The intensity of characteristic X-rays as a function of the anode current and anode voltage

Physics | Modern Physics | Production & use of X-rays

Difficulty level	Group size	Preparation time	Execution time
hard	2	45+ minutes	45+ minutes

This content can also be found online at:

http://localhost:1337/c/5f60823f7e9d5b0003e1e6e5

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General information

Application

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Setup

Most applications of X rays are based on their ability to pass through matter. Since this ability is dependent on the density of the matter, imaging of the interior of objects and even peaple becomes possible. This has wide usage in fields such as medicine or security.

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Other information (1/2)

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Prior knowledge

The prior knowledge required for this experiment is found in the Theory section.

Main principle

The X-ray spectrum of an X-ray tube with a copper anode is selected based on the wavelength with the aid of a LiF monocrystal as the analyser, and registered with a Geiger-Müller counter tube. The intensity of the characteristic K_α and K_β lines is determined as a function of the anode current and voltage.

Other information (2/2)

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Learning objective

The goal of this experiment is to get to investigate the intensity of characteristic X-rays as a function of the anode current and anode voltage.

Tasks

- Analyse the intensity of the molybdenum X-radiation as a function of the Bragg angle and with the aid of a LiF monocrystal.
- Determine the intensity of the characteristic X-ray lines as a function of the anode voltage and current.
- Compare the results of the experiment to the results that can be expected theoretically.

The parameters for the experiment with a tungsten tube are shown in the appendix.

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Theory (1/3)

The electrons coming from the cathode are accelerated towards the anode by the voltage U_A between the cathode and anode. Due to the resulting high level of kinetic energy, the electrons are capable of ejecting electrons from the inner shells of the atoms of the anode material. If this occurs on the K shell of the atoms, an electron from a higher shell, e.g. the L or M shell, can take up the free place while emitting an X-ray quantum. The energy of this X-ray quantum corresponds to the energy difference of the two shells that are involved in this process. Since this energy difference is atom-specific, the resulting radiation is also called characteristic X-radiation. X-radiation that is produced following a transition from the L shell to the K shell is called K_α radiation, while the radiation that is produced following a transition from the M shell to the K shell is called K_β radiation.

The intensity I_K of the K radiation is:

$$I_K = B \cdot I_A (U_A - U_K)^{1.5} \qquad (1)$$

(I_A anode current, U_A anode voltage, B = const. and U_K = ionisation potential of the K shell.)

Theory (2/3)

The depth of penetration of the ionising electrons into the anode material as well as the escape depth of the generated X-rays is limited. When they have both reached their maximum, the relationship given in (1) loses its validity.

In accordance with Figure 1, Bragg's law applies to constructive interference:

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

(d: interplanar spacing; n = 1, 2, 3,...)

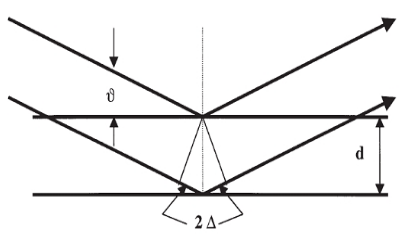

Fig. 1: Bragg scattering on a pair of lattice planes

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Theory (3/3)

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If the interplanar spacing d is known, the wavelength λ can be determined with the aid of the glancing angle θ. The energy of the radiation then results from:

$$E = h \cdot f = \frac{hc}{\lambda} \qquad (3)$$

When combining (2) and (3), we obtain:

$$E = \frac{n \cdot h \cdot c}{2d \cdot \sin(\theta)} \qquad (4)$$

Planck's constant h = 6.6256 $\cdot 10^{-34}$ Js

Velocity of light c = 2.9979 $\cdot 10^{8} \frac{m}{s}$

Interplanar spacing LiF (200) d = 2.014 $\cdot 10^{-10}$ m

Equivalent 1 eV = 1.6021 $\cdot 10^{-19}$ J

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Equipment

Position	Material	Item No.	Quantity
1	XR 4.0 expert unit, 35 kV	09057-99	1
2	XR 4.0 X-ray goniometer	09057-10	1
3	XR4 X-ray Plug-in Cu tube	09057-51	1
4	XR 4.0 X-ray solid state physics upgrade set	09125-88	1

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Setup and Procedure

Setup

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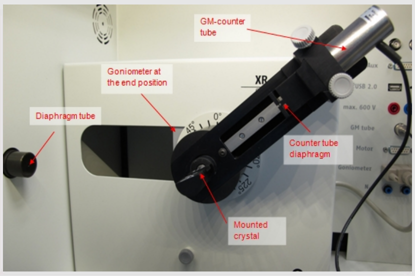
Connect the goniometer and the Geiger-Müller counter tube to their respective sockets in the experiment chamber (see the red markings in Fig. 2). The goniometer block with the analyser crystal should be located at the end position on the right-hand side. Fasten the Geiger-Müller counter tube with its holder to the back stop of the guide rails. Do not forget to install the diaphragm in front of the counter tube (see Fig. 3). Insert a diaphragm tube with a diameter of 2 mm into the beam outlet of the tube plug-in unit.

