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Observation of the ^{11}N ground state.

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Abstract

The ground state of the proton-rich, unbound nucleus ^{11}N was observed, together with six excited states using the multi-nucleon transfer reaction ^{10}B(^{14}N,^{13}B)^{11}N at 30 AMeV incident energy at GANIL. Levels of ^{11}N are observed as well defined resonances in the spectrum of the ^{13}B-ejectiles. They are localised at 1.63(5), 2.16(5), 3.06(8), 3.61(5), 4.33(5), 5.98(10) and 6.54(10) MeV above the ^{10}C+p threshold. The ground state resonance has a mass excess of 24.618(50) MeV, the experimental width is smaller than theoretical predictions.

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Recently the particle unstable neutron deficient nucleus ^{11}N has been the subject of many experimental [1, 2, 3] and theoretical studies [4, 5, 6, 7, 8]. The main interest concerns the existence and observation of a $1/2^+$ resonance as the ground state. Compared to the ground state of the mirror nucleus ^{11}Be, the ^{11}N $1/2^+$ ground state was supposed to be localised some hundreds of keV below the $1/2^-$ first excited state, which is well observed in all cited experiments at about 2.2 MeV above the ^{10}C+p threshold.

Theoretical calculations on energies and widths of low lying levels in ^{11}Be and ^{11}N have been published recently. Calculations of Fortune *et al.* [4] and Barker [5] with a valence proton in the potential well of an inert ^{10}C core 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) [4], or at 1.40 MeV (Γ=1.01 MeV) [5] above the proton decay threshold.

We have realized at GANIL an experiment to undertake the spectroscopic study of the unbound nucleus ^{11}N. We used the multi-nucleon transfer reaction ^{10}B(^{14}N,^{13}B)^{11}N, the states of ^{11}N are observed in the ^{13}B-spectrum. The energies of ^{11}N resonances are given later on in the paper with respect to the $^{10}C_{g.s.}$+p threshold, the corresponding Q-value of this threshold being $Q = -24.635$ MeV. The ^{14}N beam had an energy of 30 AMeV, and the isotopically enriched ^{10}B target was a "sandwich" of four targets of 0.1 mg/cm^2 thickness each. The ^{10}B targets had some content of ^{11}B and impurities of ^{16}O and ^{12}C. To measure the contribution of these other isotopes to the spectrum, we also performed measurements on an isotopically enriched ^{11}B target (0.2 mg/cm^2), a Li_2O target (0.15 mg/cm^2) evaporated on 50 $\mu g/cm^2$ carbon backing and on a 0.2 mg/cm^2 carbon target.

The ejectiles were analysed by the high-precision magnetic spectrometer SPEG. The laboratory angles subtended by SPEG were θ=1.2° to 4.5° and $\phi = 0^o \pm 2.0^o$ in the horizontal and vertical planes, respectively. 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. 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.

The reaction products were momentum analysed by the horizontal and vertical position measurements carried out by the two drift chambers. The positions (x,y) and the angles (θ, ϕ) of each particle in the focal plane were reconstructed by two position measurements 1.2 m apart. The scattering angles Θ were calculated from the measured (θ, ϕ) angles, they range from 1.2° to 4.9° and the medium angle was 3.05°. Two-dimensional plots of the 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, which have been analysed. The momentum and energy calibrations were easily performed with the reactions producing ^{12}B and ^{13}B ejectiles on the different targets allowing also the precise determination of the ^{16}O and ^{11}B contents in the isotopically enriched ^{10}B target. The two-proton stripping reactions ^{10}B(^{14}N,^{12}B)^{12}N, ^{11}B(^{14}N,^{12}B)^{13}N, ^{16}O(^{14}N,^{12}B)^{18}Ne were observed on the different targets and were very useful for the energy calibration.

