Absorption of X-rays (Item No.: P2541101)

Curricular Relevance

Area of Expertise: ILIAS
Education Level: Physik
Topic: Hochschule
Subtopic: Moderne Physik
Experiment: Röntgenphysik

Difficulty	**Preparation Time**	**Execution Time**	**Recommended Group Size**
Difficult	1 Hour	2 Hours	2 Students

Additional Requirements:

- PC

Experiment Variations:

Keywords:

Bremsstrahlung, characteristic X-radiation, Bragg scattering, law of absorption, mass absorption coefficient, absorption edges, half-value thickness, photoelectric effect, Compton effect, pair production

Overview

Short description

Principle

The polychromatic X-radiation that is emitted by an X-ray tube is filtered in terms of its energy with the aid of a monocrystal. The resulting monochromatic radiation is used as the primary radiation source for examining the absorption behaviour of various metal foils of different thicknesses.

This experiment is included in the "XRP 4.0 X-ray solid state" and "XRC 4.0 X-ray characteristics" up-grade sets. Optionally, a tungsten tube (09057-80) can be used for the experiment.

Fig. 1: P2541101

Equipment

Position No.	Material	Order No.	Quantity
1	XR 4.0 expert unit, X-ray unit, 35 kV	09057-99	1
2	XR 4.0 X-ray goniometer	09057-10	1
3	XR 4.0 X-ray Plug-in Cu tube	09057-51	1
4	Geiger-Mueller counter tube, 15 mm (type B)	09005-00	1
5	XR 4.0 X-ray LiF crystal, mounted	09056-05	1
6	XR 4.0 X-ray Absorption set for X-rays	09056-02	1
7	XR 4.0 Software measure X-ray	14414-61	1
8	XR 4.0 X-ray Diaphragm tube d = 2 mm	09057-02	1
9	Data cable USB, plug type A/B, 1.8 m	14608-00	1

Tasks

1. Determine the attenuation of the X-radiation by aluminium and zinc foils of different thicknesses and at two different wavelengths of the primary radiation.
2. Determine the mass absorption coefficient μ/ρ for aluminium, zinc, and tin absorbers of constant thickness as a function of the wavelength of the primary radiation. Prove the validity of $\mu/\rho = f(\lambda^3)$ in a graphical manner.
3. Determine the absorption coefficients μ for copper and nickel as a function of the wavelength of the primary radiation. Determine the energy values of the corresponding K shells based on the graphical representation. Prove the validity of $\mu/\rho = f(\lambda^3)$.

Set-up and procedure

Set-up

Connect the goniometer and the Geiger-Müller counter tube to their respective sockets in the experiment chamber (see the red markings in Fig. 2). 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. 3).

Insert a diaphragm tube with a diameter of $2\,mm$ into the beam outlet of the tube plug-in unit for the collimation of the X-ray beam.

