# Atomic and nuclear physics

X-ray physics
*Physics of the atomic shell*

## Investigating the energy spectrum of an x-ray tube as a function of the high voltage and the emission current

### Objects of the experiment

■ To recorde the energy spectra of an x-ray tube with Mo anode by means of Bragg reflection of the x-radiation at an NaCl crystal in the first diffraction order.

■ To understande the energy spectra as a superpositioning of the continuum of bremsstrahlung radiation and the lines of the characteristic x-ray radiation of the anode material.

■ To investigate how the bremsstrahlung radiation and the characteristic radiation depend on the high voltage and the emission current.

## Principles

X-rays are created when fast-moving electrons are rapidly decelerated in matter. According to the laws of classical electrodynamics, this deceleration gives rise to electromagnetic radiation which is mainly radiated perpendicular to the direction of acceleration for energies below 50 keV, i.e. in this case perpendicular to the direction of the electrons striking the anode. For historical reasons, this x-ray component is referred to as "bremsstrahlung" after the German word for the deceleration process by which it occurs. The bremsstrahlung radiation has a continuous spectrum which extends to a certain maximum frequency $\nu_{max}$ or a minimum wavelength $\lambda_{min}$.

If the energy of the electrons exceeds a critical value, the characteristic x-radiation is generated, which appears in the spectrum as individual lines in addition to the continuous bremsstrahlung spectrum. These lines are generated when high-energy electrons penetrate deep into the atomic shells of the anode material and eject electrons from the innermost

orbitals by collision. The gaps created in this process are filled by electrons from the outer orbitals under emission of x-rays. The resulting x-radiation is characteristic of that anode material and is roughly comparable to the optical line spectrum of a material in a gaseous or vapor state. Solid bodies also emit individual, sharply defined lines in the x-ray range; unlike the visible light excited in the outer orbitals of the electron shell, their position is virtually independent of the chemical situation of the emitting atoms or the aggregate state of the material.

Fig. 1 serves to illustrate the nomenclature adopted for the orbital model of the atomic shell for the lines of the characteristic x-radiation: the individual orbitals are characterized by a particular binding energy and are designated from the innermost to the outermost with the letters K, L, M, N, etc. Electrons can move between the orbitals in accordance with the laws of quantum mechanics; these transitions entail either the absorption or emission of radiation, depending on the direction. For example, radiation from transitions to the K-orbital occur as a series of sequential lines designated $K_\alpha$, $K_\beta$, $K_\gamma$, etc. Starting from $K_\alpha$, the energy of the transitions increases and the corresponding wavelength decreases.

This experiment records the energy spectrum of an x-ray tube with a molybdenum anode. A goniometer with an NaCl crystal and a Geiger-Müller counter tube in the Bragg configuration together comprise the spectrometer. The crystal and counter tube are pivoted with respect to the incident x-ray beam in $2\vartheta$ coupling (cf. Fig. 2).

Fig. 1 Simplified term diagram of an atom and definition of the K, L and M series of the characteristic x-ray radiation



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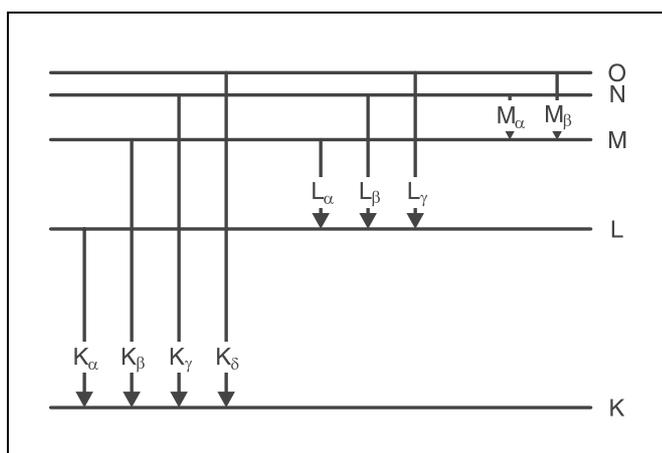
## Apparatus

