The Diffraction of Electrons by a Crystal of Nickel

By C. J. DAVISSON

This article is taken from the manuscript prepared by the author for his address at the joint meeting of Section B of the American Association for the Advancement of Science and the American Physical Society on December 28, 1927, at Nashville, Tennessee. An account of this work giving fuller experimental details is given by Davisson and Germer in the December, 1927, issue of the *Physical Review*.

These experiments are fundamental to some of the newer theories in physics. Until they were performed, it could be said that all experimental facts about the electron could be explained by regarding it as a particle of negative electricity. It now appears that in some way a "wave-length" is connected with the electron's behavior. The work thus shows an interesting contrast with the discovery of A. H. Compton that a ray of light (a light pulse) suffers a change of wave-length upon impact with an electron, the change of wave-length corresponding exactly to the momentum gained by the electron. Until Compton's work, all the known facts about light could be explained by thinking of light as a wave motion. The Compton effect seems to prove the existence of particles of light.

Physics is thus faced with a double duality. Compton showed that light is in some sense *both* a wave motion and a stream of particles. Davisson and Germer have now shown that a beam of electrons is in some sense *both* a stream of particles and a wave motion.

At the same time, theoretical advances have been made which seem to pave the way for an understanding of this curious situation. A general account of these new developments was given by K. K. Darrow in his series "Contemporary Advances in Physics" in the *Bell System Technical Journal* for October, 1927. Some remarks on the relation of the Davisson and Germer experiments to the new mechanics were given in this article, p. 692 *et seq.*—EDITOR.

THE experiments which I have been asked to describe are the most recent of an investigation of the scattering of electrons by metals on which we have been engaged in the Bell Telephone Laboratories for the last seven or eight years.

The investigation had its inception in a simple but significant observation. We observed some time in the year 1919 that when a beam of electrons is directed against a metal target, electrons having the same speed as those in the incident beam stream out in all directions from the bombarded area. It seemed to us at the time that these could be no other than particular electrons from the incident beam that had suffered large deflections in simple elastic encounters with single atoms of the target. The mechanism of scattering, as we pictured it, was similar to that of alpha ray scattering. There was a certain probability that an incident electron would be caught in the field of an atom, turned through a large angle, and sent on its way without loss of energy. If this were the nature of electron scattering it would be possible, we thought, to deduce from a statistical study of the deflections some information in regard to the field of the deflecting atom. It was with these ideas in mind that the investigation was begun. What we were attempting, it will be seen, were atomic explorations similar to those of Sir Ernest Rutherford and his collaborators but explorations in which the probe should be an electron instead of an alpha particle. I shall not stop to recount the earlier experiments of this investigation, but shall pass at once to the most recent ones—those in which Dr. Germer and I have studied the scattering of electrons by a single crystal of nickel.

The unusual interest that attaches to these experiments is due to their revealing the phenomenon of electron scattering in a new and, I may say, fashionable rôle. Electron scattering is not, it would seem, the mildly interesting matter of flying particles and central fields that we supposed, but is instead a much more interesting phenomenon in which electrons exhibit the properties of waves. The experiments reveal that the way in which electrons are scattered by a crystal is very similar to the way in which x-rays are scattered by a crystal. The analogy is not so much with the alpha ray experiments of Sir Ernest Rutherford, as with the x-ray diffraction experiments of Professor von Laue.

My task of describing these experiments is much simplified by the fact that the experiments of Professor von Laue are so well known and so thoroughly comprehended. I remind you very briefly that in the original Laue experiment a beam of x-rays was directed against a crystal of zincblende, that about the transmitted beam was found an array of regularly disposed subsidiary beams proceeding outward from the irradiated portion of the crystal, and that these subsidiary beams could be interpreted completely and precisely in terms of the then already popular wave theory of x-radiation. They could indeed be explained as diffraction beams that resulted from the superposition of secondary wave trains expanding from the regularly arranged atoms of the crystal lattice.

There are two features of the Laue experiment which we shall need particularly to remember. The first is that diffraction beams issue not only from the far side of the crystal along with the transmitted beam, but also from the near or incidence side of the crystal—these latter being disposed in a regular array about the incident beam. The second is that each diffraction beam is characterized by a particular wave-length, and that a given beam appears in the diffraction pattern if the incident beam contains radiation of its characteristic wave-length, or of some submultiple value of this wave-length, but not otherwise. If the incident beam is monochromatic, no diffraction beams appear at all unless the wave-length of the incident beam happens to coincide with a wave-length of one or more of the diffraction beams. In that case the favored beams appear but no others.

With this picture of x-ray scattering in mind one sees at once the significance of the main results of the present experiments. A homogeneous beam of electrons is directed against a crystal of nickel, and at certain critical speeds of bombardment full speed scattered electrons issue from the incidence side of the crystal in sharply defined beams —a few beams at each of the critical speeds—the totality of such beams making up a regularly disposed array similar to the array of Laue beams that would issue from the same side of the same crystal if the incident beam were a beam of x-rays.

