Solar neutrinos and the role of exchange currents in the *pp* reaction

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It is shown that allowance for exchange mesic currents can increase the cross section of the *pp* reaction by a factor of two or more. Methods of experimentally verifying this possibility are discussed.

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It was shown in[1,2] that allowance for the exchange mesic currents in the reaction

$$p + p \to d + e^+ + \nu \tag{1}$$

can increase its cross section σ_{pp} by $\sim 10\%$[1] to $\sim 40\%$.[2] Reaction (1) plays an important role in solar astrophysics. If the sun is an energywise balanced star, then its central temperature is determined by the value of σ_{pp}, and a two- or threefold increase of σ_{pp} could solve completely the problem of solar neutrinos. The purpose of the present article is to show that the estimate obtained in[2] is far from maximal, and to discuss the experimental possibilities of investigating this important problem.

The relative increment to the matrix element of the *pp* reaction (the dominant term corresponding to a transition to the deuteron D state), due to the exchange currents, is given by the expression

$$\delta \approx \frac{2\sqrt{2}}{3} \int u_{pp}(r)h(r)w(r)dr \Big/ \int u_{pp}(r)u(r)dr, \tag{2}$$

where u_{pp}, u, and w are the radial wave functions of the two protons and of the S and D states of the deuteron, respectively, and $h(r)$ is a quantity determined by the lepton-nuclear interaction diagram. If we use the one-pion exchange approximation[1,2] (Fig. 1a) and the low-energy theorem for the axial current,[3] we have in this case[4]:

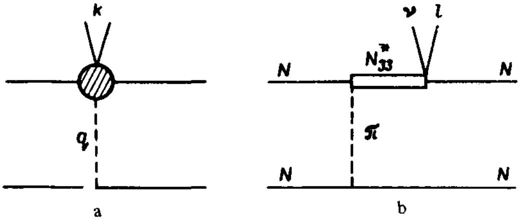

FIG. 1.

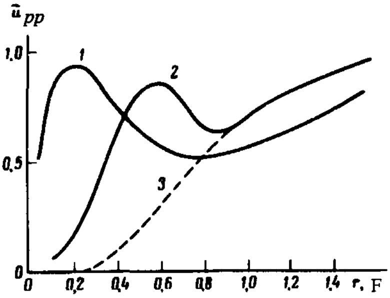

FIG. 2.

$$h(r) = \frac{2.25}{8\pi}\frac{g_r}{g_A}\frac{\mu}{M}Y_2(\mu r),$$

$$Y_2(\mu r) = \left(1 + \frac{3}{\mu r} + \frac{3}{(\mu r)^2}\right)\frac{e^{-\mu r}}{\mu r}, \tag{3}$$

where $g_r = 13.5$ is the pion-nuclear coupling constant, $g_a \equiv G_A/G_V = 1.23$, and μ and M are the masses of the pion and the proton.

According to (2) and (3), the value of δ is determined by the behavior of the two-nucleon potential in the region $r \lesssim 1$ F. The use of different phenomenological repulsion-core potentials leads to results that are close, ~3—4%. It was shown in[2] that the use of a nonlocal potential yields $\delta \sim 20\%$. The value of δ, obviously, depends strongly on the character of nonlocality. Just as in[2], we introduce the nonlocality by means of a unitary transformation of the Reid potential with soft core, but in contrast to[2] we use a transformation of the Haftel-Tabakin type[5]:

$$\tilde{u}_{iL}(r) = u_{iL}(r) - 2r g_{iL}(r) \int g_{iL}(r')u_{iL}(r')r'dr', \tag{4}$$

$$g_{iL}(r) = C_{iL} e^{-a_{iL} r} r^{L/2}(1 - \beta_{iL} r), \tag{5}$$

where i is the set of quantum numbers J, S, and T.

We choose the parameters α and β such as not to contradict the available data on pp and nn scattering and on the electrodisintegration of the deuteron, and with the measurements of the quadrupole moment and the electromagnetic form factor of the deuteron. These requirements are satisfied by the following set: $a = 3.0, \beta = 1.25$ for $J = S = L = 0, T = 1$; $a = 4.0, \beta = 1.3$ for $J = S = 1, L = T = 0$; $a = 3.6, \beta = 1.0$ for $J = S = 1, L = 2, T = 0$.