1 X-ray apparatus . . . . . . . . . . . . . .     554 811

1 End-window counter
  for α, β, γ and x-ray radiation   . . . . . .     559 01

*additionally required:*
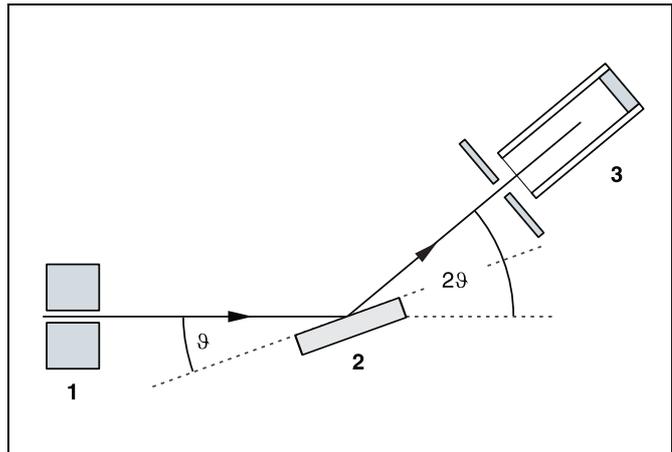
1 PC with Windows 95/98 or Windows NT



Fig. 2   Schematic diagram of diffraction of x-rays at a monocrystal and $2\vartheta$ coupling between counter-tube angle and scattering angle (glancing angle)
**1** collimator, **2** monocrystal, **3** counter tube

In accordance with Bragg's law of reflection, the scattering angle $\vartheta$ in the first order of diffraction corresponds to the wavelength

$$\lambda = 2 \cdot d \cdot \sin \vartheta \qquad (I).$$
$d = 282.01$ pm: lattice plane spacing of NaCl

Together with the relationships valid for electromagnetic radiation

$$\nu = \frac{c}{\lambda} \qquad (II)$$
$\nu$: frequency, $c$: velocity of light

and

$$E = h \cdot \nu \qquad (III)$$
$E$: energy, $h$: Planck's constant

equation (I) gives us the energy of the x-radiation. The spectrometer thus provides the wavelength, frequency or energy spectrum of the radiation, depending on the selected representation mode.

This experiment investigates the effect of the tube high voltage $U$ and the emission current $I$ on the energy spectrum of the x-ray tube. The high voltage $U$ is applied as the accelerating voltage for the electrons between the cathode and the anode (see Fig. 3). The emission current $I$, i.e. the current flowing between the anode and the cathode, can be controlled by changing the heating voltage $U_K$ of the cathode.

## Safety notes

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 (see Instruction Sheet for x-ray apparatus).

■  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.

