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Comparison of 0° (p,n) cross sections and $B(M1)$ values for separating current and spin contributions to isovector $M1$ transitions

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We present the ratio of experimental 0° (p,n) cross sections with the measured $B(M1)$ values for transitions in several nuclei. Taking the strong spin-flip transition in ^{12}C for normalization, we find overall good agreement with shell-model predictions for ^{24}Mg, ^{28}Si, and ^{48}Ca. The values of the ratios vary considerably and are very sensitive to the relative amounts of spin and current contributions to each transition. Experimental ratios are also presented for ^{16}O and ^{26}Mg.

NUCLEAR REACTIONS Charge exchange (p,n) at 0°, $E_p = 62-160$ MeV, cross sections; targets ^{12}C, ^{16}O, ^{24}Mg, ^{26}Mg, ^{28}Si, ^{48}Ca. Compared $\sigma_{p,n}(0°)$ with $B(M1)$ values from inelastic electron scattering.

The study of $M1$ strength in nuclei has received increased attention with the availability of new intermediate-energy proton and electron accelerators with improved energy resolutions and beam currents. Isovector $M1$ transitions are important to study because they are often dominated by a simple spin-flip, isospin-flip nuclear excitation whose strength should be able to be estimated by realistic shell-model calculations; however, recent (p,n) measurements[1-3] support earlier indications from magnetic-moment data and $M1$ gamma-decay strengths[4] that a significant fraction of the expected $M1$ strength in medium and heavy-weight nuclei is missing. Backward-angle inelastic electron scattering also preferentially excites isovector transitions and has been extensively used to study the excitation of $M1$ strength.[5] Especially because of the increased interest in $M1$ strength, it is important to determine how the (p,n) cross section results are related to the available inelastic electron-scattering measurements.

Berg *et al.*[6] recently compared angle-integrated (p,n) cross sections at 35 MeV on $^{24-26}$Mg with $B(M1)$ values obtained from inelastic electron-scattering experiments for the same transitions. They observed general correspondence of the integrated (p,n) cross sections with the $B(M1)$ values using one overall normalization factor; however, as noted by Berg *et al.*[6] and discussed in detail by Petrovich, Love, and McCarthy,[7] inelastic electron scattering is sensitive to *both* spin and orbital current contributions to isovector $M1$ transitions, while the (p,n) reaction, at low momentum transfers, is sensitive primarily to spin contributions. Because specific $M1$ transitions may be expected to have different relative contributions (from spin-dominated and orbital current-dominated interactions), one should not expect that there is a single overall normalization between (p,n) cross sections at low momentum transfer and $B(M1)$ values obtained from inelastic electron scattering. As discussed by Petrovich *et al.*[7] the (p,n) reaction at angles away from 0° will involve significant momentum transfer so that orbital current contributions as well as spin contributions would be expected. It may be because Berg *et al.* used angle-integrated (p,n) cross sections, that the orbital current contributions were significant so that one overall normalization factor was obtained.

Using shell-model wave functions from Cohen and Kurath,[8] and Wildenthal and Chung,[9] Petrovich *et al.* provided estimates of the spin and orbital current contributions for known $M1$ transitions in ^{12}C, ^{24}Mg, and ^{28}Si. Following the method of Petrovich *et al.*, and using measured 0° (p,n) cross sections and published $B(M1)$ values, we present here a test of their predictions for these transitions. Also, we extend their analysis to include additional (p,n) cross section to $B(M1)$ ratios for transitions in ^{16}O, ^{26}Mg, and ^{48}Ca.

With the approximations that the contributions from the tensor interaction, the spin-orbit interaction, and from the $L=2$ transition densities are small near $q=0$, we obtain for $0^+ \rightarrow 1^+$ transitions the expressions

$$B(M1\uparrow;q) \approx 9\left[\frac{e\hbar}{2Mc}\right]^2 \left\{\sum_t (-1)^t \langle T_i T_{iz} t 0 \mid T_f T_{fz}\rangle \left[\tfrac{1}{2} g_s^t \rho_{10}^{st}(q) + g_l^t \rho_{10}^{lt}(q)\right]\right\}^2 , \tag{1}$$

$$\sigma_{p,n}(q) \approx 8\pi N_D \left[\frac{\mu}{2\hbar^2}\right]^2 \left[\frac{k_f}{k_i}\right] 3 \,|\, \langle T_i T_{iz} 1 -1 \mid T_f T_{fz}\rangle v_1^c(q) \rho_{10}^{s1}(q) \,|^2 , \tag{2}$$

where the g's are the isoscalar and isovector spin and orbital g factors, $t=0$ or 1, and $v_1^c(q)$ is the central spin-flip, isospin-flip term in the nucleon-nucleon effection interaction. The distortion factor N_D is a function of both the incident proton energy and the mass of the target. The spin and orbital transition densities are defined by

$$\rho_{JL}^{kt}(q) = \langle J_f T_f \,|||\, \sum_i j_L(qr_i)[Y_L(\hat{r}_i)\mathcal{O}^k(i)]^J \mathcal{O}^t(i) \,|||\, J_i T_i \rangle , \tag{3}$$

where the triple bar matrix elements are reduced in both spin and isospin,

$$\mathcal{O}^k(i) = s(i)[l(i)]$$

for $k=s[l]$ and $\mathcal{O}^t(i) = \tau[1]$ for $t=1[0]$.

