Proton decay of states in ^{11}N

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The proton-unbound nucleus ^{11}N has been studied via kinematic reconstruction of the emitted proton in coincidence with the residual ^{10}C daughter nucleus. Resonances in ^{11}N were populated by using a 40 MeV/nucleon radioactive beam of ^{12}N to induce the reaction ^{9}Be(^{12}N,^{11}N), followed by the proton decay of ^{11}N. The decay energy spectrum was constructed from the energies and separation angle of the ^{10}C and the proton. In addition to protons from the known $1/2^-$ state, at 2.24 MeV above the proton decay threshold, another peak is seen near 1.45 MeV. This peak could potentially be due to the predicted $1/2^+$ ground state and/or due to the decay of the $3/2^-$ state to the first excited state of ^{10}C [S0556-2813(98)06102-0]

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I. INTRODUCTION

The first study of ^{11}N was performed using the three-neutron pickup reaction ^{14}N(^{3}He,^{6}He)^{11}N [1]. A state at an energy of 2.24(10) MeV above the $^{10}\mathrm{C}+p$ threshold was interpreted as the analog of the $1/2^-$ first excited state of ^{11}Be based on the isobaric mass multiplet equation (IMME) using the known $1/2^-$ states in ^{11}Be, ^{11}B, and ^{11}C. However, the $1/2^+$ ground state was not observed and was deduced from the IMME to be 1.9 MeV above the proton decay threshold [1].

Given the current interest in nuclei near the drip lines, new information on the structure of ^{11}N is desirable. In particular, the excitation energy and width of the expected $1/2^+$ ground state has been a subject of theoretical attention [2,3]. The mass table [4] lists an extrapolated mass excess for the ground state which corresponds to nearly the same energy separation between the $1/2^+$ and $1/2^-$ states in ^{11}Be and ^{11}N. Fortune *et al.* [2] note that uncertainties in both the assignments and the degree of isospin mixing of the $1/2^+$ states in ^{11}B and ^{11}C obviate the use of the IMME for the determination of the ground state energy of ^{11}N and calculated a decay energy of 1.60(0.22) MeV from a potential model under the assumption of a pure $1s_{1/2}$ single-particle state. Calculations by Barker [3] agree with the value of 1.6 MeV but only after the inclusion of significant d-wave parentage in the ground state. Our own calculations, which combine shell-model parentages with single-particle Coulomb energy shifts calculated in a potential model, agree very well with similar calculations by Sherr [5] and suggest that the ^{11}N ground state should lie at about 1.35 MeV above the $^{10}\mathrm{C}+p$ threshold.

In addition to shedding light on the theoretical discrepancies, a detailed knowledge of the ground state of ^{11}N is also important for the recently measured two-proton emission of ^{12}O [6]. If the ground state of ^{11}N is located at 1.9 MeV, a sequential decay of ^{12}O via ^{11}N would not be energetically possible. Therefore ^{12}O was predicted to be a candidate for diproton (^{2}He) emission. However, Kryger *et al.* [6] did not observe any evidence for the diproton decay branch and determined an upper limit of 7%. The sequential decay through the tail of a broad ($\Gamma=1.5$ MeV) ^{11}N state at 1.9 MeV is strongly suppressed and does not reproduce the measured width for the ^{12}O decay. However, the data could be reproduced with the assumption of an intermediate state in ^{11}N at $\sim$900 keV.

Finally, quite a number of relatively narrow states are known in ^{11}Be, mainly from the ^{9}Be$(t,p)^{11}$Be reaction [7]. Of these, only the $1/2^+$ ground state, the $1/2^-$ first-excited state at 0.32 MeV, and the $5/2^+$ state at 1.78 MeV have firm spin assignments. It is a reasonable expectation that the analogs of some of the higher states will have modest widths in ^{11}N. Therefore we studied the structure of ^{11}N via one-neutron pickup from a radioactive beam of ^{12}N, looking for peaks from decays into the $^{10}\mathrm{C}+p$ channel.

The experimental procedure is described in Sec. II, along with the results of the one-neutron stripping reaction populating known proton-unbound states of ^{13}N which provide a test of the feasibility of the method. The results for ^{11}N are given in Sec. III, together with our interpretation of the proton decay spectrum. The results are summarized and conclusions drawn in Sec. IV.

