Physics Faculty Publications and Presentations | Physics

6-1-1984

Energy losses of solar neutrinos and the oscillation hypothesis

P.T. Leung
Portland State University

S. Boedo

M. L. Rustgi

Let us know how access to this document benefits you.

Follow this and additional works at: http://pdxscholar.library.pdx.edu/phy_fac

Part of the Physics Commons

Citation Details

Energy losses of solar neutrinos and the oscillation hypothesis

P. T. Leung

Physics Department, Tamkang University, Tamsui, Taiwan 251, Republic of China

S. Boedo* and M. L. Rustgi

Physics Department, State University of New York, Buffalo, New York 14260

(Received 12 December 1983)

A formula for the stopping power of neutrinos interacting via the standard weak-interaction model, but incorporating the possibility of neutrino oscillations among the three flavors, is derived. The results are applied to study the solar-neutrino anomaly and it is found that the anomaly cannot be accounted for by many orders of magnitude from consideration of the energy losses of the neutrinos interacting with the solar matter, even if the oscillation hypothesis is found to be valid.

Ever since the experiment performed by Davis and his collaborators[1] and the discrepancy observed between the experimental data and the theoretical results calculated based on the standard solar model, the solar-neutrino anomaly has puzzled theorists and experimentalists. In two previous publications,[2,3] the possibility of explaining the anomaly from consideration of the energy losses of the neutrinos interacting with the electrons in the solar plasma has been investigated. In particular, by considering the possible electromagnetic and weak interactions between the neutrinos and the electrons, it had been concluded that the anomaly is not likely to be accounted for from considerations of the energy losses of the solar neutrinos. In order to have a more complete conclusion, in this note we reinvestigate the problem of the energy losses taking into account the possibility of oscillations of the neutrino among its three flavors: ν_e, ν_μ, and ν_τ.

Because of the possibility of the mixing of the neutrino mass eigenstates and weak eigenstates in the standard Weinberg-Salam model, a neutrino can oscillate among the three flavors ν_e, ν_μ, and ν_τ (corresponding to the three known leptons e, μ, and τ) as it travels in space.[4] Taking into consideration this oscillation process, we shall work out the ν_e-e scattering cross section. For antineutrinos, the $\bar{\nu}_e$-e scattering process has been worked out by Halls and McKellar,[5] in terms of the recoil energy Q of the electron; the result is[6]

$$
\frac{d\sigma}{dQ} = \frac{G^2 m_e}{2\pi} \left\{ P_e(t) \left[4\left(1 - \frac{Q}{E_\nu}\right)^2 + 4(g_A + g_V)\left(1 - \frac{Q}{E_\nu}\right)^2 + (g_A - g_V)\frac{m_e Q}{2E_\nu^2} \right] \right.
$$
$$
\left. + (g_A + g_V)^2\left(1 - \frac{Q}{E_\nu}\right)^2 + (g_A - g_V)^2 + \frac{m_e Q}{E_\nu^2}(g_A^2 - g_V^2) \right\} ,
\tag{1}
$$

where m_e is the mass of the electron, E_ν is the energy of the incident neutrino, and

$$
\frac{G^2 m_e}{2\pi} = 4.1 \times 10^{-45} \text{ cm}^2/\text{MeV}, \quad g_V = -\tfrac{1}{2} + 2\sin^2\theta_W, \quad g_A = -\tfrac{1}{2} .
\tag{2}
$$

The quantity $P_e(t)$ in Eq. (1) is the probability of the electron antineutrino to preserve its identity at a time t satisfying the relation

$$
P_e(t) + P_\mu(t) + P_\tau(t) = 1 .
\tag{3}
$$

Though the results quoted in Ref. 5 indicate the insensitivity of the energy loss in the sun of solar neutrinos to ν_e, ν_μ, and ν_τ oscillations, the ν_e-e scattering cross section cannot be obtained simply by replacing g_A by $-g_A$ in Eq. (1), since the scattering occurs via a mixture of charged and neutral currents for the ν_e-e (Ref. 7) process, while only the neutral current contributes to the ν_μ-e and[8] ν_τ-e scattering processes. To do this, we have to go back to the original formalism with the constants C_L and C_R associated with the left and the right electron currents, respectively.[9] The result reexpressed in terms of the g_A and g_V in Eq. (2) is

