**Exam question: Muon Decay**

Cosmic rays mostly consist of high-energy protons. These protons can collide with atomic nuclei in the Earth’s upper atmosphere producing pions (π−). Pions are unstable and decay into high-energy muons (μ−).

(a)     (i)      Which of the following is the particle group for pions (π−)?

Tick (✔) the correct answer.

|  |  |
| --- | --- |
| Baryons |  |
| Leptons |  |
| Mesons |  |
| Photons |  |

**(1)**

(ii)     Complete the equation for the decay of a pion (π−).

π−     ⟶     μ−     +     \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

**(1)**

(b)     2.5 × 108 muons are created simultaneously above the EarthÙs surface.

These muons are unstable and have a half-life of 2.2 μs. They are created at a height of 10.7 km and travel towards the Earth’s surface with a constant vertical velocity of 2.85 × 108 m s−1.

(i)      Show that, for the reference frame of an observer on Earth, the time taken for the muons to reach the Earth’s surface is approximately 17 muon half-lives.

**(2)**

(ii)     Estimate the number of these muons that an observer on Earth would expect to remain after 17 half-lives.

number \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

**(2)**

(iii)     The number of muons that reach the Earth’s surface is considerably different from the estimated number in part **(b)(ii)**.

Identify the theory that explains the difference between the estimated and observed number of muons.

\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

**(1)**

(iv)     Outline why the number of muons that actually reach the Earth’s surface is different from the estimated number in part **(b)(ii)**.

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**(1)**

(v)     Calculate, for the reference frame of a muon, the time taken for the muons to travel this distance.

time \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ s

**(3)**

(vi)     Calculate the number of muons that remain at the end of the time interval calculated in part **(b)(v)**.

number \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

**(3)**

**(Total 14 marks)**

Mark schemes

**Q1.**

(a)     (i)      Only Box Ticked: Mesons

**1**

(ii)     (Muon) anti−neutrino symbol

*Not electron anti−neutrino*

*Penalise incorrect subscript*

**1**

(b)     (i)      Use of Speed = distance / time by rearrangement and 3.75 × 10−5 (s) seen

Or

10.7 × 103 ÷ 2.85 × 108 = 3.75 × 10−5 (s) seen

Or substitution **and** 3.75 × 10−5 (s) seen

No. of half-lives = 3.75 × 10−5 ÷ 2.2 × 10−6 = 17.065 or 17.07

**not 17.05 not 17.06**

At least 3 sf for answer 17.1

*3.75 × 10−5 ÷ 17 = 2.208 or 2.21 μs*

*At least 3 sf*

*Or*

*17 × 2.2 × 10−6 = 37.4 × 10−5* ***with comparison***

**2**

(ii)     2.5 × 108 × (1/2)17 or equivalent

1900 to 1910 (1910 maximum to 4 sf)

Answer consistent with any working seen

*Use of N = N0 𝑒−λt and λ =  correct sub*

*Answer in range 1.8 × 103 to 1.91 × 103*

*(1820 minimum and 1910 maximum to 4 sf)*

**2**

(iii)     (Theory of special) relativity

*Time dilation / length contraction treat as neutral*

*Not general relativity*

**1**

(iv)     •       Travelling close to speed of light less time passes in muon’s reference frame for the journey (so fewer decay)

•       Travelling close to speed of light so journey is shorter in length for the muon’s frame of reference (so fewer decay)

•       Travelling close to speed of light so muons are observed to travel further in a half−life (on Earth) than expected (so fewer decay during journey)

•       Travelling close to speed of light so muon’s half−life is observed to be longer (on Earth) (so fewer decay)

*Allow:*

*• travelling close to speed of light so time is slower (for muons) so fewer decay*

*• travelling close to speed of light so time dilates so fewer decay*

**1**

(v)     Attempted use of *L* = *L*o (1−*v*2/*c*2)1/2 or *t* = *t*o /(1−*v*2/*c*2)1/2

*Correct use of L = Lo (1−v2/c2)1/2* ***and*** *(to=L/v )= 3341/2.85 × 108*

**or** correctly makes *to* subject of *t = to /(1−v2/c2)1/2*

(to =) 1.17 × 10−5 or 1.2 × 10−5 (s)

*Condone mix up on L / Lo or t / to*

*1.2 × 10−4 s gets 1 mark*

*Sub for Lo as 10.7 × 103*

*Or sub for t = 3.75 × 10−5*

**3**

(vi)    Use of *T*½ = *ln*2/λ seen with sub for *T* ½

allow if seen in partial sub in *N* = *N*o *e− λt*

Use of *N* = *N*o *e− λt* with λ = 3.15 × 105 (or equivalent) and *t* = answer from b(v)

5.7 × 106 to 6.3 × 106

no ecf on answer

*Or use of no half−lives = *

**

***Only accept answers in this range***

*No ecf on answer*

**3**

**[16]**