The electron beams are not identical in disposition with the Laue beams, and yet it is possible to treat them as diffraction beams, and from their position and from the geometry and scale of the crystal to calculate "wave-lengths" of the incident beam—just as we might do if we were dealing with x-rays or with any other wave radiation. When this is done we arrive at a definite and simple relation between the speed of the electron beam and its apparent wave-length—the wave-length is inversely proportional to the speed.

Surprising as it is to find a beam of electrons exhibiting thus the properties of a beam of waves, the phenomenon is less surprising today than it would have been a few years ago. We have been prepared, to a certain extent, by recent developments in the theory of mechanics for surprises of just this sort—for the discovery of circumstances in which particles exhibit the properties of waves. We have witnessed, during the last three years, the inception and development of the idea that all mechanical phenomena are in some sense wave phenomena—that the rigorous solution of every problem in mechanics must concern itself with the propagation and interference of waves. The wave nature of mechanical phenomena is not ordinarily apparent, we are told, because the length of the waves involved is ordinarily small compared to the dimensions of the system. It is only in such small scale phenomena as the intimate reactions between atoms and electrons that the wave-lengths are comparable with the dimensions of the system. Here only are we to expect notable departures from classical mechanics, and here only are we to find evidence of a more comprehensive wave mechanics.*

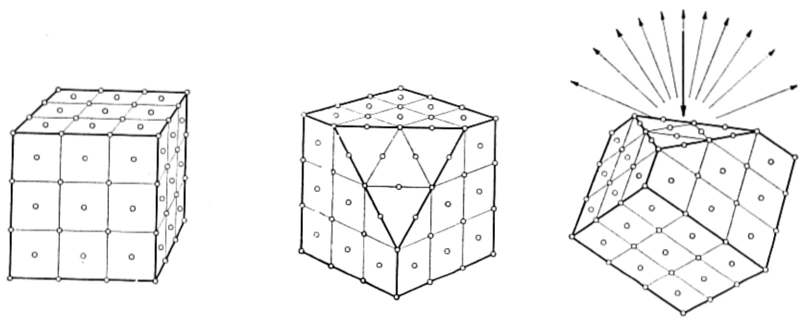
The success of this new theory has been confined, up to the present time, to explanations of certain of the data of spectroscopy. In this field the theory has appealed very strongly to all of us because of the

* It was predicted by W. Elsasser in 1925 (Naturwiss., *13*, 711 (1925)) that evidence for the wave mechanics would be found in the interaction between a beam of electrons and a crystal.

elegance of its methods and because of its remarkable facility in accounting for various of the inhibitions with which the radiating atom is afflicted. We have been prepared by these successes to view with not too great surprise—or alarm—evidence for the wave nature of phenomena involving freely moving electrons. And any reluctance we may feel in treating electron scattering as a wave phenomenon is apt to be dispelled when we find that the value calculated for the wave-length of the equivalent radiation is in acceptable agreement with that which L. de Broglie assigned to the waves which he associated with a freely moving particle—that is to say, the value h/mv (Planck's constant divided by the momentum of the particle).

In this account of the experiments I will describe the general method of the measurements and the general character of the results rather than attempt to go into these matters in detail.

Nickel forms crystals of the face centered cubic type. In Fig. 1 (*a*) the crystal which we had at our disposal is represented by a block of unit cubes of this type.



a *b* *c*

Fig. 1—Diagrams of nickel lattice, of cut lattice, and of lattice with incident and scattered beams

Our first step in preparing the crystal for bombardment was to cut through this structure at right angles to one of the cube diagonals. The appearance of the crystal after the cut was made, and the corner of the cube removed, is indicated in Fig. 1 (*b*). It is this newly formed triangular surface that was exposed to electron bombardment. The bombardment was at normal incidence as indicated in Fig. 1 (*c*). We are to think of electrons raining down normally upon this triangular surface, and of some of these emerging from the crystal without loss of energy, and proceeding from it in various directions.

What is measured is the current density of these full speed scattered electrons as a function of direction and of bombarding potential. The way in which the measurements are made is illustrated in Fig. 2. The electrons proceeding in a given direction from the crystal enter the inner box of a double Faraday collector and a galvanometer of high sensitivity is used to measure the current to which they give rise. An appropriate retarding potential between the parts of the collector excludes from the inner box all but full speed electrons.

