# Spectroscopic Study of the Unbound $^{11}$N Nucleus

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The nuclear structure of the unbound $^{11}$N nucleus has been investigated by the $^{14}$N($^{3}$He,$^{6}$He)$^{11}$N reaction. The energies and widths of the observed states are compared with other measurements. Angular distributions for the first five states are obtained for the first time for this reaction and DWBA analysis confirms the spin assignments for the lowest levels.

## I Introduction

$^{11}$N is the mirror nucleus of the known halo nucleus $^{11}$Be and all its levels are unbound for proton decay to $^{10}$C. In $^{11}$Be the lowest $\frac{1}{2}^+$ level lies lower in energy than the $\frac{1}{2}^-$ level expected as the ground state in the standard shell model. This level inversion has been partly explained as due to halo formation by the weakly-bound valence neutron [1], although the association is still not clear. Thus, the investigation of the structure of the $^{11}$N nucleus would be interesting in association with the isospin characteristic of the halo effect.

The structure of $^{11}$N nucleus was first investigated by Benenson *et al.* [2] using the $^{14}$N($^{3}$He,$^{6}$He)$^{11}$N reaction. In this early work, only one clear peak was observed at 2.24 MeV above the $^{10}$C+p threshold, and based on its measured width of 0.74(10) MeV, the level was assumed to be $\frac{1}{2}^-$.

Other reactions were used to investigate the structure of $^{11}$N [3, 4, 5, 6, 7]. The energies and widths of the observed levels are shown in Table I for comparison. The experimental values for the energy and width of the $\frac{1}{2}^+$ ground state of $^{11}$N show considerable variations among these works. It appears that not all of this is due to the use of different definitions for the energy and width of an unbound level [8] or due to the different reactions used to populate this level. The energy and width of this level are significant in the consideration of a possible halo structure in $^{11}$N. Also, the energy and width of the $^{11}$N ground state are very important in the interpretation of the two-proton decay of the $^{12}$O ground state [9], where depending on the energy of this level, the exotic diproton decay might be expected to compete with the sequential decay through the $^{11}$N ground state.

## II Experiment and energy spectra analysis

To populate the low-lying levels of the unbound $^{11}$N nucleus we have used the three-neutron $^{14}$N($^{3}$He,$^{6}$He)$^{11}$N pick-up reaction in a more precise, acurate and complete experiment. The experiment was carried out with a sector-focusing cyclotron of the Center for Nuclear Study, University of Tokyo, Japan. The incident energy of the $^{3}$He beam was 73.40 $\pm$ 0.05 MeV and the average current obtained was about 0.5 $\mu$A. The beam was transported into the scattering chamber, where a gas target with 99.95% isotopically enriched $^{14}N_2$ gas was placed. The gas cell was filled to a pressure of about 21 cm Hg during the measurements. A rectangular double-slit system was used to prevent particles from the windows (Havar foils) of the gas cell from entering the detectors.

The momentum of the $^{6}$He particles and other products from the reaction were analysed by a QDD-spectrograph and detected by a hybrid-type gas proportional counter [10] placed in the focal plane. A thin plastic scintillator was set just behind the proportional counter for energy and time-of-flight measurements. The particle identification was performed using a set of signals, namely, the energy signal from the plastic scintillator, energy loss from the proportional counter and time-of-flight.

The momentum spectra for the outgoing $^6$He nuclei were obtained at 8 angles from ($\theta_{\mathrm{LAB}}$ = 6.8$^o$ to 30.0$^o$). The momentum spectra were then converted to energy spectra. In order to improve the statistics and to better determine the parameters of the levels, a summed spectrum was obtained by adding the normalized energy spectra from each angle, with the uncertainty at each energy in the sum spectrum equal to the square root of the sum of the squares of the uncertainties in each individual angle spectrum. This sum spectrum is shown in Fig. 1. The energy axis corresponds to the energy above the $^{10}$C+p threshold (decay energy), for which the Q-value is -22.788 MeV. The overall energy resolution obtained was about 200 keV FWHM and it is due mainly to the different energy losses of the $^3$He beam and $^6$He particles in the gas target system.

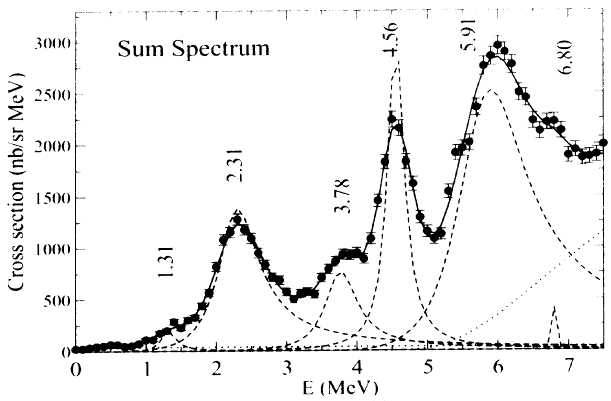


Figure 1. The summed $^6$He energy spectra from the $^{14}$N($^3$He,$^6$He)$^{11}$N reaction at the laboratory angles indicated. Energies are measured from the $^{10}$C+p threshold.

