The *hep* reaction and the solar neutrino problem

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The results of a new calculation of the astrophysical $S$-factor for the proton weak capture on $^3$He are here reviewed. The methods used to obtain very accurate initial and final state wave functions and to construct the nuclear weak current operator are described. Finally the implications of these results for the Super-Kamiokande solar neutrino data are discussed.

1. INTRODUCTION

In the present talk, I will report about a recent study of the process $^3$He($p,e^+\nu_e)^4$He, also known as *hep* reaction \[1\]. This process has recently received considerable attention \[1,2\], triggered by the results presented by the Super-Kamiokande (SK) collaboration of the energy spectrum of electrons recoiling from scattering with solar neutrinos. In fact, while over most of the spectrum, a constant suppression of about 0.5 is observed relative to the Standard Solar Model (SSM) predictions \[3\], above 12.5 MeV there is an apparent excess of events. Accordingly with the SSM, the *hep* reaction is the only source of solar neutrinos with energy higher than 14 MeV (their end-point is about 19 MeV). This fact has led to questions about the reliability of the calculations of the *hep* reaction cross section, upon which the SSM bases its currently accepted value for the astrophysical $S$-factor, $2.3 \times 10^{-20}$ keV b \[4\]. In particular, the SK collaboration \[5\] has shown that a large enhancement, by a factor of about 17, of the *hep* $S$-factor would essentially fit the observed excess of recoiling electrons.

The theoretical description of the *hep* process, as already known since long time, constitutes a challenging problem from the standpoint of nuclear few-body theory. In fact, as discussed in detail in Ref. \[1\], the *hep* reaction is extremely sensitive to: (i) small components in the wave functions, in particular the D-state admixtures generated by the tensor interactions; (ii) relativistic corrections and many-body terms in the weak transition operator; (iii) P-wave capture contributions.

The outline of the talk is as follow: I will first briefly review the main steps of the calculation, in particular discussing the method used to describe the initial and final state wave functions and the model of the weak transition operators. Then I will present the $S$-factor results and discuss their implication for the SK solar neutrino spectrum. Some concluding remarks are given in Section \[4\].

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2. REVIEW OF THE CALCULATION

This Section is divided in three parts: in Subsection 2.1, I first summarize all the relevant formulas for the \( hep \) astrophysical \( S \)-factor and the cross section; a detailed description can be found in Ref. [1]. In Subsection 2.2, I then discuss the correlated-hyperspherical-harmonics method used to describe the initial and final state wave functions; finally in Subsection 2.3, I present the model for the weak transition operator.

2.1. The \( hep \) cross section and astrophysical \( S \)-factor

The astrophysical \( S \)-factor at center-of-mass (c.m.) energy \( E \) is defined as

\[
S(E) = E \sigma(E) e^{2\pi \eta}, \tag{1}
\]

where \( \sigma(E) \) is the \( hep \) cross section and \( \eta \) is given by \( \eta = 2\alpha/v_{\text{rel}} \), \( \alpha \) being the fine structure constant and \( v_{\text{rel}} \) the \( p^3\text{He} \) relative velocity. The cross section \( \sigma(E) \) is written as:

\[
\sigma(E) = \int 2\pi \delta \left( \Delta m + E - \frac{q^2}{2m_4} - E_e - E_\nu \right) \frac{1}{v_{\text{rel}}} \frac{1}{4} \sum_{s_\nu s_\nu' s_1 s_3} |\langle f | H_W | i \rangle|^2 \frac{d\mathbf{p}_e}{(2\pi)^3} \frac{d\mathbf{p}_\nu}{(2\pi)^3}, \tag{2}
\]

where \( \Delta m = m + m_3 - m_4 = 19.29 \text{ MeV} \) (\( m \), \( m_3 \), and \( m_4 \) are the proton, \( ^3\text{He} \), and \( ^4\text{He} \) rest masses, respectively), and the transition amplitude is given by

\[
\langle f | H_W | i \rangle = \frac{G_V}{\sqrt{2}} f^\pi \langle -q^4 \text{He} | j_{\pi}^i (\mathbf{q}) | p ^3\text{He} \rangle. \tag{3}
\]

