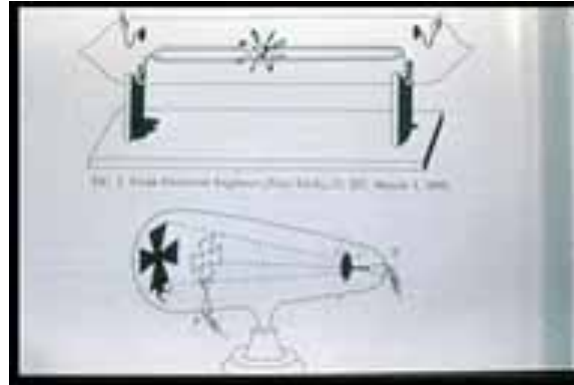




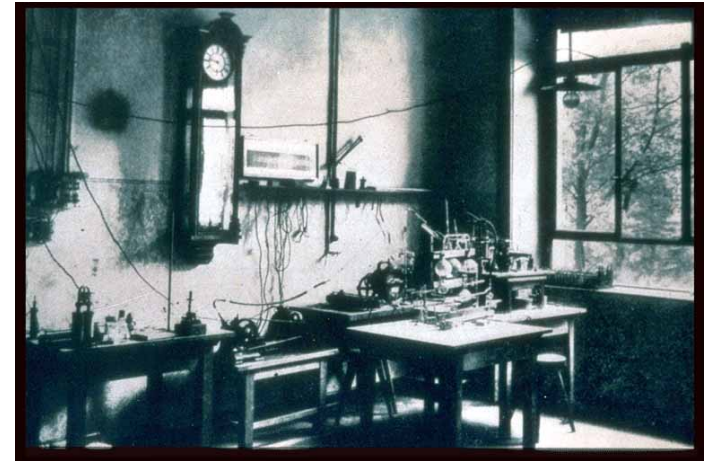
**Wilhelm Conrad
Roentgen (1845-1923)**
Prémio Nobel 1901

Raios X



Ampolas de Crookes

Fotografias cortesia de
Radiology Centennial, Inc.



Laboratório Wurzburg

Primeiras radiografias de Roentgen (Nov/1895 – Jan/1896) :