In the $^{14}$N($^3$He,$^6$He)$^{11}$N reaction, the populated levels in $^{11}$N are observed as peaks in the $^6$He spectrum; because all levels of $^{11}$N are unstable against breakup into $^{10}$C+p, these peaks sit on a background due, at least in part, to alternative reaction processes. Also, for energies above about 4 MeV, other breakup channels, such as $^9$B+2p decay, are open.

Therefore, we attempt to fit the spectrum with a function of the form:

$$N(E,\theta) = \sum_i b_i \times N_i(E) + c + d \times P_b(E) \qquad (1)$$

where,

$$N_i(E) = \frac{\Gamma_i(E)}{[E_{ri} + \Delta_i(E) - E]^2 + 1/4\Gamma_i^2(E)} \qquad (2)$$

The sum is over the levels of $^{11}$N, each of which is described by the one-level, one channel approximation of R-matrix theory [11]. The decay width is given by $\Gamma_i(E) = 2\gamma_i^2 P_i(E)$ and $\Delta_i(E) = -\gamma_i^2[S_i(E) - S_i(E_{ri})]$. $P_i(E)$ and $S_i(E)$ are the energy-dependent penetration and shift factors for the $^{10}$C+p channel. The background is assumed to be part flat, c, (to allow for possible random coincidences) and part proportional to an $s$-wave penetration factor for the $^9$B+2p channel, $P_b(E)$. Then, for each $^{11}$N level i, the adjustable parameters are resonance energy $E_{ri}$, reduced width $\gamma_i^2$, and strength $b_i$. The observed width $\Gamma_i^0$ used to compare with the width from other works is defined by: $\Gamma_i^0 = 2\gamma_i^2 P_i(E_{ri})/[1 + \gamma_i^2 (dS_i/dE)_{E_{ri}}]$. For comparison with the data, the function $N(E)$ given by Eq. (1) is smeared over the experimental energy resolution of 200 keV. The best fit to the sum spectrum is shown in Fig. 1; it has a $\chi^2_{\mathrm{min}}$ = 100.2, for 76 data points and 20 adjustable parameters, giving a reduced $\chi^2_\nu$ = 1.79. The values of the parameters $E_{ri}$ and $\Gamma_i^0$. are given in Table I. The uncertainties in these parameters correspond to increases in $\chi^2$ to $\chi^2_{min} + \chi^2_\nu$.

# III Angular distribution analysis

The differential cross section for the $^{14}$N($^3$He,$^6$He)$^{11}$N reaction were obtained at eight angles for each level in $^{11}$N, and these are shown in Figs. 2 and 3 for the first five levels. The analysis of the characteristic behavior at the forward angles in the experimental angular distributions has been made in terms of the exact finite-range Distorted Wave Born Approximation (DWBA), using the computer code TWOFNR [12]. The optical potential parameters used in the DWBA calculations were basically the same as used before in the analysis of angular distributions for the $^{20}$Ne($^3$He,$^6$He)$^{17}$Ne reaction [13]. No clear attempt to fit the data has been made by changing any optical potential parameters. For the bound state parameters of the 3n-cluster in $^{14}$N and $^6$He the conventional $r_0 = 1.25$ fm and $a = 0.65$ fm were adopted. The radius was defined as $R = r_0 \cdot A^{1/3}$, and the potential depths were adjusted to reproduce the binding energies.

In the case of the $^{14}$N($^3$He,$^6$He)$^{11}$N reaction, the spin of the $^{14}$N target nucleus is $1^+$ and for $^3$He it is $\frac{1}{2}^+$ and thus, more than one transferred angular momentum L can contribute to produce the angular momentum J of the final state in the residual $^{11}$N nuclei. For instance, to produce the final J$^\pi = \frac{1}{2}^+$ state, the reaction can proceed by tranferring angular momentum L=0 and/or L=2, to give J$^\pi = \frac{3}{2}^-$ by L=1 and/or L=3, and J$^\pi = \frac{5}{2}^+$ by L=2 and/or L=4. However, for J$^\pi = \frac{1}{2}^-$ only L=1 is possible. The parity of any transition is given by $\pi = (-1)^{\mathrm{L}}$.

The results of the DWBA calculations for the angular distributions are presented in Figs. 2 and 3. Since few angles have been measured and due to the complexity of this reaction and of the approximations assumed in the calculations, such as the cluster transfer of three neutrons, only a qualitative analysis of the angular distributions is possible. The angular distributions calculated by the DWBA show strong oscillation and distinct patterns at forward angles for different L.

