Response of ^{127}I to Solar Neutrinos

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We use a configuration-mixing quasiparticle Tamm-Dancoff approximation to calculate the expected event rate for an ^{127}I solar neutrino detector. Our cross section for ^{8}B solar neutrinos is 2.2×10^{-42} cm^2 [corresponding to about 13 solar neutrino units (SNU) in the standard solar model], a factor of more than 3 below an estimate by Haxton. This value may increase by about 30% when quadrupole correlations are included. The cross section for ^{7}Be neutrinos is 2.0×10^{-45} cm^2 (9.4 SNU), in agreement with a calculation by Dellagiacoma and Iachello. The total event rate per nucleus from all solar neutrinos is about 3 times that in ^{37}Cl.

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In 1988 Haxton [1] proposed the use of ^{127}I as the active element in a solar neutrino detector. Extrapolating from the results of (p,n) experiments on ^{98}Mo and ^{71}Ga, he estimated the cross section of ^{8}B neutrinos on ^{127}I to be between 7.2×10^{-42} and 8.9×10^{-42} cm^2, considerably larger values than the cross section on ^{37}Cl (1.2×10^{-42} cm^2) [2]. Since, in addition, the natural abundance of ^{127}I is 4 times higher than that of ^{37}Cl, a tank containing 1000 tons of iodine would have an expected count rate about 20 times that of the chlorine experiment at Homestake, enough of an improvement to shed new light on, e.g., the question of whether the neutrino flux is correlated with solar activity. Furthermore, one excited state in ^{127}Xe is accessible to ^{7}Be neutrinos, and while Haxton was unable to estimate the strength to this state, he noted that if the ratio of ^{7}Be and ^{8}B cross sections was substantially different from that in chlorine, the two experiments combined could determine the flux of ^{7}Be and ^{8}B neutrinos separately. Added to the ease with which ^{127}Xe can be extracted from ^{127}I and counted, these points constitute a strong case for building an iodine solar neutrino detector.

Unfortunately, the ^{8}B cross-section estimates are based on extrapolations from data in much lighter nuclei than ^{127}I and must be verified before the solar neutrino experiment can proceed relatively free from doubt. Measurements to calibrate both the ^{8}B and ^{7}Be cross sections are in fact planned or are already in progress. To date, however, no data have been published and it is therefore worthwhile examining the estimates more carefully from a theoretical standpoint. Here we present a calculation of the solar neutrino cross sections. Our ^{8}B result, while larger than in ^{37}Cl, is smaller than the original estimates. Furthermore, our ^{7}Be cross section is so large that the ^{7}Be/^{8}B ratio is very different from that in ^{37}Cl. This last conclusion is weaker than the first and can be reliably confirmed only by measurement.

To determine the solar neutrino cross sections, we need to calculate the matrix elements of the Gamow-Teller operator $\sigma\tau_+$ connecting the $J^\pi=\frac{5}{2}^+$ ground state of ^{127}I to all states in ^{127}Xe below the neutron-emission threshold at 7.23 MeV. Our approach, a configuration-mixing quasiparticle Tamm-Dancoff approximation (QTDA), is to diagonalize the nucleon-nucleon interaction in a space of one- and three-quasiparticle states, the selection of which we describe below. A similar though less comprehensive procedure was adopted in Ref. [3] in a calculation of the Gamow-Teller strength from ^{71}Ga.

We begin by solving the BCS equations for both protons and neutrons to determine the quasiparticle vacuum $|0\rangle$, adjusting the average number of particles so that the one-proton-quasiparticle state $\pi^\dagger_{d_{5/2}}|0\rangle$ of the target ^{127}I nucleus has 53 protons and 74 neutrons. We then construct the following set of positive-parity states in iodine:

$$\pi^\dagger_{d_{5/2}}|0\rangle,\quad [\nu_i^\dagger(\pi_k^\dagger\nu_l^\dagger)^K]^{5/2}|0\rangle\,, \tag{1}$$

where i,k,l represent valence single-particle orbitals (to be specified later), K can take any allowed value, and $\pi_j^\dagger$ ($\nu_j^\dagger$) creates a proton (neutron) quasiparticle in orbit j. Diagonalizing the effective Hamiltonian in this (overcomplete) basis yields the states of ^{127}I, the lowest of which represents the $J^\pi=\frac{5}{2}^+$ target ground state.

To obtain the states in ^{127}Xe, we generalize the above construction to $J^\pi=(\frac{3}{2},\frac{5}{2},\frac{7}{2})^+$ and consider the set

$$\nu_j^\dagger|0\rangle,\quad [\pi_i^\dagger(\pi_k^\dagger\nu_l^\dagger)^K]^J|0\rangle\,, \tag{2}$$

where j now represents a $d_{3/2}$, $d_{5/2}$, or $g_{7/2}$ orbital. Diagonalizing the Hamiltonian in this space yields the relevant part of the ^{127}Xe spectrum.

