PART II

The Beginnings

From W. C. Röntgen's Third Communication, *March 1897:*

'The experiments on the permeability (for X-rays) of plates of constant thickness cut from the same crystal in different orientations, which were mentioned in my first Communication, have been continued. Plates were cut from calcite, quarz, turmaline, beryl, aragonite, apatite and barytes. Again no influence of the orientation on the transparency could be found.'

'Ever since I began working on X-rays, I have repeatedly sought to obtain diffraction with these rays; several times, using narrow slits, I observed phenomena which looked very much like diffraction. But in each case a change of experimental conditions, undertaken for testing the correctness of the explanation, failed to confirm it, and in many cases I was able directly to show that the phenomena had arisen in an entirely different way than by diffraction. I have not succeeded to register a single experiment from which I could gain the conviction of the existence of diffraction of X-rays with a certainty which satisfies me.'

Contents

CHAPTER 2

X-rays

2.1. Physics at the Time of Röntgen's Discovery of X-rays

The first half of the nineteenth century was a period of tumultuous development of the exact sciences. The great mathematicians—Cauchy, Euler, Gauss, Hamilton, to name only a few—not only perfected the methods of analysis, but they also laid the foundations for a mathematical, quantitative, understanding of celestial and other Mechanics, of Hydrodynamics, Elasticity, Magnetism, and Optics. Following Lavoisier's introduction of the balance for checking reactions, Chemistry became a quantitative science. A series of brilliant experiments between 1820 and 1831 disclosed the relation of magnetism to galvanic electricity, and Faraday developed his notion of an electromagnetic field which was amplified and given mathematical expression by Maxwell in the 1860's. By 1848 the concept of Energy was clearly defined and the equivalence of energy and heat demonstrated. Clausius and Maxwell formulated the basic laws of Thermodynamics. The Kinetic Theory of Matter, long but vaguely foreshadowed in the works of Lucretius and of Boscovich, reached the first quantitative stage in the Theories of Gases of Maxwell and of Boltzmann. The discovery of the polarization of light (Malus, 1808) had proved that light was a transverse wave motion, and although hardly anything was known about the production of light, nearly all seemed to be known about its propagation. As a consequence, much improved telescopes, microscopes and other ingenious optical devices were being constructed and helped to open up vast new regions of the skies and of the animal and plant world. The application of the laws of physics to chemistry, engineering, and physiology made great strides and rational, quantitative and ever more precise relations replaced the former vague empiricism.

Considering the enormous advances in the mathematical description of nature, some scientists thought that science had reached such a stage of perfection that little more fundamental work remained to be done; working out new problems along the given lines was all that could be expected of future scientists.

Instead, in the last one or two decades of the century a hidden new world of physical entities and facts was discovered which stood quite apart from the classical system of physics. It turned out eventually to be the foreshore of the twentieth century physics. This discovery began in 1854 when, among other physicists, Julius Plücker in Bonn studied the spectra produced by the electric discharge in rarified gases. These brilliantly coloured and variable discharges in evacuated glass tubes, usually manufactured by the Bonn glassblower Geisler, were being very gradually classified and analysed in a descriptive way by their dark spaces, luminous band structure etc. A full understanding of the processes producing these effects came only in the 1930's when atomic theorie was well advanced. In 1859 Plücker observed that in highly evacuated tubes a bright luminescence occurred on the glass wall opposite to the cathode and that this was influenced in a peculiar way by the approach of a magnet. Johann Wilhelm Hittorf found in 1869 that with increasing evacuation of the discharge tube the dark space adjoining a disc-shaped negative pole (cathode) gains in length until it finally suppresses all the luminosity in the gas and reaches out to the glass wall opposite the cathode which then shines up in a bright green light called fluorescence. Hittorf in Münster, Crookes in London and other physicists investigating this form of discharge showed that the bright spot on the glass is produced by something that leaves the cathode surface at right angles and travels in straight lines, so that the shadow of an opaque metal cross is formed in the fluorescent spot. For this reason the name of cathode *rays* was given to the invisible something. If these rays fell on pieces of calcite or fluorite these minerals glow in beautiful colours, which differ according to the mineral species. Here then was a novel mode of producing light which attracted many investigators. Meanwhile two important developments took place regarding cathode rays: while Plücker had already indicated that the 'rays' were, perhaps, streams of electrically charged particles emitted by the cathode and deflected by a magnet, this view was shaken by experiments undertaken by Heinrich Hertz which showed no deflection of the rays by the electric field when they passed between the plates of a condenser. (Only much later the reason for this negative result was recognized in the electrical leakage between the condenser plates caused by too poor a vacuum.)

