Mass of ^{16}Ne

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(Received 23 August 1982)

The mass of ^{16}Ne has been measured using the ^{20}Ne(^{4}He, ^{8}He)^{16}Ne reaction. The Q value of the reaction was determined to be -60.197 ± 0.023 MeV, which corresponds to a mass excess of 23.984 ± 0.024 MeV. The weighted average of this result with two previous measurements yields a mass excess of 23.994 ± 0.020 MeV. This value is in reasonable agreement with the quadratic isobaric multiplet mass equation. The four parameter isobaric multiplet mass equation suggests a cubic or quartic coefficient of 4 ± 3 keV for the $A=16$ multiplet.

NUCLEAR REACTIONS ^{20}Ne(^{4}He,^{8}He)^{16}Ne. Measured ^{16}Ne mass. Deduced coefficients of the isobaric multiplet mass equation for the $A=16$ quintet.

I. INTRODUCTION

In the past few years, a large number of precision mass measurements of isobaric multiplets have been completed which provide tests of the isobaric multiplet mass equation (IMME). In many of the multiplets, the measurements also determine a complete set of Coulomb energies. The quadratic IMME predicts that masses of isobaric multiplets are related by the 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 constants for a multiplet.[1] This simple equation has been remarkably successful in fitting isobaric quartets and quintets. Tests of the IMME have been carried out on p, sd, and f shell nuclei[2] and only two of the lightest systems, $A=8$ (Ref. 3) and $A=9$,[4] deviate from the quadratic form. Many unsuccessful attempts have been made to explain the deviation in $A=9$.[5] In $A=8$, isospin mixing in the $T_z=0$ state and a possible level shift in the unbound $T_z=-2$ state could both contribute to deviations from the simple form.[3]

It is particularly interesting to test the IMME in systems where one of the members of the multiplet is unbound to particle decay. The radial wave function for the unbound level will be extended compared to that for a bound level, thereby reducing its Coulomb energy over that expected for the equivalent bound state. The wave function of the unbound level no longer represents a good analog-state wave function and the energy of the level will likely be perturbed from that of the same bound state. This perturbation will be reflected by positive higher order coefficients in the IMME. Three systems, $A=8$, 12, and 16, have a $T_z=-2$ member which is unbound to particle decay. With the following measurement reported for ^{16}Ne, we have reduced the uncertainties in the higher order IMME coefficients in $A=16$ down to a level nearly comparable to the uncertainties in $A=8$.

II. EXPERIMENTAL PROCEDURE

The mass of ^{16}Ne was determined by measuring the Q value of the ^{20}Ne(^{4}He,^{8}He)^{16}Ne reaction. An alpha beam of 129 MeV was supplied by the Texas A&M University 224 cm cyclotron and transported to the target chamber of an Enge split-pole magnetic spectrograph where it impinged upon a gas target of ^{20}Ne. The Ne gas (99.5% isotopically enriched in ^{20}Ne) was contained in a gas cell at the center of the scattering chamber. Entrance and exit window foils were 1.7 mg/cm^2 Havar. They were tested up to gas pressures of 27.6 kPa and sustained beam currents of over 2 μA. Tantalum collimators were used in front of the gas cell to define the beam position and size. A double collimator was used to define the acceptance solid angle 2.6 msr into the spectrograph. These collimators were designed to allow for reaction scattering angles as small as $\theta_{lab}=5°$ without interference from entrance and exit foil scattering. The spectrograph entrance slit width and gas pressure were varied to obtain a target thickness of 1.00 ± 0.04 mg/cm^2.

