Isovector $M1$ transitions in ^{28}Si and the role of meson exchange currents

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At the newly installed 180° Darmstadt electron scattering facility we have measured the isovector $M1$ transition strengths in ^{28}Si in the excitation energy range from 10 to 18 MeV. Overall agreement with a shell-model calculation using the unified sd-shell interaction and effective g factors is obtained. Comparison with Gamow-Teller strength deduced from (p,n) data reveals the presence of meson exchange current contributions of the order of 25% to the summed $M1$ transition strength.

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The role of non-nucleonic degrees of freedom, i.e., that of meson exchange currents (MEC) and isobars to the magnetic dipole ($M1$) and Gamow-Teller (GT) transition strengths in nuclei, has been a subject of long-standing theoretical and experimental interest [1,2]. It becomes a formidable task to quantitatively determine these contributions in complex nuclei. On the experimental side, the transition strengths are usually distributed over many levels and one has to ensure that almost all the transitions are observed. Theoretically, one has to be sure that all structural effects at the nucleonic level are taken into account. For sd-shell nuclei, the wave functions obtained with the Brown-Wildenthal unified sd-shell (USD) effective interaction [3] in the full $1s0d$ shell-model space, take into account all possible $0\hbar\omega$ excitation strengths. They were able to deduce the effective g factors by fits to reliable data sets [4]. These calculations, along with the data for $M1$ strengths from reactions such as (e,e') and the GT strengths from (p,p'), (p,n), and (n,p) reactions provide a sensitive method of evaluating the MEC contributions, as has been shown recently [5].

As was pointed out in Ref. [5], self-conjugate nuclei are special candidates for such tests of MEC's, as all these processes can be studied with the same target nucleus, and the pure isovector ($\Delta T=1$) nature of the $M1$ transitions is well assured. For transitions from the ground state to the $1^+,T=1$ final states, one may write approximately [1]

$$B(M1)=\frac{3(\mu_p-\mu_n)^2}{8\pi}[M(\sigma)+M(l)+M_\Delta+M_V^{\mathrm{MEC}}]^2, \quad (1)$$

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

where the numerical factor in Eq. (1) is $2.643\mu_N^2$. The ratio of coupling constants (g_A/g_V) is not included in the definition of $B(\mathrm{GT})$. The spin matrix element $M(\sigma)$ and the isobar contribution M_Δ appear in both expressions. Pion exchange is the main source of MEC contributions which are predicted [1] to be large for isovector $M1$ currents, but should be strongly suppressed for axial-vector GT currents as a result of G parity conservation.

The ratio

$$R(M1/\mathrm{GT})=\frac{\Sigma B(M1)/2.643\mu_N^2}{\Sigma B(\mathrm{GT})} \quad (3)$$

measures the combined effects of orbital and MEC contributions, independent of the complexity of the nucleonic wave function and the Δ-isobar component. In the absence of these contributions the ratio R should be unity. In sd-shell nuclei the orbital contributions can be predicted reliably from large scale shell-model calculations [3]. Earlier, a comparison of $M1$ and GT strengths was carried out in ^{24}Mg and gave clear evidence for the important role of MEC's in isovector $M1$ transitions [5].

Here we aim at a similar investigation of the nucleus ^{28}Si. Recently, high-precision data on GT strength in ^{28}Si have become available [6]. In this paper we present results on the $M1$ strength distribution extracted from inelastic electron scattering data measured with the just installed high resolution 180° scattering facility [7] at the superconducting Darmstadt electron linear accelerator (S-DALINAC).

