Question 14 **(15 marks)**

Muons and anti-muons are unstable, with the decay process producing three particles. When an anti-muon ($\overline{\mu}$) decays, one of these particles is an electron neutrino (ν_e).

(a) Complete the table below and use your answers to identify the missing particle X. (3 marks)

$$\overline{\mu} = X + \nu_e + \overline{\nu_\mu}$$

Reaction	$\overline{\mu}$	=	X	ν_e	$\overline{\nu_\mu}$
Conservation of electron charge	+1	=		0	0
Conservation of Lepton number	−1	=		+1	−1

Particle X: _____

Muons created in the upper atmosphere (approximately 10 km above the Earth's surface) are secondary products from highly-energetic cosmic ray interactions with nuclei of atmospheric particles. In their own frame, muons have a mean lifetime of 2.20×10^{-6} s, with some lasting for up to 3.0×10^{-6} s.

The speed of muons from cosmic rays entering the Earth's atmosphere moving in the direction of the observer on the Earth is in the range of $2.960 \times 10^8 - 2.997 \times 10^8$ m s^{-1}.
(Ignore the effect of the Earth's magnetic field on the muons when answering the following questions.)

(b) Use non-relativistic physics to calculate the mean distance muons moving at 2.991×10^8 m s^{-1} could travel. (2 marks)

_____ m

(c) (i) Calculate the mean lifetime of muons travelling at $0.997c$ as observed from the Earth. (2 marks)

_____ s

(ii) What is the actual mean distance travelled by such muons through the atmosphere as observed from the Earth? (2 marks)

(d) Using information from the question, explain why a small number of muons reach the Earth. (2 marks)

(e) With the use of a calculation, explain why these muons reach the Earth from the perspective of the muons. (4 marks)