This Tel-X-ometer X-Ray machine produces hazardous radiation levels inside the instrument. It is interlocked so that the high voltage is turned off and grounded when the cover is opened. With the cover in place, the radiation from the machine a few centimeters outside the cover is a negligible increase above the radiation due to cosmic rays and natural radioactivity. Because of the potential hazard, Tennessee law requires that this machine be registered with and inspected by the the Vanderbilt Radiation Safety Department. The first step in each use of the machine is the verification that the interlocks operate correctly. This verification that the interlocks work properly is also performed every quarter and the record of checks is maintained by the Vanderbilt Radiation Safety Office. The machine must **NEVER** be operated in any way which circumvents the interlocks and any proposed modification to the interlock circuitry must have approval of the Vanderbilt Radiation Safety Office prior to implementation. M. Webster, ext. 22842, room 6901, is the authorized "operator" in charge of the machine and has the key needed to turn it on. Tennessee Law requires the posting of radiation signs:

1. A "Notice to Employees" sign must be posted by each access door to the room in which the machine is stored or operated.
2. When the machine is in use, the radiation sign on the top of the unit must be visible and one of the smaller "X-Ray Room - Enter With Caution" signs must be posted at every access door of the room in which it is operated.

In the event of suspected radiation exposure,

1) turn the unit off,
2) inform the instructor, and
3) call radiation safety at 22057.
   (After hours call the Vanderbilt Operator - Dial 0.)

X-Ray Emission and Bragg Reflection

Med Webster

January 22, 2001

Introduction

The study of X-rays has played an important role in the verification of the fundamental principles of quantum theory, in measuring the spacing and configuration of atoms in crystals, and in the determination of the quantum states of the inner electrons in the heavier atoms of the periodic table. In this experiment you will use Bragg reflection to measure Planck's constant from the short wavelength cutoff of the X-ray spectrum and to measure the wavelengths of the K_α and K_β X-ray lines of the anode material of the X-ray tube, copper.

Bragg reflection depends upon cooperative effects of reflection from different planes of atoms within the reflector. Of course the angle of incidence must equal the angle of reflection in order to have coherent reflection from atoms within each of the planes, just as for visible light. The Bragg condition of coherence from different planes is approximately satisfied by visible light independently of angle because the wavelength of visible light is very large compared with the distance between the planes of atoms in the reflecting substance. For the much shorter wavelengths of X-rays, the coherence of reflection from different planes depends sensitively upon the angle, so the sharp peak of Bragg reflection can be used to measure the wavelength in terms of the spacing of the planes in the reflecting substance. For substances such as NaCl and LiF which form simple cubic lattices, we can calculate the volume per atom and thus the spacing between planes from Avogadro's number and the density and atomic weight of the substance. Thus we can use Bragg reflection from these simple crystals to measure the wavelengths of several features in the spectrum of X-rays. The most interesting of these features are a) the short wavelength cutoff which corresponds to the transfer of all of the kinetic energy of an electron accelerated across the X-ray tube to a single X-ray photon and b) the emission lines of the anode material. The short wavelength cutoff is used to determine Planck's constant, and the wavelengths of the K_α and K_β lines are used to calculate the Rydberg constant.

This experiment uses the Tel-X-Ometer X-ray tube, Spectrometer mount, and Geiger counter which are sold by Teletron Limited, 98 Victoria Road, London, NW10, England (US agent is Tel-Atomic, Inc.,P.O. Box 904, Jackson MI 49204, (800) 622-2866). Portions of the instruction manual which is distributed with the apparatus are reproduced and appended. Particular attention must be paid to the procedures for safety checks. This instrument is, in fact, imported and registered as an X-ray machine. Consequently Tennessee law requires that it be checked periodically by the Vanderbilt Radiation Safety Office, that a prescribed radiation notice be posted on the door of the room, that a notice of responsibilities and rights of workers be posted, and that a properly instructed "operator" be in charge of its operation. Tennessee law also requires that you be provided with information which would enable you to seek help if you develop the symptoms of radiation sickness. The last two pages of this document are a copy of the required material. The review of the safety procedures and regulations is the first step of each experiment which uses the apparatus. If the safety procedures are followed, the additional radiation exposure which you receive from the apparatus during the course of the experiment is such a slight increase above the background exposure which you receive during the same time interval from cosmic rays and natural radioactivity that it is difficult to measure. We take radiation exposure to be a very serious matter and require that the machine be used only with an additional collimator which reduces the radiation well below that which the radiation safety office has certified to be in compliance with the applicable statutes.

Objective: To measure Planck's Constant and the wavelengths of the copper K_α and K_β X-ray lines.

Apparatus:

Teletron Tel-X-Ometer X-ray machine and spectrometer mount
Teletron Geiger Müller Tube and tube holder assembly
Scaler and high voltage power supply for Geiger-Müller tube TEL-Atomic Digicounter
Sodium chloride crystal TEL 582.004
Lithium fluoride crystal TEL 563.05
1mm primary beam collimator TEL 582.001
3mm slide collimator TEL 562.016

Radiation Safety Procedure

The X-rays for this experiment are produced by a current (80 μA) of electrons which have been emitted from a heated filament and accelerated through a potential of 20,000 or 30,000 Volts to strike a copper anode. The glass envelope of the tube is made of a special glass which contains lead. Thus most of the X-rays are absorbed in the envelope except for an X-ray transparent window which faces the middle of the spectrometer. The radiation check by the safety office was done with no collimator in front of this window. All of the experiments which we do require collimation, so there is no reason to operate the tube without the 1mm primary beam collimator (TEL 582.001) in place in front of this window. This reduces the radiation which escapes by a factor of approximately six. The dome which covers the machine is a special leaded plastic which absorbs X-rays very effectively. This dome and the metal base form a very effective shield. The region of greatest radiation escape is just beside the metal latch, directly opposite the tube. The counting rate observed with the Geiger counter is only 4.5x normal room background with no primary beam collimator and with the Geiger tube held directly against the shield next to the latch plate. With the 1mm primary beam collimator, the counting rate in this location is 1.5x the normal background rate in the room. Inside the dome, the rates are thousands of times greater. Since the dome is such an important shield, the required safety procedures for this experiment focus upon preventing the operation of the machine with the dome open. The primary safeguard is an interlock which turns off and discharges the high voltage supply for the tube when the dome is opened. **You are required to verify the integrity of the dome and the correct operation of this interlock at the beginning of every laboratory session with this machine. These interlocks are designed and tested to insure that you cannot receive significant exposure during these experiments. However, in the event of suspected radiation exposure, 1) turn**

the unit off, 2) inform the instructor, and 3) call radiation safety at 22057. The safety verification procedure is:

1. Inspect the dome for cracks or holes.
2. The dome must be displaced to the right or left to release a latch and permit it to be opened on the hinge at the back. The direction must be toward the side on which the arm is located unless the arm is positioned next to the latch. See Sec. 10.7 of the attached instructions.
3. Install the Geiger tube in one of the slots in the arm and position the arm at 90^o on the right. The 1mm primary beam collimator should be in place, but with no other collimators or scattering crystals in the system.
4. Determine the background counting rate (with the X-ray tube off) due to cosmic rays and residual radioactivity in the environment: Turn on the Geiger counter at 400 V and measure the counting rate with the dome open. Close the dome and repeat the measurement of the counting rate. Record these two readings as your background counting rates.
5. Post the X-ray machine warning sign on the door of the room and obtain the key for the machine from the instructor. With the key in the on position the white timer knob turns on the filament current and the "power on" light beside the tube, but no X-rays are produced until the high voltage is applied.
6. Turn on the high voltage by pressing the red plastic button light to the left of the timer knob and observe the counting rate. The difference in the rates should be very obvious. The red "X-ray on" light beside the tube will come on when the high voltage comes on. If it fails to come on and the red switch button does not stay on, the dome probably is not properly centered in its locked down position.
7. While the machine is on and the scaler is running, move the dome to the right to release the latch as if you were opening the dome, but do not open it. Verify that the red "X-ray on" light goes off and that the rate of the Geiger counter drops dramatically. **If the red light does not go out or if the counting rate does not immediately decrease to the previous level which was observed with the machine off, call the instructor and do not turn the machine back on.** Otherwise record in your notes that the safety interlock on the right does turn the machine off and proceed.
8. Repeat the previous step moving the dome to the left. You will have to close the dome, move the arm to a position near the latch, open the dome by moving to the left, and then position the arm at 90^o on the left in order to do this check. (The dome cannot be shifted from right to left while it is open.)
9. The preceding two steps verify that the safety interlocks are operating and that it is not possible to produce X-rays without having the protective dome in place.

You may, if you are concerned about the effectiveness of the shielding by the dome, remove the Geiger tube from the mount inside the dome and operate the machine with the tube held outside the dome. Since the counter just measures counts and is not calibrated in Rems, the units of radiation safety standards, you cannot make absolute radiation measurements, but you can make comparisons of natural background counting rates to rates with the machine on and thus assure yourself that the radiation with the machine on is not very different from the radiation with it off. Note however, that this ratio is still not the ratio of exposures because the relative sensitivity of the Geiger tube to very low energy X-rays decreases more rapidly than the sensitivity of a good radiation meter.

Procedure

The objective is to measure energies or wavelengths of the prominent X-ray lines emitted by copper and to determine the short wavelength cut-off of the spectrum. You are to take a complete spectrum with the 30 kV setting with point spacing judiciously chosen to measure the physics features of the spectrum. The smallest angle for the spectrometer setting is about 12°, and the short cut-off at 30 kV is below that angle. The position markers are in 1° steps and you can set the arm to about a quarter of the spacing if you avoid parallax in reading the setting. It is better to take points as you increase the angle rather than coming back later to fill in because the sensitivity of the counter may drift slightly with time. The detailed procedure is:

1. Show the structure of the continuous spectrum by taking data in 2° steps at small angles out to about 40° and in larger steps at larger angles where the continuous spectrum is nearly flat. As you increase the angle, you will find pairs of lines at about 30°, 60°, and 100°. These are the first, second, and third order diffraction peaks of the copper K_β and K_α lines. You want to find the centers of these lines, so you will need to take closely spaced points near the peaks, at 0.25° intervals. Ten second runs provide adequate statistics for each point.
2. Turn off the key, open the lid and set the red switch to 20 kV. Explore the detailed shape of the spectrum in the 12° to 20° region to find the short wavelength cut-off. There is a background of X-rays which are scattered by air, so the threshold shows up as a kink rather than going to zero. The rates are low here and you will need 100 second data taking periods in order to obtain adequate statistics.
3. Verify that the positions of the peaks in the 30 kV spectrum are properties of the copper anode material rather than of the accelerating voltage by showing that the peaks are located at the same angles with the 20 kV setting as in the previous spectrum. A few points at the locations of the peaks in the previous spectrum should enable you to make this point convincingly and 10 second data periods are adequate.

Report

Your report should include a plot of the spectrum you measured at 30 kV and the points you measured near the peaks at 20 kV. The error in the number of counts at a point is the square root of the number of counts and errors should be shown on a few typical points. Note the best estimate of the angle at each of the six peaks and calculate the wavelength of the X-ray at each peak. The Bragg formula for the diffraction peaks is:

$$n \lambda = 2 \, d \sin\theta$$

where n is the order, d is the crystal plane spacing (0.282 nm for NaCl), and θ is the angle between the incident beam and the plane of the crystal. Note that the crystal rotates through half the angle of the detector, so your measurements are 2θ. Combine your three measurements of each X-ray line to obtain your best estimate of the wavelength. The first order is so narrow that it is difficult to position the spectrometer with sufficient accuracy. How should you combine your measurement for the best estimate of each line?

