X-ray Experiments

Experiment I (Bragg Diffraction)

Background

Sir Lawrence Bragg assumed that the atoms of a crystal such as Sodium Chloride were arranged in a cubic structure with a regular three-dimensional pattern. For Sodium chloride, this is a correct assumption and the structure is face centered cubic. The face centered cube can be constructed from eight smaller cubes with alternating atoms at the each corner (Fig. 1).

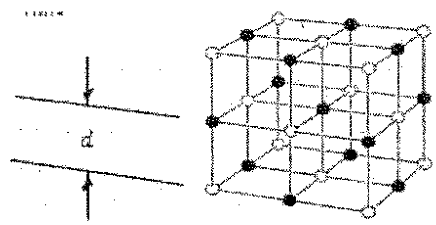


Figure 1

Under the assumption that this structure is correct, one can compute the separation between layers of atoms **d** in this crystal. The mass of a molecule of NaC1 is (**M/N**) kg, where **M** is the molecular weight (58.46 x 1 0^{-3} kg per mole) and **N** is Avagadro's number (6.02 x 10^{23} molecules per mole). The number of molecules per unit volume is **ρ/(M/N)** molecules per cubic meter, where **ρ** is the crystal density (2.16 x 10^3 kg m-^{3}). Since NaCl is diatomic, there are two atoms per molecule, and the number of atoms per unit volume is **2ρ/(M/N)**. If you look at the diagram, you see that each atom at the corner of the cube is shared with 8 adjacent cubes. Since there are eight corners to the cube, and each atom contributes 1/8 to each cube, there is one atom in a cube of size **d**. This may be used to test determine the distance between atoms.

$$d^3 = \frac{1}{2\rho \frac{N}{M}} \text{ or } d = \sqrt[3]{\frac{M}{2\rho N}}$$

The value of **d** may also be obtained using the interference of light which has been reflected by atoms in the crystal. In Fig 2, we see the method of Bragg reflection. The first condition for obtaining Bragg reflection is that the angle of incidence of the wavefront relative to the reflecting layer, be equal to the angle of the reflected wavefront. This requires that the detector of the reflected rays must move through an angle 2θ relative to the incident wavefront. The experiment is designed so that the crystal moves at 1/2 the speed of the detector, which satisfies this condition. The second condition is that the reflections from several layers must combine constructively.

$$n\lambda = 2d\sin(\theta)$$

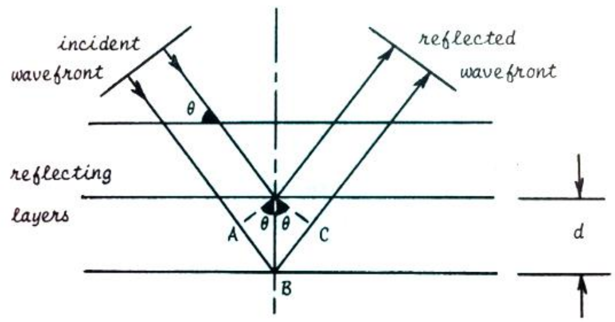


Figure 2

Since the separation between layers in a crystal is approximately a few Angstroms, one must use short wavelength radiation (x-rays).

Experiment Set Up

1. You must attend the x-ray safety seminar prior to operating this experiment. Steps 2-4 must be done with the X-ray machine turned off. The machine interlocks will prevent turning on the machine until the lead glass cover is locked down.
2. Read the SAFETY PROTOCOL document for the Tel-X_OMETER.
3. Verify and set the following (Teacher/TA will help) :
    a. Make sure that the machine is off. Open the lead glass cover. Mount the NaCI in the crystal post. Make sure that the major face having the "flat matt" appearance is in the reflecting position.
    b. Locate the primary beam collimator in the basic port with the 1mm slot vertical.

c. Mount slide collimator (3mm) at slide slot 13, and slide collimator (1 mm) at slide slot 18.

d. Zero-set and lock the slave plate and the carriage arm cursor as precisely as possible.

e. Look through the collimating slits and verify that the primary beam direction lies on the surface of the crystal.

f. Mount the Geiger-Muller tube and its holder at slot 26.

g. For the first part of the experiment, apply 30 kV across the anode and cathode by setting the switch located below the TEL-X Driver 2590 (blue box) to 30 kV. The instrument may be set to 20 kV or 30 kV by a switch located under the driver module for automated scanning (See Figure 3). To access this switch, swing the blue driver to the left and lift the module out.

