Spin-parity assignments and evidence for mixed-symmetry states in ^{100}Ru

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Spin and parity of some low-lying levels in ^{100}Ru have been assigned by measuring K-internal conversion coefficients of the deexciting transitions. The new information, combined with the available experimental data, has been analyzed in the framework of the interacting boson model (IBM-2) to clarify the structure of the 2_3^+, 2_4^+, and 3_1^+ levels in terms of their mixed-symmetry character. [S0556-2813(96)05506-9]

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In a recent work [1] we have analyzed, in the framework of the interacting boson model (IBM-2) [2], the excitation energy patterns and electromagnetic properties of low-lying positive-parity states in even $^{98-114}$Ru isotopes in an attempt to identify states which possess a mixed-symmetry (MS) character. We concluded that, to correctly reproduce the properties of the levels, it is necessary to take into account the presence of MS states, the lowest ones being the 2_3^+ and 3_1^+ levels. For example, in low-mass ruthenium isotopes, which display a structure close to the U(5) limit of the model [1,3,4], it is apparent that the presence of additional 2^+ and 3^+ states at an excitation energy close to the one expected for the $3d$-boson multiplet in no way can be reproduced in a scheme limited to fully symmetric (FS) states. However, for some isotopes an extended comparison of experimental and theoretical data was prevented by the uncertain spin-parity assignment to several low-lying states. As a part of an experimental program [5] aimed at gaining new information on levels in even ruthenium isotopes which could possess MS properties, we report in this paper on some spin-parity assignments obtained from K-internal conversion coefficient measurements in ^{100}Ru. On the basis of the new data, we extend the comparison, given in [1], between experimental data and predictions of the IBM-2.

Low-lying levels of ^{100}Ru were populated in the β^+-electron-capture (-EC) decay of the ($J^\pi=1^-$) ground state of ^{100}Rh produced via a (p,n) reaction on a 93%-enriched, 1-mg/cm^2-thick ^{100}Ru target, obtained by sputtering on an aluminum backing. The irradiation was performed using the proton beam of the 7-MV CN Van de Graaff accelerator of Laboratori Nazionali di Legnaro (Padua) at an energy of 6.75 MeV. In order to withstand the high beam current (1.5 μA), the target was cooled to liquid nitrogen temperature. The bombardment lasted about 18 h, and measurements were performed over a time interval of 20 h, starting shortly after the end of the irradiation. Internal conversion electrons were detected by means of a 6-mm-thick Si(Li) detector (cooled to liquid nitrogen temperature) connected to a magnetic transport system (described in detail elsewhere [6]), having a momentum acceptance $\Delta p/p \sim 18\%$. The energy resolution [full width at half maximum (FWHM)] of the Si(Li) detector was typically 2 keV at an energy of 1.5 MeV. Gamma rays were detected by means of a HPGe detector having a FWHM of 2.5 keV at an energy

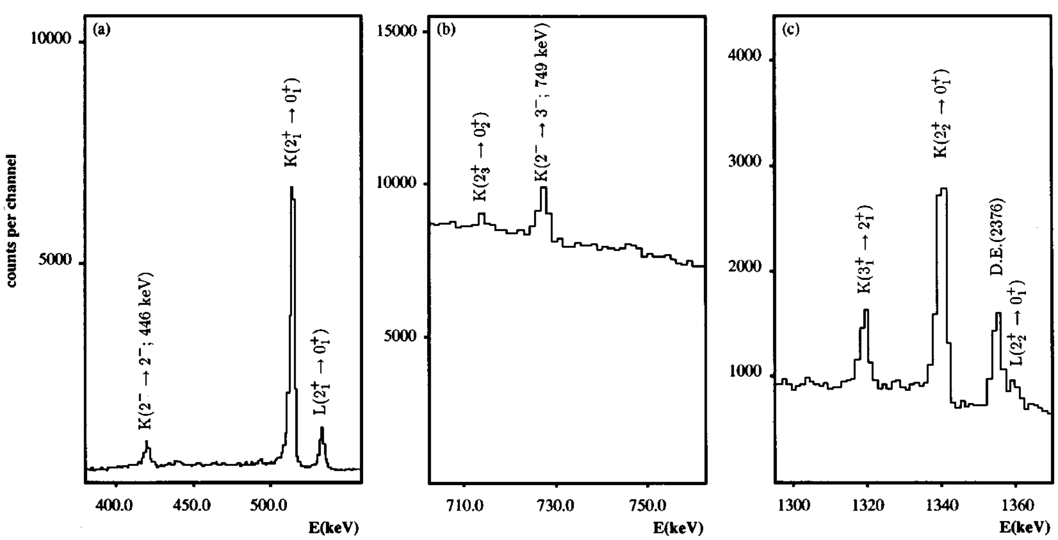

FIG. 1. Relevant sections of the electron-energy spectra showing the K- and L-conversion lines of (a) the 446-keV, $2^-\to2^-$ and the 540-keV, $2_1^+\to0_1^+$ transitions; (b) the 735-keV, $2_3^+\to0_2^+$ and 749-keV, $2^-\to3^-$ transitions; (c) the 1341-keV, $3_1^+\to2_1^+$ and 1362-keV, $2_2^+\to0_1^+$ transitions. The label D.E. in (c) indicates the double escape peak of the 2376-keV, $2^-\to2_1^+$ gamma transition.

