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Identification of mixed-symmetry states in odd-A ^{93}Nb

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Abstract. The low-spin structure of ^{93}Nb has been studied using the $(\mathrm{n,n'}\gamma)$ reaction at neutron energies ranging from 1.5 to 2.6 MeV and the ^{94}Zr$(\mathrm{p,2n}\gamma)^{93}$Nb reaction at bombarding energies from 11.5 to 19 MeV. Excitation functions, lifetimes, and branching ratios were measured, and multipolarities and spin assignments were determined. The $J^\pi = 3/2^-$ and $5/2^-$ states at 1840 and 2013 keV, respectively, are identified as mixed-symmetry states associated with the $(2^+_{1,\mathrm{ms}}) \otimes 2p_{1/2}$ particle-core coupling. These assignments are in agreement with energy systematics, spins and parities, and the observed strong $M1$ transitions to the $2p_{1/2}$ one-phonon structure.

PACS. 21.10.Re Collective levels – 21.10.Tg Lifetimes – 25.20.Dc Photon absorption and scattering – 27.60.+j $90 \le A \le 149$

Mixed-symmetry (MS) states can be viewed as low-energy collective modes in which protons and neutrons move uncoupled relative to each other. These collective excitations were first identified at about 3 MeV in the rotational nucleus, ^{156}Gd [1], where the large $B(M1; 1^+ \to 0^+_{\mathrm{gs}})$ was associated with the 1^+ scissor mode excitation predicted by Lo Iudice and Palumbo [2] and soon after discovered in a wider range of deformed nuclei [3]. In the vibrational $U(5)$ limit of the IBM-2, the lowest MS state has $J^\pi = 2^+_{1,\mathrm{ms}}$, and is coupled to the first 2^+_1 phonon structure by an $M1$ isovector transition (unlike isoscalar transitions between fully symmetric states). MS states have been identified at a rather constant energy of about 2 MeV in the so-called vibrational $A \sim 110$ region [4,5]. Recently, new species of two-phonon MS states have been discovered [6,7] in the nearly spherical even $N = 52$ isotones, indicating that the one-phonon $2^+_{1,\mathrm{ms}}$ state acts as a building block of vibrational nuclear structure. In particular, in $^{92}_{40}$Zr, the MS state $(2^+_{1,\mathrm{ms}})$ has been identified as the 2^+_2 state at 1.847 MeV, with a strong $B(M1; 2^+_{1,\mathrm{ms}} \to 2^+_1) = 0.46(15)\ \mu_N^2$ and a weakly collective $B(E2; 2^+_{1,\mathrm{ms}} \to 0^+_1) = 3.7(8)$ W.u. [8]. In $^{94}_{42}$Mo, the $2^+_{1,\mathrm{ms}}$ MS state has been identified as the 2^+_3 state at 2.067 MeV. It also displays a strong $M1$ transition with $B(M1; 2^+_{1,\mathrm{ms}} \to 2^+_1) = 0.56(5)\ \mu_N^2$ and a weakly collective $E2$ transition with $B(E2; 2^+_{1,\mathrm{ms}} \to 0^+_1) = 2.2$ W.u. [9]. From systematics, MS states in the odd-Z $N = 52$ isotone, $^{93}_{41}$Nb, are expected at similar excitation energies as their even-Z, $N = 52$ isotone neighbors with feeding of the symmetric one-phonon structures coupled to the low-lying $1g_{9/2}$ and $2p_{1/2}$ single-particle states. We have identified, for the first time in a nearly spherical odd-A nucleus, MS states from $M1$ strengths, energy systematics, and spin and parity assignments.

