EXPERIMENT 6

ELECTRON DIFFRACTION

I GOALS

Physics--Demonstrate that accelerated electrons have an effective wavelength, λ, by diffracting them from parallel planes of atoms in a carbon film. Measure the spacings between two sets of parallel planes of atoms in carbon.

Techniques--Control the wavelength of the electron beam by varying the accelerating voltage. Use the De Broglie expression for the wavelength of the electrons and the Bragg condition for analyzing the diffraction pattern.

Error Analysis--Calculating the uncertainties in the data points on your graph gives you a good opportunity to use the principles of error propagation.

II QUESTION (work out in lab book before class)

Derive an expression for the extrapolated value of the diffraction ring of diameter D' shown in Fig. 12.

III REFERENCES

Wehr, Richards, and Adair; 6.9, 7.1-7.4.
Halliday and Resnick; 43.1.

BACKGROUND

Several of your laboratory experiments show that light can exhibit the properties of either waves or particles. The wave nature is evident in the diffraction of light by a ruled grating and in the interferometer experiments. In these experiments, wavelength, phase angle, and coherence length of wave trains were investigated--all features of wave phenomena. However, the photoelectric effect cannot be explained by a wave picture of radiation. It requires a model in which light consists of discrete bundles or quanta of energy called photons. These photons behave like particles. There are other examples illustrating this dual nature of light. Generally, those experiments involving propagation of radiation, e.g. interference or diffraction, are best described by waves. Those phenomena concerned with the interaction of radiation with matter, such as absorption or scattering, are more readily explained by a particle model. Some connection between these models can be derived by using the principal of the equivalence of mass and energy introduced by Einstein in 1905 in his special theory of relativity, namely,

$$E = mc^2$$

In this equation E is the total energy of a body, m is its mass, and c is the velocity of light. From the photoelectric experiment we learned that light may be considered to consist of particles called photons whose energy is

$$E = h\upsilon$$

where υ is the frequency of light and h is Planck's constant. We may equate these two energies and obtain

$$mc^2 = h\upsilon, \text{ or}$$

$$mc = h\upsilon/c = h/\lambda$$

where λ is the wavelength of the light. Now mc is the momentum of a photon traveling with velocity c and m is its equivalent mass. Thus the momentum of radiation may be expressed either in terms of the wave characteristic λ or by the mass and velocity of the equivalent particle.

This dual situation with respect to radiation led de Broglie in 1925 to suggest that since nature is likely to be symmetrical, a similar duality should exist for those entities which had previously been regarded as particles. Thus, a particle such as an electron with mass m, traveling with velocity v, has a momentum mv. De Broglie stated that this particle could also behave as a wave and its momentum should equal the wave momentum, i.e.

$$mv = h/\lambda, \text{ or } \lambda = h/mv.$$

It was now a question of verifying this hypothesis experimentally. If an electron is accelerated through a potential difference V, it gains a kinetic energy

$$\frac{1}{2}mv^2 = eV, \quad v = \sqrt{\frac{2eV}{m}}$$

where e is the electron charge and m is its mass.

Substituting this value for v in the de Broglie expression for the wavelength gives

$$\lambda = \frac{h}{mv} = \frac{h}{\sqrt{2meV}} = \frac{1.23}{V^{\frac{1}{2}}}\text{nm}. \qquad (1)$$

Thus it should be fairly simple to produce a beam of electrons of a known wavelength by accelerating them in a voltage V. This beam could then be used in experiments designed to demonstrate wave properties, e.g. interference or diffraction. One might try to diffract the beam of electrons from a grating. However, the spacings between the rulings in man-made gratings are of the order of several hundred nm. From Equ. (1), we find that even with an accelerating voltage as low as 100V, the electron wavelength is only 0.12 nm. As we will see shortly, such a large difference between the grating spacing and the electron wavelength would result in an immeasurably small diffraction angle. It was recognized, however, that the spacings between atoms in a crystal were of the order of a few tenths of a nm. Thus, it might be feasible to use the parallel rows of atoms in a crystal as the "diffraction grating" for an electron beam. This possibility seemed particularly promising since it had been found that x-rays could be diffracted by crystals, and x-ray wavelengths are of the order of the wavelengths of 100eV electrons.

Figure 1 shows some of the possible arrangements of atoms in a cubic pattern. (a) is the simple cubic form. When an atom is placed in the center of the simple cube, we get (b), the body-centered-cubic form. When atoms are placed on the faces of the cube, as in (c), the arrangement is called face-centered-cubic. For example, the atoms in nickel and sodium chloride are arranged in the face-centered-cubic pattern. In an iron crystal, the body-centered-cubic arrangement is found. Figure 2 shows a view of

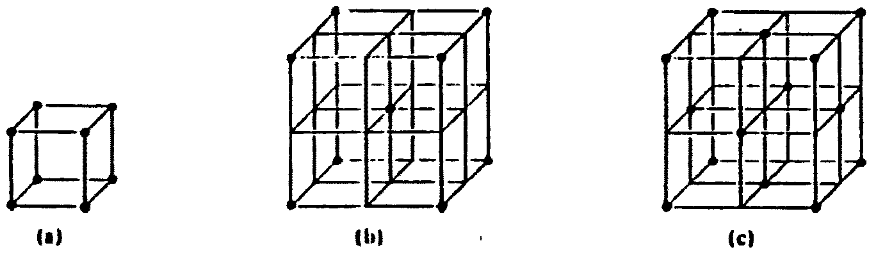


Fig. 1: Three cubic arrangements of atoms in a crystal. (a) simple cubic, (b) body-centered-cubic, (c) face-centered cubic..

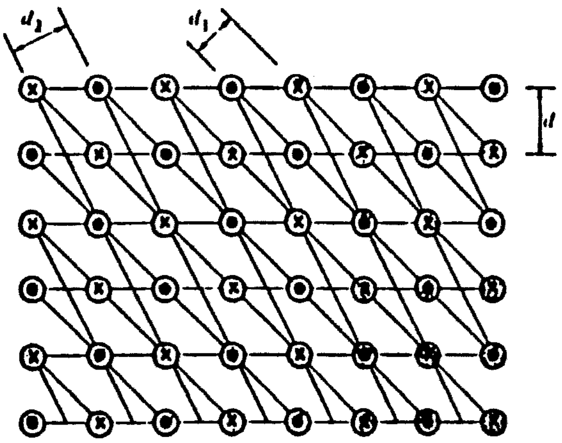


Fig. 2: Interplanar spacings, d, of different families of parallel planes in a cubic array of atoms.

the atoms looking perpendicular to one of the cubic faces. Three different orientations of parallel rows of atoms are distinguished with different spacings between the parallel rows. These parallel rows of atoms lie in parallel atomic planes and it is evident that there are a large number of families of parallel planes of atoms in a crystal. We consider the scattering of waves from a single plane of atoms as shown in Fig. 3. The

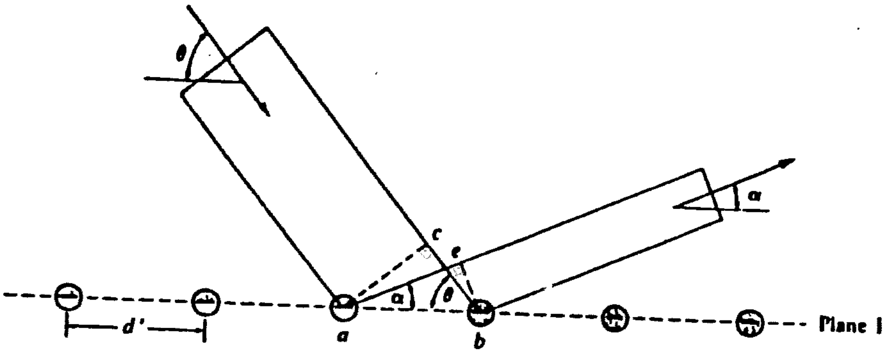


Fig. 3: Scattering of waves from a plane of atoms. Path difference for waves from adjacent atoms.

