Some Facts about X-Rays

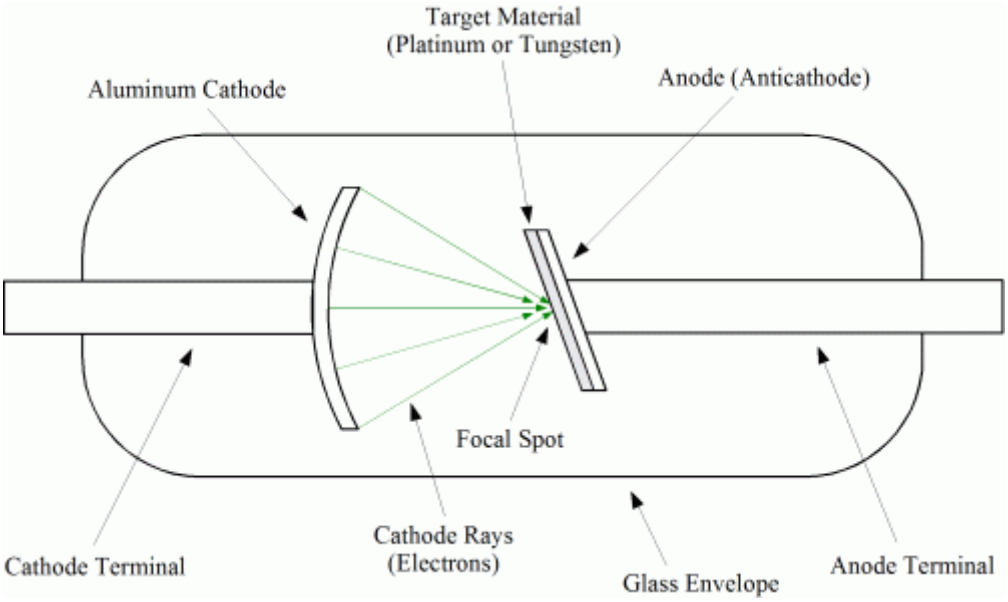
by Henning Umland

X-rays were discovered by the German physicist W. C. Röntgen in 1895 when he accidentally noticed that fluorescent materials showed a faint glow when placed near a cathode-ray tube powered by a high voltage induction coil. Although others had observed similar phenomena earlier, Röntgen was the first one who concluded that he had found "a new kind of rays". He called them "X-rays" (X = unknown) and began a systematic research on their properties. His work was so thorough that it took seventeen years until significant new facts became known. Some scientists thought that X-rays were a kind of ultraviolet light, but nobody was able to prove it at that time. Finally, crystal diffraction experiments done by M. v. Laue in 1912 confirmed that X-rays are electromagnetic waves.

With a wavelength of approx. 10nm to 0.001nm, X-rays occupy the range between UV light and gamma rays in the electromagnetic spectrum. The definition of the upper and lower wavelength limit is more or less arbitrary and not marked by a sudden change of properties. X-rays with a short wavelength, for example, overlap with gamma rays of long wavelength. Radiation in this region is usually named after the mechanism of emission. Gamma rays are released by nuclear processes, X-rays are emitted when fast electrons collide with matter. Technically, X-rays are produced by means of an X-ray tube, a simple form of a linear particle accelerator.

