Original Article

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TMU Journal of Basic & Applied Chemistry
Vol.6
Jan-December, 2026: P.45-53

A Review of Cathode Rays and Anode (Canal) Rays: Discovery, Properties, Experimental Evidence, and Their Role in the Development of Atomic Structure

Abstract

The experiments that led to the discovery of cathode rays and anode (canal) rays significantly changed the scientific understanding of matter by demonstrating that atoms contain smaller charged particles. Before these investigations, atoms were widely regarded as indivisible units according to Dalton's atomic theory. In 1897, J. J. Thomson established that cathode rays are streams of negatively charged particles, later named electrons, providing the first direct evidence of a subatomic particle. Earlier, in 1886, Eugen Goldstein identified canal rays, which consist of positively charged ions formed in gas discharge tubes. His observations later contributed to the understanding of positive charge within atoms and supported the eventual discovery of the proton. Together, these pioneering experiments laid the experimental foundation for the atomic models proposed by Thomson, Rutherford, and Bohr. This review examines the historical background, experimental techniques, formation mechanisms, physical characteristics, and scientific importance of cathode and anode rays. It also outlines their influence on the development of atomic theory and highlights their continued relevance in technologies such as electron microscopy, mass spectrometry, plasma processing, and particle accelerator systems.

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Received on: 06.07.2026

Revised on: 18.07.2026

Accepted on: 21.07.2026

Keywords: Cathode rays, Canal rays, Anode rays, Electron, Proton, Atomic structure, Crookes tube, Gas discharge tube, J. J. Thomson, Eugen Goldstein.

1. Introduction

The understanding of atomic structure has developed gradually through a series of important experimental discoveries. During the early nineteenth century, John Dalton proposed that matter is composed of tiny, indivisible particles called atoms. Although this theory successfully explained several fundamental laws of chemistry, it could not explain the electrical behavior of matter or the existence of charged particles (Atkins & de Paula, 2018).

As experimental techniques improved, scientists began investigating the behavior of gases under reduced pressure, leading to discoveries that transformed the concept of the atom. One of the most influential developments was the study of electrical discharge in partially evacuated glass tubes. When a high potential difference is applied between two electrodes inside such a tube, the remaining gas becomes ionized and emits luminous beams. Careful investigation revealed that these beams were not ordinary light but streams of charged particles (Crookes, 1879). Two different types of rays were identified: cathode rays, which originate from the negatively charged electrode and consist of electrons, and anode (canal) rays, which are composed of positively charged ions moving in the opposite direction (Thomson, 1897).

Research carried out by Sir William Crookes, and J. J. Thomson provided convincing evidence that atoms possess an internal structure. Thomson's measurement of the charge-to-mass ratio of cathode ray particles confirmed the existence of electrons, while Goldstein's work on canal rays demonstrated the presence of positive ions within gases. These discoveries challenged Dalton's concept of the indivisible atom and provided the experimental foundation for the atomic models proposed by Thomson, Rutherford, and Bohr (Rutherford, 1911).

Beyond their historical importance, the principles established through these investigations continue to support modern scientific and industrial technologies. Electron and ion beams are widely used in electron microscopy, semiconductor manufacturing, plasma engineering, surface modification, ion implantation, and particle accelerators (Williams & Carter, 2009). Consequently, the study of cathode and anode rays remains an essential topic for understanding both the historical evolution of atomic theory and the technological developments that followed.

This review presents a concise discussion of the discovery, experimental investigation, physical properties, and scientific significance of cathode and anode rays, together with their contributions to modern atomic theory and contemporary technological applications.

2. Historical Development

The investigation of electrical discharge through gases began during the nineteenth century following improvements in vacuum technology. Scientists observed that gases maintained at very low pressure produced a visible glow when subjected to a sufficiently high voltage. These unusual observations encouraged further experimentation and eventually led to the discovery of charged particles within atoms.

