Using a TV set to show electron diffraction

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Abstract

We show the feasibility of constructing a simple set-up to demonstrate the diffraction of electrons starting from a standard TV set. Two concentric rings around a central maxima appears on the screen of the modified TV set corresponding to atomic planes (1, 0, 0) and (1, 1, 0) of a hexagonal structure of graphite sample. A reasonable Planck's constant value is determined through the slope of a plot of λ_d^2 vs $1/V$ where we used the average Bragg wavelength for both diffraction rings for each value of accelerating voltage. Since wave particle behavior of matter is shown, we believe this simple set-up is useful for introductory physics courses at high school and undergraduate levels.

Keywords: Cathode ray tube, electron diffraction, Planck's constant.

Resumen

Se demuestra la viabilidad de construir una sencilla configuración inicial para demostrar la difracción de electrones a partir de un televisor estándar. Dos anillos concéntricos alrededor de un centro de intensidad máxima aparece en la pantalla del televisor modificado, que corresponden a los planos atómicos (1, 0, 0) y (1, 1, 0) de una estructura hexagonal de la muestra de grafito. Un valor razonable de la constante de Planck se determina a través de la pendiente de una gráfica de λ_d^2 vs $1/V$, donde se utilizó la media de la longitud de onda de Bragg para ambos anillos de difracción para cada valor de la tensión voltaica de aceleración. Dado que se muestra el comportamiento de las partículas de la onda de la materia, creemos que esta sencilla configuración es útil para los cursos introductorios de física en las escuelas secundarias y las que dan a un nivel de pregrado.

Palabras clave: Tubo de rayos catódicos, difracción de electrones, constante de Planck.

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I. INTRODUCTION

In spite of being at the beginning of the XXI century, and despite the numerous efforts by all levels of teaching, our students have a barely superficial notion of the basic physics behind many of the wonders of technology. Most important, the so-called Modern Physics seems distant from the student's everyday life. In a society that is more and more dependent on technology, such perception leads to dependence and mystification. If we want our students to follow the changes in life and appreciate the benefits of technology without that "magic" aura around these subjects, we must expose them to the concepts, no matter how much against common sense they may seem at first sight, with as many "hands-on" experiments as possible. This might be a reasonable approach for developed countries, or even some regions of the less developed, but it is an insurmountable problem in most regions of the world.

We took one of the most important experiments of the turn of the last century as a possible route to the minds of our students: the diffraction of electrons by a polycrystalline sample. The basic concept dealt with in this experiment is wave-particle duality that has earned J. J. Thomson a Nobel Prize in 1906 for the particle behavior of matter [1]. Later on, 1928, R. L. De Broglie won another Nobel Prize for the wave behavior of matter [2], and G. P. Thomson and C. J. Davisson yet another in 1937 for the experimental confirmation of that theory [3, 4, 5]. All of these contributions, and the numerous others that were published at the time, helped to establish Quantum Mechanics and all the revolutionary concepts that came along. Most of the wonders of modern technology are rooted in the concepts established then, and it seems logical to use the same steps that convinced (most) physicists of the new ideas at that time to expose our students to this highly non-common-sense perception of nature.

We present here the results of a set-up built around a modified standard old fashioned TV set (Phillips model R17T630) where a polycrystalline film (graphite) was installed in transmission geometry for in-class or laboratory demonstration of the effect. Therefore, an electron diffraction experiment is accomplished using a cathode ray tube (CRT) where the electron gun furnishes an electron beam that provides demonstration of a quantum mechanical effect.

Although good equipment to demonstrate this effect is available on the market, we believe that adapting a CRT from a standard TV set as an electron source to show wave particle behavior is an exciting idea. Also, through an association between University and local industry, we intend to suggest an alternative way that could be used to overcome lack of good equipment for Modern Physics teaching concepts in the less developed regions of the world. It should be noted that this does not intend to replace a commercial product or a low-cost alternative for lacking education budget. Great efforts in order to increase education budget should always be done. Therefore, our main intend is to accomplish an exciting idea.

II. EXPERIMENTAL

The requirement to obtain well-defined interference patterns in a diffraction experiment is that the beam be composed of "homogeneous" electrons, that is, the wave associated to each electron should be formed from coherent waves and produced by a point source. It so happens that a TV tube provides a beam with those characteristics: focusing, collimating, and speed and energy where relativistic effects are negligible. There is, nonetheless, a small chromatic aberration [6] of ΔE=0.1 to 0.4 eV in the emission, as is evident in the width of the rings in figure 5. The beam's total energy is 10,5 to 16,5 keV so ΔE is small.

