Effective Interaction for Charge-Exchange Analogs of Gamow-Teller Transitions

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Ratios of cross sections for ^{7}Li(p,n)^{7}Be leading to the ground and first excited states of ^{7}Be have been measured at 24.8, 35, and 45 MeV. An analysis of these ratios yields the ratio of spin-flip to spin-nonflip strength, $|V_{\sigma\tau}/V_\tau|^2$, free of many of the uncertainties usually associated with distorted wave analyses for such light nuclei. The ratio increases by about 60% in the observed energy range. A comparison with known values of V_τ yields $V_{\sigma\tau}$. The isovector tensor force is also obtained.

It has been recognized for some time that the operators mediating charge exchange via hadronic reactions and β decay are identical in spin-isospin space, so that strong transitions observed in a (p,n) reaction should also be strong in β decay.[1] Charge exchange without spin transfer (mediated by the two-body effective interaction $V_\tau \vec{\tau}_1 \cdot \vec{\tau}_2$) corresponds to Fermi β decay and with spin flip [mediated by $V_{\sigma\tau}(\vec{\sigma}_1 \cdot \vec{\sigma}_2)(\vec{\tau}_1 \cdot \vec{\tau}_2)$] to Gamow-Teller β decay. Recently this correspondence has been exploited to search with (p,n) and (^{3}He,t) reactions for Gamow-Teller strength in nuclei.[2] There are strong indications[2] that such strength is concentrated in 1^+ states located near the isobaric analog state in $^{90-96}$Nb and $^{112-124}$Sb. However, quantitative evaluation of the observed strength can only be made when one has a reliable estimate of $V_{\sigma\tau}$. Unfortunately only a little empirical information is available[3] and since that is for light nuclides (mostly $A=6$ and 7) the results are subject to substantial model uncertainties. Theoretical estimates have been made[4] but those for $V_{\sigma\tau}$ have not been tested against experiment to any great extent.

In this Letter we present the results of a measurement, at 25, 35, and 45 MeV, of the *ratio* of the cross sections σ_0 and σ_1, for the reaction ^{7}Li(p,n)^{7}Be leading to the ground ($\frac{3}{2}^-$) and first excited ($\frac{1}{2}^-$, 0.429 MeV) states of ^{7}Be (see Fig. 1). Anderson, Wong, and Madsen[5] (AWM) noted some time ago that σ_1 and σ_0 depend differently on $V_{\sigma\tau}$ and V_τ and that cross-section ratios could be analyzed in a simple model, discussed later, to yield $V_{\sigma\tau}/V_\tau$ with most of the model dependence vanishing in the ratio. However, until now, limitations on energy resolution for neutrons have made it impossible to separate the yields of the two states at energies above 25 MeV. An analysis of our measured ratios with the simple model of AWM indicates that $|V_{\sigma\tau}/V_\tau|^2$ increases by about 60% between 25 and 45 MeV. Should this increase continue, spin-flip transitions will dominate the spin-nonflip ones above about 65 MeV and studies at these energies will be extremely useful in searches for concentrations of spin-flip strength in nuclei. A detailed distorted-wave Born-approximation (DWBA) analysis carried out at $E_p = 35$ MeV indicates that the approximations of AWM are realistic and yields as a by product a more reliable estimate of the tensor force than has been available in this energy range. Values of $V_{\sigma\tau}$ were obtained from $V_{\sigma\tau}/V_\tau$ and known values of V_τ.[3]

The measurements were performed with protons from the Michigan State University sector-focused cyclotron and a time-of-flight system[6]

