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# Solar Neutrinos from the $^3$He$(p,e^+\nu)^4$He Reaction[*]

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The cross section for the $\beta^+$ decay of continuum states of $^4$Li has been recalculated using and improved normalization for the $S$-wave proton inside the nucleus and the newly measured value of the thermal-neutron capture cross section of $^3$He. In addition, the contributions of first-forbidden transitions have been added. The new value of the $S$ factor is found to be $8.1\times10^{-20}$ keV b, too small for this reaction to produce a measureable flux of solar neutrinos on Earth.

## I. INTRODUCTION

In a previous paper[1] the authors showed that the reaction

$$^3\text{He}+p\rightarrow{}^4\text{He}+e^++\nu \qquad (1)$$

has a cross section which is about two orders of magnitude smaller than Salpeter's original estimate[2] because of the violation of a symmetry selection rule. Thus the suggestion, by Kuzmin,[3] that this source of neutrinos might be a significant part of the solar-neutrino flux was shown to be invalid. Recent continued interest in the solar neutrino problem, together with some new experimental data that bear on our estimates, have led us to refine our calculation. These refinements will be shown to lead to an enhancement of our predicted neutrino production by about a factor of 3. However, this is not enough to make the reaction (1) a significant contributor to the solar-neutrino flux.

## II. $S$-WAVE CAPTURE

In our previous paper, we pointed out that the ordinary allowed $\beta$-decay contribution to reaction (1) would vanish because the initial and final nuclear wave functions belong to different representations of the symmetry group $S_4$. This also explains why the $M1$ neutron capture rate

$$^3\text{He}+n\rightarrow{}^4\text{He}+\gamma \qquad (2)$$

is so small and we used an upper limit on this rate to estimate the $^3$He$+p$ cross section. This capture rate has just been measured by Bollinger, Specht, and Thomas[4] and turns out to be only 60% of the upper limit we had previously assumed.

We based our estimate of the neutrino rate on the assumption that, even though meson exchange effects are perhaps responsible for most of the neutron capture and $\beta$ decay, the $\langle M_\beta\rangle$ and $\langle M_\gamma\rangle$ are still related to each other by a simple rotation in isospin space. This was based on an apparent proportionality between corresponding matrix elements in the three-body system. Recent experimental results[5] have caused a reevaluation of the $ft$ values for the neutron and tritium and seem to have lowered the size of the exchange correction to the axial-vector matrix element from about 11 to 8%. Perhaps the comparison between the $S$-wave capture of neutrons and protons by $^3$He is still justified without depending upon explicit forms for the exchange contributions. We note that recently Alburger and Wilkinson[6] have argued that in odd-$A$ nuclei the matrix element $\langle\sigma\tau^-\rangle\propto\langle\sigma\tau^z\rangle\simeq\langle\sigma\rangle$.

In the absence of any more accurate knowledge of the four-body wave function, we maintain the basic assumption of the previous paper that the $S$-wave capture processes are proportional to each other. We are aware of Phillips's results[7] for the doublet $n$-$d$ capture cross section which show a sensitive dependence both on the total of the three-body wave function and the exchange moment operators. This takes place because of strong correlation between the direct and exchange operators. We do not believe that this cancellation occurs in the $n$-$^3$He capture because the matrix element is reduced by one order of magnitude from the quar-

TABLE I. Partial contribution to the $S$ factor and the total $S$ factor ($R=4.0$ fm, $a=3.15$ fm).

| $E_p$ (keV) | $S(1^+)$ [a] | $S(2^-+0^-+1^-)$ | $S$ ($10^{-20}$ keV b) |
|---|---|---|---|
| 5 | 7.6 | 0.50 | 8.1 |
| 10 | 7.5 | 0.58 | 8.1 |
| 20 | 7.4 | 0.66 | 8.1 |
| 40 | 7.2 | 0.81 | 8.0 |
| 60 | 7.0 | 0.94 | 7.9 |

[a] These values have an uncertainty of at least 50% because of the experimental uncertainty in the neutron capture cross section.

