to lie in the measurements of the viscosity of air. During the past year Kelletrop, of Uppsala, has thus published a revised "oil-drop" determination of electronic charge as $4.800(10)^{-10}$ e.s.u., which is in excellent agreement with the "x-ray" determinations. This morning Beardon has presented his own confirmation of this agreement before the American Physical Society.

It is an interesting coincidence that this best value of the electron's charge is exactly the same as the figure given by Rutherford thirty years ago, though then determined with so much less precision that not much confidence was placed in it, except as to order of magnitude. It was then known that the alpha rays from radium are helium atoms which have lost two electrons and are therefore doubly positively charged. Rutherford caught a lot of these alpha rays in a metal trap, measuring their aggregate electric charge with an electroscope, and counting them by the scintillations which they produced on striking a fluorescent screen or otherwise. Dividing the total charge by the number gave him double the electronic charge, which he thus calculated to be $4.8(10)^{-10}$ e.s.u.

Already knowing the ratio of charge to mass with high precision, this value of the charge enables us to fix the electron's mass as $9.051(10)^{-28}$ grams.

But when we speak of an electron's mass, we enter a whole new field of ideas. Some years before the discovery of electrons, J. J. Thomson had pointed out that an electrified particle will possess inertia, *i.e.,* mass, simply in virtue of its charge alone, irrespective of whether or not it has any mass of the gravitational type which we have been accustomed to think of. This "electromagnetic" mass comes about from the fact that any mechanical energy which is expended in accelerating an electric charge is transformed into the energy of the magnetic field which surrounds the electrified particle in virtue of its motion. In fact, the kinetic energy of a moving electric charge is found to be simply the energy of its magnetic field and depends only on the square of the velocity of the charge, the amount of charge and the geometrical shape of the charge.

Making the simplest possible assumptions about the shape of an electron, such as a solid sphere or a hollow spherical shell of electricity, and assuming all its mass to be of electromagnetic origin, the diameter of an electron was calculated to be of the order of $(10)^{-13}$ cm. It must be emphasized, however, that this estimate of size is not, like the charge and mass, a definite measurement, but is simply an estimate based on assumptions at least one of which is quite uncertain. For while we have both logic and experiment to back up the assumption that all the electron's mass is of this electromagnetic origin, we must confess to utter ignorance regarding the electron's shape. Indeed, some facts suggest that it may have different sizes and shapes in different environments, as in the free state or in an orbit of an atom or in the nucleus of an atom. So our estimate of $(10)^{-13}$ cm. for the size of an electron is, at best, very crude.

The idea of electromagnetic mass was strongly supported by the fact that measurements of the mass of very fast moving electrons, through measurements of the ratio of charge to mass of beta rays from radium or cathode rays in high voltage discharge tubes, showed that their mass is not really a constant thing but increases with the speed of the electron. The value of electron mass given above applies, strictly speaking, only to an electron at rest. Practically, however, it is accurate enough for practical purposes for electron speeds below about one tenth the speed of light. At this speed the electron's mass is about half of one per cent. larger than if it were at rest. At still higher speeds, the mass increases more and more rapidly, approaching infinite mass as the speed of light is approached.

These facts, experimentally determined, were shown by Abraham to be of the type expected if the entire mass of an electron is of electromagnetic origin, due entirely to its electric charge. It was this argument, which has since received confirmation from other directions, which was the basis of the theory that all mass, *i.e.*, all matter, is electrical. However, the simple electromagnetic concepts were not quite adequate to give an accurate quantitative interpretation of these experiments, and it required the additional introduction by Lorentz of the concepts of the special theory of relativity to bring about complete interpretation of the experiments.

Just two things more do we know accurately about the properties of electrons, in addition to their charge and mass. We know that they are also tiny magnets of strength equal to the basic unit of magnetic moment generally called the Bohr magnetron. Once the electron had been discovered, it became natural to seek in it also the explanation of magnetic phenomena, since it was only necessary to assume that the electricity of an electron is whirling about an axis and the electron becomes endowed with the properties of a tiny magnet. Parsons, Webster and others examined the possibilities inherent in various assumed configurations, with interesting results. But it was only with the introduction of the quantum theory for the interpretation of atomic structure and spectra that the magnetic character of the electron has, within the last dozen years, been put on a well-established basis.

