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^{16}N from ^{10}B(^{7}Li,p)

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Results are presented for the reaction ^{10}B(^{7}Li,p)^{16}N, at $E(^7\mathrm{Li})=16.0$ MeV, leading to states up to 6.61 MeV excitation.

Spin-parity combinations in ^{16}N are summarized in a recent compilation.[1] An earlier investigation[2] of the reaction ^{10}B(^{7}Li,p)^{16}N reported results for only five states between 3.3 and 4.4 MeV excitation. The present paper contains complete data for all states up to and including $E_x = 6.61$ MeV.

Experimental details are outlined in Ref. 2. Spectra at two angles are plotted in Fig. 1. Peaks from the reaction ^{10}B(^{7}Li,p)^{16}N are labeled by their excitation energies in ^{16}N. Peaks arising from the (^{7}Li,p) reaction on impurities in the target are labeled by the final nucleus and excitation energy. Data were collected at 22 angles for states up to 6.4 MeV. Above that energy, states begin to be lost off the lower end of the focal plane at the most backward angles.

Data were analyzed for the reaction of interest and for all identifiable impurity reactions. Angular distributions of impurity groups were interpolated at angles at which they were obscured by a peak of ^{16}N, in order to be able to approximately subtract out their contributions at those angles.

Listed in Table I are J^π and E_x values from Ref. 1, and excitation energies measured in the present work. The latter are averages at (usually) 22 angles and appear to have uncertainties of about 3 keV. Angular distributions are plotted in Fig. 2, and angle integrated cross sections are listed in Table I for the range 0°–90° and 0°–180°. Error bars in Fig. 2 include statistical errors and uncertainties arising from subtraction of background and impurity peaks.

Up to about 7 MeV excitation, we observe all known states of ^{16}N, except for the ones with large widths. The sensitivity of the present experiment is such that states with widths $\Gamma \gtrsim 200$ keV are too weak to observe. Our peak corresponding to the 4.39-MeV state is slightly narrower (50–60 keV) than the 82 ± 20 keV width in the compilation, but not really in disagreement. Our results for the 4.78-MeV state are consistent with a width of about 60 keV. For other states, our resolution does not allow accurate width determinations. (Other than the two states just mentioned, there are *no* levels with widths in the range 40 keV $\leq \Gamma \leq$ 200 keV.) We appear to populate two states not previously known—at $E_x = 5.318$ and 6.002 MeV, both of which are much too narrow to correspond to known states at 5.24 and 6.01 MeV, with widths of 320 ± 80 and 270 ± 30 keV, respectively. We discuss these two new levels further in the following.

Of the previously-known states that we observe below $E_x = 6$ MeV, all now have J^π assignments, except for the 5.13-5.15-MeV doublet. We can thus extract values of

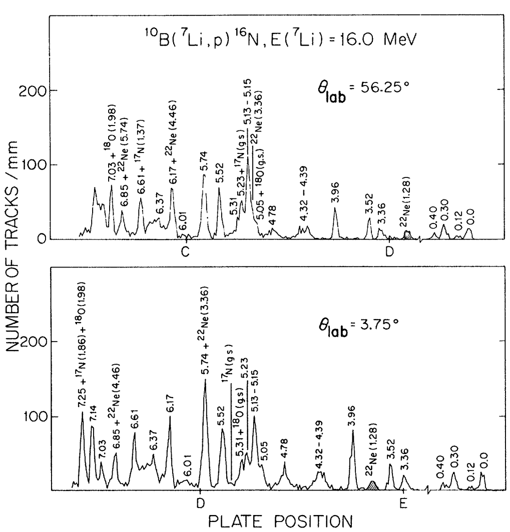

FIG. 1. Spectra for the reaction ^{10}B(^{7}Li,p)^{16}N, at the bombarding energy 16.0 MeV and laboratory angles of 56.25° (top) and 3.75° (bottom).