atoms are spaced a distance d' apart. The incident wave makes an angle θ with a row of atoms in the surface plane waves of atoms; $\overline{ac}$ is the wave front. The scattered wave makes an angle α with the atom row; its wavefront is $\overline{be}$. Constructive interference will occur for the rays scattered from neighboring atoms if they are in phase--if the difference in path length is a whole number of wavelengths. The difference in path length is $\overline{ae} - \overline{cb}$. Therefore $\overline{ae} - \overline{cb} = d'\cos\alpha - d'\cos\theta = m\lambda$, where m is an integer. Another condition is that rays scattered from successive planes also meet in phase for constructive interference. Figure 4 shows the construction for determining this

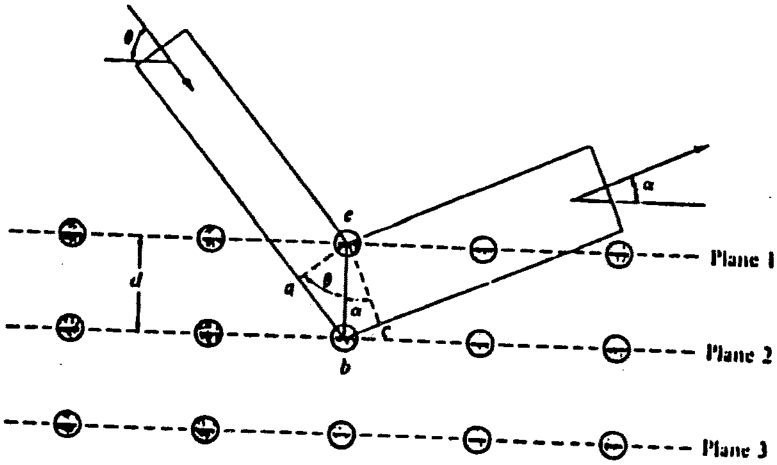


Fig. 4: Path difference for waves scattered from successive planes of atoms.

condition. The difference in path length for rays traveling from planes 1 and 2 is seen to be $\overline{ab}+\overline{bc}$, the extra distance traveled by the ray scattered from plane 2. This path difference must again be an integral number of wavelengths. Therefore

$$\overline{ab}+\overline{bc} = d\sin\theta + d\sin\alpha = n\lambda$$

These conditions can be satisfied simultaneously if $\theta = \alpha$. In that case $m = 0$ for the first condition and

$n\lambda = 2d\ \sin\theta$ for the second condition.

This relation was developed by Bragg in 1912 to explain the diffraction of x-rays from crystals. n is the order of the diffraction spectrum. Thus the conditions for constructive interference are that the incident and scattered beams make equal angles θ and that the relation $n\lambda = 2d\sin\theta$ must be obeyed where d is the spacing between parallel adjacent planes of atoms.

In 1927, Davisson and Germer at the Bell Telephone Laboratories, investigated the scattering of a beam of electrons from a nickel crystal. Figure 5 shows, schematically, the essentials of their apparatus. Electrons from the heated filament F, were accelerated through a potential difference of order 100V to a plate P with a small diameter hole. A narrow beam of electrons emerged from the opening in P and was incident normally on the face of the nickel crystal C. The electrode E was connected to a sensitive galvanometer and measured the intensity of the electrons scattered by the

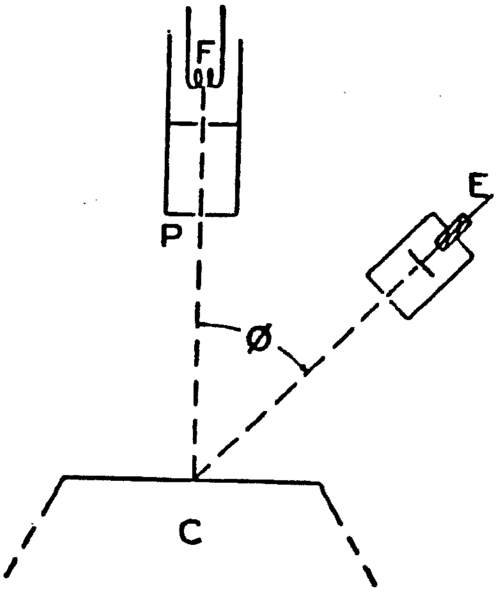


Fig. 5: Experimental arrangement for the Davisson-Germer electron diffraction experiment.

nickel crystal at various angles ϕ. Some of these results are shown in Fig. 6. These are polar plots of the beam intensity as a function of the angle ϕ for various accelerating voltages which correspond to the wavelengths indicated. In each plot, a line drawn from the origin to any point on the curve makes the angle ϕ; the length of a

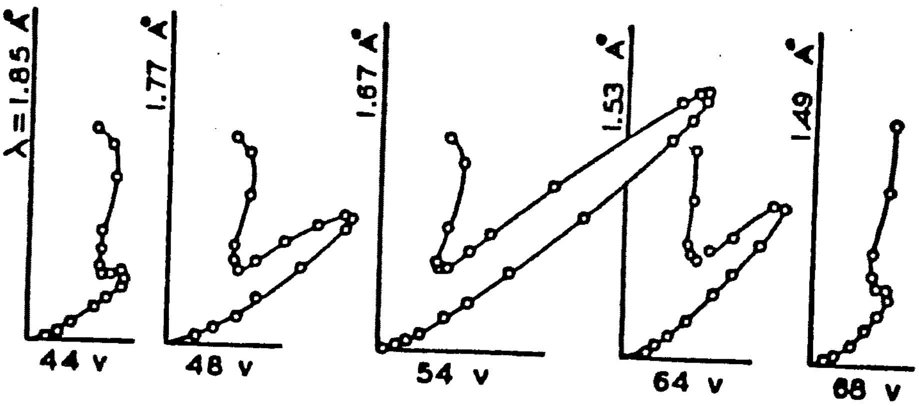


Fig. 6: Polar plot of Davisson and Germer's data for the scattered electron beam intensity as a function of scattering angle for different incident electron energies.

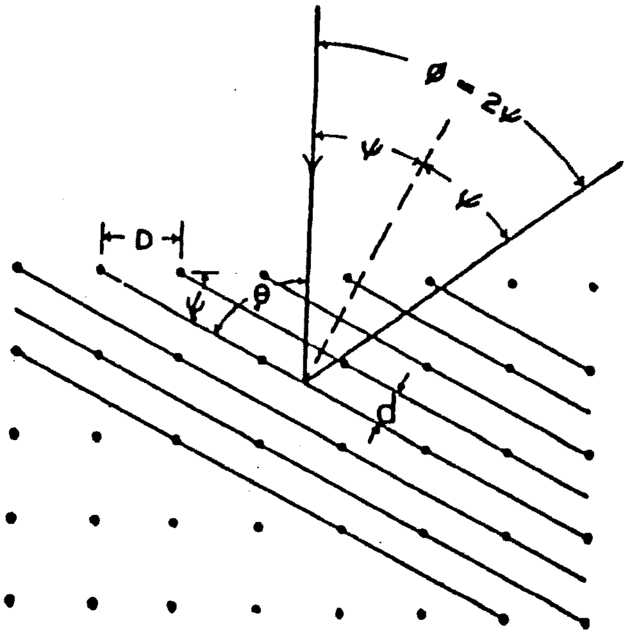


Fig. 7: Illustrating the Bragg condition for electron waves scattered from planes of atoms in the nickel crystal used by Davisson and Germer.

line is proportional to the electron beam intensity at that angle ϕ. As the voltage was increased from 40 to 68 volts, a characteristic peak gradually appears and then disappears. It reaches a maximum for electrons with an energy of 54 eV (.167nm) at an angle of 50°. Davisson and Germer concluded that this peak was due to Bragg reflection from a set of regularly spaced atomic planes within the crystal as shown in Fig. 7. The angle $\phi = 2\Psi$ is measured in the experiment. The diffracting planes must be normal to the bisector of ϕ. Therefore, $\Psi = \phi/2$, and the angle of incidence,

$$\theta = 90^\circ - \psi = 90^\circ - \phi/2$$

The spacing between the planes involved in the diffraction is d. From x-ray measurements, the spacing D between the surface atoms was known to be 0.215nm.

