2004

Val, Pat and Bruce are discussing the meaning of Einstein's famous equation *E* = *mc2*, when applied to an electron with mass *m*. **Val** says that an electron will transform its mass *m* into an amount of pure energy *E*, when it is travelling at the speed of light (*c*).

Pat disagrees, and says that if it were moving at a high velocity inside a cathode ray tube it would convert its mass *m* into a light photon of energy *E* when it hits the glass face.

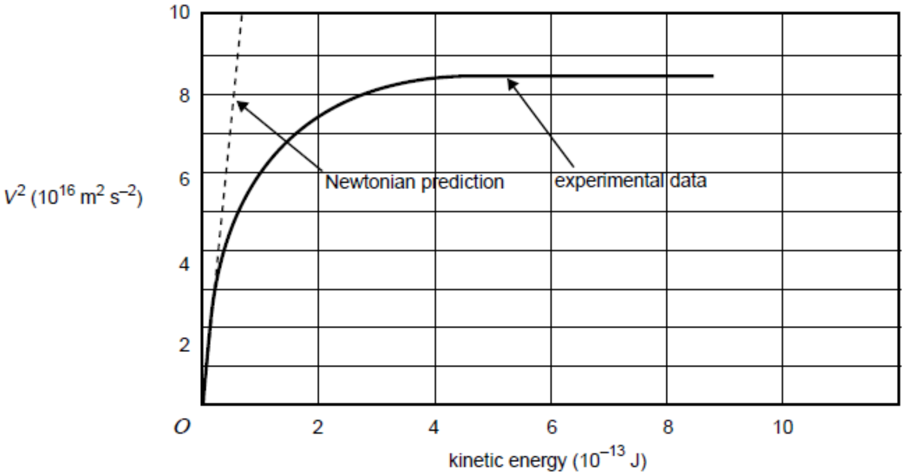
Bruce, on the other hand, thinks that just by its existence, the electron of mass *m* has an energy of *E*.

Question 1

In the box below write the name of the student with the best explanation of the equation.

Bruce is correct.

In an experiment done at Massachusetts Institute of Technology, electrons were given a series of known kinetic energies (KE) by accelerating them across a range of electric potentials, and measuring the electron's velocity, *v*, for each value of KE.



Question 4

According to Newtonian mechanics, what would be the **speed** of an electron with a KE of 10 × 10^–13 J?

The mass of an electron is 9.1 × 10^–31 kg.

$E = \frac{mv^2}{2} \quad 10 \times 10^{-13} = \frac{9.1 \times 10^{-31} v^2}{2} \quad v = 1.5 \times 10^9$

Question 5

Using the experimental data shown in Figure above, indicate in the box provided which one of the statements below gives the best estimate of the **measured speed** of an electron with a KE of 10 × 10^–13 J.

A. It is approximately 9 × 10^16 m s–1.

B. It is approximately 3 × 10^8 m s–1.

C. It is approximately 9.1 × 10^–31 m s–1.

D. It cannot be estimated.

B

To obtain the answer **B** extrapolate the graph to a kinetic energy of 10×10^{-13} and read the value of v^2.

2005

According to Einstein's special theory of relativity, mass and energy are related. The mass of an electron when it is at rest is 9.1 × 10^-31 kg.

Question 8
Show that this is equivalent to an energy of 8.20 × 10^-14 J.
$E = 9.1 \times 10^{-31} \times 9 \times 10^{16}$

The electron accelerator at the ARPANSA laboratory at Yallambie, near Melbourne, can accelerate an electron to a speed such that its mass increases **by a factor of 22**.
Question 10 30%
Which of the following (**A-D**) gives the kinetic energy of the electron as it leaves the accelerator?
A. 8.20 × 10^-15 J
B. 1.72 × 10^-12 J
C. 1.80 × 10^-13 J
D. 5.11 × 10^-6 J
B
$E = (\gamma - 1) \times 9.1 \times 10^{-31} \times 9 \times 10^{16}$

2006

A linear accelerator (LINAC) is a device that is used to accelerate electrons using electromagnetic fields. As the electron energy increases, the speed of the electron approaches c (*the speed of light*).
Question 10 49%
Which of the following (**A–D**) is true with regard to the electron's speed, and its mass, **as the speed of the electron approaches c**?
A. Its speed increases slightly while its mass remains fixed at 9.11 × 10^-31 kg.
B. Its speed increases slightly while its mass increases substantially.
C. Its speed increases substantially while its mass increases slightly.
D. Both its speed and its mass continue to increase at a steady rate.
B

Question 11 38%
Which of the statements (**A–D**) below best describes the 'mass-energy' (*E* = *mc*^2) of the electron?
A. It is the rest energy.
B. It is the kinetic energy of the electron.
C. It is the sum of the rest energy and the kinetic energy of the electron.
D. It is the difference between the rest energy and the kinetic energy of the electron.
C

2007

The Sun produces energy by fusing light elements such as helium into heavier elements. In this fusion process mass is lost. The Sun radiates energy at a rate of 4.0 × 10^26 W.

