The Discovery of Electron Diffraction by Davisson and Germer

The Davisson-Germer experiments in low-voltage electron diffraction established the wave nature of the electron and confirmed the de Broglie theory upon which wave mechanics is based. For this discovery, Davisson, jointly with G. P. Thomson who at the same time discovered electron diffraction using much higher-voltage electrons, was awarded the Nobel Prize.
The discovery that an index of refraction that varied in voltage must be assigned to the bombarding electrons confirmed the Fermi theory of electrons in metals. The anomalies observed in the index led to the initial development of the dynamical theory of electron diffraction.
The occurrence of diffraction beams due to ordered adsorption of gas atoms on the crystal surface is now leading to a new understanding of the physics of surfaces.

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The discovery of electron diffraction is a classic example of the interplay of theory and experiment. Remembering that the scientist stands on the shoulders of those who went before him, let us take our historical starting point at the opening of the 20th century. The wave theory of light was triumphant, for it appeared impossible to explain interference phenomena if light were a beam of particles. It had been extended by Maxwell and Hertz to radio waves, but not yet to x-rays. Planck was investigating radiation from heated surfaces (blackbody radiation). The way the intensity of this light varied with wavelength could not be explained by the wave theory, so Planck formulated a corpuscular theory that introduced his famous constant h, which now is recognized as a fundamental constant of physics. In 1905, Einstein, studying photoelectric emission, found that here also light acted as if it were composed of particles, each endowed with energy equal to h times the frequency. The fact that atoms in the vapor phase, when suitably excited as by an electric discharge, emit light of discrete frequencies could not be reasonably explained on the wave theory; and, in 1913, Bohr introduced the "planetary" model of the atom, with negative electrons revolving in orbits around a charged nucleus. Again, the emission of light of a particular frequency when an electron dropped from one orbit to another required that light be composed of particles, now called photons, and not of continuous waves. But, of course, light continued to show interference effects, which could be explained only by the wave theory. So the wave-particle duality of light was established experimentally. Of course, theories of the ways in which particles and waves should behave were an essential part of the paradox. Somehow an overriding principle must be discovered, which would explain the contradiction.

The electron was established definitely as a particle in 1897 when J. J. Thomson measured the ratio of its charge e to its mass m. Later, Millikan measured the charge e by his famous oil-drop experiment. But Bohr's planetary model was in trouble. It was well-known that a charge revolving in an orbit would radiate an electromagnetic wave, that is, light. So Bohr's orbital electrons would gradually lose energy as they revolved, finally falling into the positively charged nucleus. Bohr rather arbitrarily required that electrons would not radiate, except when they fell from one orbit to another. These orbits are called stationary orbits.

A unifying idea was put forward by Prince Louis de Broglie in 1924 in his doctor's thesis. It was that matter—particles such as electrons—also would show wave properties. In both cases,

Energy = h times frequency,
Momentum = h divided by wavelength.

Since momentum is the product of mass m and velocity v, the second relation can be written

$$\lambda = h/mv. \qquad (1)$$

Chester J. Calbick joined the staff of Bell Telephone Laboratories upon graduation from Washington State College and took his graduate training in Physics at Columbia University. After working briefly with Dr. J. A. Becker on the thermionic properties of less-than-monolayer films of cesium on tungsten, he joined Davisson and Germer in the investigation of full-speed secondary electrons from a nickel crystal which led to the discovery of electron diffraction. During the war he worked with Dr. J. B. Fisk developing and testing magnetrons used for radar. For the last seventeen years he has been active in electron microscopy and electron diffraction studies of materials and techniques. He is a member of the American Physical Society, the American Association for the Advancement of Science, the Electron Microscope Society of America, the American Vacuum Society, and several other scientific societies.

For electrons whose energy is less than about 50000 electron volts,

$$\lambda = (150/V)^{\frac{1}{2}} \times 10^{-8}\,\mathrm{cm},$$

where V is the electron energy in electron volts. The stationary orbits of Bohr's theory became, in the wave mechanics developed by de Broglie, Schroedinger, and many others, standing-wave patterns within the atom.

An Accident and What It Led To

In 1921, Davisson and Kunsman were studying the "secondary" electrons emitted from a nickel target when it was bombarded by a "primary" beam of electrons. A small fraction of the secondary electrons was found to have the same energy as those in the primary beam. These were reflected electrons, that is, electrons from the primary beam that had been deflected by the atoms in the nickel target without losing energy. They were measured by a Faraday collector such as that described later. The number reflected straight back was relatively large and tapered off as the collector was moved to grazing incidence; however, a small bump appeared on the curve. In 1924, Davisson and Germer resumed the investigation with an improved tube. The nickel target could be heated by means of electron bombardment from a filament located behind it. During the course of the experiments, an accident occurred while it was hot. A vacuum bottle containing liquid air, used for cryogenically pumping the tube to a very low pressure, exploded, breaking the experimental tube. The surface of the nickel target was oxidized. After the tube was repaired, the target was heated extremely hot to drive off the oxide. The distribution-in-angle curve was then found to be greatly changed. Several spikes appeared. When the tube was opened, the nickel target was found to have recrystallized. A few large crystals had replaced the numerous small ones of the original polycrystalline target.

In 1926, Elsasser suggested that the bump on the original Davisson–Kunsman curve was a manifestation of the wave nature of the electron. It was evident that, whether this was so or not, the spikes, which were voltage sensitive, were much more probably due to diffraction of electrons. Later in 1926, Davisson journeyed to Europe to discuss the theory with Richardson, Born, Franck, and others. The author, fresh out of college, was privileged to join the investigation. The object was to find out experimentally whether a crystal diffracted electrons in the same way as x-rays. Diffraction of the latter, discovered by von Laue in 1912, had shown that they were electromagnetic radiation of such high frequencies that their wavelengths were comparable with the separations of atoms in crystals, that is, in the range of Angströms (*1*). Equation 1 shows that a 150-V electron has a wavelength of 1 Å, and Davisson and Germer proceeded to calculate at what angles and voltages beams diffracted by a nickel crystal should appear.

Diffraction by a Crystalline Lattice

If radiation, either electromagnetic or electron, falls upon an atom, it interacts with it in such a way that some part of it is found to be deflected from its original path. This behavior is called diffraction. In a crystal, there are many atoms arranged regularly in space, and, if all the atoms are the same, each will scatter the radiation in the same way. The amplitudes of the waves scattered by each atom must be added and the sum squared to find the intensity of a beam. Since the amplitude is sinusoidal, the sum may be either positive or negative; in some directions, it is zero and we say destructive interference occurs. In others, the square of the sum is greater than the sum of the squares; this is called constructive interference. In these directions, a diffracted beam appears due to constructive interference of all the little wavelets scattered by each atom.

