Comparison of ^{24,25,26}Mg$(p,n)^{24,25,26}$Al Cross Sections with Giant $M1$ Strength

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Cross sections for the ^{24,25,26}Mg$(p,n)^{24,25,26}$Al reaction have been measured at 35 MeV. The strengths of the larger spin-isospin–flip transitions correspond surprisingly well with the matrix elements of the analogous giant $M1$ transitions.

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While substantial $M1$ strength has been found in the light nuclei, much less is known about its location for $A > 40$. In these heavier nuclei the transition strength appears to be spread over a wide range of excitation and fragmented among many levels, strongly reducing the sensitivity of the usual experimental techniques. Resonance fluorescence encounters background and statistical limitations and is, of course, useful only for bound states. Backward-angle electron scattering is hindered by increasing distortion effects which must be evaluated in a model-dependent fashion and by an intense background of $M2$ transitions. For example, not more than 15% of the predicted strength has been located in ^{90}Zr in spite of a serious experimental effort. It is then useful to search for other experimental probes which, while perhaps less precise, are more sensitive or selective. The (p,n) reaction at $E_p > 30$ MeV shows promise in this regard. For example, there is convincing evidence[2] that the reaction ^{90}Zr$(p,n)^{90}$Nb at 45 MeV strongly excites analogs of $M1$ strength in ^{90}Zr.

For the charge-exchange probe to provide quantitative rather than only qualitative information one needs, given the present state of art, to calibrate it in an empirical fashion. We present in this Letter the first systematic study of the relationship between $M1$ strength and (p,n) reactions at energies where the reaction mechanism is reasonably well understood, and for nuclei where individual states can be resolved and detailed electromagnetic information is available. Our data for the ^{24,25,26}Mg$(p,n)^{24,25,26}$Al reactions at $E_p = 35$ MeV yield a total of 16 correspondences between cross sections and $M1$ matrix elements $[B(M1)]$ of which all but two are in agreement within the uncertainties. This surprisingly strong correlation lends some confidence to the idea that studies of heavier nuclei with the (p,n) interaction at high energies will yield quantitative results on the distribution of $M1$ strength.

That one can use charge exchange reactions to search for $M1$ strength lies in the similarity of the operator for the two processes. If one neglects the isoscalar part of the $M1$ operator, which is an order of magnitude smaller than the isovector part, the isovector $M1$ operator and the central (p,n) spin-isospin–flip (SISF) operator are identical in the spin-isospin space of the valence nucleons, containing $\vec{\sigma}$ and $\vec{\tau}$ which flip spin and isospin, respectively. One therefore expects strong $M1$ transitions to be strong in (p,n) reactions. There will not be a perfect match of $B(M1)$ and $\sigma(p,n)$ because the radial parts of the operators are different and because of the current $(\vec{j})$ term in the $M1$ operator, but they will bear a strong similarity. Since, e.g., absorption of magnetic dipole radiation leads to strong 1^+, $T=1$ $[T_3 = \frac{1}{2}(N-Z) = +1]$ states near 10 MeV in ^{26}Mg we expect strong (p,n) transitions to their analogs in ^{26}Al with $J^\pi = 1^+$, $T=1$ $(T_3 = 0)$ at about 10 MeV above the isobaric analog of the ^{26}Mg ground state.

The (p,n) studies were performed with 35-MeV protons from the Michigan State University cyclotron. The beam-burst interval was chosen to allow the observation of neutron energies between 14 and 30 MeV. Angular distributions from 7° to 120° were taken with a beam-swinger system[3] and a 22.48 m flight path. All three Mg targets were 5.0-mg/cm^2 foils isotopically enriched to 99.5% in ^{24,25,26}Mg, respectively. The energy resolution was 180 keV for 30-MeV neutrons [from the isobaric analog state (IAS) in ^{25,26}Al] and 90 keV for 20-MeV neutrons (from the ground state in ^{24}Al, $Q = -14.665$ MeV). The spectra show strong, well-resolved transitions even at excitation energies near 10 MeV (see Fig. 1).

To identify the SISF transitions, we used mainly the following criteria: The angular distributions should be similar to those for known SISF transitions to 1^+ states; excitation energies of analog states in the Al isotopes should correspond to the known excitation energies of the parent magnetic dipole states in the Mg nuclei.

