

Cathode Rays

The first ideas about electrons came from experiments with cathode-ray tubes. A forerunner of neon signs, fluorescent lights, and TV picture tubes, a typical cathode-ray tube is a partially evacuated glass tube with a piece of metal sealed in each end (Fig. 1). The pieces of metal are called electrodes; the one given a negative charge is called the cathode, and the one given a positive charge is called the anode.

If a high electrical voltage is applied to the electrodes, an electrical discharge can be created between them. This discharge appears to be a stream of particles emanating from the cathode. This cathode ray will cause gases and fluorescent materials to glow, and will heat metal objects in its path to red heat. Cathode rays travel in straight lines and cast sharp shadows. Unlike light, however, cathode rays are attracted toward a positively charged plate. This led to the conclusion that cathode rays are negatively charged.

Careful microscopic study of a screen that emits light when struck by cathode rays shows that the light is emitted in tiny, random flashes. Thus, not only are cathode rays negatively charged, but they are composed of particles, each one of which produces a flash of light upon collision with the material of the screen. The cathode-ray particles became known as electrons.

The charge and mass of an electron were determined by a combination of experiments by Sir Joseph John Thomson in 1897 and by Robert Andrews Millikan in 1911. Both scientists were awarded Nobel prizes, Thomson in 1906 and Millikan in 1923.

By using a specially designed cathode-ray tube (Fig. 2), Thomson applied electrical and magnetic fields to the rays. Using the basic laws of electricity and magnetism, he determined the charge-to-mass ratio of the electrons. He was able to measure neither the charge nor the mass of the electron, but he established the ratio between the two numbers and made it possible to calculate either one if the other could ever be measured. What Thomson did for the concept of the electron is like showing that a peach weighs 40 times more than its seed. What is the weight of the peach? What is the weight of the seed? Neither is known, but if it can be determined by other means that the peach weighs 120 grams, then the weight of the seed, by ratio, must be 3 grams.

An important part of Thomson's experimentation was his use of twenty different metals for cathodes and of several gases to conduct the discharge. Every combination of metals and gases yielded the same charge-to-mass ratio for the cathode rays. This led to the belief that electrons are common to all of the metals used in the experiments, and probably to all atoms in general.

Figure 1: Deflection of a cathode ray by an electric field and by a magnetic field. When an external electric field is applied, the cathode ray is deflected toward the positive pole. When a magnetic field is applied, the cathode ray is deflected from its normal straight path into a curved path.

Figure 2: J. J. Thomson Experiment. Electric field, applied by plates, and magnetic field, applied by magnet, cancel each other's effects to allow cathode ray (electron beam) to travel in straight line.

Vocabulary:

to seal
charge
discharge
to emanate from

versiegeln
Ladung
Entladung
to radiate, to come
from
to throw
to send out
without plan or aim

to be composed of

ratio
to establish
seed
by other means
to conduct
to yield
to cancel
to sensitize

to be made of, to consist of
Verhältnis
to determine
Samen, Kern
auf andere Weise
durchführen
to produce
aufheben
sensibilisieren

The Millikan Experiment

Millikan measured the fundamental charge of matter - the charge on an electron. A simplified drawing of his apparatus is shown in Figure 3. The experiment consisted of measuring the electrical charge carried by tiny drops of oil that are suspended in an electrical field. By means of an atomizer, oil droplets were sprayed into the test chamber. As the droplets settled slowly through the air, high-energy X rays were passed through the chamber to charge the droplets negatively (the X rays caused air molecules to give up electrons to the oil). By using a beam of light and a small telescope, Millikan could study the motion of a single droplet. When the electrical charge on the plates was increased enough to balance the effect of gravity, a droplet could be suspended motionless. At this point, the gravitational force would equal the electrical force. Measurements made in the motionless state, when inserted into equations for the forces acting on the droplet, enabled Millikan to calculate the charge carried by the droplet.

Millikan found different amounts of negative charge on different drops, but the charge measured each time was always a whole-number multiple of a very small basic unit of charge. The largest common divisor of all charges measured by this experiment was 1.60×10^{-19} coulomb (the coulomb is a charge unit). Millikan assumed this to be the fundamental charge, which is the charge on the electron.

With a good estimate of the charge on an electron and the ratio of charge-to-mass as determined by Thomson, the very small mass of the electron could be calculated. The mass of an electron is 9.11×10^{-18} g. On the carbon-12 relative scale, the electron would have a weight of 0.000549 atomic weight units. The negative charge on an electron of -1.60×10^{-19} coulomb is set as the standard charge of -1.

Figure 3: Charged oil drops, suspended as a result of opposing gravitational and electrostatic forces, provided Millikan with the means of calculating the charge on the electron.

