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States in ^{15}O Between 8.8 and 9.0 MeV Excitation*

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The reaction $^{14}N(p,\gamma)^{15}O$ was used to examine the resonance structure in ^{15}O between 8.8 and 9.0 MeV. The resonance previously reported at $E_p = 1.742$ MeV was found to have two components corresponding to excitations in ^{15}O of 8.920 and 8.925 MeV, respectively. The decay properties of these two levels were studied with high-resolution Ge(Li) detectors, showing that they closely resemble the properties of probable mirror levels at 9.23 and 9.155 MeV in ^{15}N.

I. INTRODUCTION

The mass-15 nuclei ^{15}O and ^{15}N have been the subject of extensive study.[1] The properties of the $T = \frac{1}{2}$ states below 8.75 MeV are well understood, and the energies and decay properties of all except the two $J^\pi = \frac{1}{2}^+$ states are as expected for mirror nuclei. The situation is much less clear above this energy range, where experiments[2,3] have shown that the state in ^{15}N previously reported at 9.16 MeV is really a close-lying doublet, with the two members having energies of 9.152 and 9.155 MeV, and spins $J^\pi = \frac{3}{2}^-$ and $\frac{5}{2}^+$, respectively. More recently, Steerman and Young[4] have studied the reaction $^{13}C(^3He, p)^{15}N$ and determined the spin of the 9.22-MeV state to be $J^\pi = \frac{1}{2}^-$. Since Coulomb shifts between mirror nuclei much greater than 300 keV are uncommon, one should expect the three corresponding states in ^{15}O to fall between 8.8 and 9.1 MeV. However, only two states have been reported. Elastic proton experiments[5-8] show a large resonance at $E_p = 1.74$ MeV and a weaker one at $E_p = 1.81$ MeV, corresponding to 8.91 and 8.98 MeV excitation in ^{15}O. The analysis of these data has been inconclusive except for fixing the parity of the 8.91-MeV state as negative. Experiments using the $^{14}N(p,\gamma)$ reaction have confirmed the existence of these two resonances,[9] but the cross section in the capture channel has been too small to determine the spins and parities.

We have reexamined the resonance structure of ^{15}O between 8.8 and 9.1 MeV in the capture channel, to search for the existence of a third state. Since it appeared unlikely that previous experiments could have overlook an isolated state in this energy range, we have examined the two known resonance structures in detail to determine if one of these could possibly be a previously unresolved doublet.

II. EXPERIMENTAL PROCEDURE

The states in ^{15}O above 7.3 MeV are unbound. Information about these states is most readily obtained, therefore, from a detailed study of the observed resonance structure. Experimentally, one measures the excitation function either for one of the particle channels or the proton-capture reaction. In the energy region of interest (8.9 to 9.0 MeV) the analysis of such an excitation function is complicated for two reasons. First, it is well known[1] that there is a large nonresonant background, originating in part from two broad states at 9.48 and 9.72 MeV, respectively. Proper subtraction of this background requires that a complete γ-ray spectrum be taken at each proton bombarding energy so that the intensity of each γ ray as a function of energy is known. Secondly, the cross section of the 1.74-MeV resonance is so small in the capture channel that it is necessary to collect data at each energy for 8 h with beam currents of 10 μA to obtain statistically meaningful results. This causes severe problems in preparing suitable targets and finding a proper procedure for normalizing the data when analyzing the results.

Various methods have been reported to prepare nitrogen targets. Most commonly used have been TaN targets, prepared by heating a Ta disk in an atmosphere of ammonia. Although such targets, when water cooled, are capable of withstanding 5 μA of beam current over a long period of time without serious depreciation, they proved unsatisfactory for this experiment. Experience showed that the target material diffused deeply into the tantalum, thus producing effectively a thick target containing a very small concentration of nitrogen. This not only smeared out the resonance structure to be observed, but also enhanced the background problems originating from the broad resonances referred to above. In addition, the formation of TaF could not be avoided. As a result, the 6.13-MeV γ ray from the $^{19}F(p, \alpha\gamma)$ reaction completely masks the 6.18-MeV and full-energy peaks of the 5.24- and 5.19-MeV γ rays resulting from the ^{15}O decay.

