Physics 1925

JAMES FRANCK

GUSTAV HERTZ

«*for* their discovery of the laws governing the impact of an electron upon an atom»

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Presentation Speech by Professor C. W. Oseen, member of the Nobel Committee for Physics of the Royal Swedish Academy of Sciences

Your Majesty, Your Royal Highnesses, Ladies and Gentlemen.

The Physics Nobel Prize for the year 1925 has been awarded to Professor James Franck and Professor Gustav Hertz for their discovery of the laws governing the impact of an electron upon an atom.

The newest and most flourishing branch of the great tree of physical research is atomic physics. When Niels Bohr founded this new science in 1913, the material at his disposal consisted of data concerning the radiation of glowing bodies, which had been accumulated over several decades. One of the earliest findings in the field of spectroscopy was that the light emitted by a glowing gas when observed through a spectroscope, splits up into a large number of different lines, called spectral lines. The fact that simple relationships exist between the wavelengths of these spectral lines, was first discovered by Balmer in 1885 for the hydrogen spectrum, and demonstrated later by Rydberg for a large number of elements. Two questions relating to theoretical physics arose as a result of these discoveries: How is it possible for a single element to produce a large number of different spectral lines? And what is the fundamental reason behind the relationships that exist between the wavelengths of the spectral lines of a single element? A large number of attempts were made to answer these two questions, on the basis of the physics which we are now accustomed to call classical physics. All were in vain. It was only through a radical break with classical physics that Bohr was able to resolve the spectroscopic puzzles in 1913. Bohr’s basic hypotheses can be formulated as follows:

Each atom can exist in an unlimited number of different states, the so-called stationary states. Each of these stationary states is characterized by a given energy level. The difference between two such energy levels, divided by Planck’s constant h, is the oscillation frequency of a spectral line that can be emitted by the atom. In addition to these basic hypotheses, Bohr also put forward a number of specific hypotheses, with the aid of which it was possible to calculate the spectral lines of the hydrogen atom and the helium ion. The extraordinarily good agreement with experience obtained in this way,

-explains why after 1913 almost a whole generation of theoretical and experimental physicists devoted itself to atomic physics and its application in spectroscopy.

Bohr's more specific assumptions have had the same fate as that which sooner or later overtakes most physical hypotheses: science outgrew them. They have become too narrow in relation to all the facts which we now know. For a year now attempts have been made to solve the puzzle of the atom in other ways. But the new theory which is now in process of being established, is yet not a completely new theory. On the contrary, it can be termed a further development of Bohr's theory, because among other things in it Bohr's basic assumptions remain completely unchanged. In this overthrowing of old ideas, when all that has been gamed in the field of atomic Physics seemed to be at stake, there is nobody who would have thought it advisable to proceed from the assumption that the atom can exist in different states, each of which is characterized by a given energy level, and that these energy levels govern the spectral lines emitted by the atoms in the way described. The fact that Bohr's hypotheses of 1913 have succeeded in establishing this, is because they are no longer mere hypotheses but experimentally proved facts. The methods of verifying these hypotheses are the work of James Franck and Gustav Hertz, for which they have been awarded the Physics Nobel Prize for 1925.

Franck and Hertz have opened up a new chapter in physics, viz., the theory of collisions of electrons on the one hand, and of atoms, ions, molecules or groups of molecules on the other. This should not be interpreted as meaning that Franck and Hertz were the first to ask what happens when an electron collides with an atom or a molecule, or that they were the originators of the general method which paved the way for their discoveries and which consists of the study of the passage of a stream of electrons through a gas. The pioneer in this field is Lenard. But Franck and Hertz have developed and refined Lenard's method so that it has become a tool for studying the structure of atoms, ions, molecules and groups of molecules. By means of this method and not least through the work of Franck and Hertz themselves, a great deal of material has been obtained concerning collisions between electrons and matter of different types. Although this material is important, even more important at the present time is the general finding that Bohr's hypotheses concerning the different states of the atom and the connexion between these states and radiation, have been shown to agree completely with reality.

Professor Franck. Professor Hertz. Through clear thinking and painstaking experimental work in a field which is continuously being flooded by different hypotheses, you have provided a firm footing for future research. In gratitude for your work and with sincere good wishes I request you to receive the Physics Nobel Prize for 1925 from the hands of our King.

JAMES FRANCK

Transformations of kinetic energy of free electrons into excitation energy of atoms by impacts

Nobel Lecture, December 11, 1926

Ladies and gentlemen!

The exceptional distinction conferred upon our work on electron impacts by the Royal Swedish Academy of Sciences requires that my friend Hertz and I have the honour of reporting to you on current problems within this province :

The division of the material between us left me with the task of presenting, in a historical setting, the development of these projects which have led to an association with Bohr s atomic theory.

Investigations of collision processes between electrons, atoms and molecules have already got well under way. Practically all investigations into the discharge of electricity through gases can be considered under this heading. An enormous amount of knowledge, decisive for the whole development of modern physics, has been gained, but it is just in this gathering that I feel it is unnecessary for me to make any special comment, since the lists of the men whom the Swedish Academy of Sciences have deemed worthy of the Nobel Prize contain a large number of names of research workers who have made their most significant discoveries in these fields.

Attracted by the complex problems of gas discharges and inspired particularly by the investigations of my distinguished teacher E. Warburg, our interest turned in this direction. A starting-point was provided by the observation that in inert gases (and as found later, also in metal vapour) no negative ions were formed by the attachment of free electrons to an atom. The electrons remained rather as free ones, even if they were moving slowly in a dense gas of this type, which can be inferred from their mobility in an electric field. Even the slightest pollution with normal gases produced, at once, a material attachment of the electrons and thus the appearance of normal negative ions.

As a result, one can perhaps divide gases somewhat more clearly than has been the case up to now from the observations described in the literature, into one class with, and one class without, an electron affinity. It was to be expected that the motion of electrons in gases of the latter kind would obey laws of a particularly simple kind. These gases have exhibited special behaviour during investigations of other kinds into gas discharges. For instance, according to Ramsay and Collie, they have a specially low dielectric strength, and this was, further, extremely dependent upon the degree of purity of the gas (see, for example, Warburg's experiments). The important theory of the dielectric strength of gases, founded by Townsend, the equations of which even today, when used formally, still form the basic foundation of this field failed in these cases. The reason for this seemed likely to be that Townsend's hypothesis on the kind of collisions between slow electrons and atoms, particularly inert-gas atoms, differed from the reality, and it seemed promising to arrive at a kinetic theory of electrons in gases by a systematic examination of the elementary processes occurring when collisions took place between slow electrons and atoms and molecules. We had the experiences and techniques to support us, which men like J. J. Thomson, Stark, Townsend, and in particular, however, Lenard, had created, and also had their concept of the free path-lengths of electrons and the ionization energy, etc., to make use of.

The free path-lengths in the light inert gases were examined first. By <<free path>> in this connection is to be understood that path which, on the average, is that which an electron traces between two collisions with atoms along a straight track. The distance is measurable as soon as the number of atoms per unit volume is sufficiently small, this being attained by taking a low gas pressure. The method of measurement itself differed but slightly from that developed by Lenard. It is unnecessary to go into closer detail since the results gave the same order of values for the free path-length as Lenard obtained for slow electrons in other gases. The value is of that order which is obtained by calculation if the formulas of the kinetic gas theory are used for the free path-length, taking for the impact radius of the electron a value which is very small compared with the gas-kinetic atom radii. With this assumption, the electrons behave, to a first approximation, like a gaseous impurity in the inert gas, not reacting chemically with it – an impurity, however, which has the special quality of consisting of electrically charged particles and having a vanishingly small impact radius. As a result of significant experiences, we know, today, from the work of Ramsauer and others on the free path-lengths of electrons in heavy inert gases that the picture we had formed at that time was a very rough one, and that for collisions of slow electrons the laws of quantum theory are of far more significance than the mechanical diameter, but as a first approximation for the establishment of the kinetics it suffices. Further, it also sufficed, as it turned out, to gain an understanding of the energy conversion on the occurrence of a collision between the slow electrons and the atoms of the inert gases and metal vapours. Since the mass of the electron is 1800 times smaller than that of the lightest atom we know, the hydrogen atom, the transfer of momentum from the light electron to the heavy atom during customary gas-kinetic collisions, i.e. collisions such as between two elastic balls, must be exceptionally small according to the laws of momentum. A slow electron with a given amount of kinetic energy, meeting an atom at rest, ought to be reflected without practically any energy loss, much the same as a rubber ball against a heavy wall. These elastic collisions can now be pursued by measurements.

I will pass over the detection of the single reflection and mention in more detail a simple experimental arrangement which, by means of an accumulation of collisions, enables us to measure the energy loss which is otherwise too small to measure in one elementary process. The mode of action might well be clear from a schematic layout (Fig. 1).

