1 (a) This part of the question is about protons.

(i) Calculate the electrostatic potential energy, in J, of **two** protons at a distance apart of 1.0×10^{-15} m.

(ii) Two protons moving in opposite directions at the same initial speed collide head-on with each other. The least distance apart of the two protons is 1.0×10^{15} m. By considering conservation of energy, estimate the initial kinetic energy, in MeV, of each proton.

(5)

(b) State the quark composition of

(i) a proton,

(ii) a positive pion, π^+.

(2)

(c) A proton collides with another proton moving in the opposite direction at the same speed, creating a positive pion and a further particle X in the process. This process is represented by the equation

$$p + p \rightarrow p + p + \pi^{+} + X.$$

(i) State the charge, Q, and baryon number, B, of X.

Q ____________________

B ____________________

(ii) State the identity and quark composition of X.

____

____

(iii) Explain why two protons with initial kinetic energies as in part (a)(ii) could not produce the reaction in part (c).

____

____

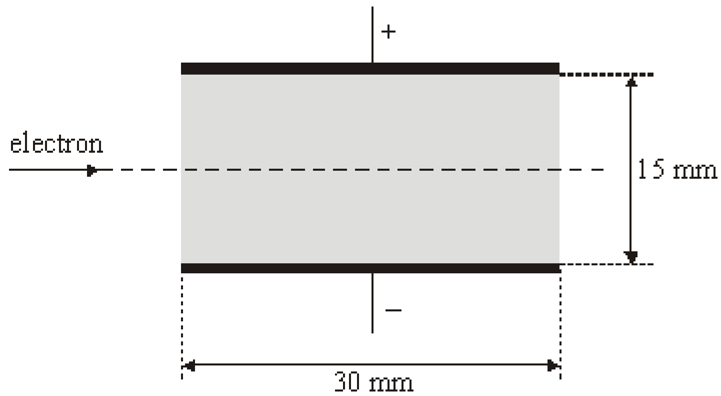
____

____

(5)

(Total 12 marks)

2 (a) An electron travels at a speed of 3.2×10^7 ms^{-1} in a horizontal path through a vacuum. The electron enters the uniform electric field between two parallel plates, 30 mm long and 15 mm apart, as shown in the figure below. A potential difference of 1400 V is maintained across the plates, with the top plate having positive polarity. Assume that there is no electric field outside the shaded area.



(i) Show that the electric field strength between the plates is 9.3×10^4 Vm^{-1}.

____

____

(ii) Calculate the time taken by the electron to pass through the electric field.

____

____

(iii) Show that the acceleration of the electron whilst in the field is 1.6×10^{16} m s^{-2} and state the direction of this acceleration.

____

____

____

____

(5)

(b) Determine the magnitude and direction of the velocity of the electron at the point where it leaves the field.

____

____

____

____

____

____

____

____

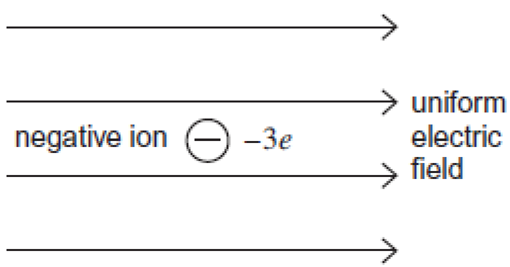
____

(3)

(Total 8 marks)

3 (a) **Figure 1** shows a negative ion which has a charge of $-3e$ and is free to move in a uniform electric field. When the ion is accelerated by the field through a distance of 63 mm parallel to the field lines its kinetic energy increases by 4.0×10^{-16} J.

Figure 1



(i) State and explain the direction of the electrostatic force on the ion.

____

____

____

____

(2)

(ii) Calculate the magnitude of the electrostatic force acting on the ion.

magnitude of electrostatic force ____________________ N

(2)

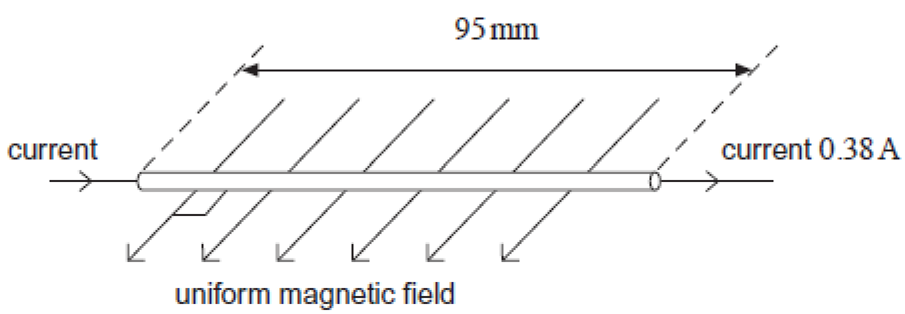
(iii) Calculate the electric field strength.

electric field strength ____________________ NC^{-1}

(1)

(b) **Figure 2** shows a section of a horizontal copper wire carrying a current of 0.38 A.
A horizontal uniform magnetic field of flux density B is applied at right angles to the wire in the direction shown in the figure.

