PHYSICAL REVIEW C VOLUME 9, NUMBER 6 JUNE 1974

$A = 9$ isospin quartet*

E. Kashy, W. Benenson, and J. A. Nolen, Jr.
Cyclotron Laboratory, Department of Physics, Michigan State University, East Lansing, Michigan 48824

(Received 13 February 1974)

New measurements of the mass excess of the lowest $T=\frac{3}{2}$ levels in ^{9}Be and ^{9}B give values of 25.7406 ± 0.0017 and 27.0711 ± 0.0023 MeV, respectively, and indicate a definite cubic dependence for the masses of the $A=9$ quartet which includes ^{9}Li and ^{9}C in their ground states. A value of 7.6 ± 1.7 keV is obtained for the coefficient of the $T_z{}^3$ term which now clearly exceeds the current theoretical estimates. Precise values of excitation energy of levels in ^{10}B and ^{11}B have been obtained as part of these measurements.

[NUCLEAR REACTIONS ^{11}B(p,t), $(p,{}^3$He$)$, $E=42$ MeV; measured E_x of $T=\frac{3}{2}$ levels of ^{9}Be and ^{9}B. ^{10,11}B(p,p') $E=35$ MeV; measured E_x of ^{10,11}B levels; deduced coefficient of multiplet mass equation for $A=9$.]

INTRODUCTION

Considerable effort has been devoted to testing the symmetry relation embodied in the mass equation for isobaric-analog nuclear states. In 1957, Wigner[1] showed that if one assumes isospin to be a good quantum number, the mass difference between members of a T multiplet is a second-degree polynomial, i.e.,

$$M(T_z) = a + bT_z + cT_z{}^2. \tag{1}$$

This relationship has proved remarkably accurate for data that now include 15 $T=\frac{3}{2}$ quartets of nuclear states. In only one of these quartets, the lowest $T=\frac{3}{2}$ $A=9$ system, does it appear that a deviation of some significance has been observed. The addition of a $dT_z{}^3$ term to Eq. (1) above with $d = 8.0 \pm 3.7$ keV was required to fit the experimental data.[2]

Deviations from Eq. (1) would not be the result of inequalities of nuclear forces, i.e., the breaking of charge symmetry, but as pointed out in Ref. 1, would be mainly produced by the electrostatic interaction in the nucleus. Various aspects of Eq. (1), also known as the isobaric multiplet mass equation (IMME) have been discussed in detail by Garvey,[3] including mechanisms which generate higher-order terms.

There has been a number of calculations of the possible contributions to this d coefficient. Two recent papers, one by Hardy, Loiseaux, Cerny, and Garvey[4] and the other by Bertsch and Kahana,[5] which were both aimed at this d-term evaluation, conclude with the suggestion that the most fruitful avenue may lie in repeating some of the experimental work to ascertain the cubic dependence with better accuracy.

For $A = 9$ the value of d for a cubic IMME is given by

$$d = \tfrac{1}{6}({}^9\mathrm{Li}-{}^9\mathrm{C}) - \tfrac{1}{2}({}^9\mathrm{Be}^* - {}^9\mathrm{B}^*), \tag{2}$$

where the symbols stand for the mass excess of corresponding $T=\frac{3}{2}$ states. Since all these states have approximately the same uncertainty in their masses of about 5 keV,[2] Eq. (2) shows that the current experimental uncertainties in ^{9}Be* and ^{9}B* $T=\frac{3}{2}$ states are 3 times more significant than those of ^{9}Li and ^{9}C in the determination of d.

