Mass of ^{24}Si

R. E. Tribble, D. M. Tanner, and A. F. Zeller*

Cyclotron Institute and Physics Department, Texas A&M University, College Station, Texas 77843

(Received 11 January 1980)

The ^{28}Si(^{4}He,^{8}He)^{24}Si reaction has been used to determine the mass of ^{24}Si. The reaction Q value and mass excess were found to be -61.433 ± 0.021 and 10.782 ± 0.022 MeV, respectively. The ^{24}Si mass completes the fifth member of the $A = 24$ isobaric quintet. The quintet members are in good agreement with the quadratic isobaric multiplet mass equation.

NUCLEAR REACTIONS ^{28}Si(^{4}He,^{8}He)^{24}Si. Measured ^{24}Si mass. Deduced coefficients of the isobaric multiplet mass equation for the $A = 24$ quintet.

INTRODUCTION

The recent observation[1] of the β-delayed proton decay of ^{24}Si yielded the first measurement of the $T = 2$ level in the $T_z = -1$ nucleus ^{24}Al. This result completed the fourth member of the $A = 24$ isobaric quintet and thereby provided the first test of the isobaric multiplet mass equation (IMME) in this system. No deviation from the simple quadratic IMME was observed. In this paper, we report the first measurement of the mass of the $T_z = -2$ member of the quintet ^{24}Si. This measurement completes the quintet thus affording an even more stringent test of the IMME in an isobaric quintet whose members are all bound to isospin allowed particle decay.

The quadratic IMME predicts that the masses of isobaric multiplets are related by the simple equation $M(A, T, T_z) = a(A, T) + b(A, T)T_z + c(A, T)T_z^2$, where a, b, and c are constant across the multiplet.[2] The equation has been remarkably successful in fitting both isobaric quartets and quintets. Out of 22 isobaric quartets that have been completed,[3] only the ground state members of the $A = 9$ quartet cannot be fit by the simple quadratic equation.[4] Similarly, of the 7 mass quintets with either four or five members known, only $A = 8$ shows a deviation from the quadratic IMME.[5]

While a systematic failure of the quadratic IMME could result from a nuclear charge dependent interaction (cdi), its success does not by reciprocity rule out such an interaction. It may prove simpler to search for alternate methods to delineate the role of a nuclear cdi than to accurately account for the trivial Coulomb contribution to the IMME coefficients. In addition to testing the IMME, mass measurements in isobaric quartets and quintets determine Coulomb energies rather far from stability. Comparisons between these Coulomb energies and those obtained closer to stability may provide one such alternate method

for determining the role of a nuclear cdi. The Coulomb energies determined for the $A = 36$ isobaric quintet already point to the need for a nuclear cdi in the $d_{3/2}$ shell.[6]

EXPERIMENTAL PROCEDURE

The mass of ^{24}Si was determined by measuring the Q value of the ^{28}Si(^{4}He, ^{8}He)^{24}Si reaction. An incident α beam of 128.8 MeV was supplied by the Texas A&M University 224 cm cyclotron; the beam current on target was typically 1.5 μA. The beam energy was determined to a precision of 20 keV by the momentum matching technique as described in Ref. 7. Reaction products were detected in the focal plane of an Enge split-pole magnetic spectrograph by a 10 cm single-wire gas proportional counter which was backed by a 50 mm × 10 mm × 600 μm Si solid-state detector. Particle position was obtained via charge division in the gas counter, and particle identification was constrained by the three parameters: (1) (dE/dx) gas, (2) E_{Si}, (3) time of flight through the spectrograph relative to the cyclotron rf. A 0.3 mm Kapton absorber foil was inserted between the gas proportional counter and the solid-state detector in order to ensure that the ^{8}He particles stopped in the Si detector. This system has been shown to reject spurious background events at a level below 100 pb/sr MeV for moderate mass targets.[8]