Fig. 2: Connectors in the experiment chamber

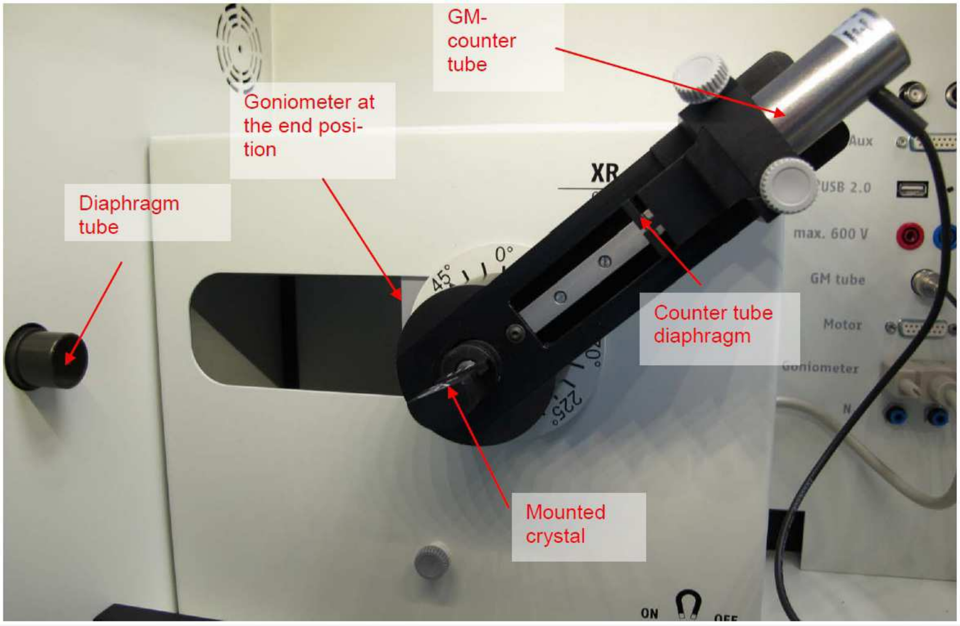


Fig. 3: Set-up of the goniometer

Note
Details concerning the operation of the X-ray unit and goniometer as well as information on how to handle the monocrystals can

be found in the respective operating instructions.

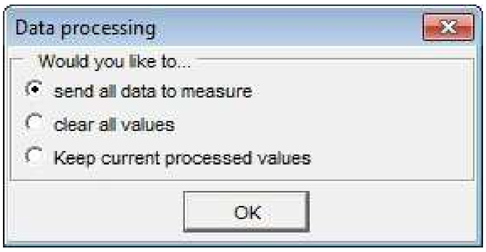
Procedure

- Connect the X-ray unit via USB cable to the USB port of your computer (the correct port of the X-ray unit is marked in Fig. 4).

Fig. 4: Connection of the computer

- Start the “measure” program. A virtual X-ray unit will be displayed on the screen (Fig. 5).
- 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.
- Click the experiment chamber (see the red marking in Fig. 5) to change the parameters for the experiment.
- If you click the X-ray tube (see the red marking in Figure 5), you can change the voltage and current of the X-ray tube. Select the settings as shown in Figure 6.
- Start the measurement by clicking the red circle:

- After the measurement, the following window appears:



Data processing

Would you like to...

● send all data to measure

○ clear all values

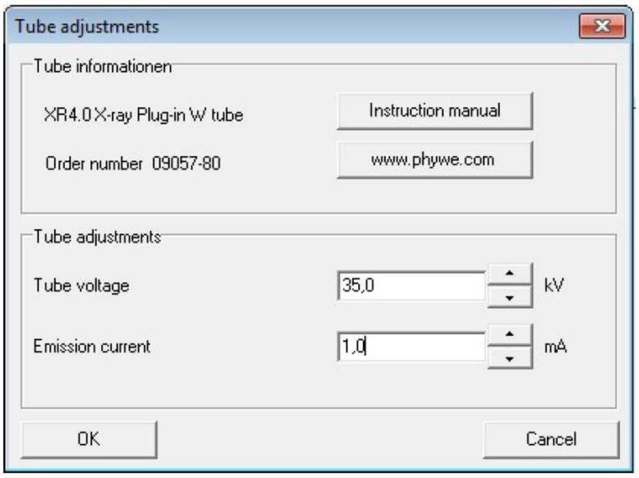
○ Keep current processed values

OK

- 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 a short introduction to the evaluation of data using the program “measure” is given.

Note
Never expose the Geiger-Müller counter tube to the primary X-radiation for an extended period of time.

Fig. 5: Part of the user interface of the software



Tube informationen

XR4.0 X-ray Plug-in W tube

Order number 09057-80

Tube adjustments

Tube voltage 35,0 kV

Emission current 1,0 mA

Fig 6: Voltage and current settings

Task 1: Absorption of X-rays as a function of the material thickness.