Sir William Bragg observed that a diffracted beam could be explained by considering it as reflected by a large number of parallel planes of atoms. In effect, each such plane is a mirror (Fig. 1) and the path traversed by each ray of an incident beam of parallel radiation is the same. A ray reflected from an adjacent plane travels a distance different by $\Delta s = 2d \cos \alpha$, as shown in Fig. 2. If the path difference Δs is equal to one wavelength, or to an integral number of wavelengths, the emerging beams are in phase and constructive interference results. If there were only two planes, a maximum rather broad in wavelengh (voltage) would occur when

$$m\lambda = 2d \cos \alpha \text{ (Bragg's law)}. \quad (2)$$

When there are many planes, the maximum becomes very sharp, and a diffraction spike will be found at an angle 2α from the incident direction.

The atoms can be thought of as located on any group of an infinite number of groups of parallel planes. For example, if we look along an axis of a cubic crystal (Fig. 3), they can be considered as located on planes parallel to one or the other of the cube faces or on the diagonal planes or, in fact, on any plane whose normal is perpendicular to the viewing direction. We are not restricted to viewing along an axis: we can go out n_1 atoms along one axis, n_2 along the second, and n_3 along the third and look back at the origin. The planes whose normals are perpendicular to this direction can be characterized by certain integers, called in crystallographic parlance the Miller indices (hkl) (*2*). The mathematical law

$$n_1h + n_2k + n_3l = 0 \quad (3)$$

is a statement that the plane normals are perpendicular to the viewing direction. The integers $[n_1n_2n_3]$ are called the zonal indices. They are always placed in square brackets, the Miller indices in curved. In Fig. 3, $[n_1n_2n_3] = [001]$. The other two coordinate

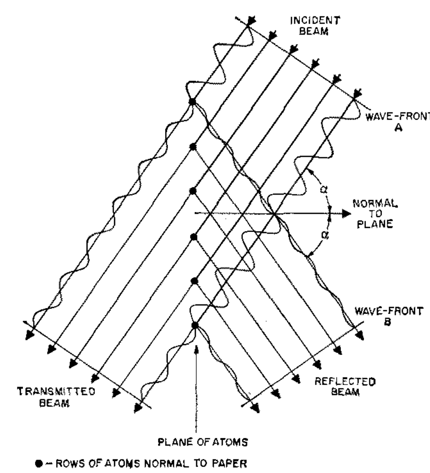


Figure 1. A single plane of atoms acts as a mirror to reflect a part of the incident beam. The path along each ray from wavefront A to wavefront B is the same, so the phase of each reflected wavelet is the same at B.

1. 1 Å = 10^{-8} cm (one one-hundred-millionth of a cm).

2. Just as $[n_1n_2n_3]$ are the coordinates of an atom in the crystal lattice, (hkl), are the coordinates of an intersection point in a "reciprocal" lattice. For a cubic system, the *directions* of the three axes in each of the lattices are the same, but the reciprocal unit cell has sides $1/a_0$ where a_0 is the side of the unit cell (Fig. 3). The geometrically important fact is that the lines from the origin to the reciprocal lattice points are perpendicular to atomic planes in the crystal lattice. Many crystals have structures less symmetrical than the cubic. For those in which the crystal axes are not at right angles, the directions of the reciprocal axes are not the same as those of the crystal.

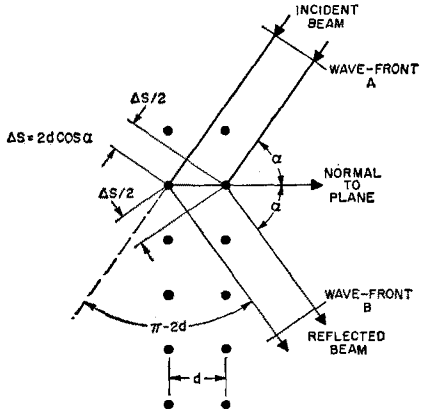


Figure 2. The pathlength from A to B is not the same for wavelets reflected from atoms in adjacent planes; it differs by $\Delta s = 2d \cos \alpha$. The phase at B of the wavelets from each atom is the same if Δs is equal to λ, 2λ, etc. This gives Braggs law for coherent reflection $m\lambda = 2d \cos \alpha$.

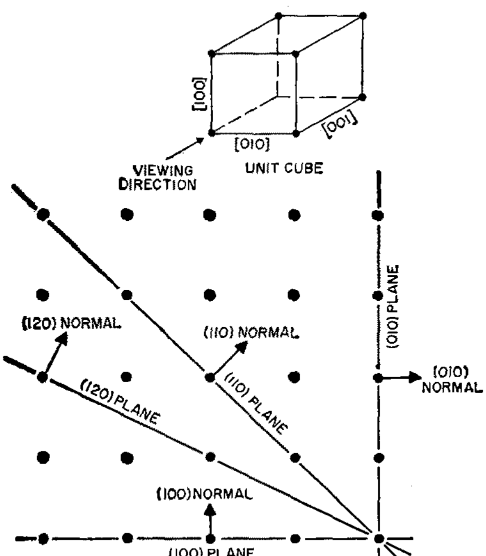


Figure 3. Looking at a cubic array of atoms along a cube axis, one sees a square array of atoms. Behind each atom are other atoms, so each dot represents a row of atoms perpendicular to the paper. All the atoms can be considered as located on the (100) planes, only one of which is shown as a broken line intersecting the paper. Alternatively, they can be considered as located on (010) planes, (110) planes, (120) planes, etc. The plane normals are defined as perpendicular to the planes.

planes are (100), (010), and the diagonal plane is (110). The spacing between neighboring planes of the first two groups is a_0, the size of the unit cube; between the planes of the diagonal group, it is $a_0/\sqrt{2}$, and, in general, for a cubic system, the interplanar spacing is

$$d = \frac{a_0}{(h^2 + k^2 + l^2)^{1/2}} \,. \qquad (4)$$

The integer m can be formally eliminated from Bragg's law by permitting the Miller indices (hkl) to have a common factor.

