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High energy solar neutrinos and *p*-wave contributions to ^{3}He$(p,\nu e^+)^4$He

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High energy solar neutrinos can come from the hep reaction, ^{3}He$(p,\nu e^+)^4$He, with a large end point energy of 18.8 MeV. Understanding the hep reaction may be important for interpreting solar neutrino spectra. We calculate the contribution of the axial-charge transition $^3P_0\rightarrow{}^1S_0$ to the hep thermonuclear S factor using a one-body reaction model involving a nucleon moving in optical potentials. Our result is comparable to or larger than previous calculations of the *s*-wave Gamow-Teller contribution. This indicates that the hep reaction may have *p*-wave strength leading to an enhancement of the S factor. [S0556-2813(99)50808-X]

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After many years of work on solar neutrinos, experimenters are now searching for proof of new neutrino physics that is independent of solar models. SuperKamiokande is looking for distortions in the shape of the ^{8}B spectrum from neutrino oscillations [1]. Indeed, the ratio of the measured super-K spectrum to the expected ^{8}B spectrum rises at high energies. Among other possibilities, this could be due to oscillations or to neutrinos from the hep reaction,

$$p+{}^3\text{He}\rightarrow{}^4\text{He}+v_e+e^+. \tag{1}$$

Although rare, hep neutrinos have a higher end point (18.8 MeV) than those from ^{8}B. Thus, the interpretation of solar neutrino spectra may depend on our understanding of the hep reaction [2,3].

The present estimate for the thermonuclear S factor for Eq. (1) is small [4],

$$S_0=2.3\times10^{-20}\ \ \text{keV-b}, \tag{2}$$

based on the calculations of Carlson *et al.* [5,6]. One would need an S factor some 20 times larger to explain the super-K data [2]. However, Carlson *et al.* only consider the contribution of a single partial wave and only keep the axial-three-vector part of the weak current. Furthermore, they neglect the radial dependence of the lepton wave functions. This dependence could be significant because of the large Q value.

Carlson *et al.* find a small S factor because of sensitive cancellations in the wave function and destructive interference between one-body and meson exchange current contributions. Given the very small Gamow-Teller strength it is important to study other forbidden transitions which may also contribute.

Some earlier work on the hep S factor assumed a relation between radiative capture ^{3}He$(n,\gamma)^4$He and Eq. (1) [7–11]. However, the weak and electromagnetic currents are very different so this relation may be unreliable [5]. Werntz and Brennan [8] estimate the contributions of *p*-wave resonances to Eq. (1). However, we are not aware of any nonresonant *p*-wave calculations.

In this Rapid Communication we study the axial-charge transition $^3P_0\rightarrow{}^1S_0$ which involves a *p*-wave initial state. Our goal is to show, in as simple a way as possible, that p waves can compete with the small *s*-wave strength. Therefore we focus on a single partial wave and operator. To calculate the total S factor one must add coherently the contribution of several other *p*-wave transitions, other operators and the original *s*-wave strength to our axial-charge result. We find the axial charge transition is comparable to the original s wave. Furthermore, our result is based on the one-body axial charge. It is known that meson exchange currents, rather than interfering destructively, significantly enhance many axial charge transitions. For example, the cross section for near threshold pion production, $pp\rightarrow pp\pi^0$, is enhanced by a factor of 5 by meson exchange currents [12].

We use a simple one-body model to estimate p waves. This model has a nucleon moving in optical potentials chosen to reproduce bound state properties and p-^{3}He phase shifts. The model is not expected to be good for the *s*-wave transition since this involves sensitive cancellations and small components of the wave function.[1] However, our model should provide a first estimate for the p waves since they involve large components of the wave functions and do not (appear to) have sensitive cancellations. We describe our model, give results for the $^3P_0\rightarrow{}^1S_0$ contribution to the S factor, and then discuss future experimental and theoretical work. Our conclusion is that *p*-wave contributions could increase the hep S factor.

The ^{4}He final state $|\Psi_f\rangle$ is modeled as a neutron moving in a real Woods-Saxon optical potential,

$$|\Psi_f\rangle=\frac{u(r)}{r}Y_{00}(\hat{r})\chi_0^0. \tag{3}$$

Here r is the relative coordinate between the nucleon and ^{3}He while χ_0^0 is a spin singlet wave function for the nucleon and ^{3}He. The bound state radial wave function $u(r)$ is a

[1]If one assumes the same optical potential for bound and scattering states, our one-body model has zero *s*-wave strength because the bound and scattering states are orthogonal.