The absorption set includes aluminium and tin foils of various different thicknesses. They are fastened to the Geiger-Müller counter tube by pushing them into the diaphragm that is installed in front of the counter tube. Manually select two different glancing angles for which the intensity is determined first without an absorber (I0) and then with an absorber (I). In the case of copper, suitable angular positions are, for example, 20.4° (K_β line) (or 21.5° in the case of tungsten, $\alpha_{1/2}$ line) and approximately 10° (in the range of the bremsstrahlung). Then, note down the corresponding pulse rates without an absorber and with the zinc and aluminium absorber of the “absorption set for X-rays”. In order to vary the thickness of the absorbers, it is also possible to use two foils at the same time.

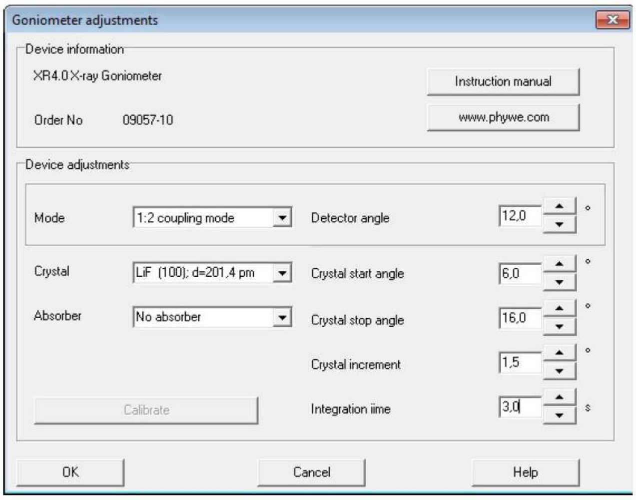
In order to keep the relative errors of the meas-urement values as small as possible, the meas-urement should be performed up to an intensity of $I \leq 1000\,\text{pulses}^{-1}$. In general, this requires measurement times of at least $50\,s$ (integration time, gate timer).

The recording of the X-ray spectrum of the copper anode is described in greater detail in P2540101.

Task 2: Determination of the mass absorption coefficient for a constant material thickness and as a function of the wavelength of the X-radiation.

For this task, you will need the aluminium foil $d = 0.08\,mm$ and the tin foil $d = 0.025\,mm$. Now, while using only one of the foils at a time, record a spectrum at an interval of $6^\circ < \vartheta < 16^\circ$ and in steps of $\Delta\vartheta = 1^\circ$ - 2°. The measuring time should be

$50\,s$ minimum (integration time, gate timer). Goniometer settings: see Figure 7. In order to determine I_0, record a third spectrum without any absorber at all. Following the conversion of the glancing angle into the associated wavelength λ, you will obtain the absorption as a function of λ.


Goniometer adjustments

Device information

XR4.0 X-ray Goniometer

Order No 09057-10

Device adjustments

Mode: 1:2 coupling mode

Detector angle: 12,0 °

Crystal: LiF (100); d=201,4 pm

Crystal start angle: 6,0 °

Absorber: No absorber

Crystal stop angle: 16,0 °

Crystal increment: 1,5 °

Integration iime: 3,0 s

Fig. 7: Goniometer settings for task 2

Task 3: Determination of the absorption coefficient μ for copper and nickel as a function of the wavelength of the primary radiation.

Proceed as described for task 2 with the copper and nickel foils with a diameter of $d = 0.025\,mm$. Record the spectra at an interval of $6^\circ < \vartheta < 25^\circ$ and in steps of $\Delta\vartheta = 1^\circ$. The measuring time should be $50\,s$ minimum (integration time, gate timer). In the area of the absorption edges, it is also possible to work with smaller angle step widths in order to better reproduce the behaviour. This part of the experiment can be performed with an anode voltage of $35\,kV$. An anode voltage of 20 to $25\,kV$, however, provides better results. On the other hand, the integration time must be increased considerably in this case.