Reaction products were detected in the focal plane of the spectrograph by a 10 cm single-wire gas proportional counter backed by a 50 mm $\times$ 10 mm $\times$ 600 μm Si solid state detector. Particle position was obtained via charge division in the gas counter, and particle identification was determined from three parameters: (1) $(dE/dx)_{gas}$, (2) E_{Si}, and (3) time of flight through the spectrograph relative to the cyclo-

tron rf. A 0.3 mm Kapton absorber foil was inserted after the proportional counter in order to ensure that the ^{8}He particles stopped in the Si detector. The three fold particle identification scheme provides extremely high sensitivity to low cross section reactions. Previous results have demonstrated background rejection to levels less than 100 pb/sr.[6]

The mass measurement was performed at a laboratory scattering angle of 7.5°. Preliminary measurements were performed at angles of 5.5° and 6.5°, but the cross section was found to be largest at 7.5°. In addition, d and t production from the beam collimators, found to be a problem during the preliminary runs, was greatly reduced through the combination of redesigning the collimators and moving to a larger angle. The triton yield was particularly troublesome because the tritons and ^{6}He particles had identical times of flight, and the tail of the E and dE/dx signals from the tritons overlapped the signals from the ^{6}He's, thus increasing the background in the ^{6}He spectra.

The beam energy was determined from the momentum matching technique by comparing ^{28}Si$(p,p)^{28}$Si ($E_x=0.0$) and ^{28}Si$(p,d)^{27}$Si ($E_x=0.781$ MeV) reactions using an incident molecular-hydrogen beam with the same magnetic rigidity as the alpha beam. The incident energy of the alpha beam was corrected to account for the energy loss in the entrance window of the gas cell and the gas region not viewed by the spectrograph.

The spectrograph focal plane calibration was determined from the ^{20}Ne(^{4}He,^{6}He)^{18}Ne reaction. The spectrograph magnetic field was varied to give five calibration spectra across the active region of the counter. With an incident beam energy of 129 MeV, the ^{6}He particles corresponding to the $E_x=9.201$ MeV state of ^{18}Ne had a magnetic rigidity nearly identical to the ^{8}He's from the ground state to ground state transition; the ^{6}He position spectrum shown in Fig. 1 was obtained simultaneously with the ^{8}He data. By using the ^{20}Ne(^{4}He,^{6}He)^{18}Ne reaction for the focal plane calibration, we were able to minimize our sensitivity to several key parameters including the corrected beam energy, target thickness, and energy loss in the exit foil of the gas cell. The actual window thickness was determined by measuring the energy loss of ^{241}Am alpha particles through the foil and by weighing the foil on a precision balance. An uncertainty of 10% was assigned to the average value obtained by these two methods. An uncertainty of 3% was assigned to the thickness of the gaseous regions of the cell which were determined by measurement and calculations from the slit geometry. The average deviation of the calibration data from a linear least squares fit was 12 keV, which, when combined with the peak centroid and Q-value uncertainties, corresponded to an 11 keV uncertainty in the mass excess of ^{16}Ne.

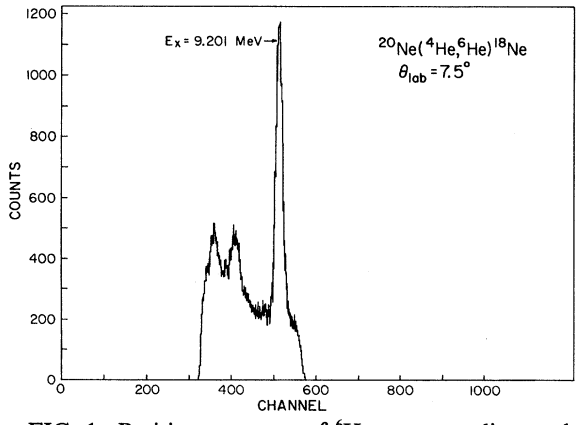

FIG. 1. Position spectrum of ^{6}He corresponding to the 9.201 MeV excitation state of ^{18}Ne. The energy dispersion is approximately 75 channels/MeV.

