

## X-Ray Production: Determination of the Wavelengths of Characteristic Radiation from a Molybdenum and a Copper Anode

### Introduction

In this apparatus, 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. The X-ray tube in this apparatus produces such x-rays by accelerating electrons from a heated cathode into an anode at high voltage. The high voltage  $U$  is applied as the accelerating voltage for the electrons between the cathode and the anode (see Fig. 1). 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.

For historical reasons, x-rays produced this way are 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  $\nu_{\max}$  or equivalently a minimum wavelength  $\lambda_{\min}$ .

If the energy of the electrons exceeds a critical value, the characteristic 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 vacancies created in this process are filled by electrons from the outer orbitals accompanied by emission of x-rays. The resulting x-radiation is characteristic of that anode material and is roughly aligned 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 state of the emitting atoms or the aggregate state of the material.

**Fig 1** Schematic diagram showing the structure of the x-ray tube

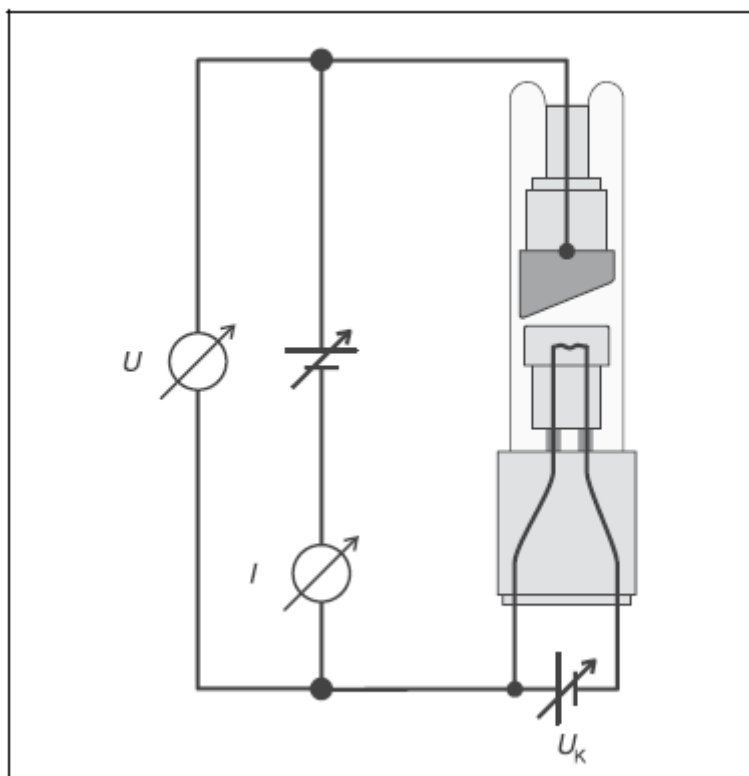
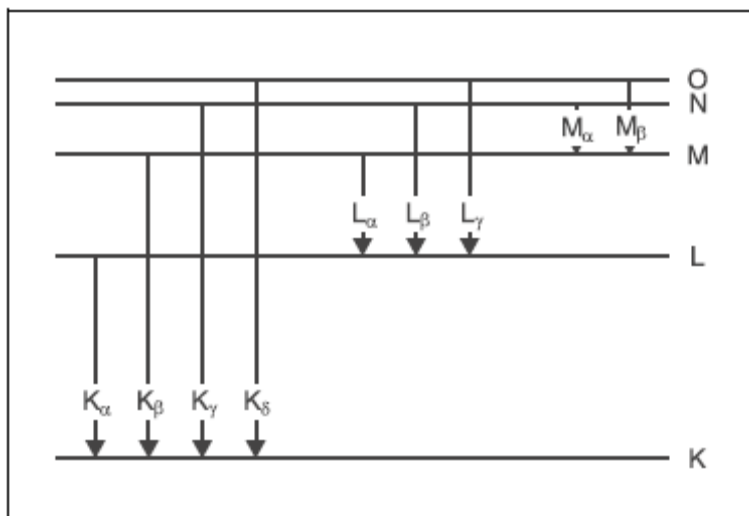


Fig. 2 serves to illustrate the nomenclature adopted for the orbital model of the atomic shell for the lines of the characteristic x-radiation: the individual orbitals are characterized by a particular binding energy and are designated from the innermost to the outermost with the letters K, L, M, N, 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

