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I. 6 Low-energy (p,n) Cross Sections in A=58-71 Nuclei and Gamow-Teller Strength

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Small angle (p,n) cross sections at intermediate energies have been shown to give a measure of the relevant β-decay rates.[1] This has provided a new technique to obtain β-decay strengths for transitions energetically inaccessible in conventional β-decay experiments. The most important application of such a technique may be the extraction of the strength for the giant Gamow-Teller (GT) states.[2] The correspondence between (p,n) cross sections and β-decay rates is less straightforward at low energies, since (p,n) cross sections and angular distribution shapes change depending on the configurations of the proton and neutron-hole pair involved, on the distortion effects and therefore on Q-values, and so on. In low-energy (p,n) experiments, on the other hand, a much better energy resolution can be achieved, making them highly valuable in studying the properties of individual levels[3] or a specific mode of excitation in nuclei[4]. For example, the extraction of the β-decay strength for the first excited state of ^{71}Ga, which is of utmost importance to astrophysics as well as to elementary particle physics,[5] requires a high resolution which so far is difficult to obtain at intermediate energies. Therefore it is of particular interest to find an appropriate method to "calibrate" the low-energy (p,n) cross sections to the β-decay strengths. In this report we present the first systematic comparison of the low-energy (p,n) cross sections with the β-decay strengths for the 0^+(g.s.) ↔ 1^+(g.s.) and $3/2^-$(g.s.) ↔ $1/2^-$(g.s.) transitions in fp shell nuclei.

We have measured the (p,n) cross sections on ^{58,64}Ni, ^{68,70}Zn and ^{71}Ga at E_p = 20 MeV. These are the nuclei in this mass region for which the transitions between the ground states are pure GT type and are clearly separated from other states with our energy resolution. The experiment was performed with use of a 20-MeV proton beam from the AVF cyclotron and time-of-flight facilities[6] at Cyclotron and Radioisotope Center, Tohoku University. Angular distributions of emitted neutrons were measured between 0° and 40°. The targets were metallic foil of enriched isotopes. Overall time resolution was typically 0.9 ns, corresponding to a energy resolution of 40 keV for 15-MeV neutrons detected at a flight path of 44 m. The errors in the absolute magnitude of cross sections are estimated to be about 20 %. Details of the experiment are given in our previous work.[7]

A sample neutron energy spectrum is presented in Fig. 1 for the $^{70}Zn(p,n)^{70}Ga$ reaction. The energy resolution is good enough to resolve the 1^+ ground state peak from that for the 2^+ first excited state at $E_x = 0.51$ MeV. Figure 2 presents the angular distributions from the $^{70}Zn(p,n)^{70}Ga$ reaction leading to the 1^+ ground state and to the isobaric analog state (IAS) at $E_x = 8.189$ MeV. It should be noted that the $0^+ \rightarrow 1^+$ transition shows a similar angular distribution pattern to that for the pure L=0 transition to IAS. The solid line in the figure is a macroscopic distorted-wave Born approximation (DWBA) calculation with optical potential parameters by Carlson et al.[8] Angular distribution shapes of the other $0^+ \rightarrow 1^+$ (or $3/2^- \rightarrow 1/2^-$) transitions studied are also similar to the $0^+ \rightarrow 0^+$ (or $3/2^- \rightarrow 3/2^-$) IAS transitions. This fact suggests that the 20-MeV (p,n) cross sections at small angles might provide a good measure of the GT strengths.

In order to facilitate more quantitative arguments, it is necessary to estimate the distortion effects which are important at this energy. The proton distortion effects are common to the $0^+(3/2^-)$ and $1^+(1/2^-)$ states of a given target, but the neutron distortion effects are quite different because of the difference in the Q values. This, as well as the change of the neutron wave number, is reflected in the Q-value dependence of the DWBA cross sections. Therefore DWBA cross sections are calculated as before but with the Q values to the ground states. Then the ratios

$$S^2 = \frac{\sigma(p,n)_{gs}}{\sigma(p,n)_{IAS}} \cdot \frac{\sigma_{DW}(Q_{IAS})}{\sigma_{DW}(Q_{gs})} \cdot (N-Z) \qquad (1)$$

are compared with the B(GT) values obtained from the known log*ft* for β-decay. They are shown in Table 1. The proportionality between the S^2 values and B(GT) is evident.