Among the earliest contributors was Julius Plücker, who demonstrated in 1858 that the luminous discharge inside a vacuum tube could be influenced by an external magnetic field. His observations suggested that the glow was associated with moving charged particles rather than ordinary light (Plücker, 1858). Later, Johann Wilhelm Hittorf showed that these rays travel in straight lines by placing solid objects in their path and observing well-defined shadows on the glass wall of the discharge tube (Hittorf, 1869).

A major advancement came with the introduction of the Crookes discharge tube, developed by Sir William Crookes. By reducing the gas pressure more effectively than previous experiments, Crookes was able to study cathode rays in greater detail. He demonstrated that these rays travel from the cathode toward the anode, produce fluorescence on certain materials, and possess sufficient momentum to move lightweight objects. Although the exact identity of the particles remained uncertain, these experiments established many of the fundamental properties of cathode rays.

In 1886, Eugen Goldstein modified the discharge tube by introducing a perforated cathode. During his experiments, he observed another beam moving in the direction opposite to cathode rays. Because these rays passed through the holes in the cathode, they became known as canal rays. Unlike cathode rays, canal rays consisted of positively charged ions whose characteristics varied depending on the type of gas present in the discharge tube (Goldstein, 1886).

The decisive breakthrough occurred in 1897, when J. J. Thomson investigated cathode rays using electric and magnetic fields. By measuring their deflection, he determined the charge-to-mass ratio of the particles and showed that the value remained constant regardless of the electrode material or the gas used. Thomson concluded that cathode rays are composed of identical negatively charged particles, later named electrons. This discovery demonstrated that atoms are divisible and contain smaller constituents, marking the beginning of modern atomic physics and paving the way for the atomic models proposed by Thomson, Rutherford, and Bohr (Bohr, 1913).

Table 1. Historical Milestones in the Discovery of Cathode and Anode Rays

Year	Scientist	Major Contribution
1858	Julius Plücker	Investigated electrical discharge in gases
1869	Johann W. Hittorf	Demonstrated straight-line motion of cathode rays
1879	William Crookes	Developed the Crookes discharge tube
1886	Eugen Goldstein	Discovered canal (anode) rays
1897	J. J. Thomson	Determined the electron charge-to-mass ratio and identified the electron
1911	Ernest Rutherford	Proposed the nuclear model of the atom
1913	Niels Bohr	Introduced the Bohr atomic model

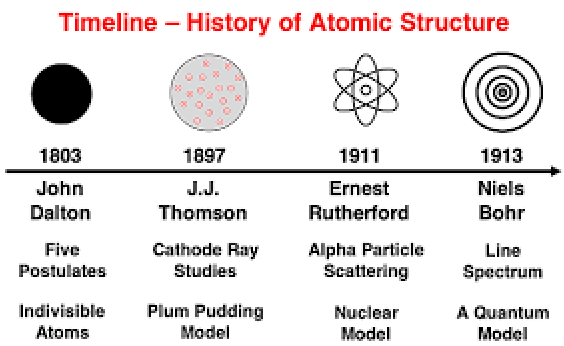

Figure 1. Historical timeline illustrating the evolution of atomic theory from Dalton's atomic model to the discoveries of cathode rays, canal rays, and the atomic models proposed by Thomson, Rutherford, and Bohr.

3. Cathode Rays

Cathode rays are high-speed streams of negatively charged particles, now known as electrons, that originate from the cathode in a gas discharge tube operated under low pressure and a high applied voltage. Their investigation represented a major milestone in physics because it provided convincing evidence that atoms are not indivisible but contain smaller fundamental particles. The pioneering experiments of William Crookes and J. J. Thomson established the nature of these rays and transformed the understanding of atomic structure.