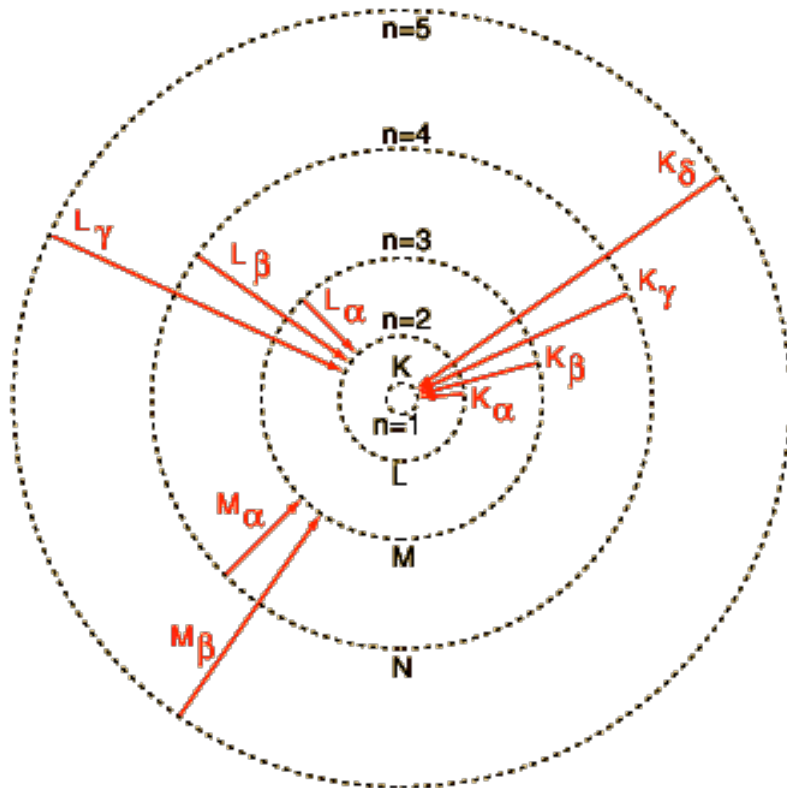


mão da Sr^a Roentgen

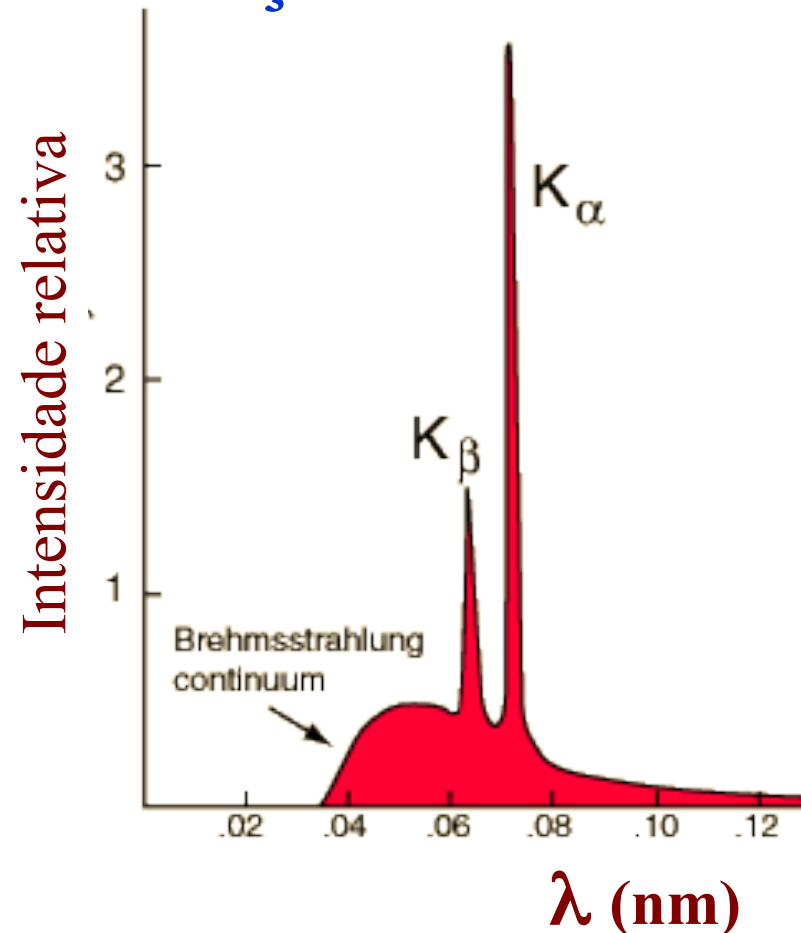
Paula Bordalo

Espectros de Raios X

- Os raios X são produzidos em elementos de elevado número atômico, através de transições de electrões nas camadas internas



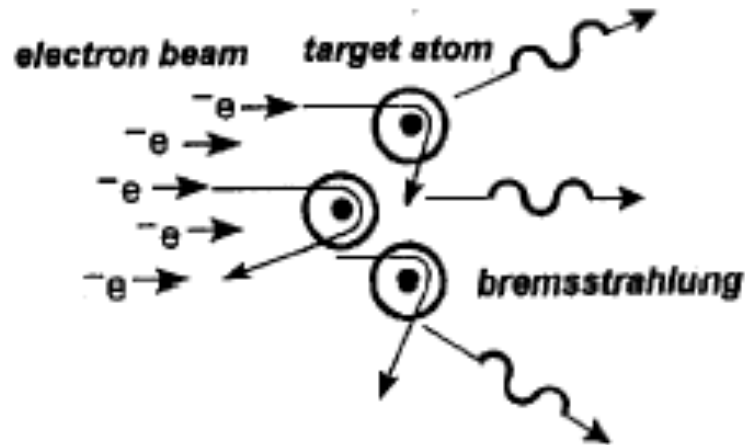
As riscas K_{α} e K_{β} correspondem a transições de electrões dos níveis **L** e **M** para o nível **K**



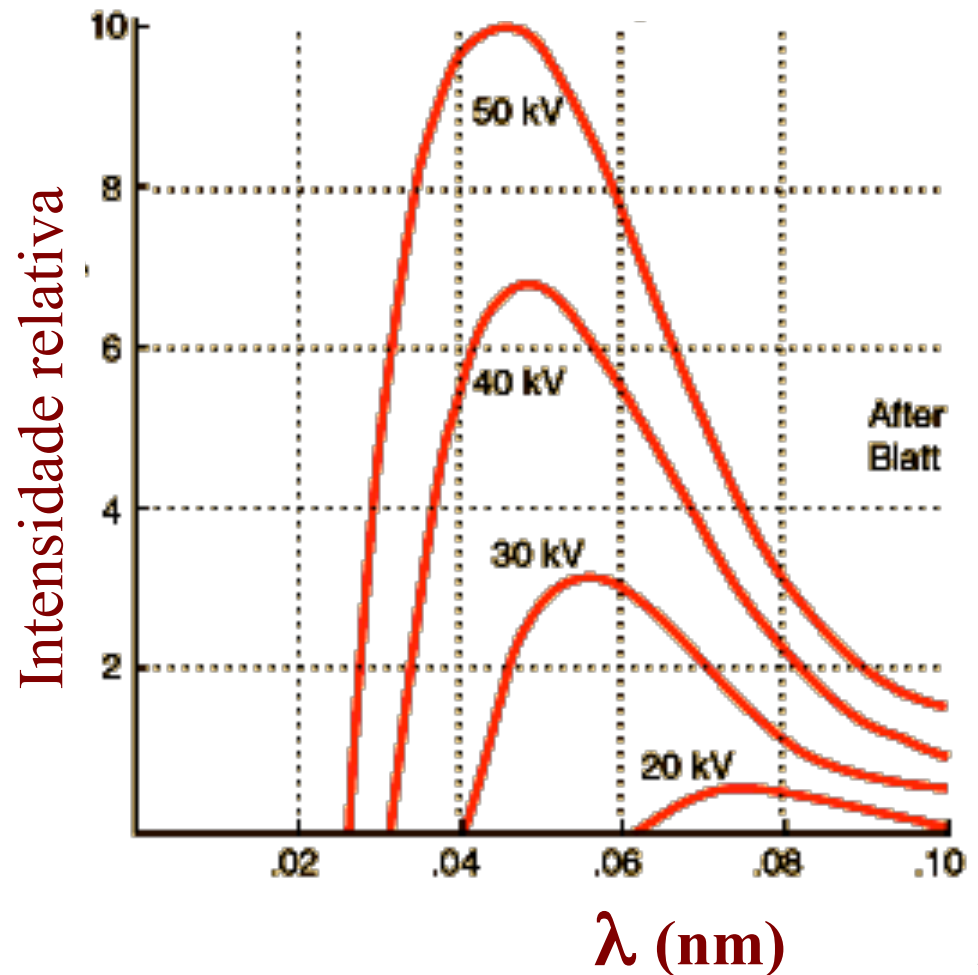
Um fundo contínuo existe sob as riscas – radiação Bremsstrahlung

