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BRIEF REPORTS

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Gamow-Teller strength of ^{26}Mg

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We have measured cross sections for $(d,{}^2\mathrm{He})$-induced reactions on ^{26}Mg at an energy of $E_d = 125.2$ MeV. The measured Gamow-Teller strength is significantly smaller than that inferred from (p,n) reactions. We demonstrate that β^+ Gamow-Teller strengths for T_0+1 states deduced from (p,n) reactions may have significant systematic uncertainties due to ambiguities in the large backgrounds that must be subtracted. [S0556-2813(96)00712-1]

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Recently significant efforts have been devoted to extract the β^+ Gamow-Teller (GT) strengths in medium-mass nuclei ($A=20$–70), particularly those related to outstanding unresolved issues in nuclear and astrophysics. The most notable issues involve those β^+ matrix elements that play roles in understanding Gamow-Teller quenching or missing strength [1–3], β capture and nucleosynthesis in supernova processes [4], and double-β-decay processes [5]. Direct measurements of β^+ strengths have been performed with intermediate energy (n,p) reactions [6–10]. However, the data are still scarce mainly because neutron beams can only be produced as a secondary beam, and so the counting rates are usually low. As a result, the energy resolution is often poor, usually 1 MeV or worse. This poor resolution can sometimes make interpretation of the data difficult [5]. Heavy-ion charge-exchange reactions such as (^{12}C, ^{12}N) have also been used in measuring β^+ strengths [11,12]. For such reactions, however, the reaction mechanisms are complicated and successive transfer reactions could dominate at energies below $E/A \approx 100$ MeV [11–13].

Isospin symmetry implies that the GT strengths in the β^+ direction can be deduced from the β^- reactions such as (p,n), using the isospin geometric factor $B(GT)_{\beta^+}/B(GT)_{\beta^-} = (T_0+1)(2T_0+1)$ for reactions on the same $N \geqslant Z$ target with ground state isospin T_0 populating analog T_0+1 final states with $T_z = T_0 \pm 1$. In contrast to (n,p) reactions, resolutions of 300 keV or better can be easily achieved in (p,n) reactions. Better resolution than achievable with (n,p) reactions is required to make critical tests of different theoretical models, particularly in those nuclei which involve double-β decay or supernova evolution. However, for a target with $N>Z$, β^- reactions excite $T_z = T_0 - 1$ states of three different isospins: T_0-1, T_0, and T_0+1. The T_0+1 states are frequently obscured by states of lower isospin, especially if they are only populated weakly. In contrast, (n,p) reactions on such a target populate a unique isospin T_0+1. To resolve the ambiguity about isospin, a novel idea has been proposed recently by Anantaraman *et al.* [14]. They argued that a comparison of (p,n) and (p,p') reactions with energy systematics and shell model calculations can identify the T_0+1 states unambiguously. They further demonstrated this idea for (p,n) reactions on ^{26}Mg and ^{60,62}Ni. However, this technique, as they argued, works only for certain nuclei whose isospin is neither too small nor too large [14].

We have investigated the $^{26}\mathrm{Mg}(d,{}^2\mathrm{He})\,^{26}\mathrm{Na}$ reaction and compared it to $^{26}\mathrm{Mg}(p,n)^{26}\mathrm{Al}$ in order to test this idea. We conclude that, while it is indeed possible to deduce β^+ Gamow-Teller strengths from (p,n) reactions, ambiguities in the large background subtraction may lead to significant uncertainties in the conclusions. ^{26}Mg was selected for this study because both (p,n) data [15] and full sd-shell-model calculations [14–16] are available; so rigorous comparisons are possible. Shell model calculations indicate that the T_0+1 strength is more sensitive to configuration mixing than is the strength of the lower isospin states. By calculating the strength for the case of ^{26}Mg and by exploring its dependence on both the model space [full sd-shell or two-particle–two-hole (2p2h) spaces] and the coupling scheme [jj or SU(3) LS coupling], it was concluded that ^{26}Mg is close to the SU(3) limit while other heavy targets, such as ^{54}Fe, are close to the jj limit [16]. Even with the full sd-shell space, 40% of additional strength for ^{26}Mg is still missing, presumely due to 2p2h correlations outside the major shell. Because of sensitivity to details of the shell model calculations, it is important to subject them to detailed experimental tests and calibration.