The 180° electron scattering facility consists of three chicane magnets and a separating magnet used in conjunction with the two-element QCLAM magnetic spectrometer [8]. The system has a maximum operating momentum of 90 MeV/c. Like any 180° facility, this system acts as a spin filter, strongly selecting transverse excitations of the nucleus. Some of the unique characteristics of the Darmstadt 180° system are (i) a very large momentum acceptance ($\Delta p/p=\pm 10\%$); (ii) the ability to reconstruct both horizontal and vertical components of the scattering angle for each event, which allows both the definition of solid angle and the ability to check the angular alignment; (iii) a large solid

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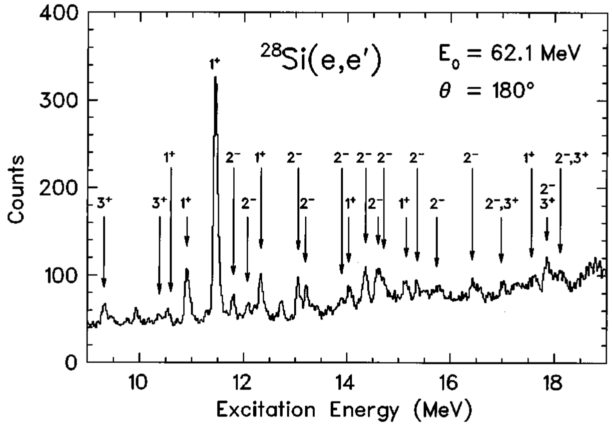

FIG. 1. Spectrum of ^{28}Si(e,e') scattering at $E_0=62.1$ MeV and $\Theta=180°$.

angle acceptance (up to 10 msr) which can be reduced to the desired size by software cuts after the data are taken. The thin-target momentum resolution of the system is better than 8×10^{-4}, limited by the energy spread of the accelerator beam. A complete description of the system is given Ref. [7].

Measurements on a ^{28}Si target of thickness 16 mg/cm^2 were taken with the 180° system at incident energies of $E_0=42.7$, 50.3, and 62.1 MeV. Two spectrometer momentum settings were taken at each energy in order to cover the excitation energy range from 10 to 18 MeV. For simplicity of analysis, the acceptance for this experiment was limited to a constant symmetric solid angle of 6.4 msr and to the momentum region of -5% to $+8\%$. The energy resolution was between 70 and 90 keV (FWHM), primarily because of the thickness of the target.

Figure 1 shows a measured spectrum at 62.1 MeV. The levels are labeled with spin and parity as determined from previous experiments [9–11]. Their energies agree with those in the literature [11] to within ±5 keV. The well-known strong $M1$ transition at $E_x=11.45$ MeV [9] serves as a useful check of the normalization. The $B(M1)$ transition strengths for the 1^+ levels were extracted by fitting to distorted-wave Born approximation (DWBA) form factors calculated using shell-model parameters from the full sd-shell analysis of Brown and Wildenthal [4]. Additional still unpublished data [10] on these transitions, measured at the high resolution energy-loss spectrometer [12] in Darmstadt at angles between 117° and 165° were in good agreement with the new data and were included in the fits together with the results of Ref. [9].

Figure 2 shows the experimental $B(M1)$ strengths along with the Brown-Wildenthal USD calculations employing effective g-factors [4]. A few observations are in order. The fragmentation of $M1$ strength over this energy region is well accounted for. The only exception occurs for the 11.45 MeV level for which the measured transition strength is nearly a factor of two larger than the model estimate. The origins of this discrepancy are not clear, especially since the model is able to identify the manifestations of orbital and spin current interferences. As an example, in ^{28}Si(p,p') scattering, a strong transition with $B(M1)\simeq0.8\mu_N^2$ was observed at $E_x=13.35$ MeV [13]. The model simultaneously accounts for this transition along with the fact that this level is not

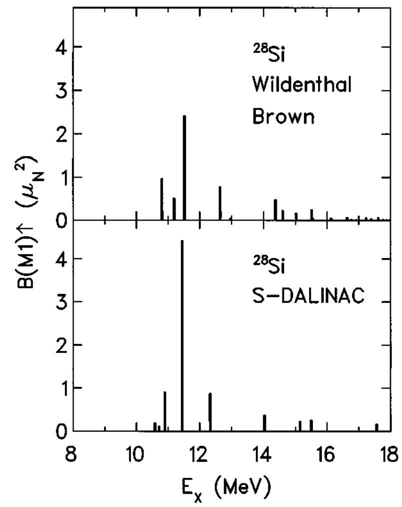

FIG. 2. Comparison of the experimental $B(M1)$ strength distribution and shell-model calculations using the USD interaction [3] and effective g factors [4].

seen in (e,e') scattering as a result of nearly equal contributions from spin and orbital currents with an almost perfect cancellation for $M1$ transitions.

