Röntgen's discovery of X-rays

by Jean-Jacques Samueli[1], PhD in physics

Wilhelm Conrad Röntgen was born on 27 March 1845 in Lennep in Germany (Westphalia). He studied in Zurich and then became a professor of physics in Strasburg (1876–1879), which was then under German occupation. This was followed by posts in Giessen (1879–1888), Würzburg (1888–1900) and Geneva (1900–1920). He received the first Nobel Prize in Physics in 1901 for his discovery of X-rays, a discovery he had made in late 1895 using a Crookes tube in a darkened room.

RÖNTGEN'S EXPERIMENT

On 8 November 1895, Röntgen wrapped some black cardboard around a Crookes tube attached to a Ruhmkorff induction coil, in other words a step-up transformer excited by repeated electrical pulses. Every pulse produced an electric discharge in the low-pressure gas in the tube. After turning off the lights in the room, Röntgen noticed a fluorescent effect on a small paper screen painted with barium platinocyanide. One of the properties of barium platinocyanide is that it is fluorescent, which means it emits light when it is excited by photons. This fluorescence appeared when the paper was fewer than two metres away from the tube, even when the paper was obscured by black cardboard. Röntgen concluded that the tube was producing invisible radiation of an unknown nature, which he called an X-ray, and that this was causing the fluorescence he had observed.

The Crookes tube

Sir William Crookes (1832–1919) invented an experimental device, which is now known as a Crookes tube (or a discharge tube, gas-filled tube or cold cathode tube), to study the fluorescence of minerals.
A Crookes tube is simply a glass bulb with an electrode at each end: a metallic (aluminium) cathode, and an anode that attracts electrons. Though the tube is a vacuum, it contains residual air pressure of 100 Pa (about one thousandth atmosphere).

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[1] Mr Samueli died in February 2014 aged 81.

An induction coil is used to apply a high voltage between the anode and the cathode. This ionises the residual air contained in the tube. Just like in a battery, the positive ions this creates are attracted to the cathode, which they collide into, and in doing so they dislodge other electrons from the metal of the cathode, which are then attracted to the anode. Before the electron was discovered, the flow of electrons arriving on the anode, or the target acting as an anode (as in the Maltese cross below), were known as "cathode rays".

***Figure 1*: A Crookes tube** *(supplied by a Ruhmkorff coil, seen on the right). Thanks to the vacuum inside the tube, the electrons come into contact with few molecules during their trajectory and maintain the high speed acquired from the electric field (around 0.1c). Some move beyond than the anode and this causes the glass to become fluorescent. The effect is heightened when the end of the tube is covered with a fluorescent material. The projection of the shadow of the Maltese cross led Hittorf (1824–1914) to speculate that something was moving rectilinearly inside the tube. This something would become known as a "cathode ray".*

In 1895, Röntgen was fifty years old. He was an experienced scientist and a shrewd experimenter with various research projects to his name. This is how he recalled his discovery:[2]

> *I had already been interested in cathode rays, which had been studied by Hertz and Lenard in particular, for some time …* [I] *said to myself that when I had some free time I would carry out some personal experiments … I found the time in late October 1895 …* [On the evening of 8 November 1895] *I was working with a Hittorf-Crookes tube, which was entirely surrounded by black paper. There was a piece of paper coated in barium platinocyanide next to the table. I sent a current through the tube and noticed a peculiar-looking black line through the paper. There was no way that the light could be coming from the tube because it was completely covered in a type of paper that let no light through … I thought it was … something new, but as yet unknown.*

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[2] Röntgen, *Mc. Clure Magazine*, 6 April 1896.

He noticed that he could see the bones in his hand when he held his hand out between the tube and the screen. On the evening of 22 December 1895, he called out to his wife to come and see this extraordinary discovery. He asked her to hold out her hand and in doing so produced the first ever X-ray.

Figure 2: *X-ray of the hand of the anatomist and physiologist Kölliker (1896).*

HOW RÖNTGEN ANNOUNCED HIS RESULTS

Röntgen's first publication about his discovery was released in the days that followed, on 28 December 1895: It was entitled "On a New Kind of Rays" (*BibNum* text). He suggested the name "X-ray" for his discovery, arguing that since the origin of the rays was unknown, it was appropriate to refer to them as X, the mathematical term for the unknown (footnote 2):

> *For the sake of brevity, I will use the term "ray" and to distinguish them from others with the same name, I will call them "X-rays".*

The success was immediate. This was how Röntgen described it to his former assistant and friend Zehnder: "My work was universally recognised. Boltzmann, Warburg, Kohlrausch and no lesser men than Lord Kelvin, Stokes, Poincaré and others expressed to me the joy they felt at this discovery, and their admiration … I hadn't told anyone about my work. I had merely told my wife that I was engaged in something which would have people saying, when they found out about it: 'Röntgen has gone completely mad!' On 1 January I sent out the offprints, and what a commotion they caused! The *Wiener Presse* was the first to wax lyrical, then others followed."

