THE WAVE NATURE OF ELECTRONS- A CLASSROOM DEMONSTRATION

by

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I. INTRODUCTION

An understanding of physical phenomena has developed through the interplay of experimental results and theoretical postulates. This is clearly demonstrated by the development of our present thinking about electromagnetic radiation and quanta. Two postulates for the structure and propogation of visible light withstood, to a limited degree, the tests of experimental evidence. Light was first considered to have a corpuscular nature. Newton extended his ideas of particle mechanics to explain light phenomena with considerable success but this concept was not satisfactory for explaining the refraction, interference and diffraction of light. During the middle of the 17th century, Christian Huygens developed a wave theory that explained refraction, interference and diffraction phenomena very nicely. In fact, the wave theory was so successful in explaining light phenomena that the particle theory was completely discarded by the middle of the 19th century.

The continued study of light phenomena and the advent of atomic investigations led to results that could not be adequately explained by the wave theory. In 1900, Max Planck developed an empirical equation to explain blackbody radiation. This equation agreed very nicely with the independent experimental results of both Wein and Rayleigh. A physical explanation of this new equation was desirable, the outcome of which was the quantum idea. Abandoning traditional ideas, Planck made the bold assumption that an ultimate source does not emit radiant energy in a continuous manner but instead intermittently, and, what is more important, in packets--quanta or photons--of very definite energy content. A photon was assumed to have, after emission, a definite wave structure with a

frequency f, and an energy content E given by E=hf, where h is called Planck's constant. The results of photoelectric experiments led Albert Einstein, in 1905, to extend Planck's postulate to include absorption of radiation by discrete units of magnitude hf. Photoelectrons emitted by a photocell exposed to monochromatic light were noted to have a kinetic energy equal to or less than hf and the kinetic energy of the electrons was independent of light intensity. Classical mechanics could not explain the photoelectric effect but the phenomena could be explained if light was considered to be a group of particles (photons) having energy hf.

A few years later Neils Bohr deviated somewhat from classical mechanics in postulating his model of the hydrogen atom. Radiant energy was considered to be emitted from the atom in discrete amounts (equal to hf) as the electron moved to an inner orbit. The great success of Bohr's model of the atom, in explaining spectroscopic results, strengthened the quantum concept of light.

By the beginning of the 1920's there was a feeling among physicists that it was no longer a question of whether the particle theory or the wave theory explained light phenomena but rather how could they be associated together to explain light phenomena. This was expressed by H. A. Lorentz (1) in a discourse delivered to the Royal Institution on June 1, 1923.

> Here is an important problem for the physics of the immediate future. We can not help thinking that the solution will be found in some happy combination of extended waves and concentrated quanta, the waves being made responsible for interference and the quanta for photo-electricity.

The theoretical solution was soon presented by Louis de Broglie in

notes (2, 3) at the end of 1923 and in a more complete exposition which constituted his thesis for a doctrate, submitted in 1924. In these de Broglie equated the energy of a wave packet and the kinetic energy of a photon, $hf=mc^2$, where m is the mass of the photon and c is the velocity of light. De Broglie extended this relationship to include material particles such as electrons and considered a wave to be associated with the electron having a wavelength given by the expression,

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

where p is the momentum, m the mass, and v the velocity of the electron. Writing about this sometime later de Broglie commented (4)

> . . . so also I foresaw, from that moment, that it must be possible to obtain with corpuscles, with electrons in particular, certain phenomena of interference or of diffraction altogether impossible to foresee with the aid of classical dynamics.

The association of waves with particles and the theoretical combination of these two concepts led to fruitful theoretical and experimental progress. In 1926 Erwin Schroedinger presented his famous wave equation using the de Broglie wavelength for a particle moving in any field of force with potential energy V.