To assess the role of meson exchange currents we follow the discussion in Ref. [5]. First, it is instructive to compare the total $M1$ and GT strengths over the $0\hbar\omega$ space. To this end, we can employ the sum of $M1$ strengths in the (e,e') reaction from this experiment and the GT transition strengths in the (p,n) reaction [6] corresponding to excitations $E_x\leqslant15.5$ MeV in ^{28}Si. The limit on the excitation energy was guided by the shell model, which shows that this energy region exhausts the $0\hbar\omega$ strengths of $M1$ and GT transitions. As noted in Ref. [6], the B(GT) strength deduced from the (p,p') data [13] are prone to ambiguities due to optical model parameters. We do not, therefore, include these results in our discussion below.

Table I summarizes the experimental and model results. The last column shows the ratio $R(M1/\mathrm{GT})$ defined in Eq. (3), which makes a direct comparison of the squares of the

TABLE I. Isovector $M1$ and GT strength comparison in ^{28}Si.

	$\Sigma B(M1)$	$\Sigma B(\mathrm{GT})$	$R(M1/\mathrm{GT})$
ESP[a]	20.27	9.60	0.80
sd free[b]	8.67	3.49	0.94
sd BW(δ_s)[c]	6.29	1.98	1.20
sd BW(δ_s,δ_l)[d]	6.38	1.98	1.22
sd BW$(\delta_s,\delta_l,\delta_p)$[e]	5.87	1.94	1.14
sd TK$(\delta_s,\delta_l,\delta_p)$[f]	6.90	2.26	1.15
Experiment	7.09(37)	1.89(5)	1.42(10)
Experiment/sd free	0.82(4)	0.54(1)	

[a]Pure $d_{5/2}\rightarrow d_{3/2}$ single-particle transition.
[b]Full sd-shell model with free nucleon g factors.
[c]δ_s contribution to the BW effective operator (Ref. [4]).
[d]δ_s and δ_l contribution to the BW effective operator.
[e]Full BW effective operator.
[f]Full TK effective operator (Ref. [14]).

transition matrix elements for $M1$ and GT processes transparent. Barring accidental cancellations, $R=1$ indicates that both $M1$ and GT transitions are purely due to nuclear spin effects. Note that the experiment gives $R=1.42(10)$. Also included are the results of various theoretical calculations: the extreme single particle (ESP) values, using the USD interaction with free nucleon g factors, the Brown-Wildenthal (BW) phenomenological effective g factors with various corrections added sequentially, and that of Towner and Khanna (TK) who calculate the corrections to the operators directly in perturbation theory [14]. Correction factors ($\delta_s,\delta_l,\delta_p$) for the spin, orbital, and tensor parts of the magnetic dipole and GT operators, respectively, are defined as in Ref. [4]. All the calculations are carried out in the full $1s0d$-shell space.

As is seen in Table I, the experimental summed transition strengths are much smaller than the ESP value. Also, the ESP result $R=0.8$ indicates that the orbital contribution interferes destructively with the spin part, as anticipated for a pure $d_{5/2}\rightarrow d_{3/2}$ transition. The USD calculation with free nucleon g factors — shown as sd free — gives results closer to the experimental values with less than 10% contribution from the orbital term. This is corroborated by Hino, Muto, and Oda [15] who studied $M1$ strength working in a jj-coupling scheme and using the wave functions of the USD interaction. Their calculations show that the orbital current contributions amount throughout the sd shell to less than 10% of the total strengths. Relative to the USD calculation, the experimental strengths are 82% and 54% for $M1$ and GT transitions, respectively, and it is clear that further refinements are necessary.

It is clear that, if the model space is adequate, the GT transitions, which are driven by the spin contributions, make it essential that the spin component of the g factors is modified. Now, with the spin correction δ_s turned on, shown as BW(δ_s) in Table I, the results for B(GT) are in excellent agreement with the experiment. This is a further indication that model space effects are properly included in the calculation. The spin corrections are fairly sizable for these transitions being about 25% for $M1$ and 40% for GT strengths.

