Experiment 4: X-ray Emission and Diffraction*

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Abstract

In this experiment we will experimentally determine Planck's constant, h, and determine the wavelengths of the K_α and K_β lines of the x-ray spectrum of copper.

1 Introduction

1.1 Bragg scattering

Sir Lawrence Bragg presumed that the atoms of a crystal such as Lithium Fluoride (LiF) were arranged in a cubic and regular three-dimensional pattern. A beam of x-rays that falls upon a such crystal will be scattered in all directions inside the crystal. In certain directions the scattered waves will interfere constructively, while in others, the interference will be destructive. The location of the points of constructive interference depends on the spacing of the atoms in the crystal, and on the wavelength of the x-rays (see Figures 1 and 2). In particular, the path-length difference for waves reflected from different crystal planes must be an integral number of x-ray wavelengths:

$$2d \sin\theta = n\lambda. \tag{1}$$

Thus, different wavelengths will be scattered at different angles. Also, particularly strong features in an x-ray spectrum will appear for multiple orders (multiple n).

The Tel-X-Ometer x-ray device produces x-rays by accelerating electrons through a large potential difference (in our case, 30 kV) toward a copper target. This results in two distinct contributions to the x-ray spectrum, one from the deceleration of the electrons as they hit the copper target, and one from the emission of x-rays by copper atoms which have lost an electron. Here we will be using Bragg's technique to distinguish these features, resulting in direct measurements of the x-ray spectrum of copper as well as an experimental determination of Planck's constant, h.

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* Adapted from the manual for the Tel-X-Ometer apparatus, *Student Enquiry Series D: The Production, Properties, and Uses of X-rays*, 1974 TELTRON Ltd., London, England.

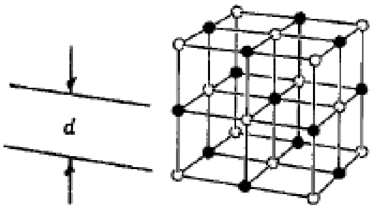

Figure 1: LiF crystal lattice.

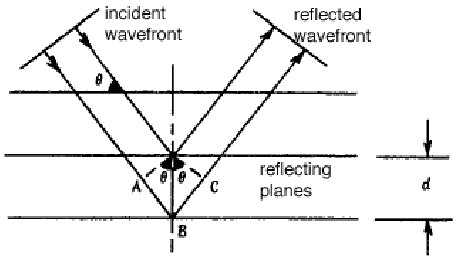

Figure 2: Bragg scattering from crystal planes.

1.2 Bremsstrahlung

In striking the copper anode, the majority of electrons experience nothing spectacular; they undergo sequential glancing collisions with particles of matter, lose their energy a little at a time and merely increase the average kinetic energy of the particles in the target (i.e. the target gets hot).

The minority of electrons will undergo a variety of glancing collisions of varying severity; the electrons are decelerated, imparting some of their energy to the target particle and some in the form of electromagnetic radiation equivalent in energy to the energy loss experienced at each collision.

Since these collisions usually occur at a slight depth within the target the longer, less energetic wavelengths are absorbed within the target material.

This *bremsstrahlung* or braking radiation is thus a continuous spread of wavelengths, the minimum wavelength (maximum energy) being determined by the accelerating voltage of the tube. That is,

$$E_{max} = eV = h\nu_{max} = \frac{hc}{\lambda_{min}}. \tag{2}$$

Using the known values of c (2.99792458×10^8 m/s) and e ($1.60217733 \times 10^{-19}$ C), and measuring values for V (here it will be 30 kV) and λ_{min}, we can use Equation 2 to experimentally determine Planck's constant, h.

1.3 X-ray Spectrum of Cu

In addition to the continuous bremsstrahlung radiation, some electrons have enough energy to completely eject an electron from an inner copper electron shell (for the K shell, $n = 1$). This "hole" is quickly filled by an outer-shell electron – i.e. one from the L ($n = 2$) or M ($n = 3$) shells (see Figure 3). X-rays produced in this way are of specific wavelengths that are characteristic of the copper target atoms. We will directly measure the wavelengths of the K_α and K_β lines of copper.