The second development came from Ph. Lenard, then a student of H. Hertz, who succeeded in letting the cathode rays pass out of the tube through a very thin aluminium foil or 'window'. The rays would traverse a few inches of air (the higher the voltage on the tube, the longer the path), while their intensity, as indicated by the brightness of a fluorescent screen, diminished exponentially as the traversed layer of air grew. The Lenard window permitted a much easier observation of fluorescence of minerals and other compounds, for no longer had a special tube to be constructed and evacuated for each observation.

It should be noted that the atomistic nature of the electric charge, which in our 'Electronics Age' is a familiar fact, was still unknown in the early 1890's. True, already in 1834 Faraday had shown that in the conduction of current through salt solutions, the charges were transported in a certain unit or a small multiple of this, and never in fractional or irregular quantities. But these electric charge units were carried by ponderable masses, say by the atoms of the silver deposited on the cathode of an electrolytic trough, and the appearance of a unit charge could be caused equally well by the carrying capacity of the atom as by some inherent property of charge itself.

In fact, the—apparent—absence of any deflection of cathode rays by electric fields, together with their power to penetrate through metal foils which are impervious to gas gave support to the view of Hertz and many other German physicists that cathode rays were a special form of electromagnetic field, perhaps longitudinal waves, rather than a stream of corpuscles. This view persisted until 1895 and 1896 when Jean Perrin in France and J. J. Thomson in Cambridge achieved electrostatic deflection of cathode rays, and the latter, soon afterwards, using a Faraday cage collected and measured the charge transported in the cathode ray. By deflection experiments, he also determined the ratio of the charge to the mass of the cathode ray particles, e/m; and found that, assuming the charge to be the same as that occurring in electrolysis, the mass of the particle would be only about 1/1800 of the smallest known atomic mass, that of the hydrogen atom. In 1891 finally, on the proposal of Johnstone Stoney, the name of electron was universally accepted for this unit of charge. Its absolute value was determined in 1910 by Robert Millikan in Chicago as $4.77 \cdot 10^{-10}$ el. static units and this value, one of the most fundamental ones in Nature, was revised in 1935 by E. Bäcklin as a consequence of Laue's discovery. The accepted value is today $4.803 \cdot 10^{-10}$ el. static units or $1.601 \cdot 10^{-19}$ Coulomb.

2.2. Röntgen's Discovery

Let us go back to the summer of 1895 and to the beautiful old Bavarian university town and former seat of an independent bishop, Würzburg. Here, six years earlier, Wilhelm Conrad Röntgen had been appointed Professor of Physics.

In the course of the summer of 1895 Röntgen had assembled equipment, such as a fairly large induction coil and suitable discharge tubes, for taking up work on the hotly contested subject of cathode rays. From Lenard's work it was known that these rays are absorbed in air, gases, and thin metal foils roughly according to the total mass of the matter traversed, and that the absorption decreases if a higher voltage is put across the discharge tube. It was also known that the intensity of the fluorescence excited in different crystals varies with the voltage used, fluorite being a good crystal for 'soft' cathode rays —those obtained with low voltage—and barium platino cyanide fluorescing strongly under bombardment by 'hard' cathode rays.

Röntgen never divulged what measurements he intended to make, nor what type of discharge tube he was using when he made his great discovery. The fact that the tube was fully enclosed in a light-tight cardboard box shows that he intended to observe a very faint luminescence. But the question of whether he was interested in the law of absorption of cathode rays or in the excitation of fluorescence in different media remains unanswered. The fact is that he noticed that a barium platino cyanide screen lying on the table at a considerable distance from the tube showed a flash of fluorescence every time a discharge of the induction coil went through the tube. This flash could not be due to cathode rays because these would have been fully absorbed either by the glass wall of the tube, or by the Lenard window and the air. Röntgen, in a breathless period of work between 8 November and the end of the year, convinced himself of the reality of his observations which at first he found hard to believe. He soon concluded that the fluorescence was caused by something, the unknown X, that travelled in a straight path from the spot where the cathode ray in the tube hit the glass wall; that the unknown agent was absorbed by metals and that these cast a shadow in the fluorescent area of the screen. He therefore spoke of X-*rays*; he showed that these rays were exponentially absorbed in matter with an exponent roughly proportional to the mass traversed, but very much smaller than the one found by Lenard for the corresponding cathode rays; he found the photographic action of X-rays and took the first pictures of a set of brass weights enclosed in a wooden box, and, soon after, the first photo of the bones in the living hand; he remarked that the output of X-rays can be increased by letting the cathode rays impinge on a heavy metal 'anticathode' (which may also be the anode of the tube) instead of on the glass wall and thereby started the development of the technical X-ray tube; he found that X-rays render air conductive and discharge an electrometer; he performed ingenious but entirely negative experiments for elucidating the nature of X-rays, in which he searched in vain for reflection or refraction or diffraction, the characteristic features of wave phenomena.

