H5. X-Rays

From 1895 to 1905, physicists are confronted to all sorts of new discoveries in a short period of time:

1895	Roentgen	discovers X-rays
1896	Becquerel	discovers radioactivity
1897	Thompson	identifies electrons
1900	Planck	sets the fundamentals of quantum theory
1905	Einstein	defines the principles of relativity

These discoveries, which are mainly focused on the atomic structure, are the basis of modern physics

I. OBJECTIVE OF THE EXPERIMENT

We shall study the production, properties, and interaction with matter of X-ray

II. BASIC THOERY

The electromagnetic radiation spectrum (Fig. 1) ranges from approximately $1\ \mathrm{Hz}$ to $10^{23}\ \mathrm{Hz}$. Electromagnetic radiation of frequency greater than $10^{12}\ \mathrm{Hz}$ comes from molecular or atomic processes.

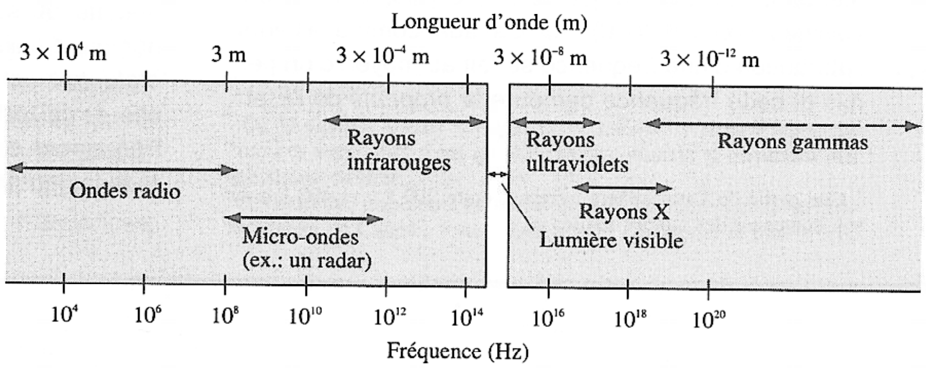

Fig. 1: Electromagnetic spectrum

We can divide electromagnetic radiation of atomic origin into three different categories:

- Light (infrared, visible and ultraviolet) whose frequency can vary between 10^{12} and $10^{17}\ \mathrm{Hz}$, comes from perturbations of the electrons on the **outermost shells of an atom**.
- X-rays have a frequency that ranges from 10^{17} to $10^{20}\ \mathrm{Hz}$ approximately, and are emitted from perturbations of electrons on the **inner shells of an atom**.
- Gamma radiation's frequency range is approximately 10^{19}-$10^{22}\ \mathrm{Hz}$. In contrast to the previous two types of radiation, these rays come from the **nucleus of radioactive atoms**.

PROPERTIES OF X-RAYS

X-rays behave differently than light in a number of different ways: no reflection on mirrors, no refraction through prisms or lenses and no diffraction through thin slits. They are transparent to most bodies, even metals. These phenomena are due to the wavelength of X-rays, which is much shorter than visible light.

PRODUCING X-RAYS

The easiest way to perturb the inner electron layers of an atom in order to cause it to radiate X-rays is to bombard it with high velocity electrons. These electrons have a high enough energy to go by the outer layers of the atom and perturb the inner ones.
In practice, this electron bombarding is achieved in a tube with a high vacuum. The **electrons** are emitted from a heated filament (cathode), and are accelerated by an electrode (grate) brought to voltage of the order of $40\ \text{kV}$. These electrons then hit an molybdenum **anticathode** that absorbs electrons and emits X-rays (Fig. 2).
Other materials can be used for the anticathode as well, e.g.: $\text{Cr}, \text{Fe}, \text{Co}, \text{Ni}, \text{Cu}, \text{W}$.

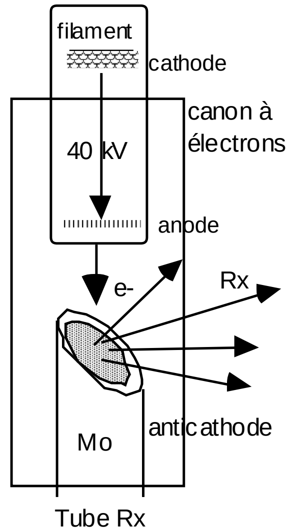

Fig. 2: Scheme of an X-ray tube.