Experimental verification of the wave nature of electrons was soon made by C. J. Davisson and L. H. Germer (5) and independently by G. P. Thomson (6). Low voltage electrons of order of 100 volts, were used to strike the (1 1 1) surface of a nickel crystal in the Davisson-Germer experiment. Davisson and Germer were studying the reflection of secondary electrons from nickel. An unusual reflection pattern was noted for those electrons that had a velocity equal to the striking velocity of the original beam. After careful study they concluded the pattern was

a result of electron diffraction. Thomson used high voltage electrons, i.e. 30,000 volts, to penetrate thin polycrystalline films and observed diffraction patterns of the Debye-Scherrer type. He observed this with films of gold and aluminum.

In both these experiments, the crystal spacings calculated by the Bragg diffraction law were the same for electron diffraction as those obtained from X-Ray diffraction experiments. This strong experimental evidence left little doubt as to waves associated with material particles and established the dual nature of matter. It established a firm foundation for the wave theory of quantum mechanics.

These concepts are important to the science student today, and, therefore, a simple experiment with electron waves is desirable for modern physics laboratories. Such an experiment could aid the student in gaining an intuitive feeling for these important facts and could provide experience in experimental techniques in this important field. Developing such an experiment was the underlying objective of the work presented in this report.

II. STATEMENT OF THE PROBLEM

The purpose of the work reported here was to develop a relatively simple and inexpensive classroom demonstration of matter waves associated with electrons. Electron diffraction by thin polycrystalline films was considered the most desirable.

III. PREPARATION OF APPARATUS

The plan for demonstrating electron diffraction was 1) insert a thin polycrystalline film into a cathode ray tube, 2) reevacuate the tube, 3) allow the electron beam to penetrate the film, and 4) observe the diffraction pattern on the screen of the cathode ray tube. The 5CP-1 Cathode ray tube was selected from a stock of surplus tubes because there were a number of them available and it was electrostatically controlled. The tubes were opened by one of two methods. The first was to file a small hole in the neck of the tube to allow air to enter and then cut the glass tube with a diamond or carborundum circular saw. This method requires cooling water for the saw which gets inside the tube and may damage the phosphor screen of the electron gun. The other method is to first scratch the neck of the tube with a file. Then heat the tip of a small glass rod and press this heated tip at the end of the scratch. The glass will crack for a short distance, and with repeated applications of the hot glass rod the crack can be guided around the neck of the cathode ray tube. For several tubes, air was allowed to fill the tube before cracking it. This was done by filing a hole in the neck of the tube. A number of cathode ray tubes were opened and no implosions occurred, however, precautions were taken to cover the tube to prevent injury from flying glass in case of an implosion.

The diffraction tube (the reassembled cathode ray tube) is shown before assembly in Plate I, Figure 1. The glass envelope was cut 3/4 of an inch from the base of the cathode ray tube and this length of tube remained an integral part of the electron gun assembly. The electron gun was fitted into one end of a 2" copper T pipe fitting. It was

positioned by the shoulder on a copper insert placed in the T fitting. The specimen holder and the glass bulb of the cathode ray tube were held in the other end of the copper T fitting. The assembled diffraction tube is shown in Plate I, Figure 2. Apezion W wax and tackiwax were used to seal the tube. A glass seal was more desirable but this was not practical because the cathode ray tube is constructed of soft glass which is very difficult to reassemble without cracking. The assembly was adequate for development purposes and a vacuum of 5×10^{-7} Torr* was attained by continual pumping. A glass seal would have made a permanently sealed tube possible.

The diffraction tube was evacuated with the pumping system shown in Plate II, Figure 3. This consisted of two mechanical pumps and two oil diffusion pumps in series. One of the mechanical pumps was used only as a roughing pump and was cut off from the system by a valve when the pressure was low enough for the diffusion pumps to operate.

A power supply was designed and constructed to accelerate and control the electron beam. The accelerating voltage was obtained with a selenium rectifier in the secondary circuit of a high voltage transformer. The brightness control, focusing and deflection voltages were taken off the high voltage circuit. The circuit diagram is shown in Plate III. The accelerating voltage potentiometer shorted out and was, therefore, removed from the circuit. This simply provided a constant-accelerating voltage equal to the maximum accelerating voltage with the potentiometer in the circuit. The filament voltage was supplied by a variac to obtain a

*Torr is a pressure unit essentially equal to 1 mm of Hg.