Here \( G_V \) is the Fermi constant, \( \mathbf{q} = \mathbf{p}_e + \mathbf{p}_\nu, |p ^3\text{He}\rangle \) and \( | -q^4 \text{He} \rangle \) represent, respectively, the \( p^3\text{He} \) scattering state with relative momentum \( p \) and \( ^4\text{He} \) bound state recoiling with momentum \( -q \), \( l_\nu \) is the leptonic weak current, \( l_\sigma = \pi_\nu \gamma_\sigma (1 - \gamma_5) v_\nu \) (the lepton spinors are normalized as \( v^\dagger_\nu v_\nu = u^\dagger_\nu u_\nu = 1 \)), and \( j^\pi (\mathbf{q}) \) is the nuclear weak current, \( j^\pi (\mathbf{q}) = (\rho(\mathbf{q}), j(\mathbf{q})) \). The dependence of the amplitude upon the spin projections of the leptons, proton and \( ^3\text{He} \) has been omitted for ease of presentation.

The c.m. energies of interest involved in the \( p^3\text{He} \) weak capture reaction, are of the order of 10 keV: the energy at which the reaction is most probable to occur, known as the Gamow-peak energy, is in fact 10.7 keV. Therefore, it is convenient to expand the \( p^3\text{He} \) scattering state into partial waves, and perform a multipole decomposition of the nuclear weak charge, \( \rho(\mathbf{q}) \), and current, \( j(\mathbf{q}) \), operators. Standard manipulations lead to [1]

\[
\frac{1}{4} \sum_{s_\nu s_\nu' s_1 s_3} |\langle f | H_W | i \rangle|^2 = (2\pi)^2 G_V^2 L_{\sigma \tau} N^{\sigma \tau}, \tag{4}
\]

where the lepton tensor \( L^{\sigma \tau} \) is written in terms of electron and neutrino four-velocities, while the nuclear tensor \( N^{\sigma \tau} \) is given in terms of the reduced matrix elements (RMEs) of the Coulomb \( (C_{\ell \ell}) \), longitudinal \( (L_{\ell \ell}) \), transverse electric \( (E_{\ell \ell}) \), and transverse magnetic \( (M_{\ell \ell}) \) multipole operators between the initial \( p^3\text{He} \) state with orbital angular momentum \( L \), channel spin \( S \) (\( S=0,1 \)), and total angular momentum \( J \), and final \( ^4\text{He} \) state. The present study includes S- and P-wave capture channels, i.e. the \( ^1S_0, ^3S_1, ^3P_0, ^3P_1, ^3P_1, \) and \( ^3P_2 \) states, and retains all contributing multipoles connecting these states to the \( J^\pi = 0^+ \) ground state of \( ^4\text{He} \).
2.2. The initial and final state wave functions

The correlated-hyperspherical-harmonics (CHH) method, developed for the four-body problem in Refs. [6,7], has been used to calculated the bound- and scattering-state wave functions. I first describe the method for the $^4\text{He}$ wave function.

2.2.1. The $^4\text{He}$ wave function

In the study of the four-nucleon systems, there are two sets of Jacobi coordinates, $\{x_A, y_A, z_A\}$ and $\{x_B, y_B, z_B\}$, corresponding to the partitions 1+3 and 2+2, respectively (note that by definition $x_A = x_B$). Their explicit expressions can be found in Refs. [1,6]. In the CHH method, the magnitudes of the Jacobi variables are replaced by the so-called hyperspherical coordinates, which in the four-body case are given by:

$$\rho = \sqrt{x_A^2 + y_A^2 + z_A^2} = \sqrt{x_B^2 + y_B^2 + z_B^2}, \quad (5)$$

$$\cos \phi_3 = x_A/\rho = x_B/\rho, \quad (6)$$

$$\cos \phi_A^2 = y_A/(\rho \sin \phi_3), \quad (7)$$

$$\cos \phi_B^2 = y_B/(\rho \sin \phi_3). \quad (8)$$

The $^4\text{He}$ wave function can be now expanded as:

