Page 18 Test yourself on prior knowledge

1 a) $Z_{Na} = 11 \Rightarrow Q = 11e$

$= 11 \times 1.6 \times 10^{-19}$ C

$= 1.76 \times 10^{-18}$ C

b) Sodium-23 nucleus contains 23 nucleons (protons + neutrons); each nucleon has a mass approximately 1 800 times that of the electron so:

$m_{Na} = 23 \times 1800 \times 9.11 \times 10^{-31}$ kg

$= 3.77 \times 10^{-26}$ kg (3 sf)

2 a) $$Mass\ of\ one\ atom = \frac{molar\ mass}{N_A}$$

$$= \frac{12.0\times10^{-3}\text{kg}}{6.02\times10^{23}}$$

$$= 1.99 \times 10^{-26}\text{kg (3 sf)}$$

b) $$Density = \frac{mass}{volume}$$

$$\Rightarrow volume = \frac{mass}{density}$$

$$= \frac{1.99\times10^{-26}\text{kg}}{3500\text{ kg m}^{-3}}$$

$$= 5.69 \times 10^{-30}\text{ m}^3\text{ (3 sf)}$$

This calculation assumes the atoms completely fill the space (they are cubes). However, if we assume atoms are spheres, as in the next calculation, some of the bulk volume will be empty space. This means the density of an atom will be greater than the density of the material so the volume – and thus the radius – of an atom is less than the value calculated here.

c) $$V = \frac{4}{3}\pi r^3$$

$$\Rightarrow r = \sqrt[3]{\frac{3V}{4\pi}}$$

$$= \sqrt[3]{\frac{3\times5.69\times10^{-30}\text{ m}^3}{4\pi}}$$

$$= 1.11 \times 10^{-10}\text{ m (3 sf)}$$

d) $$r = r_0 A^{1/3}$$

$$= 1.25 \times 10^{-15}\text{ m} \times \left(12^{1/3}\right)$$

$$= 2.86 \times 10^{-15}\text{ m (3 sf)}$$

e) $$ratio = \frac{atomic\ radius}{nuclear\ radius}$$

$$= \frac{1.11\times10^{-10}\text{ m}}{2.86\times10^{-15}\text{ m}}$$

$$= 38\,811 = 38\,100\text{ (3 sf)}$$

Page 20 Test yourself

1 The Standard Model is a theory explaining the relationships between the fundamental particles and forces that make up the universe. It describes interactions between quarks, leptons, exchange particles and the fundamental forces.

2 Particles and their antiparticles have the same mass-energy but opposite charge.

3 1 MeV = 1.6×10^{-13} J

4 Leptons: electron; electron-neutrino; muon; muon-neutrino; tau; tau-neutrino.

Quarks: up; down; strange; charm; bottom; top.

5 a) -1e

b) 0

c) $+{}^{2}/_{3}\,e$

d) +1e

e) $-{}^{1}/_{3}\,e$

f) $-{}^{1}/_{3}\,e$

6 up quark; down quark; electron; electron-neutrino

7 A particle that cannot be broken up into smaller particles / a particle with no structure.

8 3

Page 21 Test yourself

9 up; down; strange; charm; bottom; top.
They all have different **masses**.

10 C – protons and electrons

11 Current observations show that quarks cannot be broken down into simpler building blocks, they do not have internal structure.

12 Bottom quark; proton; down quark; up quark; electron

13 Deep inelastic scattering involves firing very high energy electrons at protons. The electrons have enough energy to penetrate the proton and may be scattered or produce a shower of other particles so revealing the proton structure.

Page 24 Test yourself

14 Strong nuclear force – gluon

Electromagnetic force – photon

Weak nuclear force – $W^{\pm}$, Z^0 (W and Z bosons)

Gravity – graviton (not yet detected)

15 On the quantum scale, forces act by particles exchanging exchange particles – that is, they act when one particle interacts with another.

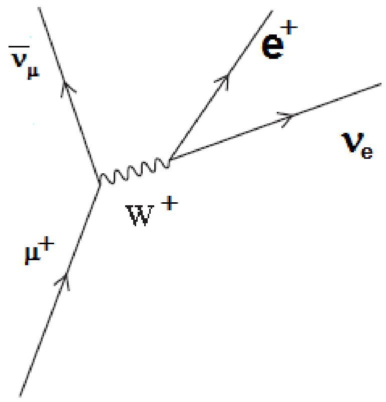
16 Exchange particles have extremely short lifetimes, effectively existing only during the actual interaction – hence virtual.