Taddeucci et al. have found[9] that the ratio $R(E_p)$ for $T > 0$ light target nuclei (A=7-42) depends linearly on E_p between 50 and 160 MeV. Here

$$[R(E_p)]^2 = \frac{\sigma_{GT}(0°)/B(GT)K_{GT}(E_p)}{\sigma_F(0°)/B(F)K_F(E_p)}$$

$$\text{and} \quad K = (E_i E_f/\pi^2)(k_i/k_f). \qquad (2)$$

Below 50 MeV they observed a mass-dependent dispersion of $R(E_p)$ about the average value. At intermediate energies and at $q \simeq 0$, tensor, spin-orbit and other $L \neq 0$ effects are generally small, and the distorted-wave impulse approximation (DWIA) is supposed to be valid. Then the ratio $R(E_p)$ reduces to $|J_{\sigma\tau}/J_\tau|(N_{\sigma\tau}/N_\tau)^{1/2}$ with $J_\alpha(\alpha=\sigma\tau,\tau)$ being the Fourier transform of the effective nucleon-nucleon interaction and $N_\alpha(q)$ a distortion factor. The distortion factor ratio is found to be approximately independent of energy between 80 and 200 MeV. Therefore their analysis seems to suggest that the convergence of

$R(E_p)$ values above 50 MeV is an indication of the onset of validity of the DWIA, while at lower energies the other effects become more significant.

Since the sum rule gives a total Fermi strength B(F) = N-Z, the ratio $S^2/B(GT)$ is essentially equal to the $R^2(E_p)$ value discussed by Taddeucci et al., assuming almost all the Fermi strength is concentrated in IAS. Therefore the proportionality between the S^2 value and B(GT) observed here suggests that the $R(E_p)$ value is constant at least in a limited mass region (A=58-71) and at a fixed incident energy (20 MeV), and thus one could use the S^2 value to extract B(GT) from 0° (p,n) cross sections.

It has been shown that at low energies the tensor and spin-orbit parts of the effective interaction and exchange terms have only small effects on these predominantly L=0 transitions according to DWBA calculations with appropriate shell-model wave functions and a reasonable choice of the effective interaction.[10,11] Furthermore the calculation indicates that the L=2 components in the $0^+ \rightarrow 1^+$ transition are very small at $\theta \simeq 0$. Indeed the experimental angular distributions for the predominantly L=2 transitions observed in this experiment fall off rapidly towards small angles.

These are necessary signatures to allow, may not be to justify, the comparing procedure we have taken. What we measure involves, in terms of DWBA, an overlap of proton and neutron waves and the form factor. A change in the neutron wave may put emphasis on a different part of the form factor. Therefore the procedure adopted here assumes the same radial dependence for the $0^+(3/2^-)$ and $1^+(1/2^-)$ form factors. Significant contribution of the exchange terms, tensor interaction or L=2 transition amplitudes would ruin this assumption. We have made another crude estimate of the distortion effects by correcting the measured (p,n) cross sections by a factor $\exp(-\frac{2m_n}{\hbar^2 k_n}\cdot 4W_D a)$, where W_D and a are the depth and the diffuseness of the surface imaginary potential for neutron obtained from Ref. 8 and used in the DWBA calculations. This factor simply represents the absorption of the neutron plane wave in the nuclear medium. The comparison of the ratio of the corrected $1^+(3/2^-)$ and $0^+(1/2^-)$ cross sections (multiplied by N-Z) with B(GT) shows slightly worse but similar proportionality to that seen in Table 1. Thus we might say that the difference in the absorption of the outgoing neutron is the main factor to be corrected and the other elements tend to be factorized and cancel out when we take the ratio of the cross section.

In conclusion, the 0° (p,n) cross sections for $0^+(3/2^-) \rightarrow 1^+(1/2^-)$ g.s. to g.s. transitions at E_p = 20 MeV, corrected for distortion effects, are found to be approximately proportional to B(GT) obtained from the known β decay log*ft* values for nuclei A=58-71 as shown in Table 1. Such a proportionality may be used to locally "calibrate" the 0° (p,n) cross sections to extract unknown B(GT) values. Of course such a procedure should be taken with some caution since the reaction mechanism is not as well established as at intermediate energies. In spite of such a limitation, the present observation combined with a much better energy resolution (60 keV or less) makes (p,n) reactions at E_p = 20 MeV an attractive and potentially rich probe of the GT strength distribution among low-lying states.