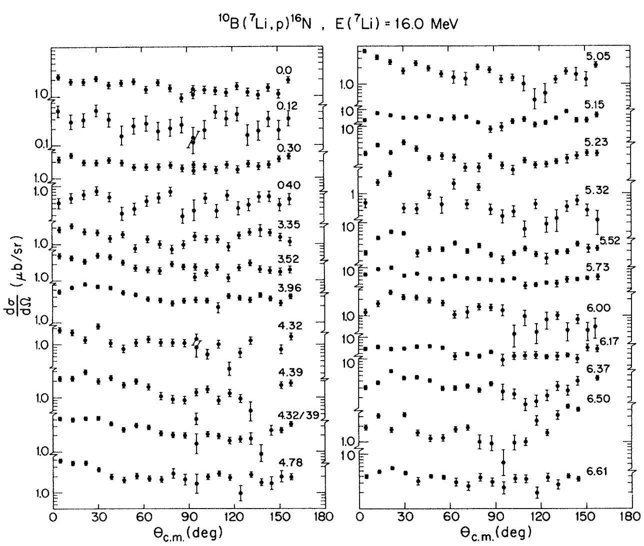

FIG. 2. Angular distributions for the reaction ^{10}B(^{7}Li,p)^{16}N.

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TABLE I. Results of the reaction $^{10}B(^7Li,p)^{16}N$ at $E(^7Li) = 16.0$ MeV.

	Compilation[a]			Present work				
				σ_{tot} (μb)		σ_{tot} (0°–180°)	$\sigma_{tot}/2J+1$ (μb)	
J^π	E_x (MeV±keV)	Γ (keV)	$E_x{}^c$ (MeV)	0°–90°	0°–180°	σ_{tot} (0°–90°)	0°–90°	0°–180°
2^-	0.0		−0.005	10.20±0.41	18.66±0.55	1.83±0.09	2.04±0.08	3.73±0.11
0^-	0.1201±0.5		0.124	1.63±0.16	3.32±0.23	2.04±0.24	1.63±0.16	3.32±0.23
3^-	0.2970±0.7		0.296	11.24±0.43	22.23±0.61	1.98±0.09	1.61±0.06	3.18±0.09
1^-	0.3975±0.7		0.400	3.55±0.24	6.85±0.34	1.93±0.17	1.18±0.08	2.28±0.11
1^+	3.355 ±5	15±5	3.352	8.23±0.34	16.78±0.50	2.04±0.10	2.74±0.11	5.59±0.17
2^+	3.519 ±5	3	3.524	12.87±0.43	22.84±0.59	1.77±0.08	2.57±0.09	4.57±0.12
3^+	3.960 ±5	≤2	3.964	20.75+0.54	37.72±0.74	1.82±0.06	2.96±0.08	5.39±0.11
1^+	4.319 ±5	20±5	4.321	7.51±0.32	13.29±0.47	1.77±0.10	2.50±0.11	4.43±0.16
1^-	4.387 ±6	82±20	4.392	10.03±0.36	17.20±0.52	1.71±0.08	3.34±0.12	5.73±0.17
Sum of the two above			4.373	17.52±0.49	29.68±0.66	1.69±0.06	2.92±0.08	4.95±0.11
1^-	4.76 ±50	250±50						
2^+	4.776 ±10	59±8	4.785	13.49±0.43	24.92±0.60	1.85±0.07	2.70±0.09	4.98±0.12
2^{-b}	(4.90 ±10)	Broad						
2^-	5.050 ±6	19±6	5.054	12.09±0.40	20.28±0.54	1.68±0.07	2.42±0.08	4.06±0.11
≥2	5.130 ±7	≤7±4	5.142	42.07±0.77	82.2 ±1.11	1.95±0.04		
$(2,3)^-$	5.150 ±7	≤7±4						
3^+	5.232 ±5	≤4	5.230	17.99±0.49	32.89±0.68	1.83±0.06	2.57±0.07	4.70±0.10
			5.318	6.11±0.29	8.91±0.36	1.46±0.09		
1^+	5.24	260						
2^-	5.25 ±70	320±80						
3^+	5.518 ±6	≤7±4	5.525	23.68±0.57	41.70±0.77	1.76±0.05	3.38±0.08	5.96±0.11
(5^+)	5.730 ±6	≤7±4	5.734	42.47±0.76	78.0 ±1.1	1.84±0.04	(3.86±0.07)	(7.09±0.10)
			6.002	10.33±0.37	15.35±0.46	1.49±0.07		
1^-	6.009 ±10	270±30						
(4^-)	6.168 ±4	≤7±4	6.172	35.14±0.69	64.82±0.96	1.84±0.05	(3.90±0.08)	(7.20±0.11)
(3^-)	6.373 ±6	30 ±6	6.374	22.58±0.54	39.96±0.76	1.77±0.05	(3.23±0.08)	(5.71±0.11)
	6.426 ±7	300±30						
1^+	6.513 ±6	34 ±6	6.504	10.01±0.36	24.64±0.69	2.46±0.11		
	6.613 ±6	≤7±4	6.608	22.91±0.55	43.42±0.85	1.90±0.06		