The experiment was performed using 125.2 MeV deuteron beams from the Texas A&M University K500 superconducting cyclotron. A self-supporting ^{26}Mg (5.3 mg/cm^2) target was used for the present study. An optimized detection system, the Texas A&M Proton Spectrometer [17], was used to detect the correlated protons from ^{2}He decay. The Proton Spectrometer includes a magnetic spectrometer with point-to-parallel optics, two drift chambers, and X and Y scintillator trigger arrays. Each of the two drift chambers consists of five sense wire layers—two x layers, one diagonal layer, and two y layers. To minimize multiple scattering,

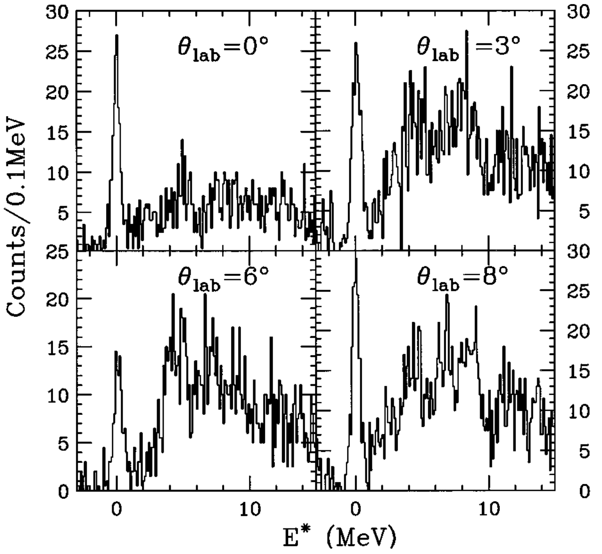

FIG. 1. The measured spectra for ^{26}Mg(d,^{2}He)^{26}Na reactions at 0° (upper left), 3° (upper right), 6° (lower left), and 8° (lower right) at $E_d = 125.2$ MeV as a function of the excitation energy E^* of the residual ^{26}Na.

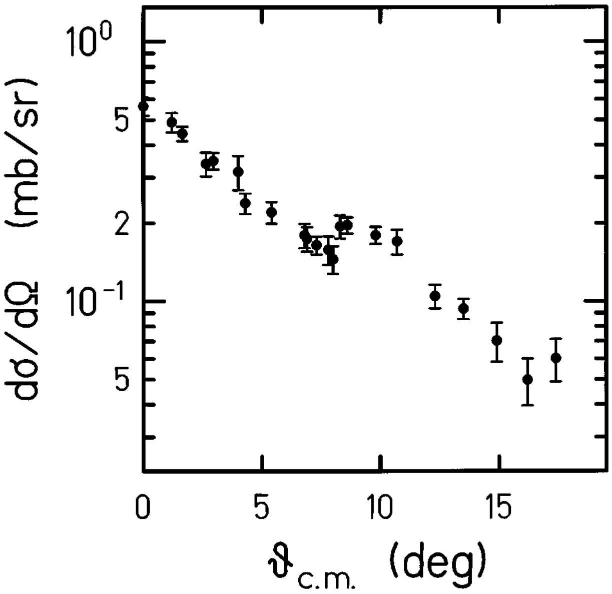

FIG. 2. The measured cross section as a function of center-of-mass angle for the ^{26}Mg(d,^{2}He)^{26}Na transition to the first 1^+ excited state of ^{26}Na at 0.09 MeV.

