

## Recording the energy spectrum of a molybdenum anode

### Objects of the experiment

- Recording the x-ray spectrum emitted by an molybdenum anode
- Identifying the continuous background called bremsstrahlung and the lines  $K\alpha$  and  $K\beta$  of the characteristic spectrum.
- Determining energy of characteristic spectrum

### Principle

When operating the x-ray tube, in addition to the continuous bremsstrahlung, the characteristic radiation is also emitted (see also e.g. Physics Leaflet P6.3.3.2). In contrast to the bremsstrahlung, the characteristic radiation does not possess a continuous distribution of radiation intensity in the spectrum – its spectrum is composed of sharp lines.

The characteristic radiation is generated when the electrons which are accelerated towards the anode in the x-ray tube, knock other electrons out of the inner shells of the atoms making up the anode material. The atom ionised in this way then has a vacancy (electron hole) in a lower shell which previously had been full. These electron holes can be filled with electrons from other, weaker bound shells of the atom: e.g. the  $K$ -shell can be closed by the transition of an electron from the  $L$ -shell. Such a transition is connected with the emission of a photon. This radiation has only particular discrete photon energies corresponding to the energy difference of the levels involved, and it is characteristic for every chemical element.

The designations of the characteristic x-ray lines are a combination of the symbol for the electron shell ( $K$ ,  $L$ ,  $M$  etc.) and a Greek letter ( $\alpha$ ,  $\beta$ ,  $\gamma$  etc.). The electron shell being referred to is the one which was ionised before the electron transition. For example the designation  $K\alpha$ -line describes the transition from the  $L$ -shell into the  $K$ -shell,  $K\beta$  refers to the transition from the  $M$ -shell to the  $K$ -shell. The  $L\alpha$ - and  $L\beta$ -lines refer to the transitions from the  $M$ -shell and the  $N$ -shell to the  $L$ -shell.

If viewed more closely, it becomes apparent that the historically developed nomenclature of the x-ray lines is not always logical.

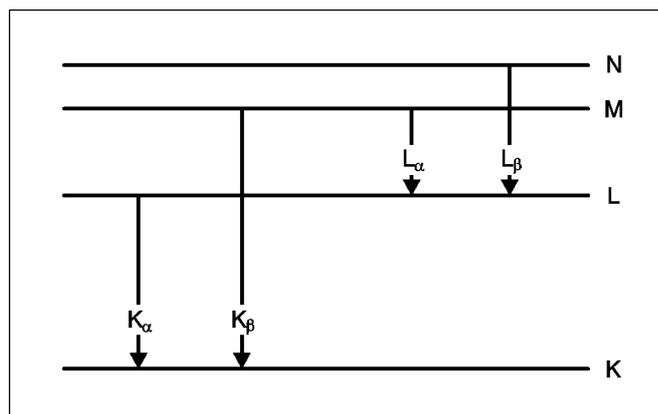


Fig. 1: Simplified terminology diagram of an atom demonstrating the characteristic x-ray lines.

In order to calculate the energies corresponding to the characteristic lines, the energy levels in the atom (binding energies in the electron shells) have to be known. These can be treated in a similar way to hydrogen by replacing the real charge of the nucleus  $Z$  by the effective charge  $Z_{eff} = Z - \sigma_n$  with an atomic screening constant  $\sigma_n$ .

### Apparatus

1 set of x-ray apparatus with Mo x-ray tube and goniometer...	554 811USB
1 x-ray energy detector.....	559 938
1 CASSY sensor .....	524 010USB
1 MCA box.....	524 058
1 CASSY Lab .....	524 200
1 HF cable, BNC, 1 m.....	501 02
1 PC with Windows 98/NT or higher	

The energy of an electron in an inner shell is then approximately represented by a modified Bohr's formula with the principal quantum number  $n$  and  $Z - \sigma_n$ :

$$E_n = -Rhc \frac{(Z - \sigma_n)^2}{n^2},$$

with  $R$  being the Rydberg constant,  $R = m_e e^4 / 8 \epsilon_0^2 h^3 c$ . The principal quantum number  $n$  refers to the electron shells:  $n = 1$  for the  $K$ -shell,  $n = 2$  for the  $L$ -shell,  $n = 3$  for the  $M$ -shell etc. This formula describes the energy structure of an electron in an inner shell. The atomic screening constant  $\sigma_n$  in general depends on  $n$  and  $Z$ .

