STUDY OF EXCITED LEVELS OF THE UNBOUND NUCLEUS ^{11}N*

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The multi-nucleon transfer reaction ^{12}C(^{14}N,^{15}C)^{11}N was performed at 30 AMeV incident energy at GANIL to study the spectroscopy of the proton-rich, particle unstable nucleus ^{11}N. Five excited levels of ^{11}N are observed as well defined resonances in the spectrum of the ^{15}C-ejectiles. They are localised 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 and with positions of ^{11}Be levels, allows the estimation of spins and parities for these resonances. They are respectively, $1/2^-$, $5/2^+$, $3/2^-$,$3/2^-$ and $5/2^-$.

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We have performed at GANIL an experiment to undertake the spectroscopic study of the neutron-deficient, proton-unbound nucleus ^{11}N. The multi-nucleon transfer reaction ^{12}C(^{14}N,^{15}C)^{11}N was used, where the particle-unstable ^{11}N is the recoiling nucleus.

Details of the experiment and some of its results were described in a previous publication [1]. Here we want to concentrate on the comparison of the observed levels, their position and widths, with properties of levels of other $A = 11$ nuclei and with R-matrix calculations. Spin and parity assignments are made for all the observed levels.

The interest in studying the ^{11}N nucleus is due to the fact that it is the mirror nucleus of ^{11}Be, which has raised much interest recently due to its one-neutron halo character. On the other hand ^{11}N is maybe the less-known member of the $A = 11$ isobaric chain.

The proton unbound nucleus ^{11}N was almost unknown until recently. Its first observation was realized in 1974, using the three neutron pick-up reaction ^{14}N(^{3}He,^{6}He)^{11}N [2]. Two peaks were visible in the energy spectrum, one lying at 2.24 MeV above the ^{10}C+p threshold, the other at 4.50 MeV. Only the lower lying resonance was analysed and the spin $1/2^-$ was deduced from its width (Γ = 0.74(10) MeV), and from the isobaric mass multiplet equation (IMME), based on the known $1/2^-$ states in ^{11}Be, ^{11}B and ^{11}C. The $1/2^+$ ground "state" was not observed and its position was deduced from IMME to be 1.9 MeV above the proton decay threshold. Thus the same spin-inversion was supposed as in ^{11}Be, with the $1/2^+$ ground "state" of ^{11}N situated 320 keV below the observed resonance, yielding almost the same energy separation between the $1/2^+$ and $1/2^-$ states in ^{11}Be and ^{11}N. The related mass excess value was then adopted for ^{11}N during the following twenty years.

Its mirror nucleus ^{11}Be shows the "inversion" of the normal shell-model order, with the $1/2^+$ ground-state lying 320 keV below the $0p_{1/2}$ level [3]. They are bound by 0.50 MeV and 0.18 MeV, respectively. The microscopic structure of ^{11}Be was recently investigated [4] by means of the p(^{11}Be,^{10}Be)d reaction. Spectroscopic factor measurements indicate that the wave-function of its $1/2^+$ ground-state is a mixture of a $[0^+ - 1s_{1/2}]$ component and a $[2^+ - 0d]$ component (a d-wave intruder coupled to the excited ^{10}Be core) with equal intensities.

The position and the spin-parity assignment of the ^{11}N ground-state is still an interesting and open question. Most theoretical calculations agree on the spin-inversion, predicting a $1/2^+$ ground-state, however the energy positions and widths show discrepancies. The position of the ground-state is also relevant for the recently measured two-proton emission of ^{12}O [5].

We used the multi-nucleon transfer reaction ^{12}C(^{14}N,^{15}C)^{11}N, with the particle-unstable ^{11}N recoiling and the ^{15}C being the detected ejectile, whose energy spectrum can give us information on the excited levels of the recoiling ^{11}N. 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. Due to the transfer dynamics and the angular momentum transfer- and spin-weighting factors the transfer to the $5/2^+$ excited state of the ejectile ^{15}C is greatly favoured (by a factor of about 7) [6]. Thus the spectrum is dominated by the transfer to this state and the spectra can be analysed unambiguously.