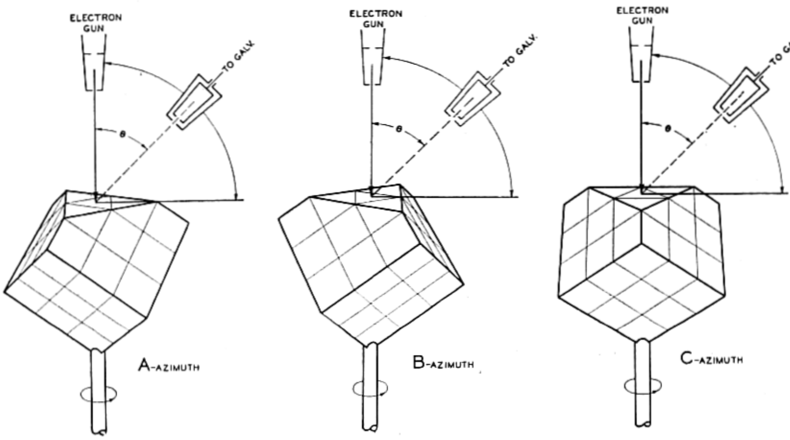


Fig. 2—Showing the three principal azimuths

The collector may be moved over an arc of a circle in the plane of the drawing as indicated, and the crystal may be rotated about an axis which coincides with the axis of the incident beam of electrons. Thus the collector may be set for measuring the intensity of scattering in any direction relative to the crystal—by turning the crystal to the desired azimuth, and moving the collector to the desired colatitude. The whole solid angle in front of the crystal may be thus explored with the exception of the region within twenty degrees of the incident beam.

Certain of the azimuths related most simply to the crystal structure we shall refer to as "principal azimuths." Thus there are the three azimuths that include the apexes of the triangle. If we find the intensity of scattering depending on colatitude in a certain way in one of these azimuths, we expect, of course, to find it depending upon colatitude in the same way in each of the other two. We shall call these the "A-azimuths." On the left in Fig. 2 the crystal has been turned to bring one of the A-azimuths into the plane of rotation of the collector.

Another triad of principal azimuths consists of the three which include the mid-points of the sides of the triangle. These we shall call the "B-azimuths." The next most important family of azimuths comprises those which are parallel to the sides of the triangle; of these there are six, the "C-azimuths."

If we turn the crystal to any arbitrarily chosen azimuth, set the bombarding potential at any arbitrarily chosen value, and measure the intensity of scattering as a function of colatitude, what we find ordinarily is the type of relation represented by the curve on the left in Fig. 3.

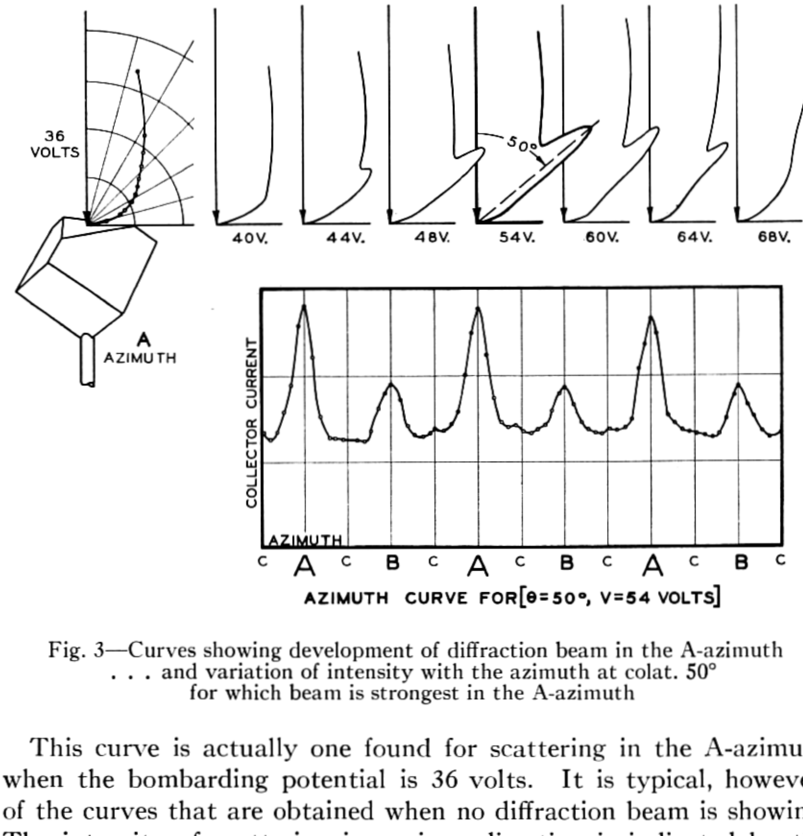


Fig. 3—Curves showing development of diffraction beam in the A-azimuth . . . and variation of intensity with the azimuth at colat. 50° for which beam is strongest in the A-azimuth

This curve is actually one found for scattering in the A-azimuth when the bombarding potential is 36 volts. It is typical, however, of the curves that are obtained when no diffraction beam is showing. The intensity of scattering in a given direction is indicated by the length of the vector from the point of bombardment to the curve. The intensity is zero in the plane of the crystal surface, and increases regularly as the colatitude angle is decreased. This type of scattering forms a background upon which the diffraction beams are superposed.