2 Equipment

TelAtomic Tel-X-Ometer	TelAtomic Tel-X-Ometer Accessory Kit
Spectrum Techniques ST350 Radiation Counter	Digital voltmeter

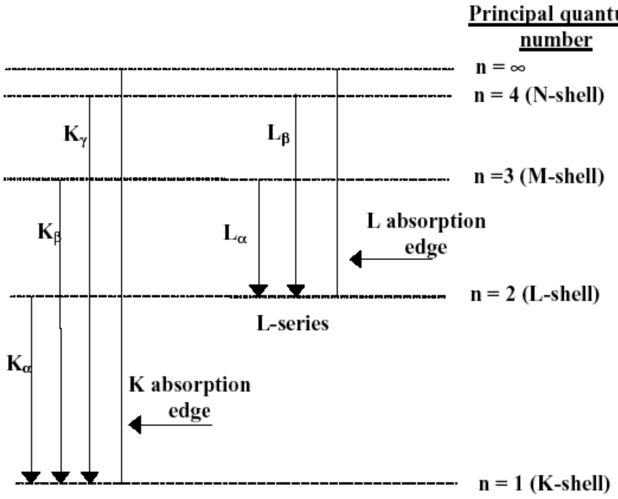

Figure 3: Atomic transitions in copper.

3 Procedure

Thoroughly read and understand the provided equipment manual *Student Enquiry Series D: The Production, Properties, and Uses of X-rays* (hereafter referred to as the *Manual*) before beginning this experiment. Pay particular attention to sections 6.5-6.7 and 10.1-10.11.

Access to the Tel-X-Ometer is limited and the device requires a key to operate. These can be obtained from your instructor or the Department's Equipment Manager.

Before beginning the laboratory, you must read the "Radiation Safety Procedures" that are included at the back of the *Manual*. This procedure has been performed by your instructor prior to this lab and the instrument is verified as operating within normal parameters. If you have any concerns, feel free to repeat the safety check. Direct any concerns or questions to your instructor or the Department's Equipment Manager.

1. Open the Tel-X-Ometer top cover and set the acceleration voltage to 30 kV.

2. Turn on the Tel-X-Ometer by turning the key to the right and the white timer knob to 55 minutes. The Power On lamp will light. Allow the filament to warm up for 5 minutes.

3. Mount the LiF crystal in the crystal post ensuring that the major face having a "flat matt" appearance is in the reflecting position (see Figure 4) – be careful not to touch these faces.

   Note: When you are done, put the crystal back in its storage container! If you don't, it will corrode the crystal post.

4. Locate the Primary Beam Collimator in the Basic Port with the 1 mm slot vertical.

5. Mount the 3 mm Slide Collimator in slot 13 of the Carriage Arm assembly. Mount the 1 mm Slide Collimator in slot 18 of the Carriage Arm assembly. Both of these slides should be

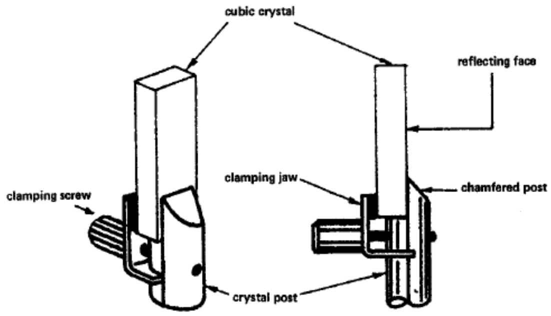

Figure 4: Mounting of cubic crystals.

mounted using a spring clip. This ensures that the slides are centered on the x-ray beam by pressing them against the numbered side of the carriage.

6. Zero-set and lock the Slave Plate and the Carriage Arm cursor as precisely as possible (see the *Manual*, section 10.6). This may not require adjustment.

7. Sight through the collimating slits and observe that the primary beam direction lies in the surface of the crystal.

8. Mount the Geiger-Mueller (GM) tube and its holder in slot 26 of the Carriage Arm assembly *without* a spring clip, ensuring that the cable is leading out from the underside and that the end-window is facing the crystal post. Connect the GM tube to the Radiation Counter, turn on the Radiation Counter and set the tube voltage to 400 V.

