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Review Article

The Fate of Solar Neutrinos

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Abstract: The history of attempts to reconcile the amount of neutrino flux arriving at the earth's surface from the sun with the profile of fusion reactions occurring on the sun is recounted. Less than half the expected number of neutrinos is actually found, which has raised questions about the reliability of the method of detection used. It is pointed out that there is a key theoretical assumption which may be incorrect, however, namely that every fusion reaction necessarily leads to the emission of a single neutrino. While this assumption is amply verified for reactions taking place under normal laboratory conditions, arguments are presented that indicate that the situation could be significantly different at the high temperatures occurring in stellar atmospheres.

Keywords: Fusion reactions, neutrino production mechanisms, activation barriers.

I. INTRODUCTION

One of the enduring mysteries in the field of particle physics is the fact that observations of fusion reactions occurring on the sun do not appear to be consistent with the neutrino flux arriving at the earth's surface. It is well established that nuclear reactions of various types dominate in processes binding stellar material together, and details regarding their rates and relative occurrence in the sun's core are well understood [1]. The neutrino plays a potentially crucial role in the field of astronomy because of its ability to penetrate through dense material such as that contained in stars. However, as mentioned in Sect. 3 of Ref. [2], careful measurements of the solar flux reaching the earth [3] have led to the conclusion that less than half of the neutrinos expected on the basis of the above theoretical conclusions are actually observed.

A number of different reactions are involved, but the overall production of neutrinos on the sun is governed by the elemental process in which two protons combine with a single electron to produce a deuteron plus one neutrino. Although vast amounts of matter are involved and the cross section for neutrino detection is extremely small, it can still be argued strongly that the discrepancy between theory and experiment cannot simply be explained away on the basis of faulty observation. On the other hand, the number of protons

undergoing fusion on the sun would appear to be equally well established, so that no legitimate doubt can be raised on this basis either. Especially since the solar neutrino puzzle has been with us for half a century [3], it seems highly possible that a solution exists which does not cast doubt on either the accuracy of the data employed to explain the sun's changing composition with time or the reliability of the pertinent experimental neutrino detection techniques.

II. THEORY OF NEUTRINO REACTIONS

The neutrino-producing reaction referred to above is closely related to eqs. (2.1) in Ref. [2], also given below: Accordingly, in eq. (ii) it is necessary *that a neutrino be created at the time of the fusion reaction.*

β decay:	$n \rightarrow p^+ + e^- + \bar{\nu}$
β+ decay	$p^+ \rightarrow n + e^+ + \nu$
electron capture:	$e^- + p^+ \rightarrow n + \nu$
$\bar{\nu}$ absorption:	$\bar{\nu} + p^+ \rightarrow n + e^+$
ν absorption:	$\nu + n \rightarrow p^+ + e^-$

In the previous discussion [2], we have consistently employed an alternative interpretation based on the corresponding eqs. (2.1'), also given below:

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i´)	$p^+e^-\nu(n)\rightarrow p^++e^-+\bar{\nu}$
ii´)	$e^+e^-+\nu\,\bar{\nu}+p^+\rightarrow p^+e^-\,\bar{\nu}\,(n)+e^++\nu$
iii´)	$\nu\,\bar{\nu}+e^-+p^+\rightarrow p^+e^-\,\bar{\nu}\,(n)+\nu$
iv´)	$e^+e^-+\bar{\nu}+p^+\rightarrow p^+e^-\,\bar{\nu}\,(n)+e^+$
v´)	$\nu+p^+e^-\,\bar{\nu}\,(n)\rightarrow p^++e^-+\nu\,\bar{\nu}$

In this view, in eq. (ii') a $\nu\,\bar{\nu}$ binary species present at the start of the reaction *is dissociated* to produce both the departing neutrino and the antineutrino required for neutron formation. Elemental balance is restored to the fusion reaction and no particles need to be either created or destroyed in the process.