tet matrix element in the $n$-$d$ capture.[8,9] In the quartet $n$-$d$ capture the $M1$ operator connects a large component of the initial state with a small compound of the final state. In the $n$-$^3$He case, the operator connects two small components. The proportionality constant relating $\langle M_\beta \rangle$ to $\langle M_\gamma \rangle$ depends on the weak and electromagnetic coupling constants and also on the ratio of the normalization of the internal proton and neutron functions. In the previous paper,[1] we had taken

$$|\psi_p(R)|^2/|\psi_n(R)|^2 = 2\pi\eta e^{-2\pi\eta} = C_0^2 . \tag{3}$$

The hard-sphere phase shifts imply that a better approximation is to take

$$|\psi_p(R)|^2/|\psi_n(R)|^2 = C_1^2 = \frac{R^2}{(R-a)^2} \frac{[F_p(kpR)G_p(kpa) - G_p(kpR)F_p(kpa)]^2}{(kpR)^2[F_p^2(kpa) + G_p^2(kpa)]} , \tag{4}$$

where $F_p$ and $G_p$ are the usual regular and irregular Coulomb wave functions, $a$ is the hard-sphere radius, and $R$ is the nuclear radius, $R > a$. We find an extremely weak dependence of $|C_1|^2$ on $R$, changing only 1% as $3.5 \leq R \leq 4.5$. The $S$-wave $^3$He + $p$ cross section can then be written[1]

$$\sigma_\beta \cong \frac{E_{\max}{}^5}{20\pi^3 M^2 E_\gamma{}^3} \left(\frac{E_n}{E_p}\right)^{1/2} \frac{4G_A{}^2 C_1{}^2}{\alpha(\mu_p - \mu_n)^2} \sigma_\gamma . \tag{5}$$

We express this in the usual thermonuclear form

$$\sigma_\beta \cong \frac{S}{E_p} e^{-2\pi\eta} , \tag{6}$$

and evaluate $S$ for several relative proton energies as is shown in Table I. This is more than twice our previous estimate, with the new relation in Eq. (4) more than compensating for the decrease coming from the smaller neutron capture cross section.

### III. $P$-WAVE CAPTURE

There are well-established negative-parity $T = 1$ resonances[10] in $^4$He which enhance $P$-wave $^3$He + $p$ capture. We have investigated the size of the first-forbidden contributions to proton capture. O'Connell, Donnelly, and Walecka[11] have given a multipole expansion for $\beta^+$ decay which is valid so long as the positron is of sufficient energy that it can be represented by a plane wave. The Coulomb correction[12] for this positron decay is no more than 5%. We have used Eq. (20) of Ref. 8 to calculated the $P$-wave capture of protons by $^3$He, taking into account the continuum nature of the negative-parity states by replacing reduced matrix elements between bound states by

$$|\langle 0 \| \mathcal{T}_J \| J \rangle|^2 \rightarrow \frac{1}{2\pi} \frac{\Gamma_p(E_p)}{[E_J + \Delta_p(E_p) - E_p]^2} |\langle 0 \| \mathcal{T}_J \| X_J \rangle|^2 . \tag{7}$$

The resonance parameters for the $2^-$, $0^-$, and two $1^-$ states were taken from Ref. 10 and the internal resonance wave functions, were represented by $(1S)^{-1}(1p)$ shell-model states,[13] with $b_{\text{osc}} = 1.38$ fm. The negative-parity, or first-forbidden, contributions to $S$ are also shown in Table I.

### IV. CONCLUSIONS

We have shown that the $P$-wave capture rate is an order of magnitude smaller than our new estimate of the $S$-wave capture. In any case, the cross section does not seem to be large enough to make a significant contribution to the solar-neutrino flux. If the average cross section for

$$^{37}\text{C} + \nu \rightarrow {}^{37}\text{Ar} + e^-$$

calculated by Bahcall[14] for neutrinos from $^4$Li decay is used, one finds that our new $S$ implies[15] that

$$\varphi\bar{\sigma} = 0.1 \times 10^{-37}\ \text{sec}^{-1} \text{ per } {}^{37}\text{Cl atom} \tag{8}$$

in the Davis experiment.[16]

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