The other thing we know is perhaps the most unexpected of all the electron's properties—it behaves like a wave when it collides with other objects. Davisson and Germer discovered this in the Bell Laboratories, while examining the way in which a beam of electrons, incident on a solid surface, was scattered or reflected by it. They found, if the surface were crystalline, that the electrons were scattered just like diffracted x-rays, but that, unlike x-rays, the wave-length of an electron is not fixed but varies inversely as its speed. J. J. Thomson's son, G. P. Thomson, has made very illuminating studies of this phenomenon, which is the inverse of the Compton effect and which together have given physicists two mottoes: "Particles behave like waves and waves behave like particles" and "Here's to the electron: long may she wave." One of the triumphs of the new wave-mechanics (a brand of quantum mechanics) is that it offers a medium of explanation of these strange phenomena. But my subject of the electron is too long to let me attempt a digression on wave mechanics.

With this sketch of the electron itself before us, let us turn to some of the more important directions in which the electron has given us an interpretation of the physical universe generally. Immediately were explained the phenomena of electrolysis and of ionization generally, for ions were simply atoms or groups of atoms which had gained or lost one or more electrons. Primary chemical forces were explained as the electrostatic attraction between atomic groups which, respectively, contained an excess or a deficiency of electrons. (The more refined interpretation of chemical forces within the past half dozen years, by Pauling and Slater, has been based upon the quantum theory of atomic structure).

The three types of rays from radioactive substances were interpreted: alpha rays as helium atoms which had lost two electrons; beta rays as electrons, and gamma rays as x-ray-like radiations. In fact Becquerel showed the magnetic deflection of beta rays in the same year, 1897, that Thomson showed the magnetic deflection of cathode rays and interpreted them as electrons.

For many years two unexplained phenomena had been studied in metals. When highly heated or when illuminated by ultra-violet light, metals had been shown to emit negative electricity. It was the work of but a year, after the discovery of the electron, for J. J. Thomson and his pupils to show that both these phenomena consist in the emission of electrons. But by what mechanisms are they thus emitted? That was a question whose study has led to most important theoretical and practical consequences.

Richardson, first as a pupil of Thomson and then as a professor at Princeton in the early nineteen hundreds, developed the theory of thermionic emission of electrons, according to which the electrons are evaporated from the surface of a metal at high temperatures by a process very analogous to evaporation of molecules. The electrons are assumed to have the same distribution of kinetic energies that molecules possess at the same temperature in accordance with the principles of kinetic theory. They escape from the surface if they reach it with enough energy to take them away in spite of the attraction tending to pull the electron back into the metal. This attraction is expressed in terms of the now famous "work-function," a sort of latent heat of evaporation of electrons, which is the work that must be done to get an electron clear of the surface. With these simple assumptions, an equation was derived for the rate of emission of electricity as a function of temperature which has stood the test of perhaps as wide a range of experimentation as any other equation of physics, a range of values of more than a million-million fold in current without any detectable departure from the theory, if this is properly applied.

Richardson's measurements of the "work-functions" of various metals showed that these values run closely parallel with one of the longest known but least understood properties of metals—their contact potential properties. By contact difference of potential is meant the voltage difference between the surfaces of two metals when they are placed in contact. Richardson found that the difference between the "work-functions" of two metals was, within the limits of accuracy of the data, the same as their contact difference of potential. He therefore proposed the theory that the contact potential property of a metal is determined simply by the work necessary to remove an electron from its surface.

