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Introductory Chapter: Charged Particles

Mahmoud Izerrouken and Ishaq Ahmad

1. Overview

Bringing history back in August 1912, Austrian physicist Victor Hess discovered cosmic rays coming from outer space. These cosmic rays consist of high-energy particles, entering from outer space, such as mainly protons, helium, and heavier nuclei up to uranium. When these cosmic rays come to earth to interact with upper atmosphere, they collide with the nuclei of atoms, creating more high-energy particles such as pions. The charged pions can quickly decay into two particles, a muon and a muon neutrino or antineutrino. Several high-energy particles were also discovered, which is long list. Studies of cosmic rays opened the door to a world class of particles.

It is concluded that charged particle is a particle that carries an electric charge. In atomic levels, the atom consists of nucleus around which the electrons turn. The nucleus is formed by proton and neutron and thus carries a positive charge (the proton charge is 1.602×10^{-19} Coulombs). The electron carries a negative charge (-1.602×10^{-19} Coulombs). An atom is called neutral if the number of protons equals the number of electrons. Thus, an atom can be positive, negative, or neutral. The charged particle is negative when it gains electron from another atom. It is positively charged if it loses electron from it. Applications of charged particles are subjected to control their motion and energy through electric field and magnetic field. Therefore, motion of charged particle in electric and magnetic fields is discussed in order to understand the beam of charged particles and their applications.

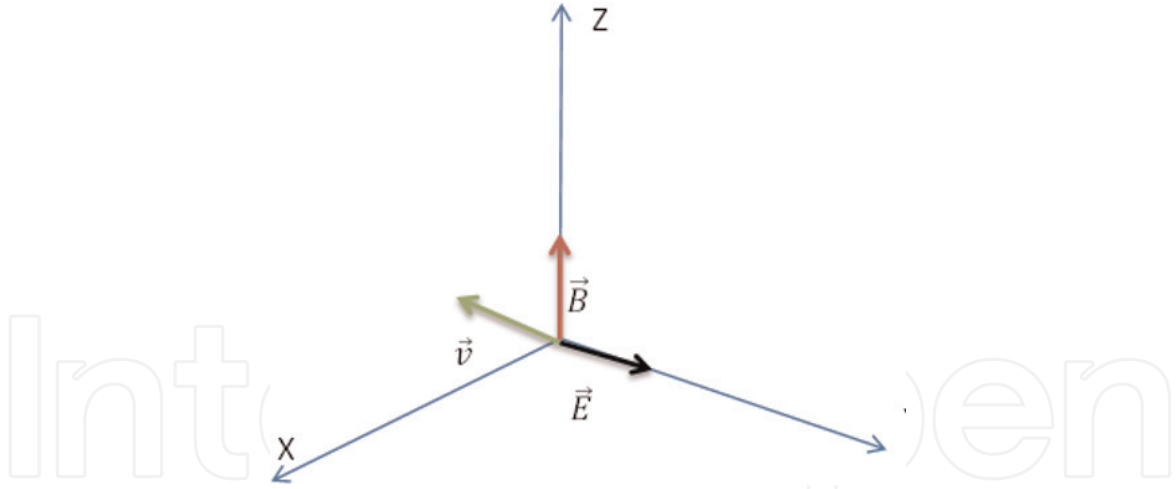
2. Charged particles motion in an electromagnetic field (\vec{E} , \vec{B})

The motion of charged particle of mass m and charge q with a velocity \vec{v} in uniform magnetic field $\vec{B} \neq \vec{0}$ and uniform electric field \vec{E} is subjected to an electromagnetic force called the Lorentz force given by:

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B} \quad (1)$$

From Newton second law, the particle's equation of motion is written as:

$$m \frac{d\vec{v}}{dt} = q(\vec{E} + \vec{v} \times \vec{B}) \quad (2)$$



Let us assume that the magnetic field is applied in the direction Oz and electric field \vec{E} is applied in the direction Oy.