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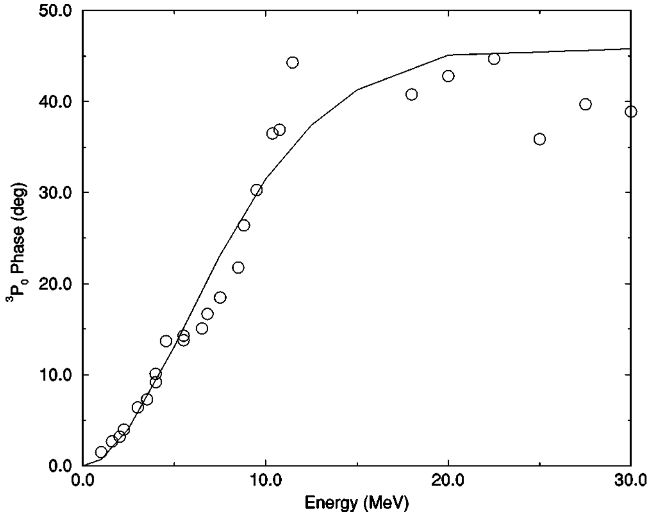

FIG. 1. Phase shift for $p+{}^3$He elastic scattering in the $^3P_0$ partial wave. The solid curve is for the optical potential, Eq. (4), with $V_0=-30$ MeV. The data are from Ref. [15] below 12 MeV and from Ref. [16] above 12 MeV.

solution to the Schrödinger equation for a reduced mass $\mu=3/4m$, with m the nucleon mass, moving in a potential $V(r)$,

$$V(r)=V_0/[1+\exp[(r-R_0)/a]]. \tag{4}$$

We arbitrarily set $a=0.6$ fm while $R_0=2$ fm was adjusted to reproduce the charge radius of ^{4}He after correcting for the center of mass and folding in the finite size of the proton. The strength $V_0=-63.9$ MeV reproduces the 20.58 MeV neutron separation energy of ^{4}He.

The $^3P_0$ initial state $|\Psi_i\rangle$ is modeled as

$$|\Psi_i\rangle=i\sqrt{4\pi}\frac{u_1^+(r)}{r}|^3P_0\rangle, \tag{5}$$

with $|^3P_0\rangle$ a spin-angle function and u_1^+ a $^3P_0$ outgoing scattering wave which we approximate as a p-wave solution in a Coulomb potential of a uniform sphere of radius $R_0=2$ fm plus $V(r)$ given by Eq. (4). We use the same $R_0=2$ fm and $a=0.6$ fm as the bound state but adjust $V_0=-30$ MeV in order to approximately reproduce $p+{}^3$He phase shifts [see Fig. 1].

The $^3P_0$ contribution to the hep cross section from the axial charge is [5]

$$\sigma=\frac{1}{(2\pi)^3}\frac{G^2m_e^5f}{v}|\langle\Psi_f|A_0|\Psi_i\rangle|^2, \tag{6}$$

with $G=1.151\times10^{-11}\,\text{MeV}^{-2}$, the Fermi constant; m_e, the electron mass; v, the p-^{3}He relative velocity; and $f=2.544\times10^6$, the lepton phase space. Note, the three-vector part of the axial current will also contribute given the spatial dependence of the lepton wave functions. For simplicity we focus on a single operator. The one-body axial-charge operator A_0 is assumed to be

$$A_0=-\frac{g_a\sigma\cdot(\vec{p}+\vec{p}\,')}{2m}\tau_-, \tag{7}$$

with $g_a=1.262$, p the initial and p' the final nucleon momenta and $\tau_-=\frac{1}{2}(\tau_x-i\tau_y)$ converts a proton into a neutron.

It is a simple matter to evaluate the matrix element using Eqs. (3), (5), and (7),

$$|\langle\Psi_f|A_0|\Psi_i\rangle|^2=\frac{4\pi g_a^2}{\mu^2}\left|\int_0^\infty dru(r)\left[\frac{d}{dr}+\frac{1}{r}\right]u_1^+(r)\right|^2. \tag{8}$$

Numerically evaluating Eqs. (6) and (8) at 7.5 keV in the center of mass yields a cross section of $\sigma=5.28\times10^{-30}$ b. Converting this to the usual S factor $S=E\sigma e^{2\pi\eta}$ with $\eta=2\alpha/v$ yields

$$S_{^3P_0}=1.67\times10^{-20}\ \text{keV-b}. \tag{9}$$

Note, because of large Coulomb effects there is little energy dependence to Eq. (9), $S(E)\propto(1+\eta^{-2})$. Again Eq. (9) only includes the contribution of the axial charge and a single partial wave. To obtain the total S factor one must add contributions of other p waves and operators and the s-wave strength. Furthermore, Eq. (9) may be enhanced by meson exchange currents.

Nevertheless, Eq. (9) is larger than the 1.3×10^{-20} keV-b S factor originally claimed by Carlson *et al.* [5] and 73% of the present value, Eq. (2). We conclude that *p-wave contributions may be comparable to the Gamow-Teller strength.* This is a major result of this Rapid Communication and will be discussed below.