As a beginning graduate student under Richardson in 1910 I was given the job of undertaking a test of this theory through experiments on the other electron-emitting phenomenon, the photoelectric effect. Einstein a few years before had proposed his famous photoelectric equation, which was a contribution to physical theory certainly comparable in importance and thus far more useful in its application than his more impressive and wider publicized general theory of relativity. According to it an electron in a metal may receive from the incident light an amount of energy proportional to the frequency of the light—to be exact, an energy equal to Planck's constant h times the frequency ν. If it escapes from the metal it must do an amount of work w to get away, so that its kinetic energy after escape from the metal would be the difference $h\nu - w$. Obviously, by measuring these kinetic energies of electrons liberated from various metals by light of various frequencies, it should be possible to find out if the "work-functions" w of different metals are indeed related to their contact differences of potential in the manner predicted by Richardson's theory.

In two papers, by me in 1911 and jointly with Richardson in 1912, it was concluded first that the contact differences of potential are related to the "work-functions" as Richardson had predicted, and second that Einstein's photoelectric equation, rather than a rival theory then under discussion, properly described the facts. Practically simultaneously with this second paper, there appeared the report of a similar verification of Einstein's equation by A. L. Hughes, then in England, though lacking the quantitative connection with contact differences of potential.

This early work was not very accurate, partly because of lack of good vacuum technique for maintaining untarnished surfaces in a vacuum, partly through lack of constant sources of ultra-violet light and partly because the ultra-violet spectrographs used to isolate the various wave-lengths of light gave a certain spectral impurity of scattered light of other wave-lengths. These sources of error were recognized but not overcome when Millikan, in 1916, made a striking advance by using doubly purified light or otherwise correcting for the effects of impurity, and secured a verification of Einstein's equation which was far more accurate than the earlier work as regards the value of Planck's constant h. In fact, Millikan's work remains to this day as one of the best determinations of this important constant. In regard to the "work-function," however, this work of Millikan's was not so successful, for, after having apparently discovered facts at variance with Richardson's interpretation of the equation and its relation to contact potentials, these differences were ultimately found to reside in faults of experimental procedure or interpretation, so that Richardson's interpretation of Einstein's equation still holds.

In both thermionic and photoelectric effects, theoretical refinements have been introduced by the recent quantum mechanics and great advances made in experimental technique. However, it is fair to say that their interpretations on the electron theory have been among the major achievements of this theory.

While we are on the subject of electricity in metals, what constitutes the phenomenon of easy flow of electricity that is the distinguishing feature of metals? J. J. Thomson at once suggested that this must be due to the existence in metals of electrons free from their parent atoms, moving freely, except for collisions, whenever an electric field was applied in the metal. The theory thus worked out was attractive, but it encountered inconsistencies. There was not even any real evidence that electricity in metals was conducted by electrons.

Then along came Tolman with one of his brilliant ideas, skilfully followed by experiment. It had earlier been suggested that, whatever are the carriers of electric current in metals, it should be possible to centrifuge them toward the periphery of a disk if this were rotated very rapidly about its axis. To be more specific, if electrons are free to move in metals and if a wire connects the center and the periphery of the rotating disk through lightly pressing brush contacts, electrons should be thrown out of the disk at its periphery and pass back into the center of the disk through the wire. It would be rather analogous to a current of water driven by a centrifugal pump through a pipe circuit. But all attempts to detect such currents proved futile, because the currents produced by the friction of the contact against the periphery were far larger than the currents to be expected from the centrifuging of electrons.

But Tolman devised two methods of giving powerful accelerations to metal conductors in such manner that he was able to measure the feeble electric currents that were produced as the carriers of electricity in the metal were shaken back and forth, and his calculations showed that these currents were indeed of the size to be expected if the current is carried by electrons. This is our direct evidence that electrons carry the electric current in metals. The mechanism by which they do this is now beginning to be disclosed by Slater, on the basis of an application of quantum mechanics and spectroscopic ideas to metals, and again is an example of the refining power of the quantum theory to succeed where older classical theory was gropingly suggestive, but inadequate.

And now that I come to the most basic of all the phenomena which the electron has been called upon to interpret, I almost lose courage, for the subject is too vast and complex for anything but encyclopedic treatment. I refer to the structure of atoms. Previous to the discovery of the electron, literally nothing was known of the internal structure or composition of atoms. With this discovery, however, it immediately became evident that all atoms contain electrons and an equivalent amount of positive electricity in some form. It was again J. J. Thomson's genius which began the investigation of the inner atom. This was only about twenty-five years ago.

