IB Physics Topic D2 Electric and Magnetic Fields; SL & HL

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1 Electrostatics — Interaction of Charges

Like charges attract; opposite charges repel. What else do you expect me to say here?

2 Conservation of Charge

The sum of the currents into a junction is equal to the sum of the currents away from the junction.

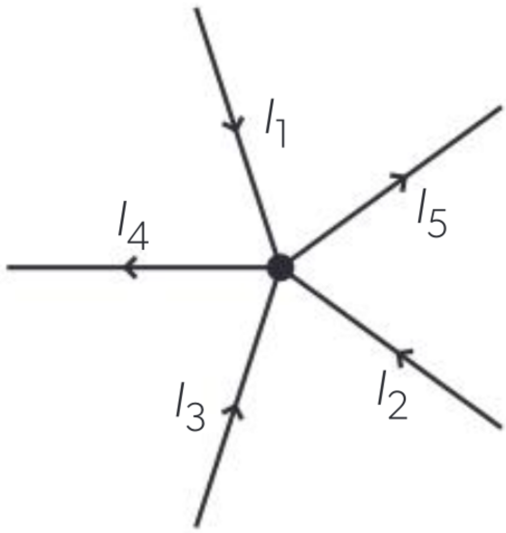

Figure 1: Conservation of Charge

In the diagram above, the currents flowing into the junction are I_1, I_2, and I_3. The currents flowing out of the junction are I_4 and I_5. By conservation of charge, $I_1 + I_2 + I_3 = I_4 + I_5$.

3 Mechanisms of Charge Transfer

3.1 Friction

- When two different materials are rubbed together, electrons can be transferred from one material to the other.
- The objects end up with opposite charges — one has a deficit of electrons and hence a positive overall charge, while the other has an excess of electrons and hence a negative overall charge, causing them to attract each other due to electrostatic forces.

3.2 Contact

- When a charged object touches a neutral object, electrons are transferred.
- If the charged object has an excess of electrons, some will move to the neutral object; if it has a deficit, it may draw electrons from the neutral object.
- After contact, both objects have similar charges, though the total charge is shared between them.

3.3 Induction

- Bringing a charged object close to but without touching a neutral one.
- This charged object causes electrons within the neutral object to move (but not transferred), either attracting them to the surface or repelling them to the other end of the object.
- The object temporarily develops opposite charges on opposite sides (polarization). If grounded, it can be left with a permanent charge opposite to the one on the inducing object.

4 Electric Fields

4.1 Coulomb's Law

This is the attractive force between two charged objects.

$$F = k\frac{q_1 q_2}{r^2} \tag{1}$$

where

- $k = 8.99 \times 10^9$ is Coulomb's constant.
- q_1 and q_2 are the charges; if they have the same sign, then the force is positive and thus repulsive; conversely, if they have opposite signs, the force is negative and attractive.

4.1.1 Coulomb's Constant

Coulumb's constant is given by

$$k = \frac{1}{4\pi\epsilon_0} \tag{2}$$

where

- $\epsilon_0 = 8.85 \times 10^{-12}$ is the permittivity of free space.

The above only applies to calculations in a vacuum. In a different medium of permitivity ϵ, k would be newly defined as $k = \dfrac{1}{4\pi\epsilon}$.

4.2 Electric Field Strength

The electric field strength E is given as

$$F = Eq \quad \text{or} \quad E = \frac{F}{q} \tag{3}$$

Formally, it is defined as the force per unit charge experienced by a small positive test charge place at that point. This is analogous to the idea of gravitational field strength.

Recall (if you don't, go read my notes) how we defined the gravitational field strength as

$$g = \frac{GM}{r^2}$$

Combining Equation (1) and Equation (3), we can derive an analogous expression for the electric field strength experienced by a small positive test charge at a distance r from a charge Q:

$$E = \frac{kQ}{r^2} \tag{4}$$

Observations of the similar forms:

- Both are instances of the inverse square law.
- Both do not require information about the test object specifically.
- Both involve a constant of proportionality, one is G and the other is k.
- Both are dependent on either the mass or charge of the source.

4.3 Field Line Patterns

A general rule of thumb is that field lines always point away from positive charges and towards negative charges. The field lines are always perpendicular to the surface of the charge. Also, the denser the field lines are in a region, the stronger the electric field in that region.

The following two diagrams show the field line patterns for two charges of opposite and similar signs respectively.

