ROBERT A. MILLIKAN

The electron and the light-quant from the experimental point of view

Nobel Lecture, May 23, 1924

The fact that Science walks forward on two feet, namely theory and experiment, is nowhere better illustrated than in the two fields for slight contributions to which you have done me the great honour of awarding me the Nobel Prize in Physics for the year 1923.

Sometimes it is one foot which is put forward first, sometimes the other, but continuous progress is only made by the use of both - by theorizing and then testing, or by finding new relations in the process of experimenting and then bringing the theoretical foot up and pushing it on beyond, and so on in unending alternations.

The terms of this year's award state that it is given for work on the fundamental electrical unit and on photoelectricity. In both fields my own work has been that of the mere experimentalist whose main motive has been to devise, if possible, certain crucial experiments for testing the validity or invalidity of conceptions advanced by others.

The conception of electrical particles or atoms goes back a hundred and seventy years to Benjamin Franklin who wrote about 1750: "The electrical matter consists of particles extremely subtle since it can permeate common matter, even the densest, with such freedom and ease as not to receive any appreciable resistance."

This theoretical conception was developed in no little detail by Wilhelm Weber[1] in papers written in 1871. The numerical value of the ultimate electrical unit was first definitely estimated by G. Johnstone Stoney[2] in 1881, and in 1891 this same physicist gave to it the name *the electron**.

* It is highly desirable that this historically correct, etymologically most suitable, and authoritatively recognized nomenclature (see among many others Rutherford's Presidential Addresses at the British Association 1923, Nemst's Theoretical Chemistry, last edition, etc., etc.) be retained. When used without a prefix or qualifying adjective, the word electron may signify, if we wish, as it does in common usage, both the generic thing, the unit charge, and also the negative member of the species, precisely as the word « man » in English denotes both the genus homo and the male of mankind. There is no gain in convenience in replacing *positive electron, by «proton», but on the other hand a distinct loss logically, etymologically, and historically.

In 1897 the experimental foot came forward with J. J. Thomson's and Zeeman's determinations of *e/m* by two wholly distinct methods. It was these experiments and others like them which in a few years gained nearly universal acceptance among physicists for the electron theory.

There remained, however, some doubters, even among those of scientific credentials, for at least two decades - men who adopted the view that the apparent unitary character of electricity was but a statistical phenomenon; and as for educated people of the non-scientific sort, there exists today among them a very general and a very serious misconception as to the character of the present evidence. A prominent literary writer recently spoke of the electron as « only the latest scientific hypothesis which will in its turn give way to the abra-ca-da-bra of tomorrow ».

It is perhaps not inappropriate then to attempt to review today as precisely as possible a few features of the existing experimental situation and to endeavour to distinguish as sharply as may be between theory and some newly established *facts*.

The most direct and unambiguous proof of the existence of the electron will probably be generally admitted to be found in an experiment which for convenience I will call the oil-drop experiment. But before discussing the significance of that advance I must ask you to bear with me while I give the experimentalist's answer to the very fundamental but very familiar query: « What is electricity? » His answer is naive, but simple and definite. He admits at once that as to the *ultimate* nature of electricity he knows nothing.

He begins rather with a few simple and familiar experiments and then sets up some definitions which are only descriptions of the experiments and therefore involve no hypothetical elements at all.

He first notes the fact that a pith ball, after contact with a glass rod that has been rubbed with silk, is found to be endowed with the new and striking property that it tends to move away from the rod with a surprisingly strong and easily measurable force. He describes that fact, and affirms at the same time his ignorance of all save the existence of this force, by inventing a new word and saying that the pith ball has been put into a *positively electrified state,* or simply has received a *charge of positive electricity.* He then measures the amount of its charge by the strength of the observed force.

Similarly he finds that the pith ball, after contact with an ebonite rod that has been rubbed with cat's fur is attracted, and he proceeds to describe this experiment by saying that it has now received a *charge of negative electricity.* Whenever the pith ball is found to have been put, by contact with any body or by any other process, into a condition to behave in either of the foregoing ways, it has, *by definition,* received a charge of either positive or negative electricity. The whole of our thinking about electrical matters starts with these two simple experiments and these two definitions.

