Measurement of the mass of ^{8}C by the ^{14}N(^{3}He,^{9}Li) reaction*

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The mass of the particle-unstable $T_z = -2$ nuclide ^{8}C has been measured by means of the ^{14}N(^{3}He, ^{9}Li) reaction, which has an observed cross section of about 5 nb sr^{-1} at 76 MeV. The mass excess found is 35.06 ± 0.05 MeV, and the width of the ^{8}C ground state is 290 ± 80 keV. The result for the mass excess is more precise than that obtained in a previous (α, ^{8}He) experiment and confirms that significant higher-order terms must be added to the isobaric multiplet mass equation to describe the mass-8 isobaric quintet.

[NUCLEAR REACTIONS ^{14}N(^{3}He, ^{9}Li), $E = 76$ MeV; measured Q, $\sigma(\theta)$. ^{8}C obtained mass, Γ. Deduced a, b, c, d, e coefficients in IMME.]

INTRODUCTION

The recent completion of the mass-8 isobaric quintet, consisting of the ground states of ^{8}C and ^{8}He, and the lowest $T = 2$ states in ^{8}B, ^{8}Be, and ^{8}Li, provided a test of the three-parameter isobaric multiplet mass equation (IMME) in a five-member multiplet.[1] The result was that a quadratic IMME

$$M(T_z) = a + bT_z + cT_z^2$$

described the five masses remarkably well, but that there were definite indications of the need for a term eT_z^4, with $e = 4 \pm 2$ keV. The presence of a significant cubic term dT_z^3 could not, moreover, be ruled out.

The largest single contribution to the uncertainties in these conclusions came from the most proton-rich member of the quintet, ^{8}C, whose mass was known only to ±170 keV. That measurement was made by the ^{12}C(α, ^{8}He) reaction,[2] which has a Q value of −64 MeV. Not only is this reaction inaccessible to the Michigan State University (MSU) cyclotron, but also it introduces an undesirable correlation between the masses of ^{8}C and ^{8}He, which are both members of the multiplet, reducing the precision with which the d and e coefficients can be derived. By using instead the ^{14}N(^{3}He, ^{9}Li)^{8}C reaction, one can eliminate that correlation, and take advantage of the accurately known properties of the MSU cyclotron-spectrograph system. No previous observation of the (^{3}He, ^{9}Li) reaction has been reported, and it is thus of interest not only in the ^{8}C mass measurement but also as a possible route to a large number of very proton-rich nuclei.

EXPERIMENTAL METHOD

In view of the very low cross section expected for the (^{3}He, ^{9}Li) reaction, every effort was made to reduce background and to provide tightly controlled and redundant identification of ^{9}Li particles. An additional problem was the need for a nitrogen target, and the experiments described here have made use of solid Melamine ($C_3N_6H_6$) targets and gaseous N_2 in a gas cell.

Beams of 76-MeV ^{3}He ions from the MSU cyclotron were brought to a focus in the target chamber of an Enge split-pole spectrograph. Reaction products were detected in the focal plane by a triple detector system consisting of two single-wire proportional counters backed by a large Si detector, 5 cm long, 1 cm high, and 1500 μm deep. Use of the Si detector in place of the usual plastic scintillator gave high-resolution total energy signals, and improved discrimination against neutron and γ-ray background. Good resolution (limited by the 2-msr entrance aperture of the spectrograph) was also obtained in the time-of-flight spectrum, in which the transit time of particles through the spectrograph is measured relative to the cyclotron rf period.