1. In the case of motion of charged particle through a stationary electric field $\vec{E} = \vec{E}_0$ and $\vec{B} = \vec{0}$, the equation of motion is:

$$m \frac{d\vec{v}}{dt} = q\vec{E} \Leftrightarrow \vec{v} = \frac{q\vec{E}}{m}t + \vec{v}_0 \quad (3)$$

The projection of (3) on the axes gives

$$\begin{aligned} m \frac{dv_x}{dt} &= 0 \\ m \frac{dv_y}{dt} &= qE \\ m \frac{dv_z}{dt} &= 0 \end{aligned} \quad (4)$$

The integration of (4) with the initial conditions $x(0) = 0, y(0) = 0$, and $z(0) = 0; v_x(0) = v_{x0}, v_y(0) = v_{y0}$, and $v_z(0) = v_{z0}$ gives:

$$\begin{aligned} x &= v_{x0}t \\ y &= \frac{qE}{2m}t^2 + v_{y0}t \\ z &= v_{z0}t \end{aligned} \quad (5)$$

If \vec{E} and \vec{v} are collinear, the motion is rectilinear and uniformly accelerated.

2. In the case of motion of charged particle in uniform magnetic field $\vec{B} \neq \vec{0}$, the projection of (2) on the axes gives:

$$\begin{aligned} m \frac{dV_x}{dt} &= qBV_y \Leftrightarrow \frac{dV_x}{dt} = \frac{qB}{m} V_y \\ m \frac{dV_y}{dt} &= -qBV_x + qE \Leftrightarrow \frac{dV_y}{dt} = -\frac{qB}{m} V_x + \frac{q}{m} E \\ m \frac{dV_z}{dt} &= 0 \end{aligned} \quad (6)$$

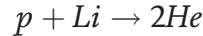
We note $\Omega = \frac{qB}{m}$ the so-called cyclotron frequency.
 The solution of (6) is:

$$\begin{aligned}x &= \frac{E}{B}t + \frac{1}{\Omega} \left(v_{x0} - \frac{t}{B} \right) \sin(\Omega t) + \frac{v_{y0}}{\Omega} (1 - \cos(\Omega t)) \\y &= \frac{1}{\Omega} \left(v_{x0} - \frac{t}{B} \right) (\cos(\Omega t) - 1) + \frac{v_{y0}}{\Omega} \sin(\Omega t) \\z &= v_{z0} t\end{aligned}\tag{7}$$

According to the above equations, we can see that the charged particle can have different trajectories. Depending on the initial conditions, the trajectory could be straight, parabolas, circles, cycloids, spirals, etc. Lorentz force is then a base of charged particle acceleration and beam guidance.

3. Charged particle accelerators

After understanding the concept of controlling and generating the charged particles, different machines were developed to deflect or accelerate the charged particles through electromagnetic fields. The machines that generate and push charged particles to very high speed and energies and contain them in well-defined beams are called charged particle accelerators. A large variety of accelerators were developed since that fabricated by Cockcroft and Walton in 1932. Using such accelerator, the authors achieved the first nuclear reaction using artificially accelerated particle:



Since then, more and more successful accelerators appeared according to the progress in particle acceleration techniques. Depending on the accelerated particle trajectory, we can distinguish linear accelerators and circular accelerators. The accelerator during the last century can be found chronologically in [1]. Currently available electrostatic accelerators and cyclotrons over the world can produce and accelerate intense and stable charged particle beams with energy varying between few keV and few TeV. Charged particle accelerators are classified as per their applications:

4. Classification of charged particles

Charged particle accelerators are classified mainly into electrostatic and electromagnetic.

4.1 Electrostatic charged particle accelerators

In electrostatic accelerators, the static high voltage was generated and then applied across the ion source. The charged particles are accelerated through static electric field generated from static high voltage due to the electrostatic force. These types of accelerators are suitable to accelerate light and heavy ions from keV to few MeV energies. These ion beams, charged particle beams of various energies, are standard research tools in many areas of sciences and engineering having many applications in nuclear physics, atomic physics, medicine, materials science,

agriculture, industry, and so on [2–6]. It is an advanced and versatile tool frequently applied across a broad range of discipline and fields.

