A2 Level Physics

Chapter 8 – Nuclear and Particle Physics

8.3.2 Particle Accelerators (Edexcel Only)

Worked Examples

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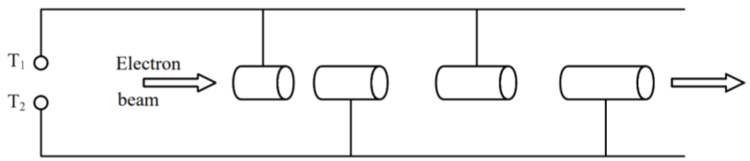
Particle Accelerators

Exam Style Question 1

Quarks were discovered using the Stanford Linear Accelerator (SLAC). The diagram below shows the principle of a linear accelerator (LINAC).



(a) State what is connected between terminals T_1 and T_2.

(b) Explain why the electrons travel with constant velocity whilst in the cylinders.

(c) Explain why the cylinders gradually increase in length along the accelerator.

Particle Accelerators

Exam Style Question 1

(a)State what is connected between terminals T_1 and T_2.
High frequency AC voltage.

(b) Explain why the electrons travel with constant velocity whilst in the cylinders.
No electric field inside the cylinders due to shielding so no force on electrons.

(c) Explain why the cylinders gradually increase in length along the accelerator.
As speed increases along the accelerator cylinders are made longer so that time in each cylinder stays the same.

Particle Accelerators

Exam Style Question 2

(a) A hydrogen ion of mass m and charge q travels with speed v in a circle of radius r in a magnetic field of flux density B.

(i) Write down an equation, in terms of these quantities only, relating the magnetic forces on the ion to the required centripetal force.

(ii) Hence show that the time T for one revolution of the ion is given by the expression $T = \frac{2\pi m}{Bq}$.

Figs 1 and 2 show plan and 3D views of a simple form of particle accelerator known as a cyclotron.

It consists of two semi-circular boxes called 'dees'. Hydrogen ions are injected near to the centre. The alternating potential difference is to accelerate the ions across the gap between the 'dees'. The ions are constrained to move in semi-circular paths when within the 'dees' by a magnetic field perpendicular to the plane of Fig 1. A charged plate P finally extracts the high speed ions from the cyclotron.

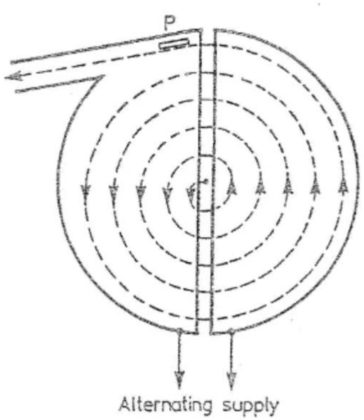


Fig. 1

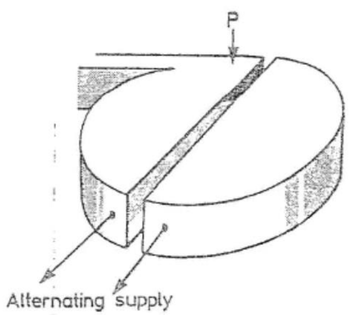


Fig. 2

Particle Accelerators

Exam Style Question 2

(b) For a particular cyclotron accelerating hydrogen ions the B field is 0.60 tesla.

(i) Calculate the time period for one revolutions of a hydrogen ion.

(ii) Why does the fact that this is independent of the speed of travel of the ion and the radius of the orbit simplify the operation of the cyclotron?

(c) If a hydrogen ion emerges with energy $2.4 \times 10^{-12}\ J$, at a measured speed of $5 \times 10^{7}\ m\,s^{-1}$, a simple calculation of the mass of the hydrogen ion gives a value of $1.9 \times 10^{-27}\ kg$.

(i) Show how this value can be obtained.

(ii) Suggest a reason for the apparent discrepancy between this value and the 'databook' value of $1.7 \times 10^{-27}\ kg$.

Particle Accelerators

Exam Style Question 2

(a) A hydrogen ion of mass m and charge q travels with speed v in a circle of radius r in a magnetic field of flux density B.

