New Evidence for Meson-Exchange-Current Enhancement of Isovector $M1$ Strength

A. Richter and A. Weiss[(a)]
Institut für Kernphysik, Technische Hochschule Darmstadt, D-6100 Darmstadt, Germany

O. Haüsser
Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6
and TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3

B. A. Brown
Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48823
(Received 10 July 1990)

We report here isovector $M1$ strength distributions in ^{24}Mg obtained in a high-resolution (e,e') experiment at the Darmstadt Electron Linear Accelerator. The $M1$ strength is strongly enhanced relative to the Gamow-Teller strength for analog transitions observed in recent (p,n) and (n,p) experiments at the Indiana University Cyclotron Facility and TRIUMF. We show that this enhancement can likely be attributed to meson-exchange contributions to the spin part of the $M1$ operator.

PACS numbers: 25.30.Dh, 21.10.Pc, 24.30.Cz, 27.30.+t

It is well known that a purely nucleonic description of nuclei is insufficient to account for electroweak observables in nuclei. Meson-exchange and Δ-isobar currents modify transition probabilities in Gamow-Teller (GT) β decay, and also lowest-order magnetic properties such as magnetic moments, $M1$ transition probabilities, and magnetic form factors.[1,2] The identification of meson-exchange currents (MEC's) is straightforward in very light nuclei where there is very little uncertainty in the nucleonic wave function. A good example is provided by the magnetic form factors of ^{3}H and ^{3}He which can only be reproduced when MEC's are included in the calculations.[3] In heavier nuclei it is difficult to isolate MEC or isobar effects because of uncertainties in the many-body nucleonic calculations. For example, the quenching of GT strength observed in many nuclei[4] can be attributed to Δ-isobar currents, or to higher-order configuration mixing, and the relative importance of these two contributions is open to debate.

In this Letter we present new data on isovector $M1$ and GT transitions to 1^+, $T=1$ analog states in open-shell $A=24$ nuclei which allow a relatively clean identification of MEC contributions to the isovector $M1$ operator. The experiments determine $M1$ and GT strength distributions from (e,e') and nucleon scattering experiments, respectively. For a self-conjugate $T_3=0$ target nucleus such as ^{24}Mg, and for $M1$ and GT transitions to 1^+, $T=1$ final states, one may write approximately[1]

$$B(M1)=\frac{3(\mu_p-\mu_n)^2}{8\pi}[M(\sigma)+M(l)+M_\Delta+M_V^{\mathrm{MEC}}]^2,$$

$$B(\mathrm{GT})=[M(\sigma)+M_\Delta+M_A^{\mathrm{MEC}}]^2,$$

where the numerical factor in the $B(M1)$ expression is $2.643\mu_N^2$, and the ratio of coupling constants $(g_A/g_V)^2$ is not included in the definition of $B(\mathrm{GT})$. The nucleonic spin matrix elements $M(\sigma)$ and the isobar contributions M_Δ are the same in both expressions. The MEC contributions are dominated by pion exchange and are predicted[1] to be large for isovector $M1$ currents. They are strongly suppressed for axial-vector (GT) currents because of conservation of G parity. Unfortunately, the $M1$/GT comparison tends to be complicated by the (nucleonic) orbital contribution $M(l)$ to the $M1$ matrix element. The combined effects of orbital and MEC contributions are measured by the ratio

$$R(M1/\mathrm{GT})=\frac{\sum B(M1)/2.643\mu_N^2}{\sum B(\mathrm{GT})}.$$

In their absence $R(M1/\mathrm{GT})$ is unity, irrespective of the complexity of the nucleonic wave functions and of the exact magnitude of Δ-isobar contributions. Thus the sensitivity to uncertainties in the dominant nucleonic spin contribution is greatly reduced in $R(M1/\mathrm{GT})$. The orbital contributions can be reliably predicted in the *sd* shell using the unified *sd*-shell (USD) effective interaction of Wildenthal[5] which has been tested against a large body of experimental data. For the target nucleus ^{24}Mg, MEC contributions are expected to dominate the orbital contributions, especially when the $M1$ strength can be summed over a large region of excitation.[6] A further advantage of ^{24}Mg results from the fact that a large fraction of the total $M1$ and GT strengths is readily identifiable in two low-lying 1^+, $T=1$ states (at 9.96 and 10.71 MeV in ^{24}Mg, at 0.45 and 1.35 MeV in ^{24}Na, and at 0.44 and 1.07 MeV in ^{24}Al, respectively).