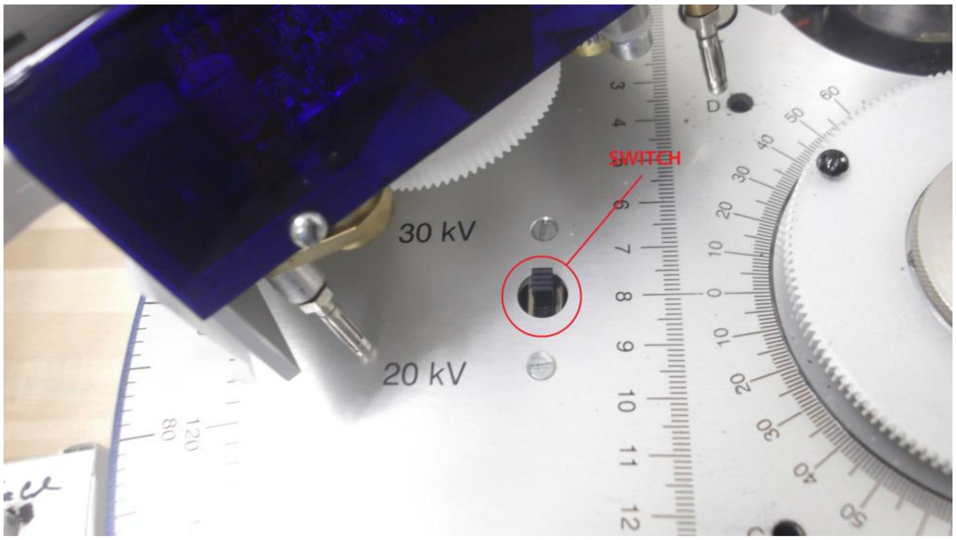


Figure 3

h. Make sure that the Teacher/TA checks the system at this point.

i. Close the lead glass cover. In doing so, make sure that the lead glass cover exactly aligns with the center line otherwise the x-ray will not start. (It is possible to miss the center slightly to the left or the right, in which case the instrument doesn't work. Check the lid position carefully if the x-rays will not turn on.)

Experiment

1. Have the Teacher/TA show you how to turn on and operate the X-ray machine. It can be turned on by adjusting the time switch knob to your preferred collection time, switching the key to on and pressing the ON button in the X-ray.

2. Start the TEL-X Driver program in the computer. A green box will appear in the screen (Figure 4) with editable dialogue box (bottom portion).

Figure 4

3. Using the scalar, collect the number of counts per second at 1^0 intervals from its minimum value (about 11^0, 2θ) to its maximum value (about 120^0, 2θ) by editing the Region of Interest (ROI). In order to get a small value for 2θ ($11\text{-}19^0$) you will have to set the carriage arm to 15^0 and use the thumb wheel. Each number on the thumb wheel corresponds to 1^0. There is a slider at the base of the meter which is used to select the optimal range for the current count rate. Table 1 gives the best setting for a given count rate. There is a speaker in the scalar, which gives an audible sound for each count. Note from the sound that the counts occur at random times.

4. Set the detector (Geiger Counter) to 550 V; arm position to the current location of the arm; count range to auto. Click the high voltage button on (small, round green button). Graph the count rate at 1^0 intervals. You should obtain a plot similar below (Figure 5).

