PHYSICAL REVIEW C **75**, 011301(R) (2007)

Anomalous behavior of the 2^+ mixed-symmetry state in ^{94}Zr

E. Elhami,[1] J. N. Orce,[1,*] S. Mukhopadhyay,[1] S. N. Choudry,[1] M. Scheck,[1] M. T. McEllistrem,[1] and S. W. Yates[1,2]
[1]*Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055, USA*
[2]*Department of Chemistry, University of Kentucky, Lexington, Kentucky 40506-0055, USA*
(Received 9 November 2006; published 2 January 2007)

The low-spin structure of ^{94}Zr has been studied with the $(n,n'\gamma)$ reaction, and branching ratios, lifetimes, multipolarities and spin assignments were determined. The 2_2^+ state at 1671.4 keV has been identified as the lowest mixed-symmetry state in ^{94}Zr. The 752.5-keV transition from this state to the 2_1^+ level has a large $B(M1)$ value of 0.33(5) μ_N^2, and the $B(E2)$ of the transition to the ground state has an unusually large value of 8(1) W.u. The $M1$ transition strength is in agreement with IBM-2 predictions in the U(5) vibrational limit, whereas the large $B(E2; 2_{1,\mathrm{MS}}^+ \to 0_1^+)$ value significantly exceeds the $E2$ strength predicted by the IBM-2. For the first time, the $2_{1,\mathrm{MS}}^+ \to 0_1^+$ $E2$ transition is observed to have a larger $E2$ transition strength than the $2_1^+ \to 0_1^+$ decay.

DOI: 10.1103/PhysRevC.75.011301 PACS number(s): 21.10.Re, 21.10.Tg, 25.40.Fq, 27.60.+j

Weakly collective nuclei near closed shells or subshells are often interpreted as vibrational within the U(5) symmetry of the interacting boson model (IBM-2) [1–3]. In the framework of the IBM-2, protons and neutrons are distinguished and treated separately. The addition of the proton-neutron (p-n) degree of freedom comes with a prescription for mixed-symmetry (MS) states [1–3]. In general, MS states are collective isovector excitations; neutron and proton intrinsic g factors are additive in the isovector part of the $M1$ magnetic dipole operator and may lead to large $B(M1)$ values of ~ 1 μ_N^2. The identification of these MS excitations in the $A \sim 90$ region [4–7] verified the idea of using separate symmetry representations for protons and neutrons. The fundamental MS mode in nearly spherical nuclei is a 2^+ excitation with a strong $M1$ transition to the one-phonon 2_1^+ level and typically a rather weak $E2$ transition to the ground state. The first low-lying MS state ($2_{1,\mathrm{MS}}^+$) in ^{92}Zr [5,6] has revealed new information about the p-n symmetry. The 2_2^+ level was identified as the $2_{1,\mathrm{MS}}^+$ state in ^{92}Zr and presents a weaker p-n interaction as compared with the $2_{1,\mathrm{MS}}^+$ state (2_3^+) in ^{94}Mo [4], which results in a partial decoupling of proton and neutron excitations. The strong $M1$ transition with $B(M1) = 0.37(4)\mu_N^2$ connecting the two lowest 2^+ states in ^{92}Zr indicates, however, that both proton and neutron configurations still make important contributions to their wave functions. To better understand this situation, we investigated the low-lying structure of ^{94}Zr in detail. With four neutrons beyond the $N = 50$ closed shell, ^{94}Zr should present both collective and individual-particle behavior.