Figure 2



(i) State the direction of the magnetic force that acts on the moving electrons in the wire as a consequence of the current and explain how you arrive at your answer.

____

____

____

____

____

(2)

(ii) Copper contains 8.4×10^{28} free electrons per cubic metre. The section of wire in **Figure 2** is 95 mm long and its cross-sectional area is 5.1×10^{-6} m^2.
Show that there are about 4×10^{22} free electrons in this section of wire.

(1)

(iii) With a current of 0.38 A, the average velocity of an electron in the wire is 5.5×10^{-6} m s^{-1} and the average magnetic force on one electron is 1.4×10^{-25} N.
Calculate the flux density B of the magnetic field.

flux density ____________________ T

(2)

(Total 10 marks)

4 (a) (i) Define the *electric field strength*, *E*, at a point in an electric field.

___

___

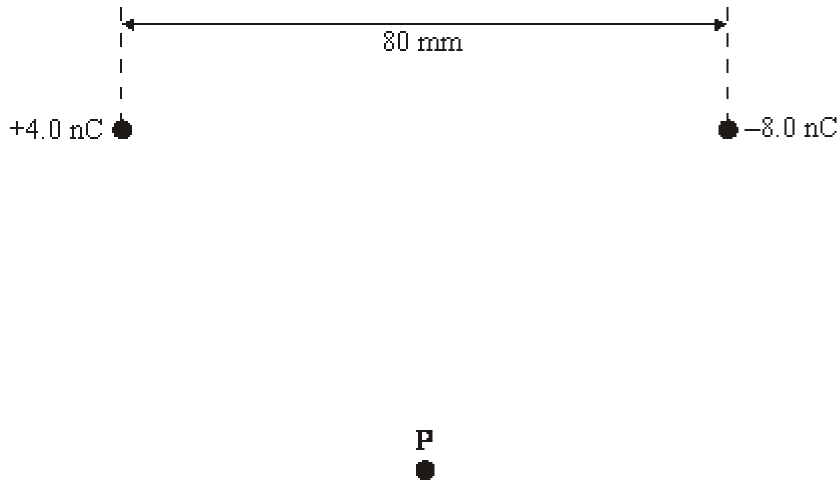
___

(ii) State whether *E* is a scalar or a vector quantity.

___

(3)

(b) Point charges of +4.0 nC and –8.0 nC are placed 80 mm apart, as shown in the figure below.



(i) Calculate the magnitude of the force exerted on the +4.0 nC charge by the –8.0 nC charge.

___

___

___

___

(ii) Determine the distance from the +4.0 nC charge to the point, along the straight line between the charges, where the electric potential is zero.

___

___

___

___

(4)

(c) Point **P** in the figure above is equidistant from the two charges.

(i) Draw two arrows on the figure above at **P** to represent the directions and relative magnitudes of the components of the electric field at **P** due to each of the charges.

(ii) Hence draw an arrow, labelled **R**, on the figure above at **P** to represent the direction of the resultant electric field at **P**.

(3)
(Total 10 marks)

5 (a) Complete the table of quantities related to fields. In the second column, write an SI unit for each quantity. In the third column indicate whether the quantity is a scalar or a vector.

quantity	SI unit	scalar or vector
gravitational potential		
electric field strength		
magnetic flux density		

(3)

(b) (i) A charged particle is held in equilibrium by the force resulting from a vertical electric field. The mass of the particle is 4.3×10^{-9} kg and it carries a charge of magnitude 3.2×10^{-12} C. Calculate the strength of the electric field.

____

____

____

____

(ii) If the electric field acts upwards, state the sign of the charge carried by the particle

____

(3)
(Total 6 marks)

6 Both gravitational and electric field strengths can be described by similar equations written in the form

$$a = \frac{bc}{d^2}.$$

(a) Complete the following table by writing down the names of the corresponding quantities, together with their SI units, for the two types of field.

