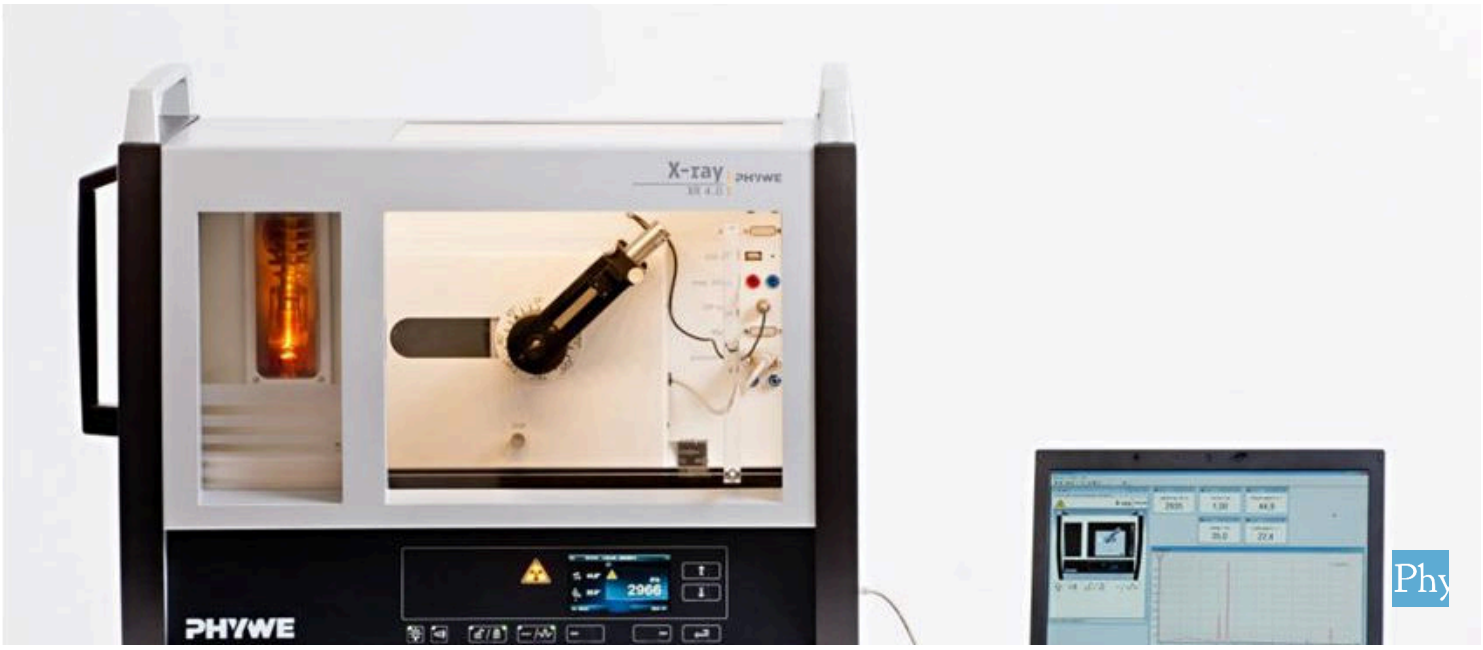
Characteristic X-rays of iron



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

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

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General information

Application

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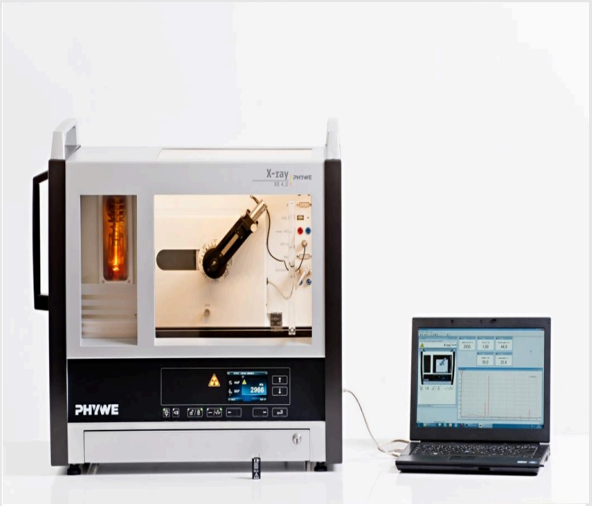