In order now to get the most crucial possible test of the correctness or incorrectness of Franklin's conception of a particle, or an atom, of electricity it was clearly necessary to reduce the charge on the pith ball to the smallest possible amount, to change that charge by the most minute possible steps, and then to see whether the forces acting upon it at a given distance from the glass rod (i.e. in a constant field) had any tendency to increase or decrease by *unitary* steps.

The success of the experiments first performed in 1909, was wholly due to the design of the apparatus, i.e. to the relation of the parts.

The pith ball itself which was to take on the smallest possible charge had of course to be the smallest spherical body which could be found and yet which would remain of constant mass; for a continuously changing gravitational force would be indistinguishable, in its effect upon the motion of the charged body, from a continuously changing electrical charge.

A non-homogeneous or non-spherical body also could not be tolerated; for the force acting on the pith ball had to be measured by the speed of motion imparted to it by the field, and this force could not be computed from the speed unless the shape was spherical and the density absolutely constant. This is why the body chosen to replace the pith ball was an individual oil-droplet about a thousandth of a millimeter in diameter blown out of an ordinary atomizer and kept in an atmosphere from which convection currents had been completely removed by suitable thermostatic arrangements. The glass rod, the purpose of which was to produce a constant electrical field, was of course replaced by the two metal plates C and D (Fig. 1) of an air condenser, one of the plates (D) being attached to the positive, the

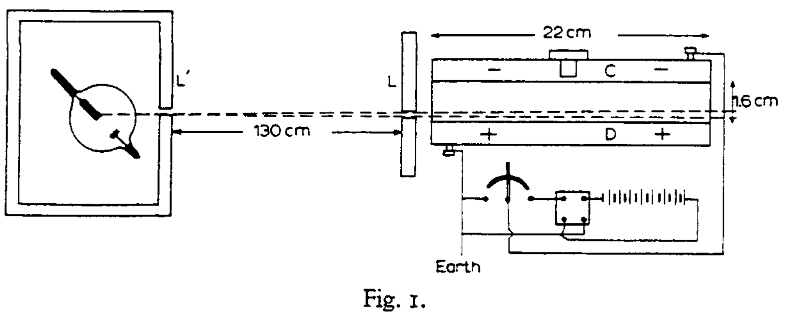

Fig. 1.

other (C) to the negative terminal of a battery, and a switch being added, as shown in the figure, so as to make it possible to throw the field on or off at will.

In order to be able to measure very accurately the force acting upon the charged oil-droplet it was necessary to give it about a centimeter of path in which the speed could be measured. This is one of the most important elements in the design, the overlooking of which has caused some subsequent observers to fall into error. The centimeter of path and the constancy of field then fixed the approximate size of the plates the diameter of which was actually 22 cm. They were placed 16 mm apart.

The Geld strength too, about 6,000 volts per cm, was vital, and new in work of anything like this kind. It was the element which turned possible failure into success. Indeed, Nature here was very kind. She left only a narrow range of field strengths within which such experiments as these are all possible. They demand that the droplets be large enough so that the Brownian movements are nearly negligible, that they be round and homogeneous, light and non-evaporable, that the distance be long enough to make the timing accurate, and that the field be strong enough to more than balance gravity by its pull on a drop carrying but one or two electrons. Scarcely any other combination of dimensions, field strengths and materials, could have

Table 1.

Time of fall 1.303 cm under gravity (sec)	*Time of rise 1.303 cm in field (sec)*	*Mean times of rise in field (sec)*	*Divisors for speeds due to field*	*The electron in terms of a speed*
120.8	26.2			
121.0	11.9			
121.2	16.5	67.73	1	3.007
120.1	16.3	26.40	2	3.009
120.2	26.4	16.50	3	2.993
119.8	67.4	11.90	4	3.008
120.1	26.6			
—	16.6			
120.2	16.6	*Mean time*		
—	16.4	*of fall under*		
120.2	68.0	*gravity*		
119.9	67.8	120.35		
—	26.4			

yielded the results obtained. Had the electronic charge been one-tenth its actual size, or the sparking potential in air a tenth of what it is, no such experimental facts as are here presented would ever have been seen.