Radiação Bremsstrahlung

- Electrões acelerados emitem continuamente energia

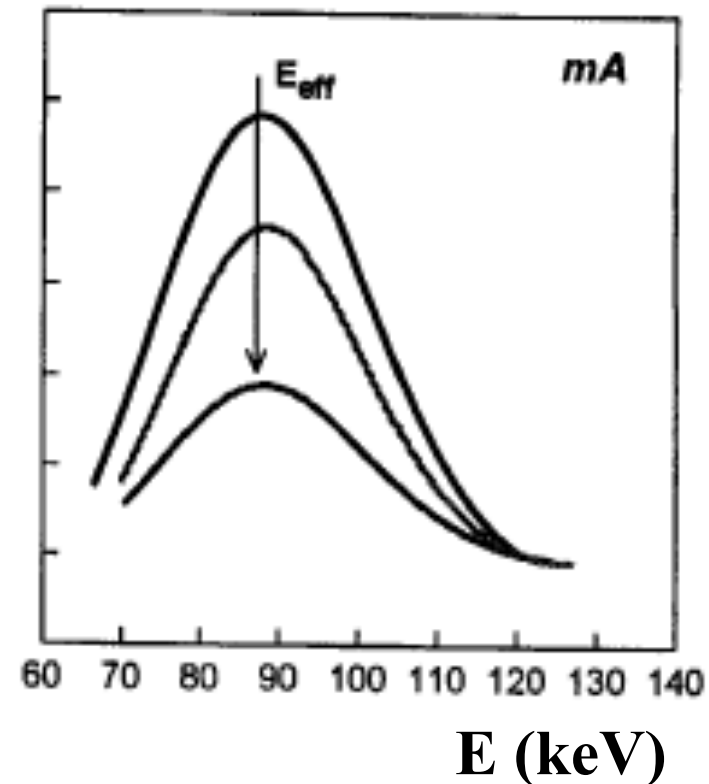
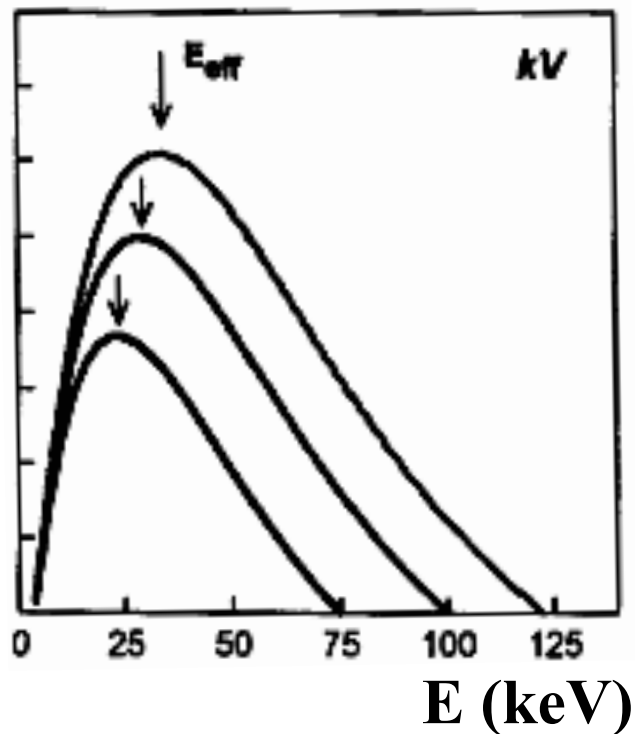


Em 1918 Ulrey obteve os seguintes espectros de R_X bombardeando um alvo de tungsténio com electrões de 4 diferentes energias



