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Low lying resonances in the unbound nuclei ^{11}N and ^{15}F have been calculated taking account of proton-core vibration couplings. For the extra-proton we have used an usual Woods-Saxon potential plus a surface interaction for the coupling which is deduced from the spectra of the mirror nuclei ^{11}Be and ^{15}C . Calculations for ^{11}N are in good agreement with experimental results and predict in ^{15}F two $1/2^+$ and $5/2^+$ narrow resonances at 1.2 and 2.35 MeV respectively.

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Experimental spectroscopic informations on the unbound ^{11}N , mirror nucleus of ^{11}Be , have been determined by different methods. The first data were obtained in the transfer reaction $^{14}\text{N}(^3\text{He}, ^6\text{He})^{11}\text{N}$ by Benenson et al [1]. A broad resonant state at 2.24 MeV above the $^{11}\text{N} \rightarrow ^{10}\text{C} + p$ threshold was observed. Guimaraes et al. [2] have repeated this experiment and deduced, through indirect arguments, that this broad resonance could result from two different states in ^{11}N . It was not clear to separate these two resonances, interpreted as $1/2^+$ and $1/2^-$ states in analogy with ^{11}Be . Informations have also been deduced by Thoennenssen et al. [3] from the $^{11}\text{N} \rightarrow ^{10}\text{C} + p$ decay using the stripping reaction $^9\text{Be}(^{12}\text{N}, ^{11}\text{N})$. The proton energy spectrum exhibits a broad peak at low energy, indicating that proton decays occur from at least two levels of ^{11}N . Guided by the mirror nuclei systematic, energies and widths of these two $1/2^+$ and $1/2^-$ states were roughly deduced. Recently, more direct and conclusive informations have been

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obtained by Axelsson et al [4] using the resonant scattering reaction $p(^{10}\text{C}, ^{11}\text{N})$ where three states below 4 MeV have been clearly identified to be $1/2^+$ (g.s.), $1/2^-$ and $5/2^+$ states. The energies of these unbound states relative to the $^{10}\text{C}+p$ threshold are 1.3 ± 0.04 , 2.04 ± 0.04 and 3.72 ± 0.04 MeV with respective width of 900_{-200}^{+100} , 690_{-100}^{+50} , 600_{-40}^{+100} keV. Three resonances ($3/2^-$, $3/2^+$ and $5/2^+$) have been tentatively assigned at higher energies of 4.32, 5.1 and 5.5 MeV respectively. The $3/2^-$ state surprisingly features a sharp resonance with a width of 70 keV.

These results show a great similitude with the ^{11}Be spectrum: one observes the same parity inversion between $1/2^+$ and $1/2^-$ states and close relative energies between the observed levels. It is therefore interesting to see if a same theoretical approach can explain both nuclei. Simultaneous description of these two mirror nuclei has already been considered by other authors [4,5] with Woods-Saxon potentials fitted on each $1/2^+$, $1/2^-$ and $5/2^+$ state in ^{11}Be or ^{11}N and used to study the corresponding states in the mirror nucleus ^{11}N or ^{11}Be . It is clear from their results that such correspondence exists but it is difficult to obtain a very good agreement for both nuclei even by changing the depth and the radius of the W-S potential .

The present paper proposes a somewhat different approach of the problem based on the suggestion that deviation from a Hartree-Fock or Woods-Saxon one-particle spectrum in ^{11}Be is due to strong correlations between the extra-neutron and the core of ^{10}Be [6-10]. In refs [9, 10] a deformed W-S potential is used for the neutron-core interaction, the core being described in a rotational model. In this model, the inversion is obtained only because the $1/2^-$ state is strongly pushed up by the use of an anomalously strong spin-orbit potential [10], different from what is used in ^{13}C where the inversion does not appear. Conversely, in ref [8] the core is assumed to be spherical. The excited states are interpreted as vibrational states and two-body correlations are introduced as couplings between the neutron and the core-vibrations. The core of ^{10}Be has a low energy 2^+ excited state at 3.37 MeV with a very large $B(E2 \downarrow)$ of 10.5 ± 1.1 $e^2\text{fm}^4$ which is responsible for the strong effect of particle-vibration couplings on neutron energies in ^{11}Be and responsible for the inversion. In normal nuclei like ^{13}C and ^{15}C , these couplings are smaller and the inversion does not appear [8]. In this microscopic approach, a surface term depending on the neutron state (energy, angular momentum,...) is added to the

