$k_2^{\pm}$) perturbations may be neglected. To demonstrate this, we shall consider the relatively simple process of two-photon scattering. The amplitude for this process may be written (neglecting the magnetic dipole and electric quadrupole terms) as

$$\sum_{\nu} \frac{\langle f|-\vec{\mathrm{D}}\cdot\vec{\mathrm{E}}(k_2^{-})|v\rangle\langle v|-\vec{\mathrm{D}}\cdot\vec{\mathrm{E}}(k_1^{+})|i\rangle}{\hbar(\omega_{iv}+i\alpha)}$$

$$+\frac{\langle f|-\vec{\mathrm{D}}\cdot\vec{\mathrm{E}}(k_1^{-})|v\rangle\langle v|-\vec{\mathrm{D}}\cdot\vec{\mathrm{E}}(k_2^{+})|i\rangle}{\hbar(\omega_{iv}+i\alpha)}$$

$$+\frac{1}{mc^2}\sum_{\nu}\langle f|\vec{\mathrm{D}}\cdot\vec{\mathrm{E}}(k_1^{-})|v\rangle\langle v|\vec{\mathrm{D}}\cdot\vec{\mathrm{E}}(k_2^{+})|i\rangle(\vec{\mathrm{n}}_1\cdot\vec{\mathrm{n}}_2). \quad (6)$$

The first term corresponds to the second-order perturbation due to the $-\vec{\mathrm{D}}\cdot\vec{\mathrm{E}}(k^{\pm})$ potential in Eq. (4), the second corresponding to the first-order perturbation due to (5). The states of the system appearing in (6) are states of the "unperturbed" molecule-plus-field system.

By replacing the denominators in the first term of (6) by "average excitation energies," $\hbar\Delta\omega$, the ratio of the second term to the first may be evaluated to be $\hbar\Delta\omega/2mc^2 \approx 10^{-21}\Delta\omega$. For radiation of optical and lower frequencies, it is certain that this ratio will be very small indeed, illustrating that the perturbation due to the potential $V(k_1^{-}, k_2^{+})$ is very small with respect to the other term. Exactly the same argument may be applied in calculating the amplitudes for other multiphoton processes, leading to the conclusion that the bilinear term of the interaction potential [when formulated in terms of Eq. (2)] may be neglected in comparison to the other terms. An additional advantage of Eq. (2) is that the molecule-(quantized) electromagnetic-field interaction potential is represented in terms of multipole-moment interactions. This work will be presented more fully elsewhere.

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# SOLAR NEUTRINOS*

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The predicted capture rate in the $\mathrm{Cl}^{37}$ experiment for detecting solar neutrinos is calculated using the results of recent nuclear experiments and solar-model investigations. It is shown that additional experiments (e.g., with $\mathrm{H}^2$, $\mathrm{Li}^7$, $\mathrm{B}^{11}$, or $\nu$-$e$ scattering) are necessary to establish the relative contributions of the proton-proton chain and the CNO cycle to solar energy generation.

An experiment is currently under way[1,2] to test directly the theory of nuclear energy generation in stars by detecting neutrinos from the interior of the sun via the reaction

$$\nu_e + \mathrm{Cl}^{37} \to \mathrm{Ar}^{37} + e^{-}. \quad (1)$$

The rate at which solar neutrinos will cause Reaction (1) has previously been calculated[3,4] using a theoretical model of the nuclear mass-37 system and the results of extensive solar-model investigations.[5] The rare mode of the proton-proton chain involving the beta decay of $\mathrm{B}^8$ (maximum neutrino energy ~14 MeV) was shown[3] to be that most important solar neutrino source when $\mathrm{Cl}^{37}$ is used as a detector. In this Letter we report the results of more accurate calculations for the cross sections of Reaction (1) leading to the ground state or any of the excited states of $\mathrm{Ar}^{37}$; these calculations were made possible by the large amount of experimental information that has recently become available for the mass-37 system.[6-9] We also discuss the expected solar neutrino fluxes using a revised set of consistent nuclear parameters. The largest remaining experimental uncertainties in predicting the solar-induced rate of Reaction (1) are noted. Finally, we show that experiments with either $\mathrm{H}^2$, $\mathrm{Li}^7$, $\mathrm{B}^{11}$, or $\nu$-$e$

scattering when combined with the $Cl^{37}$ experiment could furnish a test of the relative contribution of the CNO cycle and proton-proton chain to solar energy generation. Using the absorption cross sections and fluxes calculated in this Letter, the reaction $He^3(H^1, e^+\nu)He^4$ is shown elsewhere[10] to be of minor importance for the $Cl^{37}$ experiment.

