X-RAY MEASUREMENTS

OBJECTIVES :

To study the production, properties, and uses of X-rays.

MATERIAL :

X-ray machine model "THE TEL—X—OMETER, TEL. 580."

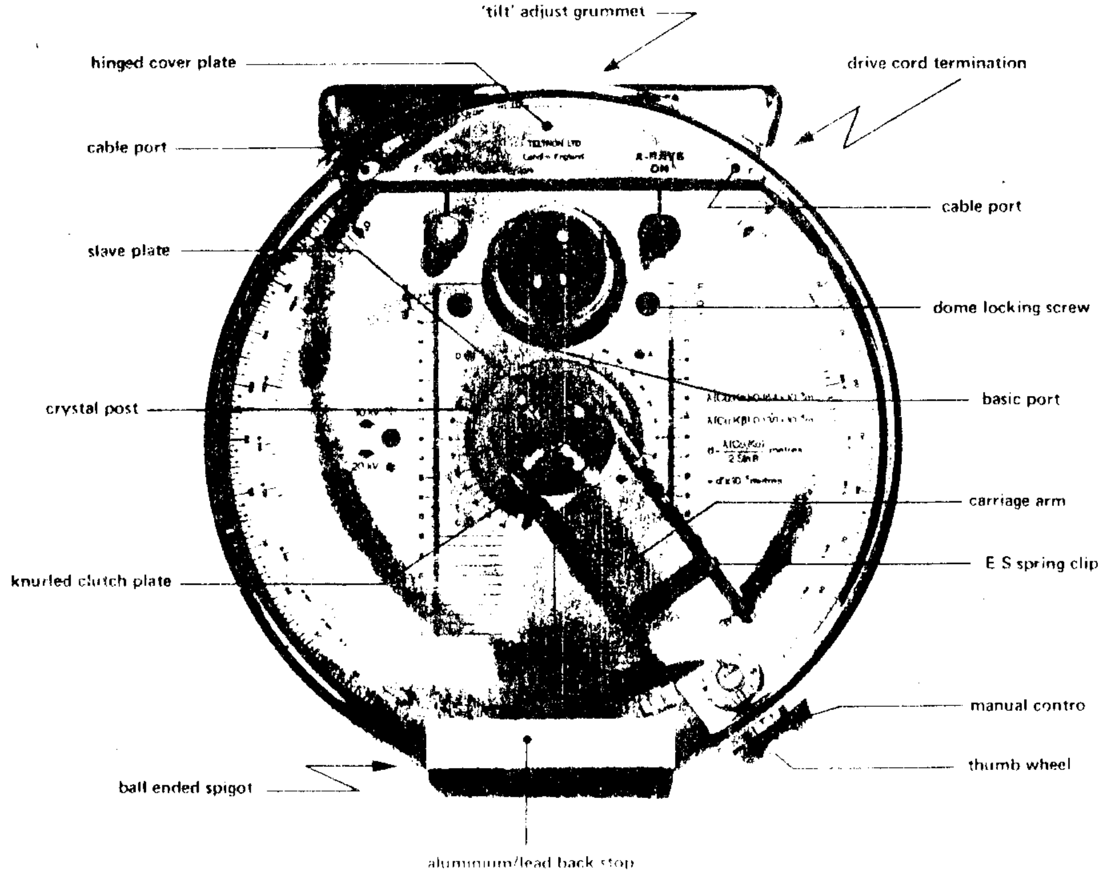


Fig. x-1 IDENTIFICATION

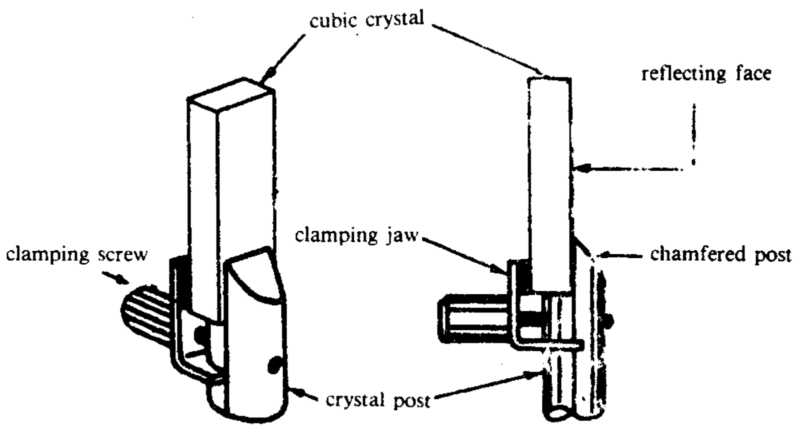


Fig. x-2 MOUNTING OF CUBIC CRYSTALS

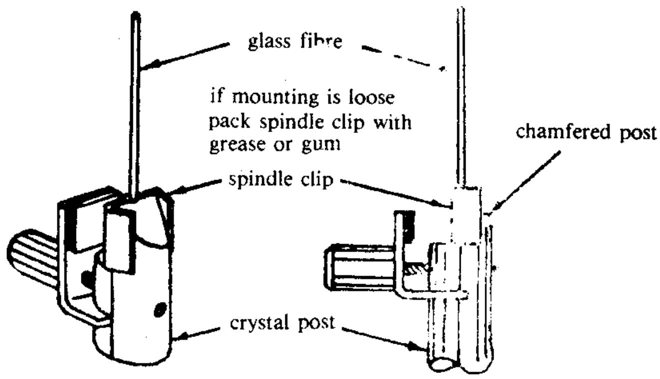


Fig. x-3 MOUNTING OF GLASS FIBRES

PROCEDURES :

D10 - PENETRATION AND ABSORPTION (45 MINUTES) ;

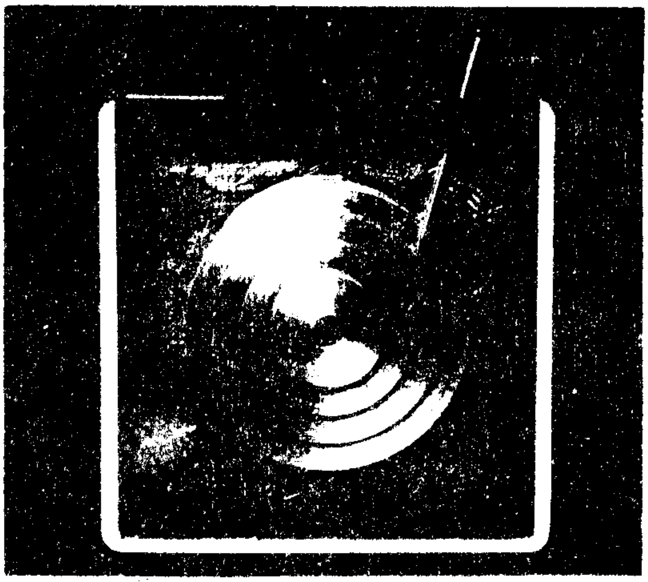
Remove Crystal Post and Jaw.

KIT 582+584	KV and μA as specified	NORMAL LAB

In the previous experiments X-rays have penetrated the glass of the X-ray tube (as does light), the black cloth, paper, cardboard and plastics ; but not the metal of the needles, the Maltese Cross, the Film Cassette Backstop and the Lead Mask.

D10.1 Place the Lead Mask 584.006 at ES.28 to expose the top right hand quadrant.

D10.2 Place Aluminium Wedge, 562.014, at E.S.29 with a pin trapped in the plastic of the surrounding slide to provide a datum on the exposed film; the datum should appear in the first exposure in the top right hand quadrant.



D10.3 Connect a 100 μA meter to the monitor tube current' jack socket and with 30kV selected, adjust the tube current to 80 μA.

D10.4 Locate Cassette 562.013 with Filmpak 750/2 at E.S.30.

D10.5 Expose to X-rays for $1\frac{1}{2}$ minutes.

D10.6 Select 20kV and rotate the Lead Mask 90 degrees to expose the bottom right hand quadrant.

D10.7 Expose to X-rays for $1\frac{1}{2}$ minutes.