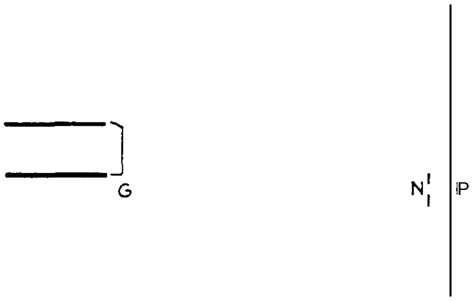

Fig. 1.

G indicates the electron source. It consists of a tungsten wire, heated to a bright-red glow by an electric current. That such a glowing wire is a source of electrons can, I think, be taken as read in this age of radio. A few centimetres away is a wire-screen electrode N. If we now charge the screen positively with respect to the glowing wire, by means of an accumulator, the electrons emitted by the wire towards the screen will be accelerated. The kinetic energy which the electrons must gain through this acceleration can easily be found for the case where no gas exists between G and N, that is, when the electrons fall through the field of force freely without collisions. We have the relationship :

$$\frac{1}{2} mv^2 = e \cdot V$$

Here, $\frac{1}{2}mv^2$ is the kinetic energy of each electron, e is its electrical elementary charge, and V the applied potential difference. If the latter is measured in volts, then, for instance, the kinetic energy of an electron which has fallen through 10 volts is approximately 10^{-11} ergs. We have become accustomed to speak of x-volt electrons, and to simply denote the acceleration voltage (x volts) as a measure of energy. Thus in our arrangement the electrons fall upon the screen with an energy of x volts (the potential difference between G and N). Some of the electrons are caught by the screen, some fly through the mesh. The latter, assuming no field between N and P which would throw the electrons back, all reach the electrode P and produce a negative current which flows to earth through a galvanometer. By introducing an electric field between N and P the energy distribution of those electrons passing through the screen can be determined. If, for example, we take only 4-volt beams, which pass perpendicularly through the screen, then the electron current measured at the galvanometer as a function of a decelerating potential difference applied between N and P, must be constant, until P becomes 4 volts more negative than N. At this point the current must become suddenly zero since henceforth all electrons will be so repelled from P that they return to N. If now we introduce an inert gas such as helium or a metal vapour between the three electrodes and choose such a pressure as will ensure that the electrons between G and N will make many impacts upon atoms, whilst passing freely through the space between N and P, we can determine, by plotting the energy distribution of the electrons arriving at P, whether the electrons have lost energy by impacts on the atoms. In discussing the resulting current-voltage curve it should be noted that the electrons no longer pass through the screen mesh perpendicularly, but are scattered in all directions due to reflection from the atoms. As a result of this, there is an easily calculable change in shape of the curve, and this holds, too, for uniform kinetic energy of the electrons. From a consideration of the resulting curves it was found that for not too high pressures, particularly for monatomic gases of high atomic weight, the kinetic energy of slow electrons was the same as for those in vacuum under the same acceleration voltage. The gas complicates the trajectory of the electrons in the same way that a ball's trajectory is affected by rolling down a sloping board bedecked with a large number of nails, but the energy (because of the large mass of the atom compared with that of the electron) is practically the same as for conditions of free fall. Only for high pressures, that is, with the occurrence of many thousands of collisions, can the energy loss corresponding to elastic collision be demonstrated.* A calculation of the number of collisions was later carried out by Hertz. Taking this as a basis and evaluating the curves measured for higher pressures accordingly, it emerges that, for example, energy is transferred to a helium atom amounting to $1.2–3.0 \times 10^{-4}$ of the energy of the electron prior to the collision, whilst the calculated value for the mass ratio under conditions of pure mechanical elastic impact is 2.9×10^{-4}. We may therefore, with close approximation to reality, speak of elastic collisions.

For polyatomic gases a significantly greater average energy loss was determined. Using the methods available at that time, it was not possible to distinguish whether this latter effect was contingent upon attachment of the electrons to the molecule, that is, the formation of negative ions, or whether a transfer of the kinetic energy of the striking electrons into vibrational and rotational degrees of freedom of the molecules was taking place. An investigation just carried out in my institute by Mr. Harries shows that the latter elementary process, even though at a low level, does occur, and is important in the explanation of the energy losses.

Can the principles of action found for slow electrons in the case of elastic collisions hold good for higher electron velocities? Apparently not, for the elementary knowledge of gas discharges teaches us that with faster electrons, i.e. with cathode rays, the impacted atoms are excited to luminescence or become ionized. Here, energy of the impacting electrons must be transferred into internal energy of the impacted atoms, the electrons must henceforth collide inelastically and give up greater amounts of energy. The determination of the least amount of energy which an electron must possess in order to ionize an atom was therefore of interest. Measured in volts, this energy is called the ionization voltage. Calculations of this value of energy by Townsend were available for some gases and these were based upon the validity of his assumptions about the course of the elementary action on collision. I mentioned already the reasons for doubting the correctness of these indirectly determined values. A direct method had been given by Lenard, but it gave the same ionization voltage for all gases. Other writers had obtained the same results within the range of measurement. We therefore repeated Lenard's investigations, using the improved pumping techniques which had become available in the meantime, and obtained characteristic, marked differences in values for the various gases. The method used by

* It is better to use here the experimental arrangements indicated later by Compton and Benade, Hertz, and others.

Lenard was as follows. Electrons, from a glowing wire, for example, were accelerated by a suitable electric field and allowed to pass through a screen grid into a space in which they suffered collisions with atoms. By means of a strong screening field these particular electrons were prevented from reaching an electrode to which was connected a measuring instrument. Atoms ionized by the impact resulted in the newly formed positive ions being accelerated through the screening field, which repelled the electrons, towards the negatively charged electrode. A positive current was thus obtained as soon as the energy of the electrons was sufficient for ionization to take place. I will talk later about the fact that a positive charge appears if the impacted atoms are excited to emit ultraviolet light, and that, as shown later, the charges measured at that time are to be attributed to this process and not to ionization, as we formerly supposed.

In any case, as already discussed, inelastic collisions were to be expected between electrons and atoms for the characteristic critical voltages appertaining to each kind of atom. And it proved easy to demonstrate this fact with the same apparatus as was used for the work on elastic collisions. Measurement of the energy distribution of the electrons, on increasing the accelerating voltage above the critical value, showed that electrons endowed with the critical translation energy could give up their entire kinetic energy on collision, and that electrons whose energy exceeded the critical by a fraction, likewise gave up the same significant amount of energy, the rest being retained as kinetic energy. A simple modification of the electric circuit diagram of our apparatus produced a significantly sharper measurement of the critical voltage and a visual proof of the discontinuously occurring release of energy from the electrons on collision. The measurement method consisted of measurements of the number of those electrons (possessing markedly different energies from zero after many collisions) as a function of the accelerating voltage.

The graph (Fig. 2) shows the results of measurements of electron current in mercury vapour. In this case, all electrons whose energy is greater than the energy of -½volt beams were measured. It can be seen that in Hg vapour this partial electron current increases with increasing acceleration, similar to the characteristic of « glow-electron » current in vacuum, until the critical energy stage is reached when the current falls suddenly to almost zero. Since the electrons cannot lose more or less than the critical amount of energy, the cycle begins anew with further increase of voltage. The number of electrons whose velocity is greater than $\frac{1}{2}$ volt, again climbs up until the critical value is

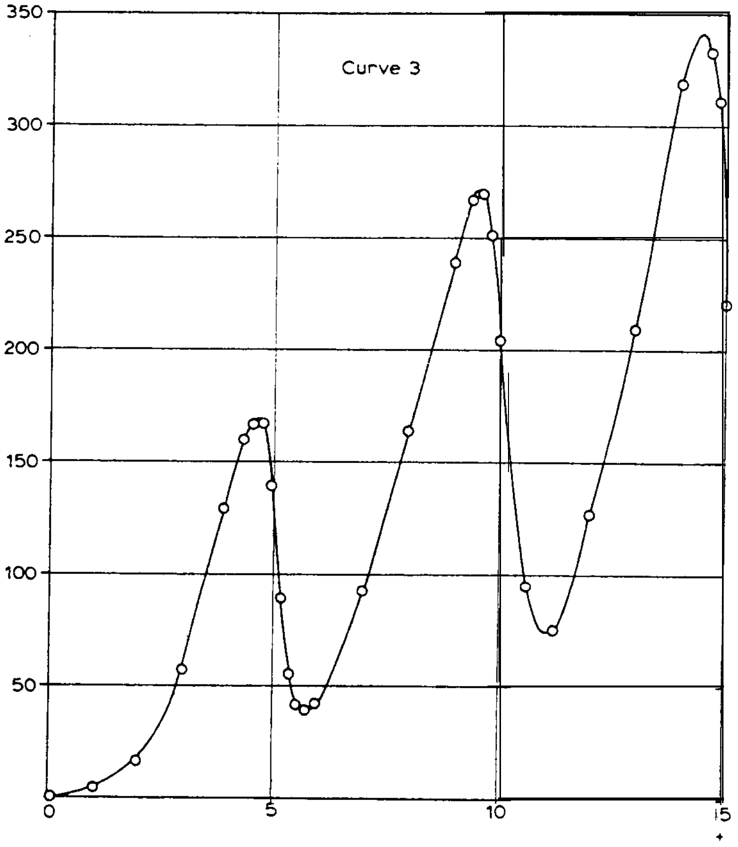

Fig. 2.

reached, the current again falls away. The process repeats itself periodically as soon as the accelerating voltage overreaches a multiple of the critical voltage. The distance between the succeeding maxima gives an exact value of the critical voltage. This is 4.9 V for mercury vapour.

