A02 X-rays

Dr.P.Rabe, H.Bender, B.Appelton Fachhochschule Oldenburg / Ostfriesland / Wilhelmshaven, University of Applied Sciences,
Department of Engineering Sciences

Doc. January 23, 2002

1.1 Introduction

1.1.1 Aim of the experiment

To gain some understanding of the many fields of application of X-rays, a basic knowledge of the characteristics of these electromagnetic waves is required. Medical applications of X radiation include diagnostic procedures such as X-ray photography, X-ray tomography and non-invasive coronary angiography. Other areas of application include for example materials analysis (X-ray fluorescence analysis to determine elementary composition and concentration, X-ray powder diffractometry to determine crystal phases, texture analysis to determine orientation distribution in polycrystalline materials, monocrystal diffractometry to determine crystal structure).

1.1.2 Tasks

1. Test the X-ray tube function and adjust the goniometer.
2. Record the the anode material's X-ray spectrum and determine it's atomic number with the help of Moseley's law (X-ray fluorescence analysis).
3. Investigate the wavelength dependency of X-ray attenuation in materials (copper and zirconium foils).
4. Investigate the dependency of attenuation upon absorber thickness (determination of the linear absorption coefficient μ of aluminium).

1.2 Note

1. Before turning on the X-ray apparatus' H.T., the H.T. and emission current controls must be on their lowest settings.
2. Satisfactory results can only be obtained with a carefully adjusted goniometer and $\varphi - 2\varphi$-coupling. Make these adjustments only after receiving instruction from the supervisor.
3. Qualitative measurements (adjustment and determination of peaks) are to be made with an analog multimeter, quantitative measurements with a digital counter and a measurement period of 30s per measurement.

1.2.1 X-ray apparatus components and accessories

Goniometer, LiFl monocrystal, Geiger-Müller tube with counter, multimeter, digital counter, Cu and Zr foils, aluminium absorber.

1.2.2 Key topics

Atomic structure, formation of X-rays, bremsstrahlung, characteristic spectrum (series, Moseley's law), spectral distribution, X-ray diffraction (Bragg reflection), dependency of absorption on wavelength, atomic number and thickness, protection from X-rays, position in electromagnetic spectrum.

1.3 Theory

1.3.1 Formation of X-rays

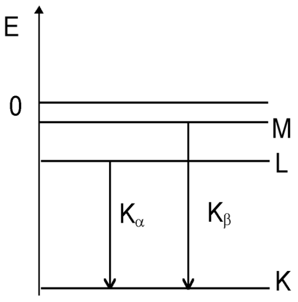

Figure 1.1: Energy level diagram with bound electron transitions between discrete energy states.

The formation of X-rays can be explained with the help of a simple energy level diagram. Characteristic X radiation is produced when an electron with sufficient energy ionizes the inner shell of an atom of anode material. This causes the transition of an electron from a state of higher energy to the now unoccupied low energy position. The resulting excess energy is emitted in the form of an X-ray quantum. The energy of the K_α radiation can be estimated with the help of Moseley's law:

$$E_{k\alpha} = \frac{3}{4} \cdot 13.6eV \cdot (Z - \sigma)^2 \tag{1.1}$$

Z is the atomic number and $\sigma \approx 1$ the so-called screening constant. Bremsstrahlung is produced when an electron with sufficiently high energy is deflected by the Coulomb field of an atomic nucleus in the anode material, i.e. when the electron is accelerated. According to the laws of classical electrodynamics, this results in the emission of electromagnetic radiation. The energy level diagram explains the electrons' energy loss through transitions within the energy state continuum.

The lost energy is emitted as an X-ray quantum. The X-ray tube's accelerating voltage can be determined from the short wave limit of the bremsstrahlung. The dependency of the bremsstrahlung's intensity upon wavelength can be described with the Kramer's formalism:

$$I_\lambda = \frac{dI(\lambda)}{d\lambda} = K \cdot i \cdot Z \cdot (\frac{\lambda}{\lambda_0} - 1) \cdot \frac{1}{\lambda^3} \tag{1.2}$$

i is the anode current, Z the atomic number of the anode material, λ_0 the limiting wavelength and K a constant.

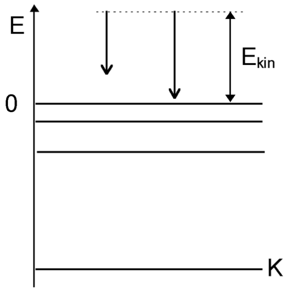

Figure 1.2: Energy level diagram with transition of free electrons within an energy state continuum.

1.3.2 Diffraction, reflection and monochromation of X-rays

Because the atomic spacing is similar to the X-ray wavelength, diffraction occurs. If a beam of parallel X-rays strikes a crystal lattice (a periodic spatial arrangement of lattice elements - atoms, atomic groups, molecules or molecular groups), the location of each element becomes, in accordance with Huygen's principle, the source of elementary waves (spherical waves) with the same wavelength as the incident radiation (elastic scattering). When the path lengths of the waves scattered by adjacent elements differ by an exact multiple of the X-ray wavelength (when observed at a relatively large distance from the crystal) the elementary waves interfere constructively. A simplified explanation for the diffraction is, according to Bragg, that the X-rays are reflected from the crystal lattice planes. The criterion for constructive interference depends upon the lattice parameter d and the glancing angle φ and is given by Bragg's equation:

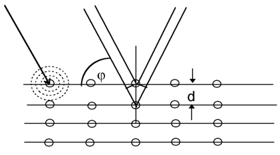

Figure 1.3: Bragg reflection of X-rays from a monocrystal

$$n \cdot \lambda = 2 \cdot d \cdot \sin\varphi \tag{1.3}$$

(n is the order of diffraction)