[a]Reference 1.
[b]From Ajzenberg-Selove, Nucl. Phys. A166, 1 (1971).
[c]±3 keV.

$\sigma_{tot}/2J+1$, and these are listed in Table I. Values of σ_{tot} (0°–180°) are plotted vs $2J+1$ in Fig. 3. Because of incomplete separation of the 4.32-4.39-MeV doublet, we plot the combined yield as a single point with $2J+1=6$. The g.s. quadruplet are significantly weaker than all other states, for reasons that we do not understand. It may be that their one-particle—one-hole character is so pure that an isospin (or some other) selectivity inhibits their cross section below that expected for a statistical compound-nucleus process. This point clearly deserves further analysis, but we leave it for now. For reasons discussed in the following, we have not plotted in Fig. 3 results for the 5.05- and 5.52-MeV states. The average value of $\sigma_{tot}/2J+1$ for all other single states of known J is then

$$\left\langle \frac{\sigma_{tot}}{2J+1} \right\rangle = 5.00 \pm 0.36 \ \mu b \ .$$

We use this result to estimate J for states without unique J^π assignments, by assuming that the angle-integrated cross section is proportional to $2J+1$. We thus define

$$R \equiv \frac{\sigma_{tot}/2}{5.00 \pm 0.36} - \frac{1}{2} \ .$$

For an unresolved doublet of states, we use

$$S_D \equiv \frac{\sigma_{tot}/2}{5.00 \pm 0.36} - 1.0 \ .$$

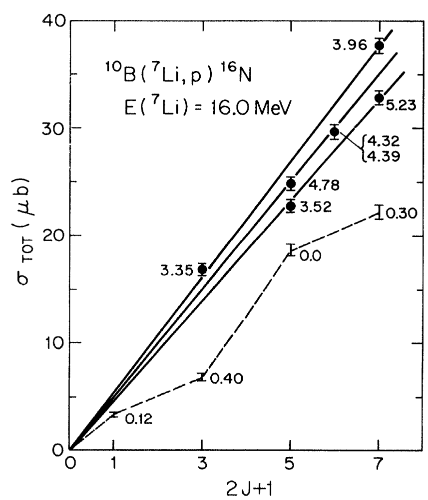

FIG. 3. Values of σ_{tot} vs $2J+1$ for $^{10}B(^7Li,p)^{16}N$ leading to states of known J^π.

TABLE II. J values in ^{16}N for states observed in ^{10}B(^{7}Li,p).