Setup

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

An X-ray tube with an iron anode generates X-radiation that is selected with the aid of a monocrystal as a function of the Bragg angle. A Geiger-Müller counter tube measures the intensity of the radiation. The glancing angles of the characteristic X-ray lines are then used to determine the energy..

Other information (2/2)

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Learning objective

The goal of this experiment is to get to investigate the characteristic X-radiation of iron.

Tasks

- Analyse the intensity of the iron X-radiation as a function of the Bragg angle and with the aid of a LiF monocrystal.
- Analyse the intensity of the iron X-radiation as a function of the Bragg angle and with the aid of a KBr monocrystal.
- Determine the energy values of the characteristic X-rays of iron and compare them with the values that were determined based on the corresponding energy-level diagram.

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Theory (1/3)

When electrons impinge on the metallic anode of the X-ray tube with a high level of kinetic energy, X-rays with a continuous energy distribution are produced. The spectrum of the bremsstrahlung is superimposed by additional discrete lines. If an atom of the anode material is ionised on the K shell following an electron impact, an electron from a higher 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. Figure 1 shows the energy-level diagram of an iron atom. Characteristic 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 ($\mathrm{M}_1 \rightarrow \mathrm{K}$ and $\mathrm{L}_1 \rightarrow \mathrm{K}$ transitions are not allowed due to quantum-mechanical selection rules).

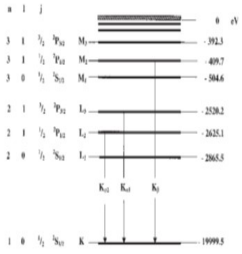

Fig. 1: Energy-level diagram of iron (Z = 26)

Theory (2/3)

The characteristic X-ray lines of iron have the following energy levels (Fig. 1):

$$E_{K_{\alpha^*}} = E_K - \frac{1}{2}(E_{L_2} + E_{L_3}) = 6.3974 \text{ keV}$$

$$E_{K_\beta} = E_K - E_{M_{2,3}} = 7.0580 \text{ keV} \qquad (1)$$

E_{K_α} is the energetic mean value of the $K_{\alpha 1}$ and $K_{\alpha 2}$ lines. The analysis of polychromatic X-rays is made possible through the use of a monocrystal. When X-rays of the wavelength λ impinge on the lattice planes of a monocrystal under the glancing angle θ, the rays that are reflected on the lattice planes interfere with each other in a constructive manner provided that their path difference Δ corresponds to an integral multiple of the wavelength. In accordance with Figure 2, Bragg's law applies to constructive interference:

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

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

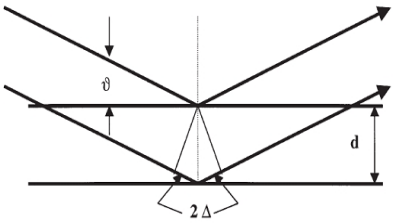

Fig. 2: Bragg scattering on a pair of lattice planes

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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:

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

Note:

The data of the energy-level diagram were taken from the "Handbook of Chemistry and Physics", CRC Press Inc., Florida.