Figure 1 is a schematic view of the electrostatic focusing electron gun used in the modified standard TV set. The source of electrons is a Phillips made 17-inch black-and-white electron gun model A44-120W. "Free electrons" are produced in the cathode by thermal ionic emission and are ready to be accelerated, collimated and focused. The number of electrons passing through the sample depends on the negative bias applied on the control grid G.1 ($V_{G.1}$ = -40 to -77 V). Applying a positive bias on grid G.2 ($V_{G.2}$ = 400 V) provides a first acceleration of the electrons. Also, this grid has the purpose of homogenizing the electron's energy. The final electron energy [7] depends on the high voltage applied on grids G.3 and G.5 ($V_{G.3}$ = $V_{G.5}$ = 9 to 17 kV).

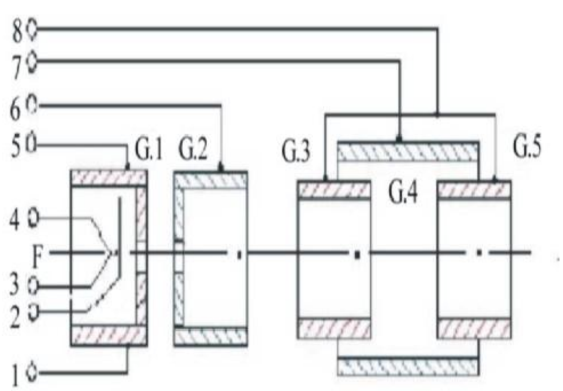

FIGURE 1. Schematic drawing of an electrostatic focusing electron gun used in the modified standard TV set.

Grids G.3, G.4 ($V_{G.4}$ = 0 to 400 V) and G.5 form an electrostatic "einzel" lens such that adjusting voltage on G.4 allows electrons that cross over this point to be moved along the horizontal axis [6]. Finally, beam collimation is accomplished by a 0.5 mm hole on grid G.1 and G.2. As can be seen on figure 1 electrical connection is done through connectors 1 to 8. A 6,3 V_{AC} (300 mA) is applied to the tungsten filament (F) through connectors 3 and 4 for indirect heating of the cathode. A 36 to 60 V with respect to grid G.1, is applied to the cathode through connector 2.

The standard TV power source for the CRT was modified to allow voltages to be controlled between 9 and 17 kV. This was achieved by adapting a 10 kΩ potentiometer to vary the flyback's power supply (+110 V) output, as shown in the block diagram in figure 2.

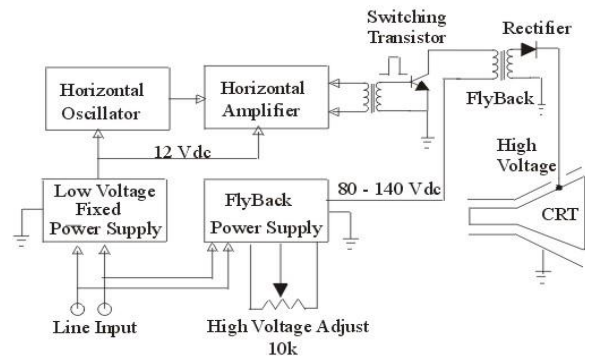

FIGURE 2. Block diagram of the source of a standard TV with the modification made to control the accelerating voltage.

A closer look to the flyback's power supply circuit is shown in figure 3. Replacing resistor R161 (2,2 kΩ) by a 10 kΩ potentiometer enabled us to vary the power supply (+110 V) output. As this power supply feeds the flyback, then is possible to control the high voltage between 9 and 17 kV. The high voltage was measured from the outside through a guarded connector using a high voltage probe connected to a digital voltmeter.

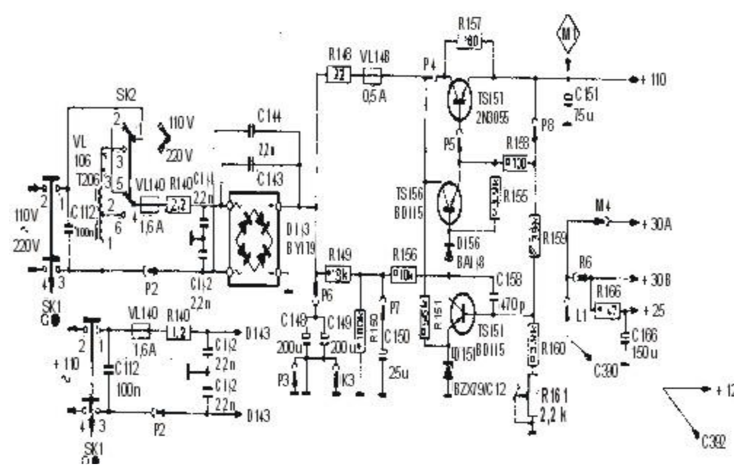

FIGURE 3. Flyback's power supply circuit. Resistor R161 (2,2 kΩ) is replaced by a 10 kΩ potentiometer.

