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WORKSHEETS
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Mass, energy and antiparticles

A gamma-converter instrument for a lunar probe

35–40 minutes independent work + 15–20 minutes review

OCR A H556 | A-level physics | Module 6 | 37 marks

Specification points covered

6.4.4(a): mass–energy equivalence, $E = mc^2$, including eV and MeV.

6.4.4(c): pair production and particle–antiparticle annihilation.

Prerequisites supplied or previously taught: photon energy $E = hf = hc/\lambda$ and conservation of energy/momentum.

Use $c = 3.00 \times 10^8$ m s^{-1}, $h = 6.63 \times 10^{-34}$ J s, $m_e = 9.11 \times 10^{-31}$ kg and 1 eV = 1.60×10^{-19} J. Retain unrounded values: these constants give $m_e c^2 = 0.5124375$ MeV. Ignore recoil energy only where the question says so.

Use a calculator and your OCR A data booklet. Show working, units and directions where relevant.

1 Start with a reliable energy scale

A lunar-probe instrument converts sufficiently energetic gamma photons into electron–positron pairs. A separate calibration module uses annihilation photons. These are simplified instrument models.

A pair consists of one electron and one positron. The positron has the same rest mass as the electron and the opposite electric charge.

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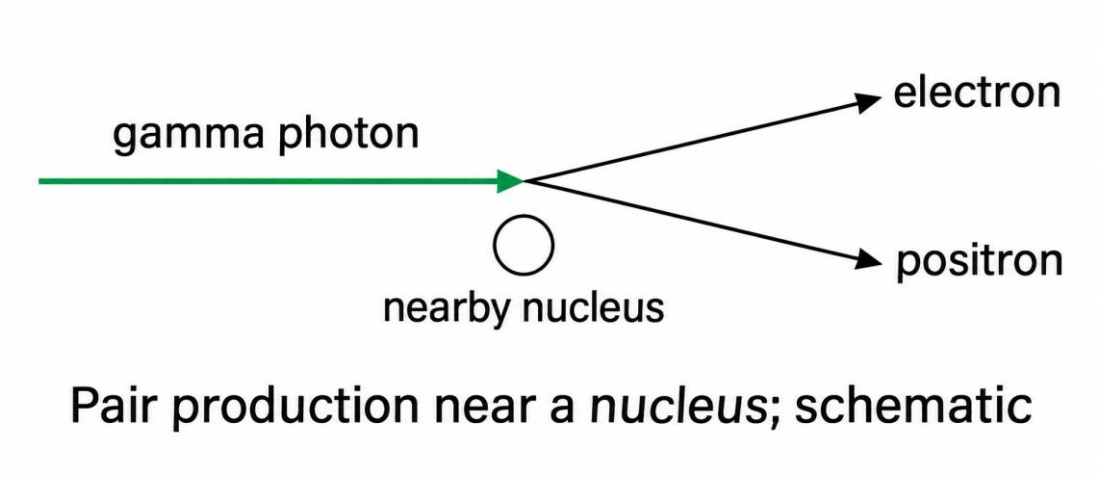


Figure 1 Conversion near a nucleus; directions are schematic

1(a) Convert a gamma-photon energy of 1.60 MeV to joules. **[1 mark]**

1(b) Calculate the rest energy of one electron in joules and in MeV using the supplied constants. **[2 marks]**

2 Decide which photons can produce a pair

2(a) Calculate the minimum photon energy required to supply the rest energies of an electron–positron pair. Ignore the small recoil-energy correction for a massive nearby nucleus. **[1 mark]**

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2(b) The converter receives photons of energies 0.900, 1.10 and 1.60 MeV. Identify which have enough energy for pair production near a nucleus, and explain why the test uses photon energy rather than beam brightness. **[2 marks]**

2(c) Calculate the largest photon wavelength that can meet the rest-energy threshold in this model. **[3 marks]**

2(d) Explain why Figure 1 includes a nearby nucleus rather than showing a lone photon producing the pair in empty space. **[2 marks]**

3 Follow the energy after conversion

3(a) A 1.60 MeV photon makes a pair. Neglect nucleus recoil energy. Calculate the total kinetic energy initially available to the electron and positron. **[2 marks]**

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3(b) In the same event the electron has kinetic energy 0.340 MeV. Calculate the positron's kinetic energy. **[1 mark]**

3(c) The tracks suggest a total pair kinetic energy of 0.900 MeV for a 1.60 MeV photon. Explain quantitatively why the event record is inconsistent with this model. **[2 marks]**

3(d) Calculate the mass equivalent of the 0.575125 MeV kinetic energy from 3(a). Explain why this is not extra electron rest mass. **[2 marks]**

4 Calibrate with annihilation photons

4(a) An electron and a positron annihilate from rest in the laboratory frame, producing two photons. Calculate the energy of each photon in joules and MeV. **[2 marks]**

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4(b) Explain the directions of the two photons in the laboratory frame for this annihilation from rest. **[2 marks]**

4(c) Calculate the wavelength of one calibration photon from this rest annihilation. **[2 marks]**

4(d) A pupil writes “the detector sees the two positrons produced in annihilation”. Correct the statement, identifying the initial and final particles. **[1 mark]**

5 Use an unfamiliar calibration setting

5(a) A second calibration event begins with an electron and a positron having equal and opposite momenta and total kinetic energy 0.240 MeV in the laboratory frame. They annihilate into exactly two photons. Calculate the energy of each photon. **[2 marks]**

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5(b) In a different event the electron–positron system has non-zero total momentum in the laboratory frame. Is it valid to assume that the two detected photons must have equal energies in that frame? Explain. **[1 mark]**

5(c) A converter absorbs incident gamma energy at a rate of 4.00×10^{-6} W, entirely from 1.60 MeV photons. Calculate the number of absorbed photons per second. **[2 marks]**

5(d) The instrument records 3.00×10^{6} pair events per second in the setting of 5(c). Calculate the fraction of absorbed photons giving a recorded pair event. **[1 mark]**

6 Review the instrument team's language

6(a) Explain why calculating E/c^2 for a photon does not give it a non-zero rest mass, and why $E = hf$ is the appropriate relationship for its energy. **[2 marks]**

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6(b) For a full-energy event, the instrument records the pair's kinetic energy and later both annihilation photons after the pair has slowed to rest. Show that their combined energies account for the original 1.60 MeV photon, neglecting recoil and other losses. **[2 marks]**

6(c) Summarise the difference between pair production and annihilation, using the direction of energy transfer and conservation of electric charge. **[2 marks]**

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