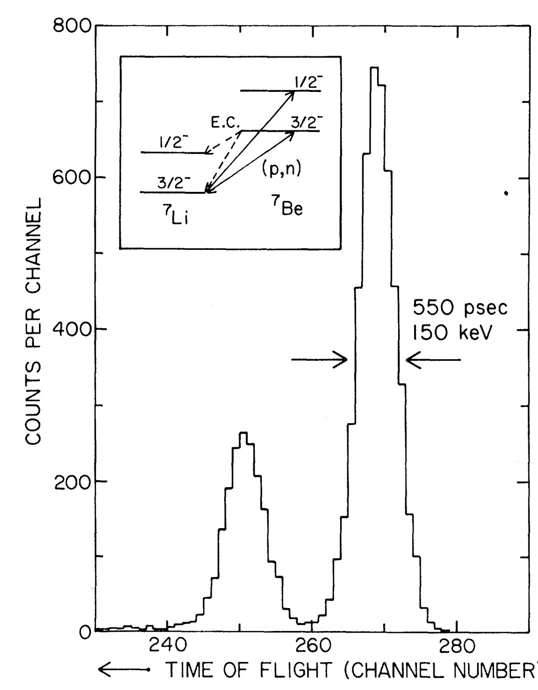

FIG. 1. Neutron time-of-flight spectrum from the reaction ^{7}Li(p,n)^{7}Be. Time of flight increases to the left. The overall time resolution is 550 psec corresponding to an energy resolution of $\simeq$ 150 keV. The inset shows the (p, n) transitions involved and the electron-capture transitions involved in the analysis.

which incorporates a beam swinger, allowing flight paths of up to 32 m. Neutrons were detected in a large-volume liquid scintillation counter operating in a mean timing mode.[6] The overall time resolution was between 0.5 and 0.7 nsec and the flight path was adjusted to clearly resolve the states of interest. Since only ratios were measured, corrections for air absorption were unnecessary. The sum $\sigma_0+\sigma_1$ had been measured earlier in a low-resolution experiment.[7] A spectrum at 35 MeV is shown in Fig. 1 and the resulting ratio in Fig. 2. Qualitatively similar results were obtained at 24.8 and 45 MeV.

We cast our initial analysis of the ratios in terms of the model of AWM.[5] The fundamental premises of this model are that the transitions are dominated by the monopole ($L=0$) matrix element and that the necessary nuclear structure information can be obtained from measured *ft* values for allowed β decay connecting the same states. In this approximation the cross section is

$$\sigma(\theta)\simeq(V_\tau{}^2\langle 1\rangle^2\delta_{S0}+V_{\sigma\tau}{}^2\langle\sigma\rangle^2\delta_{S1})\sigma_0(\theta). \qquad (1)$$

The bracketed part of the expression contains the elements of the effective interaction and the nuclear structure information, with the matrix elements $\langle 1\rangle^2$ and $\langle\sigma\rangle^2$ obtainable from β decay *ft* values for the transition,[5] while $\sigma_0(\theta)$ contains the distorted waves, kinematical information, etc.

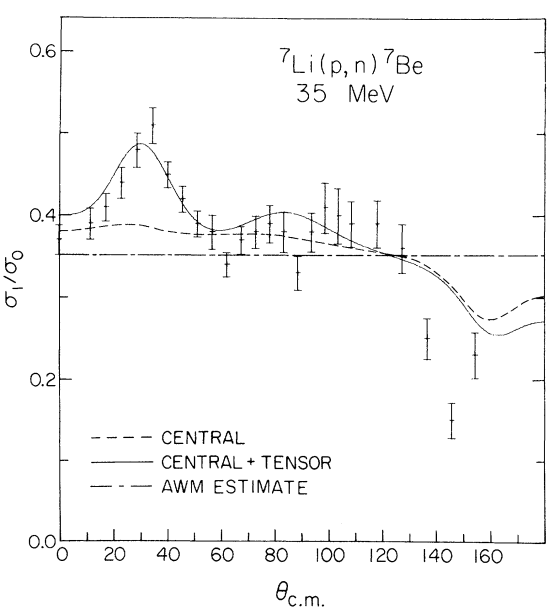

FIG. 2. Measured and theoretical values of σ_1/σ_0 for the reaction ^{7}Li$(p,n)^7$Be at E_p = 35 MeV.