E_x (MeV)	R (or S_D)[a]	Actual J^{π} [b]	Remarks
3.35	1.18±0.17	1^+	
3.52	1.78±0.22	2^+	
3.96	3.28±0.35	3^+	
4.32	0.83±0.14	1^+	
4.39	1.22±0.18	1^-	
4.78	1.99±0.24	2^+	
5.05	1.50±0.20	2^-	See text
5.13 } 5.15 }	ΣJ =7.2 ±0.7	≥2 } (2,3)$^-$ }	ΣJ =7, 8, or 6
5.23	2.79±0.30	3^+	
5.31	0.39±0.10		J =0 or 1 assigned
5.52	3.67±0.38	3^+	See text
5.73	7.3 ±0.7(6.8±0.7)	5^+	Other member of doublet has J =2,1(3)
6.01	1.04±0.16		Probably J =1
6.17	6.00±0.56 (5.5 ±0.56)	(4^-)	Probable doublet; other member has J =1 or 2
6.37	3.50±0.36	(3^-)	
6.51	1.96±0.25[c] (1.46±0.25)	1^+	If doublet, other member has J =0 or 1
6.61	3.84±0.40 (3.34±0.40)		Probably J =4 if a single state

[a] $R \equiv \frac{\sigma_{\rm tot}/2}{5.00\pm0.36} - \frac{1}{2}$; $S_D \equiv \frac{\sigma_{\rm tot}/2}{5.00\pm0.36} - 1.0$.
[b] Reference 1.
[c] Becomes 1.35±0.20 if we use only 0°–90° data.

Within the validity of our assumptions we expect R to equal the J value for a single state and S_D to equal the sum of the J values for an unresolved doublet. The J values we would expect from the observed $\sigma_{\rm tot}$'s are listed in Table II.

The uncertainties in R (or S_D) are computed by adding linearly the percentage uncertainties in $\sigma_{\rm tot}$ and $\langle \sigma_{\rm tot}/2J+1 \rangle$. Values of R for states at E_x =3.35, 3.52, 3.96, 4.78, and 5.23 MeV are within their uncertainties of the known J values. For the 4.32-4.39-MeV pair of states, the slightly larger deviations (in opposite directions) probably indicate the incomplete separation of these two states in the spectra.

The 5.05-MeV level (with Γ=19±6 keV) has an assignment of $J^{\pi}=2^-$ in the compilation, apparently from an admixed $L=1+3$ angular distribution[3] in ^{14}N(t,p). However, ^{15}N(n,n) assigns[4] $J^{\pi}=1^-$ to a state at E_x =5.050 MeV, with Γ=35 keV. A state at 5.032 MeV is said[5] to be reached via $l=2$ in ^{15}N(d,p), whereas ^{18}O(d,α) observes[6,7] a state of 5.065 MeV, apparently with unnatural parity.[7] The state is not observed[8] in ^{17}O(d,^{3}He). Our value of R for the 5.05-MeV state is 1.50±0.20—exactly half-way between values expected for $J=1$ and 2. The compiled[1] J value of 2 is only 2.5 error bars away, but it is the largest deviation observed for any states of known J. It may thus be that the 5.05-MeV level is a doublet. If so, the J values must be 1 and 0.

The 5.52-MeV state, which is thought to have $J^{\pi}=3^+$, has R =3.67±0.38, favoring $J=4$ and $J=3$ for a single state. Reference 9 has suggested that this state is in fact an unresolved doublet, with one member having $J^{\pi}=3^+$ and the other being 1^+ or (0-2)$^-$. In the present data, a doublet would have S_D =3.17±0.38, implying $J=0$ for the second member if one state is 3^+. In ^{17}O(d,^{3}He), a state at 5.53 MeV is reached[8] via an apparent $l=0$ pickup, implying $J^{\pi}=2^+$ or 3^+.

It is for the reasons outlined above that we have omitted the 5.05- and 5.52-MeV states from Fig. 3. We now turn to a discussion of all other states in order of excitation energy.