Figure 2 shows the angular distribution of the ^{26}Mg(p,n) cross section to the first 1^+ state in

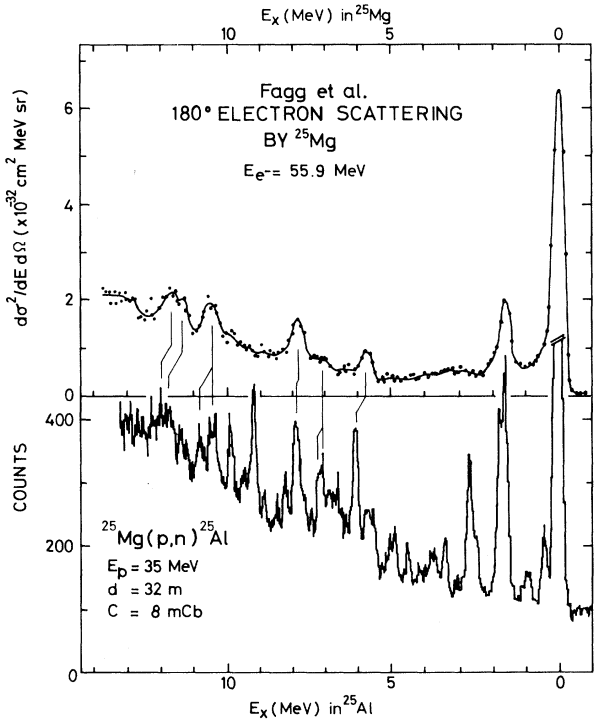

FIG. 1. Comparison of an inelastic-electron-scattering spectrum from ^{25}Mg (Ref. 8) with a ^{25}Mg$(p,n)^{25}$Al measurement.

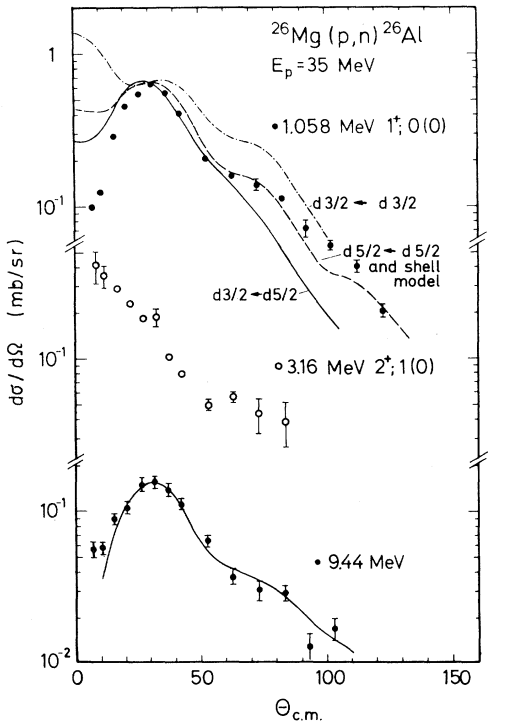

FIG. 2. Angular distribution of the well-resolved 1.06-MeV, 1^+ state in ^{26}Al together with a 2^+ state at 3.16 MeV and a representative of the 1^+ states near 10 MeV. The curve at the 9.44-MeV level follows the shape of the 1.06-MeV cross section. Inserted are microscopic DWBA results with use of partial and shell-model (Ref. 5) transition densities as described in the text.

^{26}Al at 1.06 MeV. The 1.06-MeV level is well resolved from others and the shape of its cross section has been used as a standard to identify other 1^+ states. Also shown are the results of microscopic distorted-wave Born approximation (DWBA) calculations carried out with the code DWBA 70,[4] with use of transition densities of Chung and Wildenthal,[5] the effective interaction of Bertsch *et al.*,[6] and the "best-fit" optical-model potentials of Becchetti and Greenlees.[7] These calculations show that the 1.06-MeV state is reasonably well represented by the DWBA approximation and that the shape is stable against changes in excitation energy.

We find that five states in ^{26}Al have 1^+ shapes and that they lie near 10 MeV as expected (E_x = 9.44, 9.89, 10.47, 10.83, and 11.21 MeV). The angular distribution of the 9.44-MeV state is shown in Fig. 2. Also shown is the angular distribution of a known 2^+ state at 3.16 MeV; from this plot and other measured cross sections it is clear that shapes corresponding to different J^π are sufficiently distinctive to provide unique J^π assignments.