As already mentioned we took this value to be the ionization voltage (the same applied to He which was determined by the same method and was about 20 V). Nevertheless, the quanta-like character of the energy transfer could not help but remind us-who practically from the start could witness from nearby the developments of Planck's quantum theory-to the use of the theory made by Einstein to explain the facts of the photoelectric effect ! Since here, light energy is converted into the kinetic energy of electrons, could not perhaps, in our case, kinetic energy from electrons be converted into light energy? If that were the case, it should be easy to prove in the case of mercury; for the equation $\frac{1}{2}mv^2 = h\nu$ referred to a line of 2,537 Å which is easily accessible in the ultraviolet region. This line is the longest wavelength absorption line of Hg vapour. It is often cited as Hg-resonance line since R.W. Wood has carried out with it his important experiments on resonance fluorescence. If the conjectured conversion of kinetic energy into light on impact should take place, 'then on bombardment with 4.9 eV electrons, the line 2,537 A, and only this line out of the complete line spectrum of mercury, should appear.

Fig. 3 shows the result of the experiment. Actually, only the 2,537 Å line appears in the spectrogram next to a continuous spectrum in the long-wave region emitted by the red-glowing filament. (The second spectrogram shows the arc spectrum of mercury for comparison.) The first works of Niels Bohr on his atomic theory appeared half a year before the completion of this work. Let us compare, in a few words, the basic hypothesis of this theory with our results.

According to Bohr an atom can absorb as internal energy only discrete quantities of energy, namely those quantities which transfer the atom from one stationary state to another stationary state. If following on energy supply an excited state results from a transfer to a stationary state of higher energy, then the energy so taken up will be radiated in quanta fashion according to the $h\nu$ relationship. The frequency of the absorption line having the longest wavelength, the resonance line, multiplied by Planck's constant, gives the energy required to reach the first state of excitation. These basic concepts agree in very particular with our results. The elastic collisions at low electron velocities show that for these impacts no energy is taken up as inner energy, and the first critical energy step results in just that amount of energy required for the excitation of the longest wave absorption line of Hg. Subse-

Fig. 3.

quently it appeared to me to be completely incomprehensible that we had failed to recognize the fundamental significance of Bohr's theory, so much so, that WC never even mentioned it once in the relevant paper. It was unfortunate that we could not rectify our error (due in part to external circumstances) ourselves by clearing up the still existing uncertainties experimentally. The proof that only monochromatic light was radiated at the first excitation step, as Bohr's theory required, and that the gas is not simultaneously ionized (as we were also obliged to think for reasons other than those mentioned) came about instead during the war period through suggestions from Bohr himself and from van der Bijl. The appearance of positive charge at the first excitation step in Lenard's arrangement was explained by them on the basis of a photoelectric effect at the collector electrode, an hypothesis which was substantiated by Davis and Goucher.

Time does not allow me to describe how our further difficulties were clarified in the sense of Bohr's theory. And in regard to further development, too, I would like to devote only a few words, particularly since my friend Hertz's lecture covers it more closely. The actual ionization voltage of mercury was for the first time determined by Tate as being 10.3 volts, a value which agreed exceptionally well with that resulting, according to Bohr, from the limit of the absorption series. A great number of important, elegantly carried out, determinations of the first excitation level and the ionization voltage of many kinds of atoms was made during the war years and also in the following years, above all by American scientists; research workers such as Foote and Mohler, K. T. Compton and others are to be thanked for extensive clarification in this field.

Without going into details of the experimental arrangements, I should like to mention that it later proved successful, by the choice of suitable experimental conditions, to demonstrate also, from the current-voltage curves, the stepwise excitation of a great number of quantum transitions, lying between the first excitation level and ionization. A curve plotted for mercury vapour might well serve again as an example. It shows the quantum-like appearance of higher excitation levels by kinks in the curve (Fig. 4). It is noteworthy that, in addition, transitions which under the influence of light according to Bohr's correspondence principle do not appear, manifest themselves clearly. When, as is the case with mercury, and still more decidedly so with helium, the first transition is such that it cannot be achieved by light, we have excited atoms in a so-called metastable state. The discovery of a metastable state by means of the electron-impact method was first suc-

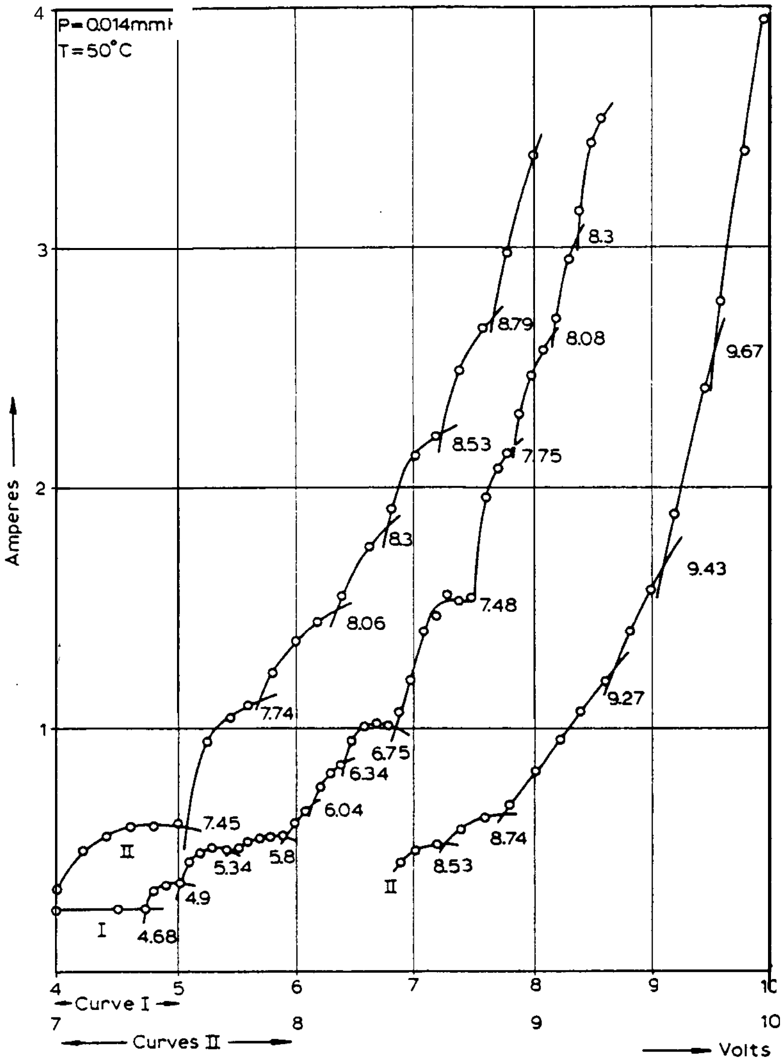

Fig. 4.

cessful with helium. Since helium is a gas in which the absorption series lies in the far ultraviolet-it was later found optically by Lyman-and on the other side, helium, apart from hydrogen, is the most simply constructed atom, the approximate determination of the energy levels of helium and perhaps too, the appearance, in particular, of the metastable level has proved useful for the development of Bohr's theory.

Much more could be said, but I think I have given you the main outline as far as is possible within the framework of a short survey, and must therefore draw to a close. The desire to describe, historically, our part in the development of the investigations leading to the establishment of the quantum transfer of energy to the atom by impacting electrons has forced me to take up your time with the description of many a false trail and roundabout path which we took in a field in which the direct path has now been opened by Bohr's theory. Only later, as we came to have confidence in his leadership, did all difficulties disappear. We know only too well that we owe the wide recognition that our work has received to contact with the great concepts and ideas of M. Planck and particularly of N. Bohr.