Petrovich *et al.*[7] considered specifically only $N=Z$ targets with $T_i=0$. For this case, Eq. (1) simplifies considerably and we obtain for the ratio

$$\frac{\sigma_{p,n}(q)/N_D}{B[M1\uparrow;(q)]} \approx C(T_p) \frac{|\rho_{10}^{s1}(q)|^2}{|\rho_{10}^{s1}(q) + 0.2\rho_{10}^{l1}(q)|^2} , \tag{4}$$

where, following the work of Petrovich *et al.*,[7] we have used the approximation $g_l^{\,1} \approx 0.1\, g_s^{\,1}$.

The energy-dependent constant $C(T_p)$ includes the ratio of all the various constants in Eqs. (1) and (2) plus the energy-dependent terms k_f/k_i and $|v_1^c(q)|^2$. The value of the constant $C(T_p)$, at a given energy, can be obtained from the observed ratio of a (p,n) cross section to a $B(M1)$ value for a transition believed to be dominated by the spin-transition density, i.e., for $\rho_{10}^{l1} \ll \rho_{10}^{s1}$,

$$\frac{\sigma_{p,n}(q)/N_D}{B(M1\uparrow)} \rightarrow C(T_p) . \tag{5}$$

The ^{12}C$(p,n)^{12}$N(g.s.) reaction presents a nearly ideal case to determine the experimental constant $C(T_p)$ in Eq. (4). The corresponding $M1$ transition is believed to be dominated by the spin-transition density (see Petrovich, Love, and McCarthy[7]), and the ^{12}N ground state is well-resolved experimentally; furthermore, the $B(M1)$ value for the analog transition between the ground state of ^{12}C and the 15.11 MeV, 1^+ state in ^{12}C, is well known.[5] In Table I we present 0° (p,n) cross sections for the ^{12}C$(p,n)^{12}$N(g.s.) reaction at several different beam energies.[10,11] Presented also are "cross sections" renormalized by a distortion factor calculated as the ratio of DWIA calculations to PWIA calculations using the computer code DWBA70.[12] The nucleon-nucleon effective interaction is taken to be the 140 MeV interaction of Love and Franey.[13] The optical-model parameters are taken from the study of Comfort and Karp[14] for the ^{12}C$+p$ system from 12 to 185 MeV. The energy dependence of the calculated distortion factors is thus determined by the energy-dependent optical-model parameters of Comfort and Karp. We note that the resulting "plane-wave" cross sections show no clear energy dependence, indicating that the energy dependence of the spin-flip, isospin-flip term of the effective interaction over the energy range considered here (from 62 to 160 MeV) must be small. Actually, the factor k_f/k_i in Eq. (2), which is not removed by the distortion factor, increases by about 10% from 62 to 160 MeV, so that a corresponding decrease in the effective interaction may be indicated. Such a decrease is consistent with the energy dependence of the spin-flip, isospin-flip term in the effective interaction of Love and Franey[13]; however, the (~10%) uncertainties of the (p,n) measurements do not permit drawing a conclusion about such a small energy dependence. Our study of this energy dependence is consistent also with the similar recent study of this reaction by Rapaport *et al.*[15] The ratios of the distortion-renormalized (p,n) cross sec-

TABLE I. Comparison of (e,e') and (p,n) measurements for the isovector $M1$ transition in ^{12}C.

	(e,e')		(p,n)						
Nucleus	Final state (MeV)	$B(M1\uparrow)$ μ_0^2	Residual nucleus	Final state (MeV)	T_p (MeV)	$\sigma_{pn}(0°)$ (mb/sr)	N_d[a]	σ_{pn}/N_D	$[\sigma/N_d]/[B(M1)]$
^{12}C	15.11	2.92	^{12}N	0.0	62	3.25	0.261	12.45	4.26
					99	4.86	0.443	10.97	3.76
					120	5.40	0.500	10.80	3.70
					135	5.90	0.527	11.20	3.83
					160	6.67	0.556	12.00	4.11
									aver. = 3.93

[a] $N_D = \sigma_{\rm DW}/\sigma_{\rm PW}$ calculated with DWBA70 (Ref. 12). See text.

tions to the experimental $B(M1)$ value (from the compilation of Fagg[5]) are listed also in Table I and are seen to be 3.93 ($\pm 8\%$). Petrovich *et al.* predict that the $M1$ transition is strongly dominated by spin contributions, but includes some orbital contributions such that this transition should have a 0° (p,n) cross section to $B(M1)$ value ratio 5% bigger than a pure spin-dominated transition. Adopting this prediction, we thus deduce that the value of the experimental constant in Eq. (4) is $C_p = 3.74$ ($\pm\sim 10\%$). Within the experimental uncertainties there is no evidence for an energy dependence as long as one uses distortion-corrected (or "plane-wave") cross sections.