For the frequencies of the characteristic lines  $\nu = (E_2 - E_1)/h$  with the transitions  $n_2 \rightarrow n_1$  ( $n_2 > n_1$ ) the following applies:

$$\nu = cR \left[ \frac{(Z - \sigma_{n1})^2}{n_1^2} - \frac{(Z - \sigma_{n2})^2}{n_2^2} \right].$$

If instead of  $\sigma_{n1}$  and  $\sigma_{n2}$  a single average atomic screening constant  $\sigma_{2,1}$  is introduced for the transitions from  $n_2$  to  $n_1$ , this formula can be re-written as *Moseley's law*:

$$\sqrt{\frac{\nu}{\nu_R}} = (Z - \sigma_{2,1}) \sqrt{\left( \frac{1}{n_1^2} - \frac{1}{n_2^2} \right)}, \quad (I)$$

with the Rydberg frequency  $\nu_R = cR$ . This means that the square root of the frequency of the characteristic lines in one series is a linear function of the atomic number  $Z$ . Rewritten to get the energy of the characteristic line, equation (I) becomes:

$$\sqrt{\frac{E}{Ry}} = (Z - \sigma_{2,1}) \sqrt{\left( \frac{1}{n_1^2} - \frac{1}{n_2^2} \right)}. \quad (II)$$

Here the numerical value of  $Ry$  is  $Ry = Rhc \approx 2.18 \cdot 10^{-18} \text{ J} \approx 13.6 \text{ eV}$ .

For the  $K\alpha$ -lines of the lighter elements ( $Z < 30$ ) the atomic screening constant is  $\sigma_{2,1} \approx 1$ . With increasing atomic

number,  $\sigma_{2,1}$  becomes smaller and for  $Z \geq 55$  it even becomes negative, i.e. at these  $Z$  the influence of the outer electrons exceeds the screening effect of the inner electrons. For molybdenum with  $Z = 42$  the screening constant has to be about  $\sigma_{2,1} \approx 0.6$  to achieve  $E = 17.48 \text{ keV}$  for  $K\alpha$  from equation (II) which fits well into the systematics of screening constants.

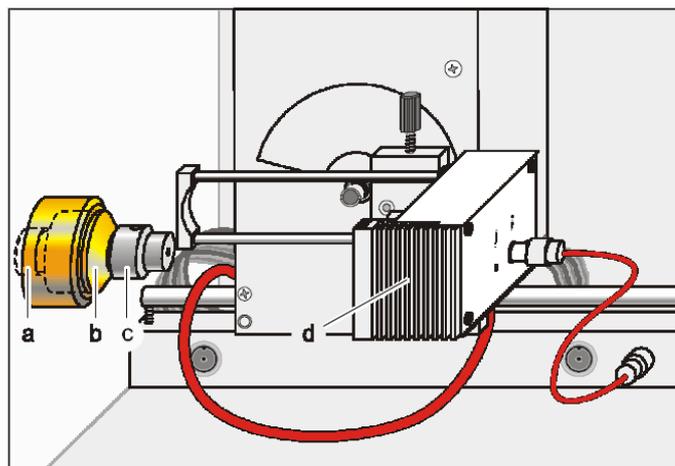


Fig. 2 Experimental setup for measuring the primary beam collimator (b), attenuating aperture (c), X-ray energy detector (d)

### Set-up

The experimental set-up is shown in fig. 2.

- Push the connection cable from the table-top power supply through the empty channel of the x-ray device and connect it to the mini-DIN socket of the x-ray energy detector.
- Secure the sensor holder with the mounted x-ray energy detector in the goniometer sensor arm.
- Connect the signal output of the x-ray energy detector to the BNC socket SIGNAL IN of the x-ray device by means of the BNC cable included.
- Feed enough connection cable through to make complete movement of the sensor arm possible.

This x-ray apparatus fulfils all regulations governing the construction of x-ray apparatus for use in schools and fully protected devices for instructional use, and it 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 the x-ray apparatus to less than  $1 \mu\text{Sv/h}$ , a value which is of the same order of magnitude as the natural background radiation.

■ Before commissioning the x-ray apparatus, inspect it for damage and check that the high voltage is switched off when the slide doors are opened (see the operating instructions for the x-ray apparatus).

■ Protect the x-ray apparatus from access by unauthorised people.

Overheating of the anode in the x-ray tube is to be avoided.

■ When switching on the x-ray apparatus, check if the fan in the tube chamber is rotating.

The goniometer is positioned exclusively by means of electric stepper motors.

■ Do not block the target arm and the sensor arm of the goniometer and do not use force to move them.

