PhysicsFactsheet

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Force Fields in Physics

A force field is a *vector fiel* . It has *magnitude and direction at each point*. Any *forces acting on a body act at a distance and are non-contact*.

Representing Force Fields

A field of force can be represented by drawing lines of force. From the lines of force we can see:

(a) The *direction of the force,* which is represented by the arrows on the *lines*.

(b) The spacing of the lines gives us the *strength of the fiel* – the *further apart the weaker the fiel* , the *closer together the stronger the field*

> *The direction of the field lines of a force field has been determined by convention.*

Similarities and Differences Between Electric, Gravitational, and Magnetic Force Fields

Electric Force Fields

Electric force fields are produced by and act between charges. Their magnitude is proportional to the charge and they give rise to attractive (between unlike charges) or repulsive (between like charges) forces. They obey an inverse square law.

Coulomb's Law $F = \dfrac{kQ_1 Q_2}{r^2}$

where F is the force (in Newtons) between point charges Q_1 and Q_2 (in coulombs) at a distance r (in metres) apart

The field strength is proportional to the charge producing it. The direction of the field lines is from positive to negative. Electric Field Strength at a point is defined as *the force exerted on a unit positive charge placed at that point*. The SI unit of electric field strength is the newton per coulomb or NC^{-1}.

Point charges and spherical charges produce a radial electric field.

Near to a spherical charge *or between two parallel plates* (e.g. a capacitor), a uniform electric field is produced.

Electric potential is defined as *the energy per unit charge*. It has the unit of joules per coulomb or volt. Lines of equal energy for a charge are called electric equipotential lines.

Quick Question 1

Explain the meaning of the term 'uniform electric field'.

Answer

An electric field is an area where a force acts on a charged particle. Uniform implies that the force is the same at all points in the field, and/or so the field strength is constant and/or the field lines will be equally spaced.

Gravitational Force Fields are produced by and act between all masses. Their magnitude is proportional to the mass and they are always attracting forces. They obey an inverse square law.

Newton's Law $F = \dfrac{Gm_1 m_2}{r^2}$

where F is the force (in Newtons) between point masses (in kilograms) at a distance r (in metres) apart

The direction of the field lines is towards the mass. Gravitational field strength is defined by g, which equals *force per unit mass* or F/m. This gives F =mg, and the field strength is proportional to the mass producing it. The SI unit of gravitational field strength is Newton per Kilogram (Nkg^{-1}).

Point masses and spherical masses produce a radial gravitational field. *Near to* a spherical very large body (e.g. the Earth), a uniform gravitational field is produced.

Gravitational potential is defined as *the energy per unit mass*. It has the unit of joules per kilogram.

Gravitational equipotential lines are lines along which a unit mass has the same energy.

***There are two types of Magnetic Force Field*:**

- **Magnetic Force Fields, which act between magnetic materials.** These force fields essentially obey an inverse square law. No point magnetic poles or monopoles have ever been detected, although forces are attractive between unlike poles and repulsive between like poles.
- **Magnetic Force Fields that are produced by and act between moving charges.** These are especially important for electromagnets.

Rules for determining the direction of the field

The direction of the field lines is **from North to South**.

Right Hand Grip Rule: Imagine gripping the coil so that the fingers follow the direction of the current. The thumb will then point in the direction of the field lines inside the coil, which is towards the north pole of the electromagnet.

Looking at an Electromagnet Coil End On: If the current circulates in a clockwise sense, then the end of the coil is the South Pole (if in an anticlockwise sense then a North Pole).

The Corkscrew Rule: Imagine screwing a corkscrew into a cork – the direction in which the corkscrew is going into the cork is the direction of the current, and then the field lines will be going around in the direction in which the corkscrew is being turned. Alternatively, the Right Hand Grip Rule can be used. This time, point your thumb in the direction of the current and the direction in which your fingers are curled gives the direction of the field.