Plate I

Figure 1. Exploded View of Electron Diffraction Tube
- A. Electron gun and deflection plates
- B. Specimen Holder
- C. Copper Insert Ring
- D. Glass Tube and Screen

Figure 2. Assembled Electron Diffraction Tube

Plate I

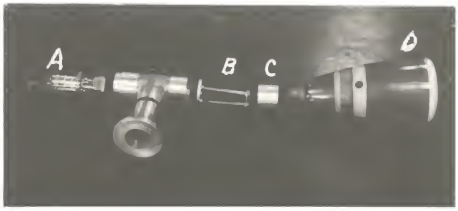


Figure 1

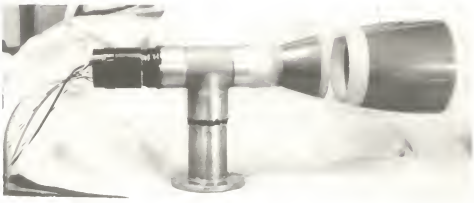


Figure 2

Plate II

Figure 3. Electron Diffraction Tube
Mounted on Vacuum Pump System

Figure 4.

A. Power Supply
B. Filament Variac
C. Vacuum Gage Indicator

Plate II

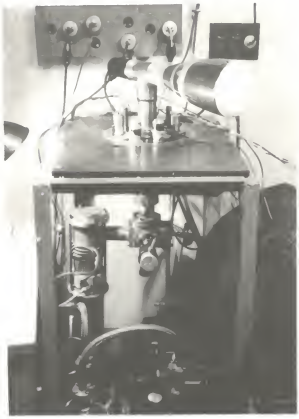


Figure 3

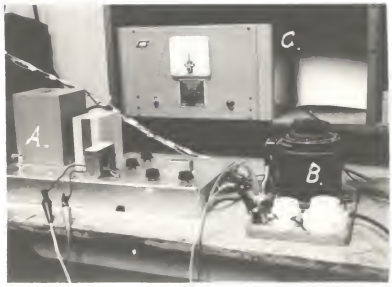


Figure 4

variable voltage from 0-13 volts. The higher voltage was needed to heat the cathodes for activation of the oxide coating. The diffraction tube was operated with a filament voltage between 7 and 12 volts. The higher voltages provided a greater intensity electron beam and did not appear to damage the electron gun although it is rated at a 6.3 filament voltage. The power supply together with the vacuum gauge indicator are shown in Plate I, Figure 4.

The phosphor screen of the cathode ray tube was not altered and was mounted perpendicular to the central electron beam. It emitted a green light.

Several attempts to re-activate the cathode coating on four different electron guns were unsuccessful. The procedure was to slowly increase the filament voltage after the diffraction tube had been evacuated. It was expected that the cathode would be heated enough for reactivation but this failed even when the filament voltage was increased on one occasion to 35 volts at which point the filament burned out.

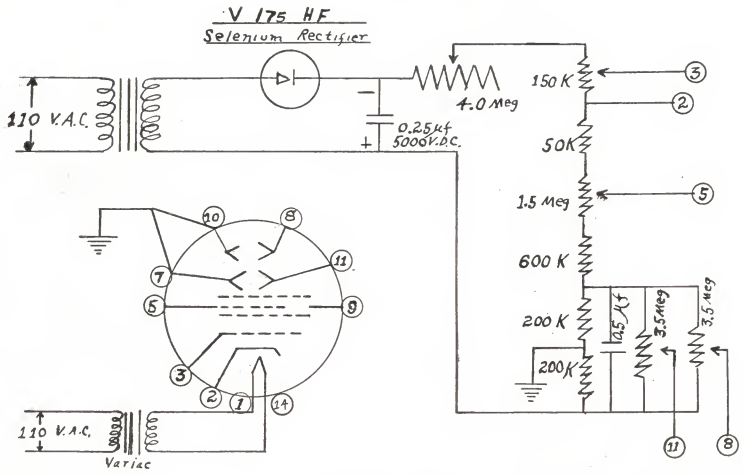
The mechanism whereby electrons are emitted from an oxide coating is not fully understood. For some unknown reason when the oxide coating is exposed to air it will not function again even in a vacuum. In some cases it is possible to reactivate the coating by heating but as stated above this was found to be unsuccessful with the indirect heating by the filament. There is a possibility that the oxide coating did not reach a high enough temperature. In some cases it is reported that the cathode coating can be reactivated by induction heating. This, however, was not tried because an induction heater was not available at the location of the vacuum pumps.