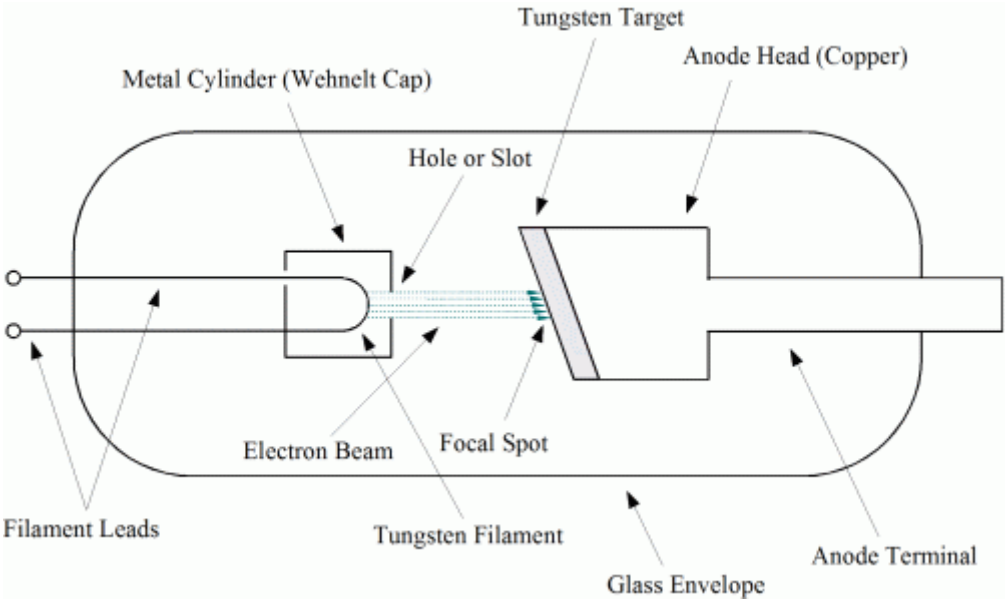
Shortly after Röntgen's discovery, the first useful X-ray tubes were designed. They consisted of a partially evacuated ($p \approx 0.02$ mbar) glass bulb containing a cold cathode on one side and an anode ("anticathode") on the other side.* A very high voltage (tens or hundreds of kilovolts) applied to the tube forms a strong electrical field between cathode and anode which causes ionization of gas molecules. Being bombarded with positive ions, the cathode emits "cathode rays" (electrons) which are accelerated toward the anode. The cathode surface has a spherical curvature so as to focus the cathode rays on a small area (focal spot) of the anode material (target) facing the cathode. Upon their impact, the fast electrons cause the focal spot to emit X-rays.

*Early models had a third electrode (connected to the anticathode) which was later omitted.



The radiation thus emitted is omnidirectional, but a significant part of it is absorbed by the target metal and the anode head. The target surface usually forms an obtuse angle (45…85°) with the tube axis. This enables a greater part of the radiation to exit the tube sideways (penetrating the glass envelope).

Gas-filled X-ray tubes have a number of drawbacks, e. g., unstable characteristics. These were overcome by the high-vacuum tubes developed by W. Coolidge in 1913. Coolidge reduced the pressure inside the tube to less than 10^{-6} mbar and replaced the cold cathode with a heated tungsten filament combined with a focusing device:



The filament is electrically heated (>2200 K) and emits electrons (thermionic emission). The electrons are focused on the target by means of a hole or slot in a metal cylinder surrounding the filament (Wehnelt cap). In contrast to a cold-cathode tube, the anode current of a Coolidge tube is virtually independent of the anode voltage and is solely controlled by the filament current.

X-rays are produced by two different mechanisms, bremsstrahlung and characteristic radiation.

Bremsstrahlung is the German word for decelerating (braking) radiation. When high-speed electrons approach the atomic nuclei of the target metal, they are deflected by strong electrical fields. A sudden change in the velocity and/or direction of an electron causes the emission of a photon. The highest possible energy of a photon thus formed equals the whole kinetic energy of the electron. The smallest possible wavelength (short-wavelength limit) is inversely proportional to the anode voltage:

$$\lambda_{\min.} = \frac{h \cdot c}{e \cdot U}$$

h: Planck's constant ($6.6262 \cdot 10^{-34}$ Js)
c: Speed of light ($2.9979 \cdot 10^{8}$ m/s)
e: Charge of an electron ($1.602 \cdot 10^{-19}$ As)
U: Anode voltage [V]