EXPERIMENTAL PROCEDURE AND RESULTS

To reach the lowest $T=\frac{3}{2}$ level of ^{9}Be, a thin (~ 30 μg/cm^2) target of ^{11}B evaporated onto a 30-μg/cm^2 carbon backing was bombarded with 42-MeV protons from the Michigan State University cyclotron. The ^{3}He particles from the $(p,{}^3$He$)$ reactions were analyzed at a laboratory angle of 8° in an Enge split-pole spectrograph. The detection system consisted of a 12-cm-long current division wire proportional counter in the focal plane of the spectrograph followed by a plastic scintillator used for time-of-flight particle identification.[6] The method for obtaining a highly precise value for the mass excess of the ^{9}Be $T=\frac{3}{2}$ level was to compare the energy of the ^{3}He in that reaction to those from the ^{12}C$(p,{}^3$He$)^{10}$B reaction leading to the 2^+ ^{10}B level at 5.166 ± 4 keV[7] for which there is a strong peak in the ^{3}He spectrum. The energy of the ^{3}He group of interest for ^{9}Be* is only 125 keV greater than that corresponding to the calibration peak in ^{10}B, and the target masses, i.e., 11 and 12, are similar, and therefore a highly accurate comparison insensitive to beam energy and laboratory angle can be expected. Since the error of 4 keV is far too large for the present purpose, the first measurements involved

TABLE I. Excitation energies of states in ^{10}B and ^{11}B.[a]

^{10}B E_x (keV) Present results	Previous results (Ref. 7)	^{11}B E_x (keV) Present results	Browne and Stocker (Ref. 9)	Alburger and Wilkinson (Ref. 10)
0	0	0	0	0
718.3 ± 0.4	718.32 ± 0.09	2124.7 ± 0.5	2124.9 ± 0.6	2125.0 ± 0.7
1740.2[a]	1740.16 ± 0.17	4445.2 ± 0.5	4445.0 ± 1.0	
2154.1 ± 0.5	2155.0 ± 1.0	5021.1 ± 0.6	5019.9 ± 1.3	5020.1 ± 1.7
3587.0 ± 0.5	3589.7 ± 2.2	6743.0 ± 0.7	6744.3 ± 1.6	6742.7 ± 1.8
4774.0 ± 0.5	4773 ± 3			
5110.3 ± 0.6	5112 ± 4			
5163.9 ± 0.6	5166 ± 4			
5919.5 ± 0.6	5924 ± 4			
6025.0 ± 0.6	6025 ± 2			
6127.2 ± 0.7	6133 ± 2			

[a] Used as part of a calibration which included also elastic scattering for ^{16}O, ^{12}C, ^{10}B, the 4439.2 ± 0.3-keV 2^+ level of ^{12}C (Refs. 11 and 12) and the 6130.66 ± 0.18-keV 3^- level of ^{16}O (Ref. 13).

remeasuring the levels of ^{10}B.

The excitation energies of ^{10}B levels were measured using inelastic proton scattering from a target containing ^{12}C, ^{16}O, ^{10}B, and a small amount of ^{11}B. The experiment consisted of taking six spectrograph exposures using nuclear emulsions, two each at angles of 10, 12, and 17°, at a proton bombarding energy of 35.3 MeV. At each scattering angle, one exposure was made with the carbon backing facing the beam and the second after the target had been rotated by a 180° angle. This procedure eliminates uncertainties from target thickness corrections. A resolution 4–6 keV full width at half-maximum was obtained after tuning the cyclotron spectrograph system as previously described by Blosser *et al.*[8]

The results for levels of ^{10}B and of ^{11}B are listed in Table I. The ^{11}B levels were much better known, and excellent agreement between the present and previous work is found.[9,10] The calibration levels are also listed in Table I. For ^{10}B levels, it can also be seen that agreement with previous work[7] is also excellent and that the present work reduces the uncertainties considerably. The ^{10}B level of interest for the measurement of the ^{9}Be* $T=\frac{3}{2}$ level is found at $E_x = 5.1639 \pm 0.0006$ MeV.

With the excitation energy of this key ^{10}B level established, the determination of the ^{9}Be* level consisted of the measurement of ten spectra, using the 180° target rotation to eliminate target thickness corrections and five different field settings so that a large part of the wire counter was used. The latter procedure helped reduce effects of wire resistance nonlinearity.

One of these spectra is shown in Fig. 1. The resulting mass excess, including the uncertainty in the ^{10}B mass[14] and in the excitation energy of the 2^+, 5.1639-MeV level of ^{10}B was 25.7406 ± 0.0017 MeV for the lowest ^{9}Be* $T=\frac{3}{2}$ level. This is in excellent agreement with the previous value of 25.7443 ± 0.0052 MeV of Lynch, Griffiths, and Lauritsen[15] and yields and excitation energy of 14.3922 ± 0.0018 MeV for the excitation energy of this state in ^{9}Be.

