Energy dependence of the ratio of isovector effective interaction strengths $|J_{\sigma\tau}/J_\tau|$ from 0° (p,n) cross sections

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(Received 1 October 1981)

Information concerning the ratio of the isovector effective interaction strengths $|J_{\sigma\tau}/J_\tau|$ may be obtained from the ratio of (p,n) Gamow-Teller and isobaric analog state 0° differential cross sections. We have examined 0° (p,n) data for the energy range 5–200 MeV and find that for energies larger than 50 MeV and for targets with $A=7$–42 the product of the interaction-strength and distortion-factor ratios $|J_{\sigma\tau}/J_\tau|(N_{\sigma\tau}/N_\tau)^{1/2}$ appears to be mass independent and linear as a function of bombarding energy.

[NUCLEAR REACTIONS ^{7}Li, ^{13,14}C, ^{26}Mg, ^{37}Cl, ^{42}Ca(p,n), measured $\sigma(\theta=0°)$, GT, IAS transitions, $E_p=60$–200 MeV. Deduced energy dependence, interaction strength ratio $|J_{\sigma\tau}/J_\tau|$.]

Recent experimental results[1–5] have shown the (p,n) reaction at intermediate energies to be a good probe of spin-excitation strength distributions in nuclei. The empirical circumstance responsible for this development[6] is the dominance at energies larger than about 50 MeV of the isovector spin-flip component $V_{\sigma\tau}\vec{\sigma}_i\cdot\vec{\sigma}_p\vec{\tau}_i\cdot\vec{\tau}_p$ of the effective interaction over the non-spin-flip component $V_\tau\vec{\tau}_i\cdot\vec{\tau}_p$. At intermediate energies and $\theta=0°$ (momentum transfer $q\simeq0$), where tensor, spin-orbit, and other $L\neq0$ effects are generally small, this dominance leads to the selective spin-flip excitation of states that are connected to the target ground state by transitions analogous to Gamow-Teller (GT) β decay.

Several studies[7–9] have attempted to quantify the interaction strength ratio $V_{\sigma\tau}/V_\tau$ in a model-independent fashion by analyzing the ratio of total or angle-integrated cross sections for spin-flip and non-spin-flip (p,n) transitions. The data considered were obtained at bombarding energies lower than 50 MeV. These low-energy results indicate that the ratio $V_{\sigma\tau}/V_\tau$ increases with increasing energy and becomes unity somewhere between 40 and 70 MeV. A recent analysis[2] of higher-energy data shows that this ratio is equal to about 2 at 120 MeV.

In this Communication we demonstrate a simple relationship between (p,n) 0° differential cross sections that can be interpreted as evidence that the ratio of interaction strengths $V_{\sigma\tau}/V_\tau$ at momentum transfer $q=0$ is approximately a linear function of the bombarding energy E_p from 50 MeV to at least 160 MeV. These results should prove useful for judging the accuracy of current theoretical effective interactions, and promise to be of great practical value for extraction of absolute Gamow-Teller strength in nuclei.

The Indiana University cyclotron and beam-swinger facility[10] has been used to obtain neutron time-of-flight data at bombarding energies between 60 and 200 MeV for targets of ^{7}Li, ^{13,14}C, ^{26}Mg, ^{37}Cl, and ^{42}Ca. The data were obtained with time-compensated neutron detectors[11] stationed on the 0° scattering line at flight paths between 26 and 95 m. In order to extend the present analysis to energies below 50 MeV we have supplemented our data set with published and unpublished cross sections obtained from other laboratories.[6–9,12–18] In some cases these lower-energy differential cross sections are not available at 0° and reasonable extrapolations have been made to 0° when possible.

The motivation for our analysis is provided by the factorized distorted-wave impulse approximation (DWIA) expression for the $L=0$ (p,n) differential cross section[2,9,19,20]

$$\sigma_\alpha(q) \simeq K_\alpha(E_p) N_\alpha(q) |J_\alpha(q)|^2 B(\alpha,q) \quad , \tag{1}$$

where $K_\alpha(E_p)=(E_i E_f/\pi^2)(k_f/k_i)$, $N_\alpha(q)$ is a distortion factor, $J_\alpha(q)$ is the Fourier transform of the effective nucleon-nucleon interaction, $B(\alpha,q)$ is a nuclear structure factor, and $\alpha=\sigma\tau(\tau)$ for spin-flip (non-spin-flip) transitions. At $\theta=0°$ and momentum transfer $q=0$ the nuclear structure factor $B(\alpha,q)$ becomes the reduced transition probability[21]