The first section of the dual proportional counter provided energy-loss information, and the second both energy-loss and position information. The anode of the second section was of 10-μm nichrome wire, and the position was obtained by the

charge-division method using an analog pulse divider which produced an output accurate to 0.1% 6 μs after the inputs.[3] To minimize energy loss for the highly ionizing 30-MeV ^{9}Li particles, the proportional counter entrance window was 2.5-μm-thick aluminized Mylar, and the internal ground planes, 150-μg cm^{-2} Al foil. A gas filling of pure propane at $\frac{1}{3}$ atmospheric pressure was used. Signals from the Si detector passed through a conventional fast-slow electronic system, the fast leg of which generated timing signals for the time-of-flight system and also initiated pulse division for the back proportional counter. In addition, a pile-up rejector inspected the signals from the Si detector. Four analog signals, the Si detector total energy, the time-of-flight signal from a time-to-amplitude converter, the particle position, and the energy loss in the back proportional counter were digitized and written on magnetic tape event by event. The analog-to-digital converters were gated by a coincidence signal derived from the four analog signals, in coincidence with a single-channel analyzer set on the front proportional counter and in anticoincidence with pileup pulses.

The 30-MeV ^{9}Li ions travel through the spectrograph at such a low speed that an ambiguity between ^{9}Li ions and faster moving particles occurs in the time-of-flight spectrum if the cyclotron beam burst interval itself (70 ns) is used. Therefore, a beam pulsing system[4] which removes every second beam burst was employed to eliminate this potential interference with the identification of ^{9}Li.

The procedure used to measure the Q value for the ^{14}N(^{3}He, ^{9}Li)^{8}C reaction relies on the known properties of the MSU spectrograph and analyzing magnets. The spectrograph was recycled in a standard way and the field then increased to bring onto the counter reaction products from, in turn, ^{14}N(^{3}He, ^{7}Be)^{10}B, ^{14}N(^{3}He, ^{8}Li)^{8}C, and ^{14}N(^{3}He, ^{8}Li)^{9}C. The (^{3}He, ^{7}Be) and (^{3}He, ^{8}Li) reactions, which closely bracket the unknown in magnetic rigidity, have, in addition, similar kinematic behavior and similar energy losses in target and counter materials. They therefore greatly reduce the sensitivity of the measurement to beam energy, reaction angle, and target thickness. The beam energy as a function of analyzing magnet field strength has been determined near $E_{^{3}\mathrm{He}} = 76$ MeV in an experiment which examined the momentum crossover between ^{27}Al(^{3}He, ^{6}He)^{24}Al and ^{27}Al(^{3}He, ^{4}He)^{26}Al. The reaction angle is known (from experiments in which elastic scattering from hydrogen is compared with that from heavier targets) to be correctly given by a mechanical readout to an accuracy no worse than $\pm 0.2°$, and typically $\pm 0.1°$.

The presence of continua of ^{6}Li, ^{7}Li, and ^{8}Li ions of the same magnetic rigidity as the ^{9}Li greatly simplified the analysis of the data by providing simultaneous internal calibrations of energy, energy loss, and time of flight. Another valuable species was ^{6}He, which, at a given magnetic field, has the same time of flight as ^{9}Li. The correct setting of windows to select the rare ^{9}Li events was thus straightforward.

Two series of experiments were carried out. The first one used targets of natural Melamine evaporated onto backings consisting of 5–20 μg cm^{-2} of carbon and about 5 μg cm^{-2} of Formvar. Melamine evaporates readily in beam, however, and it was necessary to mount the targets in a spinner mechanism which effectively distributed the beam spot over a larger area. Even so, beam currents had to be limited to 0.5 μA and corrections for loss of target material during the runs were required. It was found empirically that the total count rate in the silicon detector was a good measure of the relative thickness of Melamine on the target, the contribution from the backings alone being small. The final results are a composite of runs on eight targets of average thickness 200 μg cm^{-2}.

A second series of experiments made use of a 10° gas cell (described by Nann *et al.*[5]) filled with natural N_2 at a pressure between 80 and 100 Torr. An entrance window of 1.96-mg cm^{-2} Havar and an exit window of 0.45-mg cm^{-2} Mylar was used. This cell tolerated beam currents of 2–3 μA without difficulty.