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

Task 1

- Anode voltage $U_A = 35\,kV$; anode current $I_A = 1\,mA$

Task 2

- $2{:}1$ coupling mode
- Integration time $50\,s$ (gate time); angle step width 1°- 2°
- Scanning range: 6°- 16°
- Anode voltage $U_A = 35\,kV$, anode current $I_A = 1\,mA$

Task 3

- $2{:}1$ coupling mode
- Integration time $50\,s$ (gate time); angle step width 1°
- Scanning range: 6°- 25°
- Anode voltage $U_A = 20 - 35\,kV$, anode current $I_A = 1\,mA$

Theory and evaluation

If X-rays with intensity I_0 penetrate matter of the layer thickness d, then the intensity I of the radiation that passes through the matter is:

$$I = I_0\, e^{-\mu(\lambda,Z)\cdot d} \qquad (1)$$

The absorption coefficient $\mu\,[cm^{-1}]$ is dependent on the wavelength λ (energy) of the X-radiation and on the atomic number Z of the absorber. This relationship enables the direct determination of the absorption coefficient:

$$-\frac{\ln \frac{I}{I_0}}{d} = \mu$$

In order to be able to directly compare the absorption behaviour of various materials, it is advantageous to use the so-called half-value thickness $d_{1/2}$. Absorbers of this thickness reduce the intensity of the primary radiation by half.

$$d_{1/2} = 0.69\frac{1}{\mu} \qquad (2)$$

Since the absorption is proportional to the mass of the absorber, the mass absorption coefficient μ/ρ (density $\rho\,[gcm^{-3}]$ is often used instead of the linear absorption coefficient μ.

The following processes are responsible for the absorption:

1. photoelectric effect

2. scattering (Compton effect)

3. pair production

Pair production, however, requires a certain threshold energy that corresponds to twice the amount of the electron rest energy ($2E_0 = 2m_0c^2 = 1.02\,MeV$). As a result, the absorption coefficient only comprises two components:

$$\mu = \tau_{textphotoelectriceffect} + \sigma_{\text{scattering}} \qquad (3)$$

In addition, the following applies to the available energy range of the radiation: $\tau > \sigma$

The dependence of the mass absorption coefficient on the primary radiation energy and on the atomic number Z of the absorber is described with sufficient precision by the following (empirical) relationship:

$$\frac{\tau}{\sigma} \approx \frac{\mu}{\rho} = k(\lambda^3 \cdot Z^3) \qquad (4)$$

The numerical value of the constant k in equation (4) only applies to the wavelength range $\lambda < \lambda_K$, whereby λ_K is the wavelength corresponding to the energy of the K level. For the range $\lambda_K < \lambda$, another k value applies.

In accordance with (4), the absorption increases drastically with the wavelength as well as the atomic number of the absorbing element.

The X-ray tube emits polychromatic radiation. A monocrystal is used to transform this radiation into monochromatic primary radiation for the absorption experiments. When X-rays impinge on the lattice planes of the monocrystal, they will only be reflected if the Bragg condition (5) is fulfilled.

$$2d\sin\vartheta = n\lambda;\ (n = 1, 2, 3, \ldots) \qquad (5)$$

$\vartheta =$ glancing angle
$d = 201.4\,pm$; interplanar spacing **LiF** (200)

In the case of lower intensities, the background radiation must be taken into consideration at $U_A = 0\,kV$. At high counting rates, the true pulse rate N results from the measured rate N^* if the dead time τ of the Geiger-Müller counter tube is taken into consideration.

$$N = \frac{N^*}{1\tau N^*} \text{ (with } \tau = 90\,\mu s) \qquad (6)$$

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Task 1: Absorption of X-rays as a function of the material thickness.

Figure 8 shows the pulse rate ratio I/I_0 for different thicknesses d of the absorbers aluminium and zinc. Curves 1 and 2 apply to aluminium ($Z = 13, \rho = 2.7\,g/cm^3$) and curve 3 to zinc ($Z = 30, \rho = 7.14\,g/cm^3$). When the absorber thickness increases, the intensity that is let through decreases exponentially (1). It is also apparent that

- for the same primary radiation energy (wavelength), the absorption increases when the atomic number of the absorber increases (curves 1 and 3).
- for an increasing primary radiation energy, the absorption decreases in the same absorber material (curves 1 and 2).

