X-ray absorption spectrum

Spectral decomposition of a copper anode X-ray with Bragg's rotating crystal method; determining the wavelength λ and the energy E of the characteristic radiation K_α and K_β:

$$\lambda = 2\,d \cdot \sin\theta \qquad (1)$$

$$E = \frac{h \cdot c}{\lambda} \qquad (2)$$

d: Grating constant of Bragg's crystal
θ: Bragg's reflection angle
h: Planck's action quantum
c: Speed of light

Examining the influence of characteristic radiation on absorbers made out of varying materials, whose binding energies are in the K-shell near the radiation K_α and K_β energies.

X-radiation (electromagnetic wave radiation) becomes weaker in material because of classical scattering (radiation quantums change direction without giving up energy to the irradiated material), Compton scattering (energy of a quantum is partially given off to freely or loosely-bound electrons, giving a scattering radiation with low energy) and by absorption. Quantum energy is partially "used up" to release an electron out of the atomic shell during absorption; the released electron takes on the remaining energy as kinetic energy (photoelectric absorption).

The absorption capacity of a material is described by the absorption coefficient τ_A. It depends on

the atomic number Z of the absorber material and on the wavelength λ of the radiation:

$$\tau_A \sim Z^4\ \lambda^3$$

This equation does not apply when the energy of the radiation approaches the electron bonding energy of the absorbed material. If the radiation energy is a little smaller than the bonding energy, then there is low absorption; if the energy suffices to just detach the electron, then the absorption capacity increases radically.

The corresponding wavelength is called the absorption edge. By taking into consideration the relationship between the energy E and the wavelength λ,

$$\lambda \sim \frac{1}{E}$$

we obtain the relationship shown schematically in Fig. 1 between the absorption coefficient τ_A and the wavelength of the radiation.

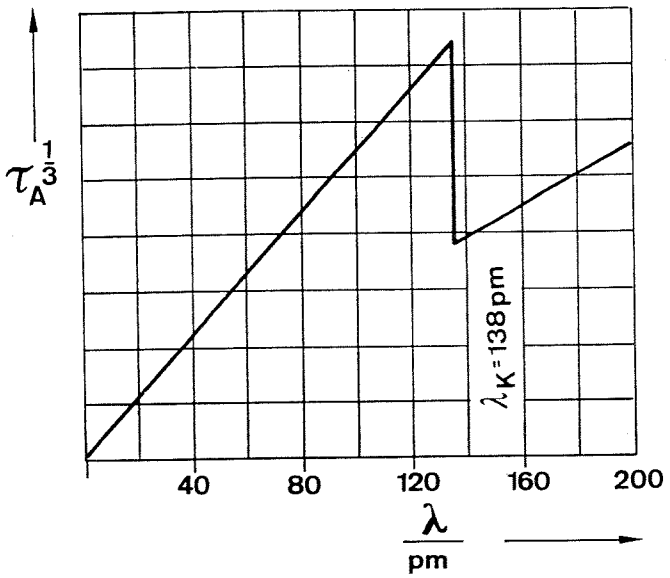

Fig. 1: Absorption coefficient τ_A as a function of wavelength λ for copper

Particularly strong absorption occurs when the wavelength of the radiation is somewhat smaller than the absorption edge, which has a characteristic size for every element in every shell of the atomic nucleus.
The absorber materials for the experiment have been chosen so that the significance of the absorption edge for the characteristic K_α and K_β radiation of an X-ray tube with copper anode can be examined.

Table 1

Element	Atomic number Z	Binding energy E_K	K-absorption edge λ_K
Co	27	7,7 keV	161 pm
Ni	28	8,3 keV	149 pm
Cu	29	9 keV	138 pm
Zn	30	9,7 keV	128 pm

Apparatus:

1 X-ray apparatus P		554 61
1 Copper filter	from basic accessories	554 66
1 Zinc filter		
1 Nickel filter		
1 Cobalt filter		
1 LiF-monocrystal		
1 Collimator split		
1 Aperture slit, 1 mm		
1 Aperture slit, 3 mm		
1 Accessory magazine		
1 Counter tube socket with cable (for 554 61)		554 63
1 End-window counter for β, γ and X-rays		559 05
1 Rate meter		575 52
1 TY-recorder, 1 channel		575 70
1 Roll of recording paper		575 73
Approx. 60 cm of fishing line ..... from		309 48
1 Connecting lead, 1 m, red		501 30
1 Connecting lead, 1 m, blue		501 31

Additionally necessary:
Adhesive tape

Important:

⚠
- Handle the end-window counter very carefully
- Remove the protective cap very carefully and put it back on after finishing the experiment.
- Protect the sensitive mica window from mechanical damage. Do not touch it!
- Consult the information given in the book "X-ray physics in student experiments" (554 661) so that you operate the X-ray apparatus P properly.