Hartree-Fock or phenomenological Woods Saxon potential. Guided by the theoretical results of ref [8] and following ref [11], we write the one body potential for a neutron in state ν as:

$$V_\nu(r) = V_{ws}(r) + 16a^2\alpha_\nu \left(\frac{df(r)}{dr} \right)^2 \quad (1)$$

where V_{ws} is the conventional Woods-Saxon potential and α_ν is the strength of the surface term adjusted in ref [11] in order to obtain the experimental energies of the $2s_{1/2}$, $1p_{1/2}$ and $1d_{5/2}$ neutron states in ^{11}Be . The Woods-Saxon potential of ref [11] is :

$$V_{ws}(r) = V_0 \left[1 - 0.44r_0^2 (\bar{l} \cdot \bar{s}) \frac{1}{r} \frac{d}{dr} \right] f(r) \quad (2)$$

$$f(r) = \left[1 + \exp\left(\frac{r-R}{a}\right) \right]^{-1}$$

with
$$V_0 = -\left(50.5 + 32 \tau_z \frac{N-Z}{A} \right) \text{ MeV}$$

$$R = r_0 A^{1/3}, \quad r_0 = 1.27 \text{ fm}, \quad a = 0.75 \text{ fm}$$

A , N and Z being respectively the mass, neutron and proton number of the core nucleus ^{10}Be . τ_z is the third component of isospin of the nucleon ($\tau_z = -1$ for a neutron, $+1$ for a proton). The resolution of Schrödinger equations with this WS potential and the surface coupling strength α_ν gives calculated energies $\epsilon_\nu^{\text{cal}}$ that are compared to experimental ones $\epsilon_\nu^{\text{exp}}$ in Table 1.

^{11}N is the mirror nucleus of ^{11}Be , and can be viewed as a proton outside a ^{10}C core. The corresponding Woods-Saxon potential for the extra-proton in ^{11}N is the same as for the extra neutron in ^{11}Be (the asymmetry term is identical since both $(N-Z)$ and τ_z change sign). The corrective term due to proton-core coupling is also expected to be the same. Indeed, ^{10}C has a 2^+ state at 3.35 MeV excitation energy with a $B(E2 \downarrow)$ of $12.6 \pm 2.1 \text{ e}^2 \text{ fm}^4$. As these values are very close to those of ^{10}Be , the nuclear potential $V_\nu(r)$ of eq. (1) is expected to be the same for neutron states in ^{11}Be and for proton states in ^{11}N . Therefore proton states of ^{11}N are calculated using the Woods-Saxon potential of eq (2), the coupling strengths α_ν of table 1 and the Coulomb potential of a uniformly charged sphere with the same radius r_0 . Since these states are unbound, calculations have been made in two different ways :

1- The continuum states are calculated as discrete states of energies ϵ_b by requiring that the radial wave function vanishes at a distance of 20 fm.

2- The Schrödinger equation is solved for positive proton energies ϵ . We know that the resonance wave function is concentrated in the interior of the potential. Therefore, to determine the resonance, we calculate the function $I_V(\epsilon)$ defined as:

$$I_V(\epsilon) = \int_0^{R_0} |\varphi_V(r, \epsilon)|^2 r^2 dr$$

where φ_V is the wave function of the proton at energy ϵ and $R_0=5$ fm. We have checked that the position and width of the resonance are independent of the adopted value R_0 between 3 and 6 fm. The resonance energy ϵ_r is determined at the maximum of the function $I_V(\epsilon)$, whereas the width of $I_V(\epsilon)$ at half maximum is associated with the width of the resonance (the correspondence is true for a square well potential [12]).

Fig. 1 shows the function $I_V(\epsilon)$ for the $2s_{1/2}$, $1p_{1/2}$ and $1d_{5/2}$ resonances. Table 2 gives the energies ϵ_b and ϵ_r calculated with the first and the second method and the widths calculated from method 2. They are compared with the experimental resonance energies ϵ_{exp} and widths Γ_{exp} . The nearly perfect agreement found between the two calculated energies ϵ_b and ϵ_r is a good test of the first method used in many calculations. Very good agreement is also found between calculated and measured energies. The agreement is improved compared with previous calculations [4,5]. This shows that the one-body potential of eq (1) is more successful than a pure Woods-Saxon potential to describe simultaneously ^{11}Be and ^{11}N and emphasizes the role of surface couplings to describe halo phenomena. The calculations of the widths Γ overestimate the experimental values. As seen in Fig. 1, the functions $I_V(\epsilon)$ are very asymmetric with a long high-energy tail, especially for the $1/2^+$ state, and the width of $I_V(\epsilon)$ at half-maximum gives qualitative information only. On the other hand we know that these states are not pure and a mixture of configurations would decrease the calculated widths [5]. However the agreement is qualitatively satisfactory : the s resonance is broader and the p and d resonances exhibit similar widths.

