EXPERIMENT 10

The X-ray Experiment

METHODOLOGY:

Theoretical Background.:

Wilhelm Röntgen discovered x-rays in 1895, and in 1901 he was awarded the very first Nobel Prize in physics for this discovery. X-Rays are invisible, highly penetrating electromagnetic radiation of a much shorter wavelength (higher frequency) than visible light. The wavelength range for X rays is from about 10^{-8} m to about 10^{-11} m,
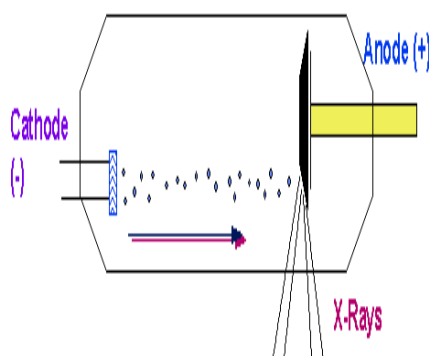

Fig.1

X rays are produced in a highly evacuated glass bulb, called an X-ray tube, see fig.1, that contains essentially two electrodes—an anode made of platinum, tungsten, or another heavy metal of high melting point, and a cathode. When a high voltage is applied between the electrodes, streams of electrons (cathode rays) are accelerated from the cathode to the anode and produce X rays as they strike the anode. Two different processes give the rise to radiation of X-ray wavelength. In one process radiation is emitted by the high-speed electrons themselves as they are slowed or even stopped in passing near the positively charged nuclei of the anode material. This radiation is often called *brehmsstrahlung* [braking radiation].If an electron passes *very close* to a nucleus it can be accelerated so much that it gives out all its energy in one quantum. Therefore this is the biggest quantum (shortest wavelength) x ray emitted, see fig.2. The minimum wavelength therefore depends on the accelerating voltage. If the accelerating voltage U Is increased the minimum wavelength of the radiation decreases.

$$\lambda_{min} \sim 1/\,U \quad \ldots\ldots\ldots\ldots(1)$$
$$(\text{where } \lambda_{min} = c\,/\,\nu_{max})$$
$$E_{max} = h\nu_{max}\ldots\ldots\ldots\ldots\ldots(2)$$

X ray has maximum energy when its kinetic energy $\;E = e\,U$

$$\nu_{max} = \; e\,U\,/\,h \;\ldots\ldots\ldots(3)$$

$$\text{and} \quad \lambda_{min} = \; hc\,/\,e\,U \;\ldots\ldots(4) \qquad (\text{Duane –Hunt relation})$$

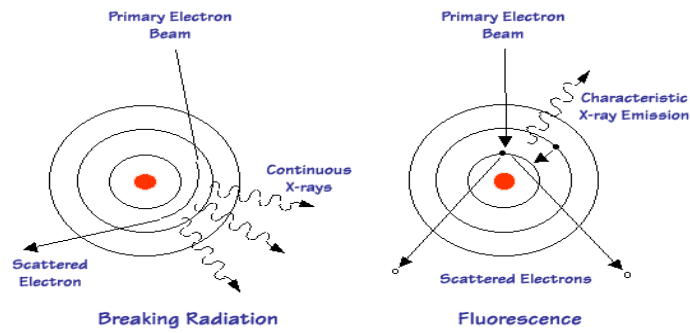where the proportionality constant $A = hc/e$, can be used to find Planck's constant.

Fig.2

In a second process radiation is emitted by the electrons of the anode atoms when incoming electrons from the cathode knock electrons near the nuclei out of orbit and they are replaced by other electrons from outer orbits. The spectrum of the wavelength given off with any particular anode material thus consists of a continuous range of wavelength (the curved) emitted in the first process and superimposed on it a number of sharp peaks of intensity corresponding to discrete wavelength at which X rays are emitted in the second process. The sharp peaks constitute the X-ray line spectrum for the anode material and will differ for different materials.see fig.3.
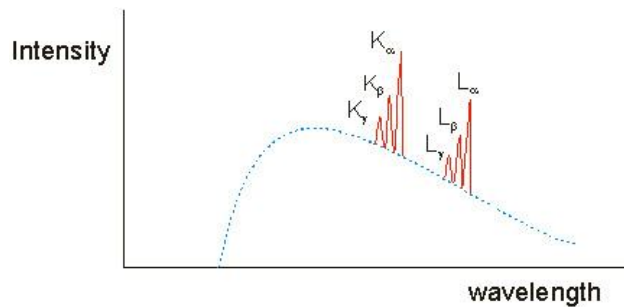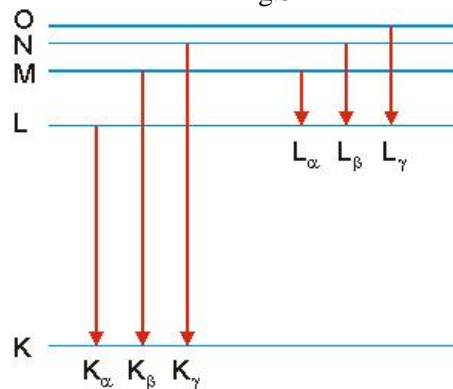