We will give a summarized description of the experiment since it has been described in more detail elsewhere [1]. The ^{14}N beam with energy of 30 AMeV bombarded the 0.5 mg/cm^2 thick ^{12}C target. The ejectiles were analysed by the high-precision magnetic spectrometer SPEG [7]. The standard SPEG detection system was used; it includes two drift-chambers, an ionisation chamber and a plastic scintillator for the measurements, respectively, of the focal plane position, the energy-loss (ΔE) and the residual energy and the time-of-flight. The reaction products were momentum analysed by the horizontal and vertical position measurement carried out by the two drift chambers. The projection of the kinematically corrected spectra on the momentum axis yielded the one-dimensional spectra used in the following discussions.

The energy spectrum of the two-nucleon transfer reaction ^{12}C(^{14}N,^{14}C)^{12}N is shown in Fig. 1. It presents many of the interesting features of this kind of multinucleon-transfer reaction, with much better statistics than the reaction of interest and was used for momentum and energy calibration purposes. The well defined peaks at low energy are constituted by the 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 res-

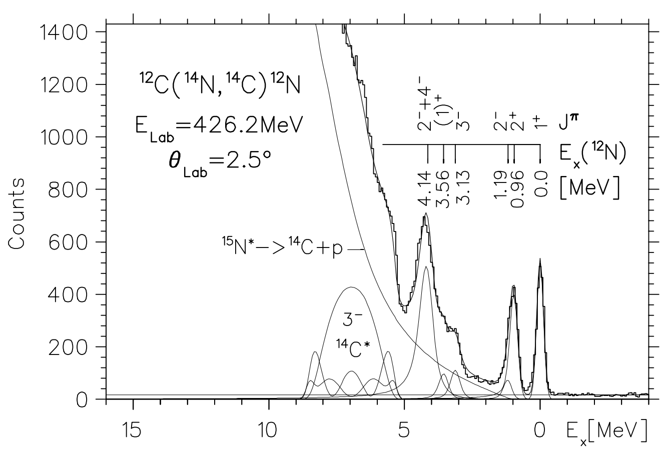

Fig. 1. Spectrum of the ^{12}C(^{14}N,^{14}C)^{12}N reaction, used for calibration purposes. See text for details.

olution of 270 keV. Excited unbound resonances are fitted by Breit-Wigner line shapes. The background is mainly originating from the decay of an intermediately formed excited ^{15}N* nucleus which decays into ^{14}C+p.

The difficulties to observe a $s_{1/2}$ resonance in the presence of a background are well illustrated by the relative population of the ^{12}N levels. The levels which have an $s_{1/2}$ proton component are all very weakly populated (the first negative parity level (2^-, 1.19 MeV) formed by the coupling of the $p_{3/2}$ neutron hole with a $s_{1/2}$ proton and its coupling partner, the 1^--state at 1.80 MeV, which cannot even be observed in the presence of the background.) 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 coupling of a $p_{3/2}$ neutron hole to a $d_{5/2}$ proton is again intensely populated.

The mechanism of the ^{12}C(^{14}N,^{15}C)^{11}N reaction is of direct one proton stripping and two neutron pick-up. The reaction time of a direct transfer process is much shorter than the life time of the observed resonances of the recoil nucleus ^{11}N, it is $\tau = \hbar/\Delta\mathrm{E}$, where ΔE is given by the resonance width Γ, *e.g.*, for Γ=0.40 MeV, the life time is around 1.6×10^{-21}s, and we may calculate how far the ^{15}C is gone during that time. We get a distance of 100 fm for our ejectile velocity $v/c = 0.22$, which is large enough to consider the kinematics of the process well defined. Therefore, observing peaks in the energy spectrum of the ^{15}C ejectile, we get information about levels in the recoiling ^{11}N nucleus, even if it is particle-unbound.