Our choice of configurations is motivated by analogy with the familiar QTDA in even nuclei. There, the Gamow-Teller operator connects the initial $J^\pi=0^+$ ground state $|0\rangle$ with 1^+ states in the final odd-odd nucleus of the form $(\pi_k^\dagger\nu_l^\dagger)^1|0\rangle$. Our procedure in the odd nucleus ^{127}I is a straightforward extension. If the ground state is predominantly the one-quasiparticle state in (1) —and this in fact appears to be the case—then essentially all the states in ^{127}Xe that can be created by the Gamow-Teller operator are contained in (2) and our calculated strength exhausts the Gamow-Teller sum rule [though, as in most such calculations, we scale the entire distribution by a phenomenological factor of $(1.0/1.25)^2$ to reflect the experimentally "missing" strength [4]; this factor is implicit everywhere in the discussion to follow]. Furthermore, the subset of three-quasiparticle states in (2) with $K^\pi = 1^+$ are the most strongly excited; the others connect only via exchange diagrams and will contribute weakly (though we have nevertheless included them). A new feature of the QTDA in odd systems is the mixing of configurations with different numbers of quasiparticles in both the initial and final nuclei. As we shall see later, even tiny three-quasiparticle admixtures can have large effects on Gamow-Teller transitions between low-lying, predominantly one-quasiparticle, states.

In even nuclei it is customary, and in some applications necessary [5,6], to go beyond QTDA and introduce correlations in the initial ground state through the quasiparticle random-phase approximation (QRPA) [7]. Gamow-Teller strength in the unblocked β^- direction, however, is not one of these applications; the QTDA and QRPA yield nearly identical results over the entire distribution. Thus though our original intent was to apply the QRPA to odd nuclei—the discussion in the previous paragraphs carries over from QTDA to QRPA in a straightforward way —we lose little by using the considerably simpler QTDA.

The one important ingredient our calculation leaves out is quadrupole collectivity. In this region of the periodic table, quadrupole phonons, involving a coherent superposition of two-quasineutron and two-quasiproton excitations, are expected to lie at roughly 400–700 keV. Our basis does include a part of the quadrupole phonon degree of freedom; in iodine, for example, the three-quasiparticle configurations in (1) can be reexpressed as a quasiproton coupled to two quasineutron excitations. Three-quasiproton states (three quasineutron in ^{127}Xe) are absent entirely, however. A more comprehensive treatment might shift the Gamow-Teller strength at low energies. We will argue later, however, that such effects are not likely to be large.

To complete the description of our procedure we will still need to specify the effective Hamiltonian. This issue is difficult for at least two reasons. First, there is no known effective shell-model Hamiltonian that properly describes the movement of spherical single-particle levels over a large range of nuclei. Thus, the use of single-particle energies from the nearest doubly magic core together with realistic effective interactions is not appropriate for the description of nuclei like ^{127}I that have large numbers of valence particles. A second point is that realistic effective interactions are often also unable to reproduce important quantities such as pairing gaps and subshell occupation numbers near the Fermi surface. With these facts in mind, we choose our effective Hamiltonian in the following way: We take single-particle energies from a one-body potential [8] that represents the spherical mean field in the specific nucleus under investigation. The two-body interaction is an analytic fit by the Paris-potential G matrix [9], with two modifications. First, we replace all the neutron-proton monopole matrix elements by their average value in the valence space. This is necessary because our single-particle energies already include effects of the n-p monopole force. Using the average interaction leaves all single-particle (and single-quasiparticle) energies unchanged while permitting us to include, at least in an average way, the monopole interaction *between* quasiparticles. Finally, we multiply all $J^\pi = 0^+$ like-particle matrix elements by a constant (between 1.0 and 1.3) in order to reproduce the experimental pairing gaps.

Before describing our results for iodine, we first present a test calculation in ^{71}Ga, where (p,n) data are available [10]. Our single-particle space here consists of the $0f$-$1p$ oscillator shell plus the $0g_{9/2}$ and $0g_{7/2}$ orbitals. We multiply the proton pairing matrix elements by 1.1 (see our earlier remarks), the neutron pairing matrix elements by 1.0, and carry out the diagonalization in the one- and three-quasiparticle basis appropriate for gallium and germanium. The giant Gamow-Teller (GT) resonance appears correctly between 12 and 13 MeV, though as in all such calculations it is considerably narrower than the experimental resonance. We plot the first 8 MeV of strength—the portion relevant for solar neutrino scattering—alongside the experimental strength in Fig. 1. Though the two plots differ in detail, they agree well in the first MeV and contain the same total strength below 3