Many crystals, and in particular nickel, have atoms located at the cen-

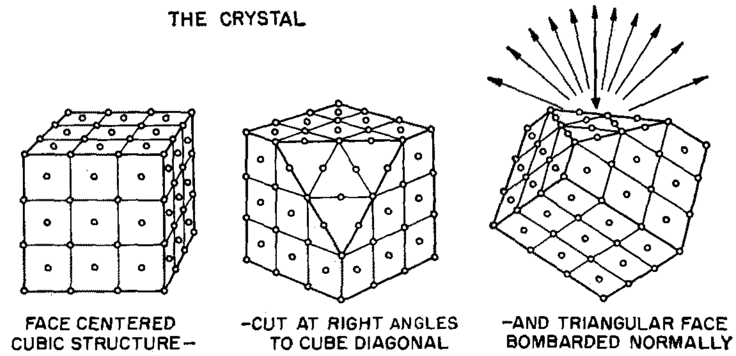


Figure 4. Schematic views of the face-centered cubic structure of nickel.

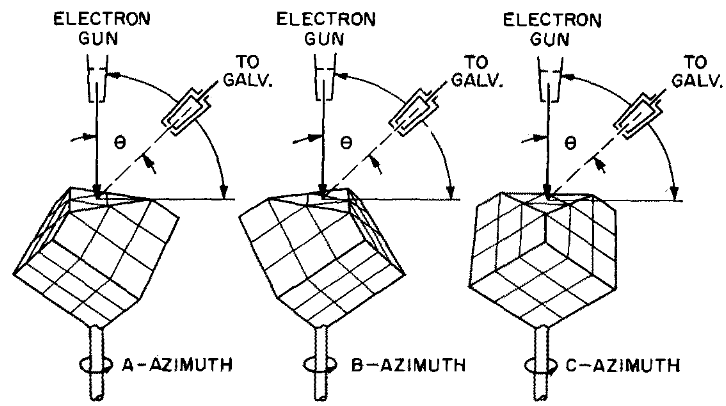


Figure 5. The first experimental arrangement for investigating electron diffraction.

ters of the cube faces as well as at the corners. These atoms also lie on any of the infinite number of groups of planes; for some groups, they lie on the same planes as the corner atoms, for others on planes half-way between. This can be taken into account by requiring that (hkl) in Eq. 4 must be all odd or all even.

Davisson-Germer Experiments

In Fig. 4, the arrangement of atoms in the nickel crystal is shown. The crystal was polished and etched to expose a face normal to the body diagonal. The essential plan of experimentation is shown in Fig. 5. Electrons are incident perpendicularly upon the (111) face of a nickel crystal. The collector could be moved in *colatitude* (that is, polar) angle from about 20° (limited by the electron gun) to 90°. The crystal could be turned in *azimuth* (that is, longitude) around the direction of the electron beam as axis. A photograph of the tube is shown in Fig. 6. The electrons scattered by the crystal entered the Faraday collector, which consisted of two platinum boxes, one inside the other, insulated from each other. The outer box was at the voltage (potential) of the crystal and had a hole in the side facing the crystal. Electrons passing through this hole continued on through a slightly larger hole in the inner box. The potential of the inner box could be adjusted so that all electrons, except those that were reflected by the crystal without loss of energy, were turned back to the outer box. The galvanometer thus measured the full-energy electrons that were scattered by the crystal within a small angle. The necessity for this is evident from Eq. 1: $\lambda = h/mv$. Electrons that lost energy in interaction with the crystal would have a lower velocity and, hence, longer wavelength, and, hence, had to be eliminated to permit significant observations.

The azimuth notations in Fig. 5 are those used by Germer (*3*) in a paper "Optical Experiments with Electrons," which is an elegant exposition of the experiments, and from which several of our illustrations have been taken. It gives a much more complete account than is possible within the scope of the present paper. In normal crystallographic notation, the azimuths *A* and *B* include all the planes

3. L. H. Germer, J. Chem. Ed. 5, 1041-1071 (1928).

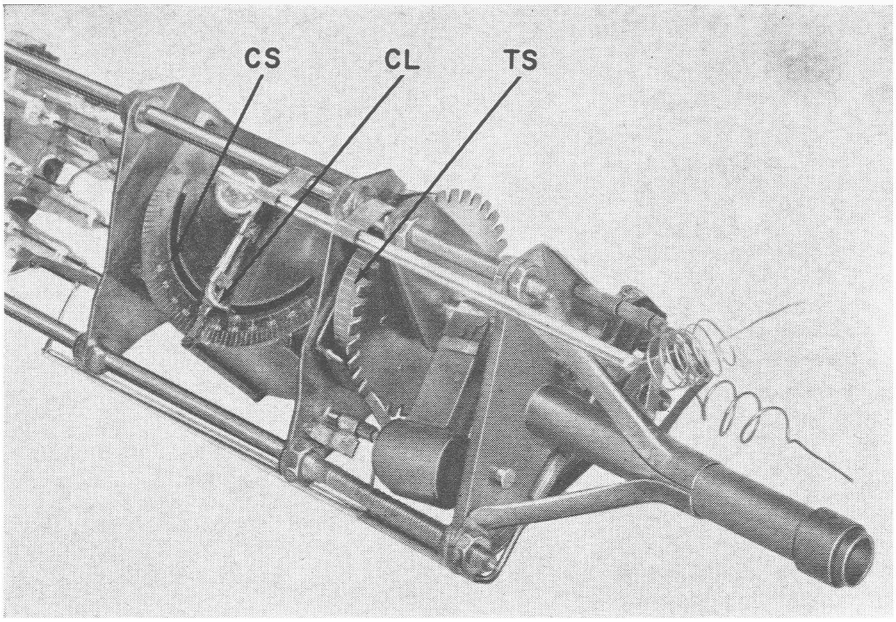


Figure 6. Photograph of the original Davisson—Germer diffraction tube. Scales TS and CS show, respectively, the azimuth of the target and the angular position of the collector; CL is the collector itself.