The ratio of cross sections for transitions proceeding via $L=0$ to nearby states in the same nucleus is given by the ratio of the prefactors of $\sigma_0(\theta)$ in Eq. 1, since the $\sigma_0(\theta)$ factors approximately cancel in the ratio. In the present case we obtain, using *ft* values from the literature[8] and recent weak-interaction coupling constants[9]

$$\frac{\sigma_1}{\sigma_0}=\frac{\langle\sigma\rangle_1{}^2V_{\sigma\tau}{}^2}{V_\tau{}^2+\langle\sigma\rangle_0{}^2V_{\sigma\tau}{}^2}=\frac{1.11\ V_{\sigma\tau}{}^2}{V_\tau{}^2+1.25\ V_{\sigma\tau}{}^2}. \qquad (2)$$

The equation reflects the fact that the $\frac{3}{2}^-\to\frac{1}{2}^-$ transition to the 0.429-MeV state can occur only via spin transfer $S=1$ while both $S=0$ and $S=1$ amplitudes contribute to the $\frac{3}{2}^-\to\frac{3}{2}^-$ ground-state transition. It is immediately clear that the approximation fails in detail since it predicts a ratio independent of angle while the measured ratio has angular structure. But since the ratios change by at most a factor of 2 while the cross sections vary by a factor of $\gtrsim 100$, we have, as a first approximation, assumed that the appropriate cross-section ratio is simply that of the total cross sections. The resulting values of $V_{\sigma\tau}/V_\tau$ are shown in column 3 of Table I.

To ascertain the accuracy of the approximations in the AWM theory and to understand the origin of the structure in the cross-section ratios, we have carried out a series of DWBA calculations at 35 MeV using the code DWBA 70 (Ref. 10) which includes knock-on exchange contributions. Initial calculations were made using the Bertsch-Borysowicz-McManus-Love (BBML) *G*-Matrix interaction,[4] Cohen-Kurath [(6-16) 2BME] wave functions,[11] and Becchetti-Greenlees "best-fit" optical-model

TABLE I. Values of $V_{\sigma\tau}/V_\tau$ and $V_{\sigma\tau}$ from ^{7}Li(p,n)-^{7}Be cross-section–ratio measurements. All values are for a 1.0-fm-range Yukawa shape.

E_p (MeV)	$\left(\frac{\sigma_1}{\sigma_0}\right)^a$	$\left(\frac{V_{\sigma\tau}}{V_\tau}\right)^b$	$\left(\frac{V_{\sigma\tau}}{V_\tau}\right)_{corr}{}^c$	$V_\tau{}^d$ (MeV)	$V_{\sigma\tau}{}^e$ (MeV)
24.8	0.353	0.727	0.678	16.0	10.9
35	0.409	0.826	0.765	15.0	11.5
45	0.461	0.928	0.852	14.0	11.9
12.8[f]	0.325	0.680	0.636	17.3	11.0

[a]Measured cross-section ratios. Uncertainties are about 3%.

[b]Obtained from Eq. 2, with use of ratios of column 2.

[c]Corrected to account for the error in the AWM approximation discussed in the text.

[d]From Ref. 3.

[e]From columns 4 and 5.

[f]Average of values between 11.6 and 14 MeV from Ref. 5.

parameters.[12] All allowed amplitudes ($J=0,1,2,3$ for σ_0; $J=1,2$ for σ_1) were included. Several conclusions were immediate: (1) The spin-orbit part of the force contributes <1% of the cross section for either state—it was thereafter ignored. (2) The cross-section ratio for central forces only, i.e., no tensor force, is only weakly dependent on angle for $\theta < 140°$. (3) The tensor force is responsible for the peak in the ratio near 30°. (4) The BBML force is incorrect in detail, predicting a ratio too large by 27%. Calculations made with other wave functions[13] other optical-model parameters[14] and with simple 1.0-fm-range Yukawa forces showed that these conclusions were not changed by reasonable variations of model parameters. While σ_1/σ_0 was stable against such changes, individual cross sections sometimes changed by more than a factor of 2.

Because the DWBA calculations are very time consuming and clumsy (several amplitudes contribute to each transition and it is necessary to include tensor forces and knock-on exchange), detailed calculations were made only at 35 MeV. We fixed V_τ at the value found in a recent survey[3] and adjusted $V_{\sigma\tau}$ and a tensor force V_τ^{ten} for best fit to σ_1/σ_0. The central forces were taken to have 1.0-fm-range Yukawa shapes and the tensor force to have the form

$$V_\tau^{\text{ten}} r^2 \frac{e^{-r/\mu}}{r/\mu} \vec{\tau}_1 \cdot \vec{\tau}_2 S_{12},$$

where $\mu = 0.816$ fm and S_{12} is the usual tensor operator. The resulting fit, shown as a solid line in Fig. 2, yields $V_{\sigma\tau} = 10.5$ MeV, $V_\tau^{\text{ten}} = 7$ MeV fm^{-2} with $V_\tau = 15.5$ MeV.