Biography

James Franck was born on August 26, 1882, in Hamburg, Germany. After attending the Wilhelm Gymnasium there, he studied mainly chemistry for a year at the University of Heidelberg, and then studied physics at the University of Berlin, where his principal tutors were Emil Warburg and Paul Drude. He received his Ph.D. at Berlin in 1906 under Warburg, and after a short period as an assistant in Frankfurt-am-Main, he returned to Berlin to become assistant to Heinrich Rubens. In 1911, he obtained the « venia legendi » for physics to lecture at the University of Berlin, and remained there until 1918 (with time out for the war in which he was awarded the Iron Cross, first class) as a member of the physics faculty having achieved the rank of associate professor.

After World War I, he was appointed member and Head of the Physics Division in the Kaiser Wilhelm Institute for Physical Chemistry at Berlin-Dahlem, which was at that time under the chairmanship of Fritz Haber. In 1920, Franck became Professor of Experimental Physics and Director of the Second Institute for Experimental Physics at the University of Göttingen. During the period 1920-1933, when Göttingen became an important center for quantum physics, Franck was closely cooperating with Max Born, who then headed the Institute for Theoretical Physics. It was in Göttingen that Franck revealed himself as a highly gifted tutor, gathering around him and inspiring a circle of students and collaborators (among them: Blackett, Condon, Kopfermann, Kroebel, Maier-Leibnitz, Oppenheimer, and Rabinovich, to mention some of them), who in later years were to be renowned in their own fields.

After the Nazi regime assumed power in Germany, Franck and his family moved to Baltimore, U.S.A., where he had been invited to lecture as Speyer Professor at Johns Hopkins University. He then went to Copenhagen, Denmark, as a guest professor for a year. In 1935, he returned to the United States as Professor of Physics at Johns Hopkins University, leaving there in 1938 to accept a professorship in physical chemistry at the University of Chicago. During World War II Franck served as Director of the Chemistry

Division of The Metallurgical Laboratory at the University of Chicago, which was the center of the Manhattan District's Project.

In 1947, at the age of 65, Franck was named professor emeritus at the University of Chicago, but he continued to work at the University as Head of the Photosynthesis Research Group until 1956.

While in Berlin Professor Franck's main field of investigation was the kinetics of electrons, atoms, and molecules. His initial researches dealt with the conduction of electricity through gases (the mobility of ions in gases). Later, together with Hertz, he investigated the behaviour of free electrons in various gases-in particular the inelastic impacts of electrons upon atoms-work which ultimately led to the experimental proof of some of the basic concepts of Bohr's atomic theory, and for which they were awarded the Nobel Prize, for 1925. Franck's other investigations, many of which were carried out with collaborators and students, were also dedicated to problems of atomic physics - those on the exchange of energy ofexcited atoms (impacts of the second type, photochemical researches), and optical problems connected with elementary processes during chemical reactions.

During his period at Göttingen most of his studies were dedicated to the fluorescence of gases and vapours. In 1925, he proposed a mechanism to explain his observations of the photochemical dissociation of iodine molecules. Electronic transitions from a normal to a higher vibrational state occur so rapidly, he suggested, that the position and momenta of the nuclei undergo no appreciable change in the process. This proposed mechanism was later expanded by E. U. Condon to a theory permitting the prediction of most-favoured vibrational transitions in a band system, and the concept has since been known as the Franck-Condon principle.

Mention should be made of Professor Franck's courage in following what was morally right. He was one of the first who openly demonstrated against the issue of racial laws in Germany, and he resigned from the University of Göttingen in 1933 as a personal protest against the Nazi regime under Adolf Hitler. Later, in his second homeland, his moral courage was again evident when in 1945 (two months before Hiroshima) he joined with a group of atomic scientists in preparing the so-called « Franck Report » to the War Department, urging an open demonstration of the atomic bomb in some uninhabited locality as an alternative to the military decision to use the weapon without warning in the war against Japan. This report, although failing to attain its main objective, still stands as a monument to the rejection by scientists of the use of science in works of destruction.

In addition to the Nobel Prize, Professor Franck received the 1951 Max Planck Medal of the German Physical Society, and he was honoured, in 1953, by the university town of Göttingen, which named him an honorary citizen. In 1955, he received the Rumford Medal of the American Academy of Arts and Sciences for his work on photosynthesis, a subject with which he had become increasingly preoccupied during his years in the United States. In 1964, Professor Franck was elected as a Foreign Member of the Royal Society, London, for his contribution to the understanding of exchanges of energy in electron collisions, to the interpretation of molecular spectra, and to problems of photosynthesis.

Franck was first married (1911) to Ingrid Josefson, of Göteborg, Sweden, and had two daughters, Dagmar and Lisa. Some years after the death of his first wife, he was married (1946) to Hertha Sponer, Professor of Physics at Duke University in Durham, North Carolina (U.S.A.).

Professor Franck died in Germany on May 21, 1964, while visiting in Göttingen.

GUSTAV HERTZ

The results of the electron-impact tests in the light of Bohr's theory of atoms

Nobel Lecture, December 11, 1926

The significance of investigations on the ionization of atoms by electron impact is due to the fact that they have provided a direct experimental proof of the basic assumptions of Bohr's theory of atoms. This lecture will summarize the most important results, and show that they agree in every detail, so far as can be observed at present, with what we should expect on the basis of Bohr's theory.

The fact that atoms are capable of exchanging energy with electromagnetic radiation, led the classical physicists to conclude that atoms must contain moving electrical charges. The oscillations of these charges produce the emission of light radiation, while light absorption was ascribed to forced oscillations of these charges owing to the electrical field of the light waves. On the basis of Lorentz's theory of the normal Zeeman effect, of the magnetic splitting of the spectral lines, it was concluded that these moving charges must be the electrons to which we are acquainted in cathode rays. If only one or several spectral lines were associated with each type of atom, then it might be assumed that the atom contained, for each spectral line, an electron of corresponding characteristic frequency. In reality, however, the number of spectral lines emitted by each atom is infinitely large. The spectral lines are certainly not randomly distributed, on the contrary there exists a certain relationship between their frequencies, but this relationship is such that it is impossible on the basic of classical physics to explain it in terms of the characteristic frequencies of a system of electrons. Here Bohr stepped in with his atomic theory. He applied Planck's quantum theory to the problem of atomic structure and light emission, and thereby greatly extended this theory. It is well-known that Planck, in evolving the law of heat radiation was in contradiction to classical physics. He had come to the conclusion that the processes of emission and absorption of light did not obey the laws of classical mechanics and electrodynamics. In Planck's quantum theory it is assumed that emission and absorption of monochromatic radiation can occur only in an electrical oscillator of the same frequency, moreover that in such processes the energy must be emitted or absorbed in discrete quantities only. According to Planck, the magnitude of such a quantum is proportional to the frequency of the radiation. The proportionality factor is Planck's constant $h = 6.55 \times 10^{-27}$ erg sec, which is fundamental to the entire later development. Bohr realized that the simple picture of emission and absorption by an oscillating electron and hence the connection between the frequency of the light wave and that of the oscillating electron, was inadequate in explaining the laws governing line spectra. But he retained from Planck's theory the basic relationship between the radiation frequency and the magnitude of the emitted and absorbed energy quanta, and based his atomic theory on the following fundamental assumptions :

(1) For every atom there is an infinite number of discrete stationary states, which are characterized by given internal energy levels in which the atom can exist without emitting radiation.

(2) Emission and absorption of radiation are always connected with a transition of the atom from one stationary state to another, emission involving transition to a state of lower energy, and absorption involving transition to a state of higher energy.

(3) The frequency of the radiation emitted or absorbed respectively during such a transition is given by the equation

$$h\nu = E_1 - E_2$$

where h is Planck's constant and E_1 and E_2 denote the energy of the atom in the two stationary states.

These basic assumptions were supplemented by special theories concerning the nature of the motion of the electrons in the atom, and here Bohr adopted Rutherford's theory that the atom consists of a positive nucleus and of a number of electrons, the total charge of the electrons being equal to the charge of the nucleus. By means of equations also containing Planck's constant, the possible states of motion are determined. These can be considered to be stationary states of the atom. The laws of the motion of the electrons in the atom constituted a major part of Bohr's theory, and in particular have enabled us to calculate the Rydberg constant on the basis of thermal and electrical data, and explain the Periodic System of the elements; however, we need not deal with them in detail here. One fact only is of importance with regard to the electron-impact tests, namely that the set of stationary states of an atom associated with a series spectrum, corresponds to a gradual decrease in binding energy of one of the electrons of atom. Moreover, the successive stationary states differ by progressively smaller amounts ofbinding energy of the electron, and converge towards the state of total separation of the electron from the atom.

