1. Physics in the immediate pre-X-ray era

The 19th century was dominated by so many brilliant minds, particularly in physics and certainly many more than in any other historical period of the natural sciences. This period was full of spectacular discoveries, inventions, measurements and new theories as well as technical and medical applications, mainly through innovations in electricity and thermodynamics which all revolutionized our world up to the present day [1]. We remember the famous names of that outstanding era, such as Michael Faraday [1791–1867] (electrolysis, electromagnetism, diamagnetism), James Clerk Maxwell [1831–1879] (classical theory of electromagnetic fields), William Thomson (Lord Kelvin) [1824–1903] (thermodynamics) and James Prescott Joule [1818–1889] (Joules laws). It is fascinating to note that four epochal discoveries in physics had been made within just four golden years: X-rays by Wilhelm Conrad Röntgen (1895), the radioactivity by Antoine Henri Becquerel (1896), the free electron by Joseph John Thomson (1897) and detection of the elements Polonium and Radium by Marie and Pierre Curie (1998). All four discoveries followed directly or indirectly from experiments with electric discharge in gases.

Following the early Greek assumption of atoms being the building particles of matter, it took about 2000 years to draw attention to what the atom itself looks like. Skilled experiments were designed and new theories for the understanding of the findings were developed. In particular, it was the study of phenomena like the electrolysis of fluids and the electric discharge in gases which resulted in a deeper insight into the atomic structure. It was Faraday, “one of the greatest scientific discoverers of all time” as Rutherford stated [2], who as chemist, or better physicochemist, was interested in the process of chemical reactions when applying a direct electric current to a dissolved salt solution. Evaluating these experiments, he found the quantitative relationship between the amount of material produced in this process and the charge passed through the electrolyte. These results, known as the Faradays laws, stimulated the search for the elementary particle of electricity. The study of electric gas discharge performed by a number of ingenious experimentalists and theoretical physicists, dating back to the 18th but culminating in the 19th century, should be acknowledged as the clue to this open question.

A systematic investigation of these previously just popular multi-colour light emission effects was initiated again by Faraday in 1836. Expecting deeper insight in the physics of atoms, he explored the gas discharge phenomenon when electricity was passing through an evacuated glass-globe under different conditions such as high-voltage, air pressure, gas type, temperature and design of glass-tubes. A few years later Julius Plücker, a German mathematician and physicist at the University of Bonn, worked with a new type of glass-tubes invented by the glass-blower and physicist Heinrich Geissler [3]. Plücker published his early results Plücker’s already in 1857 in a German newspaper [4]. Up to that time the medieval vacuum pump technique of Otto Guericke was used to evacuate discharge tubes. However, a much better vacuum was achieved when Geissler invented his new mercury displacement pump. Using that Geissler-tube, Plücker began to explore the fluorescent glow at the tube wall near the cathode, in particular he observed a shift
of this multi-colour light when applying a magnetic field. This latter observation may be considered a first hint that during the process of electric discharge the cathode emits, additionally to the locally bright light, a stream of an electric radiation which propagates in straight lines to the anode. Similarly, Johann Wilhelm Hittorf, a student of Plücker, found in experiments with Geissler-tubes that a shadow image of solid light, a stream of an electric radiation which propagates in straight lines, is emitted when applying a magnetic field. From these studies Plücker and Hittorf concluded that the cathode emits a negatively charged particle stream which in 1888 was confirmed by Philipp Lenard [5] as cathode rays (“Kathodenstrahlen”, coined by the German physicist Eugen Goldstein). In his studies of cathode rays Lenard came close to the detection of X-rays when he studied the properties of cathode rays. To determine the range in air he constructed a gas tube with a thin metal foil replacing the glass at the end of the tube (“Lenard-window”). By means of a stack of cardboards placed with some fluorescent material he found the induced light intensity being proportional to the material density and the range of the cathode rays in air being a few centimetres. If Lenard had only extended his range measurements beyond these few centimetres, in retrospect, one could speculate that he discovered X-rays first. Nevertheless, the detection of the cathode rays must be considered the fundamental step towards the epochal discoveries of the later 18-nineties.