Dependência da energia dos raios X

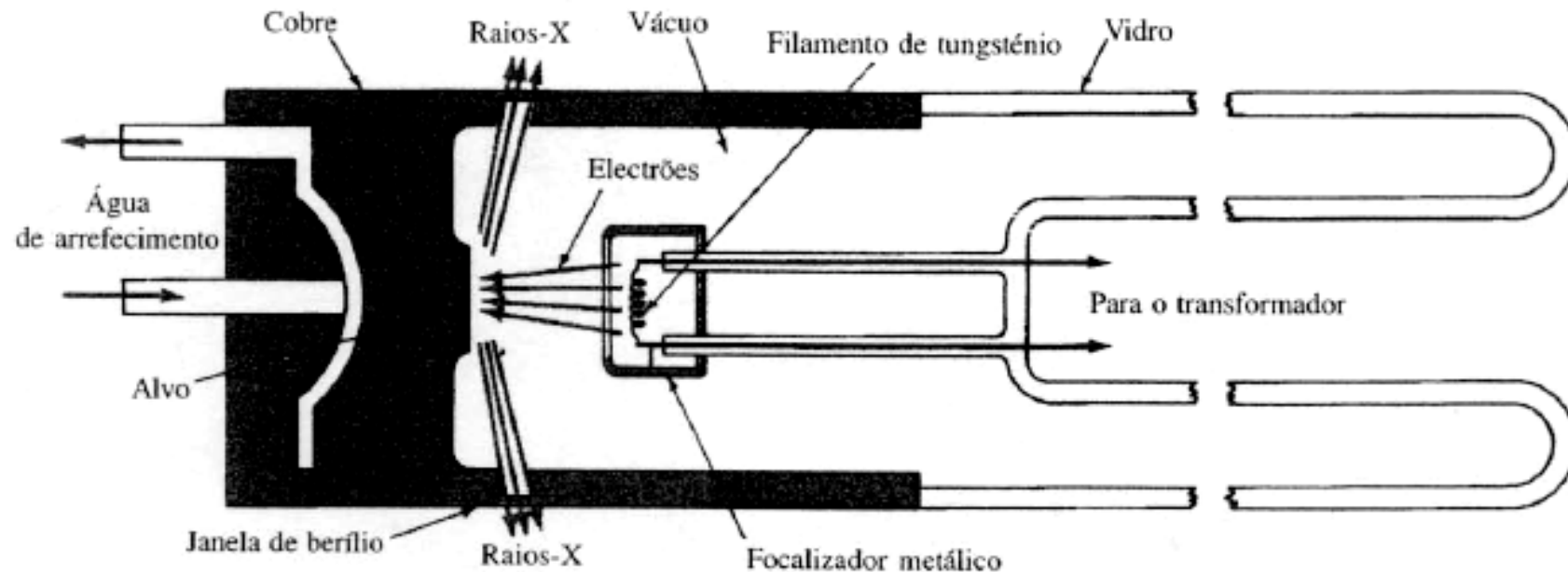
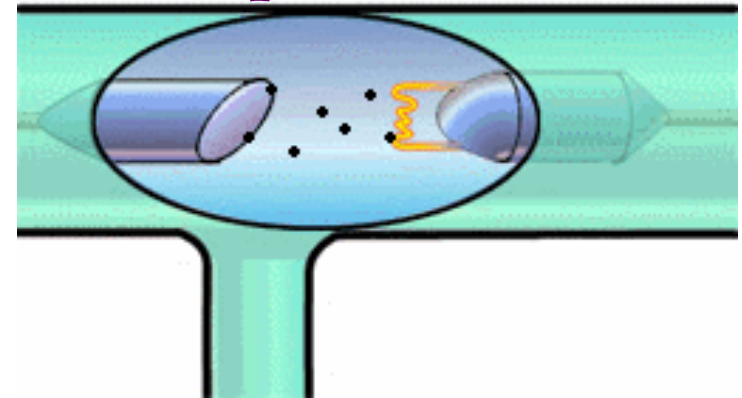
- Efeitos da tensão e da corrente da ampola na produção de raios X



- a energia efectiva dos raios X aumenta com o aumento da tensão e não depende da corrente da ampola

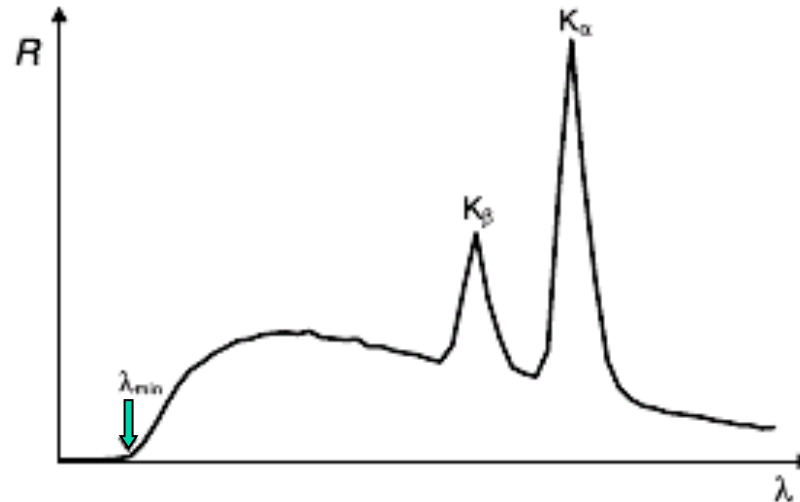
Ampola de Raios X

- Os raios X são a radiação electromagnética emitida aquando das transições de electrões entre camadas internas de átomos metálicos pesados, os quais foram excitados por electrões que neles embatem a alta velocidade
→ Um filamento aquecido emite electrões por efeito termiónico, estes são acelerados por um potencial eléctrico muito elevado (~ 40 kV)



Lei de Duane-Hunt

- A relação entre o λ_{\min} de um espectro de raios X e a alta tensão na ampola foi estabelecida por William Duane e Franklin Hunt



O λ_{\min} corresponde à energia máxima perdida pelos electrões na matéria (numa colisão frontal com os átomos do ânodo):

$$E_{\max} = h \nu_{\max} = h c / \lambda_{\min}$$

sob a acção do potencial V , os electrões emitidos pelo filamento adquirem energia cinética :

$$E = e V$$

$$\lambda_{\min} = h c / e \cdot 1/V$$

Rendimento da ampola de Raios X

- A **Lei de Kramers** dá a distribuição espectral dos **raios X** emitidos pela ampola (só componente contínua - **bremsstrahlung**), em função do seu **comprimento de onda λ** .
- A **intensidade dos raios X** emitidos pela ampola é também função da **intensidade de electrões I_e** oriundos do cátodo (filamento), do **número atómico Z** do material do ânodo, bem como de **λ_{min}** , o **limiar** dado pela **Lei de Duane-Hunt** :

$$I_X = \frac{c I_e Z_{anodo}}{\lambda^2} \frac{\lambda - \lambda_{min}}{\lambda_{min}}$$

- Incluindo na constante **K** os factores específicos do feixe e do alvo (ânodo), a **Lei de Kramers** toma a forma:

$$I_X = K \frac{\lambda - \lambda_{min}}{\lambda^2}$$

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 record 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 understand 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 ν_{\max} or a minimum wavelength λ_{\min} .