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Table 1. Transitions, final-states (spin-parities), reaction Q-values, experimental (p,n)0° cross-sections, calculated cross-section ratios, S^2 in eq. (1), logft and B(GT; p,n)

Transition	Final State (J^π)	Q (MeV)	$\sigma(0°)$ (mb/sr)	$\frac{\sigma_{DW}(Q_{IAS})}{\sigma_{DW}(Q_{g.s.})}$	S^2	logft[a] β^+	B(GT)[b] (p,n)	S^2/B(GT)
$^{58}Ni \rightarrow ^{58}Cu$	IAS (0^+)	-9.55	3.07	0.979	0.191	4.866[c]	0.165	1.16
	g.s.(1^+)	-9.35	0.300					
$^{64}Ni \rightarrow ^{64}Cu$	IAS (0^+)	-9.30	11.01	0.659	0.168	4.959[d]	0.130	1.29
	g.s.(1^+)	-2.46	0.351					
$^{68}Zn \rightarrow ^{68}Ga$	IAS (0^+)	-9.75	7.40	0.562	0.0941	5.195[e]	0.0755	1.25
	g.s.(1^+)	-3.75	0.155					
$^{70}Zn \rightarrow ^{70}Ga$	IAS (0^+)	-9.63	7.50	0.571	0.329	4.72[f]	0.225	1.46
	g.s.(1^+)	-1.44	0.432					
$^{71}Ga \rightarrow ^{71}Ge$	IAS ($3/2^-$)	-9.94	7.40	0.553	0.101	4.375[g]	0.083	1.22
	g.s.($1/2^-$)	-1.02	0.150					

a) $ft = 6163.4/(g_A/g_V)^2 B(GT)$ with $(g_A/g_V) = 1.25$.
b) $B(GT;p,n) = [(2J_f+1)/(2J_i+1)]B(GT;\beta^+)$, where J_i and J_f are the spins of the initial and final states for the (p,n) reaction, respectively.
c) Ref. 12
d) Ref. 13
e) Ref. 14
f) Ref. 15
g) Ref. 16

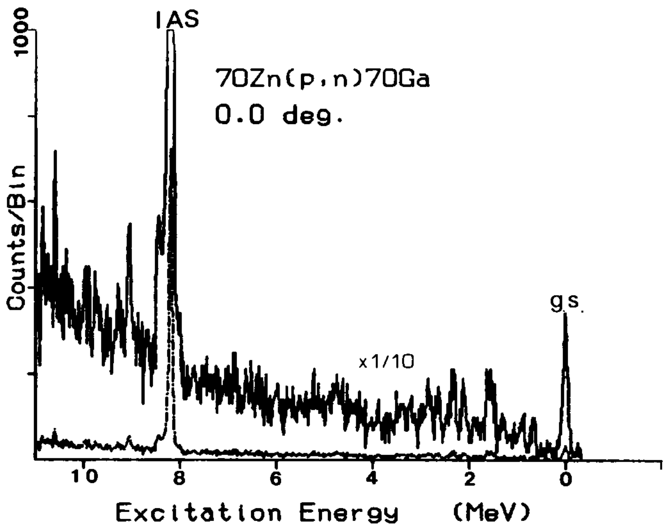

Fig. 1. A sample energy spectrum taken for the $^{70}Zn(p,n)^{70}Ga$ reaction at E_p = 20 MeV with a neutron flight path of 44 m. Energy per bin is 25 keV.

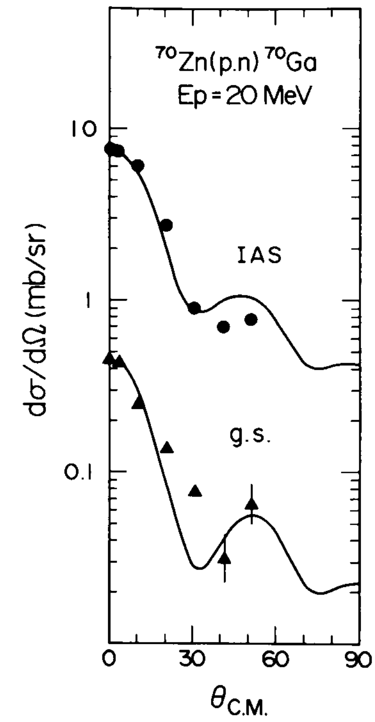

Fig. 2. Differential cross sections for the peaks corresponding to the g.s. and the 8.189-MeV IAS in ^{70}Ga. The solid curves are DWBA calculation with the corresponding Q-values.