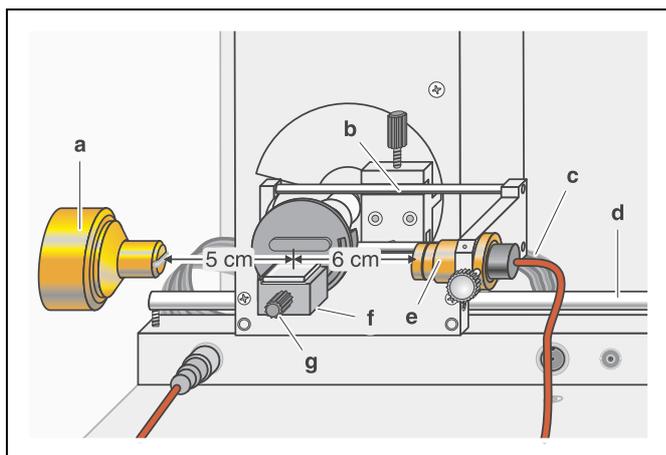Fig. 3   Schematic diagram showing the structure of the x-ray tube
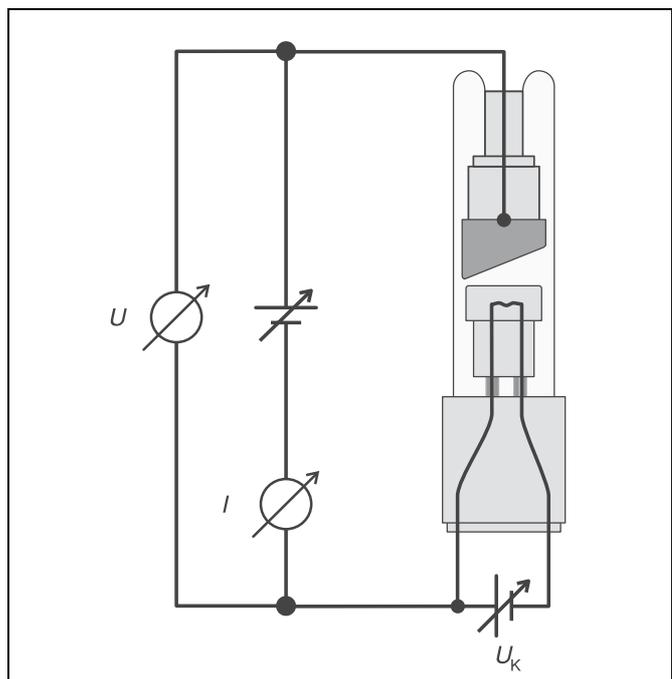
Fig. 4   Experiment setup for investigating the energy spectrum of an x-ray tube

## Setup

### Setup in Bragg configuration:

Fig. 4 shows some important details of the experiment setup. To set up the experiment, proceed as follows (see also the Instruction Sheet for the x-ray apparatus):

– Mount the collimator in collimator mount **(a)** (note the guide groove).
– Attach the goniometer to guide rods **(d)** so that the distance $s_1$ between the slit diaphragm of the collimator and the target arm is approx. 5 cm. Connect ribbon cable **(c)** for controlling the goniometer.
– Remove the protective cap of the end-window counter, place the end-window counter in sensor seat **(e)** and connect the counter tube cable to the socket marked GM TUBE.
– By moving sensor holder **(b)**, set the distance $s_2$ between the target arm and the slit diaphragm of the sensor receptor to approx. 6 cm.
– Mount target holder **(f)** with target stage.
– Loosen knurled screw **(g)**, place the NaCl crystal flat on the target stage, carefully raise the target stage with crystal all the way to the stop and gently tighten the knurled screw (prevent skewing of the crystal by applying a slight pressure).
– If necessary, adjust the zero position of the goniometer (see Instruction Sheet for x-ray apparatus).

*Notes:*

*NaCl crystals are hygroscopic and extremely 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, the distance should not be too small, as otherwise the angular resolution of the goniometer is no longer sufficient to separate the characteristic $K_\alpha$ and $K_\beta$ lines.*

### Preparing the PC-based measurement:

– Connect the RS–232 output to the serial interface on your PC (usually COM1 or COM2) using the 9-pin V.24 cable (supplied with x-ray apparatus).
– If necessary, install the software "X-ray Apparatus" under Windows 95/98/NT (see Instruction Sheet for x-ray apparatus) and select the desired language.

## Carrying out the experiment

### a) Varying the tube high voltage:

– 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 ⬚ or the F4 key.
– Set the emission current $I$ = 1.00 mA, the measuring time per angular step $\Delta t$ = 10 s and the angular step width $\Delta\beta$ = 0.1°.
– Press the COUPLED key to activate $2\vartheta$ coupling of target and sensor and set the lower limit of the target angle to 2.5° and the upper limit to 12.5°.
– Set the tube high voltage $U$ = 15 kV and start measuring and data transmission to the PC by pressing the SCAN key.
– Conduct additional measurement series using the tube high voltages $U$ = 20 kV, 25 kV, 30 kV and 35 kV.