$$
\frac{d\sigma}{dQ} = \frac{G^2 m_e}{2\pi} \left[P_e(t)\left[4(g_A + g_V + 1) + 2(g_A - g_V)\frac{m_e Q}{E_\nu^2} \right] + (g_A + g_V)^2 + (g_A - g_V)^2\left(1 - \frac{Q}{E_\nu}\right)^2 + \frac{m_e Q}{E_\nu^2}(g_A^2 - g_V^2) \right] .
\tag{4}
$$

It should be remarked that in the case when $P_e(t) = 1$, i.e., no oscillation occurs, both Eqs. (1) and (4) give back the well-known results due first to 't Hooft and others.[10]

To apply Eq. (4) to study the energy loss of solar neutrinos, we compute the stopping power for neutrinos in the high-Q limit treating the solar electrons to be free. Following the theory of energy losses,[11,12] we obtain

         ©1984 The American Physical Society

TABLE I. Stopping power and energy loss for solar neutrinos for two values of P_e.

E_ν (MeV)	Q_m (MeV)	$P_e = 0.4$ $-\frac{dE}{dS}$ (MeV/cm)	$-\Delta E$ (MeV)	$P_e = 1.0$ $-\frac{dE}{dS}$ (MeV/cm)	$-\Delta E$ (MeV)
1	0.80	1.6×10^{-20}	1.1×10^{-9}	3.1×10^{-20}	2.18×10^{-9}
2	1.77	8.1×10^{-20}	5.7×10^{-9}	15.7×10^{-20}	11.0×10^{-9}
3	2.77	19.7×10^{-20}	13.8×10^{-9}	39.1×10^{-20}	27.3×10^{-9}
5	4.76	58.5×10^{-20}	41.0×10^{-9}	116.6×10^{-20}	81.6×10^{-9}
8	7.75	155.6×10^{-20}	108.9×10^{-9}	311.2×10^{-20}	217.8×10^{-9}
10	9.75	246.3×10^{-20}	172.4×10^{-9}	493.6×10^{-20}	345.5×10^{-9}

$$\frac{-dE}{dS} = \frac{NG^2 m_e}{2\pi} \left\{ [2P_e(g_A + g_V + 1) + (g_A^2 + g_V^2)](Q_m^2 - \eta^2) \right.$$

$$\left. - \left[\frac{2}{E_\nu}(g_A - g_V)^2 - (2P_e + g_A + g_V)(g_A - g_V)\frac{m_e}{E_\nu^2} \right]\left[\frac{Q_m^3 - \eta^3}{3}\right] + \frac{1}{E_\nu^2}(g_A - g_V)^2\left[\frac{Q_m^4 - \eta^4}{4}\right] \right\} , \qquad (5)$$

where N is the number density of electrons in the medium, $Q_m = 2E_\nu^2/(m_e + 2E_\nu)$ is the maximum energy transferred to the electron, and η is approximately given by the plasmon energy of the solar electrons. Similar results can be obtained for the energy losses of antineutrinos by employing Eq. (1). Due to moderate energies of and enormous distances traveled by solar neutrinos, P_e has been estimated to lie within the range[13]

$$0.39 \leq P_e \leq 0.86 . \qquad (6)$$

For solar electrons, $N = 1.2 \times 10^{25}$ cm^{-3} and $\eta \sim \hbar(4\pi Ne^2/m_e)^{1/2} \sim 100$ eV. With all these numerical values and taking $\sin^2\theta_W = 0.224$ in (2), we have computed Eq. (5) for two different values of P_e, $P_e = 0.4$ and $P_e = 1$, corresponding to no oscillations. Furthermore, if we assume that this stopping power is constant all along the range of the neutrino, then the total energy loss $(-\Delta E)$ for a neutrino created at the center and escaping at the surface of the sun can be calculated just by multiplying the stopping power with the radius of the sun $\sim 7 \times 10^{10}$ cm. The numerical results are shown in Table I for different energies of the solar neutrinos.