Two types of radiation occur

The continuous spectrum (Fig. 3) is due to the sudden braking of electrons that pass by a nucleus, without ionizing the atom. Most of the energy is dissipated in the form of heat. However, electrodynamics predict that braking electrons must also emit electromagnetic radiation. The energy Δw that the electron loses is used to emit a photon of energy hυ. Δw can have any value below the kinetic energy of the electron eV. Therefore, the emitted photon can have any wavelength as long as it satisfies $eV \geq h\nu$.

The lower limit is given by the equation:

$$\lambda_{\min} = \frac{c}{\nu_{\max}} = \frac{ch}{eV} = \frac{12400}{V} \tag{1}$$

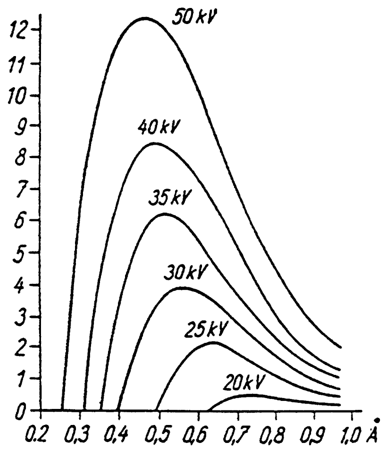

Fig. 3: Continuous spectrum of X-rays corresponding to different acceleration voltages

where h is the Planck constant, υ the frequency of the radiation, e the elementary charge, V the acceleration voltage in volts and λ the wavelength in Angstroms (10^{-10} m).

The discrete spectrum is generated when an electron loses its energy inside an atom, and tears away an electron on an internal layer (K, L,...). In a very short amount of time, an electron from an outer layer replaces the missing electron, and emits a photon in the X-ray range in the process. The frequency of the photon is **proportional to the energy difference** between the two involved electron layers.

$$\nu_{1\to 2} = \frac{1}{h}\left(E_2 - E_1\right) \tag{2}$$

The energy difference between two neighboring layers is greatest for the innermost two layers (Fig. 4).

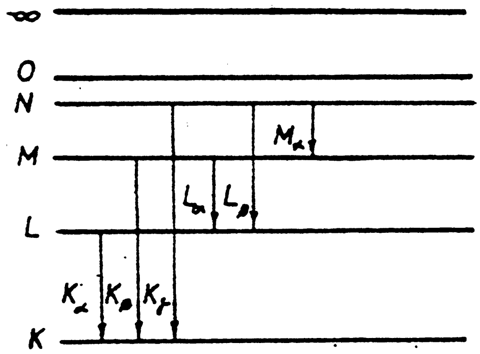

Fig. 4: Simplified energy diagram.

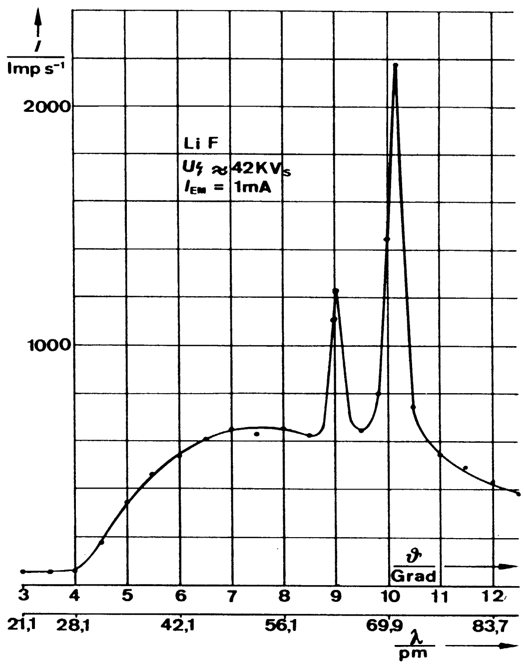

Fig. 5: Characteristic spectrum

Comments:

1) Since the E_i (i=K, L, M,...) are discrete, the corresponding spectrum will be discrete as well (line spectrum). The notation used to represent a line is the following: a letter is used to describe the final layer of the electron, and a greek letter subscript indicates the initial layer of the electron. If an electron goes from L to K, we have a $K\alpha$ line. If instead it starts from M, we have a $K\beta$ line.
2) Since the configuration of an atom's electronic layers depends on the element, the *discrete spectrum X is a characteristic of the material used for the anticathode* (Fig. 5).
3) The line spectra for X-rays tend to be much simpler than the optical spectra. They are made of a small number of lines called K, L, M, …
4) Since the configuration of the internal layers is pretty similar for all elements, the X-ray line spectra are rather similar, and depend of the atomic number Z. Mosely found a simple equation connecting the frequency of a line υ to its atomic number. The equation is:

$$v = C\left(Z - B\right)^2 \qquad (3)$$

where C B are constants characterizing an element.

