STATES IN THE MIRROR NUCLEI ^{16}N AND ^{16}F EXCITED BY THE ^{15}N($\vec{p}$,$\pi^{\pm}$) REACTIONS

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One of the important mechanisms in the (p,π) reaction is creating 2p-1h states with respect to the target. The reaction involves a large momentum transfer which leads to strong transitions with large orbital angular momentum transfer. In the A= 16 region one would expect to see transitions in which a p-shell hole is created and a pair of particles is inserted into the $d_{5/2}$ shell. If the hole is in the $p_{1/2}$ shell then states with configurations $|\, Target*(p_{1/2})^{-1}(d_{5/2})^2\rangle$ are reachable. Some of these states have already been identified from two-particle transfer reactions. If the hole is in the $p_{3/2}$ shell then stretched states with with configurations $|\, Target*(p_{3/2})^{-1}(d_{5/2})^2\rangle$ are reachable. These states are unlikley to be observed in two- or three-particle transfer reactions.

Three reactions were done, ^{14,15}N, ^{16}O($\vec{p}$,π^+) to identify 2p-1h high-spin states in ^{15}N, ^{16}N, and ^{17}O (Ref. 1). Strong states have been observed at high excitation energy, 15.80 MeV in ^{17}O, 14.15 MeV in ^{16}N, and 21.50 in ^{15}N. The cross section and analyzing power distributions of these states have similar shapes. Therefore, we have associated them with previously unknown stretched states with $|\, Target*(p_{3/2})^{-1}(d_{5/2})^2\rangle$ configurations. If these states are the stretched states then they have to be excited through the elementary $pp \rightarrow d\pi^+$ process. That process is not accessible in the (p,π^-) reaction.

In addition to the new strong state at 14.15 MeV, there are also other states seen in the ^{15}N($\vec{p}$,π^+) reaction. Some of them are known, such as the 5.74-MeV 5^+ state[2], while others at 7.59, 11.69, and 16.00 MeV are not. Therefore, the first motivation of the present work, ^{15}N($\vec{p}$, $\pi^{\pm}$) reactions, is to identify high-spin states in ^{16}N by comparing them with those excited in ^{16}F. One thinks that the (p,π^-) reaction has more selectivity, versus the (p,π^+) reaction, for 2p-1h high-spin states, since it proceeds through more restricted path[3]. Second, the ^{15}N($\vec{p}$,π^-) reaction should inform us about the structure of ^{16}F which can be studied with a few reactions only[2]. In fact, the only state known with J greater than 3 is the 1p-1h 4^- state excited in ^{16}O(p,n) (Ref. 4) and (^{3}He,t) (Ref. 5). In the ^{15}N($\vec{p}$,$\pi^{\pm}$) reactions many mirror excited states are expected in both final nuclei; some of these states are listed in Table I. Third, the results should contribute to a better understanding of both the structure of the mass 16 system and the systematics of the (p,π) reaction.

The two reactions were studied with polarized 200 MeV protons. The beam polarization was about 70%. The IUCF-QQSP pion spectrometer was used to detect pions. The targets were V^{15}N and V for background subtraction. The ^{15}N($\vec{p}$,π^+) reaction was run at 110° and 130° (the forward angles had been covered earlier[1]. The ^{15}N($\vec{p}$,π^-) reaction was run at angles between 30° and 110°. The energy resolution was about 220 keV. ^{12}C($\vec{p}$,π^+)^{13}C and ^{13}C($\vec{p}$,π^-)^{14}O reactions were used for energy calibration.

