Levels at 5.5–8.5 MeV in ^{16}N from ^{14}N(t,p)

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Earlier ^{14}N(t,p)^{16}N data for levels between 5.5 and 8.5 MeV excitation have been subjected to a distorted-wave Born-approximation analysis in order to extract L values and place limits on J^{π}. Three 1^+ levels are located at 6422, 6512, and 7006 keV, and possibly at 5520 keV. Several levels are suggested to be unresolved doublets.

[NUCLEAR REACTIONS DWBA analysis of ^{14}N(t,p), $E(t)=12.0$ MeV; ^{16}N levels deduced, L, J^{π}. $E_x=5.5-8.5$ MeV.]

I. INTRODUCTION

In an earlier paper,[1] previously published data from the ^{14}N(t,p)^{16}N reaction[2] (at $E_t=12$ MeV) were analyzed in the distorted-wave Born approximation (DWBA) and compared with results of a $1p_{1/2}$-$1d_{5/2}$-$2s_{1/2}$ shell-model calculation.[3] That analysis considered only levels up to 6.3 MeV excitation, even though the original data went higher, because at the time little was known about the higher-lying levels of ^{16}N. Since then, additional information on ^{16}N has become available,[4,5] and it was felt that a DWBA analysis of the (t,p) data to higher states could yield useful information.

It is still not possible to assign correspondences between experimental and theoretical levels at these high excitation energies. But angular-distribution shapes are characterized by the L transfer rather than by the microscopic configurations of the transferred neutrons. Thus L values can be assigned without detailed shell-model wave functions.

The DWBA calculations were performed with the two-particle transfer option of the code DWUCK.[6] Optical-model parameters were the same as those used in Ref. 1. The present work includes all states observed in the earlier (t,p) experiment between 5.5 and 8.5 MeV excitation. There is some overlap with the earlier DWBA analysis, in order to be complete, since some of the new information[4,5] affects the earlier analysis.

II. ANALYSIS AND DISCUSSION

Angular distributions are presented in Figs. 1–4. The data are from Ref. 2. Curves are from DWBA calculations. We discuss each level, in turn, below. Results are listed in Table I.

5520 keV. The angular distribution for this state was fitted with $L=1(+3)$ in Ref. 1, suggesting $J^{\pi}=(2^-)$. However, the latest compilation[4] lists $J^{\pi}=(1,2,3)^+$. This level is observed[7] with $l=3$ in ^{15}N(d,p) and has a good $L=2$ angular distribution[8] in ^{14}C(^{3}He,p). These results require positive parity and $J=1-3$. It is assigned[5] $l=0$ in ^{17}O($d,^3$He), giving $J^{\pi}=2^+$ or 3^+. We have refitted the ^{14}N(t,p) angular distribution with even L values (Fig. 1). A mixture of $L=2+4$ gives a good fit except at the first two angles. The first two data points appear to require either $L=0$ or $L=1$. Either mixture ($0+2+4$ or $1+2+4$) implies the presence of a doublet. Thus, if we combine all the data, we must have two states—possible combinations are 1^+ and $(2,3)^+$ or $(0-2)^-$ and 3^+. The ^{17}O($d,^3$He) results[5] are consistent with a doublet interpretation—$l=0$ does not give a very good fit. A mixture of $l=0+1$ would appear to produce better agreement.

5730 keV. A 5^+ state is known[4,9] to exist here from a strong $L=4$ in ^{14}C(α,d). This level also has an $L=4$ angular distribution[8] in ^{14}C(^{3}He,p). In ^{14}N(t,p), the angular distribution has an $L=4$ component, but the forward-angle data were not well fitted in Ref. 1. Also, this state was much stronger in (t,p) than expected for the first 5^+ state. In ^{17}O($d,^3$He), this state was assigned[5] $l=1$, implying $J^{\pi}=(1,2,3,4)^-$. Thus, this state also appears to be a doublet. We have refitted the (t,p) angular distribution (Fig. 2) with a mixture of L values. An admixture of $L=3+4$ gives the best fit; a fit with $L=1+4$ is possible, but not as good.