On 23 January 1896, Röntgen delivered a lecture – the only one he would give on the subject – to the Würzburg Physico-Medical Society (for which he had written his text of 28 December 1895). The famous anatomist Kölliker was one of those listening.[3] During the lecture he took an X-ray of the hand of this scientist, who suggested that the new rays should be called "Röntgen rays". From this point on, research into X-rays expanded exponentially. At the Paris Academy of Sciences alone, two papers on the subject were presented during the session of 3rd February, followed by four on the 10th, six on the 17th and six on 2nd March.[4] In total, over a thousand articles would be published on the subject in 1898, of which eight hundred were published at the French Academy of Sciences.

On 5 March 1896, Röntgen published a second article with the same title as the first ("On a New Kind of Rays"). In introduced the article as follows: "As my work had to be interrupted for a few weeks, I am taking the liberty of presenting a few new results now … But I waited until I had irrefutable results before publishing my experiments." The paper describes his many experiments into the discharge of bodies by X-rays. On 13 May 1897 he published a third and final paper on his discovery, entitled "New Observations on the Properties of X-Rays". Among other things, he confirmed that X-rays originate in the part of the tube struck by cathode rays, and then spread "in all directions".

RÖNTGEN'S TEXT OF DECEMBER 1895

In this article,[5] Röntgen draws various conclusions, which he enumerates in paragraphs marked 1 to 17. This scientific approach of characterisation is itself worthy of attention:

- §1: Description of the observed phenomenon: Fluorescence induced at a distance by a discharge in a Crookes tubes.

  The fluorescence thus produced being independent of the fact that the coated surface of the paper is pointing towards the discharge tube. This fluorescence is still visible at two metres distance.

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[3] Rudolph Albert von Kölliker (1817–1905) was a Swiss doctor who established the link between nerve fibres and neurons and demonstrated that chromosomes are involved in heredity.

[4] During the session of 2 March 1896, Becquerel presented a paper entitled "Sur les radiations invisibles émises par les corps phosphorescents", in which he described his discovery of radioactivity (article analyzed on BibNum).

[5] The English translation of the article is available online at http://onlinelibrary.wiley.com/doi/10.3322/canjclin.22.3.153/epdf.--Trans.

- §2: The fluorescence on the screen is caused by an unknown ray that originates in the tube, and not by sunlight (whether visible or ultraviolet) or by artificial light (arc-light), with which fluorescence was often observed:

  > *The most surprising property of this phenomenon is the fact that in this experiment an active agent travels through an envelope of black cardboard, which is opaque to the visible or ultraviolet rays of the sun and to arc-light; an agent which is also able to produce an active fluorescence.*

- §2: Röntgen also gives the phenomenon its name in this paragraph:

  > *For the sake of brevity, I will use the term "ray" [to denote the "agent" responsible for the observed phenomena] and to distinguish them from others with the same name, I will call them "X-rays".*

- §2: These X-rays travel through different materials to varying extents:

  > *Paper is very transparent; the fluorescent screen will light up when placed behind a book of a thousand pages … A piece of sheet aluminium, 15 mm. thick, still allowed the X-rays to pass, but greatly reduced the fluorescence … If the hand be held before the fluorescent screen, the shadow shows the bones darkly, with only faint outlines of the surrounding tissues.*

- §3: The absorption of the rays by the materials they pass through depends on the density of the materials, but density alone does not determine the transparency.
- §4: The absorption of the X-rays increases in thicker materials.
- §5: Metals have varying degrees of transparency to X-rays.

  > *The different metals possess varying degrees of transparency, even where the products of their thickness and density are the same.*

- §6: X-rays are not visible to the naked eye. They leave an impression on photographic plates.

  > *Photographic images can be obtained in an undarkened room using photographic plates either kept in their case or wrapped in paper … The eye placed close to the apparatus sees nothing.*

- §7: Unlike light rays, X-rays are not deflected by prisms made of various materials, nor are they concentrated by lenses.

  > *Investigations … in mica prisms … showed no deviation either on the photographic or the fluorescent plate.*

- §8: No regular reflection of X-rays can be detected.

