

Electron Diffraction

Equipment Teltron 2555 Electron Diffraction Tube, Daedalon EV-14 Power Supply, safety glasses, leads, 6 inch C-Thru ruler, calipers

Reading Your text book.

Precautions

1. The electron accelerating voltage in this experiment is of the order of 5 kV. This is a lethal voltage. **KEEP YOUR HANDS AWAY FROM THE LEADS WHEN THE HIGH VOLTAGE IS ON!**
2. **IF YOU DO NOT WEAR GLASSES, WEAR THE SAFETY GLASSES PROVIDED.** The probability of the glass vacuum tube breaking is small, but your eyes are precious.
3. The cathode that supplies the electrons can be damaged if high voltage is applied to the tube before the cathode is fully warmed up. **BEFORE** turning on the high voltage supply, be sure the voltage control knob is fully counter-clockwise so as to set the high voltage to zero, and after turning on the supply, wait one minute before turning the knob clockwise and applying the high voltage.
4. To lengthen the life of the tube, which is quite expensive, turn the high voltage to zero when not observing the diffraction rings.
5. Turn the high voltage to zero before turning off the power supply.

1 Introduction

One of the most dramatic illustrations of the wave nature of atomic-scale particles is the diffraction of electrons by the crystalline lattice of a solid. For reasonable electron energies the wavelength of electrons is so short that it is difficult, but not impossible, to produce man made gratings that will produce observable effects. In this experiment you will observe diffraction of a thin collimated monoenergetic electron beam that has been diffracted by planes of atoms in polycrystalline graphite. By using Bragg's Law and the de Broglie relationship the distances between atomic planes in the crystal can be determined.

2 Wavelength of Particles

In 1924 de Broglie predicted that the wavelength of particles with mass could be found by using the same relationship that held for massless photons, namely

$$\lambda = h/p, \quad (1)$$

where λ is the wavelength of the light, h is Planck's constant, and p is the momentum of the photons. De Broglie proposed that particles with mass as well as massless photons have a dual character, behaving in some circumstances like particles and in others like waves. He suggested that a particle of matter having momentum p would have an associated wavelength λ . The propagation of microscopic entities such as electrons and photons is described by the wave theory, and the exchange of energy is described by the particle theory.

The first experimental evidence of the existence of matter waves was obtained by Davisson and Germer in 1927. They reflected slow electrons from a single crystal of nickel and applied de Broglie's relationship. The wavelength of the electrons was determined and compared with that calculated from the Bragg Law. Excellent agreement was obtained.

The wavelength of an electron, as indicated above, is given by

$$\lambda = \frac{h}{p} = \frac{h}{mv}, \quad (2)$$

where mv is the classical momentum of an electron. The faster an electron is going the shorter its wavelength. The electron velocity can be obtained from the electron accelerating potential V . Since the kinetic energy of the electrons is given by

$$\frac{1}{2}mv^2 = eV, \quad (3)$$

the wavelength is given by

$$\lambda = \frac{h}{\sqrt{2meV}}, \quad (4)$$

where m is the mass and e the charge of the electron. This can be written as

$$\lambda = \sqrt{\frac{1.50}{V}} \text{ nm} \quad (5)$$

if V is in volts. Since the apparatus is operated below 10 kV , relativistic corrections are not needed.

3 Electron Diffraction

An arrangement of atoms that keeps repeating itself is called a crystal lattice. In such a material there are sets of planes with the planes in a given set parallel to one another, each plane containing a large number of atoms. The planes of a given set are separated from each other by a common distance d . Different sets of planes will have a different separation d . A given plane of atoms acts as a partial mirror for electron waves. Suppose a collimated monoenergetic electron beam (single electron wavelength) is incident on a crystal plane. The electron wave will be partially reflected by the plane, the reflection being specular. The crystal has many planes and the electron wave will be partially reflected by each of these planes. If the angle θ between the electron beam and one set of planes is such that the reflected electron waves from adjacent parallel planes differ in phase by $n2\pi$ rad, where n is an integer, all the reflected waves will add constructively and will result in a maximally reflected beam at that angle. This is the essence of the Bragg relation. We remark that the Bragg relation refers to elastically scattered electrons. $n = 1$ is called first order diffraction, $n = 2$ is second order, and so forth. Note that the angle θ is defined differently from the optical case. In that case the angle of incidence is defined as the angle between the incident beam and the *normal* to the plane.

