Physics PHYS 275
Experimental Physics Lab

Electron Diffraction

Introduction

In 1924 it occurred to Louis deBroglie, a graduate student at the time, that if light, which was normally thought of as a wave phenomenon, sometimes exhibited particle-like properties then perhaps matter, which was traditionally understood to consist of particles, would exhibit wave-like characteristics. DeBroglie hypothesized that since the energy of a photon is given by

$$E = hf$$

and hence its momentum by

$$p = \frac{E}{c} = \frac{hf}{c} = \frac{h}{\lambda},$$

perhaps particles, such as the electron, could be thought of as waves having wavelength and frequency according to these same relationships, namely,

$$f = \frac{E}{h} \quad \textbf{and} \quad \lambda = \frac{h}{p}. \qquad \textbf{(1)}$$

In 1927 these wave-like characteristics were first observed by Clinton Davisson and Lester Germer, and independently by George Thomson (son of J.J. Thomson, considered the discoverer of the electron).

In the experiment of Davisson and Germer, a beam of electrons was incident on a nickel target from which they were reflected and collected in a faraday cup. In this way, the current of electrons scattered at different angles could be measured. Davisson and Germer were surprised to discover that the electrons did not scatter independently, as if from a single atom, but rather seemed to exhibit interference effects, which would only occur if the electrons were behaving in a wave-like way. Interestingly, this observation was the result of an accident. The glass vacuum chamber in which the experiment was performed broke, and in the process of repairing and cleaning the chamber the nickel target was heated. This caused crystals of nickel to form in the target.

Thomson's experiment involved passing a collimated beam of electrons through various thin targets, and measuring the resulting electron intensities using a photographic plate. It was discovered that the electrons which pass through a crystal form a distinct interference pattern, with maxima corresponding to those angles satisfying the Bragg condition (Eq. 1) while those passing through a powder or other target consisting of many crystals formed continuous rings.

In this lab you will perform an experiment very similar to the original experiment of Thomson. A beam of electrons will be passed through a thin graphite target in which the atoms are arranged in a crystalline structure. The electron beam will then be allowed to strike a phosphorescent target on with the interference pattern may be observed.

Theory

The theoretical description for this experiment was worked out in detail in class, so only a brief outline will be given here. There were two models that we examined to describe this experiment.

A. Classical model in which electrons behave as particles.

If the electrons behave like classical particles, then when they interact with the atoms in the graphite target via the Coulomb force in a way similar to objects in our solar system which interact with the Sun via gravity. The behavior of each electron will be independent of the behaviors of the other electrons, and the resulting pattern on the screen will not show any interference effects. We would most likely expect to see a central maximum in electron intensity that decreases with distance from the center.

B. Quantum model in which electrons behave as waves.

In this case, it is possible to demonstrate wave interference. Consider the case of electron waves scattering from two planes of atoms within the crystal, as shown in Figure 1.

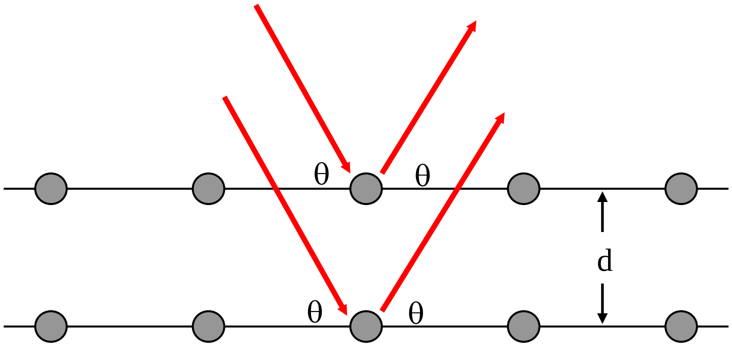


Figure 1 – Schematic diagram of the scattering process. The waves, which scatter from two different planes of atoms within the crystal, travel different path lengths.

It was shown that for a constructive interference to occur, the Bragg co9ndition must be satisfied, namely,

$$2d \sin\theta = n\lambda , \tag{2}$$

where *n* is an integer.

Experimental Apparatus

Figure 2 is a diagram of the apparatus used in this experiment, a photograph of which is shown in Figure 3. Carefully examine the specifications of the TEL 555 Electron Diffraction tube given in Appendix A. The 6 V filament supply heats the filament, which heats the cathode releasing electrons. The electrons pass through a small hole on the "cathode can". Since there exists a potential difference between the cathode and the "cathode can", only those electrons that leave the cathode with sufficient kinetic energy will be able to reach and pass through the hole. Hence, by controlling the potential on the "cathode can" we can control the intensity of the electron beam striking the graphite target. After they pass the "cathode can" they are accelerated toward the anode which is at a positive high voltage of between 2000 and 5000V. The beam current striking the anode is monitored with the ammeter, and should always be kept below 50 μA to avoid damaging the graphite target. After passing though the graphite target, which is embedded in the anode, the electron beam strikes a phosphorescent screen. The accelerating voltage is monitored using a voltmeter. Since the maximum voltage for the voltmeter is only about 1000V, a 100 MΩ resistor in series with the 10 MΩ internal resistance of the meter serves as a voltage divider. Hence, the voltage measured by the meter is about 1/10 of the actual accelerating potential.

