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SOLUTION OF THE SOLAR NEUTRINO PROBLEM

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ABSTRACT

The assumption that coulomb barrier tunneling in stars is a two-body process is incorrect. Tunneling is mediated by an electron passing between the particles as they collide. The presence of an electron lowers the potential barrier and increases the probability of tunneling by orders of magnitude. The solar luminosity can be maintained with a central temperature near 10^7K where the neutrino production rate corresponds to the observed rate. All current stellar interior and and evolutionary models are incorrect.

Subject headings: neutrinos — nuclear reactions — stars: interiors — sun: interior

I was conditioned from elementary school onward to think that the sun is powered by the proton-proton reaction in which two protons collide to form deuterium. In that reaction and in subsequent reactions in the pp chains, neutrinos are produced that travel straight from the center of the sun to the earth where they can be measured in very massive detectors. The number measured is considerably less than that predicted by our current theories of nuclear reactions and of the physical conditions at the center of the sun. This whole problem is reviewed by Bahcall (1989).

As the pp reaction $p + p > d + e^+ + \nu$ can be produced by accelerating protons in the laboratory, there is no question that it is a real reaction in which two protons move toward each other with enough energy to quantum-mechanically tunnel through their repulsive coulomb potential and combine. The proton-proton reaction, coulomb-barrier tunneling, and statistical Debye-Hückel electron shielding are discussed in many texts, for example, Rolfs and Rodney (1988). However, the fact that a reaction takes place in an accelerator does not imply that it occurs in a dense plasma at the center of a star. At the center of the sun the temperature is on the order of 15 x 10^6K, the proton density is on the order of 10^{26} protons-cm^{-3}, and the electron density in on the order of 10^{26} electrons-cm^{-3}. Typical velocities are 500 km s^{-1} for protons and 20,000 km s^{-1} for electrons. Slowly moving electrons tend to cluster around slowly moving protons. The electron cluster reduces the proton effective charge by a small amount near the proton and cuts it off completely at a radius of about 10^{-9} cm. Neither fast electrons nor fast protons are aware of a slow proton until they penetrate the shielding electron cluster at which point they are immediately attracted or repelled by the coulomb potential. As the electrons typically move 40 times faster than the protons, the electron-proton collision frequency must be about 40 times the proton-proton collision frequency. A colliding fast proton decelerates from 2000 or 3000 km s^{-1} to 0 km s^{-1} relative velocity by the time it reaches a separation of 10^{-10} cm, which is only 90% of the distance to the target proton. Unless they tunnel, protons are always far apart on a nuclear scale because the nuclear interaction radius is on the order of 10^{-13} cm. A proton-proton collision is a slow process. An electron-proton collision is much faster. A colliding fast electron passes through the shielding electron cluster at, say, 100,000 km s^{-1} and is immediately accelerated toward the central proton. In some collisions the electron passes near the proton, through the volume inaccessible in a proton-proton collision.

A proton can suffer both a proton and an electron collision simultaneously. Such collisions may be infrequent but they are more probable than tunneling. They are not independent in that the two colliding protons are not completely shielded by the electron cluster and can actually attract passing electrons. When a fast electron penetrates the electron cluster during a proton-proton collision it is attracted by both protons and can pass between them. The electron shields the protons from each other and accelerates them toward each other. When the electron leaves, the two protons are closer than they would have been on their own and the tunneling probability has greatly increased. The reaction $p + p + e > d + e + e^+ + \nu$ requires lower proton energies than the reaction $p + p > d + e^+ + \nu$. A solar central temperature of, say 10 x 10^6K produces the same yield as 15 x 10^6K for the pp reaction. The alternative branch $p + p + e > d + \nu$ is also possible. Other reactions in the various pp chains are affected by electrons as well. The net result of considering the plasma environment is that the neutrino generation rate falls to the observed rate.

The real physics of this and other coulomb barrier tunneling reactions is very complicated. They are three-body, relativistic, quantum collisions. I hope that quantum mechanicians can quickly provide us with new reaction rates because at the present time all stellar interior and evolutionary modelling is incorrect.

REFERENCES

Bahcall, J.N. 1989, Neutrino Astrophysics (Cambridge: Cambridge University Press)

Rolfs, C.E. & Rodney, W.S. 1988, Cauldrons in the Cosmos (Chicago: University of Chicago Press)