EFFECT OF X-RAYS ON MATTER

When a beam of X-rays goes through a material, we can macroscopically observe a drop in the X-ray's intensity. This effect is mostly due to two processes: the Compton effect and the photoelectric effect.

The Compton effect occurs when an X-ray photon collides with a free electron. The X photon loses energy in the collision, and the energy is recuperated by the electron in the form of kinetic energy (Fig. 6).

The photoelectric effect occurs when an X photon is absorbed by an electron tied to an atom, and thereby frees it from the atom.

Electrons freed from an atom through the photoelectric or Compton effect constitute β radiation, which define the physical, chemical and biological actions of X-rays. The Compton effect dominates high-energy X-rays (hard radiation), whereas the photoelectric effect the more important one for lower energy rays (soft radiation).

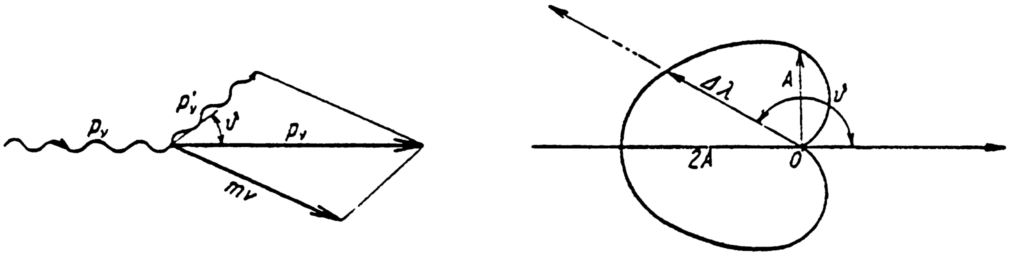

Fig. 6: Dispersion of the Compton photon

Due to their absorption by matter, the intensity of an X-ray (energy per unit surface and time) decreases as a function of thickness according to the following formula:

$$I = I_0 e^{-md} \tag{4}$$

where, m is the absorption coefficient, d the thickness of the material and I_0 the incident radiation. The m coefficient depends mostly on the material and the frequency of the incident beam. We can observe discontinuities of the absorption due to the photoelectric effect.

INTERACTION OF X-RAYS WITH ANISOTROPIC MATTER - DIFFRACTION

A diffraction phenomenon occurs when an incident wave of frequency λ hits a grating of small slits (□ λ) with regular spacing (g >□ λ). The outgoing wave's direction is modified according to the equation:

$$g \sin\theta = n \cdot \lambda$$

where n is an integer (Fig. 7).

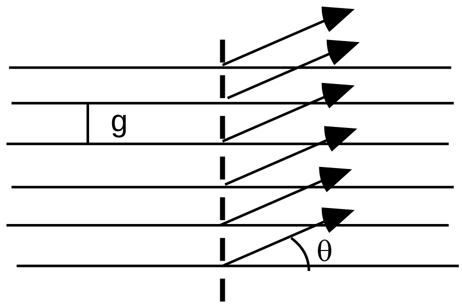

Fig. 7: Diffraction of parallel beams by a grating.

In 1912 von Laue managed to diffract X-rays by directing them through a zinc sulfate crystal. W.H. and W.L. continued von Laue's experiments and found the X-ray diffraction conditions in a crystal. They studied families of parallel planes in a crystal lattice (fig. 8).

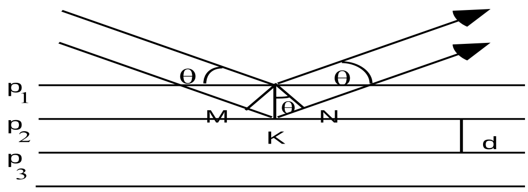

Fig. 8: X-ray – parallel plane interactions in a crystal lattice.

For two neighboring parallel planes p_1 and p_2 the reflected waves reinforce one another if the optical length $MK + KN$ (Fig. 8) is an integer multiple of the wavelength λ, i.e. if:

$$2d \sin\theta = n\lambda \tag{5}$$

This equation is called **Bragg's law**.

These discoveries have become the basis of X-ray spectroscopy, as well as the basis for studying the structure of solids.