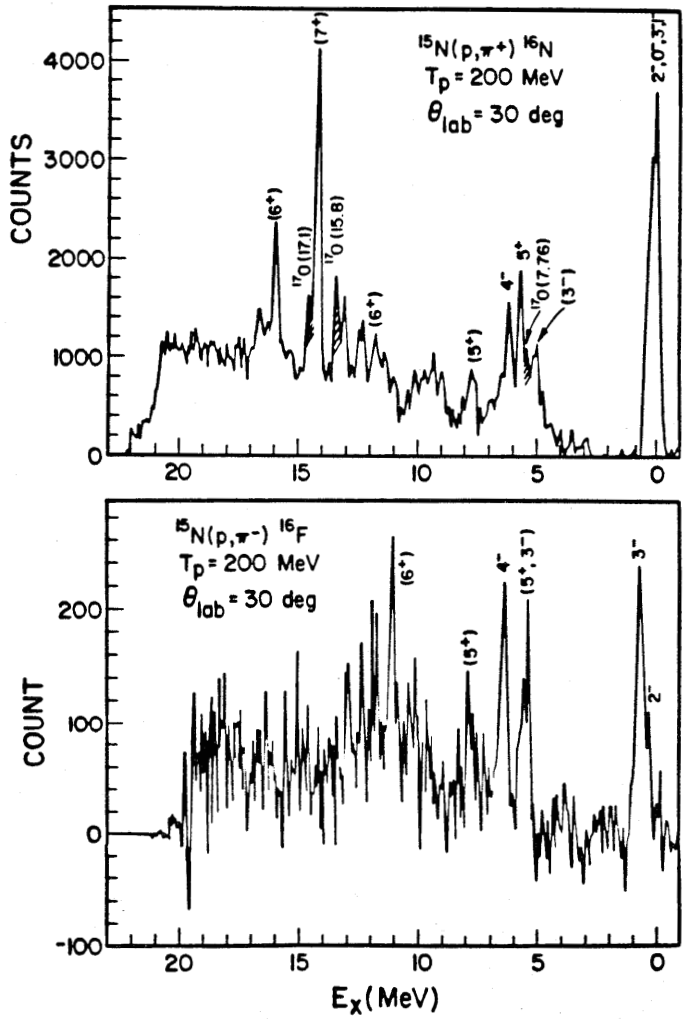
Table I: Mirror Configuration States in ^{16}N and ^{16}F From ^{15}N(p,$\pi^{\pm}$)

Nucleus	Configuration	J^{π}	E_x(MeV)	Struck Nucleon
^{16}N	$\mid {}^{16}O*\ (\pi p_{1/2})^{-1}(\nu d_{5/2})\rangle$	3^-	0.3	p,n
^{16}F	$\mid {}^{16}O*\ (\nu p_{1/2})^{-1}(\pi d_{5/2})\rangle$	3^-	0.7	n
^{16}N	$\mid {}^{16}O*\ (\pi p_{3/2})^{-1}(\nu d_{5/2})\rangle$	4^-	6.17	p
^{16}F	$\mid {}^{16}O*\ (\nu p_{3/2})^{-1}(\pi d_{5/2})\rangle$	4^-	6.37	n
^{16}N	$\mid {}^{16}O*\ (p_{1/2})^{-2}(d_{5/2})^2\ \rangle$	5^+	5.73	p,n
^{16}F	$\mid {}^{16}O*\ (p_{1/2})^{-2}(\pi d_{5/2})^{\ 2}\rangle$	5^+	?	n
^{16}N	$\mid {}^{16}O*\ (\pi p_{1/2})^{-1}(p_{3/2})^{-1}(d_{5/2})^2\ \rangle$	6^+	?	p,n
^{16}F	$\mid {}^{16}O*\ (\pi p_{1/2})^{-1}(\nu p_{3/2})^{-1}(\pi d_{5/2})^2\rangle$	6^+	?	n
^{16}N	$\mid {}^{16}O*\ (\pi p_{1/2})^{-1}(\pi p_{3/2})^{-1}(d_{5/2})^2\rangle$	7^+	?	p
^{16}F		7^+	?	none

^{15}N(p,$\pi^{\pm}$) spectra are plotted in Fig. 1. The ^{15}N(p,π^{+}) spectrum is from Ref. 1, where the target had an oxygen contaminant. There are, in addition to the ground-state quartet, states at 5.57, 5.74 (5^{+}), 6.17 (4^{-}), 7.69, 11.69, 14.15, and 16.00 MeV. In the ^{15}N(p,π^{-}) spectrum, there are states at 0.36 (2^{-}), 0.73 (3^{-}), 5.57, 6.45 (4^{-}), 7.91, and 11.23 MeV.