Around the same time, by the 1870s, the English physicist William Crooke investigated the properties of the cathode rays using several types of a modified Geissler-tube evacuated with a new ultrahigh vacuum pump (modified Sprengel mercury pump). In 1879 he observed that even under these ultrahigh-vacuum conditions when the glow effects of electric discharge slowly begin to disappear, cathode rays are capable to hit the anode and the back end of the tube. There they cause material heating and characteristic light emission – “cathodoluminescence” – at the glass. This latter effect could be amplified when painting the tube end with some phosphors like ZnS. Interesting to note the two theories on the nature of the cathode rays: Crookes claimed a kind of “radiant matter” consisting of negatively charged atoms (“atoms of electricity” as called by Hermann von Helmholtz, 1881), whilst Hertz and Goldstein speculated on a new form of electromagnetic waves, so called “ether vibrations”. In 1897, J. J. Thomson [6] demonstrated by e/m-measurements that in fact the cathode rays consist of “corpuscles”, for which, as the “fundamental unit quantity of electricity”, the Irish physicist George J. Stoney introduced the name “electron”. The identification of the free electron as the first subatomic particle ever detected was a milestone on the way to modern physics, initiating a deeper insight into the inner structure of the atom.

2. W.C. Röntgen – His personal life

On the 27th March 1845, Röntgen was born in Lennep near Remscheid in Germany as the son of a wealthy cloth manufacturer and his wife Charlotte Constanze who had family roots in the Netherlands and Italy [3]. In 1848, due to the increasing social and political tensions, the family emigrated to Apeldoorn and Utrecht in the Netherlands. Whilst showing in his youth some endowment for tinkering, Röntgen completed his primary and secondary school without notable indication of his later career. In 1862, he enrolled at the Technical School in Utrecht, however he was expelled one year later by an unjustified measure in response to a mocking affair against a teacher by another student. Unfortunately, due to adverse circumstances, he failed even at a second attempt to qualify for admittance to a university. However, Röntgen registered as visiting student at the Utrecht University attending a broad scope of lectures in physics, mathematics, botany, zoology, and old languages, obviously intending to qualify again for a university study. By chance he learned from a friend that the new “Eidgenössisches Polytechnikum” (Swiss Polytechnical School) accepted also students without a university admission degree. Interesting to note that the other famous Nobel laureate Albert Einstein, for the same reason of lacking such a certificate, was accepted at that university in Zürich. Röntgen enjoyed very much his time as student, always achieved highest scores, qualified with a diploma degree in engineering in 1868, and beyond his dedication to the study he was enthusiastically walking with friends in the nearby region of the Alps, sometimes stressing his guardian angel in highly dangerous situations. It was also in Zürich where Röntgen became acquainted with Anna Bertha, his later wife. Only one year after his diploma Röntgen defended his dissertation at the University of Zürich entitled “Studies on Gases” and earned the doctor degree Dr.phil. Proved by his teacher, the highly recognized experimental physicist August Kundt (Kundt’s tube for measuring the speed of sound in gases), with “what do you want to do in your life, why not attempting to engage with physics?", Röntgen enjoyed to accept this challenge and became Kundt’s assistant. Just one year later Röntgen followed Kundt who had received a call from the University of Würzburg to be Chair of the Institute of Physics. However, it was again the bureaucratic obstacle of the missing university entrance qualification from his former school time at Utrecht which, despite all interventions by Kundt as head of the department, blocked his access to the habilitation procedure. Not unlikely also due to this conflict Kundt accompanied by his esteemed assistant followed a call of the newly re-established university of Strassburg. Within two years Röntgen submitted his habilitation thesis and qualified as a university lecturer in physics. His private life culminated in his marriage to Anna Bertha at Apeldoorn in 1872 where his parents were still living. After short term positions at Hohenheim, again with Kundt at Strassburg, and at Giessen, Röntgen accepted the most honourable call as successor of Friedrich Kohlrausch at the University of Würzburg where he made his epochal discovery. Finally, in 1900 he went to the University of Munich as Head of the Institute for Physics. After the death of his wife he more and more pulled out of the academic life and tried to find distraction and privacy, for example by walking tours in the mountains. Suffering from colon cancer in his last months, Röntgen died on 10th February 1923 at Munich.