Make a separate plot of the 20 kV data near the cut-off and make your best estimate of the wavelength and energy of the X-ray at this limit. How does it compare with the nominal 20 kV accelerating voltage applied to the tube?

The wavelength of lines emitted from hydrogen-like (*ie.* stripped of all but one electron) atoms is given by the Bohr formula:

$$\frac{1}{\lambda} = RZ^2\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

where R is the Rydberg constant, $1.097 \times 10^7 \mathrm{m}^{-1}$, Z is the atomic number of the element, and the n's are the principal quantum numbers of the initial and final states. Use your best estimates of the wavelengths of the K_α and K_β lines to calculate the Rydberg constant from each line. In fact the K-lines you observe are not from atoms stripped of all but one electron but are transitions to a vacancy in a n=1 state which was produced by a collision with an electron which has been accelerated across the tube. The other n=1 electron is very close to the nucleus and appears to be part of the nucleus from the perspective of the electron which will fall into this vacancy in the n=1 orbit. The other electrons are effectively a uniform shell of charge outside this electron and do not contibute to the electric field acting on the electron in transition. Thus one usually uses $Z - b$ instead of Z for the effective nuclear charge of the nucleus, where b is an empirically determined constant that is approximately one. Would your value of R be improved by this correction with b=1? Alternatively you may assume the value of the Rydberg constant and compute the effective charge of the copper nucleus.

Plotting Errors with EXCEL

Jessica L. Hodges, Feb 10 2001

How to Include Error Bars on a Graph in Excel

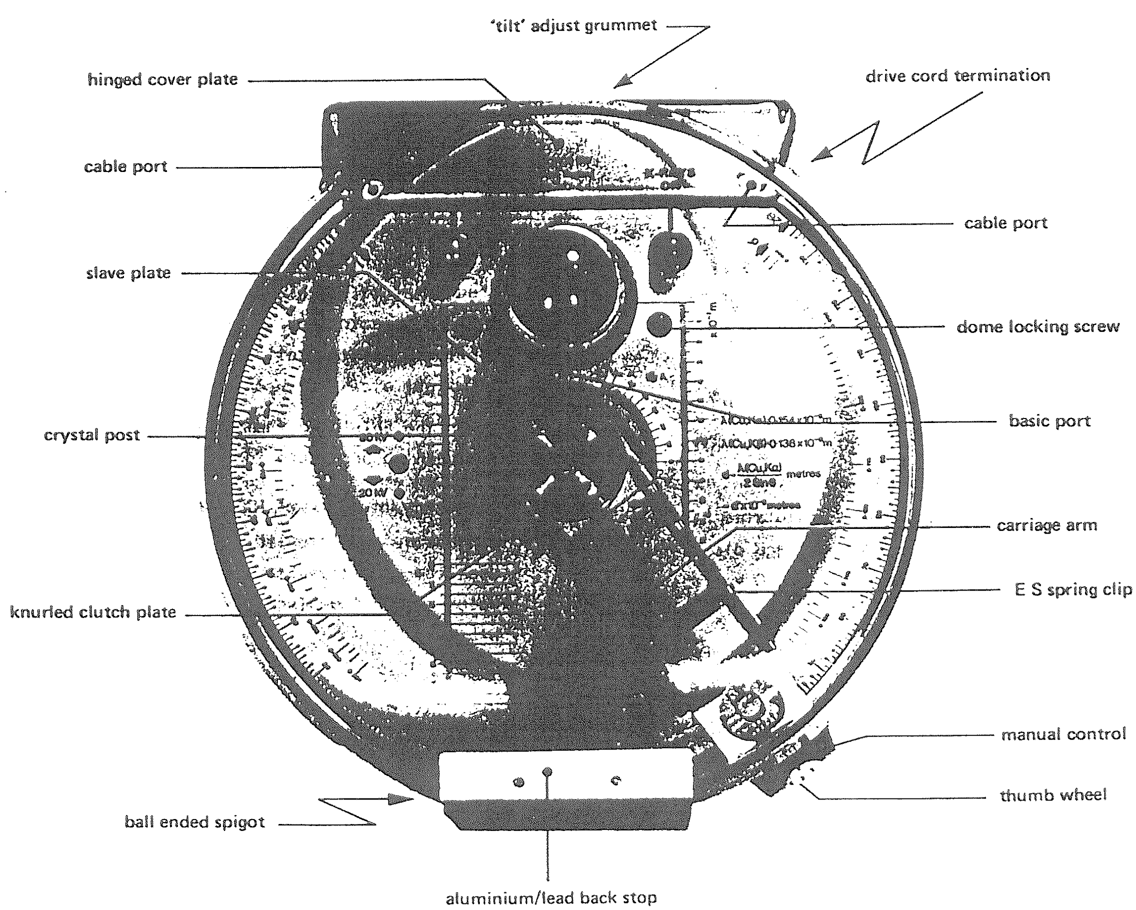
After you make your graph, type the error values you want included on the graph in a column. Right click on one of the points on the graph. Choose format data series. At the top, switch to the tab called Y error bars (or X error bars). Under display, choose Both. Then under error amount choose custom. Highlight the error values column you entered and that will become the + error. It will look something like t1!$C$53:$C$65 . Copy this into the - error box. Click ok.

THE TEL-X-OMETER, TEL. 580

PART 1 : INSTRUCTION MANUAL.

PARA

FIGURE



IF THE PEAK OF THE REFLECTION LIES OUTSIDE THIS TOLERANCE
THEN THE X-RAY TUBE SHOULD BE ADJUSTED FOR 'TILT' AS IN PARA. 14.

Now record the equivalent reflection on the opposite side of the table.

13.9 Return the Carriage Arm to about 12° (2θ) and open the Shield by displacing it <u>away</u> from the arm.

13.10 Unscrew the Clutch Plate, rotate the Slave Plate (and thereby the Crystal) through 180° and again zero-set the Slave Plate and the Carriage Arm as precisely as possible.

