ABSORPTION OF SOLAR NEUTRINOS IN DEUTERIUM

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The nuclear reactions occurring in the solar interior which are thought to be responsible for solar energy production[1] may be verified directly, by observing the neutrinos created in the over-all reaction in the cycle

$$4H^1 \to He^4 + 2e^+ + 2\nu_e. \quad (1)$$

Bahcall[2] has obtained a theoretical spectrum of solar neutrinos, and has suggested the initiation of an experimental program of solar neutrino spectroscopy, based upon an observation of neutrino-induced nuclear reactions with various thresholds. Such a program would also check on details of solar models used in the calculation of the neutrino fluxes and provide a measure for the temperature at the sun's center. Most efficient for inducing nuclear reactions would be the neutrinos from the step

$$B^8 \to Be^{8*} + e^+ + \nu_e \quad (2)$$

of the p-p cycle, because of their high energy (end point at 14.1 MeV).[3] So far, only experimental upper limits on solar-neutrino fluxes have been set;[4] positive results are expected shortly from two experiments now in progress.[5,6] The experiment of Jenkins[6] proposes to detect the solar neutrinos in the reaction

$$\nu_e + H^2 \to 2H^1 + e^-, \quad (3)$$

by observation of the Čerenkov radiation of the electrons in a 2000-liter heavy-water target. The cross section and the electron spectrum and angular distribution of Reaction (3) are obtained theoretically in the following.[7] The conclusion is that the Coulomb repulsion will reduce the cross section only by an insignificant amount, so that solar-neutrino detection via (3) appears feasible.

Calling $\vec{\nu}$ = neutrino momentum, T_e (E_e) = electron kinetic (total) energy, $\vec{p}_e$ = electron momentum, $\vec{p}$ = two-proton relative momentum, m_p = proton mass, the kinematics of (3) gives

$$\nu = Q + T_e + (p^2/m_p) \quad (4)$$

with a threshold of $Q = 1.44$ MeV. We use the conventional nonrelativistic weak-interaction Hamiltonian $G_V + G_A \vec{\sigma} \cdot \vec{\sigma}^N$, where $G_A = -1.20 G_V$ and $G_V = 10^{-5} m_p^{-2}$, and obtain the differential cross section

$$d\sigma = 2^{-2}\pi^{-3} G_A |I|^2 \times (1 - \tfrac{1}{3}\vec{\nu} \cdot \vec{p}_e / \nu E_e) m_p p d\Omega_p p_e E_e dE_e d\Omega_e; \quad (5)$$

it is isotropic in $\vec{p}$, thus $d\Omega_p \equiv 2\pi$ (identical particles), and shows a backward electron angular distribution. The following assumptions were made[7]: (1) The electron is treated as a free particle (as justified by its generally high energy). (2) The two protons emerge in a ^1S state; thus only the Gamow-Teller matrix element enters. (3) Retardation is neglected. (4) The effective-range approximation is used.[8,9] Then the matrix element I containing the wave functions u_d, u_{2p} of the relative motion (with the two-proton wave function normalized to 2) becomes

$$I = \int \mu_{2p}{}^* \mu_d dr \quad (6a)$$

$$\cong (2/p) \exp[i(\sigma_0 + \delta)] N \sin\delta [J - (r_s + r_t)/4C_0], \quad (6b)$$

where[9,10] $4\pi N^2 = 150$ MeV, $C_0{}^2 = 2\pi\eta(e^{2\pi\eta} - 1)^{-1}$, $\eta = (2pR)^{-1}$, $R = 2.88 \times 10^{-12}$ cm, and (see Preston[10])

$$C_0{}^2 p \cot\delta + R^{-1} h(\eta) = -a_s{}^{-1} + \tfrac{1}{2} r_s p^2, \quad (7)$$

$$a_s = -7.72 \times 10^{-13} \text{ cm}, \quad r_s = 2.72 \times 10^{-13} \text{ cm},$$

