Mass of ^{9}Li†

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New precise determinations of the ^{9}Li mass excess by observation of the ^{10}Be$(d,{}^3$He$)^9$Li reaction and by analysis of ^{7}Li$(t,p)^9$Li data have yielded a value of 24.9554 ± 0.0020 MeV. This value, which is 10 keV lower than previous results, makes a significant reduction in the cubic coefficient of the isobaric multiplet mass equation for the $A = 9$ ground state quartet. The new value of d, 5.8 ± 1.5 keV, is considerably closer to theoretical estimates.

[NUCLEAR REACTIONS ^{10}Be$(d,{}^3$He) and ^{7}Li(t,p). Measured ^{9}Li mass. Deduced coefficients of IMME for $A = 9$ quartets.]

INTRODUCTION

Precise mass determinations have played an important role in studies of nuclear systematics and decay phenomena. In the case of $A = 9$, the ^{9}Li ground state is the fourth member of a $T = \frac{3}{2}$ isospin quartet which includes ^{9}C in its ground state, and ^{9}Be and ^{9}B in their lowest $T = \frac{3}{2}$ excited levels. The isobaric multiplet mass equation (IMME)

$$M(T_z) = a + bT_z + cT_z^2 \quad (1)$$

which was proposed by Wigner in 1957,[1] has had a remarkable success in fitting the masses of a large number of $T = \frac{3}{2}$ quartets, and only in the lowest $A = 9$ quartet have the experimental data shown a deviation sufficiently significant to require the addition of a cubic term, dT_z^3, to Eq. (1). Recent experiments have reduced the experimental uncertainties in the masses of the other members of the quartet,[2,3] so that in the latest determination, a value of $d = 7.6 \pm 1.7$ keV is found.[3] A recent investigation of the $T = \frac{3}{2}$ quartet of states based on the first excited state of ^{9}Li ($E_x = 2.691$ MeV, $J^\pi = \frac{1}{2}^-$, $T = \frac{3}{2}$) indicates a d coefficient of 4.2 ± 3.1 keV, which is neither as large nor as significant as for the lower quartet.[4]

Previous determinations of the ^{9}Li mass have been made by the ^{7}Li$(t,p)^9$Li reaction where a value of 24 966 ± 15 keV was obtained for the mass excess[5] and also via the ^{18}O$(^7$Li, ^{9}Li$)^{16}$O reaction where a value of 24 965.4 ± 5 keV was determined.[6] The availability of a target of the radioactive isotope ^{10}Be ($t_{1/2} = 1.6 \times 10^6$ y) and of the ^{7}Li$(t,p)^9$Li plates exposed recently at Los Alamos by Ajzenberg-Selove and collaborators,[7] who have made them available to us for analysis, as well as the improved accuracy in the other $T = \frac{3}{2}$ members, provided the incentive for the present redetermination of the ^{9}Li mass.

TABLE I. Analysis of (t,p) plates. The asterisk (*) indicates states used as calibrations.

θ_{lab}	Mass Excess of ^{9}Li (keV)	E_x ^{14}C(6) (keV)	E_x ^{14}C(7) (keV)	E_x ^{18}O(15) (keV)
15°	24 956.9	7341.1*	8318.6*	7113.3
10°	24 955.2	7341.4	8318.1*	7114.5*
5.5°	24 954.3	...	8318.0*	7113.9*
Ave.	24 955.5 ± 3.0	7341.2	8318.2	7113.9
Prev. Result	24 965.5 ± 4.7 [a]	7341.4 ± 3.4 [b]	8318 ± 5 [b]	7114 ± 2 [b]

[a] References 5 and 6. [b] Reference 10.

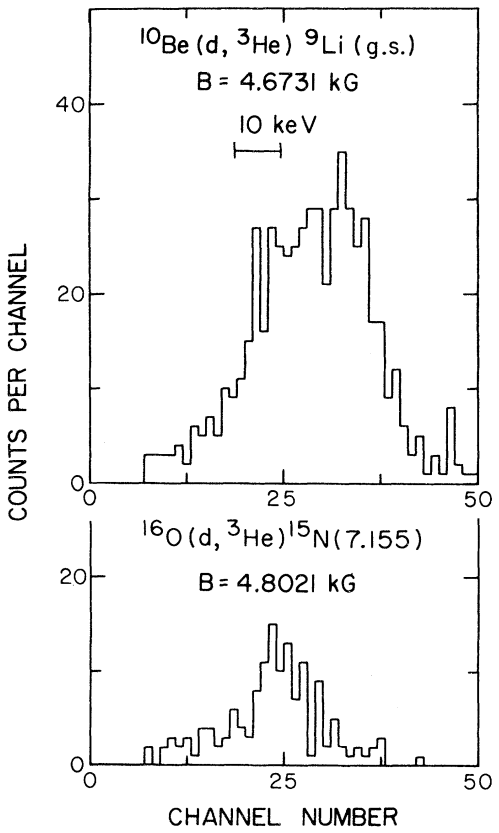

FIG. 1. Spectra of ^{3}He particles from the $(d, ^3\text{He})$ reaction on ^{10}Be and ^{16}O. The magnetic field in the spectrograph was changed to place the peaks at nearly the same position on the focal plane.