17 Alpha emission

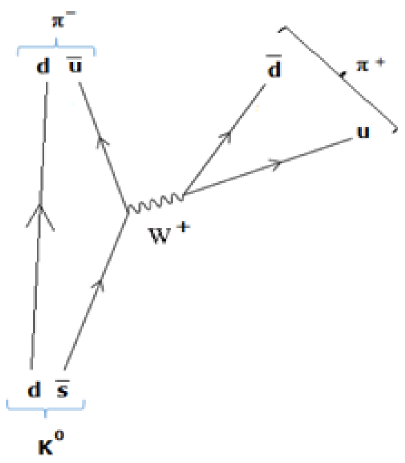
Page 26 Activity

Drawing Feynman diagrams

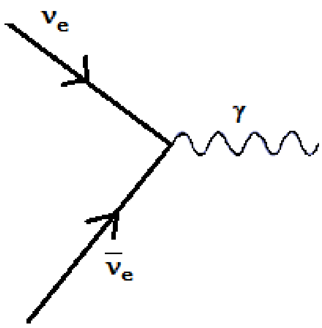
1 $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$



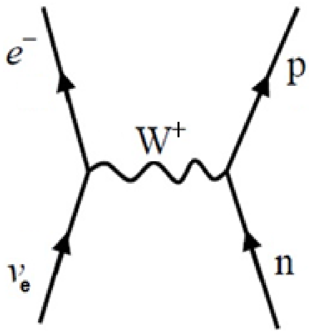
2 $K^0 \rightarrow \pi^- + \pi^+$



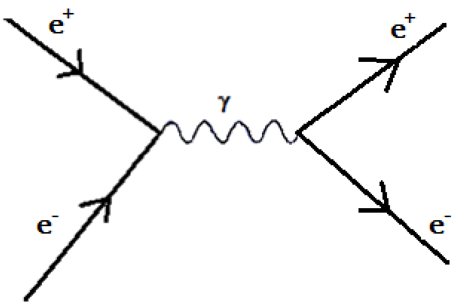
3 $\nu_e + \bar{\nu}_e \rightarrow \gamma$



4 $\nu_e + n \rightarrow e^- + p$



5 $e^- + e^+ \rightarrow e^- + e^+$



Page 27 Test yourself

18 a) muon

b) proton; pion; neutron

c) muon; photon

d) pion

e) photon

19 A meson is made up of a quark–antiquark pair, whereas a baryon contains three quarks.

20 All the leptons plus the $W^{\pm}$ and Z^0.

21 a) hadron; baryon

b) hadron; meson

c) exchange particle

d) lepton

Page 29 Test yourself

22 Total lepton number before interaction = total lepton number after interaction.

23 9.11×10^{-31} kg × 200 = 1.82×10^{-28} kg

24 L_{before} = (+1) + (-1) = 0

L_{after} = (-1) + (-1) = -2

The reaction cannot occur as it would violate the law of conservation of lepton number.

25 An anti-electron neutrino must be produced to conserve lepton number.
The neutron that decays and the resulting proton both have L = 0; the electron (β particle) has L = 1 – so an anti-lepton must be produced alongside it so that the total lepton number after emission is zero.

Page 31 Test yourself

26 Protons are made up of quarks: hadrons contain quarks.
A proton consists of two up quarks and one down quark: baryons are made of three quarks.

27 udd

28 One up quark changes into a down quark (producing a W^+ particle at the same time).

29 ${}^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}e + \nu_e$

$B: \quad +1 \longrightarrow +1 + 0 + 0$ ✓conserved

Page 33 Test yourself

30 a) proton: q = +1e; B = +1

b) antiproton: q = −1e; B = −1

c) neutron: q = 0; B = +1

d) electron: q = −1e; B = 0

e) antineutron: q = 0; B = −1

f) positron: q = +1e; B = 0

g) uds baryon: q = $(+{}^{2}/_{3}\,e - {}^{1}/_{3}\,e - {}^{1}/_{3}\,e)$ = 0; B = +1

h) $\bar{u}\bar{u}\bar{s}$ baryon: q = ($-{}^{2}/_{3}\,e - {}^{2}/_{3}\,e + {}^{1}/_{3}\,e$) = −1e; B = −1

i) dss baryon: q = ($-{}^{1}/_{3}\,e - {}^{1}/_{3}\,e - {}^{1}/_{3}\,e$) = −1e; B = +1