As an example of series spectra we will now take the simplest case, the spectrum of the hydrogen atom. The frequencies of all the lines in this spectrum can be obtained with great accuracy from the formula

$$\nu = R\left(\frac{1}{m^2} - \frac{1}{n^2}\right)$$

where m and n can represent any integers. Every line is associated with a given value of m, while n ranges over the series of integers from $m+1$ to ∞. In this way the lines form series; thus, for example, for m = 2 we get the well-known Balmer series which is shown diagrammatically in Fig. 1. The characteristic arrangement of the lines, with an accumulation of lines when approaching a given limiting frequency, the so-called series limit, is found in all spectral line series.

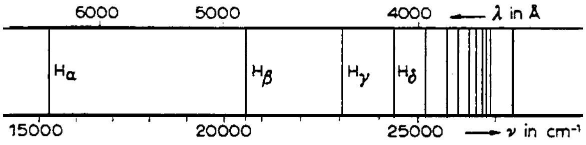

Fig. 1.

In the above formula the frequency of a given spectral line is equated to the difference between two quantities, each of which can assume an infinite series of discrete values. The interpretation of these quantities in the sense of Bohr's theory follows directly from the basic assumptions of this theory: apart from a numerical factor, they are equal to the energy of the atom in its various stationary states. Closer consideration shows that here the energy has to be given a minus sign, i.e. a lower energy is associated with a smaller value of *m* or *n*. Thus, the lines of a series correspond to transitions from a series of initial states of higher energy to one final state.

Fig. 2 illustrates diagrammatically the origination of the series associated with the first four stationary states of the hydrogen atom.

In the other elements the situation is in varying degrees more complicated than in the case of hydrogen. All series spectra however have one property in common with that of hydrogen; this is the property represented by the Ritz combination principle, which states that the frequencies of the individu-

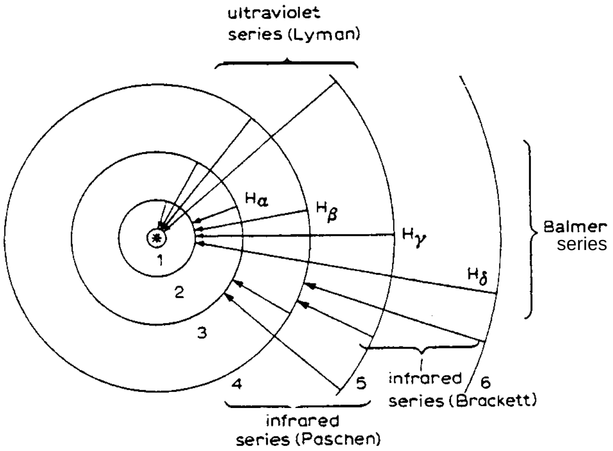

Fig. 2.

al spectral lines are always represented as differences between one or more series of discrete numerical values. These numerical values, the so-called terms, replace the quantities R/n^2 in the case of hydrogen. They differ from these quantities since the formulae representing their values are more complicated, but they agree with these quantities in so far as the differences between the successive terms become smaller and smaller and the term values converge towards zero as the current number n increases.

As an example, Fig. 3 represents diagrammatically the spectrum of mercury. The individual terms are shown by short horizontal lines with the current number at the side of them, and they are arranged in increasing order with the highest term at the top, so that the value of a term can be determined from its distance from the straight line running across the top of the figure. The terms are also presented in the figure in such a way that for a given series they always appear in a column, so that it can be seen how the terms of such a series come closer and closer together as the current number increases, finally converging towards zero. We need not discuss here the reasons for this particular arrangement of the terms. What is important, is that the frequency of every spectral line is equal to the difference between two terms. Thus, a certain combination of two terms is associated with each line. In Fig. *3* some of the lines of the mercury spectrum are indicated by a straight line connecting the two terms with which the line in question is associated. It should be noted that the length of these straight connecting lines is of no physical importance, the frequency of the line depends solely on the difference between the two terms, i.e. the difference between their heights in

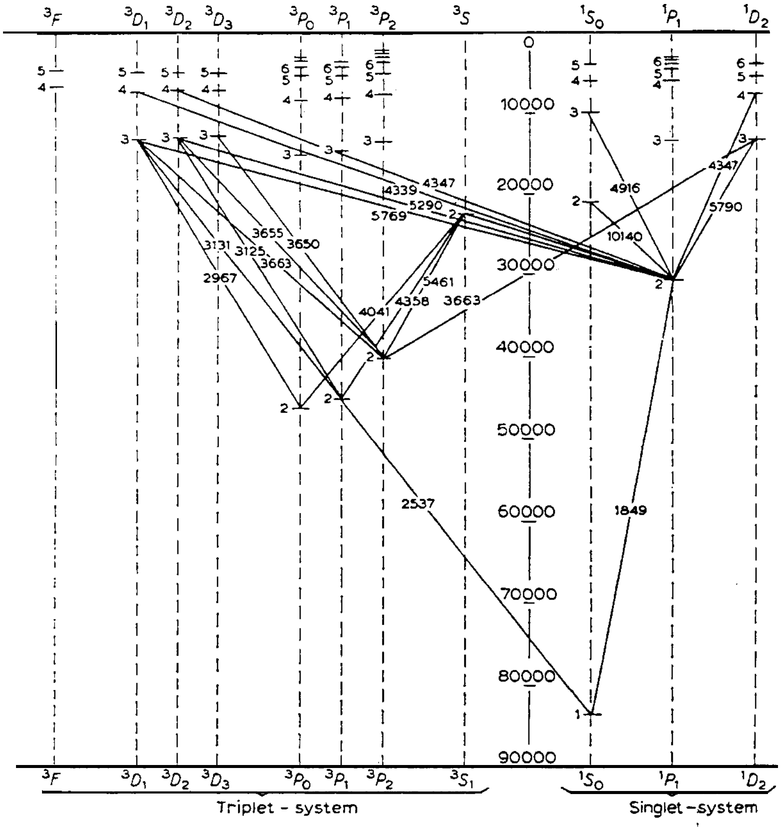

Fig. 3.

Fig. 3. Incidently, the scale included in Fig. 3 gives the terms not in frequencies but in the unit of wave numbers (reciprocal of the wavelength) commonly used in spectroscopy.

In exactly the same way as in the above case of hydrogen, we now come to the interpretation of this diagram by the Bohr theory.

A comparison of the relation between the frequency of a spectral line and the corresponding two terms namely :

$$\nu = T_1 - T_2$$

on the one hand and the Bohr frequency condition namely:

$$h\nu = E_1 - E_2$$

on the other hand, leads to the following equation:

$$T_n = -\frac{E_n}{h}$$

Thus, according to Bohr, the spectral terms denote the energy levels of the atom in the various stationary states, divided by Planck's constant and prefixed by a minus sign. The reason why the energy levels are negative here, is simply due to the omission of an arbitrary constant which has always to be added to the energy; here it is omitted because we are simply determining the energy differences. Since in our Fig. 3 the terms are arranged in vertical columns with the highest term at the top, the corresponding energy levels rise from the bottom to the top; hence the term diagram gives a direct indication of the energy levels at which the atom can exist in its stationary states. The minimum level energy is associated with the stationary state of the atom from which further transitions to states of still lower energy are impossible. The term associated with this energy level is called the ground term of the spectrum, and corresponds to the normal state of the atom. In contrast with this normal state, the states richer in energy are called excited states. To lift the atom from its ground state into a given excited state a certain work is required, and this is called the excitation energy. The magnitude of the excitation energy can be found directly from the term diagram, because it must be equal to the energy difference between the ground state and the relevant excited state. If we call the ground term T_0, we obtain the excitation energy to produce the excited state associated with a term T namely :

$$A = h\,(T_0 - T)$$

As a special case we will now consider the excitation energy for producing the state associated with the term $T = 0$. This is the term on which all the term series converge with increasing current numbers. According to Bohr's theory, this term corresponds to the state of the atom in which an electron is completely removed, i.e. the state of the positive ion. The associated excitation energy is the work required to remove an electron, the so-called ionization energy. Thus Bohr's theory requires that the ionization energy of an atom and the ground term of its series spectrum should be simply interrelated by :

$$A_{ioniz} = hT_0$$

The possibility to check this relationship experimentally by means of an electron-impact test follows from Bohr's theory. The identity of the energy difference between the terms of the series spectrum and of the energy of the atom in its various stationary states, leads to the conclusion that the amounts of energy transmitted during collisions between electrons and atoms can be measured directly, and that phenomena which occur when given amounts of energy are imparted to the atom, can be observed. What can we expect on the basis of Bohr's theory, when electrons of a given velocity collide with atoms? If energy is imparted to the atom during such a collision, the result can only be that the atom will be lifted from its ground state to a stationary state of higher energy.

