Mark schemes

Q1.

(a) Either conversion of 1 MeV to J or $W = QV$

$1.60 \times 10^{-19} \times 1.30 \times 10^{6} = 2.08 \times 10^{-13}$ ✓ (J)

At least 2 sf required.

1

(b) $Q = mc\Delta\theta = 1.5 \times 903 \times 68.0$ (= 92 106 J) **OR**

E_K of one electron $= \frac{92\,106}{4.50 \times 10^{17}}$ ✓ $(= 2.05 \times 10^{-13}\ \text{J})$

Both calculations and correct conclusion, eg
Yes, this is consistent with an accelerating voltage of 1.30 MV. ✓

Alternative route

Total E_K for all electrons =

$2.08 \times 10^{-13} \times 4.50 \times 10^{17}$ = (93 600 J) ***OR***

$\Delta\theta = \frac{Q}{mc} = \frac{93600}{1.5 \times 903}$ ✓ $(= 69.1\ \text{K})$

which is consistent with the temperature rise observed. ✓

Can also compare total E_K with $mc\Delta\theta$ for MP2.

Use of 2.0×10^{13} gives total E_K of 90 000 J and $\Delta\theta$ of 66 K which is consistent.

Allow comparison of in eV or accelerating pd (1.28×10^{6}) with 1.3×10^{6} V or MeV with MV.

2

(c) Correct calculation of non-relativistic E_K ✓a

Statement or attempted use of $E_K = mc^2 - m_0c^2$ ✓b

Correct calculation of relativistic E_K ✓c

Both calculations and comparison of with 2.1×10^{-13} or 2.0×10^{-13} J to conclusion consistent with idea that student B is correct ✓d

$E_K = \frac{1}{2}mv^2 = 3.78 \times 10^{-14}\ \text{J}$

$E = \frac{m_0c^2}{\sqrt{1-\frac{v^2}{c^2}}} - m_0c^2 = 2.11 \times 10^{-13}\ \text{J}$

For ✓d allow a comparison of $\Delta\theta$ from

$m_{Al}c\Delta\theta = N(mc^2 - m_0c^2)$ with 68°

Allow ecf for ✓d for minor calculation error, rounding error or transcription errors but there must be a relativistic KE and non-relativistic calculation to award ✓d.

Alternative

Calculation of speed using $v = \sqrt{\frac{2E_k}{m}}$ ✓a

Statement or attempted use of $E_K = mc^2 - m_0c^2$ ✓b

Calculation of speed from relativistic equation ✓c

Both calculations and comparison of results with 2.88×10^8 or 3×10^8 ✓d

$v = 6.8 \times 10^8$ m s^{-1} if using 2.08×10^{-13}

$v = 2.88 \times 10^8$ m s^{-1} if using 2.08×10^{-13}

*Allow calculations based on the total number of electrons and comparison with **part (b)**.*

Alternative for Max 2

Correct calculation of non-relativistic E_K ✓a

Calculation of relativistic mass, total energy or $\sqrt{1 - v^2/c^2}$ or $\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$ **AND** comment that **relativistic effects are significant (owtte)** so B is correct. ✓bcd

If no other marks awarded max 1 for student B is correct because speed is greater than 3.0×10^7 m s^{-1} or v is 96% of c (which is greater than 10%).

4

(d) < 29.8 ns ✓

1

(e) Max 4

- **Gain/change in** E_K is the same ✓a

  Only allow use of $\frac{1}{2}mv^2$ or $E_K \propto v^2$ if it is clear that this refers only to stage 1 for ✓b or ✓e.

- due to the same loss of potential energy
  OR
  gain in $E_K = e(\Delta)V$ and same potential difference ✓b

- **Increase/change** in speed is greater in stage 1 ✓c

- Idea that mass increases with speed ✓d

  ✓d *Allow a correct sketch of relativistic mass and speed graph if c is labelled on speed axis.*

  ✓d *Condone with reference to* $E_K = \frac{1}{2}mv^2$

• Idea that energy is used to produce a large increase of mass and a small increase in speed in stage 13 (with a small increase in mass and a large increase in speed in stage 1) ✓$_{e1}$

OR

Idea that electron speed cannot increase much when close to the speed of light since electrons cannot travel faster than the speed of light ✓$_{e2}$

✓$_e$ *must refer to relativity.*

4

[12]

Q2.

(a) Either

- Equation (for speed of light) only contains (universal) constants

OR

- Speed of light is invariant / constant / same in all reference frames / does not depend of speed of source or observer. ✓

Both bullet points above and **one** from

- Constants don't depend on reference frame or speed of source / observer

OR

- (refers to the) speed of light as being in free space / vacuum ✓

Speed of light is constant in equation is not enough for MP1.