13.11 Repeat stages 13.5 to 13.8 and record the 2θ angle of the peak CuKα reflection.

13.12 The Mean Reading of the reflections recorded at 13.8 and 13.11 should be 44° 56' ± 12'.

WHEN MAKING ACCURATE ANGULAR MEASUREMENTS EXPERIMENTAL ERRORS SHOULD BE MINIMISED BY EMPLOYING THIS TECHNIQUE OF TAKING A MEAN OF THE EQUIVALENT READING AT EACH SIDE OF THE SPECTROMETER TABLE.

13.13 The Tel-X-Ometer is now commissioned and certified as capable of measuring angular deflections (2θ) to an accuracy of ± ½%.

Before proceeding with this adjustment carefully repeat both paras 12 and 13 to ensure that no alignment errors have been introduced.

14.1 Remove the upper black rubber grummet located just below the hinge extension.

The screw-head thus exposed controls the "tilt" of the X-ray tube about a central position.

14.2 Set the cursor of the Carriage Arm at the exact mean of the reading measured at para. 13.8 and the true Bragg angle (2θ) for LiF of 44° 56'.

14.3 Obtain a peak count rate by carefully adjusting <u>ONLY</u> the 'tilt-control' without displacing the Carriage Arm.

14.4 Now seek and record a peak reflection by displacing the Carriage Arm only, without operating the tube tilt-control.

14.5 Set the cursor at the exact mean of the reading measured at para 14.4 and the true Bragg angle 44° 56' (2θ).

14.6 Iteratively repeat paras 14.2, 14.3 and 14.4 until the cursor peak reading falls within the tolerance 45° ± 30'.

14.7 Replace the black rubber grummet and carry out recommendations 13.9 to 13.12.

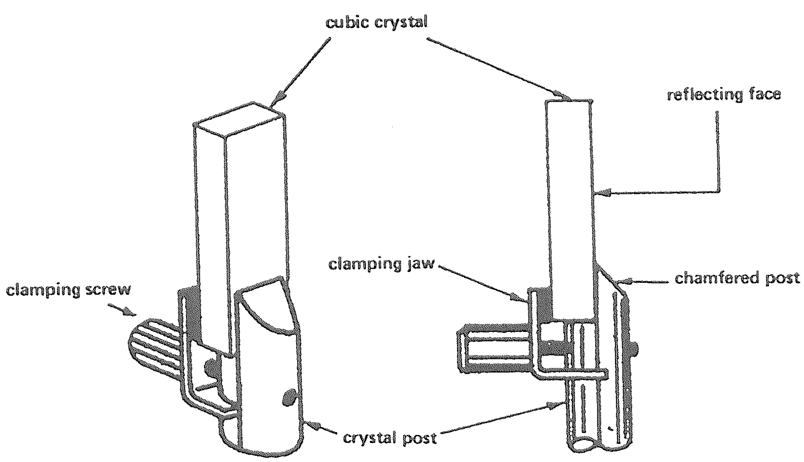


FIG. 2 MOUNTING OF CUBIC CRYSTALS

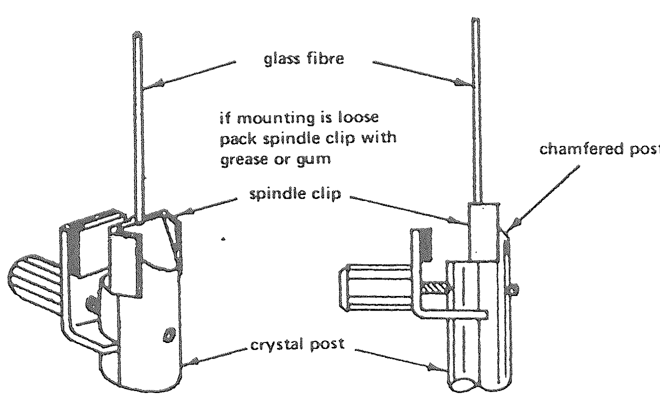


FIG. 3 MOUNTING OF GLASS FIBRES

14 – WAVELENGTH MEASUREMENT: BRAGG METHOD (1½ HOURS)

ir Lawrence Bragg presumed that the atoms of a crystal such s Sodium Chloride were arranged in a cubic and regular hree-dimensional pattern.

he mass of a molecule of $NaCl$ is M/N Kg, where M is the o ar weight (58.46×10^{-3} kg per mole) and N is vogadro's number (6.02×10^{23} molecules per mole).

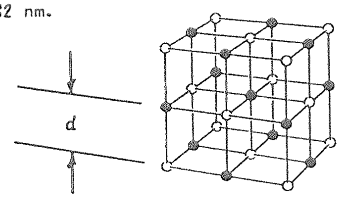
he number of molecules per unit volume is $\rho/\frac{M}{N}$ molecules er cubic metre, where ρ is the density (2.16×10^3 kg m^{-3}).

ince $NaCl$ is diatomic the number of atoms per unit volume s $2\rho N/M$ atoms per cubic metre.

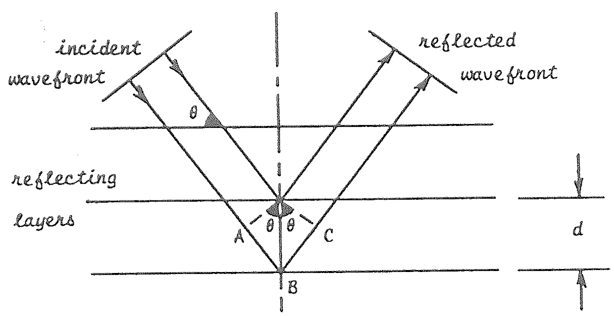
he distance therefore between adjacent atoms, d in the attice is derived from the equation

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

nd for $NaCl$, $d = 0.282$ nm.



The first condition for Bragg "reflection" is that the angle of incidence θ equals the angle of reflection – this is as for optical reflection and infers that any detector of the reflected rays must move through an angle 2θ, the 2:1 spectrometer relationship.