The observations which gave an unambiguous answer to the questions as to the atomic nature of electricity consisted in putting a charge upon the drop, in general by the frictional process involved in blowing the spray, letting the charged drop drift through a pin-hole in the center of plate C into the space between C and D, and then in changing its charge in a considerable number of different ways; for example, by ionizing the air just beneath it by alpha, beta, or gamma rays from radium and letting the field throw these ions into the drop; by illuminating the surface of the drop itself with ultraviolet light; by shooting X-rays both directly at it and beneath it, etc. The results of those changes in charge in a constant field, as is now well-known, and as is shown in particular cases in the accompanying Table 1, were

(1) that it was found possible to discharge the droplet completely so that within the limits of observational error-a small fraction of one per cent *- it fell its centimeter undergravity, when the* 6,000 *volt electrical-field was on, in precisely the same time required to fall the same distance when there was no field;*

(2) that it could become endowed with a particular speed in the electrical field (corresponding to 67.7 sec in the particular case shown), which *could be reproduced as often as desired, but which was the smallest speed that the given field ever communicated to it* - nor was this change in speed due to the capture of an electron a small one, difficult to observe and measure. It was often larger than the speed due to gravity itself and represented, as in this case shown, a reversal in *direction* so that it was striking and unmistakable;

(3) that *speeds exactly two times, three times, four times, jive times, etc.* (always within the limits of observational error - still less than a percent) *could be communicated to the droplet, but never any fraction of these speeds.*

He who has seen that experiment, and hundreds of investigators have observed it, has literally *seen* the electron. For he has measured (in terms of a speed) the smallest of the electrical forces which a given electrical field ever exerts upon the pith ball with which he is working and with the aid of whose movements he defines electricity itself. Further, he has found that that something which he has chosen to call electricity may be placed upon or removed from his pith ball only in quantities which cause the force acting upon it either to drop to zero, or else to go up by definite integral multiples of the smallest observed force.

If a man had seen a football which someone told him was the electron he would be far less certain that what he had seen corresponded to reality, than is the man who has become familiar with the foregoing experiment. By its *aid he can count the number of electrons in a given small electrical charge with exactly as much certainty as he can attain in counting his fingers and his toes.* It is true that when he has counted up to 200 electrons in a given charge, his observational error begins to make it impossible to distinguish between 200 and 201; so that the conclusion that large electrical charges are built up in the same manner as are the charges that he can count is of course in the nature of a generalization, but obviously not one of much uncertainty.

But the electron itself, which man has measured, as in the case shown in the table, is neither an uncertainty nor *an hypothesis. It is a new experimental fact that this generation in which we live has for the first time seen, but which anyone who wills may henceforth see.*

The measurement of the electron, not as above in terms of the speed that it imparts to a given oil-drop, but in absolute electrostatic units, involved observations of the foregoing sort upon thousands of drops of various sizes, made from a number of different substances, surrounded by a large number of different gases at widely differing pressures, varying from atmospheric down to a millimeter and a half of mercury.

It involved also years of work in finding accurate values of gaseous viscosities, and in determining just how « Stokes' law » must be modified to yield the complete law of fall of a particle through a gas at any density whatever.

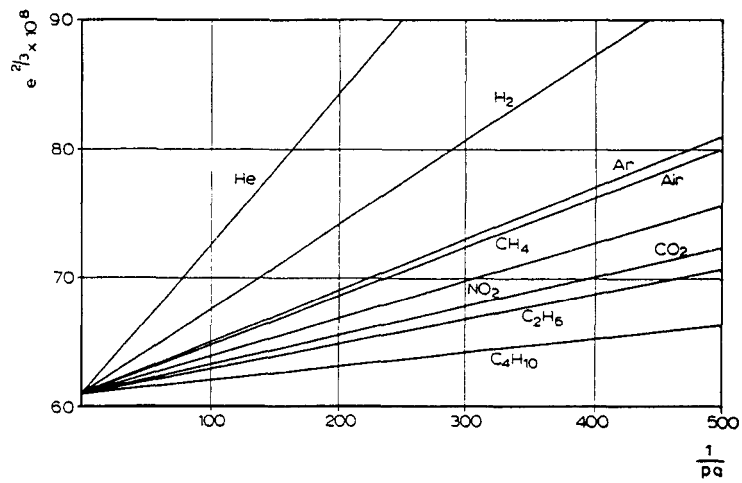

Fig. 2.