In Fig. 1 we show the kinematically corrected energy spectra of the ^{13}B ejectiles measured on Li_2O and ^{11}B targets, corresponding to the reactions ^{16}O(^{14}N,^{13}B)^{17}Ne, $Q_0 = -34.921$ MeV, (upper part) and ^{11}B(^{14}N,^{13}B)^{12}N, $Q_0 = -22.369$ MeV, (lower part), respectively. The ^{12}C(^{14}N,^{13}B)^{13}O reaction has a Q-value of −36.810 MeV, this is in excess of 10 MeV more negative than on ^{10}B. Therefore the reaction is not contributing in the energy region of interest for ^{11}N.

The spectrum measured on the ^{11}B target (Fig. 1, lower part) shows several peaks corresponding to well known levels of the ^{12}N nucleus at 0.00, 0.96, 1.19, 1.80 (very weak), 3.13, 4.14 (2^-+4^- doublet) and 5.35 MeV. The observed width (FWHM) of the *bound* ground state peak represents our energy resolution of 300 keV. All excited states of ^{12}N are unbound. The resonances were fitted with Breit-Wigner line shapes calculated with the correct dependence of the width Γ_ℓ(E) on the decay energy E and decay ℓ-value, the Γ_ℓ-values at resonance energy were taken from the literature [9]. In the peak fitting procedure these widths were convoluted with the experimental resolution. The ejectile ^{13}B has its first particle stable excited states at 3.48, 3.53, 3.68, 3.71, 4.13 and 4.83 MeV [10] and thus a clear "window" exists between its ground and excited states. The relative population strengths of these states is known [11] from transfer reactions of similar type as used in this work: only the doublet at 3.7 MeV (or one state of it) is strongly excited. This is confirmed by the observation that a reasonable fit to all states in ^{12}N could only be achieved by taking both the ground state transition and the population of the 3.7 MeV excited state in ^{13}B into account. In addition, the Doppler-broadening due to in-flight γ-deexcitation and the line shapes of the corresponding states in ^{12}N have been treated properly. These γ-broadened lines are shown in the lower part of Fig. 1 separately below the x-axis (thin lines). The different shapes result from variations of the γ-angular distributions in different m-substates. Equivalent fits are obtained for j values between $5/2^+$ and $5/2^-$. From the reaction mechanism we expect the preference for a state with *positive* parity, since the relatively large cross section indicates the well matched one-neutron transfer on ^{14}N to the 1d5/2-orbit. The two-proton pick-up from ^{14}N populates strongly the 1^+, 2^+ ground state and first excited state doublet in ^{12}B, which couple with the 1d5/2-neutron to a configuration $\alpha\{^{12}\text{B}(1^+,0.00\text{MeV})\otimes\nu5/2^+\} + \beta\{^{12}\text{B}(2^+, 0.95\text{MeV})\otimes\nu5/2^+\}$, where α and β describe the configuration amplitudes of the doublet $[\pi3/2^- \otimes \nu1/2^-]1^+,2^+$. Due to the positive parity of this ^{13}B-configuration we identify it with the state at 3.68 MeV [10]. The slowly rising background with increasing excitation energy in Fig. 1, lower part, results from the sequential decay $^{14}\text{C}^* \rightarrow {}^{13}\text{B}+\text{p}$. The excitation strength of ^{14}C* is obtained in the fit as a broad distribution at 25 MeV excitation energy with a Gaussian form and a width of 7 MeV, which is populated as an intermediate channel $^{14}\text{C}^* + {}^{11}\text{C}$ in a single charge exchange reaction.

On the ^{16}O target (Fig. 1, upper part) a strong double peak is visible around channel 55 on the energy axis, due to the excitation of the unbound levels at 3.02 and 3.55 MeV in ^{17}Ne and two lower lying states at 1.28 and 1.87 MeV (a doublet at 1.764 and 1.908 MeV [12]), with the ^{13}B ejectile in its ground state (thick lines in the fit) or in its excited state at 3.68 MeV (thin lines). The parameters of the background for the sequential decay of $^{14}\text{C}^* \rightarrow {}^{13}\text{B}+\text{p}$ were the same as in the preceding case. A linear background was summed to this in the case of the ^{16}O target.