Question 10

How much mass does the Sun lose each second?

$E = m \times c^2 \quad 4 \times 10^{26} = m \times 9 \times 10^{16} \qquad m = 4.4 \times 10^9\ kg$

2008

Question 13 **60%**

In the fusion process, a proton of rest mass 1.673 × 10–27 kg and a neutron of rest mass 1.675 × 10–27 kg combine to form a deuterium nucleus of rest mass 3.344 × 10–27 kg, with a release of energy.

According to Einstein's postulate of the equivalence of mass and energy, which one of the following is the best estimate of the energy released in this interaction?

A. 1.2 × 10^–21 J
B. 3.6 × 10^–13J
C. 4.0 × 10^–3 J
D. 3.6 × 10^14 J

B

$E = (1.673 + 1.675 - 3.344) \times 10^{-27} \times 9 \times 10^{16}$

2009

Question 7 **60%**

In a nuclear reactor, some mass is converted into energy.

Which one of the following is the best approximation to the total energy released when 1 kg of mass is totally converted into energy?

A. 10^5 J
B. 10^9 J
C. 10^13 J
D. 10^17 J

D

$E = 1 \times 9 \times 10^{16}$

Question 8 85%

According to Einstein's special theory of relativity, the relativistic mass, *m*, of a body of rest mass m_0, depends on its speed.

Which one of the curves in Figure 2 best shows how the relativistic mass varies with speed?

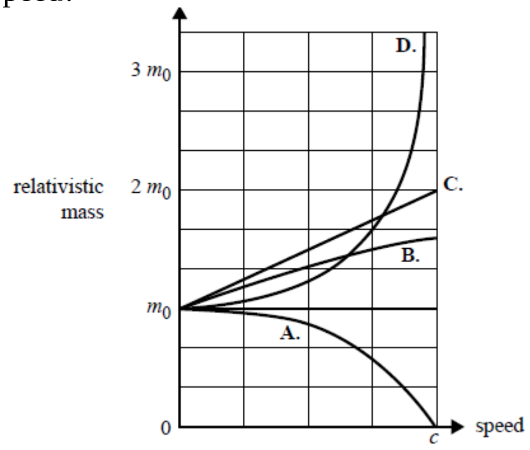


Figure 2

D

Question 11 60%

Which one of the following is closest to the work that must be done on a proton to increase its speed from zero to 0.9 *c*, that is $\gamma = 2.29$? (Take m_0 for the proton = 1.67 × 10^–27 kg.)

A. 1.9 × 10^–10 J

B. 4.0 × 10^–20 J

C. 3.5 × 10^–11 J

D. 1.7 × 10^–27 J

A

The total energy is composed of the rest energy plus the work done. $E_{Total} = E_K + E_{Rest} = mc^2$, so $E_K = mc^2 - E_{Rest} = m_o\gamma c^2 - m_o c^2 = m_o c^2(\gamma - 1) = 1.9 \times 10^{-10}$ J.

Question 12 82%

In science fiction, spacecraft sometimes travel at speeds greater than the speed of light. According to Einstein's special theory of relativity, this is not possible because

A. this would require time travel into the past.

B. when an object approaches the speed of light, the rest mass tends towards zero.

C. when an object approaches the speed of light, the value of γ tends towards zero.

D. when an object approaches the speed of light, its relativistic mass, *m*, approaches infinity.

D

2010

Question 10 50%
Muons and antimuons are anti-particles of each other. They have the same mass. When a muon meets an antimuon, both are destroyed and two photons (gamma rays) are formed. If the two particles are effectively stationary, then the two photons have a total energy of 3.38 × 10^–11 J.
Using this data, which one of the following is closest to the mass of a single muon?
A. 3.76 × 10^–28 kg
B. 1.88 × 10^–28 kg
C. 1.13 × 10^–19 kg
D. 5.64 × 10^–19 kg
B
$E = mc^2 \quad 3.38 \times 10^{-11} = 2m \times 9 \times 10^{16}$