Suitable targets were prepared by evaporating the compound adenine, $C_5H_5N_5$, onto 0.005-in. gold blanks. The target material was first melted in a tantalum boat at atmospheric pressure to prevent sputtering. Several targets were then simultaneously made by slowly heating the boat under high vacuum. Target thickness was determined by observing the 1.747-MeV resonance from the $^{13}C(p, \gamma)$ reaction. These targets were found to be essentially free from fluorine contamination. If cooled by direct contact with water, they withstood currents of 10 μA for several days. During the actual experiment, targets were changed four times over a period of 220 h to minimize the buildup of contaminants. Other laboratories which have used such targets have reported that they were not suitable with beam currents larger than a fraction of 1 μA. We believe that our success with large currents is due to more adequate cooling, as well as improved vacuum ($<2 \times 10^{-6}$ Torr) in the target chamber.

The γ-ray spectra were observed at each energy at 0° with a Ge(Li) detector with a photopeak efficiency of 10% for 1.33-MeV γ rays. The measured resolution for the ^{60}Co γ ray at 1.33 MeV was 2.1 keV full width at half maximum (FWHM), and the resolution for 9-MeV γ rays was 8.5 keV FWHM. The excellent resolution, and the consequent large peak-to-Compton ratio, made it possible to resolve all the γ rays observed and determine their intensity with a high degree of precision.

The spectra were recorded on a 4096-channel analyzer using conventional electronics. After each run the data were transferred to an IBM 1800 computer and stored for analysis on magnetic tape.

III. EXPERIMENTAL RESULTS

The excitation function was obtained between $E_p = 1.730$ and 1.820 MeV. Over this entire energy range no structure was observed that could be attributed to the $^{14}N(p, \gamma)$ reaction except that at $E_p = 1.74$ and 1.80 MeV, as previously reported.[9] These two resonances were, therefore, investigated in much greater detail to determine whether perhaps one was an unresolved doublet. Pulse-height spectra were taken in 2-keV steps, and each spectrum was analyzed to determine the intensity of all γ rays present. Figure 1 shows one of the 14 spectra obtained near the 1.74-MeV resonance. Figure 2 shows three separate portions of the spectrum in greater detail indicating the degree of resolution obtained.

Data reduction was accomplished with a computer program that fits the background at each peak with a second-order polynomial and then subtracts this computed background from the total number of counts in the peak. The χ^2 fits obtained for all peaks were less than 1.5.

Because of the low capture cross section, data were collected at each energy for eight hours. To minimize target depreciation, four different targets were used. Even so, constant monitoring of the total γ-ray counting rate made it evident that the results obtained at different energies could not be normalized by beam-current integration. An internal normalization procedure was, therefore, adopted whereby the excitation function of the three prominent peaks from the Doppler-broadened 4.43-MeV γ ray resulting from the $^{15}N(p, \alpha\gamma)$ reaction were compared with previously published results. In addition, the 6.79-MeV γ ray, due to the nonresonant background of the $^{14}N(p, \gamma)$ reaction, served as a check on the normalization.

Besides normalization, it was necessary to make an energy correction for each data point. Inspection of the targets indicated a significant buildup of carbon over a 30-h period. This was also evident from the spectra, where an abrupt decrease in the intensity of the 3.15-MeV γ ray from the $^{12}C(p, \gamma p')$ reaction was noted each time the target was changed. Unlike the carbon contained in the target material, the carbon buildup has the effect of reducing the energy of the beam, and a correction must therefore be made to determine the actual proton energy seen by the nitrogen target. This was accomplished by determining the intensity of the 3.51-MeV γ ray at each value of E_p, and estimating the thickness of the carbon deposit by comparing the measured intensity with that expected from the original target. This effect resulted in energy corrections for some points in the excitation functions as large as 2.3 keV.

Because the cross section of the 1.80-MeV resonance structure is an order of magnitude larger than that at 1.74 MeV, it was possible to obtain the data with a single target, thus avoiding the problems mentioned above.

Figures 3 and 4 show the results obtained at both energies. The four excitation functions shown at 1.74 MeV were obtained by adding the counts above background recorded for the full-energy,

