First excited $A = 9$ isospin quartet*

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The first excited state of ^{9}C and its analog in ^{9}B have been observed, and their mass excesses and widths have been measured. This completes a new mass quartet which differs from the predictions of the isobaric multiple mass equation less significantly than the ground state $A = 9$ quartet.

[NUCLEAR REACTIONS ^{12}C(^{3}He, ^{6}He), $E = 74$ MeV measured E_x of ^{9}C first excited state. ^{11}B(p, t), $E = 46.5$ MeV, measured E_x of second $T = \frac{3}{2}$ level in ^{9}B. Deduced coefficient of multiplet mass equation for first excited $A = 9$ quartet.]

The mass quartet consisting of the $\frac{3}{2}^-$ ground states of ^{9}Li and ^{9}C and their analogs in ^{9}Be and ^{9}B represents an interesting puzzle since this is the only mass quartet which deviates significantly from the predictions of the isobaric multiplet mass equations (IMME). In a recent paper on this quartet[1] we pointed out the interest in examining the $A = 9$ first excited quartet, which is based on the ^{9}Li $\frac{1}{2}^-$ first excited state. The completion of this quartet could help answer the question of why the $A = 9$ ground state quartet stands out from the 16 other complete quartets. If the phenomenon were simply the effect of the low mass number, any low mass quartet might show a deviation and particularly another $A = 9$ quartet would be expected to. Also an incorrect value for any of the $A = 9$ masses might cause all of the quartets to deviate in the same way from the predictions of the IMME. For example, if the ^{9}Li ground state mass were wrong (it has been measured only a few times), then this would effect all $A = 9$ quartets equally.

In this note we report on measurements of the mass excess and width of the ^{9}C first excited state and a new narrow state in ^{9}Be which appears to be its analog. The remaining two members, which were already known, are the $\frac{1}{2}^-$ first excited state of ^{9}Li and the second $T = \frac{3}{2}$ state in ^{9}Be, which lies at 16.98 MeV. Neither of the two new states discussed here were observed in previous experiments[1,2] on ^{9}C and ^{9}B because their very negative Q values put them under the elastically scattered particles on the focal plane of the spectrograph. Thus in the present experiment the work of Refs. 1 and 2 was essentially repeated but at 4–5 MeV higher beam energy to make the particles of interest more rigid than the beam.

The first excited state of ^{9}C was studied with the ^{12}C(^{3}He, ^{6}He)^{9}C* reaction at 74 MeV. The calibration was the same reaction to the ground state of ^{9}C. Because the same target, detection angle, beam energy, and detection apparatus were used, the resulting measurement is relatively free of systematic errors. The results are summarized in Table I. In Fig. 1 is shown the spectra taken with two field settings; one for ^{9}C ground state and one for ^{9}C first excited state at the same location on the focal plane. This mass measuring technique has been discussed in previous papers.[3] The peak corresponding to the first excited state has a noticeable width because it is unbound to allowed proton decay. The centroid of the broad peak was used as a measure of its mass excess, but the large width of the state prevents a high precision determination.

The second $T = \frac{3}{2}$ level in ^{9}B was studied with the ^{11}B(p, t)^{9}B reaction at 46.5 MeV. A narrow peak was observed at the excitation energy predicted by the IMME. This peak tracked correctly kinematically from 6° to 20° and is therefore associated with ^{9}B. The 8° spectrum from a 5 cm long position sensitive detector on the focal plane of

TABLE I. Second $T = \frac{3}{2}$ levels in $A = 9$ nuclei.

T_z	Nucleus	Mass excess	E_x (keV)	Γ (keV)	Ref.
$\frac{3}{2}$	^{9}Li	27 657 ± 7	2691 ± 5	Bound	a
$\frac{1}{2}$	^{9}Be	28 325.7 ± 1.4	16 977.3 ± 1.5	≤0.5	b
$-\frac{1}{2}$	^{9}B	29 492 ± 4	17 076 ± 4	22 ± 5	This work
$-\frac{3}{2}$	^{9}C	31 131 ± 11	2219 ± 10	100 ± 20	This work

[a] P. H. Nettles, D. C. Hensley, and T. A. Tombrello, in *Proceedings of the Second 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. 819. R. Middleton and D. J. Pullen, Nucl. Phys. 51, 50 (1964).

[b] W. L. Imhof, L. F. Chase, Jr., and D. B. Fossan, Phys. Rev. 139, B904 (1965). J. B. Woods and D. H. Wilkinson, Nucl. Phys. 61, 661 (1965).