The $M1$ strength distribution has been measured with the 30–50-MeV electron beam from the Darmstadt Electron Linear Accelerator (DALINAC). Electrons scattered inelastically from a 20-mg/cm^2-thick target of isotopically enriched (99.92%) ^{24}Mg were observed at $\theta = 117°$, 141°, and 165°. With beam line and magnetic spectrometer system in the energy-loss mode an energy resolution of about 40 keV (FWHM) was achieved. A total of 21 1^+ states could be identified in the spectra between 8.86 and 14.3 MeV. This constitutes a major improvement over a previous experiment at the DALINAC.[7] The running sum of $B(M1)$ strength in ^{24}Mg is shown in Fig. 1 (cross-hatched area) together with the USD predictions using free-nucleon values for spin and orbital g factors in the $M1$ single-particle operator (dotted line). We quote $\sum B(M1)$ for two values of $E_{\max}$, the upper limit in the running sum. The first value, $(4.85 \pm 0.36)\mu_N^2$ for $E_{\max} = 11.4$ MeV, is dominated by the well established states at 9.96 and 10.71 MeV, whereas the second value, $(5.84 \pm 0.40)\mu_N^2$ for $E_{\max} = 15$ MeV, relies more heavily on extraction of relatively weak $M1$ strength. The corresponding $M1$ enhancement factors relative to the USD predictions, 1.13 ± 0.08 and 1.11 ± 0.08, show very satisfactory agreement. The errors include contributions from counting statistics, background uncertainties, target nonuniformities, and errors in normalization to the elastic peak. A detailed discussion of the experiment will be published elsewhere.[8]

The best estimates of total GT strengths in nuclei are at present obtained from (p,n), (p,p'), and (n,p) reactions at energies between 120 and 500 MeV. The GT analogs of the isovector $M1$ transitions are driven by the strong $(\sigma\tau)$ part of the NN interaction. In the limit of vanishing energy transfer $(\omega = 0)$ and momentum transfer $(q = 0)$, the cross sections to members of a 1^+, $T = 1$ isospin triad are related by $\sigma_{pn} = \sigma_{np} = 2\sigma_{pp'}$, where the factor of 2 arises from isospin coupling coefficients for the projectile. The cross sections can be converted to $B(\mathrm{GT})$ using the "unit cross section" $\hat{\sigma} = \sigma(q=0, \omega=0)/B(\mathrm{GT})$.

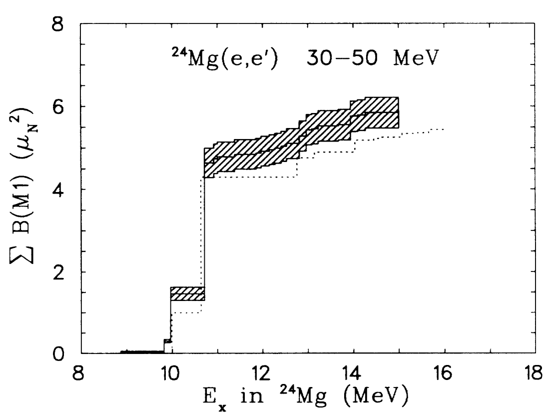

FIG. 1. Running sum of $M1$ strength in ^{24}Mg from the present experiment (cross-hatched area) and prediction of the USD shell model with free-nucleon g factors (dotted curve).