II. EXPERIMENTAL PROCEDURE

The present experiment was performed at the National Superconducting Cyclotron Laboratory where a beam of 80

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MeV/nucleon ^{16}O was used with a 1000 mg/cm^2 thick ^{9}Be target to produce a radioactive beam of ^{12}N via fragmentation reactions. The ^{12}N beam was then purified by using a 130 mg/cm^2 aluminum wedge in the A1200 mass separator [8] followed by the reaction products mass separator (RPMS) [9]. This resulted in 15 000 counts/sec of 40 MeV/nucleon ^{12}N particles at a purity of 95% with ^{13}O as the only contaminant. The secondary target and detector arrays were placed behind the RPMS. A set of two position sensitive parallel plate avalanche counters (PPAC's) were used to track the beam onto a 37 mg/cm^2 ^{9}Be secondary target. This target was used to produce the ^{11}N fragments via the reaction ^{9}Be(^{12}N,^{11}N).

The particle-unbound ^{11}N decays into ^{10}C and a proton. The energies and angles of ^{10}C and the proton were measured with two separate position sensitive telescope arrays in order to reconstruct the states of ^{11}N.

The proton detectors were placed 20 cm from the target and included a 300-μm double-sided annular silicon detector with an inner radius of 2.4 cm and an outer radius of 4.8 cm covering laboratory angles from 6.8° to 13.5°. This detector contained 16 concentric strips on the front and 16 pie-shaped pieces on the back, providing 256 pixels for position and energy loss information. The silicon detector was backed by the Maryland Forward Array (MFA) which consisted of a ring of 16 plastic phoswich detectors, each made of a 1 mm fast plastic coupled to a 10 cm thick slow plastic to completely stop the protons, thus measuring the total energy. Proton identification was achieved by pulse shape discrimination in the phoswich detectors and by ΔE-E spectra from the MFA and the segmented silicon detector. Heavier fragments, such as ^{10}C, were more forward focused and passed through the central opening in the MFA. Therefore a fragment telescope was placed behind the MFA at 62 cm from the target. This telescope consisted of a PPAC followed by a 500 μm thick 5 cm$\times$5 cm quadrant silicon ΔE detector and a 3 mm thick 5 cm radius quadrant Si(Li) detector. Particle identification with isotopic resolution was obtained from the ΔE-E spectrum.

The proton detectors were calibrated by inelastically scattered protons. Several degraders were used to provide proton energies from 10 to 70 MeV. The fragment telescope was calibrated by tuning beams of ^{10}C and ^{11}C onto a second set of degraders to provide an appropriate range of energies for carbon isotopes.

The decay energy spectra were constructed from the kinetic energy of the decay products, a proton and a daughter nucleus, and the laboratory opening angle between the two particles. The total mass of a parent nucleus following the decay $X \rightarrow a+b$ can be obtained from

$$M_X^2 = M_a^2 + M_b^2 + 2(T_a+M_a)(T_b+M_b) - 2\cos\theta\sqrt{(T_a^2+2T_aM_a)(T_b^2+2T_bM_b)},$$

where T is the measured kinetic energy, M is the rest mass including any excitation energies, and θ is the laboratory opening angle between the particles a and b. The decay energy is then calculated by $E_{\text{decay}} = M_X - M_a - M_b$.

The decay energy spectrum was compared to a Monte Carlo simulation which included the decay parameters and detector geometry. The decay was modeled by using a Breit-Wigner line shape of the form

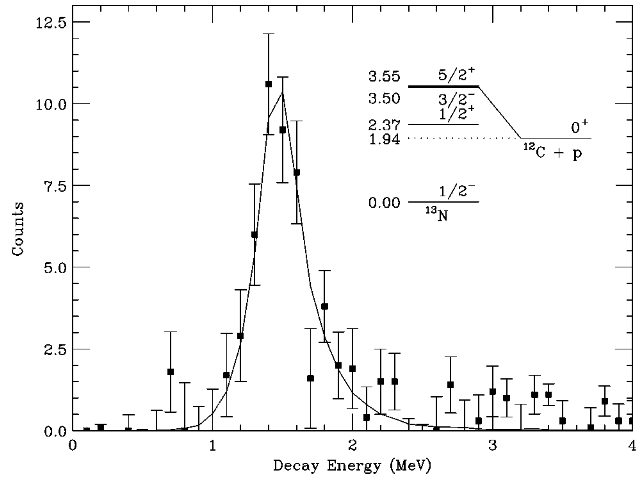

FIG. 1. Background-subtracted decay energy spectrum of ^{13}N. The solid line is a Monte Carlo simulation of a state at 3.45 MeV excitation and a width of 90 keV.