TABLE I. Decay energy above the $^{10}$C+p threshold and widths of the $^{11}$N resonances measured in this work and from the references indicated. All the energies and widths are in MeV.

| $J^\pi$ | This work $E_{ri}$ | $\Gamma_i^0$ | Oliveira $E_{decay}$ | *et al.* [6]$^{a)}$ $\Gamma$ | Lepine-Szily $E_{decay}$ | *et al.* [7]$^{b)}$ $\Gamma$ | Markenroth $E_{decay}$ | *et al.* [4]$^{c)}$ $\Gamma$ | Axelsson $E_{decay}$ | *et al.* [3]$^{c)}$ $\Gamma$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $\frac{1}{2}^+$ | 1.31(5) | 0.24(24) | 1.63(5) | 0.4(1) | - | - | $1.27^{+0.18}_{-0.05}$ | 1.44(20) | 1.30(4) | 0.99(20) |
| $\frac{1}{2}^-$ | 2.31(2) | 0.76(6) | 2.16(5) | 0.25(8) | 2.18(5) | 0.44(8) | 2.01(15) | 0.84(20) | 2.04 | 0.69 |
| - | | | 3.06(8) | $\leq$0.10(8) | (2.92) | (0.1) | - | - | - | |
| $\frac{5}{2}^+$ | 3.78(5) | 0.56(17) | 3.61(5) | 0.50(8) | 3.63(5) | 0.40(8) | 3.75(5) | 0.60(5) | 3.72 | 0.60 |
| $\frac{3}{2}^-$ | 4.56(1) | 0.28(6) | 4.33(5) | 0.45(8) | 4.39(5) | $\leq$0.2(1) | 4.33(5) | 0.27 | 4.32 | 0.07 |
| $(\frac{5}{2}^-)$ | 5.91(3) | 1.45(13) | 5.98(10) | 0.10(6) | 5.87(15) | 0.7(2) | - | - | 5.50 | 1.5 |
| $(\frac{3}{2}^-)$ | 6.80(30) | 0.01(1) | 6.54(10) | 0.10(6) | - | - | - | - | - | |

a) using heavy-ion transfer reaction $^{10}$B($^{14}$N,$^{13}$B)$^{11}$N at GANIL
a) using heavy-ion transfer reaction $^{12}$C($^{14}$N,$^{15}$C)$^{11}$N at GANIL
c) using resonant scattering $p$($^{10}$C,$^{11}$N) reaction

For the transition to the 1.31 MeV ground state, shown in Fig. 2, the angular distribution seems to be reasonably reproduced by a DWBA calculation with L = 0 only. For the 2.31 MeV transition, which is the well known $\frac{1}{2}^-$ resonance, the angular distribution seems to be due to L = 1 angular momentum transferred, as expected. The other level in $^{11}$N which has a firm spin assignment is the $\frac{5}{2}^+$ level at 3.78 MeV. This $\frac{5}{2}^+$ level also would correspond to an $sd$-shell proton coupled to $^{10}$C and its angular distribution seems to be well described by a L=2 transferred angular momentum. Thus, the first three lowest levels in $^{11}$N have an established spin assignment and our data confirm them. In particular, our data confirm the assignment $J^\pi = \frac{1}{2}^+$ and $J^\pi = \frac{1}{2}^-$ for the first two transitions, which shows the same spin inversion for the ground-state spin as observed for $^{11}$Be.

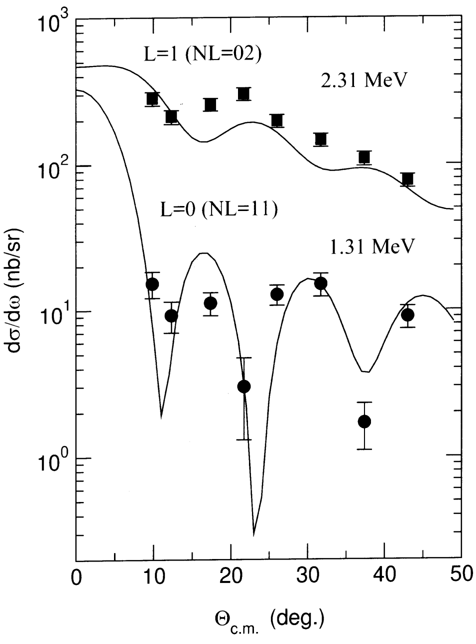


Figure 2. Angular distributions for the $^{14}$N($^3$He,$^6$He)$^{11}$N reaction for the transitions denoted. The curves are the results of DWBA calculations with the transferred angular momenta (L) indicated.