The average absorption cross sections in Reaction (1) for neutrinos from the beta decay of $B^8$ and the reaction[11] $He^3 + H^1 \to He^4 + e^+ + \nu_e$ have been calculated using the detailed results on the beta-decay spectrum of $Ca^{37}$ recently obtained by Poskanzer et al.,[7] the mass-37 level assignments of Kavanagh and Goosman,[8,9] and theoretical formulas previously given.[4] The results are:

$$\langle\sigma\rangle_{B^8} = (1.35 \pm 0.1) \times 10^{-42}\ \text{cm}^2 \qquad (2)$$

and

$$\langle\sigma\rangle_{He^3+H^1} = (4.5 \pm 0.4) \times 10^{-42}\ \text{cm}^2. \qquad (3)$$

The previously calculated[4] absorption cross sections for the other major sources of solar neutrinos (e.g., $e^- + Be^7 \to Li^7 + \nu_e$ and $N^{13} \to C^{13} + e^+ + \nu_e$) are unaffected, because of their much lower decay energies, by the recent experimental results on the mass-37 system. The calculations on which Eqs. (2) and (3) are based include 15 known levels in $K^{37}$ (and therefore with sufficient accuracy[8,9] $Ar^{37}$) and an estimate of the small contribution of levels of high excitation energy which are inaccessible in the $Ca^{37}$ decay. For both $\langle\sigma\rangle_{B^8}$ and $\langle\sigma\rangle_{He^3+H^1}$, approximately 65% of the total contribution comes from the analog state of $Cl^{37}$ which occurs at an excitation energy of 5.1 MeV in $Ar^{37}$. The $B^8$ cross section was averaged over the profile of the $Be^{8*}$ state (or states) using the experimental spectrum[12] for the resulting two alpha particles; this averaging lowers the cross section to the analog level by 14% and that to the ground state by 5%, compared with the cross section calculated for a hypothetical decay to a sharp state at 2.9-MeV excitation energy in $Be^{8*}$. The quoted uncertainties in Eqs. (2) and (3) include estimated errors in the assignment to particular levels of $K^{37}$ of unidentified transitions in the decay of $Ca^{37}$ and smaller uncertainties[13] in the Gamow-Teller part of the theoretical matrix elements for the analog transition. These results for $\langle\sigma\rangle_{B^8}$ agree with the earlier estimate[3,4] by the present author of this quantity well within the 25% stated uncertainty of the previous estimate, but differ by more than a factor of 2 from some purely theoretical calculations.[14]

Neutrino fluxes from four previously published[15-18] models of the sun have been calculated using detailed information, kindly supplied by the authors, regarding the internal parameters of their models. The results for the $He^3 + H^1$ and $B^8$ fluxes are given in Table I. The $B^8$ fluxes for the models listed in rows one, three, and four have been calculated earlier[15,17,18]; our results differ from the previously published fluxes because we have used Parker's[19] more accurate value for the $Be^7 + H^1$ cross-section factor and a consistent set of nuclear-reaction data.[20] The model labels in Table I have the following interpretation: (i) Sears J,[15] a standard solar model; (ii) Weymann and Sears,[16] an improved solar model using more accurate opacities and a nonadiabatic convective envelope, and including radiation pressure; (iii) Ezer and Cameron,[17] a solar model with a convective core, probably the result of using a special opacity law; and (iv) Ezer and Cameron varying-$G$,[18] a solar model com-

Table I. Solar neutrino fluxes at the earth.

| Solar model | $\varphi_\nu(He^3+H^1)$[a] ($10^{+5}$ cm$^{-2}$ sec$^{-1}$) | $\varphi_\nu(B^8)$ ($10^{+7}$ cm$^{-2}$ sec$^{-1}$) |
|---|---|---|
| Sears J | 1.95 | 2.80 |
| Weymann and Sears | 2.00 | 2.05 |
| Ezer and Cameron | 2.05 | 2.08 |
| Ezer and Cameron (varying $G$) | 1.70 | 10.2 |

[a] The value of this flux is proportional to the low-energy cross-section factor for the reaction $He^3 + H^1$. The numbers in Table I were derived assuming $S_0(He^3 + H^1) = 10^{-18}$ keV b (cf. Ref. 10).

puted with the assumption that the gravitational constant varies with time according to the theory of Brans and Dicke.[21] Note that the varying-*G* model of Ezer and Cameron gives a much higher $B^8$ flux than any of the other models. All the models quoted assume a primordial solar heavy-element abundance of 2%. This number is uncertain, however, and a heavy-element abundance of 3.4% would probably[15] lead to a $B^8$ flux for each model about twice that given in Table I. For the purpose of the following discussion, we assume that *G* does not vary and therefore adopt for the $B^8$ neutrino flux at the earth

$$\varphi_\nu(B^8) = (2.1^{+2}_{-1})\times 10^{+7} \text{ neutrinos cm}^{-2}\text{ sec}^{-1}. \quad (4)$$

All other neutrino fluxes are changed from the values quoted in the original sources[15,17,18] by amounts insignificant for the $Cl^{37}$ experiment.

