PHYSICAL REVIEW C VOLUME 13, NUMBER 1 JANUARY 1976

Mass of $^8C^\dagger$

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(Received 14 October 1975)

A new determination of the mass excess of ^8C by the $^{12}C(^4He, ^8He)^8C$ reaction has yielded a value of 35.10 ± 0.03 MeV. The new value is in good agreement with the quadratic isobaric multiplet mass equation prediction. Higher order cubic and quartic mass equation coefficients are found to be small for the $A = 8$ isobaric quintet.

[NUCLEAR REACTIONS $^{12}C(^4He, ^8He)$. Measured ^8C mass. Deduced coefficients of the isobaric multiplet mass equation for the $A = 8$ quintet.]

I. INTRODUCTION

Recently reported measurements of the $T = 2$ states in ^8Li and ^8B completed the first isobaric multiplet quintet,[1] thus allowing a mass quintet test of the isobaric multiplet mass equation (IMME). The IMME, which was first suggested by Wigner in 1957,[2] predicts that the mass excesses of an isobaric multiplet should be described by the equation $M(T, T_z) = a + bT_z + cT_z^2$, where $M(T, T_z)$ is the mass excess for the multiplet member with isospin T and z component T_z. The IMME has been remarkably successful in predicting the mass excesses of $T = \frac{3}{2}$ multiplets. Only for $A = 9$ has a significant deviation from the IMME been found.[3]

Isospin quintets provide a more severe test of the IMME, since the three coefficients must correctly predict five nuclear masses. A breakdown of the IMME could result from mechanisms such as isospin mixing, level shifts of unbound states, or charge-dependent many-body forces. The previous results[1] for the $A = 8$ quintet indicated a substantial deviation from the IMME. If the mass equation is parameterized to T_z^4 as $M(T, T_z) = a + bT_z + cT_z^2 + dT_z^3 + eT_z^4$, the d and e coefficients measured for $A = 8$ were 18(±14) and 13(±7) keV, respectively. The uncertainties for d and e result primarily from the uncertainty in the mass excess determination of the $T_z = -2$ member of the multiplet, ^8C. We report below a new measurement of the mass of ^8C with a substantially reduced uncertainty. Unlike the previous measurement, the new mass excess is found to be in good agreement with the IMME prediction.

II. EXPERIMENTAL PROCEDURE

The mass of ^8C was determined from the reaction $^{12}C(^4He, ^8He)^8C$. A beam of 123.5-MeV α particles from the Texas A&M University 88-inch cyclotron was magnetically analyzed and transported to a 1 mg/cm^2 carbon target. The reaction products were detected in the focal plane of an Enge split-pole magnetic spectrograph at a laboratory angle of 5°. The spectrograph solid angle was 2.1 msr. Because of the small cross sections reported for (^4He, ^8He) reactions,[4] care was exercized in minimizing background. A 0.48 cm-wide water-cooled Ta Faraday cup for monitoring the beam current was located near the wall of the scattering chamber and a baffle was placed to keep reaction products produced by the cup from entering the spectrograph. Beam scattered from the energy analyzing slits was intercepted by subsequent downstream slits.

The focal plane detector consisted of a 10-cm single-wire gas proportional counter backed by a 50 mm × 10 mm × 500 μm Si solid-state detector. The entrance to the gas counter was collimated so that the active area was 47 mm × 9.5 mm. An Ar-methane gas mixture (90% Ar) was maintained at a constant pressure (~1 atm) in the gas counter by differential pumping. Particle position was determined by division performed by an on-line computer. Three constraints were used for particle identification: (1) $(dE/dx)_{gas}$; (2) E; (3) time of flight (TOF). The solid-state detector provided signals for both the particle energy and TOF relative to the cyclotron rf. The Si detector would stop 54 MeV ^8He's, incident at a 45° angle. The actual ^8He energy was 58 MeV and the angle of incidence varied from 40 to 50°. A spectrum of E vs TOF, displayed in Fig. 1, shows a spread in the ^8He energy due to the varying angle of incidence and hence the varying detector thickness. Two other particle groups, indicated in Fig. 1 as $^4He^+$ and $^8Li^{++}$, were observed with the same TOF as the ^8He group. The thickness of the Si detector was sufficient to stop both the $^4He^+$ (27 MeV) and $^8Li^{++}$ (58 MeV), thus forming well-defined energy