It is found that the orbital-correction contributions, as seen by comparing BW (δ_s,δ_l) with BW (δ_s) in Table I, are only at the 1% level. The contribution of the tensor-correction factor, as seen by comparing BW ($\delta_s,\delta_l,\delta_p$) with BW ($\delta_s,\delta_l$) in Table I, amounts to about 7% for $M1$ transitions and is about 2% for the GT transitions. However, inclusion of the tensor term worsens the agreement for the $M1$ data.

Alternatively, one can use the correction factors of TK for the calculations [14], as shown in Table I. Similar to the BW results, the orbital and tensor contributions have little influence on the results; rather the modification of the transition strength is due to quenching of the spin operator. Excellent agreement with the experimental $B(M1)$ value is found, but the GT strength is overestimated by about 20%. Clearly, the two independent approaches, BW and TK, cannot simultaneously account for $B(M1)$ and B(GT). It is to be remarked that both of them predict the same value $R(M1/\mathrm{GT})\simeq 1.15$.

The main findings are compared in Fig. 3 to the previously studied [5] case ^{24}Mg. The experimental ratio $R(M1/\mathrm{GT})$ is clearly enhanced over unity for both nuclei. In calculations with the USD interaction and free nucleon g factors the ratio is close to unity (dashed line). Note that the somewhat larger value for ^{24}Mg results from a 10% admixture of orbital strength. When effective g factors are introduced, regardless of whether using empirical (BW, solid line) or directly calculated (TK, dotted line) correction factors, the $M1$ strength is clearly enhanced over the GT strength. The experimental $R(M1/\mathrm{GT})$ ratio is satisfactorily reproduced for ^{24}Mg, but somewhat underpredicted in ^{28}Si. It is quite interesting to note that the two different approaches (BW and TK) predict an enhancement of $R(M1/\mathrm{GT})$ of about 25% by the δ_s contribution. In the TK approach this effect is directly related to the difference between vector and axial-vector MEC contributions discussed in the introduction, which makes the $R(M1/\mathrm{GT})$ ratio a direct and sensitive measure of MEC corrections to the spin operator. These results are in line with the observation of MEC effects on magnetic dipole moments of p-shell nuclei [16].

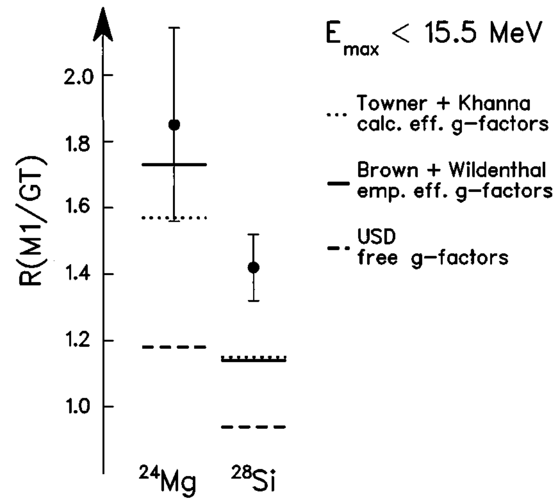

FIG. 3. Experimental ratios $R(M1/\mathrm{GT})$ defined in Eq. (3) for ^{24}Mg and ^{28}Si. Calculated ratios are shown for the USD interaction [3] with free g factors (dashed lines) and effective g factors from the BW [4] (solid lines) and the TK [14] (dotted lines) approach.

The present investigation of ^{28}Si with the newly commissioned 180° electron scattering spectrometer at the S-DALINAC highlights the importance of MEC's in complex nuclei with conclusions similar to the previous study of ^{24}Mg. These conclusions became possible only through high-precision experiments and a combined analysis of electromagnetic and hadronic cross sections. Furthermore, for sd shell nuclei reliable many-body wave functions and effective operators are available. Extension of such analyses to other regions of the sd-shell would certainly be of interest and are in fact planned.

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