Fig.3

Fig.4

These "lines" in the spectrum are named after the energy level to which an electron falls, When a monochromatic X-ray beam with wavelength λ is projected onto a crystal diffraction occurs only when the distance traveled by the rays reflected from successive planes differs by a complete number n of wavelengths.

$$n\lambda = 2d \sin\theta, n = 1,2,3,.. \ (Bragg`s \ law)$$ ....(5)

Bragg's law allow us to calculate details about the crystal structure and to determine the wavelength of x-ray incident upon the crystal.see Fig.5.

2

When X-rays passthrough matter they lose energy both by scattering and by absorption. In the absorption process an X-ray photon is absorbed by the atom, and the excess energy is transferred to an electron, which is expelled from the inner shell e.g the k-shell of the atom leaving the atom ionized. This can occur when the quantum energy is greater than the binding energy E_k of the shell,See Fig.4. The transmission of the material increase abruptly as the function of the wavelength $T = R / R_o$ where R is intensity rate behind attenuator and R_o is the intensity in front attenuator Moseley measured the k-absorption edge for various elements

$$(1 /\lambda_k)^{1/2} = R^{1/2} (Z - \sigma_k)\ldots\ldots\ldots\ldots(6)$$
where R :Rydberg constant , Z :atomic number ,σ_k : screening coefficient of the k - shell
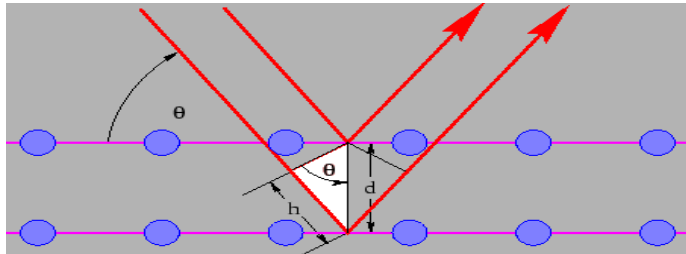

Fig.5

The x-ray apparatus fulfills all regulations governing an x-ray apparatus and fully protected device for instructional use and is type approved for school use in Germany (NW 807/97 Rö).
The built-in protection and screening measures reduce the local dose rate outside of the x-ray apparatus to less than 1 µSv/h, a value which is on the order of magnitude of the natural background radiation.
- Before putting the x-ray apparatus into operation inspect it for damage and to make sure that the high voltage is shut off when the sliding doors are opened.
- Keep the x-ray apparatus secure from access by unauthorized persons. Do not allow the anode of the x-ray tube Mo to overheat.
- When switching on the x-ray apparatus, check to make sure that the ventilator in the tube chamber is turning. The goniometer is positioned solely by electric stepper motors.
- Do not block the target arm and sensor arm of the goniometer and do not use force to move them.

Part1: Bragg reflection: diffraction of x-rays at a monocrystal
AIM:
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- To investigate Bragg reflection at an NaCl monocrystal using the characteristic x-ray radiation of molybdenum.
- To determine the wavelength for the characteristic K_α and K_β x-ray radiation of molybdenum.
- To confirm Bragg's law of reflection.
- To verify the wave nature of x-rays.

Setup:

Setting up the Bragg configuration:

Fig. 5 shows some important details of the experiment setup.

Specifically, you need to carry out the following steps

– Attach the goniometer to the guide rods (d) in such a way that the distance s_1 between the slit diaphragm of the collimator and the target arm is approx. 5 cm.

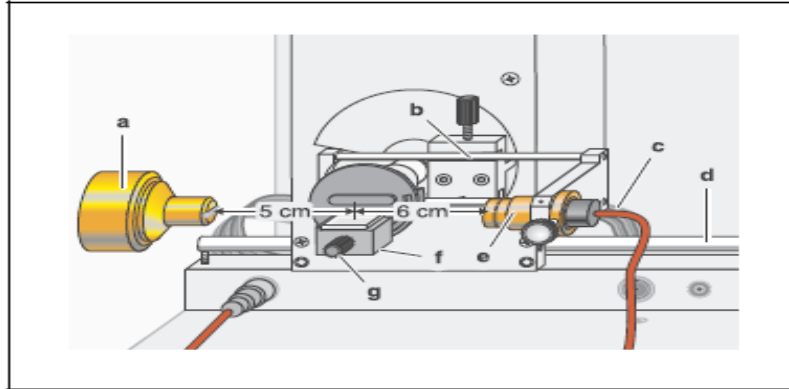– Adjust the sensor seat (b) until the distance s_2 between the target arm and the slit diaphragm of the sensor seat is approx. 6.

