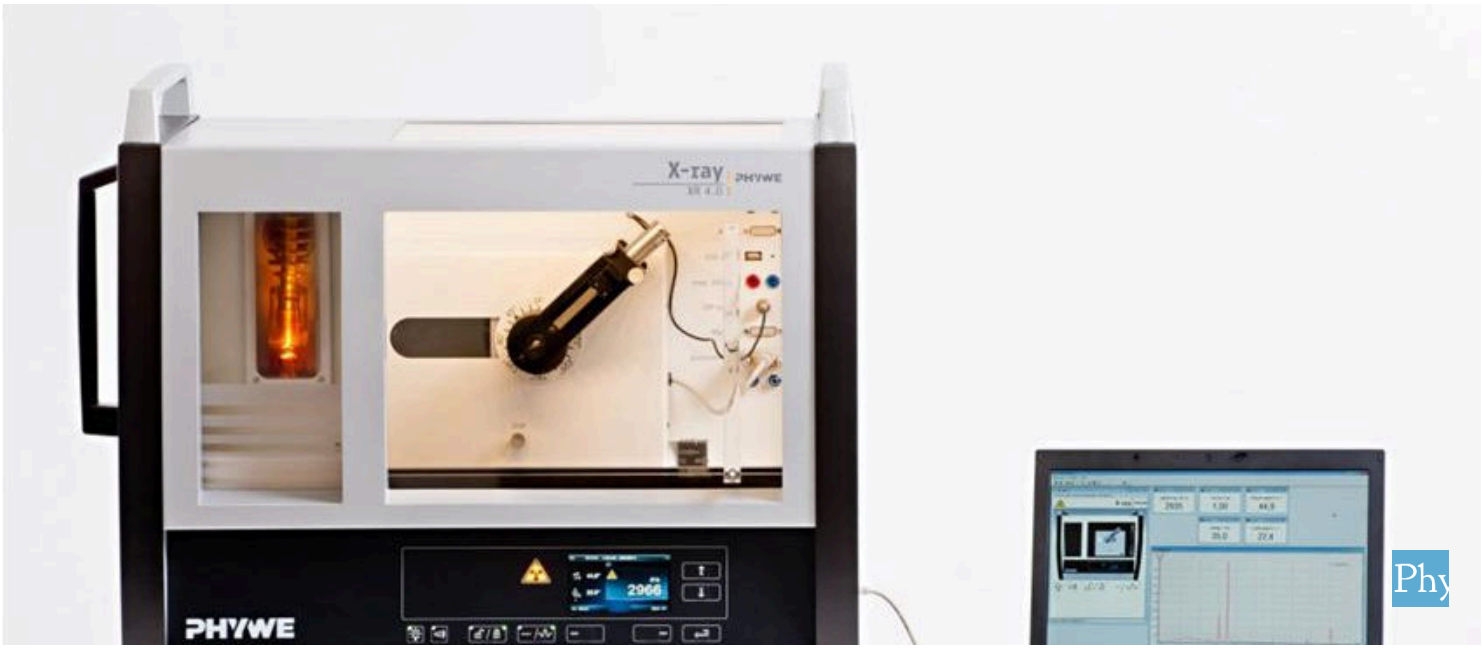
Characteristic X-rays of tungsten



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 a tungsten 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 tungsten.

Tasks

- Record the X-ray spectrum that is emitted by the tungsten anode as a function of the Bragg angle and with the aid of the LiF monocrystal that is used as the analyser.
- Determine the energy values of the characteristic X-rays of tungsten based on the spectra 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 hit the metallic anode of the x-ray tube with a high kinetic energy, x-rays with a continuous energy distribution (bremsstrahlung) are generated. The bremstrahlung is superimposed by additional discrete lines. If an atom of the anode material is ionised, for example, in a deeper shell by an electron impact, an electron from a higher shell can take the now free place while emitting inter alia an x-ray quantum. The energy of this x-ray quantum corresponds to the energy difference of the two levels that are involved in this process. Since the energy difference is atom-specific, the radiation that is generated by this process is also called the characteristic x-radiation.
When an x-ray with the wavelength λ hits the group of lattice planes of a monocrystal at the glancing angle θ, the rays that are reflected by the lattice planes only interfere in a constructive manner, if their path difference Δ corresponds to an integer of the wavelength (see Fig. 1). This condition is represented by the socalled Bragg's law:

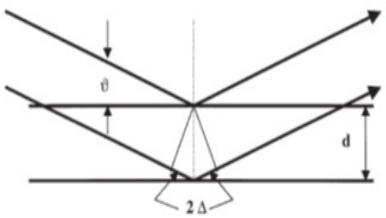

Fig. 1: Bragg scattering on the lattice planes

Theory (2/3)

$2\mathrm{d}\sin(\theta) = \mathrm{n}\lambda$ (1)

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

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:

$E = h \cdot f = \frac{hc}{\lambda}$ (2)

When combining (1) and (2), we obtain:

$E = \frac{n \cdot h \cdot c}{2d \cdot \sin(\theta)}$ (3)

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 $\cdot 10^{-10}\mathrm{m}$

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

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Theory (3/3)

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Figure 2 shows the energy level diagram of the tungsten atom. 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. An ionization is only possible for the L-level.
For clarity, Figure 2 shows the L-transitions for the dipole radition (see 4) that are possible in accordance with the quantummechanical selection rules only up to the N-shell. The quadrupole radiation with a much lower intensity can be neglected.

$\Delta l = \pm 1$ and $\Delta j = 0, \pm 1$ selection rules for the dipole radiation (4)

(l = orbital angular momentum, j = total angular momentum)

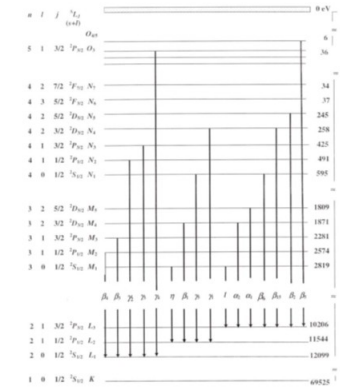

Fig. 2: Schematic representation of the energy level of tungsten (Z = 74)

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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 W tube	09057-81	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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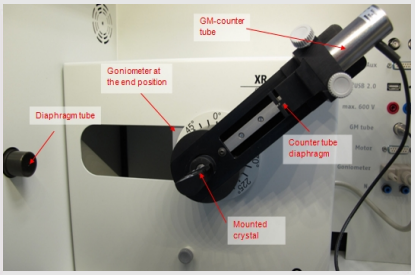
Connect the goniometer and the Geiger-Müller counter tube to their respective sockets in the experiment chamber (see the red markings in Fig. 3). The goniometer block with the analyser crystal should be located at the end position on the right-hand side. Fasten the Geiger-Müller counter tube with its 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

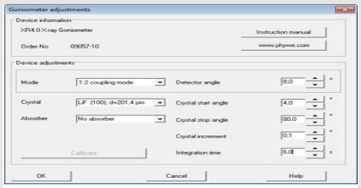

Fig 7: Settings of the goniometer

- 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 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.

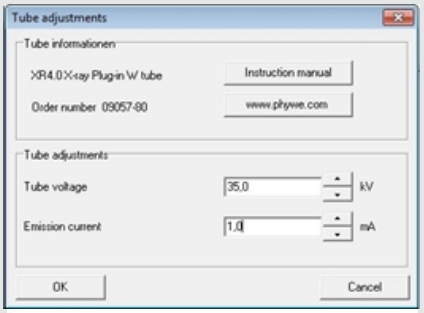

Fig 8: Voltage and current settings

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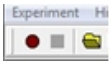
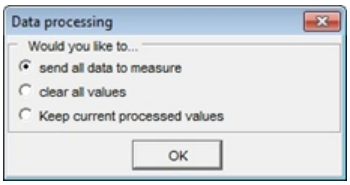
Procedure (3/3)

- 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 5 - 6 s; angle step width 0.1°
- Scanning range 4°-80° (LiF 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 tungsten 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 tungsten that was analysed with a LiF monocrystal. Well-defined lines are superimposed on the continuous bremsspectrum. The glancing angles of these lines ar uneffected by the anode voltage. This identifies them as characteristic X-ray lines. The evaluation (see the table) shows that there are only first-order lines in the angular range of 10° < θ < 30°. They reach the highest intensity level. The range of 30° < θ < 80° includes the lines with n = 2 and n = 3. The separation of lines number 2 and 10 into α_1 and α_2 or γ_2 and γ_3 can only be observed in the range with n = 2. Line number 11 can be clearly assigned to the K_α line of copper. The small circular tungsten anode is actually embedded in a cylindrical copper rod that is also partly hit by the electrons.