$$\Psi = \sum_n \frac{z_n(\rho)}{\rho^n} Z_n(\rho, \Omega), \quad (9)$$

where $z_n(\rho)$ are hyper-radial functions, yet to be determined, and $Z_n(\rho, \Omega)$ are known functions, which contain all the spin, isospin, angle and hyper-angle dependence and a Jastrow correlation factor. This factor accounts for the strong state-dependent correlations induced by the nucleon-nucleon interaction and improves the behaviour of the wave function at small interparticle distances, thus accelerating the convergence of the calculated quantities with respect to the number of required basis functions. The hyper-radial functions $z_n(\rho)$ and the bound state energy $E$ are then obtained applying the Rayleigh-Ritz variational principle, $\langle \delta | H - E | \Psi \rangle = 0$. The nuclear Hamiltonian $H$ consists here of the Argonne $v_{18}$ two-nucleon [8] and Urbana-IX three-nucleon [9] interactions. To make contact with earlier studies [4,10], however, and to have some estimate of the model dependence of the results, the older Argonne $v_{14}$ two-nucleon [11] and Urbana-VIII three-nucleon [12] interaction models have also been used. Both these Hamiltonians, the AV18/UIX and AV18/UVIII, reproduce the experimental binding energies and charge radii of the trimucleons and $^4\text{He}$ in exact Green’s function Monte Carlo (GFMC) calculations [13,14]. The results of the $^4\text{He}$ binding energy calculated with the CHH method are given in Table 1 and compared with the GFMC values. Depending on the Hamiltonian model, the CHH results [6,15] are within 1–2 %, of those obtained with the GFMC method.

2.2.2. The $p^3\text{He}$ wave function

The $p^3\text{He}$ cluster wave function $\Psi_{LSJJz}^{1+3}$, having incoming orbital angular momentum $L$ and channel spin $S$ ($S = 0, 1$) coupled to total angular $JJ_z$, is expressed as

$$\Psi_{LSJJz}^{1+3} = \Psi_C^{JJ_z} + \Psi_A^{LSJJz}, \quad (10)$$
Table 1
Binding energies in MeV of $^4\text{He}$ calculated with the CHH method using the AV18 and AV18/UIX, and the older AV14 and AV14/UVIII, Hamiltonian models. Also listed are the corresponding “exact”GFMC results \cite{13,14} and the experimental value.

| Model         | CHH  | GFMC        |
|---------------|------|-------------|
| AV18          | 24.01| 24.1(1)     |
| AV18/UIX      | 27.89| 28.3(1)     |
| AV14          | 23.98| 24.2(2)     |
| AV14/UVIII    | 27.50| 28.3(2)     |
| EXP           |      | 28.3        |

where the term $\Psi_C$ vanishes in the limit of large intercluster separations, and hence describes the system in the region where the particles are close to each other and their mutual interactions are strong. The term $\Psi_L^{SJJ_z}$ describes the system in the asymptotic region, where proton and $^3\text{He}$ interact only via the Coulomb interaction. It contains the dependence on the $R$-matrix elements, which determine phase shifts and (for coupled channels) mixing angles, and it is written in terms of the $^3\text{He}$ wave function, which is obtained using the same CHH method as discussed above, but for a three-body systems \cite{16,17}.

The “core” wave function $\Psi_C$ is expanded in the same CHH basis as the bound-state wave function, and both the $R$-matrix elements and the functions $z_n(\rho)$ occurring in the expansion of $\Psi_C$ are determined applying the Kohn variational principle \cite{1,6}.

The $^3\text{He}$ binding energy and the $p^3\text{He}$ singlet and triplet S-wave scattering lengths predicted by the Hamiltonian models considered in the present work are listed in Table 2, and are found in good agreement with available experimental values, although these are rather poorly known. The experimental scattering lengths have been obtained, in fact, from effective range parametrizations of data taken above 1 MeV, and therefore might have large systematic uncertainties.

Table 2
Binding energies, $B_3$, of $^3\text{He}$, and $p^3\text{He}$ singlet and triplet S-wave scattering lengths, $a_s$ and $a_t$, calculated with the CHH method using the AV18 and AV18/UIX, and the older AV14 and AV14/UVIII, Hamiltonian models. The corresponding experimental values are also listed.

| Model       | $B_3$(MeV) | $a_s$(fm) | $a_t$(fm) |
|-------------|------------|-----------|-----------|
| AV14        | 7.03       |           |           |
| AV18        | 6.93       | 12.9      | 10.0      |
| AV14/UVIII  | 7.73       |           | 9.24      |
| AV18/UIX    | 7.74       | 11.5      | 9.13      |
| EXP         | 7.72       | 10.8±2.6  | 8.1±0.5   |
|             |            |           | 10.2±1.5  |
2.3. The nuclear weak current