In the most recent experiment [4], apart from the three lowest well-determined resonances, some structures in the proton excitation function are also seen in the vicinity of 4.5

MeV above the $^{10}\text{C}+p$ threshold. The analysis of excitation function suggests the presence of a very narrow $3/2^-$ state at 4.35 MeV (with an excitation energy of 3.15 MeV) with a very small width $\Gamma = 70$ keV which could be the analog of the known narrow $3/2^-$ level in ^{11}Be at 3.9 MeV excitation energy with $\Gamma = 15$ keV. A plausible description of such $3/2^-$ states corresponds to two neutrons (protons) coupled to 0^+ and forming the ground state of ^{12}Be (^{12}O) plus a neutron (proton) hole in the $1p_{3/2}$ shell [4]. Neglecting the coupling between the two particles and the hole, the $3/2^-$ state energies in ^{11}Be and ^{11}N can be calculated as:

$$\begin{aligned}\epsilon(3/2^-) &= S_n(^{10}\text{Be}) - S_{2n}(^{12}\text{Be}) && \text{for } ^{11}\text{Be} \\ \epsilon(3/2^-) &= S_p(^{10}\text{C}) - S_{2p}(^{12}\text{O}) && \text{for } ^{11}\text{N}\end{aligned}\quad (3)$$

where S_{2n} (S_{2p}) and S_n (S_p) are the two-neutron (two-proton) and one-neutron (one-proton) separation energies respectively. Using the separation energies of ref [12] in eq (3) we get 3.6 MeV and 4.6 MeV for the excitation energies of the $3/2^-$ states in ^{11}Be and ^{11}N respectively.

In ^{11}Be the agreement is quite good while the $3/2^-$ state in ^{11}N is too high compared to the experimental one of 3.15 MeV [4]. In our uncorrelated model, the width is given by the widths of the two-particle states. As ^{12}Be is bound, the width in ^{11}Be is due to the coupling with other configurations only and should be small as it is found experimentally. The situation is different in ^{11}N since the ^{12}O ground state is unbound with a width $\Gamma = 400\text{-}450$ keV. Therefore the $3/2^-$ level should have a width of about 450 keV, much larger than the measured one. Within this simple model, the properties of the $3/2^-$ states in ^{11}Be and ^{11}N cannot be simultaneously reproduced.

Another interesting unbound nucleus is ^{15}F which is the mirror of ^{15}C . No spectroscopic study of ^{15}F have been investigated so far but, in a one nucleon+core model, the correspondence between ^{15}F ($p+^{14}\text{O}$) and ^{15}C ($n+^{14}\text{C}$) is the same than between ^{11}N and ^{11}Be . We then expect the ground state of ^{15}F to be a $1/2^+$ state as in ^{15}C corresponding to a proton in a $2s_{1/2}$ state. We have performed the same calculation for ^{15}F as for ^{11}N . We use the same potential of eq. (1) where the Woods-Saxon potential is the same as previously and where the parameters α_v are fitted in order to reproduce the $2s_{1/2}$ and $1d_{5/2}$ neutron states in ^{15}C . Indeed the level spectra of the core nuclei ^{14}C and ^{14}O are very similar. Thus, the correction to the Woods-Saxon potential

due to particle-core vibration couplings for a neutron state in ^{15}C (neutron + ^{14}C core) and a proton state in ^{15}F (proton + ^{14}O core) is expected to be similar and small [8]. The calculated and experimental energies of the $1/2^+$ and $5/2^+$ states in ^{15}C are given in Table 3. They correspond to $\alpha_v = -1.55$ MeV for the $2s_{1/2}$ neutron-state and to $\alpha_v = 0$ for the $1d_{5/2}$ neutron-state. With this potential we have calculated the unbound $1/2^+$ and $5/2^+$ states in ^{15}F which are given in Table 4 and Fig. 2. We predict the $1/2^+$ ground state of ^{15}F at an energy of 1.2 MeV above the $^{14}\text{O}+p$ threshold with a width $\Gamma = 500$ keV and a $5/2^+$ excited state at 2.35 MeV above the threshold with a narrow width $\Gamma = 150\text{-}200$ keV.

