

G U S T A V H E R T Z

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 basis 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 proces-

ses 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 of binding 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.

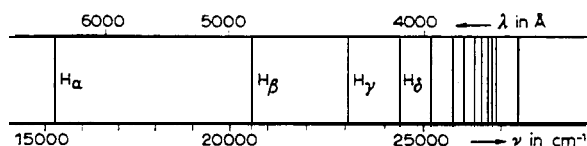


Fig. 1.

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-

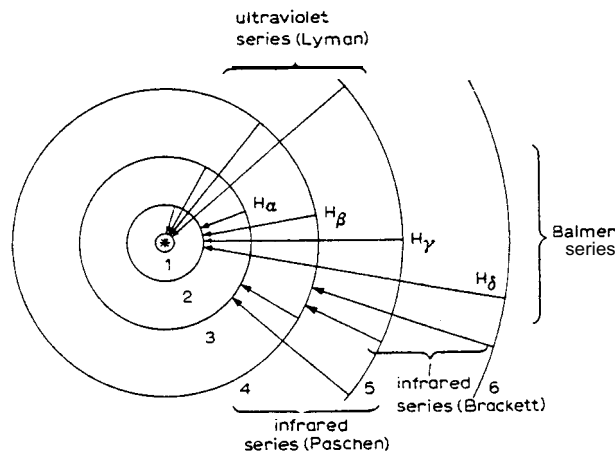


Fig. 2.

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

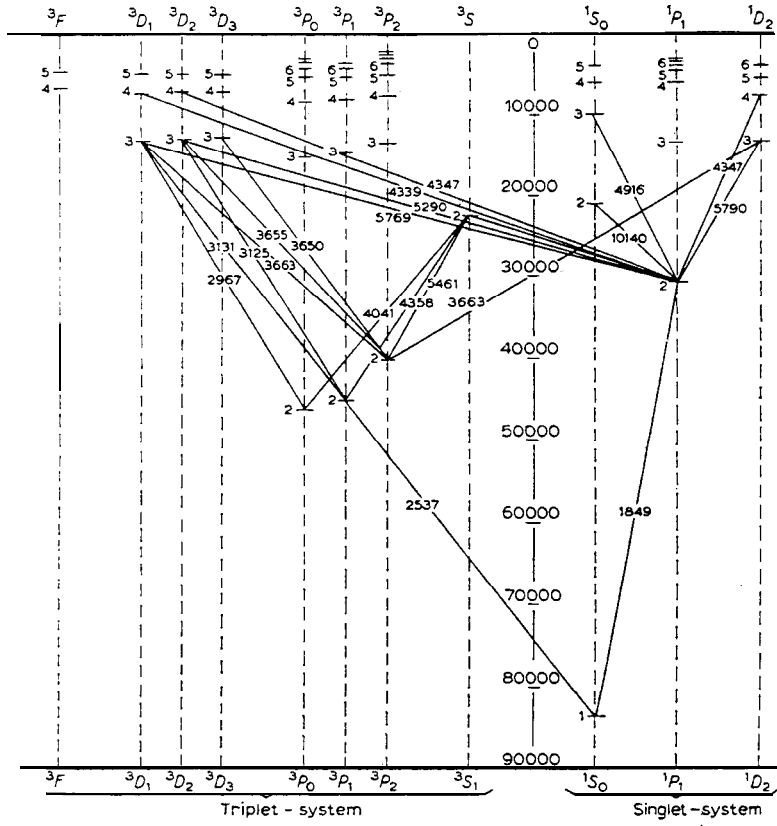


Fig. 3.

Fig. 3. Incidentally, 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 inter-related 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;

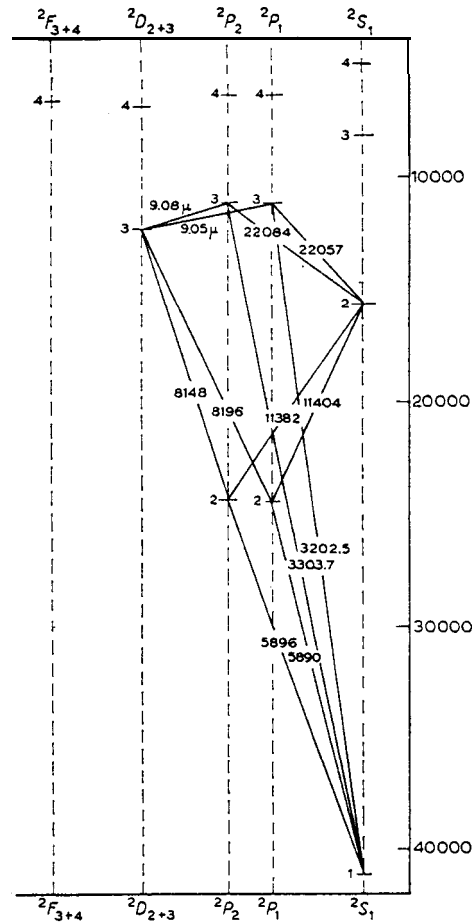


Fig. 4.