**Fig 2** Simplified term diagram of an atom and definition of the K, L and M series of the characteristic x-ray radiation

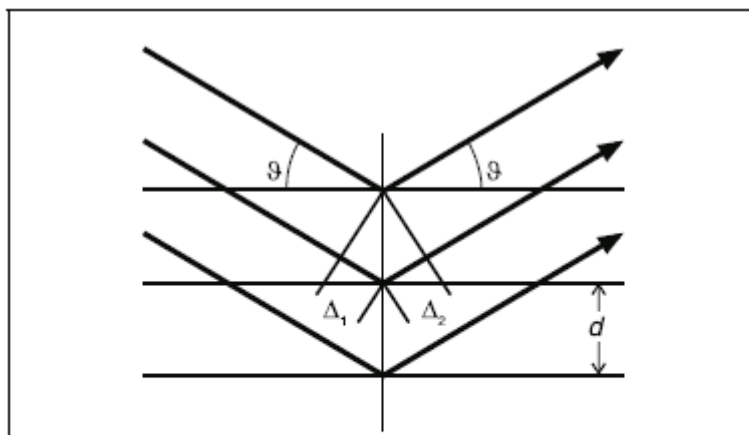


occur as a series of sequential lines designated  $K_{\alpha}$ ,  $K_{\beta}$ ,  $K_{\gamma}$ , etc. Starting from  $K_{\alpha}$ , the energy of the transitions increases and the corresponding wavelength decreases.

### Theoretical Preliminaries

In 1913, *H. W. and W. L. Bragg* realized that the regular arrangement of atoms and/or ions in a crystal can be understood as an array of lattice elements on parallel lattice planes. When we expose such a crystal to parallel x-rays, additionally assuming that these have a wave nature, then each element in a lattice plane acts as a “scattering point”, at which a spherical wavelet forms. According to *Huygens*, these spherical wavelets are superposed to create a “reflected” wavefront. In this model, the wavelength  $\lambda$  remains unchanged with respect to the “incident” wave front, and the radiation directions which are perpendicular to the two wave fronts fulfill the condition “angle of incidence = angle of reflection”.

Figure 3 shows a diagram of the Bragg scattering of x-rays from a crystal lattice of lattice spacing  $d$ . The total path difference traveled by the x-rays in the top two rays is given by the symbols  $\Delta = \Delta_1 + \Delta_2$  as shown in the figure.



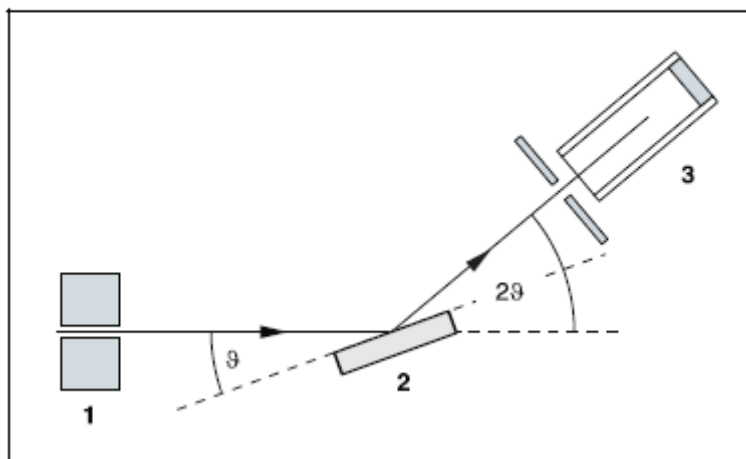
**Exercise:** Using the diagram in figure 3 and your knowledge of constructive interference, derive the Bragg scattering law

$$n\lambda = 2d \sin \theta .$$

**Fig 3** Diagram of the reflection of x-rays at the lattice planes of a monocrystal.  
 $\Delta_1, \Delta_2$ : path differences,  
 $\theta$ : glancing angle,  
 $d$ : spacing of lattice planes

The relative orientation of the incident x-ray beam (1), crystal (2) and x-ray detector (3) are shown in figure 4 at right. The angular orientation of the crystal and detector relative to the incoming beam is as indicated for all possible incident x-ray angles (so-called “glancing angles”) in a typical scan.