The energy levels of the ^{11}N nucleus, observed in the energy spectrum of the ^{12}C(^{14}N,^{15}C)^{11}N reaction are presented in Fig. 2. The energy axis represents the decay energy of the recoiling ^{11}N nucleus with the ^{15}C-ejectile in its $5/2^+$ excited state at 0.74 MeV, and with the origin of the energy axis set to the ^{10}C+proton decay threshold.

The most prominent peaks in the spectrum of Fig. 2 are resonances of ^{11}N situated at ^{11}N decay energies of E_{decay} = 2.18(5), 3.63(5), 4.39(5), 5.12(8) and 5.87(15) MeV with experimental widths of 0.44(8), 0.40(8), $\leq$0.22(10), $\leq$0.22(10) and 0.7(2) MeV respectively. The statistical significance of these peaks are respectively 20, 22, 8, 3, 5σ, giving a strong confidence in their existence. The background is due to the 3-body sequential decay of excited ^{16}N nuclei into ^{15}C+p. It 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 $2n$ pick-up of the beam particles, with a relatively large cross-section. The excited ^{16}N nucleus decays in flight with a small branch into either $^{15}\mathrm{C}^*_{5/2^+}$ or $^{15}\mathrm{C}_{\mathrm{g.s.}}$ by proton emission, the strength was adjusted by the fit.

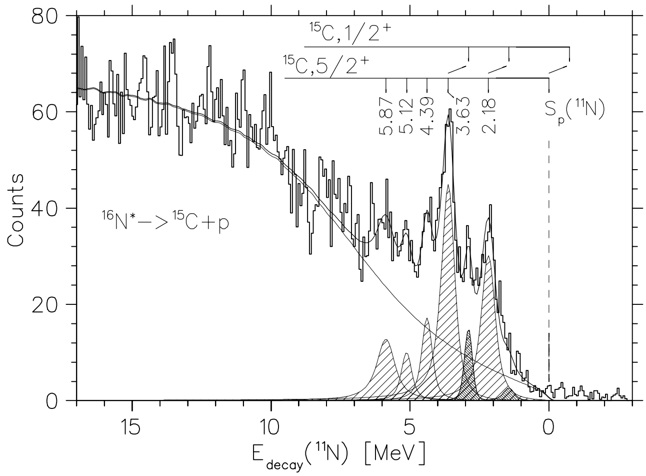

Fig. 2. Spectrum of the $^{12}C(^{14}N,^{15}C)^{11}N$ reaction obtained at 2.5°. The origin of the energy axis is given by the proton decay threshold ($^{11}N \rightarrow ^{10}C+p$) in combination with the $^{15}C_{5/2+}$ excited state. The resonances populated in combination with the ^{15}C ground state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

The differential cross-sections of the $^{12}C(^{14}N,^{15}C)^{11}N$ reaction populating the levels at 2.18 MeV, 3.63 MeV and 4.39 MeV are 0.6(3), 0.9(3) and 0.26(10) $\mu b/sr$, respectively. A small and narrow peak can be seen between the 2.18 MeV and 3.63 MeV resonances. It 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 MeV 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. This imposes the observation of a small peak at an energy $2.18-0.74$ MeV $= 1.44$ MeV, with an intensity approximately seven 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 $s_{1/2}$ ground state resonance of ^{11}N.