Figure 4 shows the schematic drawing of the modified CRT. The sample installed is a polycrystalline graphite film from a Leybold set-up [8]. Similar samples were grown in our laboratories afterwards. The film is evaporated over several clusters of salt working as substrate. Later, using electron microscope transmission grid for sample preparation, the film is catch from a non-ionized water solution. Finally, the microscope grid is mounted on a metallic ring welded to three short stripes for centering. This support system is welded to the last accelerating grid (G. 5) as can be seen in figure 4.

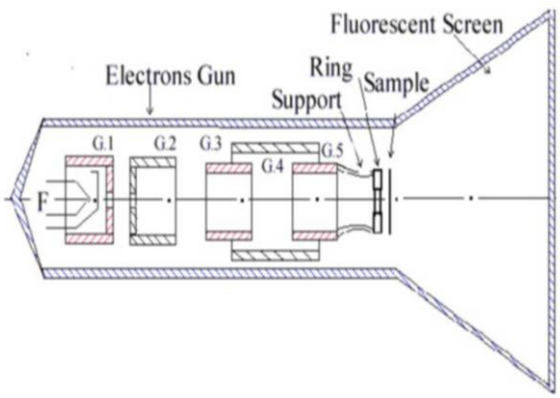

FIGURE 4. Schematic drawing of the modified CRT for diffraction of electrons in a transmission geometry.

Using university and local industry facilities, the modified CRT (see figure 4) was pumped for 4.5 hours while heated to 350 °C in high vacuum (base pressure ~10^{-5} Pa). The CRT was then sealed and the cathode conversion process accomplished for a new electron gun. The cathode conversion consists in melt-reacting the layers of Ba, Sr and Ca that cover the Tungsten (W) core through an injected high AC current during a period of time. This is a standard procedure used in the television industry to activate a new electron gun. Therefore, this modified CRT is a sealed unit keeping the electron gun (cathode) and sample (graphite) in high vacuum which enables us to use the screen to display the electron's diffraction pattern. Also, keeping the system as a sealed unit avoids undesirable oxidation of the cathode (poisoning). We must remark that for this kind of electron gun, it is difficult to re-activate emission from a poisoned cathode.

III. RESULTS AND DISCUSSION

The sealed unit was used to conduct the tests for it allowed changes in the electrical parameters to be made without the danger of breaking the vacuum on the gun. We have observed that for accelerating voltages below 10 kV the beam produces a single point in the screen of about 1 mm diameter. This corresponds nicely to the fact that for E~10 keV the size of the inside ring should be larger than the screen of the CRT.

From 10.5 kV up, two clear diffraction rings are visible, as can be seen in figure 5 (for 15.5 kV). The wavelength of the incident electron according to the Bragg relation is given by:

$$\lambda = \frac{d\,D}{2\,N\,L}, \qquad (1)$$

where D stands for the ring diameter, L is the distance from the sample to the screen, N is the interference pattern order and d is the spacing between atomic planes. Following Klug and Alexander [9] the spacing between planes for the hexagonal structure of graphite can be written as:

$$d = \frac{N}{\left[\left(\frac{4}{3a^2}\right)\left(h^2+k^2+hk\right)+\left(\frac{\ell^2}{c^2}\right)\right]^{1/2}}, \qquad (2)$$

where $a = 2.463 \times 10^{-10}$ m and $c = 6.714 \times 10^{-10}$ m represent the lattice parameters [10], (h ,k, l) the Miller's indices for the atomic planes and N the interference pattern order as mentioned above. Atomic planes corresponding to (1, 0, 0) and (1, 1, 0) show interference pattern. Due to factors affecting the diffraction intensities [9] other possible planes for the hexagonal structure of graphite do not contribute to the interference pattern.