To show the wavelength-dependency, open the "Settings" dialog with the button ⬚ or F5 and enter the lattice plane spacing for NaCl.

Save the measurement series under an appropriate name by pressing the button ⬚ or the F2 key.

### b) Varying the emission current:

Clear existing measurement data using the button ⬚ or the F4 key and set the tube high voltage to $U$ = 35 kV.

– Set the emission current $I$ = 0.40 mA and start measuring and data transmission to the PC by pressing the SCAN key.
– Record additional measurement series using the emission currents $I$ = 0.60 mA, 0.80 mA and 1.00 mA.
– To show the wavelength-dependency, open the "Settings" dialog with the button ⬚ or F5 and enter the lattice plane spacing for NaCl.
– Save the measurement series under an appropriate name by pressing the button ⬚ or the F2 key.

## Measuring example

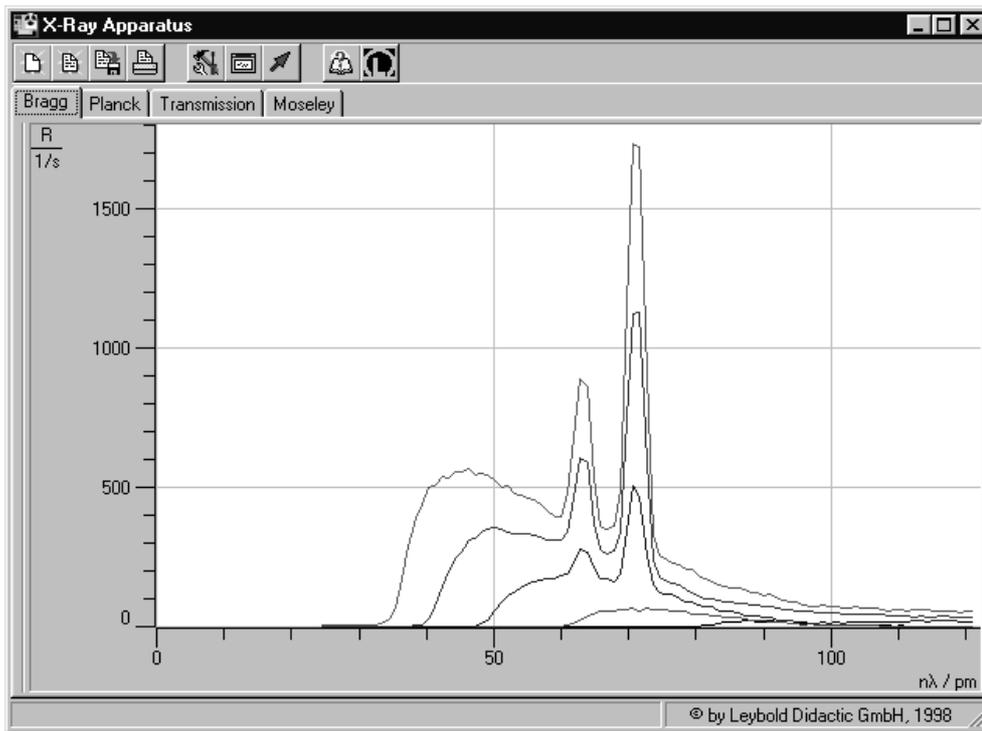**a) Varying the tube high voltage:**



Fig. 5   Spectra of x-ray tube Mo for tube high voltages $U$ = 15 kV (bottom), 20 kV, 25 kV, 30 kV, 35 kV (top);
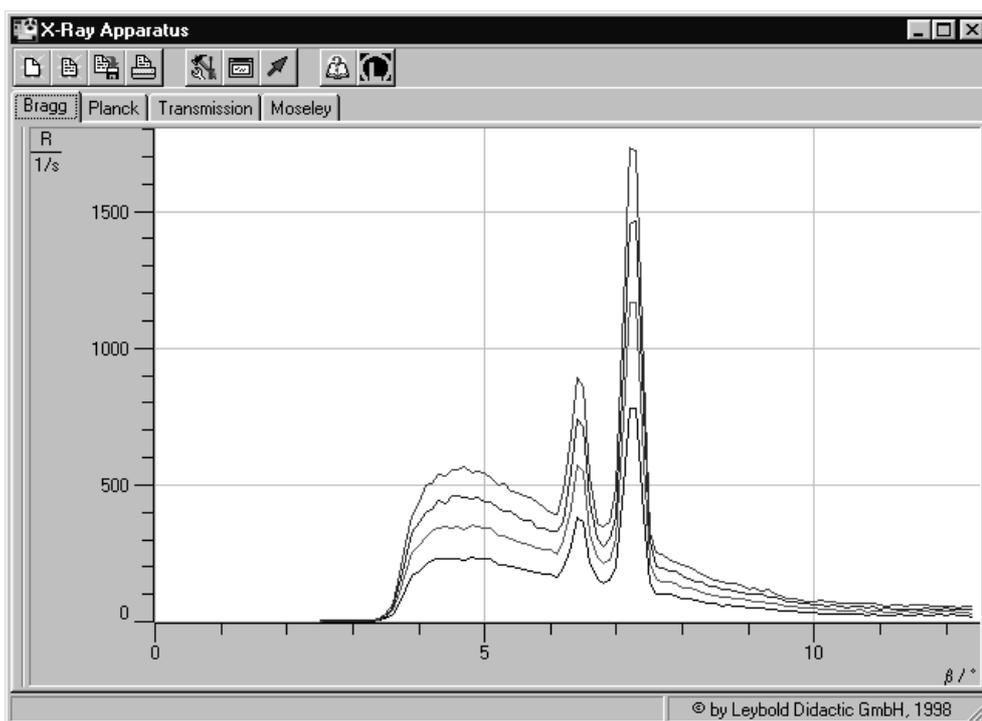
**b) Varying the emission current:**



Fig. 6   Spectra of x-ray tube Mo for emission currents $I$ = 0.4 mA (bottom), 0.6 mA, 0.8 mA, 1.0 mA (top); x-ray high voltage $U$ = 35 kV.

## Evaluation

### a) Varying the tube high voltage:

– Load the saved measurement series.