31 a) baryons (D)

b) baryons (D)

c) leptons (A)

d) exchange particles (C)

e) leptons (A)

f) mesons (E)

g) quarks (B)

h) baryons (D)

32 b, c, d, e, f and g

33 a, d, and e

34 a) ${}^{2}_{1}H$ – 2 baryons and 1 lepton: 1p; 1e; 1n

b) ${}^{4}_{2}He$ – 4 baryons and 2 leptons: 2p; 2e; 2n

c) ${}^{14}_{6}C$ – 14 baryons and 6 leptons: 6p; 6e; 8n

d) ${}^{23}_{11}Na$ – 23 baryons and 11 leptons: 11p; 11e; 12n

e) ${}^{238}_{92}U$ – 238 baryons and 92 leptons: 92p; 92e; 146n

f) ${}^{294}_{118}Uuo$ – 294 baryons and 118 leptons: 118p; 118e; 176n

Page 35 Activity

1 $p + \pi^- \rightarrow \Sigma^- + K^+$

Conservation Quantity	Before interaction			After interaction			Quantity conserved? ✓ or ×
	p	π^-	**Total**	Σ^-	K^+	**Total**	
Q	+1	−1	**0**	−1	+1	**0**	✓
B	+1	0	**+1**	+1	0	**+1**	✓
L	0	0	**0**	0	0	**0**	✓
S	0	0	**0**	−1	+1	**0**	✓

Possible: all quantities conserved

2 $p + \bar{\nu}_e \rightarrow e^+ + \Sigma^0$

Conservation Quantity	Before interaction			After interaction			Quantity conserved? ✓ or ×
	p	$\bar{\nu}_e$	**Total**	e⁺	Σ^0	**Total**	
Q	+1	0	**+1**	+1	0	**+1**	✓
B	+1	0	**+1**	0	+1	**+1**	✓
L	0	−1	**−1**	−1	0	**−1**	✓
S	0	0	**0**	0	−1	**−1**	×

Possible: strangeness is not conserved in a weak interaction

3 $n \rightarrow p + e^+ + \nu_e$

Conservation Quantity	Before interaction		After interaction				Quantity conserved? ✓ or ×
	n	**Total**	p	e⁺	ν_e	**Total**	
Q	0	**0**	+1	+1	0	**+2**	×
B	+1	**+1**	+1	0	0	**+1**	✓
L	0	**0**	0	−1	+1	**0**	✓
S	0	**0**	0	0	0	**0**	✓

Not possible: it violates conservation of charge

4 $p + e^+ \rightarrow e^- + \Sigma^0 + K^+$

Conservation Quantity	Before interaction			After interaction				Quantity conserved? ✓ or ×
	p	e⁺	**Total**	e⁻	Σ^0	K⁺	**Total**	
Q	+1	+1	**+2**	−1	0	+1	**0**	×
B	+1	0	**+1**	0	+1	0	**+1**	✓
L	0	−1	**−1**	+1	0	0	**+1**	×
S	0	0	**0**	0	−1	+1	**0**	✓

Not possible: it violates conservation of charge and lepton number

5 $n \rightarrow p + e^- + \bar{\nu}_e$ –

Conservation Quantity	Before interaction		After interaction				Quantity conserved? ✓ or ×
	n	**Total**	p	e⁻	$\bar{\nu}_e$	**Total**	
Q	0	**0**	+1	−1	0	**0**	✓
B	+1	**+1**	+1	0	0	**+1**	✓
L	0	**0**	0	+1	−1	**0**	✓
S	0	**0**	0	0	0	**0**	✓

Possible: all quantities conserved

6 $\pi^- + p \rightarrow n + \pi^0 + \bar{\nu}_e$

Conservation Quantity	Before interaction			After interaction				Quantity conserved? ✓ or ×
	π^-	p	**Total**	n	π^0	$\bar{\nu}_e$	**Total**	
Q	−1	+1	**0**	0	0	0	**0**	✓
B	0	+1	**+1**	+1	0	0	**+1**	✓
L	0	0	**0**	0	0	−1	**−1**	×
S	0	0	**0**	0	0	0	**0**	✓