There are now four different experiments which determine the GT strength for the $A = 24$ isospin triad. Spin-flip cross sections σS_{nn} in (p,p') from Sawafta *et al.*[9] and cross sections from Crawley *et al.*[10] have been converted to $B(\mathrm{GT})$ using distorted-wave impulse-approximation (DWIA) calculations with a free t-matrix interaction to estimate $\hat{\sigma}$. More recently, $B(\mathrm{GT})$ results have become available from a (p,n) experiment performed at 135 MeV with the Indiana University Cyclotron Facility time-of-flight setup,[11] and from an (n,p) experiment at 198 MeV using the charge-exchange facility at TRIUMF.[12] The $\hat{\sigma}$ values used to extract $B(\mathrm{GT})$ from these experiments were estimated by directly relating (n,p) and (p,n) cross sections to $B(\mathrm{GT})$ values from β^- and β^+ decays. The $B(\mathrm{GT})$ strengths from the (n,p) and (p,n) experiments agree within errors, but are slightly smaller than those from the 250-MeV (p,p') data, and nearly a factor of 2 smaller than those from the 200-MeV (p,p') data of Crawley *et al.* The discrepancy arises mainly from an underestimate of the unit cross section $\hat{\sigma}$ by the DWIA.

A data set of seventeen known $\hat{\sigma}$ values, including recent accurate TRIUMF results on the isospin triads in $A = 6,12$ nuclei,[13] for nuclei with A between 6 and 54, and for energies E between 135 and 492 MeV, have recently been fitted with a five-parameter expression to describe the A and E dependence.[12] The fit to the $\hat{\sigma}$ data is excellent and implies $\hat{\sigma}(A=24)$ of 7.45, 8.52, and 8.39 mb/sr at energies of 135, 200, and 250 MeV, respectively. Using these unit cross sections the results of the four experiments are shown in Fig. 2 (details are described in

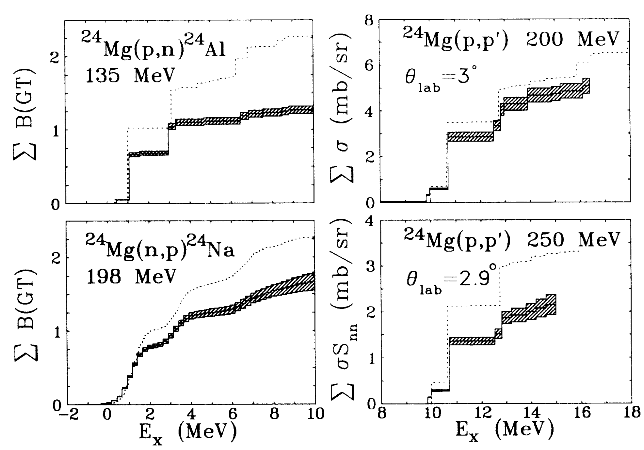

FIG. 2. Running sums of the GT strength from recent (p,n) (top left panel, from Ref. 11) and (n,p) (lower left panel, from Ref. 12) experiments. The σ data (from Ref. 10) and σS_{nn} data (from Ref. 9) in the right panels have been renormalized with consistent values of the unit cross section as explained in the text. The dotted lines represent predictions of the USD shell model with free-nucleon g factors. The theoretical (n,p) curve has been folded with the experimental resolution (1 MeV FWHM).

Ref. 12). The dotted lines correspond to the USD GT predictions with free-nucleon values for the spin g factor. All four experiments are now in reasonable agreement although the 200-MeV (p,p') results are still high by about 20%. The average $\sum B(\mathrm{GT})$ is mainly determined by the accurate (p,n) and (n,p) data which do not suffer from uncertainties due to the inclusion of (weakly excited) 1^+, $T=0$ states in the data set. For E_{max} corresponding to 11.4 and 15 MeV in ^{24}Mg the $\sum B(\mathrm{GT})$ values are[12] 0.74 ± 0.09 and 1.20 ± 0.17, respectively. This implies quenching of the GT strength relative to the USD predictions by factors of 0.72 ± 0.09 and 0.71 ± 0.10, respectively. The errors include uncertainties of the individual measurements, their observed spread, and, added in quadrature, an estimated systematic error of $\pm10\%$ in the unit cross section $\hat{\sigma}$.

