$B(E2;0^+_{\mathrm{g.s.}}\rightarrow 2^+_1)$ in ^{26}Si and mirror symmetry in the $A=26$ system

P. D. Cottle,[1] B. V. Pritychenko,[2,3,*] J. A. Church,[2,3] M. Fauerbach,[1] T. Glasmacher,[2,3] R. W. Ibbotson,[2,†] K. W. Kemper,[1] H. Scheit,[2,3,‡] and M. Steiner[2]

[1]*Department of Physics, Florida State University, Tallahassee, Florida 32306*

[2]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824*

[3]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824*

(Received 6 July 2001; published 18 October 2001)

We have measured the electromagnetic matrix element $B(E2;0^+_{\mathrm{g.s.}}\rightarrow 2^+_1)$ in the radioactive nucleus ^{26}Si using the method of intermediate energy Coulomb excitation. Our result, $B(E2;0^+_{\mathrm{g.s.}}\rightarrow 2^+_1)=336(33)$ e^2 fm^4, resolves a conflict in previous measurements of this matrix element. In addition, the present measurement allows us to determine M_n/M_p for ^{26}Mg using the mirror nucleus method. The mirror method result of $M_n/M_p=1.05(6)$ is consistent with the most recent pion scattering results and is near the simple collective model expectation.

DOI: 10.1103/PhysRevC.64.057304 PACS number(s): 23.20.Js, 27.30.+t, 21.10.Hw

The symmetry of mirror nuclei has been one of the central observations of nuclear physics because it demonstrates the charge independence of the nuclear force. Detailed measurements of mirror nuclei have been particularly interesting and practical in the sd shell where the line of stable nuclei is at or near the $N=Z$ line. Tests of mirror symmetry often focus on the energies of excited states: the energy spectra of mirror nuclei should be identical once Coulomb shifts are subtracted, since a proton excitation in one nucleus corresponds to a neutron excitation in the mirror nucleus and *vice versa*.

However, mirror symmetry should apply to transition rates as well. If the proton (neutron) multipole matrix element for a transition is defined to be

$$M_{p(n)}=\langle J_f||\Sigma_{p(n)}r_i^{\lambda}Y_{\lambda}(\Omega_i)||J_i\rangle, \quad (1)$$

then M_n for a transition in one nucleus should be equal to M_p for the corresponding transition in the mirror nucleus [1] (and M_p in the first nucleus should be equal to M_n in the mirror). M_p is related to the reduced electromagnetic matrix element $B(E2;J_i\rightarrow J_f)$ by

$$B(E2;J_i\rightarrow J_f)=M_p^2/(2J_i+1). \quad (2)$$

Therefore, M_p can be determined via a measurement of the electromagnetic transition strength. This can be done using a lifetime measurement, Coulomb excitation, or electron scattering. However, there is no equivalently precise way to measure M_n. M_n can be determined indirectly using the scattering of hadrons such as protons, neutrons, or pions, which are sensitive to both M_n and M_p [2]. Results from these probes can be compared with M_p values extracted from electromagnetic measurements to determine M_n. Alternatively, hadronic probes can be compared with each other (π^+ vs π^-, p vs n) since their relative sensitivities to M_n and M_p are different. Bernstein, Brown, and Madsen [1] argued that the most precise way to determine M_n for a nuclear transition is to extract M_p for the corresponding transition in the mirror nucleus using an electromagnetic measurement, a prescription called the "mirror nucleus method." The authors of Ref. [1] demonstrated this method for several nuclei in the mass range $A=17$–42. At any rate, the results for M_n and M_p determined using the mirror nucleus method should be the same as those obtained using hadronic probes.

In the present report, we give a measurement of $B(E2;0^+_{\mathrm{g.s.}}\rightarrow 2^+_1)$ in the radioactive nucleus ^{26}Si that resolves a discrepancy in previous measurements of this transition. We used the technique of intermediate energy Coulomb excitation [3] with a beam of the radioactive ^{26}Si isotope. According to Bernstein, Brown, and Madsen [1], we can use the present measurement to obtain M_n in the mirror nucleus ^{26}Mg. Some ambiguity has existed in the ^{26}Mg M_n values obtained previously with the mirror method and pion scattering, and the present results help to resolve this issue.

This experiment was performed at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. The secondary beam of 54.5 MeV/nucleon ^{26}Si was produced with a primary beam of 100 MeV/nucleon ^{36}Ar from the NSCL K1200 cyclotron. The primary beam was fragmented on a ^{9}Be production target of thickness 564 mg/cm^2 located at the midacceptance target position of the A1200 fragment separator [4]. The setting of the A1200 separator that yielded ^{26}Si also yielded several other isotopes including the stable isotope ^{24}Mg. This "cocktail" of secondary beams was focused on a 518 mg/cm^2 gold foil target and then stopped in a cylindrical fast/slow plastic phoswich detector located at 0°, which provided nuclear charge identification. The phoswich-detected particles scattered through angles up to 4.48° in the center-of-mass frame. Both the

*Present address: Plumtree Software, Inc., San Francisco, CA 94111.