<table>
<tr><td rowspan="2">symbol</td><td colspan="2">gravitational field</td><td colspan="2">electrical field</td></tr>
<tr><td>quantity</td><td>SI unit</td><td>quantity</td><td>SI unit</td></tr>
<tr><td>a</td><td>gravitational field strength</td><td></td><td></td><td></td></tr>
<tr><td>b</td><td></td><td></td><td>$\frac{1}{4\pi\varepsilon_0}$</td><td>m F^{-1}</td></tr>
<tr><td>c</td><td></td><td></td><td></td><td></td></tr>
<tr><td>d</td><td></td><td></td><td></td><td></td></tr>
</table>

(4)

(b) Two isolated charged objects, A and B, are arranged so that the gravitational force between them is equal and opposite to the electric force between them.

(i) The separation of A and B is doubled without changing their charges or masses. State and explain the effect, if any, that this will have on the resultant force between them.

____

____

(ii) At the original separation, the mass of A is doubled, whilst the charge on A and the mass of B remain as they were initially. What would have to happen to the charge on B to keep the resultant force zero?

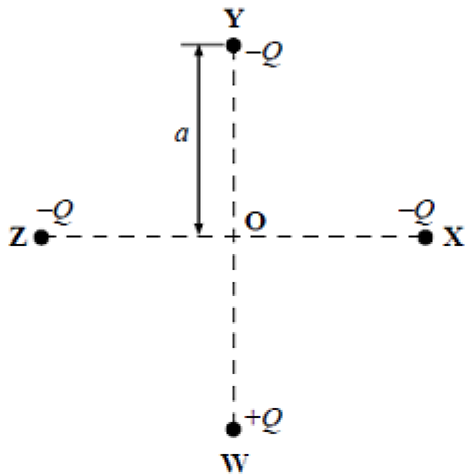
____

____

(3)

(Total 7 marks)

7 Four point charges **W**, **X**, **Y** and **Z** are each placed at a distance a from **O** as shown in the diagram. **X**, **Y** and **Z** each have a charge $-Q$ and **W** has a charge $+Q$.



The resultant electric field strength at **O** is

A $\dfrac{Q}{\pi\varepsilon_0 a^2}$ toward **Y**

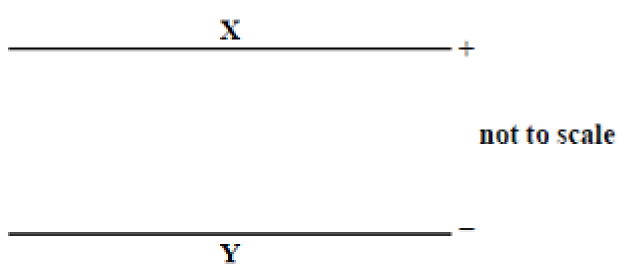
B $\dfrac{Q}{2\pi\varepsilon_0 a^2}$ toward **Y**

C $\dfrac{Q}{2\pi\varepsilon_0 a^2}$ toward **W**

D $\dfrac{Q}{4\pi\varepsilon_0 a^2}$ toward **W**

(Total 1 mark)

8 An electric field is maintained in the region between two circular parallel metal plates, the separation of which is small compared with their diameter.