a gas mixture of 20% Ne and 80% C_2H_6 is used for the drift chambers [18]. Charged particles are traced through the two drift chambers. Their energies and scattering angles are then determined using the results of a detailed field map of the magnet. The solid angle for detecting an individual proton is nearly 20 msr, while the effective solid angle for detecting a ^{2}He within a fiducial region ($\Delta\theta \leqslant 3°$, $\Delta\phi \leqslant 1°$) is ≈ 1.3 msr. The acceptance in θ is flat over the fiducial region. A beam stop mechanism, consisting of several Faraday cups, stops the beam inside the spectrometer magnet at small scattering angles ($\theta \leqslant 7°$), near the entrance to the magnet at intermediate scattering angles, and outside the magnet in the target chamber at large scattering angles ($\theta \geqslant 15°$). Using the kinematic constraints of (d,^{2}He) reactions on several targets, notably ^{1}H, ^{6}Li, and ^{12}C, we were able to determine the incident beam angle to better than 0.1° and the beam energy to better than 200 keV. The ^{2}He energy resolution for the present study was 600–700 keV full width at half maximum (FWHM). The ^{2}He angular resolution was better than 0.4° FWHM. We have recently measured the (d,^{2}He) cross sections on several p-shell nuclei and an sd-shell nucleus ^{24}Mg with the Proton Spectrometer [19]. The measured 0° cross sections for these nuclei show a well-defined linear relation with the known Gamow-Teller strengths deduced from β decay and from (p,n) studies, thus providing a calibration for the present study.

Figure 1 shows the excitation functions of ^{26}Mg(d,^{2}He)^{26}Na reactions measured at 0°, 3°, 6°, and 8°, respectively, after subtracting the random coincidence backgrounds obtained from two protons triggering in neighboring beam bursts. The spectra are shown as a function of E^*, the excitation energy in ^{26}Na, after correcting for the reaction Q value. Very few events are recorded at excitation energies $E^* < 0$ after subtracting the random backgrounds, indicating that the backgrounds were well understood. (The backgrounds, however, are typically only a few counts per bin or less for Fig. 1.) To ensure that the two protons are from the $^1S_0$ state of ^{2}He, an off-line cut on the relative energy of ^{2}He, $E_{\rm rel} \leqslant 1$ MeV, has been used. The strongest peak at $E^* \approx$ 0.09 MeV, which decreases at larger angles, indicates the dominant $\Delta L=0$ transition to the 1^+ first excited state of ^{26}Na. [The transition from ^{26}Mg(g.s.,0^+) to ^{26}Na(g.s.,3^+) would have a different angular distribution characteristic of $\Delta L=2$.] The detailed angular distribution for this transition is shown in Fig. 2 as a function of center-of-mass angle. Overall, the measured cross sections decrease rapidly with angle, similar to (d,^{2}He) reactions on other targets we measured [19]. However, in contrast to the p-shell targets where the diffraction patterns characteristic of $\Delta L=0$ transfer are damped due to the $L=2$, tensor interactions [12,13,19], one now sees clearly a diffraction minimum near 8°. (The minimum occurs at $\theta_{\rm c.m.} \approx 8°$. The next bin at $\theta_{\rm c.m.} \approx 8.3°$, which shows the sudden increase, was obtained simultaneously. Thus data on both sides of the diffraction minimum share a common normalization.) The minimum can also be clearly seen in Fig. 1, where this state is seen to be populated strongly at $\theta_{\rm lab}=0°$. It becomes comparable to the broad transitions at higher excitation energies at $\theta_{\rm lab}=3°$, *smaller* than those at higher excitations at $\theta_{\rm lab}=6°$, and become larger again at $\theta_{\rm lab}=8°$.

Figure 3 shows our measured 0° (d,^{2}He) cross sections at $E_d=125.2$ MeV as a function of the corresponding Gamow-Teller strengths deduced from β-decay studies, when available, or from (p,n) reactions, taken from our earlier studies [19]. Though the data are shown for nuclei in two different major shells and include transitions with momentum transfers ranging from $q \approx$ 0.05 to 0.22 fm^{-1} (q being the half momentum transfer), a well-defined linear relation has been observed, indicating the usefulness of the (d,^{2}He) reaction to study Gamow-Teller strengths. The solid line in Fig. 3 indicates a least-squares fit of a linear relation, $d\sigma/d\Omega(0°)=\alpha B(\mathrm{GT})$, to the data from ^{6}Li, ^{12}C, ^{13}C, and ^{24}Mg [19]. This fit yields a slope parameter $\alpha = 1.30 \pm 0.04$