Do NOT allow speed of light is invariant in all inertial reference frames for MP2 but condone for MP1.

Ignore calculations of speed of light

2

(b) Use by manipulation or substitution of

$$l = l_0\sqrt{1-\frac{v^2}{c^2}}$$ ✓

to give 69 m ✓

Condone substitution and working leading to 21 m

e.g. $38\sqrt{1-\frac{2.5^2}{3^2}}$ *= 21 for 1 mark only. (mixes up* l_0 *and* l*)*

$$l_0 = \frac{l}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{38}{\sqrt{1-\frac{2.5^2(\times 10^8)^2}{3.0^2(\times 10^8)^2}}}$$

Allow use of $v = \frac{s}{t}$ *and* $t = \frac{t_0}{\sqrt{1-\frac{v^2}{c^2}}}$ *for either route.*

93 m comes from $\frac{38}{\sqrt{1-\frac{2.5}{3.0}}}$ *and gains 1 mark.*

2

(c) Evidence of idea that kinetic energy = total energy - rest energy ✓

$$E_k = \frac{m_0 c^2}{\sqrt{1-\frac{v^2}{c^2}}} - m_0 c^2$$

with substitutions correct ✓

1.21 or 1.22 × 10^{-10} (J) ✓

If no other mark awarded, give one mark for calculation of total energy (2.72 × 10^{-10}J) or rest energy (1.5 × 10^{-10} J)

Use of $m = \frac{m_0}{\sqrt{1-\frac{v^2}{c^2}}}$ *with* $E_k = \frac{1}{2} mv^2$ *is 0 marks*

In MP2 allow use of γ from earlier (b) but value must be seen here.

Allow rest energy = 938.3 × 10^6 × 1.60 × 10^{-19} as part of calculation.

At least 3 sf

Allow 1.23 × 10^{-10} (J)

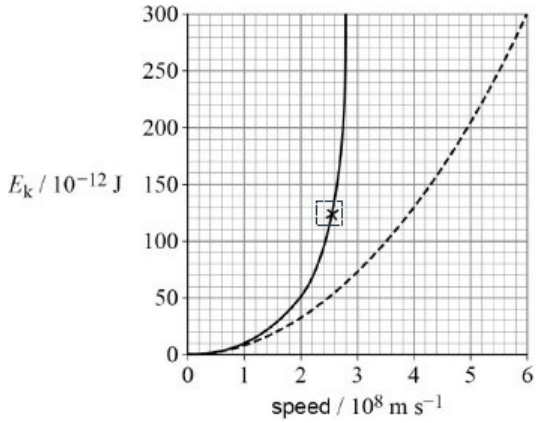
A substitution missing the squares and showing 2.2 × 10^{-10} J is eligible for MP2.

3

(d) Follows dashed line up to v = 1; condone divergence starting anywhere from v = 0.3 to v = 1.1 ✓

Increasing gradient passing within one grid square of (2.5, 122) ✓

Increasing gradient and does not go beyond v = 3 ✓



For MP3, if line reaches v = 3 must be asymptoti'c

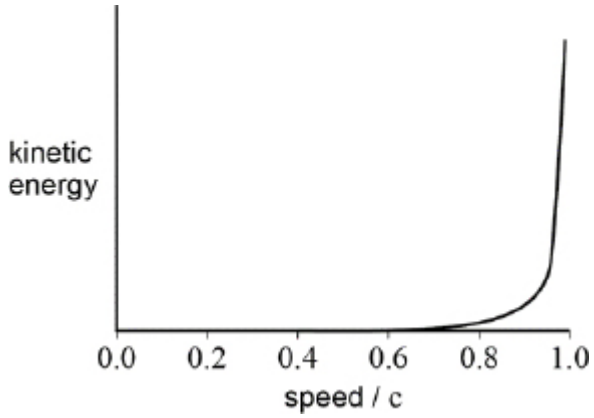
MP3 should not be awarded if continuing the line would clearly cross v = 3

3

[10]

Q3.

(a) C ✓



Only answer

1

(b) KE = total energy – rest energy ✓

$$m_0c^2 = \frac{m_0c^2}{\sqrt{1-\frac{v^2}{c^2}}} - m_0c^2 \checkmark$$

To give $v = 0.87c$ OR 2.6×10^8 m s^{-1} ✓

MP2 requires the use of the idea that the KE is equal to the rest energy.

(calculator values are 0.8660 and 2.59808×10^8)

3

(c) mass is related to energy through

$E = mc^2$ ✓

When an object stores energy this appears as an increase in observed mass.

OR

A spring gains (elastic potential) energy so observed mass must also increase. ✓

Treat any idea that 'the difference in observed mass is negligible' as neutral.

Max 2

[6]