The lower part of Fig. 2 shows the energy spectrum of the ^{13}B ejectiles for the isotopically enriched ^{10}B target. Contributions of the $^{11}\text{B}(^{14}\text{N},^{13}\text{B})^{12}\text{N}$ and $^{16}\text{O}(^{14}\text{N},^{13}\text{B})^{17}\text{Ne}$ reactions due to ^{16}O and ^{11}B contents in the target could be easily identified and subtracted, since the amount of these impurities could be precisely determined with the corresponding spectra and also using the $(^{14}\text{N},^{12}\text{B})$ reaction channel (not shown here). All spectra, the unsubtracted and the ones to be subtracted had the same kinematical correction (for the $^{10}\text{B}(^{14}\text{N},^{13}\text{B})^{11}\text{N}$ reaction). The well defined peaks of the ^{12}N and ^{17}Ne recoil nuclei allowed the exact superposition and posterior subtraction of the different components, i.e., the subtraction of contributions from ^{11}B is precisely controlled due to the presence of the well defined ^{12}N peaks at excitation energies of 0.00, 0.96 and 3.13 MeV, where there are no contributions from other target constituents. The upper part of Fig. 2 shows the final energy spectrum obtained after subtractions of the normalised energy spectra from the ^{16}O and ^{11}B impurities. In both parts of Fig. 2 the fit results are shown using (i) Breit-Wigner resonances for the unbound states (thick lines), (ii) $\gamma-$recoil broadened lines of mutual excitation of ^{11}N-states and ^{13}B at 3.68 MeV excitation energy (thin lines) and (iii) the two sequential decay distributions from the proton-decay of the broad ^{14}C* resonance at 25 MeV ($\Gamma = 7$ MeV) populated in this case in combination with the ground state (curve 1, Fig. 2) and with the first excited state at 3.35 MeV (curve 2) of the ^{10}C recoil nucleus.

The results of the $^{10}\text{B}(^{14}\text{N},^{13}\text{B})^{11}\text{N}$ reaction are presented in Fig. 3 on a decay energy scale for ^{11}N with the origin of the energy axis set to the ^{10}C+proton decay threshold (with the ^{13}B-ejectile in its ground state). The existence of a peak located on the high energy, right side of the well-known $1/2^-$ first excited state at 2.16 MeV, is clear evidence for the observation of the ^{11}N ground state in this reaction. As we can see in the lower part of Fig. 2, it is situated at channel 206.6, close to the position of the 4.14 MeV peak of ^{12}N in the contaminant spectrum, but exceeding this peak by about 22 counts per channel. A significance of 9 σ results for the ^{11}N ground state. The fitted line shape is calculated with a resonance energy of 1.63 MeV, a width of 400 keV and assuming $\ell = 0$ for the Breit-Wigner resonance.

The decay energy of 1.63(5) MeV for the ground state resonance corresponds to a mass excess of ^{11}N of M.E. = 24.618(50) MeV. All other prominent peaks in the spectrum of Fig. 3 up to 6.6 MeV are also resonances of ^{11}N situated at decay energies of 2.16, 3.06, 3.61, 4.33, 5.98 and 6.54 MeV (Table I). A narrow peak at 3.06 MeV, which is a clearly visible shoulder on the right side of the 3.61 MeV resonance and which has a significance of 11 σ, is reported for the first time as well as the peak at 6.54 MeV. The peaks at 5.98 and 6.54 MeV are small.

but their statistical significance is 6.4 σ and 4.9 σ, respectively. The differential cross-sections at Θ_{lab}=3.05° of the ^{10}B(^{14}N,^{13}B)^{11}N reaction populating the ^{11}N levels at 1.63, 2.16, 3.06, 3.61, 4.33, 5.98 and 6.54 MeV are 15(5), 28(5), 11(5), 78(15), 63(15), 12(5) and 14(5) *nb/sr*, respectively.