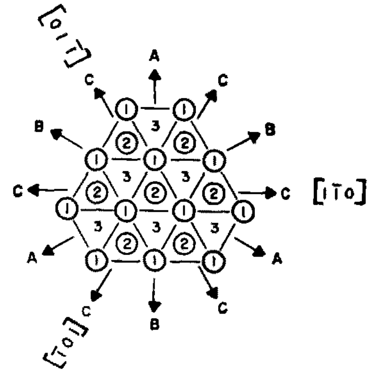


Figure 7. Looking down on a (111) face, one sees three triangular arrays of atoms. The uppermost atoms are in array (1). The next layer down is array (2) located in the centers of alternate triangles of the top layer. The third layer down is array (3). The fourth layer is vertically under the first, the fifth under the second, etc. The arrangement can be easily modeled by close-packing billiard balls first in one layer, building on a second layer with the balls nested in alternate triangles, and continuing the process for the additional layers. The azimuths ABC are shown; three zones of type [110] show the threefold symmetry of the arrangement.

lying in zones of type $[1\bar{1}0]$ (*4*). By Eq. 3 for planes in this zone,

$$n_1h + n_2k + n_3l = 1 \times h - 1 \times k + 0 \times l = 0$$

so $h = k$. In this zone, the planes are not symmetrical on the two sides of the surface normal. The reason for this can be seen in Fig. 7, which shows the atoms in the top three planes. The planes in azimuth *C* are not further considered here; most attention is paid to the (331) and (224) beams, both of which lie in the $(1\bar{1}0)$ zone, but, respectively, in azimuths *A* and *B* of Fig. 5.

Table I gives the interplanar spacings *d*, wavelength, and electron energy to be expected for these two beams.

TABLE I

(hkl)	d(Å)	α	λ(Å)	V(eV)	2α
(331)	0.808	22	1.495	68	44
(224)	0.718	19.5	1.355	82	39

To calculate λ from Eq. 2, the angle α between the (111) direction of incidence and the *hkl* plane is required. It can be shown that

$$\cos \alpha = \frac{(h + k + l)}{[3(h^2 + k^2 \times l^2)]^{1/2}}. \qquad (5)$$

The reflected beam should appear at colatitude angle $\theta = 2\alpha$. In this manner, we calculated that, at a voltage of 68 volts (V), a spike should appear on the colatitude curve in azimuth *A* and have its maximum at 44°.

We set the tube in azimuth *A*, the voltage at 68 V, and ran the curve. The expected spike was not there! I was adjusting the angle, Germer recording the data, and Davisson was observing. Severe gloom descended; Davisson and Germer retired to Davisson's office to check their calculations. I proceeded to vary the voltage, observing that current increased as voltage was reduced. Then I ran a colatitude curve. There was a spike. Quickly, I maximized the spike by reducing the voltage to 54 V, and took the colatitude curve, showing the spike at 50°, not 44°, in to Davisson and Germer. The first diffraction beam had been experimentally demononstrated; de Broglie's theory was confirmed. (Figure 8 shows a small spike at 68 V, but the curves in Fig. 8 were taken after the surface had been cleaned by heating the crystal.)

We proceeded to explore completely in angle and voltage; every expected spike was found to be displaced both in angle and voltage; Fig. 9 shows the (224) spike in azimuth *B*. At the time, it was not certain which spike was to be associated with a given crystal plane. It was obvious that an index of refraction μ, which varied with voltage, would explain the displacements. The beam entered the (111) surface perpendicularly, but the reflected beam emerged at an angle. As it passed through the surface, it would be deflected in angle, exactly as a beam of light is deflected in passing from air into water if the index were less than unity; or from water into air if it were greater (see Fig. 10). In fact, in the early papers Davission and Germer concluded that the evidence favored $\mu < 1$. But even while these papers were going to press, a tube to resolve the question experimentally was under construction (Fig. 11). If the angle of incidence could be changed, the (111) surface plane could be adjusted to a reflecting position. Thus, d would be known. The law of refraction is $\mu \sin \beta' = \sin \beta$, (Fig. 10). The angle of incidence upon the (111) planes is $\alpha = \beta'$, not $\alpha = \beta$, as it would be if there were no refraction. However, the angle of emergence is equal to the angle of incidence so the beam reflected by the (111) planes should always appear in the regularly reflected position $\theta = 2\alpha$. But the voltage—that is, wavelength—at which it appeared would determine the index of refraction. By the time Germer's paper (*3*) was published, data from this tube established that μ was greater than 1 (Fig. 12).

The index of refraction curve of Fig. 12(b) can be explained by assuming that, as they pass through the surface, the electrons experience an accelerating potential difference of about 16 V. This observation confirmed the Fermi theory of an "inner potential" due to the "Fermi sea" of

4. A bar over a numeral indicates a negative value. The three zones of type $[1\bar{1}0]$ are $[1\bar{1}0]$, $[01\bar{1}]$, and $[\bar{1}01]$ obtained by permutation of the numbers. They make angles of 120° with one another.

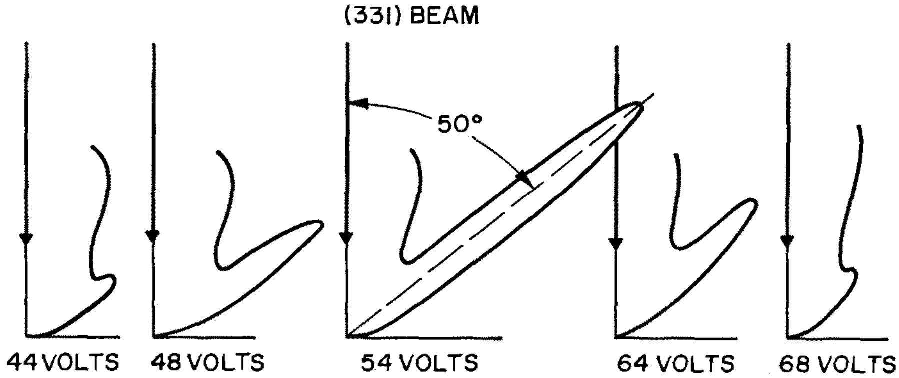


Figure 8. Growth and decay of the (331) beam in azimuth *A* as the wavelength (or velocity) is changed. The data were taken immediately after the crystal surface was cleaned by heating. The maximum occurs at $\theta = 50°$, $V = 54V$. If there were no refraction the maximum would occur at $\theta = 44$, $V = 68V$. In the first experiments, beam intensities were much less because of adsorbed gas on the surface and the 68V spike was almost completely missing.