†Present address: Brookhaven National Laboratory, Upton, NY 11973.

‡Present address: Max-Planck-Institut für Kernphysik, Postfach 10 39 80, D-69029 Heidelberg, Germany.

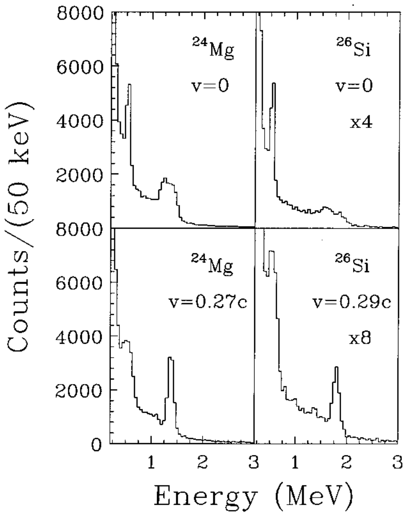

FIG. 1. The γ-ray spectra measured in coincidence with ^{24}Mg and ^{26}Si particles. The upper panels show the laboratory-frame spectra with the 547 keV $7/2^+ \rightarrow 3/2^+$ transition in the ^{197}Au target visible as peaks. The lower panels illustrate projectile-frame spectra that are adjusted for Doppler shifts. The $2_1^+ \rightarrow 0_{g.s.}^+$ transitions in ^{24}Mg at 1367 keV and in ^{26}Si at 1796 keV are prominent in these spectra.

energy loss in the phoswich detector and the time of flight relative to the cyclotron rf signal were used to give positive isotope identification.

The γ-ray spectra measured in coincidence with beam particles identified as ^{24}Mg and ^{26}Si are shown in Fig. 1. The upper panels show the background subtracted spectra in the laboratory frame. The lower panels show the corresponding spectra in the projectile frame (that is, with a Doppler correction). The 547 keV $7/2^+ \rightarrow 3/2_{g.s.}^+$ γ ray in the ^{197}Au target nucleus appears strongly in the laboratory-frame spectra. The only strong peak in the projectile-frame ^{26}Si spectrum is the 1795.9 keV γ ray corresponding to the $2_1^+ \rightarrow 0_{g.s.}^+$ transition. The cross section for producing this γ ray (integrated only over center-of-mass scattering angles from 0° to 4.48°, the range of angles covered by the phoswich detector) is 55.8(55) mb.

We extracted the reduced transition matrix element $B(E2;0_{g.s.}^+ \rightarrow 2_1^+)$ from the experimental cross section using the relativistic Coulomb excitation theory of Winther and Alder [5]. The analysis (described in [3]) yielded the result $B(E2;0_{g.s.}^+ \rightarrow 2_1^+) = 336(33)$ $e^2\,\mathrm{fm}^4$. The analysis matched the cross section measured for center-of-mass scattering angles 0° to 4.48° to that calculated using the Winther-Alder formalism for the same range of scattering angles. To check the credibility of the ^{26}Si result, we also analyzed the γ-ray spectrum in coincidence with ^{24}Mg (a 47.2 MeV/nucleon beam impinging onto a 518 mg/cm^2 gold target), for which the $B(E2;0_{g.s.}^+ \rightarrow 2_1^+)$ value is well known. The cross section of 78.7(48) mb yields $B(E2;0_{g.s.}^+ \rightarrow 2_1^+) = 467(28)$ $e^2\,\mathrm{fm}^4$, which is consistent with the value of 432(12) $e^2\,\mathrm{fm}^4$ adopted by Raman *et al.* [6].

Prior to the present experiment, two measurements of $B(E2;0_{g.s.}^+ \rightarrow 2_1^+)$ had been made in ^{26}Si, and the results of these measurements were in conflict. Both measurements used the Doppler shift attenuation method to determine the lifetime of the 2_1^+ state. The first [7] yielded $B(E2;0_{g.s.}^+ \rightarrow 2_1^+) = 160(70)$ $e^2\,\mathrm{fm}^4$, while the second [8] gave $B(E2;0_{g.s.}^+ \rightarrow 2_1^+) = 352(34)$ $e^2\,\mathrm{fm}^4$. Our result clearly supports the latter value, resolving this conflict.