The occurrence of a diffraction beam is illustrated in the series of curves to the right in Fig. 3. When the bombarding potential is increased from 36 to 40 volts, the curve is characterized by a slight hump at colatitude 60 degrees. With further increase in bombarding potential this hump moves upward, and at the same time develops into a strong spur. The spur reaches its maximum development at 54 volts in colatitude 50 degrees, then decreases in intensity, and finally vanishes from the curve at about 70 volts in colatitude 40 degrees.

We next make an exploration in azimuth through this spur at its maximum; we adjust the bombarding potential to 54 volts, set the collector in colatitude 50 degrees, and make measurements of the intensity of scattering as the crystal is rotated. The results of this exploration are exhibited by the curve at the bottom of Fig. 3, in which current to the collector is plotted against azimuth. We find that the spur is sharp in azimuth as well as in latitude and that it is one of a set of three spurs as required by the symmetry of the crystal.

We observe also that there are small spurs showing in the B-azimuths. We turn the crystal to bring the B-azimuth under observation, and again make explorations in latitude for various speeds of bombardment. We find that the spur in the B-azimuth is similar to the "54 volt" spur in the A-azimuth, but that it attains its maximum development at a higher voltage and at a higher angle. Curves exhibiting its growth and decay are shown in Fig. 4. Maximum

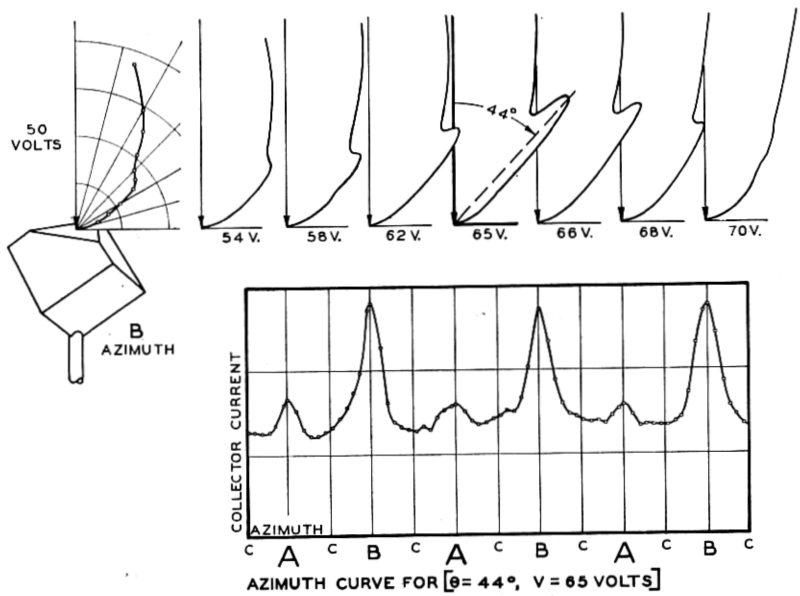


Fig. 4—Similar for the B-azimuth

development is attained at 65 volts in colatitude 44 degrees. At the bottom of the figure we show the intensity-azimuth curve through this spur at its maximum. The small maxima in the A-azimuths represent the remnants of the "54-volt" spurs.

We have thus a set of spurs at colatitude 50 degrees in the A-azimuths when the bombarding potential is 54 volts and a set of 44 degrees in the B-azimuths when the bombarding potential is 65 volts. These spurs are due to beams of full speed scattered electrons which are comparable in sharpness and definition with the beam of incident electrons. This is inferred from the widths of the spurs and the resolving power of the apparatus.

It is hardly necessary to point out that these sharply defined beams of scattered electrons are similar in their behavior to x-ray diffraction beams. If the incident beam were a beam of monochromatic x-rays of adjustable wave-length instead of a homogeneous beam of electrons of adjustable speed, quite similar effects could be produced. If the wave-length of the x-ray beam were varied, critical values would be found at which intense diffraction beams would issue from the crystal in its A-azimuths and others at which such beams would issue in the B-azimuths. The x-ray diffraction beams would indeed be more sharply defined in wave-length than the electron beams defined in voltage. No diffraction beam would be observed until the wave-length of the incident x-rays were very close indeed to its critical value, and the beam would disappear again when the wave-length had passed only very slightly beyond the critical value. This "wave-length sharpness" or "wave-length resolving power" is dependent, however, upon the number and disposition of the atoms involved in the diffraction. If the crystal were only a few atom layers in thickness, or if the x-rays were extinguished on penetrating through only a few atom layers of the crystal, then the x-ray diffraction beams would be much less sharply defined in wave-length; they would behave more like the electron beams. We may say then that the electron beams exhibit the general behavior of diffraction beams resulting from the scattering of a beam of very soft wave radiation—radiation that is very rapidly extinguished in the crystal.