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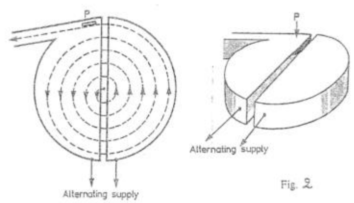

Fig. 1 Fig. 2

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Particle Accelerators

Exam Style Question 2

(a) (i) Write down an equation, in terms of these quantities only, relating the magnetic forces on the ion to the required centripetal force.

Magnetic force $F_m = Bqv$

Centripetal force $F_c = \frac{mv^2}{r}$

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

(a) (ii) Hence show that the time T for one revolution of the ion is given by the expression $T = \frac{2\pi m}{Bq}$.

We know $v = \frac{2\pi r}{T}$ and

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

Therefore:

$$v = \frac{Bqr}{m}$$

So:

$$\frac{2\pi r}{T} = \frac{Bqr}{m}$$

Rearrange the above for T. To do that start by timings both sides by T:

$$\frac{2\pi r}{T}(\times T) = \frac{Bqr}{m}(\times T)$$
$$2\pi r = \frac{TBqr}{m}$$
$$2\pi rm = TBqr$$
$$\therefore T = \frac{2\pi rm}{Bqr}$$

Cancel the r:

$$T = \frac{2\pi m}{Bq}$$

Particle Accelerators

Exam Style Question 2

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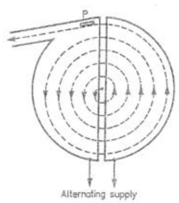


Fig. 1

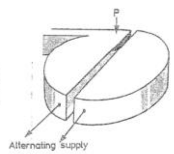


Fig. 2

(b) For a particular cyclotron accelerating hydrogen ions the B field is 0.60 tesla.

(i) Calculate the time period for one revolutions of a hydrogen ion.

Mass of a hydrogen ion = $1.67 \times 10^{-27}\ kg$.

(ii) Why does the fact that this is independent of the speed of travel of the ion and the radius of the orbit simplify the operation of the cyclotron?

(c) If a hydrogen ion emerges with energy $2.4 \times 10^{-12}\ J$, at a measured speed of $5 \times 10^{7}\ m\ s^{-1}$, a simple calculation of the mass of the hydrogen ion gives a value of $1.9 \times 10^{-27}\ kg$.

(i) Show how this value can be obtained.

(ii) Suggest a reason for the apparent discrepancy between this value and the 'databook' value of $1.7 \times 10^{-27}\ kg$.

Particle Accelerators

Exam Style Question 2

(b) (i) Calculate the time period for one revolutions of a hydrogen ion.

We already how to calculate the time period which is $T = \frac{2\pi m}{Bq}$

$$T = \frac{2\pi(1.67 \times 10^{-27}\ kg)}{(0.60\ T)(1.6 \times 10^{-19}\ C)}$$
$$T = 1.1 \times 10^{-7}\ s\ (2\ s.f.)$$

(b) (ii) Why does the fact that this (time period) is independent of the speed of travel of the ion and the radius of the orbit simplify the operation of the cyclotron?

By applying an alternating voltage of a constant high frequency, ions are accelerated every time they pass through the gap. The frequency of the voltage, denoted by $f = \frac{1}{T}$, where $T = \frac{2\pi m}{Bq}$. Therefore, $f = \frac{Bq}{2\pi m}$. This indicates that the frequency is not affected by the speed or the radius of the ion's orbit. As a result, a constant frequency can be used, and the particle will complete each semicircle through a dee in the same amount of time. This constant frequency simplifies the operation of the cyclotron.

(c) (i) Show how this value can be obtained.