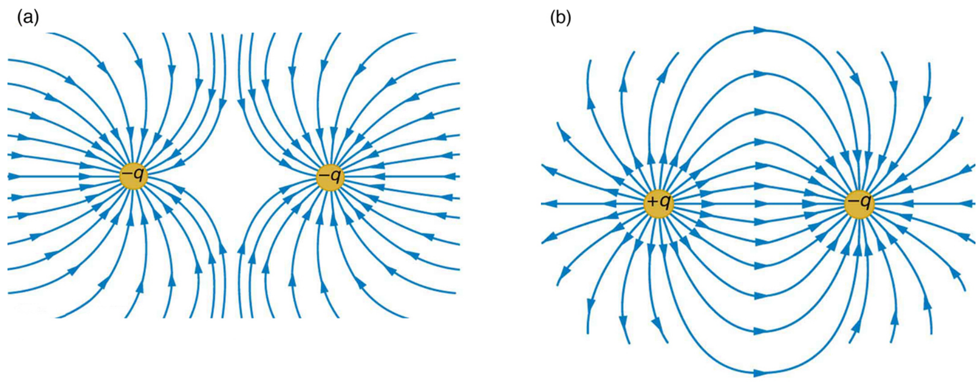

Figure 2: Field Line Patterns

The following is the field line pattern between two plates of opposite charges

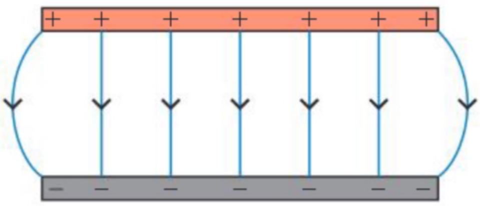

Figure 3: Field Line Patterns for Parallel Plates

- In the middle, the field lines are parallel and equidistant; this is a region of uniform electric field.
- On the edges, the field lines are curved and weaker; these are known as the edge effects.

4.4 Parallel Plates Equations

Recall that the definition of potential in general is the work done **per unit charge** to move a positive test charge from infinity to that point. Using the $F = Eq$ equation, we can derive the following equation for the **potential difference** between two plates of opposite charges:

$$\Delta V = Ed \tag{5}$$

where d is the separation distance between the plates. This equation only works for uniform fields.

This equation is not merely used for parallel plates; it applies to the calculation of any change in potential in a uniform electric field through a distance d.

4.5 Electron Volt Conversions

One electronvolt (eV) is the energy gained by one electron when it moves through a potential difference of one volt. This is equivalent to 1.6×10^{-19} Joules.

Conversely, one Joule is equivalent to 6.24×10^{18} electronvolts.

4.6 Field Close to a Conductor

Consider a plate with area A and total charge q, we define its surface charge density as $\sigma = \frac{q}{A}$. We desire to find the electric field close to the plate.

It is known that the total charge q is given as the following

$$q = \frac{VA}{4\pi kd} \tag{6}$$

We can then use $E = \frac{V}{d}$ to obtain

$$\begin{aligned} q &= \frac{V}{d} \times \frac{A}{4\pi k} \\ &= \frac{EA}{4\pi k} \\ E &= \frac{q}{A} \times 4\pi k \\ &= 4\pi k\sigma \end{aligned}$$

This expression gives the electric field between the two parallel plates, where each plate contributes half and so close to one plate, the field is $2\pi k\sigma$.

Recall that $E = \frac{V}{d}$ uses the assumption that the field is uniform; this gives away why we need the "close to the conductor" condition, because at the surface, the surface is locally flat and so the field can be treated as a uniform field.

4.7 Millikan's Oil Drop Experiment

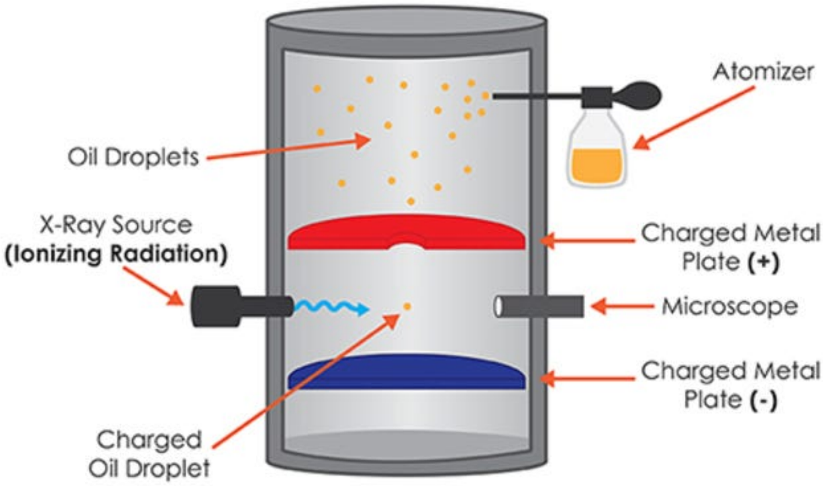

Figure 4: Millikan's Oil Drop Experiment

Set-up:

- Millikan sprayed a fine mist of oil droplets between two parallel, horizontal conducting plates.
- The droplets were tiny enough to remain suspended in the air for a while and were able to be observed through a microscope.
- An electric field was applied across the plates by connecting them to a power source, with one plate positively charged and the other negatively charged.
- X-rays were used to ionize the air, causing some oil droplets to pick up extra electrons, giving them a net negative charge.

Measurements:

- Before turning on the electric field, the droplets were allowed to fall and eventually reach a terminal velocity.
- At this constant velocity, weight = drag force + upthrust.

  - The upthrust the buoyancy force acting on the droplet due to the air and can be found by $\rho g V$.
  - The drag force can be approximated as $6\pi\eta r v$.

- Thus, he was able to work out the mass of the droplet.
- With the electric field present, the droplets were observed to be eventually suspended in air, at which stage, the forces of the electric field ($F_e = Eq$, upwards) and the weight of the droplet ($w = mg$, downwards) were balanced.
- Rearranging gives that the charge on the droplet is $q = mg/E$.

Evidence for quantization of charge:

- Millikan measured the charge on many droplets and found that these charges were always whole-number multiples of a smallest, consistent value, e.
- This observation led to the conclusion that charge is quantized — it comes in discrete packets, rather than being continuous.
- Experiments failed to find any charge less than 1.6×10^{-19} Coulombs; this is then the value of the elementary charge, e.

4.8 Electric Potential

Recall the definition of electric potential

"The work done per unit charge to move a positive test charge from infinity to a point."

Which means that the electric potential different between two points is given by

$$\Delta V_e = \frac{W}{q} \tag{7}$$

The unit for electric potential is the volt, which is equivalent to a Joule per Coulomb ($\mathrm{V} \equiv \mathrm{J\,C^{-1}}$).

4.8.1 Equipotentials

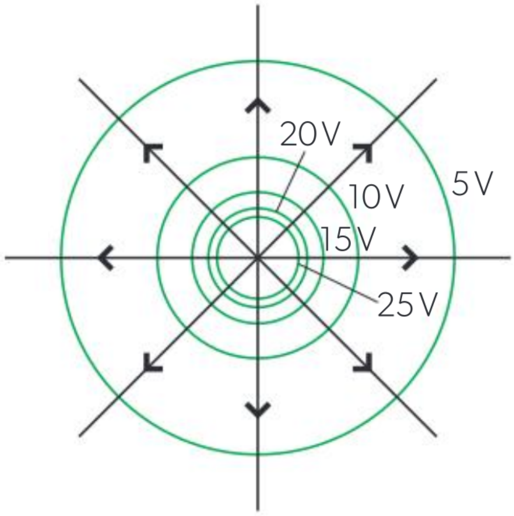

Figure 5: Equipotentials

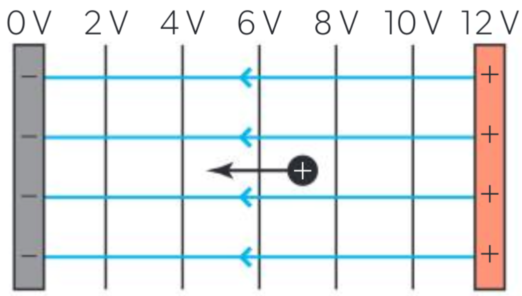

Figure 6: Equipotentials for Parallel Plates

We have met this idea in D1. Around a charge Q, the equipotentials are *concentric spheres* not equally spaced. The closer the spheres are to the charge, the closer they are to each other. As before, the electric field lines are always perpendicular to the equipotentials.

For parallel plates, the equipotentials are *parallel lines* equally spaced. The electric field lines are always perpendicular to the equipotentials.

4.9 Electric Potential Energy

5 Magnetic Fields

5.1 Field Line Patterns

5.1.1 Straight Wire

5.1.2 Circular Coil

5.1.3 Solenoid