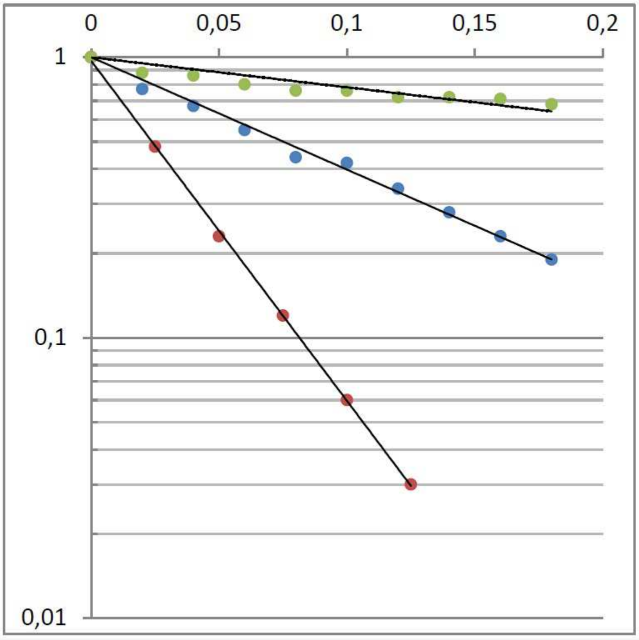
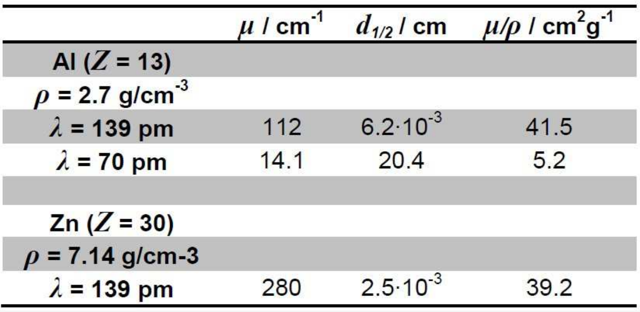


Fig. 8: Semi-logarithmic representation of the quotient I/I_0 as a function of the absorber thickness d $U_A = 35\,kV, I_A = 1\,mA,$ Curves 1 and 2: Al $(Z = 13); \lambda = 139\,pm,$ Curve 3 : Al $(Z = 13); \lambda = 70\,pm$

The results of Figure 8, which can be obtained from equations (1) and (5), are listed in table 1. For aluminium, the dependence of the absorption on the wavelength ($\mu/\rho = f(\lambda^3)$) is confirmed in an exemplary manner:

$$\frac{\mu_1/\rho}{\mu_2/\rho} = 7.98; \left(\frac{\lambda_1}{\lambda_2}\right)^3 = 7.83$$

The Z dependence of the mass absorption coefficient in accordance with (4) cannot be determined here, since the primary radiation energy lies within the K level of zinc. Equation (4) is only valid outside of the absorption edges.



	μ / cm^{-1}	$d_{1/2}$ / cm	μ/ρ / cm^{2}g^{-1}
Al (Z = 13)			
ρ = 2.7 g/cm^{-3}			
λ = 139 pm	112	$6.2\cdot10^{-3}$	41.5
λ = 70 pm	14.1	20.4	5.2
Zn (Z = 30)			
ρ = 7.14 g/cm-3			
λ = 139 pm	280	$2.5\cdot10^{-3}$	39.2

Table 1: Dependence of the absorption on the wavelength

Task 2: Determination of the mass absorption coefficient for a constant material thickness and as a function of the wavelength of the X-radiation.