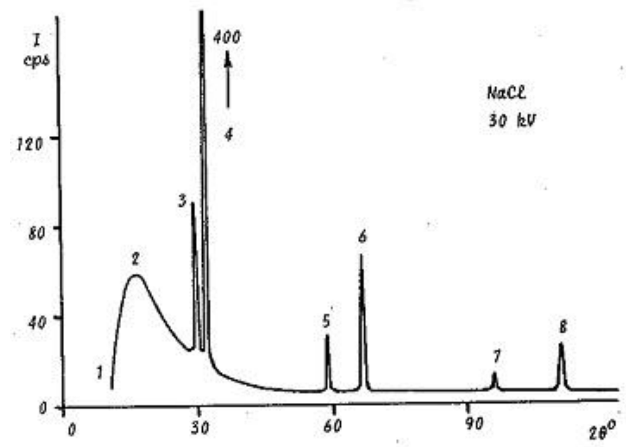


Figure 5

5. Save your data in txt or Excel format.

6. Turn off x-ray. Reduce the voltage to 20 kV and repeat steps 3-5.

7. Turn off the machine and replace the NaCl crystal with LiF crystal. Make sure that the major face having the "flat matt" appearance is in the reflecting position.

8. Repeat steps 1-5 for the LiF crystal. You should also get the same spectrum.

Analysis

1. Compute the value of d for the two crystals.

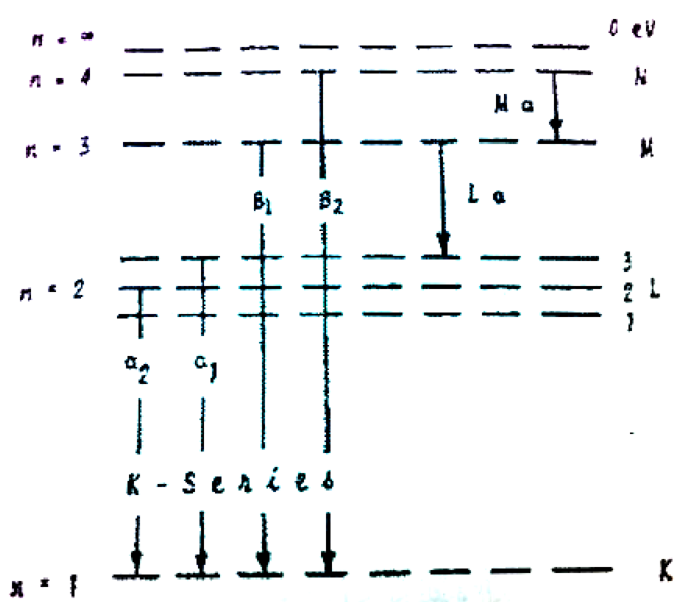
2. Tabulate the results from the six superimposed peaks of the graph and calculate the value of λ and n. Observe that the sharp peaks are a pair of "emission lines" which re-appear in second and third orders of diffraction.

Experiment II (Planck's Constant)

Background

The x-rays are generated by the collision of a high energy electron with an atom. The high energy electron causes one of the inner core electrons (for example in the 1st state) of the atom to be excited and become a free particle independent of the atom. In order to achieve the minimum energy, the empty 1s state in the positive ion is then filled by the transition of an electron in one of the occupied higher energy states of the atom. The x-ray is emitted in this transition to preserve energy conservation. For our machine the electrons collide with copper atoms, and the x-ray emission is emitted by the transition of K_α or K_β (see Fig 6). The atomic ion then emits photons of various frequencies as the

Figure 6



electrons arrange to populate all of the lower states, and an electron is absorbed to make the atomic ion become neutral.