The second condition is that reflections from several layers must combine constructively :-

$$n\lambda = AB + BC = 2d \sin\theta$$

KIT 582	30/20 kV	50 μA	NORMAL LAB

D14.1 Mount the $NaCl$ crystal, TEL 582.004, in the crystal post (see Part I, para 10.9) ensuring that the major face having "flat matt" appearance is in the reflecting position (see Para D27.30).

D14.2 Locate Primary Beam Collimator 582.001 in the Basic Port with the 1mm slot vertical.

D14.3 Mount Slice Collimator (3mm) 582.016 at E.S.13 and Collimator (1mm) 582.015 at E.S.18.

D14.4 Zero-set and lock the Slave Plate and the Carriage Arm cursor as precisely as possible (see Part I, para. 10.6).

D14.5 Sight through the collimating slits and observe that the primary beam direction lies in the surface of the crystal.

D14.6 Mount the G.M tube and it's holder at E.S.26.

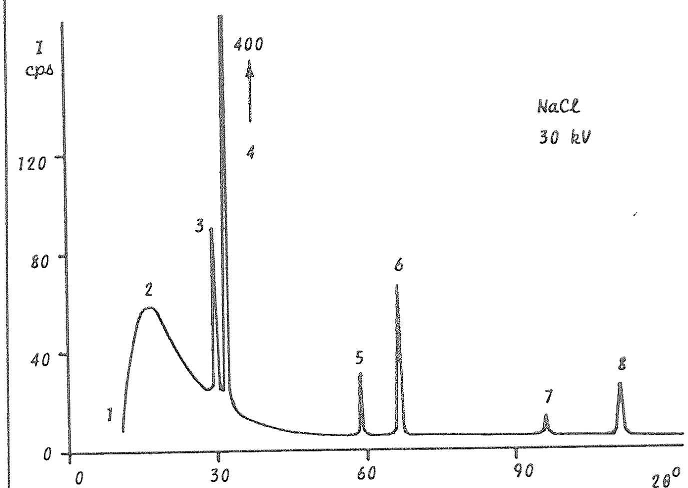
D14.7 Using a Ratemeter track the Carriage Arm round from it's minimum setting (about 11°, 2θ) to maximum setting (about 124°, 2θ).

Plot on graph paper the count rate per second at 1° (2θ) intervals, allowing time at each reading to estimate the mean of the fluctuations of the needle.

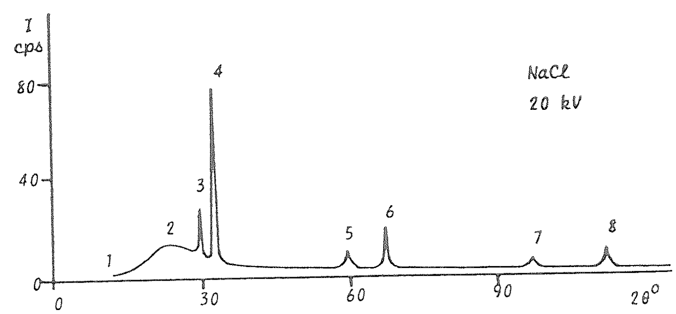
The Carriage Arm should be indexed to 15° (2θ) and the thumb wheel set to zero; when the Scatter Shield is closed, settings from 11° to 19° can be achieved using only thumb-wheel indications.

If the ratemeter has a loud speaker, note the random "quantum" nature of the beam of radiation at low count rates.

Where the count rate appears to peak, plot intervals of only 10' arc using the thumb-wheel (see Part I, para 10.8); at each peak, measure and record the maximum count rate and the angle 2θ as precisely as possible.



D14.8 Select 20kV and repeat D14.7.



Observe that the continuous spectra of "white" radiation exhibit peak intensities (feature 2) and intercepts on the 2θ axis (feature 1) which only vary with the voltage setting of the X-ray tube.

The six peaks, features 3 to 8, superimposed on the continuous spectrum do not vary in angle 2θ with voltage setting, but only in amplitude.

D14.9 Tabulate the results from the six superimposed peaks of the graph and calculate λ and n.

Feature	2 θ	θ	sin θ	2 d	n λ	n
3				0.564		
4				0.564		
5				0.564		

Observe that the sharp peaks are a pair of "emission lines" which re-appear in second and third orders of diffraction.

The more energetic radiation, termed Kβ, is successively less intense than the longer wavelength, Kα, line.

In the absence of micro-gratings, the "reasonable argument" was formulated by Sir Lawrence Bragg that the NaCl crystal could be used as a 3-dimensional grating which would reveal diffraction information by means of which the wavelength of the primary radiation could be established; but in the second sentence of D14 a bland assumption is made for Avogadro's number. If, however, the wavelength of the radiation is obtained by using a man-made grating, as in D13 then a contemporary approach is to reverse the sequence of the Bragg argument to provide an accurate evaluation of Avogadro's number.

Whichever didactic sequence is adopted, the Bragg experiment verifies that the incident radiation is both electromagnetic and heterogeneous and that co-operative interference can be induced using a crystal as a diffraction grating.

The crystal itself cannot be considered as the source of the 'dual' spectrum due to photon bombardment; the continuous spectrum is modified in both minimum wavelength and general intensity only by changing the X-ray tube accelerating voltage, without any variations in crystal parameters; the "emission lines" are particularly discreet in angle (2θ) whereas radiation from the crystal due to photon bombardment would be multi-directional.

The radiation must be derived through some "inverse photo-electric effect" from the impact of the thermionic electrons on the Copper target within the X-ray tube.

D15 — X-RAY EMISSION (1¼ HOURS)

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 ; 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 (or maximum energy) being determined by the accelerating voltage of the tube.

$$\lambda_{min} = f(\tfrac{1}{V}) \quad \text{or} \quad V\lambda_{min} = k$$

where V is the X-ray tube voltage selected.

D15.1 Minimum Wavelength, Planck's Constant.