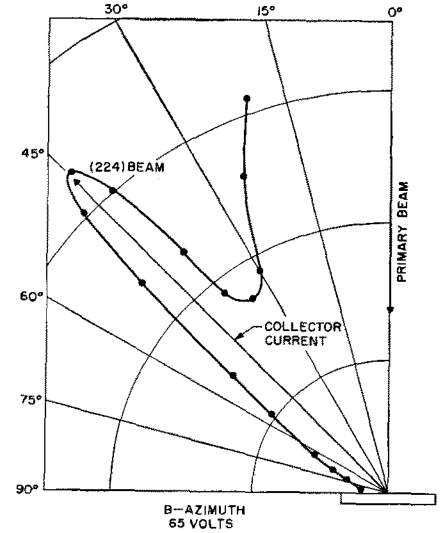


Figure 9. The (224) beam in the B azimuth. The polar coordinate system, with the collector current plotted radially, is omitted for clarity from Figs. 8 and 14.

electrons existing in low-energy states in a metal. It showed that the electrons in a metal obeyed the Fermi and not the classical statistics—a very important conclusion.

When the angle of incidence was varied, the results were much more complicated (Fig. 13). An "anomalous dispersion" break occurred, and two loops indicating possible double refraction were obtained. The explanation for these effects was not at all clear. Morse spent the summer of 1929 at Bell Laboratories on this problem and developed the beginnings of the dynamical theory of electron diffraction. Later, it was extended by Bethe, Slater, and many others. In this theory, when two beams can occur simultaneously from two sets of planes, resonance occurs, in consequence of which the diffraction spike becomes bifurcated. (An entirely similar effect occurs between two identical mechanical oscillators, such as weights on springs, if they are coupled together by a transverse spring.) In detail, the process is very complicated, and, in fact, a different approach is necessary in low-voltage electron diffraction. It is not discussed further here.

Application of Low-Voltage Electron Diffraction to Surface Physics

In the years since the Davisson–Germer experiments, an enormous amount of work has been done on high-voltage electron diffraction (5), but only a few scientists have, until recently, pursued the study of low-voltage electron diffraction. The fact that the beams are affected seriously by a layer of absorbed gas was forced on our attention in the very earliest experiments. Then we discovered a whole family of beams that could be destroyed by heating the crystal, but slowly reappeared. They did not behave like the nickel–crystal beams, which were reasonably fixed in angle and voltage, but appeared near grazing incidence at low voltage, and moved upward continuously in angle as voltage increased (Fig. 14). It was true that the intensity could decline sharply, as in the middle curves of the series. The relation between angle and wavelength could be accounted for by assuming that an ordered array of gas atoms condensed on the surface with a spacing twice that of

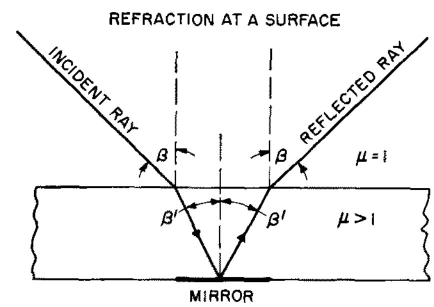


Figure 10. *Illustrative diagram showing ray paths as electrons enter and leave a metal surface.*

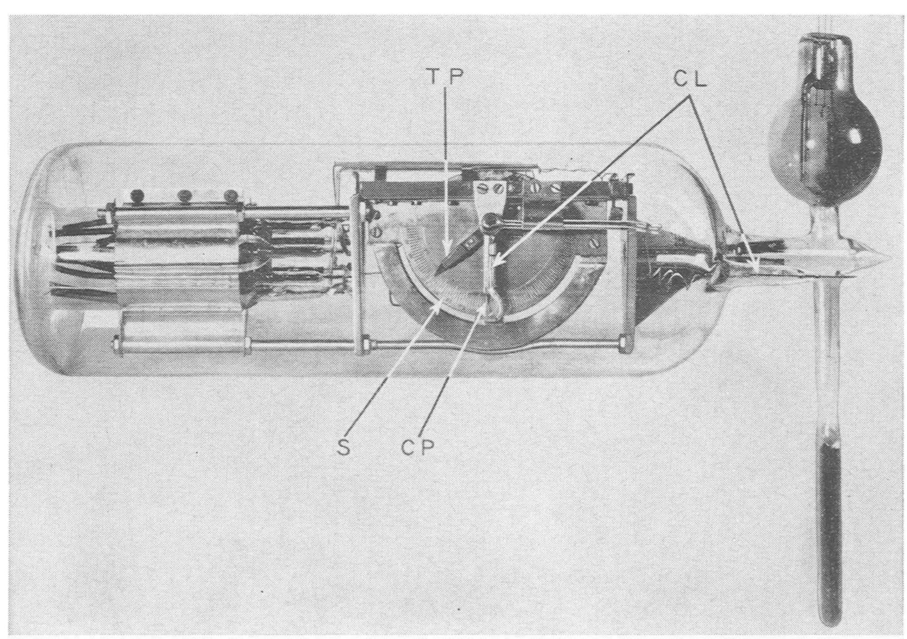


Figure 11. Photograph of the second tube, used to study the reflection of electrons from the (111) planes parallel to the surface. The crystal could be tilted but not rotated in azimuth, which was fixed in azimuth A; TP and CP are the nickel target and collector pointers respectively; CL is the collector lead. Target and colatitude angles are read on the scale S. *This tube is now on permanent display at the Smithsonian Institution.*

5. G. P. Thomson reported the discovery of high-voltage electron diffraction at nearly the same time as Davisson and Germer did low-voltage. Davisson and Thomson were jointly awarded the Nobel Prize in 1937.

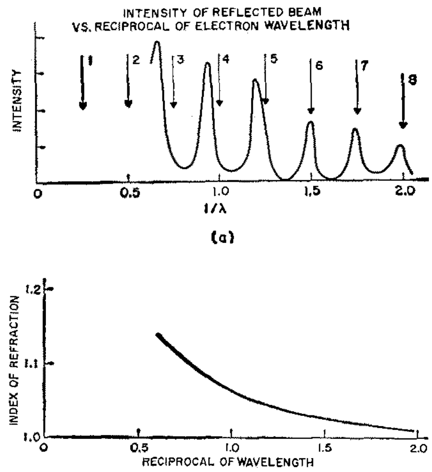


Figure 12. (a) Several orders of the (111) reflected beam, at $\alpha = 10°$, shown vs $1/\lambda$. The vertical lines show that the locations of $m = (2d \cos \alpha)/\lambda$ from Bragg's law are equally spaced when so plotted. The peak almost coincides with the line for $m = 8$, but progressively departs from it for smaller m. (b) From the displacements, an index of refraction μ can be calculated. The observed curve indicates that electrons are speeded up by an "inner potential" of about 16 V as they pass from vacuum into nickel.