Question 11 34%
In a particle accelerator, an alpha particle of mass 6.64424 × 10–27 kg is accelerated from rest to high speed. The total work done on the alpha particle is equal to 7.714 × 10^–10 J. Which one of the following is closest to its final speed?
A. 0.90*c*
B. 0.95*c*
C. 0.85*c*
D. 0.80*c*
A
$W = (\gamma - 1)m_0c^2 \qquad 7.714 \times 10^{-10} = (\gamma - 1) \times 6.64424 \times 10^{-27} \times 9 \times 10^{16}$

$$\gamma = 2.29 \quad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \quad 1 - \frac{v^2}{c^2} = \frac{1}{2.29^2} \quad \frac{v}{c} = 0.9$$

2011
Question 1 39%
An experiment is done where two protons with very high kinetic energy collide in order to try to create a single stationary
'Higgs' particle.
Each proton in the reaction has a kinetic energy of 1.1 × 10–6 J. No other particles are produced in the reaction and the protons will not exist after the production of the Higgs particle. The proton rest mass is equal to 1.6726 × 10^–27 kg.
Which of the following options is the best estimate of the mass of the Higgs particle?
A. 1.2 × 10^–23 kg
B. 2.4 × 10^–23 kg
C. 3.3 × 10^–27 kg
D. 1.7 × 10^–27 kg
B
$E_k = (\gamma - 1)m_oc^2$ gives γ = 7308.32. This gives m $= m_o\gamma = 1.222 \times 10^{-23}$ kg.
This is doubled for the best estimate of the mass of the Higgs particle: m = 2.44×10^{-23} kg.

Question 2 62%
According to the theory of special relativity, the mass, *m*, of a particle, and its total energy, *E*, are equivalent.
The relationship is $E = mc^2$ where $m = \gamma m_0$, and $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$

The amount of energy required to increase the speed of an electron from 0.18*c* to 0.19*c* is 0.004 J. By contrast, the amount of energy required to increase this electron's speed by the same amount (0.01*c*) from 0.98*c* to 0.99*c* is 27.7 J.
Which of the following best explains why much more energy is required to produce the same change in speed for the electron when it is moving at the higher speed?
A. The rest mass (m_0) of the electron is not a constant but depends on the speed *v*.
B. The electron mass-energy is proportional to *v*, so it is more massive at high speed.
C. Because $E = \frac{1}{2}mv^2$, the larger *v*, the more energy is required to increase it further.
D. The total mass-energy of the electron depends on *γ*, which increases rapidly as *v* approaches *c*.
D

Question 3 47%
When stationary, a proton has a rest mass-energy of 1.50 × 10^–10 J.
A proton is accelerated from a speed with *γ* = 1.05 to a speed with *γ* = 1.10.
Which of the following is closest to the work done on the proton during its acceleration from the first speed to the second speed?
A. 2.9 × 10^6 J
B. 3.2 × 10^–10 J
C. 7.5 × 10^–12 J
D. 8.3 × 10^–29 J
C
Work done = $\Delta E_k = \Delta \gamma m_o c^2 = \Delta\gamma \times$ rest mass energy = $0.05 \times 1.50 \times 10^{-10} = 7.5 \times 10^{-12}$ J.

Question 10 41%
Which of the following statements best explains why it is impossible to accelerate particles (such as electrons) so that they are travelling at the speed of light?
A. It is directly forbidden by one of Einstein's postulates.
B. As particles increase in speed, the rest mass (m_0) tends towards an infinite value
C. The kinetic energy of particles, given by $E_k = (\gamma - 1)m_0c^2$, tends towards an infinite value
D. The speed of particles is given by *L*/*t*; this is equal to $L_0/t_0\gamma^2$ and this value tends towards infinity
C

2012

Question 6 56%

The rest mass of every proton is 1.67 × 10^–27 kg. A particular proton has a kinetic energy of 9.00 × 10^–11 J.

Which of the following is the best estimate of the **total** energy of the proton?