The proposed $M1$/GT comparison of experimental data and calculations is quantified in Table I. We have concentrated on the total strengths which show the phenomena most clearly, although a detailed state-by-state comparison would also be reasonable. The first two parts of the table give the summed $B(M1)$ and $B(\mathrm{GT})$ values, respectively, and the last part of the table gives the ratio $R(M1/\mathrm{GT})$ which we will show provides the most model-independent and sensitive test of the MEC contribution.

First, we point out that configuration mixing causes a redistribution and, since there is no $M1$ or GT sum rule, a reduction of strength within the sd shell. The full sd-shell calculation based on the USD interaction of Wildenthal gives the best available estimate of configuration mixing. Relative to the extreme (j-j coupling) single-particle model the overall strength should be reduced by a factor of 0.31, whereas an even smaller factor of 0.23 applies to the 0–15-MeV region. The shell model must have some uncertainties in predicting these reduction factors. However, $R(M1/\mathrm{GT})$ is changed by a much smaller amount and is thus much less sensitive to the sd-shell interaction.

$B(M1)$ and $B(\mathrm{GT})$ are given in Table I for the free-nucleon operator as well as for the effective operators which include the effects due to higher-order configuration mixing, Δ-isobar admixtures, and MEC's. These are taken from two sources. One is the empirical effective operator obtained by Brown and Wildenthal (BW) from a global fit to individual magnetic moments and $M1$ and GT transitions in the sd shell.[14] The other is the effective operator from direct theoretical calculations of these effects by Towner and Khanna (TK).[1,15] The close similarity between the theoretical and the empirical effective operators is indirect evidence for the success of the theoretical calculations. The isovector $M1$ and GT results with these two effective operators are almost the same, except that the TK operator gives somewhat less quenching for $B(\mathrm{GT})$ compared to the BW operator.

The dominance of the spin part of the effective operator is demonstrated by comparing the results with the full effective operator [δ_s, δ_l, and δ_p are defined as in Ref. 14, i.e., $(M1)_{\mathrm{eff}}=g_s\mathbf{S}+g_l\mathbf{L}+g_s(\delta_s\mathbf{S}+\delta_l\mathbf{L}+\delta_p\mathbf{P})$, and $(\mathrm{GT})_{\mathrm{eff}}=(1+\delta_s)\mathbf{S}+\delta_l\mathbf{L}+\delta_p\mathbf{P}$, where g_s and g_l are free-nucleon g factors and $\mathbf{P}=\sqrt{8\pi}(Y^{(2)}\times\mathbf{S})^{(1)}$] to those obtained with only the δ_s and δ_l contributions, and to those obtained with only the δ_s contribution of the BW effective operators. $B(\mathrm{GT})$ is seen to be completely dominated by the δ_s term, whereas $B(M1)$ is mostly sensitive to δ_s but is slightly modified by δ_l.

From Table I, we see that the $R(M1/\mathrm{GT})$ ratio is enhanced about 40% by the δ_s contribution. In the Towner-Khanna calculations this enhancement in the spin operator is essentially due entirely to the difference

TABLE I. Isovector $M1$ and GT comparison in ^{24}Mg.

	$\sum B(M1)(\mu_N^2)$ E_{max} [a]		$\sum B(\mathrm{GT})$ E_{max}		$R(M1/\mathrm{GT})$ E_{max}	
	11.4 MeV	15.0 MeV	11.4 MeV	15.0 MeV	11.4 MeV	15.0 MeV
ESP [b]		19.24		7.49		0.98
sd free [c]	4.30	5.26	1.02	1.68	1.59	1.18
sd BW (δ_s) [d]	3.45	4.11	0.56	0.99	2.17	1.57
sd BW (δ_s,δ_l) [e]	3.85	4.48	0.61	0.99	2.38	1.71
sd BW $(\delta_s,\delta_l,\delta_p)$ [f]	3.92	4.48	0.61	0.98	2.43	1.73
sd TK $(\delta_s,\delta_l,\delta_p)$ [g]	3.96	4.68	0.71	1.13	2.12	1.57
Experiment	4.85(36)	5.84(40)	0.74(9)	1.20(17)	2.49(35)	1.85(29)
Experiment/free	1.13(8)	1.11(8)	0.72(9)	0.71(10)		