But all this is only of interest here in showing, as Fig. 2 does*, *how inevitably all observations on all gases and all substances converge upon the same absolute value of the electron at the intercept on the* $e^{\frac{2}{3}}$ *axis of the figure.* It is from this intercept that the value of the electron e = 4.774 (± 0.005) x 10^{-10} absolute electrostatic units is directly obtained.

After ten years of work in other laboratories in checking the methods and the results obtained in connection with the oil-drop investigation published from 1909 to 1923, there is practically universal concurrence upon their correctness, despite the vigorous gauntlet of criticism which they have had to run.

Electrons, of both the positive and negative variety, are then merely observed centers of electrical force, just as was the charged pith ball from which we got our original definition of an electric charge, the difference being that electrons are invariable in their charge while pith-ball charges are built up out of them.

The dimensions of electrons may in general be ignored; i.e. they may both, for practical purposes, be considered as point charges, though, as is well known, the positive has a mass 1,845 times that of the negative. Why this is so no one knows. It is another experimental fact.

It is also well-known that we can now count the exact number of positives and of negatives in every atom; that we can locate all the positives in the nucleus; that we find the negatives scattered partly through the outer regions and partly held within the nucleus; that the number of outer negatives varies from 1 in hydrogen by unit steps up to 92 in uranium, and that the number of negatives in the nucleus is given by the difference between the atomic weight and the atomic number.

Shall we ever find that either positive or negative electrons are divisible? Again no one knows; but we can draw some inferences from the history of the chemical atom. This is sometimes said by the unthinking to have exploded, but of course every scientist knows that it has never lost an iota of its old reality nor of its old vitality. From an experimental point of view the atom of the chemist was all contained in the facts of definite and multiple proportions in combining powers. For the purposes for which the concept was used, viz. those of chemical combination, the chemical atom is just as much the ultimate unit now as it ever has been.

* This is taken from a repetition of my observations in different gases by my assistant Dr. Yoshio Ishida. For similar observations upon different drop-substances, see *The Electron, rev.* ed., University of Chicago Press, 1924.

Similarly it is not likely that the field in which the electron has already been found to be the unit, namely that of atomic structure, will ever have to seek another unit. The new *facts* which this generation has discovered are certainly the permanent heritage of the race. If the electron is ever subdivided it will probably be because man, with new agencies as unlike X-rays and radioactivity as these are unlike chemical forces, opens up still another field where electrons may be split up without losing any of the unitary properties which they have now been found to possess in the relationships in which we have thus far studied them.

The second domain in which, as your award indicates, I have been attempting to take another step, and to assist in bringing the experimental foot up to parallelism at least with the theoretical, is the field of ether waves. In this domain I have been seeking since the year 1904 to find some crucial test for the Thomson-Planck-Einstein conception of localized radiant energy.

This conception in its most general form was introduced by J. J. Thomsons in 1903 to account for two newly discovered experimental facts, viz.:

(1) that X-rays pass over all but an exceedingly minute fraction, say one in a billion, of the atoms contained in the space traversed without spending any energy upon them, but here and there find an atom from which they hurl an electron with enormous speed;

(2) that ultraviolet light has the amazing property, discovered by Lenard[4] in 1902, of ejecting electrons from metal surfaces with an energy which is independent of the intensity of the source.

This Thomson semicorpuscular conception of localized radiant energy was taken up in 1905 by Einstein who, by combining it with the facts of quanta discovered by Planck[6] through his analysis of black-body radiation, obtained an equation which should govern, from his viewpoint, the interchange of energy between ether waves and electrons, viz. $\frac{1}{2}mv^2 = h\nu - P$, the first term representing the energy with which the electron escapes, the second term Planck's energy quantum for the particular light employed, and the last the work necessary to get the electron out of the metal.