Röntgen was well aware of the fact that he had found something fundamentally new and that he had to make doubly sure of his facts. He hated nothing more than premature or incorrect publications. According to his habit he did the work single-handed and spoke not even to his assistants about it. Finally, in December 1895 he wrote his famous *First Communication* for the local Würzburg Scientific Society. In its 10 pages he set out the facts in a precise narrative, but he omitted—as also in all of his previous and his later work—all personal or historical indications, as transitory elements which he considered to detract from the finality of scientific publication. The paper was quickly set and Röntgen sent out proofs or reprints as New Year's Greetings to a number of his scientific friends.

After three months (March 1896) the *First Communication* was followed by a second one of seven printed pages. In it, Röntgen reported careful experiments on the discharge of charged insulated metals and dielectrics, by irradiation when in air, gases or vacuum; he finds that an anode of platinum emits more X-rays than one of aluminium and recommends for efficient production of X-rays the use of an aluminium cathode in form of a concave mirror and a platinum anode at its focus, inclined at 45° to the axis of the cathode. Finally he states that the target need not be simultaneously the anode of the tube.

A year later (March 1897) a third and final Communication appeared, slightly longer than the first two taken together and containing further observations and measurements. From it, the Motto on page 5 of this book is taken. Together these 31 pages of the three Communications testify to the classical conciseness of Röntgen's publications.

⁂

The response which this discovery prompted was unheard of at a time when, in general, Science was still a matter for the select few. In seeing on the fluorescent screen the bones of a living hand divested of the flesh around them, medical and lay public alike were overcome by an uncanny memento mori feeling which was vented in many serious and satirical contributions to the contemporary newspapers. The first medical applications were promptly made, and the demand for 'Röntgen Tubes' quickly initiated an industry that has been expanding ever since. Röntgen, a fundamentally shy and retiring character, was ordered by the young Emperor William II to demonstrate his discovery in the Berlin palace—an invitation Röntgen could not well refuse, as he did many other demands. The writer remembers the unveiling of the four seated figures on the buttresses of the remodelled Potsdamer Brücke in Berlin which on orders of the Emperor were placed there as representative of German Science and Industry: Carl Friedrich Gauss, Hermann von Helmholtz, Werner Siemens and Wilhelm Conrad Röntgen. This must have been in 1898 or '99 and there was much discussion in the family circle whether it was appropriate to put such a novel and poorly understood discovery on an equal footing with the well-established achievements of the three other figures.—The reader will find an entertaining account of the post-discovery period (and many interesting details besides) in O. Glasser's book *Wilhelm Conrad Röntgen and the History of X-rays.*

2.3. Progress in the Knowledge of X-rays up to 1912

In spite of the universal enthusiasm for X-rays and the great number of physicists and medical men working in the field, only very few fundamental facts were discovered in the next fifteen years. True, a constant technical development of the X-ray tubes and of high-tension generators took place in response to the increasing demands of the medical profession, especially when the therapeutic use of very hard X-rays began to be recognized at the end of this period. The commercial availability of fairly powerful X-ray equipment greatly facilitated Friedrich and Knipping's later experiments in 1912. But of experiments disclosing something of the nature of X-rays only four need be mentioned:

a. *Polarization of X-rays* (*Barkla 1905*). That X-rays are scattered, i.e. thrown out of their original direction, when passing through a body, was already noticed by Röntgen in his second communication.

Barkla used this property for an experiment similar to that by which Malus had detected the polarization of light. Malus (1808) had found that the rays of the setting sun, reflected on the windows of the Palais du Luxembourg acquired a new property by this reflection; for if they were once more reflected under a certain angle by a glass plate which could be rotated around the direction of the ray coming from the windows the intensity of the twice reflected ray would vary with the angle of rotation of the glass plate, being smallest when the twice reflected ray travels at right angles to its previous two directions, and strongest if it travels in their plane. This was a proof that light is a transverse wave motion, not, like sound, a longitudinal one, which has axial symmetry. Barkla repeated this experiment with X-rays, with the only difference that, there not being any specular reflection of X-rays, he had to substitute for the reflections the much weaker scattering under an angle of approximately 90°. He found the dependence he was looking for and concluded that *if* X-rays were a wave motion, they were, like light, transverse waves. This was fully confirmed by later experiments of the same type by Herweg (1909) and H. Haga (1907).