D10.8 Remove the Film Cassette, select 3OkV and adjust for 40 μA tube current.

D10.9 Rotate the Lead Mask to quadrant 3, replace the Film Cassette and expose for 2 minutes.

D10.10 Repeat in Quadrant 4 with the tube current set to 60 μA and expose for 2 minutes.

The developed film reveals that X-rays can penetrate a light metal such as aluminium but the degree of penetration depends not only on the thickness of the material but also on the voltage applied to the X-ray tube; quadrants 1 and 2.

Variation in the tube current does not effect the degree of penetration but only the density of film blackening and therefore the intensity of radiation in the beam; quadrants 3, 4 and 1.

The greater the tube voltage the greater the penetration and the greater the tube current the less the exposure time for a given intensity.

D10.11 Hard and Soft Radiation

Early researchers noticed that the better the vacuum in an X-ray tube the greater the power of penetration.

The gas discharge X-ray tubes of the period, with a low order of vacuum and relatively 'gassy', were known as 'soft' tubes and discharged at relatively low voltages and conversely, tubes with a high order of vacuum were 'hard' tubes and only discharged at high voltages. X-radiation from the tubes was called 'hard' or 'soft' and these terms are still used. The higher the voltage applied to the X-ray tube the 'harder' the resultant radiation. The selection of 20 KV with the Tel-X-Ometer will result in softer radiation than that emitted at the 30 kV selection.

D10.12 Linear absorption.

KIT 583*584	30 kV	50 μA	NORMAL LAB

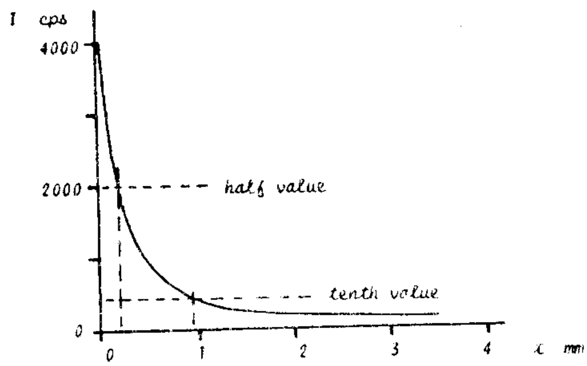
Insert the G.M. Tube, TEL 546, in the Holder, TEL 547, mount the assembly at E.S.22 and connect to a Ratemeter or Scaler.

Mount the Auxiliary Slide Carriage in Mode H using the lmm diameter Collimator 582.002; reduce the tube current until a count rate is registered of about 1,000 cps below the saturation point recorded in Experiment D4.3.

D10.13 Locate in turn the slides indicated in the following table and record the intensity of radiation (counts per second)

Slide No.	ES	Thickness mm	I cps	Log I	$Log\ I_0 - Log\ I$
562.033	4	0			——
.017	4	0.10			
.018	4	0.25			
.019	4	0.50			
.018 .019	3 4	0.75			
.020	4	1.00			
.018 .020	3 4	1.25			
.019 .020	3 4	1.50			
.018 .019 .020	2 3 4	1.75			
.021	4	2.00			
.020 .021	3 4	3.00			
.019 .020 .021	2 3 4	3.50			

D10.14 Plot Graph as illustrated.

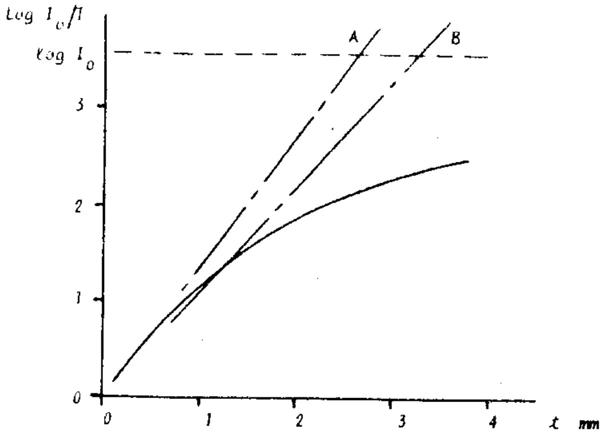


The graph is characteristic of an exponential curve where $I = I_0 e^{-\mu t}$
and μ is the linear or total absorption coefficient

$$\mu = \frac{\log I_0/I}{t}, \ m^{-1}$$

D10.15 Tabulate and plot the graph of *log* I_0/I as a function of t; if the practical curve of D10.14 is truly exponential then all points on the 'log' curve should lie on a straight line passing through zero.