Hence, only given amounts of energy can be transferred to the atom, and each of the possible energy amounts is equal to the excitation energy of a given excited state of the atom. Hence, according to what we have said above, each possible energy amount should be calculable from the associated series term. Among the excited states of an atom, there is always one state for which the excitation energy is a minimum. Thus, the excitation energy associated with this state represents the minimum amount of energy that can be imparted to the atom as a result of an electron impact. So long as the energy of the colliding electron is smaller than this minimum excitation energy, no energy will be transferred to the atom by this collision, which will be a purely elastic one, and the electron will then lose only the extraordinarily small amount of energy which owing to the conservation of momentum takes the form of kinetic energy of the atom. But as soon as the energy of the electron exceeds the minimum excitation energy, some energy will be transmitted from the electron to the atom by the collision, and the atom will be brought into its first excited state. If the energy of the electron rises further, so that it progressively equals and exceeds the excitation energy of higher excited states, the electron will lift the atom into these higher states by the collision, while the energy quantum transmitted will always be equal to the excitation energy of the excited state. If the energy of the electron finally equals the ionization energy, an electron will be removed from the atom by the collision, so that the atom will be left as a positive ion.

In the experimental investigation of these processes a given energy is usually imparted to the electrons by accelerating them by a given voltage. The energy of an electron after the collision is studied by determining the retarding potential which it can still overcome. Therefore, the excitation energy of a given state corresponds to the potential difference through which an electron with zero initial velocity has to fall in order to make its energy equal to the excitation energy of the atom. This excitation potential is thus equal to the excitation energy divided by the charge of the electron. The ionization potential is associated with the ionization energy in the same way. The main object of the electron-impact experiments was the measurement of the excitation and of the ionization potentials. The methods used can be divided into three main groups. Those of the first group are similar to the Lenard method we used in our first tests. They are characterized by the fact that the occurrence of non-elastic collisions of given excitation potentials is studied by investigating electrically the resulting phenomena. The phenomena concerned here are the photoelectric release of electrons by the ultraviolet light produced as a result of excitation collisions, and the positive charging of collector electrodes by positive ions in the case of impacts of electrons with energies above the ionizing potential. The improvement made to this method by Davis and Goucher, which made it possible to distinguish between these two phenomena, was of fundamental importance. This consisted of introducing a second wire gauze within a short distance from the collector ‘plate. To this gauze a small positive or negative potential respectively as compared with the collector plate was applied. When this potential was positive, then the test equipment operated exactly as in the original Lenard method, i.e. the photo-electrons released at the plate were carried away from the plate, while the positive ions produced as a result of ionizing collisions were drawn on to the collector plate. On the other hand, if a negative potential was applied to the wire gauze, the positive charging up of the plate was prevented, since the photo-electrons were returned to the plate by the electrical field. Instead, negative charging of the plate occurred by the photo-electrons released at the wire gauze. Another way of improving the Lenard method consists in arranging the effective collisions between the electrons and the gas molecules in a field-free space, again by introducing a second wire gauze, so that all the collisions occur at a uniform electron velocity. There, the inelastic collisions occur from a given excitation potential onwards far more sharply. In this way it was possible to determine, not only the lowest excitation potentials but also the higher ones, from kinks in the curve representing the photo-electric current released on the plate as a function of the accelerating potential of the electrons.

The methods of the second group follow closely those which we used first in the case of mercury vapour, where we did not study the phenomena caused by the electron impact, but the primary electrons themselves, in order to find out whether or not they lost energy during the collision. In its original form this method is particularly suitable for measuring the first excitation potential of metal vapours. Like the Lenard method, this method was modified in such a way that the electric collisions occurred in a field-free space, i.e. at a uniform electron velocity. Here too it was possible to measure the higher excitation potentials. A special version of this method, which has been found particularly useful in the case of the inert gases, consists of measuring the number of electrons with zero velocity after the collisions. This can be the case only when the energy of the electrons before the collision is exactly equal to the excitatron energy of a given stationary state. Hence, a sharply defined peak in the measured curves is obtained for every excitation potential.

Whereas in the first two groups of experimental methods the excitation and ionization potentials were determined by electrical measurements, in the third group of methods we carried out a spectroscopic examination of the light emitted as a result of collisions between electrons and molecules, or so far mostly of collisions between electrons and atoms. The method of observation is that which we used to determine the quantum excitation of the mercury resonance line, and it was refined in exactly the same way as the methods described earlier, by making the collisions take place in a field-free space. Since this method has been used mainly to determine the successive appearance of the individual lines of a spectrum at the corresponding excitations potentials, and not to carry out accurate measurements of excitation potentials, we shall not discuss the results obtained thereby until we have dealt with those obtained with the other methods.

By comparing the values of the excitation and ionization potentials found experimentally, with the values calculated from the series terms, we will now show that extremely good agreement has been obtained in all the cases studied so far. The position is simplest in the case of the alkali metals. Fig. 4 illustrates the series diagram of sodium graphically; the spectra of the other metals of this group are of a similar type. The ground term is the term denoted by $1S$; proceeding from this term to the states of higher energy, we first find two different terms, the energies of which differ very little from each other and which are denoted by 2^2P_1 and 2^2P_2. The transitions of the atom from the stationary states associated with these terms, to the ground state, are connected with the emission of the so-called resonance lines; in the case of sodium these are the two components of the well-known yellow sodium line. They are called resonance lines because an atom that has been excited through absorption of radiation of the frequency of these lines must;

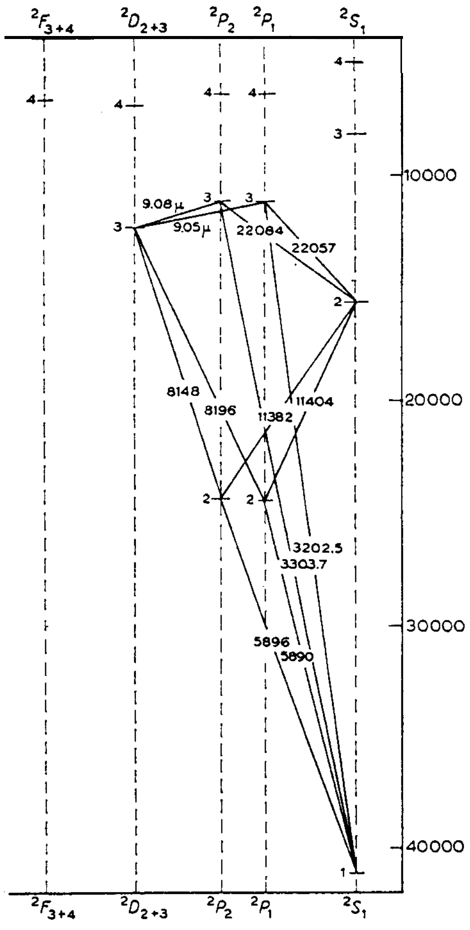

Fig. 4.

on returning to the ground state, emit as radiation of the same frequency, all the energy which it gained by absorption. Hence in relation to the radiation of this frequency, the atom behaves as an electrical oscillator of this characteristic frequency. The first excitation potential V_{exc} of the alkali metals is found, not only as in all the other cases from the difference between the ground term and the next term above it, but, on the basis of Bohr's frequency condition, very simply from the frequency ν_{res} of the resonance line, viz. :

$$V_{exc} \cdot e = h\nu_{res}$$

where e is the charge of the electron. It will be seen from Fig.4 that for electron impacts leading to this first excitation potential, emission of the resonance lines must take place; hence, the name of resonance potential has been given to this excitation potential of the resonance lines. It should be noted, however, that it is only in the case of the alkali metals that the resonance potential is identical with the first excitation potential. Table 1 compares the spectroscopic data, the data calculated therefrom on the basis of Bohr's theory, and the resonance and ionization potentials observed in electron-impact tests, for the alkali metals. The agreement between the calculated and observed values shows that the conclusions from Bohr's theory are completely verified by the electron-impact tests.

In the case of the metals of the second column of the Periodic Table the spectrum is rather more complicated, because it is made up of two systems, the singlet and the triplet system, as can be seen for example in the diagram of the mercury spectrum shown in Fig. 3. Each of these systems contains a resonance line, in the case of mercury these are the lines 1849 and 2537 Å drawn in the diagram. Here, however, the first excitation potential is not equal to the excitation potential of a resonance line, because there is still another stationary state at a slightly lower energy level than that to which

Table 1.