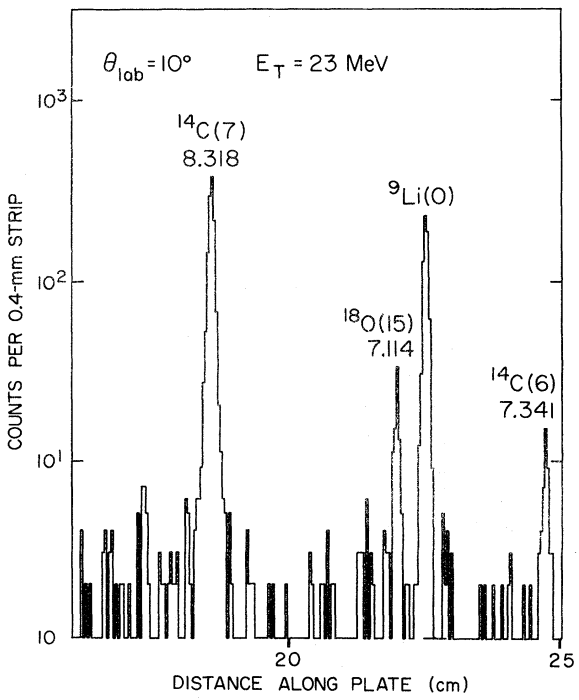

FIG. 2. Proton spectrum from the (t, p) reaction on ^{7}Li (Ref. 7).

EXPERIMENTAL PROCEDURE AND RESULTS

A. ^{10}Be$(d, ^3\text{He})^9$Li reaction

The target used consisted of ^{10}BeO of 35 ± 8 μg/cm^2 thickness on a 1.06-mg/cm^2 platinum foil.[8] The measurements consisted of bombarding the target with 23.92-MeV deuterons from the Michigan State University cyclotron, with the target positioned so that the deuteron beam impinged first on the platinum backing and then on the ^{10}BeO. The reaction ^{3}He particles were magnetically analyzed in a split-pole magnetic spectrograph at the laboratory angle of 6.1°. The detection and particle identification were made in a 1-cm long silicon position-sensitive detector located on the focal plane of the spectrograph. The particle identification was made from the energy deposited in the detector, and an analog pulse divider designed in the laboratory[9] was used to determine the position of the particle groups along the focal plane. The basis for the calibration was the comparison of the ^{3}He rigidities in the $(d, ^3\text{He})$ reaction on ^{10}Be to those from the ^{16}O in the ^{10}BeO target. The latter reaction leads to well known states in ^{15}N.[10] Since both calibration and unknown are in the same target, the uncertainty originating from target thickness corrections was minimized. In addition to the ground state, levels of ^{15}N at 6323.5 ± 0.4, 7155.0 ± 0.4, and 8312.6 ± 0.7 keV were used in the calibration. Figure 1 shows spectra resulting from the $(d, ^3\text{He})$ reaction on ^{16}O and ^{10}Be.

TABLE II. Mass of ^{9}Li.

Reaction	Mass excess (keV)	Reference
^{7}Li$(t, p)^9$Li	24 966 ± 15	5
^{18}O$(^7$Li, ^{9}Li$)^{16}$O	24 965.4 ± 5.0	6
^{7}Li$(t, p)^9$Li	24 955.5 ± 3.0	Present work [a]
^{10}Be$(d, ^3\text{He})^9$Li	24 955.4 ± 2.5	Present work

[a] Data from Ref. 7.

The beam energy was determined using the momentum-matching method[11] for the (d, p) and (d, t) reactions on a 40-μg/cm^2 carbon foil. The (d, t) reaction led to the first excited level of ^{11}C at 1999.7 ± 0.5 keV[12] and the (d, p) reaction to the ground state of ^{13}C. The procedure used in making the measurements was to place in turn each of the reaction groups at the same position in the focal plane of the spectrograph and then to increase

TABLE III. Mass excesses of ground and first excited levels for $A=9$.