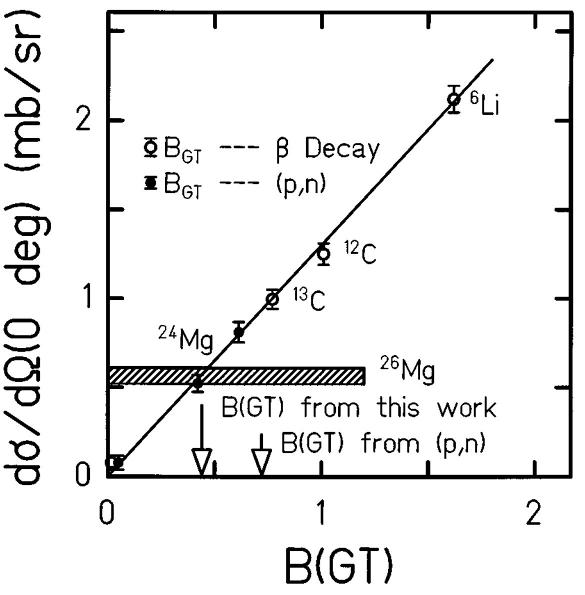

FIG. 3. The measured center-of-mass $(d,^2\mathrm{He})$ cross sections at 0° as a function of the Gamow-Teller strengths deduced either from β-decay studies or from (p,n) reactions [19]. The solid line is a linear fit to the ^{6}Li, ^{12}C, ^{13}C, and ^{24}Mg data [19]. The vertical width of the hatched area indicates the 1σ uncertainty of our new measurement of the $^{26}\mathrm{Mg}(d,^2\mathrm{He})^{26}\mathrm{Na}(0.09\ \mathrm{MeV})$ 0° cross section. The B(GT) values deduced from this work and from the previous (p,n) study [15] are indicated by the arrows.

(mb/sr)/B(GT). Using this linear relation, we find $B(\mathrm{GT}^+) \approx 0.44 \pm 0.04$ for the ^{26}Mg first excited state. This value is consistent with the low value $B(\mathrm{GT}^+) \approx 0.37$ deduced from $(d,^2\mathrm{He})$ reactions at much higher energies [20]. It is also consistent with the shell-model calculation $B(\mathrm{GT}^+)=0.48$ after inclusion of the 40% empirical correction factor [16,21]. Furthermore, it is notable that the similarities in the target masses, momentum transfers, and measured cross sections for $^{24}\mathrm{Mg}(d,^2\mathrm{He})^{24}\mathrm{Al}$ and $^{26}\mathrm{Mg}(d,^2\mathrm{He})^{26}\mathrm{Al}$ reactions imply that our deduced B(GT) is essentially model independent in this case.

Our new B(GT) value for ^{26}Mg, $B(\mathrm{GT}^+) \approx 0.44 \pm 0.04$, however, is significantly smaller than the value $B(\mathrm{GT}^+) = 6B(\mathrm{GT}^-) = 0.72$ obtained from the best determination, $B(\mathrm{GT}^-)=0.12$ for the $T=2$, 1^+ state in $^{26}\mathrm{Mg}(p,n)^{26}\mathrm{Al}$ reactions [15]. In Figs. 3(a)–3(c) of Madey *et al.* [15], the narrow peak near channel 1640 was identified as a transition to the lowest $T=2$, 1^+ state in ^{26}Al at an excitation energy of $E^*=13.6$ MeV. The analog of this state is the first 1^+ excited state of ^{26}Na at an excitation energy of 0.088 MeV that we find to be populated strongly in $^{26}\mathrm{Mg}(d,^2\mathrm{He})^{26}\mathrm{Al}$. Indeed, better energy resolution, 370 keV FWHM, was achieved in the (p,n) study, compared to 650 keV FWHM in our $(d,^2\mathrm{He})$ reactions. However, in (p,n) reactions, the $T=2$, 1^+ states, which can be used to deduce the analog T_0+1 GT strength in the β^+ direction, are positioned on top of a large background. This background, caused mainly by (p,pn) quasifree scattering and population of 1^+, T_0-1, and T_0 final states, is comparable to or larger than the peaks of $T=2,1^+$ states. Furthermore, several smaller peaks, observed at higher excitation energies in Ref. [15], are results of overlapping states with $T=0$, 1, and 2, which are difficult to separate. In contrast, as one can see from Fig. 1, these backgrounds are absent in our $(d,^2\mathrm{He})$ reaction.