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 I 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 I.

	Z		ν	λ in Å	Volts	
					Spectroscopic	Electrical
Li	3	1S	43484.45		5.368	
		1S—2P ₂	14903.09	6708.2	1.840	
		1S—2P ₁				
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		
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		
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 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 known immediately 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 of helium. 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 \AA	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
		1^1S-2^1P	35050.3	2852.2	4.32	...
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
		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
		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.

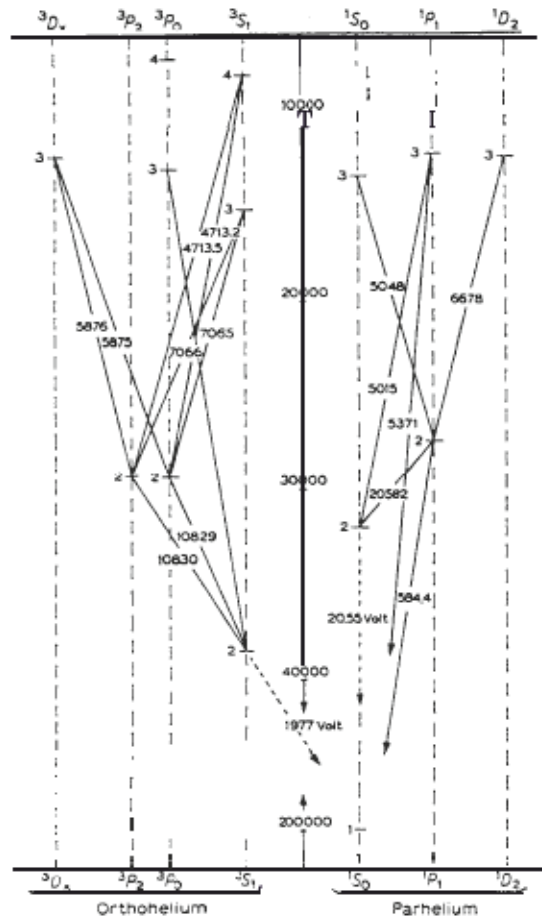


Fig. 5.

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 short-wave 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.

	<i>First excitation potential— measured (volts)</i>	<i>Excitation potential of long-wave resonance line— calculated (volts)</i>	<i>Ionizing potential— measured (volts)</i>	<i>Ionizing potential— calculated (volts)</i>
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

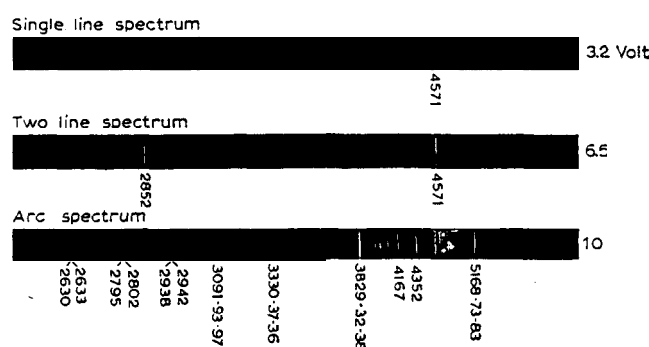


Fig. 6.

are clearly visible. According to Bohr it was 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

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

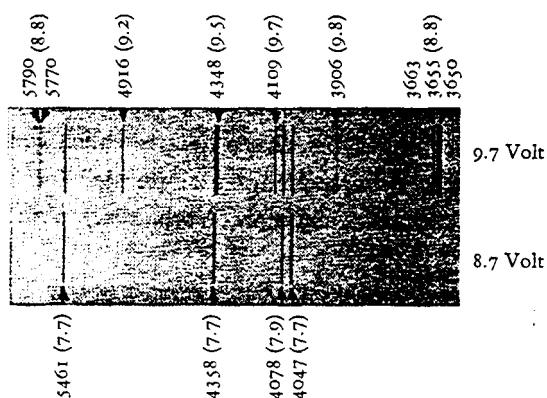


Fig. 7.

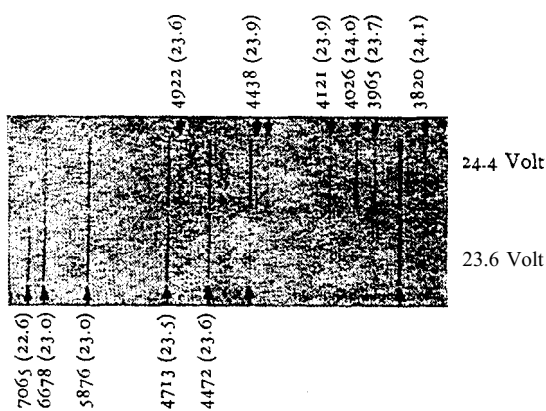


Fig. 8.

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.