Theoretical calculations [8–12] on energies and widths of low lying levels in ^{11}Be and ^{11}N have been published recently. Recent calculations of Fortune *et al.* [8] and Barker [9] for the ^{11}N assume a potential model, with a valence proton in the potential well of an inert ^{10}C core. They predict the level inversion for the ^{11}N nucleus and give the level energies and widths of its first three levels, situating the $s_{1/2}$ resonance respectively at: 1.60 MeV (Γ=1.58 MeV) [8], or at 1.40 MeV (Γ=1.39 MeV) [9] above the proton decay threshold. Grévy *et al.* [10] add a surface term to the potential, in order to simulate a particle-core vibration coupling and calculate the $s_{1/2}$ resonance at 1.20 MeV (Γ=1.1 MeV). The core excitation to the 2^+-state has been taken into account in the calculations of Nunes *et al.* [11] and Descouvemont [12] for ^{11}Be and ^{11}N.

The search for the $s_{1/2}$ ground state and for the mass excess value of ^{11}N was intensified in recent times. The experimental observation of an $s_{1/2}$ resonance, very broad due to the lack of centrifugal barrier, is not an easy task. However, due to the strong d-wave admixture in the ground-state wave-function of the ^{11}Be nucleus one could expect a smaller width for the ^{11}N ground-state resonance (its mirror state), due to the existence of a centrifugal barrier for the l=2 component of the ground-state wave function.

New experiments [13, 14] claim to observe the $1/2^+$ ground-state below the $1/2^-$ state. However the experimental discrepancy in its position and width is comparable to the theoretical: Axelsson [13] presumes the resonance at 1.3 MeV (Γ=0.99 MeV), Azhari [14] at 1.45 MeV (Γ=2.4 MeV).

The ^{10}C+p resonance scattering [13] was 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 MeV 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 result of the ^{12}N induced single neutron stripping, where the proton decay of the ^{11}N nucleus is measured [14] yields a peak at 2.24 MeV above the ^{10}C+p threshold, with a barely separable shoulder at 1.45 MeV. Since the method only measures relative energy, this shoulder could be due to the $1/2^+$ ground-state and/or due to the proton decay of a $3/2^-$ excited state around 4.6 MeV in ^{11}N (our resonance at 4.39 MeV) to the first excited 2^+ state of ^{10}C at 3.35 MeV. As a matter of fact, Azhari *et al.* [14], who also studied the proton decay spectrum of ^{13}N, did not observe the $s_{1/2}$ resonance situated 0.421 MeV above the proton decay threshold in ^{13}N, but only the $3/2^-$ resonance at 1.558 MeV.

In our energy spectrum the first peak is at 2.18 MeV, it is the $1/2^-$ resonance of ^{11}N, also observed by other authors (at 2.24 MeV by Benenson *et al.* [2] and Azhari *et al.* [14] and at 2.04 MeV by Axelsson *et al.* [13]). The peak at 3.63 MeV is the $5/2^+$ resonance observed at 3.72 MeV by [13]. The energy separation between the $1/2^-$ and $5/2^+$ levels in ^{11}N is 1.45 MeV, while in the ^{11}Be mirror nucleus it is 1.46 MeV.

R-matrix calculations were performed for the observed ^{11}N resonances, obtaining Γ=0.46 MeV for an l=1 level at 2.18 MeV ($1/2^-$) and 0.60 MeV for an l=2 level at 3.63 MeV ($5/2^+$), confirming our findings.

The resonances at 4.39 MeV 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.

Shell-model calculations [14,15] in ^{11}N and ^{11}Be predict a $K = 1/2$ band whose $1/2^-, 3/2^-$ and $5/2^-$ states lay respectively at energies 2.24, 4.61 and 5.7 MeV (with widths of 0.74, 0.50 and 0.64 MeV and spectroscopic factors of 0.617, 1.168 and 0.681) in ^{11}N and at 0.320 MeV, 2.69 MeV and 3.96 MeV in ^{11}Be. More recent (t, p) data of Liu and Fortune [16] suggest that the 3.96 MeV level (in ^{11}Be), which was previuosly assigned $3/2^-$ [17], is probably a $5/2^-$ [15]. Our observed peaks at 2.18 MeV, 4.39 MeV and 5.87 MeV (with widths of 0.44, 0.22 and 0.7 MeV) have energies very close to these predictions supporting strongly the $3/2^-$ and $5/2^-$ spin-parity assignments for the 4.39 MeV and 5.87 MeV peaks.