Setting up:

Preparing the X-ray apparatus:

Perpendicularly place the collimator slit into the outlet opening for the beams of the lead crystal protective screen (a) and clamp the accessory magazine (b) onto the collimator holder;
After having attached the counter cable, put the counter in the counter holder and center it at the positions marked "22" and "25";
Insert the 3 mm aperture slit at the position marked "4" and the 1 mm aperture slit at the position marked "18";
Clamp the LiF monocrystal (c) carefully into the crystal holder (see sketch 1 in Fig. 2).

High voltage: 30 kV (switch (d)).

Before closing the X-ray apparatus, place the counter cable in the experimental chamber so that it does not hinder the movement of the measuring arm during spectra recording.

Create a traction apparatus for the measuring arm of the X-ray apparatus from a strip (approx. 80 cm x 2 cm) of perforated TY-recorder-recording paper and approx. 60 cm of fishing line. Shove the paper strip (f) under the cover (e), and with the clamping plate (g) lifted, lay it exactly over the counting wheels of the recorder transport apparatus, so that the edge of the recorder's paper and strip coincide exactly; carefully attach the strip (f) to the recorder's paper with adhesive tape and properly snap in the clamping plate; attach the fishing line to the other end of the strip with adhesive tape; guide the fishing line below the cover around the casing of the X-ray apparatus to the measuring arm, so that the movement of the transport wheel (h) is not influenced (check this!); align the recorder and the X-ray apparatus as shown in Fig. 2.

