Investigating the attenuation of x-rays as a function of the absorber material and absorber thickness

Objects of the experiment

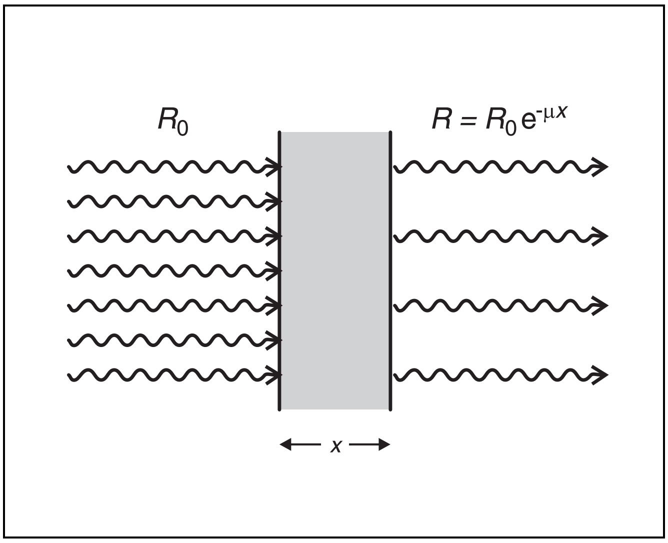
- To investigate the attenuation of x-rays as a function of the absorber thickness.
- To verify Lambert's law of attenuation.
- To investigate the attenuation of x-rays as a function of the absorber material.
- To confirme the wavelength-dependency of attenuation.

Principles

When we speak of attenuation of x-rays, we mean the decrease in intensity that occurs when the radiation passes through matter. This attenuation is caused mainly by two effects: scattering and absorption.

Although absorption and attenuation are different physical phenomena, the transilluminated object is often referred to —inaccurately— as an absorber; this should more properly be termed an attenuator. However, this description will follow the traditional usage in some places and refer to absorbers instead of attenuators.

The scattering of x-ray quanta at the atoms of the attenuator material causes a part of the radiation to change direction. This reduces the intensity in the original direction. This scattering can be either elastic or entail an energy loss or shift in wavelength, i. e. inelastic scattering.



In absorption, the entire energy of the x-ray quanta is transferred to the atoms or molecules of the irradiated material as excitation or ionizing energy.

If R_0 is the original counting rate in front of the attenuator and R is the counting rate behind it, we can quantify the transmission of the radiation to characterize the permeability of an attenuator using:

$$T = \frac{R}{R_0} \quad \text{(I).}$$

The greater the so-called transmittance of an attenuator is, the lower is its attenuating capacity.

The transmittance depends on the thickness of the attenuator. If we assume that the properties of the incident radiation remain unchanged in spite of attenuation, an increase in the thickness x by the amount dx will cause a decrease in the transmittance T by the amount dT. The relative reduction in transmission is proportional to the absolute increase in thickness:

$$-\frac{dT}{T} = \mu \cdot dx \quad \text{(II).}$$

The proportionality factor μ is referred to as the linear attenuation coefficient.

As the transmittance $T = 1$ for $x = 0$, integration of equation (II) gives us

$$T = e^{-\mu \cdot x} \quad \text{(III)}$$

or

$$\ln T = -\mu \cdot x \quad \text{(IV).}$$

This relationship is known as Lambert's law of attenuation after *Johann Heinrich Lambert,* the 18th century scientist and philosopher.

The aim of this experiment is to verify Lambert's law of attenuation. It also demonstrates that the attenuation depends on the attenuating material and the wavelength of the x-rays.

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Apparatus

1 X-ray apparatus 554 811
or
1 X-ray apparatus 554 812
1 Goniometer 554 83

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

1 Set of absorbers x-ray 554 834

Setup

Set up the experiment as shown in Fig. 1.

- Mount the collimator in the collimator mount **(a)** (note the guide groove).
- Attach the goniometer to guide rods **(d)** and 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 in the experiment chamber marked GM TUBE.
- Demount the target holder **(g)** of the goniometer and remove the target stage from the holder.
- Place the guide edge of the set of absorbers I **(f)** in the 90° curved groove of the target holder and carefully slide it into the target holder as far as it will go.

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.