RESULTS

Spectra from the calibration reactions ^{14}N(^{3}He, ^{7}Be)^{10}B and ^{14}N(^{3}He, ^{8}Li)^{9}C using the gas cell are shown in Fig. 1. The resolution is dominated by energy loss in the gas, and is about 210 keV for the ^{7}Be lines and 150 keV for ^{8}Li. Figure 2 summarizes the data obtained on the ^{14}N(^{3}He, ^{9}Li)^{8}C reaction in the form of a Q-value plot. The upper spectrum is a composite of eight runs with Melamine targets, at $\theta_{\mathrm{lab}} = 8°$, with a total accumulated charge of 60 mC. Owing to small changes in beam energy caused by retuning the cyclotron between runs, only the region indicated by the arrows was common to all runs. The lower half of Fig. 2 shows the spectrum obtained from a single run at $\theta_{\mathrm{lab}} = 10°$ using the gas cell with a total accumulated charge of 45 mC. These spectra correspond to laboratory cross sections of about 3 nb sr^{-1} at 8° and 5 nb sr^{-1} at 10°, with uncertainties of ~40%. The recently measured mass excess of ^{9}Li, 24.955 MeV,[6] implies a Q value for ^{14}N(^{3}He, ^{9}Li)^{8}C of -42.29 ± 0.09 MeV from the Melamine runs and -42.18 ± 0.06

MeV from the gas cell run. Combining these results, one finds a mass excess for ^{8}C of 35.06 ±0.05 MeV. This result disagrees somewhat with the early $^{12}C(\alpha, ^8He)$ result[1,2] of 35.36±0.17 MeV, but is in excellent accord with a very recent $(\alpha, ^8He)$ measurement by Tribble, Kenefick, and Spross,[7] who obtain 35.10±0.03 MeV. Combining the results of the present work and those of Tribble *et al.* but omitting that of Ref. 2, leads to a mass excess for ^{8}C of 35.089±0.026 MeV.

The width of the ^{8}C ground state can be extracted from the gas cell run (in which the target thickness remained constant and accurately known). Assuming a Gaussian line shape, we find $\Gamma_{c.m.} = 290 \pm 80$ keV, a result in good agreement with those of Ref. 2, 220^{+80}_{-140} keV, and Ref. 7, 230±50 keV.

DISCUSSION AND CONCLUSIONS

The present results for the mass excess of ^{8}C combined with those of Tribble *et al.*[7] improve the experimental situation in the mass-8 isobaric quintet. In addition, a new measurement of the mass excess of the $T=2$ state in ^{8}Be has been reported by Noé, Geesaman, Paul, and Suffert,[8] who have reexamined the forbidden resonance in ^{6}Li + d. They find a mass excess of 32.4379 ±0.0023 MeV. Table I summarizes our present knowledge of the mass excesses and total widths of the $T=2$ states in mass 8. The mass excesses M have been calculated using the revision by Serduke[13] of the 1971 Wapstra and Gove mass table.[14] In Table II are presented the coefficients in the IMME derived from three-, four-, and five-parameter fits to the masses. Where applicable, χ^2 (unnormalized) is also shown. It is clear that the purely quadratic IMME does not give a very good fit to the data ($\chi^2 = 6.6$). Addition of a cubic term, $d = 6.0 \pm 2.6$ keV, however, gives an entirely acceptable fit, $\chi^2 = 1.2$. On the other hand, a nonzero e term in the absence of a d term also gives a lower χ^2 per degree of freedom than does the quadratic fit, although the quality of fit is not as good as can be obtained with the cubic term alone. There are, in fact, physical reasons for expecting