After ten years of testing and changing and learning and sometimes blundering, all efforts being directed from the first toward the accurate experimental measurement of the energies of emission of photoelectrons, now as a function of temperature, now of wavelength, now of material (contact e.m.f. relations), this work resulted, contrary to my own expectation, in the first direct experimental proof[7] in 1914 of the exact validity, within

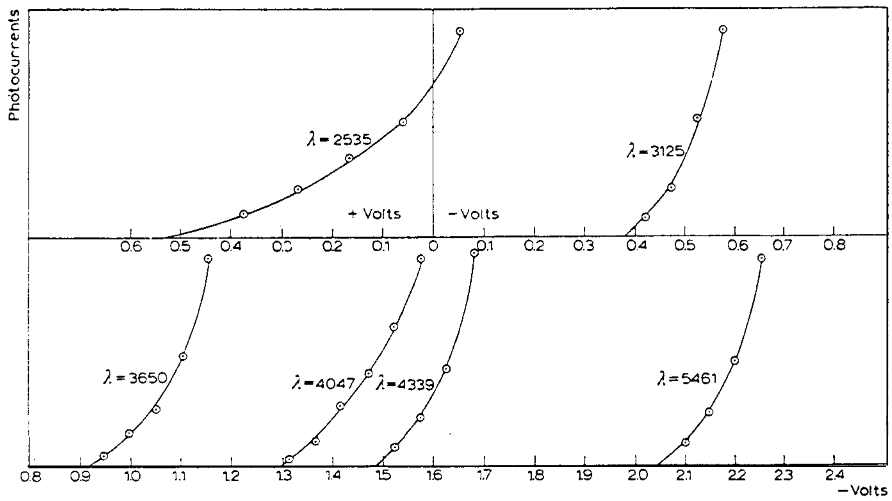

Fig. 3.

narrow limits of experimental error, of the Einstein equation, and the first direct photoelectric determination of Planck's *h*. The accuracy obtained was about 0.5% which was much the best available at the time. Figs. 3 and 4, which represent the most accurate work done on an individual metal (sodium), will illustrate the entire lack of ambiguity of the result.

This work, like that on the electron, has had to run the gauntlet of severe criticism, for up to 1916 not only was discussion active as to whether there were any limiting velocity of emission, but other observers who had thought that a linear relation existed between energy and frequency had not found the invariable constant *h* appearing as the ratio. But at the present time it is not too much to say, that the altogether overwhelming proof furnished by the experiments of many different observers, working by different methods in many different laboratories, that Einstein's equation is one of exact validity (always within the present small limits of experimental error) and of very general applicability, is perhaps the most conspicuous achievement of Experimental Physics during the past decade.

A brief historical summary of this advance is as follows: A year or two after the foregoing photoelectric work was completed, Duane[8] and his associates found unambiguous proof of a relation which is just the inverse of Einstein's. They bombarded a metal target with electrons of known and constant energy and found that the maximum frequency of the ether waves (general X-radiation) thereby excited was given, with much precision, by $\frac{1}{2} mv^2 = h r$.

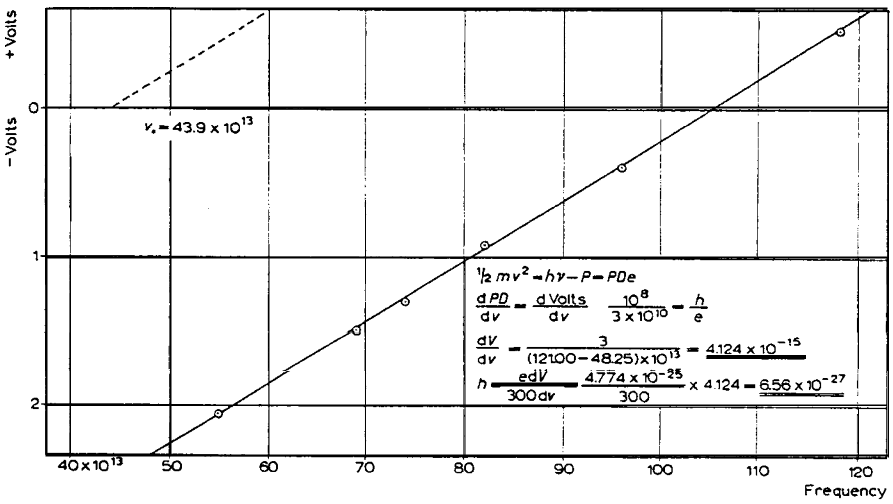

Fig. 4.