$$\frac{d\sigma}{d\Omega} = N \frac{\Gamma_l(E)}{(E-E_r)^2 + [\Gamma_l(E)/2]^2}. \tag{1}$$

N is a normalization constant and the width is defined as

$$\Gamma_l(E) = 2\gamma_l P_l(\eta,\rho), \tag{2}$$

where γ_l is the reduced width, $\rho = kR$, and $P_l(\eta,\rho)$ is the penetrability, with η the Sommerfeld parameter and R the channel radius.

Background events were identified from software gates applied to the low energy tail of the fragment energy spectra and subtracted from the decay energy spectra.

In addition to the one-neutron stripping reaction forming ^{11}N, one-neutron pickup reactions populating states in ^{13}N were recorded simultaneously. The excited states of ^{13}N are well known and proton unbound, and thus could be used to test the feasibility of the method. In fact, the only low-lying states of ^{13}N with any significant parentage to the ^{12}N ground state are the $1/2^-$ ground state and the $3/2^-$ state at 3.502 MeV; the positive-parity states have dominant parentages to ground and first-excited states of ^{12}C, the 7.536 MeV $5/2^-$ state is essentially L forbidden, and higher negative-parity states (of [432] spatial symmetry) would give rise to high energy proton decays for which the detection efficiency is low. The 3.50 MeV $3/2^-$ state has a proton decay energy of 1.56 MeV and a width of 62(4)keV [10]. Fig. 1 shows that the decay energy spectrum for ^{13}N does indeed exhibit a single peak. The solid line is a fit obtained from χ^2 minimization of Monte Carlo simulations for the decay of the $3/2^-$ state. The parameters extracted from this calculation result in an excitation energy of 3.45(5) MeV and a width of 90^{+390}_{-90} keV, which are in good agreement with the known values quoted above.

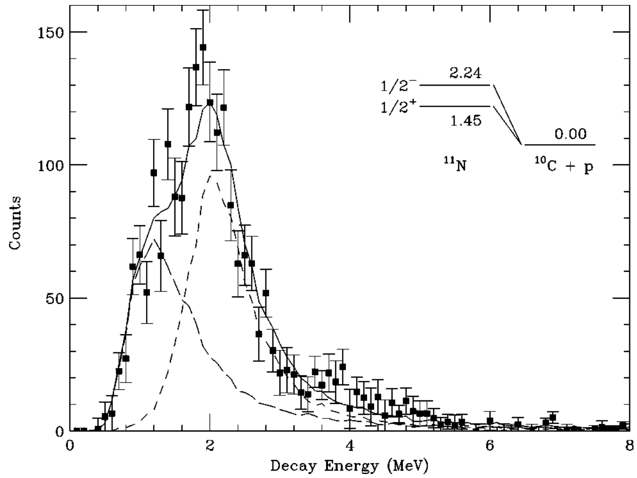

FIG. 2. Background-subtracted decay energy spectrum of ^{11}N. The fit to the data (solid line) is a sum of the contributions from the known $1/2^-$ state (short dashed line) and a $1/2^+$ state at $E_{\mathrm{decay}} = 1.45$ MeV and $\Gamma = 2.4$ MeV (long dashed line).

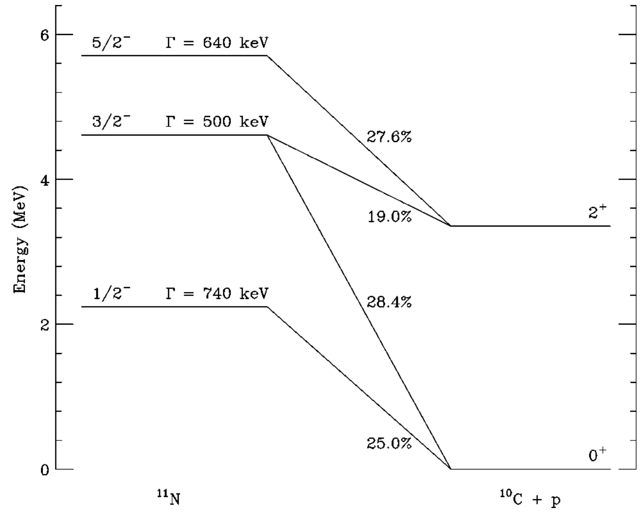

FIG. 3. Calculated decay scheme for the excited states of ^{11}N. The spectroscopic factors and branching ratios were folded in to obtain the relative contribution of each state to the decay energy spectrum, shown as percentages.