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TABLE I. Experimental values of the K-internal conversion coefficients (in units of 10^{-3}) for the specified transitions are compared with the theoretical values for $E1$, $E2$, $M1$, and $M2$ transitions. In column 10 are reported the parity assignment and restriction on the possible spin range deduced from the present work.

E_{level}	J_i^π [8]	E_γ	J_f^π [8]	α_K^{expt}	$\alpha_K^{\text{theor}}(E1)$	$\alpha_K^{\text{theor}}(E2)$	$\alpha_K^{\text{theor}}(M1)$	$\alpha_K^{\text{theor}}(M2)$	J_i^π
1362.2	2_2^+	822.6	2_1^+	1.23(5)	0.493	1.24	1.31	3.37	
1865.1	(2_3^+)	1325.5	2_1^+	0.422(57)	0.200	0.423	0.465	1.00	2_3^+
		734.8	0_2^+	1.63(28)	0.622	1.64	1.69	4.55	
		638.7	4_1^+	2.28(48)	0.846	2.37	2.34	6.70	
		503.1	2_2^+	4(1)	1.46	4.59	4.08	13.1	
1881.1	$(2^+,3^+)$	1341.5	2_1^+	0.413(13)	0.196	0.413	0.453	0.977	3_1^+
		654.7	4_1^+	2.13(13)	0.799	2.21	2.20	6.24	
		519.1	2_2^+	4.11(22)	1.36	4.19	3.79	12.0	
2099.0	$(1,2,3)^+$	1559.5	2_1^+	0.387(38)	0.153	0.309	0.335	0.692	2_4^+
		736.3	2_2^+	0.98(57)	0.619	1.63	1.68	4.52	
2166.8	3^-	1627.3	2_1^+	0.144(27)	0.143	0.286	0.309	0.631	
2240.6	(2^+)	499.8	0_3^+	4.41(67)	1.49	4.67	4.15	13.4	$1^+,2^+$
2469.4	$(1^-,2^-)$	2469.4	0_1^+	0.207(40)	0.0752	0.132	0.137	0.250	2^-
		604.9	(2_3^+)	1.20(28)	0.953	2.73	2.65	7.77	
		588.3	$(2^+,3^+)$	1.04(5)	1.02	2.95	2.83	8.41	
		370.6	$(1,2,3)^+$	3.86(89)	3.13	11.6	8.54	32.7	
		302.3	3^-	19.4(11)	5.38	22.7	14.3	61.7	
		229.1	(2^+)	8(2)	11.4	57.7	29.0	151	
2516.8	$(1^+,2^+)$	651.6	(2_3^+)	0.84(12)	0.809	2.24	2.23	6.34	$1^-,2^-$
2915.5	2^-	1553.4	2_2^+	0.159(9)	0.157	0.318	0.346	0.698	
		446.2	$(1^-,2^-)$	5.37(27)	0.599	6.54	5.44	18.7	
3070.0	(1,2)	599.9	$(1^-,2^-)$	2.75(40)	0.971	2.79	2.70	7.95	$1^-,2^-$

of 1.3 MeV. Internal conversion coefficients were determined by means of the normalized peak-to-gamma (NPG) method [7]. In most cases it has been possible to normalize the electron peak area of the transition of interest to that of a strong transition of known multipolarity lying close in energy, both transitions being recorded simultaneously, i.e., for the same setting of the magnetic field. In other cases reference was made to the K-conversion line of the 540-keV, $2_1^+ \rightarrow 0_1^+$ transition recorded in a separated run. Sections of typical electron energy spectra are shown in Fig. 1. The experimental values of the measured K-internal conversion coefficients (α_K) are shown in the fifth column of Table I. The information on spin and parity of the relevant levels available previous to this work [8] is given in the second and fourth columns of the same table. To give an idea of the internal consistency of our data, the experimental values of α_K for some transitions of known multipolarity are also reported. Most of the additional information on spin-parity provided by the present work stems from a comparison of the experimental values of α_K with the theoretical ones [9] given in columns 6–9 for $E1$, $E2$, $M1$, and $M2$ multipolarities and is summarized in the last column. In the cases discussed hereafter, some specific additional arguments have been used to deduce the assignment given in the last column.

