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THE MASS 13 T = 3/2 QUARTET*

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The completion of isobaric multiplets of four or more members permits an independent test of the isobaric multiplet mass equation[1], which is based on the assumption of charge independence of nuclear forces. A first such study[2] completed the mass nine T = 3/2 quartet through the determination of the mass of ^{9}C. We would like to report measurements of the lowest T = 3/2 states in ^{13}C, ^{13}N, and ^{13}O, thereby completing a second quartet.

It has been shown previously[3] that the (p,t) and (p,^{3}He) reactions are valuable spectroscopic tools in the study of high isospin states. We have used these reactions to locate the T=3/2 levels in ^{13}N and ^{13}C via the $^{15}N(p,t)$ and $^{15}N(p,^{3}He)$ reactions. These experiments were performed with a 43.7 MeV proton beam from the Berkeley 88" cyclotron. Tritons and ^{3}He particles emitted from a pure ^{15}N gas target were simultaneously detected by a (dE/dx)-E counter telescope which fed a particle identifier[4]. Figure 1 shows energy spectra for both the $^{15}N(p,t)^{13}N$ and $^{15}N(p,^{3}He)^{13}C$ reactions with typical resolutions (FWHM) of 150 keV.

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The lowest T=3/2 states in ^{13}C and ^{13}N are expected to lie near 15.3 MeV excitation, as calculated from the ^{13}B mass after correction for Coulomb energy and neutron-hydrogen atom mass differences. As previously reported[5], two new states near 15 MeV excitation are observed in these reactions—they are the presumed T=3/2 ground state analogs and lie at 15.065 ± 0.037 and 15.103 ± 0.045 MeV in ^{13}N and ^{13}C, respectively. These new analog states are sharp, with a resolution comparable to that of the respective ground state transitions; this is consistent with a T=3/2 assignment since there are no T=3/2 channels energetically available for decay.

The angular distributions confirm these assignments. To first order, the $(p,^3He)$ reaction proceeds via the pick-up of a ^1S,T=1 or ^3S, T=0 neutron-proton pair whereas the (p,t) reaction is restricted to ^1S, T=1 two-neutron pick-up. Therefore, one might in general expect the angular distributions of the T=1/2 mirror states of ^{13}C and ^{13}N formed in these reactions to differ in shape and/or magnitude. Marked differences are generally observed in such transitions, as exemplified by the ground state transitions shown in Fig. 2. However, assuming the charge independence of nuclear forces, transitions to the analog states proceed from identical initial states to identical final states through only ^1S, T=1 pick-up of the two nucleons. Since these T=3/2 states, analogs of the known ^{13}B ground state $(3/2-)$[6], must also be $3/2^-$, conservation of angular momentum and parity restrict the transitions populating them to an L=2 transfer. (Angular distributions to known states in ^{13}N requiring solely L=0 or L=2 transfer are shown in Fig. 2 for comparison.) Identical cross sections with L=2 behavior are therefore expected for these analog transitions, after isospin coupling and phase space corrections[3]. Indeed, Fig. 2 shows

that the angular distributions in question are essentially identical and that both distributions show the same structure as the known L=2 transfer to the ^{13}N(7.38 MeV, $5/2^-$) state [7].

The (^3He,^6He) reaction has been used previously [2] to obtain the mass of ^9C and was employed here to measure the ^{13}O ground state mass, thus completing the quartet. A 65.3 MeV ^3He beam was focused on an ^{16}O gas target from which emergent ^6He particles were separated by means of a particle identifier (general experimental details are given in reference 2). Typical resolutions (FWHM) were 250 keV. Simultaneous measurement of the ^6Li spectra, in conjunction with a ^6He-^6Li vs. pulser calibration, permitted absolute energy measurements.