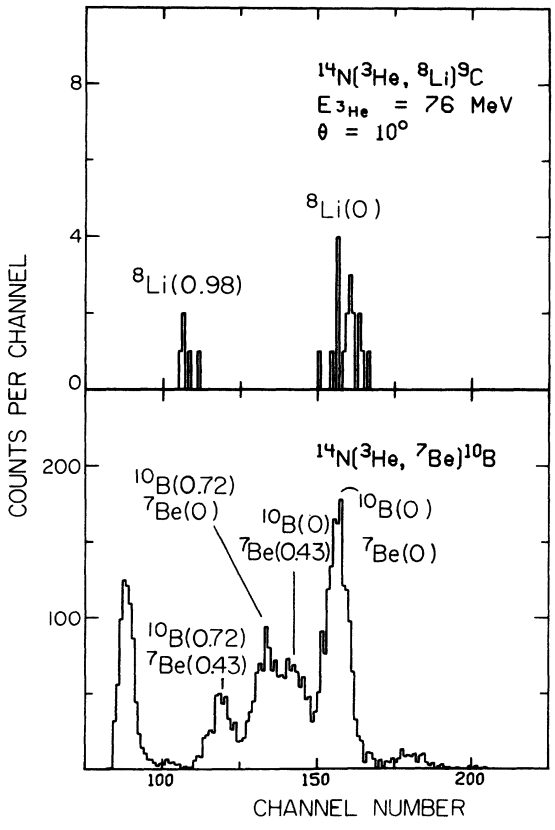

FIG. 1. Spectra from reactions used for calibration of the magnetic spectrograph and detector.

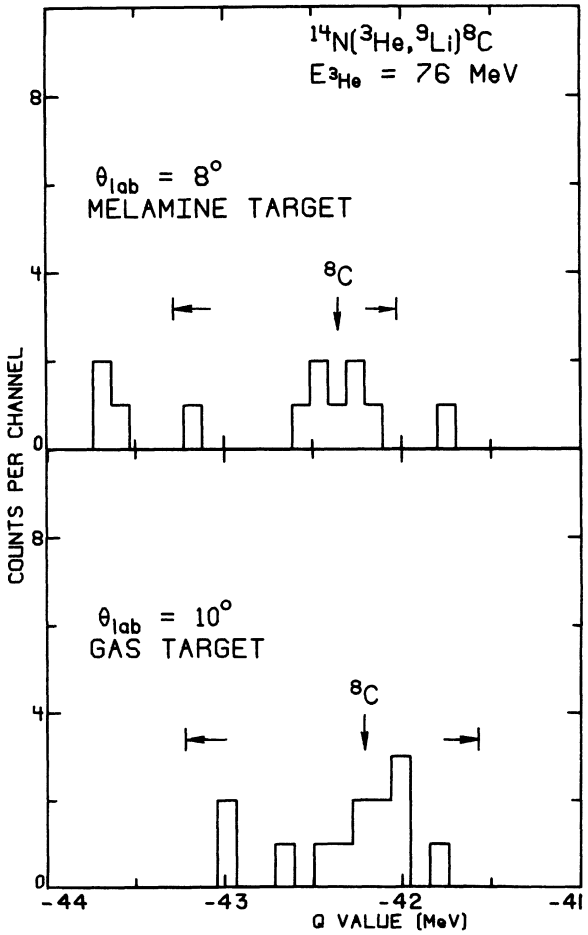

FIG. 2. Spectra of events identified as ^{9}Li.

TABLE I. Summary of the properties of the $A=8$ isobaric quintet.

	T_z	M (MeV)	Width $\Gamma_{c.m.}$ (keV)
^{8}C [a]	−2	35.089 ±0.026	245±40
^{8}B [b]	−1	33.542 ±0.009	32±25
^{8}Be [c]	0	32.4360±0.0017	9± 2
^{8}Li [b]	+1	31.7694±0.0054	<12
^{8}He [d]	+2	31.597 ±0.013	Bound

[a] Weighted average of present results with those of Ref. 7.
[b] Reference 1.
[c] Weighted average of results of Refs. 1, 8, and 9.
[d] Weighted average of results of Refs. 10–12.

the presence of both terms, and it appears that the experimental data are not quite at the level of precision needed to separate them unambiguously.