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

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

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

Interplanar spacing KBr (200) d = 3.290 $\cdot 10^{-10}\,\mathrm{m}$

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

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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 Fe tube	09057-71	1
4	XRC 4.0 X-ray characteristics upgrade set	09135-88	1

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Setup and Procedure

Setup

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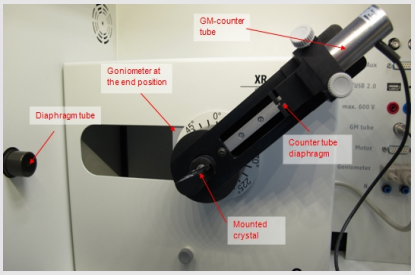
Connect the goniometer and the Geiger-Müller counter tube to their respective sockets in the experiment chamber (see the red markings in Fig. 3). The goniometer block with the analyser crystal should be located at the end position on the right-hand side. Fasten the Geiger-Müller counter tube with its holder to the back stop of the guide rails. Do not forget to install the diaphragm in front of the counter tube (see Fig. 4). 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. 3: Connectors in the experiment chamber



↓ Fig. 4: Set-up of the goniometer

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Procedure (1/3)

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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 5).
- 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. 5: Connection of the computer

Procedure (2/3)

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Fig. 6: Part of the user interface of the software

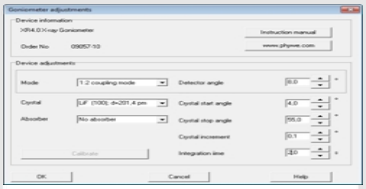

Fig 7: Settings of the goniometer (LiF crystal)

- Click the experiment chamber (see the red marking in Figure 6) to change the parameters for the experiment. Select the parameters as shown in Figure 7 for the LiF crystal. If you use the KBr crystal, select a start angle of 3° and a stop angle of 75°.
- If you click the X-ray tube (see the red marking in Figure 6), you can change the voltage and current of the X-ray tube. Select the parameters as shown in Fig. 8.

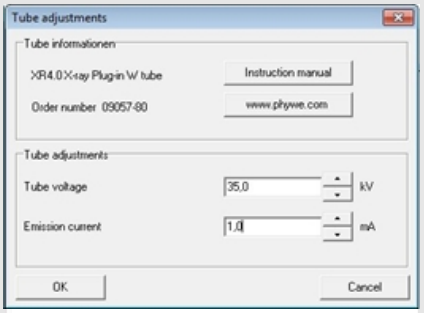

Fig 8: Voltage and current settings

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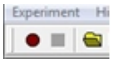
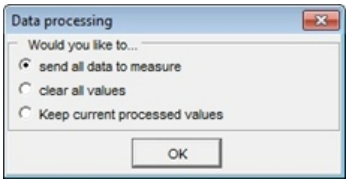
Procedure (3/3)

- 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.

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

- 1:2 coupling mode
- Gate time 2 s; angle step width 0.1°
- Scanning range 4°-55° (LiF monocrystal) and 3°-75° (KBr monocrystal)
- Anode voltage U_A = 35 kV; anode curren I_A = 1 mA

Evaluation

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Task 1

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Analyse the intensity of the iron X-radiation as a function of the Bragg angle and with the aid of a LiF monocrystal.

Figure 9 shows the X-ray spectrum of iron that was analysed with a LiF monocrystal. Well-defined lines are superimposed on the continuous bremsspectrum. The glancing angles of these lines are uneffected by the anode voltage. This identifies these lines as characteristic X-ray lines. The two line pairs can be assigned to first-order and second-order interferences. In Figure 9, the separation of the K_α doublet can be observed at n = 2. In addition, another weak line can be observed at θ = 22.5°. It can be clearly assigned to the K_α line of copper. The small iron anode plate is actually embedded in a cylindrical copper block so that some of the electrons can still hit the copper.

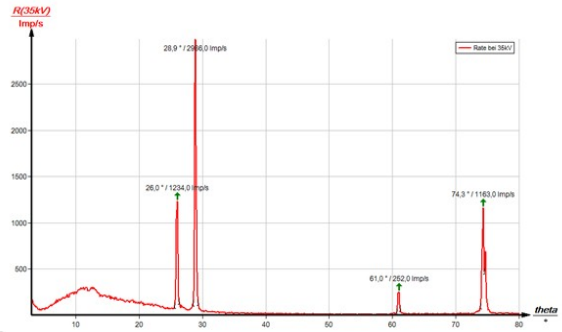

Fig. 9: Intensity of the X-radiation of iron as a function of the glancing angle ϑ; analyser crystal: LiF

Task 2

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Analyse the intensity of the iron X-radiation as a function of the Bragg angle and with the aid of a KBr monocrystal.