Fig.6 Experiment setup in Bragg configuration

Notes:

NaCl crystals are hygroscopic and fragile. Store the crystals in a dry place. Avoid mechanical stresses on the crystal; handle the crystal by the short faces only. If the counting rate is too low, you can reduce the distance s_2 between the target and the sensor somewhat. However, this distance must not be too small, as otherwise the angular resolution of the goniometer is no longer great enough to separate the characteristic k_α and k_β lines.

Carrying out the experiment:

– Start the program "X-ray Apparatus", check to make sure that the x-ray apparatus is properly connected and delete any existing measurement data by clicking the button ⬚ or pressing F4.
– Set the x-ray high voltage U = 35.0 kV, emission current I = 1.00 mA, measuring time per angular step Δt = 10 s and angular step width $\Delta\beta = 0.1°$.
– Press the COUPLED key on the device to enable 2θ coupling of the target and sensor; set the lower limit value of the target angle to $2°$ and the upper limit to $25°$.
– Press the SCAN key to start the measurement and data transmission to the PC.
– When the measurement is finished, save the measurement series to a file under a suitable name using the button ⬚ or F2.

Evaluation
– Access the evaluation functions of the software "X-ray Apparatus" by clicking the right-hand mouse button and select the command "Calculate Peak Center".
– Using the left mouse button, mark the "entire width" of the peaks; if desired, insert the calculated peak center β and the peak width σ in the diagram with Alt +T and note the center as the glancing angle in the measurement table (see tables 1 and 2).

– Save your measurements and evaluations to a suitably named file with the button ⬚ or by pressing F2.
– Using the glancing angle θ and the lattice plane spacing d = 282.01 pm, calculate the wavelength λ using Bragg's law of reflection (5) (see tables 1 and 2).
– Find the mean values for the individual diffraction orders of the measured wavelengths (see table 3).

n	$\theta(k_\alpha)$	$\lambda(k_\alpha)$/ pm
1		
2		
3		

Table 1: Measured glancing angles of the Mo k_α line and the calculated wavelengths λ for the first through third diffraction orders.

n	V(k_β)	λ(k_β)/pm
1		
2		
3		

Table 2: Measured glancing angles of the Mo K_β line and the calculated wavelengths λ for the first through third diffraction orders.

	λ(k_α)/ pm	λ(k_β)/pm
Mean value		
Literature value		

Table 3: Mean value and literature value for the characteristic Wavelength λ.

Part2: Duane-Hunt relation and determination of Planck's constant
AIM:

- To determine the limit wavelength λ_{min} of the bremsstrahlung continuum as a function of the high voltage U of the x-ray tube.
- To confirmed the Duane-Hunt relation.
- To determine Planck's constant h= 6.626×10^{-34} Js.

Setup: *the same as in part 1*
Carrying out the experiment:

 – Start the software "X-ray Apparatus", check to make sure that the apparatus is connected correctly, and clear any existing measurement data using the F4 key.
– Set the tube high voltage U = 22 kV, the emission current I = 1.00 mA, the measuring time per angular step Δt = 30 s and the angular step width Δβ = 0.1º.
– Press the COUPLED key to activate 2θ coupling of target and sensor and set the lower limit of the target angle to 5.2º and the upper limit to 6.2º.
– Start measurement and data transfer to the PC by pressing the SCAN key.
– Additionally record measurement series with the tube high voltages U= 24 kV, 26 kV, 28 kV, 30 kV, 32 kV, 34 kV and 35 kV; to save measuring time, use the parameters from table 4 for each series.

U/KV	I/mA	Δt/s	β min/grd	β max/grd	Δβ /grd
22	1.00	30	5.2	6.2	0.1
24	1.00	30	5.0	6.2	0.1
26	1.00	20	4.5	6.2	0.1
28	1.00	20	3.8	6.0	0.1
30	1.00	10	3.2	6.0	0.1
32	1.00	10	2.5	6.0	0.1
34	1.00	10	2.5	6.0	0.1
35	1.00	10	2.5	6.0	0.1

Tab. 4: Recommended parameters for recording the measurement series

–To show the wavelength-dependency, open the "Settings" dialog with the button 🔲 or F5 and enter the lattice plane spacing for NaCl.
– When you have finished measuring, save the measurement series under an appropriate name by pressing

the button 🔲 or the F2 key.
Evaluation
Determining the limit wavelength λ_{min} **as a function of the tube high voltage *U*:**
For each recorded diffraction spectrum:
 – In the diagram, click the right mouse button to access the evaluation functions of the software "X-ray Apparatus" and select the command "Best-fit Straight Line".