Therefore, $d = D \sin \Psi = 0.215 \sin (50^\circ/2) = 0.215 \sin (25^\circ)$
$\theta = 90^\circ - 50/2^\circ = 65^\circ$

Then, the Bragg condition for the first order reinforcement is

$$\lambda = 2d \sin \theta = 2\,[0.215 \sin 25^\circ] \sin 65^\circ = .165 \text{ nm.}$$

The calculation from the de Broglie relation is

$$\lambda = h/mv = 0.167 \text{ nm}$$

This close agreement convinced Davisson and Germer that they had observed the diffraction of electron waves from the nickel crystal. In this experiment and in a number of subsequent ones, Davisson and Germer observed that while agreement was close between the observed and calculated diffraction data, there was usually a small discrepancy that was larger for the low energy (longer wavelength) electron beams. They were able to show that this discrepancy was due to the fact that the electrons were refracted as they entered the crystal. The index of refraction, μ, of a crystal was greater than 1, due to the fact that the electrons gained energy on entering the crystal. For those low energy beams where μ is significant, the Bragg relation is modified to

$$n\lambda = 2d\,(\mu^2 - \cos 2\theta)^{1/2}$$

Thus far, only single crystals have been considered. Most materials are polycrystalline. They are composed of a large number of small crystallites (single crystals) that are randomly oriented. An electron diffraction sample may be a polycrystalline thin film, thin enough so that the diffracted electrons can be transmitted through the film. The experimental arrangement shown in Fig. 8 was used by Thomson in 1927 to study the transmission of electrons through a thin film C. The transmitted electrons struck the photographic plate P as shown. The pattern recorded on the film was a series of concentric rings. This pattern arises from the polycrystalline

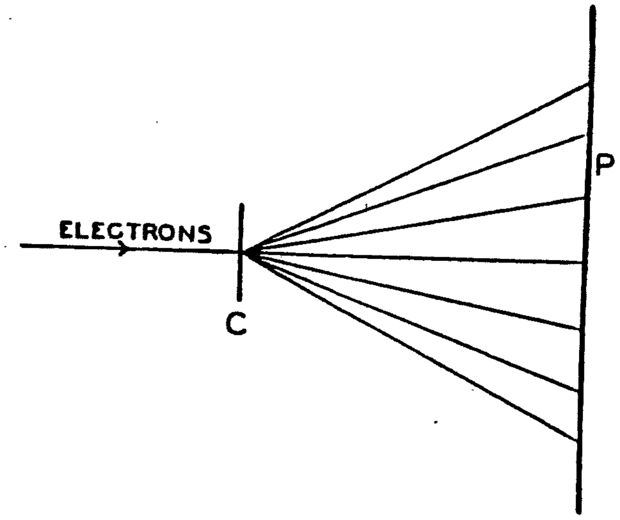
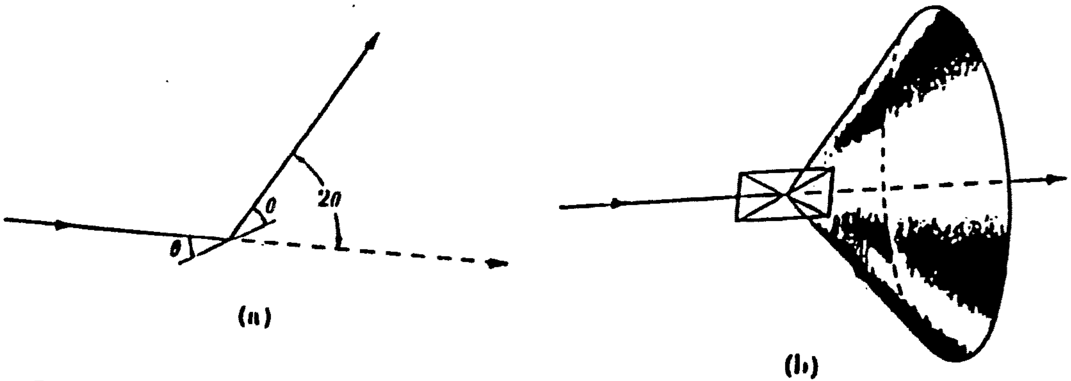


Fig. 8: The experimental arrangement used by Thomson for his transmission electron diffraction research.

nature of the film. Figure 9(a) shows a beam of electrons of wavelength λ traveling from the left and striking a plane of atoms in a crystallite. If this plane makes the angle θ with the incident beam such that $\lambda = 2d \sin \theta$, where d is the spacing of successive atomic planes, the beam will be diffracted into the angle θ with respect to the atom plane (or the angle $\phi = 2\theta$ that the diffracted beam makes with the incident beam).



(a)

(b)

Fig. 9: Showing how the randomly oriented crystallites in a polycrystalline film scatter into a cone when the Bragg condition is fulfilled by planes of atoms disposed symmetrically about the incident beam.

Now there are many randomly oriented crystallites in this film. Thus we may expect that there will be crystallites in which this diffracting plane makes the same angle θ with the beam direction but rotated around the beam in a cone as shown in Fig. 9(b). The diffracted beams from this plane from all the crystallites in the sample will fall on a circle whose diameter may be determined from the cone angle θ and the distance from the sample to the film or other detector. The Bragg condition becomes

$$n\lambda = 2d \sin \theta/2$$

For ϕ small, $\sin \theta/2 \approx \theta/2$, giving

$$n\lambda = 2d\, \theta/2 = d\theta$$

Thus, in 1927 the wave nature of electrons was verified by reflection and transmission diffraction experiments. For this work Germer and Thomson were awarded the Nobel prize in 1937. De Broglie received the Nobel prize in 1929 for his basic insight on the wave nature of matter.

THE EXPERIMENT

Equipment:

Electron diffraction tube with carbon thin film target.

High and low voltage power supplies.

Digital voltmeter for monitoring anode current.

Calipers for measuring diffraction ring diameters.

Precautions:

The 5kV power source can give you a very nasty shock. Verify that your circuit is correctly wired before turning on power. Have your instructor or TA check the circuit.

Check that the anode current monitoring meter is on the grounded side of the circuit as shown in the diagram below.

Never permit the anode current to exceed 0.2 mA; otherwise the target may be damaged.

Procedure:

The electron diffraction tube is sketched in Fig. 10. The carbon film is mounted in the anode as shown. The variable anode voltage is provided by the 5kV dc supply. Use the outer high voltage terminals. The electrons are emitted from an indirectly heated oxide coated cathode. The heater voltage, V_F, is supplied by the 6V output on the 5kV supply. V_F is applied to the 4 mm terminals in the plastic cap at the end of the tube. The external bias for the can surrounding the cathode is provided by the separate

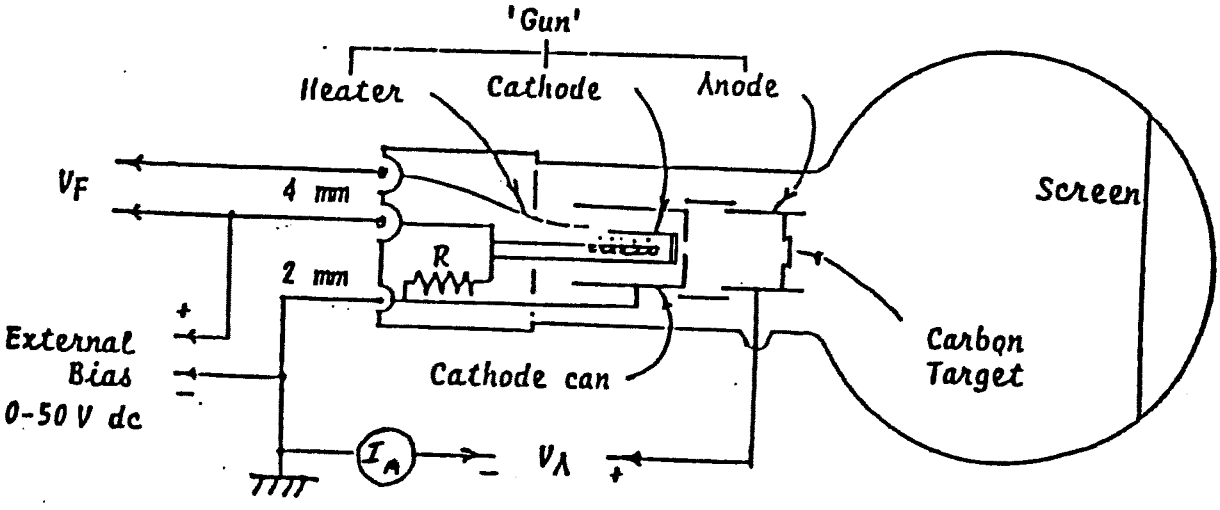


Fig. 10: The electron diffraction tube.

power supply. The negative biassing of the can surrounding the cathode serves to focus the electron beam. The beam current varies with both anode and bias voltages. Be sure to keep the beam current below 0.2 mA as monitored on the DVM in the grounded side of the anode circuit. The 2 mm pin on the back of the tube is the terminal for the negative side of the anode voltage. The positive side of the anode voltage is connected to the 4 mm pin on the side of the tube. The diffraction rings are viewed on the phosphor screen on the glass bulb. After having your circuit checked, start the experiment by stabilizing the heater current for about a minute before turning on the anode voltage. The external bias voltage helps to focus the diffraction rings as well as limiting the anode current to 0.2 mA.