D. L. Webster[9] then proved that the characteristic X-ray frequencies of atoms begin to be excited at just the potential at which the energy of the stream of electrons which is bombarding the atoms has reached the value given by hv = $\frac{1}{2} mv^2$ in which v is now the frequency of an absorption edge.

De Broglie[10] and Ellis[11], on the other hand, measured with great precision the speed of electrons ejected from different atomic levels by high-frequency radiations and thus beautifully verified, in this high-frequency field, precisely the same Einstein equation $\frac{1}{2} mv^2$ = hv - P which I had found to hold for ultraviolet and visible frequencies.

Parallel with these developments has come the very full working out of the large field of ionizing and radiating potentials. This has also involved the utilization and verification of the same reciprocal relation between frequency and electronic energy which is stated in the Einstein equation and which constitutes in its inverse form the cornerstone of Bohr's epoch-making treatment of spectral lines. This work all takes its start in Franck and Hertz' fundamental experiments[12], but the field has been most actively and successfully explored since 1916 in America, especially by Foote and Mohler, Wood, Davis and Goucher, McLennan, and others[13].

In view of all these methods and experiments the general validity of Einstem's equation is, I think, now universally conceded, and *to that extent the reality of Einstein's light-quanta may be considered as experimentally established.* But the conception of *localized* light-quanta out of which Einstein got his equation must still be regarded as far from being established. Whether the mechanism of interaction between ether waves and electrons has its seat in the unknown conditions and laws existing within the atom, or is to be looked for primarily in the essentially corpuscular Thomson-Planck-Einstein conception as to the nature of radiant energy is the all-absorbing uncertainty upon the frontiers of modern Physics.

In 1921[14] I thought I had taken another step toward its solution in proving that in the photoelectric process the light energy $h\nu$ is taken up, not only by electrons within atoms, but also by the free (i.e. the conduction) electrons in metals. For this seemed to take the absorbing mechanism out of the atom entirely and to make the property of imparting the energy $h\nu$ to an electron, whether free or bound, an intrinsic property of light itself.

But a beautiful discovery by Klein and Rosseland[15] a year later in Bohr's Institute made this conclusion unnecessary. For it showed, as Dr. Epstein first pointed out, that there was an intermediate process, namely a collision of the second kind, by which the energy might be transferred, without loss, *indirectly* from the light wave to the conduction electron, thus obviating the necessity of a direct transfer. The act of absorption could still, then, be an atomic process and the absorbed energy be afterward passed on by a collision of the second kind to a free electron. This important discovery then left the evidence for localized light-quanta just where it was before.

Within the past year, however, a young American physicist, Arthur H. Compton[16] of the University of Chicago, by using the conception of localized light-quanta, has brought forward another new phenomenon which at least shows the fecundity of the Einstein hypothesis. Compton goes a step farther than Einstein in that he assumes not only the existence of light-quanta but also that in the impact between a light-quant and a free electron the laws of conservation of energy and of conservation of momentum both hold. This assumption enables him to compute exactly how much the frequency of ether waves which have collided with free electrons will be lowered because of the energy which they have given up to the electron in the act of collision, and therefore the loss which their own $h\nu$ has experienced. He then finds experimentally that there is approximately the computed lowering in frequency when monochromatic X-rays from molybdenum are scattered by carbon. Further Ross[17] at Stanford University has checked this result by the photographic method.