Following the conversion of the glancing angle to the associated wavelength λ in accordance with (5), you will obtain the absorption as a function of λ. Formula (1) can now be used to determine μ and – as a next step – the mass absorption coefficient μ/ρ. If one plots $\sqrt[3]{\mu/\rho}$ as a function of the wavelength in pm, straight lines, like the ones shown in Figure 9, will result. These straight lines represent the correlation $\mu/\rho = f(\lambda^3)$.

Figure 9 shows the course of $\mu/\rho = f(\lambda^3)$ for aluminium and tin ($Z = 50, \rho = 7.28\,gcm^{-3}$).

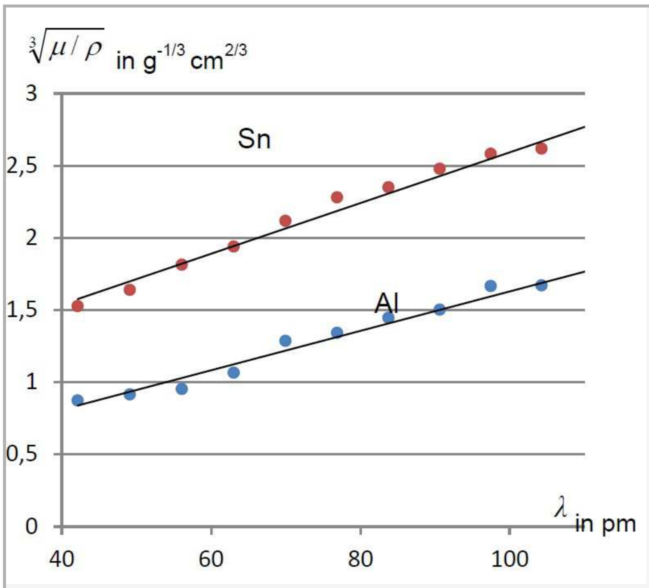


Fig. 9: $\sqrt[3]{\mu/\rho}$ for aluminium and tin as a function of the primary radiation energy; $U_A = 25\,kV$.

Task 3: Determination of the absorption coefficient μ for copper and nickel as a function of the wavelength of the primary radiation.

Figures 10 and 11 show the absorption behaviour of copper ($Z = 29, \rho = 8.96\,gcm^{-3}$) and nickel ($Z = 28, \rho = 8.99\,gcm^{-3}$). In both cases, the correlation $\mu/\rho = f($\(λ^3)\) is shown in the areas where $\lambda \neq \lambda_K$. However, at the so-called absorption edges where $\lambda = \lambda_K$, the absorption changes abruptly since now the associated primary radiation energy can ionise the relevant atoms on the K shell.

Both curves deviate from the linearity of the absorption edge at $\lambda < 70\,pm$. This is due to an increase in intensity of the primary radiation because of second-order interferences. The short-wave onset of the bremsspectrum is given by the acceleration voltage U_A (see P2540901). If it is $35\,kV$, for example, the following applies to the shortest wavelength in accordance with (7): $\lambda_c = 35.4\,pm$. In accordance with the Bragg condition, radiation of this wavelength is reflected under the angle $\vartheta = 10.1^\circ$ with $n = 2$. Under this angle, however, the wavelength of the first-order radiation portion ($n = 1$) is $\lambda = 70.8\,pm$ so that – as of a glancing angle of $\vartheta > 10.1^\circ$ ($\lambda > 70.8pm$) – the primary radiation that impinges on the absorber comprises a radiation portion with shorter wave-lengths. As a consequence, the absorber appears to be more “transparent” than it really is at this wavelength. Nevertheless, the absorption edge can be determined with a sufficient level of accuracy.

Equation (7) can be used to determine the energy levels of the K levels.

$$E_K = \frac{h \cdot c}{e \lambda_K} \qquad (7)$$

where

Planck’s constant	h	$= 6.6256 \cdot 10^{-34}\, Js$
Velocity of light	c	$= 2.9979 \cdot 10^{8}\, m/s$
Elementary charge	e	$= 1.6021 \cdot 10^{-19}\, C$

With $\lambda_K = 138\, pm$ of Figure 10, the following results for copper: $E_K = 8.98\, keV$ (literature value $8.98\, keV$).
Correspondingly, with $\lambda_K = 149\, pm$ of Figure 11, the following results for nickel: $E_K = 8.32\, keV$ (literature value $8.33\, keV$).
Since $Z(Ni) < Z(Cu), E_K(Ni) < EK(Cu)$ and correspondingly also $\lambda_K(Ni) > \lambda_K(Cu)$.