Magnetic Flux Density: Refers to the strength of a magnetic field. This is the magnetic flux ÷ area. Thus magnetic flux φ = magnetic flux density B multiplied by area A. The SI unit is tesla metre squared (Tm^2), also called the Weber (Wb).

Magnetic Flux Linkage: If a coil of N turns surrounds a magnetic flux ϕ, then each turn of the coil will link a flux φ and the total magnetic flux link will be Nφ. Thus Nφ = NBA.

Charged Particles in Magnetic Fields

Flemings' Left Hand Rule can be used to predict the behaviour of charged particles in magnetic fields:

Hold the first and second fingers and thumb of the left hand mutually perpendicular so that the **F**irst finger points in the direction of the **F**ield, the se**C**ond finger points in the direction of the conventional **C**urrent, then your **T**humb will point in the direction of the **T**hrust or force on the particle beam.

Note: The second finger denotes the current, and so for a beam of electrons (beta particles) point it in the direction opposite to the beta particle beam.

The Effect of a Force Field on a Fundamental Particle Moving Through the field

Electric Fields

Alpha particles and other positively charged particles are attracted to the negative plate in an electric field whereas beta particles are negatively charged and are attracted to the positive plate in an electric field. Both these particles can be accelerated by an electric field. Gamma rays are electromagnetic radiation and uncharged, and will therefore be unaffected.

Magnetic Fields

The force acting on a current flowing at 90° to a magnetic field is given by magnetic field strength x current x length of conductor. Alpha and beta radiation follow circular paths. Flemings' left hand rule can be used to predict the sense.

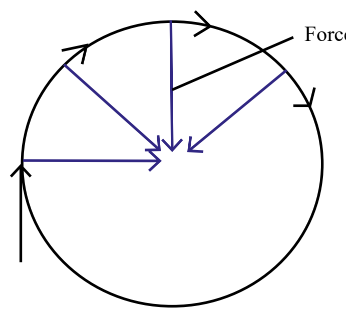
Some Common Uses of Force Fields

Electric fields are used to accelerate/deflect particles. The direction of acceleration/deflection is used to deduce the sign of the charge.

Consider the force F on a charge Q placed in a uniform field between two parallel plates. Combining the equation field strength E = F/Q, where F/Q is the force per unit charge, with the equation for the strength of a uniform field E = - V/d, where V is the potential difference and d is the distance between the parallel plates, gives F = QE = - QV/d. In the case of an electron of charge e we have F = eV/d. For example, for an electron moving between two parallel plates, a parabolic path is traversed, with the electron being attracted and moving towards the positive plate.

Acceleration of the particle, a = E Q ÷ m where E is the electric field applied, Q is the charge on the particle and m is the mass of the particle.

Magnetic fields are used to produce circular motion or to provide centripetal force or cause spirals or arcs. If the particle is charged, the direction of the force, curvature, or deflection can be used to find the sign of the charge. The momentum, speed, and mass may be found from the radius of curvature of the path.



An electron beam forced into circular path by uniform magnetic field applied into page is shown above.

Quick Question 2
Give the sense in which a proton beam would move. Would the radius of curvature be greater or smaller?

Answer
A circular path in the opposite sense/anticlockwise. The radius would be greater.

Radius of curvature, r = momentum, p ÷ (magnetic field strength B × charge on the particle Q)

The force acting on a charged particle is the centripetal force given by: magnetic field strength B × charge of the particle q × velocity of the particle v = mass of particle m × (velocity of particle v)^2 ÷ radius of curvature r.

$$Bqv = \frac{mv^2}{r}$$

The radius of curvature is then r = mass m of particle multiplied by the velocity v of the particle divided by the magnetic field strength B multiplied by the particle charge q.

$$r = \frac{mv}{Bq}$$

Common Instrumentation Using Force Fields

The **cyclotron** is a particle accelerator that uses a uniform magnetic field to force particles to travel in a circular path. The particles move within two large D-shaped semi-circular chambers. A high frequency, alternating voltage pulls and pushes the particles from one D to the other. The rotational frequency of the particles is constant and they spiral outwards as their speed increases. Cyclotrons take up less space than a linear accelerator and are used in hospitals to produce particle beams to treat cancer.