Let us try now to forget that what we are measuring in these experiments is a current of discrete electrons arriving one by one at our collector. Let us imagine that what we are dealing with is indeed a monochromatic wave radiation, and that our Faraday box and galvanometer are instruments suitable for measuring the intensity of this radiation. We are to think of the incident electron beam as a beam of monochromatic waves, and of the "54-volt beam" in the A-azimuth and the "65-volt beam" in the B-azimuth as diffraction beams that owe their intensities, in the usual way, to constructive interference among elements of the incident beam scattered by the atoms of the crystal. With this picture in mind we try next to calculate wave-lengths of this electron radiation from the data of these beams and from the geometry and scale of the crystal.

To begin with, we shall need to look more closely into our crystal. The atoms in the triangular face of the crystal may be regarded as arranged in lines or files at right angles to the plane of the A- and B-azimuths. If a beam of radiation were scattered by this single layer of atoms, these lines of atoms would function as the lines of an ordinary line grating. In particular, if the beam met the plane of atoms at normal incidence, diffraction beams would appear in the A- and B-azimuths, and the wave-lengths and inclinations of these beams would be related to one another and to the grating constant d by the well-known formula, $n\lambda = d \sin \theta$, as illustrated at the top of the figure.

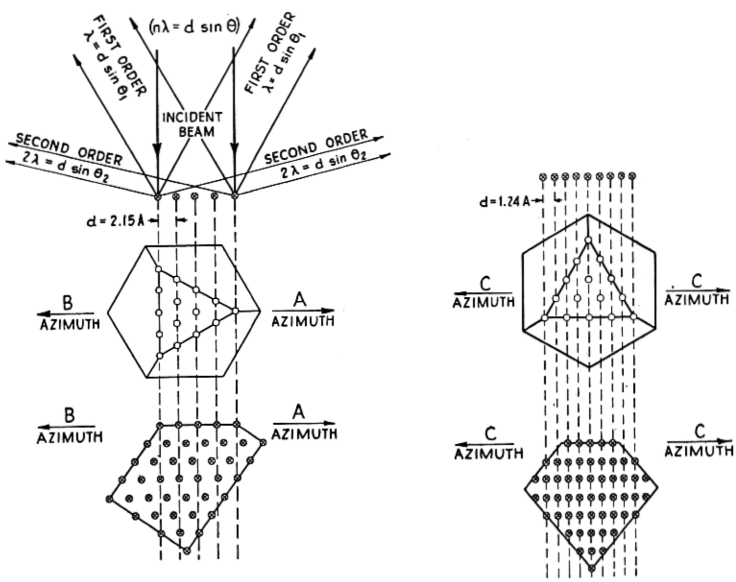


Fig. 5—Showing $n\lambda = d \sin \theta$ relation in the A-, B- and C-azimuths

In the actual experiments the diffracting system is not quite so simple. It comprises not a single layer of atoms, but many layers; it is equivalent not to a single line grating, but to many line gratings piled one above the other, as shown graphically at the bottom of the figure. What diffraction beams will issue from this pile of similar and similarly oriented plane gratings?

The answer to this question is twofold. In respect of position all the beams which appear will coincide with beams which would issue from a single grating. We get no additional beams by adding extra layers to the lattice. In respect of intensity, however, the results are greatly changed. A given beam may be accentuated or it may be diminished, both absolutely and relatively to the other beams; it may in fact be blotted out completely, or reduced to such an extent that it can no longer be perceived. These are effects of interference among the similar beams proceeding from the various plane gratings that make up the pile. Later we shall consider under what conditions these component beams combine to produce a resultant beam of maximum intensity; for the present, however, I wish only to stress the fact that whenever and wherever a space lattice beam appears its wave-length and colatitude angle θ will be related to the constant d of the plane grating through the ordinary plane grating formula. We therefore apply this formula to the 54- and 65-volt beams that have been described. The grating constant d has the value 2.15 Å., the 54-volt beam occurs at $\theta = 50°$ so that $n\lambda$ for this beam should have the value $2.15 \times \sin 50°$, or 1.65 Å. For the 65-volt beam we obtain for $n\lambda$ the value 1.50 Å.

We now compare these wave-lengths with the wave-lengths associated with freely moving electrons of these speeds in the theory of wave mechanics. Translated into bombarding potentials, de Broglie's relation

$$\lambda = h/mv \text{ becomes } \lambda = \sqrt{\frac{150}{V}}\ \text{Å.},$$

where V represents the bombarding potential in volts. The length of the phase wave of a "54-volt electron" is $(150/54)^{1/2} = 1.67$ Å., and for a 65-volt electron 1.52 Å. The 54- and 65-volt electron beams do very well indeed as first order phase wave diffraction beams.