Plate III

Power Supply for

Electron Diffraction Tube

Plate III


V 175 HF
Selenium Rectifier
110 V.A.C.
4.0 Meg
0.25μf
5000V.D.C.
150 K
50K
1.5 Meg
600 K
200 K
200K
.145 μf
3.5 Meg
3.5 Meg
110 V.A.C.
Variac

It was supposed that oxygen in the air might be responsible for the deactivation of the oxide coating. Therefore, a cathode ray tube was opened, reassembled and connected to the vacuum system while in a nitrogen atmosphere to prevent oxygen from reaching the cathode coating. This procedure, however, failed to produce an electron beam. Oxygen may have inadvertently reached the cathode or it may be that nitrogen also has a deactivating effect upon the oxide coating.

The oxide coatings are usually obtained (7) by applying a 50-50 mixture of barium and strontium carbonates in a binding material to the cathode. The cathode is activated by heating the coated cathode to 1500°K and simultaneously applying a voltage, about 150 volts. In the process barium and strontium oxides are formed on the cathode and become profuse electron emitters. Nottingham (8) proposed that oxygen vacancies in the oxide are responsible for the unusual electron availability and that when exposed to the air these vacancies are filled. However, he considered it also possible that other electro-negative gases may also fill the vacancies and prevent normal operation of the prepared oxide.

An electron beam was obtained in the diffraction tube by re-coating the cathode with a type 50 emission coating produced by the Callite Products Co. It is supposed that this was a mixture of barium corbonate and stronium carbonate. This method was at first avoided because of the inacessability of the cathode. The cathode was surrounded by a metal cylinder that functioned as the grid of the tube. To remove and then realign either grid or the cathode would be both tedious and time consuming. However, it was noted that the cathode could be seen through two small openings on the side of the grid. By inserting a very small piano

wire through one of these openings it was possible to remove some of the old oxide coating from the cathode. The emission coating was applied with a very small diameter capillary tube with a rubber bulb on one end used as a dropper. The piano wire was used to remove the excess coating material from the cathode and to open the small hole in the center of the grid, if it was blocked by the coating material.

The procedure for activating the cathode was 1) to evacuate the diffraction tube to a pressure of 10^{-4} Torr or better; 2) to increase the filament voltage slowly and allow the cathode to outgas slowly; 3) to connect power supply when filament has reached 5 volts and the pressure is below 10^{-4} Torr; 4) to increase the filament voltage slowly until an electron beam appears. In one case the electron beam appeared with the filament voltage as low as 9 volts but at other times the filament voltage was between 11 and 13 volts.

Two materials were used for electron diffraction specimens, magnesium oxide and aluminum. The MgO specimens were prepared in two ways: 1) a fine mesh brass screen was partially coated by merely holding it in the "smoke" of burning magnesium, and 2) a brass screen was first coated with a thin nitrocellulose film and then the MgO smoked onto the nitrocellulose film. In the second method a coarse mesh brass screen was used as well as the fine mesh screen. The aluminum specimens were prepared by coating both fine and coarse mesh copper screens with a nitrocellulose film and then vapor depositing a very thin aluminum coating on the nitrocellulose film. The specimens were mounted in the diffraction tube with the surface of the film perpendicular to the electron beam. Some dimensions of the diffraction tube are shown in Plate IV, Figure 5 and Figure 6.