- Mount the target holder.
- Press the ZERO key to return the target and sensor arms to the zero position.
- Check the zero position of the empty diaphragm of the set of absorbers and the sensor and correct this if necessary (see “Adjusting the zero position of the measuring system” in the Instruction Sheet of the x-ray apparatus).
- By moving the goniometer, set a distance of approx. 5 cm between the collimator of the x-ray apparatus and the empty diaphragm, and set a distance of approx. 5 cm between the empty diaphragm and the sensor slit by moving the sensor holder **(b)**.

Carrying out the experiment

a) Attenuation as a function of the absorber thickness:

a1) Without zirconium filter:

- Set the tube high voltage to U = 21 kV.
- Set the emission current I = 0.05 mA.

Note: The counting rate should not appreciably exceed 1500/s. This avoids having to correct for dead time.

- Press the key TARGET.
- Set the angular step width $\Delta\beta$ = 0° (see “Activating an exposure timer” in the Instruction Sheet of the x-ray apparatus).
- Set the measuring time Δt = 100 s.
- Using the ADJUST knob, set the angular positions of the absorbers (approx. 0°, 10°, 20°, 30°, 40°, 50° and 60°) one after another, start the measurement with the SCAN key and display the mean counting rate R after the measuring time elapses by pressing REPLAY. Write down your experiment results (see table 1).

a2) With zirconium filter:

- Mount the zirconium filter on the collimator (this suppresses the short-wave component of the bremsstrahlung radiation generated at U = 21 kV almost entirely).
- Set the emission current I = 0.15 mA and the measuring time Δt = 200 s.
- Using the ADJUST knob, set the angular positions of the absorbers (approx. 0°, 10°, 20°, 30°, 40°, 50° and 60°) one after another, start the measurement with the SCAN key, display the mean counting rate R after the measuring time elapses by pressing REPLAY and write down your results (see table 2).

b) Attenuation as a function of the absorber material:

b1) Without zirconium filter:

- Replace set of absorbers I (absorbers of different thicknesses) with set of absorbers II (absorbers of different materials, d = 0.05 cm).
- Remove the zirconium filter.
- Set the tube high voltage to U = 30 kV (this ensures that the radiation also penetrates the thick absorbers).
- Set the emission current I = 0.02 mA and the measuring time Δt = 30 s.

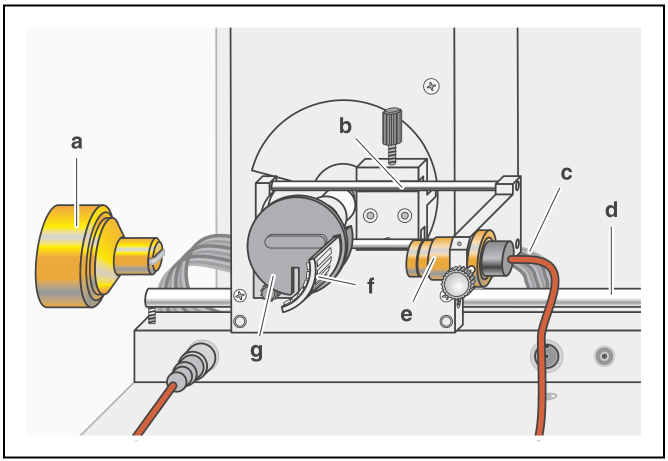

Fig. 1 Setup for investigating the attenuation of x-rays as a function of the thickness of the absorber material.

– Using the ADJUST knob, set the angular positions of the first three absorbers (approx. 0°, 10° and 20°) one after another, start the measurement with the SCAN key and display the mean counting rate R after the measuring time elapses by pressing REPLAY. Write down your results.
– Set the emission current I = 1.00 mA and the measuring time Δt = 300 s.
– Using the ADJUST knob, set the angular positions of the four remaining absorbers (approx. 30°, 40°, 50° and 60°) one after another, start the measurement with the SCAN key and display the mean counting rate R after the measuring time elapses by pressing REPLAY. Write down your experiment results (see table 3).

b2) With zirconium filter:

– Attach the zirconium filter and repeat the measurement as described for b1) (see table 4).

b3) Measuring the background effect:

– Set the parameters U = 0 kV and I = 0 mA and measure the counting rate R_1 of the background effect for a measuring time of Δt = 300 s.