Observe that this is not so and the curve has a tendency to fall away at greater values of t.



Since log (I_0/I) is smaller than the correct exponential value, then I alone must be responsible for the deviation and is larger than theory predicts; this in turn infers that the X-radiation is becoming more penetrating as it passes through the aluminium. This is only consistent with the law of conservation of energy if not just one homogeneous wavelength but a heterogeneous mixture of wavelengths comprises the primary X-ray beam. This is similar to white light and such heterogeneous X-radiation is called 'white' radiation.

The least energetic, soft radiation (longer wavelength) is progressively absorbed by the aluminium such that the mean wavelength of the transmitted beam progressively decreases; it thus appears that the quality of the radiation gets harder the deeper the penetration.

To avoid the necessity to constantly analyse the whole spectrum of the white radiation, radiographers refer to an "effective wavelength" of the heterogeneous primary beam; the "effective wavelength" is defined as that wavelength which requires the same thickness of absorbing medium to reduce the intensity to one half of that of the incident beam as does the 'white' heterogeneous beam.

D10.16 Half-Value and Tenth-Value Thickness.

From D10.14 *(I_0/I) or D10.15* (where *Log* I_0/I = *log 2 = 0.301)* the Half-Value Thickness in aluminium for 30 kV radiation is about 0.2 mm. If a theoretically exponential 'log-line', A is plotted on graph D10.15 through (0.2, 0.3010) and zero the radiation will be theoretically completely absorbed by 2.4 mm of aluminium where *log* $I = O$ and so *log* I_0-*log* I is a maximum.

Since the value 2.4 mm is seriously in error it is apparent that Half-Value Thickness is mainly of relevance to radiographers concerned with the effects of soft radiation, for example in medicine where the damage to the outer body tissues due to absorption of soft radiation is closely studied.

Radiographers concerned with hard radiation and with protection calculations more commonly use the Tenth Value Thickness where $I = I_0/10$; from graph D10.14 the Tenth Value Thickness in aluminium for 30 kV radiation is about 0.9 mm.

The straight line B through zero and the point (0.9,1.0) where $\log I_0/I = \log 10 = 1.0$ predicts that the radiation will be completely absorbed by about 3.25 mm of aluminium which more nearly approximates to practic. See also para D39.*

D14-WAVELENGTH MEASUREMENT : BRAGG METHOD (1½ HOURS)

Sir Lawrence Bragg presumed that the atoms of a crystal such as Sodium Chloride were arranged in a cubic and regular three-dimensional pattern.

The mass of a molecule of $NaC\ell$ is M/N Kg, where M is the molecular weight (58.46×10^{-3} kg per mole) and N is Avogadro's number (6.02×10^{23} molecules per mole).

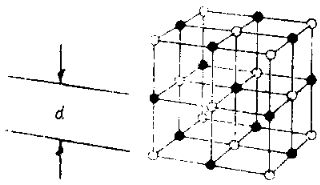
The number of molecules per unit volume is $\rho/\frac{M}{N}$ molecules per cubic metre, where ρ is the density. (2.16×10^3 kg m^{-3}).

Since $NaC\ell$ is diatomic the number of atoms per unit volume is $2\rho N/M$ atoms per cubic metre.

The distance therefore between adjacent atoms, d in the lattice is derived from the equation

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

and for $NaC\ell$, $d = 0.282$ 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.