III. RESULTS AND INTERPRETATION

The background-subtracted spectrum for ^{11}N is shown in Fig. 2. A simulation containing only the known 2.24 MeV $1/2^-$ state (short dashed curve) is not sufficient to explain the whole spectrum and clearly shows the presence of an enhancement at lower energies. This can be interpreted as evidence for the $1/2^+$ ground state of ^{11}N which has also been recently reported by Axelsson *et al.* [11]. However, the method used in this experiment only measures the relative energy and not the absolute energy of a state. Thus, contributions from the decay of an excited state in ^{11}N to the first excited state of ^{10}C cannot be ruled out and were also considered.

Using the known values and uncertainties for the energy and width of the $1/2^-$ excited state [1], χ^2 optimizations resulted in a resonance energy of 1.45 ± 0.40 MeV and a lower limit on the width of 400 keV. An upper limit for the width could not be obtained experimentally due to the finite geometric efficiency. The fit in Fig. 2 was calculated with a resonance energy of $E_r = 1.45$ MeV and a width of $\Gamma_r = 2.4$ MeV, corresponding to the minimum χ^2 value. The present result is in good agreement with the predicted values of $E_r = 1.6\pm0.2$ MeV, $\Gamma_r = 1.6^{+0.8}_{-0.5}$ MeV by Fortune *et al.* [2] and $E_r = 1.6$ MeV, $\Gamma_r = 1.4$ MeV by Barker [3]. It also agrees with the recent measurement of Axelsson *et al.* ($E_r = 1.30\pm0.02$ MeV, $\Gamma_r = 1.1^{+0.1}_{-0.2}$ MeV) [11].

While the enhancement at lower energies in the ^{11}N decay energy spectrum occurs in the energy range expected for decay of the ground state of ^{11}N, normalization of the prospective $1/2^+$ and $1/2^-$ states to the data yields a relative population of $\sim$45%. This is substantially higher than expected for a neutron pickup reaction from ^{12}N. For example, a shell-model calculation [12] predicts a relative population of only 1% for the $1/2^+$ state. However, this model assumes the one-step transfer reaction ^{9}Be(^{12}N,^{11}N)^{10}Be. The energy spectrum of ^{10}C fragments shows significant contributions at lower energies, resulting from other reaction processes such as fragmentation for the population of excited states. Similar contributions from fragmentation reactions were also observed in a study of the lifetime of ^{16}B [13]. Thus, higher order processes could enhance the production of the $1/2^+$ ground state of ^{11}N.

However, since our method is sensitive to the relative energy between the initial and final states and not the absolute energies, it is possible that the decay of an excited state in ^{11}N to the only bound excited state in ^{10}C, a 2^+ state at 3.354 MeV, contributes to the enhancement around 1.2 MeV [14].

Shell-model calculations were employed to obtain the decay parameters and population ratios for the excited states of ^{11}N, Fig. 3. In addition to the known $1/2^-$ excited state, a $3/2^-$ and a $5/2^-$ state were predicted. The $1/2^-$ state proton decays to the ground state of ^{10}C with a decay energy of 2.24 MeV and a width of 740 keV. The $3/2^-$ level decays to the ^{10}C ground state with a decay energy of 4.61 MeV and width of 300 keV, and to the exited state with a decay energy of 1.26 MeV and width of 200 keV. The $5/2^-$ state decays mainly to the 2^+ state of ^{10}C at 3.35 MeV since the $f_{5/2}$ parentage to the ground state should be small and the centrifugal barrier is large. The energy of this decay is 2.35 MeV with a width of 640 keV. The calculated spectroscopic factors are 0.617, 1.168, and 0.681 for the $1/2^-$, $3/2^-$, and $5/2^-$ states, respectively.