The nuclear weak current \( j^\sigma(q) = (\rho(q), j(q)) \) has vector (\( V \)) and axial-vector (\( A \)) parts, with corresponding one- and many-body components. All the one-body terms can be obtained in a standard way from a non-relativistic reduction of the covariant single-nucleon vector and axial-vector currents, including terms proportional to \( 1/m^2 \). The two-body components of the weak vector current \( j(q; V) \) are constructed from the isovector two-body electromagnetic currents in accordance with the conserved-vector-current (CVC) hypothesis, and consist \([1]\) of “model-independent” (MI) and “model-dependent” (MD) terms. The MI terms are obtained from the nucleon-nucleon interaction, and by construction satisfy current conservation with it. The leading MI two-body contribution is given by the “\( \pi \)-like” operator, obtained from the isospin-dependent spin-spin and tensor nucleon-nucleon interactions. The latter also generate an isovector “\( \rho \)-like” current, while additional isovector two-body currents arise from the isospin-independent and isospin-dependent central and momentum-dependent interactions. These currents are short-ranged, and numerically far less important than the \( \pi \)-like current. With the exception of the \( \rho \)-like current, they have been neglected in the present work. The MD currents are purely transverse, and therefore cannot be directly linked to the underlying two-nucleon interaction. The present calculation includes the currents associated with excitation of \( \Delta \) isobars which, however, are found to give a rather small contribution in weak-vector transitions, as compared to that due to the \( \pi \)-like current.

The many-body weak charge operators can also be obtained from their electromagnetic correspondents applying the CVC hypothesis. However, while the main parts of the two-body electromagnetic or weak vector current are linked to the form of the nucleon-nucleon interaction through the continuity equation, the most important two-body electromagnetic or weak vector charge operators are model dependent, and should be viewed as relativistic corrections. The model commonly used \([20]\) for the electromagnetic many-body charge operators includes the \( \pi \)–, \( \rho \)–, and \( \omega \)-meson exchange terms with both isoscalar and isovector components, as well as the (isoscalar) \( \rho \pi \gamma \) and (isovector) \( \omega \pi \gamma \) charge transition couplings (in addition to the single-nucleon Darwin-Foldy and spin-orbit relativistic corrections). The \( \pi \)– and \( \rho \)-meson exchange charge operators are constructed from the isospin-dependent spin-spin and tensor interactions, using the same prescription adopted for the corresponding current operators \([20]\). At moderate values of momentum transfer \((q < 5 \text{ fm}^{-1})\), the contribution due to the “\( \pi \)-like” exchange charge operator has been found to be typically an order of magnitude larger than that of any of the remaining two-body mechanisms and one-body relativistic corrections \([17]\). In the present study therefore we retain, in addition to the one-body operator, only the “\( \pi \)-like” and “\( \rho \)-like” weak vector charge operators.

The axial charge operator \( \rho(q; A) \) includes, in addition to the one-body component, the long-range pion-exchange term \([21]\), required by low-energy theorems and the partially-conserved-axial-current relation, as well as the (expected) leading short-range terms constructed from the central and spin-orbit components of the nucleon-nucleon interaction, following a prescription due to Kirchbach \textit{et al.} \([22]\). The \( \Delta \)-excitation terms have also been included, but they have been found to be unimportant \([1]\).

In contrast to the electromagnetic case, the axial current operator \( j(q; A) \) is not conserved. Thus, its two-body components cannot be linked to the nucleon-nucleon interac-
tion and, in this sense, should be viewed as model dependent. In the model presented here, the two-body axial current operators due to $\pi$- and $\rho$-meson exchanges, and the $\rho\pi$-transition mechanism have been included. The leading many-body terms in the axial current are however due to $\Delta$-isobar excitation. They have been treated non-perturbatively in the transition-correlation-operator (TCO) scheme, originally developed in Ref. [4] and further extended in Ref. [17]. In the TCO scheme—essentially, a scaled-down approach to a full $N+\Delta$ coupled-channel treatment—the $\Delta$ degrees of freedom are explicitly included in the nuclear wave functions.

The largest model dependence is in the weak axial current. To minimize it, the poorly known $N\Delta$ transition axial coupling constant $g_A^*$ has been adjusted to reproduce the experimental value of the Gamow-Teller matrix element in tritium $\beta$-decay [1,23]. While this procedure is model dependent, its actual model dependence is in fact very weak, as has been shown in Refs. [1,23].