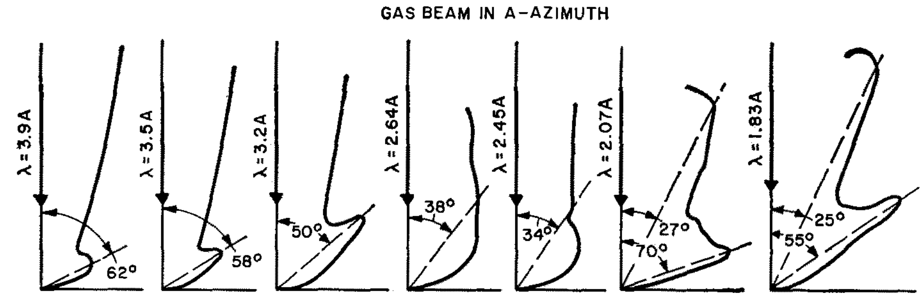


Figure 14. Growth and decay of a gas beam in the A azimuth. Data taken at normal incidence, from the tube shown in Fig. 6.

the underlying nickel atoms. (Fig. 15). It was necessary further to assume that the index of refraction from these beams was unity—as, of course, it should be if the electrons never entered the crystal. Such a layer is a two-dimensional lattice; the atoms are arranged in lines on the surface. In azimuths normal to the important lines—actually, the same azimuths, of course, as for the nickel crystal itself—these lines act similarly to the line grating often used in optical spectographs, which disperses light into a spectrum such that the shorter wavelength blue light appears at higher angles than the longer wavelength red light.

This phenomenon, the *adsorption* or growth of one material on another in an ordered or crystalline form geometrically related to, but not necessarily identical with, the crystal form of the underlying crystal, is called epitaxial growth. It has recently become of great commercial importance in the manufacture of transistors and other solid-state devices. Minor amounts of impurities can be incorporated in an epitaxially grown layer to produce, for example, either *p*-type or *n*-type germanium. Because the boundaries are very sharp, transistors made in this way can function at much higher frequencies than those made by other processes.

The importance of this discovery of ordered growth to the science of surface physics was recognized from the beginning: "Information of the nature of that which we have obtained may turn out to be of great scientific importance. The whole problem of chemical catalysis concerns itself with what occurs on the surface of a solid body. We believe that this electron diffraction analysis offers the only means which has been suggested for a direct study of questions of this nature" (*6*). Yet, until a few years ago, only a few scientists, notably Farnsworth and his school at Brown University, have pursued such studies. Davisson and the author developed electron optics and became interested in electron microscopy, and Germer conducted extensive studies using high-voltage electron diffraction. The reason for this neglect was largely that each beam had to be delineated by point-by-point recording of the current to a movable collector. This made a complete survey of the beams corresponding to a particular surface condition very time consuming; consequently, changes in surface conditions could not easily be followed. In 1934, Ehrenburg suggested a pattern-display technique in which the complete pattern at any particular voltage is displayed on a fluorescent screen. In its most recently improved version (*7*), the reflected electrons pass through two hemispherical grids that perform for electrons reflected at *all* angles the functions of the outer and inner boxes of the Faraday collector (Fig. 16). Only full-energy electrons pass the second grid, which is at the potential of the filament. They are then accelerated by a high voltage and strike a fluorescent screen. All the beams occurring at any particular voltage are thus simultaneously visible. The complete pattern over a wide range of voltage can be rapidly re-

6. Quotation from Ref. 1.

7. A. U. MacRae, Science **139**, 379 (1 February, 1963).

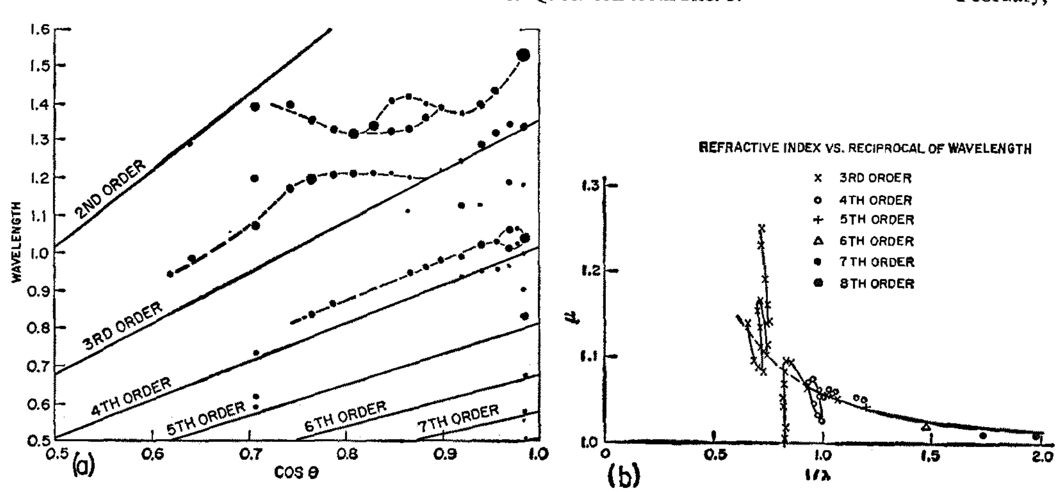
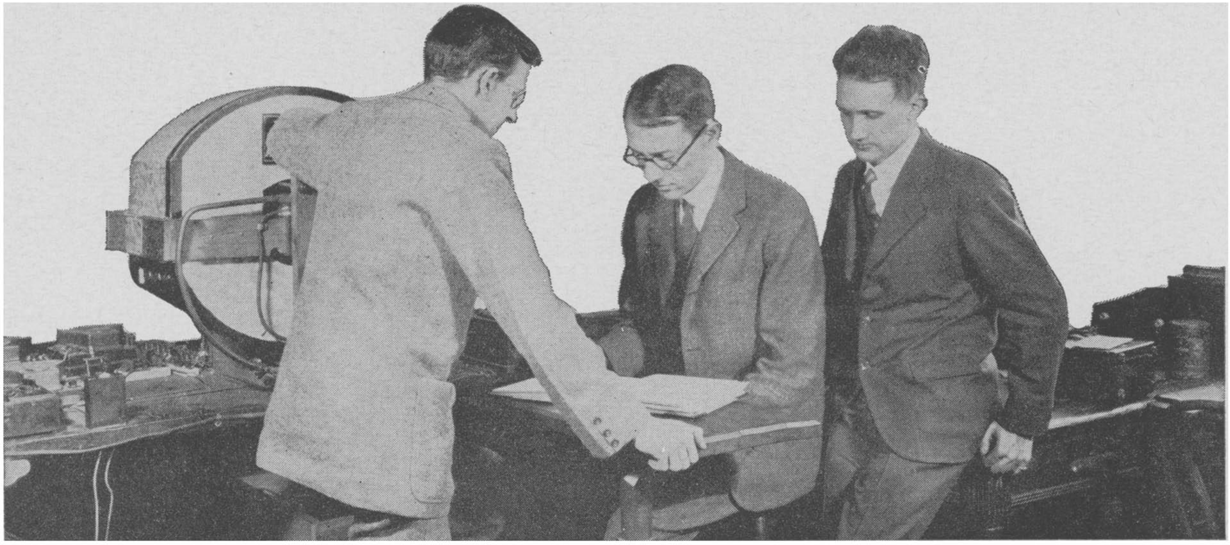