Using the present result for $B(E2;0_{g.s.}^+ \rightarrow 2_1^+)$ in ^{26}Si and the adopted value [6] for ^{26}Mg of 305(13) $e^2\,\mathrm{fm}^4$, we can calculate M_n/M_p for the $0_{g.s.}^+ \rightarrow 2_1^+$ transition in ^{26}Mg using the mirror method. We obtain $M_n/M_p = 1.05(6)$, which can be understood in the context of a simple collective model. If the 2_1^+ state is a simple collective excitation in which the motions of the proton and neutron fluids have the same amplitudes, then $M_n/M_p = N/Z$, which for ^{26}Mg would be 1.17. Deviations from $M_n/M_p = N/Z$ systematically occur in 2_1^+ states of even-even single closed shell nuclei [2] because the configurations of these states are dominated by the valence nucleons. In a closed neutron shell nucleus, we expect $M_n/M_p < N/Z$, while in a closed proton shell nucleus we systematically observe $M_n/M_p > N/Z$ [2,9]. The M_n/M_p result obtained for ^{26}Mg using the mirror method is close to N/Z and is consistent with the picture of ^{26}Mg as a collective nucleus without neutron or proton shell closures.

With the value of $B(E2;0_{g.s.}^+ \rightarrow 2_1^+)$ in ^{26}Si now settled, we can use this value to cast new light on a conflict that exists in the pion scattering data for the mirror nucleus ^{26}Mg. Wiedner *et al.* [10] measured the scattering of both π^+ and π^- at 180 MeV from ^{26}Mg and deduced that $M_n/M_p = 0.62(7)$, which differs significantly from the mirror method result we determined here. The result obtained by Wiedner *et al.* suggested that the filling of the $d_{5/2}$ neutron orbit in ^{26}Mg caused a subshell closure and was qualitatively reproduced with a shell model calculation reported by Brown and Wildenthal [11]. Like the Wiedner *et al.* experimental result, the Brown and Wildenthal theoretical result, $M_n/M_p = 0.80$, was considerably lower than the simple collective model expectation $M_n/M_p = N/Z$.

Several years later, Tacik *et al.* [12] measured π^+ and π^- scattering on ^{26}Mg at 50 MeV and obtained the result $M_n/M_p = 0.83(6)$. Morris *et al.* [13] repeated the 180 MeV pion measurements and deduced $M_n/M_p = 0.92(9)$, while an analysis of pion scattering at three energies (116 MeV, 180 MeV, and 292 MeV) by Blanpied *et al.* [14] arrived at the result $M_n/M_p = 1.02$. All three of these latter results seem to supercede the earlier result of Wiedner *et al.* [10]. In fact, while the Wiedner *et al.* result would have given serious conflict with the present mirror result, the pion scattering experiments of Morris *et al.* [13] and Blanpied *et al.* [14] give a different picture. The two latter pion scattering experiments and the mirror nucleus analysis all suggest an interpretation at or near the simple collective model for the $T=1$ mass 26 system.

In summary, we have measured $B(E2;0_{g.s.}^+ \rightarrow 2_1^+)$ in the radioactive nucleus ^{26}Si using the technique of intermediate energy Coulomb excitation. Our result is consistent with the most recent Doppler shift attentuation method result [8]. A calculation of M_n/M_p for the $0_{g.s.}^+ \rightarrow 2_1^+$ transition in ^{26}Mg using the mirror nucleus method [that is, using $B(E2;0^+_{\mathrm{g.s.}}\rightarrow 2^+_1)$ values for ^{26}Si and ^{26}Mg] gives an answer that is close to those found in the most recent pion scattering measurements on ^{26}Mg [13,14]. The results of both methods are close to the value $M_n/M_p = N/Z$ expected in the simple collective model in which the proton and neutron fluid motions have the same amplitude.

This work was supported by the U.S. National Science Foundation through Grant Nos. PHY-9528844, PHY-9875122, and PHY-9970991, and the State of Florida.

[1] A.M. Bernstein, V.R. Brown, and V.A. Madsen, Phys. Rev. Lett. **42**, 425 (1979).

[2] A.M. Bernstein, V.R. Brown, and V.A. Madsen, Phys. Lett. **103B**, 255 (1981).

[3] T. Glasmacher, Annu. Rev. Nucl. Part. Sci. **48**, 1 (1998).

[4] B.M. Sherrill *et al.*, Nucl. Instrum. Methods Phys. Res. B **56**, 1106 (1991).

[5] A. Winther and K. Alder, Nucl. Phys. **A319**, 518 (1979).

[6] S. Raman *et al.*, At. Data Nucl. Data Tables **36**, 1 (1987).

[7] R.A.L. Bell *et al.*, Nucl. Phys. **A133**, 337 (1969).

[8] T.K. Alexander *et al.*, Phys. Lett. **113B**, 132 (1982).

[9] M.A. Kennedy, P.D. Cottle, and K.W. Kemper, Phys. Rev. C **46**, 1811 (1992).

[10] C.A. Wiedner *et al.*, Phys. Lett. **97B**, 37 (1980).

[11] B.A. Brown and B.H. Wildenthal, Phys. Rev. C **21**, 2107 (1980).

[12] R. Tacik *et al.*, Phys. Rev. Lett. **52**, 1276 (1984).

[13] C.L. Morris *et al.*, Phys. Rev. C **35**, 1388 (1987).

[14] G.S. Blanpied *et al.*, Phys. Rev. C **41**, 1625 (1990).