Plate IV

Figure 5. Electron Diffraction Tube
D. Deflection Plates
G. Grid
H. Specimen Holder
S. Phosorescent Screen

Figure 6. Electron Gun
A. Anode Apertures 0.20 cm.
C. Cathode
D. First Deflection Plates
F. Focus Aperture 0.12 cm.
G. Grid Aperture 0.07 cm.

Plate IV

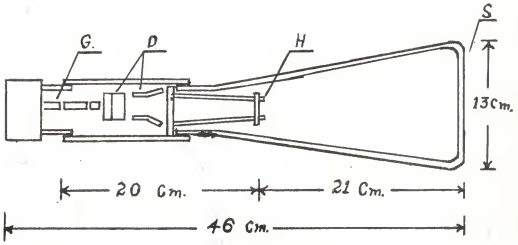


Figure 5

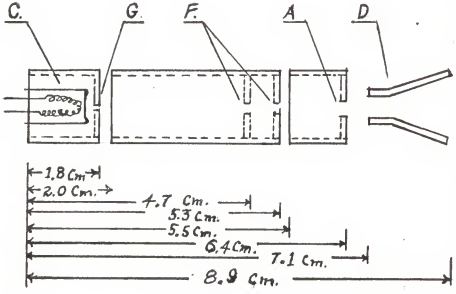


Figure 6

IV. EXPERIMENTAL PROCEDURE

Electron diffraction was expected by electron transmission through thin polycrystalline layers of magnesium oxide or aluminum. This would give a Debye-Scherrer type diffraction pattern with a small bright spot as the center of several concentric circles. The surface of the specimen that could be exposed to the electron beam was a circular area with a diameter of 2 cm. The electron beam had an approximate diameter of 2 to 4 mm and could be electrostatically deflected to explore all parts of the specimen. A slight a-c ripple on the deflection plates made the beam cross-section appear ellipitical on the screen but it was probably very nearly circular. It was supposed that by searching over the specimen surface that a spot could be located that would produce a diffraction pattern. This would require a thin layer of crystals that could be penetrated by the electron beam and yet have enough properly oriented crystals to produce a visible diffraction pattern.

Three MgO specimens and one Al specimen were used in an attempt to produce a diffraction but a pattern was not detected. Time exposure photographs of the screen gave no indication of a diffraction pattern from the specimen. There was, however, a diffraction pattern produced by the electron gun that may have obscured diffraction patterns produced by the specimen.

Photographs of several observed diffraction patterns are shown in Plate V. These were time exposures taken with a Polaroid camera mounted on a Type 2614 oscilloscope camera.

V. CALCULATIONS AND RESULTS

The diffracted electron waves, according to Bragg's diffraction law, will be reinforced at angles which satisfy the formula,

$$n = 2 d \sin \theta. \qquad (1)$$

Where, λ is the electron wavelength, d the spacing between reflecting planes, θ the grazing angle of incidence, and n = 1, 2, 3, - - -.
The de Broglie wavelength for electrons is,

$$\lambda = \sqrt{\frac{h^2}{2 m e E}}, \qquad (2)$$

or,

$$\lambda = \sqrt{\frac{150}{V}} \text{ Angstroms.}$$

Where, h is Planck's constant, m the mass and e the charge of the electron, E is the accelerating potential, and V is the accelerating voltage in volts. The electron wavelength was 0.33 Angstroms for the 1400 volt electrons used in this study.

The diameter of a diffraction pattern projected on the tube screen can be calculated by solving equations 1 and 2 simultaneously for sin θ, then substituting $\frac{D}{2S}$ for sin θ, where D is the diameter of the diffraction pattern circle and S is the distance from the crystal specimen to the screen. The expression for the diameter is,

$$D = \frac{n S}{d} \sqrt{\frac{150}{V}}.$$

The diameters expected from a MgO crystal diffraction pattern are shown in Table I. These values are all larger than patterns that were observed as listed in Table II. The aluminum crystals are face-centered

cubic and have a lattice constant nearly the same as MgO. Therefore, the aluminum diffraction pattern diameters would also be larger than the observed values.