Settings on recorder:
1 V/cm, var.; 1 mm/s

Settings on rate meter:
Counting tube (control (i)):
approx. 450 V

Proportionality factor for output voltage (control (j)):
100 Imp. s^{-1} V^{-1}

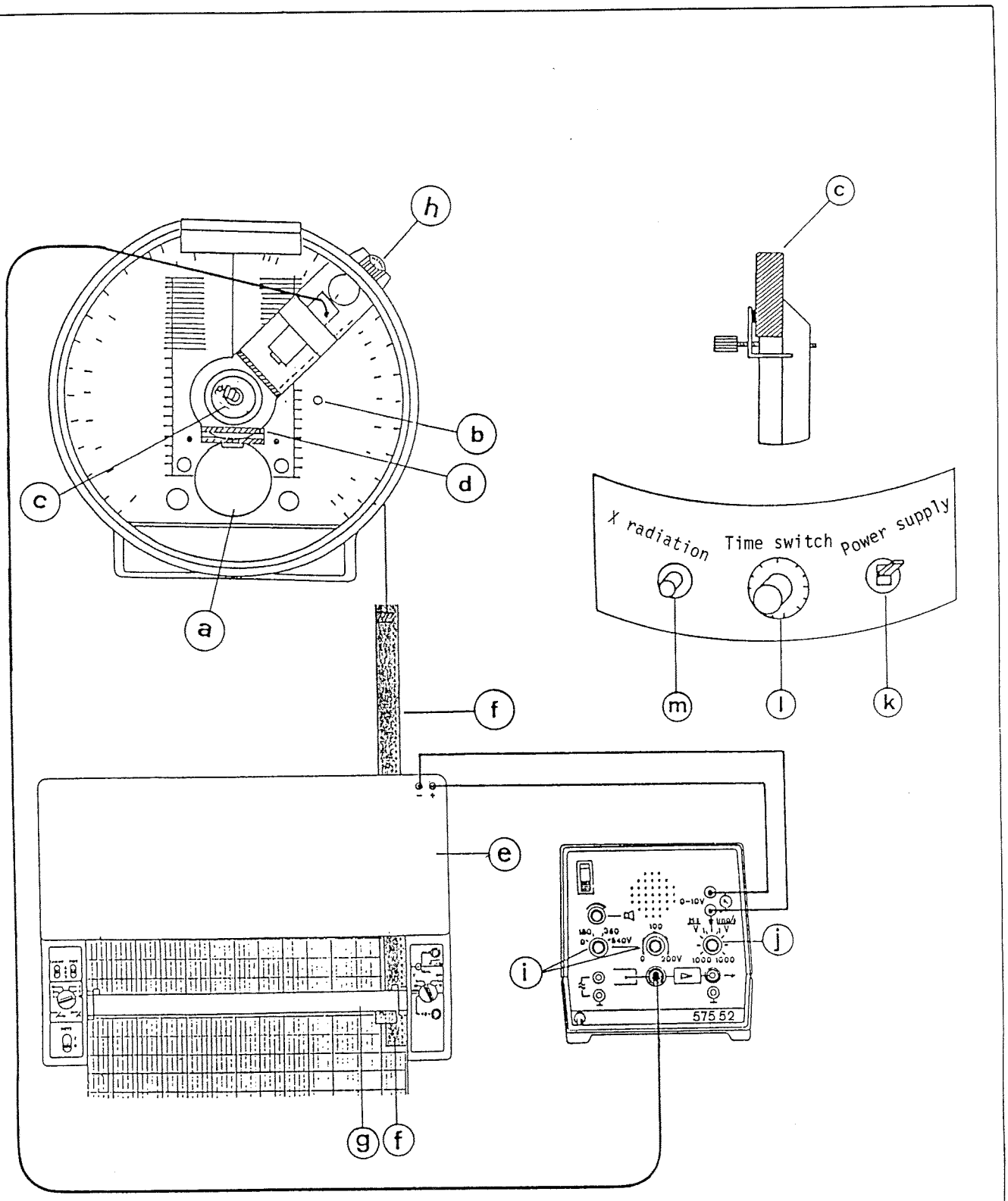

Fig. 2:

Experiment setup
to
record
X-ray spectra

Carrying out the experiment:

Important: The high voltage can only be turned on when the cover is closed properly (should be snapped in during horizontal displacement) and when time is preselected on clock (l) with key (m) (red lamp shows when it is turned on)

1.1 Put the measuring arm in the position with the smallest angle and, if necessary, stretch the traction arrangement by operating the paper feed on the recorder for a short time. Operate the X-ray apparatus by turning on the mains supply (k), preselect a time (for example 30 min) on clock (l) and press the high voltage pushbutton (m).

Lower the recorder pen and start the paper feed;
observe the recording of the spectrum and take a reading of the angles $2\theta_\beta$ and $2\theta_\alpha$

between the measuring area and the bundle axis of the X-rays on the angle scale of the X-ray apparatus when the intensity maxima of K_β and K_α have been reached. Stop

the paper feed and lift the recorder pen when the K_α line is completely recorded.

1.2 If necessary, repeat the recording with a changed recorder sensitivity, until the height of the K_α line is adapted to the width of the paper.

Important: Do not change the recorder sensitivity any more!

2.1 Open the X-ray apparatus (undo the lock by moving the cover)and bringing the Cu-filter at position mark "2" into the path of the rays.
Close the X-ray apparatus properly and turn on the X-rays by pressing pushbutton m;
record the absorption spectrum as described in Section 1.1.

2.2 Repeat experiment part 2.1 with the other filters (Zn, Ni, Co).

Measuring example:

Fig. 3
Spectra of X-rays (tube with copper anode)

3.1	Unfiltered	
3.2-3.5	after absorption by	
3.2	copper	filter
3.3	zinc	
3.4	nickel	
3.5	cobalt	

θ: Bragg's angle after reflection on a lithium-fluoride monocrystal
N: pulse rate

Fig. 3:

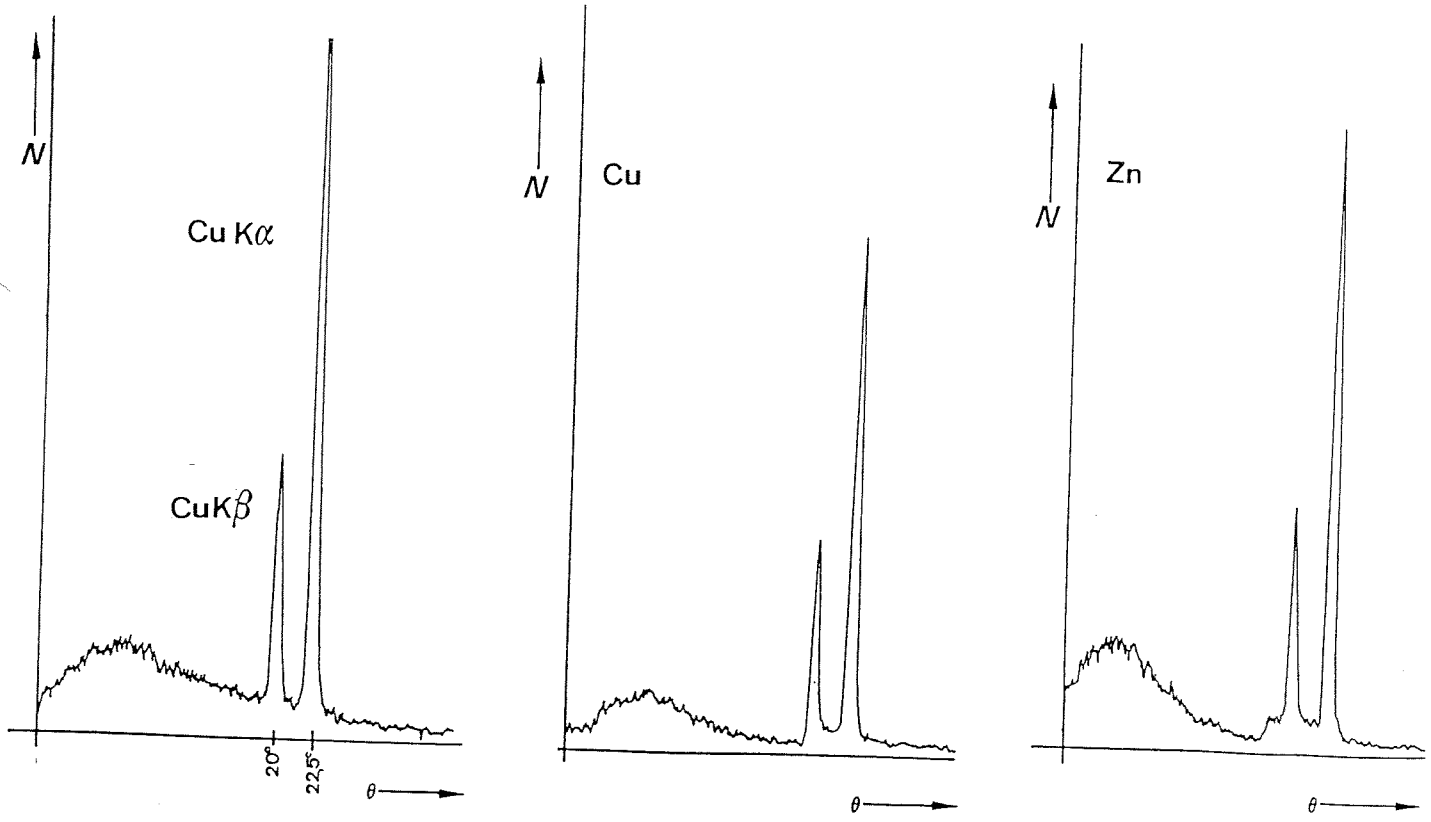

Fig 3.1

Fig. 3.2

Fig. 3.3

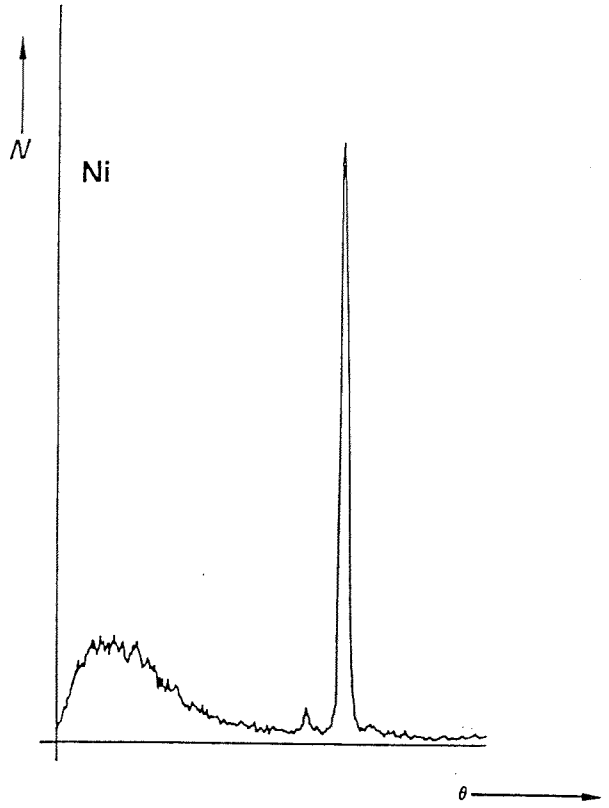

Fig. 3.4

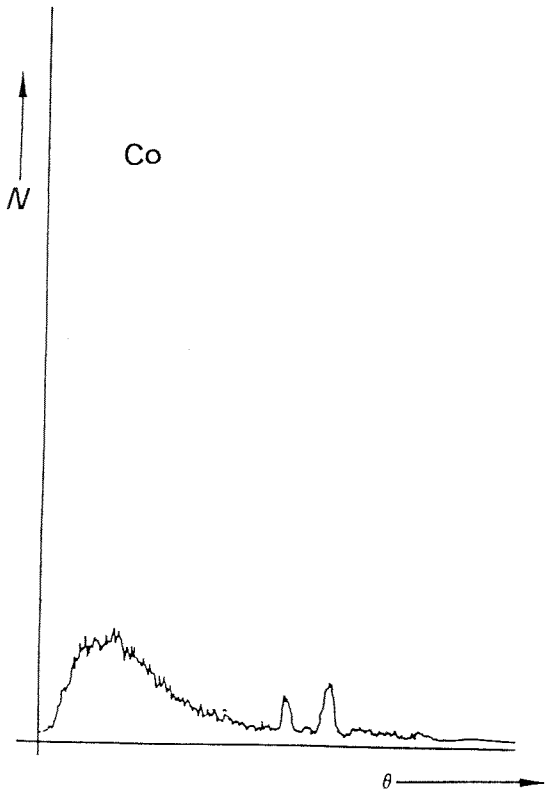

Fig. 3.5

Evaluation and results:

1. The absorption spectra (Fig. 3.2 - Fig. 3.5) have the same progression for X-rays as for the spectrum recorded without absorber (Fig. 3.2): continuous braking spectrum and line spectrum of characteristic radiation.

2. The characteristic radiation of all spectra is recorded spectroscopically with the same Bragg's angle:

$$2\Theta_\alpha = 45°$$
$$2\Theta_\beta = 40°$$

The wavelength λ and Energy E of the characteristic radiation were thus not changed when passing through the material (because of (1) and (2)).

From (1) and (2)

$$\lambda = 2d \cdot \sin\theta \qquad (1)$$

$$E[\text{keV}] = \frac{h \cdot c}{\lambda} \cdot \frac{1}{e} \qquad (2)$$

$\frac{1}{e}$: Conversion factor between [J] and [eV]

we obtain the results with

$$2\,d(\text{LiF}) = 403 \text{ pm}$$
$$\theta_\alpha = 22{,}5°$$
$$\theta_\beta = 20°$$
$$h = 6{,}626 \cdot 10^{-34} \text{ J s}$$
$$c = 3 \cdot 10^8 \text{ m s}^{-1}$$
$$e = 1{,}6 \cdot 10^{-19} \text{ A s:}$$