The existence of a nonzero cubic term can be understood in terms of the increasing Coulomb repulsion in the proton-rich members of the multiplet. Since the IMME is a result of first-order perturbation theory, it is implicitly assumed that the radial wave functions remain the same in all members. However, not only are the proton-rich members unbound to particle decay (which implies a larger nuclear radius) but also the Coulomb repulsion tends to increase the radius of the nucleus. Both of these lead to positive (odd-order) terms in the IMME (in a scheme where T_z is negative for proton-excess nuclei) because the nuclear size increase leads to a slight increase of binding over the fixed-size case. Such an effect may be responsible for at least part of the d coefficient found in the lowest $A=9$, $T=\frac{3}{2}$ multiplet.[6,15] No appreciable even-order terms are expected from this mechanism.

The existence of a nonzero quartic term is qualitatively expected due to the known presence of isospin mixing in the $T=2$ state of ^{8}Be. Experimentally, the state was first observed[9] as a resonance in the $T=0$, ^{6}Li+d channel, following a prediction by Barker and Kumar[16] that the $T=2$ state should be principally admixed with a nearby (still unobserved) $T=0$ state. Since $T=0$ states occur only in $T_z=0$ nuclei, this admixture has a simple consequence for the IMME. The shift in position of the $T_z=0$ member of the quintet directly gives rise to an even-order term, eT_z^4. By symmetry, no odd-order term is introduced. The Barker-Kumar picture can thus successfully account (qualitatively) for both the observation of the $T=2$ state in ^{8}Be as a resonance in ^{6}Li+d and a nonzero e term. In fact, using the level spectrum and Coulomb matrix elements calculated by Barker and Kumar, one finds $e=-1$ keV, but this value depends sensitively on the relative location of the $T=0$ and $T=2$ states, which are nearly degenerate, and one should not expect detailed agreement in magnitude or even sign. However, the calculation should be able to characterize in a reliable way the wave function of the state which is responsible for the $T=0$ admixture.

The interesting possibility now exists of extracting a value for the $\Delta T=2$ charge-dependent nuclear matrix element between two states whose wave functions are known. The Barker-Kumar calculation indicates that the Coulomb matrix elements between the $T=2$ state and other 0^+ states are rather small except for the one connecting the 0^+, $T=0$ state which lies closest in energy. It would appear, then, that a simple system of two interacting levels may give a good description of the actual situation.

We consider the case shown schematically in Fig. 3. A $T=2$ state of energy H_{22} and negligible width interacts with a broad $T=0$ state of energy H_{00} and width Γ_0. As a result of the interaction, represented by an off-diagonal matrix element H_{02}, the $T=2$ state is shifted to its physical position E_A and acquires a width Γ_A. Similarly the $T=0$ state moves to E_B and has an actual width Γ_B. As Shanley[17] has pointed out, when broad states are involved, their eigenenergies should be treated as complex to avoid violating the unitarity of the S matrix for the decay channels to which they are coupled. The Hamiltonian matrix has the following form:

$$\begin{pmatrix} H_{00}-\frac{1}{2}i\Gamma_0 & H_{02} \\ H_{02} & H_{22} \end{pmatrix}.$$

Diagonalizing yields eigenvalues $E_A-\frac{1}{2}i\Gamma_A$ and

TABLE II. Coefficients of the IMME for the $A=8$ quintet (keV).

a	b	c	d	e	χ^2
32435.2±1.7	−882.9±4.2	226.8±3.0	···	···	6.6
32435.6±1.7	−894.5±6.5	224.7±3.1	6.0±2.6	···	1.2
32436.0±1.7	−881.8±4.3	213.6±7.0	···	4.0±1.9	2.2
32436.0±1.7	−890.7±7.4	217.3±7.4	4.4±3.0	2.4±2.2	···

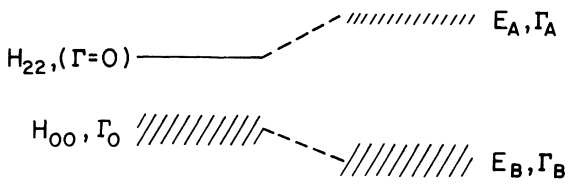

FIG. 3. Perturbation of a narrow level by a nearby broad level.