  > *Regular reflection does not exist, but … bodies behave to the X-rays as turbid media to light.*

- §9: It is possible that the internal structure of a material influences the transparency of X-rays.
- §10: The intensity of detected X-rays varies with the inverse of the squared distance of the anode from the emitting tube. Air does not attenuate X-rays, whereas it does have this effect on cathode rays.

  I find … that the intensity … varies nearly as the inverse square of the distance between screen and discharge tube. This result is obtained from three very consistent sets of observations.

  Hence air absorbs the X-rays much less than the cathode rays. This result is in complete agreement with the previously described result (NB: ¶1), that the fluorescence of the screen can be still observed at 2 metres from the vacuum tube.

- §11: Unlike cathode rays, X-rays are not deflected by a magnetic field.

  Until now, the deviation of cathode rays by a magnet has been one of their peculiar characteristics … I have not succeeded in observing any deviation of the X-rays even in very strong magnetic fields.

- §12: X-rays are produced by cathode rays on the wall of the glass discharge tube.

  It appears that the place of most brilliant phosphorescence of the walls of the discharge tube[6] *is the chief seat whence the X-rays originate and spread in all directions … If one deviates the cathode rays within the tube by means of a magnet, it is seen that the X-rays proceed from a new point, i.e. again from the end of the cathode rays.*

- §13: An aluminium – as opposed to a glass – tube also produces X-rays.
- §14: The term "ray" is justified because X-rays propagate rectilinearly.

  The justification of the term "rays", applied to the phenomena, lies partly in the regular shadow pictures produced by the interposition of a more or less permeable body between the source and a photographic plate or fluorescent screen.

- §15: Interference experiments have produced no results.
- §16: Deflection experiments using an electric field have not yet been completed.
- §17: Röntgen does not know exactly what X-rays are but speculates that they may be "longitudinal waves in the ether":

  Should not the new rays be ascribed to longitudinal waves in the ether?

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[6] Here Röntgen is referring to the fluorescence produced by the cathode rays on the wall of the Crookes tube (cf. image 1, right), and not the fluorescence produced by the X-rays on the screen.

THE MODERN-DAY EXPLANATION FOR THE PHENOMENON OF X-RAYS

Röntgen was first and foremost an experimenter. He did not play a part in the general characterisation of X-rays, apart from their generation in a Crookes tube. He stopped publishing papers on the subject in 1897 and no longer undertook research into the nature of the rays he had discovered. What might have been the reason for this? Max von Laue, who demonstrated that X-rays were electromagnetic radiation in 1912,[7] wrote on this subject[8]: "I have often been asked what may have caused this man to make such a withdrawal after his discovery … In my opinion, he was so overwhelmed by the impression produced by the discovery he had made, when he was then fifty years old, that he never recovered from it."

We now know that electrons which have accelerated as a result of a difference in potential produce the emission of X-rays through the *Bremsstrahlung* effect, i.e. by braking when they come into contact with the field of atomic nuclei in the target material encountered.

Braking radiation: The source of X-rays in the Crookes tube

Braking radiation (*Bremsstrahlung* in German) is wide-spectrum electromagnetic radiation created by the deceleration of electric charges. When a target is bombarded with a beam of electrons, the electric field of the nuclei in the target cause the electrons to brake and be deflected. According to Maxwell-Lorentz equations, electric charges whose velocity varies, whether in magnitude or direction, will emit electromagnetic radiation.

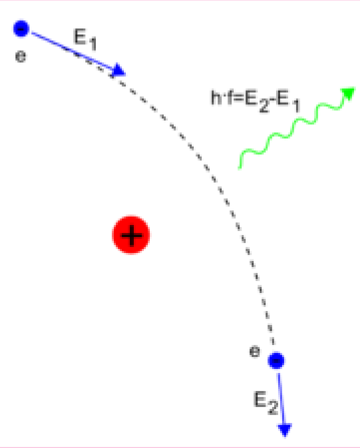

***Figure 3*: Braking radiation.** *The electrons moving close to the (positive) nuclei in the atoms in the target are deflected. They lose energy and, for*

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7. Friedrich W, Knipping P, von Laue M, *Interferenz-Erscheinungen bei Röntgenstrahlen.* Sitzungsberichte der Mathematisch-Physikalischen Klasse der Königlich-Bayerischen Akademie der Wissenschaften zu München, 1912, pp. 303–322.

8. von Laue Max, *Geschichtedes physik*, Bonn, 1946.

each electron, the energy difference corresponds to that of the emitted photon.