**Fig 4** Diagram showing the principle of diffraction of x-rays at a monocrystal and  $2\theta$  coupling between counter-tube angle and scattering angle (glancing angle)  
1 collimator, 2 monocrystal, 3 counter tube



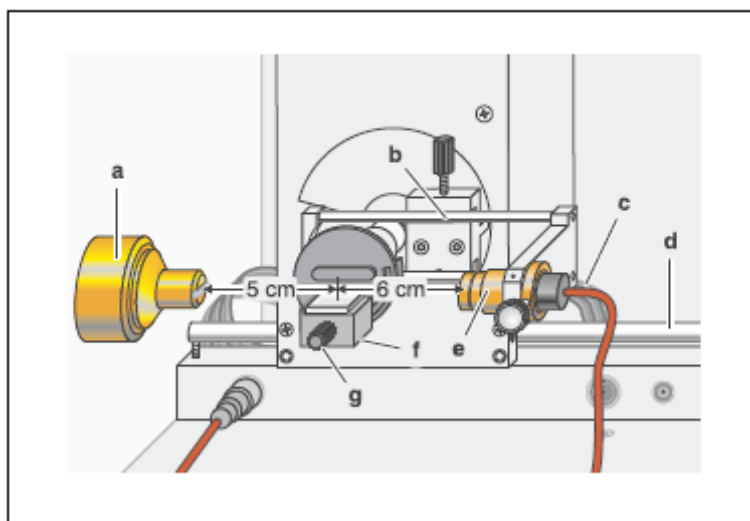
**Exercise:** Explain why the angles of the crystal and the detector relative to the incident beam are related as  $\theta - 2\theta$ .

### Experimental Setup

Figure 5 shows a few experimental details associated with the setup of the goniometer in preparation for making scans to observe an x-ray spectrum diffracted from the NaCl crystal.

1. Check to make sure that the middle of the target stage is approximately 5 cm from the face of the x-ray collimator (a). If you need to adjust this, loosen the knurled screws locking the goniometer to the guide rails (d) and slide the goniometer box accordingly.
2. Adjust the detector (e) position such that the face of the detector is approximately 6 cm from the center of the target stage.
3. Mount the NaCl crystal on the target stage ( refer to “*Mounting Crystal on Target Stage*” in **General Overview of Apparatus** ).
4. Perform the procedure *Zero Position of Goniometer* as described in part 3 of **General Overview of Apparatus**.
5. If you have not done so already, start the software interface program by double-clicking the “X-Ray” icon on the desktop. Select the “Bragg” tab and then

**Fig 5** Experiment setup in Bragg configuration



- select the “Settings” option from the menu bar followed by the “X-ray Apparatus” tab.
6. Set the X-ray high voltage to  $U = 35.0$  kV, emission current  $I = 1.00$  mA, measuring time per angle step  $\Delta t = 10$ s and angular step width  $\Delta\beta = 0.1^\circ$ .
  7. Check the COUPLED box and set the angular limits of the scan to  $2^\circ$  and  $25^\circ$ .
  8. Click on the SCAN check box to start the measurement.
  9. When the scan has completed, save the scan to a file using a suitable filename.

### **Evaluation of Data**

1. Examine the resulting spectrum from your scan and identify all of the features (i.e. Bremsstrahlung, characteristic peaks  $K_\alpha$ ,  $K_\beta$ , etc.).
2. Determine the exact peak centers of the characteristic radiation by an appropriate fitting of the peaks to a Gaussian curve.
3. Using the Bragg law and the information from your scan, determine best estimates for the values of the wavelengths of the characteristic peaks from the Mo anode. (Note: this is kind of cheating for the  $K_\alpha$  line because the zeroing procedure uses that line to align the sample. But the  $K_\beta$  measurement is independent.)

### **Characteristic X-Rays from Copper**

1. Carefully remove the Mo anode x-ray tube from the apparatus and replace it with the Cu anode x-ray tube. (You’ll probably have to do this with your instructor!)
2. Using the same NaCl crystal as in the Mo anode experiment (so it shouldn’t be necessary to re-zero everything), perform the same set of measurements to identify the characteristic diffraction peaks from NaCl using the Cu anode. Determine best estimates for the values of the wavelengths of the characteristic peaks.
3. Compare the values for the wavelengths of the  $K_\alpha$  peaks with those predicted from Moseley’s relation.