KIT 582	30/20 kV	80 μA	NORMAL LAB

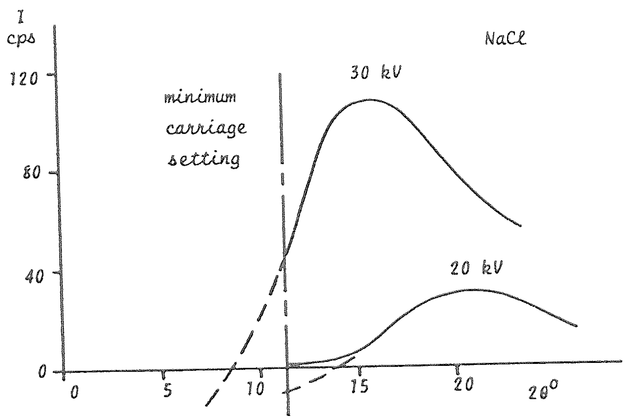
An accurate determination of the minimum wavelength intercept on the x-axis requires that the Ratemeter be replaced by a Scaler; counts should be recorded ... counting period the greater the accuracy of the results.

D15.2 Mount the auxiliary slide carriage in Mode H (see Part I, para 10.4) using the 1mm slot Primary Beam Collimator, vertical.

D15.3 Position the Slide Collimator, (1mm slot) 562.015 at E.S.4 and Slide Collimator (3mm) 562.016 at E.S.13.

D15.4 With the *NaCl* crystal mounted as in 14.1, set up as for 14.4, 5 and 6; select 30kV.

D15.5 Measure, tabulate and plot the count rate at every 30' arc, commencing at 11°, 30', until the "whale back" appears to fall off.

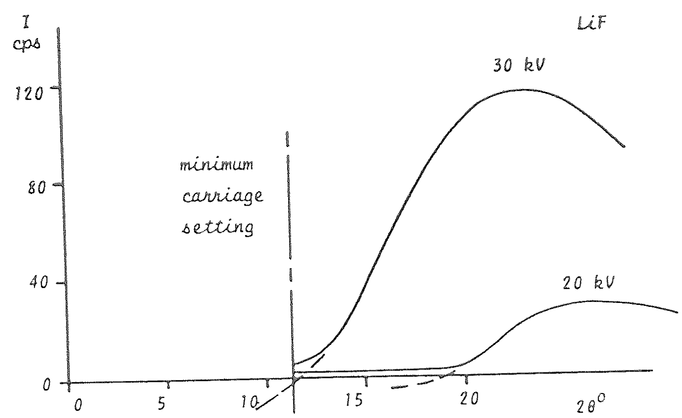


D15.6 Repeat for 20kV.

Observe that the minimum setting of the Carriage Arm requires an extended extrapolation of the 30kV curve to obtain and intercept on the x-axis ; curves of similiar nature can be drawn for the *KCl* and the *RbCl* crystals.

With *LiF* however a more precise intercept can be plotted.

D15.7 Replace *NaCl* crystal by the *LiF* crystal, zero set and repeat 15.5 and 15.6.



Observe that the curves flatten out before intercepting the axis, due to the contribution of the general background radiation.

D15.8 Extrapolate the theoretical intercepts and tabulate the results:

Crystal	*V*	*2θ*	*θ*	*sin θ*	*2d*	*λ* nm	*V λ*
NaCl	*30 kV*				*0.564*		
NaCl	*20 kV*				*0.564*		
LiF	*30 kV*				*0.403*		
LiF	*20 kV*				*0.403*		

If the theory of the "inverse photoelectric effect" is valid then Einstein's assumption of 1905, that both emission and absorption are "quantised", must be tested in relation to Planck's formula for photo-electron emission

$$w = h\nu \text{ joules}$$

where w is the energy associated with each quanta, ν is the frequency of radiation and h is Planck's constant.

Since $\nu = c/\lambda$ for electromagnetic radiation where c is the velocity of light, and $w = Ve$, the maximum energy that can be acquired by any electron within the X-ray tube system, then

$$Ve = hc/\lambda \quad \text{or} \quad h = V\lambda\left(\frac{e}{c}\right).$$

D15.9 Calculate the mean value for $V\lambda$ from D15.8 and evaluate h.

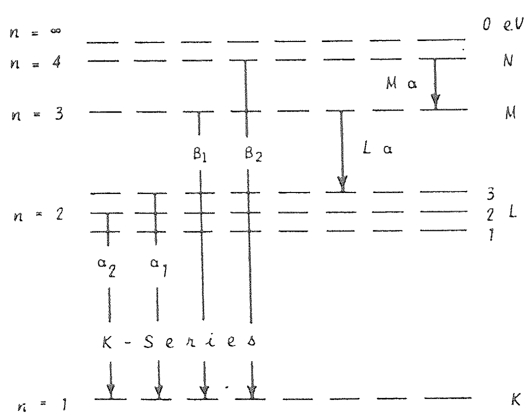
($e = 1.60 \times 10^{-19}$ coulombs ; $c = 3.00 \times 10^{8}$ m sec^{-1})

Compare with the international value for h of

$$6.62 \times 10^{-34} \text{ joule-sec}$$

The difference between the accepted standard value and the evaluated result for h of about 5% is well within experimental limits and illustrates why the 'inverse photo-electric effect' is considered to be a very accurate method of determining h, the fundamental constant in the Quantum Theory.

It is assumed that previous studies of optical spectra have established that "characteristic lines" in the visible region of the electromagnetic spectrum are emitted from atomic energy-levels of high principal quantum number, the O, P and Q levels; the relatively much shorter wavelengths of the characteristic Kβ and Kα lines indicate that these shorter emissions are due to electron transitions at energy-levels of low principal quantum number. Any electron from the X-ray tube filament having sufficient energy to eject a K electron in a collision process will ionise the Copper atom; the ionised atom will revert to it's stable state through electron transitions, each transition being accompanied by the emission of a photon of equivalent energy.