A comparison[8] of (e,e') and (p,n) spectra for ^{25}Mg(^{25}Al) is shown in Fig. 1. The analogs of strong $M1$ transitions at 1.60, 5.77, 7.03, 7.81, 10.43, and 11.76 MeV in ^{25}Mg are populated in the (p,n) reaction. Corresponding (p,n) and (e,e') excitations are noted in Fig. 1. In many cases the spins of the ^{25}Al(^{25}Mg) states are unknown but given $\Delta J = 1$, they must have $J^\pi = \frac{3}{2}^+$, $\frac{5}{2}^+$, or $\frac{7}{2}^+$. In the case where $J^\pi = \frac{5}{2}^+$, a $\Delta J = 0$ amplitude can also contribute. Based on the transition to the IAS in ^{26}Mg, this amplitude could fill in the forward-angle dip seen for 1^+ states (Fig. 2). The cross sections for some states show this effect.

Finally we turn to ^{24}Mg where two strong transitions to 1^+ states at 9.966 and 10.712 MeV are known from inelastic-electron-scattering[9] and resonance-fluorescence work.[10] The analog states of these levels are at 0.439 and 1.13 MeV in ^{24}Al, but unfortunately, are not resolved from close-lying 2^+ states at 0.514 and 1.14 MeV. With use of the ratios of integrated cross sections between

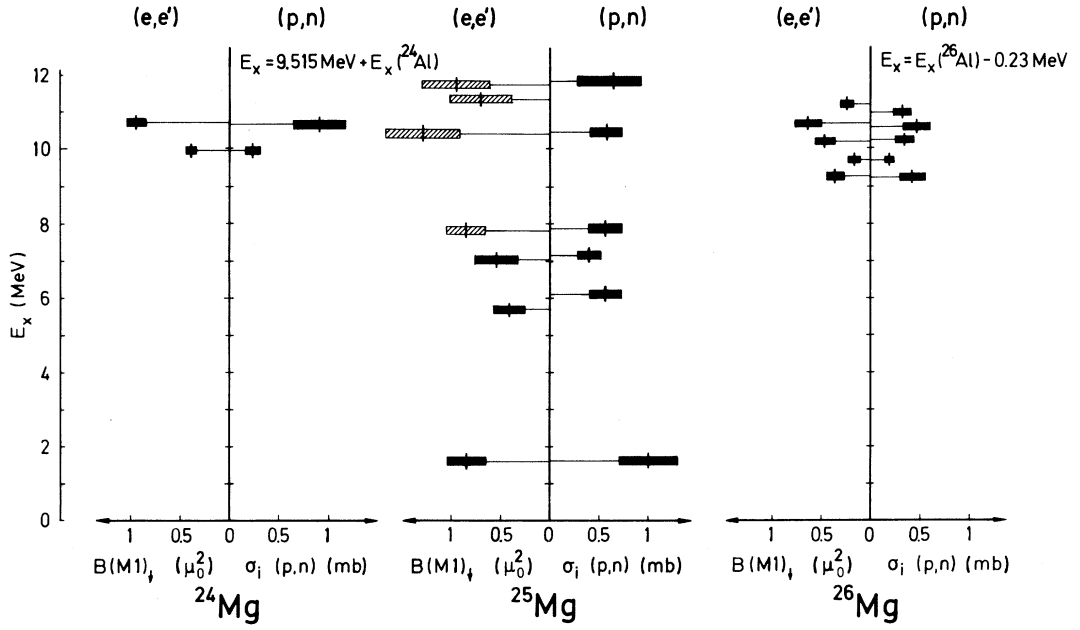

FIG. 3. Comparison of $B(M1)\downarrow$ strengths from the electromagnetic interaction (Ref. 8) with (p,n) cross sections integrated for 7°–103°.

the 2^+ and the 1^+ states from a ^{24}Mg(p,p') experiment,[11,12] the integrated cross sections (7°–103°) for the population of the first two 1^+ states in ^{24}Al are $\sigma_i = 0.20$ and 0.9 mb, respectively.

