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July 1994**Charge Exchange Reactions and the Efficiency of Solar Neutrino Detectors**

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The efficiencies of solar neutrino detectors are often based in part on weak interaction strengths determined by (p, n) and other charge exchange reactions. Although the (p, n) determinations are surprisingly good, it is shown that they may be inaccurate for important Gamow-Teller transitions whose strengths are a small fraction of the sum rule limit. This emphasizes the importance of direct calibration with ν sources for detectors such as ^{127}I and ^{115}In where direct β -decay information cannot be obtained. It may also bear on recent attempts to compare charge exchange and beta decay in the mass-37 system.

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A major experimental and theoretical effort is under way to resolve the solar neutrino problem, the long standing discrepancy between the predicted and observed neutrino fluxes from the sun[1-3]. It is now generally accepted (but see[4]) that the cause of this discrepancy lies not in uncertainties in the cross sections of the neutrino producing reactions or in the solar models but rather in the behavior of neutrinos during their flight to terrestrial detectors. A widely accepted scenario is that neutrinos have mass and that matter-induced oscillations (the MSW effect[1,2]) convert the electron neutrinos into other neutrino types, for example muon neutrinos, to which the detectors are less sensitive or are insensitive.

The experimental effort involves a variety of detectors with different sensitivities (see Refs. [1-3], for a more detailed discussion and further references). For example, the ^{37}Cl detector which first observed solar neutrinos is sensitive mainly to the high energy neutrinos from the decay of ^8B produced by hydrogen burning in the solar core. The Cherenkov detector at Kamiokande which confirmed these observations is sensitive only to ^8B neutrinos. On the other hand the gallium based detectors (GALLEX and SAGE collaborations) are sensitive primarily to the low energy neutrinos from the $p + p \rightarrow D + e^+ + \nu$ reaction. Detectors based on ^{81}Br , ^{115}In , and ^{127}I may have a significant sensitivity to neutrinos from the decay of ^7Be . The results for these different detectors put different limits on the allowed neutrino masses and mixing angles, and with good fortune will both strongly constrain these parameters and provide consistency checks on our understanding.

The efficiency of many neutrino detectors, including ^{37}Cl , ^{115}In , and ^{127}I , depends on the cross section for absorption of neutrinos, through inverse β -decay, in the detector material. When the corresponding matrix elements for allowed Gamow-Teller (GT) β -decay ($J = 1$, $L = 0$, $S = 1$ where J , L , and S are the total, orbital, and spin angular momentum transferred to the target) cannot be measured in β -decay experiments, for example, if the β -decay is not energetically allowed, it is common to obtain these matrix elements using charge exchange reactions (CEX reactions) such as (p, n) and $(^6\text{Li}, ^6\text{He})$. This approach relies on the similarity in spin isospin space of the CEX and β -decay operators. As a result of this similarity, the cross section $\sigma(p, n)$ at small angles (small momentum transfer q) is closely proportional to $B(\text{GT})$ for strong transitions[5,6].

However, the processes and the mediating operators are not identical, and the correspondence may not be accurate for the weak transitions that are often of importance in solar neutrino detectors. An attempt to determine whether such effects might limit the accuracy of the β -decay strengths $B(\text{GT})$ extracted from charge exchange reactions is the principal subject of this letter. We find that for weak transitions the $L = 0$ contribution to the CEX cross section is closely but not precisely proportional to $B(\text{GT})$. But more important, charge exchange amplitudes with $L > 0$, i.e. non-Gamow-Teller amplitudes, contribute importantly to the cross sections for some states and their effects cannot readily be disentangled using a multipole decomposition. Since one cannot know in advance which states these are, the usefulness of (p, n) reactions for calibration of transitions of interest for solar neutrino detection is compromised.

The case of ^{37}Cl provides a good starting point for this study. Detailed full-s-d shell model wave functions are available[7] and there have been detailed measurements of (p, n) cross sections[8] at 90 and 120 MeV, and of spin-transfer probabilities. We have calculated the (p, n) cross sections at 120 and 200 MeV, using the Distorted-Wave code DW81[9], which includes exact calculations of the knock-out exchange amplitudes,

and the Franey-Love effective interaction[10], evaluated at 140 MeV and 210 MeV. Optical model potentials were taken from Ref.[11]. The nuclear structure information was obtained from wave functions calculated in the full 1s-0d shell using the effective interaction (denoted "W") of Brown[7].