$$r_t = 1.71 \times 10^{-13} \text{ cm},$$

and

$$J = \int_0^\infty e^{-\gamma r} [G_0(pr) + F_0(pr) \cot\delta] dr; \quad (8)$$

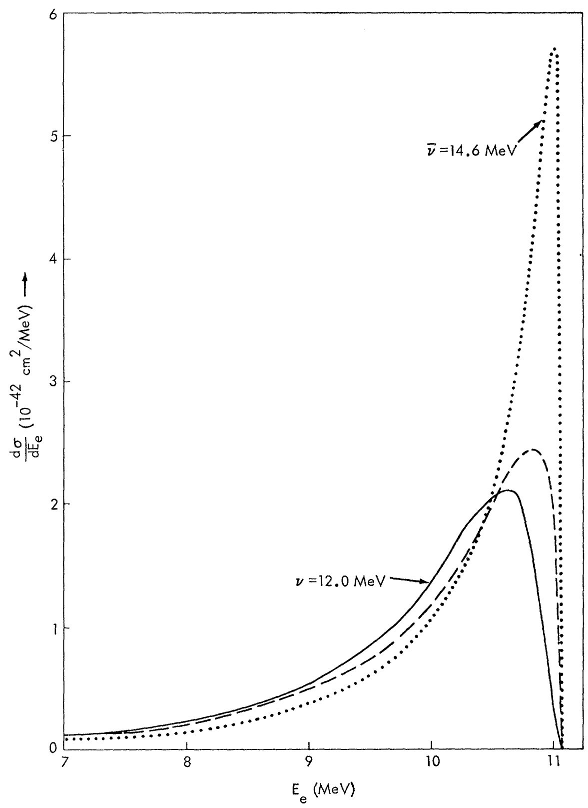

FIG. 1. Electron spectrum of Reaction (3) at a neutrino energy $\nu = 12$ MeV (solid line); for "uncharged protons" (broken line); and for the corresponding antineutrino reaction[7] (dotted line) at the equivalent energy $\bar{\nu} = 14.6$ MeV (giving rise to the same values of E_e, p).

$\gamma = 2.31 \times 10^{12}$ cm^{-1}. Here, F_0 and G_0 are the regular and irregular Coulomb wave functions, with asymptotically unit amplitude, and related to the confluent hypergeometric functions. Integration gives[11]

$$J = \frac{p\,|\Gamma(1-i\eta)|}{(\gamma+ip)^2} e^{-\frac{1}{2}\pi\eta} \left\{ \frac{e^{i\delta}}{\sin\delta} \left(\frac{\gamma+ip}{\gamma-ip} \right)^{1-i\eta} + \frac{2ie^{\pi\eta}}{\Gamma(1+i\eta)} \frac{F(1-i\eta, 2; 2-i\eta; z)}{\Gamma(2-i\eta)} \right\}, \tag{9}$$

$z = (\gamma - ip)/(\gamma + ip)$, with F the hypergeometric function.[12] Using all this, we have evaluated numerically the electron spectrum at fixed neutrino energies. Figure 1 presents the spectrum at $\nu = 12$ MeV (solid line), showing a large peak near the upper end, because of the almost two-body kinematics due to the strongly attractive ^1S p-p interaction. The repulsive Coulomb force diminishes this attraction somewhat, as seen by comparison with the broken line for fictitious "uncharged protons"[13]: Its effect is a shift of the peak to smaller electron energies with a broadening (i.e., less resemblance with a two-body kinematics), but practically no decrease of area. Mainly as a consequence of the different scattering lengths, therefore, the total cross section (shown in Fig. 2) is reduced on the order of 10% as compared to Weneser's[7] antineutrino cross section (dotted curve).[14] As mentioned before, detection of solar neutrinos via Reaction (3) in the experiment now carried out by Jenkins[6] therefore seems possible.