The particle stability of ^{13}O has been predicted [8] and ^{13}O has been recently observed as a delayed proton emitter [9]. A mass-excess of about 23.0 MeV on the ^{12}C scale is expected. Fig. 3 presents typical $^{16}O(^3He,^6He)^{13}O$ and $^{16}O(^3He,^6Li)^{13}N$ energy spectra. Although there is a fairly high background, one can clearly see the sharp ground state transition in the ^6He spectrum. The average cross section for measurements at four angles between 10 and 20 degrees (lab) was only 1 μb/sr. The experimental mass excess of ^{13}O was found to be 23.11 ± 0.07 MeV.

Within the framework of charge independence of nuclear forces, the masses of the members of an isobaric multiplet are related by [1]

$$M = \underline{a} + \underline{b}T_z + \underline{c}T_z^2$$

This equation can now be tested by predicting the ^{13}O mass from the masses of the other three members of the multiplet. Using our experimental excitations

(^{13}N,T=3/2 at 15.065 ± 0.037 and ^{13}C,T=3/2 at 15.103 ± 0.045 MeV), and the ground state mass-excess of ^{13}B (16.562 ± 0.004 MeV[10]), the mass-excess of ^{13}O is calculated to be 23.11 ± 0.18 MeV. Though the agreement is excellent, the error on the predicted mass is large. Better error limits can be obtained by noting (1) a recent measurement of the ^{14}C(^{3}He, α)^{13}C reaction [11] which populated a sharp state at 15.108 ± 0.014 MeV (which the above has shown to be the lowest T=3/2 state) and (2) a measurement using the ^{11}B (^{3}He,n)^{13}N reaction [12] observing a sharp state at 15.068 ± 0.008 MeV. These data predict a mass excess for ^{13}O of 23.10 ± 0.05 MeV. Essentially complete agreement is also observed in the mass nine quartet [2] where a remeasurement of the ^{9}C mass-excess gave 28.99 ± 0.07 MeV instead of the earlier 28.95 ± 0.15 MeV [2]; the prediction for ^{9}C using the mass equation is 29.00 ± 0.05$_4$ MeV.

The above results comprise the most rigorous test of the isobaric multiplet mass equation to date; the data are sufficient to show that the coefficient of a possible term dT_z^3 in the mass equation is no greater than order $(Z\alpha)c$. (Unfortunately, no explicit theoretical estimate of the expected magnitude of d is available.) This accuracy is clearly sufficient to guide experimental searches for missing members of isobaric multiplets, such as, for example [3], the T=2 states in ^{16}F and ^{16}Ne. However, as noted earlier [2,13], the best method of investigating a charge dependence of nuclear forces through use of the mass equation still remains a detailed study of the mass and/or isospin dependence of the b and c coefficients as more data become available.

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FIGURE CAPTIONS

Fig. 1. Energy spectra of the $^{15}N(p,t)^{13}N$ and $^{15}N(p,^{3}He)^{13}C$ reactions at 22°. The spectra have been adjusted to match the ground state channels. There is a nonlinearity in the triton spectrum at the higher energies.

Fig. 2. a) Angular distributions of the $^{15}N(p,t)^{13}N$ transitions to the ground ($1/2^-$) and 7.38-MeV ($5/2^-$) levels and the angular distribution of the $^{15}N(p,^{3}He)^{13}C$ g.s. ($1/2^-$) transition.

b) Angular distributions for the T=3/2 states at 15.065 MeV in ^{13}N and 15.103 MeV in ^{13}C. The cross sections for the ^{13}C transition have been corrected for phase-space and isospin coupling [3] by the factor of 0.924. The error bars are based on counting statistics only.

Fig. 3. Energy spectra for the $^{16}O(^{3}He,^{6}He)^{13}O$ and $^{16}O(^{3}He,^{6}Li)^{13}N$ reactions at 12°.