Comparing the results of the (^{14}N,^{13}B) reaction with our recently published results [1] obtained using the ^{12}C(^{14}N,^{15}C)^{11}N transfer reaction, we can notice that the decay energies obtained for ^{11}N are very similar in both reactions (see Table I). Moreover in the previous measurement we already had an evidence for a narrow state around 3.0 MeV decay energy and a state around 1.5 MeV, but they were credited respectively to the population of the $5/2^+$ (3.63 MeV) and $1/2^-$ (2.18 MeV) levels of ^{11}N with the ^{15}C ejectile in its $1/2^+$ ground state. There are also important differences between them: the cross-sections were much higher in the former reaction (a factor of 20 for the 2.18 and 3.63 MeV states), and the reaction was more selective, populating intensely only the levels at 2.18 and 3.63 MeV. The (^{14}N,^{14}C) reaction used in the preceding work to populate states of the ^{12}N nucleus was also much more selective. There, only the ground state, the 0.96 and 4.14 MeV states of ^{12}N had sizable yields. In the present work, the (^{14}N,^{13}B) reaction leading to the ^{12}N nucleus is clearly less selective, six states are populated with comparable yields (see Fig. 1). In Table I we summarise the decay energies and experimental widths of this work together with results obtained formerly and by other authors.

The search for the $1/2^+$ ground state and for the mass excess value of ^{11}N has intensified in recent times. New experiments [2, 3] 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 [2] reports the resonance at 1.3 MeV (Γ=0.99 MeV), Azhari [3] at 1.45 MeV ($\Gamma \geq 0.4$ MeV). The result of the ^{12}N induced single neutron stripping reaction, where the proton decay of the ^{11}N nucleus is measured [3], 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 energies, 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 4.33 MeV) to the first excited 2^+ state of ^{10}C at 3.35 MeV.

The peak at 1.63(5) MeV decay energy in our energy spectrum (Fig. 3) is the $1/2^+$ ground state resonance. In the analysis its width can range between Γ = 300-600 keV for a fit of the experimental spectrum, an optimum value is found at 400 keV using ℓ=0 for the proton decay. A DWBA analysis with vibrational coupling form factors [13] of recent p(^{11}Be,^{10}Be)d data yielded respectively spectroscopic factors of 0.67-0.79 and 0.16-0.22 for the $[0^+ \otimes s_{1/2}]$ and $[2^+ \otimes d_{5/2}]$ configurations of the ^{11}Be ground-state, thus a 20% d-wave admixture. Recent analyses by Johnson and collaborators [14, 15] of the p(^{11}Be,^{10}Be)d data [13] and older ^{10}Be(d,p)^{11}Be data [16] including the break-up of the deuteron and of the ^{11}Be in the calculations arrive at a d-wave admixture of ~50% with spectroscopic factors of about 0.2-0.3 for both configurations. If we assume the same spectroscopic factor for the ground-state resonance and use Γ_{sp}= 2.1 MeV for the single particle width of an $s_{1/2}$ resonance 1.60 MeV above the ^{10}C+p threshold [4], then Γ_{pred}= S Γ_{sp} = 0.4±0.2 MeV, in good agreement with our experimental width for the 1.63 MeV ground-state resonance.