If the LiF monocrystal is replaced by the KBr monocrystal (Fig. 10), interferences up to the fourth order can be observed due the larger interplanar spacing of the crystal. The spectrum of the bremsstrahlung in Figure 10 shows a clear intensity step at θ = 8.0°. This corresponds to the K-edge absorption value of bromine (E_K = 13.474 keV) with n = 1 that can be expected in theory. The K-edge absorptions of potassium, lithium, and fluorine cannot be observed in this area of the bremsspectrum, since the intensity is too low (for K- and L-edge absorption experiments, please refer to experiment P2541205).

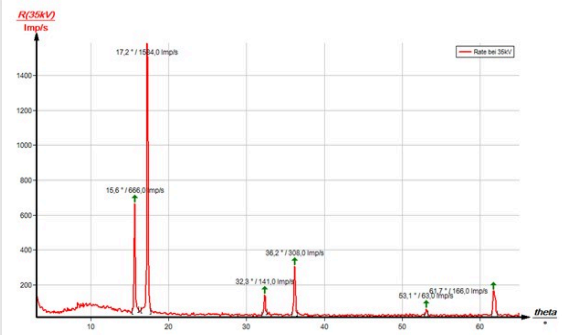

Fig. 10: Intensity of the X-radiation of iron as a function of the glancing angle ϑ; analyser crystal: KBr

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Task 3

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Determine the energy values of the characteristic X-rays of molybdenum and compare them with the values that were determined based on the corresponding energy-level diagram.

Table 1 shows the glancing angles θ that were determined with the aid of Figures 9 and 10 and also the energy values for the characteristic X-ray lines of copper that were calculated with the aid of equation (4).

Based on the energy values of the characteristic lines of Tasks 1 and 2, the following mean values result: E_{K_α} = 6.391 keV and E_{K_β} = 7.046 keV. A comparison with the corresponding values of (1) shows good correspondence.

The evaluation of the two spectra can be varied as follows: Use the energy values of the characteristic lines that were determined for one of the spectra in order to determine the interplanar spacing of the analyser crystal that was used for the other spectrum.

Table 1

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LiF crystal	$\theta/^\circ$	Line	$\mathrm{E/keV}$
n = 1	28.9	K_α	6.369
	26.0	K_β	7.027
n = 2	74.3	K_α	6.394
	61.0	K_β	7.035

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Table 1 (part 2)

KBr crystal	$\theta/^\circ$	Line	E/keV
n = 1	17.2	K_α	6.372
	15.6	K_β	7.007
n = 2	36.2	K_α	6.376
	32.3	K_β	7.052
n = 3	61.7	K_α	6.416
	53.1	K_β	7.066

Note

"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. 11). 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.

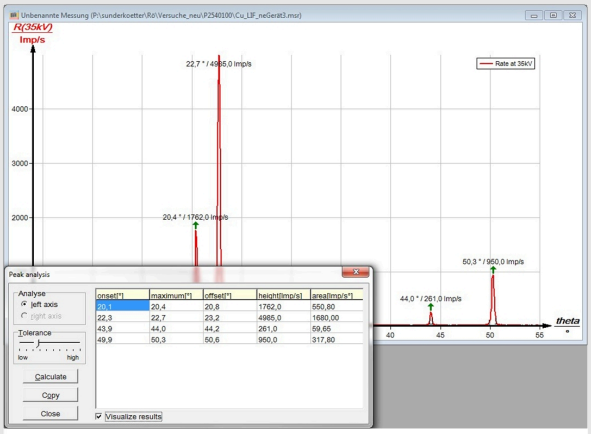

Fig. 11: Automatic peak analysis with "measure"

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