For calibration: Make sure, that the correct crystal is entered in the goniometer parameters. Then, select “Menu”, “Goniometer”, “Autocalibration”. The device now determines the optimal positions of the crystal and the goniometer to each other and then the positions of the peaks.

← Fig. 2: Connectors in the experiment chamber

↓ Fig. 3: Set-up of the goniometer



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Procedure (1/4)

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- Connect the X-ray unit via the USB cable to the USB port of your computer (the correct port of the X-ray unit is marked in Figure 4).
- Start the “measure” program. A virtual X-ray unit will be displayed on the screen.
- You can control the X-ray unit by clicking the various features on and under the virtual X-ray unit. Alternatively, you can also change the parameters at the real X-ray unit. The program will automatically adopt the settings.

Fig. 4: Connection of the computer

Procedure (2/4)

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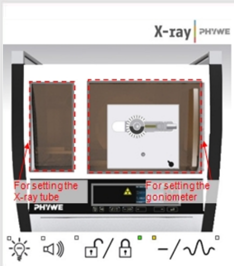

Fig. 5: Part of the user interface of the software

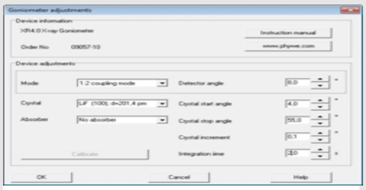

Fig 6: Settings of the goniometer (LiF crystal)

- Click the experiment chamber (see the red marking in Figure 5) to change the parameters for the experiment. Select the parameters as shown in Figure 6 for the LiF crystal.
- If you click the X-ray tube (see the red marking in Figure 5), you can change the voltage and current of the X-ray tube. Select the parameters as shown in Fig. 7.

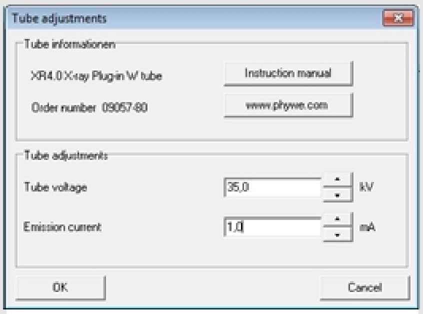

Fig 7: Voltage and current settings

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Procedure (3/4)

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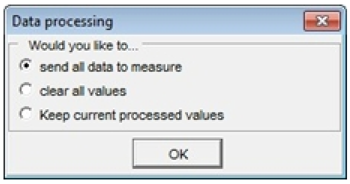
- Start the measurement by clicking the red circle: 

- After the measurement, the following window appears:



- Select the first item and confirm by clicking OK. The measured values will now be transferred directly to the "measure" software.
- At the end of this manual, you will find a brief introduction to the evaluation of the resulting spectra.

Procedure (4/4)

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Task 2: Determine the intensity of the characteristic X-ray lines of copper as a function the anode voltage and current.

- Click the experiment chamber (see the red mark-ing in Figure 5) in order to change the parameters for the experiment. Select a scanning range of 19°-24°.
- If you want to determine the dependence of the intensity on the anode current, record a spectrum with various different anode currents. Settings: U_A = 35 kV = const; I_A = 35 kV ... 11 kV in steps of 2-3 kV.
- If you want to determine the dependence of the intensity on the anode voltage, record a spectrum with various different anode voltages. Settings: I_A = 1 mA = const; U_A = 1 mA ... 0.1 mA in steps of 0.1 mA.
- The evaluation is the same as for task 1.

Overview of the settings of the goniometer and X-ray unit:

- 1:2 coupling mode
- Gate time 2 s; angle step width 0.1°

For recording a complete spectrum:

- Scanning range 4°-55° (LiF monocrystal)
- Anode voltage U_A = 35 kV; anode curren I_A = 1 mA

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Evaluation

Task 1

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Task 1: Analyse the intensity of the X-radiation of copper as a function of the Bragg angle and with the aid of a LiF monocrystal.