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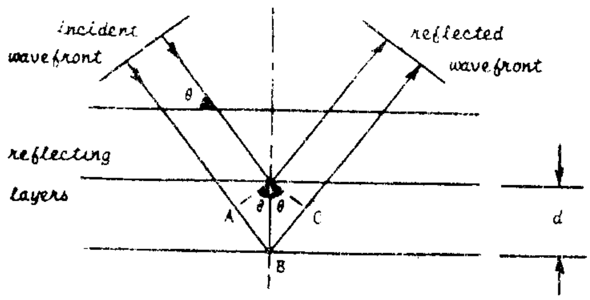
*D39 = build up factor



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 1, 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 lmm slot vertical.

D14.3 Mount Slide Collimator (3mm) 563.016 at E.S.13 and Collimator (1mm) 562.015 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 surface of the crystal.

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

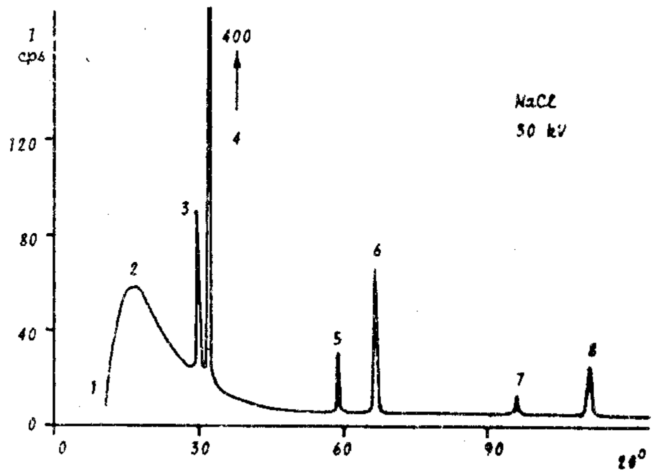
D14.7 Using a Ratemeter track the Carriage Arm round from it's minimum setting (about 11°, 2θ) to maximum setting (about 124°, 2θ).

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.

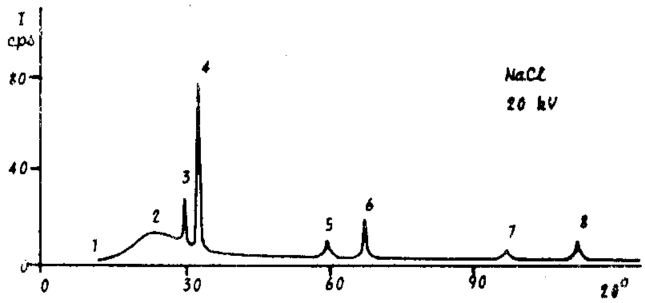
The Carriage Arm should be indexed to 15° (2θ) and the thumb wheel set to zero; when the Scatter Shield is closed, settings from 11° to 19° can be achieved using only thumb-wheel indications.

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.



DI4.8   Select 20kV and repeat DI4.7.



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 continous 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	2θ	θ	$\sin\theta$	2 d	$n\lambda$	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 $K\beta$, is successively less intense than the longer wavelength, $K\alpha$, line.

In the absence of micro-gratings, the "reasonable argument" was formulated by Sir Lawrence Bragg that the NaCℓ crystal could be used as a3-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, hawever, 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 photoelectric 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 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.*

$$\lambda_{min} = f\left(\frac{1}{V}\right) \text{ or } V\lambda_{min} = k$$

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 over at least 10 second durations, the longer the counting period the greater the accuracy of the results.

D15.2 Mount the auxiliary slide carriage in Mode H* using the lmm 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.

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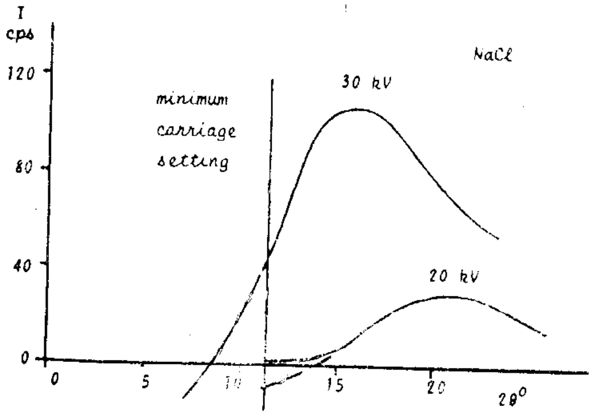
* **Mode H (Horizontal)** The hole in the end face of the Auxiliary Carriage is placed over the Basic Port in the glass dome and then held in that position by one or other of the Primary Collimators. In this mode the axis of the centre of each experimental slide is HORIZONTAL and is transcribed by the X-ray beam.