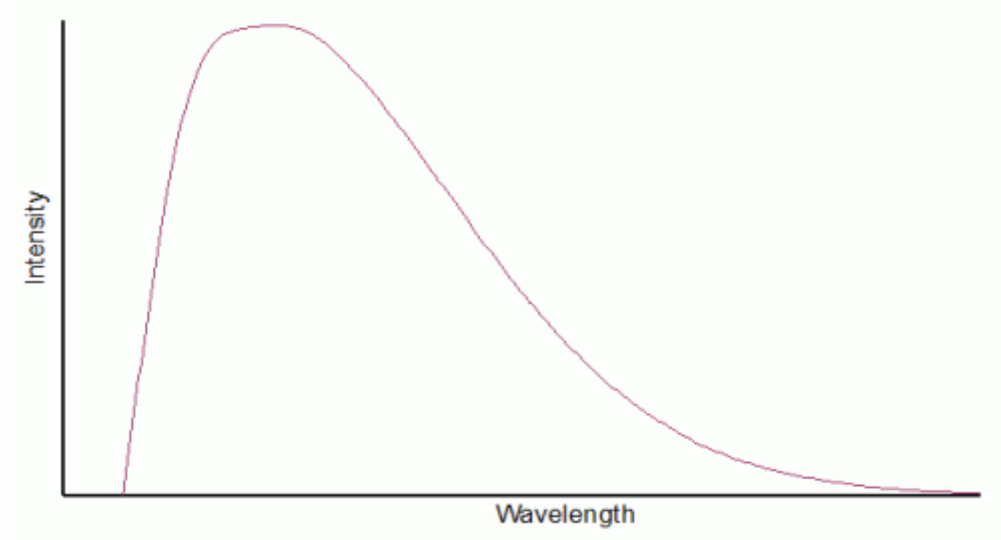
The product e·U is the kinetic energy of the incident electron, E. The unit for E is the electron volt (1 eV = $1.602 \cdot 10^{-19}$ J). Combining the constants h, c, and e, we get:

$$\lambda_{\min.}\ [nm] = \frac{1.24}{U\ [kV]}$$

The short-wavelength limit at 50kV anode voltage, for example, is approx. 0.025 nm. Accordingly, a short-wavelength limit of 0.001 nm would correspond with an anode voltage of approx. 1.24 MV. X-rays in this wavelength range have the same properties as soft gamma rays.

In most cases, an electron undergoes a number of collisions until it finally comes to a stop. Most of the kinetic energy is absorbed by the crystal lattice of the target metal and dissipated as vibrational energy (heat). Only a small portion of the kinetic energy is transformed into X-ray photons. Photons formed during these collisions can assume any energy level between zero and the maximum defined by the product e·U, resulting in a continuous emission spectrum.

The intensity distribution curve of the bremsstrahlung diplays a sharp drop-off at the short-wavelength limit. Toward greater wavelengths (lower energies), the intensity curve flattens out gradually. Thus, the curve has the shape of an asymmetric bell:



The efficiency of X-ray generation is very low. The fraction of the total power emitted as X-rays is:

$$w\ [\%] = 100 \cdot C \cdot Z \cdot U$$

C is a constant ($C = 10^{-9}\ V^{-1}$). Z is the atomic number of the target metal. For example, a tube with a tungsten (Z = 74) target operated at 100 kV has an efficiency of 0.74 %. Accordingly, 99.26 % of the electrical energy pumped into the system is dissipated as heat. A tube with a copper target (Z = 29) would have an efficiency of only 0.29% at the same voltage.

The total power of the emitted X-rays, P, at a given anode voltage, U, and anode current, I, is:

$$P = C \cdot Z \cdot I \cdot U^2$$

For example, a tube with a tungsten target operated at 80 kV and 10 mA emits 4.7 W X-ray power and produces 795.3 W heat.

The so-called characteristic radiation is produced when a high-speed electron hits an atom of the target metal and ejects an electron from an inner shell (inner ionization). When the resulting void is filled by an electron of an outer shell, the difference between both energy levels is emitted in the form of an X-ray photon.