9. Turn on the x-ray beam by pressing the X-Rays On button. The button will light and the X-rays On lamp will light.

10. Use the digital voltmeter and the specialized cord to ensure that the filament voltage is about 50 μA. **Do not let the filament current exceed 80 μA!**

11. Using the Radiation Counter, determine the count rate at 1° intervals between the Carriage Arm's minimum setting (about 11°, 2θ) and maximum setting (about 124°, 2θ). This can be done using the ratemeter mode on the Radiation Counter. A better alternative is to use the Radiation Counter as a scaler – i.e. use the count and timer functions to determine a time-average rate. At each interval, be sure to collect enough counts to get a reasonable average rate (this may take several minutes at low count rates). To achieve measurements of 2θ between 11° and 19°, index the Carriage Arm to 15° and set the thumb-wheel to zero. Settings in this range can be achieved using only thumb-wheel indications.

12. Plot the count rate (in counts/second) vs. 2θ in 1° intervals. Where the count rate appears to peak, plot intervals of only $10'$ arc using the thumb-wheel. At each peak, measure and record the maximum count rate and the angle 2θ as precisely as possible. Your plot should look similar to Figure 5; however, the LiF crystal will only allow you to observe the first two orders ($n = 1$ and $n = 2$).

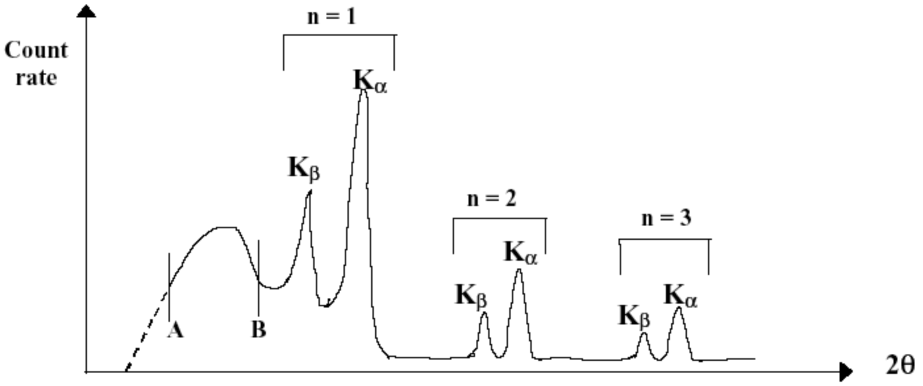

Figure 5: The x-ray spectrum of copper.

4 Analysis

4.1 Bremsstrahlung

1. Due to the shield at the front of the x-ray device, your rate vs. 2θ plot will probably start at point A on Figure 5 rather than on the x-axis. Extrapolate the curve down to the axis and determine θ_{min}. Note that the curve may flatten out before intercepting the axis due to background; neglect this effect in your extrapolation.

2. Use Equation 1 to calculate λ_{min} (here $n = 1$). The scattering plane spacing d can be calculated from the density of LiF, the molecular weight of LiF, and Avogadro's number. This yields $d_{\text{LiF}} = 0.2014$ nm.

3. Use Equation 2 to calculate h. How does it compare to the currently accepted value? What can you say about your accuracy? To help get a feel for the uncertainty, it is known that in counting experiments like this one, the uncertainty is given by $\sigma = \sqrt{N}$, where N is the number of counts in a given time. To determine θ_{min} you will draw a line to the axis as stated above. For two of the points that you will use for the extrapolation, calculate the error, and by hand draw lines that will fit through both of those error bars to get a feel for the uncertainty in θ_{min}. Use that uncertainty in your propagation for λ_{min} and h.

4.2 X-ray Spectrum of Cu

1. Determine θ for each of the K_α and K_β peaks on your graph as carefully as possible.

2. Use these θ and Equation 1 to get values for the K_α and K_β transitions in copper. Here, the values of n are as in Figure 5, and $d_{\text{LiF}} = 0.2014$ nm. You should have two values for each line (one from each order). To deterimine the uncertainties in where the peak lies, a decent estimate is the full width at half max (FWHM). This is just what it sounds like. Measure the width of the peak half-way between the base of the peak and the top of the peak. One-half of this value is a good approximation of σ.

3. Calculate the average value of the wavelength for each transition, with uncertainty, and use this value to calculate the energy of these transitions.

4. Compare your x-ray energies to the values quoted in the CRC *Handbook of Chemistry and Physics, 71st ed* for copper: $K_\alpha = 8.038$ keV, $K_\beta = 8.905$ keV.