Spectroscopy of the Unbound Nucleus ^{11}N by the ^{12}C(^{14}N, ^{15}C)^{11}N Transfer Reaction

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A spectroscopic study of the proton-rich, particle unstable nucleus ^{11}N has been performed using the multinucleon transfer reaction ^{12}C(^{14}N,^{15}C)^{11}N at 30*A* MeV incident energy at GANIL. Levels of ^{11}N are observed as well defined resonances in the spectrum of the ^{15}C ejectiles. They are localized at 2.18(5), 3.63(5), 4.39(5), 5.12(8), and 5.87(15) MeV above the ^{10}C + p threshold. The comparison of the measured widths with R-matrix calculations allows the estimation of spins and parities for these resonances. [S0031-9007(98)05329-0]

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The study of light neutron-rich nuclei has led to the discovery of unexpected new phenomena, as the neutron halo in ^{11}Li and ^{11}Be. The proton-rich side is much less studied, in particular, the particle unstable nucleus ^{11}N was almost unknown until recently. The mirror nucleus ^{11}Be has two bound states [1], the $1/2^+$ ground state and the $1/2^-$ first excited state, bound by 0.50 and 0.18 MeV, respectively. The first unbound level ($5/2^+$) is situated 1.278 MeV above the ^{10}Be + n threshold. All three states have large spectroscopic factors in ^{10}Be(d, p) [2,3], being well described by the coupling of a ^{10}Be$_{\text{g.s.}}$ core and a neutron in a $2s_{1/2}$, $1p_{1/2}$, and $1d_{5/2}$ state, respectively. The structure of ^{11}Be shows the typical behavior of an sd-shell intruder, presenting the "inversion" of the normal shell-model order.

Until recently only one resonance has been observed in the particle unstable nucleus ^{11}N, lying at 2.24 MeV above the ^{10}C + p threshold [4]. The spin $1/2^-$ was deduced from the width of this resonance [$\Gamma = 0.74(10)$ MeV], and the $1/2^+$ ground state in ^{11}N was supposed to lie 320 keV lower, from analogy with the ^{11}Be. The related mass excess value was then adopted for ^{11}N during the following twenty years. Recent experiments [5–7] on the ^{11}N nucleus claim to observe the $s_{1/2}$ ground state below the $1p_{1/2}$ state; however, they disagree in the position.

Theoretical calculations [8–12] on energies and widths of low lying levels in ^{11}Be and ^{11}N have been published recently and demand a comparison with reliable and precise experimental data. Recent calculations of Fortune *et al.* [8] and Barker [10] for the ^{11}Be and ^{11}N mirror pair assume a model of the type of an inert core times a valence neutron or proton, respectively. They predict the level inversion for the ^{11}N nucleus and give the level energies and widths for the first three levels of these nuclei. The core excitation to the 2^+ state has been taken into account in the recent calculations of Nunes *et al.* [11] and Descouvemont [12] for ^{11}Be and ^{11}N.

Recently new experimental efforts shed more light on the spectroscopy of ^{11}N. The ^{14}N(^{3}He,^{6}He)^{11}N reaction was recently investigated by Guimarães *et al.* [5] and the authors claim that the state observed by Benenson *et al.* [4] is resolved as a doublet. They also observe higher lying levels of ^{11}N. The result of the ^{12}N induced single neutron stripping [6] consists of a peak at 2.24 MeV above the ^{10}C + p threshold, with a barely separable shoulder, which is also partly produced by a decreasing detector efficiency, but is still attributed to a low lying level in ^{11}N at 1.5 MeV.