[a]Maximum energy considered in the summation.
[b]Extreme $d_{5/2}$ single-particle model.
[c]Full sd-shell model with free-nucleon operator.
[d]δ_s contribution to the Brown and Wildenthal effective operator (Ref. 14).
[e]δ_s and δ_l contributions to the Brown and Wildenthal effective operator.
[f]Full $(\delta_s,\delta_l,\delta_p)$ effective operator from Brown and Wildenthal.
[g]Full $(\delta_s,\delta_l,\delta_p)$ effective operator from Towner and Khanna (Ref. 15).

between MEC contributions to $M_V^{\rm MEC}$ and $M_A^{\rm MEC}$ discussed in the introduction and is the effect we are looking for. There is an additional 10% enhancement in $R(M1/{\rm GT})$ due to the δ_l contribution to the orbital part of the $B(M1)$. In the Towner-Khanna calculations this term originates from a strong cancellation between effects due to MEC's and those due to higher-order nuclear configuration mixing. However, the δ_l contribution is a factor of 4 less important than the δ_s contribution in this case. The δ_p contribution is negligible.

Thus, the $R(M1/{\rm GT})$ ratio clearly is a sensitive and direct measure of the MEC correction to the spin operator. The experimental value of $R(M1/{\rm GT})$ is in excellent agreement with expectations based on both the TK and BW effective operators, and hence directly confirms the importance of MEC's in nuclei, as has been shown with the example of ^{24}Mg. This has become possible through higher precision of electromagnetic and hadronic cross sections and their combined analysis, an improved knowledge of the effective nucleon-nucleon interaction in nuclei, and the existence of reliable many-body wave functions and effective operators for *sd*-shell nuclei. It will be interesting in the future to extend this type of comparison to other regions of the *sd* shell.

The authors are indebted to the TRIUMF CHARGEX Collaboration and to B. Anderson for permission to quote the (n,p) and (p,n) results prior to publication. This work was supported by grants from the Bundesministerium für Forschung und Technologie of Germany (06DA184I), the Natural Sciences and Engineering Research Council of Canada, and the U.S. National Science Foundation (PHY 87-14432).

[(a)]Present address: Gesellschaft für Schwerionenforschung, D-6100 Darmstadt, Germany.

[1]I. S. Towner, Phys. Rep. **155**, 263 (1987), and references therein.

[2]D. O. Riska, Phys. Rep. **181**, 209 (1989).

[3]W. Strueve, Ch. Haiduk, P. U. Sauer, and W. Theis, Nucl. Phys. **A465**, 651 (1987).

[4]C. D. Goodman, Comments Nucl. Part. Phys. **10**, 117 (1981).

[5]B. H. Wildenthal, in *Progress in Particle and Nuclear Physics,* edited by D. H. Wilkinson (Pergamon, Oxford, 1984), Vol. 11, p. 5.

[6]B. A. Brown and B. H. Wildenthal, Phys. Rev. C **27**, 1296 (1983).

[7]O. Titze, Z. Phys. **220**, 66 (1969).

[8]A. Richter *et al.* (to be published).

[9]R. S. Sawafta *et al.*, Phys. Lett. B **201**, 219 (1988).

[10]G. M. Crawley *et al.*, Phys. Rev. C **39**, 311 (1989).

[11]B. D. Anderson *et al.*, Phys. Rev. C (to be published); (private communication).

[12]TRIUMF experiment E489; O. Häusser *et al.* (to be published).

[13]J. Mildenberger *et al.*, Phys. Rev. C **42**, 732 (1990).

[14]B. A. Brown and B. H. Wildenthal, Nucl. Phys. **A474**, 290 (1987).

[15]I. S. Towner and F. C. Khanna, Nucl. Phys. **A399**, 334 (1983).