The nucleus $^{94}_{40}$Zr was studied using the $(n, n'\gamma)$ reaction [8]. Neutrons were provided by the 7 MV electrostatic accelerator at the University of Kentucky through the ^{3}H$(p,n)^3$He reaction. The scattering sample was 20.03 g (2.6 × 3.9 cm cylinder) of ZrO_2 powder enriched to 98.6% in ^{94}Zr. With beam pulses separated by 533 ns and bunched to about 1 ns, the time-of-flight technique was used for background suppression by selecting prompt γ rays detected with a 55% HPGe detector with BGO Compton suppression [9]. The spectrometer had 1.8-keV resolution at 1.3-MeV γ-ray energy. Excitation function and angular distribution measurements yielded information on branching and mixing ratios of γ-ray transitions, level spin assignments, and lifetimes of excited levels. Both excitation functions and angular distributions were normalized to the neutron flux. Lifetimes were measured through the Doppler-shift attenuation method (DSAM) following the $(n,n'\gamma)$ 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 unshifted γ-ray energy, v_0 the initial maximum 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]. Finally, the lifetimes of the states can be determined by comparing the experimental $F(\tau)$ values with the calculated ones using the Winterbon formalism [12].

As shown in Fig. 1, three 2^+ states lie below 2.3 MeV in ^{94}Zr. Analogy with the $2_{1,\mathrm{MS}}^+$ states identified in the $N = 52$ spherical isotones would suggest a strong $M1$ transition from one of the upper 2^+ states to the 2_1^+ level, thus leading to the identification of the $2_{1,\mathrm{MS}}^+$ state. Table I lists the relevant results obtained in this work.

The 2_2^+ state at an excitation energy of 1671.4 keV is depopulated (see Fig. 1) by the 752.5-keV γ ray to the 2_1^+ state and the 1671.4-keV transition to the ground state. We disagree with the branching ratios in the nuclear database [13], where the 752.5-keV γ ray is given a larger relative intensity, 100, than that of the 1671.4-keV transition, 71. From the angular distribution measurements, we have determined a relative intensity of 100(4) for the 1671.4-keV γ ray, and 76(4) is measured for the 752.5-keV transition to the 2_1^+ state, in general agreement with previous ^{94}Y β^--decay measurements (see Ref. [14] and references therein). Although the 1671.4-keV transition is clearly of pure $E2$ character, the mixing ratio for the 752.5-keV γ ray must be experimentally determined. From the angular distribution measurements, we determined the differential cross sections of the excited state decays and compared them with theoretical calculations given by a code modified from the computer code

*URL: http://www.pa.uky.edu/ jnorce

TABLE I. Results obtained from the ^{94}Zr(n,$n'\gamma$) measurements at 2.3-MeV neutron bombarding energy, including level energies, lifetimes, spins of initial and final states, γ ray energies, branching and mixing ratios, and experimental $B(M1)\downarrow$ and $B(E2)\downarrow$ transition rates. An asterisk labels newly identified γ-ray transitions.

E_L (keV)	τ (fs)	J_i^π	$\rightarrow J_f^\pi$	E_γ (keV)	I_γ	δ	$B(M1)$ (μ_N^2)	$B(E2)$ (W.u.)
1671.4(1)	175(20)	2_2^+	0_1^+	1671.4(1)	100(4)	$E2$		8(1)
			2_1^+	752.5(1)	76(4)	0.02(2)	0.33(5)	0.13(2)
2151.3(1)	316^{+110}_{-70}	2_3^+	0_1^+	2151.3(3)*	2(2)	$E2$		0.04(5)
			2_1^+	1232.4(1)	100(2)	−0.74(5)	0.06(2)	11.9(34)
			2_2^+	479.9(2)*	5(2)	$1.59^{+0.71}_{-0.59}$	0.01(1)	130(90)