A. 1.50 × 10^–10 J
B. 9.00 × 10^–10 J
C. 1.50 × 10^–11 J
D. 2.40 × 10^–10 J

D

Total energy = rest mass energy + kinetic energy

$= m_o c^2 + 9.00 \times 10^{-11}$

$= (1.67 \times 10^{-27})(9.0 \times 10^{16}) + 9.00 \times 10^{-11}$

$= 2.4 \times 10^{-10}$ (option D)

Question 11 70%

A sealed container of gas is heated from a low temperature to a very high temperature. The particles of the gas have greatly increased their speed. Students are debating whether special relativity predicts that the mass of the gas will increase, remain constant or decrease. Which one of the following statements is correct?

A. The mass will increase.
B. The mass will decrease.
C. The mass will remain constant.
D. Special relativity does not apply to gas particles.

A

Question 12 63%

A helium ion is accelerated from a speed of 9.0 × 10^7 m/s to a speed of 1.5 × 10^8 m/s. Scientists calculate accurately the **work done** on the helium ion during this acceleration.

Data

• Rest mass of a helium ion: 6.64 × 10^–27 kg
• Rest mass energy of a helium ion: 5.98 × 10^–10 J
• At a speed of 9.0 × 10^7 m/s, γ = 1.05; at a speed of 1.5 × 10^8 m/s, γ = 1.15

Which of the options below is the best estimate of the answer they obtain?

A. 2 × 10^–19 J
B. 6 × 10^–11 J
C. 1 × 10^–9 J
D. 6 × 10^–9 J

B

$W = (1.15 - 1.05) \times 6.64 \times 10^{-27} \times 9 \times 10^{16}$

2013

Question 3 46%
Scientists accelerate a proton from rest to a final speed where its relativistic mass is 5.1 × 10^–27 kg.
The rest mass of a proton is 1.7 × 10^–27 kg.
How much work was done on the proton?
A. 3.1 × 10^–10 J
B. 3.1 × 10^–17 J
C. 1.0 × 10^–18 J
D. 3.4 × 10^–27 J
A
Work done = $(m - m_0) \times c^2 = (5.1 - 1.7) \times 10^{-27} \times 9 \times 10^{16} = 3.1 \times 10^{-10}$ J

Question 6   38%
A neutral pion is a type of particle. In a collider experiment, a neutral pion with γ = 10.0 decays into two photons.
The total energy of both photons together is measured to be 2.17 × 10^–10 J. Before the decay, only the neutral pion exists; after the decay, only the photons exist.
What is the rest mass of the neutral pion?
A. 2.41 × 10^–28 kg
B. 2.41 × 10^–27 kg
C. 7.23 × 10^–27 kg
D. 7.23 × 10^–20 kg
A
$E_{total} = mc^2$. So $m = 2.17 \times 10^{-10}/(9 \times 10^{16}) = 2.41 \times 10^{-27}$. Now relativistic mass $m = m_o\gamma$. So $m_o = 2.41 \times 10^{-27}/10 = 2.41 \times 10^{-28}$ kg.

Question 7 57%
It is not possible for a particle with a rest mass greater than zero to be accelerated to a speed of *c*. Which one of the following is the best explanation for this?
A. It would violate causality and is therefore impossible.
B. As *v* approaches *c*, the rest mass of the particle approaches infinity.
C. Massless particles such as photons are constrained to travel at a speed of *c*.
D. An infinite amount of work would be required in order to accelerate the particle to a speed of *c*.
D

2014

A pion and its antiparticle, each at rest, annihilate to produce two photons whose total energy is 4.5 × 10^–11 J. Apart from the two photons, nothing else is produced in this process. The masses of a pion and its antiparticle are the same.

Question 10 52%

The rest mass of the pion is

A. 1.3 × 10^–28 kg
B. 2.5 × 10^–28 kg
C. 5.0 × 10^–28 kg
D. 7.5 × 10^–20 kg

B

$m_0c^2 = 2.25 \times 10^{-11} \quad m_0 = \frac{2.25 \times 10^{-11}}{c^2}$

Question 11 39%

The pion is now accelerated from rest before colliding with its antiparticle.
What work must be done on one pion so that it has γ equal to 3.00?

A. 4.5 × 10^–11 J
B. 2.2 × 10^–11 J
C. 1.1 × 10^–11 J
D. 9.0 × 10^–11 J

A

The rest mass energy of one pion must be 2.25×10^-11 J (from the data given before Question 10). To increase to $\gamma\, m_0c^2 = 3 \times m_0c^2$ requires an extra energy input of $(\gamma - 1)\, m_0c^2 = 4.5 \times 10^{-11}$ J.