The ^{28}Si target was prepared by a vacuum evaporation of SiO$_2$ (99.9% enriched in ^{28}Si) onto a thin carbon backing. A target thickness of ~1 mg/cm^2 was found to be the practical limit for this technique. Beyond this thickness, targets showed a high probability to either break or peel. The carbon backing was essential in order to prevent the target from breaking with high beam current (up to 2 μA). The thickness of the target used for the present measurement was determined to be 0.9 mg/cm^2 by measuring the alpha energy loss from
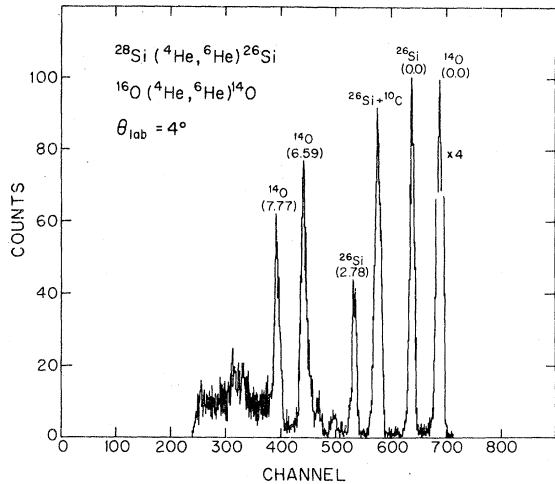
FIG. 1. Typical spectrum from the (^{4}He, ^{6}He) reaction on a SiO target showing the population of the low-lying states in ^{26}Si and ^{14}O. The dominant peaks have been identified as belonging to either ^{14}O of ^{26}Si.

an ^{241}Am source. We assigned a 20% uncertainty to the thickness to reflect the uncertainty in the measurement technique and the exact target composition.

The mass measurement was performed at a laboratory angle of 3° with a spectrograph solid angle of 2 msr. This small angle was achieved by combining the spectrograph entrance slit and beam stop into one unit. Earlier attempts to measure the ^{24}Si mass had been carried out at $\theta_{lab} = 5°$. The cross section to the ground state was less than 2 nb/sr at this angle. By moving into 3°, the cross section increased at least a factor of 3.

The spectrograph focal plane calibration was determined both from the elastic scattering of α particles and from the (^{4}He, ^{6}He) reaction on ^{28}Si and ^{16}O; final states populated by the (^{4}He, ^{6}He) reaction were observed at the same magnetic rigidity as the ^{8}He events. The overlap excitation energy was quite high for these states in both ^{26}Si ($E_x \approx 10$ MeV) and ^{14}O ($E_x \approx 12$ MeV). Since very little is known about the energies or the levels at these excitations, it was necessary to perform a separate calibration of the ^{6}He spectrum in order to use the states (perhaps better characterized as "structures") that were populated. For these measurements, we utilized the same experimental geometry; however, the short detector was replaced by a focal plane detector that consisted of two 20 cm single-wire gas proportional counters backed by a thin plastic scintillator (1 mm) that was optically coupled to a lucite light guide. The particle identification for this system was sufficient to provide quite clean ^{6}He spectra. An example of a spectrum showing the population of the low-lying states
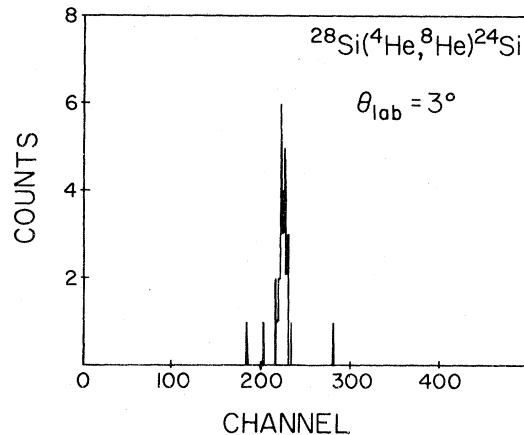

FIG. 2. Spectrum of ^{8}He events. The peak represents the yield to the ground state of ^{24}Si.

in ^{14}O and ^{26}Si is shown in Fig. 1. The uncertainty assigned to the calibration of the high-lying states (structures) was 16 keV. This number includes peak fitting uncertainties as well as the standard deviation observed in the fit to the known peaks.