Use $E = \frac{1}{2}mv^2$ and rearrange for m

$$m = \frac{2E}{v^2} = \frac{2(2.4 \times 10^{-12}\ J)}{(5 \times 10^{7}\ m\ s^{-1})}$$
$$m = 1.9 \times 10^{-27}\ kg$$

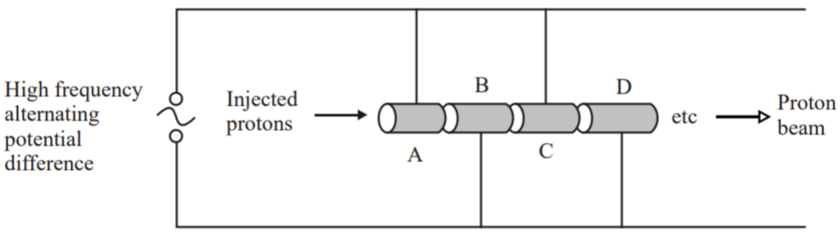
(c) (ii) Suggest a reason for the apparent discrepancy between this value and the 'databook' value of $1.7 \times 10^{-27}\ kg$.

The mass of a body in motion, also known as relativistic mass, is higher than its rest mass. The value recorded in the databook is the rest mass of hydrogen and does not account for the mass of hydrogen in motion, which causes the difference between the two values.

Particle Accelerators

Exam Style Question 3

The diagram shows part of a linear accelerator - a linac. Alternate metal tubes are connected together and to opposite terminals of a high-frequency alternating potential difference of fixed frequency.



(a) Describe how the protons are accelerated as they move along the linac and explain why the tubes get longer towards the right. You may be awarded a mark for the clarity of your answer

(b) A particular linac has $420\ metal\ tubes$ and the peak voltage of the alternating supply is $800\ kV$.

(i) Show that the emerging protons have gained a kinetic energy of about $5 \times 10^{-11}\ J$ and express the mass equivalent of this energy as a fraction of the mass of a stationary proton. Take the mass of a proton m_p as $1.01\ u$.

(ii) The frequency of the alternating supply is $390\ MHz$. Calculate how long it takes a proton to travel along the linac.

(c) The emerging protons can be made to collide with

(i) a target of fixed protons, e.g. liquid hydrogen, or

(ii) a similar beam of protons travelling in the opposite direction.

State some advantages of either or both experimental arrangement(s).

Particle Accelerators

Exam Style Question 3

(a)Describe how the protons are accelerated as they move along the linac and explain why the tubes get longer towards the right.

Protons move uniformly inside tubes and are accelerated in the gaps between the tubes using an alternating voltage supply. The voltage changes when electrons reach the middle of tube A, causing tube A to become negative and tube B to become positive. The electrons are repelled out of the end of tube A and attracted towards tube B, which accelerates them towards it.

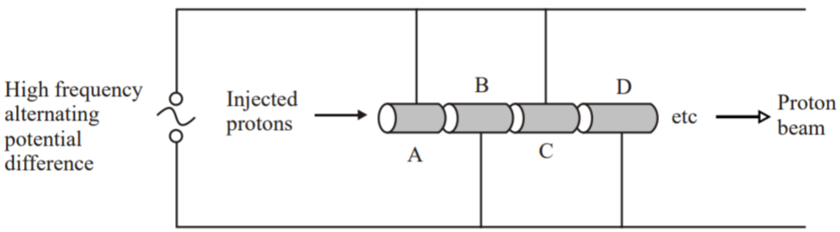
The process of alternating between positive and negative tubes, caused by the AC voltage, repeats until the electrons reach the end of the line and have enough energy to collide with a target.

To continue accelerating faster-moving particles, longer acceleration tubes must be used to ensure that the electrons spend enough time inside the tubes to be accelerated again.

Particle Accelerators

Exam Style Question 3

The diagram shows part of a linear accelerator - a linac. Alternate metal tubes are connected together and to opposite terminals of a high-frequency alternating potential difference of fixed frequency.



(a) Describe how the protons are accelerated as they move along the linac and explain why the tubes get longer towards the right. You may be awarded a mark for the clarity of your answer

(b) A particular linac has 420 *metal tubes* and the peak voltage of the alternating supply is 800 kV.

(i) Show that the emerging protons have gained a kinetic energy of about $5 \times 10^{-11}\ J$ and express the mass equivalent of this energy as a fraction of the mass of a stationary proton. Take the mass of a proton m_p as 1.01 u.