2015

Question 9 74%

A nucleus in an excited energy state emits a gamma ray of energy 1.8 × 10^–13 J as it decays to its ground state. The initial mass of the excited nucleus is *M*i.
The final mass of the nucleus after decay is

A. *M*i + 2 × 10^–30 kg
B. *M*i
C. *M*i – 2 × 10^–30 kg
D. *M*i – 4 × 10^–30 kg

C

$Loss\ in\ mass\ m = \frac{1.8\times10^{-13}}{c^2}$

Question 10 43%

A particle of rest mass m_0 is accelerated from rest to 0.6*c* relative to Earth's frame. Which one of the following statements is true?

A. In its own frame, the mass of the particle is now $1.25m_0$.

B. The work done to accelerate the particle is equal to the kinetic energy of the particle.

C. The kinetic energy of the particle in Earth's frame is $\frac{1}{2}m_0(0.6c)^2$

D. The increase in total energy of the particle (measured in Earth's frame) is due to an increase in both the kinetic energy of the particle and the rest energy of the particle.

B

Option A was incorrect as in its own frame, the mass will be unchanged. Option C did not take into account the relativistic increase in the mass of the particle. Option D suggested that the rest mass can increase, but this is not correct.

Question 11 59%

According to Einstein's relativity theory, the rest energy is m_0c^2 for a particle of rest mass m_0 and the kinetic energy of the particle is $(\gamma - 1)\, m_0c^2$, where $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$

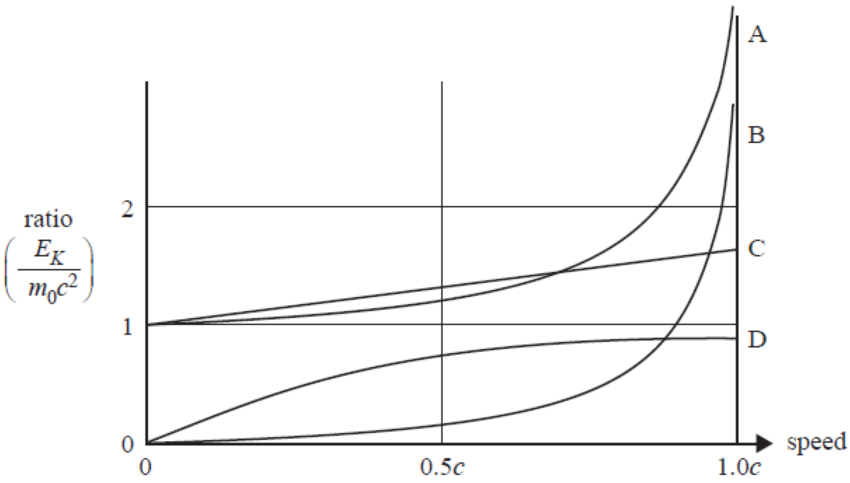


Figure 3

Which one of the curves in Figure 3 best gives the relationship of kinetic energy to rest energy $\left(\frac{E_K}{\text{rest energy}}\right)$ as a function of speed *v*?

A. curve A

B. curve B

C. curve C

D. curve D

B

Should start at 0 as when v=0, kinetic energy is 0. When v is approaching c, γ is approaching infinity.

2016

Question 9 61%

When a proton is accelerated from rest, it gains a kinetic energy of 1.20 × 10^–10 J. What value of γ is reached? (The rest mass of a proton is 1.67 × 10^–27 kg.)

A. 2.2
B. 1.8
C. 1.5
D. 1.3

B

$(\gamma - 1)m_0c^2 = 1.2 \times 10^{-10}$ $\quad\quad$ $\gamma - 1 = \dfrac{1.2 \times 10^{-10}}{1.67 \times 10^{-27} \times 9 \times 10^{16}}$

Question 10 38%

A high-energy proton with γ = 3 collides with a stationary nucleus and rebounds in the opposite direction to its original motion. The kinetic energy of the proton after the collision is m_0c^2, where m_0 is the rest mass of a proton. The nucleus gains kinetic energy and there is no other change to the energy of the nucleus. Which one of the following is the kinetic energy of the nucleus after the collision?