Not possible: it violates conservation of lepton number

Page 36–37 Test yourself

35 $\pi^0 = u\bar{u}$ (or $d\bar{d}$, although this not given in the question)

$\pi^+ = u\bar{d}$

$\pi^- = d\bar{u}$

36 d) $\pi^+ \rightarrow \mu^+ + \mu^-$ (charge is not conserved)

37 a) R

b) S

c) Q

38 a)

Quark pair	$s\bar{s}$	$s\bar{d}$	$d\bar{s}$	$d\bar{d}$
Name	phi	kaon^0 (anti-symmetric)	kaon^0 (symmetric)	rho^0
Baryon number	0	0	0	0
Charge/e	0	0	0	0
Strangeness	0	-1	+1	0

b) They will have different mass-energies.

39 a) The existence of the top quark can be predicted from the Standard Model by symmetry: if there are 6 leptons, it would be odd to have only the 5 observed quarks.
The large mass-energy of the top quark meant it could only be observed when particle accelerators with enough energy to produce them had been built.

b) The detectors have a magnetic field at right angles to the path of the collision. The top quark and antiquark have opposite charges that travel in opposite directions inside the magnetic field.

c) X = W^-
Y = $\bar{\nu}_e$

40 $J/\psi \rightarrow e^{+} + e^{-}$

	J/ψ	e^{+}	e^{-}	Conserved, ✓ or ✗
(Rest) Energy, E	3.1 GeV	0.51 MeV	0.51 MeV	✓ – excess energy is transferred to kinetic energy
Momentum, *p*	0	+*p*	−*p*	✓ – electron and positron emitted in opposite directions
Charge, Q	0	+1e	−1e	✓
Baryon number, B	0	0	0	✓
Lepton number, L	0	−1	+1	✓

	J/ψ	μ^{+}	μ^{-}	Conserved, ✓ or ✗
(Rest) Energy, E	3.1 GeV	105.7 MeV	105.7 MeV	✓ – excess energy is transferred to kinetic energy
Momentum, *p*	0	+*p*	−*p*	✓ – muon and antimuon emitted in opposite directions
Charge, Q	0	+1e	−1e	✓
Baryon number, B	0	0	0	✓
Lepton number, L	0	−1	+1	✓

Pages 38–40 Practice questions

1 **a)** Hadrons are subject to the strong force. [1]

b) Quark–antiquark pair, $q\bar{q}$ [1]

c) Three quarks, qqq [1]

d) Similar: same mass-energy [1]

Different: opposite charge; opposite baryon number [1]

e) **i)** Q = -1e [1]

ii) B = -1 [1]

iii) $\bar{u}\bar{u}\bar{d}$ [1]

2 **a)** Lepton: electron *OR* muon [1]

Hadron: proton *OR* neutron *OR* pion [1]

b) Hadrons are subject to the strong force (leptons are not) *OR* hadrons are composed of quarks (leptons are not) [1]

c) Baryons are composed of three quarks (or three antiquarks) and mesons are composed of a quark–antiquark pair. [1]

d) Baryon: proton *OR* neutron [1]
Meson: pion [1]

3 a) [1 mark per correct row]

Sub-atomic particle	Quark structure	Baryon *OR* Meson	Relative charge	Baryon number	Strangeness
π^+, pion$^+$	$u\bar{d}$	meson	**+1**	0	**0**
n, neutron	udd	**baryon**	0	+1	0
Σ^+, sigma$^+$	**uus**	**baryon**	+1	**+1**	-1

b) e.g. proton: uud; and antiproton: $\bar{u}\bar{u}\bar{d}$ [1]

c) Same: mass-energy (*OR* strangeness *OR* baryon number) [1]

Different: charge *OR* lepton number [1]

4 a) electromagnetic [1]
photon [1]

b) Charge *OR* lepton number *OR* baryon number *OR* strangeness [1]

c) A: neutron [1]
B: electron-neutrino [1]
C: W+

d) Electron capture [1]

e) Charge *OR* baryon number *OR* lepton number [any 2]

Conservation Quantity	Before interaction			After interaction			Quantity conserved?
	p	e^-	Total	n	ν_e	Total	
Q	+1	-1	0	0	0	0	✓
B	+1	0	+1	+1	0	+1	✓
L	0	+1	+1	0	+1	+1	✓

[1 mark per correct row]

f) [Any 3 from the following:]

- Models can make predictions about (as yet) unobserved physics.
- Experiments can be set up to test the predictions of a model.
- Observations from experiments can support/disprove model (or lead to further experiments)
- If the model makes predictions that do not match reality, it is incorrect (or incomplete).
- Experimental observations that match the predictions support (or confirm) the model.