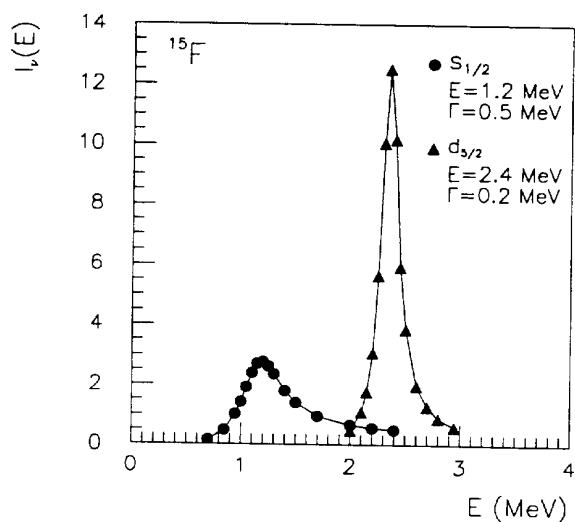
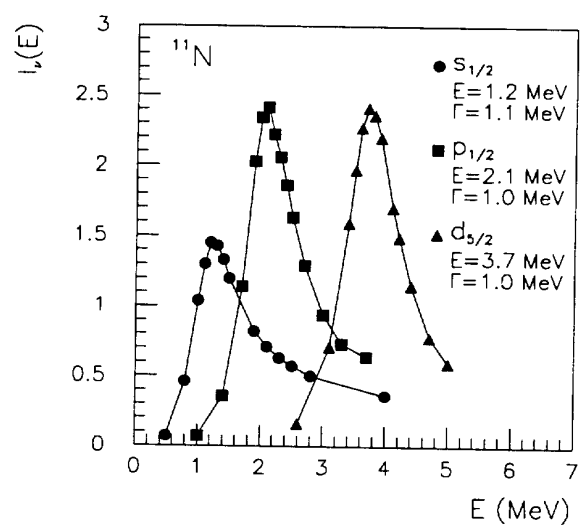
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Figure captions

Fig. 1 : Functions $I_\nu(E)$ for the $2s_{1/2}$, $1p_{1/2}$ and $1d_{5/2}$ resonances in ^{11}N . E is the energy above the $p+^{10}\text{C}$ threshold.

Fig. 2 : Functions $I_\nu(E)$ for the $2s_{1/2}$ and $1d_{5/2}$ resonances in ^{15}F . E is the energy above the $p+^{14}\text{O}$ threshold.



Tables:

Table 1: α_v strengths and neutron energies in ^{11}Be

states v of ^{11}Be	α_v [MeV]	ϵ_v^{cal} [MeV]	ϵ_v^{exp} [MeV]
$1p_{1/2}$	5.45	-0.21	-0.18
$2s_{1/2}$	-10.56	-0.53	-0.5
$1d_{5/2}$	-4.0	1.29	1.27

Table 2: Calculated proton resonance energies ϵ_b , ϵ_r and widths Γ_r in ^{11}N compared to experimental values ϵ_{exp} and Γ_{exp} . Values of energies are relative to the the $p+^{10}\text{C}$ threshold.

^{11}N states	ϵ_b [MeV]	ϵ_r [MeV]	ϵ_{exp} [MeV]	Γ_r [MeV]	Γ_{exp} [keV]
$s_{1/2}$	1.29	1.2	1.3 ± 0.04	1.1	990^{+100}_{-200}
$p_{1/2}$	2.17	2.1	2.04 ± 0.04	1	690^{+50}_{-100}
$d_{5/2}$	3.9	3.7	3.72 ± 0.04	1	600^{+100}_{-40}

Table 3: α_v strengths and neutron energies in ^{15}C

states v of ^{15}C	α_v [MeV]	ϵ_v^{cal} [MeV]	ϵ_v^{exp} [MeV]
$2s_{1/2}$	-1.55	-1.25	-1.21
$1d_{5/2}$	0	-0.73	-0.5

Table 4: Predicted proton resonance energies and widths in ^{15}F . Values of energies are relative to the the $p+^{14}\text{O}$ threshold.

^{15}F states	ϵ_r [MeV]	Γ_r [MeV]
$s_{1/2}$	1.2	0.5
$d_{5/2}$	2.35	0.15