As the deceleration is unquantified, the braking radiation is a flow of photons with a continuous energy spectrum.[9] The energy emitted as X photons is taken from the kinetic energy Ec of the e-charged electron, which continues its trajectory with a lower kinetic energy E'c such as:

$$E_c' = E_c - h\nu$$

If the electron was accelerated with a difference in potential U and all the energy of the incident electron was transformed into radiation, this would give

$$eU = h\nu_{max.} = \frac{hc}{\lambda_{min}}$$

and, for the minimum wavelength of the spectrum: $\lambda_{min} = \dfrac{hc}{eU}$.

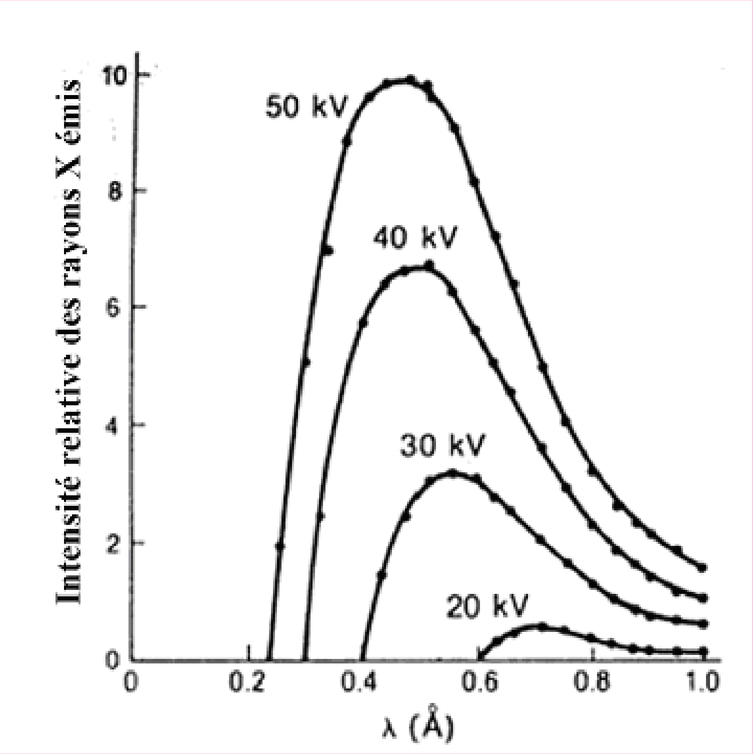

***Figure 4**: In 1918 C. T. Ulrey (Phys. Rev, 12, 47) described the spectra obtained by bombarding tungsten with electrons whose energy varied between 20 and 50 kV. The graph shows that the greater U is, the shorter the wavelength becomes (U = 20kV, λ_{min} = 0,6Å; U = 40 kV, λ_{min} = 0,3Å). The graph also shows that most of the spectrum corresponds to a wavelength of between 0.3 and 1Å, and therefore to a frequency C/λ of between 3.10^{18} Hz and 10^{19} Hz, in the X-ray range.*

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[9] X-rays are produced in the material bombarded with electrons in two different ways: 1) by braking radiation (described here), which produces a continuous spectrum; and 2) by monoenergetic rays if the kinetic energy of the incident electrons is greater than the ionisation energy of an electron from the electron shell of the target atom. In this situation, the electron in the shell changes level and the return to a state of stability occurs by the emission of an X-ray characteristic of this atomic transition. These monoenergetic rays, characteristic of the material constituting the target, are then added to the continous specturm. This part of the spectrum is not represented in Figure 4.

THE CHARACTERISATION OF X-RAYS … SHORTLY AFTER RÖNTGEN'S TIME

Although Röntgen himself went no further in his research, X-rays were the subject of numerous in-depth studies, six of which were directly rewarded with Nobel prizes. X-rays also led to other discoveries, the most far-reaching of which was the discovery of radioactivity in 1896.

By the time of Röntgen's death in 1923, knowledge about X-rays had considerably advanced thanks to the contributions of a large number of physicists. After studying the scattering of X-rays, the Englishman C. G. Barkla (1877–1944, Nobel Prize 1917) demonstrated[10] that the scattered radiation is characteristic of the material used as a target. In 1912, Max von Laue (1879–1960, Nobel Prize 1914) observed the diffraction of X-rays by crystals and established that X-rays are undulatory. This technique is a way of measuring the wavelengths of X-rays. It involves using a single crystal (a monocrystalline solid) to collect the diffraction image of a beam of X-rays with a continuous spectrum.