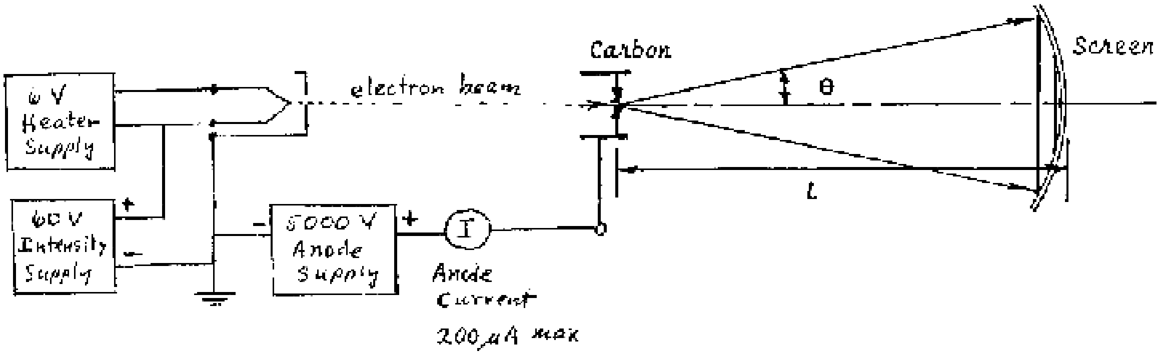


Figure 2 – A schematic diagram of the apparatus. Electrons are emitted by the cathode, which is heated by the filament. The high positive voltage accelerates them toward the anode and into a graphite target. After passing through the target the strike a screen. The intensity of the beam is controlled by placing a negative potential on the “cathode can”.

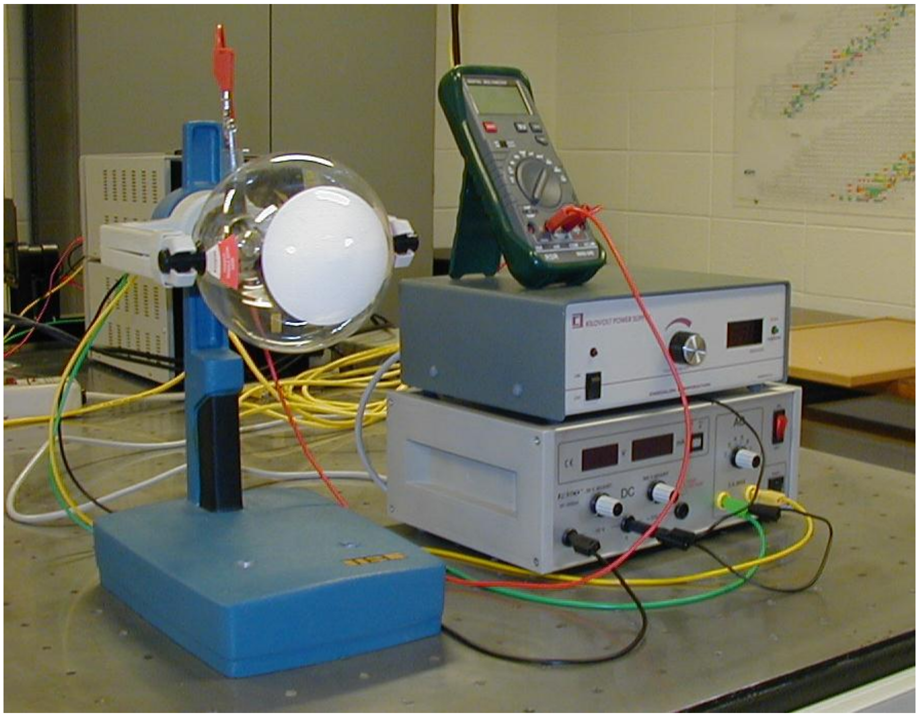


Figure 3 – A photograph of the apparatus showing (from left to right) the meters, the high voltage and filament power supply, the electron diffraction tube (front), the intensity power supply (rear), and the variac.

Experimental Procedure

A. Look over the experimental setup to make sure you understand how it works, and that it is still correctly assembled. Make a diagram of the setup in your logbook. Do not assume that the circuit is assembled as shown in Figure 2.