The ^{9}B* lowest $T=\frac{3}{2}$ level was reached via the ^{11}B$(p, t)^{9}$B reaction using 40- and 42-MeV proton beams and observing the reaction particles at a laboratory angle of 8°. The target consisted of

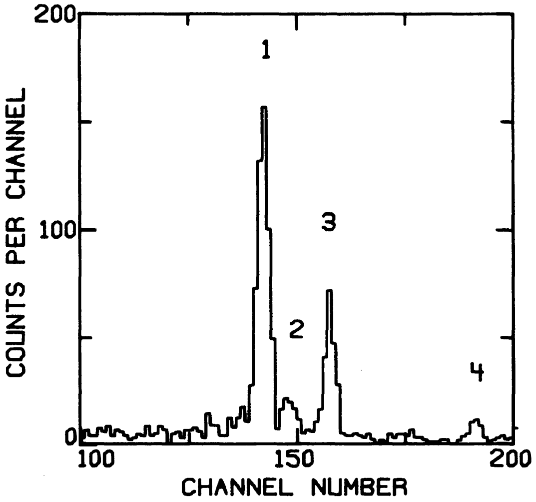

FIG. 1. Spectrum of ^{3}He from the reactions ^{11}B$(p,{}^{3}$He$)$-^{9}Be and ^{12}C$(p,{}^{3}$He$)^{10}$B. $E_p = 42$ MeV and $\theta_{\text{lab}} = 8°$. The peaks 1, 2, and 4 correspond to ^{10}B levels at 5.164, 5.110, and 4.774 MeV. Peak 3 corresponds to ^{9}Be* at 14.392 MeV.

TABLE II. Mass excess of lowest $T=\frac{3}{2}$ states for $A=9$.

Nucleus	T_z	Mass excess (keV)	Reference
^{9}Li	$\frac{3}{2}$	24 966 ± 5	17, 18
^{9}Be	$\frac{1}{2}$	25 740.6 ± 1.7	Present work
^{9}B	$-\frac{1}{2}$	27 071.1 ± 2.3	Present work
^{9}C	$-\frac{3}{2}$	28 912 ± 3	2, 16, 19

TABLE III. Parameters for the $A=9$ quartet for a quadratic and cubic fit to the IMME (in keV).

a	b	c	d	χ^2
26 337.9 ± 1.6	−1320.1 ± 1.6	265.6 ± 1.6	···	19
26 339.2 ± 1.6	−1332.4 ± 3.2	266.6 ± 1.6	7.6 ± 1.7	···

150-μg/cm^2 ^{11}B evaporated on a 30-μg/cm^2 carbon backing. The energy calibration procedure in this case used the deuteron peaks corresponding to the newly measured levels of ^{10}B (see Table I). Deuteron peaks from the ^{12}C(p, d)^{11}C reaction leaving ^{11}C in its ground and first excited state at 1.9997 ± 0.0005 MeV[12] were also used in the calibration. Even though the tritons from ^{12}C(p, t)^{10}C g.s. were not used in the calibration, the average of four runs on this transition gave the same Q value as the 1971 Mass Table so that out measurement of ^{9}B* can also be considered to be tied to the ^{10}C ground-state mass excess. Target thickness effects were somewhat more important since the calibration relied upon deuteron peaks, and therefore the tritons from the reaction ^{12}C(p, t)^{10}C g.s. served as an important check on this correction.

The value obtained for the mass excess of the lowest ^{9}B*, $T=\frac{3}{2}$ level was 27.0711 ± 0.0023 MeV. This result agrees with previous work of Barnes *et al.*[16] who measured 27.0746 ± 0.005 MeV. The excitation energy of the level in ^{9}B* from the present work is 14.6554 ± 0.0025 MeV. The methods described above can in principle be used to get even more precise results for these energies, i.e., uncertainties ≈ 1 keV. Unfortunately this is typical of the level of uncertainty of ground-state masses, and at that level we find many discrepancies which take a large number of measurements to resolve.

The results for $A=9$ quartet are summarized in Table II. The values listed reflect the readjustment of earlier results to the 1971 Mass Table.[14] Table III shows the results of a quadratic and a cubic fit to these masses. The χ^2 value of 19 in the quadratic fit eliminates an experimentally fortuitous cubic dependence in these masses. For a cubic fit, a d coefficient of 7.6 ± 1.7 keV is a well determined parameter.