$$B(GT)=(2J_i+1)^{-1}\left|\left\langle f\left\|\sum_k \sigma_k t_k^-\right\|i\right\rangle\right|^2$$

or

$$B(F)=(2J_i+1)^{-1}\left|\left\langle f\left\|\sum_k t_k^-\right\|i\right\rangle\right|^2$$

for the analogous Gamow-Teller ($\alpha=\sigma\tau=$GT) or Fermi ($\alpha=\tau=F$) β-decay transition, respectively. These reduced transition probabilities are related to measured β-decay lifetimes according to[22] $B(F)+(1.250\pm0.009)^2 B(\mathrm{GT})=(6163.4\pm3.8\ \mathrm{sec})/ft$, where $B(F)=N-Z$ for isobaric analog state (IAS) transitions and is zero otherwise.

The (p,n) reaction on even-A, $T\neq0$ targets leads to $0^+\to1^+$ and $0^+\to0^+$ transitions that are analogous to GT and F β decay, respectively. For such targets, the proportionality between $\sigma_\alpha(0°)$ and $B(\alpha,q=0)$ suggests defining the empirical ratio

$$[R(E_p)]^2=\frac{\sigma_{\mathrm{GT}}(0°)/B(\mathrm{GT})K_{\mathrm{GT}}(E_p)}{\sigma_{\mathrm{F}}(0°)/B(\mathrm{F})K_{\mathrm{F}}(E_p)} \quad , \tag{2}$$

which may be interpreted in terms of the quantities in Eq. (1) as

$$R(E_p)\simeq|J_{\sigma\tau}/J_\tau|(N_{\sigma\tau}/N_\tau)^{1/2} \quad . \tag{3}$$

DWIA calculations indicate that at intermediate energies the distortion-factor ratio is approximately independent of energy (less than 10% variation between 80 and 200 MeV) and has the value $N_{\sigma\tau}/N_\tau\simeq1.2\pm0.1$ for GT and F transitions not widely separated in excitation energy.[2,23] The empirical and model-independent quantity defined in Eq. (2) and interpreted in Eq. (3) thus represents very nearly the ratio of interaction strengths $|J_{\sigma\tau}/J_\tau|$ at momentum transfer $q\simeq0$.

IAS transitions on odd-A targets involve both F and GT strength and Eq. (1) becomes the sum of two terms.[8,9] We can make the reasonable assumption (confirmed by explicit DWIA calculations[2,23]) that the $N_{\sigma\tau}$ distortion factor for such a mixed transition is approximately the same as for the pure GT transition ($J_i\neq J_f$). With the further assumption that only $L=0$ amplitudes are important at 0°, the interpretive result of Eq. (3) can be obtained by defining the empirical quantity $R(E_p)$ for odd-A targets to be

$$[R(E_p)]^2=\frac{B(\mathrm{F})}{rB(\mathrm{GT})-B_M(\mathrm{GT})} \quad , \tag{4}$$

where

$$r=[\sigma_M(0°)/\sigma_{\mathrm{GT}}(0°)][K_{\mathrm{GT}}(E_p)/K_M(E_p)] \quad ,$$

$\sigma_M(0°)$, $B_M(\mathrm{GT})$, and $B(\mathrm{F})$ are the 0° differential cross section, GT strength, and F strength for the mixed ($M=$F+GT) IAS transition, and $\sigma_{\mathrm{GT}}(0°)$ and $B(\mathrm{GT})$ are the corresponding quantities for the pure GT transition.

The specific transitions considered here are detailed in Table I. The experimental results for even- and odd-A targets are plotted separately in Fig. 1. An ft value for the ^{13}C(g.s.)$\to^{13}$N(3.51 MeV) transition is not available from β decay; therefore, for this target we have obtained $B(\mathrm{GT})$ by using Eq. (4) and the average value for $R(E_p)$ obtained from the even-A target data at 120 and 160 MeV. While this does not provide an independent determination of $R(E_p)$ from this target, it does allow us to estimate $R(E_p)$ at 200 MeV.