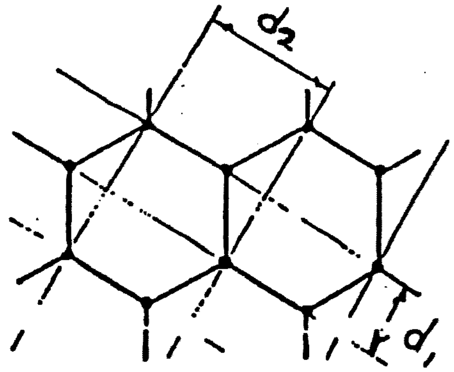


Fig. 11: Atom arrangements in carbon showing the two sets of planes that produce the diffraction rings.

Figure 11 shows the arrangement of the atoms in a carbon crystal. They are located on the corners of a hexagon and two principal spacings of the atom planes are indicated. These spacings are 0.123 nm and 0.213 nm. As you turn up the anode voltage you will see two rings on the screen, as shown in Fig. 12. Each ring corresponds to one of the carbon d spacings. As explained in the text, the diffraction condition for the polycrystalline carbon film is

$$\lambda = d\theta$$

Measure the ring diameter D on the screen with the calipers. To determine θ, you must calculate the extrapolated ring diameter D', as shown in the figure. Take into account both the curvature and thickness of the glass bulb. Hint: start with the fact that D is the chord of a circle with a 66 mm radius.

The value for D' permits you to calculate θ from the small angle approximation

$$\theta = \frac{D'}{2L}$$

Writing λ in terms of the anode voltage gives

$$\frac{1.23}{V^{\frac{1}{2}}} = \frac{D'd}{2L}$$

for the Bragg condition. For each ring, plot $V^{-1/2}$ as a function of D' for a number of values of V. Determine d_1 and d_2 from the slopes of these curves. Using error analysis, compare your values to the d spacings for carbon.

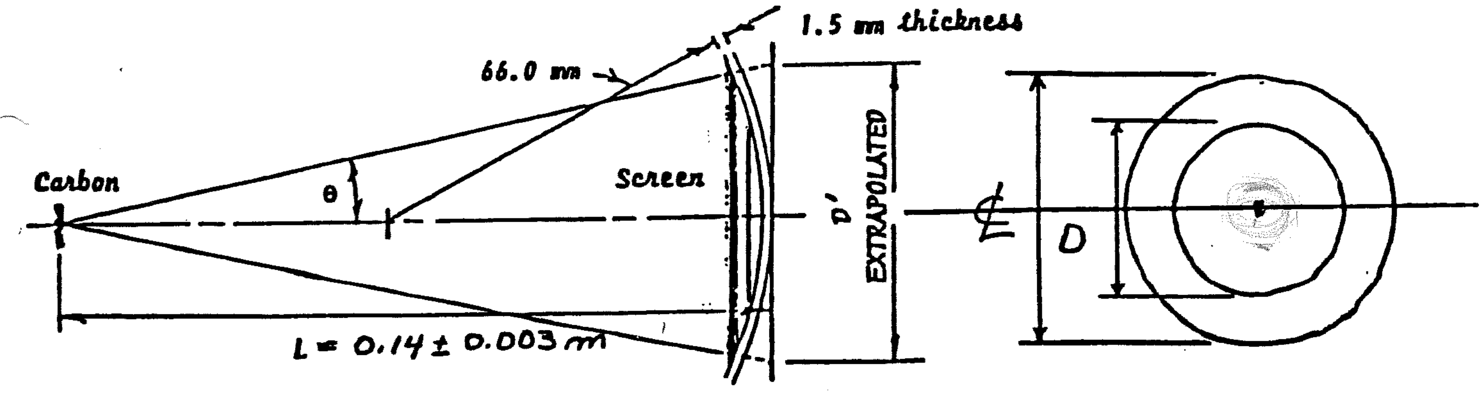


Fig. 12: Sketch of the geometry involved in determining the extrapolated ring diameter, D'.

ELECTRON DIFFRACTION TUBE 555

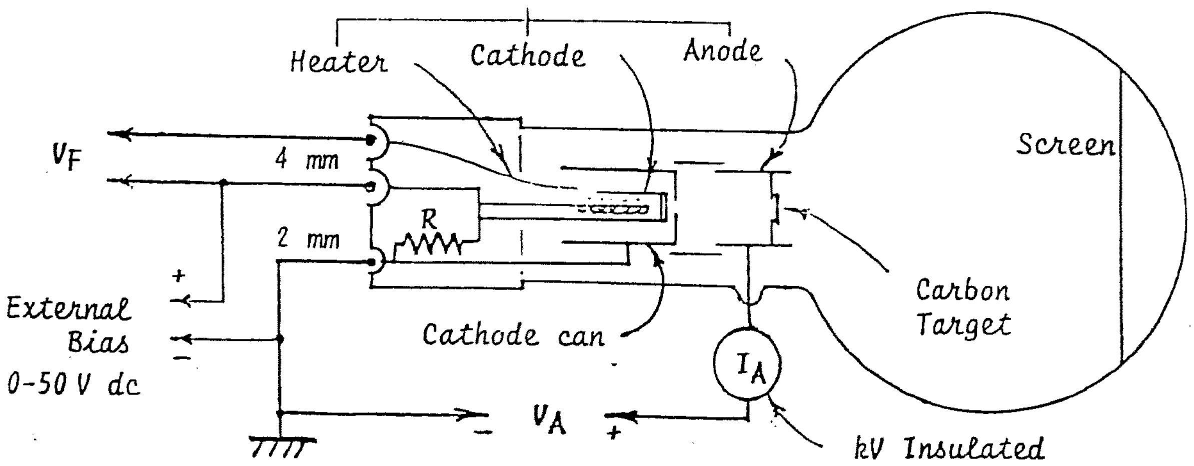
THE ELECTRON DIFFRACTION TUBE, TEL.555, comprises a 'gun' which emits a narrow converging beam of electrons within an evacuated clear glass bulb on the surface of which is deposited a luminescent screen. Across the exit aperture of the 'gun' lies a micro-mesh nickel grid onto which has been vapourised a thin layer of graphitised carbon; the beam penetrates through this carbon 'target' to become diffracted into two rings corresponding to separations of the carbon atoms of 0.123 and 0.213 nanometers. The source of the beam of electrons is an indirectly-heated oxide-coated cathode, the heater of which is connected to 4mm sockets in a plastic cap at the end of the neck; a 2mm plug is supplied with each tube for connecting the negative line of E.H.T supply to the can surrounding the cathode via a 2mm socket in the base-cap; this socket is internally connected to the negative heater socket by a resistor, R , to achieve 'negative auto-bias' of the cathode-can. The E.H.T positive potential is applied to the anode of the 'gun' through a 4mm plug mounted on the side of the neck.

The tube can be mounted on the Universal Stand, TEL.501.

Specification:

FILAMENT VOLTAGE	(V_F)	...	6.3 V ac/dc (8.0 V max.)
ANODE VOLTAGE	(V_A)	...	2500 - 5000 V dc
ANODE CURRENT	(I_A)	...	0.15 mA at 4000 V (0.20 mA max.)