In Table II we present the shell-model predictions of Petrovich *et al.* for the various $M1$ transitions in ^{12}C, ^{24}Mg, and ^{28}Si, compared to the distortion-corrected ratios of $\sigma_{p,n}/B(M1)$ from experimental results. The ^{24}Mg and ^{28}Si(p,n) cross sections are taken from the work of Knudson *et al.*[10] and Anderson *et al.*,[16] respectively. The distortion factors are calculated in the same way as for the ^{12}C$(p,n)^{12}$N reaction described above. The optical-model parameters for ^{28}Si are from Schwandt *et al.*[17] The optical model parameters for ^{24}Mg were interpolated between the ^{12}C parameters and the ^{28}Si parameters. The $B(M1)$ values are from the compilation of Fagg.[5] The cross-section-to-

TABLE II. Comparison of (p,n) to $B(M1)$ with the shell-model predictions for ^{12}C, ^{24}Mg, and ^{28}Si.

	(e,e')		(p,n)						
Nucleus	Final state (MeV)	$B(M1\uparrow)$ (μ_0^2)	Nucleus	Final state (MeV)	T_p (MeV)	$\sigma_{pn}(0°)$ (mb/sr)	σ_{pn}/N_D	$R_{\rm exp} = \dfrac{\sigma_{pn}/N_D}{B(M1\uparrow)} \times \dfrac{1}{3.74}$	$R_{\rm th}{}^{\rm a} = \dfrac{\lvert \rho_{10}^{s1}(q) \rvert^2 \rvert}{\lvert \rho_{10}^{s1}(q) + 0.2\, \rho_{10}^{l1}(q) \rvert^2}$
^{12}C	15.11	2.92	^{12}N	0.00	62−160		11.48	1.05	1.05
^{24}Mg	9.97	1.18	^{24}Al	0.4	62	0.082	0.37	0.08	0.11
	10.72	3.72		1.1	62	1.69	7.58	0.54	0.71
	13.30 and 13.59	0.54[b]		3.1	62	0.64	2.87	1.42	2.71
^{28}Si	10.48 and 10.86	1.70	^{28}P	1.3	135	1.64	3.66	0.58	0.60
	11.41	3.64		2.1	135	4.83	10.78	0.80	1.00
	12.27	1.02		3.0	135	0.68	1.52	0.40	1.00

[a] Transition densities obtained from Ref. 7.

[b] Theoretical estimates of $B(M1)$ values from Ref. 7.

$B(M1)$ ratios are normalized by the factor 3.74 as indicated by the carbon results discussed above. Thus, the carbon results are forced to have the ratio 1.05. It is reassuring that the strong $M1$ transition in ^{28}Si (to the 2.1 MeV state in ^{28}P) is in reasonable agreement with the prediction. Considering that each comparison includes two separate experimental results, and that the predicted ratios are based on shell-model calculations which certainly are not exact, the overall agreement of the observed ratios with the predicted ratios is encouraging. The biggest discrepancy is for the $^{28}\mathrm{Si}(p,n)^{28}\mathrm{P}$ (3.0 MeV) comparison with the $B(M1)$ value for the transition to the 12.3 MeV state of ^{28}Si. We note that the shell-model prediction[7,8] of the $B(M1)$ value for this transition is low by a factor of 2, so that the shell-model prediction for R_{th} may be unreliable. Note that the "observed" ratio for the sum of the transitions to the 13.3 + 13.6 MeV states in ^{24}Mg necessarily uses the shell-model predicted $B(M1)$ values since the transition was too small to be seen in the (e,e') experiment.[18] Thus, since the $B(M1)$ value for this transition is probably smaller than the theoretical estimate adopted, the experimental ratio should be larger and would be in better agreement with the predicted ratio; more simply stated, the predicted ratio (2.71) indicates that this transition should be easily seen in (p,n), but hardly seen in (e,e'), in good agreement with the observations.