Measuring example

a) Attenuation as a function of the absorber thickness:

Tab. 1: Counting rate R as a function of thickness d of the aluminum absorber (U = 21 kV, I = 0.05 mA, Δt = 100 s, without zirconium filter)

	$\frac{R}{s^{-1}}$
0	977.9
0.5	428.6
1.0	210.1
1.5	106.1
2.0	49.10
2.5	30.55
3.0	16.11

Tab. 2: Counting rate R as a function of thickness d of the aluminum absorber (U = 21 kV, I = 0.15 mA, Δt = 200 s, with zirconium filter)

$\frac{d}{mm}$	$\frac{R}{s^{-1}}$
0	969.4
0.5	426.1
1.0	197.3
1.5	84.29
2.0	40.51
2.5	19.48
3.0	9.52

b) Attenuation as a function of the absorber material:

Tab. 3: Counting rate R as a function of the absorber material (U = 30 kV, d = 0.05 cm, without zirconium filter)

Absorber	Z	$\frac{I}{mA}$	$\frac{\Delta t}{s}$	$\frac{R}{s^{-1}}$
none		0.02	30	1841
C	6	0.02	30	1801
Al	13	0.02	30	1164
Fe	26	1.00	300	93.3
Cu	29	1.00	300	16.63
Zr	40	1.00	300	194.3
Ag	47	1.00	300	106

Tab. 4: Counting rate R as a function of the absorber material (U = 30 kV, d = 0.05 cm, with zirconium filter)

Absorber	Z	$\frac{I}{mA}$	$\frac{\Delta t}{s}$	$\frac{R}{s^{-1}}$
none		0.02	30	718.3
C	6	0.02	30	698.4
Al	13	0.02	30	406.1
Fe	26	1.00	300	29.24
Cu	29	1.00	300	6.016
Zr	40	1.00	300	113.9
Ag	47	1.00	300	24.52

Background effect: R_1 = 0.243 s^{-1}

Evaluation and results

a) Attenuation as a function of the absorber thickness:

When we insert the measurement data from tables 1 and 2 in equation 1, we obtain the transmittance *T*. Fig. 2 shows how this depends on the thickness *d* of the absorber. The plotted curve conforms to the exponential function to be expected from equation (III).

Fig. 3 shows a floating-point representation in accordance with equation (IV). In this representation, the attenuation of x-ray radiation (monochromatized using the zirconium filter) can be described very well using a straight line through the origin that has a slope which corresponds to the linear attenuation coefficient $\mu = 15.7\ \text{cm}^{-1}$.

For non-monochromatic (unfiltered) x-ray radiation, the slope of the straight line through the origin fitted according to equation (IV) gives us a slightly smaller value of $\mu = 14.2\ \text{cm}^{-1}$ for the attenuation coefficient. Also, we can note deviations from the linear curve. The attenuation cannot be described using a single attenuation coefficient; rather, the radiation has a larger high-energy component than the measurement with Zr filter, so that less attenuation occurs for the same absorber thickness.

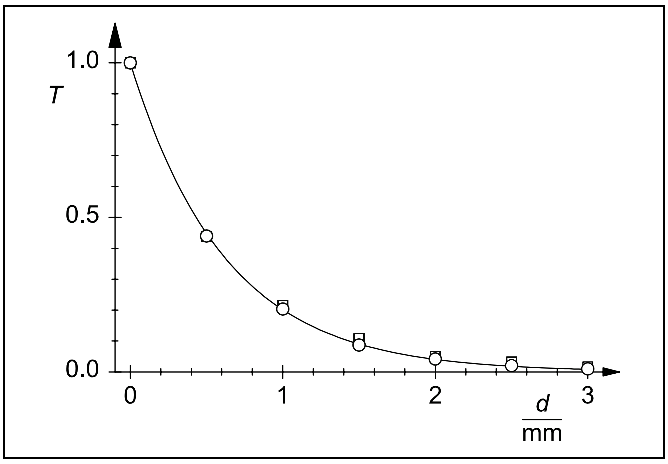

Fig. 2 Transmittance *T* as a function of the thickness d of the aluminum absorbers
Circles: measurement with zirconium filter
Squares: measurement without zirconium filter