How can this axial-charge transition compete with the Gamow-Teller? First the centrifugal barrier's effects are significantly reduced by the strong Coulomb interaction. The ratio of $l=1$ to $l=0$ Coulomb wave functions is much larger than that for plane waves. Second, the axial-charge operator is of order $v_N/c\approx0.25$ and the nucleon's velocity v_N is relatively large in ^{4}He because of the large separation energy. The product of these two factors, centrifugal barrier times v_N/c, is not very small and can compete with a strongly reduced s-wave matrix element.

We now discuss some of the details of the calculation. We use a very simple one-body wave function with an optical potential fit to phase shifts. To explore the sensitivity to the p-wave optical potential, we consider other values for the strength V_0, see Eq. (4). A very conservative choice is to set $V_0=0$ and thus the incoming p wave sees only the Coulomb potential. This is unrealistic because we expect some attractive nuclear interaction. Nevertheless, setting $V_0=0$ only reduces the axial-charge matrix element by 30%. We conclude that changes in the p-wave optical potential are unlikely to significantly reduce the S factor in Eq. (9).

Alternatively, resonances could significantly enhance the cross section. If we use the same value of $V_0=-63.9$ MeV as was used for the bound state then there will be a strong p-wave resonance and the S factor rises by a factor of 37 to 62.5×10^{-20} keV-b. Such a strong resonance is not seen in the p-wave phase shifts. Therefore this very large S factor is probably unrealistic. However there could be contributions from smaller resonances.

We have not explicitly antisymmetrized the incident proton with those bound in ^{3}He. This omission could be important for s waves. However we do not expect it to be a large correction for p waves.

It is important to repeat our calculation with more realistic microscopic four-body wave functions. However, the p-wave transition does not appear to involve sensitive cancellations. Furthermore, the axial-charge operator can connect the large components of the wave functions. Thus the matrix element should not depend strongly on small components in the wave functions of ^{3}He and ^{4}He. Therefore, we expect Eq. (9) to provide a useful first estimate.

Meson exchange currents (MEC) can be important for axial-charge transitions because both the one-body and MEC are of the same order v_N/c. Pion exchange currents enhance the axial charge in a number of first forbidden β decays. In addition, shorter range MEC could also enhance the axial charge. In relativistic models, σ meson exchange increases the axial charge from order p/m to p/M^* where the nucleon's effective mass $M^*<m$. This and ω exchange enhance the near threshold pion production cross section by a factor of 5 [12]. Thus we expect a significant MEC contribution and we expect it to increase the S factor.

For simplicity we have focused on a single partial wave $^3P_0$. There are a number of other p waves that can also contribute, such as, $^1P_1$, $^3P_1$, and $^3P_2$. As a very crude estimate we expect these partial waves to each be of the same order of magnitude as the $^3P_0$. Therefore, it is possible that the total S factor, involving the coherent sum of several contributions, could be significantly larger than Eq. (9).

Our results suggest several areas for future theoretical and experimental work.

(i) One should calculate all forbidden transition strength in a variety of phenomenological models. These calculations should include all incoming p and s waves and all parts of the weak current including vector and axial-charge components. The calculations should also include corrections for the spatial dependence of the lepton wave functions.

(ii) One should calculate meson exchange current contributions for the above transitions.

(iii) One should repeat microscopic four-body calculations similar to those of Carlson *et al.* [5] including all s and p partial waves, all vector and axial parts of the weak current, and the spatial dependence of the lepton wave functions.

(iv) It may be useful to compare these calculations to experimental data for related, nonweak, reactions. One should look at radiative capture ^{3}He$(n,\gamma)^4$He and ^{3}H$(p,\gamma)^4$He. Spin-observable data may provide information on p-wave contributions. We caution that simple relations between radiative and weak capture, which have been used in the past, may be unreliable because of the very different currents involved. Nevertheless, radiative capture may still provide useful tests of the models. In addition, it may be possible to test calculations of axial-charge strength by comparing to near threshold s-wave pion production in ^{3}He$(p,\pi^+)^4$He. Finally, there could be forbidden $0^+\to 0^+$ Fermi strength. This might be observable via ^{3}H$(p,e^+e^-)^4$He.

(v) Solar neutrino experiments such as SuperKamiokande, SNO [13], and Icarus [14] should carefully search for hep neutrinos at energies near 14 MeV and above. Although the flux is relatively small there could be a significant number of events in an energy region with very low background. *It is important to set experimental limits on the hep flux that are independent of theory*.

In conclusion, high energy Solar neutrinos can come from the hep reaction, ^{3}He$(p,\nu e^+)^4$He. Therefore, the interpretation of measured spectra may depend on our understanding of the hep S factor. The present very small estimate for S assumes a pure Gamow-Teller transition that is greatly reduced by cancelations and destructive interference from meson exchange currents. We use a simple model of a nucleon moving in optical potentials to show that the axial-charge transition $^3P_0\to {}^1S_0$ may have comparable strength. It is important to calculate the contribution of other forbidden transitions. This strength could significantly enhance the hep S factor.

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