5 a) Weak interaction, as it involves leptons (and is mediated by W^- exchange particle). [1]

b) Charge and lepton number (or baryon number) [2]

c) Strange particles experience the strong interaction but decay via the weak interaction *OR* strange particles contain the strange quark. [1]

d) $K^+ \rightarrow \mu^+ + \overline{\nu_\mu}$ is not possible
as it violates law of conservation of lepton number. [2]

e) Weak interaction [1]

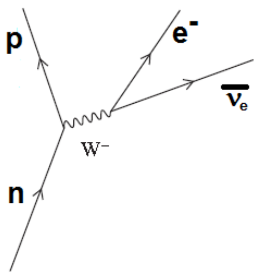
f) X must have lepton number = 0 as μ^- has L = +1 and $\bar{\nu}_\mu$ has L = -1 [1]
X cannot be a baryon as that would violate baryon conservation (all the other particles have B = 0). [1]
Therefore, it must be a meson.

g) Zero charge. [1]

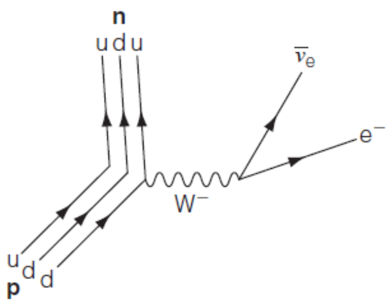
6 a) ${}^1_0n \rightarrow {}^1_1p + {}^0_{-1}e + \overline{\nu_e}$

b) In order for lepton number, L, to be conserved, [1]
since the electron emitted has L = +1, the other lepton must have L = -1. [1]
Therefore it must be an antineutrino, rather than a neutrino.

c)



OR



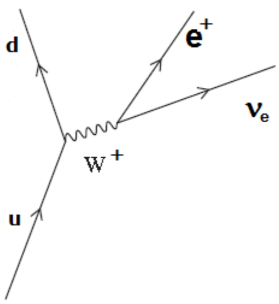
Correct particle symbols [1]
correct exchange particle [1]
correct connections of diagram [1]

d) electron-neutrino [1]

e) Na-23 nucleus – made of baryons *OR* daughter neutron (in Na-23 nucleus) – baryon [1]
positron – lepton [1]
electron-neutrino – lepton [1]

f) neutron – udd [1]
proton – uud [1]

g)



Correct particle symbols [1]
correct exchange particle [1]
correct connections of diagram [1]

7 a) [1 mark per correct row]

Conservation Quantity	Before interaction			After interaction			Quantity conserved?
	p	e⁻	Total	n	ν_e	Total	
Q	+1	-1	0	0	0	0	✓
B	+1	0	+1	+1	0	+1	✓
L	0	+1	+1	0	+1	+1	✓

b) Electron capture: ${}^{40}_{19}K + {}^{0}_{-1}e \rightarrow {}^{40}_{18}Ar + \nu_e$ [1]

Positron emission: ${}^{40}_{19}K \rightarrow {}^{40}_{18}Ar + {}^{0}_{+1}e + \nu_e$ [1]

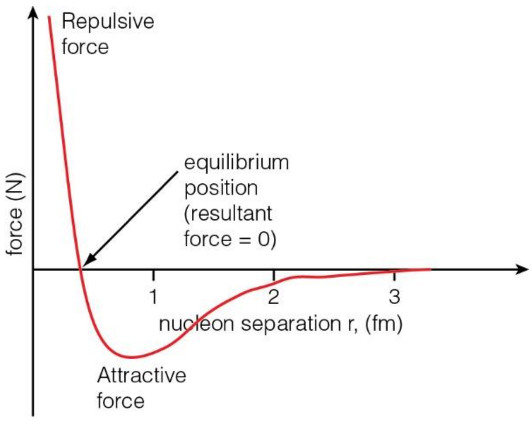
Beta minus decay: ${}^{40}_{19}K \rightarrow {}^{40}_{20}Ca + {}^{0}_{-1}e + \bar{\nu}_e$ [1]

8 a) Similarity: same charge [1].