The nucleus ^{93}Nb was studied using the $(\mathrm{n,n'}\gamma)$ reaction at the University of Kentucky and the ^{94}Zr$(\mathrm{p,2n}\gamma)^{93}$Nb reaction at the University of Cologne. Figure 1 shows the partial level scheme of interest for ^{93}Nb. One of the proposed MS states in ^{93}Nb, the 1840 keV level, has been identified from excitation function and coincidence data in the current work and assigned as a $J^\pi = 3/2^-$ state by the analysis of the angular correlation between the 1153 and 656 keV transitions depopulating states at 1840 and 687 keV, respectively $(3/2^- \to 3/2^- \to 1/2^-)$. As shown at the bottom of fig. 2, a mean life of 26(4) fs has been measured for the 1840 keV state through the Doppler-shift attenuation method following the $(\mathrm{n,n'}\gamma)$ reaction [10]. Here, the shifted γ-ray energy is given by $E_\gamma(\theta_\gamma) = E_{\gamma_0}[1 + \frac{v_0}{c} F(\tau) \cos\theta_\gamma]$, with E_{γ_0} being the

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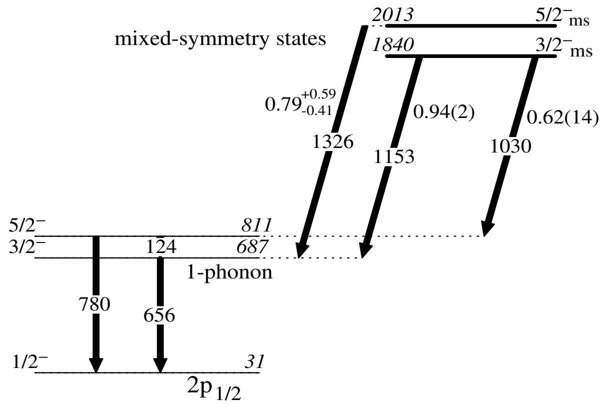

Fig. 1. ^{93}Nb partial level scheme showing the $2p_{1/2}$ single-particle, 1-phonon, and mixed-symmetry structures. $M1$ strengths in μ_N^2 are given for decays depopulating MS states.

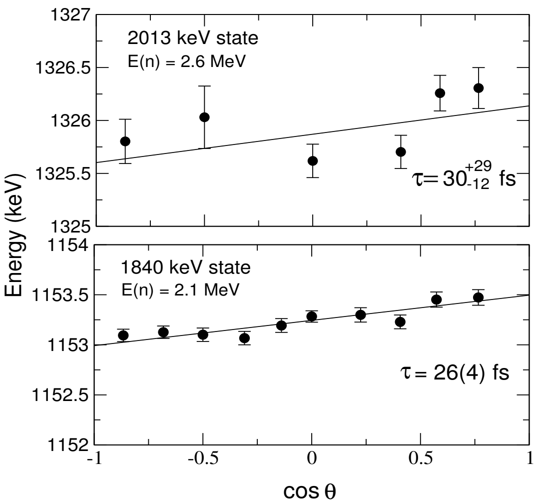

Fig. 2. Lifetime of the 1840 (bottom) and 2013 keV (top) levels from the Doppler-shift attenuation method at different neutron energies [10]. The fits to the experimental data give lifetimes of 30^{+29}_{-12} fs and 26(4) fs, respectively, for these levels.

unshifted γ-ray energy, v_0 the initial recoil velocity in the center of mass frame, θ the angle of observation and $F(\tau)$ the attenuation factor, which is related to the nuclear stopping process described by Blaugrund [11]. The 1030 and 1153 keV transitions depopulating this state to the $2p_{1/2}$ one-phonon structure present branching ratios of 49(4) and 100(4), respectively, and mixing ratios, δ, of $-0.23(7)$ and $-0.13(6)$, respectively. Hence, the 1030 keV transition has a $B(M1)$ value of 0.62(14) μ_N^2 and a $B(E2)$ strength of 18(4) W.u., while the 1153 keV transition presents similar properties with an even stronger $B(M1)$ value of 0.94(2) μ_N^2 and $B(E2) = 6.9(2)$ W.u.