By definition, the Kβ emission results from transitions from the N and M levels to the K level and Kα from transitions from the L to the K level (see para. D19); the N and M levels have greater energy difference with respect to the K level than does the L level and hence the wavelength of the Kβ photon is shorter and more energetic than that of Kα. But the closer proximity of the L and K levels results in more frequent transitions than for the N or M levels and hence there is a greater "population" of Kα exhibited by the relative intensities of the peaks 3 and 4 of graphs D14.7 and 8. (See also

The Bragg experiment has established that a crystal can be used to demonstrate the co-operative interference of X-rays; the wavelength limit of the continuous "white" spectrum is dependent uniquely on the energy imposed upon the electrons by the potential difference between the electron emitting filament and the anode, regardless of it's material; the "characteristic" line spectrum, superimposed upon the white spectrum is due to the elemental composition of the anode and the energy-levels associated with it's individual electron system.

The lines are unique to emission from a Copper target and are thus termed CuKβ and CuKα emission lines.

Spectral analysis by the Bragg technique can accurately evaluate a) an unidentified voltage, using both a known crystal and anode material, b) an unknown crystal structure using an identified voltage and anode material and c) the chemical composition of a material serving as an anode to emit characteristic radiation, using an established crystal and an accurately defined voltage.

The process of X-ray emission is such that the wavelength may well overlap both the ultra-violet and the Gamma regions of the broad electromagnetic spectrum; in the "Teltron Approach to Atomic Physics" the phenomenon of Gamma radiation has yet to be studied.

By its mode of emission X-radiation is therefore defined, through the "inverse photoelectric effect", and not by wavelength; "ultra-violet" radiation results from classical photoelectric events and "Gamma" radiation from nuclear disintegrations.

However, consequent upon the similarities between diffraction of optical and X-ray wavelengths, the student will surely anticipate 'absorption' effects in X-ray, as in optical, spectra.

D16 — X-RAY ABSORPTION (1 HOUR)

KIT 582	30 kV	80 μA	NORMAL LAB

D16.1 Locate the NaCl crystal in the crystal post as in 14.1.

D16.2 Mount the Auxiliary Slide Carriage in Mode H (see Part I, para 10.4) using the 1mm slot Primary Beam Collimator, vertical. Locate the Slide Collimator (3mm slot) 562.016 at E.S.4.

D16.3 Position Slide Collimator (1mm) 562.015 at E.S.18 and the G.M. Tube Holder assembly at E.S.26; connect the G.M. Tube to a Scaler; due to the low count rates of this experiment, counts should be recorded over at least 10 second durations; the longer the counting period the greater the accuracy of the results; it is also advisable to monitor the tube current and adjust as necessary to 80 μA.

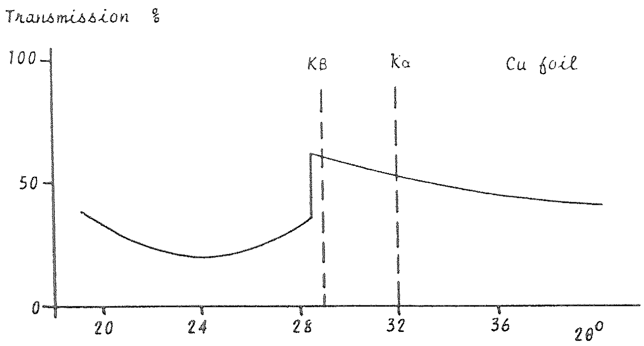
Ensure that 30kV is correctly selected.

D16.4 Tabulate counts, I_0 from 20° (2θ) to 40° at 1° intervals.

$2\theta^{\circ}$	I_c cps	I_{cu} cps	I_{cu}/I_o %
20			
21			
22			

D16.5 Locate the Copper Filter 564.006 at E.S.2 and tabulate counts I_{cu}.

D16.6 Calculate the ratio I_{cu}/I_0 and plot as a Percentage Transmission against angle 2θ.



Observe that the whole spectrum has been reduced in intensity but that the expected "self-reversal" of the Kβ and Kα lines is not evident; a very abrupt discontinuity is revealed however at a wavelength just shorter than the Kβ line.

D16.7 From the graph, determine the angle 2θ at which this discontinuity occurs and calculate the equivalent wavelength in accordance with the Bragg equation:

$$\lambda = 2\,d\,\sin\theta$$

The Copper Foil interposed at E.S.2 has a finite thickness, 12.5 x 10^{-6} metres and, applying the Linear Absorption Co-efficient as studied at D10.14 some absorption of the spectrum must be expected.

That Copper does not 'reversibly' absorb it's own characteristic emission lines Kβ and Kα is in agreement with the theory outlined in the comments following D15.9. To ionise an atom of the Copper target in the tube any electron from the filament must have sufficient energy to liberate an electron in the K level or indeed the L level for Lβ or Lα emission not detectable with the compact geometry of the Tel-X-Ometer. Thus, in hypothetical terms:

$$W_o \geqslant W_{k \to \infty} = -10 \times 10^3 \text{ eV}.$$

Following an M to K electron transition a Kβ photon is emitted having energy $W_{m \to k}$ or -9.9 x 10^3 eV (ie -10,000 + 100 eV); there is therefore a relatively small energy difference of 100 eV.

The discontinuity occurs at a wavelength of 0.138 nm (from D16.7) which is just shorter in wavelength than the Kβ emission (about 0.140 nm from D14.9) and it is evident therefore that a "classical photoelectric effect" has occurred wherein some photons in the primary X-ray beam have sufficient energy to ionise the Copper atoms in the foil placed at E.S.2.

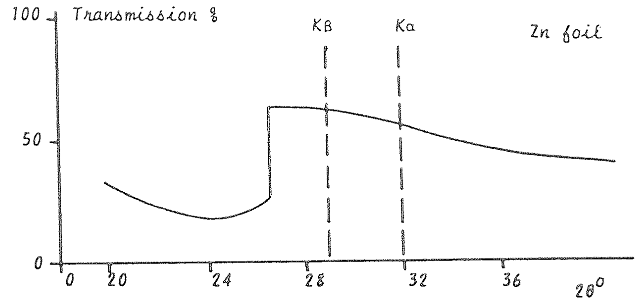
Furthermore, the value of the wavelength indicates that the incident photons must be a component part of the "white" radiation; the inference is therefore that the Copper foil will exhibit the "absorption edge" when exposed to radiation containing energies equivalent to 0.138 nm, regardless of the material of the source.