<u>^{16}N and ^{16}F Ground-State Quartet:</u>

The four low-lying states 0^{-}, 1^{-}, 2^{-}, and 3^{-} are known in ^{16}N at 0.12, 0.40, 0.0, and 0.30 MeV, which correspond to 0.0, 0.19, 0.42 and 0.72 MeV in ^{16}F and to T= 1 analogs at 12.80, 13.09, 12.97, and 13.26 MeV in ^{16}O (Ref. 2). These states are identified as 1p-1h



<u>Figure 1</u>. Typical ^{15}N(p,π^{+})^{16}N and ^{15}N(p,π^{-})^{16}F spectra. The spins of some states are labeled as given by Ref. 1. Others, in brackets, are suggested by the present work.

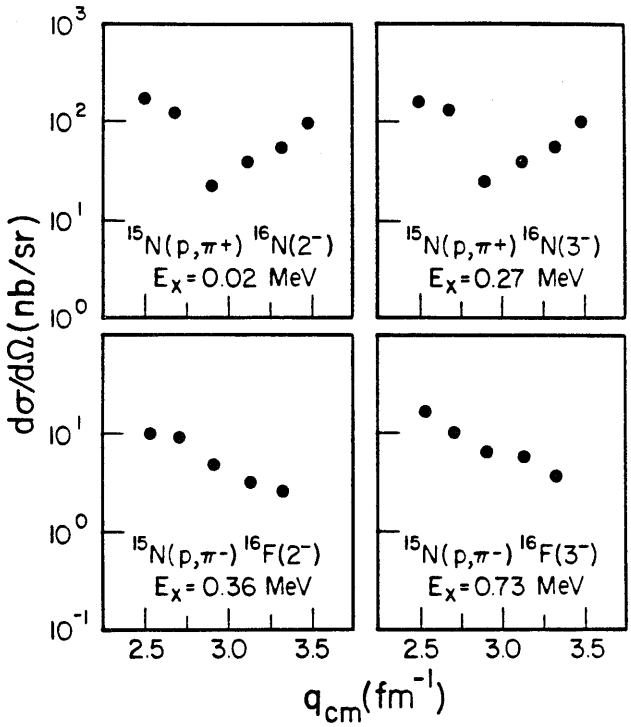


Figure 2. Differential cross section for the ^{15}N(p,π^+) transitions to the ^{16}N ground and 0.27-MeV states (top), and for the ^{15}N(p,π^-) transitions to the ^{16}F 0.37-MeV and 0.73-MeV states (bottom).

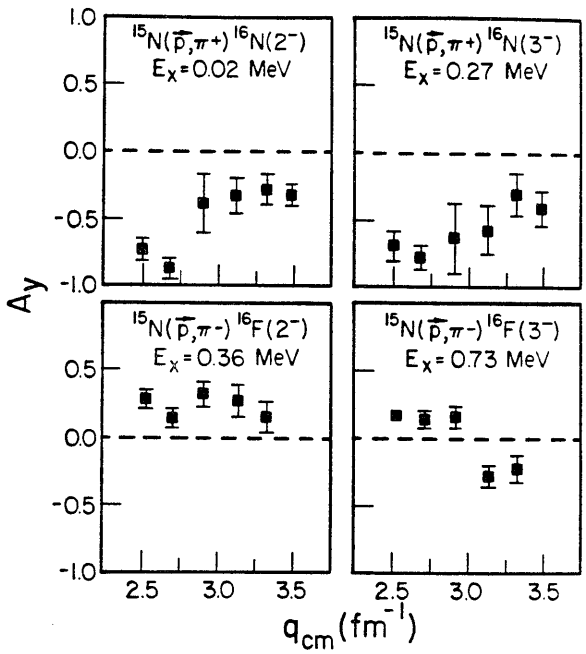


Figure 3. Analyzing power for the ^{15}N(p,π^+) transitions to the ^{16}N ground and 0.27-MeV states (top), and for the ^{15}N(p,π^-) transitions to the ^{16}F 0.37-MeV and 0.73-MeV states (bottom).

states and have mainly the following configurations:

$$|(1p_{1/2})^{-1}(2s_{1/2})\rangle_{0^-,1^-} \text{ and } |(1p_{1/2})^{-1}(1d_{5/2})\rangle_{2^-,3^-}.$$

The four low-lying states in ^{16}N are expected to be excited, but since the energy differences between them are small (with respect to the energy resolution), they look like a 'bump' near zero excitation energy. The energy difference between the ^{16}F states is big enough so the four states should be separated, but we see only the 0.36- (2^-) and 0.73-MeV (3^-) states. That supports the assumption that the ^{15}N(p,π^-) reaction preferentially excites states with higher ΔL.