Figure 8 shows the X-ray spectrum of copper up to the second-order interference. The table shows the resulting glancing angles θ of the characteristic lines as well as the corresponding wavelengths that were calculated based on (2).

	n =1		n=2	
	ϑ/°	λ/pm	ϑ/°	λ/pm
Cu (Z=29)K_α	22.6	154.8	50.2	154.7
Cu (Z=29)K_β	20.4	140.4	43.9	139.6

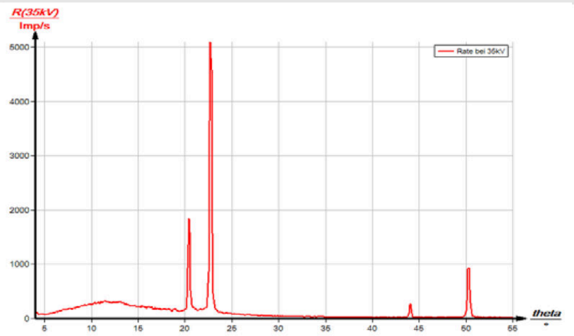

Fig. 8: X-ray spectrum of copper, LiF monocrystal as the analyser

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Task 2

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Task 2: Determine the intensity of the characteristic X-ray lines of copper as a function of the anode voltage and current.

Intensity as a function of the anode voltage

Figure 9 shows the relevant scanning range with the pulse rates for various different selected anode voltages. In Figure 10, the lower curves show the measured intensity (pulse rate) of the characteristic lines (intensity maximum of the lines) as a function of the anode current I_A at a constant anode voltage U_A = 35 kV. However, excessively high pulse rates cause the Geiger-Müller counter tube to become saturated. The deviation of the measurement curves from the expected linearity can be eliminated by taking the dead time of the Geiger-Müller counter tube into consideration at high pulse rate values. These corrected values are represented by the upper curves in Figure 10.

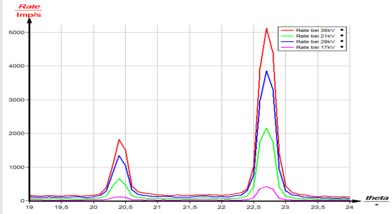

Fig. 9: Scanning range 19° < θ < 24° at different anode voltages

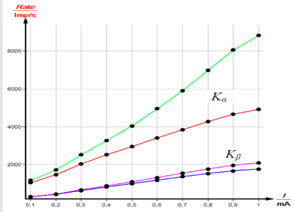

Fig. 10: Intensity of the K_α and K_β lines (n = 1) as a function of the anode current I_A.

Task 2 (part 2)

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If $\tau(\tau \approx 90\ \mu s)$ is the dead time of the Geiger-Müller counter tube and N_0 is the measured pulse rate, the true pulse rate N is:

$$N = \frac{N_0}{1-\tau \cdot N_0}$$

Intensity as a function of the anode current

Figure 11 shows the relevant scanning range with the pulse rates for various different selected anode currents.
Figure 12 shows the intensity course of the two characteristic lines as a function of the anode voltage U_A (I_A = const = 1 mA). The lower curves represent the measured pulse rates while the upper curves show the pulse rates that were corrected in terms of the dead time of the Geiger-Müller counter tube.

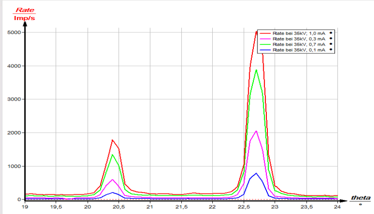

Fig.11: Scanning range 19° < θ < 24° at different anode voltages

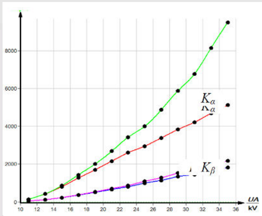

Fig. 12: Intensity of the K_α and K_β lines (n = 1) as a function of the anode voltage U_A.

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Task 3

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Task 3: Compare the results of the experiment to the results that can be expected theoretically.

If the experimental results are compared to the results that can be expected theoretically, the linear relationship between $U_A - U_K$ and the pulse rate of (1) is confirmed. If one plots the true pulse rates of the characteristic lines of Figure 12 as a function of $(U_A - U_K)^{1.5}$ (with U_K = 8,979 keV for copper, see the experiment P2540105), a straight line results.