The ^{10}C + p resonance scattering [7] was also measured with the intention of pinning down resonances in the unbound ^{11}N nucleus. The authors claim the observation of the ground state resonance at 1.3 MeV, as well as two excited levels at 2.04 and 3.72 MeV above the proton threshold. However, the presence of the $1/2^+$ ground state level is not really visible as a peak. The description of this flat part of the spectrum with the interference pattern of a $1/2^+$ resonance and the $1/2^-$ resonance, whose position has been shifted down for the fit by at least 200 keV from the observed maximum, appears rather arbitrary. The background of the proton spectrum at 0° could be, e.g., better explained taking also into account the inelastic excitation of ^{10}C to the 2^+ state at 3.35 MeV. Since the incident ^{10}C projectile is slowed down in the gas inside the scattering chamber, the precise center-of-mass (c.m.) energy for $^{10}\mathrm{C} + p$ is not known at the collision and one cannot distinguish by the detection of *only* the proton energy at 0° between the two cases: (i) whether the recoiling ^{10}C was in the ground state or (ii) whether it was excited to the particle stable 2^+ state at 3.35 MeV. The yield for the inelastic excitation increases from a minimum, near the threshold; the latter is expected in the spectrum at $E_{\mathrm{c.m.}} \approx 0.9$ MeV, as observed by Axelsson *et al.* The contributions from the two kinematical solutions (due to inelastic scattering at 0° with inverse kinematics) give rise to the observed shape of the background with increasing c.m. energy. The shifted-down component of the two kinematical solutions is limited by the energy threshold due to energy conservation, and therefore the counting rate piles up in the spectrum near the threshold below $E_{\mathrm{c.m.}} = 0.9$ MeV (in addition to the Rutherford scattering at $\theta_{\mathrm{c.m.}} = 180°$), whereas the upward shift is not limited. The inclusion of this process would probably result in a good fit of the spectrum without the $1/2^+$ resonance at 1.3 MeV.

In [7] the ^{12}C scattering on ^{1}H was performed for calibration and test purposes. Low lying resonances of ^{13}N can be populated at 0.421 MeV ($1/2^+$), 1.558 MeV ($3/2^-$), and 1.603 MeV ($5/2^+$) above the proton threshold of ^{13}N. The $^{12}\mathrm{C} + p$ spectrum presented in this paper starts at around 0.60 MeV, not covering the 0.421 MeV region of the $2s_{1/2}$ resonance, and shows only the strong $d_{5/2}$ level at 1.603 MeV. The observation of the $2s_{1/2}$ resonance of ^{13}N with the relatively narrow width of 32 keV in the $^{12}\mathrm{C} + p$ spectrum would be a strong demonstration of the method for observing a $1/2^+$ level. The absence weakens considerably the arguments in favor of the observation of this level in ^{11}N.

Multinucleon transfer reactions have been used successfully for the spectroscopy of very neutron-rich unstable nuclei [13,14]. We have recently realized at GANIL an experiment to undertake the spectroscopic study of the neutron-deficient, particle-unstable nucleus ^{11}N [15]. We used the multinucleon transfer reaction ^{12}C(^{14}N,^{15}C)^{11}N, where the particle-unstable ^{11}N is the recoiling nucleus. The ^{15}C ejectile has two particle-stable states, the $1/2^+$ ground state, and the $5/2^+$ first excited state at 0.74 MeV excitation energy. The spectrum is dominated by the transfer to the $5/2^+$ excited state of the ejectile ^{15}C, due to the transfer dynamics and the angular momentum transfer- and spin-weighting factors (by a factor of about 7) [16], and the spectra can be analyzed unambiguously. The excited $^{15}\mathrm{C}^*$-nuclei decay in flight by γ emission, which introduces a broadening of 0.2 MeV on the average of the observed resonances of ^{11}N. This has been taken into account in the analysis qualitatively by folding in a Gaussian with this width. The Q value for the three-particle threshold of $^{15}\mathrm{C}_{\mathrm{g.s.}} + {}^{10}\mathrm{C}_{\mathrm{g.s.}} + p$ is $Q = -29.997$ MeV.

The ^{14}N beam had an energy of $30A$ MeV, and the thickness of the ^{12}C target was 0.5 mg/cm^2. The ejectiles were analyzed by the high-precision magnetic spectrometer SPEG [17]. The laboratory angles subtended by SPEG were $\theta = 2.5° \pm 1.2°$ and $\phi = 0° \pm 2.0°$ in the horizontal and vertical planes, respectively. The detection system included two drift chambers, an ionization chamber, and a plastic scintillator for the measurements, respectively, of the focal plane position, the energy loss (ΔE), and the residual energy. The time of flight (TOF) was measured using the fast scintillator signal with respect to the cyclotron radio frequency. The two-dimensional particle identification spectrum (Z vs A/q), where Z and A/q are calculated from ΔE and TOF, allows a clear separation of all mass groups due to its very good resolution. Consequently, the peaks observed in the ^{15}C energy spectrum cannot be attributed to a background or tail from other mass groups, other charge states, or other reactions. Targets of ^{12}C are usually pure and background spectra measured with the V_2O_5 target have shown that none of the peaks observed in the ^{15}C spectrum can be due to oxygen in the target. The reaction products were momentum analyzed by the horizontal and vertical position measurement carried out by the two drift chambers. The incident position (x, y) and the incident angles (θ, ϕ) of each particle in the focal plane were reconstructed by two position measurements at a distance of 1.2 m. The scattering angle Θ was calculated from the measured (θ, ϕ) angles. Two-dimensional plots of focal-plane position versus scattering angle were used to perform the kinematical corrections. The projection of the kinematically corrected spectra on the momentum axis yielded the one-dimensional spectra used in the following discussions.