Transitions which transfer $S = 1$ and total angular momentum $J = 1$ can in principle proceed through $L = 0$ and $L = 2$ transfer to the target. Only the $L = 0$ amplitudes contribute significantly to allowed β -decay or to neutrino absorption cross sections, but $L = 2$ amplitudes can contribute to CEX reaction cross sections. Cross sections were calculated for $L = 0$, $L = 2$, and $L = 0 + 2$. It was necessary to have radial wave functions independent of $j = l \pm 1/2$ to permit the decomposition into $L = 0$ and $L = 2$ amplitudes; harmonic oscillator wave functions were used. We note that $L = 1$ amplitudes can also contribute when exchange processes are included, but these were entirely negligible at 0 deg for the sample cases examined.

Figure 1 shows the results of calculations with the W interaction at 120 MeV for the eight lowest states in ^{37}Ar (calculated $E_x \leq 5.5$ MeV) and for the stronger transitions with $E_x \leq 14.1$ MeV. The normalization of the $B(\text{GT})$ is chosen so the GT strength for neutron decay is 3. The ratio $R \equiv \sigma(q \approx 0)/B(\text{GT})$ for the total $J = 1$ cross section, containing both $L = 0$ and $L = 2$ amplitudes, is shown in the lower panel and for $L = 0$ only in the upper panel. This ratio must have a constant value if (p, n) reactions are to provide an accurate measure of allowed Gamow-Teller strength.

For the stronger transitions, $B(\text{GT}) \geq 0.4$, R is nearly constant whether or not $L = 2$ amplitudes are included. This reflects the relative weakness of the $L = 2$ amplitudes for the strong transitions, at least at small angles. However, these $L = 2$ amplitudes contribute significantly to the weaker transitions: increases in R of up to a factor of two above the average for strong states are observed when $L = 2$ amplitudes are included. The discrepancies at 200 MeV are very similar, sometimes even larger; this suggests that the situation would not be improved by measurements at higher energy. We have also found that other total angular momentum transfers (i.e. $J \neq 1$, and mainly $J = 2$), contribute 2-4% at 0 deg and lead to an additional overestimate of $B(\text{GT})$.

Thus, obtaining values of $B(\text{GT})$ for weak transitions in ^{37}Cl from (p, n) measurements, using the total observed cross section at 0 deg, might result in a significant overestimate, up to a factor of two. This can happen even if one normalizes to a known $B(\text{GT})$ in the same nucleus. A large effect on the neutrino detection efficiency is then possible, because low-lying transitions, often with small $B(\text{GT})$, are favored by the available phase space. Obtaining the neutrino absorption cross sections from the ratio of (p, n) cross sections to $B(\text{GT})$ determined in the present calculation, overestimates the detection efficiency by 17% for the ^7Be neutrinos and by about 11% overall. In this particular case the predicted reaction rate is strongly constrained by β -decay information and only smaller effects are possible[12]. On the other hand, if the detection efficiency of interest depends only on the properties of a single state, as is the case for some other detectors we discuss below, the situation could be still worse.

It might appear that this uncertainty could be reduced, since R is much more nearly constant when only $L = 0$ transfers are considered. With sufficiently good and complete data one could attempt to fit a sum of $L = 0$ and $L = 2$ shapes to the cross section data, thus isolating the $L = 0$ strength. Indeed related procedures have been employed in some of the (p, n) experiments. Unfortunately, complications arise for weak transitions. Figure 2 shows the calculations for transitions to the $J^\pi = 3/2^+$ ground state with and

without the tensor force. For central forces alone a multipole decomposition is possible. But the tensor force introduces significant interference between the $L = 0$ and $L = 2$ amplitudes, with the result that the cross section is poorly described by the sum of an $L = 0$ and an $L = 2$ shape. Thus it will be very difficult to extract the relevant $L = 0$ strength.

The results for the other weakly populated low lying states are similar, although the precise nature of the interference between $L = 0$ and $L = 2$ amplitudes differs in detail. Shell model wave functions obtained with the CWH interaction[7] show even larger deviations from a constant value of R for some low-lying states.

Although there are deviations of a factor of two in R for ^{37}Cl , the transitions to the low-lying states in ^{37}Ar have only 0.4 to 4% of the sum rule strength $B(\text{GT}) \geq 3(N - Z) = 9$. One might then regard even factor-of-two agreement as surprisingly good, since the results of [5,6] indicate deviations of $\pm 3\%$ even for strong transitions. For such weak transitions, there are presumably strongly cancelling amplitudes that could have led to much greater deviations.