Despite his spectacular achievements and celebrity Röntgen’s character was described as quiet and withdrawn having not many deep friendships. He was a hardworking meticulous scientist, always self-critical, diligent and never publishing scientific results before being cast-iron confident about the content. In particular, Röntgen was always modest, never tried to appear brilliant rather to focus strictly on facts, so that some students found his lectures a bit dry. The dominant character was his sense of justice even in case of his own disadvantage, known from his clear position in the early conflict in school up to war time when food had to be rationed and he refused any personal privileges.

3. W.C. Röntgen – His epochal discovery

Motivated by Plücker’s, Hittorf’s and in particular Lenard’s observation of the cathode rays, Röntgen conducted further experiments to explore the properties of this stream of free electrons created in an electric gas discharge tube [5,7]. One of these experiments was repeating Lenard’s extra-tube measurements of the range of the cathode rays. Applying a more sensitive technique and recording the electric discharge with an electrometer Röntgen found an effect ranging far more distant than the few centimetres Lenard observed with his fluorescent screen. In another experiment he covered the whole glass tube with cardboard to exclude light effects coming from inside the tube, and in the completely darkened laboratory he observed by chance next to the experimental set-up a deposited bariumplatinoxyanide-coated screen fluorescing. After exclusion of artefacts, such as external light or cathode ray effects, he wondered the reason for that green light emitted from the crystals of that screen. It was that fateful Friday the 8th November 1895 when Röntgen performed a systematic investigation of this phenomenon by varying distance, direction and absorption of the invisible radiation by different materials. Fascinated by these experiments Röntgen worked day and night, he even ordered his bed to be transferred into his lab. He
observed the fluorescing effect at larger distances fluctuating with electric tube current, found the high penetrative power of the radiation when exposing different materials, noticed the protective capability of heavy metals like lead, and blackening of films as the first step to radiography. The key experiment which revolutionized medicine fundamentally and is considered the birth day of radiology was that moment when holding with his fingers a small object in the beam, Röntgen recognized the image of his fingers on the cardboard-screen, in fact the first X-ray image ever. However, still hesitating about what he has observed he complemented his investigations by a number of further experiments including the well-known image of the hand of his wife before writing his modestly entitled preliminary communication on a new type of radiation (‘Über eine neue Art von Strahlung. (Vorläufige Mitteilung’) which he submitted to the Physical-Medical Society (‘Physikalisch-Medizinische Gesellschaft’) in Würzburg on 28th December 1895. Suspecting its explosiveness, the paper was reviewed in a fast-track mode and published already on New Year’s day 1896, and then disseminated worldwide. The echo on this new radiation type which Röntgen himself called X-rays was extraordinary, triggering an avalanche in the science world, beginning with Röntgen’s friend and colleague Professor Exner at the Vienna University. He managed to get communication shared with the local Vienna newspaper Die Presse at 5th January 1896 from where at the next day the discovery was cabled to the Daily Chronicle in London and a few days later spread via the prime scientific journals such as Nature, Science, and L’Eclairage Electrique and public media to the United States and globally. Never before had a discovery been disseminated so quickly around the world. Multiple applications and further technical improvements of the X-ray tube itself have been reported, such as the first case of an image guided surgery in Birmingham/England where surgeons localized a foreign object in the hand of a patient. In February 1896 the first studies were initiated to demonstrate the potential of X-ray imaging even of non-bony structures such as the vascular anatomy by injecting a contrast medium and the gastro-intestinal tract by swallowing a barium meal. Just within the first months after the discovery of the X-rays so called fluoroscopes were developed, a widely used apparatus for medical examination of a patient which consisted of a box shielding the ambient light and a barium cyanate coated cardboard as screen. Already in 1896, substantial technical progress was achieved by industrial developments initiated by Thomas Alva Edison who improved both the technique to better focus the X-ray beam and to optimize the fluorescing screen by choosing calcium tungstate as it was six times more sensitive a substance than platinbariumcyanate. In summary, 1044 scientific papers on X-rays had the communication shared with the local Vienna newspaper colleague Professor Exner at the Vienna University. He managed to get fundamentally and is considered the birth day of radiology was that moment when holding with his fingers a small object in the beam, Röntgen recognized the image of his fingers on the cardboard-screen, in fact the first X-ray image ever. 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4. Developments stimulated by Röntgen’s discovery