$\lambda_\alpha = 154$ pm ; $\lambda_\beta = 138$ pm
$E_\alpha = 8{,}1$ keV ; $E_\beta = 9$ keV

3. The intensity of the characteristic radiation decreases when it passes through the material. The intensity decrease is dependent on the absorber material as well as on wavelength and therefore is also dependent on the energy of the radiation. The spectra in Fig. 3.2 to Fig. 3.5 confirm the theory about the absorption capacity of materials whose absorption edges λ_K or K-binding energy E_K lie right next to the wavelength λ_α and λ_β or energies E_α and E_β of the characteristic radiation (compare table 1 as well as section 2 of the λ- and E-calculation.

Zinc and copper (Fig. 3.2/3) weaken the characteristic radiation only slightly

$\lambda_K < \lambda_\alpha, \lambda_\beta$; $E_K > E_\alpha, E_\beta$;

Cobalt absorbs (Fig. 3.5) the radiation almost completely

$\lambda_K > \lambda_\alpha, \lambda_\beta$; $E_K < E_\alpha, E_\beta$;

Nickel (Fig. 3.4) absorbs the K_β radiation almost completely, whereas the K_α radiation penetrates the filter almost completely without attentuation.

$\lambda_K < \lambda_\alpha$; $E_K > E_\alpha$

$\lambda_K > \lambda_\beta$; $E_K < E_\beta$.