It may be mentioned that beams occur at different voltages in the A- and B-azimuths because the plane gratings that make up the crystal are not piled one immediately above the other. There is a lateral shift from one grating to the next amounting to one third of the grating constant. Because of this shift the phase relation among the elementary beams emerging in the A-azimuth is not the same as that among those emerging in the B-azimuth—and coincidence of phase among these beams occurs at different voltages, or at different wave-lengths, in the two azimuths.

We next make similar calculations for a beam occurring in the C-azimuth. One such beam attains its maximum development in colatitude 56° when the bombarding potential is 143 volts. For diffraction into the C-azimuth we must regard the atoms in the surface layer as arranged in lines normal to the plane of this azimuth as illustrated in Fig. 5. The grating constant is 1.24 Å., and the similar gratings that make up the whole crystal are piled up without lateral shift. For this reason the C-azimuth is six-fold instead of only three-fold. For a beam occurring in this azimuth in colatitude 56°, $n\lambda$ should be equal to $1.24 \times \sin 56°$ or 1.03 Å. The value of h/mv for electrons that have been accelerated from rest through 143 volts is $(150/143)^{1/2}$ or 1.025 Å. Again the beam does very well as a first order diffraction beam.

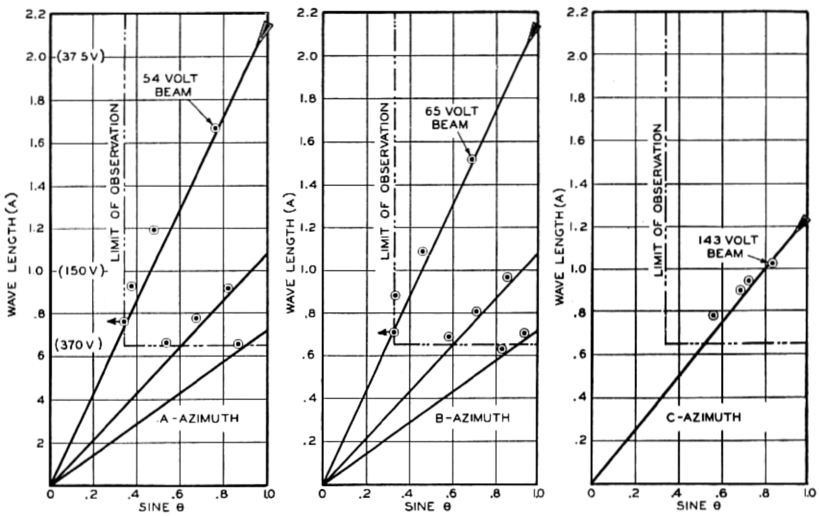


Fig. 6—Plot of λ against $\sin \theta$ for various beams

The total number of such beams which we have observed in all azimuths in explorations up to 370 volts is twenty-four—nine in the A-azimuth, ten in the B-azimuth, and five in the C-azimuth. It would be possible to calculate an observed wave-length for each of these beams from $n\lambda = d \sin \theta$, and to compare this in each case with the theoretical wave-length calculated from $\lambda = h/mv$, just as we have done already for three of the beams. We have chosen, however, to display the results graphically rather than numerically.

The data for the twenty-four beams are exhibited in diagrams in Fig. 6, in which wave-length λ is plotted against the sine of the colatitude, θ. There is a separate diagram for each azimuth and in each the straight lines passing through the origin represent the plane grating formula $n\lambda = d \sin \theta$ in its different orders. Each of the twenty-four beams is represented by a point or by a wedge-shaped symbol in one of these diagrams. The quantities coordinated in each case are the wave-length of the incident beam as calculated from $\lambda = h/mv = (150/V)^{1/2}$ and the sine of the colatitude angle of the diffraction beam as observed. There are no points to the left of the line $\theta = 20°$ as this represents the lower limit of our colatitude range of observation, and none below the line $\lambda = 0.637$ Å. as this corresponds to the upper limit of our voltage range, 370 volts. The bombarding potentials corresponding to various wave-lengths are shown by figures enclosed in brackets.

When the data are exhibited in this fashion the question as to whether or not the observed wave-length of a beam agrees with its theoretical wave-length is answered by whether or not the point representing the beam falls on one or another of the lines representing the plane grating formula. If there were perfect agreement in all cases, each of the points would lie on some one of these lines.

It will be seen that the points all lie close to the lines, though not as a rule exactly on them. It is of course very important to decide whether the departures of the points from the lines are or are not too great to be attributed to uncertainties of measurements. It is our belief that they are in fact due to experimental error in the determination of the colatitude angles. If we accept the theoretical values of the wave-lengths as correct, and calculate the values of θ which we should have observed, we find that in no case do they deviate by more than 4 degrees from the values of θ actually set down. Corrections of this magnitude do not seem excessive when it is considered that we are making measurements with what amounts to a rather crude spectrometer, that the arm of the spectrometer is but 11 mm. in length, that the opening in the collector is 5 degrees in width, and that the spectrometer itself is sealed into a glass bulb. We therefore assume that in every case the value of the wave-length assigned by de Broglie is the correct one.