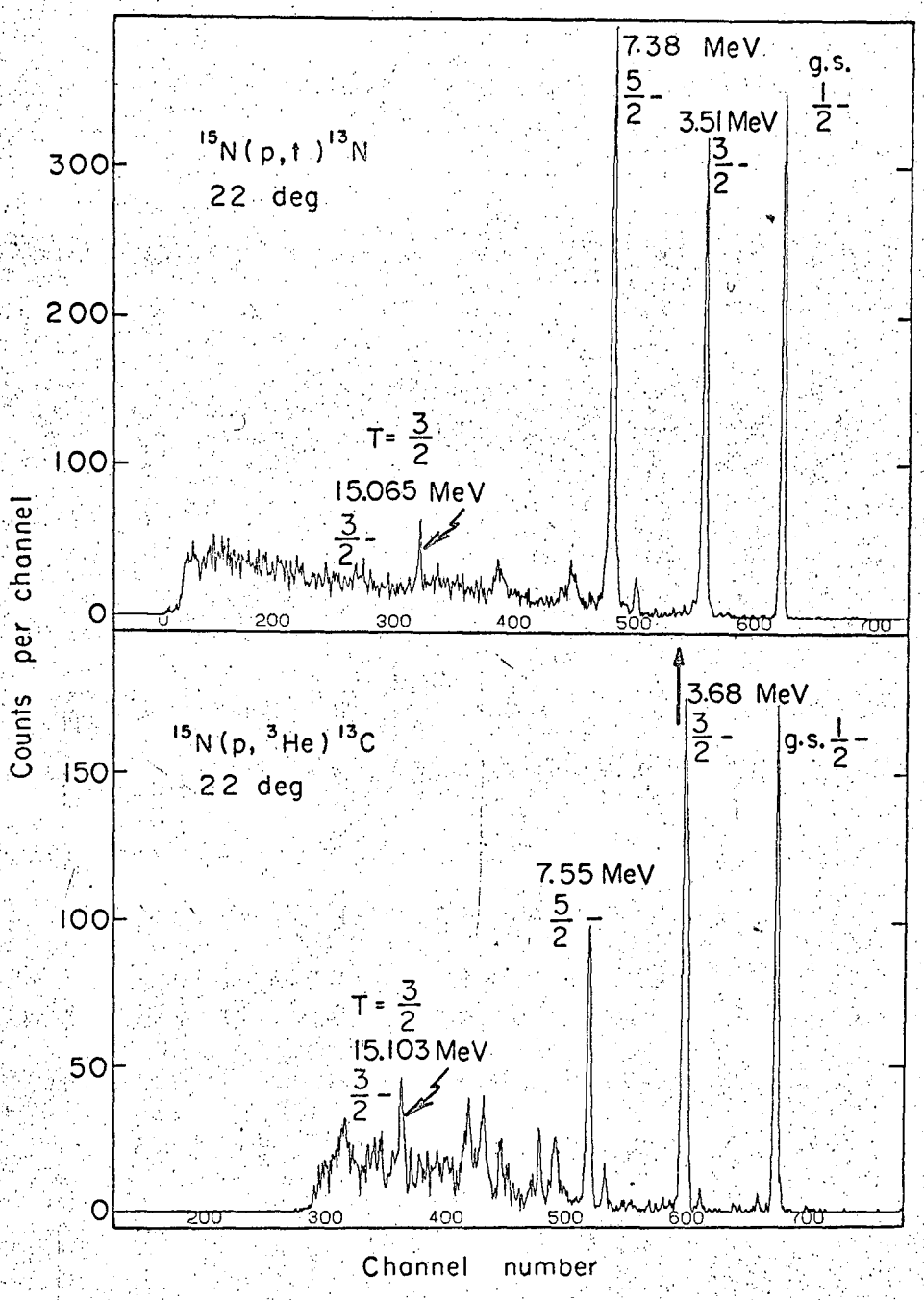
$^{15}N(p,t)^{13}N$
22 deg
7.38 MeV
5/2-
3.51 MeV
3/2-
g.s.
1/2-
T= 3/2
15.065 MeV
3/2-
$^{15}N(p,{}^3He)^{13}C$
22 deg
3.68 MeV
3/2-
g.s. 1/2-
7.55 MeV
5/2-
T = 3/2
15.103 MeV
3/2-
Counts per channel
Channel number
MUB-4742