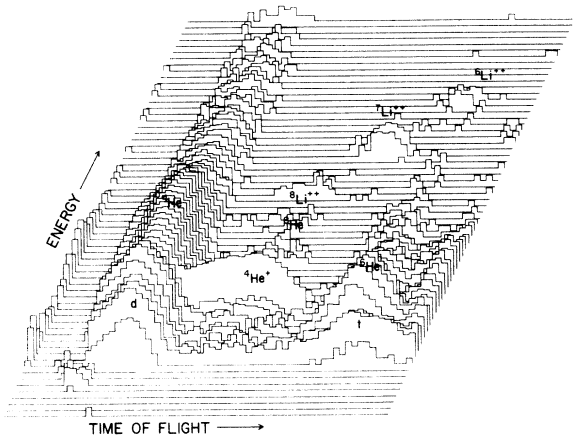

FIG. 1. A typical spectrum of E vs TOF with the Z dimension (number of counts) logarithmic. The ^{8}He group is spread out since the detector thickness was not sufficient to stop the ^{8}He's.

groups. Pileup rejection was used on the solid-state detector to reduce the background in the region of the ^{8}He's. The observed background level corresponded to a cross section of $< \frac{1}{2}$ nb/sr MeV. The position spectra for both $^{8}Li^{++}$ and $^{4}He^{+}$ are expected to be featureless since they represent excitations into the continuum. A comparison of the position spectra of the three groups, $^{4}He^{+}$, $^{8}Li^{++}$, and ^{8}He, shown in Fig. 2, displays the lack of structure in the $^{4}He^{+}$ and $^{8}Li^{++}$ spectra, indicative of continuum excitations.

The accurate determination of the ^{8}C mass excess requires a precise knowledge of (1) beam energy, (2) reaction angle, (3) focal plane calibration, and (4) target thickness. The beam energy was determined by the momentum matching technique[5] using an H_2^+ beam incident on a 280 $\mu g/cm^2$ SiO target. The magnetic rigidity of the H_2^+ beam was identical to that of the $^{4}He^{++}$ beam. Thus the energy analyzing system was not changed during the calibration runs. The proton reaction products from $^{28}Si(p, p)$ and $^{16}O(p, p)$ elastic scattering were observed simultaneously with deuterons from the $^{28}Si(p, d)\,^{27}Si$(g.s.) reaction at a laboratory angle of 20°. Reaction Q-value uncertainties, target thickness corrections, and peak centroid determinations lead to a 5 keV uncertainty in the proton energy determination. Since the magnetic rigidity remained constant, the $^{4}He^{++}$ beam energy was directly determined from the measured proton energy by using the appropriate nuclear masses and accounting for the electron attached to the H_2^+. The beam energy was monitored continuously during the experiment by nuclear magnetic resonance measurement of the energy analyzing magnetic field.

The reaction angle was determined optically to a precision of 0.05°. In order to correct for possible

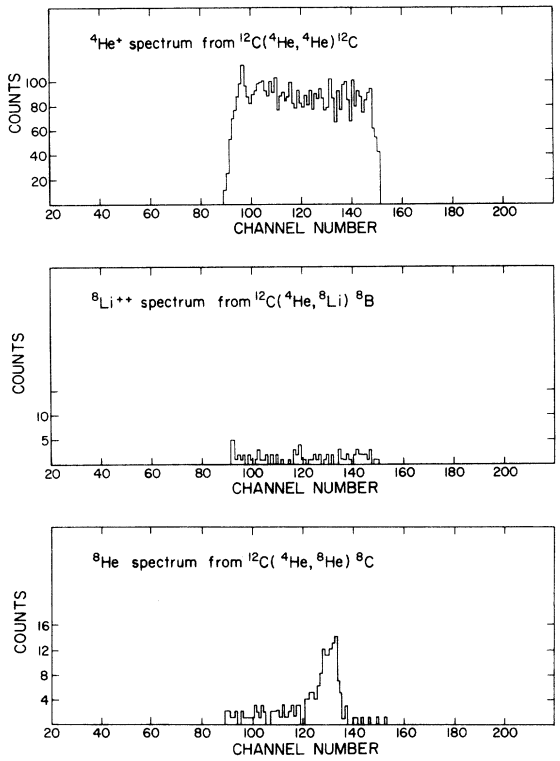

FIG. 2. A comparison of the position spectra $^{4}He^{+}$, $^{8}Li^{++}$, and ^{8}He. The three groups had identical TOF. However, the $^{4}He^{+}$ and $^{8}Li^{++}$ spectra show no distinguishing peaks.

beam misalignment, $^{12}C(^{4}He, ^{4}He)$ elastic scattering was measured at $\theta = \pm 15°$. The energy shift of the elastic peak corresponded to an angular shift of ±0.04°. The uncertainty in the angle was therefore set at ±0.05°, or ±6 keV for the mass excess of ^{8}C.