Also shown in Fig. 2 are calculations with central forces only and the ratio of Eq. 2 with $\langle\sigma\rangle$ evaluated from the Cohen-Kurath wave functions. The agreement between these two calculations is surprisingly good, validating the earlier use of the AWM approximation, although a detailed examination of contributing amplitudes shows that this is somewhat fortuitous ($L \neq 0$ amplitudes contribute ~10% of σ_0 and ~15% of σ_1). Nevertheless, given this close agreement, ratio measurements should provide reliable estimates of $V_{\sigma\tau}/V_\tau$. As V_τ is rather well determined, values of $V_{\sigma\tau}$ immediately follow. To account for the effect of $L \neq 0$ amplitudes and other inaccuries of AWM, the measured σ_1/σ_0 of Table I were corrected prior to use of Eq. (2). The correction (−8%) was evaluated from the DWBA calculations at 35 MeV. The resulting $V_{\sigma\tau}/V_\tau$ are in column 4 of Table I.

Perhaps the most interesting result is that

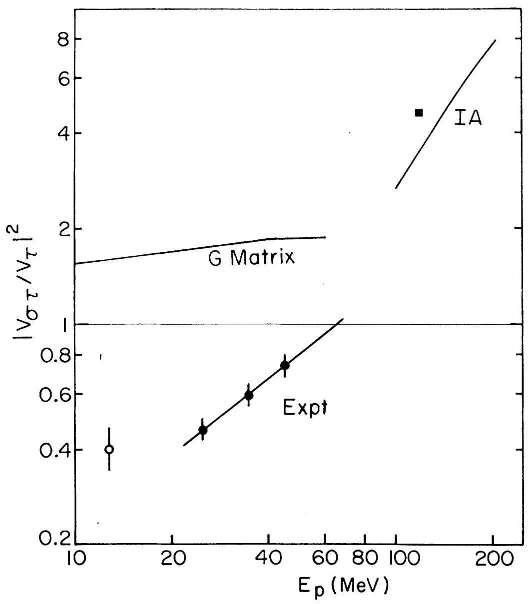

FIG. 3. Values of $|V_{\sigma\tau}/V_\tau|^2$. Those labeled "expt" are from Table I, and that denoted by a square is from Goodman, Ref. 15. The lines labeled G Matrix and IA are the estimates (see Ref. 16) described in the text. The other line is drawn through the results of the present experiment.

$|V_{\sigma\tau}/V_\tau|^2$ increases by 60% between 25 and 45 MeV. Should this rate of increase continue, spin-flip transitions would dominate above 65 MeV. The present result is the first reliable determination of the rate of increase for $V_{\sigma\tau}/V_\tau$ in this energy region. There is preliminary data indicating that spin-flip $|V_{\sigma\tau}/V_\tau|^2 \gg 1$ at 120 MeV.[15]

Love[16] has based an estimate of $|V_{\sigma\tau}/V_\tau|^2$ on effective interactions derived from the G matrix at low energy and an impulse approximation (IA) at higher energies. The predicted ratio, shown in Fig. 3, also tends to increase with energy, but is not in quantitative agreement with present results, being too large at lower energies. This is perhaps a reflection of the fact noted previously that the BBML interaction[5] overestimates σ_1/σ_0 at 35 MeV. The value obtained for the tensor force can be compared to the BBML prediction in terms of the integral $J_2 = \int r^2 V_\tau^{\text{ten}} dV$. One finds $J_2(\text{BBML}) \simeq 2300\text{–}2800$ MeV fm^5 and $J_2(^7\text{Li}(p,n)^7\text{Be}) = 25\,000$ MeV fm^5.

In summary, measurements of the ratio of the cross sections for the reaction ^{7}Li$(p,n)^7$Be leading to the ground and first excited states of ^{7}Be provide a nearly model-independent estimate of the ratio of spin-flip and spin-nonflip strength $|V_{\sigma\tau}/V_\tau|^2$. This ratio increases by 60% between

25 and 45 MeV. Simple theoretical estimates also predict an increase, but substantially overestimate the ratio. An estimate of the tensor force is in good agreement with G-matrix predictions.

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