Figure 13. (a) As angle of incidence α is varied, the beams appearing at $\theta = 2\alpha$ follow very peculiar paths. The dot size represents approximately the beam intensity. The locations of a few half-order (gas) beams are shown. Figure 13. (b) As a result, the calculated values of index of refraction pursue a very complicated path, showing a break similar to optical dispersion and loops similar to optical double refraction.

"Let us encourage ourselves by a little more imagination tied to experiment. . . ."
—Michael Faraday



Davisson, Germer, and Calbick, 1927.

corded photographically. An example is shown in Fig. 17. The application of low-voltage electron diffraction to surface physics is now beginning to fulfill its early promise.

Heisenberg's Uncertainty Principle

The fundamental principle that resolved the paradox "How can something be both a particle and a wave?" was given by Heisenberg in 1927. It is called the "Uncertainty Principle." The quantum of action h is the mimimum value of the uncertainty in measuring "something" in the physical world. What we know about a particle can only be what we measure. Thus, for example, if we wish to know its position and speed at a given time, we look at it, in a very refined way, of course. A single quantum of light strikes it and is reflected to a very sensitive measuring device, which could be called our eyes. A short time later the experiment is repeated. *Each of these quanta strikes the particle and changes its speed and direction a little.* Consequently, we do not know *exactly* just where it was or how fast

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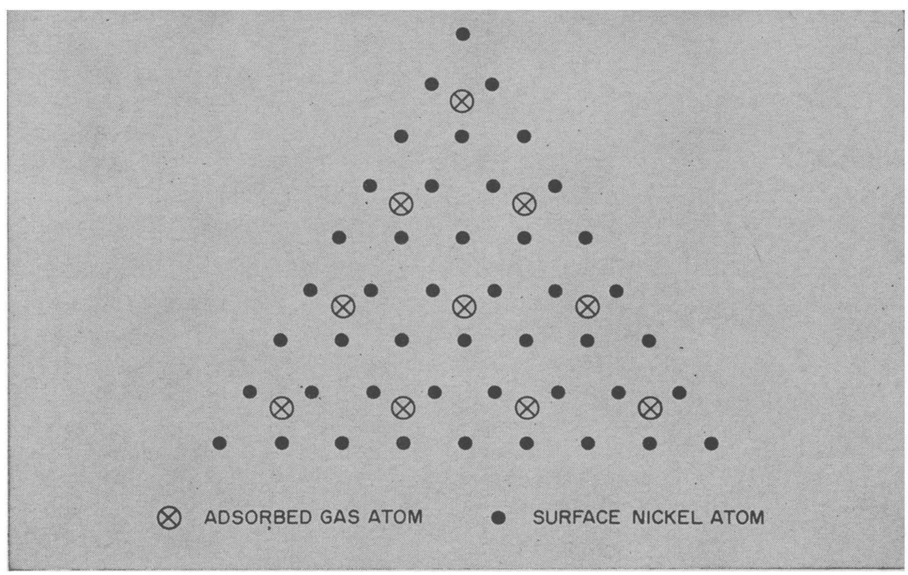

Figure 15. A layer of gas atoms adsorbed in a triangular array with double the spacing of the nickel-atom array.

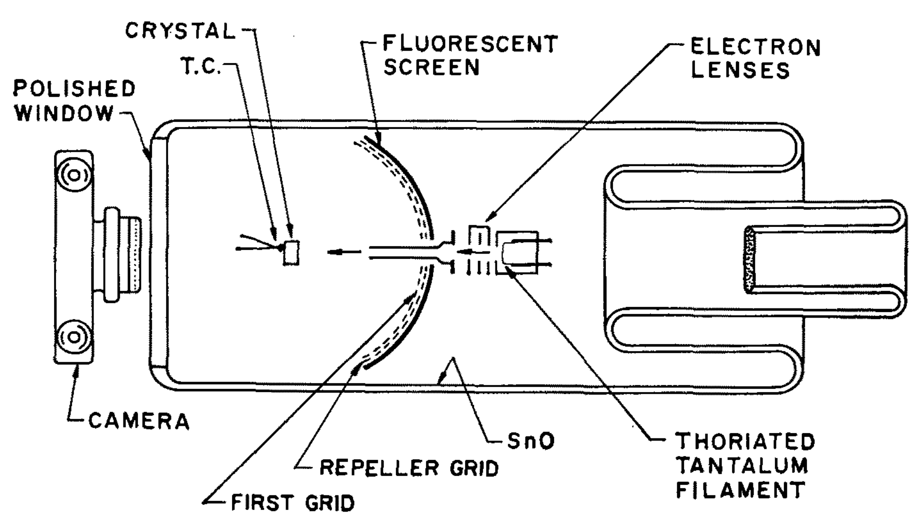

Figure 16. Schematic drawing of postacceleration low-voltage electron-diffraction tube. Electrons reflected by the crystal travel to the spherical first grid. Immediately behind it, the repeller grid only slightly above filament potential turns back all electrons except those that have lost no energy. The full-speed electrons are then accelerated through several thousand volts, and form a pattern of beam spots on the fluorescent screen.

above by the Executive Board and the Section Representatives.

The Secretary, for the Executive Board, moved that Frank Verbrugge and Vincent E. Parker be elected to the Governing Board of the American Institute of Physics. This motion was seconded and voted without dissent.