The discontinuity is thus unique to the system and is referred to as the CuK Absorption Edge.

Since the elements in the periodic table have different energy-level structures and densities the student could now expect to find an element which will discreetly absorb Copper K emission by a systematic study using foils of different elements, but equal thickness.

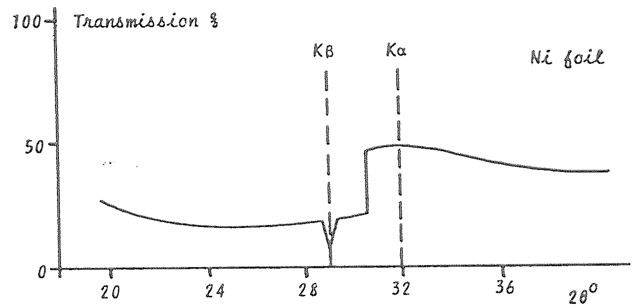
D16.8 Remove the Copper Filter from E.S.2 and replace with the Zinc Filter 563.009.

Repeat 16.5, 16.6 and 16.7.



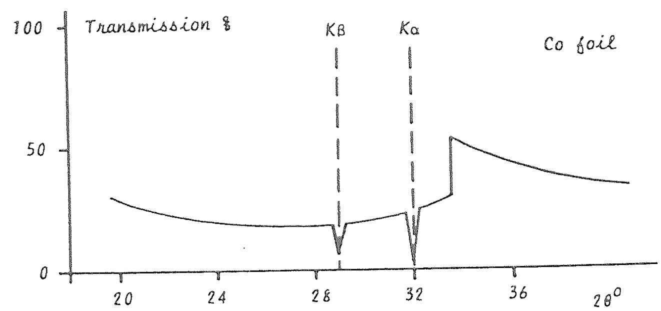
D16.9 Remove the Zinc Filter and replace with the Nickel Filter 564.004.

Repeat 16.5, 16.6 and 16.7.



D16.10 Remove the Nickel Filter and replace with the Cobalt Filter 564.008.

Repeat 16.5, 16.6 and 16.7.



Observe that only the Cobalt Foil has absorbed or "filtered out" both the CuK emission lines but that Nickel has dramatically discriminated between the Kβ and Kα radiation.

Clearly the absorption of X-rays is dependent not only on the thickness of the absorbing material but also on the nature of the material itself.

The Linear Absorption Co-efficient is not therefore sufficiently definitive for X-ray purposes, especially with thin foils where the effect due to the material is greater than that due to thickness.

RADIATION SAFETY PRECAUTIONS AND INFORMATION

Received Dec 88,

1. Exposure to the beam and to scattered radiation must be prevented as far as this is practicable.

2. General principles, beam alignment:
   a. Energize the equipment for the minimum time necessary and at the minimum current and voltage that are practicable.
   b. Use temporary shielding when necessary.
   c. Use long handled tools to make adjustments with hands out of regions where the dose rate is high.

3. Personnel monitoring badges will be issued by the Radiation Safety Office. A body badge should be worn at all times when operating x-ray equipment to indicat the general level of scattered radiation. If a ring badge is issued, it should be worn especially during alignment procedures. Exposure of an individual to the primary beam or narrow beams of scattered radiation may not be recorded on the monitoring badge because of the low probability of the badge intercepting such a small beam. Thus, a low badge reading is not assurance that no exposure has been received.

4. Maximum Permissible Doses

	Rems/Quarter
Whole Body; lens of eyes or gonads	1.25
Skin of Whole Body	7.5
Hands and Forearms	18.75

5. X-ray beam intensities can be as high as 6,000 R/sec at a distance of 5 cm.

6. Clinical symptoms of overexposure. Surveys have indicated that about every 30th unit has been involved in accidents resulting in clinical symptoms.

Of the nine persons with clinical symptoms in Pennsylvania, only two were initially recognized as suffering from radiation injuries. In two cases no explanation was ventured until a more thorough investigation had been carried out, but in five cases it was initially believed that there was some other cause of the injury. For three persons this was believed to be an infection, and for two persons the injury was thought to have resulted from metal splinters.

It therefore seems important that hospitals and physicians that may be consulted be made aware of the possibility of this type of injury and learn the symptoms.

The "typical" clinical picture of the injury that follows a high radiation dose to a finger starts with an erythema developing 1–3 weeks after the exposure (or even after 1 day at very high doses), followed by ulceration in the more severe cases. This primary injury may become completely healed during the first months. During the following months an atrophy of the skin may be observed. After perhaps a year, in connection with irritation (e.g. exposure to the sun), blisters may appear and non-healing ulceration may follow. In such cases it may be necessary even to amputate the finger. This is a likely development at radiation doses exceeding 10,000 rads, while a dose of less than 5000 rads usually has no severe consequences. However, the estimate of the radiation dose after an accident is usually very uncertain, as the information on exposure time and distance may not be very reliable. The estimate is particularly difficult if the exposed hand has been moved during exposure to a very narrow beam.

The data in the table are too scant to permit any firm conclusions, but it is interesting to note that of the eight persons having severe injuries, as many as seven were exposed in exceptional operations where the equipment was de-mounted or shielding covers removed without knowledge of dangerous radiation still emanating from the tube. At least from the data available for this preliminary report, this seems to be the major risk of severe injury and

Excerpts from "Occupational Hazards in X-Ray Analytical Work," Health Physics 15, 481 (1968).

7. Some of the most common causes of unnecessary radiation exposures:

   a. Placement of fingers in the primary beam while changing samples because of failure to either block primary beam or stop x-ray production.
   b. Visual beam alignment without using a leaded glass shield.