8 Read the passage below and answer the questions that follow.

The Sun Only Shines Because of Quantum Physics

The Sun delivers light and heat, over a distance of 150 million kilometres to Earth, making life possible. Each square metre of Earth receives about 1400 W of power from the Sun, enough to maintain liquid water. Like all stars, the Sun's energy comes from nuclear fusion in its core, enabled by the principles of quantum physics.

Starlight has been the primary energy source in the Universe since the Big Bang. Stars form from large clouds of hydrogen and helium that contract under gravity, heating their cores to extreme temperatures. In the Sun, nuclear fusion starts at about 4 million kelvins and requires densities higher than solid lead. However, classical physics calculations show that protons in the Sun's core don't have enough energy to overcome their mutual electrostatic repulsion, known as the Coulomb barrier.

Despite this, the Sun shines because of quantum mechanics. Inside the Sun, temperatures range from 4 million to 15 million kelvins. Protons (hydrogen nuclei) fuse into helium in a process that releases energy. This energy is transported as photons, which take around 100,000 years to reach the Sun's surface, and as neutrinos, which escape almost immediately.

The fusion process involves combining four protons to form a helium nucleus, releasing about 0.70% of the mass as energy according to $E = mc^2$. Each second, the Sun converts around 10^{38} protons into energy, producing a power output of 4×10^{26} Watts. Given the Sun's immense size, with a diameter 109 times that of Earth and a mass 300,000 times greater, this process occurs over a vast volume.

However, when you do your calculations, you find a shocking conclusion: there are zero collisions happening to lead to nuclear fusion. Zero. None at all. Here's where quantum mechanics, specifically quantum tunnelling and the Heisenberg Uncertainty Principle, come into play.

Furthermore, protons behave as waves, and their wavefunctions can overlap. When this happens, there's a finite probability that protons can "tunnel" through the Coulomb barrier, even without the required classical energy. The odds of fusion occurring during a proton-proton collision are about 1 in 10^{28}.

The Sun's energy output is a testament to the principles of quantum mechanics. Without quantum tunnelling and the uncertainty principle, the Sun would not shine, and Earth would be a cold, lifeless rock. Our very existence hinges on these quantum phenomena, highlighting the profound impact of quantum physics on the cosmos.

(a) Considering the Sun to be a point mass,

(i) show that the Sun emits a total power of 4.0×10^{26} W.

[2]

(ii) The Stefan-Boltzmann law states that the power P radiated by a black body is proportional to the fourth power of its temperature T and its surface area A,

$$P = \sigma A T^4,$$

where $\sigma = 5.7 \times 10^{-8}$ W m^{-2} K^{-4}.

1. Use SI base units to show that the equation is homogeneous.

[2]

2. Use your answer in **(a)(i)** to determine the effective surface temperature of the Sun. Radius of Earth = 6370 km.

temperature = ………………….. K [2]

(b) **(i)** Given the range of the temperature in the Sun and considering that the proton behaves as an ideal gas, determine the maximum speed that a proton can move in the Sun.

speed = ………………... m s^{-1} [2]

(ii) Hence, determine the closest distance that two protons will come together, assuming that they are initially very far apart.

distance = …………………... m [2]

(iii) Explain why the value in **(b)(ii)** suggest that that the protons would not undergo fusion.

…………………………………………………………………………………………………...

…………………………………………………………………………………………………...

…………………………………………………………………………………………………...

………………………………………………………………………………………………….. [2]

(iv) Suggest how Heisenberg Uncertainty Principle implies that the protons can still undergo fusion reaction.

…………………………………………………………………………………………………...

…………………………………………………………………………………………………...

…………………………………………………………………………………………………...

………………………………………………………………………………………………….. [2]

(c) **(i)** The overall nuclear reaction can be summarised as:

$$4p \rightarrow He + 2e^{+} + 2\nu + \text{gamma}.$$

Given the mass of proton to be 1.007276*u* and mass of helium nucleus to be 4.002603*u*, determine the energy release in each nuclear fusion reaction.

energy = ………………... J [2]

(ii) The passage says that "The fusion process involves combining four protons to form a helium nucleus, releasing about 0.70% of the mass."

By making appropriate calculations, comment on the validity of this statement.

…………………………………………………………………………………………………...

……………………………………………………………………………………………. [2]

(d) **(i)** Quantum tunneling is a quantum mechanical phenomenon where particles can pass through a potential barrier that they classically should not be able to pass. This occurs because, at a quantum level, particles like protons can behave both as particles and as waves, described by a probability wavefunction.

The probability P of a particle tunneling through a barrier can be approximated using the relationship:

$$P \approx e^{-2\gamma d}$$

where

- d is the width of the barrier = 1.8×10^{-13} m,
- $\gamma = \dfrac{\sqrt{2m(U-E)}}{\hbar}$
  - m is the mass of the proton,
  - U is the height of the potential barrier = 10^{-13} J,
  - E is the energy of the particle = 10^{-16} J,
  - $\hbar$ is the reduced Planck constant = $\dfrac{h}{2\pi}$.

Determine the probability P of the proton tunneling through the potential barrier to undergo fusion.

probability = …………………... [2]

(ii) Despite the small probability that protons can tunnel through the potential barrier, the Sun still burns brightly.

Suggest a reason how this can happen.

………………………………………………………………………………………...

……………………………………………………………………………………… [1]

[Total: 21]