$E_B - \frac{1}{2}i\Gamma_B$. A complete solution for the eigenvalues and eigenvectors cannot be found when only two of the relevant experimental numbers, e and Γ_A, are known. The quantity e can be expressed as

$$e = \tfrac{1}{4}(E_A - H_{22}) \equiv \tfrac{1}{4}\epsilon_A \ .$$

We note that the experimental determination of e fixes the sign of $E_A - H_{22}$. Since e appears to be positive, the perturbing $T=0$ state lies below the $T=2$ state.

The unperturbed position and width of the $T=0$ state can be written

$$H_{00} = E_A - \frac{\epsilon_A H_{02}^{\,2}}{\epsilon_A^{\,2} + \frac{1}{4}\Gamma_A^{\,2}} \ ,$$

$$\Gamma_0 = \Gamma_A\left(\frac{H_{02}^{\,2}}{\epsilon_A^{\,2} + \frac{1}{4}\Gamma_A^{\,2}} + 1\right) .$$

Expressions for E_B and Γ_B (the perturbed position and width of the broad state) are complicated and differ insignificantly from the unperturbed values when $\Gamma_0 \gg \Gamma_A$.

Before Γ_A can be identified with the observed width of the "$T=2$" state, 9 ± 2 keV, a correction must be made for an isospin-allowed particle decay mode

$$^8\mathrm{Be}(27.5) \rightarrow {}^6\mathrm{He} + 2p + 0.28 \text{ MeV}.$$

The simplest approach is to assume the same reduced width for this decay as for the two-proton decay of ^{6}Be, which yields

$$\Gamma_{2p} \sim 2 \text{ keV}.$$

The electromagnetic partial widths, and particle decay branches enabled by isospin-breaking components in the transition matrix element, are presumably negligible.

It is interesting to set H_{02} equal to the pure Coulomb $\Delta T = 2$ matrix element calculated by Barker and Kumar (51 keV). Then the observed values of e, $0 < e < 6$ keV, and of Γ_A, ~7 keV, imply a 0^+, $T=0$ state lying no more than 400 keV below the $T=2$ state and having a width between 40 and 1500 keV. If the charge-dependent matrix element were as large as 100 keV, then the perturbing state can be as wide as 6 MeV and lie 1.6 MeV below the $T=2$ state. Goldhammer[18] has calculated $\Delta T = 1$ Coulomb matrix elements consistently about a factor of 2 larger than those obtained by Barker.[19] Goldhammer's results, which assume a purely Coulombic interaction for the $\Delta T = 1$ matrix elements in mass 8, are in excellent agreement with experiment.

Clearly the observation of the 0^+, $T=0$ state which perturbs the $T=2$ state is of the greatest interest as a means for determining the off-diagonal charge-dependent matrix element H_{02}. The distinguishing feature of the state will, of course, be its particle decays, which are known through its admixture with the $T=2$ state.[20] If both the width and position of the $T=0$ state are measured, the problem is overdetermined, and one can not only extract a value for H_{02}, but also check the validity of the two-state mixing assumption.

To summarize, the mass excess of the $T_z = -2$ nuclide ^{8}C has been measured by the ^{14}N(^{3}He, ^{9}Li)^{8}C reaction. The (^{3}He, ^{9}Li) reaction, with a cross section of several nanobarns per steradian in this case, thus appears to be a useful reaction for reaching proton-rich nuclei although with such a light target, the cross section may be atypical. The result of this and another new measurement by Tribble *et al.* is substantially improved accuracy in the determination of higher-order coefficients in the IMME for the mass-8 quintet. There is evidence for cubic and/or quartic terms, consistent with the presence of a $T=0$ admixture in the $T=2$ state of ^{8}Be. The importance of locating the perturbing $T=0$ state experimentally is considerable, for it may permit a clear-cut determination of the $\Delta T = 2$, charge-dependent, matrix element in a case where the wave functions of the states are known.

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