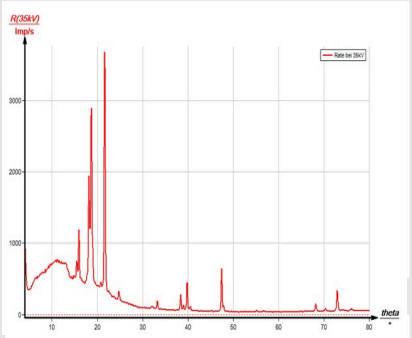

Fig. 9: X-ray spectrum of tungsten

Task 2

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

Column B of the table shows the glancing angles θ that were determined with the aid of Figure 9 and also the energy values for the characteristic X-ray lines of tungsten that were calculated with the aid of equation (4). The wavelength λ and the corresponding energies E_{exp} that were calculated with (1) and (3) are shown in columns D and E. Column H shows the energy values E_{lit} that were calculated with the aid of Figure 8. The correspondence between the two energy values provides evidence concerning the assignment of the lines to the various transitions. As expected, there are only those lines that comply with the selection rules. It is not possible to discern all of the possible transition, since for some of them the intensity is too low.

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Task 2 (part 2)

A	B	CD		E	F	G	H
Line	θ [°]	n	λ [pm]	E_{exp} [eV]	Line	Transition	E_{lit} [eV]
1	14.69	1	102.15	12138	γ_4	L_1O_3	12063
2	15.23	1	105.81	11717	$\gamma_{3/2}$	L_1N_3/L_1N_2	
3	15.74	1	109.27	11346	γ_1	L_2N_4	11286
4	16.28	1	112.92	10980	γ_5	L_2N_1	10949
5	17.92	1	123.94	10003	β_2	L_3N_5	9961
6	18.21	1	125.87	9849	β_3	L_1M_3	9818
7	18.47	1	127.61	9716	β_1	L_2M_4	9673
8	18.79	1	129.74	9556	β_4	L_1M_2	9525
9	20.60	1	141.72	8748	η	L_2M_1	8725

A	B	CD		E	F	G	H
Line	θ [°]	n	λ [pm]	E_{exp} [eV]	Line	Transition	E_{lit} [eV]
10	21.47	1	147.43	8409	$\alpha_{1/2}$	L_3M_5/L_3M_4	
11	22.51	1	154.21	8040	Cu-$K_{\alpha_{1/2}}$		
12	24.57	1	167.49	7402	I	L_3M_1	7387
13	31.80	2	106.13	11682	γ_3	L_1N_3	11674
14	32.01	2	106.76	11613	γ_2	L_2N_4	11608
15	33.03	2	109.79		γ_1	L_3N_5	11286
16	38.12	2	124.33	9972	β_2	L_1M_3	9961
17	38.80	2	126.20	9824	β_3	L_1M_2	9818
18	39.52	2	128.16	9674	β_1	L_2M_4	9673

Task 2 (part 3)

A	B	CD		E	F	G	H
Line	θ [°]	n	λ [pm]	E_{exp} [eV]	Line	Transition	E_{lit} [eV]
19	40.24	2	130.10	9529	β_4	L_1M_2	9525
20	47.12	2	147.58	8401	α_1	L_3M_5	8397
21	47.58	2	148.68	8339	α_2	L_3M_4	8335
22	54.88	3	109.71	11300	γ_1	L_2N_4	11286
23	56.47	2	167.88	7385	I	L_3M_1	7387
24	67.90	3	124.28	9976	β_2	L_3N_5	9961
25	70.09	3	126.12	9831	β_3	L_1M_3	9818
26	72.66	3	128.04	9683	β_1	L_2M_4	9673
27	75.79	3	130.03	9535	β_4	L_1M_2	9525

Table 1

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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. 10). 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.

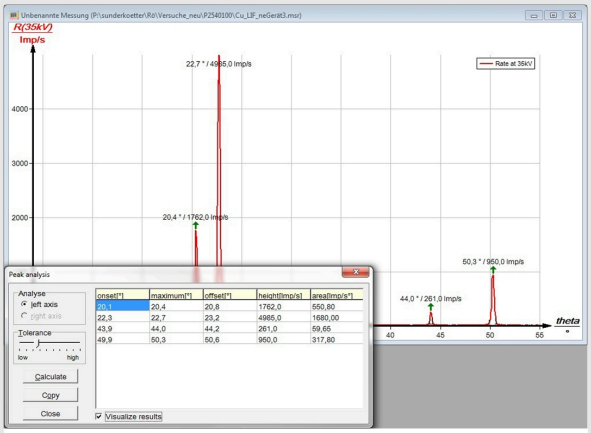

Fig. 10: Automatic peak analysis with "measure"

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