b. *Barkla's discovery of 'characteristic' X-rays (1909)*. X-rays could at that time only be characterized by their 'hardness', i.e. penetrating power. In general, the higher the voltage applied to the X-ray tube, the harder is the X-radiation emitted, that is, the smaller is its absorption coefficient in a given material, say aluminium or carbon. The absorption coefficient is, however, not a constant, because, since the soft components of the radiation leaving the tube are absorbed in the first layers of the absorber, the remaining radiation consists of harder X-rays. Thus the variability of the absorption coefficient with penetration depth is an indication of the inhomogeneous composition of the X-radiation. Barkla, studying tubes with anticathodes of different metals, found that under certain conditions of running the tube the emergent X-rays contained one strong homogeneous component, i.e. one whose absorption coefficient was constant. He found that the absorption coefficient decreased with increasing atomic weight of the anticathode material, and that this relation was shown graphically by two monotonic curves, one for the lighter elements and one for the heavier ones. He called these two types of radiation, characteristic for the elements from which the X-rays came, the K- and the L-Series. This discovery formed the first, if still vague, link between X-rays and matter beyond the effects determined by the mere presence of mass.

c. *Photoelectric Effect.* The photoelectric effect consists in the emission of electrons when light or X-rays fall on the atoms in a gas or a solid.

Its first observation goes back to Heinrich Hertz, 1887, who noticed that the maximum length of the spark of an induction coil was increased by illuminating the gap with ultraviolet light. In the following year W. Hallwachs showed that ultraviolet light dissipates the charge of a negatively charged insulated plate, but not that of a positively charged plate. This happens in air as well as in vacuum and in the latter case it was proved by magnetic deflection that the dissipation of the charge takes place by the emission of electrons. In 1902 Philipp Lenard found the remarkable fact that the intensity of the light falling on the metal plate influences the rate of emission of electrons, but not their velocity. Three years later Albert Einstein recognized the importance of this result as fundamental, and in one of his famous four papers of the year 1905 he applied Planck's concept of quantized energy to the phenomenon by equating the sum of kinetic and potential energy of the emitted electron to the energy quantum $h\nu$ provided by a monochromatic radiation of frequency ν:

$$\tfrac{1}{2}mv^2 + p = h\nu \quad (p = \text{potential energy})$$

At the time this was a very bold application and generalization of the concept of quantized energy which Planck had been proposing for deriving the laws of black body radiation, and whose physical significance was by no means assured. Einstein's equation was at first not at all well corroborated by the experimental results with ultraviolet light, because the unknown work term p in the equation is of the same order of magnitude as the two other terms. This is not so if the much larger energy $h\nu$ of an X-ray is used, and the fully convincing proof of Einstein's relation had therefore to wait until the wave-length and frequency of X-rays could be determined with accuracy by diffraction on crystals, and the equation could then in turn be used for a precision method of measuring the value of Planck's constant h.

Prior to this, in 1907, Willy Wien made a tentative determination of the X-ray wave-length (provided X-rays were a wave motion) by reversing the sequence of the photoelectric effect: he considered the energy of the electron impinging on the target as given by the voltage applied to the tube and, neglecting the small work term p, calculated the frequency and wave-length of the radiation released. Assuming a voltage of 20000 volt this leads to $\lambda = 0.6$Å.

W. H. Bragg interpreted the ionization of gases by X-rays (the amount of which served as a measure for X-ray intensity) as primarily a photoelectric effect on a gas molecule, with further ionizations produced by the swift ejected electrons. The fact that in this process a large amount of energy has to be transferred from the X-ray to the gas in a single act led him to consider this as a collision process and further to the concept that X-rays are a particle stream of neutral particles, or doublets of ± charge.