The results of the ^{12}C(^{14}N,^{14}C)^{12}N reaction have been used for momentum and energy calibration purposes; the spectrum is shown in Fig. 1. The lower lying well defined peaks are the bound ground state and the unbound unresolved doublet states with $E^* = 0.96$ MeV/1.19 MeV of ^{12}N. The width of the ground state peak represents our energy resolution of 270 keV. Excited unbound resonances are fitted by Breit-Wigner line shapes. The particle stable 3^- state of the ejectile ^{14}C at 6.73 MeV is strongly excited and is also included in the fit taking the Doppler broadening into account. The background is mainly originating from the decay of an intermediately formed excited $^{15}\mathrm{N}^*$ nucleus which decays into $^{14}\mathrm{C} + p$.

The relative population of the ^{12}N levels illustrates directly the difficulties to observe a $2s_{1/2}$ resonance in the presence of a background. The first negative parity level (2^-, 1.19 MeV) formed by the coupling of the $p_{3/2}$ neutron hole with a $2s_{1/2}$ proton is a tiny peak in the spectrum and its coupling partner, the 1^- state at 1.80 MeV, cannot be observed in the presence of the background. On the other hand, the intensely populated positive parity levels in ^{12}N (1^+ ground state and 2^+ first excited state at 0.96 MeV) can be described by the coupling of a $p_{1/2}$ proton to the $p_{3/2}$ neutron hole. The negative parity doublet at 4.14 MeV, formed by the

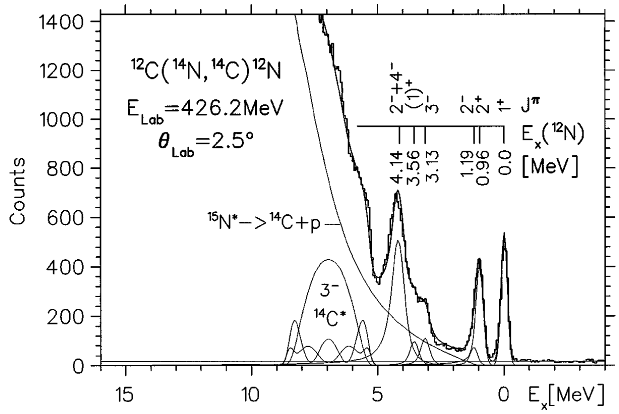

FIG. 1. Spectrum of the $^{12}C(^{14}N,^{14}C)^{12}N$ reaction, used for calibration purposes. See text for details.

coupling of a $p_{3/2}$ neutron hole to a $d_{5/2}$ proton, is again intensely populated.

The relative population of ^{13}N levels, also observed in this experiment in the reaction $^{12}C(^{14}N,^{13}C)^{13}N$, shows the same trend (Fig. 2). The $2s_{1/2}$ resonance at 2.365 MeV is 30 times less intense than the $p_{1/2}$ ground state, and 100 times less than the $d_{5/2}$ resonance at 3.55 MeV.

Figure 3 shows the results for the $^{12}C(^{14}N,^{15}C)^{11}N$ reaction. The origin of the energy axis is set to the ^{10}C + proton decay threshold, *with the ^{15}C ejectile in its $5/2^+$ excited state at 0.74 MeV*. The most prominent peaks in the spectrum of Fig. 3 are resonances of ^{11}N situated at ^{11}N decay energies of $E_{\text{decay}} = 2.18(5)$, 3.63(5), 4.39(5), 5.12(8), and 5.87(15) MeV. The three-body sequential decay background was calculated using a Breit-Wigner shaped resonance in ^{16}N at 17 MeV excitation energy (with a width of 6 MeV), that could be part of E1 or E2 giant resonances. The strength in ^{16}N is populated in a direct $2n$ pickup with a relatively large cross section. The excited ^{16}N nucleus decays in flight with a small branch into either $^{15}C^*_{5/2^+}$ or $^{15}C_{\text{g.s.}}$ by proton emission; the strength was adjusted by the fit.