RESULTS AND DISCUSSION

The ^{8}He position spectrum obtained at $\theta_{lab} = 3°$ is shown in Fig. 2. The 36 events in the peak correspond to a laboratory cross section of 5 ± 2 nb/sr averaged over the 2 msr solid angle. The peak width is 150 keV FWHM, which results in a centroid uncertainty of 11 keV; energy loss and straggling by the projectile and ejectile in the target were dominant contributors to the observed width. Other experimental quantities that contribute to the uncertainty in the mass determination are the ^{6}He centroids in the calibration spectra (9 keV), the ^{6}He calibration (12 keV), target thickness (8 keV), beam energy (5 keV), and scattering angle (negligible); the numbers in parentheses reflect the size of the uncertainties.

The Q value for the ^{28}Si(^{4}He, ^{8}He)^{24}Si reaction was found to be -61.443 ± 0.021 MeV where the quoted uncertainty was determined by adding the uncertainties listed above in quadrature. Combining this result with the ^{8}He mass excess of 31.595 ± 0.007 MeV (Ref. 9) and the ^{4}He and ^{28}Si masses from Ref. 10, we find a ^{24}Si mass excess of 10.782 ± 0.022 MeV.

The ^{24}Si mass excess represents the fifth member of the $A = 24$ isobaric quintet. The mass excess and excitation energies of all five members of the quintet are displayed in Table I. We note that the measurements of both the $T_z = -1$ and -2 members of this quintet are the most precise of any of this series. As indicated in Table II, the quintet is well described by the quadratic IMME

TABLE I. Properties of the $A = 24$ isobaric quintet members.

Nucleus	T_z	Mass excess (keV)	E_x (keV)	Reference
^{24}Si	−2	10 782(22)	0	this work
^{24}Al	−1	5 903(9)	5 955(10)	1
^{24}Mg	0	1 505.8(9)	15 436.4(6) [a]	11
^{24}Na	1	−2 447.3(12)	5 970.2(9)	12
^{24}Ne	2	−5 949(10)	0	10

[a] This result, which was determined directly from gamma-ray energies, is in good agreement with several less precise resonance measurements.

with a normalized χ^2 for the three parameter fit of 0.58. The full five parameter fit gives d and e coefficients of -2.5 ± 2.5 keV and 1.9 ± 1.9 keV, respectively. Both coefficients are consistent with zero as expected from the small χ^2 for the quadratic fit. For completeness, the four parameter fits obtained with either the d or e coefficient set to zero are also included in the table; the χ^2 does not indicate a preference for either a nonzero d or e coefficient.

Four members of the $A = 12$, 16, 32, and 36 isobaric quintets have been determined, and in $A = 8$, 20, and 24 all five members are now known. The results in $A = 24$ are consistent with all of the other quintets except $A = 8$ in that no deviation from the simple quadratic IMME is observed. These results underscore the excellent quadratic IMME fits that have been obtained in the series of isobaric quartet measurements. That the quadratic IMME is so successful is not surprising since any two-body charge dependent interaction would produce the same quadratic equation in first order perturbation theory. Many-body charge dependent interactions would directly lead to higher order coefficients, but again their main effect would be to renormalize the a, b, and c coefficients of the quadratic formula. Clearly, we must be able to predict accurately the size of the a, b, and c coefficients caused by trivial Coulomb effects in order to unfold the possible contributions from a nuclear cdi. Several attempts at such calculations have met with only marginal success.[3]

As we have already mentioned, an alternate approach to ascertain the role of a nuclear cdi may possibly lie in Coulomb energy comparisons. Calculations by Sherr and Talmi[13] in the $d_{3/2}$ shell suggest the need for a rather sizable correction to the Coulomb energies far off the stability line; such corrections could arise through a two-body nuclear cdi. These calculations have now been extended by Sherr[14] throughout the s-d and $f_{7/2}$ shells, and the deviations seen in the $d_{3/2}$ shell are found to persist.