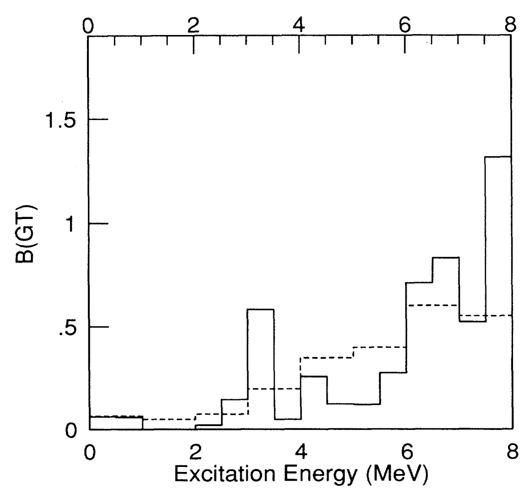

FIG. 1. The calculated strength $B(\mathrm{GT}) = (2J_i+1)^{-1} \times |\langle J_f || \sigma\tau_+ || J_i \rangle|^2$ from ^{71}Ga to states below 8 MeV of excitation energy in ^{71}Ge, in 0.5-MeV bins (solid line), and experimental strength from Ref. [10] (where errors are discussed), in 1-MeV bins (dashed line).

and below 8 MeV. Weighing the strength to each state with the ^{8}B neutrino spectrum [11] and a relativistic Coulomb function (that includes nuclear finite-size effects and electron screening), and integrating over phase space, we find a total calculated cross section of 2.4×10^{-42} cm^2, in good agreement with the value deduced from the experiment. Since our procedure seems to work reasonably well here, we now can turn to iodine, the element of interest, with some confidence.

The physics here is similar. Our valence single-particle space is now the $2s$-$1d$-$0g$ oscillator shell plus the $0h_{11/2}$ and $0h_{9/2}$ orbitals. The proton pairing matrix elements are multiplied by 1.3 and the neutron pairing matrix elements again by 1.0. The first 8 MeV of the spectrum are shown as the solid line in Fig. 2. Most of the strength is in the giant resonance, centered at about 15 MeV, and does not appear in the figure; the portion below 7.2 MeV totals only 2.1, or 7% of the full strength. (This illustrates just how difficult it is to accurately calculate the solar neutrino response.) The distribution translates into a ^{8}B cross section of 2.2×10^{-42} cm^2 or, assuming the standard solar neutrino flux, a total of 13 solar neutrino units (SNU) for ^{8}B neutrinos. This result is more than 3 times smaller than Haxton's scaling estimate [1].

It may in fact be slightly *too* small. The solid line shows very little strength in the region between 0 and 2 MeV. Phase space associated with the ^{8}B spectrum weighs the states in this region considerably more than those 3 or 4 MeV higher; an error in the strength to the lowest states will therefore have the largest effect on the predicted cross section. But as we mentioned earlier, our

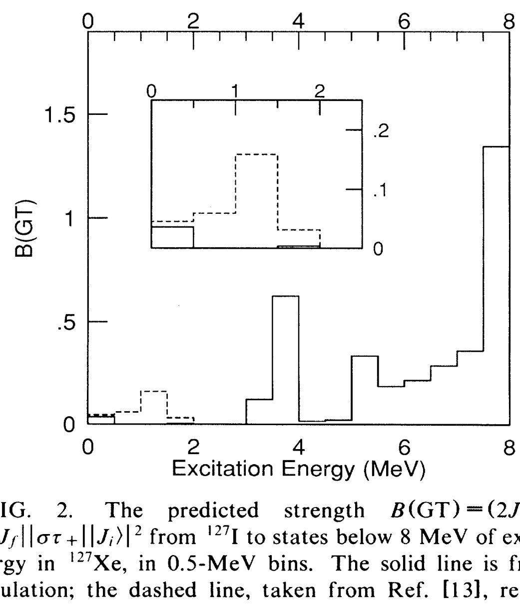

FIG. 2. The predicted strength $B(\mathrm{GT})=(2J_i+1)^{-1}\times|\langle J_f||\sigma\tau_+||J_i\rangle|^2$ from ^{127}I to states below 8 MeV of excitation energy in ^{127}Xe, in 0.5-MeV bins. The solid line is from our calculation; the dashed line, taken from Ref. [13], represents the collective strength below 2 MeV in an interacting boson-fermion model calculation. Inset: Expansion of the first 2 MeV of the figure.