	Z		ν	λ *in Å*	*Volts*	
					Spectroscopic	*Electrical*
Li	3	$1S$	43484.45		5.368	
		$1S—2P_2$ $1S—2P_1$	14903.09	6708.2	1.840	
Na	11	$1S$	41448.59		5.116	5.13[1] 5.18[2]
		$1S—2P_2$	16955.88	5895.9	2.093	2.12[1] 2.13[2]
		$1S—2P_1$	16973.52	5889.9		
K	19	$1S$	35005.88		4.321	4.1[1] 4.41[2]
		$1S—2P_2$	12985.05	7699.1	1.603	1.55[1,2]
		$1S—2P_1$	13042.95	7664.9	1.610	1.63[4]
Rb	37	$1S$	33684.80		4.159	4.1[3]
		$1S—2P_2$	12579.01	7947.6	1.553	1.6[3]
		$1S—2P_1$	12816.72	7800.2	1.582	
cs	55	$1S$	31406.70		3.877	3.9[3]
		$1S—2P_2$	11178.4	8943.6	1.380	1.48[3]
		$1S—2P_1$	11732.5	8521.2	1.448	

[1] I. T. Tate and P. D. Foote; [2] A. Campetti; [3] P. D. Foote, O. Rognley, and F. L. Mohler; [4] R. C. Williamson.

the atom is excited by absorption of the longer-wave resonance line. Such a state is called metastable by Franck, because an atom which has reached such a state cannot return to the normal state spontaneously through emission. In the case of mercury, where this initial excitation potential is located 0.22 V below the resonance potential, the separation of the two terms can be proved experimentally. In the other metals of this column of the Periodic Table the difference is only a few hundredths of a volt, so that the two terms cannot be distinguished by the electron-impact method. Table 2, which is similar to Table I, compares the experimental values with the values obtained from the series terms, for the metals of the second column of the Periodic Table.

In addition to metal vapours, the inert gases are suitable for investigation by the electron-impact method, because they too are monatomic and have no electron affinity. Compared with metal vapours, it is of the great advantage that the inert gases can be examined at room temperature, and this is very important for accurate measurements. Since their excitation potentials are greater than those of all other gases, they are highly sensitive to impurities. Another drawback, especially in the case of the heavy inert gases, is due to the fact that the yield of the excitation collisions is far smaller than that of the metal vapours. Hence, the methods that can be used with metal vapours are more or less unsatisfactory in the case of the inert gases. For example, the method of determining the absolute value of the first initial excitation potential from the distance between successive peaks, cannot be used here. This makes it very difficult to find the absolute values of the excitation potentials. The velocity of the impacting electrons does generally not correspond accurately to the applied accelerating potential Instead, owing to the initial velocity of the electrons, the potential drop along the hot filament, and any Volta potential difference between the hot filament and the other metal parts of the test equipment, a correction has to be made, amounting to a few tenths of a volt. If, as in the case of the metal vapours, the initial excitation potential can be determined by a method in which this error is eliminated, then the correction is knownimmediately for the other excitation potentials as well. If this is impossible, then an uncertainty arises; this in fact proved to be very troublesome in the first measurement of the excitation potential ofhelium. It was only after the excitation potentials of helium had been determined accurately by spectroscopic means, that this gas could be used to calibrate the apparatus, i.e. to determine the correction required. In this way, especially after the introduction of the above-mentioned method, it became possible to measure accurately the excitation and ionization potentials of the other inert gases.

Already our first measurements had indicated that the initial excitation potential of helium was about $_{20}$V (at the time we erroneously believed that this was the ionization potential). Later and more accurate measurements by Franck and Knipping confirmed this result, they also showed that the true ionization potential is 4.8 V higher than this. Fig. 5 gives the diagram of the helium spectrum as it was known at the time when these measurement were made. The spectrum consists of two series systems, the terms of which do

Table 2.

	Z		ν	λ *in Å*	*Volts*			
					Calculated	*Observed*		
Be	4	1^1S						
		1^1S—2^3P_1						
		1^1S—2^1P						
Mg	12	1^1S	61663.0		7.61	7.75[1]		8.0[2]
		1^1S—2^3P_1	21869.5	4571.33	2.70	2.65[1]		2.65[2]
		1^1S—2^1P	35050.3	2852.2	4.32	...		4.42[2]
Ca	20	1^1S	49304.8		6.08	6.01[3]		
		1^1S—2^3P_1	15210.1	6572.8	1.88	1.90[3]		
		1^1S—2^1P	23652.4	4226.7	2.92	2.85[3]		
Sr	38	1^1S	45924.31		5.67			
		1^1S—2^3P_1	14502.9	6892.8	1.79			
		1^1S—2^1P	21697.66	4607.5	2.68			
Ba	56	1^1S	42029.5		5.19			
		1^1S—2^3P_1	12636.6	7911	1.56			
		1^1S—2^1P	18060.2	5535.5	2.23			
Zn	30	1^1S	75758.6		9.35	9.5[4]		9.3[2]
		1^1S—2^3P_1	32500.7	3076.0	4.02	4.1[4]		4.18[2]
		1^1S—2^1P	46743.6	2139.3	5.77			5.65[2]
Cd	48	1^1S	72532.8		8.95	9.0[2]		8.92[5]
		1^1S—2^3P_1	30655.2	3261.2	3.78	3.95[2]		3.88[5]
		1^1S—2^1P	43691.2	2288.8	5.39	5.35[2]		
Hg	80	1^1S	84181.5		10.39	10.2[2]	10[6]	10.1[7]
						10.8[8]	10.3[9]	10.4[10]
		1^1S—2^3P_1	39412.6	2536.5	4.86	4.9[2]		
		1^1S—2^1P	54068.7	1849.5	6.67	6.7[2]		

[1] P. D. Foote and F. L. Mohler; [2] F. L. Mohler, P. D. Foote, and W. F. Meggers; [3] F. L. Mohler, P. D. Foote, and H. F. Stimson; [4,5] I. T. Tate and P. D. Foote; [6] F. M. Bishop; [7] C. G. Found; [8] G. Stead and B. S. Gossling; [9] I. T. Tate; [10] B. Davis and F. S. Goucher.

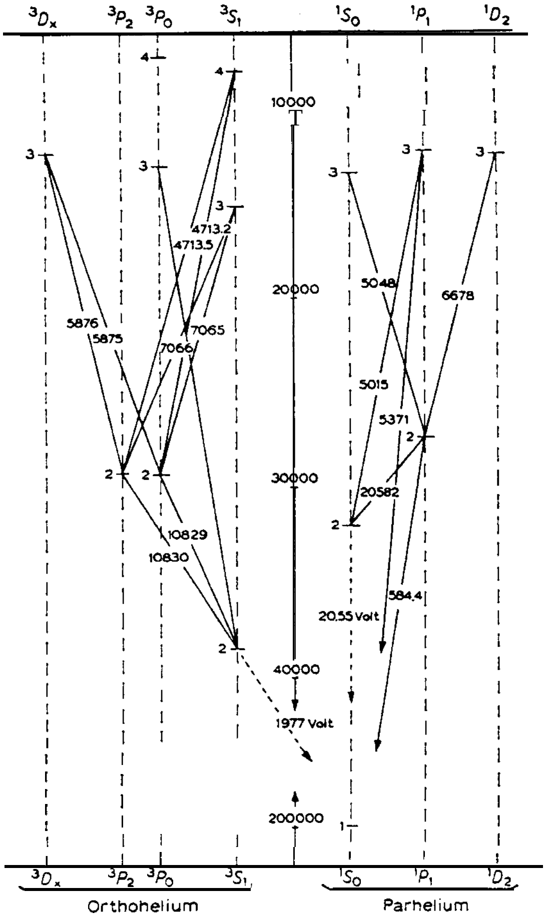

Fig. 5.

not combine with each other. This means that there are two systems of stationary states, having the property that by light emission the atom will always pass from an excited state in one of the two systems, to a state of the very same system. A comparison with the measured values of the excitation and ionization potentials shows immediately that the lowest term of this diagram is not by any means the ground term, though it is the term corresponding to the normal state of the helium atom. This term is not equal to the ionization energy divided by h, but it is equal to the difference between the initial excitation energy and the ionization energy, divided by h. Hence the diagram of helium has to be supplemented by another term, the ground term, which lies about 20 V below the term with the lowest energy of those previously known. The existence of this term was soon demonstrated by Lyman's spectroscopic measurements of the helium spectrum in the extreme ultraviolet region, when its magnitude was also determined accurately. The resulting values of the critical potentials are: for the initial excitation potential 19.77 V, for the ionizing potential 24.5 V. Franck recognized as metastable the first excited state of helium on the basis of Paschen's observation of resonance fluorescence in electrically excited helium, and thus was the first to demonstrate the existence of atoms in the metastable state.

The other inert gases are also very interesting as regards to the verification of Bohr's theory by means of electron-impact tests. Their excitation and ionization potentials were measured at a time when the spectra in the shortwave ultraviolet region which were required for the spectroscopic determination of these critical potentials, were still unknown. Table 3 illustrates the close agreement between the values of the initial excitation potentials and the ionization potentials measured by the electron-impact method, and the values obtained later from measurements in the short-wave spectrum. Because the time here is not available we have to refrain here from discussing other interesting features of the results.