B. Make sure all the voltages are adjusted to zero. Turn on the meters and the power supplies.

C. Look to see that the filament is heated up. Let it warm up for a few minutes.

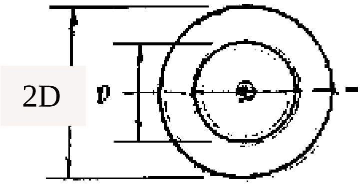


Figure 4 -- Typical intensity pattern on the screen. The radius of the ring is D.

D. Begin to slowly turn up the HV. Monitor the beam current. When the current gets close to 50 μA, turn up the voltage on the intensity power supply to reduce it. Stop turning up the HV when it is at 2500 V.

E. Observe the pattern on the screen. It should look something like Figure 4.

F. Measure D for each ring and record these values along with the anode voltage.

G. Repeat E and F for 3000 V, 3500 V, 4000 V, 4500 V, and 5000 V.

I. Experimental Analysis

The electrons that leave the cathode can have very little kinetic energy, but a potential energy of eV. When they reach the anode, all of this potential energy has been converted into kinetic, so

$$T = \frac{p^2}{2m} = eV$$

which gives the momentum of the electrons

$$p = \sqrt{2meV}$$

and thus the wavelength

$$\lambda = \frac{h}{\sqrt{2meV}} .$$

Using this result with Eq. 2 gives

$$D = L\sqrt{\left(\frac{n^2h^2}{4d^2meV} - 1\right)^{-2} - 1} \qquad \textbf{(3)}$$

or, using the small angle approximation

$$D = \frac{nhL}{d\sqrt{2meV}} . \qquad \textbf{(4)}$$

The values of d for this calculation are the interatomic separations for the scattering planes in graphite, which may be obtained from Figure **5**.

II. Laboratory Report

1. In your laboratory report be sure to include a detailed description of how you made your measurement -- describe the apparatus and the procedure you used to make the measurement.
2. You definitely should include a schematic diagram of the experiment as it actually was (i.e. don't count on it being exactly what is in this lab handout.)
3. You should record the experimental procedure you actually used.

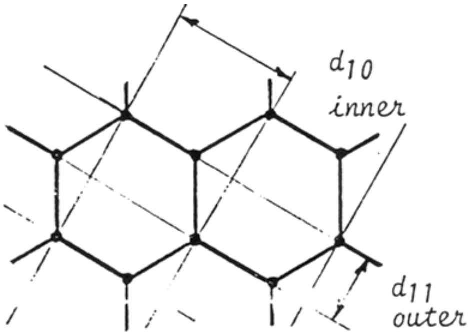


Figure 5 - The graphite crystal structure in the plane of the anode. d_{10}=0.213 nm, d_{11}=0.123 nm.

4. You should have a table of the values of D at each voltage. Also, you should have a plot of D versus voltage which includes the measured values with error bars as well as the theory predictions of Eq. 3 and 4.
5. You should you should discuss the uncertainties present in your measurement.

III. Questions to ponder

1. How can I measure D and L? You may find Appendix B helpful, but how accurate is it?
2. Why are we seeing rings rather than dots at the correct angles given by the Bragg condition?
3. Why are the rings so think? Can I make them sharper? How does this affect the uncertainty in my measurements?
4. How do I know what *n* is? Why don't I see lots of rings, one for each *n*?
5. How do I know Figure 5 is correct?

Appendix A – Electron Diffraction Tube Data

1 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 the 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.

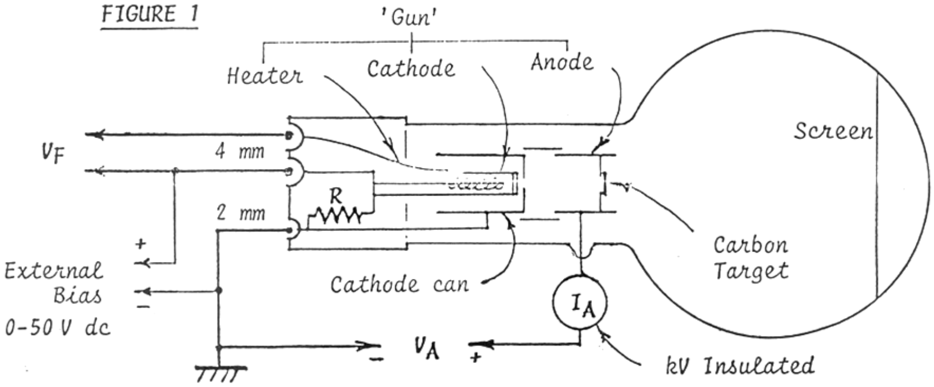
Specification:

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.

Appendix B – Dimensions of the TEL 555 Electron Diffraction Tube