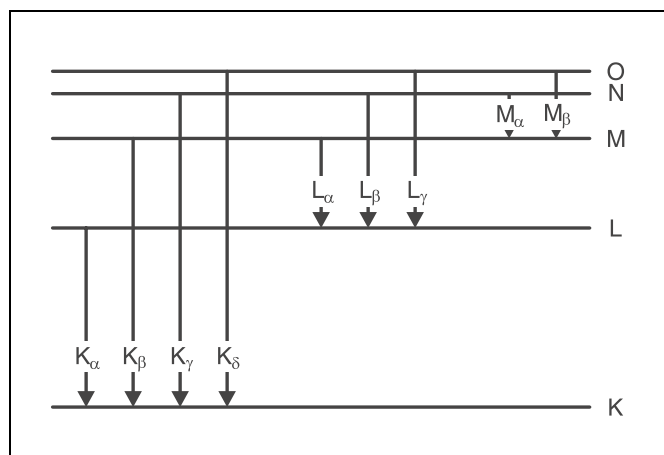
If the energy of the electrons exceeds a critical value, the characteristic x-radiation is generated, which appears in the spectrum as individual lines in addition to the continuous bremsstrahlung spectrum. These lines are generated when high-energy electrons penetrate deep into the atomic shells of 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_{α} , K_{β} , K_{γ} , etc. Starting from K_{α} , 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 θ 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



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

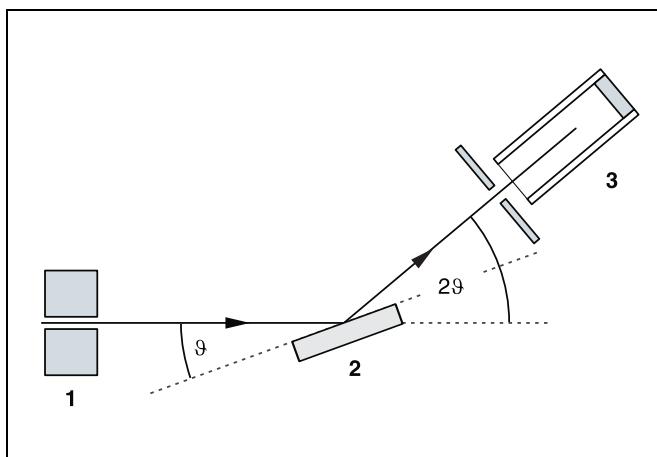


Fig. 2 Schematic diagram of diffraction of x-rays at a monocrystal and 2θ coupling between counter-tube angle and scattering angle (glancing angle)

1 collimator, 2 monocrystal, 3 counter tube

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

$$\lambda = 2 \cdot d \cdot \sin \vartheta \quad (\text{I}).$$

$d = 282.01 \text{ pm}$: lattice plane spacing of NaCl

Together with the relationships valid for electromagnetic radiation

$$\nu = \frac{c}{\lambda} \quad (\text{II})$$

ν : frequency, c : velocity of light

and

$$E = h \cdot \nu \quad (\text{III})$$

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 R0).

The built-in protection and screening measures reduce the local dose rate outside of the x-ray apparatus to less than $1 \mu\text{Sv/h}$, 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.

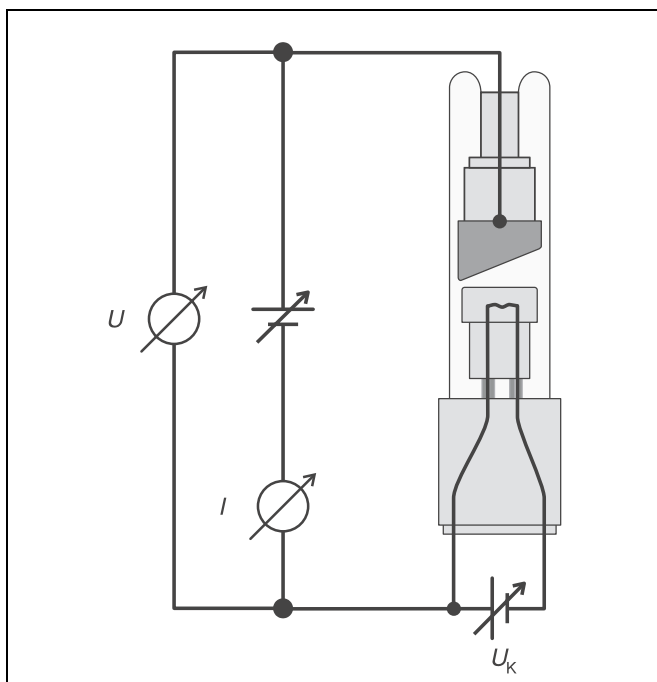
Do not allow the anode of the x-ray tube Mo to overheat.

- 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



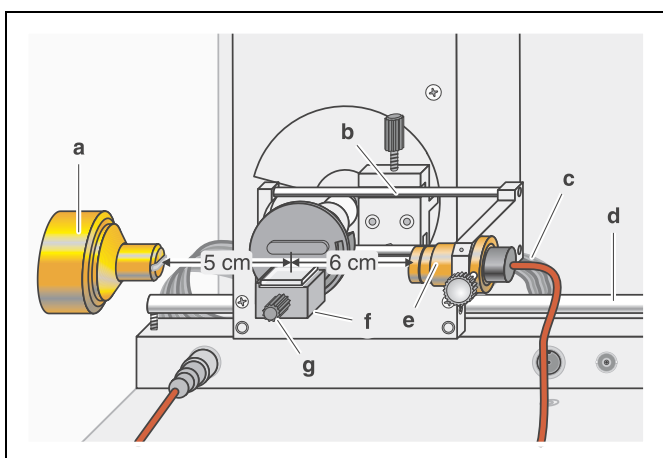


Fig. 4 Experiment setup for investigating the energy spectrum of an x-ray tube

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_α and K_β lines.