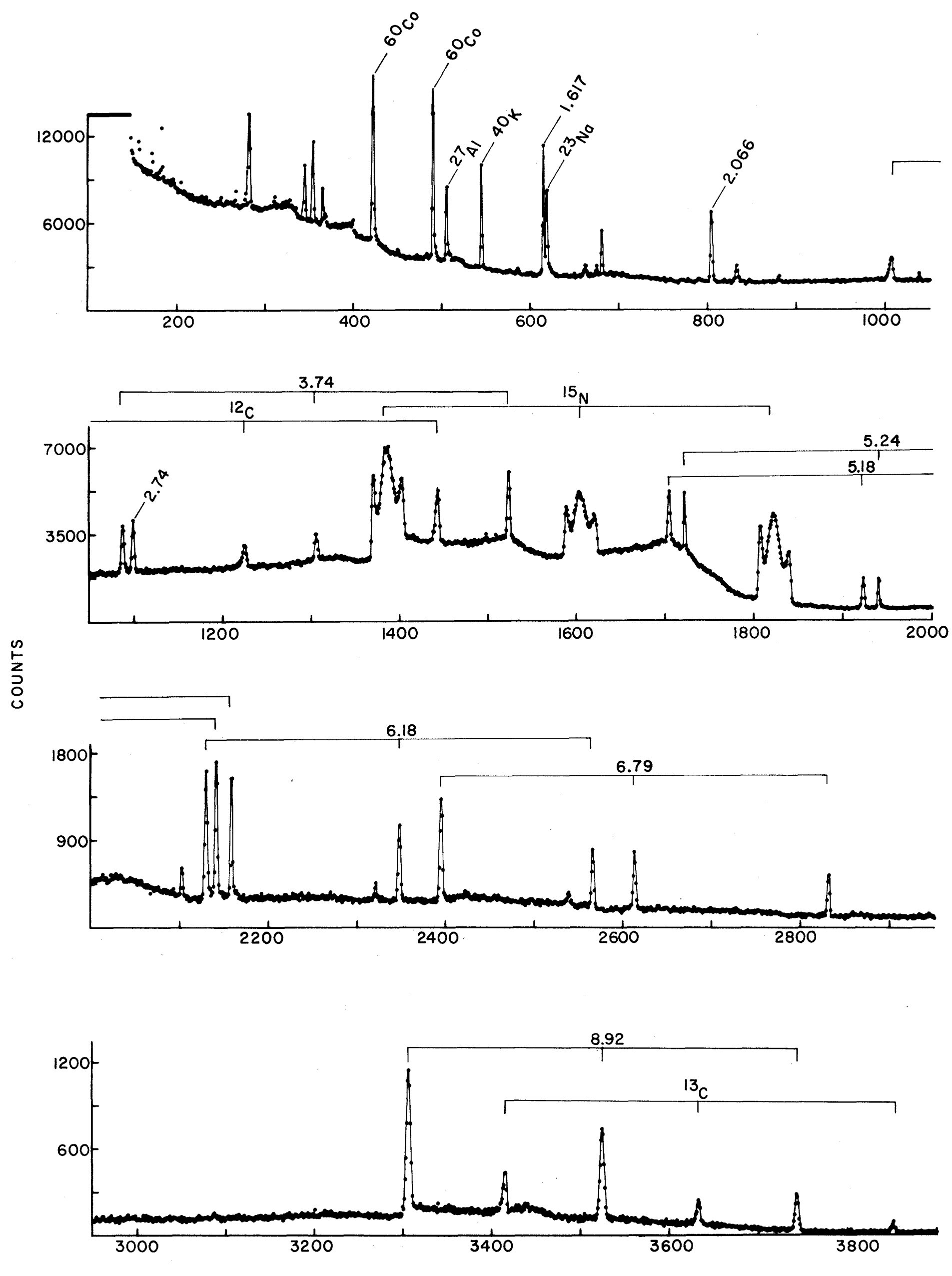

FIG. 1. γ-ray spectrum obtained at $E_p = 1.744$ MeV, $\theta_{\mathrm{lab}} = 0°$.

pair-minus-one, and pair-minus-two peaks for all γ rays belonging to a given cascade, making appropriate corrections for the efficiency of the Ge(Li) detector for γ rays of different energy. Thus, the 5.18-MeV excitation function includes the results of the 3.74-MeV feeder γ ray as well. This served as a check on the internal consistency of the results and tended to smooth out any fluctuation due to background subtraction. The major new result is that the ground-state transition has a strong component at $E_p = 1.747 \pm 0.002$ MeV, whereas the other three cascades have their maximum peaks at $E_p = 1.742 \pm 0.002$ MeV. An attempt has been made to analyze the four excitation functions to determine branching ratios at the two energies. The results are shown in Table I. The values listed were obtained by decomposing the experimental data into two resonance structures, with the excitation function for each cascade assumed to have the same FWHM. Although there is little question that each of the branches listed exists, it is estimated that the branching ratios at 1.747 MeV are not reliable to better than 50%.