The **magneto train** uses computer controlled electromagnets. which support the train at a given, very precise distance above the track. The advantage is the frictionless nature of the supporting magnetic field.

Electron beams are used in televisions, oscilloscopes, and computer monitors. The electron beam is produced by a heated cathode and accelerated towards an anode. The direction of the electron beam is then altered by electric and/or magnetic fields. The electric field is typically produced by two plates, and the magnetic field is created by electromagnetic coils.

The **MR Scanner** uses the magnetic properties of the protons in the patient's body. This has the advantage that *the patient is not exposed to any of the ionising radiation associated with CT scans. The MR scan also gives better, more detailed images of soft tissue.*

The protons form the nuclei of every hydrogen atom in the human body, and because they spin they generate their own magnetic field. Placing the patient in a strong magnetic field orientates these spinning protons, so they are aligned. Directing a pulse of radio waves at the patients' body disturbs the proton orientation, and when the pulse ends the protons return to their original spin states, emitting a radio-frequency signal. This gives information about the proton density, which is dependent on the amount of water in the cells of the patient, and enables reconstruction of a cross-section through the patient's body. Disadvantages include that the time taken is longer, the process is noisy, the patient needs to be still for longer periods, and it's more expensive.

Quick Question 3
Alpha particles, β particles and gamma rays are passed through a magnetic field directed into the page. Give the direction of deflection of each of these particles.

Answer
Alpha particles are deflected into the arc of a circle upwards. Beta particles are deflected into the arc of a circle downwards. Gamma rays are not deflected as they are not charged.

Practice Questions
1. Explain the process used to give protons energy in a particle accelerator. Include a relevant equation in your answer. (3 marks)

2. A particle detector uses electric and magnetic fields. Explain the roles of the electric and magnetic fields. (2 marks)
   Give a relevant effect on the particle track for each type of field. (2 marks) Include a relevant equation for the electric field and a relevant equation for the magnetic field. (2 marks)

3. Name the type of force field used for an MR scan. (1 mark)
   Give one advantage and one disadvantage of an MR scan compared to a CT scan. (2 marks)

4. Which of the following is a unit of electric field strength? NmC^{-1}, JmC^{-2}, JC^{-2}, Nm^2C^{-1}, NC^{-1} (1 mark)

5. Explain why two parallel wires carrying a current in the same direction will attract each other. (3 marks)

Answers To Practice Questions
1. An electric field (1 mark) is applied, which applies a force (repels or attracts) and so does work on the proton. (1 mark) Work done is given by charge, q × voltage, V, or by force F × distance d. (1 mark)

2. The electric field will accelerate/deflect particles. The magnetic field will give a centripetal force/produce circular motion or arcs or spirals. (2 marks). The sign of the charge can be found from the direction of deflection in the electric field and from the direction of curvature in the magnetic field. (2 marks) The relevant equation for an electric field is acceleration = electric field strength E multiplied by charge on particle Q divided by mass of the particle. A relevant equation for a magnetic field would be radius of curvature = momentum divided by (magnetic field x charge). Or magnetic field strength multiplied by charge of particle = mass multiplied by particle velocity divided by radius of curvature of track. (2 marks)

3. An extremely strong magnetic field. (1 mark)
   Advantage: MR scan does not expose patients to ionising radiation or MR scan gives more detailed information. (1 mark)
   Disadvantage: MR scan is more expensive or requires the patient to be still for longer periods or MR scan is very noisy. (1 mark)

4. NC^{-1} (1 mark)

5. A wire carrying a current will produce a magnetic field. (1 mark)
   This means that each wire will be in the magnetic field of the other wire. (1 mark)
   By Flemings Left Hand Rule, each wire will experience a force of attraction. (1 mark)

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