Note that the Carriage Arm is now restricted to a maximum 2θ angle of 100°

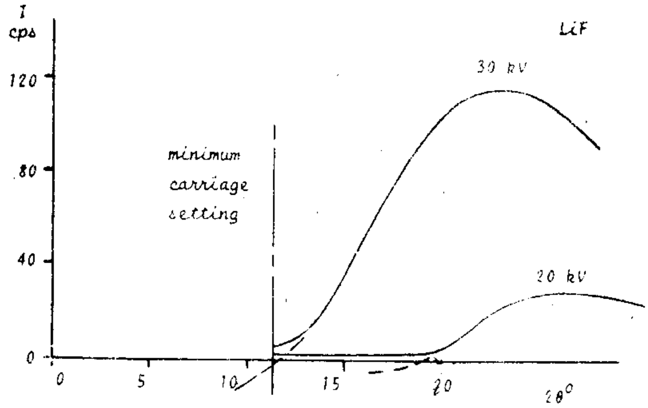


D15.6 Repeat for 20KV

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 similar 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

$w = hv$ joules

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

Since $v = c/\lambda$ *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.

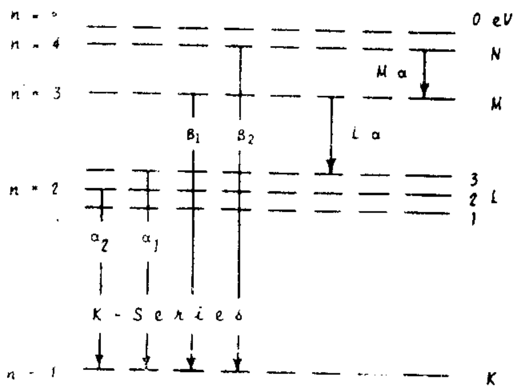
($e = 1.60 \times 10^{-19}$ coulombs ; $c = 3.00 \times 10^{8}$ m sec^{-1})

Compare with the international value for h of

6.62×10^{-34} joule-sec

The difference between the accepted standard value and the evaluated result for h of about 5 % is well with in 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 sumed 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 N, 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 law 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 a 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 para. D19.7).

The Bragg experiments has established that a crystal can be used to demostrate 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 and 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 therfore 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 students 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 post as in 14.1.

D16.2 Mount the Auxiliary Slide Carriage in Mode H (see Part 1, para 10.4) using the lmm 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.

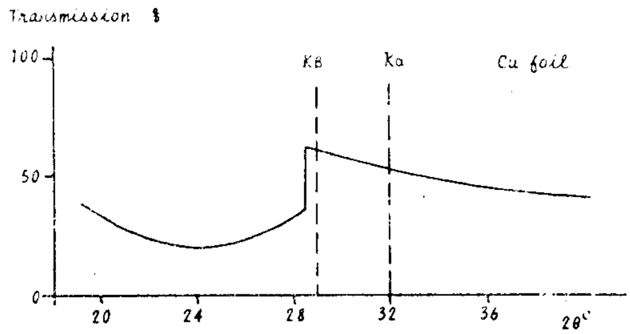
Ensure that 30 kV is correctly selected.

D16.4 Tabulate counts, I_o from 20^0 (2θ) to 40^0 at 1^0 intervals.

$2\theta^0$	I_o 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_o 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, 12.5×10^{-6} *metres and, applying the Linear Absorption Coefficient 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 :*

$$w_o \geqslant w_{k \to \infty} = -10 \times 10^3 \ eV.$$

Following an M to K electron transition a Kβ *photon is emitted having energy* $w_{m \to k}$ or -9.9×10^3 *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 occured 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.