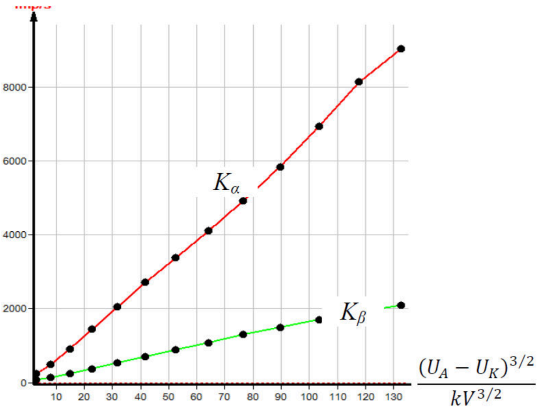

Fig. 13: The true pulse rates of the K_α and K_β lines as a function of $(U_A - U_K)^{1.5}$; (I_A = const = 1 mA)

Note

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"measure" software
With the "measure" software, the peaks in the spectrum can be determined rather easily:

- Click the button "Mark" and select the area for the peak determination.
- Click the button "Peak analysis".
- The window "Peak analysis" appears (see Fig. 14). Then, click "Calculate".
- If not all of the desired peaks (or too many of them) are calculated, readjust the error tolerance accordingly.
- Select "Visualise results" in order to display the peak data directly in the spectrum.

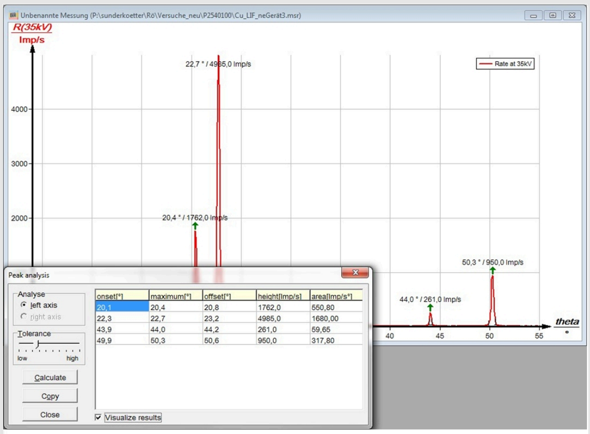

Fig. 14: Automatic peak analysis with "measure"

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Appendix

Procedure

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Procedure using a tungsten tube:

Task 1: Record the entire spectrum:

Overview of the settings of the goniometer and X-ray unit:

- 1:2 coupling mode
- Gate time 5 - 6 s; angle step width 0.1°
- Scanning range 4°-80° (LiF monocrystal)
- Anode voltage U_A = 35 kV; anode current I_A = 1 mA

Task 2: Determine the intensity of a single line

For the evaluation, examine the lines α_1 and α_2 that appear as one single line.

Determination of the intensity of the characteristic lines as a function of U_A and I_A.

- Gate time 3 s; angle step width 0.1°
- Scanning range 4°-25° (LiF monocrystal)
- U_A = 35 kV; I_A = 1mA .. 0.1mA in steps of 0.1 mA
- I_A = 1mA; I_A = 35 kV .. 11 kV in steps of 2 - 3 kV

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Theory and evaluation

Since the energy of the K shell is approximately 70 keV, the maximum available energy of the primary beam of the X-ray unit of 35 keV is insufficient for exciting the K shell. Only the L level can be ionised. P2542805 includes the corresponding energy-level-diagram.

For the evaluation, the lines α_1 and α_2 are examined. They result from the L_3M_5/L_3M_4 transition. These two lines are so close to each other that they cannot be separated but rather appear as a single line.

The evaluation follows that of copper, but in this case with only one single line. For task 3, the ionisation potential of the L_3 shell U_K = 10.206 keV is used since the transition takes place to this shell.

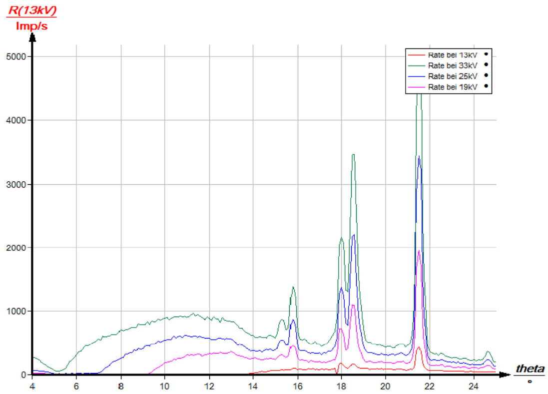

Fig 15: Scanning range 4° < θ < 25° at different anode voltages for the tungsten tube

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