In striking the copper anode the majority of electrons do not generate x-rays. They undergo sequential glancing collisions with particles of matter, lose their energy a little at a time and increase the average energy of the particles in the target. The only effect is to cause the target to get hot. The rest of the electrons will undergo a variety of glancing collisions. The electrons are decelerated, and give some of their kinetic energy to the target particle and some in the form of electromagnetic radiation equivalent in energy to the 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 (or maximum energy) is determined by the accelerating voltage of the tube

$$V\lambda_{\min} = \text{constant}$$

where V is the tube voltage. Since Einstein's theory of the photoelectric effect is valid for both emission and absorption of radiation, the optical energy must be quantized into photons:

$$\omega = h\upsilon$$

where ω is the energy associated with each photon, v is the frequency of radiation and h is Planck's constant. One can relate the frequency to the wavelength for electromagnetic radiation using the equation: $v_{max}=c/\lambda_{min}$, where c is the speed of light. For the maximum energy photon (minimum wavelength), all of the energy of the electron is converted into a single photon. In this case the total kinetic energy of the electron is converted into a photon.

$$Ve = \frac{hc}{\lambda}$$

This equation may be used to obtain the value of Planck's constant.

Experiment

1. Mount the LiF crystal as you did in experiment 1.
2. Select the 30 kV energy and turn on the machine.
3. Starting at 11^0 measure, tabulate and plot the count rate at 30' intervals (1/2 degree). You need to set the slider on the scalar to 0-100 counts or 100-200 counts. Continue until you go over the first peak (only the Bremsstrahlung region).
4. Repeat steps 1-4 using 20 kV energy.
5. Extrapolate the curves to find where they intercept the x axis.

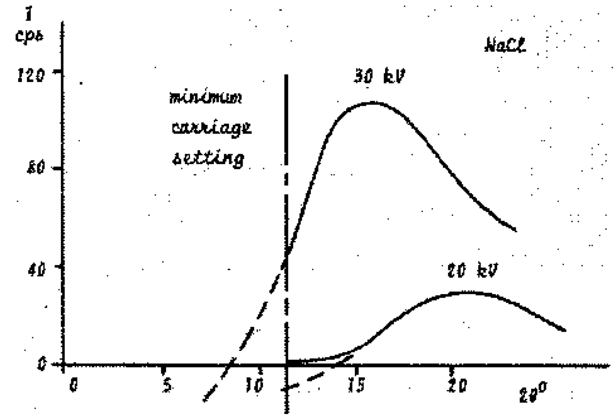


Figure 7

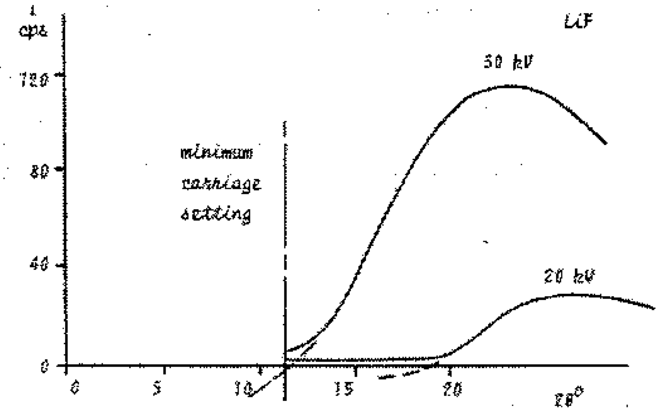


Figure 8

Analysis

Following the idea in Figures 7 and 8, use the extrapolated values of the curve to obtain λ_{min} for the two samples and for each of the two voltages.

Use these values to obtain a measurement of Planck's constant and compare it with the current value.

Table I

Operation of Slider on Scalar (counts = meter reading X MuIt. Factor)			
Range of Counts (cts/sec)	Count Time (sec)	Multiplication Factor	Optimal Range of Counts (cts/sec)
0-100	60,	1	0-200
100-200	30	1	0-200
200-1K	15	10	200-1K
1K-2K	3	10	1K-2K
1K-2K	1	10	1K-2K
2K-20K	1	100	2K-20K