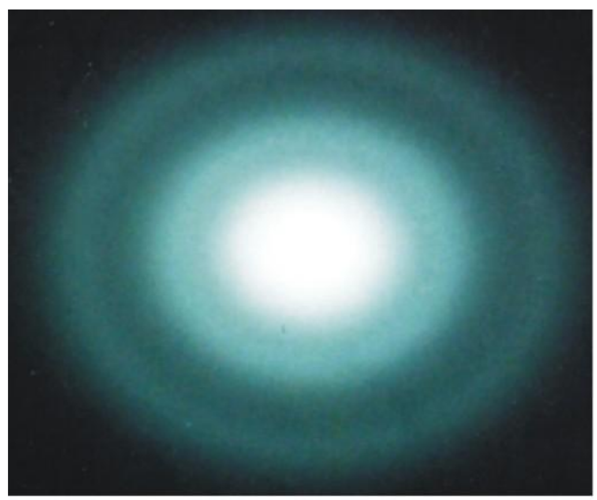

FIGURE 5. Ring diffraction pattern of polycrystalline graphite for an accelerating voltage of 15.5 kV.

Thus, the wavelength associated with the internal ring (1, 0, 0), and the external one (1, 1, 0) can be written as:

$$\lambda_{d_1} = \frac{D_1}{2\,L}\, 2{,}13 \times 10^{-10} m \quad \text{internal ring} \qquad (3)$$

$$\lambda_{d_2} = \frac{D_2}{2\,L}\, 1{,}23 \times 10^{-10} m \quad \text{external ring} \qquad (4)$$

The simple fact that these diffraction rings are observable shows, at least qualitatively, the wave character of the electron. On increasing the accelerating potential, reduction of the ring's diameter is observed, which is associated to a decrease in the wavelength. This is the necessary connection to establish the correlation of larger (smaller) energies and smaller (larger) wavelengths.

As a result of our experimental set-up, better-defined rings are obtained for larger energies (accelerating voltages), perhaps indicating that in these conditions, by obtaining smaller radii, the error induced by non-homogeneities reduces accordingly.

The de Broglie wavelength for negligible relativistic effects is given by:

$$\lambda_B^2 = \frac{h^2}{2\,q\,M_o}\,\frac{1}{V}\ , \quad (5)$$

where h stands for Planck's constant, M_o for the electron mass and V for the applied voltage.

If one takes: $\lambda_B = \lambda_d$, then

$$\lambda_d^2 = \frac{h^2}{2\,q\,M_o}\,\frac{1}{V}\ . \quad (6)$$

Figure 6 shows a plot of λ_d^2 vs $1/V$ where we used the average Bragg wavelength for both diffraction rings for each value of accelerating voltage. The slope (P) of this plot allows the determination of Planck's constant (h). The slope is found to be

$$P = 1{,}839\,(\pm 0{,}024)\ \text{x}\,10^{-18}\,\text{m}^2\text{V}$$

and

$$h = 7{,}32\,(\pm 0.05)\,\text{x}\,10^{-34}\ \text{J s}$$

The value found in the Handbook of Chemistry and Physics [11], is:

$$h = 6{,}6260755\ (\pm 0.000004)\ \text{x}\,10^{-34}\ \text{Js}$$

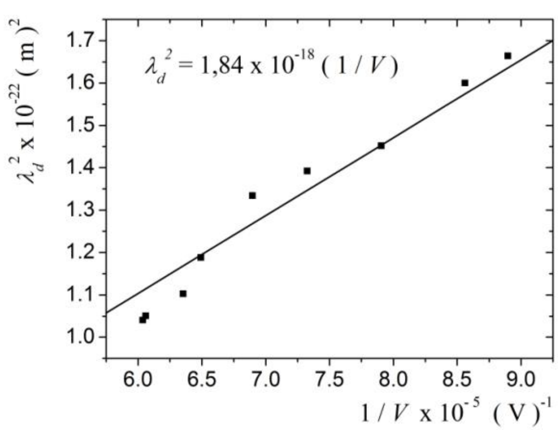

FIGURE 6. Bragg wavelength vs the reciprocal of the accelerating voltage.