3. RESULTS

I present here the results for the hep astrophysical $S$-factor, and their implications to the SK solar neutrino spectrum.

3.1. Results for the S-factor

The results for the astrophysical $S$-factor, calculated using CHH wave functions with the AV18/UIX Hamiltonian model, at three different c.m. energies, are given in Table 3. By inspection of the table, it can be noted that: (i) the energy dependence is rather weak: the value at 10 keV is only about 4\% larger than that at 0 keV; (ii) the P-wave capture states are found to be important, contributing about 40\% of the calculated $S$-factor. However, the contributions from D-wave channels are expected to be very small. It has been explicitly verified that they are indeed small in $^3D_1$ capture. (iii) The many-body axial currents play a crucial role in the (dominant) $^3S_1$ capture, where they reduce the $S$-factor by more than a factor of four.

Table 3
The hep $S$-factor, in units of $10^{-20}$ keV b, calculated with CHH wave functions corresponding to the AV18/UIX Hamiltonian model, at $p^3He$ c.m. energies $E=0$, 5, and 10 keV. The rows labelled "one-body" and "full" list the contributions obtained by retaining the one-body only and both one- and many-body terms in the nuclear weak current. The contributions due the $^3S_1$ channel only and all S- and P-wave channels are listed separately.

| E=0 keV | E=5 keV | E=10 keV |
|---------|---------|----------|
| $^3S_1$ | S+P | $^3S_1$ | S+P | $^3S_1$ | S+P |
| one-body | 26.4 | 29.0 | 25.9 | 28.7 | 26.2 | 29.3 |
| full | 6.38 | 9.64 | 6.20 | 9.70 | 6.36 | 10.1 |

The different contributions from the S- and P-wave capture channels to the zero energy $S$-factor are given in Table 4. The results obtained using the two-nucleon AV18 and the
older two- and three-nucleon AV14/UVIII interaction models are also listed. Note that the sum of the channel contributions is a few % smaller than the total result reported at the bottom of the table, due to the presence of interference terms among multipole operators connecting different capture channels [1].

The dominant contribution to the S-factor is obtained from the $^3S_1$ capture channel. Among the P-wave capture channels, the $^3P_0$ does not give the largest contribution, as instead expected in previous studies [3], although this is the only contribution surviving in the limit $q=0$.

Table 4
Contributions of the S- and P-wave capture channels to the hep S-factor at zero $p^3$He c.m. energy in $10^{-20}$ keV b. The results correspond to the AV18/UIX, AV18 and AV14/UVIII Hamiltonian models.

|          | AV18/UIX | AV18 | AV14/UVIII |
|----------|----------|------|------------|
| $^1S_0$  | 0.02     | 0.01 | 0.01       |
| $^3S_1$  | 6.38     | 7.69 | 6.60       |
| $^3P_0$  | 0.82     | 0.89 | 0.79       |
| $^1P_1$  | 1.00     | 1.14 | 1.05       |
| $^3P_1$  | 0.30     | 0.52 | 0.38       |
| $^3P_2$  | 0.97     | 1.78 | 1.24       |
| **TOTAL** | 9.64     | 12.1 | 10.1       |

By comparing the AV18 and AV18/UIX results, it can be concluded that inclusion of the three-nucleon interaction reduces the total S-factor by about 20 %. This decrease is mostly in the $^3S_1$ contribution, and can be traced back to a corresponding reduction in the magnitude of the one-body axial current matrix elements. The latter are sensitive to the triplet scattering length, for which the AV18 and AV18/UIX models predict, respectively, 10.0 fm and 9.13 fm (see Table 2). This 20 % difference in the total S-factor values for AV18 and AV18/UIX emphasizes the need for performing the calculation using a Hamiltonian model that reproduces the binding energies and low-energy scattering parameters for the three- and four-nucleon systems. This is true for the AV18/UIX model, but not for the AV18 model.