The peak at 2.16(5) MeV is the $1/2^-$ resonance of ^{11}N, also observed by the other authors (at 2.18(5) MeV in our previous work [1], at 2.24 MeV by Benenson *et al.* [17] and Azhari *et al.* [3] and at 2.04 MeV by Axelsson *et al.* [2]). The peak at 3.06(8) MeV has a very narrow width and is difficult to assign. The peak at 3.61(5) MeV is the $5/2^+$ resonance observed at 3.63(5) MeV in our previous work [1] and at 3.72 MeV by [2]. The resonance at 4.33(5) MeV was observed at 4.39(5) MeV in our previous work and at 4.32 MeV by Axelsson [2], while the peak at 5.98(10) MeV was at 5.87(15) MeV in our previous work. A new peak at 6.54(10) MeV has not been observed before. Shell-model calculations [3, 18] for ^{11}N predict a K=1/2 band, whose $1/2^-, 3/2^-$ and $5/2^-$ states lie respectively at 2.24, 4.61 and 5.7 MeV. Our observed peaks at 2.16 MeV, 4.33 MeV and 5.98 MeV (formerly at 2.18, 4.39 and 5.87 MeV) have energies very close to these predictions supporting a $3/2^-$ and $5/2^-$ spin-parity assignments for the 4.33 MeV and 5.98 MeV peaks.

We can conclude that by means of the ^{10}B(^{14}N,^{13}B)^{11}N reaction, we could clearly observe the ^{11}N ground state resonance ($1/2^+$) at 1.63 MeV decay energy, followed by six well-resolved resonances of ^{11}N in the spectrum of ^{13}B ejectiles up to decay energies of 6.54 MeV. To our opinion this is the clearest evidence up to now of the existence and observation of this long searched for ground state of the ^{11}N nucleus. Its width is smaller than predicted, but by analogy with the ^{11}Be nucleus, one could expect a strong d-wave admixture in the ground state wave function of the ^{11}N nucleus resulting in a smaller width.

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This work			Ref.[1]		Ref.[2]		Ref.[4]		Ref.[5]	
J^π	E_{decay}	Γ	E_{decay}	Γ	E_{decay}	Γ	E_{decay}	Γ	E_{decay}	Γ
	[MeV]	[MeV]	[MeV]	[MeV]	[MeV]	[MeV]	[MeV]	[MeV]	[MeV]	[MeV]
$1/2^+$	1.63(5)	0.4(1)	-	-	1.30(4)	0.99(20)	1.60	1.58	1.40	1.01
$1/2^-$	2.16(5)	0.25(8)	2.18(5)	0.44(8)	2.04	0.69	2.48	0.91	2.24	0.64
	3.06(8)	$\leq$0.10(8)	(2.92)	(0.1)	-	-	-	-	-	-
$5/2^+$	3.61(5)	0.50(8)	3.63(5)	0.40(8)	3.72	0.6	3.90	0.50	3.84	0.46
$(3/2^-)$	4.33(5)	0.45(8)	4.39(5)	$\leq$0.2(1)	4.32	0.07				
$(5/2^-)$	5.98(10)	0.10(6)	5.87(15)	0.7(2)	5.5	1.5				
	6.54(10)	0.10(6)								

Table 1: Decay energies and widths of ^{11}N-resonances. measured in this work, by our former work [1] by Axelsson [2] and compared to theoretical calculations of Fortune *et al.* [4] and Barker [5].