On account of the fact that Duane and his co-workers at Harvard University could not find a trace of the Compton effect, Messrs. Becker[18], Watson, and Smythe have within a month, at the California Institute at Pasadena, repeated the same type of scattering experiments as those made by Ross, using however aluminium as a scatterer, and *have found on one plate, taken with high resolution, the alpha doublet line of molybdenum shifted as a clearly observable doublet toward longer wavelengths.* Further the amount of the shift was here measurable with an accuracy of about 1% and agreed within this narrow limit with that predicted by Compton's equations. Fig. 5 shows one of these

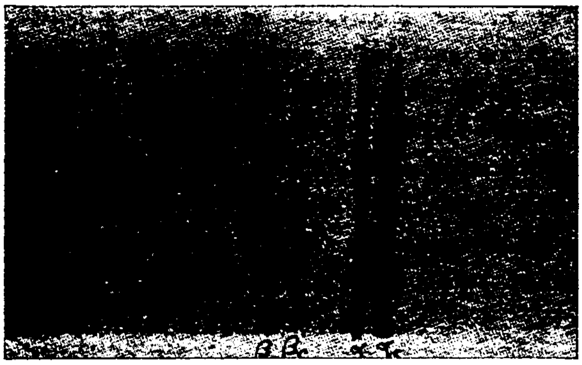

Fig. 5.

new photographs in which both the α and β lines of molybdenum are shifted toward longer wavelengths the correct amount, i.e. to α_c and β_c, through being scattered by aluminium. It may be said then without hesitation that it is not merely the Einstein equation which is having extraordinary success at the moment, but the Einstein conception as well.

But until it can account for the facts of interference and the other effects which have seemed thus far to be irreconcilable with it, we must withhold our full assent. Possibly the recent steps taken by Duane[19], Compton[20], Epstein and Ehrenfest[21] may ultimately bear fruit in bringing even interference under the control of localized light-quanta. But as yet the path is dark.

1. W. Weber, *Werke,* Vol. 4 (1871), p. 281.
2. G. J. Stoney, *Phil. Mug.,* II (1881) 384.
3. J. J. Thomson, *Silliman* Lectures, Yale University, 1903.
4. P. E. A. Lenard, *Ann. Pkysik, 8* (1902) 149.
5. A. Einstein, *Ann. Pkysik,* 17 (1905) 132; 20 (1906) 199 .
6. M. Planck, *Verkandl. Deut. Pkys. Ges.,* Dec. 14 (1900).

7. R. A. Millikan, Phys. *Rev.,* 4 (1914) 73; 6 (1915) 55; 7 (1916) 362.
8. W. Duane et al., Phys *Rev.,* 6 (1915) 66; 7 (1916) 599; 9 (1917) 568; IO (1917) 624; *Proc. Natl. Acad. Sci., 2 (1916) go.*
9. D. L. Webster, *Proc. Natl. Acad. Sci.,* 3 (1917) 181; 6 (1920) 26, 39.
10. L. de Broglie, paper read before the Third Solvay Congress, 1921.
11. C. D. Ellis, *Proc. Roy. Soc.,* A **99** (1921) 261; C. D. Ellis and H. W. B. Skinner, *ibid.,* A 105 (1924) 165, 185.
12. J. Franck and G. Hertz, *VerhandI. Deut. Phys. Ges., 15* and 16 (1914).
13. Report Photoelectric Conference, Natl. Research Council, 1921; see also: P. D. Foote and F. L. Mohler, *The Origin of Spectra, New* York, 1922.
14. R. A. Mihikan, *Phys. Rev.,* **18 (1921)** 236.
15. O. Klein and S. Rosseland, Z. *Physik, 4 (1921) 46.*
16. A. H. Compton, *Phys. Rev.,* 21 (1923) 483 ; 22 (1923) 409.
17. P. A. Ross, Proc. *Natl. Acad. Sci., g (1923) 246.*
18. J. A. Becker, *Proc.* Phys. Soc. (London), April 25 (1924); *Phys. Rev., 24 (1924) 478.*
19. W. Duane, *Proc. Natl. Acad. Sci., 9 (1923) 158.*
20. A. H. Compton, ibid., g (1923) 359.
21. P. S. Epstein and P. Ehrenfest, *ibid.,* **IO (1924) 133.**