III. RESULTS AND DISCUSSIONS

The ^{8}He position spectrum corresponding to the ground state of ^{16}Ne at a laboratory scattering angle of 7.5° is shown in Fig. 2. The 25 events obtained in the peak correspond to a reaction cross section of 1 ± 0.5 nb/sr averaged over the 2.6 msr solid angle. The peak width of 177 keV FWHM results in a centroid uncertainty of 15 keV. This value comes from assuming a Gaussian shape for the peak and represents a one standard deviation uncertainty for the centroid. Other factors contributing to the uncertainty in the mass of ^{16}Ne are the ^{6}He focal-plane calibration (11 keV), beam energy (6.5 keV), target thickness (10 keV), and scattering angle (5 keV).

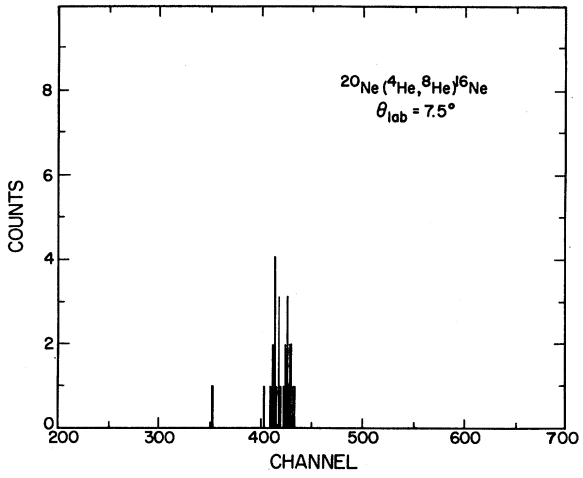

FIG. 2. Position spectrum of ^{8}He events corresponding to the ground state of ^{16}Ne.

TABLE I. Properties of the members of the $A=16$ isobaric quintet.

Nucleus	T_z	Mass excess (keV)[a]	E_x (keV)	Ref.
^{16}Ne	−2	23 994(20)	0	11
^{16}O	0	17 984(3)	22 721(3)	12
^{16}N	1	15 610(7)	9928(7)	12
^{16}C	2	13 692(4)	0	13

[a]Ground state mass excesses of ^{16}O and ^{16}N are obtained from Ref. 8.

When inherent electronic spread of the peak and energy loss and straggling of the projectile and ejectile in the target are taken into account, ^{16}Ne has an experimentally determined natural peak width of 110±40 keV.

The Q value of the ^{20}Ne(^{4}He,^{8}He)^{16}Ne reaction is found to be −60.197±0.023 MeV where the uncertainty is obtained by adding in quadrature the uncertainties listed above. Combining this result with the ^{8}He mass excess of 31.595±0.007 MeV (Ref. 7) and the mass excesses of ^{4}He and ^{20}Ne from Ref. 8, we find ^{16}Ne to have a mass excess of 23.984±0.024 MeV. This result is in agreement with the measurement of 23.92±0.08 MeV from KeKelis *et al.*,[9] also obtained using the (^{4}He,^{8}He) reaction, and with the result of 24.051±0.045 MeV from the (π^+,π^-) reaction, performed by Burleson *et al.*[10] A weighted average of the three values listed above gives a mass excess of 23.994±0.020 MeV for ^{16}Ne. The natural peak width was reported by KeKelis *et al.* to be 200±100 keV, a value consistent with our result.

The mass excess of ^{16}Ne represents the fourth known member of the $A=16$ isobaric quintet. The $T_z=-1$ member, ^{16}F, has not been observed yet because of difficulties in finding a reaction which preferentially populates the $T=2$ excited state. The mass excesses and excitation energies of the four measured members of the quintet are listed in Table I. The results for the fit to the quadratic IMME and for the four parameter fit determining the d or e coefficient are shown in Table II. The four members of the quintet are described reasonably well by the quadratic IMME, as the normalized χ^2 of 2.81 indicates. The four parameter fit gives a value of 4±3 keV for both d and e coefficients, indicating no preference for either order term. These values are consistent with the results of the two measurements mentioned above which predict a d coefficient of 8±5 keV (Ref. 9) and 2.5±3.7 keV.[10]