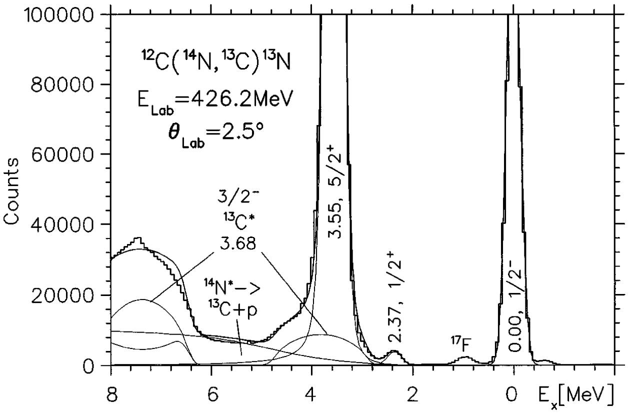

FIG. 2. Spectrum of the $^{12}C(^{14}N,^{13}C)^{13}N$ reaction. The broad line shapes correspond to the Doppler-broadened excited state of ^{13}C at 3.68 MeV; it is excited in combination with the two strong ^{13}N states, the ground state, and the $5/2^+$ state (3.55 MeV) at the sum energy of 7.23 MeV.

The differential cross sections of the $^{12}C(^{14}N,^{15}C)^{11}N$ reaction populating the levels at 2.18, 3.63, and 4.39 MeV are 0.6(3), 0.9(3), and 0.26(10) μb/sr, respectively.

A small peak between the 2.18 and 3.63 MeV resonances was attributed to the resonance at 3.63 MeV *with ^{15}C in its ground state,* since the small peak has exactly the distance of 0.74 from the 3.63 MeV resonance and the cross-section ratio follows the spin-weighting factor ratio (7). This peak is more narrow, because it does not involve the Doppler-broadening effect, since ^{15}C is in the ground state. We conclude that any narrow ^{11}N resonance, which is strongly populated with the ^{15}C excited state, should also be visible with ^{15}C in its ground state. This imposes the observation of a small peak at an energy in the plotted scale at 2.18 − 0.74 MeV = 1.44 MeV, with an intensity approximately 7 times smaller than the 2.18 MeV resonance, which corresponds to the 2.18 MeV resonance of ^{11}N and ^{15}C in its ground state. With this interpretation all the observed counting rate around 1.44 MeV is exhausted, leaving no room for a possible $2s_{1/2}$ ground state resonance of ^{11}N.

R-matrix calculations were performed for the observed ^{11}N resonances, and the comparison of the experimental and calculated widths allows a preliminary assignment of the spin parity of these states. In Table I we summarize the decay energies and experimental widths obtained in this work together with results obtained by other authors.

As discussed above, we have no clear evidence of the population of the $2s_{1/2}$ ground state of ^{11}N; however, our spectra of ^{12}N and ^{13}N, which have much better statistics, clearly corroborate the strong hindrance of any $2s_{1/2}$ resonance. The peak at 2.18 MeV is the $p_{1/2}$ resonance of ^{11}N, also observed by the other authors (at 2.24 MeV by Benenson *et al.* [4] and Thoennessen *et al.* [6] and at

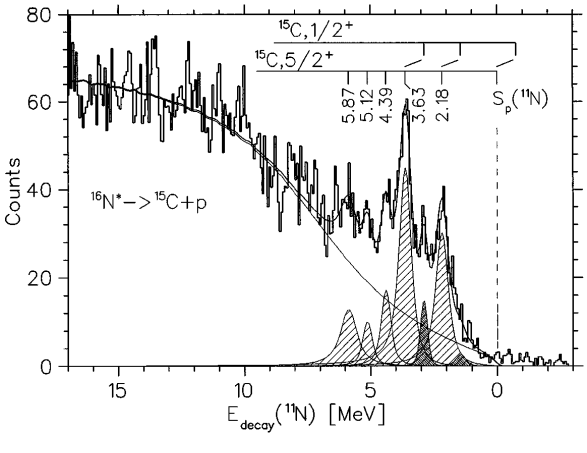

FIG. 3. Spectrum of the $^{12}C(^{14}N,^{15}C)^{11}N$ reaction obtained at 2.5°. The origin of the energy axis is given by the proton decay threshold ($^{11}N \rightarrow {}^{10}C + p$) in combination with the $^{15}C_{5/2^+}$ excited state. The resonances populated in combination with the ^{15}C ground state and with the excited state at 0.74 MeV are hatched, respectively, by darker and lighter filling. The corresponding scales are shown in the upper part of the figure; the energies indicated are decay energies of the ^{11}N nucleus in MeV.