Denoting the spectroscopic factors for the three states of interest by S_{2J}, the number of 1.26 MeV protons relative to 2.3 MeV protons is given by

$$N = \left(S_3 \frac{\Gamma_{p1}}{\Gamma} \right) \Bigg/ (S_1 + S_5) = R \frac{\Gamma_{p1}}{\Gamma}, \tag{3}$$

in terms of a simple ratio of spectroscopic factors and the branch for the $p1$ decay of the $3/2^-$ state. The ratio R is 0.9 for the S values given above.

The results of these calculations folded with the proton detection efficiency and the experimental resolution are compared to the data in Fig. 4. The individual contributions for the decay of the $1/2^-$, $3/2^-$, and $5/2^-$, depicted as the dotted, dashed, and dot-dashed peaks, respectively, were

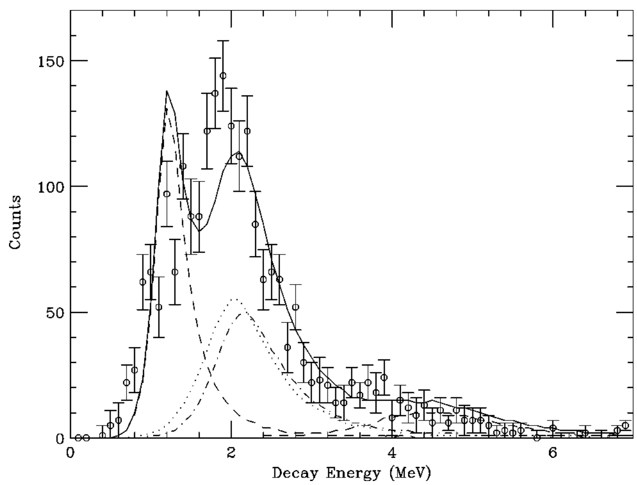

FIG. 4. ^{11}N decay energy spectrum. The dotted, dashed, and dot-dashed peaks are simulations of the first three excited states, respectively, using the values obtained from shell-model calculations. The solid line corresponds to the sum of these contributions.

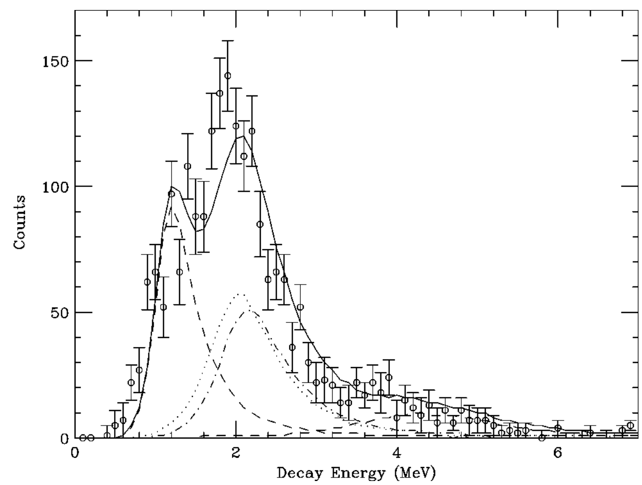

FIG. 5. Similar to Fig. 4. The total decay width of the $3/2^-$ state was increased to 1 MeV.

summed to obtain the total contribution shown as the solid line. The peak from the decay of the $3/2^-$ state in ^{11}N to the 2^+ state in ^{10}C is too narrow and overpredicts the data in the 1.2 MeV region.

In order to achieve a reasonable fit it was necessary to increase the total decay width of the $3/2^-$ from 500 keV to at least 1 MeV as shown in Fig. 5.

IV. SUMMARY AND CONCLUSIONS

An experimental study of the proton-unbound nucleus ^{11}N was performed. New information on the level structure of ^{11}N was obtained from kinematic reconstruction of these states through coincidence measurement of the emitted proton and the ^{10}C daughter nucleus. The known $1/2^-$ first excited state was observed in addition to an enhancement at lower decay energies. This enhancement is consistent with the $1/2^+$ ground state, yielding a decay energy of 1.45 ± 0.40 MeV and a decay width of >400 keV. However, the experimental methods applied were only sensitive to the relative decay energy and not absolute energies, and contributions of an excited state in ^{11}N decaying to an excited state in ^{10}C were also considered. A satisfactory description of the data was achieved based on shell-model calculations that include the first three excited states of ^{11}N, $1/2^-$, $3/2^-$, and $5/2^-$. However, the decay width for the $3/2^-$ state had to be increased by a factor of 2 relative to the calculations.

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