6009 keV. This level, which has a good $L=1$ angular distribution in ^{14}N(t,p), now has a 1^- assignment.[4]

6167 keV. The ^{14}N(t,p) angular distribution for this state is well fitted by $L=3$, though a mixture of $L=2+4$ also gives reasonable agreement. This level has an assignment[4] of $(2,3,4)^-$ in the compilation and has an $l=1$ angular distribution[5] in ^{17}O($d,^3$He), with a large spectroscopic factor. A $(4)^-$ assignment is suggested[5] by comparison with

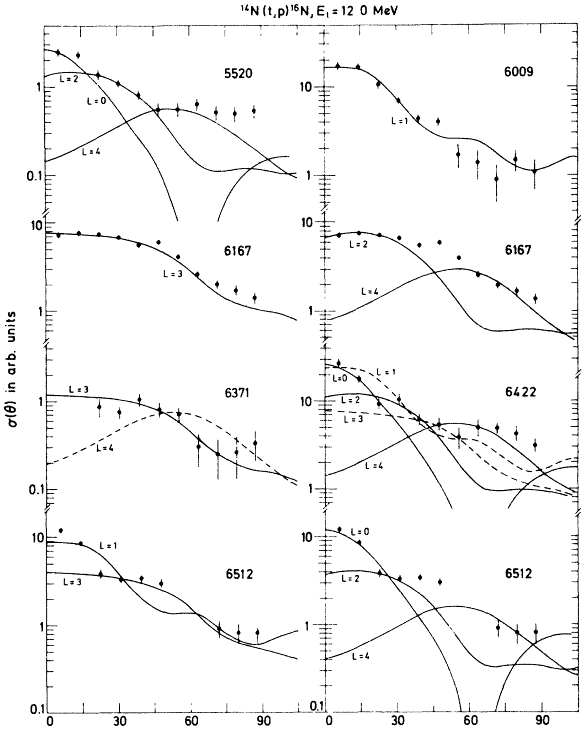

FIG. 1. Angular distributions for $^{14}N(t,p)^{16}N$ leading to levels between 5.5 and 6.6 MeV excitation. Data are from Ref. 2. Curves are results of DWBA calculations. Bombarding energy was 12 MeV.

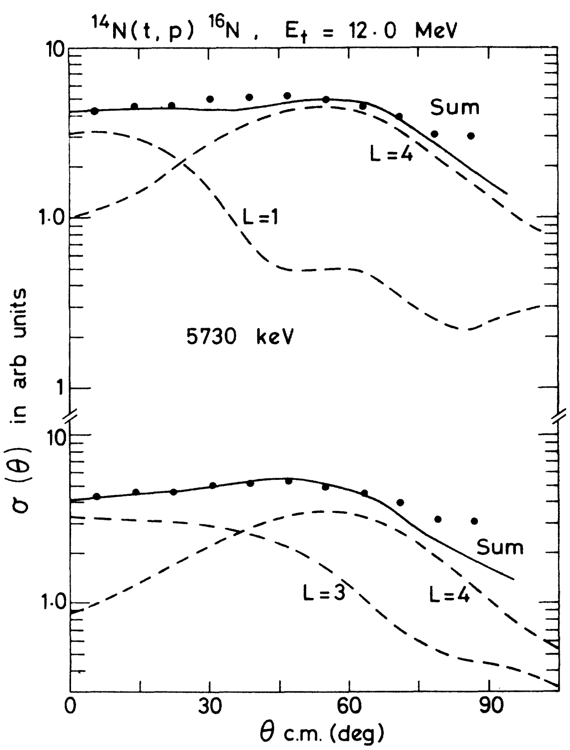

FIG. 2. Same as Fig. 1, but for the 5.73 MeV state.