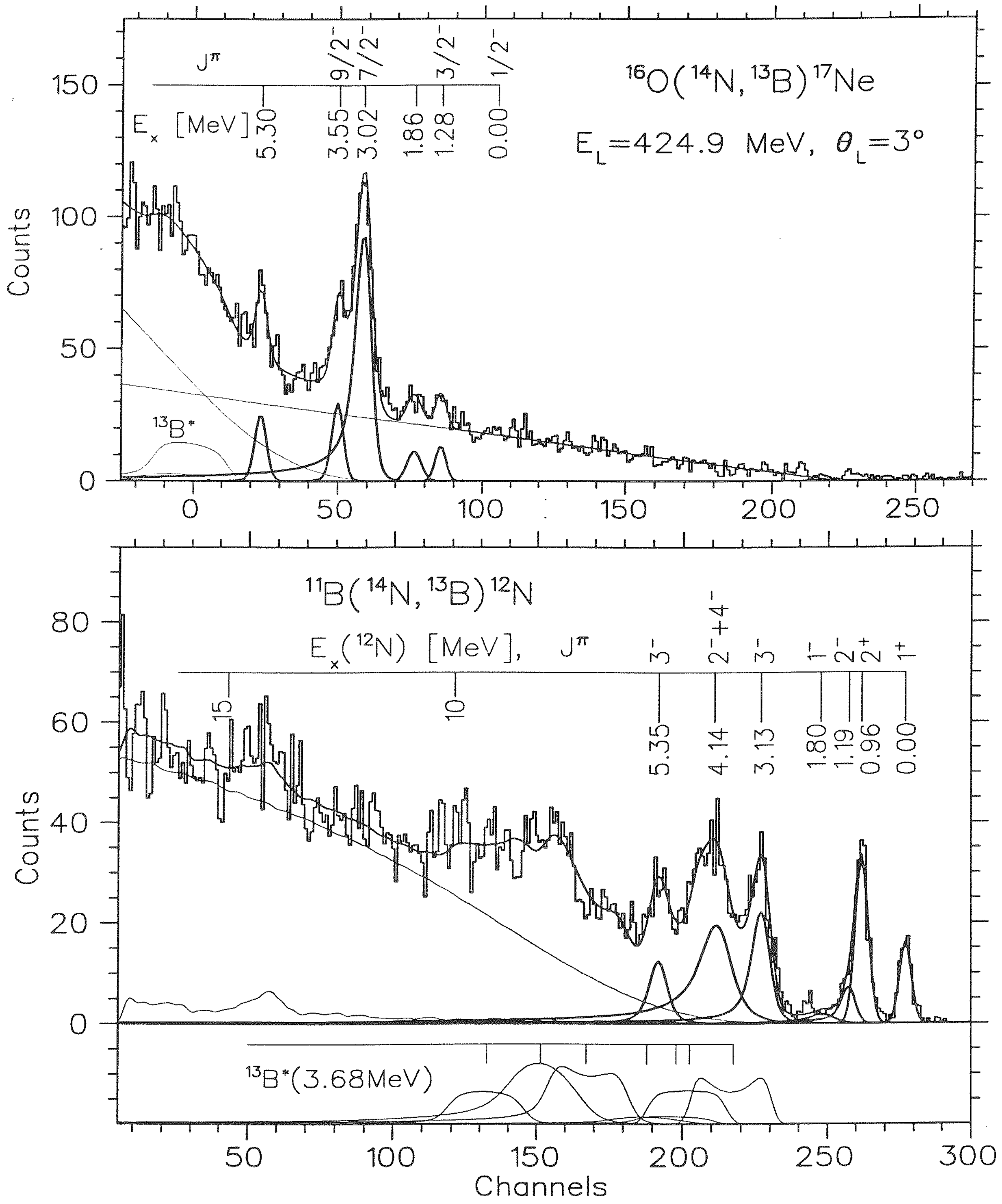

Figure 1: Energy spectra of the (^{14}N,^{13}B) reactions on the ^{11}B (lower part) and ^{16}O (upper part) target contaminants used for calibration purposes and for subtraction from the spectrum measured on the ^{10}B target. See text for details.