Fig. 1

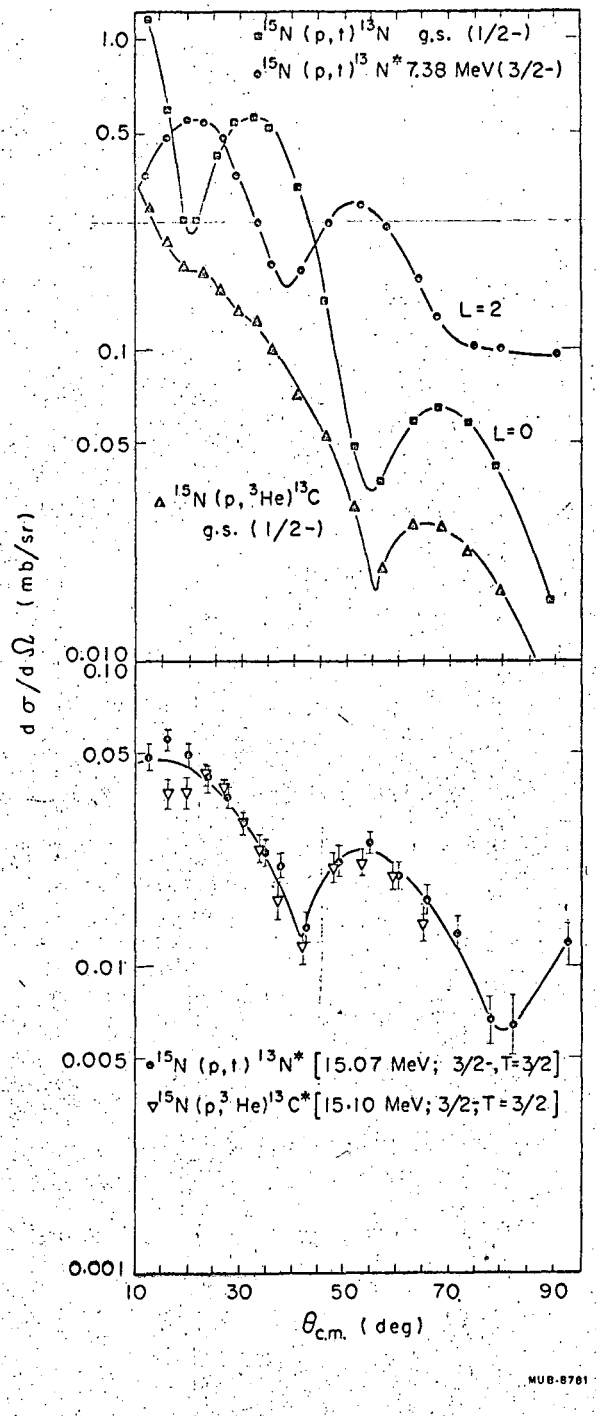
^{15}N (p,t) ^{13}N g.s. (1/2-)
^{15}N (p,t) ^{13}N* 7.38 MeV(3/2-)
L=2
L=0
^{15}N (p, ^{3}He) ^{13}C
g.s. (1/2-)
^{15}N (p,t) ^{13}N* [15.07 MeV; 3/2-, T=3/2]
^{15}N (p, ^{3}He) ^{13}C* [15.10 MeV; 3/2; T=3/2]
d σ/d Ω (mb/sr)
θc.m. (deg)
MUB-8761