Five elastic and inelastic α groups were used to determine the focal plane calibration. The reactions were $^{12}C(^{4}He, ^{4}He')\,^{12}C$ ($E_x = 0.0$, 4.439, and 7.653 MeV), $^{16}O(^{4}He, ^{4}He')\,^{16}O$ ($E_x = 6.916$ MeV), and $p(^{4}He, ^{4}He)p$. The latter reaction served as an independent check of the reaction angle because of its large kinematic shift. The average deviation from a linear least squares fit was ±14 keV, corresponding to a ±7 keV uncertainty in the mass excess.

The target thickness was measured by the energy loss from an ^{241}Am α source. Two separate measurements were performed indicating a thickness of 1 ± 0.15 mg/cm^2. This measurement agreed with the thickness determined by the elastic energy loss which was found by using a thin ^{12}C target and measuring the energy shift relative to the thick target. The uncertainty in the mass excess due to target thickness correction was estimated to be ±15 keV.

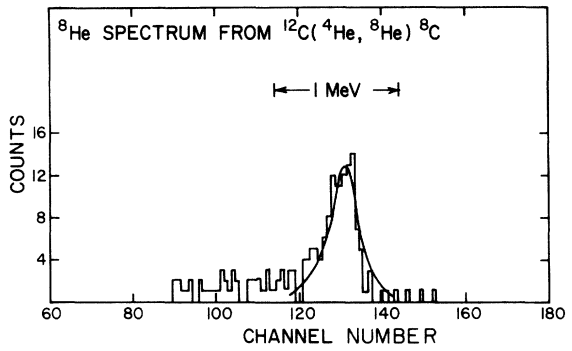

FIG. 3. The peak shape from the Gaussian fit is shown compared to the experimental data.

III. RESULTS AND DISCUSSION

The data corresponding to the ^{8}He group shows a definite peak, taken to be the excitation of the ^{8}C ground state, with possible excitations to a continuum in ^{8}C. The counts above the peak were taken as a measure of the background and, as stated above, correspond to a cross section of $<\frac{1}{2}$ nb/sr MeV. A χ^2 peak fitting computer program was used to extract the width and centroid for the ^{8}C ground-state excitation. Both Gaussian and Breit-Wigner peak shapes were tested, with the Gaussian producing a slightly smaller reduced χ^2 ($\chi_\nu^2 = 1.3$). The predicted peak shape from the Gaussian fit is compared to the data in Fig. 3. The centroid was essentially unaffected by the peak shape choice; however, the derived width did change as indicated in Table I. Since the ^{8}C nucleus is unbound, the peak shape would not be expected to be symmetric because barrier penetrability effects would tend to enhance the tail region on the high excitation side of the peak. Our data do not have sufficient statistics to define the asymmetry. However, we expect that including the penetrability would change the peak width estimate while having very little effect on the centroid determination.

The experimental result for the ^{8}C mass excess is 35.10± 0.03 MeV, where the uncertainty was found by adding the uncertainties listed in Table I along with the ^{8}He mass uncertainty in quadrature. The previous measurement of the ^{8}C mass excess reported the result 35.36± 0.17 MeV, which is not in good agreement with the present determination.[4] As this manuscript was being prepared, the authors were informed of another determination of the ^{8}C mass excess with the result 35.06± 0.05 MeV, in excellent agreement with our measurement.[6] The natural width was determined from the experimental width by removing the broadening due to target thickness and finite resolution. These contributions were 150± 21 keV for target thickness and straggling, 88± 20 keV for the detector resolution, and 160± 40 keV for the beam energy spread and finite image size. The resulting natural width $\Gamma_{\text{c.m.}}$ was found to be 230± 50 keV for the Gaussian fit and 183± 56 keV for the Breit-Wigner fit. These results compare favorably with the previously reported width of 222^{+80}_{-140} keV.[4] The laboratory cross section measured at $\theta_{\text{lab}} = 5°$ was 9^{+2}_{-3} nb/sr, where the uncertainty includes contributions from statistics, solid angle, and beam integration.

The relevant parameters for the $A = 8$ quintet are displayed in Table II. A least-squares fit to the quadratic IMME yields an unnormalized $\chi^2 = 5.7$. Examining the residuals of the quadratic fit, shown in Fig. 4, indicates that the $T_z = +1$ and $+2$ masses contribute significantly to the χ^2, while the other three members show good agreement to the quadratic fit. Also listed in Table II are the results of four-parameter least-squares fits where d and e were alternatively set to zero. The χ^2 in both cases is near 1, indicating that either fit would be acceptable. A five-parameter fit predicts that the d and e coefficients are 4.0(±3.2) and 2.5(±2.3)

TABLE I. Error estimates and results of peak fitting for ^{8}C mass excess determination.