CINDY, which is based on the statistical compound nucleus theory of Hauser-Feshbach-Moldauer [15]. Cross sections are dependent on incident neutron energies and the quantum numbers of the states of interest. The comparison of theoretical cross sections with experimental values provides information about the spins of the excited states and multipolarities of the transitions depopulating these levels. Figure 2 shows an angular distribution plot for the 752.5-keV γ ray, and the fit to the data gives a multipole mixing ratio of $\delta = 0.02(2)$. Figure 2 also shows another minimum for the same transition at $\delta = 2.21(20)$; this mixing ratio gives a $B(E2; 2_2^+ \rightarrow 2_1^+)$ value of about 250(50) W.u., which is physically unrealistic and is rejected. Using the DSAM explained above, as shown in Fig. 3, a lifetime of $\tau = 175(20)$ fs has been determined for the 1671.4-keV level. These data give a large $B(M1; 2_2^+ \rightarrow 2_1^+)$ value of 0.33(5) μ_N^2, as expected for an isovector excitation. Despite the lower excitation energy as compared with the $2^+_{1,\mathrm{MS}}$ states observed in the $N = 52$ isotones, and the 2_2^+ level having an energy appropriate to a two-phonon structure, together with the nearby 0_2^+ and 4_1^+ states at 1.300 and 1.470 MeV, respectively, the $M1$ strength signature is clear; hence, we propose the 1671.4-keV level instead as the $2^+_{1,\mathrm{MS}}$ state in ^{94}Zr. It is important to point out here that the $2_2^+ \rightarrow 0_1^+$ $E2$ transition is stronger, 8(1) W.u., than the $2_1^+ \rightarrow 0_1^+$ decay. $B(E2; 2_1^+ \rightarrow 0_1^+)$ values obtained from Coulomb excitations and plunger lifetime experiments range from 3.5 to 7.7 W.u. [16–20] with a final weighted value of 4.9(3) W.u. [13]. The $B(E2; 2_2^+ \rightarrow 0_1^+)$ value is also larger than those observed from $2^+_{1,\mathrm{MS}}$ states in the $N = 52$ isotones. This peculiar behavior is discussed below.

Although closer to the ~2 MeV energy range expected for a MS state in this region, the 2_3^+ level at 2151.3 keV has a very weak $M1$ transition to the 2_1^+ level. The 2_3^+ state is depopulated by the 479.9, 1232.4, and 2151.3 keV γ rays to the 2_2^+, 2_1^+, and 0_1^+ levels, respectively (see Fig. 1). The 479.9-keV γ ray is identified in this work and has a multipole mixing ratio of $\delta = 1.59^{+0.71}_{-0.59}$; the 1232.4-keV γ ray has $\delta = -0.74(5)$. The weak 2151.3-keV transition (also identified in this work) is a pure $E2$ transition. We have determined a lifetime of $\tau = 315^{+110}_{-70}$ fs for this level, giving a smaller $B(M1; 2_3^+ \rightarrow 2_1^+) = 0.06(2)\mu_N^2$ compared to

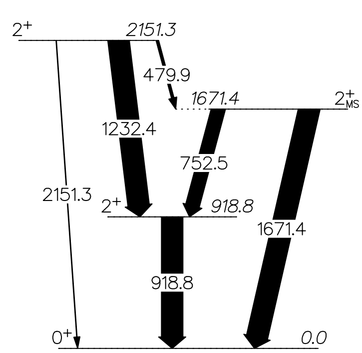

FIG. 1. Partial ^{94}Zr level scheme showing the low-lying 2^+ states. The widths of the arrows are proportional to the relative intensities of the γ-ray transitions depopulating a particular state.

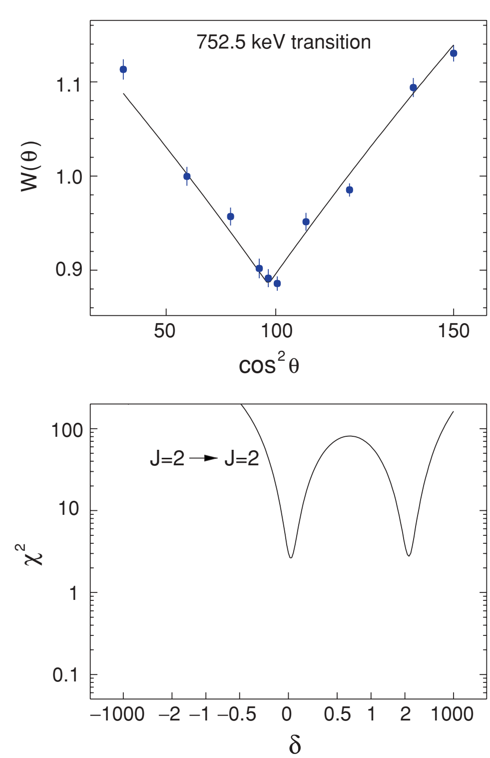

FIG. 2. (Color online) The top panel shows an angular distribution plot for the 752.5-keV γ ray from the 2_2^+ state at 1671.4 keV to the 2_1^+ state. The abscissa scale is linear in $\cos^2\theta$, but the axis labels indicate θ. The bottom panel shows χ^2 as a function of the multipole mixing ratio, δ. The fit to the data gives a minimum for $\delta = 0.02(2)$.