Perhaps the most interesting comparison is the one for the 9.97 MeV state in ^{24}Mg. For this transition, the predicted ratio is 0.11, in excellent agreement with the observed ratio of 0.08. This case shows clearly that there is *not* one overall normalization factor and that the observed ratios can vary considerably; furthermore, the results presented in Table II confirm that the observed ratios of 0° (p,n) cross sections to measured $B(M1)$ values provide a determination of the relative contributions of spin and current contributions to $M1$ transitions.

In Table III we present additional (p,n) cross-section-to-$B(M1)$ ratios for transitions on targets of ^{16}O, ^{26}Mg, and ^{48}Ca. The (p,n) cross sections are from Fazely *et al.*[19] for ^{16}O and from Anderson *et al.*[16], for ^{26}Mg and ^{48}Ca. The distortion factors were calculated using optical-model parameters for ^{16}O and ^{26}Mg interpolated between the ^{12}C parameters of Comfort and Karp[14] and the ^{28}Si parameters of Schwandt *et al.*[17] The ^{48}Ca parameters were calculated from a global parameter set for $A \geq 40$ from Schwandt.[20] The experimental $B(M1)$ values for ^{26}Mg are taken from the compilation of Fagg[5]; for ^{16}O from the $(\vec{p},\gamma)$ work of Snover *et al.*[21]; and for ^{48}Ca from the (e,e') measurement of Friebel *et al.*[22] Note that the ^{16}O transitions would not exist if ^{16}O were a perfect closed-shell nucleus. Since ^{16}O has both $l+\frac{1}{2}$ and $l-\frac{1}{2}$ subshells filled in the pure shell model, any observed $M1$ strength is a direct

TABLE III. $\sigma(p,n)$ to $B(M1)$ ratios for ^{16}O, ^{26}Mg, and ^{48}Ca.

Nucleus	(e,e') Final state (MeV)	$B(M1\uparrow)$ (μ_0^2)	Nucleus	(p,n) Final state (MeV)	T_p (MeV)	$\sigma_{pn}(0°)$ (mb/sr)	σ_{pn}/N_D	$R_{\mathrm{exp}}=\dfrac{\sigma_{pn}/N_D}{B(M1\uparrow)}\times\dfrac{1}{3.74}$
^{16}O	16.22	0.311	^{16}F	3.76	135	≈ 0.03	≈ 0.06	≈ 0.05
	17.14	≈ 0.413		4.65		0.38	0.75	≈ 0.49
	18.80	$\gtrsim 0.117$		6.23		0.33	0.65	$\lesssim 1.49$
^{26}Mg	8.52	0.21	^{26}Al	8.93	135	0.86[a]	1.88	2.39
	9.24	1.09		9.46		1.05[a]	2.29	0.56
	9.67	0.49						
	10.20	1.40		10.38		2.23	4.87	0.93
	10.65	1.96		10.79		2.76	6.02	0.82
	11.20	0.72		11.61		1.07[a]	2.33	
	13.33	1.59		13.59		0.6[a]	1.3	0.2
^{48}Ca	10.23	4.0	^{48}Sc	16.8	135	1.85	5.84	0.39
					160	2.22	6.38	0.43

[a] The uncertainties in these $^{26}\mathrm{Mg}(p,n)$ cross sections are estimated to be ±25%.

indication of ground-state correlations.

The $M1$ transitions in ^{26}Mg and ^{48}Ca contain both isoscalar and isovector contributions so the ratio given in Eq. (4) is no longer applicable. All four transition densities in Eq. (2) are needed to describe the ^{26}Mg transitions and we present the $\sigma(p,n)$ to $B(M1)$ ratios as a test for future shell-model calculations; for ^{48}Ca the ratio of $\sigma(p,n)$ to $B(M1)$ can be considerably simplified, however, if we assume that only the valence neutrons are active in the transition. For active neutrons only

$$\frac{\sigma_{p,n}(q)/N_D}{B(M1\uparrow;q)}=C(T_p)\left[\frac{g_s{}^1}{g_s{}^1-g_s^0}\right]^2\frac{1}{T_i}\,, \qquad (7)$$

where $C(T_p)$ is the same ratio of various constants in Eq. (4) and is determined from the $\sigma(p,n)$ to $B(M1)$ ratio for ^{12}C. Using the standard values of the g's (found, for example, in the compilation of Chaloupka *et al.*[23]), Eq. (7) gives a ratio of $0.38C(T_p)$ for ^{48}Ca. This ratio is seen to be in good agreement with the observed ratios presented for this transition in Table III. The good agreement obtained for this case indicates that the $M1$ transition in ^{48}Ca is dominated by the valence neutrons and corroborates the method presented here.

In conclusion, we observe reasonable agreement between measured 0° (p,n) cross sections and $B(M1)$ values from inelastic electron scattering using the method of Petrovich *et al.* These results show that the measured ratio of (p,n) cross sections to $B(M1)$ values can provide an important test of shell-model wave functions.

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