While the effect is observed systematically throughout the shells, it is by far the largest in the $d_{3/2}$ shell. In Table III we compare experimental Coulomb energies for the $A = 24$ quintet to Sherr's prediction. The last four columns in the table represent the experimental Coulomb energy, the calculated Coulomb energy, the difference between these two (Δ), and the size of the "nuclear cdi" contribution (δ). For comparison, the δ found for the extremes of the $A = 36$ isobaric quintet is 144 keV. In general, the experimental and theoretical results are in good agreement and tend to support the need for the "extra" interaction. As Sherr has pointed out, however, the problem of configuration mixing, which is especially relevant to the results in the $d_{5/2}$ shell region, has not been considered in detail. The calculated δ in Table III also assumes that the Coulomb matrix elements are constant across a subshell, i.e., they are not A dependent. In fact, Sherr has shown that the observed deviations could be equally well described

TABLE II. Predicted coefficients (in keV) for the IMME parametrized as $M = a + bT_z + cT_z^2 + dT_z^3 + eT_z^4$.

a	b	c	d	e	χ_ν^2 [a]
1505.7(9)	−4178.8(27)	225.8(25)			0.58
1505.7(9)	−4178.3(31)	226.0(26)	−0.6(16)		1.05
1505.8(9)	−4177.9(36)	224.2(48)		0.5(12)	1.01
1505.8(9)	−4177.6(64)	220.2(62)	−2.5(25)	1.9(19)	

[a] Normalized χ^2.

TABLE III. Coulomb energies (in keV) for the $A = 24$ quintet. The theoretical predictions are from Ref. 14.

Nuclides	Experimental ΔE_c	Predicted ΔE_c	Δ [a]	δ [b]
^{24}Si$-^{24}$Al	5661(24)	5646	15	+37
^{24}Al$-^{24}$Mg	5179(9)	5184	−5	+12
^{24}Mg$-^{24}$Na	4735(2)	4722	12	−12
^{24}Na$-^{24}$Ne	4284(10)	4260	24	−37

[a] $\Delta = \Delta E_c^{exp} - \Delta E_c^{theor}$.

[b] $\delta =$ contribution to ΔE_c^{theor} due to charge dependent interaction (see Ref. 14).

by allowing the Coulomb matrix elements to be A dependent. At the present time there is no way to resolve the question of the A dependence versus the role of a nuclear cdi. It is clear, however, that precision measurements of Coulomb energies off the stability line will be extremely useful in systematically unfolding these effects.

ACKNOWLEDGMENTS

*Present address: Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824.

[1] J. Äystö, D. M. Moltz, M. D. Cable, R. D. von Dincklage, R. F. Parry, J. M. Wouters, and J. Cerny, Phys. Lett. 82B, 43 (1979).

[2] E. P. Wigner, in Proceedings of the Robert A. Welch Foundation Conference on Chemical Research, Houston, Texas, edited by W. O. Milligan (Robert A. Welch Foundation, Houston, 1957), p. 67.

[3] W. Benenson and E. Kashy, Rev. Mod. Phys. 51, 527 (1979).

[4] E. Kashy, W. Benenson, D. Mueller, R. G. H. Robertson, and D. R. Goosman, Phys. Rev. C 11, 1959 (1975).

[5] R. E. Tribble, J. D. Cossairt, D. P. May, and R. A. Kenefick, Phys. Rev. C 16, 1835 (1977).

[6] R. E. Tribble, J. D. Cossairt, and R. A. Kenefick, Phys. Rev. C 15, 2028 (1977).

[7] R. E. Tribble, R. A. Kenefick, and R. L. Spross, Phys. Rev. C 13, 50 (1976).

[8] R. E. Tribble, J. D. Cossairt, D. P. May, and R. A. Kenefick, Phys. Rev. C 16, 914 (1977).

[9] R. G. H. Robertson, E. Kashy, W. Benenson, and A. Ledebuhr, Phys. Rev. C 17, 4 (1978).

[10] A. H. Wapstra and K. Bos, At. Data Nucl. Data Tables 20, 1 (1977).

[11] J. V. P. Heggie and H. H. Bolotin, Aust. J. Phys. 30, 407 (1977).

[12] D. F. H. Start, N. A. Jelley, J. Burde, D. A. Hutcheon, W. L. Randolph, B. Y. Underwood, and R. E. Warner, Nucl. Phys. A206, 207 (1973).

[13] R. Sherr and I. Talmi, Phys. Lett. 56B, 212 (1975).

[14] R. Sherr, Phys. Rev. C 16, 1159 (1977).