There are different groups of spectral lines, depending on the respective inner shell from which an electron is ejected. The K shell (n = 1) produces the K series, the L shell (n = 2) the L series, the M shell (n = 3) the M series, etc. Traditionally, the spectral lines of a series are marked by indices (Greek letters) indicating the number of shells changed by the electron filling the void. For example, the Kα line is produced when an electron from the L shell (n = 2) drops back to fill the K shell (n = 1). An electron dropping from the N shell (n = 4) to fill the L shell (n = 2) would produce the Lβ line, etc.*

* n is the principal quantum number of a shell

Each element produces its own characteristic X-ray spectrum. A particular line of the spectrum, for example the Lα line, shifts to smaller wavelength with increasing atomic number of the element (Mosley's law):

$$\lambda = \frac{K}{(Z-\sigma)^2}$$ (K and σ are constants.)

The lines of the characteristic radiation are superimposed on the continuous spectrum and appear as sharp peaks protruding from the bell curve. Characteristic lines play an important part in X-ray diffraction experiments and X-ray Fluorescence Analysis (XFA).

X-ray tubes used for diffraction experiments usually have copper or molybdenum targets which give greater characteristic wavelengths than tungsten.

Properties of X-rays:

X-rays are characterized by their intensity and energy.

The intensity can be measured, e. g., as the number of photons passing through an area per time unit (counts per second). At a given anode voltage, the intensity of the radiation is proportional to the anode current of the tube. Since the radiating area of a tube is very small, the intensity is inversely proportional to the square of the distance.

The energy of a photon, E, is inversely proportional to the wavelength:

$$E = \frac{h \cdot c}{\lambda}$$

X-rays penetrate materials which are opaque to electromagnetic waves of greater wavelength like infrared, visible, or UV light. The attenuation of X-rays of a given wavelength traversing a sample is described by Lambert's law:

$$I = I_0 \cdot e^{-\left(\frac{\mu}{\rho}\right) \cdot \rho_b \cdot t}$$

I:	Radiation intensity [counts per second]
I_0:	Incident radiation intensity [counts per second]
μ:	Linear attenuation coefficient of the pure and compact material [cm^{-1}]
ρ:	Density of the pure and compact material [g/cm^3]
μ/ρ:	Mass attenuation coefficient [cm^2/g]
ρ_b:	Bulk density of sample [g/cm^3]
	(ρ_b is smaller than ρ when the sample is porous)
$(\mu/\rho)\cdot\rho_b$:	Linear attenuation coefficient of sample [cm^{-1}]
t:	Thickness of sample [cm]

The thickness of a sample attenuating the incident intensity by 50% is called half-thickness, $t_{½}$:

$$t_{1/2} = \frac{0.6931}{\left(\frac{\mu}{\rho}\right) \cdot \rho_b}$$

The mass attenuation coefficient of a mixture of n components or a chemical compound of n elements is calculated from the mass attenuation coefficients of the components or elements:

$$\frac{\mu}{\rho} = \sum_{i=1}^{n} x_i \cdot \left(\frac{\mu}{\rho}\right)_i$$

x_i: Mass fraction of component or element

$(\mu/\rho)_i$: Mass attenuation coefficient of component or element

For example, the half-thickness of calcium carbonate ($CaCO_3$) powder is calculated as follows (monochromatic X-rays, E = 50 keV):

x_{Ca}	=	0.4004	$(\mu/\rho)_{Ca}$	=	1.0190 cm^2/g
x_C	=	0.1200	$(\mu/\rho)_C$	=	0.1871 cm^2/g
x_O	=	0.4796	$(\mu/\rho)_O$	=	0.2132 cm^2/g

$(\mu/\rho)_{CaCO3} = 0.4004 \cdot 1.0190 + 0.1200 \cdot 0.1871 + 0.4796 \cdot 0.2132 = 0.5327\ cm^2/g$

$\rho_b = 0.65\ g/cm^3$ (powder!)

$$t_{1/2} = \frac{0.6931}{0.5327 \cdot 0.65} = 2.002\,cm$$

Thus, a layer of 2 cm $CaCO_3$ powder halves the intensity of the radiation.

The attenuation caused by the air in the voids of the powder can be ignored because the density of a gas is about three orders of magnitude smaller than the density of a solid.