Figure 1 shows that the empirical quantity $R(E_p)$ defined in Eqs. (2) and (4) is well described by the linear form $R(E_p)=aE_p$ for energies $E_p\geq50$ MeV. The value for $a=R(E_p)/E_p$ determined from the even-A data is $a=(54.9\pm0.9\ \mathrm{MeV})^{-1}$, and for the odd-$A$ targets we find $a=(54.6\pm5.4\ \mathrm{MeV})^{-1}$. Below 50 MeV there is a mass-dependent dispersion about the average value of $R(E_p)/E_p$. These deviations are probably due to the effects of compound-nucleus and shape resonances, channel coupling, multistep reactions, and other nondirect mechanisms which tend to be most significant at lower energies. It is tempting to regard the convergence at 50 MeV as evidence for the onset of validity of the DWIA.

The simple empirical relationship between $\sigma_{\mathrm{GT}}(0°)$ and $\sigma_{\mathrm{F}}(0°)$ illustrated in Fig. 1 offers a convenient means of estimating absolute GT strength independent of calibration transitions,[2] cross section normalization, and DWIA mass-dependence extrapolations.[5]

TABLE I. Targets, final-state spin parities and excitation energies, and GT transition strengths for the (p,n) transitions studied in this work. Transition strengths are from the references indicated.

Target	J^π	E_x (MeV)	B(GT)	Reference
^{7}Li	$\frac{3}{2}^-$	0.000	1.25 ± 0.01	a
	$\frac{1}{2}^-$	0.429	1.11 ± 0.01	a
^{13}C	$\frac{1}{2}^-$	0.000	0.209 ± 0.003	b
	$\frac{3}{2}^-$	3.511	0.85 ± 0.03	c
^{14}C	0^+	2.313	0	
	1^+	3.948	2.81 ± 0.11	22,d
^{26}Mg	0^+	0.228	0	
	1^+	1.058	1.11 ± 0.03	22
^{37}Cl	$\frac{3}{2}^+$	0.000	0.031 ± 0.001	e
	$\frac{3}{2}^+$	4.993	0.052 ± 0.004	e
^{42}Ca	0^+	0.000	0	
	1^+	0.611	2.67 ± 0.10	e

[a]F. Ajzenberg-Selove, Nucl. Phys. A320, 1 (1979).
[b]F. Ajzenberg-Selove, Nucl. Phys. A268, 1 (1976).
[c]Obtained by normalizing to $R(E_p)/E_p=(54.9\text{ MeV})^{-1}$ at $E_p=120$ and 160 MeV.
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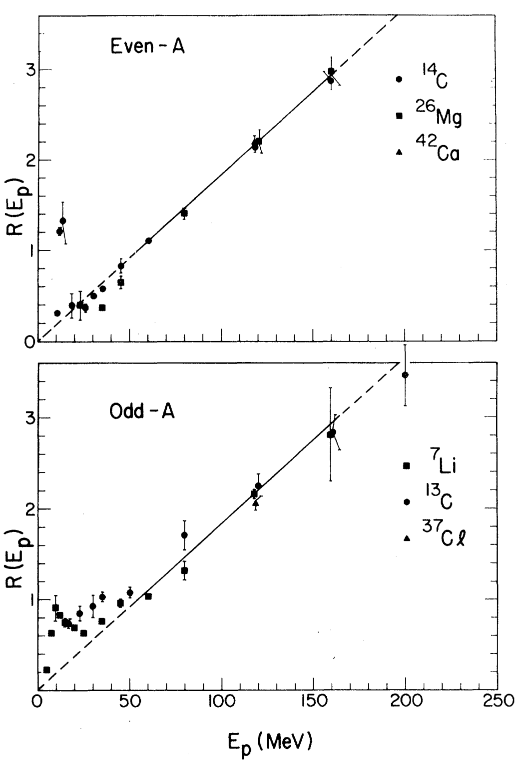

FIG. 1. The empirical quantity $R(E_p)$ for odd- and even-A targets. The solid line represents the average value $R(E_p)/E_p=(54.9\pm0.9\text{ MeV})^{-1}$ determined from the even-A target data for bombarding energies $E_p \geq 50$ MeV.

For targets with $A \leq 42$ and $T \neq 0$, the GT strength can be directly obtained from the inverted forms of Eqs. (2) or (4) for data obtained at energies larger than about 50 MeV. Small corrections for the momentum transfer dependence of the ratio $N_{\sigma\tau}/N_\tau$ will still be required for GT transitions to states widely separated in excitation energy from the IAS and for heavier targets ($A >> 42$) it is reasonable to assume that a mass-dependence correction may be necessary as well. However, since we are dealing with ratios much of the model dependence involved in such corrections should cancel out.