Nucleus	T_z	Mass excess (keV) Ground State	Excited State	References
^{9}Li	$\frac{3}{2}$	24 955.4 ± 2.0	27 646 ± 5	4, present work
^{9}Be	$\frac{1}{2}$	25 740.6 ± 1.7	28 325.7 ± 1.4	3, 15
^{9}B	$-\frac{1}{2}$	27 071.1 ± 2.3	29 492 ± 4	3, 4
^{9}C	$-\frac{3}{2}$	28 912 ± 3	31 131 ± 11	2, 3, 4

the magnetic field until the next particle group of interest was deflected to that same position. Then, by means of magnetic field ratios, together with knowledge of the characteristics of our spectrograph, we obtained a mass excess for ^{9}Li of 24 955.4 ± 2.5 keV. This result is 10 keV smaller than the 24 965.5 ± 4.7-keV value from previous work.[5,6] In addition, an earlier determination we carried out using a resistive wire proportional counter as focal plane detector gave identical results, but with a larger uncertainty of 5 keV.

B. ^{7}Li(t,p)^{9}Li reaction

The mass of ^{9}Li discussed in this section is the result of the analysis of nuclear plates exposed at the Los Alamos tandem accelerator by Ajzenberg-Selove, Flynn, Garrett, and Hansen.[7] The 50-μm nuclear emulsions which they exposed by bombarding a ^{7}Li target with 23-MeV tritons were scanned and the results analyzed to obtain the ^{9}Li mass. The target consisted of 50-μg/cm^2 ^{7}Li (enriched to 99% in ^{7}Li) on a 40-μg/cm^2 carbon backing and was positioned during bombardment so that the triton beam hit the ^{7}Li side first. The data for $\theta_{lab}=5.5°$, 10°, and 15° were scanned and the reaction angle accurately checked via the ^{1}H(t,p)^{3}H reaction which showed up as a broad proton peak on the plate. The calibration was based on a linear fit to known states[10] of ^{14}C and ^{18}O and was made in a way similar to that described by Nolen *et al.*[12] A portion of the proton spectrum showing a peak corresponding to ^{9}Li and also the principal calibration peaks are shown in Fig. 2. The results of the fitting procedure are shown in Table I where the asterisk (*) indicates that the states were used as calibrations. The value for the ^{9}Li mass thus obtained is again about 10 keV smaller than earlier work, and the 3-keV uncertainty assigned to this mass excess reflects uncertainties in beam energy, scattering angle, target thickness corrections, and the ^{14}C and ^{18}O excitation energies used in the calibration.

A summary of the results for the ^{9}Li mass is given in Table II. The agreement between the (t,p) and (d, ^{3}He) results is excellent, and, since both the procedure and calibration standards are entirely independent, the weighted average of the present results for the ^{9}Li mass has an uncertainty of only 2.0 keV when both sets of measurements are included.

DISCUSSION

Table III lists the values for the mass excesses of the members of the $A=9$ ground and first excited $T=\frac{3}{2}$ multiplets. A recent check[13] on the ^{9}C ground state mass in our laboratory yielded 28.905 ± 0.007 MeV for its mass excess leaving the average value in Table III unchanged. Both multiplets are of interest since the ^{9}Li ground state mass change affects them both. The coefficients of the IMME for quadratic and cubic fits are shown in Table IV. A significant cubic term

TABLE IV. Parameters of the two $A=9$ quartets for a quadratic and cubic fit to the IMME (keV) (uncertainties shown in parentheses).

^{9}Li excitation energy	J^π	a	b	c	d	χ^2
0	$\frac{3}{2}^-$	26 338.1(1.6)	−1320.6(1.1)	265.1(1.1)	···	14
2.691 MeV	$\frac{1}{2}^-$	28 847.5(1.8)	−1163.9(2.9)	241.4(2.5)	···	0.6
0	$\frac{3}{2}^-$	26 339.9(1.6)	−1332.0(3.2)	263.9(1.2)	5.8(1.5)	···
2.691 MeV	$\frac{1}{2}^-$	28 848.9(2.5)	−1166.9(4.8)	239.8(3.2)	2.3(2.9)	···

still remains for the ground state quartet with $d = 5.8 \pm 1.5$ keV, and no experimentally significant term is found for the excited levels, i.e. $d = 2.3 \pm 2.9$ keV. The cubic term for the ground state quartet is still large, compared to the +3.6 keV estimated by Bertsch and Kahana.[14] They considered the effect that the small proton separation energy in ^{9}C had on the Coulomb energy and also estimated the contribution of non-Coulomb charge-dependent forces to the same effect. However, the difference between theory and experiment is now considerably smaller than before. Nevertheless, it may be remarked that the size of the effect calculated by Bertsch and Kahana would be expected to increase rapidly with decreasing binding of protons. Therefore the fact that the measured d coefficient in the excited quartet is actually lower than that in the ground quartet represents an apparent anomaly for which there is at present no theoretical understanding.

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