BIOLOGICAL EFFECTS

Biological effects of X-rays are due to chemical or structural modifications of the cell composition. These modifications can be of two types: somatic and genetic.

Somatic effects are internal or external lesions, and sometimes even burns, leading to poor health, and possibly death. Genetic effects affect the eventual descendants of the irradiated organism. Living tissues are damaged by X-rays, and it is therefore crucial to control the amount of energy received by the organism. This is how we shall define radiation dosage.

The absorbed dose of radiation is the physical quantity that measures the amount of absorbed ionizing radiation per unit mass of the material. The SI unit is gray, defined as 1 Gy = 1 J/kg. The corresponding cgs unit is rad, defined as 1 rad = 0.01 Gy $=10^{-2}\ \mathrm{J/kg}$ ".

III. EXPERIMENTAL SETUP

The apparatus producing the X-rays is mounted of a chassis that contains all necessary elements for completing its task, including those for security purposes. The direct heating X-ray tube is directly supplied by a self-rectifying high voltage transformer. The X-ray tube, the anti-radiation protection and the high voltage transformer are all grouped in a grounded metallic box (Fig. 9).

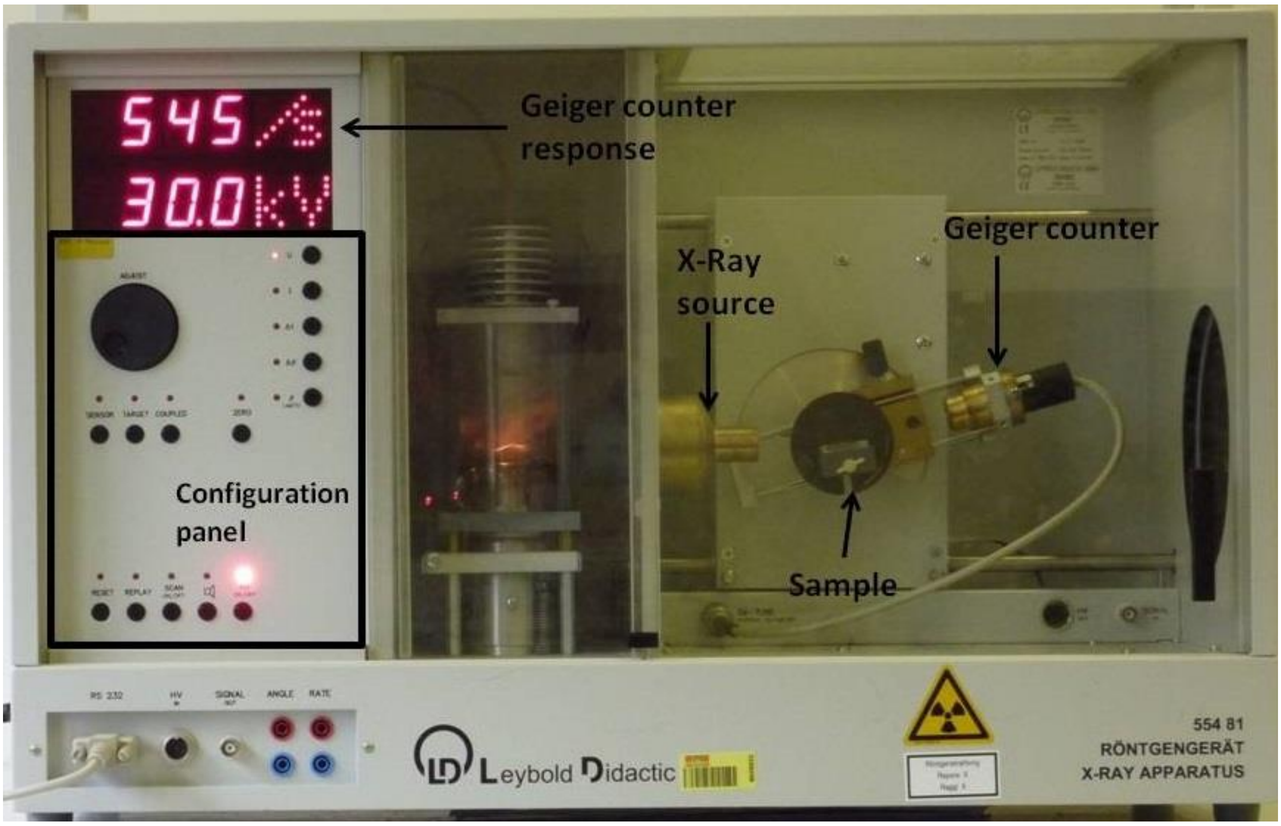

Fig. 9 : X-Ray machine

Using the apparatus

All settings are done from the configuration panel.
X-rays are only emitted when the **HV On/Off** indicator is blinking. The button allows to activate and deactivate the radiation.
To set the voltage or the current, press *U* or *I* respectively, and adjust the value using the wheel.
The Δt, $\Delta\beta$ and β *limits* are used to setup automatic scanning. Δt fixes the measuring time at each position,. $\Delta\beta$ sets the step between two measurements, and β *limits* lets you determine the minimal (↓) and maximal (↑) angles of the automatic scanning.
To start the automatic scanning, hit *coupled*, and then *scan on/off*. Data is collected using the program `appareil à rayon X` found on the computer.
The *sensor*, *target*, and *coupled* buttons allow you to manually change the angle of the sensor, the target, or both simultaneously. The *zero* button sets all angle back to 0 °.

The “counter tube" (Geiger-Müller) is a cylinder containing a low pressure gas. A magnetic wire of small diameter stretches along the axis of the tube. We then apply a voltage slightly lower than one that would create a spontaneous discharge in the gas. When a fast particle enters the tube, it provokes an electric discharge in the gas. In order to know how many particles go through the tube, we simply count the number of electric pulses. This is how a Geiger counter works.

IV. EXPERIMENTS

1) a) *Response of the Geiger-Müller tube as a function of the acceleration voltage and the emission current of the electrons. (saturation domains?).*