Thomson reasoned that if x-rays were made to fall on any substance the electrons in the atoms of the substance would be forced to vibrate back and forth by the powerful alternating electric forces in the x-ray waves. But, in thus vibrating back and forth, these electrons would reradiate secondary x-rays in all directions. He calculated just what fraction of the original x-ray energy ought to be thus reradiated by each electron and then set his pupils to measure just what this fraction was in specific cases. From the experimental results he was thus able to calculate the number of electrons which performed the reradiation in each case. These results indicated that the number of such acting electrons in each atom was about half the value of the chemical atomic weight of the atom. Thus first were counted the electrons in an atom.

Rutherford and his pupils, aided by the mathematical analysis of Darwin, tackled the problem from a different point of view. They studied the distribution of deflection of alpha particles, shot out of radioactive materials, as these alpha particles traversed thin sheets of solid materials. They found that this distribution was quantitatively what would be expected if the deflections were produced by ordinary electrostatic forces, varying inversely as the square of the distance, between the alpha particle and a very small object containing most of the mass in each atom. They were thus able to show that this small object was not more than one ten-thousandth of the diameter of the atom, that it contained substantially all the mass of the atom and that it carried a positive electric charge equal, in electronic units, to about half the chemical atomic weight of the atom.

Thus arose the concept that the atom is composed of a positive nucleus of small dimensions, surrounded by electrons to the number of about half the atomic weight.

This had scarcely become established when it was brilliantly refined and extended by Moseley, just before he went to his untimely death in the war in 1914. Moseley had made a most ingenious study of the spectra of x-rays of a large number of the chemical elements, using a modification of the x-ray spectroscopy technique developed by the Braggs. He found that the square roots of the frequencies of the characteristic x-ray lines were numerically very simply related to the number which gave the place of the element in the periodic table of the elements, so useful to chemists but so far entirely without explanation. Thus this number acquired a definite physical significance and is now well known as the "atomic number."

For all the elements heavier than hydrogen, this atomic number is about half the atomic weight and, to make a long story short, this atomic number turns out to be exactly the number of electronic units of charge on an atomic nucleus, or the number of electrons in the atom outside the nucleus. At the same time, Moseley's work proved to be one of the greatest advances ever made in the basic interpretive side of chemistry.

Now that the number of electrons in each atom was known, the next step was to wonder about how they were arranged, what held them in place and what they were doing in their spare time. Suggestions were not slow in coming. In fact, even before Moseley's work, two rival theories had appeared, one devised by chemist Lewis and extended by Langmuir to explain the directional symmetries of atoms as indicated by their molecular combining forms, and the other devised by physicist Bohr to account for spectra. Gradually the Bohr theory has been developed to include the symmetries of the Lewis-Langmuir theory, so that both may be said to be merged, with many major additions too numerous to mention.

It was Bohr's bold genius to cast off some of the fetters of classical mechanics, which had been pretty well proved inadequate to meet the situation, and to devise a new mechanics frankly to meet the simplest known facts of atomic structure and spectroscopy—the hydrogen atom and the atomic hydrogen spectrum. In doing so, he at one stroke brought into the same picture the quantum theory of radiation, the electronic structure of the atom and the facts of spectroscopy. He had his electron moving in a circular orbit around the nucleus under the regular laws of electrostatic attraction and centrifugal force. But he stipulated that only such orbits were possible in which the angular momentum of the electron was an integral multiple of Planck's constant h divided by 2π. And he stipulated that the electrons should not radiate energy while revolving in their orbits, but only when they jumped from one orbit to another. In this case the frequency of light radiated was equal to the change of energy of the electron between the two orbits, divided by Planck's constant h. With these assumptions, the spectra of hydrogen and of ionized helium were quantitatively explained in their main features, but not in their finer details.