The difference between both values is probably due to the following factors:

1. The high voltage source in a standard TV supplies the desired DC values, but contains a ripple of around 50 V at higher frequencies (~ 15 kHz) and around 100 V at low frequencies (~ 60 Hz). This implies that there is dispersion in the energy values (wave numbers) for the electrons in the beam. This means we must have stable high supply voltage so that all of the electrons have small energy dispersion (ΔE), thus giving a well defined wavelength. Usually for an applied voltage of 100 kV there is an energy dispersion of 3 eV [12].
2. The high voltage measurement, due to the fact that digital multimeters, by construction, measure an average of the applied voltage.
3. The chromatic aberration in the emission of the electrons by the cathode introduces an additional $\pm\Delta\lambda$ variation to the associated wavelength.
4. The most important factors to be considered, nevertheless, are the determination of the distance from sample to screen and the diameter of the rings (also affected by the previously cited factors).

Using IRAF, the well-known software Image Reduction and Analysis Facility [13], usually employed for research in Astronomy, we plotted the normalized intensity as a function of the number of pixels for the ring diffraction pattern shown in figure 5, as can be seen in Fig. 7.

The plateau from 325 to 450 pixels shows the direct beam portion. This makes clear that the polycrystalline graphite does not diffract a good part of the electron beam. On the other hand, we can see two small peaks of lower intensities for the internal ring (1, 0, 0) and the external one (1, 1, 0) respectively, which correspond to the small proportion of the diffracted electron beam.

In figure 7 there was a clear loss of sample information, which is evident from the poor resolution, due mainly to the scanning processes. A better, quantitative analysis, could be performed using a CCD camera, which in turn will allow us to get more structural information from the graphite sample.

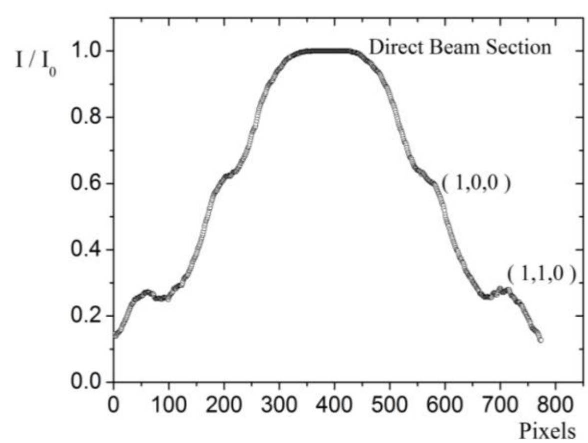

FIGURE 7. Normalized intensity as function of pixels for the ring diffraction pattern shown in figure 5.

IV. CONCLUSIONS

We have succeeded in producing a simple set-up to teach the basic concepts of electron diffraction. The device has the form of a "compact" TV set that performs electron diffraction on a graphite sample in transmission geometry which allows taking it to high-school and undergraduate students for in-class or laboratory demonstration of the effect. All this has been done involving a local industry together with human resource from the University. Therefore, this paper suggests an alternative way that could be used to overcome lack of good equipment for Modern Physics teaching concepts in the less developed regions of the world.

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REFERENCES

[1] Thomson, J. J., *Cathode rays*, Phil. Mag. **44**, 293 (1897).

[2] De Broglie, R. L., *A tentative theory of light quanta*, Phil. Mag. **47**, 446–458 (1924).

[3] Thomson, G. P., *Experiments on the diffraction of cathode rays*, Proc. Roy. Soc. A. **117**, 600-609 (1928).

[4] Thomson, G. P., *Experiments on the diffraction of cathode rays II*, Proc. Roy. Soc. A **119**, 651-662 (1928).

[5] Davisson, C. and Germer, L. H., *Diffraction of electrons by a crystal of nickel*, Phys. Rev**.** **30**, 705-740 (1927).

[6] Moore, J. H., Davis, C. C. and Coplan, M. A., *Building scientific apparatus* 4th Ed., (Addison Wesley, New York, 1989).

[7] Cooper, W. D., *Electronic instrumentation and measurement techniques*, (Prentice Hall, Englewood Cliffs, NJ, 1970).

[8] Leybold–Heraeus, *Diffraction of Electrons Set up*, Model 55517.

[9] Klug, H. P. and Alexander, L. E., *X-ray diffraction procedures*, (John Wiley, New York, 1974).

[10] Joint Committee on Powder Diffraction Standards. *Powder diffraction file*, (Swarthmore: International Centre For Diffraction Data, 1978).

[11] CRC PRESS, *Handbook of Chemistry and Physics*, 72nd Edition, (David Lide, editor in Chief, USA, 1991–1992).

[12] Williams, D. B. and Carter, C. B., *Transmission electron microscopy: a textbook for materials science*, (Plenum Press, New York and London, 1996).

[13] More information about Image Reduction and Analysis Facility software can be found at <www.iraf.noao.edu>