In fact, three different backgrounds—(1) a calculated quasifree (p,pn) background [22] plus a cosmic-ray background, (2) a polynomial background for the entire spectrum, and (3) a separate polynomial background for each of three different excitation energy regions—were considered in Ref. [15]. These different background treatments, however, yielded significantly different values in cross sections, with deviations as large as 50%, particularly in the high excitation energy region where the T_0+1 states start to be populated. It was argued [15] that, because methods (1) and (2) yielded similar results, with differences of 8% to 20% in the three regions, and because method (1) is based on a model for the observed background, it provided the best estimate of the underlying background. This led Madey *et al.* [15] to adopt the largest of their three sets of extracted GT strengths as their preferred value. Determining the quasifree background, however, requires the renormalization of the calculated continuum at a certain cutoff energy $E^*=39.3$ MeV. It is not known how the extracted cross sections depend on this cutoff energy. Moreover, it is unclear whether the calculated quasifree line shape is reliable at 0° since the model has only been compared to data at angles larger than 15° [22]. Even at 15°, the calculations started to deviate from data at high excitation energies [22] where the calculated background was normalized in [15]. In contrast, Ref. [15] would have obtained a B(GT) value consistent with our result if the third (largest) background had been adopted. The problem is that, given the (p,n) cross section data alone, one does not known how to treat the continuum background unambiguously.

Perhaps the most important implication of this discrepancy is not for ^{26}Mg alone. Indeed, as shown in Fig. 3, the (p,n) and $(d,^2\mathrm{He})$ reactions provide consistent results concerning the β^+ Gamow-Teller strengths for the other sd-shell nucleus, ^{24}Mg, for which $T_0=0$ and no quasifree background is present in (p,n) reactions in the region of interest [23]. As the target ground state T_0 increases, the T_0+1 Gamow-Teller strengths become smaller (roughly proportional to $1/T_0^2$) in (p,n) reactions. At the same time, they shift to higher excitation energies in the residual, where the quasifree backgrounds become bigger. For ^{26}Mg where $T_0=1$, the GT peak is already comparable to the continuum background in (p,n) reactions. For this system, we find a 30% systematic uncertainty in extracting the B(GT) yield from (p,n) reactions. Comparable or larger uncertainties could be expected for (p,n) reactions for targets with larger ground state T_0, such as double β-decay daughters and nuclei in the fp shell that play a role in supernova evolution. We also note that, while in (p,n) reactions the GT cross sections become diminishingly smaller as T_0 increases due to isospin geometric factors, the corresponding β^+ GT cross sections are roughly independent of T_0. Thus the T_0+1 strengths can be readily measured in direct β^+ reactions.

In conclusion, we have measured $^{26}\mathrm{Mg}(d,^2\mathrm{He})^{26}\mathrm{Na}$ cross sections at 125 MeV. The Gamow-Teller strength that we determined for the ^{26}Na first excited state is significantly smaller than that inferred in the $^{26}\mathrm{Mg}(p,n)^{26}\mathrm{Al}$ reaction, populating its analog state. Our message is simple: For targets with large ground state T_0 values, the β^+ Gamow-Teller strengths for T_0+1 states deduced from (p,n) and (p,p') reactions, though with better resolutions, may have large systematic uncertainties due, not to detector resolutions, but to ambiguities in the large backgrounds which must be subtracted. Final conclusions concerning their GT strengths can only be reached when a better understanding of the backgrounds is obtained or when the detailed comparisons with direct β^+ measurements, such as (n,p), $(d,{}^2\text{He})$, and $(t,{}^3\text{He})$, are available.

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