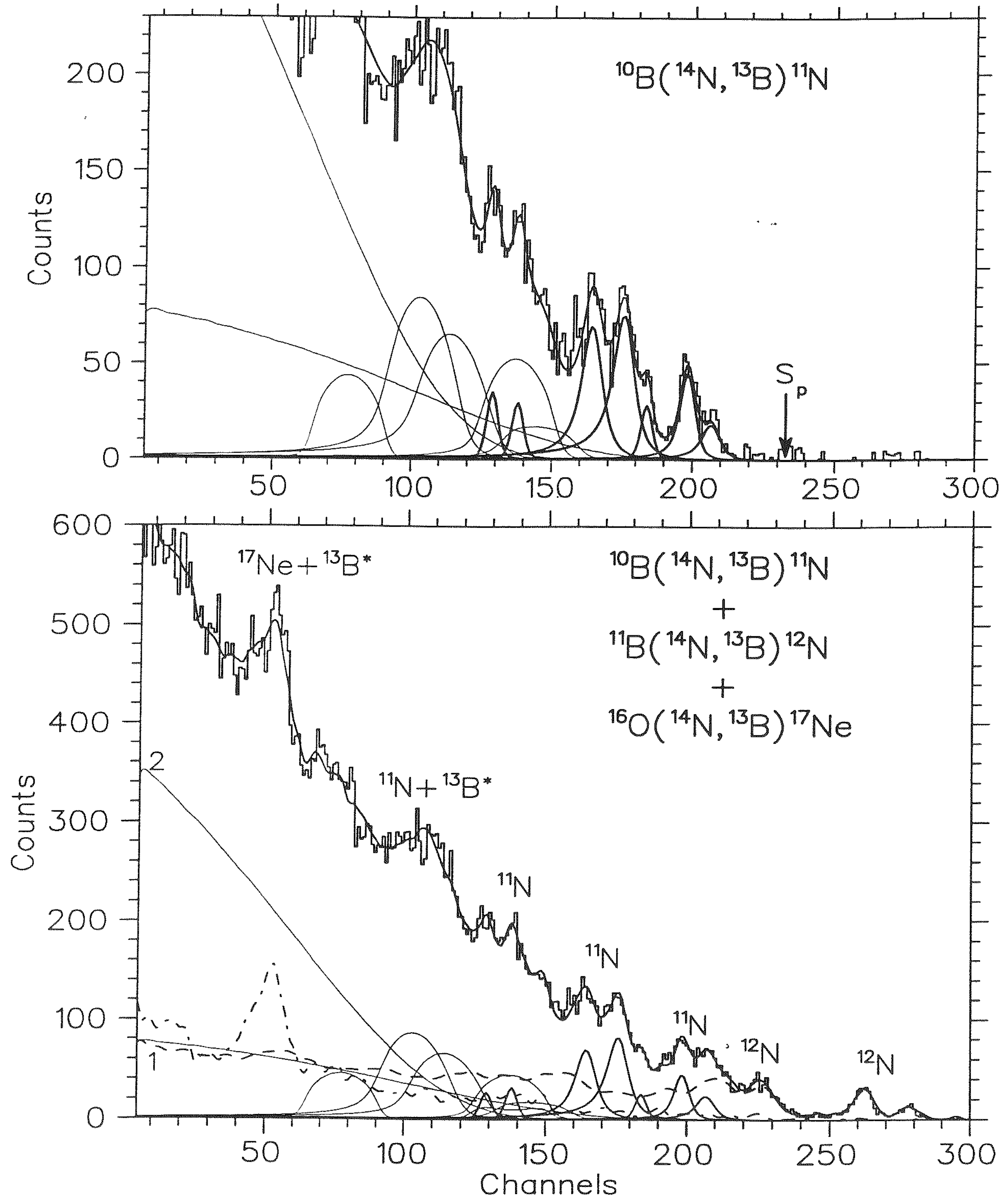

Figure 2: Lower part: Energy spectrum of ^{13}B ejectiles measuered for the (^{14}N,^{13}B) reaction on the ^{10}B target including the contaminants ^{11}B and ^{16}O. Sequential decay contributions are displayed by the curves 1 and 2 (see text). Upper part: The spectrum of the $^{10}B(^{14}N,^{13}B)^{11}N$ reaction is shown after subtraction of normalised spectra from the ^{11}B and ^{16}O contaminants, which are shown in the lower part as dashed and dashed-dotted lines, respectively.