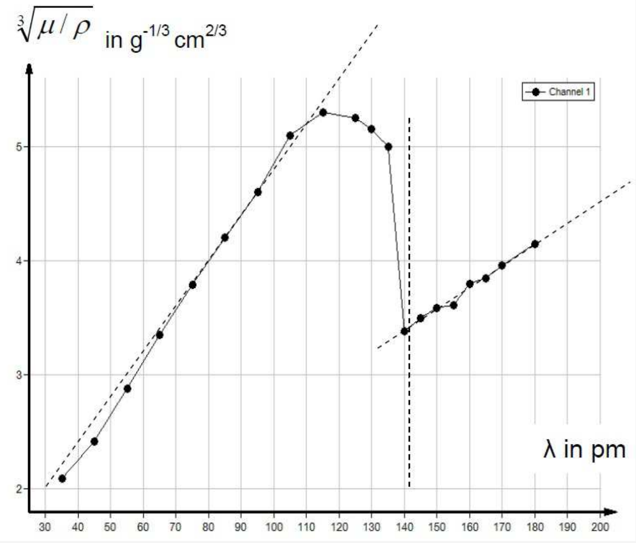


Fig. 10: Absorption edge of copper; $U_A = 25\, kV$; $\lambda_K = 138\, pm$

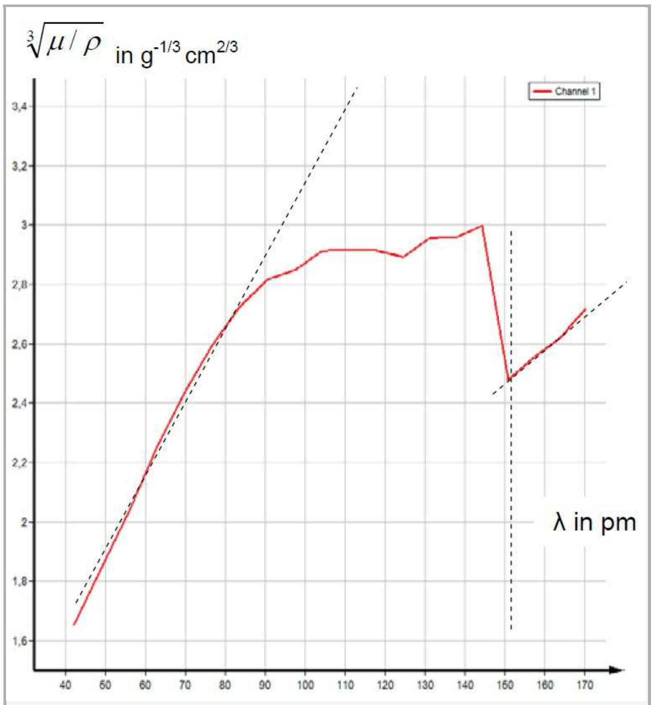


Fig. 11: Absorption edge of nickel; $U_A = 25\,kV$; $\lambda_K = 149\,pm$

Note
Nickel filters are used to monochromatise the radiation of copper X-ray tubes.
In this case, only the intensity of the characteristic $K\alpha$ radiation is slightly reduced ($E_{K_\alpha} = E_K - E_{L_{2,3}} = (8.98–0.95)\,keV = 8.03\,keV$), while the K_β radiation is reduced very strongly due to the edge absorption of nickel ($E_{K_\beta} = E_K - E_{M_{2,3}} = (8.98–0.074)\,keV = 8.9\,keV$) (see also P2541201).