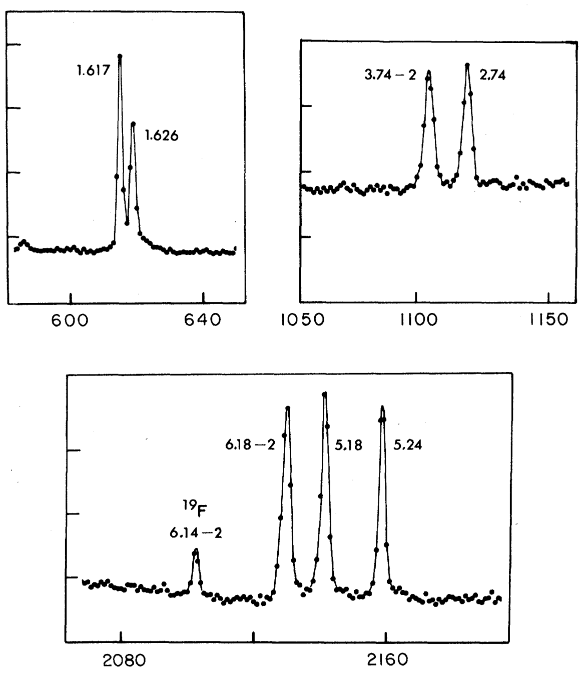

FIG. 2. Three different enlarged parts of the spectrum shown in Fig. 1 indicating the degree of resolution available. This permitted, for example, positive identification between the 1.611-MeV γ ray that results from a transition between the 6.795- and 5.184-MeV levels and the observed 1.617-MeV γ ray resulting from a transition between the 6.859- and 5.242-MeV levels. The −2 indicates that these are the pair-minus-two peaks in the spectrum, whereas the other peaks correspond to full-energy γ rays.

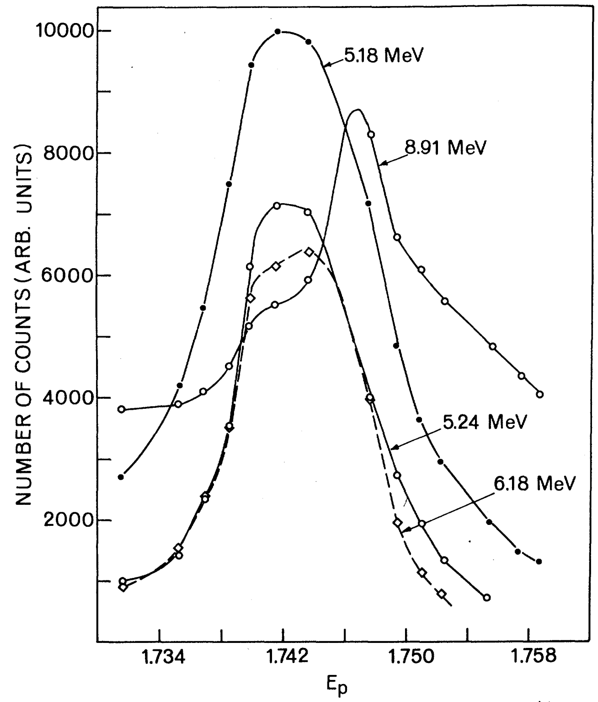

FIG. 3. Excitation function at 0° for the reaction ^{14}N-$(p,\gamma)^{15}$O between E_p=1.734 and 1.758 MeV. The curves shown represent the weighted average of all the γ rays belonging to the four different cascades observed. The data shown have been corrected for carbon built up on the target.

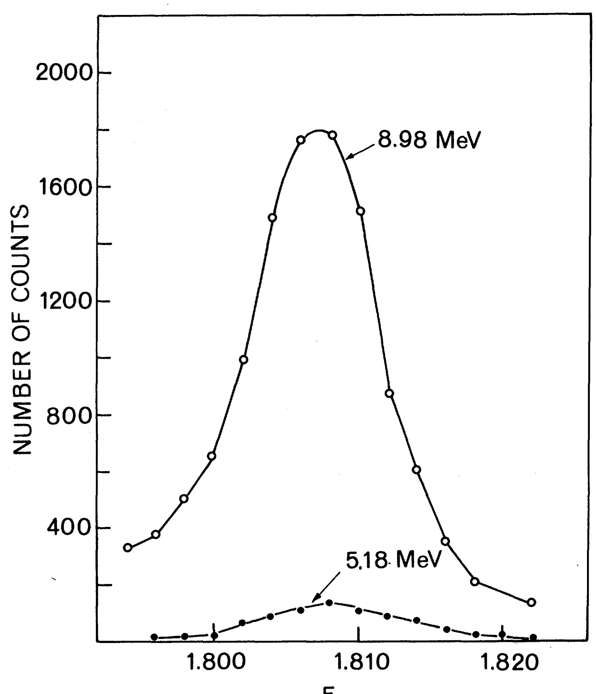

FIG. 4. Excitation function at 0° for the reaction ^{14}N-$(p,\gamma)^{15}$O between E_p=1.794 and 1.822 MeV.