From the early beginning, i.e. with the worldwide dissemination of Röntgen’s X-ray phenomenon in 1896, remarkable progress has been made in the technology, novel methods and new fields of application. Of course, medical use of X-rays was the prime focus, first radiological practices were founded already in 1896, radiology as a new discipline was rapidly growing, foundation of scientific radiological societies are traced back to 1897 with The X-Ray Society and The Röntgen Society later emerged as the British Institute of Radiology being the first. New branches sprouted from radiology: the first documented radiation treatment performed by Leopold Freund in Vienna who irradiated a patient with a nevus in three fractions in 1896, inaugurated radiotherapy as a new specialty [8]. Closely linked to Freund’s radiation treatment which was based on early observation of somatic and genetic changes of radiation exposed biological object, radiobiology originated as another specialty. In particular, the progress in X-ray technologies was the result of the engagement of many physicists and engineers who also stimulated the establishment of new professional societies.

New findings, medical, biological, physical and technical innovation were shared at scientific gatherings and in special scientific journals such as the American Journal of Roentgenology, founded as the first one in 1907. It is a tragedy that scientists, practitioners, technical and medical staff fascinated by the potential of the new radiation were not aware the radiation hazards – mostly not known or explored yet – and ignored proper radiation protection measures. One exception, however, is Röntgen himself: he ordered a huge box made of zinc and with a special lead shielding in front from where he observed his experiments. In contrary to many radiologists manipulating with their hands the X-ray tube Röntgen’s hands were free of any radiation injuries. A cenotaph in Hamburg commemorates the hundreds of pioneers who ultimately died from the exposure of X-rays in radiology.

Most innovations stimulated by Röntgen’s discovery refer still today to radiation medicine. As an example of this innovation trend the widespread computer tomography may be considered which ranges from the first idea suggested by Gabriel Frank in Budapest in 1938, the first clinical product designed by Godfrey Hounsfied in 1972 up to the modern breaking advancements of spiral scanning [9], dual energy [10] or phase contrast [11] imaging machines.

Yet there emanated also a lot of X-ray applications beyond medicine. The potential of radiography in material sciences originates from Röntgen himself when he imaged his deer rifle. Today, X-rays are used to track crazing or cavities in critical structures such as pipes in nuclear power plants or traffic bridges. Other applications extend over orders of magnitude from subatomic scales with the observation of quantum effects, to X-ray microscopy with its unique advantages of nano-scale resolution offering novel insights into molecular biology structures and processes. The far end application scale is X-ray astronomy where for instance X-ray emission of objects with extreme hot gas atmospheres can be investigated. Beyond these examples from natural science other fields benefit from the application of X-rays. For instance, radiography of cultural materials became a powerful method e.g. to study the ancient Ninstints totem poles in Canada or by analysing the pigment type and distribution to study paintings and to evaluate its origin [3]. Finally, as a literary apercu it may be mentioned that Röntgen’s discovery found entrance in Thomas Mann’s novel Der Zauberberg, published 1924 where he described a scene of a medical examination in a so called “Röntgen-Kabinett” installed at a sanatorium for patients suffering from lung disease.

Declarations of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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