The cross section distributions of the ground and 0.27-MeV states in ^{16}N and their analogs (0.36- and 0.73-MeV states) in ^{16}F are plotted in Fig. 2. The $d\sigma/d\Omega$(q) of the states in each nucleus are similar and different from those of the other nucleus. Analyzing power distributions of the ^{16}N and ^{16}F states are displayed in Fig. 3. A_y(q) of the ^{16}N states are negative and similar (within the uncertainties), while those of the ^{16}F states tend to be more positive.

^{16}N 6.17-MeV and ^{16}F 6.45-MeV States:

In the ^{15}N(p,π^+) spectrum, a strong state is observed at 6.17 MeV. A state at the same energy has been identified in the ^{15}N(d,p)^{16}N and ^{17}O(d,^{3}He)^{16}N reactions as a 1p-1h 4^-;1 state[6,7]. There is also a strong state in the ^{15}N(p,π^-) spectrum at E_x= 6.45 MeV. A state at 6.37 MeV is observed in other reactions[4,5]. The energies of the observed states, 6.17 MeV in ^{16}N and 6.45 MeV in ^{16}F (in the present work), match the energies (within the uncertainties) of the known 4^- states, and since they are reachable in the ^{15}N(p,$\pi^\pm$) reactions and expected to be excited, we think the 6.17 and 6.45-MeV states are the known 6.17- and 6.37-MeV 4^- states.

The cross section and analyzing power distributions of the 6.17-MeV and the 6.45-MeV states are plotted in Fig. 4. The $d\sigma/d\Omega$(q) of the 6.17-MeV state decreases as q increases. The cross section distribution of the 6.45-MeV state in ^{16}F has a shape that is similar to those of the 0.36-MeV (2^-) and 0.76-MeV (3^-) states but slightly flatter. A_y(q) of the 6.17-MeV state is negative, in general, while that of the 6.45-MeV state is positive, in general. The A_y(q) of the two states look like they are opposite to each other. The importance of the A_y(q) distribution comes from the information one can extract about the reaction mechansim. To excite the 6.17-MeV state the reaction has to proceed through the elementary pp $\rightarrow$ pnπ^+ process, while other ^{16}N states (except stretched states, e.g., 7^+, see Table I) may proceed through the elementary pn $\rightarrow$ nnπ^+ process, too. The 6.45-MeV state must process through the elementary pn $\rightarrow$ ppπ^- process, as usual.

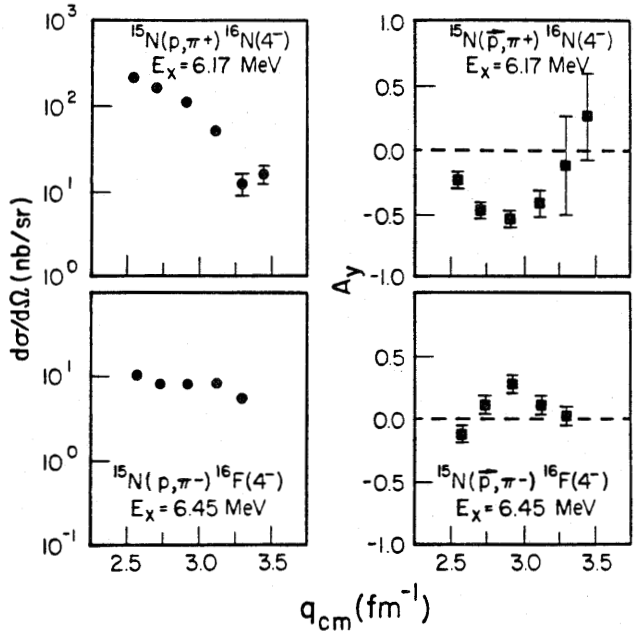


Figure 4. Differential cross section (left) and analyzing power (right) for the ^{15}N(p,$\pi\pm$) transitions to the ^{16}N 6.17-MeV and ^{16}F 6.45-MeV states.