3.1 Experimental Setup and Formation of Cathode Rays

Cathode rays are generated in a Crookes discharge tube, a sealed glass tube fitted with a cathode, an anode, a vacuum system, and a high-voltage source. After the gas pressure inside the tube is reduced, applying a high potential difference causes the remaining gas molecules to become ionized. Positive ions move toward the cathode and release electrons when they strike its surface. These electrons are then accelerated by the electric field toward the anode, forming a narrow beam called cathode rays. Because the tube contains very little gas, the electrons experience minimal collisions and travel almost freely across the tube.

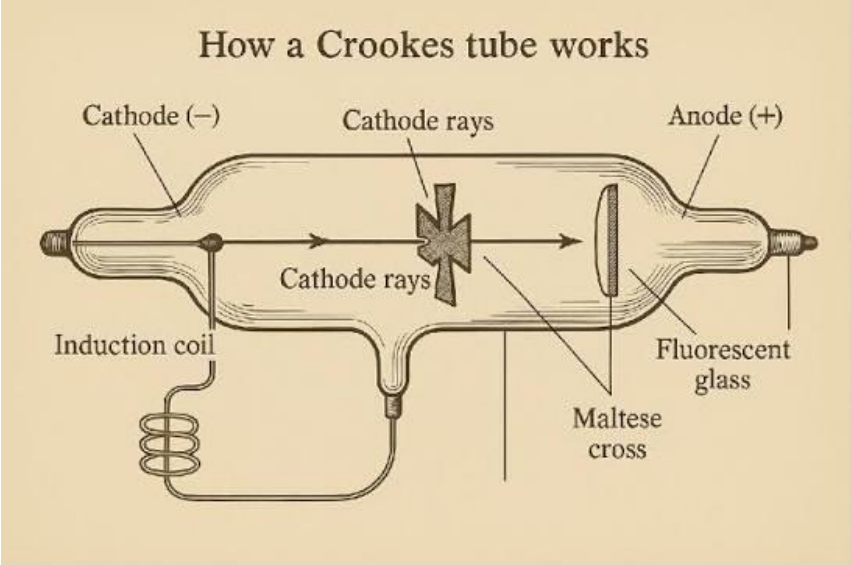

Figure 2. Schematic representation of a Crookes discharge tube illustrating the generation of cathode rays.

3.2 Characteristics of Cathode Rays

A series of experiments revealed several important characteristics of cathode rays:

- They propagate in straight lines, as demonstrated by the formation of sharp shadows when an object is placed in their path.
- They possess a negative electrical charge, which is evident from their deflection toward the positive plate in an electric field.
- They are influenced by magnetic fields, confirming that they consist of charged particles.
- They produce fluorescence when they strike fluorescent materials such as zinc sulfide or specially coated glass.
- They carry momentum and kinetic energy, enabling them to rotate a light paddle wheel and generate heat upon impact with metal surfaces.
- They can ionize gases through collisions, thereby increasing the electrical conductivity of the gas.
- Their behavior is independent of both the gas present and the electrode material, indicating that electrons are common constituents of all atoms.

3.3 Discovery of the Electron

A decisive advance in the study of cathode rays was achieved by J. J. Thomson in 1897. By examining the deflection of cathode rays in combined electric and magnetic fields, he determined their charge-to-mass ratio ($e/m = 1.76 \times 10^{11}$ C kg^{-1}). The measured value remained unchanged regardless of the gas inside the tube or the material used for the electrodes, demonstrating that cathode rays consist of identical particles present in every atom.

Thomson identified these particles as electrons, establishing the existence of the first known subatomic particle. This finding overturned Dalton's concept of the indivisible atom and led to the proposal of the Thomson atomic model, in which electrons were embedded within a sphere of positive charge. The discovery of the electron marked the beginning of modern atomic physics and earned Thomson the 1906 Nobel Prize in Physics.