TABLE I. Decay energies, widths (Γ), and statistical significances (signif) of ^{11}N resonances measured in this work and by Axelsson *et al.*, and comparison with theoretical calculations of Fortune *et al.* and Barker. Experimental spin parities were estimated by R-matrix calculations.

	This Letter			Axelsson *et al.* [7]		Fortune *et al.* [8]		Barker [10]	
J^π	E_{decay} (MeV)	Γ (MeV)	Signif. (σ)	E_{decay} (MeV)	Γ (MeV)	E_{decay} (MeV)	Γ (MeV)	E_{decay} (MeV)	Γ (MeV)
$1/2^+$	⋯	⋯	⋯	(1.30)	0.99(15)	1.60(22)	1.58	1.60	1.39
$1/2^-$	2.18(5)	0.44(8)	20	2.04	0.69(8)	2.48	0.91	2.24	0.64
$5/2^+$	3.63(5)	0.40(8)	22	3.72	0.60(7)	3.90	0.50	3.84	0.46
$(3/2^-)$	4.39(5)	$\leq$0.22(10)	8	4.32	0.07				
$(5/2^-)$	5.12(8)	$\leq$0.22(10)	3	(5.1)	1.1				
$(7/2^-)$	5.87(15)	0.7(2)	5	(5.5)	1.5				

2.04 MeV by Axelsson *et al.* [7]). The peak at 3.63 MeV is the $d_{5/2}$ resonance. The energy separation between the $p_{1/2}$ and $d_{5/2}$ levels in ^{11}N is 1.45 MeV, while in the ^{11}Be mirror nucleus it is 1.46 MeV, demonstrating the very similar structure of these quite pure single-particle levels.

The resonances at 4.39 and 5.87 MeV are observed as significant peaks on top of the background, whereas the peak at 5.12 MeV is less significant. However, it is needed to obtain a fit also between the two other resonances. If we assume a single particle nature for the 4.39 and 5.12 MeV levels, their widths indicate an l value of 2 or higher, and we might suggest the splitting of the $d_{3/2}$ strength between these levels, attributing $3/2^+$ to both of them. However, we can also assume for the structure of these two levels a ^{10}C core excited to its 2^+ .state at $E^* = 3.35$ MeV coupled to a $p_{1/2}$ proton at 2.18 MeV resonance energy with the sum energy of 5.53 MeV. This coupling results in two levels with $3/2^-$ and $5/2^-$, slightly shifted down in energy, which is a common feature in this mass region, also observed in ^{11}Be. This assignment seems to be more probable than the single particle $d_{3/2}$ structure. A theoretical estimate [12] gives too large widths as compared to the experimental values (see Table I) and more theoretical work is needed to understand the structure of these states. The 4.39 MeV level could be the mirror state of the 3.96 MeV $3/2^-$ level in ^{11}Be, which has a width of only 15 keV. R-matrix calculations suggest an $l = 3$ orbital angular momentum for the 5.87 MeV level, according to its width, for a single particle structure, but core excitations probably also contribute.

To summarize, we can conclude that the ^{12}C(^{14}N,^{15}C)^{11}N reaction yielded well resolved resonances of ^{11}N in the spectrum of the ^{15}C ejectiles. We have no clear evidence of the population of the $2s_{1/2}$ ground state of ^{11}N; however, our spectra of ^{12}N and ^{13}N, also obtained in this experiment with much better statistics, clearly corroborate the strong hindrance of the population of a $2s_{1/2}$ resonance. This does not exclude the existence of the $1/2^+$ resonance in ^{11}N; however, the reported observation of the $1/2^+$ resonance in other experiments is rather questionable, as discussed above. We observe a strong population of the $p_{1/2}$ and $d_{5/2}$ resonances at 2.18 and 3.63 MeV above the ^{10}C + p threshold. Somewhat lower widths [respectively, 0.44(8) and 0.40(8) MeV] are obtained in the analysis than quoted before, probably due to our good energy resolution. These widths are in agreement with R-matrix calculations ($\Gamma = 0.46$ MeV for an $l = 1$ level at 2.18 MeV and $\Gamma = 0.60$ MeV for an $l = 2$ level at 3.63 MeV decay energies). For the resonances at 4.39, 5.12, and 5.87 MeV the spin-parity assignments are difficult and the estimated values of $3/2^-$, $5/2^-$, and $7/2^-$ are only preliminary.

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