The 4.56 MeV level and, in particular, the level at 5.91 MeV are strongly populated by this 3-neutron pickup reaction. The angular distribution for the 4.56 MeV level seems to be well reproduced by a combination of L =1+3 angular distribution, which would favor a negative parity assignment (see Fig. 3). This L assignment and the narrow width observed for this level in this and in the other experiments [3, 4, 5, 6, 7] would indicate that it is the analog of the $J^\pi = \frac{3}{2}^-$ state at 2.69 MeV in $^{11}$Be [14]. The level at 5.91 MeV has been tentatively assigned by the other experiments as $J^\pi = \frac{5}{2}^-$, based on shell model calculations for $^{11}$N [5]. The angular distribution for this level seems to be reproduced by an L = 3 angular momentum transferred, although L = 2 is also possible (dashed line in Fig. 3). L = 3 is consistent with the $\frac{5}{2}^-$ assignment.

# IV Discussion on the energies and widths

The energies and widths $E_{ri}$ and $\Gamma_i^0$ obtained in this work for the six lowest levels in $^{11}$N and their uncertainties are presented in Table I, where they are compared with the values obtained by other experimental works. Our data seem to be in good agreement with the results of most experiments, although some important differences are apparent. The $\frac{1}{2}^+$ ground state is observed at 1.31(5) in this work. This value agrees with the energy obtained by Markenroth *et al.* [4] and Axelsson *et al.* [3] but is lower when compared with the results by Oliveira *et al.* [6]. The width for this level is obtained in the range of Γ = 0 to 500 keV, and it is in better agreement with the value obtained in another transfer reaction experiment by Oliveira *et al.* which gives Γ=400(100) keV. As pointed out by Barker [8], there may be some difference in the definitions of energy and width for unbound levels used in these experimental works; and although all the definitions are expected to give practically the same value for narrow levels they can differ for broad levels. However, even by taking into account possible diferences in the energy

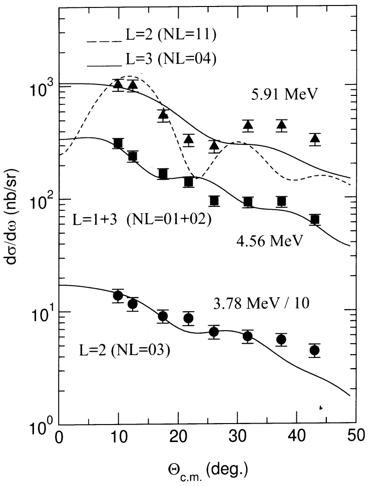


Figure 3. Angular distributions for the $^{14}$N($^3$He,$^6$He)$^{11}$N reaction for the transitions denoted. The curves are the results of DWBA calculations with the transferred angular momenta (L) indicated. The N and L in parentheses are choices for the number of radial nodes and the orbital angular momentum of the 3n-cluster relative to the core of the residual nucleus adopted in the calculation.

and width definition for the $\frac{1}{2}^+$ level, the difference from the resonance scattering and transfer reactions works seems to be too large. The width for this state is directly related to the single particle nature of this state. Assuming $\Gamma_{sp}$=1.28 MeV, from Sherr and Fortune [16], we obtain a spectroscopic factor in the range of 0.1 to 0.2. This low spectroscopic factor would be consistent with a large d-wave admixture in the configuration of the J$^{\pi}$ $= \frac{1}{2}^+$ level. A similar value for the spectroscopic factor is obtained in the analysis of Oliveira *et al.* [6] for the $^{11}$N ground state and also for the $^{11}$Be ground state in the recent analysis of the $^{11}$Be(p,d)$^{10}$Be reaction by Johnson *et al.* [15].

The $\frac{1}{2}^-$ level in $^{11}$N is strongly populated in most reactions. The energy and width $E$=2.31(2) MeV and Γ=0.73(6) MeV obtained in this work agree very well within the experimental error with the values obtained in the earlier experiment using the same $^{14}$N($^3$He,$^6$He)$^{11}$N reaction by Benenson *et al.*, E=2.24(10) MeV and Γ=0.74(10). The energy for this state is, however, about 200 keV higher here when compared with the other works.

In summary, the angular distributions have been measured for the first time for this $^{14}$N($^3$He,$^6$He)$^{11}$N reaction. An analysis with DWBA calculations confirms the assignment of J$^{\pi}$ $= \frac{1}{2}^+$ and J$^{\pi}$ $= \frac{1}{2}^-$ for the ground state and the first excited state. Thus, in $^{11}$N, the anomalous situation that the $\frac{1}{2}^+$ state comes lower than the $\frac{1}{2}^-$ is the same as observed in $^{11}$Be. The narrow width found in this work for the $\frac{1}{2}^+$ ground state favors a small spectroscopic factor.

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