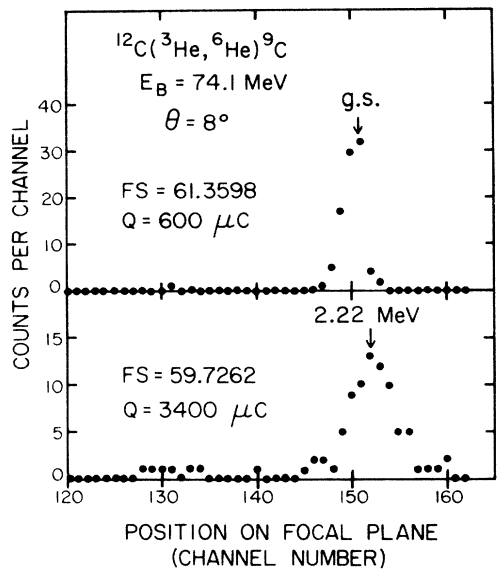

FIG. 1. Spectra from the $^{12}C(^3He,^6He)^9C$ reaction at two different field settings. The peak on the lower spectrum is due to the first excited state of ^9C. One channel is equivalent to 20 keV in excitation energy.

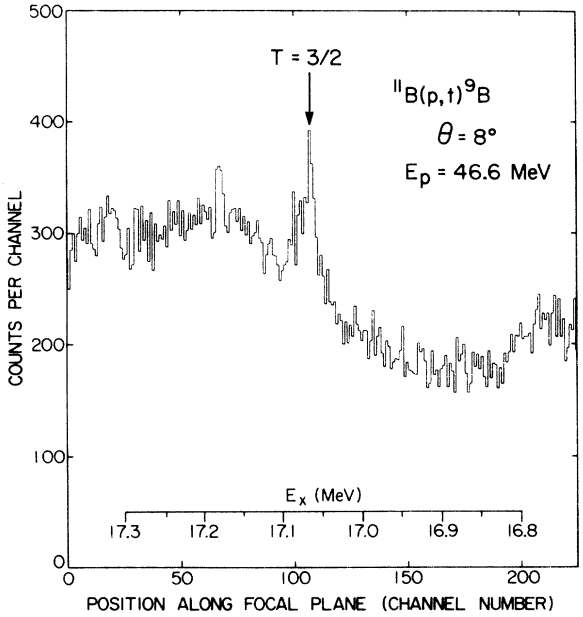

FIG. 2. Spectrum from the $^{11}B(p,t)^9B$ reaction at 46.6 MeV and 8°.

the spectrograph is shown in Fig. 2. The excitation energy given in Table I is based on the $^{11}B(p,t)^9B$ reaction to the first $T=\frac{3}{2}$ level, which is now known to a high accuracy.[1] The $^{12}C(p,t)^{10}C$ reaction to the first excited state was also used. The indication from this and previous work[1] is that the excitation energy for the first excited state of ^{10}C should be 3350.0 ± 1.0 as compared to the previous most accurate measurement 3352.7 ± 1.5.[4]

The parameters found by fitting a quadratic and a cubic IMME to the mass excesses of the two complete quartets in $A=9$ are given in Table II. The new quartet based on the first excited states does not show a significant deviation from the predictions of the IMME yet the resulting d coefficient does not differ from that of the ground state either. The presence of two members which have an appreciable width does not enhance the d coefficient. This may be an accidental effect due to cancellation of two phenomena; the displacement of the ^9B state due to mixing with $T=\frac{1}{2}$ states and the expansion of the wave function of the unbound ^9C state. The b and c coefficients for the two quartets are markedly different, but this can be explained even within the framework of the most simple model, a uniformly charged sphere, which predicts

$$\frac{\Delta b}{\Delta c} = -(A-1) = -8 \ ,$$

in this case the experimentally determined ratio is -7 ± 1. Or in geometric terms an increase in the charge radius of the nucleus can account for the change in the coefficients. However, this simple model does not account for the relative change in b and c in higher A multiplets[5] but should be modified to at least include the fact that exciting the nucleus mainly affects the radius of the valence particles. Attempts to make more serious shell model calculations are hindered by the absence of $p_{3/2}$ single particle energies for ^5Li and ^5He, which are both unbound.

The present results do not answer the question

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

^9Li excitation energy	J^π	a	b	c	d	X^2
Ground state	$\frac{3}{2}^-$	26 337.9 ± 1.6	−1320.1 ± 1.6	265.6 ± 1.6	···	19
2.691 MeV	$\frac{1}{2}^-$	28 846.2 ± 2.1	−1162.2 ± 3.1	244.6 ± 3.1	···	1.8
Ground state	$\frac{3}{2}^-$	26 339.2 ± 1.6	−1332.4 ± 3.2	266.6 ± 1.6	7.6 ± 1.6	···
2.691 MeV	$\frac{1}{2}^-$	28 848.2 ± 2.6	−1167.3 ± 4.9	242.6 ± 3.4	4.2 ± 3.1	···

of why the $A = 9$ ground state quartet is the only one to deviate significantly from the predictions of the IMME. The ambiguousness of the results, however, is due to the relatively large experimental error and leads one to wonder; if all the quartets were known with the accuracy of the $A = 9$ ground state quartet, how many would deviate significantly? Alternately, since very accurate measurements are needed to observe deviations, the IMME can be used with confidence to predict unknown masses or to calculate Coulomb energies in an incomplete multiplet.

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