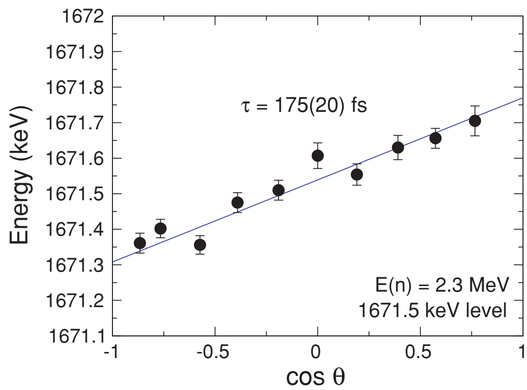

FIG. 3. (Color online) Doppler-shift attenuation data for γ rays de-exciting the 1671.4 keV level.

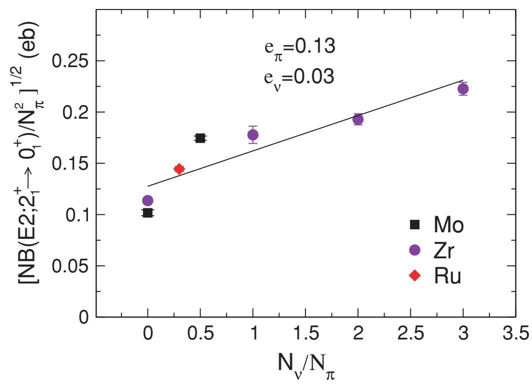

FIG. 4. (Color online) The least-squares fit for the plot of $[NB(E2;2_1^+ \to 0_1^+)/N2_\pi]^{1/2}$ against N_ν/N_π gives the boson proton (intercept) and neutron (slope) effective charges. $B(E2;2_1^+ \to 0_1^+)$ data are taken from the national nuclear data center (NNDC) [24].

the similar transition from the 1671.4-keV 2_2^+ level, whereas a large $B(E2;2_3^+ \to 2_1^+) = 11.9(34)$ W.u. is determined. With about twice the strength of the $2_1^+ \to 0_1^+$ decay, the decay properties of this state are in a closer agreement with a two-phonon excitation, although single-particle contributions are certainly present. A very weak $E2$ transition to the ground state, $B(E2) = 0.04(5)$ W.u., is also determined

Even-even nuclei in the vibrational U(5) limit of the IBM-2 exhibit $M1$ transition strengths from the 2_1, MS$^+$ state to the 2_1^+ state given by [2],

$$B(M1;2_{1,\mathrm{MS}}^+ \to 2_1^+) = \frac{3}{4\pi}(g_\nu - g_\pi)^2\ \frac{6N_\nu N_\pi}{N^2}\ \mu_N^2, \qquad (1)$$

where N_π and N_ν are the number of proton and neutron pairs, respectively, and $N = N_\pi + N_\nu$. The standard boson g factors, g_π and g_ν, are $g_\pi = 1$ for proton bosons and $g_\nu = 0$ for neutron bosons (in contrast to the values employed in nucleon-based models). Considering ${}^{88}_{38}\mathrm{Sr}_{50}$ as the inert core [21,22], the proton and neutron boson numbers for ^{94}Zr are $N_\pi = 1$ and $N_\nu = 2$, giving $B(M1;2_{\mathrm{MS}}^+ \to 2_1^+) = 0.32\ \mu_N^2$, which is in very good agreement with our experimentally determined value.