Table 1. Ring diameters expected from electron diffraction patterns of MgO crystals. Accelerating voltage 1400 volts. Electron wavelength 0.33A.

Reflection Plane	Crystal Spacing (A)	Diameter of Expected Bright Ring Diffraction Pattern (cm.)		
		n = 1	n = 2	n = 3
1 0 0	2.102	3.26	6.25	9.78
1 1 0	1.485	4.64	9.28	13.92
1 1 1	1.820	3.78	7.56	11.34

Table 2. Ring diameters of electron diffraction patterns as measured from photographs shown in Plate V.

Diffraction Pattern Plate V	Diameter of Dark Rings (cm.)			Diameter of Bright Rings (cm.)		
	1st	2nd	3rd	1st	2nd	3rd
(a) MgO	0.5	1.2	1.9	0.9	1.6	2.4
(b) Aluminum	0.7	1.5	2.4	1.0	1.8	2.7
(c) Edge of Holder	0.5	1.3	2.0	0.9	1.7	2.4
(d) Aluminum	0.6	1.3	---	0.9	1.7	---
Average	0.6	1.3	2.1	0.9	1.7	2.5

VI. DISCUSSION OF RESULTS

The inability to produce a definite diffraction pattern from the specimen was very disconcerting. It seems most likely that the difficulty arose in the preparation of the specimen. The specimen's thickness may be rather critical. It was presumed that by having a large area of the specimen that a few positions could be located where diffraction would occur. The aluminum specimen had a good appearance. There was a definite layer of aluminum on the nitrocellulose film, and it was thin enough for light to pass through it. No attempt was made to measure the thickness of the layer. The electron beam was definitely able to penetrate parts of the aluminum layer but was stopped in other positions. The magnesium oxide layer on the nitrocellulose film appeared thin in places but was not particularly uniform. A diffraction pattern of the electron beam passing through this MgO specimen is shown in Plate V, (a). Three concentric rings were visible but the inner two were definitely too small for MgO diffraction. The third ring was the proper diameter for diffraction from the (1 1 1) plane, but it is very unlikely that this occurred because the first order diffraction from the other planes should also appear at a greater diameter. The three concentric rings were also visible in the 5CP-1 cathode ray tubes that were not opened. Therefore, this diffraction pattern is most certainly caused by the electron gun. The six bright spots to the left of the diffraction pattern resulted from the geometry of the brass screen holding the specimen. The specimen was thin at that point and sufficient number of stray electrons penetrated between the wire grids to produce the spots.

A similar diffraction pattern was obtained by passing the electron

Plate V

Figure 7. Diffraction Patterns from 1400 Volt Electrons
(a) Magnezium Oxide Polycrystalline Film. 20 minutes exposure.
(b) Aluminum Evaporated Film. 20 minutes exposure.
(c) Edge of Specimen Holder. 40 second exposure.
(d) Aluminum Evaporated Film. 65 minute exposure.

Plate V

Figure 7 (a)

Figure 7 (b)

Figure 7 (c)

Figure 7 (d)

beam through an aluminum specimen as shown in Plate V, (b). The diameters of these rings were slightly larger than those from the MgO specimen but were also considered to result from the electron gun. Different electron guns were used in obtaining these two patterns which may account for the difference in ring size.

The accelerating voltage of 1400 volts may have been inadequate to produce the diffraction patterns from the specimens that were used. Although the electrons definitely penetrated the specimen it may be that an insufficient number of electrons were diffracted to be visible on the fluorescent screen. If the intensity of the diffracted waves was small it could be masked by the diffraction from the gun. Higher accelerating voltages should reduce this masking effect.

The diameter of the electron beam was not measured accurately but it was estimated to be between 2 and 4 millimeters. A smaller beam is required for a sharp diffraction pattern; however, this size beam was considered adequate to demonstrate diffraction. The combination of a higher accelerating voltage and a smaller diameter beam would most likely be beneficial in obtaining a diffraction pattern.