Then came the war, and we heard little of atomic structure in this country. But in Germany, Sommerfeld was extending Bohr's ideas in most interesting ways. He showed that, by considering elliptic as well as circular orbits and taking account of the variation of the electron's mass with speed, the fine details as well as the main features in the spectra of hydrogen and ionized helium were accurately explained. He also showed how the theory could be extended to deal with atoms where there were many electrons moving in orbits. He showed that these additional concepts were in the right direction to explain the more complicated spectra both in the visible and in the x-ray regions.

When this new work first was known in America, it started the most feverish and earnest scientific activity that the country has ever known and which is still in progress with undiminished zeal and with increasing productive effectiveness.

I well remember when the first copy of Sommerfeld's "Atombau und Spektrallinien" came to America in the possession of our friend, P. W. Bridgman. Until later copies arrived he knew no peace and enjoyed no privacy, for he was besieged by friends wanting to read the book, which he would not allow to go out of his possession. I recall too the sudden popularity of the only two or three men in this country who knew what a spectral series was. Heretofore practically our only interest in spectra had been in the culinary variety of spectroscopy used by chemists in identifying chemical elements. No interpretive quality to speak of had hitherto been attached to the peculiar numerical regularities which had been discovered in the vibration frequencies of groups of spectrum lines.

I recall, too, the dismay with which we found only a handful of mathematical physicists versed in the analytical dynamics underlying the new atomic structure theories. In the summer of 1921, having been taught by one of these few mathematical physicists, I went to the University of Michigan to lecture on Sommerfeld's theory, and found there also F. A. Saunders, invited to impart his knowledge of spectrum series. In the winter of 1926, Born and Jordan having just announced a new development in quantum mechanics, I found over twenty Americans in Göttingen at this fount of quantum wisdom. A year later they were at Zurich, with Schroedinger. A couple of years later Heisenberg at Leipzig and then Dirac at Cambridge held the Elijah mantle of quantum theory. In our own country contributions are coming rapidly, particularly in the fields of application to chemical interpretations, metals and other complex situations.

From all this has come the situation which permitted Dirac, a few years ago, to write: "The underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known, and the difficulty is only that the exact application of these laws leads to equations much too complicated to be soluble." But if any ambitious young scientist be discouraged lest there be little left to do, let him consider the unexplored atomic nucleus or the fact that every attempt to apply these laws, which look so satisfactory to us now, discloses new realms of knowledge still unexplored.

Time forbids mention of the most interesting work which was done to check and extend the theories of atomic structure, through direct measurement of the energy states of atoms and molecules by carefully controlled bombardment of these molecules by electrons. Begun by Frank and Hertz in Germany, much of this work was done in America by Foote and Mohler at the Bureau of Standards, by my students at Princeton and by Tate's group at Minnesota, all since 1920. In fact, both the addresses in Section B to-morrow morning are on this subject, retiring vice-president Tate discussing "Electron Impacts in Gases" and President Richtmyer, of the Physical Society, speaking on "Multiple Ionization of Atoms."

Before leaving the interpretive triumphs of the electron, however, I can not refrain from jumping from the atom to the universe, to the interpretation of conditions on the stars. Spectra of stars had long been known, and these were interpreted as indicating that some stars consist principally of hydrogen, others of helium and others of many chemical elements like our sun. But in 1922 a young Indian physicist, Megh Nad Saha, first applied atomic structure theory and knowledge of ionizing potentials to the sun and stars. He considered ionization in the hot vapors of the stars to be like a chemical dissociation produced by heat, in which the products of dissociation are electrons and the positive ionic residues of the atoms, and in which the heats of dissociation are given by the ionizing potentials of the atoms. In this way was developed a rational quantitative interpretation of stellar spectra which has thrown enormous light on the problem of conditions of temperature, pressure and condition of the chemical elements in stars. Russell in America and Milne in England have ably applied and extended this theory.

And now, finally, I come to the last phase of my subject, the social significance of the electron. By this I mean, of course, its useful applications. The first of these was Edison's invention of a thermionic rectifier, based on his discovery that negative electricity would flow across a vacuum from a hot filament to an adjacent electrode, but would not flow in the opposite direction. This was some years before the electron was discovered as the responsible agent in this phenomenon. But within a few years after the discovery of the electron, Fleming had shown that this same device will operate to rectify radio wave impulses, and thus permit their detection with a sensitive direct current instrument. From this was patented the Fleming valve.

