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**Low Lying states in  $^{11}\text{N}$  and  $^{15}\text{F}$ .**

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## Low Lying states in $^{11}\text{N}$ and $^{15}\text{F}$ .

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Low lying resonances in the unbound nuclei  $^{11}\text{N}$  and  $^{15}\text{F}$  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  $^{11}\text{Be}$  and  $^{15}\text{C}$ . Calculations for  $^{11}\text{N}$  are in good agreement with experimental results and predict in  $^{15}\text{F}$  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  $^{11}\text{N}$ , mirror nucleus of  $^{11}\text{Be}$ , 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  $^{11}\text{N}$ . It was not clear to separate these two resonances, interpreted as  $1/2^+$  and  $1/2^-$  states in analogy with  $^{11}\text{Be}$ . 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  $^{11}\text{N}$ . 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  $1.3\pm 0.04$ ,  $2.04\pm 0.04$  and  $3.72\pm 0.04$  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  $^{11}\text{Be}$  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  $^{11}\text{Be}$  or  $^{11}\text{N}$  and used to study the corresponding states in the mirror nucleus  $^{11}\text{N}$  or  $^{11}\text{Be}$ . 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  $^{11}\text{Be}$  is due to strong correlations between the extra-neutron and the core of  $^{10}\text{Be}$  [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  $^{13}\text{C}$  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  $^{10}\text{Be}$  has a low energy  $2^+$  excited state at 3.37 MeV with a very large  $B(E2 \downarrow)$  of  $10.5 \pm 1.1$   $e^2\text{fm}^4$  which is responsible for the strong effect of particle-vibration couplings on neutron energies in  $^{11}\text{Be}$  and responsible for the inversion. In normal nuclei like  $^{13}\text{C}$  and  $^{15}\text{C}$ , 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  $\nu$  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  $\alpha_\nu$  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  $^{11}\text{Be}$ . 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  $^{10}\text{Be}$ .  $\tau_z$  is the third component of isospin of the nucleon ( $\tau_z = -1$  for a neutron,  $+1$  for a proton). The resolution of Shrödinger equations with this WS potential and the surface coupling strength  $\alpha_\nu$  gives calculated energies  $\epsilon_\nu^{\text{cal}}$  that are compared to experimental ones  $\epsilon_\nu^{\text{exp}}$  in Table 1.

$^{11}\text{N}$  is the mirror nucleus of  $^{11}\text{Be}$ , and can be viewed as a proton outside a  $^{10}\text{C}$  core. The corresponding Woods-Saxon potential for the extra-proton in  $^{11}\text{N}$  is the same as for the extra neutron in  $^{11}\text{Be}$  (the asymmetry term is identical since both  $(N-Z)$  and  $\tau_z$  change sign). The corrective term due to proton-core coupling is also expected to be the same. Indeed,  $^{10}\text{C}$  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  $^{10}\text{Be}$ , the nuclear potential  $V_\nu(r)$  of eq. (1) is expected to be the same for neutron states in  $^{11}\text{Be}$  and for proton states in  $^{11}\text{N}$ . Therefore proton states of  $^{11}\text{N}$  are calculated using the Woods-Saxon potential of eq (2), the coupling strengths  $\alpha_\nu$  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  $\epsilon_b$  by requiring that the radial wave function vanishes at a distance of 20 fm.

2- The Schrödinger equation is solved for positive proton energies  $\epsilon$ . 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  $\varphi_V$  is the wave function of the proton at energy  $\epsilon$  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  $\epsilon_r$  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  $\epsilon_b$  and  $\epsilon_r$  calculated with the first and the second method and the widths calculated from method 2. They are compared with the experimental resonance energies  $\epsilon_{exp}$  and widths  $\Gamma_{exp}$ . The nearly perfect agreement found between the two calculated energies  $\epsilon_b$  and  $\epsilon_r$  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  $^{11}\text{Be}$  and  $^{11}\text{N}$  and emphasizes the role of surface couplings to describe halo phenomena. The calculations of the widths  $\Gamma$  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  $^{11}\text{Be}$  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  $^{12}\text{Be}$  ( $^{12}\text{O}$ ) 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  $^{11}\text{Be}$  and  $^{11}\text{N}$  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  $^{11}\text{Be}$  and  $^{11}\text{N}$  respectively.

In  $^{11}\text{Be}$  the agreement is quite good while the  $3/2^-$  state in  $^{11}\text{N}$  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  $^{12}\text{Be}$  is bound, the width in  $^{11}\text{Be}$  is due to the coupling with other configurations only and should be small as it is found experimentally. The situation is different in  $^{11}\text{N}$  since the  $^{12}\text{O}$  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  $^{11}\text{Be}$  and  $^{11}\text{N}$  cannot be simultaneously reproduced.