Source of uncertainty	Estimated error (keV)
Beam energy	11
Focal plane calibration	7
Reaction angle	6
Target thickness	15
Centroid uncertainty	15

Peak parameters fitting function	Mass excess (MeV)	Peak width (keV)	Reduced χ^2
Gaussian	35.102(±0.030)	330	1.3
Breit-Wigner	35.096(±0.030)	300	1.5

TABLE II. Properties of $A=8$ isobaric quintet and the predicted IMME coefficients.

	T_z	Mass excess (MeV)	E_x (MeV)	Width $\Gamma_{c.m.}$ (keV)	Reference
^{8}C	−2	35.10(0.03)	0.0	230 ± 50	Present work
^{8}B	−1	33.542(0.009)	10.619(0.009)	32 ± 25	1
^{8}Be	0	32.4340(0.0027)	27.4922(0.0026)	12 ± 3	1
^{8}Li	1	31.7697(0.0054)	10.8222(0.0055)	<12	1
^{8}He [a]	2	31.603(0.0013)	0.0	Bound	11, 12, 13

Predicted coefficients in units of MeV for the IMME

a	b	c	d	e	χ^2
32.4321	−0.8836	0.2300	0	0	5.72
32.4332	−0.8940	0.2270	0.0058	0	1.14
32.4340	−0.8827	0.2162	0	0.0040	1.50

For five parameters: $d=0.0040(\pm 0.0032)$, $e=0.0025(\pm 0.0023)$

[a] The ^{8}He mass excess is the average of three determinations: 31.57 ± 0.03 (Ref. 11), 31.600 ± 0.025 (Ref. 12), and 31.613 ± 0.016 (Ref. 13).

keV, respectively. The large χ^2 for the three-parameter fit may indicate that higher order terms are necessary for $A=8$. However, the results including cubic and quartic terms do not show a clear delineation of these higher order effects.

At least two mechanisms should cause deviations from a quadratic IMME in $A=8$. The width and separation energies listed in Table II indicate that three of the members are unbound to particle decay and subsequently have measurable widths (> a few keV). A Thomas-Ehrman shift[7] should cause the physical mass of these states to deviate from the mass of a corresponding bound state. In general, such level shifts could not be absorbed by the quadratic IMME. Isospin mixing would also cause deviations. A theoretical analysis by Barker predicts that the dominant admixture to the ($T_z=0$, $T=2$) level would come from a nearby $T=0$ level.[8] Such mixing would lead directly to a nonzero e coefficient. Results of a recent measurement of the $T=2$ particle decays in ^{8}Be show strong branches to ($d+^6$Li), indicative of ($T=0$, $T=2$) mixing.[9] However, significant ($p+^7$Li) branches, not predicted by Barker, were also observed.[10] Since the model for isospin admixtures proposed by Barker does not account for the observed particle decays, it should not be expected to provide an accurate prediction of the isospin mixing in the ^{8}Be $T=2$ state.

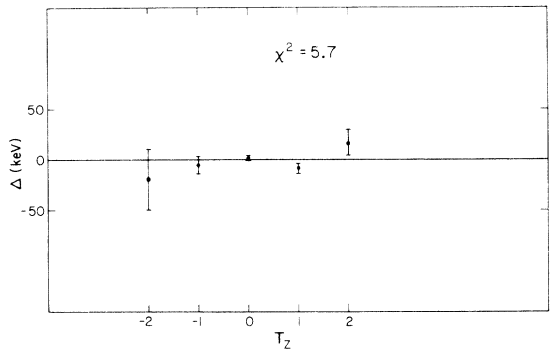

FIG. 4. The residuals from a quadratic isobaric mass equation fit, with $\Delta = M_{\rm calc} - M_{\rm exp}$.

The relatively good agreement of the first complete isobaric mass quintet with the quadratic IMME may be fortuitous, especially since the members of the quintet range from bound to unbound, and at least one of the members contains isospin admixtures. Completing other isobaric mass quintets, where the perturbing effects should be quite different, would provide further severe tests of the IMME.

ACKNOWLEDGMENTS

The authors would like to thank W. Burns, K. Clark, and S. Talley for their assistance during the experiment. We also thank Dr. J. D. Bronson for his help in writing the data acquisition computer code.

†Work supported in part by the National Science Foundation.

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