The decrease in energy loss with decrease in P_e can be seen if one collects all the terms involving P_e in Eq. (5) and

employs Eq. (2). One obtains

$$4P_e \sin^2\theta_W \left[1 - \frac{2}{3(1 + 2E_\nu/m_e)} \right] , \qquad (7)$$

where use has been made of the fact that for all the neutrino energies considered $\eta \ll Q_m$. It is obvious that (7) decreases as P_e decreases implying a decrease in $(-dE/dS)$.

From the results, we see that the energy losses of the solar neutrinos are of the same order of magnitude when compared with those values when no oscillation occurs.[3] The exact numerical values are even smaller in this case. The energy lost by 1-MeV neutrinos traversing through the sun is $\sim 10^{-9}$ MeV and that for 10-MeV neutrinos is $\sim 10^{-7}$ MeV, which are completely insignificant. Thus, together with the two previous investigations,[2,3] we can conclude more safely and completely that the solar-neutrino anomaly is not likely to be accounted for from considerations of energy losses of the neutrinos due to interaction with the solar matter as it escapes through the sun.

*Now at the Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, New York 14853.

[1]See, e.g., R. Davis, Jr., Phys. Rev. Lett. 12, 303 (1964); B. Kuchowicz, Rep. Prog. Phys. 39, 21 (1976); J. Bernstein, M. Ruderman, and G. Feinberg, Phys. Rev. 132, 1227 (1963); J. N. Bahcall et al., Rev. Mod. Phys. 54, 767 (1982).

[2]M. L. Rustgi, P. T. Leung, J. E. Turner, and W. B. Brandt, Phys. Rev. A 24, 2425 (1981); 25, 2417 (1982).

[3]P. T. Leung and M. L. Rustgi, Phys. Rev. A 25, 2588 (1982).

[4]See, e.g., A. DeRújula, M. Lusignoli, L. Maiani, S. T. Petcov, and R. Petronzio, Nucl. Phys. B168, 54 (1980); V. Barger, K. Whisnant, D. Cline, and R. J. N. Phillips, Phys. Lett. 93B, 194 (1980); J. N. Bahcall, S. H. Lubow, W. F. Huebner, N. H. Magee, Jr., A. L. Merts, M. F. Argo, P. D. Parker, B. Rozsnyai, and R. K. Ulrich, Phys. Rev. Lett. 45, 945 (1980); V. Barger, K. Whisnant, and R. J. N. Phillips, Phys. Rev. D 24, 538 (1981).

[5]B. Halls and B. H. J. McKellar, Phys. Rev. D 24, 1785 (1981).

[6]We believe that there is an error in the result obtained by Halls

and McKellar; our Eq. (1) should be compared and contrasted with Eq. (4) of Ref. 5.

[7]For an experimental detection of the only reaction in which both W^- and Z^0 are involved, see F. Reines, H. S. Gurr, and H. W. Sobel, Phys. Rev. Lett. 37, 315 (1976).

[8]For the experimental observation of $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$, see L. A. Ahrens et al., Phys. Rev. Lett. 51, 1514 (1983). This paper contains a detailed bibliography of the earlier publications.

[9]See, e.g., J. C. Taylor, Gauge Theories of Weak Interactions (Cambridge University, Cambridge, England, 1974), pp. 57–61.

[10]G. 't Hooft, Phys. Lett. 37B, 195 (1971); also see, e.g., H. H. Chen and B. W. Lee, Phys Rev. D 5, 1874 (1972); L. M. Sehgal, Nucl. Phys. B70, 61 (1974).

[11]H. A. Bethe, in Handbuch der Physik, Vol. 24, edited by H. Geiger and K. Scheel (Springer, Berlin, 1933), pp. 491ff.

[12]U. Fano, Annu. Rev. Nucl. Sci. 13, 1 (1963).

[13]See De Rújula et al. (Ref. 4).