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

due to particle-core vibration couplings for a neutron state in  $^{15}\text{C}$  (neutron +  $^{14}\text{C}$  core) and a proton state in  $^{15}\text{F}$  (proton +  $^{14}\text{O}$  core) is expected to be similar and small [8]. The calculated and experimental energies of the  $1/2^+$  and  $5/2^+$  states in  $^{15}\text{C}$  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  $^{15}\text{F}$  which are given in Table 4 and Fig. 2. We predict the  $1/2^+$  ground state of  $^{15}\text{F}$  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.

### References:

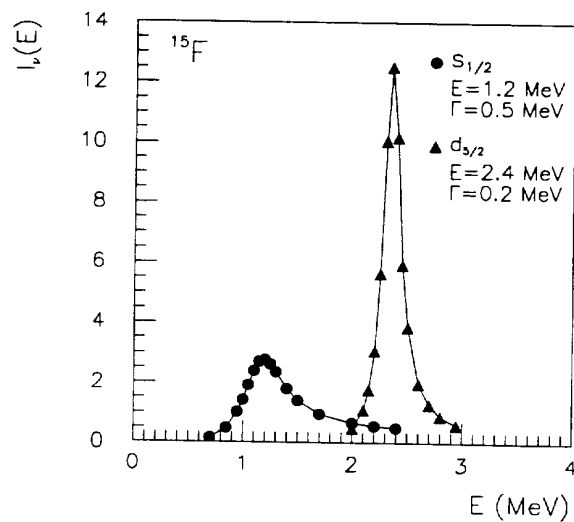
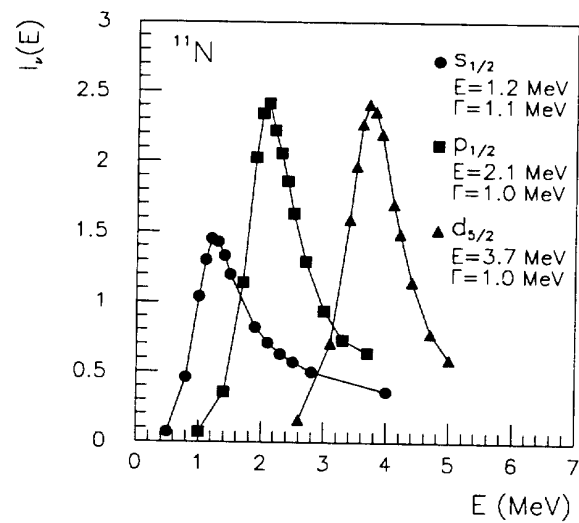
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Figure captions

Fig. 1 : Functions  $I_\nu(E)$  for the  $2s_{1/2}$ ,  $1p_{1/2}$  and  $1d_{5/2}$  resonances in  $^{11}\text{N}$ .  $E$  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  $^{15}\text{F}$ .  $E$  is the energy above the  $p+^{14}\text{O}$  threshold.



Tables:

**Table 1:**  $\alpha_v$  strengths and neutron energies in  $^{11}\text{Be}$

states $v$ of $^{11}\text{Be}$	$\alpha_v$ [MeV]	$\epsilon_v^{\text{cal}}$ [MeV]	$\epsilon_v^{\text{exp}}$ [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  $\epsilon_b$ ,  $\epsilon_r$  and widths  $\Gamma_r$  in  $^{11}\text{N}$  compared to experimental values  $\epsilon_{\text{exp}}$  and  $\Gamma_{\text{exp}}$ . Values of energies are relative to the the  $p+^{10}\text{C}$  threshold.

$^{11}\text{N}$ states	$\epsilon_b$ [MeV]	$\epsilon_r$ [MeV]	$\epsilon_{\text{exp}}$ [MeV]	$\Gamma_r$ [MeV]	$\Gamma_{\text{exp}}$ [keV]
$s_{1/2}$	1.29	1.2	$1.3 \pm 0.04$	1.1	$990^{+100}_{-200}$
$p_{1/2}$	2.17	2.1	$2.04 \pm 0.04$	1	$690^{+50}_{-100}$
$d_{5/2}$	3.9	3.7	$3.72 \pm 0.04$	1	$600^{+100}_{-40}$

**Table 3:**  $\alpha_v$  strengths and neutron energies in  $^{15}\text{C}$

states $v$ of $^{15}\text{C}$	$\alpha_v$ [MeV]	$\epsilon_v^{\text{cal}}$ [MeV]	$\epsilon_v^{\text{exp}}$ [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  $^{15}\text{F}$ . Values of energies are relative to the the  $p+^{14}\text{O}$  threshold.

$^{15}\text{F}$ states	$\epsilon_r$ [MeV]	$\Gamma_r$ [MeV]
$s_{1/2}$	1.2	0.5
$d_{5/2}$	2.35	0.15