If the Bragg relation is not satisfied the electron waves scattered by various planes do not add up constructively. The intensity of scattered electrons in any given direction is low.

In the Davisson-Germer experiment the electron scattering was off a single large Ni crystal. The incident collimated electron beam produced a more or less collimated scattered beam.

In the experiment you are about to do, which is similar to the experiment of G.P. Thompson, the target for the collimated electron beam is a very thin film of polycrystalline carbon. The myriad small crystals are randomly oriented. For those crystals that do not satisfy the Bragg condition the scattering is small. For crystals that satisfy the Bragg condition the scattering is strong at the Bragg angle. Furthermore, due to the random orientation of these crystals, the strongly scattered electrons will be in a cone. If the scattered electrons are allowed to fall on a phosphor, the scattered electrons will create a circle of light on the phosphor. See Figs. 3-5. If there is more than one set of planes with different distances d between the planes, there will be more than one ring. Second order diffraction will also produce additional rings, although this is not observed in this experiment.

The Bragg relation, which gives the angles θ at which maximum scattering occurs, may be written as

$$2d \sin \theta = n\lambda, \quad (6)$$

where d is the distance between planes in a given set, n is the order of the diffraction, and λ is the electron wavelength. The angle between the incident and diffracted electron beam is 2θ , as shown in Fig. 5. In this experiment with polycrystalline carbon, there are two sets of planes with separations given by

$$\begin{aligned} d_{10} &= 0.213 \text{ nm (inner ring)} \\ d_{11} &= 0.123 \text{ nm (outer ring)}. \end{aligned}$$

The two rings, which are due to first order diffraction ($n=1$), are shown in Fig. 5. Note that $d_{10}/d_{11} = \sqrt{3}$, which suggests a hexagonal pattern for the carbon atoms. See Fig. 2.

4 Apparatus

The apparatus is shown in Fig. 1. An evacuated glass bulb with a neck has an electron gun in the neck. The electron beam passes through a nickel grid that has a thin polycrystalline carbon film deposited on it. The carbon film is thin enough so that many electrons pass through unscattered, but enough electrons are scattered to produce an observable effect. The unscattered and scattered electrons strike a phosphor surface that has been deposited on the inside of the bulb.

The geometry of the bulb is shown in Fig. 3, where L is the distance of the carbon film from the phosphor and D is the diameter of a ring. The angle θ is given approximately by

$$\theta = \frac{D}{4L}. \quad (7)$$

The geometry given here is obviously not precise, but perhaps good enough for our purposes. Instead of measuring the diameter of a ring with calipers, you can use a piece of paper laid over the bulb, and making pencil marks, measure the arc length. Another improvement could be made by noting that the spherical surface of the bulb has its center at the center of the bulb and not at the carbon film.

A high voltage power supply provides power to heat the electron emitting cathode and voltage to accelerate the electrons. The power supply has an off-on switch and a multi-turn

knob to adjust the high voltage. Be sure the knob is fully counter clock-wise before turning on the switch.

A wiring diagram is provided. Although the apparatus has been wired for you, check that it is wired correctly with the power supply off. This is always a good procedure. It could have been wired incorrectly by the person setting up the apparatus, or someone could have maliciously changed the wiring.

5 Examining the Apparatus

Refer to Fig. 1 and take a close look at the vacuum tube. The target electrode has a hole in the middle of it. In this hole is a very fine nickel mesh on which has been deposited the carbon film. Looking at this hole from the back (the filament side), can you see through the film? This is a thin film!

Note the two metal cylinders. This is standard electron beam optics, and these cylinders serve not only to accelerate the electrons but to focus them. You will find the spot on the phosphor due to unscattered electrons to be reasonably small.

Fig. 1 shows the cathode to be indirectly heated. When this writer looked closely at the heating wire, this wire appeared to have been coated, which would suggest that the electrons are emitted directly from the heating wire and not from an indirectly heated cathode. Look at the filament both hot and cold. What do you think?