Along the line **X** to **Y** between the plates

A the electric field strength decreases uniformly

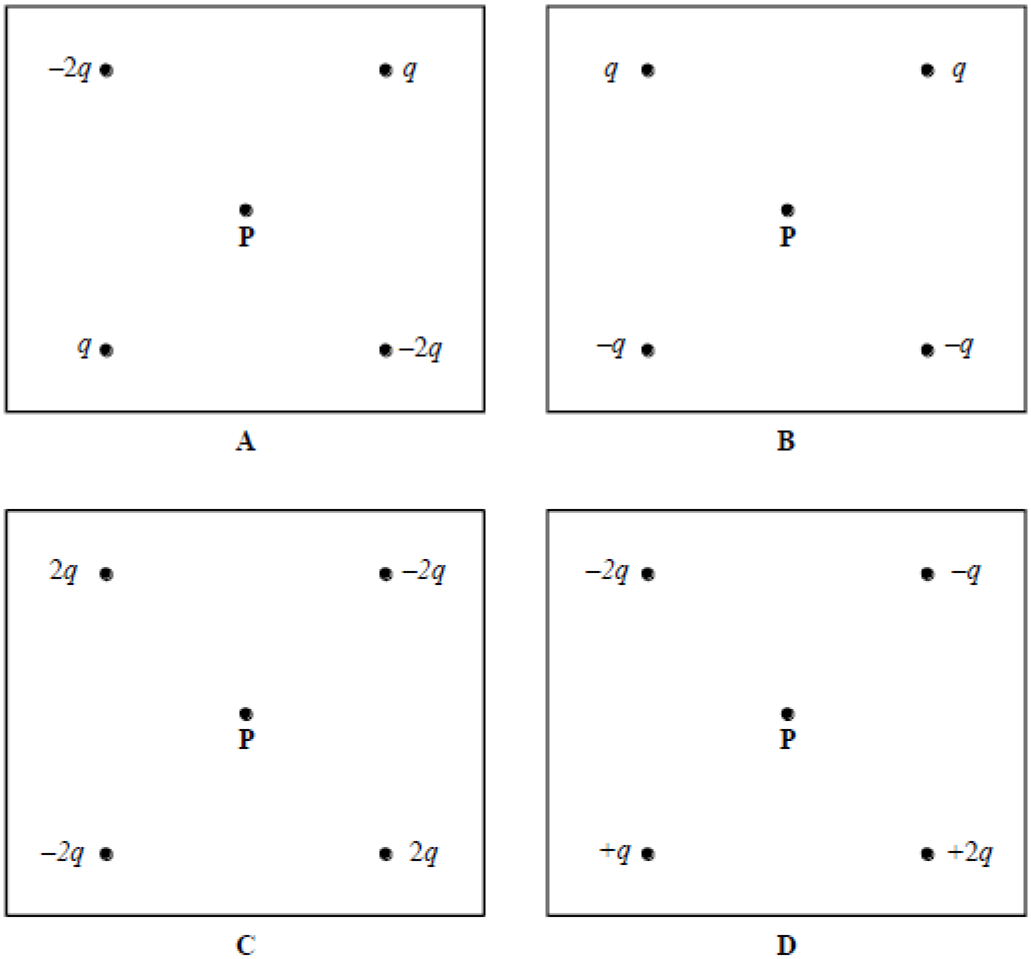
B the electric field strength increases uniformly

C the electric field strength increases and then decreases again

D the electric field strength is the same everywhere

(Total 1 mark)

9 Which one of the following arrangements of charge will produce zero electric field strength and zero electric potential at the point labelled **P**?



(Total 1 mark)

10 **X** and **Y** are two points in an electric field a distance d apart. The potential difference between **X** and **Y** is V. A particle carrying a charge Q is accelerated by that field from **X** to **Y** in a time t. The gain in kinetic energy of the particle is

A QV

B $\frac{1}{2}QV^2$

C $\frac{QVt}{d}$

D QVd

(Total 1 mark)

11 Which one of the following statements about electric potential and electric field strength is correct?

A Electric potential is zero whenever the electric field strength is zero.

B Electric field strength is a scalar quantity.

C Electric potential is a vector quantity.

D Electric potential due to a point charge varies as $\frac{1}{r}$ where r is the distance from the point charge.

(Total 1 mark)

12 Which one of the following statements about *electric field strength* and *electric potential* is **incorrect**?

A Electric potential is a scalar quantity.

B Electric field strength is a vector quantity.

C Electric potential is zero whenever the electric field strength is zero.

D The potential gradient is proportional to the electric field strength.

(Total 1 mark)

13 If the potential difference between a pair of identical, parallel, conducting plates is known, what is the only additional knowledge required to determine the electric field strength between the plates?

A the permittivity of the medium between the plates

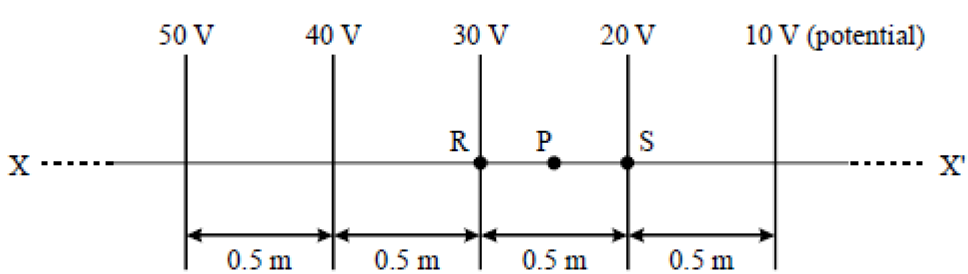
B the separation and area of the plates

C the separation and area of the plates and the permittivity of the medium between the plates

D the separation of the plates

(Total 1 mark)

14



The diagram shows how the electric potential varies along a line XX’ in an electric field. What will be the electric field strength at a point P on XX’ which is mid−way between R and S?