Reviewing briefly the mechanisms so far proposed for the d coefficient, it appears that the contribution due to mixing of the $T=\frac{3}{2}$ states with $T=\frac{1}{2}$ states in the $T_z=\pm\frac{1}{2}$ nuclei contributes negligibly,[4] in view of the very narrow (~0.3 keV[20]) width of these states in both ^{9}B and ^{9}Be. It has been shown[5] that the decrease in Coulomb repulsion arising from the small binding of the last proton in ^{9}C can account for a positive contribution to the d coefficient of 1.6 keV, this effect being often referred to as the Thomas-Ehrman shift. An estimate of charge-dependent nuclear effects from the same source yields an additional contribution of +2 keV.[5] Thus the present experimental cubic coefficient exceeds significantly theoretical calculations of its value, and indicates that the effect of three-body interactions should be considered. In order to help clarify the problem of why this cubic dependence occurs only in this one quartet of the 15 known, we have begun a study of the second $T=\frac{3}{2}$ multiplet in $A=9$ which is based on the first excited levels of ^{9}Li and ^{9}C.

ACKNOWLEDGMENTS

We wish to thank D. Mueller for his help in obtaining some of these data and J. Chien for making some of the boron targets used in this work.

---

*Work supported by the National Science Foundation.

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

[2] J. M. Mosher, R. W. Kavanagh, and T. A. Tombrello, Phys. Rev. C 3, 438 (1971).

[3] G. T. Garvey, in *Proceedings of the Conference on Nuclear Isospin, Asilomar-Pacific Grove, March, 1969,* edited by J. D. Anderson, S. D. Bloom, J. Cerny, and W. W. True (Academic, New York, 1969), p. 703.

[4] J. C. Hardy, J. M. Loiseaux, J. Cerny, and G. T. Garvey, Nucl. Phys. A162, 552 (1971).

[5] G. Bertsch and S. Kahana, Phys. Lett. 33B, 193 (1970).

[6] E. Kashy, W. Benenson, I. D. Proctor, P. Hauge, and G. Bertsch, Phys. Rev. C 7, 2251 (1973).

[7] F. Azjenberg-Selove and T. Lauritsen, Energy Levels of Light Nuclei: A = 10 (to be published).

[8] H. G. Blosser, G. M. Crawley, R. deForest, E. Kashy, and B. H. Wildenthal, Nucl. Instrum. Methods 91, 61 (1971).

[9] C. P. Browne and H. Stocker, Phys. Rev. C 4, 1481 (1971).

[10] D. E. Alburger and D. H. Wilkinson Phys. Rev. C 3, 1492 (1971).

[11] A. V. Nero, Nucl. Phys. A185, 213 (1972).

[12] J. A. Nolen, Jr., G. Hamilton, E. Kashy, and I. D. Proctor, Nucl. Instrum. Methods 115, 189 (1974).

[13] F. Ajzenberg-Selove, Nucl. Phys. A166, 1 (1971).

[14] A. H. Wapstra and N. B. Gove, Nucl. Data A9, 265 (1971).

[15] B. Lynch, G. M. Griffiths, and T. Lauritsen, Nucl. Phys. 65, 641 (1965).

[16] C. A. Barnes, E. G. Adelberger, D. C. Hensley, and A. B. MacDonald, *Proceedings of the International Conference on Nuclear Physics, Gatlinberg, Tennessee, September, 1966,* edited by R. L. Becker and A. Zucker (Academic, New York, 1967), p. 261.

[17] P. H. Nettles, D. C. Hensley, and T. A. Tombrello, in *Proceedings of the Conference on Nuclear Isospin, Asilomar-Pacific Grove, March, 1969* (see Ref. 3), p. 819.

[18] R. Middleton and D. J. Pullen, Nucl. Phys. 51, 50 (1964).

[19] G. F. Trentelman, B. M. Preedom, and E. Kashy, Phys. Rev. Lett. 25, 530 (1970).

[20] F. Ajzenberg-Selove and T. Lauritsen, Energy Levels of Light Nuclei: A = 9 (to be published).