The other proposed MS state at 2013 keV is also identified from excitation function and coincidence data in the current work. The angular correlation of the 1326 and 656 keV transitions ($5/2^- \to 3/2^- \to 1/2^-$) confirms its assignment as $J^\pi = 5/2^-$. From the angular correlation, the mixing ratio of the 1326 keV transition is determined as $\delta = -0.14(5)$. A mean life of 30^{+29}_{-12} fs has been measured for this state (as shown at the upper panel of fig. 2), giving $B(M1) = 0.79^{+0.59}_{-0.41}\ \mu_N^2$ and $B(E2) = 4.9^{+2.5}_{-3.5}$ W.u. This enhanced M1 strength supports its assignment as the $5/2^-_{\rm ms}$ MS state in spite of the large uncertainty of the lifetime. In fact, the $B(M1)$ values from the MS states are greater than from any other negative-parity states feeding the one-phonon structure, with the exception of a 1289 keV transition depopulating the $7/2^-$ state at 2099 keV, which has a $B(M1)$ value of 0.62(17) μ_N^2 and a weak $B(E2)$ of 1.2(3) W.u. However, the assignment of this state as a $J^\pi = 7/2^-$ prevents it from being part of the $(2^+_{1,\rm ms})\otimes 2p_{1/2}$ particle-core coupling. This observation, together with the fact that transitions from other levels in the region are predominantly $E2$, support the assignment of the 1840 and 2013 keV states as MS states. Indeed, these other negative-parity states with $E2$ character might be part of the 2-phonon symmetric quadrupole structure.

According to the IBM-2, even-even nuclei in the vibrational $U(5)$ limit present an $M1$ transition strength from the one-phonon 2^+ MS state $(2^+_{1,\rm ms})$ to the one-phonon fully symmetric 2^+_1 state given by, $B(M1; 2^+_{1,\rm ms} \to 2^+_1) = \frac{3}{4\pi}(g_\nu - g_\pi)^2\, 6\, \frac{N_\nu N_\pi}{N^2}\mu_N^2$ [12]; where $N = N_\pi + N_\nu$ and the standard boson g-factors, g_π and g_ν, are $g_\pi = 1$ for protons and $g_\nu = 0$ for neutrons. Considering the lowest MS state in ^{94}Mo and $^{88}_{38}$Sr$_{50}$ as the inert core [13], the proton and neutron boson numbers are $N_\pi = 2$ and $N_\nu = 1$, giving $B(M1; 2^+_{\rm ms} \to 2^+_1) = 0.32\ \mu_N^2$.

In the weak coupling limit, the IBFM predicts that the strength of $B(M1; 2^+_{\rm ms} \to 2^-_1)$ in the IBM-2 should equal the strength of the sum of $B(M1)$'s for MS states in ^{93}Nb, that is, $\sum_J B(M1; 1-\text{phonon}_{\rm MS}, J \to 1-\text{phonon}, J')$; giving $\sum B(M1; \text{MS} \to 1-\text{phonon}, 5/2^-) = 0.62(14)\ \mu_N^2$ and $\sum B(M1; \text{MS} \to 1-\text{phonon}, 3/2^-) = 1.73(59)\ \mu_N^2$, respectively, both exceeding the schematic $U(5)$ estimate from above. However, the $M1$ strength from the $5/2^-_{\rm ms}$ state equals within the errors the $2^+_{1,\rm ms} \to 2^+_1$ $M1$ strength found in the even isotone ^{94}Mo [9]. The $M1$ strength from the $3/2^-_{\rm ms}$ state is still larger than the value found in ^{94}Mo (although with large uncertainties). This might be due to the spin contribution of the unpaired proton to the $M1$ strength which is absent in the IBM-2 for even-even nuclei. Shell model calculations are being carried out in order to quantify the spin contribution to the $M1$ transitions in ^{93}Nb and for understanding the large $B(M1)$ values found for the $3/2^-_{\rm ms}$ state, or that one of the anomalous 1289 keV transition. Finally, the quintuplet of MS states associated with the $(2^+_{1,\rm ms}) \otimes 1g_{9/2}$ particle-core coupling has not yet been identified.

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