We find, using Eqs. (2) and (4) and previously published values for the neutrino fluxes[15,17,18] and absorption cross sections[4] for other neutrino sources, the following value for the sum of the fluxes times cross sections for all known sources of solar neutrinos:

$$\sum(\varphi_\nu\sigma) = (3.0^{+3}_{-1.5})\times 10^{-35} \text{ per } Cl^{37} \text{ atom per second} \quad (5)$$

or six captures per day in the experiment, using $10^{+5}$ gal of $C_2Cl_4$, that is under way. After $B^8$, the largest contribution to the predicted counting rate comes from $Be^7$ neutrinos and is about 7% of the total rate. The value ($3.0 \times 10^{-35}$ $sec^{-1}$) given in Eq. (5) is only a factor of 5 below the upper limit ($16\times 10^{-35}$ $sec^{-1}$) obtained in a preliminary experiment[2] with $10^{+3}$ gal. The prediction $15\times 10^{-35}$ $sec^{-1}$ obtained using the Ezer and Cameron model with a varying gravitational constant[18] and including $N^{13}$, $O^{15}$, and $Be^7$ neutrinos is only 10% below the present upper limit.

The primordial (or surface) composition assumed in computing the solar models represents the largest recognized uncertainty in the predicted capture rate; the errors given in Eq. (5) are no more than guesses for the magnitude of this uncertainty. The assumed composition is based largely on interpretations[15,22] of rocket observations with nuclear emulsions[23] of solar cosmic rays. Further experimental and theoretical work on the determination of the He, C, O, and Ne abundances on the solar surface is essential to an increased understanding of the solar interior.

If the CNO cycle were the dominant mode of energy production in the sun, then the reaction rate for the $Cl^{37}$ experiment would be $3.5\times 10^{-35}$ $sec^{-1}$, independent of the central temperature of the sun.[24] This rate agrees within the recognized uncertainties with the value, given in Eq. (5), based on the assumption that the proton-proton chain is dominant. Thus, the $Cl^{37}$ experiment alone cannot establish whether the sun operates on the proton-proton chain or the CNO cycle. (The solar models used in compiling Table I all have a CNO contribution to the total energy generation of only a few per cent. However, no direct experimental proof is available that the proton-proton chain is dominant in the sun.) Fortunately, a number of other possible detectors of solar neutrinos have been proposed, and the contribution of various solar neutrino sources to the expected counting rates have been calculated.[25] For the four likely detectors recently discussed in this Journal[26-28] ($H^2$, $Li^7$, $B^{11}$, and $\nu$-$e$ scattering), $B^8$ is again predicted to be the most important solar neutrino source. (In fact, the decay of $B^8$ provides the only important source[10] of solar neutrinos above the threshold for a $B^{11}$ detector; the proposed experimental conditions[27,28] would preclude the lower-energy neutrinos from the CNO cycle in the $Li^7$ and $\nu$-$e$ scattering experiments.) If the proton-proton chain is dominant, then the flux inferred from any of the above-mentioned four experiments, by assuming that the source spectrum has the same shape as the $B^8$ spectrum, should equal the flux inferred from the $Cl^{37}$ experiment.[29] This is an important prediction to check since (1) it is independent of the absolute value of the $B^8$ flux; (2) it is true only if the spectrum of the primary neutrino source has essentially the same shape as the $B^8$ spectrum; and therefore, (3) it would not be true if the CNO cycle contributed significantly to the energy production in the sun.

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# INTERSTELLAR AND INTERGALACTIC ABSORPTION OF COSMIC X RAYS*

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Calculations using improved element abundances and atomic photoelectric cross-section data indicate sizable interstellar x-ray absorption edges at 0.532 and 0.874 keV due to *K*-shell photoionization of O and Ne, respectively. Results are applied to recent and prospective observations.

By employing a rocket-borne proportional counter and pulse-height analyzer, experimenters at the Lawrence Radiation Laboratory in Livermore have obtained a fairly detailed spectrum of the strongest cosmic x-ray source Sco X-1.[1] Their spectrum extends down to 0.9 keV and shows a turnover at the low-energy end; they caution that this turnover may be partly instrumental, but suggest that it may also be due to interstellar photoelectric absorption. We have calculated the opacity of gaseous matter with a "cosmic" element abundance and shall present the essential results here. These results differ from previous, oft-cited calcu-