6 Procedures

1. With the high voltage off, check the wiring.
2. With the high voltage knob fully counter clockwise, turn on the supply and wait one minute. You should be able to see the glow of the filament.
3. Apply voltages up to 4.5 kV and observe the two rings. Note how the size of the rings changes as you change the high voltage. As you twiddle the knob, you are changing the wavelength of the electrons!
4. Take data for voltages (V) from 2.5 to 4.5 kV in steps of 0.5 kV. At each voltage measure the diameter (D) or arc length of the two rings. Give measured values of d_{10} and d_{20} with estimated errors. One way to proceed here would be to plot for each ring (inner and outer) $1/\sqrt{V}$ versus D , and calculate the d from the best straight line.

7 Historical Comment

Davisson and Germer did not set out to measure electron diffraction and initially were not using a crystal of nickel as their electron target. They had a vacuum accident and to outgas the surface of their nickel sample they heated the sample in vacuum. A crystal was formed giving them strange results which they correctly interpreted as diffraction off a crystal. Moral: if you get strange results, don't dismiss them out of hand.

8 Questions

1. Derive the Bragg relation.
2. Make a rough estimate of the spacing between carbon atoms using Avogadro's number and the density of carbon. Assume a cubic lattice.
3. The electron rings are not very sharp. What do you think are the major reasons for this? Does this play a role in your error analysis?
4. Do you think the thickness of the carbon film is important? Discuss.
5. From Fig. 2 show that $d_{10}/d_{11} = \sqrt{3}$.

9 Finishing Up

Please leave the bench as you found it. Thank you.

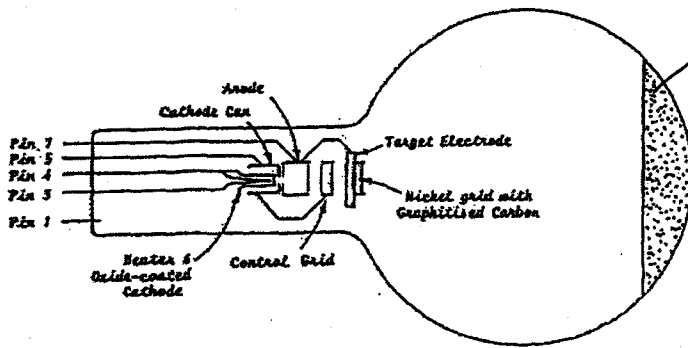


Fig. 1 The electron diffraction tube, model TEL 2555.

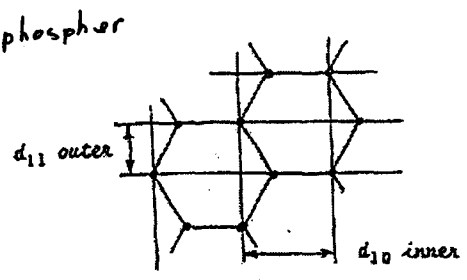


Fig. 2 Graphite crystal structure.

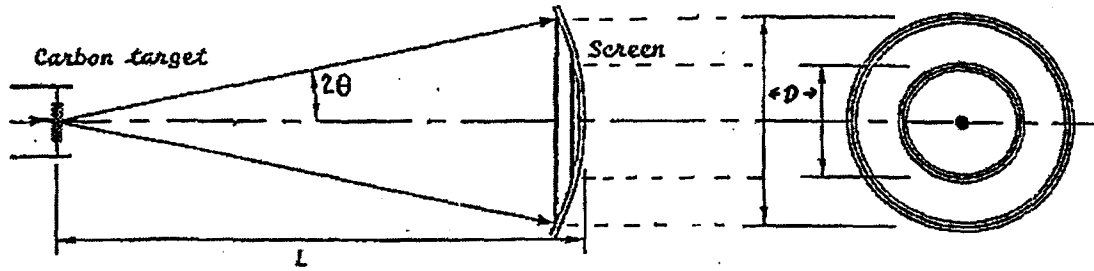
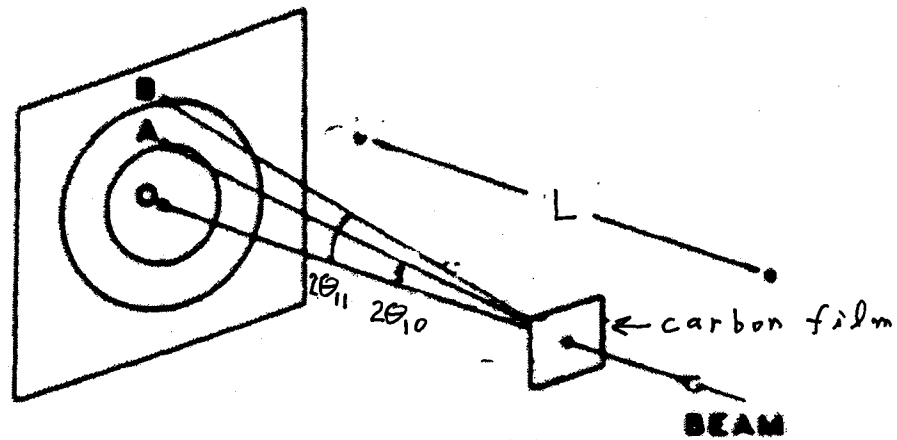