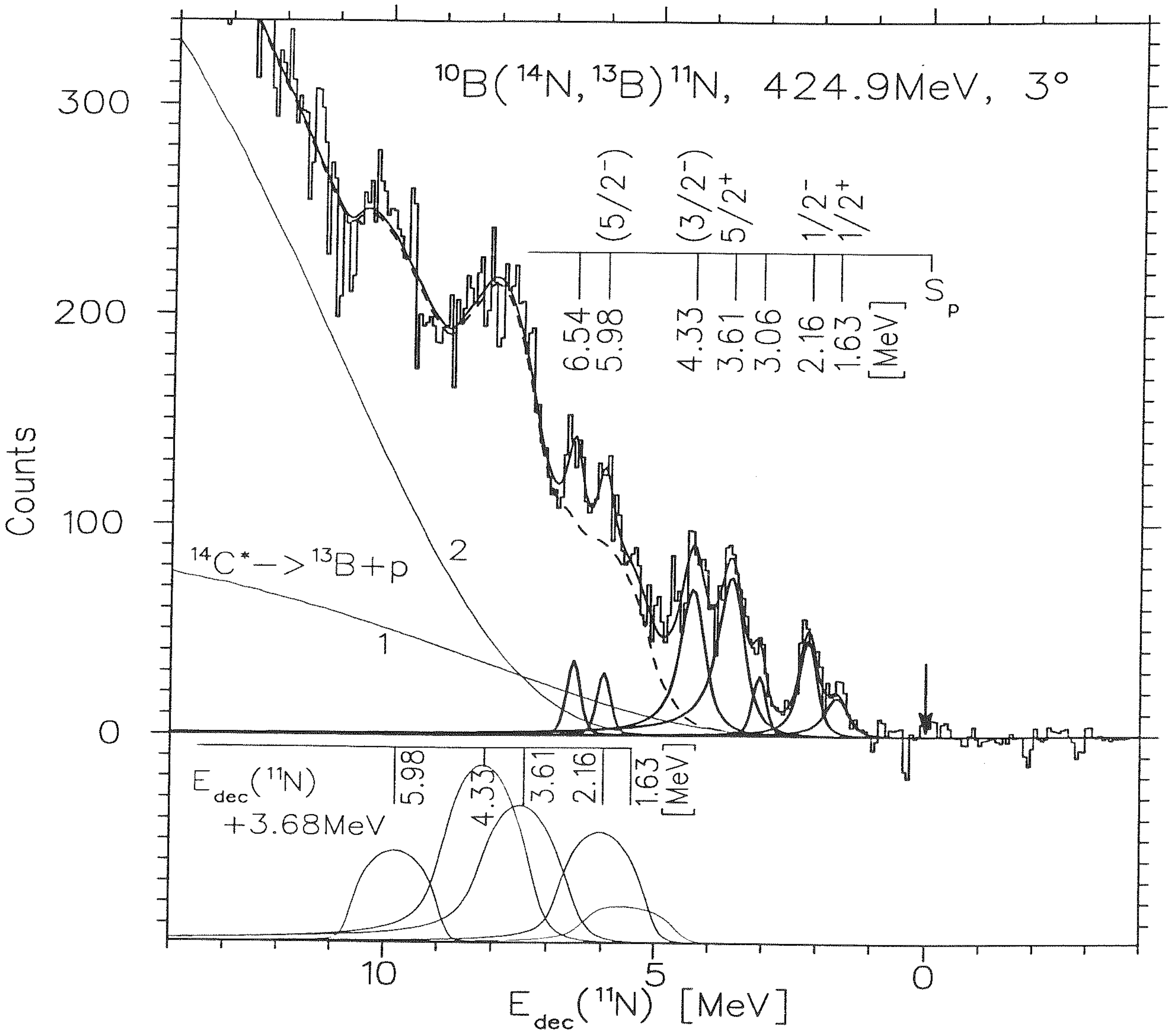

Figure 3: Energy spectrum of the $^{10}B(^{14}N,^{13}B)^{11}N$ reaction obtained after subtraction of the spectra of the contaminants. The arrow indicates the proton threshold.