Investigating the wavelength dependency of the coefficient of attenuation

Objects of the experiment

- To measure the transmittance T of a copper foil and a zirconium foil for x-rays as a function of the wavelength λ between 30 and 120 pm.
- To investigate the wavelength-dependency of the attenuation coefficient μ outside of the absorption edges.
- To confirm the λ^3 law as a function of the absorption coefficient τ .

Principles

The attenuation of x-rays passing through matter is described by Lambert's law (see experiment P6.3.2.1):

$$R = R_0 \cdot e^{-\mu x} \quad (I)$$

Here, R_0 is the intensity of the x-ray radiation in front of the attenuator, R is the intensity behind the attenuator, μ is the linear attenuation coefficient and x is the thickness of the attenuator.

Absorption and scattering both contribute to attenuation. The linear attenuation coefficient μ is thus composed of the linear absorption coefficient τ and the linear scattering coefficient σ .

$$\mu = \tau + \sigma \quad (II)$$

These coefficients are proportional to the mass and the density ρ of the irradiated material respectively. That is why we often use the so-called mass coefficients

$$\mu_m = \frac{\mu}{\rho}, \tau_m = \frac{\tau}{\rho}, \sigma_m = \frac{\sigma}{\rho} \quad (III)$$

or – for the pure metals observed here – the atomic coefficients or cross-sections

$$\mu_a = \mu_m \frac{A}{N_A}, \tau_a = \tau_m \frac{A}{N_A}, \sigma_a = \sigma_m \frac{A}{N_A} \quad (IV)$$

A : atomic weight

$$N_A = 6.022 \cdot 10^{23} \frac{1}{\text{mol}}, \text{ Avogadro's number}$$

Analogously to equation (II), we can say that

$$\mu_m = \tau_m + \sigma_m \quad (V)$$

and

$$\mu_a = \tau_a + \sigma_a \quad (VI)$$

The absorption of x-rays is essentially due to the ionization of atoms, which release an electron from an inner shell. The absorption cross-section is thus strongly dependent on the quantum energy $h\nu$ resp. the wavelength λ of the x-ray radiation as well as on the excitation energy of the atoms and thus the atomic number Z . For ionization to occur, the quantum energy of the x-rays must be greater than the binding energy E of the electrons of the respective shell. The absorption cross-section is thus very small once the quantum energy is just slightly below the binding energy. The limit wavelength at which the quantum energy is just sufficient is called the absorption edge (see Fig. 1).

Outside of the absorption edges, absorption is described to within a close approximation by the relationship

$$\tau_a = C \cdot \lambda^3 \cdot Z^4 \quad (VII).$$

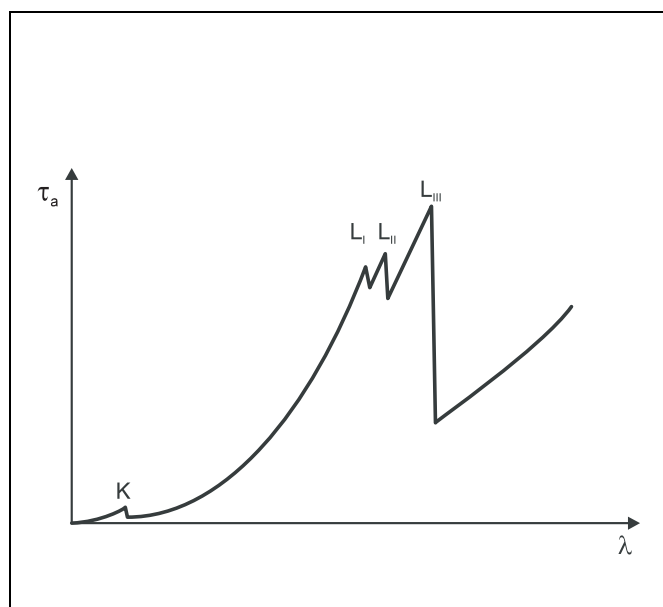


Fig. 1 Absorption coefficient as a function of the x-ray wavelength (schematic)

K: absorption edge of K shell

L_I, L_{II}, L_{III} : absorption edges of L shell

Apparatus

1 X-ray apparatus 554 811

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

1 Set of absorber foils 554 832

additionally required:

1 PC with Windows 95/98 or Windows NT

This experiment verifies the dependence on the wavelength λ for two different metals, i.e. two different atomic numbers Z .

The evaluation exploits the fact that the scattering cross-section σ_a in the wavelength range $\lambda = 35\text{--}100\text{ pm}$ is significantly less than the absorption cross-section and can be estimated approximately using

$$\sigma_a = 0.2 \frac{\text{cm}^2}{\text{g}} \cdot \frac{A}{N_A} \quad (\text{VIII})$$

By applying a series of transformations to equations (III)-(VII), we can calculate the absorption cross-section as:

$$\tau_a = \frac{\mu}{\rho} \cdot \frac{A}{N_A} = 0.2 \frac{\text{cm}^2}{\text{g}} \cdot \frac{A}{N_A} \quad (\text{IX})$$

This experiment measures the transmittance

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

of the transilluminated material as a function of the wavelength of the x-ray radiation. When we apply Lambert's law of attenuation

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

we can calculate the linear attenuation coefficient μ and, using this value and equation (IX), the absorption cross-section τ_a :

$$\tau_a = \frac{-\ln T}{\rho \cdot x} \cdot \frac{A}{N_A} = 0.2 \frac{\text{cm}^2}{\text{g}} \cdot \frac{A}{N_A} \quad (\text{XII})$$

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 R  ).

