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Solar neutrinos and the ^{37}Cl neutrino absorption experiment

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Abstract. On the basis of a certain lepton–hadron relation and the dynamical origin of charge, the cross section for the scattering process $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ has been computed. The product of the neutrino flux and the cross sections for all sources of solar neutrinos, when calculated using this modified value of the scattering cross section are found to agree well with the experimental observations. Also, from this analysis, we conclude that there is no reason to rule out the possibility that the sun derives most of its radiated energy from the CNO cycle.

Recently Davis *et al* (1968) have conducted an experiment to detect solar neutrinos in the reaction $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ and have found that the upper limit of the product of the neutrino flux and the cross sections for all sources of neutrinos is $0{\cdot}3 \times 10^{-35}\ s^{-1}$ per ^{37}Cl atom. The theoretical prediction for this product $\Sigma\phi\sigma$, when neutrino fluxes are taken from calculations of Bahcall and Shaviv (1968) is $(2{\cdot}0 \pm 1{\cdot}2) \times 10^{-35}\ s^{-1}$ per ^{37}Cl atom. However, a revised estimate using a more accurate rate for the p–p reaction and the improved determination of the abundance ratio of heavy elements to hydrogen was computed by Bahcall *et al* (1968). They found for the most probable model $\Sigma\phi\sigma = 0{\cdot}76 \times 10^{-35}\ s^{-1}$ per ^{37}Cl atom. This value is also significantly larger than the experimentally observed upper limit, though the discrepancy is not serious enough to cast doubts on the correctness of the solar models in view of the uncertainties in the various parameters that enter the calculations. One of the major conclusions which follows from the experimental observation is that the sun does not derive most of its radiated energy from the CNO cycle, since this implies, independent of solar models, a counting rate of $3{\cdot}5 \times 10^{-35}\ s^{-1}$ per ^{37}Cl atom (Bahcall 1964b, 1966). In the present letter, we shall show that according to a new model of weak interactions suggested on the basis of a certain lepton–hadron relation and the dynamical origin of charge (Bandyopadhyay 1970) the cross section for the absorption of neutrinos by ^{37}Cl is substantially modified. The counting rate, when calculated using this modified value of the cross section, is found to be in good agreement with the experimental observation. Also, from this analysis, we conclude that there is no reason to rule out the possibility that the sun derives most of its radiated energy from the CNO cycle.

It has been suggested by several authors that a certain lepton–hadron relation is solicited to understand their systematics in terms of only a limited number of fundamental particles. In a previous paper (Bandyopadhyay 1964), it has been shown that if μ^-, ν_μ (and their antiparticles) are taken to be associated with baryonic matter to form all types of hadrons, it is possible to explain certain characteristic features of weak interactions. For the proton and neutron, the following configurations were

$q^2 = |\boldsymbol{q}|^2 - q_0^2 = 4EE' \sin^2 \theta/2$ is the four-momentum squared, positive in the spacelike region

$W = \sqrt{s_0}$ the mass of the outgoing hadronic system
$E_\gamma = K = (W^2 - M^2)/2M$ the equivalent photon energy
$\nu = E - E'$ the energy loss of the electron
$\omega = 2M\nu/q^2$ the scaling variable
$\epsilon = \{1 + 2(|\boldsymbol{q}|^2/q^2)\tan^2(\theta/2)\}^{-1}$ the degree of polarization of the virtual photon
$\Gamma = \alpha/2\pi^2 \, \{E'K/Eq^2(1-\epsilon)\}$.

Then the cross section, if one detects only the scattered electron, can be written in the following way:

$$\frac{d^2\sigma}{d\Omega_e \, dE'} = \Gamma\Sigma \qquad \text{with} \qquad \Sigma = \sigma_T + \epsilon\sigma_L .$$