1.3.3 X-ray absorption

X-rays are partially absorbed by every form of material. The attenuation depends upon the thickness D of the absorber as well as upon the wavelength λ of the radiation and the atomic number Z of the absorbing atoms. The dependency of the attenuation upon the absorber thickness D is described by the Beer-Lambert law:

$$I = I_0 \cdot e^{-\mu D} \tag{1.4}$$

I_0 and I are the intensities of the X-ray beam before and after passing through the absorber and μ is the wavelength and material dependent absorption coefficient (linear attenuation coefficient). The absorption coefficient decreases together with decreasing wavelength ($\mu \sim \lambda^3$) and with decreasing atomic number ($\mu \sim Z^4$). For absorbing atoms with a given atomic number, sudden changes in the absorption coefficient appear at certain wavelengths. Because the absorption process is nearly always connected with ionization in an inner shell, these wavelengths correspond to photon energies which are equal to the ionization energies. The energy level of an absorption edge therefore corresponds to the ionization potential (electron binding energy) of the electrons in the related shell.

A cubic LiF monocrystal with the lattice constant a = 0.40276nm is used to monochromate the X radiation. The experiments investigate diffraction by the lattice plane atoms with the lattice constant a, for the second order of diffraction (n=2). When analysing the recorded spectra, it is important to note that the fourth order of diffraction can also produce a noticeable intensity. Due to the particular structure of the LiF crystal, the first and third orders do not appear.

1.4 Experiment

1.4.1 Procedure

1. Test the goniometer function and turn on the X-ray tube in accordance with the following steps:

   Set the toggle switch for the mains voltage to I, the rotary switch for the X-ray tube H.T. to 1 and the switch for the emission current to 0.05mA.

   Switch the tube H.T. to 6 and the emission current to 1mA.

   Uncouple the φ - 2φ mechanism.

   Set the glancing angles to 11^0 for the crystal and around 22^0 for the detector.

   By alternately adjusting the detector and crystal positions the combination which produces the maximum intensity can be found by trial and error. (Satisfactory results can only be obtained with a carefully adjusted goniometer and $\varphi - 2\varphi$ coupling).

   When the position giving the maximum intensity has been found, recouple the φ - 2φ mechanism.

2. Spectral distribution of X radiation:

   For glancing angles from $\varphi = 3^0$ to $\varphi = 15^0$, measure the radiation emitted by the X-ray tube in the coupled φ - 2φ mode and in $\Delta\varphi = 0.5^0$ steps.

   Note that the whole degree 2φ values should be set as exactly as possible because they have to be reproduced for another part of the experiment.

   In the part of the spectrum showing linear structures (characteristic spectrum), determine the angle at which the maximum intensity appears as exactly as possible.
   As a rule, this requires three extra measurements: K_0, K_β and the minimum between them. (Measurement time per angle 30 s, H.T. level 6, level 8 for adjustment)

3. Wavelength dependency of X-ray absorption:

   Place a piece of copper foil (thickness D = 0.07 mm) and a piece of zirconium foil (D = 0.05 mm) one at a time in the X-ray tube beam.

   For each foil measure the transmitted intensity in the coupled φ - 2φ mode and in 0.5^0 steps from $\varphi = 5^0$ to $\varphi = 15^0$.

   Note that the measurement angles from part 2 of the experiment are to be reproduced as exactly as possible. This is particularly important for the range of angles in which the characteristic spectrum appears. The X-ray tube parameters must also be identical to those used for part 2. (Measurement time per angle 30s, H.T. level 6, level 8 for adjustment)

4. Dependency of X-ray absorption upon absorber thickness:

   For absorber thicknesses from D=0.5mm to D=3.0mm, measure the radiant powers of the incident and transmitted K_α radiation (part 2) in 0.5mm steps. In addition, the piece of zirconium foil used for the part 3 measurements is to be placed in the beam path. The foil strongly absorbs the K_β radiation, but only absorbs the K_α radiation slightly (K_β filter). In this way a near to monochromatic X radiation is produced.

   For these measurements, disconnect the φ - 2φ coupling and remove the crystal.

   Position the detector so that it is in line with the X-ray source and the absorber. (Measurement time 30s, H.T. level 1)

1.4.2 Analysis

1. Part 2:

   Plot the X-ray intensity as a function of wavelength.

   Use the wavelength of the observed K_α radiation to determine the anode material's atomic number according to Moseley's law.

   Use the short wave limit of the Bremsstrahlung to calculate the X-ray tube's H.T. voltage. Calculate the value's error.

   Compare the Bremsstrahlung with Kramer's formalism, i.e. show the spectrum according to Kramer's formalism together with the experimentally determined spectrum. Scale the two curves so that they coincide at the point of maximum intensity. When making the comparison, note that in the experiment the intensity is measured at constant angular intervals, while the theory gives the intensity at constant wavelength intervals.

2. Part 3: Determine the wavelength dependency of the absorption coefficients μ from the measured intensities I and the incident intensities I_0 measured in part 2 of the experiment. Present the results in the form of a table and a graph.

   Explain the relationship of absorption coefficient to wavelength.

   Use the zirconium spectrum to determine the ionization energy of the zirconium's K-shell electrons and calculate the error of the result.

   Explain the influence of the fourth order of diffraction.

3. Part 4:

   Use the measured intensities to calculate the transmission $\frac{I}{I_0}$ in relation to absorber thickness. Show the results as a table and as a graph with linear and with half logarithmic scale.

   Calculate the linear absorption coefficient (and error) for the wavelength of the K_α radiation.