Table 2. Major Characteristics of Cathode Rays

Property	Observation	Scientific Importance
Nature	Stream of electrons	First experimentally identified subatomic particle
Electrical charge	Negative	Deflected toward the positive electrode
Motion	Straight-line travel	Produces distinct shadows
Magnetic behavior	Deflected by magnetic field	Confirms charged-particle nature
Fluorescence	Causes visible glow	Indicates transfer of energy
Mechanical effect	Rotates paddle wheel	Demonstrates momentum
Heating effect	Produces heat on impact	Shows kinetic energy transfer
Universality	Independent of gas and electrode	Electrons exist in all atoms

4. Anode (Canal) Rays

The discovery of anode rays, also referred to as canal rays or positive rays, was reported by Eugen Goldstein in 1908 during experiments with a modified discharge tube. By introducing a perforated cathode, Goldstein observed a luminous beam moving opposite to the direction of cathode rays. Since these rays passed through the openings in the cathode, they were named canal rays. Unlike cathode rays, canal rays are composed of positively charged ions produced from the ionization of gas molecules inside the discharge tube.

4.1 Formation of Anode Rays

When a high voltage is applied to a low-pressure gas discharge tube, energetic electrons collide with gas atoms and remove one or more electrons, producing positive ions. These ions accelerate toward the negatively charged cathode. In tubes containing a perforated cathode, some ions pass through the holes and continue their motion beyond the cathode, forming the beam known as anode or canal rays. Because these ions originate from the gas itself, their mass and composition vary depending on the gas present inside the tube.

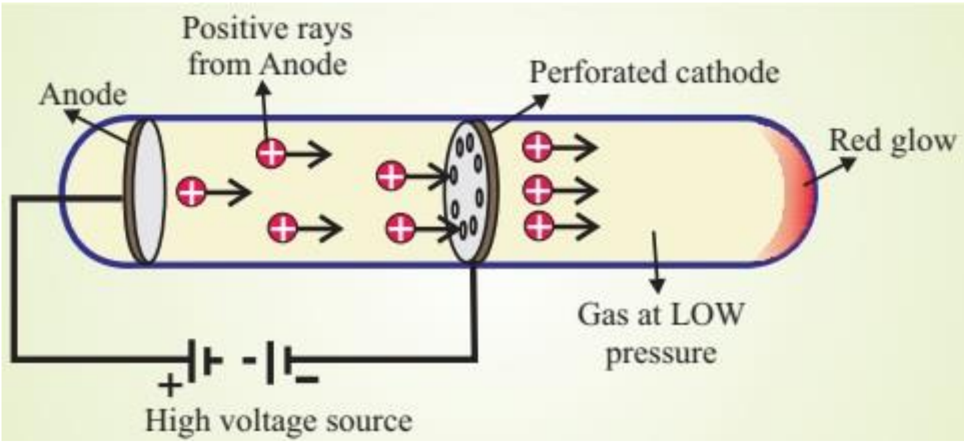

Figure 3. Formation of canal rays in Goldstein's perforated cathode discharge tube.

4.2 Characteristics of Anode Rays

The main characteristics of anode rays include:

- They are composed of positively charged ions and therefore move toward the negative electrode in an electric field.
- They travel in straight lines, producing shadows when obstacles are placed in their path.
- Their deflection in electric and magnetic fields is relatively small because positive ions have much greater mass than electrons.

- Their composition depends on the type of gas inside the discharge tube, resulting in different ions for different gases.
- They are capable of producing fluorescence and ionizing gases through energetic collisions.

The observation of canal rays provided convincing evidence for the existence of positively charged particles and played an essential role in the later identification of the proton, contributing significantly to the development of atomic theory.

5. Comparison Between Cathode Rays and Anode Rays

Although cathode and anode rays are produced under similar experimental conditions, they differ in their origin, composition, and physical behavior. Cathode rays are streams of electrons that exhibit identical properties irrespective of the gas used, whereas anode rays consist of positive ions whose characteristics depend on the gas present in the discharge.

Together, these discoveries established the existence of both negative and positive charged particles within atoms and greatly advanced the understanding of atomic structure, providing the experimental foundation for the atomic models proposed by Thomson, Rutherford, and Bohr.