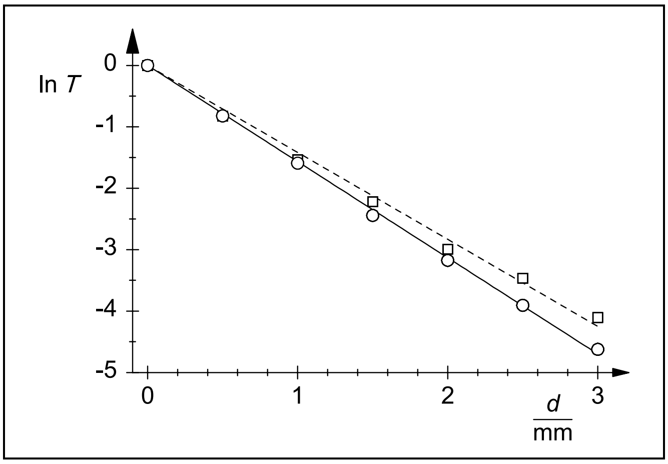

Fig. 3 Floating-point representation of transmission *T* as a function of the thickness *d* of the aluminum absorbers
Circles: measurement with zirconium filter
Squares: measurement without zirconium filter

b) Attenuation as a function of the absorber material:

Assuming that the counting rate is proportional to the emission current *I,* it is possible to scale the counting rates from tables 3 and 4 (after subtracting the background effect) to the emission current $I = 1.00$ mA.

Using the scaled data, equation (I) gives us the transmission *T* (see tables 5 and 6), which we can use to calculate the linear attenuation coefficient μ for $d = 0.05$ cm by means of equation (IV).

Fig. 4 shows the relationship between the linear attenuation coefficient μ and the atomic number *Z*. Below $Z = 40$ (Zr), the attenuation coefficient increases steeply as the atomic number rises. When *Z* reaches 40, we observe an abrupt decrease, which is more apparent for the filtered radiation. This reduction is due to the fact the certain excitations are no longer possible in Zr (binding energy of the K shell is too great, see experiment P6.3.4.5). The unfiltered radiation contains a high-energy component which can still generate this excitation, so that the decrease in μ is less.

Tab. 5: Counting rate *R* ($I = 1.00$ mA), transmittance *T* and linear attenuation coefficient μ as a function of the atomic number *Z* of the absorber material ($U = 30$ kV, $d = 0.05$ cm, without zirconium filter).

Z	$\frac{R}{s^{-1}}$	T	$\frac{\mu}{\text{cm}^{-1}}$
none	$92.0 \cdot 10^3$	1.000	0
6	$90.0 \cdot 10^3$	0.978	0.445
13	$58.3 \cdot 10^3$	0.634	9.11
26	93.1	$1.01 \cdot 10^{-3}$	138
29	16.4	$0.178 \cdot 10^{-3}$	173
40	194	$2.11 \cdot 10^{-3}$	123
47	106	$1.15 \cdot 10^{-3}$	135

Tab. 6: Counting rate R (I = 1.00 mA), transmittance T and linear attenuation coefficient μ as a function of the atomic number Z of the absorber material (U = 30 kV, d = 0.05 cm, with zirconium filter).

Z	$\frac{R}{s^{-1}}$	T	$\frac{\mu}{cm^{-1}}$
none	$35.9 \cdot 10^3$	1.000	0
6	$34.9 \cdot 10^3$	0.972	0.568
13	$20.3 \cdot 10^3$	0.565	11.4
26	29.0	$0.808 \cdot 10^{-3}$	142
29	5.77	$0.161 \cdot 10^{-3}$	175
40	114	$3.18 \cdot 10^{-3}$	115
47	24.3	$0.677 \cdot 10^{-3}$	146

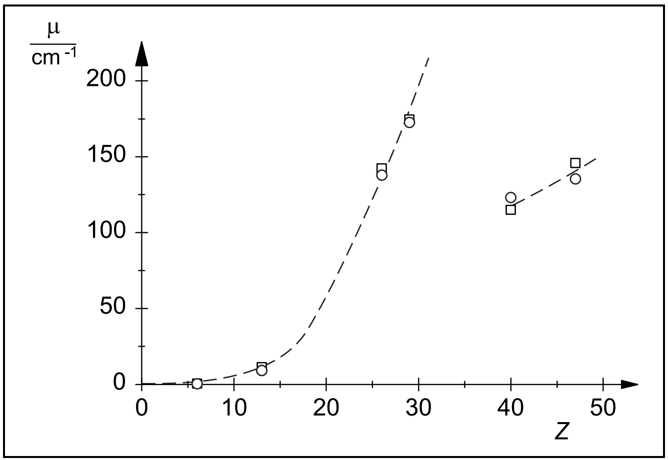

Fig. 4 Linear attenuation coefficient μ as a function of the atomic number Z of the absorber
Circles: measurement with zirconium filter
Squares: measurement without zirconium filter