^{16}N 5.74-MeV State:

The strongest state in the region of 5 to 7 MeV is the one at E_x= 5.74 MeV. The cross section and analyzing power distributions are plotted in Fig. 5. The $d\sigma/d\Omega$(q) of the 5.74-MeV state decreases smoothly as q increases. A_y(q) is negative and reaches a minimum at q $\simeq$ 3 fm^{-1}. The same state has been observed in the ^{14}C(α,d)^{16}N reaction and it has been identified as 2p-2h, 5$^+$;1 state, mainly of the configuration ^{14}C(0$^+$;1)$\otimes^{18}$F(5$^+$;0) (Ref. 8). This state proceeds in the ^{15}N(p,π^+) reaction through the elementary pp $\rightarrow$ dπ^+ process, which has no analogue in the ^{16}F nucleus. The absence of a state near this energy in the ^{15}N(p,π^-)^{16}F spectrum supports that.

^{16}N 7.59-MeV and ^{16}F 7.91-MeV States:

In the ^{15}N(p,π^+) spectrum, there is a state at E_x = 7.59 MeV. It is weaker than the states discussed so far. The $d\sigma/d\Omega$(q) and A_y(q) of the 7.59-MeV state are plotted in Fig. 5. The cross section distribution has a similar pattern to that of the 5.74-MeV (5$^+$) state. A_y(q) starts positive and becomes negative at q $\geq$ 2.7 fm^{-1}. A second 5$^+$;1 state has been predicted[9] with a configuration $^{14}N(1^+;0)\otimes^{18}O(4^+;1)$, and a strong state has been observed in two neutron stripping reactions at 7.65 MeV[9,10]. The 7.59-MeV state is a good candidate for the second 5$^+$;1 state since it is reachable by the elementary pn $\rightarrow$ nnπ^+ process and the cross section and A_y(q) distribution are similar to those of the 5.74-MeV 5$^+$;1 state. Since the analogue of the second 5$^+$ state is reachable in the ^{15}N(p,π^-) reaction, one expects to see it in the ^{16}F spectrum too. There is a state at 7.91 MeV. It becomes very weak at large scattering angle. Since the energy of the 7.91-MeV state is close to where the analogue of the 7.65-MeV 5$^+$ state expected then it is natural to assume that it is also a 5$^+$ state with a configuration ^{14}N(1$^+$;0)$\otimes^{18}$Ne(4$^+$;1). A state at 7.82 MeV has been observed in the two proton-stripping reaction[9].

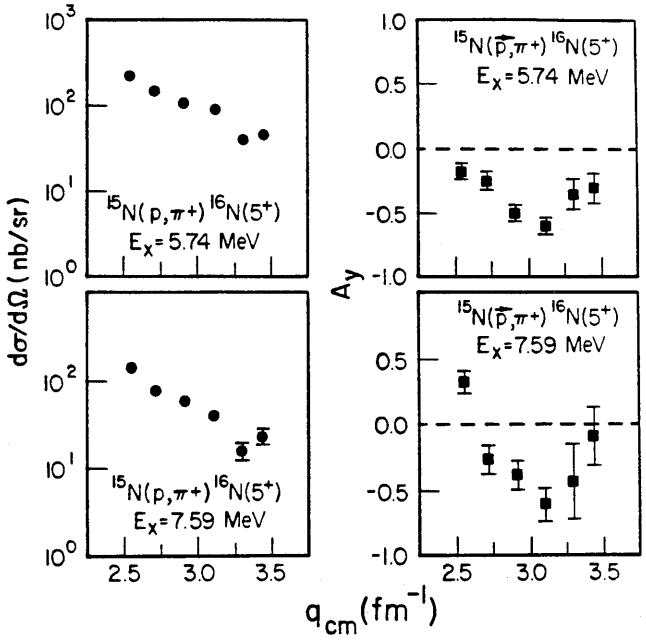


Figure 5. Differential cross section (left) and analyzing power (right) for the ^{15}N(p,π^+) transitions to the ^{16}N 5.74-MeV and 7.59-MeV states.