The built-in protection and screening measures reduce the local dose rate outside of the x-ray apparatus to less than $1\text{ }\mu\text{Sv/h}$, 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.

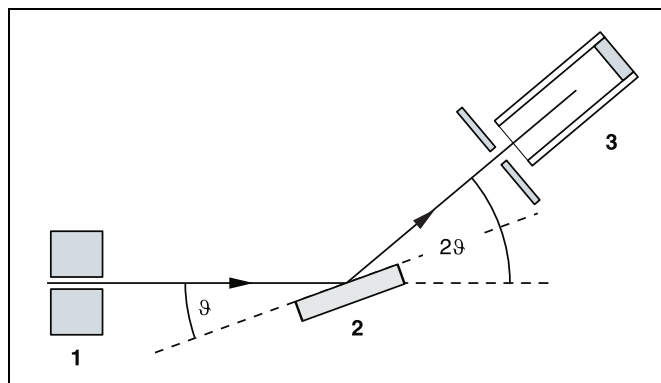


Fig. 2 Diffraction of x-rays at a monocrystal and for 2θ coupling between counter-tube angle and scattering angle (glancing angle)

1 collimator, 2 monocrystal, 3 counter tube

A goniometer with NaCl crystal and a Geiger-M  ller counter tube in the Bragg configuration are used to record the intensities as a function of the wavelength. The crystal and counter tube are pivoted with respect to the incident x-ray beam in 2θ coupling, i.e. the counter tube is turned at an angle twice as large as the crystal (see Fig. 2).

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

$$\lambda = 2 \cdot d \cdot \sin \vartheta \quad (\text{XIII})$$

$d = 282.01\text{ pm}$: lattice plane spacing of NaCl

Setup

Setup in Bragg configuration:

Set up the experiment as shown in Fig. 3. To do this, proceed as follows (see also the Instruction Sheet for the x-ray apparatus):

- Mount the collimator in the 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 the sensor holder **(b)**, set the distance s_2 between the target arm and the slit diaphragm of the sensor receptor to approx. 5 cm.
- Mount the target holder with target stage.
- Loosen knurled screw **(g)**, place the NaCl crystal flat on the target stage **(f)**, carefully raise the target stage with crystal all the way to the stop and carefully tighten the knurled screw (prevent skewing of the crystal by applying a slight pressure).
- If necessary, adjust the mechanical 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 K_α and K_β lines.

Preparing the PC-based measurement:

- Connect the RS-232 output and the serial interface on your PC (usually COM1 or COM2) using the 9-pin V24 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.

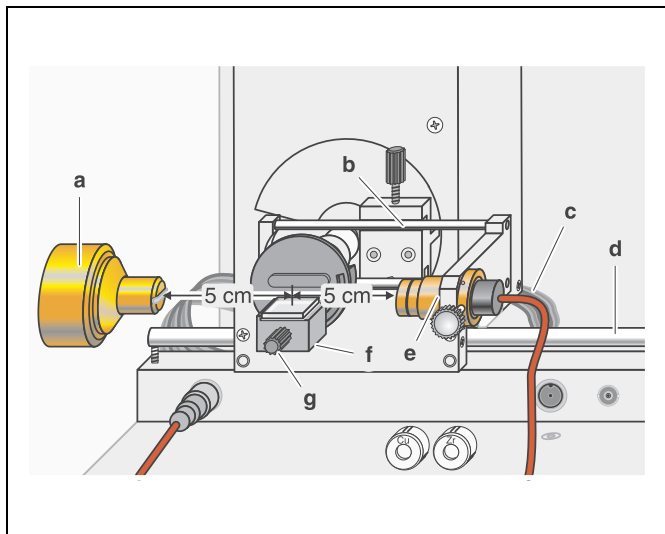


Fig. 3 Experiment for investigating the wavelength-dependency of the attenuation coefficient

Duane-Hunt relation and determination of *Planck's* constant

Objects of the experiment

- To determine the limit wavelength λ_{\min} of the bremsstrahlung continuum as a function of the high voltage U of the x-ray tube.
- To confirm the Duane-Hunt relation.
- To determine Planck's constant.

Principles

The bremsstrahlung continuum in the emission spectrum of an x-ray tube is characterized by the limit wavelength λ_{\min} (see Fig. 1), which becomes smaller as the tube high voltage increases (see experiment P6.3.3.2). In 1915, the American physicists *William Duane* and *Franklin L. Hunt* discovered an inverse proportionality between the limit wavelength and the tube high voltage:

$$\lambda_{\min} \sim \frac{1}{U} \quad (\text{I})$$

This Duane-Hunt relationship can be sufficiently explained by examining some basic quantum mechanical considerations: As the wavelength λ and the frequency ν for any electromagnetic radiation are related in the manner

$$\lambda = \frac{c}{\nu} \quad (\text{II})$$

$c = 2.9979 \cdot 10^8 \text{ m s}^{-1}$: velocity of light

the minimum wavelength λ_{\min} corresponds to a maximum frequency ν_{\max} respectively a maximum energy