Our results indicate the possible need for the addition of higher order terms to the quadratic IMME for the $A=16$ quintet. In fact, it is not unreasonable to expect a third or fourth order term added to the quadratic IMME. Such a deviation from the quadratic IMME could be caused by isospin mixing of states or a Thomas-Ehrman shift[14] of a member of the multiplet. The $A=16$ quintet is similar to the $A=8$ quintet, which also showed a positive d or e coefficient, in that it has a member which is unbound to particle decay; ^{16}Ne is unbound to decay by diproton emission. The deviation of the unbound wave function from that of its bound counterpart results in a smaller mass excess than that predicted by the quadratic IMME, consequently giving rise to positive d or e coefficients in the four parameter fit. Solutions to the simultaneous equations indicate that the magnitudes of both of these coefficients should be $\frac{1}{24}$ of the mass change due to the level shift in the $T_z=-2$ state, assuming that all the other states do not deviate from the unmixed, bound state wave function. If this is the case, our results predict a level shift resulting in a decrease in the mass excess of ^{16}Ne by 100±70 keV from that of the bound state of the nucleus. The binding energy for the diproton decay of ^{16}Ne is roughly 1.4 MeV, significantly more than any level shift suggested by our result.

It is possible to improve the fits to the IMME for the $A=16$ multiplet in several ways. One is to improve the measurement of the excitation energy of the $T=2$ state of ^{16}N. Since both d and e coefficients are strongly dependent upon the $T_z=+1$ member of the multiplet, any decrease in the uncertainty of the mass excess of ^{16}N would substantially improve the uncertainty in these coefficients. Also, the measurement of the $T_z=-1$ level would be useful as it would complete the measurement of all members of the quintet. By reducing the uncertainties in the $A=12$ and 16 quintets to a level consistent with $A=8$, it may be possible to find some systematic trends in the higher order coefficients of the IMME for these three quintets.

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

a	b	c	d	e	χ^{2a}
17 982.6(2.9)	−2578(5)	216.3(2.5)			2.81
17 984(3)	−2593(12)	215(3)			
17 984(3)	−2576(5)	198(9)	4(3)	4(3)	

[a]Normalized χ^2.

ACKNOWLEDGMENTS

We wish to thank R. E. Neese, Y. Mihara, and C. S. Whiddon for their assistance during the experiment. This research was supported in part by the Department of Energy and the Robert A. Welch Foundation.

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

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

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

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

[5]For a review of the various calculations, see Ref. 2.

[6]R. E. Tribble, J. D. Cossairt, D. P. May, and R. A. Kenefick, Phys. Rev. C 16, 917 (1977).

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

[8]A. H. Wapstra and K. Bos, At. Data Nucl. Data Tables 19, 177 (1977).

[9]G. J. KeKelis, M. S. Zisman, D. K. Scott, R. Jahn, D. J. Vieira, J. Cerny, and F. Ajzenberg-Selove, Phys. Rev. C 17, 1929 (1978).

[10]G. R. Burleson, G. S. Blanpied, G. H. Daw, A. J. Viescas, C. L. Morris, H. A. Thiesson, S. J. Greene, W. J. Braithwaite, W. B. Cottingame, D. B. Holtkamp, I. B. Moore, and C. F. Moore, Phys. Rev. C 22, 1180 (1980).

[11]Weighted average of this work and Refs. 9 and 10.

[12]F. Ajzenberg-Selove, Nucl. Phys. A281, 1 (1978).

[13]R. R. Sercely and R. J. Peterson, Phys. Rev. C 17, 1919 (1978).

[14]A. M. Lane and R. G. Thomas, Rev. Mod. Phys. 30, 257 (1958).