Cathode Rays

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The detection of cathode rays was a by-product of the investigation of the discharge of electricity through rarefied gases. The latter phenomenon had been studied since the early eighteenth century. By the middle of the nineteenth century it was known that the passage of electricity through a partly evacuated tube produced a glow in the gas, whose color depended on its chemical composition and its pressure. Below a certain pressure the glow assumed a stratified pattern of bright and dark bands.

During the second half of the nineteenth century the discharge of electricity through gases became a topic of intense exploratory experimentation, primarily in Germany [21]. In 1855 the German instrument maker Heinrich Geißler (1815–1879) manufactured improved vacuum tubes, which made possible the isolation and investigation of cathode rays [23]. In 1857 Geissler's tubes were employed by Julius Plücker (1801–1868) to study the influence of a magnet on the electrical discharge. He observed various complex and striking phenomena associated with the discharge. Among those phenomena were a "light which appears about the negative electrode" and a fluorescence in the glass of the tube ([9], pp. 122, 130).

The understanding of those phenomena was advanced by Plücker's student and collaborator, Johann Wilhelm Hittorf (1824–1914), who observed that "if any object is interposed in the space filled with glow-light [emanating from the negative electrode], it throws a sharp shadow on the fluorescent side" ([5], p. 117). This effect implied that the "rays" emanating from the cathode followed a straight path. Furthermore, Hittorf showed that those rays could be deflected by the action of a magnet. In 1876 they were dubbed cathode rays (Kathodenstrahlen) by Eugen Goldstein (1850–1930) [2, 24]. Thus, by the late 1870s cathode rays had been identified and some of their main observable properties had been established.

The nature of cathode rays remained a controversial subject for some years to come. There were two opposing views concerning their constitution. The first view was maintained by British and French scientists, who identified cathode rays with streams of charged particles. A well-known advocate of that view was the British experimentalist William Crookes (1832–1919). Crookes studied electrical discharges through highly rarefied gases: "[T]he exhaustion carried out [is so high] that the dark space around the negative pole . . . entirely fills the tube." ([1], p. 6) Under those conditions the behavior of cathode rays could be studied in isolation, without interference from other discharge phenomena. Thus, Crookes determined, in a particularly clear manner, several properties of cathode rays: their "power of exciting phosphorescence" (p. 7), their propagation in straight lines (p. 12), their power to cast shadows (p. 15), their capacity to "exert strong mechanical action where they strike" (p. 17) and to "produce heat when their motion is arrested" (p. 24), and their deflection by a magnet (p. 20). He put forward the hypothesis that cathode rays were charged molecules, "molecular bullets", which he justified on the basis of their magnetic deflection and their capacity to perform mechanical work. Furthermore, from the direction of their magnetic deflection he inferred that they were negatively charged. Several years later, in 1895, Jean B. Perrin (1870–1942) would arrive at the same conclusion by means of a different experiment [8].

Another eminent scientist who defended the particulate interpretation of cathode rays was Arthur Schuster (1851–1934). In 1884 he suggested that they were negatively charged atoms [10]. In 1890 he calculated the upper and lower bounds of their charge to mass ratio (e/m), based on measurements of their magnetic deflection and an estimate of their velocity. The lower limit was close to the charge to mass ratio of electrolytic ions. The upper limit was three orders of magnitude higher ([11], pp. 546–547).

The second view concerning the nature of cathode rays was advocated by some German physicists, who identified them with processes in the ether. Their main argument was that cathode rays have some of the properties of light-waves. For instance, they both travel in straight lines and produce fluorescence. The ethereal interpretation of cathode rays received additional support in 1883, when Heinrich Hertz (1857–1894) failed to deflect them by an electric field [3,22]. In the following years, new experimental facts were discovered which seemed to undermine further the interpretation of cathode rays as charged particles. In 1892 Hertz showed that they could penetrate thin sheets of metal (e.g., gold, silver, aluminum) [4]. In 1893 his student, Philipp Lenard (1862–1947), built upon Hertz's work to investigate the behavior of cathode rays outside the vacuum tube. He devised a tube with a thin metallic "window" facing the cathode. The cathode rays passed through that window and, thus, Lenard could measure their mean free path outside the tube. As it turned out, it was much longer than that of atoms and molecules. Furthermore, he showed that their absorption depended only on the density of the absorbing substance [7].

Thus, different experimental results supported different accounts of the nature of cathode rays. Furthermore, the evidential import of some of those results was ambiguous. On the one hand, the magnetic deflection of cathode rays, which indicated that they were charged particles, was compatible with an ethereal interpretation of their nature. It was conceivable that the magnetic field altered the state of the ether so as to produce a deflection of the rays ([17], p. 285). On the other hand, the capacity of cathode rays to pass through thin metallic sheets, which suggested that they were waves in the ether, could be accommodated by the hypothesis that cathode rays were charged particles. In 1893 J. J. Thomson (1856–1940) argued that the capacity in question was only apparent: what really happened, according to Thomson, was that the material bombarded by cathode rays turned into a source of cathode rays itself.

The cathode ray controversy was resolved by Thomson in 1897. He had studied electrical discharges in gases since 1883 and the discovery of ► X-rays by Wilhelm Conrad Röntgen (1845–1923) rekindled his interest in cathode rays. In a lecture to the Royal Institution on 30 April 1897, Thomson argued that cathode rays were composed of minute, sub-atomic particles that he named "corpuscles". Their small size followed, according to Thomson, from Lenard's results concerning their mean free path outside the cathode ray tube. A further indication of their small size was provided by Thomson measurements of their mass to charge ratio, which turned out to be very small in comparison to the corresponding ratio of hydrogen ions [12].

A few months later, in October 1897, Thomson presented his case for the particulate interpretation of cathode rays in more detail [13]. He reported a novel result favoring that interpretation: the deflection of cathode rays by an electric field. Furthermore, he reported a series of measurements of the mass to charge ratio (m/e) of cathode ray particles, whose purpose was to enable him to figure out their identity. He obtained those measurements by means of two different approaches. The first one was based on measurements of the charge carried by cathode rays, the heat produced by their impact on a target, and the effect of a magnetic field on their trajectory. A combination of those data led to an estimate of m/e. The guiding idea behind the second approach was to place cathode rays under the influence of an electric and a magnetic field and to adjust the intensity of the latter "so that the electrostatic deflexion [sic] was the same as the magnetic" ([13], p. 309). It was then possible to calculate m/e on the basis of directly measurable parameters. Thomson obtained the following value: $m/e = H^2 l / F\Theta$, where H and F were, respectively, the intensities of the magnetic and the electric fields, l the length of the region under the influence of the field, and Θ the angle of electric (or magnetic) deflection. Both methods indicated that the value of m/e was three orders of magnitude smaller than "the smallest value of this quantity previously known, and which is the value for the hydrogen ion in electrolysis" ([13], p. 310). Furthermore, the value of m/e was independent of the material of the cathode and the chemical composition of the gas within the cathode ray tube. This independence suggested to Thomson that the "corpuscles" were universal constituents of all material substances.

In the early months of 1897 analogous results of the charge to mass ratio of cathode rays were reported by Emil Wiechert (1861–1928) and Walter Kaufmann (1871–1947). Those physicists, however, drew different conclusions from their experiments. Wiechert identified the constituents of cathode rays with disembodied charges [14, 15]; and Kaufmann suggested that the unexpectedly large ratio of e/m refuted the particulate interpretation of cathode rays [6]. According to our knowledge today, the cathode rays are nothing but swiftly moving ► electrons.

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