It may be of interest to compare counting rates in this experiment, as predicted by our theory, with expected counting rates in other experiments believed to be suitable for solar-neutrino detection. Using the graph for the solar-neutrino flux from Reaction (2) per cm^2 sec MeV at the earth's position as given by Bahcall,[2] we obtain for the integrated product of flux and cross section for Reaction (3), per ^{2}H atom,

$$\int \sigma(\nu_e + {}^2\mathrm{H})\varphi({}^8\mathrm{B})d\nu = 2.3 \times 10^{-35}\ \mathrm{sec}^{-1}. \tag{10}$$

For the reaction studied by Davis,[5] the corresponding expression is,[15] per ^{37}Cl atom,

$$\int \sigma(\nu_e + {}^{37}\mathrm{Cl})\varphi({}^8\mathrm{B})d\nu = (4 \pm 2) \times 10^{-35}\ \mathrm{sec}^{-1}. \tag{11}$$

Similarly, for the quantity of importance in Reines and Kropp's experiment,[4] which is based

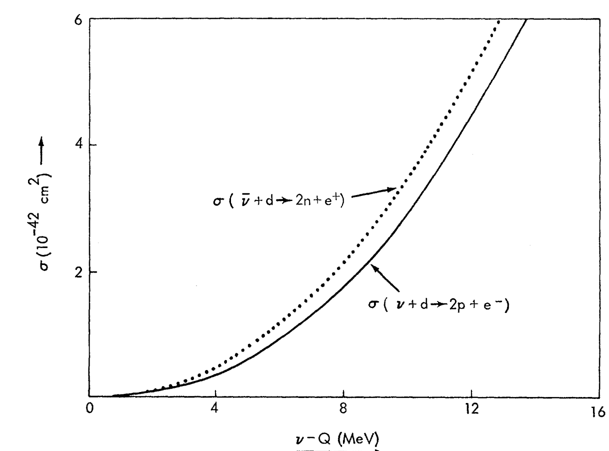

FIG. 2. Total cross section of Reaction (3) plotted versus (ν−1.44) MeV (solid line), and of the corresponding antineutrino reaction[7] plotted versus ($\bar{\nu}$−4.04) MeV (dotted line).

on the hypothetical reaction

$$\nu_e + e^- \rightarrow \nu_e + e^-, \quad (12)$$

we find, using expressions for the total cross section of Reaction (12) given in the literature,[16]

$$\int \sigma(\nu_e + e^-)\varphi(^8\mathrm{B})d\nu = 2.5\times10^{-36}\ \mathrm{sec}^{-1} \quad (13)$$

per target electron.

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[5]R. Davis and D. S. Harmer, based on $\nu_e + Cl^{37} \rightarrow Ar^{37} + e^-$.

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[13]Obtained by setting $e \rightarrow 0$, i.e., $R^{-1}h(\eta) \rightarrow 0$, $\eta \rightarrow 0$ and keeping all other parameters unchanged.

[14]We used, like Weneser, the value $a_s = -23.8\times10^{-13}$ cm (the experimental n-p scattering length) for the n-n scattering length needed in the antineutrino reaction.

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[16]See, e.g., J. N. Bahcall, Phys. Rev. 136, B1164 (1965).

π^+ CHARGE FORM FACTOR AND ELECTROPRODUCTION*

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We report e-π coincidence measurements on the electroproduction reaction $e^- + p \rightarrow e^- + n + \pi^+$ with kinematic conditions chosen to maximize the contribution from the exchange of longitudinally polarized photons. The yield is sensitive to the charge form factor of the pion, and the data have been compared with a theoretical model with the conclusion that the pion charge structure is not very different from that of the proton.

The electroproduction of a pion is assumed to take place through the exchange of a single photon.[1] Figure 1 illustrates the kinematic definitions we will use (in general, lower case letters refer to the laboratory frame, capitals denote the corresponding quantities measured in the final pion-nucleon rest frame). We wish to maximize the effect of the pion-pion amplitude corresponding to the direct absorption of the virtual photon by a virtual charged pion emitted by the target proton. The pole occurs at $(q-k)^2 - \mu^2 = 0$, or $\cos\Theta = 1/\beta_\pi$, so we should expect the largest contribution in the physical region at $\Theta = 0$, that is, for pions emitted forward along the momentum-transfer direction $\vec{K}$. Transversely polarized photons cannot transfer their helicity to forward-going pions, so at $\Theta = 0$ the pion pole can contribute only when the photon is longitudinally polarized. Furthermore, since the dominant 33 resonance contributes mainly to the magnetic dipole amplitude (a transverse multipole), the pion-pole term does not have to compete with the resonance in the longitudinal part of the electroproduction yield

Fortunately the contributions of transversely and longitudinally polarized virtual photons are readily separable experimentally in the