d. *Diffraction by a Slit.* Röntgen himself reports in his *First Communication* inconclusive attempts at producing diffraction effects by letting the X-rays pass through a fine slit. These attempts were repeated by the Dutch physicists Haga and Wind (1903). They claimed to have recorded faint diffraction fringes, but their results were challenged as possibly due to a photographic effect caused by the developing. In 1908 and 1909 B. Walter and R. Pohl in Hamburg repeated essentially the same experiment taking utmost care in the adjusting. The slit was a tapering one produced by placing the finely polished and gilded straight edges of two metal plates in contact at one end and separated by a thin flake of mica at the other. The X-rays fell normally on the slit and the photographic plate was placed behind the slit parallel to its plane. If diffraction took place, one would expect the narrowest part of the slit to produce the widest separation of fringes. On the other hand, they would be the least intense because of the narrowness of the slit. Since for complete absorption of the X-rays the plates forming the slit must have a thickness of the order of 1–2 mm and the slit width in the effective part is of the order of 1/50 mm, the slit is in reality a deep chasm through which the X-rays have to pass. Walter and Pohl's plates showed the otherwise wedge-shaped image of the slit to fan out at its narrow end into a brush-like fuzzy fringe system. Fortunately, in 1910, one of Röntgen's assistants, P. P. Koch, was engaged in constructing the first automatic microphotometer by using a pair of the recently improved photoelectric cells for the continuous registration of the blackening of a photographic plate. As soon as the instrument had been completed and tested, Koch traced several sections through the original plates of Walter and Pohl, and these showed variations which could be caused by diffraction.

So, once more, the probability rose that X-rays were a wave phenomenon. The order of magnitude of the wave-length could have been obtained roughly from the fringe separation and the width of the slit on any of the cross sections taken. But since the intensity profiles departed considerably from those obtained by diffracting light waves on a slit, Sommerfeld, the master-mathematician of diffraction problems, developed the theory of diffraction of light waves by a deep slit before discussing the Walter-Phol-Koch curves. Both papers, Koch's and Sommerfeld's, were published together in 1912. Sommerfeld's conclusion was that the fuzziness of the fringes was caused by a considerable spectral range of the X-rays, and that the centre of this range lay at a wave-length of about 4.10^{-9} cm. This possible but by no means unique explanation was known among the physicists in Munich several months before it appeared in *Annalen der Physik* in May 1912. The wave-length checked approximately with W. Wien's estimate.

e. *Waves or Corpuscles?* At the end of 1911 X-rays still remained one of the enigmas of physics. There was, on the one hand, the very strong argument in favour of their corpuscular nature presented by the photoelectric effect. The explanation of this concentrated and instantaneous transfer of relatively large amounts of energy from a radiation field into kinetic energy of an electron was utterly impossible according to classical physics.

On the other hand some phenomena fitted well with a field- or wave concept of X-rays. As early as 1896 a plausible explanation of X-ray generation had been given independently by three physicists: in Manchester by Stokes, in Paris by Liénard, and in Königsberg by Wiechert. They assumed the cathode rays to consist of a stream of charged particles, each surrounded by its electromagnetic field. On impact with the target (or 'anticathode') these particles are suddenly stopped and the field vanishes or changes to the static field surrounding a particle at rest. This sudden change of field spreads outward from the anticathode with the velocity of light and it constitutes the single X-ray pulse. In many ways X-rays seem then analogous to the acoustical report of shot hitting an armour plate. In order to work out this theory so as to check it on experiments, assumptions about the impact process in the target had to be made, the simplest being a constant deceleration over a few atomic distances in the target. The theory accounted readily for the non-periodicity or spectral inhomogeneity of X-rays as shown by their non-uniform absorption; also for the polarization as shown in the double scattering experiments. It was, however, desirable to obtain more information regarding the actual stopping process, and for this purpose measurements were made in 1909 by G. W. C. Kaye on the angular distribution of the intensity of X-rays generated in thin foils, where it seemed likely that only few decelerating impacts occurred. Sommerfeld, who was one of the protagonists of the impact or 'Bremsstrahl' theory, calculated the angular distribution and found as a general result that the higher the applied voltage and therefore the velocity of the electrons, the more the emission of the field was confined to the surface of a cone surrounding the direction of the velocity, the opening of which decreased with increasing voltage. This was well confirmed by the measurements for X-rays as well as for γ-rays, provided the conditions were such that no characteristic radiation was excited in the target. One has thus to distinguish between the general X-rays generated as 'Bremsstrahlen' or 'pulses' or 'white X-rays' i.e. through the decelerating impact, and those much more homogeneous ones with respect to absorption which are determined by the emitting material ('characteristic X-rays').

The problem arose whether polarization and directional emission could also be found for characteristic radiation. In order to study this experimentally, Sommerfeld, towards the end of 1911, appointed an assistant, Walter Friedrich, who had just finished his Doctor's Thesis in the adjoining Institute of Experimental Physics of which Röntgen was the head. The subject of his thesis had been the investigation of the directional distribution of the X-rays obtained from a platinum target; he was thus fully acquainted with the technique to be used in extending the investigation to a target, and a mode of operating the tube, which yielded strong characteristic rays, instead of Bremsstrahlung.

Next Section