The Regional Representatives were called upon to report the activities of their sections. Each one had a written report and these reports were made available on a table at the rear of the room. The Secretary stated that reports had been received from Sectional Representatives who could not be present and that copies of all reports would be placed in the Secretary's file of Regional Sections. The Secretary read the list of Regional Representatives as it appears in his records and received corrections.

The meeting adjourned at 9:55 P.M.

Respectfully submitted,
RALPH P. WINCH, *Secretary*

Minutes of the Annual Business Meeting

The Annual Business Meeting of the Association was held on Saturday, 26 January 1963, in the Georgian Room of the Statler–Hilton Hotel in New York City.

The meeting was called to order by President Frank Verbrugge at 11:00 A.M. Minutes of the Annual Business Meeting on 27 January 1962 were declared approved as published in the July 1962 issue of the *American Journal of Physics* since no corrections had been received.

President Verbrugge read citations for distinguished service and presented certificates to Charles Luther Andrews, Kenneth E. Davis, R. Bruce Lindsay, and Melba Phillips. These citations will be published in the *American Journal of Physics* in the near future.

The President announced that the judges in the apparatus competition, made possible by a grant from The Welch Scientific Company, were Dr. Alfred G. Redfield, Dr. Robert Pohl, and Dr. Byron L. Youtz. The awards were announced by the President and presented by Dr. Allan M. Sachs, Chairman of the Apparatus Committee, as follows:

Undergraduate laboratory apparatus: First Prize of $500 to Dr. Anthony P. French; Second Prize of $200 to Dr. Robert B. Leighton; Third Prizes of $50 each to Dr. Alan J. Bearden and Dr. Kenneth W. Billman.

Demonstration lecture apparatus: First Prize of $500 to Harold M. Waage; Second Prize of $200 to Gary D. Gordon.

The Secretary announced the future meeting dates, set by the Council, as 27-29 June 1963, at the University of Maine, Orono, Maine; the next Annual Meeting 22-25 January 1964, at the Statler–Hilton Hotel in New York City; and 18-20 June 1964, at the University of Wisconsin in Madison, Wisconsin. He also announced that, as a result of the mail ballot last fall, Edward U. Condon was named President-Elect, Ralph P. Winch was renamed Secretary, and Robert S. Shankland was elected to the Executive Board. At their meeting Thursday, 24 January 1963, the Section Representatives reelected Mario Iona as their Chairman and thus a member of the Executive Board.

The Secretary announced that the Council had admitted the following new Regional Sections: (a) the Southwestern Section, which takes in the panhandle of Oklahoma, the panhandle of Texas, and about half of New Mexico; (b) the Arkansas – Oklahoma – Kansas Section, which includes all of these three states except the panhandle of Oklahoma; (c) the New Jersey Section. He further announced that the Council had elected Frank Verbrugge and Vincent Parker for three-year terms on the Governing Board of the American Institute of Physics.

Chilean Examination

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5. Fifty cm from the optic center of a convergent lens a vertical image having the double height of the object is formed. Calculate the distance at which the object is from the lens, and the convergence or power of the lens.

6. In order to calculate the depth of a lake, a sound is produced immediately under its surface, and the echo is received by means of an echo sounder after 1.4 seconds. If the speed of sound in the water is 1440 meters per second, and the frequency of the wave 300 oscillations per second, what is the depth of the lake, and what is the wavelength of the sound?

7. A heater receives water at 18°C and delivers it at 35°C. What minimum quantity of heat is required when a tub is filled with 120 liters of water. If, through the delivering tap three liters per minute run, what is the calorific value (heat produced in each unit of time) of the heater?

Electron Diffraction

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it was going. The process of measurement itself changes these so they are forever unknowable *exactly*. Heisenberg's Uncertaintly Principle states that Planck's constant h is the product of the minimum uncertainties in energy and in time of the most-refined possible methods of measurement. Of course, h is very small [6.6×10^{-27} erg·sec]; the uncertainty is quite undetectable for all ordinary objects. By the second of the relations, h is also the product of the minimum uncertainties in momentum and wavelength. These relations exist together and are inseparable. Energy and momentum are attributes of a particle, frequency and wavelength those of a wave. The fact that "something" appears to be both a particle and a wave is inherent in the process of measurement. Even more fundamentally, the dual aspect is inherent in the way in which a human mind acquires knowledge of the external world.

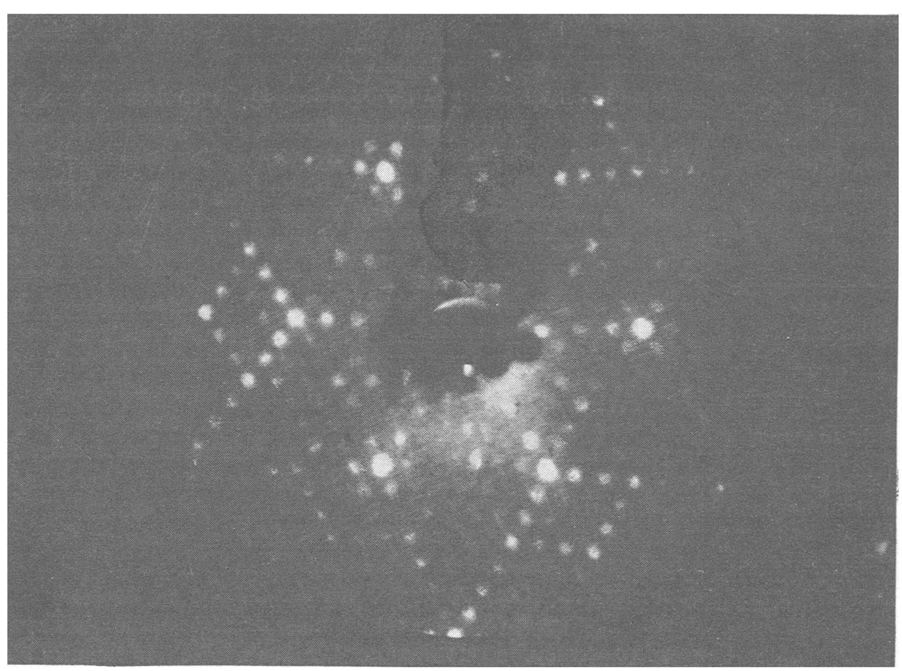

Figure 17. Low-energy electron-diffraction pattern from the clean (111) surface of a silicon-crystal pattern obtained at 120 V. Most of the pattern is due to a surface structural array with seven times the spacing of the underlying silicon. The black shadowed structure is due to the specimen support.