– Place the cursor in each diagram, click the right mouse button to access the evaluation functions of the software "X-ray Apparatus" and, for each curve, select "Calculate Peak Center" and mark the "full width" of the peak with the left mouse button.
– Write down the peak centers in a measuring table (see table 1) and calculate the mean values.

Tab. 1: Wavelengths of the characteristic radiation of molybdenum determined from the spectra under variation of the tube high voltage $U$

| $\dfrac{U}{kV}$ | $\dfrac{\lambda(K_\alpha)}{pm}$ | $\dfrac{\lambda(K_\beta)}{pm}$ |
|---|---|---|
| 25 | 71.04 | 62.13 |
| 30 | 71.09 | 63.14 |
| 35 | 71.04 | 63.10 |

Mean values:

$\lambda(K_\alpha)$ = 71.06 pm, $\lambda(K_\beta)$ = 63.12 pm

Literature values [1] for comparison:

$\lambda(K_\alpha)$ = 71.080 pm, $\lambda(K_\beta)$ = 63.095 pm

### b) Varying the emission current:

– Load the saved measurement series.
– Place the cursor in each diagram, click the right mouse button to access the evaluation functions of the software "X-ray Apparatus" and, for each curve, select "Calculate Peak Center" and mark the "full width" of the peak with the left mouse button.
– Write down the peak centers in a measuring table (see table 2) and calculate the mean values.
– Now select the menu command "Display Coordinates", find the maxima $R(K_\alpha)$ and $R(K_\beta)$ of the characteristic lines, and determine the maximum of the continuum of bremsstrahlung radiation $R_C$ and write it down (see table 3) and display it in the graph (see Fig. 7).