Table 3. Comparison of Cathode Rays and Anode (Canal) Rays

Property	Cathode Rays	Anode (Canal) Rays
Nature	Electrons	Positive ions
Charge	Negative	Positive
Direction of motion	Cathode → Anode	Anode → Cathode
Discovery	Electron identified by J. J. Thomson	Canal rays discovered by Eugen Goldstein
Dependence on gas	Independent	Depends on gas used
Deflection	Large	Comparatively small
Mass	Very low	Relatively high
Scientific significance	Led to the discovery of the electron	Provided evidence for positive particles and the proton

6. Importance in the Development of Atomic Theory

The investigation of cathode and anode rays played a decisive role in shaping modern atomic theory. Before these experiments, atoms were widely regarded as indivisible particles according to Dalton's atomic model. The discovery of cathode rays demonstrated that atoms contain negatively charged particles, later identified as electrons, while the observation of canal rays confirmed the existence of positively charged ions within matter. These findings fundamentally changed the scientific understanding of atomic structure and established that atoms are composed of smaller constituents.

The experimental evidence obtained from discharge tube studies directly influenced the development of successive atomic models. Thomson proposed the plum pudding model, Rutherford introduced the concept of a dense central nucleus, and Bohr explained the arrangement of electrons in quantized energy levels. Collectively, these discoveries provided the foundation for modern atomic physics and significantly advanced research in both physics and chemistry.

7. Modern Applications

Although cathode and anode ray experiments were first performed to understand the nature of matter and electricity, their underlying principles remain highly relevant in present-day science and technology. Electron beams and ion beams derived from these discoveries are now widely employed in research laboratories, industrial manufacturing, medical diagnostics, and advanced materials characterization.

7.1 Applications of Cathode Rays

Electron beams generated on the same principles as cathode rays have numerous practical applications, including:

- **Cathode Ray Tubes (CRTs):** Formerly used in televisions, radar displays, computer monitors, and oscilloscopes for image formation (Streetman & Banerjee, 2016)**.**
- **Electron Microscopy:** Electron beams provide exceptionally high-resolution images of materials, biological tissues, and nanostructures.
- **X-ray Generation:** High-speed electrons striking a metal target produce X-rays that are widely used in medical imaging and crystallographic analysis **(**Bushberg et al., 2021**).**
- **Electron Beam Welding:** Focused electron beams enable precise and high-strength welding for aerospace, automotive, and nuclear engineering **(**Cary & Helzer, 2005**).**
- **Electron Spectroscopy:** Techniques such as X-ray Photoelectron Spectroscopy (XPS) and Auger Electron Spectroscopy (AES) are employed to investigate the composition and electronic properties of materials (Briggs & Grant, 2003)

7.2 Applications of Anode (Canal) Rays

The principles associated with positively charged ion beams have also found extensive technological applications, including:

- **Mass Spectrometry:** Identification and analysis of chemical species based on their mass-to-charge ratio (Murray et al, 2013).
- **Ion Implantation:** Controlled introduction of dopant ions into semiconductor materials during integrated circuit fabrication.
- **Particle Accelerators:** Acceleration of charged particles for nuclear physics, medical research, and fundamental particle studies.
- **Plasma Processing:** Surface cleaning, plasma etching, thin-film deposition, and coating processes used in modern manufacturing (Lieberman & Lichtenberg, 1994).
- **Focused Ion Beam (FIB) Technology:** Precise machining, microfabrication, and imaging of materials at the micro- and nanoscale (Giannuzzi & Stevie, 2005).

8. Future Perspectives

Research based on electron and ion beam technologies continues to expand into new scientific and engineering fields. Modern electron beam systems play an essential role in nanotechnology, quantum materials research, additive manufacturing, and next-generation microscopy. Likewise, ion beam technologies are increasingly being applied in semiconductor processing, advanced surface engineering, cancer treatment through ion-beam therapy, and electric propulsion systems for spacecraft.