In 1914, Moseley (1887–1915) showed that the intensity of X-rays is proportional to Z^2, Z being the atomic number of the element in question. From 1913 onwards, Maurice de Broglie (1875–1960) led pioneering research in France and developed the "revolving crystal" method to measure angular distributions. From 1912 onwards, Sir William Henry Bragg (1862–1942) and his son, Sir William Lawrence Bragg (1890–1971), who were jointly awarded the Nobel Prize in 1915, studied crystals using X-rays and established a law that gives the direction of their diffraction between reticular planes: when a crystal is bombarded with radiation with a wavelength in the range of the inter-atomic distance, a diffraction phenomenon occurs. This diffraction is dependent on the angle of incidence, as set out in Bragg's Law. In 1922, Arthur Compton (1892–1962, Nobel Prize 1927) studied the scattering of X-rays in graphite, thereby discovering what became known as the Compton effect.

The Compton effect

Arthur Compton was the first person to study the scattering of X photons by electrons in a target. When the photon transfers some of its energy to an ejected electron, the frequency of the scattered photon decreases, in line with Planck's energy–frequency relation. Compton

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[10] Barkla C. G., "Secondary radiation from gases subject to X rays", *Phil. Mag.* 5, 1903, pp. 685–98.

would show that the change in frequency depends only on the diffusion angle of the target particle in question.[11] Compton's experiment, which he described in his memoir of 1923, used the molybdenum K-alpha X-ray to bombard a carbon target. A Bragg spectrometer can be used to compare the spectra of primary X-rays with those of scattered X-rays.

Compton's scattering formula

Let's imagine that a photon with a momentum $\vec{p}_i$ and an energy of $E_i = \vec{p}_i c$ is travelling towards a resting electron with an initial energy of $m_e c^2$. The photon is scattered by the electron in a direction that makes an angle θ with the original direction. As the electron has taken direction Φ, the momentum of the photon after scattering will be $\vec{p}_f$, while the electron's will be $\vec{p}_e$.

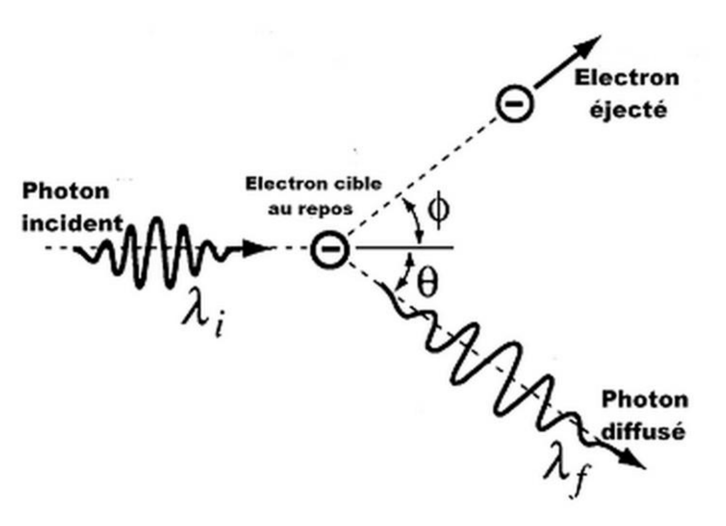

***Figure 5*: Diagram of Compton scattering.** *Clockwise the text reads: Incident photon; resting target electron; ejected electron; scattered photon.*

The conservation of the momentum and the energy give the equation for Compton scattering between the wavelength of the incident photon and that of the scattered photon:

$$\lambda_f - \lambda_i = \frac{h}{m_e c}(1 - \cos\theta)$$

Röntgen also gave his name to two units of measure. When radiation penetrates matter, it interacts with that matter and transfers energy to it. This energy transfer is characterised by the dose absorbed by the matter: the röntgen (R) is the dose of ionising radiation which produces a CGS electrostatic unit of

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[11] *A Quantum Theory of the Scattering of X-Rays by Light Elements*, *Phys. Rev.* 21, 1923, pp. 483–502.

electricity in a square centimetre of dry air at 0 °C and at atmospheric pressure. Secondly, the rem is the abbreviation of Röntgen Equivalent Man: this is a legacy unit that was previously used to measure the dose of radiation in human tissue. It was superseded by the Sievert.

CONCLUSION

The discovery of X-rays earned Röntgen the Rumford Medal in 1896, followed by the first Nobel Prize in Physics in 1901. It was crucial in advancing knowledge about physics and forms the basis of an incalculable number of applications in all areas of knowledge. The discovery was inevitable, because in the late nineteenth century experimentation into "cathode rays" was being carried out in all laboratories.

Röntgen died on 10 February 1923, in Munich.

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