The results from (p,n) measurements are summarized and compared with $B(M1)\downarrow$ values from inelastic electron scattering[8] in Fig. 3. For ^{24,26}Mg, where spin assignments are known, Fagg's observations[8] represent over 85% of the sum-rule strength.[5] In almost all cases there is a surprisingly good 1:1 agreement [in principle, there is one overall normalization factor relating $B(M1)$ and integrated cross sections; fortuitously this factor is close to 1.0 and this value is used in Fig. 3]. The spins of the four high-lying states in ^{25}Mg are unknown, and for these the statistical factor $g = (2J_0+1)/(2J+1)$ has been arbitrarily set to 1. The total error bars for these states have been hatched, indicating that the three values, $g = 1.5$, 1.0, and 0.75 are possible. Transition strengths of close-lying states, when resolved in the (p,n) experiment but not in (e,e'), have been added together before comparison. We restricted our comparison to the inelastic-electron-scattering results of Fagg,[8] because he investigated ^{24,25,26}Mg with energy resolution only slightly worse than ours, and we wished to make a systematic comparison with the electromagnetic interaction. The agreement with a more recent ^{26}Mg(e,e') experiment from Lees *et al.*[13] yielding $B(M1)\downarrow$ values of $0.39\mu_0^2$ and $0.46\mu_0^2$ for the 10.20- and 10.65-MeV states, respectively, is even better; but, on the other hand, high-resolution resonance-fluorescence work[14] indicates that the states at 9.24, 9.67, and 10.20 MeV consist of doublets (spins 1^+ or 1^-), which are not resolved in the (e,e') experiment. Discrepancies between (e,e') and (p,n) occur for the 11.76-MeV state in ^{25}Mg and the 13.33-MeV state in ^{26}MeV seen in inelastic electron scattering. Their analogs are populated much less strongly in (p,n) reactions. We speculate below on a possible reason for this difference, but note here that a conceivable compound-nucleus contribution, certainly small in any case, would only increase the (p,n) cross section. For the 7.03-MeV state in ^{25}Mg it appears from the raw (e,e') spectra of Ref. 8 that the $B(M1)$ value may be overestimated.

The close agreement of the (e,e') and (p,n) results is somewhat surprising since the isoscalar current terms in the $M1$ operator, while generally of secondary importance, are not always negligible.[15] Indeed, the shell-model calculations[5] predict strong current effects, inconsistent with the (e,e') data, for the strong $M1$ states in ^{26}Mg. The data shown in Fig. 3 can be taken to indicate that current effects are about the same, and presumably small, and the isoscalar part is negligi-

ble for those strong $M1$ states in the Mg isotopes. It is possible that current effects explain the two discrepancies noted above.

In summary, we have shown that (p, n) cross sections and $B(M1)$ values obtained with electromagnetic interactions are strongly correlated for ^{24,25,26}Mg, as shown in Fig. 3. It appears then that (p, n) reactions at energies above 30 MeV will be a powerful probe for spin-isospin-flip strength in nuclei and may be especially useful in the heavier nuclei.

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Breakdown of the Point-Group Symmetry of Vibration-Rotation States and Optical Observation of Ground-State Octahedral Splittings of $^{32}SF_6$ Using Saturation Spectroscopy

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It is shown that the mixing of vibration-rotation states by nuclear hyperfine interactions causes crossover resonances to appear in infrared saturation spectra. Examples are displayed in the ν_3 band of SF_6 and obtain the tensor centrifugal-distortion constant t_{044} and the tensor spin-rotation constant c_d. The value of t_{044} (5.7 Hz) obtained is in excellent agreement with the theoretical value. A splitting is also demonstrated between vibration-rotation states which differ only in their parity.

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In this Letter we report the first direct experimental observation of the breakdown of the point-group labeling of molecular states through the mixing of vibration-rotation (VR) states of different symmetry species by nuclear hyperfine interactions. This mixing is the basis for a new method in molecular spectroscopy, which applies crossover resonances in saturation spectroscopy to the determination of fine-structure spectroscopic constants. We illustrate this method in the case of the ν_3 band of SF_6 and determine the very small tensor centrifugal-distortion constant t_{044}. In the course of this work we have also made the first determination of the hyperfine tensor spin-rotation constant c_d. We expect this method to have wide applicability to the determination of small spectroscopic constants in molecules.

The origin of this work lies in the observation in the ν_3-band saturation spectrum of SF_6 of many