(ii) The frequency of the alternating supply is 390 MHz. Calculate how long it takes a proton to travel along the linac.

(c) The emerging protons can be made to collide with

(i) a target of fixed protons, e.g. liquid hydrogen, or

(ii) a similar beam of protons travelling in the opposite direction.

State some advantages of either or both experimental arrangement(s).

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Particle Accelerators

Exam Style Question 3

(b) (i) Show that the emerging protons have gained a kinetic energy of about $5 \times 10^{-11}\ J$ and express the mass equivalent of this energy as a fraction of the mass of a stationary proton. Take the mass of a proton m_p as $1.01\ u$.

- KE gained:

Remember if a charge, $Q = e = 1.6 \times 10^{-19} C$ moves through a p.d. of 1V, the kinetic energy (E) gained is given by:

$$E = QV$$

But also remember the linac has 420 tubes and the peak voltage is 800 kV so we need to take that into consideration, therefore:

$$E = (420)(1.6 \times 10^{-19}\ C)(800 \times 10^3\ V)$$
$$E = 5.4 \times 10^{-11}\ J\ (2\ s.f.)$$

- The mass equivalent of this energy as a fraction of the mass of a stationary proton:

Use $E = mc^2$ and rearrange for m:

$$\therefore m = \frac{E}{c^2} = \frac{5.4 \times 10^{-11}\ J}{(3 \times 10^8\ m\ s^{-1})^2}$$
$$m = 6.0 \times 10^{-28}\ kg$$

So, the mass equivalent of this energy as a fraction of the mass of a stationary proton is given by:

$$\frac{6.0 \times 10^{-28}\ kg}{(1.01\ u)(1.66 \times 10^{-27}\ kg)} = 0.36\ (2\ s.f.)$$

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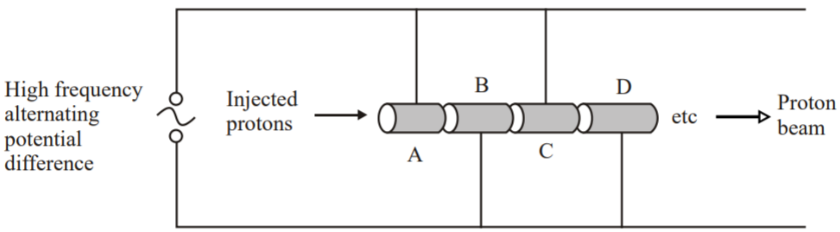
Particle Accelerators

Exam Style Question 3

The diagram shows part of a linear accelerator - a linac. Alternate metal tubes are connected together and to opposite terminals of a high-frequency alternating potential difference of fixed frequency.



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(ii) The frequency of the alternating supply is $390\ MHz$. Calculate how long it takes a proton to travel along the linac.

(c) The emerging protons can be made to collide with

(i) a target of fixed protons, e.g. liquid hydrogen, or

(ii) a similar beam of protons travelling in the opposite direction.

State some advantages of either or both experimental arrangement(s).

Particle Accelerators

Exam Style Question 3

(b) (ii) The frequency of the alternating supply is $390\ MHz$. Calculate how long it takes a proton to travel along the linac.

Use $f = \frac{1}{T}$ and rearrange for T

$$T = \frac{1}{f}$$

However, remember the linac is 420 tubes long therefore we need to times the time period by 420:

$$T = 420 \times \frac{1}{390 \times 10^6\ Hz}$$
$$T = 1.08 \times 10^{-6}\ s\ (3\ s.f.)$$

(c) The emerging protons can be made to collide with

(i) a target of fixed protons, e.g. liquid hydrogen, or

(ii) a similar beam of protons travelling in the opposite direction.

State some advantages of either or both experimental arrangement(s).

(i) Fixed:

Larger number of collisions or more likely to get collisions.

(ii) Colliding beams:

More energy available for new particles.

Please see **'8.3.1 Particle Accelerators notes'** pack for revision notes.

For more revision notes, tutorials and worked examples please visit **www.tutorpacks.co.uk.**