4.2 Electromagnetic charged particle accelerators

Electrostatic charged particle accelerators have limitations on its beam energy due to high electrical voltage discharge. To avoid electrical discharge and increase charged particle energies, techniques involved electromagnetic fields instead of electrostatic fields. Electromagnetic acceleration is possible from two mechanisms either nonresonant magnetic induction or resonant circuits or cavities excited by oscillating radio frequency. High-energy charged particle colliders are installed around the world for forefront of scientific discoveries. These colliders are based on electrostatic charged particle accelerators. Through high-energy colliders, standard models are verified experimentally. Moreover, the cutting-edge and important research topic of flavor (particle physics) to search for new physics via charged particles that appears in the different extension of standard model is presented in this book. The latest research on analysis of ultrahigh-energy muon using pair-meter technique is also presented in Geant4 simulation study for iron plates. In this study, the feasibility for detection of high-energy muons at the underground iron calorimeter detector is demonstrated. The basic aim of this study is to detect high-energy muons (1–1000 TeV). The idea of the Eloisatron to Pevatron is also included in this book.

5. Charged particles applications

Charged particles interact with electrons and atom nuclei via Coulomb force, also called electrostatic force. When two charges are placed near to each other, they will be repulsed if they have the same charge or attract each other if they are of opposite charges. Each particle exerts a force on each other given by Coulomb's law expressed as:

$$F = k \frac{Q_1 Q_2}{r^2}$$

where Q_1 , Q_2 , and r are the charge of the two particles (1 and 2) in Coulomb and the distance between the charges and k is the proportionality constant:

$$k = \frac{1}{4\pi\epsilon}$$

Thus, when accelerated charged particle moves in materials, it interacts with orbital electron and nuclei via Coulomb interaction depending on its energy. At low energy (<0.01 MeV/u), the interaction is with nuclei, known as elastic interaction. This interaction leads to atomic displacement. At high energy (>0.01 MeV/u), the interaction is mainly with orbital electron known as inelastic interaction and leads to ionization and excitation. At very high energy, nuclear reactions can be produced and give rise to new particles (neutron, proton alpha, gamma rays). The basic interaction process of charged particle with matter is well known, and much performed detectors are now available. So ion beam is actually used in several applications. Electrostatic waves in magnetized electron-positron plasmas are covered in this book where the behavior of arbitrary amplitude of electrostatic wave propagation in electron-positron plasma is discussed. The well-known fluid and kinetic approaches have been used to describe linear waves, whereas the nonlinear

analysis of ESW is done via fluid modeling. Apart from the high-energy particle physics, charged bodies are also included in this book such as immune effects of negative charged particles dominated by indoor air conditions and many others.

6. Charged particle beams for materials analysis

Several techniques of ion beam analysis (IBA) are being used for the study of the chemical composition and structure of surfaces, interface, and thin layers and are explained as below.

6.1 Rutherford backscattering spectroscopy

The accelerated charged particle with energy E_0 and mass M_1 scatters from the analyzed surface containing the particle M_2 with energy E_1 and scattering angle θ . From the conservation laws of energy and momentum and the known Rutherford cross section, it is possible to deduce the mass M_2 and estimate its abundance [7, 8].

6.2 Nuclear reaction analysis (NRA)

The NRA technique is very useful as a tool for the detection and profiling of light elements. The fast charged particle (few MeV) initiates a nuclear reaction with target atom. The reaction products are characteristic for this reaction and can be used to identify the target atom and its concentration. For example, determination of hydrogen content in material: for this purpose, $H(^{15}\text{N}, \alpha\gamma)^{16}\text{O}$ nuclear reaction is used. This reaction produces alpha particle and excited ^{12}C isotope. The disintegration of the excited ^{12}C to ground state emits a gamma photon with a well-defined energy of $E_\gamma = 4.43$ MeV, which identifies hydrogen content in material.

6.3 Elastic recoil detection analysis (ERDA)

ERDA technique is a unique method to measure the H and D content in thin films. When He ion (alpha particle) interacts with material containing hydrogen (H) and deuterium (D), the H and D will be scattered in the forward direction. From the detection of the forwarded H and D, one can measure the quantitative depth profiling of these elements in the material. Similar experiments can be performed using heavy ion beam to study light element profiling.

6.4 Particle-induced X-ray emission (PIXE)

Ion beam of energy typically 1–2 MeV induces ionization of the target atom. If the ejected electron belongs to K-shell, an X-ray characteristic of the irradiated element is emitted. Using this technique, qualitative and quantitative analysis can be used where the trace element of about 1 ppm can be achieved [9].

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