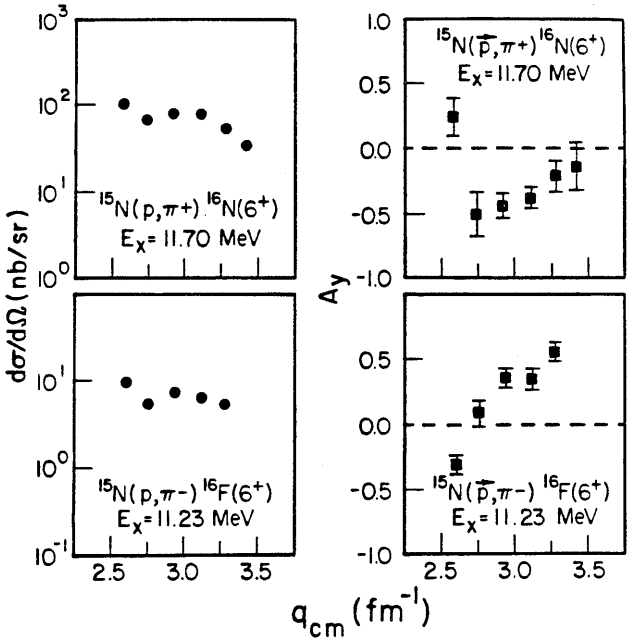


Figure 6. Differential cross section (left) and analyzing power (right) for the ^{15}N(p,$\pi\pm$) transitions to the ^{16}N 11.69-MeV and to the ^{16}F 11.23-MeV states.

^{16}N 11.69-MeV and ^{16}F 11.23-MeV States:

There is a strong state at 11.23 MeV in the ^{15}N(p,π^-)^{16}F spectrum. No state has been known at this energy[2]. The strength of the state at that excitation energy indicates that it is excited with large ΔL. $d\sigma/d\Omega$(q) and A_y(q) are plotted in Fig. 6. The cross section distribution is similar to those of other states excited by (p,π^-). The A_y(q) is similar to those of the stretched states[11]. The stretched state in ^{16}F has spin-parity 6^+, see Table I. This may have a configuration ^{14}N(2^+;0)$\otimes$^{18}Ne(4^+;1). A weak coupling calculation predicts a 6^+;1 state with that configuration in that region[12].

A mirror of the 6^+ state is also expected in ^{16}N, see Table I. The cross section of such a state is expected to be smaller than those for states excited through the elementary pp $\rightarrow$ pnπ^+ process. A state at 11.69 MeV in the ^{15}N(p,π^+)^{16}N spectrum has this characteristic; it is weaker than the 14.15 MeV and 16.00 MeV states which we believe are excited via the elementary pp $\rightarrow$ pnπ^+ process (see next section). The cross section and A_y(q) distributions (Fig. 6) are similar to those of high-spin states excited by the same reaction (see Fig. 5), and the excitation energy is close to that of the ^{16}F 6^+ state. Thus, the 11.69-MeV state may have spin-parity 6^+ with a configuration ^{14}N(2^+;0)$\otimes$^{18}O(4^+;1).

^{16}N 14.15- and 16.00-MeV States:

The strength of the 14.15- and 16.00-MeV states is very large compared to their neighbours excited in the ^{15}N(p,π^+)^{16}N process. That indicates they have been excited mainly by the elementary pp$\rightarrow$ dπ^+ reaction since this has the largest cross section near threshold. This conclusion is also confirmed by the absence of states at that excitation

energy in the $^{15}N(p,\pi^-)^{16}F$ spectrum. Therefore, spin 7^+ and 6^+ were assigned for the 14.15, and 16.00 MeV states, respectively. Their configurations are given in Table I.

Excitation energy and spin for some states excited in the $^{15}N(p,\pi^{\pm})$ reactions are listed in Table II.

Table II: Excited States in the Mirror ^{16}N and ^{16}F Nuclei

J^π	^{16}N (MeV)	^{16}F (MeV)
2^-	0.02	0.36
3^-	0.27	0.73
5^+	5.74	.....
4^-	6.17	6.45
$(5)^+$	7.59	7.91
$(6)^+$	11.70	11.23
$(7)^+$	14.15	.....
$(6)^+$	16.00	.....

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