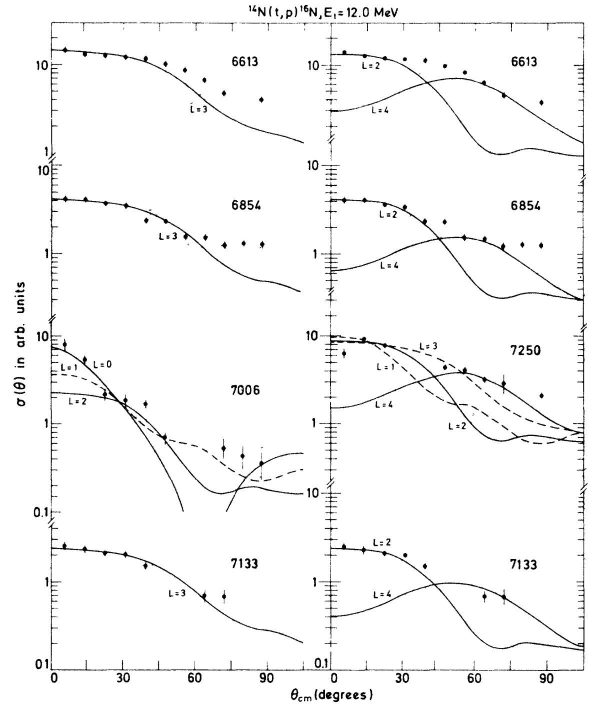

FIG. 3. Same as Fig. 1, but for states between 6.6 and 7.5 MeV excitation.

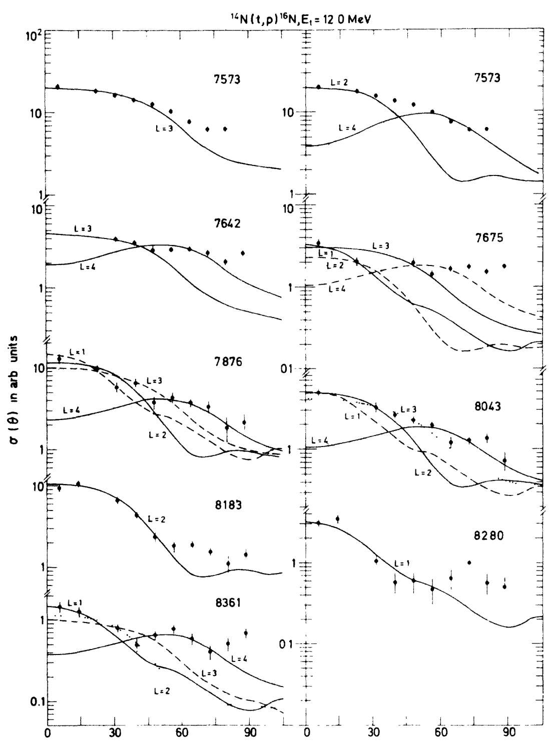

FIG. 4. Same as Fig. 1, but for states between 7.5 and 8.5 MeV excitation.

$T=1$ levels in ^{16}O.

6371 keV. In the compilation,[4] this state has a $(3)^-$ assignment which is made firm[5] in $(d,{}^3\text{He})$. The (t,p) angular distribution is incomplete, but is well fitted by $L=3$ (Fig. 1).

6422 keV. This state has no J^π assignment in the compilation.[4] The (t,p) angular distribution (Fig. 1) requires an $L=0$ component because of the rapid rise at forward angles. But an additional, large, L value is also present. A mixture of $L=0+2$ does not produce a good fit. Best agreement is obtained with $L=0+4$. Thus, this state also appears to be a doublet, one member having $J^\pi=1^+$.

6512 keV. This level has a $(0,1,2)^+$ assignment in the compilation.[4] Its (t,p) angular distribution has a strong $L=0$ component—implying $J^\pi=1^+$. The best fit is for $L=0+3$, but $L=0+2$ gives acceptable agreement.