In Fig. 2 we compare our results to predictions obtained from several currently popular theoretical effective interactions[24–26] and to the results of a recent analysis by Brown, Speth, and Wambach[27] (BSW). The line labeled "EXPT" in this figure is our average experimental value for $R(E_p)$ divided by $\sqrt{1.2}$ to compensate approximately for the distortion factor ratio in Eq. (3). The BSW analysis[27] provides a good qualitative reproduction of the observed energy dependence of $|J_{\sigma\tau}/J_\tau|$ over a wide energy range, but the magnitude of the $V_{\sigma\tau}$ component of their interaction is much larger than that obtained from empirical studies,[2,8] and as a consequence the well-known dominance of V_τ over $V_{\sigma\tau}$ at low energies is not reproduced. The "$M3Y$" G-matrix interaction of Bertsch *et al.*[24] has a similarly large[20] $V_{\sigma\tau}$ component. Between 100 and 200 MeV the ratio $|J_{\sigma\tau}/J_\tau|$ obtained from the "$G3Y$" t-matrix interaction discussed by Love and Petrovich in Ref. 6 is in reasonable agreement with our experimental results. In the

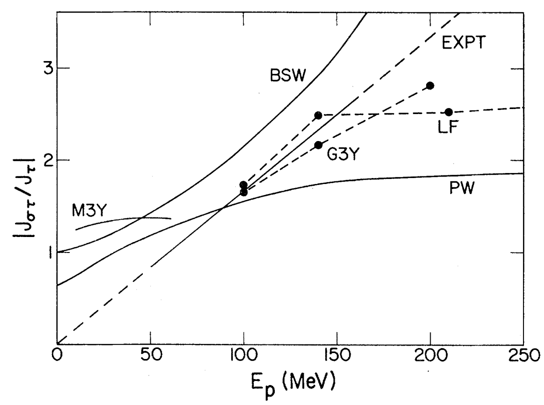

FIG. 2. Comparison of experimental and theoretical values of the energy-dependent ratio $|J_{\sigma\tau}/J_\tau|$. The line labeled "EXPT" is the average experimental value for $R(E_p)/E_p$ divided by $\sqrt{1.2}$ to account approximately for distortion effects (see text). The theoretical lines are derived from the interactions described in Ref. 24 (*M3Y*), Ref. 25 (PW), Ref. 26 (LF), Ref. 27 (BSW), and by Love in Ref. 6 (*G3Y*).

energy range 100–140 MeV the interaction strength ratios obtained from the more recent *t*-matrix interaction of Love and Franey (LF) show similar agreement. The significantly smaller ratio predicted by the interaction of Picklesimer and Walker[25] (PW) is due to a $V_{\sigma\tau}$ component that is about 30% smaller than in the LF interaction.[28]

Of particular interest is the comparison of our results with theoretical predictions for energies larger than about 140 MeV. Both the LF and PW *t*-matrix interactions exhibit a plateau in the ratio $|J_{\sigma\tau}/J_\tau|$ that is not evident in the data. The *G3Y* interaction does not show this behavior, but it does give an energy-dependent ratio smaller than that indicated by our data. If the value of $|J_{\sigma\tau}/J_\tau|$ obtained from our datum at 200 MeV is confirmed by future measurements on additional targets, this would indicate a consistent deficiency in the *t*-matrix descriptions of the relative strengths of $J_{\sigma\tau}$ and J_τ at this energy.

In summary, we have demonstrated a linear and model-independent relationship between 0° (p,n) cross sections that may be interpreted as evidence for a linear energy dependence for the product of ratios $|J_{\sigma\tau}/J_\tau|(N_{\sigma\tau}/N_\tau)^{1/2}$ for bombarding energies above about 50 MeV. A more detailed analysis aimed at extracting the energy dependences and absolute strengths of the individual $J_{\sigma\tau}$ and J_τ components is currently underway[23] and should provide some insight into the indicated discrepancy between the experimental ratio and theoretical predictions for energies larger than about 140 MeV.

This work was supported in part by the National Science Foundation, the U.S. Department of Energy (under Contract No. W-7405-eng-26 with the Union Carbide Corporation and Contract No. DE-AC-81-ER-40016 with the University of Colorado), and the Danish Natural Science Research Council. One of us (C.A.G.) acknowledges support from the Robert A. Welch Foundation.

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