I now direct your attention to a particular group of these beams—the group comprising the beam of greatest wave-length in each of the three azimuths, which are represented in the figure by wedge-shaped symbols. The interpretation of these three is quite simple.

The radiation to which our electron beam is equivalent is extremely soft as already noted. Its intensity suffers a considerable decrement when the beam passes normally through only a single layer of atoms. This characteristic is inferred from the low resolving power of the crystal, and is consistent with what we know of the penetrating power of low speed electrons. When the beam passes through a layer of atoms at other than normal incidence the decrement in its intensity is greater still—and in the limit as the angle of incidence approaches grazing to the atom layer the intensity of the transmitted beam will approach zero. Thus we may expect that when a diffraction beam leaves the crystal at near grazing emergence the contributions to the resultant beam which come from the second and lower layers of atoms will be much less important than when the beam emerges from the crystal at a higher angle. Near grazing the radiation proceeding from the second and lower layers will be heavily absorbed in its passage through the overlying layers. Within a limited angular range near grazing the diffraction beam will be made up almost entirely of radiation scattered by the uppermost layer of atoms. The diffracting system becomes essentially a single plane grating and what we should observe is ordinary plane grating diffraction.

The first order diffraction beam from a line grating appears at grazing emergence when the wave-length of the incident radiation is equal to the grating constant. The grating constant for diffraction into the A- and B-azimuths is 2.15 Å. and grazing beams should appear in both azimuths when the wave-length of the incident electron beam has this value. The bombarding potential corresponding to wave-length 2.15 Å. is 32.5 volts, and at just 32.5 volts diffraction beams appear at grazing in both these azimuths. As the bombarding potential is increased the beams move up from the surface to satisfy the relation $\lambda = d \sin \theta$. Ten or fifteen degrees above the surface radiation from the second and lower layers escapes in sufficient amounts to reduce the intensity of the resultant beam through interference, and at a somewhat higher angle the beam disappears.

An exactly similar beam is found at grazing in the C-azimuth. The grating constant here is 1.24 Å. and the bombarding potential corresponding to wave-length 1.24 Å. is 97.5 volts. The beam appears at grazing at just this voltage. These three beams occurring and behaving exactly as required by the theory constitute the strongest evidence we have in favor of the wave interpretation of electron scattering.

We have been less successful in trying to account for the occurrences of the remaining 21 sets of beams. We do not know why they occur where they do. The most we have been able to do is to relate their occurrences with those of the Laue beams that would issue from the same crystal if the incident beam were a beam of x-rays.

In Fig. 7 we indicate by crossed circles in a (λ, sin θ) diagram the x-ray diffraction beams that would be observed in the B-azimuth. We show also again the electron beams as actually observed. It is obvious that the law of occurrence of electron beams is not the same as the law of occurrence of Laue beams, and yet we see that the occurrences of the two sets of beams have certain features in common. The dots representing electron beams occur along the plane grating lines at about the same intervals as the crossed circles representing the Laue beams. Other points of similarity are found with further study of the data and one is led finally to the conviction that each electron beam is the analogue of a particular Laue beam. The electron beam represented by a given dot appears to be the analogue of the Laue beam of the same order represented by the crossed circle occurring next above it in the diagram. This association of beams is indicated in the figure.

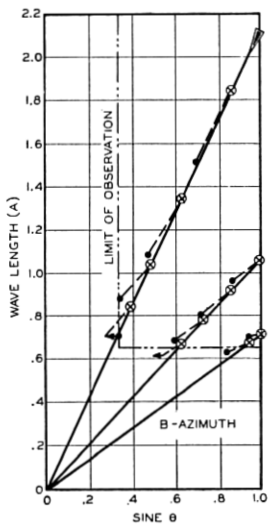


Fig. 7—λ sin θ diagram for B-azimuth

The occurrences of the Laue beams are determined in part by the separation between the atomic plane gratings that make up the crystal. If the separation between adjacent planes were increased the crossed circles representing the Laue beams would be moved upward along the plane grating lines; if the separation were decreased the crossed circles would be moved downward. Merely as a mode of description, then, we may say that a given electron beam has the wave-length and position that its Laue beam analogue would have if the separation between planes were decreased by a certain factor.

We have calculated this spacing factor for each of the 21 beams and the values found are plotted in the upper part of Fig. 8 against the voltages of the beams. The points form a very bad curve. They do indicate, however, that the factor increases with the speed of the electron, and there is the suggestion that it approaches unity as a limiting value. There is the suggestion, that is, that at high voltages the law of occurrence of electron beams is the same as the law of occurrence of Laue beams.