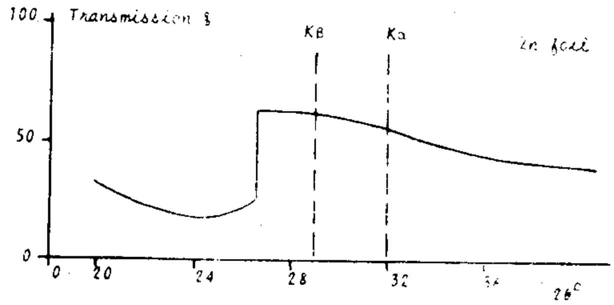
Furthermore, the value of the wavelength indicates that the incident photons must be a component part of the "white" radiation ; the inference is therefore that the Copper foil will exhibit the "absorption edge" when exposed to radiation containing energies equivalent to 0.138 nm, regardless of the material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

The discontinuity is thus unique to the system and is refered 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.

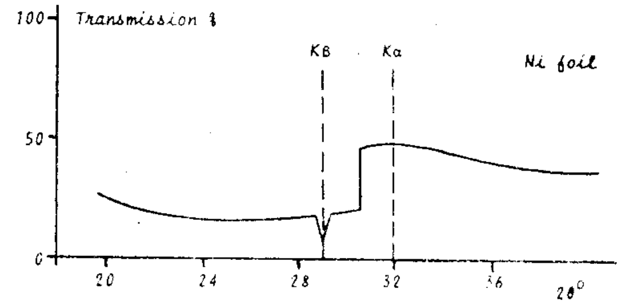
D16.8 Remove the Copper Filter from E.S.2 and replace with the Zinc Filter 563.009.

Repeat 16.5, 16.6 and 16.7.



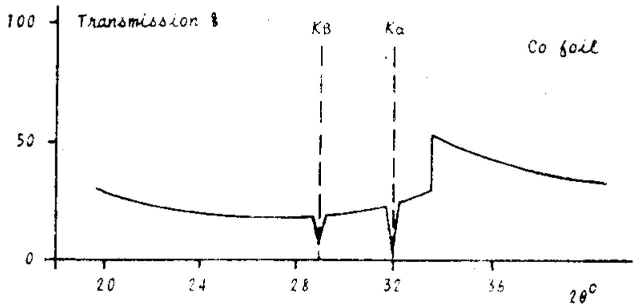
D16.9 Remove the Zinc Filter and replace with the Nickel Filter 564.004.

Repeat 16.5, 16.6 and 16.7.



D16.10 Remove the Nickel Filter and replaces 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 $K\beta$ and $K\alpha$ 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.

The thickness t is related to the material itselt by the equation $t = m/\rho$ per unit area, where m is the mass and ρ is the mass densily of the material.

D16.11 The equation for the Absorption Co-efficient can therefore be re-written

$$I = I_0 e^{-\mu m/\rho} \quad \text{or } \mu/\rho = \frac{\text{Log } I_0/I}{m} = \mu_m,\ m^2\ kg^{-1}$$

μ_m is defined as the Mass Absorption Co-efficient

On examination of the transmission graphs drawn during the experiment, it is apparent that μ_m is dependent not only on mass but also on wavelength ; where an absorption edge occurs two values of μ_m a maximum and a minimum, are defined for the particular wavelength.

The student may determine the maximum and minimum Mass Absorption Co-efficients from the graphs for each absorption edge but due to the relatively broad width of the beam, accounting also for the lack of linearity in the practical curves, the results will bear little relationship to published standards.

The experiments have demonstrated that Characteristic Radiation is only emitted when the energy of the incident photon or electron equals or exceeds that of the Characteristic Absorption Edge.

Conversely if an Absorption Edge is observed there must be X-radiation present which is characteristic of the absorbing material ; this radiation will "fluoresce" indiscriminately in all directions, but the wavelength of this "secondary emission" will always be slightly longer than that of the incident radiation.

D16.12 Set up for Bragg Reflections as in D14.1 to 7. Without Plotting the results on paper, insert each of the 4 filters at E.S.14 and observe the effect on count rate at features 3 and 4.

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