Differences: protons are baryons, positrons are leptons *OR* different mass-energy *OR* protons contain quarks, positrons do not [1]

b) Gravity – graviton
Strong – gluon
Weak - $W^{\pm}$, Z
Electromagnetic – photon [All correct = 3; 2 correct = 2; 1 correct = 1]

c) Best described by drawing the graph:



repulsion/attraction in correct place [1]
equilibrium position identified [1]
values (approx.) [1]

d) Strong force [1]
exists only between quarks, positron is not a quark [1].

9 [Any 6 from the following:]

- Pions are mesons.
- Muons are leptons.
- Other mesons e.g. kaon
- Other leptons: electron; electron-neutrino; muon-neutrino; (tau and antiparticles)
- Properties in common: charge; zero baryon number; interact via the weak interaction.
- Charged pions and the muon can interact with other charged particles via the electromagnetic interaction.
- Pions and muons can interact with other particles via the weak interaction.
- Pions and muons are attracted to each other via the gravitational force because they have mass.
- Pions can interact with other hadrons via the strong interaction.

Page 41 Stretch and challenge

10 a) $Sigma^+$ = uus

b) π^+ = $pion^+$ = $u\bar{d}$

n = neutron = udd

c) Charge and baryon number (*OR* lepton number)

d) Strangeness

e) Weak interaction

f) ${}^1_0n \rightarrow {}^1_1p + {}^{0}_{-1}e + \bar{\nu}_e$

11 a) Weak interaction

b) 1 – up quark, u

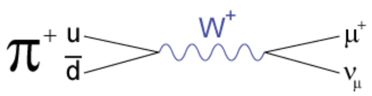
2 or 3 – electron anti-neutrino, $\bar{\nu}_e$

3 or 2 – electron, e^-

12 a) Weak interaction

b) W^+

c)



d) Conservation of momentum gives that $p_1 = -p_2$

Multiplying both sides by c and squaring:

$$c^2{p_1}^2 = c^2{p_2}^2 \qquad \textbf{[1]}$$

Using $E^2 = c^2p^2 + {m_0}^2c^4$ gives that:

$$c^2{p_1}^2 = {E_1}^2 - {m_1}^2c^4 \qquad \textbf{[2]}$$

and

$$c^2{p_2}^2 = {E_2}^2 - {m_2}^2c^4 \qquad \textbf{[3]}$$

Substituting **[2]** and **[3]** into **[1]** gives

$${E_1}^2 - {m_1}^2c^4 = {E_2}^2 - {m_2}^2c^4$$

Collecting terms and using the difference between squares:

$${E_1}^2 - {E_2}^2 = (E_1 + E_2)(E_1 - E_2) = ({m_1}^2 - {m_2}^2)\,c^4 \qquad \textbf{[4]}$$

Conservation of energy gives that:

$$E_1 + E_2 = Mc^2 \qquad \textbf{[5]}$$

Dividing **[4]** by **[5]** gives

$$E_1 - E_2 = \frac{({m_1}^2 - {m_2}^2)c^2}{M}$$

Adding **[5]** to each side gives

$$2E_1 = \frac{\left(M^2 + {m_1}^2 - {m_2}^2\right)c^2}{M}$$

hence

$$E_1 = \frac{\left(M^2 + {m_1}^2 - {m_2}^2\right)c^2}{2M}$$ as required.

Taking the square root of each side of **[2]** gives

$$cp_1 = \sqrt{E_1^2 - m_1^2c^4}$$ as required.

e) Taking $M = M_\pi$ =139.6 MeV/c^2, $m_1 = m_\mu$ = 105.7 MeV/c^2, $m_2 = m_\nu = 0$

and using $E_1 = \frac{\left(M^2 + {m_1}^2 - {m_2}^2\right)c^2}{2M}$

the total energy of the muon, $E_1 = E_\mu = \frac{\left(139.6^2 + 105.7^2 - 0^2\right)/c^2}{2 \times 139.6/c^2} = 109.8\ \text{MeV}$

Hence the kinetic energy is:

$$E_k = E_\mu - m_\mu c^2 = 109.8\ \text{MeV} - \left(\frac{105.7\text{MeV}}{c^2} \times\ c^2\right) = 4.1\ \text{MeV}$$