A 5.0 V m^{-1}

B 10 V m^{-1}

C 20 V m^{-1}

D 30 V m^{-1}

(Total 1 mark)

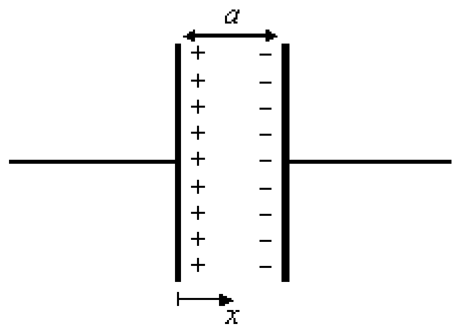
15 Two horizontal parallel plate conductors are separated by a distance of 5.0 mm in air. The lower plate is earthed and the potential of the upper plate is + 50 V.

Which line, **A** to **D**, gives correctly the electric field strength, *E*, and the potential, *V*, at a point midway between the plates?

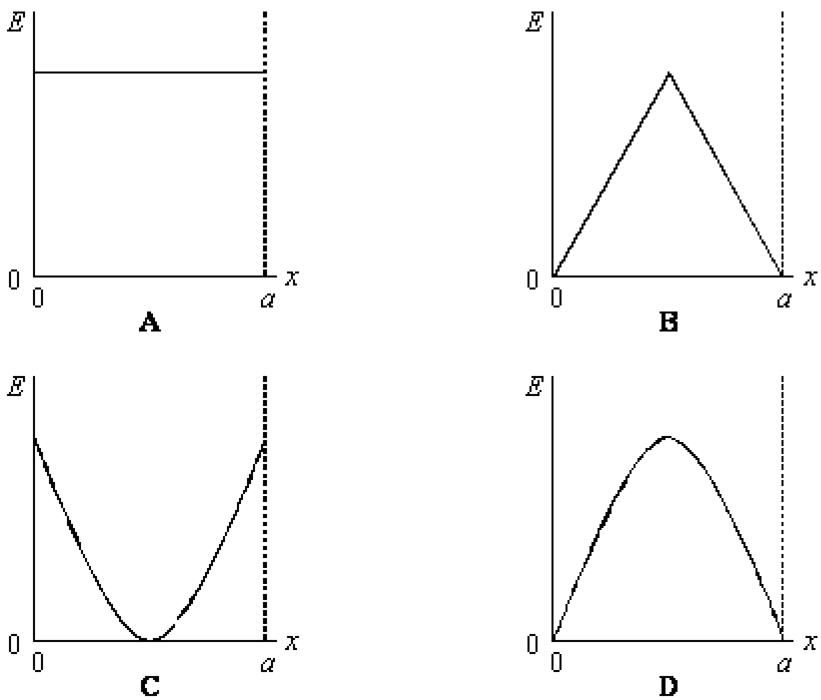
	electric field strength $E/\text{V m}^{-1}$	*potential* V/V
A	1×10^4 upwards	25
B	1×10^4 downwards	25
C	1×10^4 upwards	50
D	1×10^4 downwards	50

(Total 1 mark)

16



Two parallel metal plates of separation *a* carry equal and opposite charges. Which one of the following graphs, **A** to **D**, best represents how the electric field strength *E* varies with the distance *x* in the space between the plates?



(Total 1 mark)

17 The force between two point charges is F when they are separated by a distance r. If the separation is increased to $3r$ what is the force between the charges?

A $\frac{F}{3r}$

B $\frac{F}{9r}$

C $\frac{F}{3}$

D $\frac{F}{9}$

(Total 1 mark)

Mark schemes

1

(a) (i) (use of $E_P = \frac{e^2}{4\pi\varepsilon_0 r}$ gives) $E_P = \frac{(1.6 \times 10^{-19})^2}{4\pi \times 8.85 \times 10^{-12} \times 1.0 \times 10^{-15}}$ **(1)**

$= 2.3 \times 10^{-13}$ (J) **(1)**

(ii) E_K at least distance apart = 0

E_K of (each) proton = $0.5 \times 2.3 \times 10^{-13}$ (J) **(1)**

$= (1.15 \times 10^{-13}\text{(J)}) = 0.72$ MeV **(1)** (0.719 MeV)

5

(b) (i) uud **(1)**

(ii) $u\bar{d}$ **(1)**

2

(c) (i) $Q = -1$(e) **(1)**

$B = 0$ **(1)**

(ii) π^- **(1)**

$\bar{u}d$ **(1)**

(iii) mass of extra particles produced from total initial kinetic energy **(1)**

extra mass possible in (a) = 1.4 MeV / c^2 **(1)**

pions rest mass in (b) >> extra mass in (a) **(1)**

max 5

[12]

2

(a) (i) $E\left(= \frac{V}{d}\right) = \frac{1400}{15 \times 10^{-3}}$ **(1)** $\left(= 9.3 \times 10^4 \text{ V m}^{-1}\right)$