Recently (May, 1963), the Welch Scientific Company placed an electron diffraction tube on the market. The tube was developed by Harry F. Meiners and Stanley A. Williams of Rennsselaer Polytechnic Institute with the cooperation of the General Electric Company. This electron diffraction tube is quite similar to the one described in this report. However, the commercial tube has the added feature that it is permanently sealed. Two materials are mounted on a 2x2-cm. target located about halfway between gun and screen. Accelerating voltages are variable up to 10,000 volts

and it was indicated that diffraction patterns have been obtained with potentials between 3500 to 10,000 volts. A report of a preliminary developmental tube had been published (9) by Meiners and Williams but only recently came to the writers attention.

The source of the electron diffraction pattern produced by the electron gun is somewhat questionable. It seems most likely that it is produced by the electrons passing through one of the four circular apertures of the gun. The size of the diffraction pattern, however, is much too large, approximately 60 thousand times, to be produced by 1400 volt electrons going through the smallest opening. There is the possibility that low voltage electrons passing through the 0.07 cm. circular aperture in the grid produced a diffraction pattern that is then magnified by the focussing and accelerating electrodes. For example, a 3 volt electron, which has a wavelength of approximately 7Å, would produce a diffraction pattern with the inner bright ring having a diameter of 1.3×10^{-4} cm. at the screen. A magnification of 6000 to 7000 times would enlarge the diffraction pattern to the degree observed on the screen. This amount of magnification appeared reasonable although no attempt was made to calculate the magnification caused by the electrostatic field. These low energy electrons are possible at the grid but are accelerated rapidly beyond that point, which is another reason for believing the diffraction originates at the grid.

A diffraction pattern of this type could be used to demonstrate the wave nature of electrons. Particles would not be expected to concentrate in concentric rings as they come out of the gun so it would be concluded that the rings resulted from waves associated with the electrons. The

demonstration could be further extended by allowing the electron beam to pass near the edge of a barrier. The full diffraction pattern appears on the screen even though a portion of it is in the "shadow" of the barrier. This is shown in (c) of Plate V. The barrier in this case was the outer edge of the circular specimen holder. The specimen holder is between the gun and the right half of the diffraction pattern shown on the screen. Particles travel in a straight line so they would be unable to get around the holder; therefore, only the left hand part of the diffraction pattern would be visible on the screen if the beam was made up of particles alone. The appearance of the full diffraction pattern can be explained if waves are associated with the electrons. This effect can also be noted from (a), (b), and (d) of Plate V. The diffraction pattern in (d) is from the electron beam which had passed through a thin aluminum specimen. The asymmetry of the pattern is caused by a slight a-c ripple on the deflection plates of the tube. In other words the beam is oscillating between two positions a small distance apart. In (a) and (b) the beam was oscillating in the same manner but only penetrated the specimen at one end position. The beam was unable to penetrate the specimen at the other end position, but the diffraction pattern appears to have "passed through" the specimen. Again this must be explained by waves associated with the electron beam.

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The writer wishes to express his appreciation to Dr. Basil Curnutte for suggesting this study and for his helpful supervision of the experimental work. Also to Dr. Dean Dragsdorf for his interest in the project and for his continued encouragement.

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AN ABSTRACT OF A REPORT

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Department of Physics

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1964

An electron diffraction apparatus was constructed by modifying a 5-inch cathode ray tube, and building a 1500 volt regulated power supply. This apparatus was intended for classroom demonstrations of electron diffraction. A simple and economical method of studying matter waves was expected and the quantitative measurement of crystal spacings by Bragg angle scattering of electrons was considered possible.

Electron diffraction patterns were not obtained from the two types of polycrystalline films (MgO and Al) used. However, an electron diffraction pattern (concentric circles) was produced by the cathode ray tube. It is supposed that this electron diffraction develops from the circular apertures in the electron gun. According to calculations, a 3 volt electron diffraction pattern magnified 6000 times will correspond to the pattern obtained on the screen. Magnification of this order may be possible with the accelerating and focusing potentials used in the apparatus. This diffraction pattern provides a method for demonstrating matter waves.