One can also compare the experimental values, $B(E2;2_1^+ \to 0_1^+) = 4.9(11)$ and $B(E2;2_{1,\mathrm{MS}}^+ \to 0_1^+) = 8(1)$ W.u., with the predictions from the U(5) limit [2] given by Eqs. (2) and (3), respectively,

$$B(E2;2_1^+ \to 0_1^+) = \frac{(e_\nu N_\nu + e_\pi N_\pi)^2}{N}\ e^2b^2 \qquad (2)$$

and

$$B(E2;2_{1,\mathrm{MS}}^+ \to 0_1^+) = (e_\nu - e_\pi)^2\frac{N_\nu N_\pi}{N}\ e^2b^2 \qquad (3)$$

The $B(E2)$ value in the latter equation depends on the difference of boson effective charges, $e_\nu - e_\pi$, and, therefore, it may be expected to be small. We have calculated the boson effective charges for the region of interest, from Zr to Ru, using the same formalism as in Ref. [23]. From Eq. (2), it is deduced that the plot of the quantity $[NB(E2;2_1^+ \to 0_1^+)/N_\pi^2]^{1/2}$ versus N_ν/N_π should be linear, giving e_π (intercept) and e_ν (slope) as the fitting coefficients, i.e.,

$$\left[NB(E2;2_1^+ \to 0_1^+)/N_\pi^2\right]^{1/2} = e_\pi + e_\nu N_\nu/N_\pi. \qquad (4)$$

As shown in Fig. 4, the least-squares fit to the data gives $e_\nu = 0.03$ and $e_\pi = 0.13$, and $B(E2;2_1^+ \to 0_1^+) = 4.7$ W.u. for ^{94}Zr. Again, the IBM-2 prediction is in excellent agreement with the experimental value. For the $2_{1,\mathrm{MS}}^+$ state to ground-state transition, we obtain $B(E2;2_{1,\mathrm{MS}}^+ \to 0_1^+) = 2.6$ W.u. using the effective charges calculated in this work. Recent quasiparticle phonon model (QPM) calculations have shown the proton dominance of the $2_{1,\mathrm{MS}}^+$ state in ^{92}Zr [25]. Similar decay properties of the $2_{1,\mathrm{MS}}^+$ state in ^{94}Zr might indicate that the extra collectivity in the $E2$ strength comes from proton core excitations not included in the IBM-2. ^{94}Zr is the first observed case in a nearly spherical nucleus where the $2_{1,\mathrm{MS}}^+$ state decays to the ground state by a stronger $E2$ transition than that observed for the $2_1^+ \to 0_1^+$ decay.

In conclusion, the lowest mixed-symmetry state in ^{94}Zr is identified as the 2_2^+ state at 1671.4 keV. This assignment is supported by the strong $M1$ transition to the 2_1^+ state of $0.33(5)\ \mu_N^2$, which is in good agreement with the IBM-2 prediction in the U(5) vibrational limit. The 2_3^+ level at 2151.3 keV has a weaker $M1$ strength of $0.06(2)\ \mu_N^2$. The $B(M1;2_{1,\mathrm{MS}}^+ \to 2_1^+)$ value in ^{94}Zr is similar to that obtained for ^{92}Zr and supports a weaker p-n interaction for the $2_{1,\mathrm{MS}}^+$ state as compared with the $2_{1,\mathrm{MS}}^+$ in ^{94}Mo. However, the p-n symmetry still plays an important role as is implied from our simple IBM-2 calculations in ^{94}Zr and previous shell model [5,6] and QPM calculations [25] in ^{92}Zr. Finally, it is the first time in nearly spherical nuclei that $B(E2;2_{1,\mathrm{MS}}^+ \to 0_1^+) > B(E2;2_1^+ \to 0_1^+)$; this anomalous behavior cannot be explained from a simple IBM-2 approach. Large-scale shell-model calculations using a large proton valence space and including core polarization effects might lead to an interpretation of this strength inversion.

The authors are pleased to acknowledge and thank Gene Baber for technical support. This material is based upon work supported by the U.S. National Science Foundation under Grant No. PHY-0354656.