FIGURE 1



Protection of the Carbon Target.

The graphitised carbon through which the electron beam is confined to pass is only a few molecular layers in thickness and can be punctured by current overload.

The purpose of 'negative auto-bias' is to reduce the likelihood of damage to the target due to accidental user-abuse. The total emitted current passes through the resistor R ; increase in the current causes the cathode-can to become more negatively biassed, so reducing the emitted current.

CONNECT THE E.H.T NEGATIVE TO THE 2MM SOCKET ONLY.

Practical precautions.

Current overload causes the target to become overheated and to glow dull-red; it is good practise to inspect the target periodically during an experiment and especially at switch-on when at least one minute should be allowed for the cathode temperature to stabilise before applying anode voltage.

As an additional safeguard, the anode current should be metered and never allowed to exceed 0.2 mA; higher anode voltages can be achieved without exceeding this limit by reducing the heater voltage.

CONNECT THE E.H.T NEGATIVE TO THE 2MM SOCKET ONLY.

External biassing.

The focus of the beam of electrons may be varied by the degree of bias of the cathode-can; improved focussing sharpens the diffraction pattern for better observation at lower E.H.T settings.

External control can be achieved by connecting the negative heater socket and the 2mm socket (and thus the cathode-can) to a 0-50 V variable source; negligible current is required and the beam can be 'cut-off' at about -40 Volts.

CONNECT THE E.H.T NEGATIVE TO THE 2MM SOCKET ONLY.

Recommended Experiments:

Experiments with the Maltese Cross Tube, TEL.523, demonstrate that cathode rays exhibit some properties that seem similar to those of light and other properties that appear to be consistent with those of electrically charged particles. It was suggested by **Louis de Broglie** in 1926 that particles could have wave properties where the wavelength, λ , is inversely proportional to momentum, M ($= mv$).

The Teltron Series 'A' Experiments confirm that electrons obey the laws of motion and lead to a measure of the specific charge e/m . The Millikan experiment establishes the discrete nature of the electron, gives a measure of charge e and thereby an evaluation of its mass m . Sufficient information is thus available to test the de Broglie hypothesis.

The possibility of diffraction:

A calculation using de Broglie's equation shows that electrons accelerated through a p.d. of 4 kV have a wavelength of about 0.02 nanometers. Interference and diffraction effects, as studied in physical optics, demonstrate the existence of waves, where for a simple ruled grating, the condition for diffraction is $\lambda = d \sin \theta$, where d is the spacing of the grating and where for small angles $\sin \theta = \theta$.

The best man-made gratings are ruled at 2,000 lines per mm and with a wavelength of 0.02 nm , the angle θ will be less than one second of arc or only 0.5 mm at 10 m from the grating. If electron diffraction is to be observed in a Teltron tube with a pathlength of 140 mm, the spacing between 'rulings' to produce a first order of interference at 14 mm from zero (i.e $\sin \theta = 0.1$), must be 0.2 nm.

In 1912, **Prof. Max von Laue** had suggested, in connection with X-ray studies, that if fine gratings could not be made by man because of the basic granularity of matter, then perhaps this very granularity might provide a suitable grating. **Sir Lawrence Bragg** used the cubic system of NaCl to calculate interatomic spacings and showed them to be of the right order for X-rays. This salt, like most salts, is not suitable for sealing into an evacuated tube; however Carbon is vacuum-stable and can be formed in many different ways.

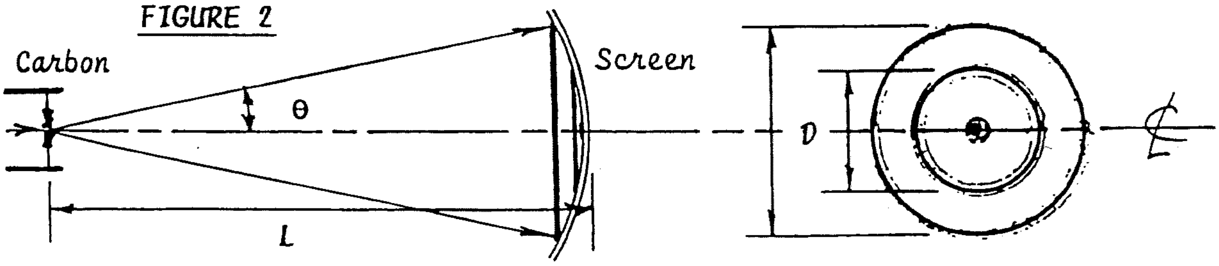
EXPERIMENT A.23 : Demonstration of Electron Diffraction.

A similar calculation can be made using Carbon and assuming that its atomic system is also cubic; 12 gms of Carbon contain 6 X 10^{23} atoms (Avogradro's Number); the density of Carbon is about 2 gms/cm^3, 1 cm^3 contains 10^{23} atoms so that adjacent Carbon atoms will be about $^3/_{10}$ or a little over 0.2 nm apart. It is thus reasonable to expect that Carbon should provide a grating of suitable spacing for an experiment.

The nature of the effect to be observed however is not evident from these calculations; before proceeding with the electron diffraction experiment it is recommended that students are prepared for the probable results by observing an Optical Analogue such as TEL.555A.

Connect the tube TEL.555 into the circuit shown in Fig. 1, switch on the heater supply and wait one minute for the cathode to heat stabilise. Adjust the E.H.T setting to 4.0 kV.

FIGURE 2



Two prominent rings about a central spot are observed, the radius of the inner ring being in fair agreement with the calculated value of 14 mm. Variation of the anode voltage causes a change in diameter, a decrease in voltage resulting in an increase in diameter. This is in accord with de Broglie's suggestion that wavelength increases with decrease in momentum. Evidence of the particulate nature of the electron has been previously obtained and so this demonstration, which so closely resembles the optical one, reveals the dual nature of the electron.

The de Broglie wavelength of a material particle is

$$\lambda = \frac{h}{mv} \qquad \ldots \quad \ldots \quad \ldots \qquad 23.1$$

where h is Planck's constant. The velocity, v can be obtained from the classical expression

$$eV_a = \tfrac{1}{2} m v^2 \qquad \ldots \quad \ldots \quad \ldots \qquad 23.2$$

and substituted into the de Broglie relation, obtaining

$$\lambda = \frac{h}{mv} = \frac{h}{\sqrt{2emV_a}} = 1.23 \; V_a^{-\frac{1}{2}} \; \text{nm} \qquad \ldots \quad \ldots \qquad 23.3$$

The condition for diffraction for small angles is

$$\lambda = d\theta \qquad \ldots \qquad \ldots \qquad \ldots \qquad 23.4$$

where the small angle θ can be calculated from the geometrical relationship of Figure 2 as

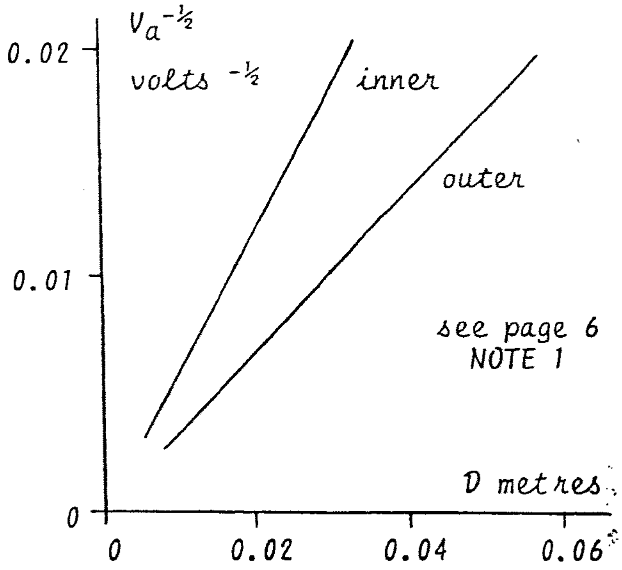
$$\theta = \frac{D/2}{L} \qquad \ldots \qquad \ldots \qquad \ldots \qquad 23.5$$

and so from 23.3

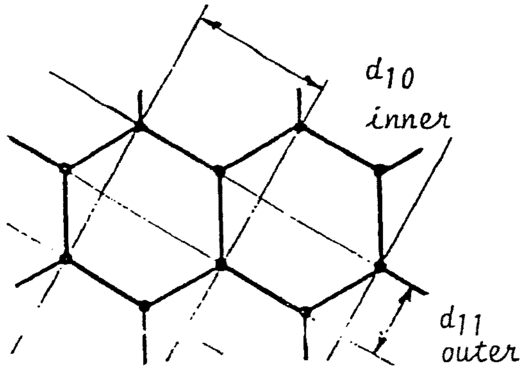
$$D \cdot \frac{d}{2L} = 1.23\ V_a^{-\frac{1}{2}} \qquad \ldots \qquad \ldots \qquad 23.6$$

D and V_a are the only variables; tabulate D for different anode voltages V_a and plot the graph D proportional to $V_a^{-\frac{1}{2}}$.