low-energy results are somewhat suspect. The three predicted states in this region are largely one quasiparticle, with admixtures of three-quasiparticle configurations that are relatively small but nevertheless act to cancel the one-quasiparticle strength. We know that this picture cannot be completely right; the measured spectrum [12] in the first few MeV is considerably denser than ours. The reason, as noted above, is that the quadrupole phonon lies between 400 and 700 keV and couples to the one-quasiparticle configuration; including the phonon will introduce more low-energy states and shift the strength in ways that are difficult to predict. Dellagiacoma and Iachello [13], however, explicitly addressed the collective states below 2 MeV in the context of the interacting boson-fermion model, which incorporates quadrupole degrees of freedom. The strength from their calculation is plotted alongside ours in the figure. Though this collective strength is a small fraction of the total below 7.2 MeV, its inclusion increases our ^{8}B cross section by about 30% because it lies so low. Unless the ground state of ^{127}I contains significant phonon admixtures, the strength at higher energies should not be significantly modified. Thus the dashed line in the figure estimates the degree to which quadrupole collectivity is likely to modify our results. We are in the process of incorporating the collective phonon in our basis and hope to report the results in a future publication.

We now recall that the lowest $\frac{3}{2}^+$ state in ^{127}Xe will also be excited by neutrinos produced by solar ^{7}Be. Both the calculation of Ref. [13] and the one reported here yield a Gamow-Teller strength of about 0.035 (or 9.4 SNU) for this state. While the agreement may be coincidental—our calculation leaves out quadrupole vibrations—this value corresponds to a ^{7}Be event rate in iodine that is about 40% of the predicted total (^{7}Be+^{8}B) rate; by contrast, in the chlorine detector the fraction is only about 15%. These very different ratios suggest that data from the two experiments can be combined to determine the ^{8}B and ^{7}Be fluxes separately.

Neutrinos from CNO sources (e.g., ^{13}N and ^{15}O), which also excite only the lowest $\frac{3}{2}^+$ state, complicate the separation of ^{7}Be and ^{8}B event rates because their flux is uncertain [11]. On the other hand, they also increase the total event rate by roughly a quarter of the ^{7}Be rate. Combining our results for all three neutrino sources, we find a total solar neutrino event rate of 24.6 SNU. Though this number is obviously sensitive to details of the lowest $\frac{3}{2}^+$ state and therefore somewhat uncertain, it is about 3 times larger than the corresponding rate in ^{37}Cl (7.9 SNU). Should these results hold up under further scrutiny, an iodine detector would be useful both as a high-statistics experiment (though less high than previously hoped) and as an extremely sensitive ^{7}Be counter.

As was mentioned earlier, several experiments to confirm these conclusions either are planned or are under way. The results of a recent (p,n) measurement of the Gamow-Teller strength from ^{127}I are currently being analyzed [14]. The overall normalization of the spectrum will be uncertain, however, and the energy resolution will not be good enough to isolate the strength to the lowest excited state in ^{127}Xe. The first of these concerns will be addressed by an additional ^{127}I experiment with neutrinos from muon decay at LAMPF [15]. Because these neutrinos are much higher in energy, forbidden operators will affect the cross section at least slightly; we intend to use the same techniques outlined here to estimate their strength. The strength to the lowest state will be obtained in a third measurement, involving an ^{37}Ar source. Together these experiments, the current calculation, and its future extensions should allow the relevant neutrino cross sections to be determined to a satisfactory degree of accuracy.

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[1] W. C. Haxton, Phys. Rev. Lett. **60**, 768 (1988).
[2] J. K. Rowley, B. T. Cleveland, and R. Davis, Jr., in *Solar Neutrinos and Neutrino Astronomy—1984*, edited by M. L. Cherry, K. Lande, and W. A. Fowler, AIP Conf. Proc. No. 126 (American Institute of Physics, New York, 1984), p. 1.
[3] K. Grotz, H. V. Klapdor, and J. Metzinger, Phys. Rev. C **33**, 1263 (1986).
[4] See, e.g., I. S. Towner, Nucl. Phys. **A444**, 402 (1985).
[5] J. Engel, P. Vogel, and M. R. Zirnbauer, Phys. Rev. C **37**, 731 (1988).
[6] O. Civitarese, A. Faessler, and T. Tomoda, Phys. Lett. B **194**, 11 (1987).
[7] J. A. Halbleib, Sr., and R. A. Sorensen, Nucl. Phys. **A98**, 542 (1967).
[8] R. Madey *et al.*, Phys. Rev. C **40**, 540 (1989).
[9] A. Hosaka, K. I. Kubo, and K. Toki, Nucl. Phys. **A444**, 76 (1985).
[10] D. Krofcheck *et al.*, Phys. Rev. Lett. **55**, 1051 (1985).
[11] J. N. Bahcall, *Neutrino Astrophysics* (Cambridge Univ. Press, Cambridge, 1989).
[12] A. Garcia *et al.*, Phys. Rev. C **41**, 775 (1990).
[13] F. Dellagiacoma and F. Iachello, Phys. Lett. B **218**, 399 (1989).
[14] E. Sugarbaker (private communication).
[15] K. Lande (private communication).