– Mark the curve range to which you want to fit a straight line to determine the limit wavelength λ_{min} using the left mouse button.

– Save the evaluations under a suitable name using the pressing F2.

Confirming the Duane-Hunt relation and determining Planck's constant

– For further evaluation of the limit wavelengths λ min determined in this experiment, click on the register "Planck".

– Position the pointer over the diagram, click the right mouse button, fit a straight line through the origin to the curve $\lambda_{min} = f(1/U)$ and read the slope A (pm kv) from the bottom left corner of the evaluation window .

Part3: Moseley's law and determination of the Rydberg constant
AIM:

- Measuring the K-absorption edges in the transmission spectra of Zr, Mo, Ag and In.
- Verifying Moseley's law.
- Determining the Rydberg constant.

Setup:

The same as in part 1 but the following step will change :

- By moving the sensor holder (b), set the distance s2 between the target arm and the slit diaphragm of the sensor seat to approx. 5 cm in Fig. 7.

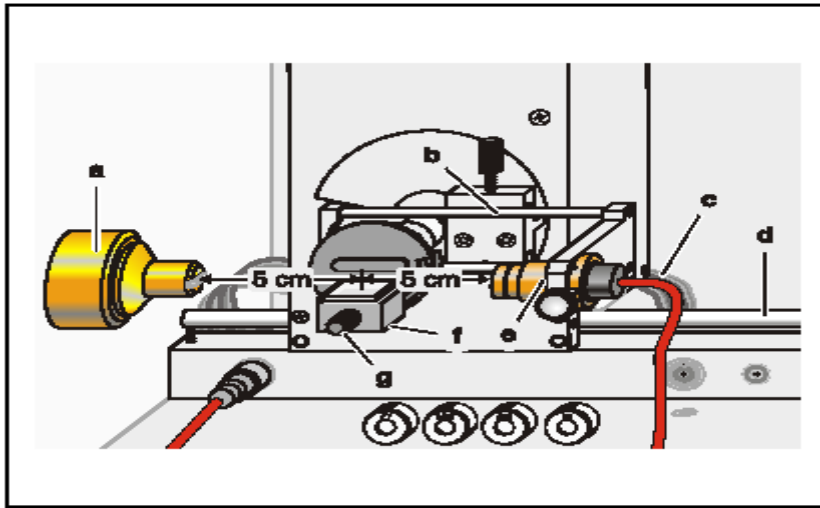Note: do your calibration after this step.

Fig. 7 Experiment setup for measuring the K-absorption edges.

Carrying out the experiment

– Start the software "X-ray Apparatus", check to make sure that the apparatus is connected correctly, and clear any existing measurement data using the button [icon] or the F4 key.

– Set the tube high voltage U = 35.0 kV, the emission current I = 1.00 mA and the angular step width $\Delta\beta$ = 0.1°.

– Press the COUPLED key to activate 2θ coupling of target and sensor and set the lower limit of the target angle to 3.7° and the upper limit to 7.5°.

– Set the measuring time per angular step to Δt = 5 s.

– Start measurement and data transfer to the PC by pressing the SCAN key.

– When the scan is finished, mount the zirconium foil on sensor seat (e) of the goniometer and start a new measurement by pressing the SCAN key.

– Replace the Zr foil with the Mo, Ag and In foils one after another and conduct further measurements.

– When you have finished measuring, save the measurement series under an appropriate name by pressing the Button ![] or the F2 key.

– To display the measurement data as a function of the wavelength λ , open the "Settings" dialog with the Button ![] or F5, and in the tab "Crystal", click on the button "Enter NaCl".

Evaluation:

– Click on the "Transmission" tab in the software "X-ray Apparatus" to generate the transmission spectra from the diffraction spectra.
– In the diagram, click the right mouse button to access the evaluation functions of the software "X-ray Apparatus" and select the command "Draw K-Edges".
– Mark the range of each K-edge in the transmission spectra using the left mouse button.
– Click on the tab "Moseley" and enter the atomic numbers of the respective foils (Zr: 40, Mo: 42, Ag: 47 and In: 49) in the column Z .
– Place the mouse pointer over the diagram, click the right mouse button and select the evaluation command "Best-fit Straight Line"; then hold down the left mouse button to mark the range in the diagram to which you want to fit the line. Read off the result for the Rydberg constant R and the screening coefficient σ_K in the bottom left corner of the window.

Results:

	R	σ_K
The graphical evaluation		
Literature values	$R=1.097373 \times 10^7$ m^{-1}	3.6