- Press the SENSOR button and set the sensor angle with the ADJUST knob manually to  $0^\circ$ .
- Connect sensor CASSY to the computer and connect the MCA box.
- Connect the SIGNAL OUT output in the connection panel of the x-ray device to the MCA-box by means of the BNC cable.
- Set the distances between the slit aperture of the collimator and the axis of rotation as well as between the axis of rotation and the window of the x-ray energy detector both to 5 to 6 cm.

### Carrying out the experiment

- Connect the table-top power supply to the mains (after approx. 2 min the LED of the x-ray energy detector will glow green and the device will be ready for use).
- Call CASSY Lab and set the measuring parameters "Multi-channel measurement, 256 channels, negative pulses, Gain = -2.5, Measuring Time = 300 s".
- Put the attenuating aperture onto the collimator, and align it carefully (the screws should point upwards and downwards, respectively).
- Select the tube high voltage  $U = 35$  kV and the emission current  $I = 0.1$  mA, and switch the high voltage on.
- Start recording the spectrum with  or with the F9 key.
- In steps of  $0.1^\circ$  around  $0^\circ$  look for the sensor angle at which the total counting rate is maximal and reduce the emission current if the total counting rate clearly exceeds 200 1/s.

#### If no or only a small counting rate is measured:

- Check the alignment of the attenuating aperture and possibly rotate the attenuating aperture by  $180^\circ$ .

### Evaluation and results

#### Molybdenum K-Lines

With the aid of the Molybdenum K-lines, the energy calibration can be carried out.

- Delete registered events, and record the primary spectrum with  or with the F9 key.
- Next open the "Energy Calibration" dialog window with the shortcut Alt+E, select "Global Energy Calibration", and enter the energies of the Mo  $K\alpha$  line (17.48 keV) and the Mo  $K\beta$  line (19.61 keV [1]).
- Select the menu item "Other Evaluations" → "Calculate Peak Center" in the pop-up menu of the diagram window, mark the region of the Mo  $K\alpha$  line, and enter the result in the "Energy Calibration" dialog window.
- Then determine and enter the peak center of the Mo  $K\beta$  line.

#### Bremsstrahlung

Looking into the spectrum one can clearly distinguish the different lines placed on a continuous background called bremsstrahlung. Comparing the Mo spectrum of the direct

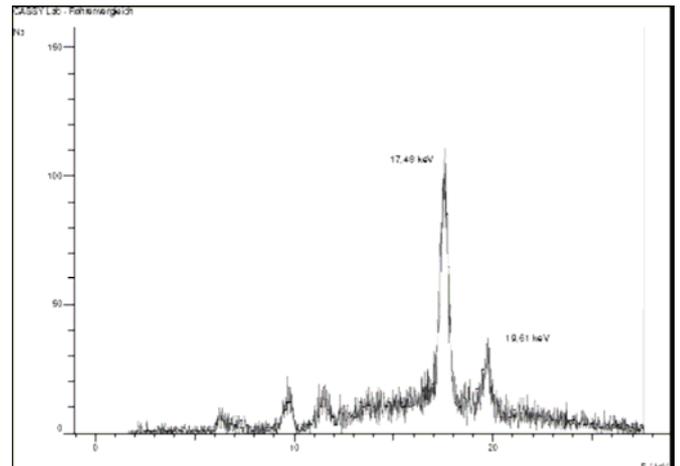


Fig.3: X-ray spectrum of a tube with molybdenum anode

beam with a Mo-spectrum measured from fluorescence of a Mo foil clearly shows the additional background by bremsstrahlung which is missing in the fluorescence spectrum, see experiment P6.3.5.4. The result from Bragg spectroscopy P 6.3.3.1 is also very similar, but now the energy spectrum had been obtained directly.

#### Identifying the L-lines from Au:

The X-rays to be measured produce additional fluorescence X-rays in the housing of the Si-PIN photodiode of the X-ray energy detector, which are also registered. Therefore the Au  $L\alpha$  and the Au  $L\beta$  lines are to be expected in the primary spectrum apart from the Mo  $K\alpha$  and the Mo  $K\beta$  lines (see Fig. 3).

- Call the menu item "X-Ray Energies" in the pop-up menu of the diagram window, and click on the element symbol Au.
- Close the window with the "OK" button

It turns out that in addition to measured peaks for Molybdenum there are at least two Au L-lines which can be identified, i.e.  $L\alpha$  and  $L\beta$ .

#### Identifying the K-Lines from Fe

There is a lot of iron around the Si-PIN photodiode and therefore a small peak at 6,4 keV is also visible, which comes from the iron K-lines.

- Call the menu item "X-Ray Energies" in the pop-up menu of the diagram window, and click on the element symbol Fe.
- Close the window with the "OK" button