Fig. 7 Counting rates as a function of the emission current
　　　Circles: $K_\alpha$-line
　　　Squares: $K_\beta$-line
　　　Triangles: bremsstrahlung continuum
　　　Lines: straight lines through origin
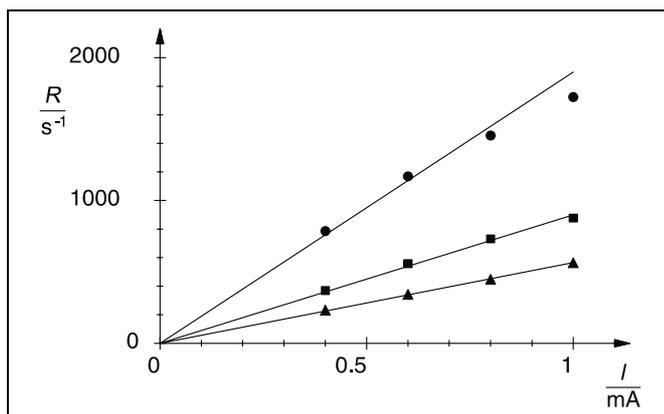


Tab. 2: Wavelengths of the characteristic radiation of molybdenum determined from the spectra under variation of the emission current $I$

| $\dfrac{I}{mA}$ | $\dfrac{\lambda(K_\alpha)}{pm}$ | $\dfrac{\lambda(K_\beta)}{pm}$ |
|---|---|---|
| 0.4 | 71.09 | 63.15 |
| 0.6 | 71.05 | 63.15 |
| 0.8 | 71.08 | 63.15 |
| 1.0 | 71.04 | 63.10 |

Mean values:

$\lambda(K_\alpha)$ = 71.07 pm, $\lambda(K_\beta)$ = 63.14 pm

Tab. 3: Counting-rate maxima of the characteristic lines and the bremsstrahlung continuum as a function of the emission current $I$

| $\dfrac{I}{mA}$ | $\dfrac{R(K_\alpha)}{s^{-1}}$ | $\dfrac{R(K_\beta)}{s^{-1}}$ | $\dfrac{R_C}{s^{-1}}$ |
|---|---|---|---|
| 0.4 | 786 | 369 | 232 |
| 0.6 | 1169 | 558 | 343 |
| 0.8 | 1455 | 731 | 448 |
| 1.0 | 1724 | 877 | 564 |

## Results

### a) Varying the tube high voltage:

Fig. 5 clearly shows how the continuum of bremsstrahlung changes as the tube high voltage $U$ increases. The intensity of the radiation increases, as the electrons generate more x-ray quanta on deceleration as the energy increases. The limit wavelength $\lambda_{min}$ is shifted to smaller values, i. e. higher-energy, "harder" radiation is generated. For quantitative investigation of the relationship between the limit wavelength and the tube voltage see experiment P6.3.3.3.

A minimum energy of the electrons is required to excite the characteristic energy. The $K_\alpha$ and $K_\beta$ lines thus only become apparent above $U$ = 20 kV. Their intensity increases with the tube high voltage. However, the tube high voltage has no effect on the positions of the characteristic lines (see table 1).

### b) Varying the emission current:

As we can see from Fig. 6, the emission current $I$ has no effect on the shape of the x-ray spectrum. The positions of the characteristic lines remain unchanged (see table 2). However, the intensity of the bremsstrahlung spectrum and the characteristic lines decreases proportionally with the emission current (see table 3 and Fig. 7). Deviations from this proportionality at counting rates above 1000 $s^{-1}$ are due to dead-time effects in counting-rate measurements.

## Literature

[1] C. M. Lederer and V. S. Shirley, Table of Isotopes, 7th Edition, 1978, John Wiley & Sons, Inc., New York, USA.