$$E_{\max} = h \cdot \nu_{\max} \quad (\text{III})$$

h : Planck's constant

of the emitted x-ray quanta. However, an x-ray quantum attains maximum energy at precisely the moment in which it acquires the total kinetic energy

$$E = e \cdot U \quad (\text{IV})$$

$e = 1.6022 \cdot 10^{-19} \text{ A s}$: elementary charge

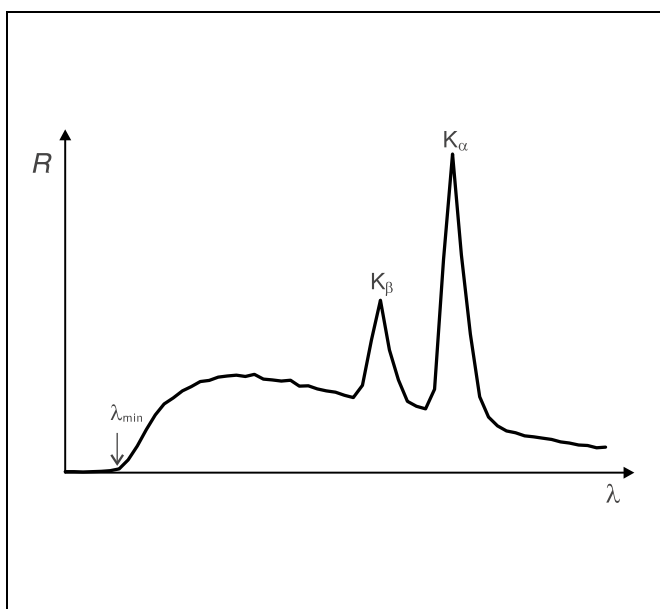
of an electrode decelerated in the anode. It thus follows that

$$\nu_{\max} = \frac{e}{h} \cdot U \quad (\text{V})$$

respectively

$$\lambda_{\min} = \frac{h \cdot c}{e} \cdot \frac{1}{U} \quad (\text{VI})$$

Fig. 1 Emission spectrum of an x-ray tube with the limit wavelength λ_{\min} of the bremsstrahlung continuum and the characteristic K_{α} and K_{β} lines.



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/NT

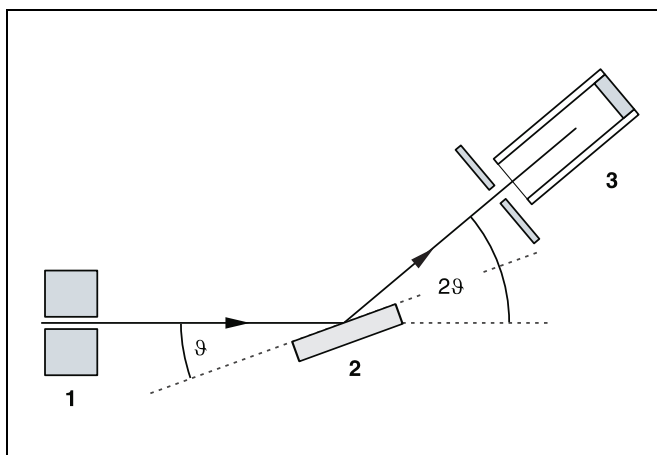


Fig. 2 Schematic diagram of diffraction of x-rays at a monocrystal and 2θ coupling between counter-tube angle and scattering angle (glancing angle)

1 collimator, 2 monocrystal, 3 counter tube

Equation (VI) corresponds to Duane and Hunt's law. The proportionality factor

$$A = \frac{h \cdot c}{e} \quad (\text{VII})$$

can be used to determine Planck's constant h when the quantities c and e are known.

A goniometer with NaCl crystal and a Geiger-Müller counter tube in the Bragg configuration together comprise the spectrometer in this experiment. The crystal and counter tube are pivoted with respect to the incident x-ray beam in 2θ coupling (cf. Fig. 2).

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

$$\lambda = 2 \cdot d \cdot \sin \vartheta \quad (\text{VIII})$$

$d = 282.01$ pm: lattice plane spacing of NaCl

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 $1 \mu\text{Sv/h}$, 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.

Setup**Setup in Bragg configuration:**

Fig. 3 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 the 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 the 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 the 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

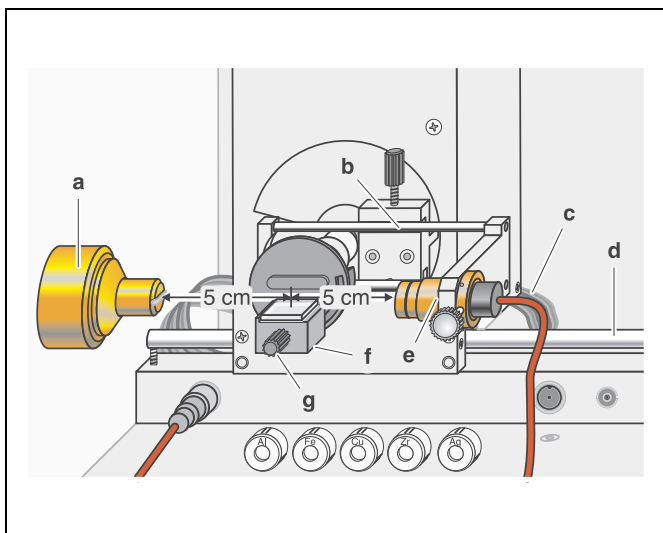


Fig. 3 Experiment setup in Bragg configuration

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 mechanical 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.

Preparing the PC-based measurement:

- Connect the RS-232 output and 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.