Line up the Geiger-Müller tube with the source. For acceleration voltages of $20/25/30/35 \ \mathrm{kV}$, measure the response R of the G-M tube as a function of current ($I = 0 \rightarrow 1 \ \mathrm{mA}$).

Discuss the results. (Hint: paralyzable and unparalyzable dead time)

b) *Detailed calibration for $U = 30 \ \mathrm{kV}$.*

Suppose $I \propto R$ where R is the response of the Geiger-Müller tube. Set $U = 30 \ \mathrm{kV}$, and measure the response of the tube more precisely, for $I = 0 \rightarrow 0.1 \ \mathrm{mA}$. Determine the range for which the response is linear (verify for both high and low R values), and determine the slope p. Later on, we will approximate $R = p \cdot I$ for values of I that are to big to be measured by the Geiger counter.

2) *Measure of the X-ray diffractogram for different acceleration voltages (Bragg experience).*

Using the automatic scan function, establish the diffractogram of a NaCl rock salt crystal. Scan with a measuring time of 1s and a step of $0.1°$ from $2.5°$ to $25°$. Do these measurements for $U = 20/25/30/35 \ \mathrm{kV}$.

Talk about the observed curves, and point out the different lines on the graph. Determine the wavelengths of K_α et K_β lines.

Determine the numerical value f the Planck constant h using $\lambda_{\min}$ of the continuous spectrum (supposing that we know the lattice constant of the used crystal).

3) *Absorption versus width*

We will use a cylinder with seven slits that are blocked by aluminum samples ranging in thickness from 0.5 to 3 mm. By placing the Geiger counter behind the slits, we can determine the absorption coefficient for aluminum.

Verify the exponential relationship between the X-ray intensity and the sample thickness, and determine the absorption coefficient of aluminum.

4) *Absorption versus atomic number.*

We will use a cylinder with 7 slits blocked by samples of plastic ($Z = 6$), Al ($Z = 13$), Fe ($Z = 26$), Cu ($Z = 29$), Zr ($Z = 40$), ($Z = 47$), all 0.5 mm thick.

Determine the absorption coefficient for each one of these materials, and discuss the relationship with the atomic number.

For certain measurements, you will need to use the detailed calibration explicated in 1b).

5) *Bragg experiment and X-ray diffractogram*

Using a rotating apparatus, when the target rotates by an angle θ, the counter rotates by 2θ.

Calibrate the X-ray diffractogram using a known crystal (LiF or NaCl) (exp. 2).

Using this, determine the lattice parameter (distance between atomic planes) of an unknown crystal.

You can also use a zirconium filter in front of the X-ray source, in order to isolate the $K\alpha$ line of molybdenum.

6) *Compton Effect (extra)*

A first measure is done with an absorbent (copper sheet) placed in front of the diffuser (aluminum plate). A second measure is done where the absorbent is placed behind the diffuser. The reduced measured intensity in the second case with respect to the first, shows that the wavelength of the X-ray photon is increased during the diffusion.