Future developments are expected to improve the precision, efficiency, and sustainability of these technologies, enabling innovations in quantum computing, nanoelectronics, biomedical engineering, and energy-related materials. As research progresses, the principles first demonstrated in cathode and canal ray experiments will continue to support advances across multiple scientific disciplines.

Conclusion

The discoveries of cathode rays and anode (canal) rays represent some of the most significant milestones in the evolution of atomic science. Experimental investigations of cathode rays established the existence of the electron, whereas studies of canal rays confirmed the presence of positively charged ions, which ultimately contributed to the identification of the proton. These findings demonstrated that atoms possess an internal structure and replaced the earlier concept of atoms as indivisible particles.

In addition to their historical importance, the principles revealed through these experiments continue to underpin numerous modern technologies. Electron microscopy, X-ray generation, mass spectrometry, plasma processing, ion implantation, and particle accelerator systems all rely on concepts that originated from early discharge tube investigations. Consequently, the study of cathode and anode rays remains a fundamental topic in physics and chemistry, providing both historical insight into the development of atomic theory and a foundation for many contemporary scientific and technological applications.

References

1. Atkins, P., De Paula, J., & Keeler, J. (2018). Molecular Spectroscopy. Atkins' Physical Chemistry.
2. Crookes, W. (1879). V. The Bakerian Lecture On the illumination of lines of molecular pressure, and the trajectory of molecules. *Philosophical Transactions of the Royal Society of London*, (170), 135-164.
3. Thomson, J. J. (1897). XL. Cathode rays. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, *44*(269), 293-316.
4. Rutherford, E. (1911). LXXIX. The scattering of α and β particles by matter and the structure of the atom. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, *21*(125), 669-688.
5. Williams, D. B., & Carter, C. B. (2009). Scattering and diffraction. In *Transmission Electron Microscopy: A Textbook for Materials Science* (pp. 19-33). Boston, MA: Springer US.
6. Plücker, M. (1858). XLVI. Observations on the electrical discharge through rarefied gases. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, *16*(109), 408-418.
7. Hittorf, W. (1869). Ueber die Elektricitätsleitung der Gase. *Annalen der physik*, *212*(2), 197-234.
8. Goldstein, E. (1908). XXXVI. On the canal-ray group. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, *15*(87), 372-385.
9. Bohr, N. (1987). The philosophical writings of Niels Bohr.
10. Streetman, B. G., & Banerjee, S. K. (2016). Solid state electronic devices, Seventh. *Edinburgh Gate: Pearson Education Limited*.
11. Bushberg, J. T., Seiberg, J. A., Leidholdt Jr, E. M., & Boone, J. M. (2020). *The essential physics of medical imaging*. Lippincott Williams & Wilkins.
12. Cary, H. B., & Helzer, S. C. (2005). Welding background. *Modern Welding Technology*, 6.
13. Seah, M. P., Briggs, D., & Grant, J. T. (2003). Instrument calibration for AES and XPS. *Surface analysis by Auger and X-ray photoelectron spectroscopy*, 167-189.
14. Murray, K. K., Boyd, R. K., Eberlin, M. N., Langley, G. J., Li, L., & Naito, Y. (2013). Definitions of terms relating to mass spectrometry (IUPAC Recommendations 2013). *Pure and Applied Chemistry. Chimie Pure et Appliquee*, *85*(7), 1515.

15. Lieberman, M. A., & Lichtenberg, A. J. (1994). Principles of plasma discharges and materials processing. *MRS Bulletin*, *30*(12), 899-901.
16. Stevie, F. A., Giannuzzi, L. A., & Prenitzer, B. I. (2005). The focused ion beam instrument. In *Introduction to focused ion beams: instrumentation, theory, techniques and practice* (pp. 1-12). Boston, MA: Springer US.