Once the basic character of thermionic emission was understood, and spurred on by the opportunities opening up in the radio field, new inventions, improvements and applications of thermionic devices came rapidly. Of major importance was the three-electrode tube amplifier of De Forest. Industrial research laboratories in the communications and electric manufacturing business took the lead in developing techniques and in penetrating scientific exploration. Noteworthy were the vacuum techniques and the monomolecular layers of activating materials developed by Langmuir and the high-vacuum thermionic x-ray tube of Coolidge. In the Bell Laboratories, oxide-coated filament tubes of good performance were developed and applied particularly to use in long-distance telephony. Let me give just two illustrations of the marvelous powers of some of these instruments.

It has been calculated that the energy of a transatlantic radio signal caught by the receiving station in Newfoundland comes in at about the rate required to lift a fly seven inches in a year!

What is the largest number that has any physical significance? This is impossible to answer, being largely a matter of definition. But one common answer to this is $(10)^{110}$, or one followed by 110 ciphers. This is about the number of electrons (the smallest things known) which would be required to fill up the universe to the greatest distances discovered by astronomy, if the electrons could be imagined to be closely packed side by side to fill up this whole space. Yet this number, large as it is, is very small indeed compared with the aggregate factor by which the energy of a voice striking a telephone transmitter in San Francisco is amplified by electronic tubes in the process of a long distance telephone conversation to London. This amplification factor is about $(10)^{256}$, or unity followed by 256 ciphers. If the universe were multiplied in size by the number of times it is larger than an electron, it could still not hold as many electrons as the number of this telephone amplification factor!

Then, mostly within ten years or so, has come an active introduction of thermionic devices which are not highly evacuated, but operate with supplementary action of intense ionization of the gas in the tube. First of these were the low voltage arc rectifiers, like the Tungar. Most interesting and versatile are the thyratrons, which permit easy control of powerful currents and machinery, and which give a new means of converting alternating into direct current, or *vice versa*. In this group also are some of the new types of lamps, of high efficiency or special color.

Not so striking, but equally interesting have been the useful applications of the photoelectric effect. First was the use of sensitive photoelectric cells to replace the eye or photographic plate in astronomical telescopes. Then came sunshine meters, devices to open doors or count people or sort merchandise automatically or to register the speed and license number of the unwary autoist. Most important thus far are the current-producing mechanisms in the sound-movie apparatus and in television equipment.

While, commercially, radio, sound movies and long-distance telephony are at present of greatest importance, of no less importance, especially to us as scientists, are the marvelous tools which have been put into our hands for further research in practically every field of science, from physics and chemistry to psychology and criminology.

So we see how, within one generation, the electron has been discovered and examined, with its aid our intellectual outlook upon the universe has expanded in content and simplified in basic concept, and in its use mankind has the most versatile tool ever put to use. The end of the story is far from told. Every fact or relationship of the electron appears fuzzy with uncertainties when closely examined, for it can truly be said that every discovery discloses a dozen new problems. The field of practical and commercial uses of electronic devices is certainly still largely in its early stages of exploration.

This story illustrates in vivid manner a number of characteristics of scientific work, some of which I shall simply enumerate: (1) progress comes by spurts of advance as some big new idea opens up new territory, alternating with periods of consolidation; (2) progress comes not by revolution or discarding of past knowledge and experience, but is built upon past experience and is its natural extension once the vision from new vantage points is secured; (3) there is nothing so practical in its values as accurate knowledge, and the pursuit of such knowledge has been most successful when not fettered with the initial demand that it be directed toward practical ends.

I would not give you the impression that it is only the electron which has given new life to modern physical science. A story of similar interest could be built around the new concepts of radiation and atomic energy as expressed in the quantum theory, or about the electron's big brother, the proton, or his rather nondescript cousin, the neutron. In the atomic nucleus is a field of further exploration of enormous promise, now only beginning to be opened up by use of radioactive materials, cyclatrons and high-voltage generators.