The different contributions to the astrophysical S-factor when the older AV14/UVIII potential model is used are given in the last column of Table 4. By comparing these results with the ones obtained with the AV18/UIX, it can be observed that both the S- and P-wave contributions are not significantly changed; in particular, the $^3S_1$ capture S-factor values differ for only about 3 %. It is important to emphasize that this is due to the procedure of constraining the model dependent two-body axial currents by fitting the Gamow-Teller matrix element of tritium $\beta$-decay, as discussed at the end of the previous Section. Note that the AV14/UVIII Hamiltonian also reproduces the low-energy properties for the three- and four-nucleon systems.
3.2. Implications for the Super-Kamiokande solar neutrino spectrum

The Super-Kamiokande (SK) experiment detects solar neutrinos by neutrino-electron scattering. It is sensitive, according to the SSM [3], to the very energetic neutrinos from the $^8\text{B}$ weak decay ($^8\text{B} \rightarrow ^4\text{He} + ^4\text{He} + e^+ + \nu_e$) and from the $hep$ reaction. The SK results are presented as ratio of the measured to the SSM predicted events when no neutrino oscillations are included, as function of the recoil electron energy. Over most of the spectrum, this ratio is constant at $\approx 0.5$ [5]. At the highest energies, however, there is an excess of events relative to the 0.5×SSM prediction. This is seen in Fig. 1 where the SK results from 825 days of data acquisition [3] are shown by the points (the error bars denote the combined statistical and systematic error); the dotted line is the 0.5×SSM prediction.

To study the effects of the new value for the $S$-factor presented here, $10.1 \times 10^{-20}$ keV b (see Table 3) to the SK spectrum, it is useful to introduce the ratio $\alpha$ of the $hep$ flux to its SSM value, defined as $\alpha \equiv S_{\text{new}}/S_{\text{SSM}} \times P_{\text{osc}}$, where $P_{\text{osc}}$ is the observed suppression factor due to neutrino oscillations. Therefore, if $hep$ neutrino oscillations are ignored, then $\alpha = (10.1 \times 10^{-20}$ keV b$)/(2.3 \times 10^{-20}$ keV b$) = 4.4$, while if the $hep$ neutrinos are suppressed by $\approx 0.5$, then $\alpha = 2.2$. The long-dashed and solid lines in Fig. 1 indicate the effect of these two different values of $\alpha$ on the ratio of the electron spectrum with both $^8\text{B}$ and $hep$ to that with only $^8\text{B}$ (the SSM). Two other arbitrary values of $\alpha$ (10 and 20) are shown for comparison.

4. CONCLUSIONS

In this talk, I have reported about a recent new calculation of the astrophysical $S$-factor for the $hep$ reaction. The chief conclusion of this calculation is that the best estimate for the $S$-factor at 10 keV, close to the Gamow-peak energy, is $10.1 \times 10^{-20}$ keV b. This value is $\approx 4.5$ times larger than the value adopted in SSM, based on Ref. [4], of $2.3 \times 10^{-20}$ keV b. It is therefore important to point out the differences between the present and the previous study of Ref. [4]: (i) all P-wave contributions are included; (ii) the CHH method has been used to describe the initial and final state wave functions, corresponding to the latest generation of realistic interactions. The CHH method is known to be more accurate than the variational Monte Carlo (VMC) technique used in Ref. [4], and it better describes the small components of the wave function to which the one-body axial current operator is most sensitive. (iii) The $1/m^2$ relativistic corrections in the one-body axial current operator are included. In $^3\text{S}_1$ capture, for example, these terms increase by 25% the $L_1$ and $E_1$ matrix elements calculated with the one-body axial current operator.

Finally, the implications of this new estimate for the SK solar neutrino data have been investigated. The results are summarized in Fig. 1 from which it can be concluded that the enhancement of the $S$-factor reported here, although large, is not enough to completely resolve the discrepancies between the present SK results and the SSM predictions. However, this accurate calculation of the $S$-factor, and the consequent absolute prediction for the $hep$ neutrino flux, will allow much greater discrimination among the proposed solutions to this problem, based on different solar neutrino oscillation scenarios.
Figure 1. Electron energy spectrum for the ratio between the Super-Kamiokande 825-days data and the expectation based on unoscillated $^8$B neutrinos \[3\]. The data were extracted graphically from Fig. 8 of Ref. \[3\]. The 5 curves correspond respectively to no $hep$ contribution (dotted line), and an enhancement $\alpha$ of 2.2 (solid line), 4.4 (long-dashed line), 10 (dashed line) and 20 (dot-dashed line).

5. ACKNOWLEDGMENTS

I wish to thank R. Schiavilla, M. Viviani, A. Kievsky, S. Rosati and J.F. Beacom for their many important contributions to the work reported here. I also would like to gratefully acknowledge the support of the U.S. Department of Energy under Contract No. DE-AC05-84ER40150.

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