The energy separation between the $1/2^-$ (E*=0.320 MeV) and $3/2^-$ (E^*=2.690 MeV) levels in ^{11}Be is 2.37 MeV. The energy separation between the 4.39 MeV peak and the $1/2^-$ state is 2.21 MeV in ^{11}N, strongly supporting its $3/2^-$ assignment. The energy differences between levels should be the same in mirror nuclei neglecting the Thomas–Ehrmann shift, which affects the Coulomb energy difference between levels which are bound in one nucleus and unbound in its mirror-partner. However, the experimental width of the 4.39 MeV peak ($\Gamma \leq$220 keV) has a width much narrower than predicted by the calculations assuming a K=1/2 band. The state observed at 4.32 MeV decay energy by Axelson also has a very small width (Γ=70 keV).

The energy separation between the $1/2^-$ (E^*=0.320 MeV) and $5/2^-$ (E^*=3.96 MeV) levels in ^{11}Be is 3.64 MeV. The energy separation between the 5.87 MeV peak and the $1/2^-$ state is 3.69 MeV in ^{11}N, strongly supporting the $5/2^-$ assignment. However its width is much larger than its analog in ^{11}Be.

The level at 5.12 MeV could be the analog of the 3.42 MeV $3/2^-$ state in ^{11}Be and there are strong arguments for a dominant ^{9}Be $*(sd)^2$ structure for this state, which implies a weak excitation in our experiment [15].

In Table I we summarise the decay energies and experimental widths obtained in this work together with results obtained by other authors.

We can conclude that by means of the ^{12}C(^{14}N,^{15}C)^{11}N reaction, we could observe five well-resolved resonances of ^{11}N in the spectrum of the ^{15}C-ejectiles up to decay energies of 5.87 MeV. Assuming that the ground state resonance was not observed, all these five resonances correspond to excited virtual levels of the unbound ^{11}N system. By comparison with known levels of ^{11}Be and from the widths of the resonances, the spin parity values could be established. The population of the $1/2^+$ ground-state of ^{11}N was not clearly seen in our spectrum, however our spectrum of ^{12}N also obtained in

TABLE I

Decay energies, widths and statistical significances of ^{11}N-resonances measured in this work and comparison with theoretical calculations of Fortune *et al*. and Barker. For experimental spin-parity estimations see text.

This work				Fortune *et al*. [8]		Barker [9]	
J^{π}	E_{decay}	Γ	signif.	E_{decay}	Γ	E_{decay}	Γ
	[MeV]	[MeV]	[σ]	[MeV]	[MeV]	[MeV]	[MeV]
$1/2^+$	–	–	–	1.60(22)	1.58	1.60	1.39
$1/2^-$	2.18(5)	0.44(8)	20	2.48	0.91	2.24	0.64
$5/2^+$	3.63(5)	0.40(8)	22	3.90	0.50	3.84	0.46
$3/2^-$	4.39(5)	$\leq$0.22(10)	8				
$3/2^-$	5.12(8)	$\leq$0.22(10)	3				
$5/2^-$	5.87(15)	0.7(2)	5				

this experiment with much better statistics, clearly corroborate the strong hindrance of the population of a $s_{1/2}$ resonance. This does not exclude the existence of the $1/2^+$ resonance in ^{11}N. We observe a strong population of the $1/2^-$ and $5/2^+$ resonances at 2.18 MeV 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. For the resonances at 4.39 MeV and 5.87 MeV the spin-parity assignments are $3/2^-$ and $5/2^-$ respectively, while the 5.12 MeV level is probably the second $3/2^-$ state. Nevertheless more experimental and theoretical efforts would be desirable to confirm our results.

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