Fig. 3 Tube geometry with diffraction angle. $L = 13.0 \pm 0.2$ cm

Fig. 4 The diffraction ring pattern.

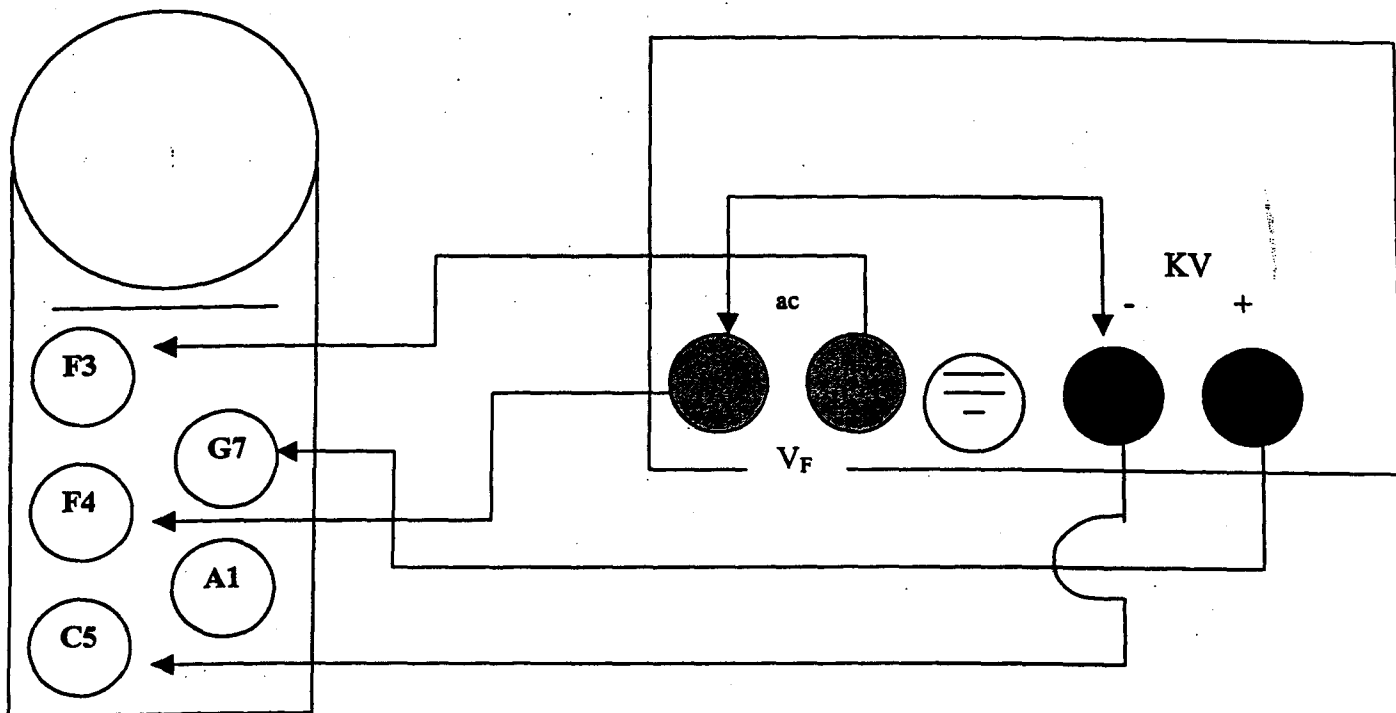


$$2\theta = \frac{D/2}{L}$$

Figure 5

2501 Stand Front View

EV14 Power Supply Rear View



Wiring diagram for the TEL-2555 Electron Diffraction Tube