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## P1 1 Could the Sun Survive without Quantum Mechanics?

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### Abstract

This paper explores the conditions required for proton-proton fusion to occur in the Sun without the aid of quantum mechanics. It is found that, in its current form, the Sun could not sustain fusion without quantum tunnelling [1]. For fusion to occur classically, the Sun would need to reach a minimum temperature of approximately  $T = 1.1 \times 10^{10}$  K. At such a high temperature, the resulting radiation pressure would exceed the gravitational pressure required to maintain hydrostatic equilibrium, rendering the star unstable. Other potential conditions for classical fusion include star collisions and areas of extreme magnetic confinement.

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### Introduction

All stars produce energy from nuclear fusion, and in the Sun's case, hydrogen nuclei (protons) fuse to form helium, generating the sunlight we see. This process depends on whether the protons can overcome the electrostatic repulsion between them and get close enough to fuse, a process that is difficult through classical mechanics and may require quantum mechanics to be sustained. This paper will explore why quantum mechanics is required for fusion in the Sun, a topic that has been discussed in Carroll and Ostlie's *An Introduction to Modern Astrophysics* [1]. However, the main focus of this paper will be to explore under what circumstances, and to what extent, it would be feasible for the Sun to produce energy in the absence of quantum mechanics.

### Why Quantum Mechanics is Needed

Classically, proton-proton fusion requires overcoming the Coulomb barrier arising from the electrostatic repulsion displayed by two similarly charged particles [2]. The magnitude of this bar-

rier can be calculated using Coulomb potential equation, and evaluating the equation for two protons with separation  $1 \times 10^{-15}$  m yields a Coulomb repulsion value of 1.44 MeV. This value is a factor of  $\sim 10^3$  larger than the average particle energy ( $\frac{3}{2}k_B T$  [3]) found at the core of the Sun [4]. Based on these calculations alone, nuclear fusion in the solar core would be effectively impossible, and the Sun should not produce the sustained luminosity that we see today. However, in reality, it is the Gamow peak that gives rise to proton-proton fusion within the Sun. This peak is given by the product of the probability of quantum tunnelling [5] with the probability of a higher proton energy in the Maxwell-Boltzmann distribution [6]. In the case of proton-proton fusion in the Sun the Gamow peak is  $\sim 6$  keV [7].

### Is Classical Fusion Possible?

Now it is clear that our current Sun would not be able to sustain energy production without quantum mechanics. What circumstances would be required for quantum mechanics to no longer be

needed? The simplest way to give the protons enough energy to overcome the Coulomb barrier is to increase the temperature of the star. Assuming that sustainable proton-proton fusion can take place if the mean proton energy matches the Coulomb potential, and taking this potential to be 1.44 MeV, star temperatures can be calculated with the equation,

$$T = \frac{2E}{3k_B} \quad (1)$$

This yields minimum temperatures in the order of  $T = 1.1 \times 10^{10}$  K, a star at this temperature would exhibit extreme luminosity, greater than that displayed by even the most massive stars currently known. Temperatures at this level are only seen in the most violent cosmic events such as supernovae and neutron star mergers. To assess whether the Sun at this high *classical* temperature could remain hydrostatically balanced, we can compare the radiation pressure with the characteristic pressure required to support the Sun against gravity. Using the calculated *classical* temperature and a core density of  $\rho = 1.5 \times 10^5 \text{ kg m}^{-3}$  [1], the radiation pressure is [1],

$$P_{\text{rad}} = \frac{\alpha T^4}{3} \quad (2)$$

This yields a result of  $3.69 \times 10^{24}$  Pa. For comparison, the central gravitational pressure found in the core of the Sun that can be estimated using [1],

$$P_{\text{grav}} \approx \frac{3GM_{\odot}^2}{8\pi R_{\odot}^4} \quad (3)$$

Which gives a gravitational pressure of  $\sim 1.34 \times 10^{14}$  Pa. From these calculations, it can be seen that the radiation pressure is a factor of  $\sim 2.75 \times 10^{10}$  larger than the characteristic gravitational pressure. Therefore the Sun would not be able to remain stable at this temperature. It should be noted that a gas pressure also contributes to outward pressures, however in these conditions the radiation pressure dominates. Other problems also arise at such high temperatures such

as neutrino cooling, which becomes significant at high core temperatures and densities. Loss of energy due to neutrino cooling would dominate over energy gained from nuclear fusion. Another possible condition that could give rise to classical proton-proton fusion is extreme shock heating during the collisions of massive stars. In white dwarf mergers, for example, shocks can heat material to temperatures exceeding  $10^9$  K [8]. However, in violent events such as these, if particles are given sufficient energy to fuse classically, the energy output would not be continuous but highly explosive. Moreover, in such violent events competing processes need to be taken into account such as neutron capture and photodisintegration, as under these conditions these processes become dominant, making the survival of a bound stellar remnant implausible. The final condition that could make classical proton-proton fusion possible is extreme magnetic confinement. Intense magnetic reconnection where magnetic field lines break and reconnect, can convert stored magnetic energy into particle acceleration and plasma heating, reaching temperatures of order  $10^8$  K [9]. However, these regions are low in density and classical fusion would be rare, therefore it would be an unrealistic suggestion for suitable survival of our Sun.

### Conclusion

To conclude, it can be said that the Sun in its current form could not survive without quantum mechanics. For it to do so, it would need to be at a temperature of approximately  $T = 1.1 \times 10^{10}$  K, and at such high temperatures it was found that the radiation pressure would far exceed the gravitational pressure, suggesting the star would be unable to remain stable. Other possible conditions that might permit classical proton-proton fusion include star mergers, although the energy output would be highly explosive rather than steady. Another possibility is in areas of extreme magnetic confinement, however, in this situation fusion would still be rare and localised to sustain the entire Sun.

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