It has been pointed out by Eckart that if the index of refraction of the crystal for the electron radiation is other than unity diffraction beams will occur as if the separation between atom planes were other than normal. We have computed the indices of refraction that would

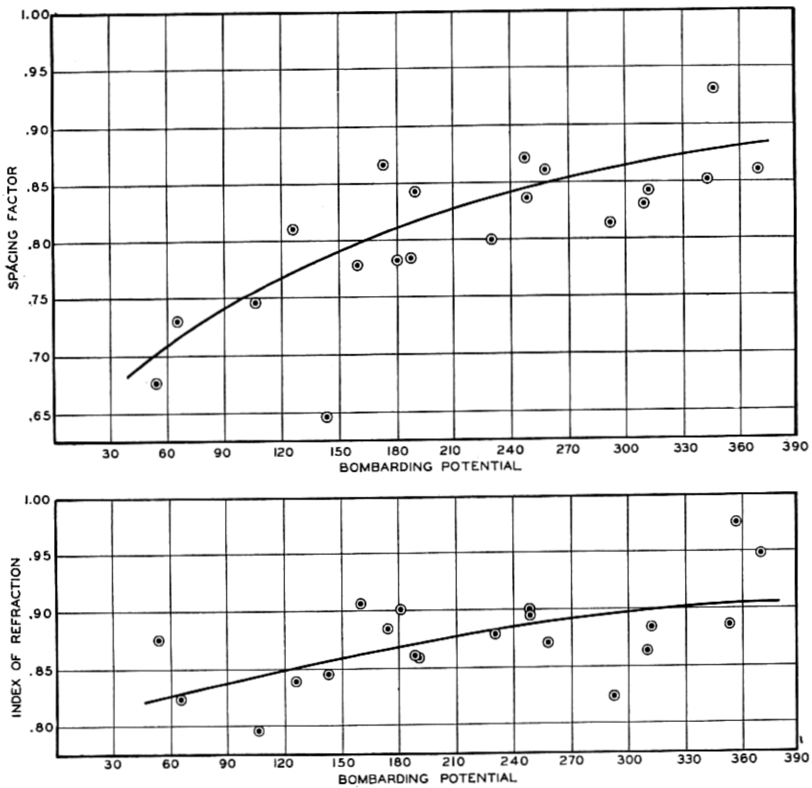


Fig. 8—Plot of values of spacing factor and associated values of refractive index for twenty-one beams

give rise to the observed occurrence of beams and these are plotted in the lower part of the diagram against bombarding potential. Again the points fall very irregularly. While it cannot be said that there is at present a satisfactory explanation of the peculiar occurrence of the space lattice electron diffraction beams, it should be clearly understood that this deficiency in no way affects either the wave-length measurements of these beams or the agreement of these wave-lengths with the values of h/mv.

The electron diffraction beams which I have described are the only ones observed when the surface of the crystal is free from gas. When the surface is not free from gas still other beams appear. These beams are due to the scattering of electrons by the adsorbed gas and therefore we shall not consider them at this time.

In closing I should like to say a few words about the conceptual difficulty in which these experiments involve us. When Laue and his collaborators investigated the scattering of x-rays by crystals the results of their observations were accepted at once as establishing the wave theory of x-rays. It was a very simple matter for W. H. Bragg and others to give up the corpuscular theory because of the hypothetical nature of the x-ray corpuscle. It was only necessary to recognize that Laue's results were contrary to hypothesis and the corpuscle disappeared.

If the electron were not the well-authenticated particle we know it to be, it is possible that the experiment I have described would cause it to vanish in like manner. We do not, however, anticipate any such event. The electron as a particle is too well established to be discredited by a few experiments with a nickel crystal. The most we are apt to allow is that there are circumstances in which it is more convenient to regard electrons as waves than as particles. We will allow perhaps that electrons have a dual nature—when they produce tracks in a C. T. R. Wilson cloud experiment they are particles, but when they are scattered by a crystal they are waves.

A quite similar situation exists, of course, in the case of x-rays. It has been evident for some years that the adherents of the corpuscular theory of x-rays were too enthusiastic in their recantations. X-rays also exhibit a dual nature—when they give rise to diffraction patterns they are waves, but when they exhibit the Compton effect or cause the emission of electrons from atoms they are particles—quanta or photons.

This state of affairs is one that should appeal to us as intolerable. There must, it would seem, be comprehensive modes of description applicable to all electron and x-ray phenomena, but what these are we do not yet know. We do not know whether we shall eventually believe with de Broglie and Schroedinger that electrons and x-rays are waves that sometimes masquerade as particles, with Duane that electrons and x-rays are particles that sometimes masquerade as waves, or whether eventually we shall believe with Born that we are dealing in both cases with actual particles and phantom waves.

I believe, however, that for the present and for a long time to come we shall, in describing experiments, worry but little about ultimate realities and logical consistency. We will describe each phenomenon in whatever terms we find most convenient.