6613 keV. The (t,p) angular distribution for this state (Fig. 3) can be fitted either with $L=3$ or $L=2+4$, with some preference for the latter. Thus $J^\pi=3^+$ or $(2,3,4)^-$.

6854 keV. The (t,p) angular distribution for this level also implies $L=3$ or $L=2+4$, but with a slight preference for the former. Thus $J^\pi=(2,3,4)^-$ or 3^+.

7006 keV. This state has a clear $L=0$ component in its angular distribution, giving $J^\pi=1^+$. There is a hint of a small $L=2$ contribution. This is probably the state listed in the compilation at 7020 ± 20 keV, with $J>0$.

7133 keV. The angular distribution for this state is well fitted by $L=3$, though $L=2$ cannot be completely ruled out. Thus $J^\pi=(2,3,4)^-$ or $(1,2,3)^+$.

7250 keV. A state at 7250 ± 7 keV in the compilation has $J\geq2$. The (t,p) angular distribution can be fitted either with $L=3$ or $L=2+4$. Thus, $J^\pi=3^+$ or $(2,3,4)^-$.

7573 keV. This state also has an angular distribution that can be fitted either with $L=3$ or $L=2+4$, implying $J^\pi=3^+$ or $(2,3,4)^-$. The compilation lists $J\geq3$. Thus $J^\pi=3^\pm$ or 4^-.

TABLE I. Levels of ^{16}N between 5.5 and 8.5 MeV excitation.

Literature				^{14}N(t,p)		
E_x (keV)[a]	$J^{\pi\,a}$	E_x[b] (MeV)	$J^{\pi\,b}$	E_x (keV)	L	Remarks
5518 ±6	$(1,2,3)^+$	5.53	$(2,3)^+$	5520	0+2+4 or 1+2+4	Doublet? $3^+ + (0^-,1^\pm,2^-)$
5730±6	5^+	5.74	$(1-4)^-$	5730	1+4 or 3+4	Doublet
6009±10	1^-	···	···	6009	1	
6168±4	$(2,3,4)^-$	6.17	$(4)^-$	6167	3	
6373±6	(3^-)	6.36	3^-	6371	3	
6426±7	···	···	···	6422	0(+ 4) or 0(+ 2)	Doublet? One state is 1^+
6513±6	$(0,1,2)^+$	···	···	6512	0(+ 2)	$J^\pi=1^+$
6613±6	···	···	···	6613	2+4 or 3	$J^\pi=3^+$ or $(2,3,4)^-$
6848±6	···	···	···	6854	3 or 2+4	$J^\pi=(2,3,4)^-$ or 3^+
7020±20	≥1	···	···	7006	0(+2)	$J^\pi=1^+$
7134±7	···	···	···	7133	3 or 2(+4)	$J^\pi=(2,3,4)^-$ or $(2,3)^+$
7250±7	≥2	···	···	7250	2+4 or 3	$J^\pi=3^+$ or $(2,3,4)^-$
7573±6	≥3	···	···	7573	3 or 2+4	$J^\pi=(3,4)^-$ or 3^+
7637±5	···	···	···	7640	4	$J^\pi=(3,4,5)^+$
7675±5	···	7.66	$(2,4)^-$	7675	(1+4)	
7877±9	≥4	···	···	7876	1+4	Doublet?
8048 ±9	···	···	···	8043	2+4 or 3	$J^\pi=3^+$ or $(2,3,4)^-$
8182±9	···	···	···	8183	2(+4)	$J^\pi=(3,2)^+$
8282±8	···	···	···	8280	1	$J^\pi=(0,1,2)^-$
8365±8	≥1	···	···	8361	1+4 or (2+4)	Doublet? $J^\pi=3^+$ if a single state

[a]Reference 4.
[b]Reference 5.