A. 0.5 m_0c^2
B. 1.0 m_0c^2
C. 1.5 m_0c^2
D. 2.5 m_0c^2

B

By conservation of energy:

$(\gamma-1)\, m_0c^2 = m_0c^2 + KEnucleus$

$(3-1)\, m_0c^2 = m_0c^2 + KEnucleus$

$2m_0c^2 = m_0c^2 + KEnucleus$

$\therefore KEnucleus = 1.0\, m_0c^2$

2017

Question 11 M/C 66%

On average, the sun emits 3.8×10^{26} J of energy each second in the form of electromagnetic radiation, which originates from the nuclear fusion reactions taking place in the sun's core.

The corresponding loss in the sun's mass each second would be closest to

A. 2.1×10^{9} kg

B. 4.2×10^{9} kg

C. 8.4×10^{9} kg

D. 2.1×10^{12} kg

$m = \frac{E}{c^2} = \frac{3.8 \times 10^{26}}{9 \times 10^{16}} = 4.2 \times 10^{9}\ kg$ **ANS: B**

2018 NHT

Question 10 M/C

A linear accelerator (linac) accelerates an electron beam to an energy of 100 MeV over a distance of about 10 m. After the first metre of acceleration in the linac, the electrons are travelling at approximately 99.9% of the speed of light.

The Lorentz factor, γ, for an electron travelling at this speed would be closest to

A. 22.4

B. 44.8

C. 500

D. 1000

$\gamma = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}} = \frac{1}{\sqrt{1-(0.999)^2}} = 22.4$ **ANS: A**

Question 15 (2 marks)

An unstable subatomic particle, known as a π_0 meson, decays completely into electromagnetic radiation.

The rest mass of this π_0 meson is 2.5×10^{-28} kg.

How much energy would be released by this π_0 meson if it decays at rest?

$$E = mc^2 = 2.5 \times 10^{-28} \times 9 \times 10^{16} = 2.3 \times 10^{-11} J$$

2018

Question 14 M/C 60%
Which one of the following statements about the kinetic energy, *E*k, of a proton travelling at relativistic speed is the most accurate?
A. The difference between the proton's relativistic *E*k and its classical *E*k cannot be determined.
B. The proton's relativistic *E*k is greater than its classical *E*k.
C. The proton's relativistic *E*k is the same as its classical *E*k.
D. The proton's relativistic *E*k is less than its classical *E*k.

At low speed relativistic kinetic energy is the same as classical. When speed increases relativistic kinetic energy approaches infinity. **ANS: B**

Question 15 (3 marks) **36%**
A stationary scientist in an inertial frame of reference observes a spaceship moving past her at a constant velocity. She notes that the clocks on the spaceship, which are operating normally, run eight times slower than her clocks, which are also operating normally. The spaceship has a mass of 10 000 kg.
Calculate the kinetic energy of the spaceship in the scientist's frame of reference. Show your working.

$$\gamma = 8 \quad E = (\gamma - 1)m_0c^2 = 7 \times 10000 \times 9 \times 10^{16} = 6.3 \times 10^{21} J$$

2019 NHT

Question 18 M/C
If a particle's kinetic energy is 10 times its rest energy, *E*rest , then the Lorentz factor, *γ*, would be closest to
A. 9
B. 10
C. 11
D. 12

$E = (\gamma - 1)E_{rest} \quad \frac{E}{E_{rest}} = \gamma - 1 \quad \gamma - 1 = 10$ **ANS: C**

Question 19 (2 marks)
In a nuclear fusion reaction in the sun's core, two deuterium nuclei, each with a mass of 3.3436×10^{-27} kg, fuse to produce one helium-4 nucleus with a mass of 6.6465×10^{-27} kg. Ignore the kinetic energy of the nuclei before the reaction.
Calculate the energy released. Show your working.

$$\Delta m = 2 \times 3.3436 \times 10^{-27} - 6.6465 \times 10^{-27} = 4.07 \times 10^{-29} kg$$
$$E = \Delta mc^2 = 4.07 \times 10^{-29} \times 9 \times 10^{16} = 3.7 \times 10^{-12} J$$

2020

Question 13 56%
Matter is converted to energy by nuclear fusion in stars.
If the star Alpha Centauri converts mass to energy at the rate of 6.6×10^9 kg s^{-1}, then the power generated is closest to
A. 2.0×10^{18} W
B. 2.0×10^{18} J
C. 6.0×10^{26} W
D. 6.0×10^{26} J

$E = mc^2$

$E = 6.6 \times 10^9 \times (3.0 \times 10^8)^2$

$E = 6.0 \times 10^{26}\ J$

Since this conversion occurs every second the output is 6.0×10^{26} W.

ANS: C