V_a	$V_a^{-\frac{1}{2}}$	D metres	
kV	volts $^{-\frac{1}{2}}$	inner	outer
2.5	0.0200		
3.0	0.0183		
3.5	0.0169		
4.0	0.0158		
4.5	0.0149		
5.0	0.0141		



Measure the pathlength from the Carbon target at the gun exit aperture to the luminescent screen, L m, as accurately as possible using a back-reflection technique (0.140 ± 0.003 m).



Rearrange the equation 23.6 to evaluate interatomic spacings d using the gradients of the graphs of the outer and inner circles; compare with the established figures of d_{11} (0.123) and d_{10} (0.213) nm.

These results verify the theory and substantiate the de Broglie hypothesis; note that the ratio of the spacings is √3:1 which suggests that the arrangement of the Carbon atoms is more likely to be hexagonal rather than the assumed cubic.

NOTE : GRAPHICAL CONSTRUCTION.

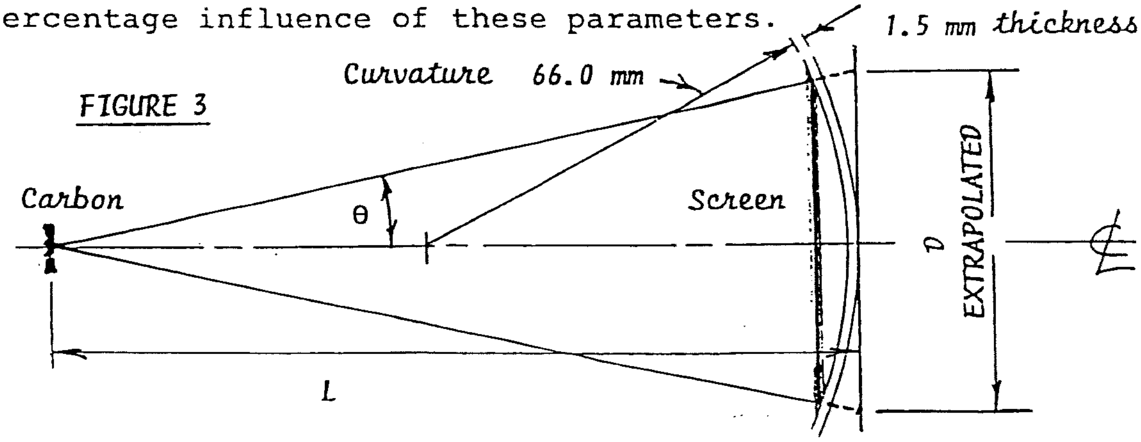
The convention of proportionality has been inverted for the purposes of this graphical construction in order to facilitate the calculations of d_{11} and d_{10} from the gradients of the respective lines.

The accuracy of these calculations depends on the length of the gradient line and the caliper measurement of the ring diameters.

NOTE : MEASUREMENT OF RING DIAMETERS.

For maximum accuracy the ring diameter should be extrapolated as in Figure 3 in order to compensate for both the curvature and the thickness of the glass envelope; the lower the anode voltage, the larger the ring diameter and the greater the percentage influence of these parameters.

FIGURE 3



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Operating Instructions

Electron Diffraction Tube
with mounting
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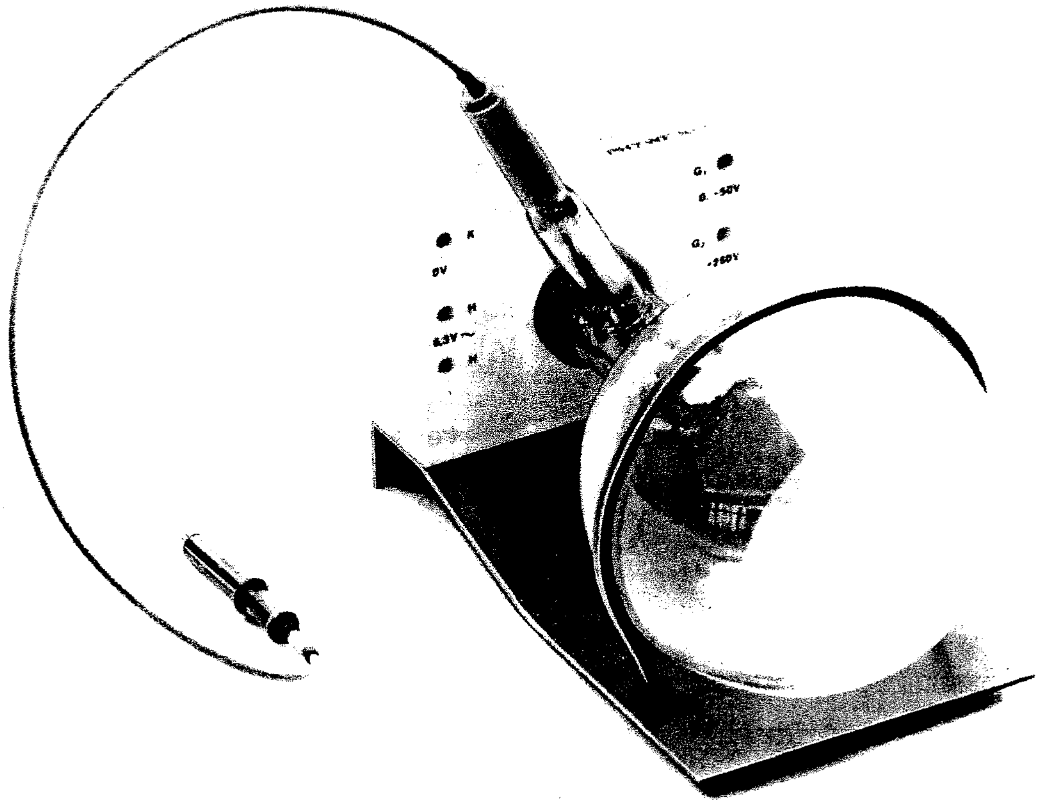

CONTENTS

1. PURPOSE

With the electron diffraction tube, the corpuscular and wave characteristics of electrons can be demonstrated and studied. In comparison with other experiments in the quantum physics of electrons, the method of electron diffraction on a crystal grid proves particularly advantageous because:

- the diffracted image can be made directly visible with the help of a fluorescent screen and

- only one simple to operate, compact test instrument is required.

The electron diffraction tube enables the de-Broglie principle to be proved experimentally and with considerable accuracy, as a basis for wave particle dualism applicable to electrons.

2. DESCRIPTION AND MODE OF OPERATION

The electron diffraction tube has a mounting to which the necessary power supply units and measuring equipment can be connected.

In the electron diffraction tube, an electron beam is produced which can be controlled, as it is dependent on external, experimental parameters. The electron diffraction tube beam emission system is shown schematically in Fig. 2. Thermionic cathode K is heated by a heating coil H. The electrons emitted from the cathode are accelerated in an electric field created by the grid system G_1 to G_4. Wehnelt cylinder G_1 deflects a narrow electron bundle in the direction of the symmetrical axis (optical axis). The electrons from the Wehnelt cylinder are easily accelerated forward by Grid G_2, which has a positive potential. Then the electrons flying through the opening at Grid G_2 are accelerated very vigorously because of the strong positive potential at the anode, G_3. Finally, Grid G_4 is used to focus the electron beam, providing, with the anode, an electron optic lens system. The accelerated particles land on a film attached vertically to the optical axis. This film consists of a copper mesh on which there is a layer of polycrystalline graphite. As the particles penetrate this film, they are deflected from their path to varying degrees and enter the spherical section of the electron tube, see also Fig. 5.