The attenuation of a beam of X-rays traversing a sample is caused by several kinds of interaction between photons and matter. For example, an X-ray photon may lose its total energy ionizing a target atom, i. e., ejecting an electron from a shell (photoelectric absorption). When the photon energy is high enough to eject an electron from an inner shell, the target atom emits characteristic radiation of lower energy (X-ray fluorescence). When colliding with a free or loosely bound electron, a photon may change its direction with partial energy loss (inelastic scattering) or without energy loss (elastic scattering).

Scattering phenomena were observed by Röntgen already. In his *Further Observations on the Properties of X-rays* (third communication, 1897), he notes:

"…*one must conclude from the experiment described that air emits X-rays in all directions while it is being irradiated. If our eye were as sensitive to X-rays as it is to light rays, a discharge apparatus* [X-ray tube] *in operation would appear to us like a light burning in a room that is uniformly filled with tobacco smoke, perhaps the colour of the direct radiation and that coming from the air particles would be different*."

Since scattered radiation is not directed, it reduces image contrast (see fluoroscopy & radiography). For the same reason, it poses a potential safety risk to X-ray operators and requires proper shielding measures.

Generally, the mass attenuation coefficient of an element decreases with increasing photon energy and, consequently, with decreasing wavelength.

X-rays with a small wavelength (λ < approx. 0.1 nm) are usually called "hard", those with a greater wavelength are called "soft". This distinction is arbitrary and refers to the relative "penetrating power" of the radiation. Since soft X-rays are attenuated to a greater extent than hard X-rays when traversing matter, bremsstrahlung can be "hardened" by means of a suitable filter material, e.g., aluminum. In this case, the maximum of the intensity distribution curve shifts to smaller wavelength. Thus, the bandwidth of the radiation decreases because the short-wavelength limit remains unchanged. In diagnostic applications, aluminum filters are used to remove the undesirable portion of soft radiation which would be completely absorbed by the human body, increasing the radiation dose unnecessarily.

When the energy of the incident photons becomes high enough to ionize atoms of an irradiated element, the mass attenuation coefficient rises abruptly, but decreases again as the wavelength decreases further (absorption edge). In this way, it is possible to remove selected wavelengths from the spectrum by means of suitable filters. Absorption edges of lighter elements ($Z \leq 30$) occur below 10 keV.

At a given wavelength, the mass attenuation coefficient of an element increases rapidly as the atomic number increases.

The attenuation characteristics of X-rays form the basis for their technical and diagnostic application. Bones, for example, attenuate X-rays to a greater extent than soft tissue not only because they have a higher bulk density but also because they contain a high concentration of calcium and phosphorus. Both elements have higher atomic numbers and mass attenuation coefficients than the elements C, H, O, and N which are the main constituents of soft tissue.

X-rays exhibit a very low refractive index and are not reflected by ordinary mirrors. Thus, it is not possible to produce images through conventional lens- or mirror-based optical systems. X-ray images are obtained as shadows of objects placed between an X-ray source and a fluorescent screen (fluoroscopy) or photographic film (radiography).* If the material distribution inside the object is inhomogeneous, the shadow image may reveal details of the internal structure. Since the radiation is emitted by a very small area (focal spot) inside the X-ray tube, the image is formed by central projection and may show distortions. Therefore, proper positioning of the object is important. It may also be necessary to rotate the object in order to separate details which overlap in the projected image. The enormous importance of fluoroscopy and radiography was immediately recognized when X-rays were discovered and had a huge impact on the further development of medicine and material testing.

* Today, more sophisticated, computer-aided imaging techniques are available, e.g., tomography.

According to the small wavelength, X-ray photons have a much higher energy than, e. g., the photons of visible light (λ = 400…800 nm). As a result, X-ray photons can ionize atoms and trigger chemical reactions to a greater extent than visible or UV light.

The chemical activity of high-energy photons is the reason why X-rays damage living tissue. This is useful for tumor therapy but highly undesirable in diagnostic applications. An overdose of X-rays can cause symptoms ranging from mild skin irritation to severe radiation sickness. Long-term effects of damaged genetic material may include leukaemia and other forms of cancer. Genetic defects may also be passed on to descendants. Therefore, X-rays have to be handled and applied with care.