The function $\tilde{u}_{pp}$ normalized to the asymptotic form ($E_{pp} \to 0$),

$$\tilde{u}_{pp}(r) \to C_0(F_0 \operatorname{ctg}\delta_0 + G_0), \tag{6}$$

is shown in Fig. 2 (curve 1). The figure shows also $\tilde{u}_{pp}$ from[2] and and u_{pp} for the local Reid potential (curves 2 and 3).

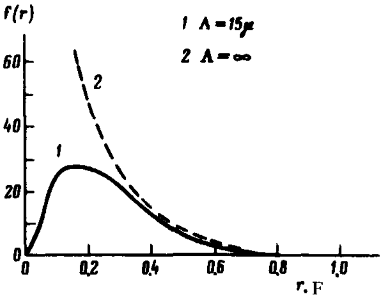

FIG. 3.

The form factors of the vertices of the diagrams of Fig. 1(a) were not taken into account in[1,2], so that formula (3) used in[1,2] is valid only in the region $q^2 \lesssim \mu^2$. Part of the q^2-dependence has already been taken into account in the wave functions.[4] Introducing the monopole form factor $(1+q^2/\Lambda^2)^{-1}$, we obtain a formula that differs from (3) in the substitution

$$Y_2 \to Y_2' = (1-\mu^2/\Lambda^2)^{-1}\left\{Y_2(\mu r) - \frac{\Lambda^3}{\mu^3}\,Y_2\left(\frac{\Lambda}{\mu}\,r\right)\right\}. \tag{7}$$

The dependence $f \equiv \widetilde{u}_{pp} h \widetilde{w}$ on r, obtained with the aid of (4—7), is shown in Fig. 3. When Λ changes from 15 μ to ∞, the value of δ changes from ~ 0.35 to ~ 0.9, and the cross section of reaction (1), $\sigma_{pp} \sim (1+\delta)^2$, increases from ~ 1.8 to ~ 3.6 times.

As seen from Fig. 3, an important role is played by distances $r \lesssim M^{-1} = 0.2$ F. In this region of r we cannot neglect in the derivation of (2,3) the relativistic corrections to the wave functions and the kinetic terms $\sim (p/M)^k$ with $k \geqslant 2$, so that the estimates obtained for δ serve only for orientation purposes. On the other hand, the one-meson approximation is quite realistic at $r \sim M^{-1}$ so that $k^2 \sim 0$ only small virtual excitations of the nucleons are significant, and the leading diagrams are those of Fig. 1(b) with the isobar having the lowest mass.

Using the result of[6], we easily find that when σ_{pp} is changed by a factor 2—3.5 the solar-neutrino counting rate in a chlorine detector is decreased by a factor of 3—6.

Analogous calculations for the reaction

$$\bar{\nu} + d \to n + n + e^+ \tag{8}$$

yield at $\Lambda = 15\,\mu$ a value $\delta = 0.43$, i.e., they increase the cross section $\sigma_{\bar{\nu}}$ of reaction (8) by approximately 2 times. The small deviation from the results obtained for the reaction (1) is due to the fact that $\widetilde{u}_{nn}(r)$ has an asymptotic form $1 - r/\widetilde{a}_{nn}$ which is different from (6), where $\widetilde{a}_{nn} = -18.3$ F is the nn-scattering length obtained for the transformed potential after exclusion of the Coulomb interaction.

Experiment with reactor antineutrinos yields $\bar{\sigma}_{\bar{\nu}} = (3 \pm 1.5) \times 10^{-45}$ cm^2 at a theoretical value $\bar{\sigma}_{\bar{\nu}} = (2.4 \pm 0.4) \times 10^{-45}$ cm^2.[7] We see therefore that the experimental data do not exclude the possibility of increasing $\sigma_{\tilde{\nu}}$ by an approximate factor of two, so that it is necessary to repeat the reactor measurements of $\sigma_{\tilde{\nu}}$ with greater accuracy. A more direct method of investigating reaction (1) would be to measure the cross section of the reaction $\nu + d \to p + p + e^-$ for neutrinos from a meson factory.

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