Fig. 2

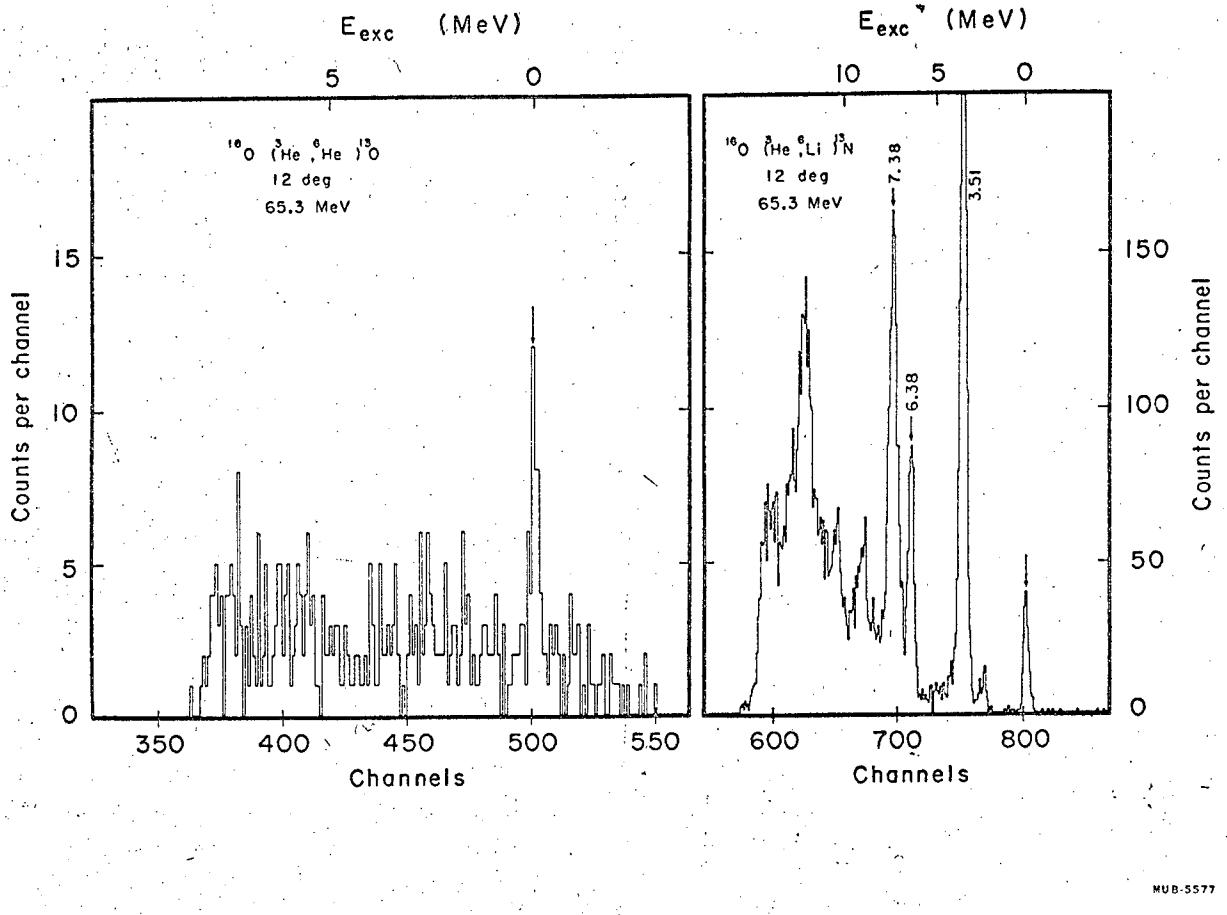
E exc (MeV)
5
0
^{16}O (^{3}He, ^{6}He) ^{13}O
12 deg
65.3 MeV
Counts per channel
15
10
5
0
350
400
450
500
550
Channels
E exc (MeV)
10
5
0
^{16}O (^{3}He, ^{6}Li) ^{13}N
12 deg
65.3 MeV
7.38
6.38
3.51
150
100
50
0
Counts per channel
600
700
800
Channels
MUB-5577

Fig. 3