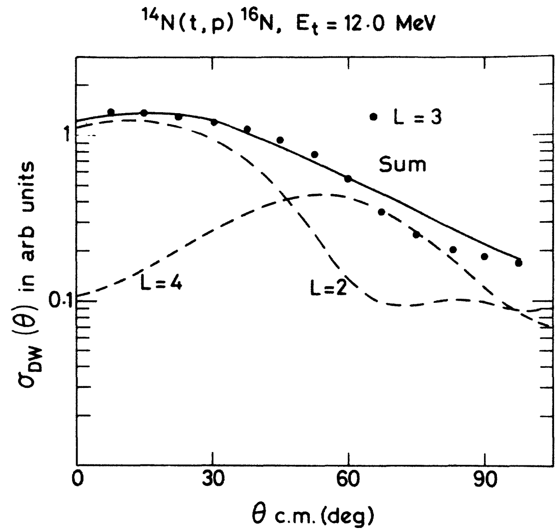

FIG. 5. Comparison of DWBA curves for $L=3$ ("data points") with adjusted mixtures of $L=2$ and 4 (dashed). The summed $L=2+4$ curve (solid) is seen to agree with $L=3$ at all except largest angles.

7640 keV. The angular distribution for this state is well fitted with $L=4$, but forward-angle data are missing, so the absence of $L=2$ cannot be firmly established. Thus $J^\pi=(3,4,5)^+$.

7675 keV. The angular distribution for this state is incomplete. The $^{17}O(d,{}^3He)$ work reports an $l=1$ angular distribution to a state at 7.66 MeV, to which the authors assign $J^\pi=(2,4)^-$. No combination of L values gives a good fit to the (t,p) angular distribution, though the best agreement is with $L=1+4$. Such an admixture, if correct, would require a doublet.

7876 keV. The angular distribution for this state is well fitted with an admixture of $L=1+4$; $L=2+4$ gives an inferior fit. A level at 7877 ± 9 keV is listed in the compilation with $J\geq 4$. An $L=4$ curve alone does not fit the data. This level is probably a doublet.

8043 keV. This state has an angular distribution that can be fitted either by $L=3$ or by a combination of 2+4, implying $J^\pi=3^+$ or $(2,3,4)^-$.

8183 keV. This state has a good $L=2$ angular distribution, with perhaps a hint of a small $L=4$ component. The absence of any $L=0$ contribution argues against 1^+. Thus $J^\pi=(3,2)^+$.

8280 keV. An $L=1$ curve gives a moderately good account of the angular distribution for this state, suggesting $J^\pi=(0,1,2)^-$.

8361 keV. A state is listed in the compilation at 8365 ± 8 keV, with $J\geq 1$. The (t,p) angular distribution is best fitted with $L=1+4$, implying a doublet. However, a combination of $L=2+4$ cannot be completely eliminated. If it is a single state, $J^\pi=3^+$.

III. CONCLUSIONS

A DWBA analysis of earlier $^{14}N(t,p)$ data allows a number of J^π assignments to be made for states in the region $E_x=5.5-8.5$ MeV. 1^+ states are located at $E_x=6422$, 6512, 7006, and perhaps 5520 keV. A number of states are proven or suggested to consist of unresolved doublets. Additional J^π restrictions are placed on most levels in this region of excitation. One difficulty encountered in the present analysis is the ability to reproduce an $L=3$ angular-distribution shape with an admixture of $L=2$ and 4. This is demonstrated in Fig. 5, where we have fitted an $L=3$ DWBA curve (the points) with a mixture of $L=2$ and 4, by requiring the $L=2+4$ curve to pass through the $L=3$ "data" at 15° and 60°. With 5% error bars, the $L=3$ and $L=2+4$ curves are indistinguishable except at very large angles ($\theta\gtrsim 65°$). Usually, at such large angles the uncertainties in the data are rather large. And in any event, the reaction mechanism is somewhat questionable at larger angles.

Preliminary DWBA calculations at a slightly higher bombarding energy (15 MeV) suggest that the relative importance of $L=4$ increases rapidly with increasing bombarding energy. Thus, when data at 15 MeV become available, it should be possible to distinguish between $L=3$ and $L=2+4$ by simultaneously comparing data and calculations at the two energies.

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