[1] F. Iachello and A. Arima, *The Interacting Boson Model* (Cambridge University Press, Cambridge, 1987).
[2] P. van Isacker, K. Heyde, J. Jolie, and A. Sevrin, Ann. Phys. (NY) **171**, 253 (1986).
[3] F. Iachello, Phys. Rev. Lett. **53**, 1427 (1984).
[4] C. Fransen *et al.*, Phys. Rev. C **67**, 024307 (2003).
[5] V. Werner *et al.*, Phys. Lett. **550B**, 140 (2002).
[6] C. Fransen, V. Werner, D. Bandyopadhyay, N. Boukharouba, S. R. Lesher, M. T. McEllistrem, J. Jolie, N. Pietralla, P. von Brentano, and S. W. Yates, Phys. Rev. C **71**, 054304 (2005).
[7] N. Pietralla, C. Fransen, D. Belic, P. von Brentano, C. Frießner, U. Kneissl, A. Linnemann, A. Nord, H. H. Pitz, T. Otsuka, I. Schneider, V. Werner, and I. Wiedenhöver, Phys. Rev. Lett. **83**, 1303 (1999).
[8] P. E. Garrett, N. Warr, and S. W. Yates, J. Res. Natl. Inst. Stand. Technol. **105**, 141 (2000).
[9] M. T. McEllistrem, *Nuclear Research with Low Energy Accelerators* (Academic Press, New York, 1967), p. 167.
[10] T. Belgya, G. Molnár, and S. W. Yates, Nucl. Phys. **A607**, 43 (1996).
[11] A. E. Blaugrund, Nucl. Phys. **88**, 501 (1966).
[12] K. B. Winterbon, Nucl. Phys. **A246**, 293 (1975).
[13] D. Abriola and A. A. Sonzogni, Nucl. Data Sheets **107**, 2423 (2006).
[14] B. Singh, H. W. Taylor, and P. J. Tivin, J. Phys. G **2**, 397 (1976).
[15] E. Sheldon and V. C. Rogers, Comput. Phys. Commun. **6**, 99 (1973); P. A. Moldauer, Phys. Rev. C **14**, 764 (1976).
[16] D. Rychel, R. Gyufko, B. van Krüchten, M. Lahanas, P. Singh, and C. A. Wiedner, Z. Phys. A **326**, 455 (1987).
[17] B. J. Lund, N. P. T. Bateman, S. Utku, D. J. Horen, and G. R. Satchler, Phys. Rev. C **51**, 635 (1995).
[18] D. K. Alkhazov, D. S. Andreev, V. D. Vasilov, Y. P. Gangrskii, I. K. Lemberg, and Y. I. Udralov, Izv. Akad. Nauk. SSSR, Ser. Fiz. **27**, 1285 (1963).
[19] L. N. Galperin, A. Z. Ilyasov, I. K. Lemberg, and G. A. Firsonov, Yad. Fiz. **9**, 225 (1969).
[20] D. J. Horen, R. L. Auble, C. Y. Wu, D. Cline, M. Devlin, R. Ibbotson, and M. W. Simon, Phys. Rev. C **48**, 433 (1993).
[21] A. F. Lisetskiy, N. Pietralla, C. Fransen, R. V. Jolos, and P. von Brentano, Nucl. Phys. **A677**, 100 (2000).
[22] J. N. Orce, J. D. Holt, A. Linnemann, C. J. McKay, S. R. Lesher, C. Fransen, J. W. Holt, A. Kumar, N. Warr, V. Werner, J. Jolie, T. T. S. Kuo, M. T. McEllistrem, N. Pietralla, and S. W. Yates, Phys. Rev. Lett. **97**, 062504 (2006).
[23] W. D. Hamilton, A. Irbäck, and J. P. Elliott, Phys. Rev. Lett. **53**, 2469 (1984).
[24] NNDC, http://www.nndc.bnl.gov/useroutput/AR_34138_1.html
[25] N. Lo Iudice and Ch. Stoyanov, Phys. Rev. C **73**, 037305 (2006).