TABLE I. Observed branching ratios (%) for the 8.920-, 8.925-, and 8.979-MeV states in ^{15}O.

	E_x (MeV)		
	8.920	8.925	9.979
resonance → g.s.	9 ± 4	50 ± 25	94 ± 1
resonance → 6.86 → 5.24 → g.s.	28 ± 3	10 ± 10	<1
resonance → 6.18 → g.s.	24 ± 3	20 ± 10	<1
resonance → 5.18 → g.s.	39 ± 3	20 ± 10	6 ± 1

This is due to the fact that the intensity of these cascades is small in comparison with those at 1.742 MeV and that the results for this resonance are particularly sensitive to the energy shift used to compensate for the carbon buildup on the target. The branching ratios at 1.742 MeV are not subject to these uncertainties and result chiefly from the subtraction of the nonresonant background. This was particularly serious for the ground-state transition, as is evident from an inspection of Fig. 3.

The results at $E_p = 1.807$ MeV confirm the previous results reported by Evans,[9] showing only two branches, a 94% branch to the ground state and a 6% branch through the 5.18-MeV state.

The uncertainties in target thickness and composition (because of carbon buildup) prevented the measurement of absolute yield. Relative yields were determined from the excitation function and corrected for the branching ratios obtained from the pulse-height distributions. Angular-distribution effects were taken into account at the 1.807-MeV resonance using the results published by Evans.[9] At the two lower-energy resonances, corrections were made using the asymmetry in the yield observed between 0 and 90°. Values of $\omega\Gamma_\gamma$,

TABLE II. Energies (MeV) of states in ^{15}O.

Present results	Previous results Ref. 1
5.184 ± 1	5.181 ± 5
5.241 51 [a]	5.241 51 ± 0.52
6.176 ± 2	6.177 ± 3
6.795 ± 2	6.788 ± 4
6.859 ± 2	6.859 ± 1
	7.2760 ± 0.6
	7.5522 ± 0.5
	8.2833 ± 1.5
	8.739 ± 6
8.920 ± 2	8.918 ± 1.4
8.925 ± 2	
8.979 ± 2	8.9781 ± 1.6

[a] Calibration point.