(ii) $t\left(= \frac{l}{v}\right) = \frac{30 \times 10^{-3}}{3.2 \times 10^7} = 9.38 \times 10^{-10}$ s **(1)**

(iii) $ma_y = Ee$ **(1)**

$ay = \frac{9.3 \times 10^4 \times 1.60 \times 10^{-19}}{9.11 \times 10^{31}}$ **(1)** (= 1.64×10^{16} m s^{-2})

acceleration is upwards [or towards + plate]**(1)**

5

(b) vy (= $a_y t$) = $1.64 \times 10^{16} \times 9.38 \times 10^{-10}$ **(1)** (= 1.54×10^7 m s^{-1})

$v = \sqrt{(1.54 \times 10^7)^2 + (3.2 \times 10^7)^2} = 3.55 \times 10^7$ m s^{-1}**(1)**

at $\tan^{-1}\left(\frac{1.54}{3.2}\right) = 26°$ above the horizontal **(1)**

3

[8]

3 (a) (i) force acts towards left or in opposite direction to field lines ✓
because ion (or electron) has negative charge
(∴ experiences force in opposite direction to field) ✓

Mark sequentially.
Essential to refer to negative charge (or force on + charge is to right) for 2nd mark.

2

(ii) (use of $W = F s$ gives) force $F = \dfrac{4.0 \times 10^{-16}}{63 \times 10^{-3}}$ ✓

$= 6.3(5) \times 10^{-15}$ (N) ✓

If mass of ion m is used correctly ***using algebra*** *with F = ma, allow both marks (since m will cancel). If numerical value for m is used, max 1.*

2

(iii) electric field strength $E\left(=\dfrac{F}{Q}\right)=\dfrac{6.35\times10^{-15}}{3\times1.6\times10^{-19}}$ = 1.3(2) ✓ 10^4 (N C^{-1}) ✓

[**or** $\Delta V\left(=\dfrac{\Delta W}{Q}\right)=\dfrac{4.0\times10^{-16}}{3\times1.60\times10^{-19}}$ (833 V)

$E\left(=\dfrac{\Delta V}{d}\right)=\dfrac{833}{63\times10^{-3}}$ = 1.3(2) ✓ 10^4 (V m^{-1}) ✓]

Allow ECF from wrong F value in (ii).

1

(b) (i) (vertically) downwards on diagram ✓
reference to Fleming's LH rule **or** equivalent statement ✓

Mark sequentially.
1st point: allow "into the page".

2

(ii) number of free electrons in wire = $A \times l \times$ number density
$= 5.1 \times 10^{-6} \times 95 \times 10^{-3} \times 8.4 \times 10^{28} = 4.1\ (4.07) \times 10^{22}$ ✓

Provided it is shown correctly to at least 2SF, final answer alone is sufficient for the mark. (Otherwise working is mandatory).

1

(iii) $B\left(=\frac{F}{Qv}\right)=\frac{1.4\times10^{-25}}{1.60\times10^{-19}\times5.5\times10^{-6}}$ ✓ = 0.16 (0.159) (T) ✓

[**or** $B\left(=\frac{F}{Il}\right)=\frac{1.4\times10^{-25}\times4.07\times10^{22}}{0.38\times95\times10^{-3}}$ ✓ = 0.16 (0.158) (T) ✓]

In 2nd method allow ECF from wrong number value in (ii).

2

[10]

4 (a) (i) force per unit charge **(1)**
acting on a positive charge **(1)**

(ii) vector **(1)**

3

(b) (i) $F\left(=\frac{Q_1Q_2}{4\pi\varepsilon_0 r^2}\right)=\frac{4.0\times10^{-9}\times8.0\times10^{-9}}{4\pi\times8.85\times10^{-12}\times(80\times10^{-3})^2}$ **(1)**

=4.5(0) × 10^{-5}N **(1)**

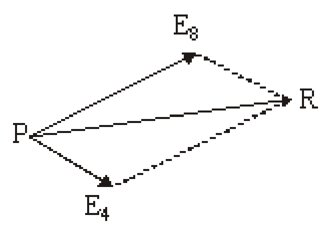
(ii) (use of $V=\frac{Q}{4\pi\varepsilon_0 r}$ gives) $0=\left(\frac{4.0\times10^{-9}}{4\pi\varepsilon_0 x}\right)-\left(\frac{8.0\times10^{-9}}{4\pi\varepsilon_0(80\times10^{-3}-x}\right)$

or $\frac{4}{x}=\frac{8}{80-x}$ **(1)**

x = 26.7mm **(1)**

4

(c) correct directions for E_4 and E_8 **(1)**
E_8 approx twice as long as E_4 **(1)**
correct direction of resultant R
shown **(1)**