Given the above results, it appears that one should be concerned whenever important transitions have less than a few percent of the sum rule limit. A particular case of interest is the ^{127}I detector[13,14] which has now been funded[15]. Its efficiency depends on transition strengths that can only be obtained from charge exchange reactions. It has been hoped that this detector would provide a strong sensitivity to neutrinos from ^7Be and this may be true. However, the only energetically allowed GT transition for ^7Be neutrinos is to a $3/2^+$ state at 125 keV in ^{127}Xe with less than 0.04% of the sum-rule strength[16]. It seems overly optimistic to expect CEX reactions to provide an accurate measure of $B(\text{GT})$. A similar situation arises for the ^{115}In detector[17,14] whose sensitivity is governed mainly by a single $7/2^-$ state at 0.614 MeV in ^{115}Sn . This state has a $B(\text{GT}) \approx 0.17$, less than 0.4% of the sum rule strength. Again it may be overly optimistic to expect the (p, n) reaction to provide an accurate estimate of $B(\text{GT})$.

The present results may also be pertinent to the apparent discrepancy between strength observed[12] in the $^{37}\text{Cl}(p, n)^{37}\text{Ar}$ reaction and in isospin-mirror β -decay transitions $^{37}\text{Ca} \rightarrow ^{37}\text{K} \rightarrow ^{36}\text{Ar} + p$. New (p, n) experiments with better resolution[18], and new experiments on the β decay of ^{37}Ca [19] are in progress. It has been pointed out[20] that if the 3.24 MeV level in ^{37}Ca mainly decayed by emission of a γ ray rather than a proton, the discrepancies could be reduced. A resonance experiment by Iliadis, *et al.*[21] suggested that the decay of this state was dominated by γ rays, and a recent paper[22] showed that an appropriately chosen value of the ratio of gamma to proton decay of the 3.24 MeV level, could remove the discrepancy. However, the recent GSI measurements[19] show that the situation is more complex, and that several of the involved levels decay by γ emission and affect the extracted values of $B(\text{GT})$. In summary, it appears the new results for (p, n) and β decay are in better agreement than initially indicated[12], but that differences of a factor of two remain[23] for some states. These may arise from the non-proportionality of cross sections and $B(\text{GT})$ for weak states as is discussed here.

The considerations above provide an estimate of a lower limit on the strength of transitions where CEX reactions can provide a reliable estimate of $B(\text{GT})$. This limit is due mainly to the presence of appreciable $L = 2$ nuclear matrix elements and the properties of the tensor force. Other effects may make it difficult to reach this limit. For

example, two-step reactions such as successive pickup-stripping $((p,d)(d,n))$ [24] may not be negligible for weak transitions. Such reactions may contribute to $\sigma(\text{CEX})$, yet have no clear relationship to β decay. Another issue, relevant even for strong transitions, is the existence of large exceptions[25] to the proportionality of $B(\text{GT})$ and $\sigma(\text{CEX})$ for (p,n) reactions on some odd- A nuclei including ^{13}C , ^{15}N , ^{35}Cl and ^{39}K . It has been suggested [25] that this discrepancy is especially pronounced in nuclei whose transition densities contain strong $j_{<}j_{<}$ configurations which are particularly sensitive to the $L = 2$ part of generalized Gamow-Teller (and CEX) operators. However, this issue is not settled[5] and until it is, one cannot reliably estimate to what extent other transitions of interest may be affected.

We conclude that it will be difficult to obtain reliable estimates of Gamow-Teller strength from CEX reactions for weak transitions (and perhaps even for strong transitions in odd- A nuclei, until the anomalies mentioned above are understood). In the context of the solar neutrino problem, this situation reinforces the conclusion that efficiency calibrations of neutrino detectors in which weak transitions are important must be made independently of charge exchange reactions. Possibilities are the use of neutrino sources as is anticipated for the Gallium detectors and also planned for the ^{127}I detector.

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Figure Captions

1. Values of $\sigma(q \approx 0)/B(\text{GT})$ calculated with full-sd-shell wave functions using the W interaction for some of the states populated in the $^{37}\text{Cl}(p,n)^{37}\text{Ar}(1^+)$ reaction. The lower panel shows these ratios for the total $J = 1$ cross section (including angular momentum $L = 0$ and $L = 2$ amplitudes); the upper panel shows these ratios for only the $L = 0$ amplitudes. The large value of the ratio in the lower

panel is for the third excited ($J^\pi = 5/2^+$) state near 3.17 MeV. The horizontal lines are the B(GT) weighted averages of the ratios for the five states with largest B(GT). Note the different scale and suppressed zero for the upper panel.

2. Cross sections calculated as described in the text for the $^{37}\text{Cl}(p,n)^{37}\text{Ar}(3/2^+)$ reaction. The dashed line is for $L = 0$, the dot-dashed line for $L = 2$ and the solid line for their coherent sum. The lower panel shows the results for central forces (C) and the upper panel for Central plus Tensor forces ($C + T$).

Fig. 1

Fig. 2