σ_T and σ_L are the photoabsorption cross sections for transverse and longitudinal photons. They can also be expressed in terms of the structure functions W_1 and W_2:

$$W_1 = \frac{K}{4\pi^2\alpha}\sigma_T$$

$$W_2 = \frac{Kq^2}{4\pi^2\alpha|\boldsymbol{q}|^2}(\sigma_T + \sigma_L).$$

In order to separate σ_L from σ_T one needs measurements of Σ for two different values of ϵ or different scattering angles, but the same values of q^2 and W. For coincidence measurements on a specific final state such as single pion production, the cross section can be written, again in the one-photon exchange approximation

$$\frac{d^3\sigma}{d\Omega_e \, dE' \, d\Omega^*} = \Gamma \frac{d\rho}{d\Omega^*}$$

$$\frac{d\sigma}{d\Omega^*} = A + \epsilon B + \epsilon C \sin^2\theta^* \cos 2\phi + \{\epsilon(1+\epsilon)\}^{1/2} D \sin\theta^* \cos\phi.$$

θ^* and ϕ are the polar and azimuthal angles of the outgoing π in the π, N rest system. The coefficients of the angular distribution are functions of q^2, W and $\cos\theta^*$. The terms are the cross sections for unpolarized transverse photons A, for longitudinal B and polarized transverse photons C, and the interference between transverse and longitudinal photons D. Since there are no results where ϵ has been varied, I will use the sum

$$\bar{A} = A + \epsilon B.$$

However, it should be observed that in *certain cases of low energy scattering*, the cross section will be given by the conventional current–current coupling theory and the concept of nonlocality as introduced here will not be effective. In fact, in the low energy region, the kinetic energy of the outgoing charged lepton can be taken to be negligible, and the factor $K^2 = (q'-q)^2$ approaches zero. But in this limit, the system of photons responsible for the charge of the system and propagating between the hadron and the lepton concerned behave as real photons and this just amounts to the unphysical charge nonconserving process $n \rightarrow p + \gamma$. So, the concept of nonlocality breaks down in this case and the process can take place only in the local limit. This is true in the low energy inverse β decay experiment $\bar{\nu}_e + p \rightarrow n + e^+$ performed by Rienes and Cowan, the result of which is found to be in good agreement with the predictions of the current–current coupling theory.

However, it should be mentioned here that such a limiting case might not arise in the case where the target is a heavy nucleus. For nucleons bound to a heavy structure might be expected to take much less recoil energy than a free nucleon. Consequently, the fourth component of the outgoing nucleon momentum can be taken to be very close to iM where M represents the mass of the nucleon. However, in this approximation, the four momentum transfer square should satisfy the relation $k^2 = (q'-q)^2 > 0$ as the equality case $k^2 = 0$ is not likely to arise when the recoil energy is vanishingly small. Thus the concept of local interaction will not be valid in the weak interaction scattering case when the target is a heavy nucleus. However, as mentioned earlier it should be remembered that for decay processes this structural consideration for the nucleon gives a good explanation for the validity of the current–current coupling theory (Bandyopadhyay 1964, 1970) and hence the β-decay shape spectrum, in any case, will not be altered.

In view of the above arguments, we now consider the process $\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$ involving solar neutrinos. It is observed that, according to the current–current coupling theory, the cross section for the absorption of neutrinos in ^{37}Cl to form the ground state of ^{37}Ar is given by (Bahcall 1964a)

$$\sigma(\nu_e) = \sigma_0 p_e \omega_e \left(\frac{F}{2\pi\alpha z}\right) \tag{1}$$

where $F = F(\omega_e, z)$ is the well known Fermi function, and p_e and ω_e are the electron momentum in units of $m_e c$ and the total electron energy in units of $m_e c^2$ respectively. The coupling constant here does not occur explicitly as the cross section $\sigma_0 = 1{\cdot}9 \times 10^{-46}$ cm^2 is obtained from the experimentally measured properties of the ^{37}Ar decay. It is now noted that if we calculate $\sigma(\nu_e)$ considering figure 1, the cross section (1) will be modified by the factor $1/(p'-p)^4$. Neglecting the momentum transfer between ^{37}Cl and ^{37}Ar nuclei, the factor $1/(p'-p)^4$ just reduces to the expression $1/(M_n'-M_p)^4$. Hence the modified cross section for the neutrino absorption process can be written as

$$\sigma(\nu_e) = \frac{\sigma_0 p_e \omega_e}{(m_n - m_p)^4}\left(\frac{F}{2\pi\alpha z}\right) \tag{2}$$

where m_n and m_p are in units of m_e. This gives

$$\sigma(\nu_e) = \frac{\sigma_0}{40{\cdot}96} p_e \omega_e \left(\frac{F}{2\pi\alpha z}\right). \tag{3}$$

Taking this modified value for $\sigma(\nu_e)$, we now calculate the cross sections for the reaction $^{37}Cl(\nu_e, e^-)\,^{37}Ar$ for different neutrino sources in the sun and the corresponding values of $\sigma\phi$, where ϕ is the neutrino flux at the earth. The results are shown in table 1. The tabulated fluxes are due to the calculations of Bahcall and Shaviv (1968).