3

[10]

5 (a)

quantity	SI unit	
(gravitational potential)	J kg^{-1} or N m kg^{-1}	scalar
(electric field strength)	N C^{-1} or V m^{-1}	vector
(magnetic flux density	T or Wb m^{-2} or N A^{-1} m^{-1}	vector

6 entries correct **(1) (1) (1)**
4 or 5 entries correct **(1) (1)**
2 or 3 entries correct **(1)**

3

(b) (i) $mg = EQ$ **(1)**

$$E\left(\frac{mg}{Q} = \frac{4.3\times10^{-9}\times9.81}{3.2\times10^{-12}}\right) = 1.32 \times 10^{4}\ (\text{V m}^{-1})\ \textbf{(1)}$$

(ii) positive **(1)**

3

[6]

6 (a)

________	N kg^{-1}	electric field strength	N C^{-1} or V m^{-1}	**(1)**
gravitational constant	N m^2 kg^{-2}	________	________	**(1)**
mass	kg	charge	C	**(1)**
distance (from mass to point)	m	distance (from charge to point)	m	**(1)**

(4)

(b) (i) none **(1)**

both F_E and $F_G \propto \frac{1}{r^2}$ (hence both reduced to $\frac{1}{4}$ [affected equally] **(1)**

(ii) charge on B must be doubled **(1)**

(3)

[7]

7 B

[1]

8 D

[1]

9 C

[1]

10 A

[1]

11 D

[1]

12 C

[1]

13 D

[1]

14 C

[1]

15 B

[1]

16 A

[1]

17 D

[1]

Examiner reports

1 Few good answers were seen for part (a). Some candidates were unable to calculate the potential energy correctly in part (i), and in part (ii), although the general principle was usually known, candidates often did not realise the question asked for the initial kinetic energy of each proton.

Part (b) was more successful and many candidates scored both marks. However, some sought to include a strange quark in the positive pion.

The majority of candidates scored both marks in part (i) and many gave the correct quark composition in part (ii) although they failed to identify the particle X. In part (iii) only one or two candidates were able to give an adequate answer. Although some candidates stated that the extra mass needed to be created from the kinetic energy of the initial protons, they usually failed to use data to support this statement.

2 Application of $E = V/d$ and $t = d/v$ brought two straightforward marks for most candidates in the first two parts of (a). Part (iii) caused greater difficulty, often because $F = EQ$ was not known. One incorrect approach, adopted in several scripts, involved assuming a vertical displacement of 7.5 mm, corresponding to half the vertical separation of the deflecting plates. Using t = 9.4×10^{-10} s from part (ii), $a = 2s/t^2$ was then applied, giving a vertical acceleration of 1.7×10^{16} m s^{-2}. The question required candidates to give the direction of the acceleration as well as its magnitude, but this requirement was often overlooked. A few candidates wrote more than they need have done, and in doing so condemned their own answer; 'the acceleration is upwards *in a parabola*'. Confusion between the trajectory and the directions of acceleration and velocity are understandable, but cannot be tolerated in examination answers.

Part (b) was either omitted or answered in a descriptive, non-mathematical way in more than half of the scripts. Those who understood the principles of projectile motion usually had little difficulty in gaining all three marks. A very common mistake however, was attempting to find the new velocity by use of $v = u + at$ with u taken to be 3.2×10^7 m s^{-2}. In the work of the more able candidates, whether the direction of the calculated angle (about 26°) was 'up' or 'down' was often clarified by a diagram.

3 The direction of the force on the negatively charged ion in part (a)(i) was mainly correct. Explanations of the direction of the force were good and marks for this part were high.

At A2 level the students are expected to have retained a comprehensive knowledge of earlier work, which is tested by synoptic components within the questions. Part (a)(ii) was an example of this, because the simplest solution followed directly from “energy gained = work done = force × distance”. This eluded most students, many of whom were completely defeated. Many of them became successful after taking a very roundabout route, involving calculation of the pd from $V = W / Q$, the field strength from $E = V / d$ and the force from $F = EQ$. Others produced answers based on the uniform acceleration equations and $F = ma$. When this was done using algebra the mass m of the ion could be cancelled and the answer was accepted. When a numerical value was chosen for m the mark that could be awarded was limited to 1 out of 2. There were fewer difficulties in part (a)(iii), where $E = F / 3e$ gave the most direct answer but where $E = V / d$ offered an alternative method. Incorrect force values from part (a)(ii) were permitted for full credit in part (a)(iii).