In the third group of tests, i.e. those in which the radiation produced by electron-collisions was studied in relation to the energy of the colliding electrons by spectroscopic methods, the results appeared for some time to contradict Bohr's theory. In fact, our results concerning the mercury resonance line showed that the impact of electrons with energies immediately above the resonance potential excited the mercury atom to emit this line without the appearance of the other lines, and this was confirmed by a study of the corresponding lines of other metals of the second column of the Periodic

Table 3.

	First excitation potential– measured (*volts*)	*Excitation potential of long-wave resonance line– calculated* (*volts*)	*Ionizing potential– measured* (*volts*)	*Ionizing potential– calculated* (*volts*)
Neon	16.6	16.60	21.5	21.47
Argon	11.5	11.57	15.4	15.7
Krypton	9.9	9.99	13.3	still unknown
Xenon	8.3	8.40	11.5	

Table. These investigations, which were carried out mainly by American workers, also showed that the behaviour of the second resonance line was exactly the same. It will be seen directly from the diagram of the mercury spectrum in Fig. 3 (cf. also Table 2), that this line must also appear, as soon as by an increase of the accelerating potential above the excitation potential of the longer-wave resonance line, the excitation potential of the shorter-wave resonance line is reached. The emitted spectrum now contains only the two resonance lines. In Fig. 6, which shows photographs of the magnesium spectrum obtained from excitation by the impact of electrons of various velocities (taken from a work by Foote, Meggers, and Mohler), these two stages are clearly visible. According to Bohr it was be expected that on further rise in. the velocity of the impacting electrons the other spectral lines would appear in succession at the excitation potentials calculated from the series diagram. Surprisingly, the tests first gave a different result, namely that the higher-series lines all seemed to appear simultaneously once the ionizing potential was exceeded. But it is the behaviour of these higher-series lines which is of greatest importance for the experimental verification of Bohr's theory. In the case of the resonance lines, which correspond to transitions of the atom from an excited state to the normal state of the atom, the excitation potential is determined by the simple relation $V \cdot e = h\nu$; in relation to the emission of a resonance line, the atom thus behaves like a Planck oscillator having the frequency of this line. It is in fact characteristic for Bohr's theory that in the case of the higher-series lines the excitation potential must be calculated, not from the frequency of the line on the basis of the $h\nu$-relation, but from the series terms in the manner described in detail above. When the tests were

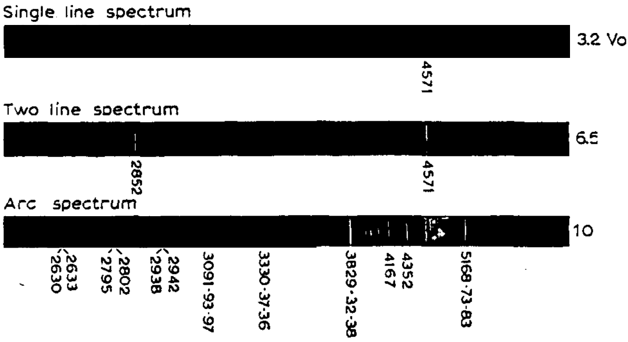

Fig. 6.

further refined, mainly by eliminating the interference of space charges, the higher-series lines were also found to behave in the manner predicted according to Bohr's theory. As examples to illustrate this behaviour we present in Figs. 7 and 8 photographs of the spectra of mercury and helium which were excited by the impact of slow electrons of various velocities. The wavelengths of the individual lines are given, together with (in brackets) the excitation potentials in volts, calculated from the series terms.

Summarizing therefore, it can be stated that all the results so far attained with the electron-impact method agree very closely with Bohr's theory and in particular that they verify experimentally Bohr's interpretation of the series terms as a measure of the energy of the atom in its various stationary states. We can hope that further applications of this method of investigation will provide more material for testing recent developments of the theory. So

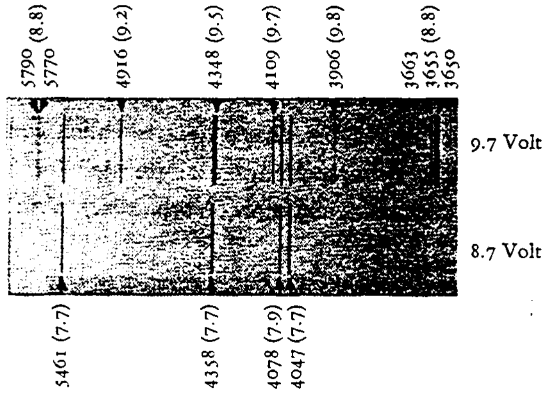

Fig. 7.

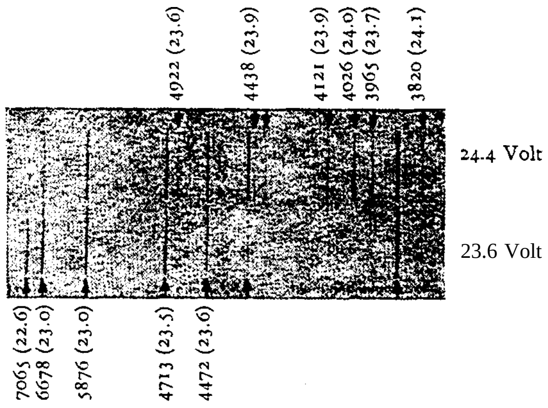

Fig. 8.

far the tests are concerned almost exclusively with the amount of energy transmitted by electron-impact. The next important task consists in the measurement of the yield of non-elastic electron-collisions, i.e. of the probability that in a collision between an electron of sufficient velocity and an atom, energy will in fact be transferred. Exploratory tests in this field have already been made, but no definitive conclusions have yet been reached. Naturally such tests will also lead to a closer investigation of the elastic collisions, and to a study of problems of the mean free path, which have become particularly interesting as a result of Ramsauer's measurements, and of many other problems, so that there is ample scope for further experimental work in this field.

Biography

Gustav Ludwig Hertz was born in Hamburg on July 22nd, 1887, the son of a lawyer, Dr. Gustav Hertz, and his wife Auguste, née Arning. He attended the Johanneum School in Hamburg before commencing his university education at Göttingen in 1906; he subsequently studied at the Universities of Munich and Berlin, graduating in 1911. He was appointed Research Assistant at the Physics Institute of Berlin University in 1913 but, with the onset of World War I, he was mobilized in 1914 and severely wounded in action in 1915. Hertz returned to Berlin as Privatdozent in 1917. From 1920 to 1925 he worked in the physics laboratory of the Philips Incandescent Lamp Factory at Eindhoven.

In 1925, he was elected Resident Professor and Director of the Physics Institute of the University of Halle, and in 1928 he returned to Berlin as Director of the Physics Institute in the Charlottenburg Technological University. Hertz resigned from this post for political reasons in 1935 to return to industry as director of a research laboratory of the Siemens Company. From 1945 to 1954 he worked as the head of a research laboratory in the Soviet Union, when he was appointed Professor and Director of the Physics Institute at the Karl Marx University in Leipzig. He was made emeritus in 1961, and since then he has lived in retirement, first in Leipzig and later in Berlin.

Hertz's early researches, for his thesis, involved studies on the infrared absorption of carbon dioxide in relation to pressure and partial pressure. Together with J. Franck he began his studies on electron impact in 1913 and before his mobilization, he spent much patient work on the study and measurement of ionization potentials in various gases. He later demonstrated the quantitative relations between the series of spectral lines and the energy losses of electrons in collision with atoms corresponding to the stationary energy states of the atoms. His results were in perfect agreement with Bohr's theory of atomic structure, which included the application of Planck's quantum theory.

On his return to Berlin in 1928, it was his first task to rebuild the Physics Institute and re-establish the School, and he worked tirelessly towards this end. There he was responsible for a method of separating the isotopes of neon by means of a diffusion cascade.

Hertz has published many papers, alone, with Franck, and with Kloppers, on the quantitative exchange of energy between electrons and atoms, and on the measurement of ionization potentials. He also is the author of some papers concerning the separation of isotopes.

Gustav Hertz is Member of the German Academy of Sciences in Berlin, and Corresponding Member of the Göttingen Academy of Sciences; he is also Honorary Member of the Hungarian Academy of Sciences, Member of the Czechoslovakian Academy of Sciences, and Foreign Member of the Academy of Sciences U.S.S.R. He is recipient of the Max Planck Medal of the German Physical Society.

Professor Hertz was married in 1919, with Ellen neé Dihlmann, who died in 1941. They had two sons, both physicists. Dr. Hellmuth Hertz, Professor at the Technical College in Lund, and Dr. Johannes Hertz, working at the Institute for Optics and Spectroscopy of the German Academy of Sciences in Berlin.

Since 1943, Professor Hertz is married with Charlotte, *née* Jollasse.