Where the electrons reach the inner wall of the glass sphere, they encounter a fluorescent layer. In areas where individual electrons land in clusters on the fluorescent layer, they produce a clearly visible luminescence, due to the fluorescent rays.

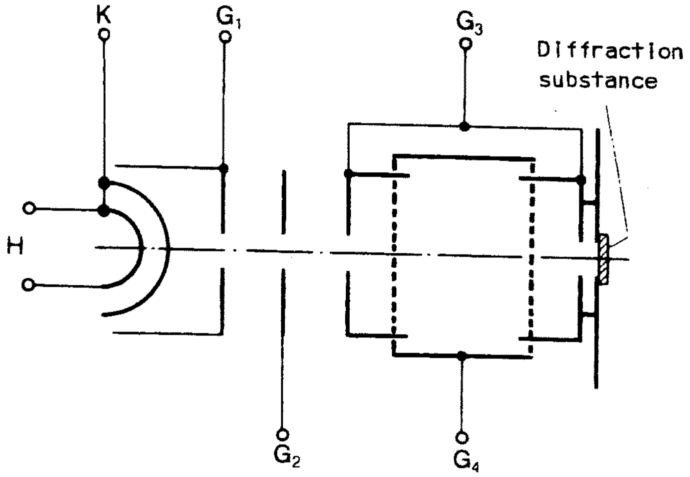

Fig. 2

3. OPERATION

The functional elements of the electron diffraction tube's beam emission system (H, K, G_1 to G_4) connect with the correspondingly marked sockets on the mounting. The tube and the mounting form one unit which should not be split. If this does happen, then care must be taken when the tube is re-fitted that the small connecting pins are not bent. It should also be noted that one of the sockets on the tube mounting is sealed so that the tube can only be plugged in in the correct way for the contact arrangement.

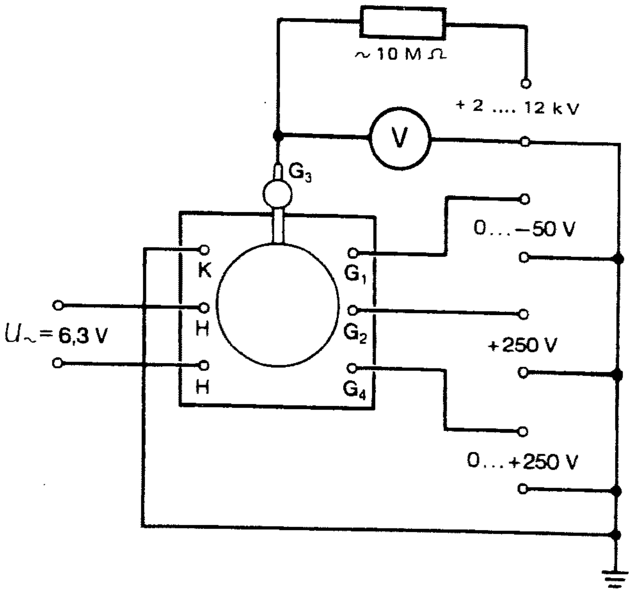

Fig. 3

Fig. 3 shows the electrical wiring for the electron diffraction tube, taking in a meter for the anode voltage. An AC current is sufficient for the heating. To power the other functions, well-filtered DC voltages are always required. The individual voltage ranges and values are also reproduced in Fig. 3. All voltages (apart from the anode voltage) can be taken from a universal power supply 11725.93.

The anode current should not far exceed 1 mA. Therefore, a limiter resistor of some 10 MΩ (e.g. 10 MΩ resistor with plug and socket, Order no. 07160.00) should generally be wired in front of the anode. If a HV unit with short-circuit current < 1 mA is used to provide the anode voltage (e.g. HV power supply 25 kV, Order no. 11730.93), then a limiter resistor is not required. The HV cable coupled firmly to the anode has dialectric strength, so that no special conductor lead is required.

If HV power supply 11730.93 is used, no separate earthing of the cathode is needed, as the negative pole on the unit has a zero potential.

For all the experiments described in Paras. 4 and 5, the following initial setting, based on the cathode, should be selected for the grid voltages (any further adjustment then depends on the aim of each experiment):

- Wehnelt cylinder (Grid G_1): -25 V
- Grid G_2: +250 V
- Anode (Grid G_3): +10 kV
- Grid G_4: approx. +250 V

4. DIFFRACTION OF THE ELECTRONS ON GRAPHITE

The graphite layer on the diffraction film is made up of many micro-crystals which are spatially randomly oriented. Each crystal shows the typical structure for graphite. The two largest grid-level distances are:

$$d_1 = 213 \text{ pm}$$

and

$$d_2 = 123 \text{ pm}$$

The electrons deflected at the graphite have a de-Broglie wave length dependent on the anode voltage U_a, as follows:

$$\lambda = \sqrt{\frac{1500 \text{ kV}}{U_a}} \text{ pm},$$

Where U_a is the anode voltage (acceleration voltage), or the potential to earth at Grid G_3. Since the anode voltage should not exceed 12 kV, the smallest de-Broglie wavelength that can be achieved with the electron diffraction tube is:

$$\lambda_{min} = 11.2 \text{ pm}$$

This value is clearly smaller than the grid constants for the structure of graphite. Thus, there may be interference on the diffraction rings of the individual wave packages.

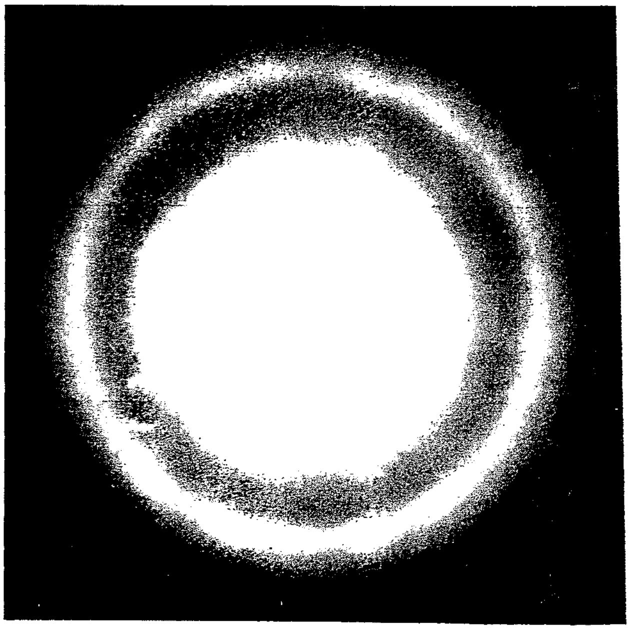

Fig. 4

In the experiment, the additional electric power supply equipment is first of all adjusted to the initial setting. The negative voltage at the Wehnelt cylinder (Grid G_1) is reduced until the strongest possible diffraction rings have formed.

Fig. 4 shows the diffraction image in an experimental example. Both rings seen in the image comply with the Bragg definition

$$2\,d_{1.2}\sin\theta_{1.2} = \lambda = \sqrt{\frac{1500\text{ kV}}{U_a}}\ \text{pm},$$

Where $\theta_{1.2}$ represents the angles of diffraction of the electron beam, dependent on anode voltage U_a (see Fig. 5).