The 5.13-5.15 doublet has S_D =7.2+0.7, implying ΣJ =7, 8, or 6 in order of preference. The compilation[1] lists $J \geq 2$ for the 5.13-MeV state and $J^{\pi}=(2,3)^-$ for the 5.15-MeV level. Results[8] of ^{17}O(d,^{3}He) favor 3^- for the latter, which is reached via $l=1$ in that reaction, and by $l=2$ in ^{15}N(d,p) (Ref. 5). The 5.13-MeV state has a probable $l=(2)$ in ^{17}O(d,^{3}He), implying $J^{\pi}=0^+-5^+$, and $l \geq 2$ in ^{15}N(d,p), in which $l=3$ would require $J^{\pi}=2^+-4^+$. Our best estimate is $J^{\pi}(5.13)=4^+(5^+,3^+)$, with $J^{\pi}(5.15)=3^-(2^-)$, but the combination 3^+, 2^- is extremely unlikely.

The state we observed at 5.32 MeV has $R=0.39\pm0.10$, allowing only $J=0$ or 1, with some preference for $J=0$. Of course, a 0^+-0^- doublet is also possible.

A state at 5.74 MeV has been assigned[10] $J^{\pi}=5^+$ from ^{14}C(α,d), while observation[8] of $l=1$ in ^{17}O(d,^{3}He) suggests negative parity and $J=1-4$ for a state at 5.74 MeV. The ^{14}N(t,p) angular distribution can be fitted[9] with either a sum of $L=1+4$ or $3+4$. In the present experiment, $S_D=6.8\pm0.7$, implying $J=2(1,3)$ for the negative-parity member of the doublet.

Our new 6.01-MeV state has $R=1.04\pm0.16$, implying $J=1$. It is perhaps interesting to note that the level at 6.009 MeV in the compilation, with $\Gamma=270\pm30$ keV, has $J^{\pi}=1^-$. However, as noted above, our level does not have such a large width.

A state at 6.17 MeV has a rather firm 4^- assignment.[8] If our results are for a single state, we have $R=6.00\pm0.56$, and $J=4$ is more than three errors away. We thus suggest an unresolved doublet with $S_D=5.50\pm0.56$, i.e., with the second member having $J=2$ or 1.

The 6.37-MeV level has a probable (3^-) assignment. Our value of $R=3.50\pm0.36$ is consistent with that result.

We observe $R=1.96\pm0.25$ for a state at 6.50 MeV. A 1^+ level is known[1,9] at 6.51 MeV, so we might at first expect another doublet. However, the 6.50-MeV state, alone among all states discussed in the present work, has an enhanced back-angle cross section. If we use only the data for 0°–90°, and compare with the average values for all other states, we get $R=1.35\pm0.20$ or $S_D=0.85\pm0.20$. The former is consistent with a single 1^+ state.

Finally, for the 6.61-MeV level, we get $R=3.84\pm0.40$, implying $J=4$ for a single state or $S_D=3.34\pm0.40$, implying $\Sigma J=3$ or 4 for a doublet. A state at 6.61 MeV is observed in (t,p), with $L=3$ or $2+4$. Combining results, we thus would expect $J^{\pi}=4^-$ for a single state.

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[1]F. Ajzenberg-Selove, Nucl. Phys. A375, 1 (1982).

[2]H. T. Fortune and L. R. Medsker, Phys. Rev. C 12, 1364 (1975).

[3]D. J. Crozier and H. T. Fortune, Phys. Rev. C 11, 308 (1975).

[4]B. Zeitnitz *et al.*, Nucl. Phys. A166, 443 (1971).

[5]H. Fuchs *et al.*, Nucl. Phys. A196, 286 (1972).

[6]T. I. Bonner, Phys. Rev. C 1, 1699 (1970).

[7]A. M. Baxter *et al.*, Nucl. Phys. A305, 213 (1978).

[8]G. Mairle *et al.*, Nucl. Phys. A299, 39 (1978).

[9]H. T. Fortune, Phys. Rev. C 17, 861 (1978).

[10]C. C. Lu, M. S. Zisman, and B. G. Harvey, Phys. Rev. 186, 1086 (1969).