Calculations with the exponentially damped Breit-Pauli Schrödinger (XBPS) Hamiltonian [4] lead to a relatively deep energy minimum for the $\nu\,\bar{\nu}$ system (Fig.1) as a function of basis set scale factor, which can be interpreted in terms of a mass-less bound state with a relatively small inter-particle distance ($r \leq \alpha^2$). In this model the $\nu\,\bar{\nu}$ system can be looked upon as a diatomic system undergoing a reaction in which the bond holding the two component particles together first needs to be broken. If a molecule such as N_2 reacts with a heavy atom according to the equation, $N_2 + X \rightarrow NX + N$, it is generally necessary to add an amount of energy equal to the N_2 D_0 value of 9.92 eV to break the strong N-N bond. If the molecule exists in one of its high-lying ro-vibrational states, a much smaller amount of energy is needed for this purpose, however, and the probability of inducing a reaction is likely to be enhanced as a result. More generally, one speaks of an activation barrier [5,6] to such reactions, with the reaction rate increasing as the higher vibrational levels of the reactant complex become more densely populated.
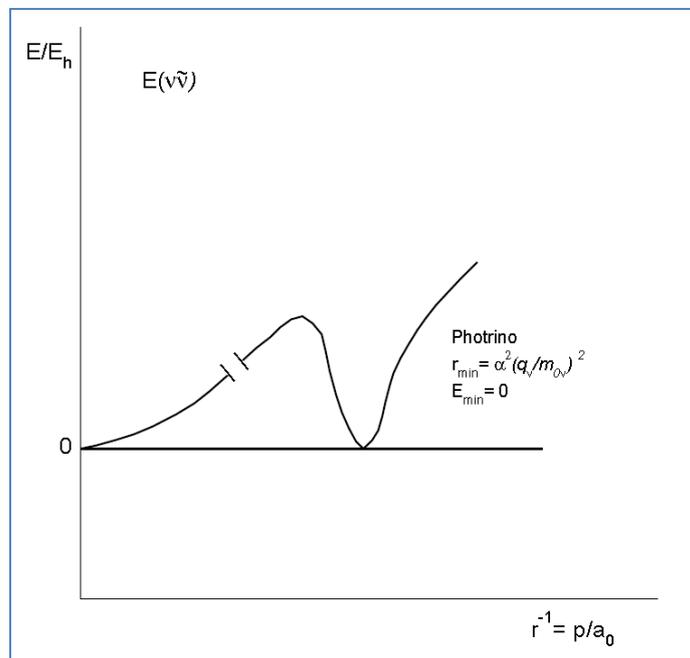
Fig-1: Schematic diagram showing the proposed variation of the $\nu\,\bar{\nu}$ system's internal energy as a function of the reciprocal of the distance between the two constituent particles. Only one minimum is expected, in contrast to the e^+e^- case shown in Fig. 1 of Ref. [7], at which point the total energy vanishes exactly, i.e. corresponding to a binding energy of $2m_{0\nu}c^2$ for the tightly bound $\nu\,\bar{\nu}$ (photrino) system.

The $\nu\,\bar{\nu}$ binary system discussed in Sect. 2 of Ref. [4] does not have a series of ro-vibrational levels comparable to those of a diatomic molecule, but it does have a definite energy barrier for dissociation (Fig. 1), the value of which could be a key factor in understanding the results of the solar neutrino observations [3]. It seems at least conceivable that at the high temperatures present in the solar environment (for which kT is on the order of a keV), the equilibrium distribution between bound and separated $\nu, \bar{\nu}$ pairs, would be shifted significantly toward the side of free neutrinos and antineutrinos compared to what is observed under typical laboratory conditions. If, as seems likely, the probability of (essentially) free antineutrinos participating in the key solar fusion processes is considerably greater than for their counterparts found in tightly bound $\nu\,\bar{\nu}$ binary systems, a relatively small change in the position of the above equilibrium could lead to a significant variation in the energy profile of the neutrinos produced in such reactions.

$$\nu\,\bar{\nu} \rightleftarrows \nu + \bar{\nu} \qquad (1)$$

III. DETAILS OF THE SOLAR FUSION REACTIONS

In terms of eq. (iv'), the simplest fusion reaction (deuteron d production),

$$p^+ + p^+ + e^+ e^- + \nu\, \bar{\nu} \rightarrow d^+ + e^+ + \nu \qquad (2)$$
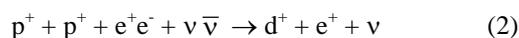
would now be replaced in a large number of cases by its "neutrinoless" counterpart,

$$p^+ + p^+ + e^+ e^- + \bar{\nu} \rightarrow d^+ + e^+. \qquad (3)$$
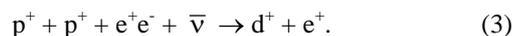
In the latter process the positron is emitted with a mono-energetic spectrum, rather than the continuous range of values expected from eq. (2), and none of the excess energy is transmitted to a neutrino. Similarly, the other most commonly occurring solar fusion reaction,

$$^7Be + e^- + \nu\, \bar{\nu} \rightarrow {}^7Li + \nu \qquad (4)$$
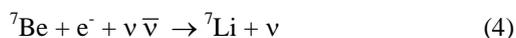
in which mono-energetic neutrinos are produced (0.86 Me V), becomes

$$^7Be + e^- + \bar{\nu} \rightarrow {}^7Li \qquad (5)$$

When free antineutrinos are available. Again, no neutrino is expected to result from this reaction, at least as long as the excess energy can be carried away by another particle such as a photon. In both cases the effect would be a substantial reduction in the number of neutrinos otherwise expected to reach the earth's surface with sufficient energy to undergo the capture reaction employed in the experimental detection scheme of Davis and coworkers [3].

IV. CONCLUSION

If one assumes that the neutrinos produced in fusion reactions are simply created from nothing as a means of carrying off the energy expended in such processes, there is seemingly no need to consider initial reaction conditions in attempting to predict the energy distribution of the emitted particles. The situation changes dramatically, however, if one recognizes the possibility that the antineutrinos and neutrinos normally observed are actually produced by the dissociation of binary systems in which these particles are strongly bound together. In this case, questions about the equilibrium concentration of bound and unbound species under a given set of experimental conditions, as well as their comparative re-activities, need to be answered in order to obtain a reliable prediction of the outcome of such processes.

This could mean, for example, that the standard eqs. (2) and (4) are replaced by eqs. (3) and (5), respectively, in a significant number of cases. This occurrence would provide a clear explanation of why the amount of the neutrino flux reaching the earth's surface is notably less than expected, without finding fault with either the data believed to be accurate for the frequency of solar reactions or the experimental methods used to detect the neutrinos once they have arrived at the earth's surface. That could be the key to finally solving the neutrino puzzle after so much time has passed since Davis and Bahcall [3] first pointed out its existence.is 1964.

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