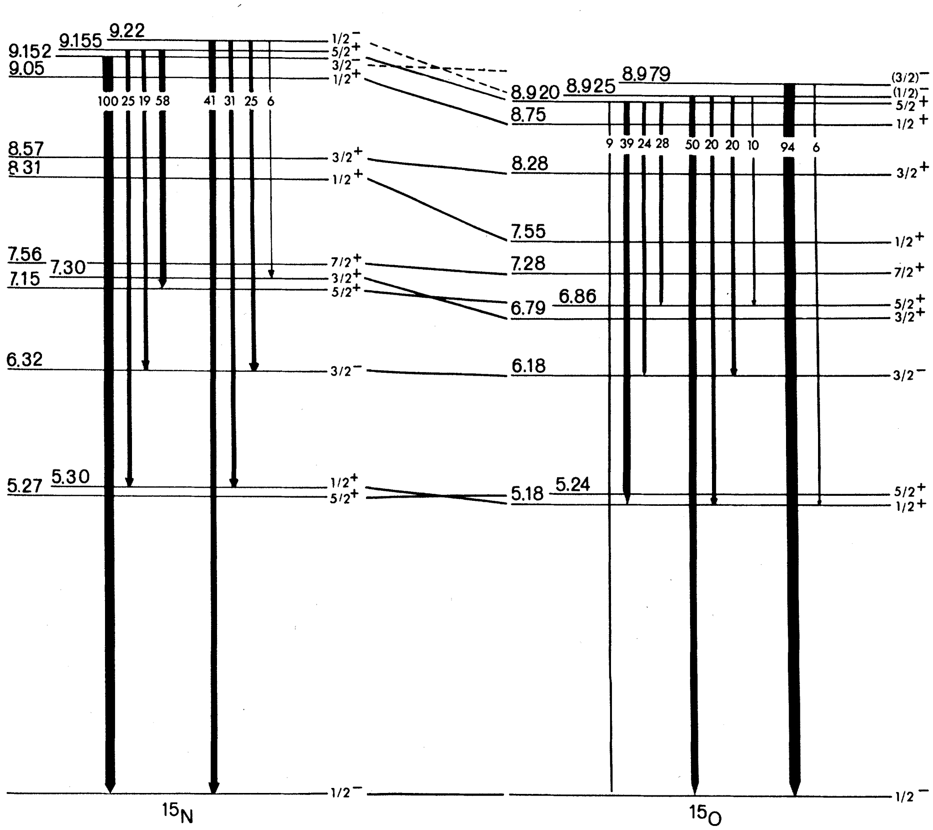

FIG. 5. Energy-level diagrams of ^{15}N and ^{15}O indicating observed γ-ray transitions. Energies are given in MeV.

based on the value of 0.52 eV obtained by Evans for the 8.98-MeV state, are 0.16 and 0.06 eV for the 8.920- and 8.925-MeV resonances, respectively. The relative errors are primarily those of the observed branching ratios, and hence the values given depend on the quoted value for the 8.98-MeV state. The combined values are in good agreement with the value of 0.21 eV reported by Evans at that energy.

A pulse-height spectrum obtained at 90° was used to determine γ-ray energies. By examining various cascades, precise values of the energies of a number of states in ^{15}O were calculated. For calibration purposes it was assumed that the second excited state has an energy of 5.2415 MeV, as this energy is reported known to ±0.52 keV. Other calibration points used were the 1.3325-MeV ^{60}Co γ ray and the 9.172-MeV γ ray resulting from the ^{13}C(p,γ) reaction. The results obtained are displayed in Table II. Inspection shows that the values obtained are in good agreement with previously published results except at 6.795 MeV, where the discrepancy is just outside the stated errors.

IV. DISCUSSION

The present experiment shows that the level structure in ^{15}O at 8.92 MeV results from two states having energies of 8.920 and 8.925 MeV, respectively. The upper state is excited at a proton bombarding energy which is within less than 1 keV equal to that at which the strong 9.17-MeV resonance in ^{13}C(p,γ) is observed. This is undoubtedly the reason why this state has been overlooked in earlier experiments[9] which did not have available high-resolution γ-ray detectors.

Because of the low cross section in the capture channel, it is not practical to attempt angular-distribution measurements to determine the spins of these states. A more hopeful procedure to obtain this information would be to reanalyze the proton elastic scattering data in this energy range, assuming the existence of a close-lying doublet at 8.92 MeV. Such analysis is currently under way by Koshel.[10] Preliminary results show that the data can indeed be fitted if one assumes that the 8.920- and 8.925-MeV states are formed by $l=2$ and $l=1$ protons, respectively. This would support the conjecture that the 8.920-MeV state in ^{15}O is the $\frac{5}{2}^+$ mirror state of the 9.155-MeV state in ^{15}N. A comparison between the γ-ray decays of these two states (see Fig. 5) strongly supports such an assignment, particularly if one recognizes that a branch to the ground state from the 9.155-MeV state in ^{15}N could not have been distinguished[2] from the reported ground-state transition of the 9.152-MeV state.

The 8.979-MeV state is known[1] to have negative parity and $J=\frac{1}{2}$ or $\frac{3}{2}$. Its predominant decay to the ground state (94%) makes it likely that it is the mirror level to the $\frac{3}{2}^-$ state in ^{15}N at 9.152 MeV. This would indicate that the $\frac{1}{2}^-$ state in ^{15}N at 9.23 MeV corresponds to the 8.925-MeV state in ^{15}O. Both states have strong ground-state transitions and weaker branches to the $\frac{1}{2}^+$ and $\frac{3}{2}^-$ states near 5 and 6 MeV, respectively. The 8.925-MeV state in ^{15}O also decays through the $\frac{5}{2}^+$ state at 6.868 MeV. The corresponding cascade in ^{15}N is less certain.[11,12] A recent high-resolution spectrum taken at the 10.71-MeV resonance of the ^{14}C(p,γ)-^{15}N resonance shows a very weak cascade through the 9.23- and 7.30-MeV states, but no evidence of a cascade through the 7.16-MeV state. However, the 9.22-MeV level is populated at this resonance less than 2% of the time, and any conclusion about its decay must therefore be considered in doubt.

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