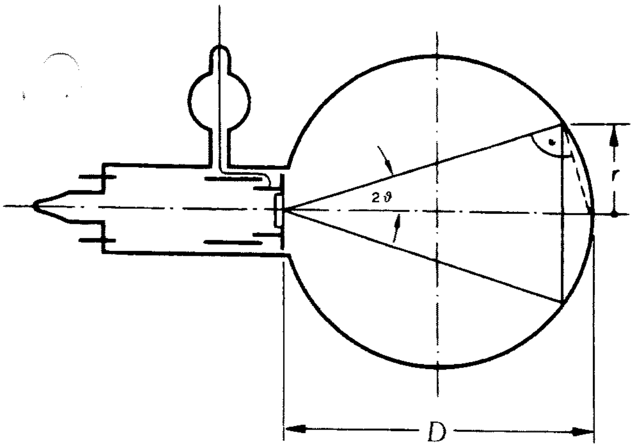

Fig. 5

If the relationship between the angles of diffraction θ_1 and θ_2 and the anode voltage U_a is to be studied, then the latter must be increased step by step (say from U_a = 2 kV up to U_a = 12 kV), and, at the same time, the voltage at the Wehnelt cylinder must be adjusted, so that the diffraction image is as clear as possible (when increasing the Wehnelt voltage, the anode voltage previously set will always drop slightly, because there is increasing load on the HV supply unit).

Angles of diffraction $\theta_1 + \theta_2$ can be determined from the definitive equation:

$$\theta_{1.2} = \frac{1}{4}\arcsin\frac{2r}{D}_{1.2}$$

using the appropriate diffraction ring diameters $2\,r_1$ and $2\,r_2$. The ring diameters can best be measured with a slide rule, noting that the rule should be aligned with the maximum intensity of the rings. (Relatively accurate results can be obtained if the diameter is measured from the edges of the rings in each case and the position of maximum intensity calculated by finding mean values.)

D is the greatest distance of the graphite layer, the diffraction substance, from the wall of the glass sphere. The nominal dimension to be used in the calculation is:

D = 127 mm

The graphs in Fig. 6 show the relationship found between angles of diffraction θ_1 and θ_2 and the anode voltage, U_a in a measuring example.

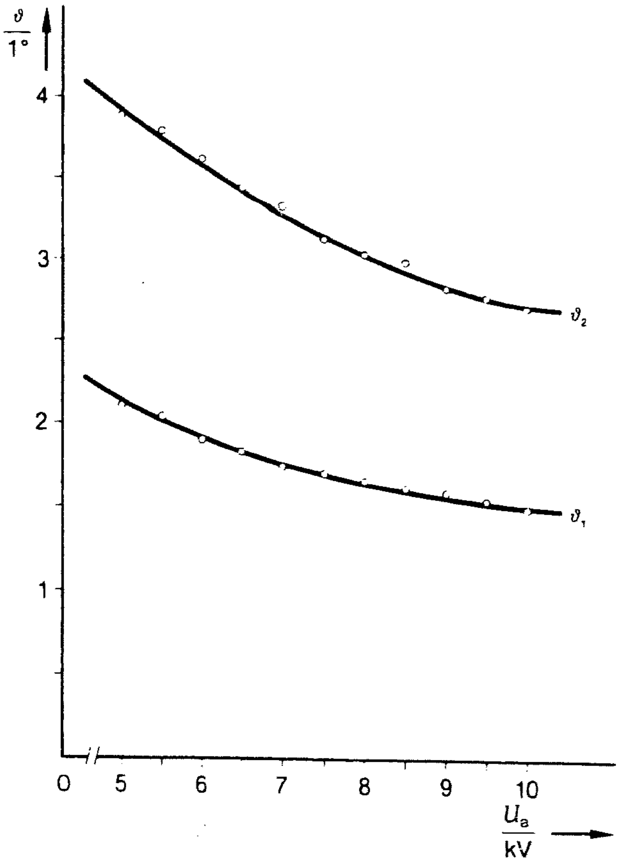

Fig. 6

The values of $\lambda/2 \sin \theta_{1,2}$ are, according to Fig. 7, mostly identical to the values of the grid-level distances d_1 and d_2.

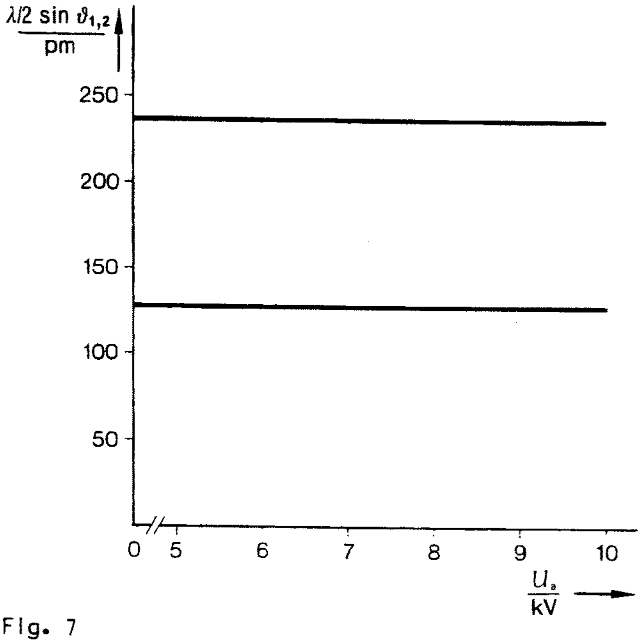

Fig. 7

5. ELECTRON OPTIC REPRESENTATION OF THE CARRIER MESH

If the electron bundle that hits the sample is expanded sufficiently, the copper mesh that carries the graphite layer necessary for diffraction can be shown on the screen.

The connected electrical power supply equipment is adjusted to the initial setting. The voltage at the Wehnelt cylinder (Grid G_1) is reduced until the diameter of the patch of light is large enough for the shadow of the carrier mesh to be seen.

The mesh structure seen on the screen shows that objects can be represented geometrically with the help of electrons in an optical context.

6. FAULT LEVELS

With an anode voltage of 12 kV, the speed of the electrons in relation to the speed of light is some 22%. It is therefore acceptable to regard the electrons as non-relativistic. For the de-Broglie wavelength, this approximation relates to a fault level of max. 1.2%.

Systematic or equipment-related deviations in the experiment results as compared with theoretical values arise from the inevitable inaccuracy of D (distance from graphite layer to glass sphere). In accordance with the tolerances set for D, a fault level of up to 2.5% can be expected.

7. ADDITIONAL INFORMATION

As well as the two strong diffraction rings, other less intense rings of larger diameter can be seen. If the room is in complete darkness, these rings can also be seen clearly.

To demonstrate the diffraction phenomenon in a large room or lecture theatre, it is advisable to use TV transmission equipment.

8. PROTECTION FROM RAYS

When using the electron diffraction tube, X-rays are produced. As defined by the regulations with regard to protection against damage by ionising rays, 13th October, 1976 (Regulations on Radiation Protection) and the regulations with regard to protection against damage by X-rays of 1st March, 1973 (Regulations on X-rays), the electron diffraction tube emits hazardous rays. Clause 5 (2) of the regulations on X-rays states how the instrument should be handled. Since, under operating conditions (maximum operating voltage: U_a = 12 kV), the localised emission of X-rays at a distance of 5 cm from the surface of the instrument is less than 36 pA/kg, the electron diffraction tube can be used in the lecture room without hesitation and without any special measures to protect against radiation. The legislation demands no design permit. The instrument can be used without special permission from or notification to authorities.

It should, however, be pointed out in this connection, that, if the maximum operating voltage of 12 kV is exceeded, not only could the instrument be damaged, but the radiation emission becomes unacceptably high.

9. EXPERIMENT LITERATURE

Experiments in Physics
Wave Particle Dualism
Order No. 16052.41

University Laboratory
Experiments - Physics
Part 2, Order No. 16500.41

10. TECHNICAL DATA

Diffraction substance:	Graphite
Carrier Mesh:	Copper
Nominal distance from diffraction substance to inner wall of sphere:	127 mm ± 3 mm
Diameter of fluorescent screen	10 cm
Heating voltage:	U AC = 6.3 V, 300 mA
Wehnelt voltage (filtered):	0 to -50 V
Acceleration voltage (filtered):	+250 V
Anode voltage (filtered):	+2 to +12 kV
Anode current:	< 1 mA
Focussing voltage (filtered):	0 to +250 V

11. EQUIPMENT LIST

The most important instruments used in connection with the electron diffraction tube are given below with their order nos. The complete equipment lists required for various experiments can be found in the experiment literature quoted.

Order No.	Equipment
11151.00	Electrostatic voltmeter 26 kV
11725.93	Power supply, universal
11730.93	HV power supply 25 kV

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