Table 1. Solar neutrino fluxes and cross sections for the reaction $^{37}Cl(\nu_e, e^-)^{37}Ar$. The values corresponding to the current–current coupling theory have been taken from Davis *et al* (1968).

Neutrino	Cross section (cm²)		Neutrino flux	$\sigma\phi \times 10^{35}(s^{-1})$	
	current–current coupling	present model	$(cm^{-2}\,s^{-1})$	current–current coupling	present model
$H+H+e^- \rightarrow D+\nu_e$	$1{\cdot}72\times10^{-45}$	$0{\cdot}42\times10^{-46}$	$1{\cdot}7\times10^{8}$	0·03	0·001
^{7}Be decay	$2{\cdot}9\times10^{-46}$	$0{\cdot}7\times10^{-47}$	$3{\cdot}9\times10^{9}$	0·11	0·0027
^{8}B decay	$1{\cdot}35\times10^{-42}$	$0{\cdot}3\times10^{-43}$	$1{\cdot}3(1\pm0{\cdot}6)\times10^{7}$	$1{\cdot}8(1\pm0{\cdot}6)$	$0{\cdot}004(1\pm0{\cdot}6)$
^{13}N decay	$2{\cdot}1\times10^{-46}$	$0{\cdot}5\times10^{-47}$	$1{\cdot}0\times10^{9}$	0·02	0·0005
^{15}O decay	$7{\cdot}8\times10^{-46}$	$0{\cdot}19\times10^{-46}$	$1{\cdot}0\times10^{9}$	0·08	0·002
				$\Sigma\sigma\phi = 2{\cdot}0(1\pm0{\cdot}6) \times10^{-35}\,s^{-1}$	$\Sigma\sigma\phi = 0{\cdot}05(1\pm0{\cdot}6) \times10^{-35}\,s^{-1}$

With the revised estimates of the neutrino fluxes using a more accurate rate for the proton–proton reaction and a new value for the heavy element composition of the sun, the value of $\Sigma\phi\sigma$ has been estimated to be $0{\cdot}76\times10^{-35}\,s^{-1}$ per ^{37}Cl atom, according to the current–current coupling theory of weak interactions (Bahcall *et al* 1968). With this solar model, our theory predicts $\Sigma\phi\sigma \simeq 0{\cdot}02\times10^{-35}\,s^{-1}$ per ^{37}Cl atom.

These discussions show that the predicted value of the counting rate, according to the probable solar models, when calculated according to our present view of weak processes, is in good agreement with the experimental upper limit of $0{\cdot}3\times10^{-35}\,s^{-1}$ per ^{37}Cl atom. Recently Davis (1971) has put new bounds on his current measurements. The result is reported to be $(1{\cdot}5\pm1{\cdot}0)\times10^{-36}\,s^{-1}$ per ^{37}Cl atom.

An important consequence of our present calculation is that it does not rule out the possibility of the dominant role of the CNO cycle in solar energy production, contrary to the conclusion reached when considered from the current–current coupling theory of weak interactions. Bahcall (1964b, 1966) has calculated the total flux cross section product for the CNO cycle to be $3{\cdot}5\times10^{-35}\,s^{-1}$ per ^{37}Cl atom, based on this cycle being the only source of the sun's energy. According to our present estimate of the value of $\sigma(\nu_e)$ as given by equation (3), this counting rate is reduced to the value $0{\cdot}085\times10^{-35}\,s^{-1}$ per ^{37}Cl atom. So, the experimentally observed upper limit does not rule out the possibility of the CNO cycle being dominant in solar energy production.

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