Vocabulary:

charge	Ladung	to enable	to make possible
fundamental charge	Elementarladung	whole-number	ganzzahliges
matter	Materie	multiple	Vielfaches
to be suspended in	to hang in	largest common	grösster gemein-
atomizer	Zerstäuber	divisor	samer Teiler
X ray	Röntgenstrahl	to assume	to suppose
beam	ray	estimate	Schätzung
equation	Gleichung	means	Mittel

Canal Rays

The first experimental evidence of a fundamental positive particle came from the study of canal rays. A special type of cathode-ray tube produces canal rays (Fig. 4). The cathode is perforated, and the tube contains a gas at very low pressure. When high voltage is applied to the tube, cathode rays can be observed between the electrodes as in any cathode-ray tube. On the other side of the perforated cathode, a different kind of a ray is observed. These rays are attracted to a negative plate brought alongside the rays. The rays must therefore be composed of positively charged particles. Each gas used in the tube gives a different charge-to-mass ratio for the positively charged particles. When hydrogen gas was used, the largest charge-to-mass ratio was obtained, indicating that hydrogen provides the positive particles with the smallest mass. This particle was considered to be the fundamental positively charged particle of atomic structure, and was called a proton (from Greek for "the primary one").

Experiments on canal rays were begun in 1886 by E. Goldstein and further work was done later by W. Wien. The production of canal rays is caused by high-energy electrons moving from the negative cathode to the positive anode, hitting the molecules of gases occupying the tube. Electrons are knocked from some atoms by the high-energy electrons, leaving each molecule with a positive charge. The positively charged molecules are then attracted to the negative electrode. Since the electrode is perforated, some of the positive particles go through the holes or channels (hence the name canal rays).

The mass of the proton is 1.67261×10^{-24} g, which is 1.00727 relative weight on the carbon-12 scale. The charge of +1 on the proton is equal in size but opposite in effect to the charge on the electron.

Figure 4:

- (a) Electrons rush from the negative electrode to the positive electrode due to high voltage.
- (b) Electrons collide with gas molecules to produce positive ions that are accelerated toward the negative electrode.
- (c) Some of the positive ions escape capture by the electrode and rush through the opening due to their kinetic energy.
- (d) Some of the positive ions in the positive ray collide with gas molecules to produce a characteristic glow, and strike the end of the glass tube to produce a luminous spot.

Vocabulary:

to contain
alongside
charge
ratio

enthalten
neben
Ladung
Verhältnis

to obtain
to accelerate
to strike

to get
beschleunigen
to hit

The Rutherford Experiment

When Ernest Rutherford and his students directed alpha particles toward a very thin sheet of gold foil in 1909, they were amazed, to find a totally unexpected result (Fig. 5). As they had expected, the paths of most of the alpha particles were only slightly changed as they passed through the gold foil. The extreme deflection of a few of the alpha particles was a surprise. Some even „bounced“ back toward the source. Rutherford expressed his astonishment by stating that he would have been no more surprised if someone had fired a 15-inch artillery shell into tissue paper and then found it in flight back toward the cannon.

What allowed most of the alpha particles to pass through the gold foil in a rather straight path? According to Rutherford’s interpretation, the atom is mostly empty space and, therefore, offers little resistance to the alpha particles (Fig. 6).

What caused a few alpha particles to be deflected? According to Rutherford’s interpretation, concentrated at the center of the atom is a nucleus containing most of the mass of the atom and all of the positive charge. When an alpha particle passes near the nucleus, the positive charge of the nucleus repels the positive charge of the alpha particle; the path of the smaller alpha particle is deflected. The closer an alpha particle comes to a target nucleus, the more it is deflected. Those alpha particles that meet a nucleus head on are „bounced“ back toward the source by the strong positive-positive repulsion, since the alpha particles do not have enough energy to penetrate the nucleus.

Rutherford’s calculations, based on the observed deflections, indicate that the nucleus is a very small part of an atom. An atom occupies about a million million times more space than does a nucleus; the radius of an atom is about 10,000 times greater than the radius of its nucleus. Thus, if a nucleus were the size of a baseball, then the edges of the atom would be about one third of a mile away. And most of the space in between would be absolutely empty.

Since the nucleus contains most of the mass and all of the positive charge of an atom, the nucleus must be composed of the most massive atomic particles, the protons and neutrons. The electrons are distributed in the near-emptiness outside the nucleus.

Truly, Rutherford’s model of the atom was one of the most dramatic interpretations of experimental evidence to come out of this period of significant discoveries.

Figure 5: Rutherford’s gold foil experiment. A circular scintillation screen is shown for simplicity; actually, a movable screen was employed. Most of the alpha particles pass straight through the foil to strike the screen at point A. Some alpha particles are deflected to points B, and some are even „bounced“ backwards to points such as C.

Figure 6: Rutherford’s interpretation of how alpha particles interact with atoms in a thin gold foil. Actually, the gold foil was about 1000 atoms thick. For illustration purposes, points are used to represent the gold nuclei and the pathwidths of the alpha particles are drawn larger than scale.

Lord Rutherford (**Ernest Rutherford**, 1871-1937) was Professor of Physics at Manchester when he and his students discovered the scattering of α particles by matter. Such scattering led to the postulation of the nuclear atom. For this work he received the Nobel prize in 1908. In 1919, Rutherford discovered and characterized nuclear transformations.

Vocabulary:

charge
to bounce back
tissue paper
shell
to repel
target
repulsion

Ladung
zurückprallen
Seidenpapier
Granate
abstossen
aim
Abstossung

to penetrate
10,000
scintillation screen
lead
shield
width

to get into
10'000
Leuchtschirm
Blei
Schutz
Breite