In part (b)(i) the successful application of Fleming’s left hand rule readily showed the majority that the magnetic force on the wire would be downwards (or into the page). Most students gained both marks. It seemed that some students who thought too deeply about the direction of this force eventually got it wrong: their line of thought was that the force due to the current was downwards, but electrons carry a negative charge so the force on them must act upwards. It had not occurred to them that the force on the complete wire has to act in the same direction as the force on all of the free electrons within it.

The simple calculation that led to the number of free electrons in the section of wire was almost always worked out correctly in part (b)(ii). This was a “show that” question, so students should have realised that a more precise answer than 4×10^{22} (such as 4.07×10^{22}) would be expected before the mark became available. Part (b)(iii) offered two approaches to the value of the flux density B. By considering the average force on a single electron, $F = BQv$ could be used. Alternatively, by considering the force on the section of wire, $F = BIl$ could be used. In the latter method many got into difficulty by forgetting to consider the number of electrons in the wire.

4 Many candidates appreciated that E is defined as the force acting per unit charge, but very few were able to state that it is the force acting per *mat positive* charge. Consequently in part (a) (i), it was uncommon for more than one of the two available marks to be awarded. Confusion with the definition of electric potential was evident in many candidates’ responses. In part (a) (ii), fewer candidates than expected knew that E is a vector quantity.

The Coulomb’s law equation was usually correctly recalled at the start of candidates’ answers to part (b) (i), and was often followed by an acceptable value for the force. The principal difficulties here included using the wrong constant of proportionality, failing to square the denominator, and not knowing that nano means 10^{-9}. The correct value of 27 mm in part (b) (ii) was usually given after little or no proper explanation, leading to a loss of one of the two marks. Examiners were expecting that something of the form $4/x = 8/(80 - x)$ would be given as a necessary step in the working.

It was clear from their attempts to answer part (c) that a large number of candidates could not follow simple instructions. The direction of the arrows was often wrong, whilst many arrows were not drawn *at P.* The 2:1 length ratio was often correct for the second mark. The third mark was awarded to those candidates who drew an arrow, labelled R, along the correct resultant of two correct component vectors. This final mark was not often awarded.

5 Units of the various physical quantities related to fields and the scalar/vector nature of them, are generally not well known by the candidates. Part (a) showed that the 2004 cohort were no better than their predecessors. Six correct entries in the table were required for three marks, and it was very rare for all three to be awarded. The unit of N m kg^{-1} was accepted as an alternative to J kg^{-1} for gravitational potential, but candidates regularly put N kg^{-1} in the table. The unit of electric field strength was known better, and that of magnetic flux density was usually shown correctly. Candidates often resorted to guesswork when completing the second column of the table. Many did not appreciate that the concept of potential arises from energy considerations and that it is therefore a scalar quantity, whilst the other two quantities are force-related and therefore vectors.

Completely correct answers to part (b) were encountered in many of the scripts. Since the unit of E had already been tested in the table in part (a), no penalty was imposed for wrong or missing units in the answer to part (b)(i). A worrying error, made by a significant minority of the candidates, was to equate the electric force on the particle to its mass, rather than to its weight.

6 Although part (a) was relatively novel, most candidates could handle the comparison of gravitational and electric fields. The gaps in the second line of the table could be filled directly by use of the *Data Booklet*, but most of the other entries required a little more thought. Derived units were sometimes quoted (but not accepted) for the electric field strength: candidates were expected to know that this is N C^{-1} or V m^{-1}. In the fourth line, distance (or radius) *squared* was a surprisingly common wrong answer.

In pan (b)(i) quite a large number of candidates did not state that the resultant force would be unchanged, even though they had correctly considered the separate effects of a $1 / r^2$ relationship on both the gravitational and electric forces. The most frequent wrong response was that the force (presumably the resultant force) would decrease by a factor of four. In part (b)(ii) many candidates stated that the charge should be increased, without indicating that it should be doubled – this was expected for the mark to be awarded.

15 Teachers preparing students for these examinations might like to ponder over why almost as many candidates chose distractor D (implying a constant *potential* of 50V between the parallel plates) as the correct answer. The facility of this question was only 38% and it was a weak discriminator.

16 In this question three-fifths of the candidates appreciated that the electric field strength is constant between parallel charged plates. Over 20% of them chose distractor C, where the field strength is shown as decreasing to a minimum value midway between the plates.

17 This question demanded an understanding of the inverse square aspect of Coulomb's law.

It showed that many candidates do not understand proportion when the relationship is not direct. 49% selected the correct response, but over 25% settled for distractor B (F /9r) instead of D (F /9).