Although these things have happened very recently, no one has better described the process and intellectual value of this type of scientific research than did Aristotle in the quotation which is inscribed in Greek on the façade of the National Academy of Sciences Building in Washington: "The search for truth is in one way hard and in another easy, for it is evident that no one can master it fully nor miss it wholly. But each adds a little to our knowledge of Nature, and from all the facts assembled there arises a certain grandeur."

OBITUARY

THEODORE JAMES BRADLEY

ON Friday, December 11, American pharmacy was made immeasurably poorer by the death of Dr. Theodore James Bradley, dean of the Massachusetts College of Pharmacy and president of the American Association of Colleges of Pharmacy. Dean Bradley was born in Albany, New York, sixty-two years ago last August.

He was graduated from the Albany College of Pharmacy in 1895 and taught in this institution for seventeen years following graduation. He was professor of mathematics in the Albany Academy for sixteen years and taught chemistry at the Albany Medical College from 1897–1907, inclusive. In 1912 he became dean of the Massachusetts College of Pharmacy, where he would have completed his 25th year of service in June, 1937.

Under Dean Bradley's administration, the Massachusetts College of Pharmacy has enjoyed a most unusual development and growth. It is housed in one of the finest pharmacy college buildings in the United States, is well equipped and enjoys a very substantial endowment.

Dean Bradley was a member of the U. S. Pharmacopoeia X and XI Revision Committees. He acted as secretary-treasurer of the American Association of Colleges of Pharmacy from 1917 to 1922. He was a member of the American Pharmaceutical Association for forty years, an association which he served as president in 1926. In August, 1936, he was elected president of the American Association of Colleges of Pharmacy, an organization which he served long and faithfully for many years. He was a member of the American Chemical Society and various other professional and scientific organizations.

He was given the honorary master of arts degree by Union University in 1912. In 1927 the Massachusetts College of Pharmacy conferred upon him the honorary degree of doctor of pharmacy and in 1927 the Philadelphia College of Pharmacy and Science granted him the degree of master of pharmacy.

Dean Bradley was the author of two text-books which are widely used in colleges of pharmacy in this country. He has written many articles for the pharmaceutical press and has made almost innumerable addresses at national and state conventions of various pharmaceutical bodies.

Dean Bradley is survived by his widow and three children, to whom we extend heartfelt sympathy.

Dean Bradley was one of the most respected men in American pharmacy to-day. He was admired for his fundamental honesty and profound loyalty to his friends and the various worthy enterprises for which he worked during his lifetime. Pharmacy has been greatly enriched by his splendid life of sacrifice and service. His death will be deeply felt and mourned by his great host of friends in various parts of the country.

E. L.

GEORGE C. CROWE

GEORGE C. CROWE, assistant park naturalist of Yellowstone National Park, died in the Park Hospital in Livingston on October 27, after a week's illness. His body was taken to Oakland, California, for burial. Mr. Crowe, who was 47 years old, was first taken ill on October 21 and rushed to the Park Hospital. He is survived by his widow and three children—Helen, 9; Margaret, 17; Robert, 20—his mother and two sisters.

He had served the National Park Service since 1929, as junior naturalist at Yosemite National Park, custodian at Devils Tower National Monument and as junior and assistant park naturalist at Yellowstone since March, 1932. His student days were spent at the University of California, majoring in mining and geology.

On leaving college, he toured the United States lecturing on the contemplated Panama-Pacific Exposition in San Francisco. Then followed several years of service with the Boy Scouts of America. After demonstrating his ability as a nature guide in Yosemite, he joined the naturalist staff.

His enthusiasm for his work was unbounded, and his endeavor to be of service to the park visitor was conspicuous. As a result he led thousands to an intimate knowledge of the scientific features of the national parks and made countless friends for park ideals and standards. Around the evening campfire, he exhibited great ability as a leader and entertainer, but never forgot the importance of the educational opportunities which such gatherings possess. Every museum enterprise with which he was connected showed the result