1881.1-keV level. From the values of α_K for the three transitions deexciting this level, the limitation $J^\pi = 2^+, 3^+$ is obtained. The absence of any decay to the 0_1^+ and 0_2^+ states [intensity $<0.1\%$ and $<0.7\%$ (at the 90% confidence level) of the transition to the 2_1^+ level, respectively] strongly favors the 3^+ assignment. This assignment is also supported by the fact that the level is populated in the β^+-EC decay of the (5^+) isomeric state of ^{100}Ru [8].

2099.0-keV level. From the experimental values of α_K reported in Table I, the whole range $J^\pi = 0^+ – 4^+$ would be allowed. Spins 0 and 4 are excluded by the $E1$ multipolarity of the 371-keV transition from the 2^- state at 2469 keV. Spin 3 is excluded by the log*ft* value of the β^- decay from the $J^\pi = 1^+$ ground state of ^{100}Tc [8], according to the rules given in [10]. Moreover, careful inspection of the gamma-energy spectrum in the 800–900 keV energy region has revealed the presence of a weak 872.6(3)-keV line, which matches with a transition to the 4_1^+ level at 1226.6 keV. Its intensity ratio with respect to the other lines corresponding to

TABLE II. Branching ratios from the 2_3^+ and 2_4^+ states in ^{100}Ru. Values from present work (last column) are compared with the data available in the literature [8].

J_i^+	J_f^+	E_γ (keV)	I_γ [8]	I_γ
2_3^+	2_2^+	503	18(3)	17(2)
	4_1^+	639	22(3)	10(1)
	0_2^+	735	100(12)	57(1)
	2_1^+	1325	86(10)	83(3)
	0_1^+	1865	100(12)	100(19)
2_4^+	3_1^+	218	4(1)	<0.2
	2_3^+	234	13(3)	<0.2
	2_2^+	736	16(3)	13.3(7)
	4_1^+	872		1.8(2)
	0_2^+	968		3.3(7)
	2_1^+	1559	100(12)	100(5)

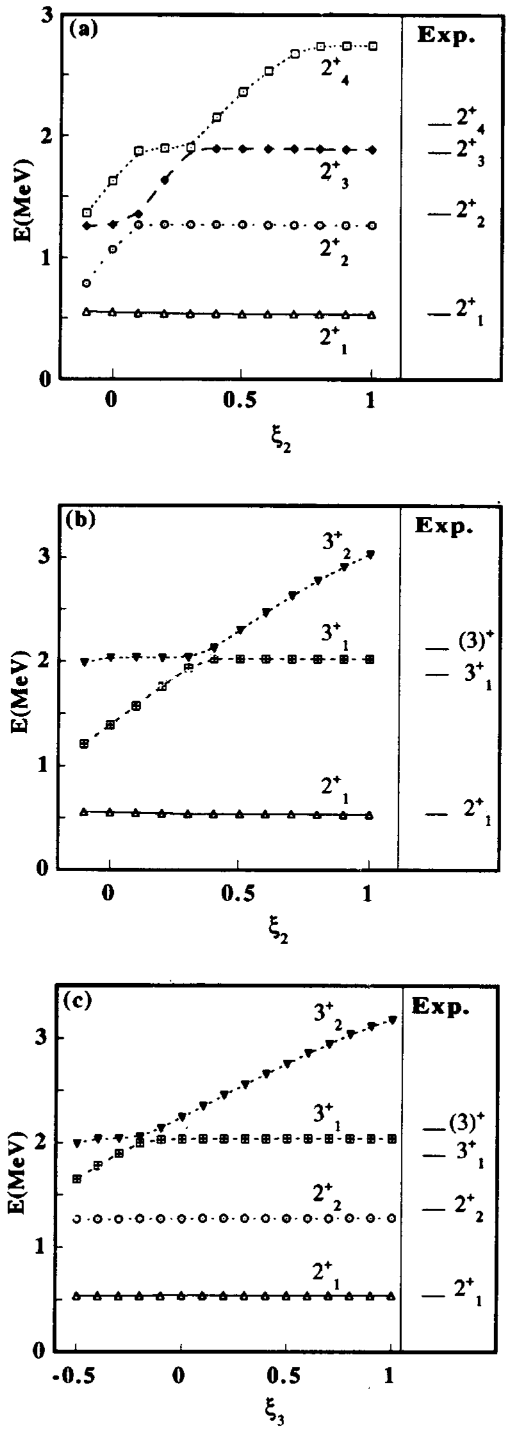

FIG. 2. (a),(b) ξ_2 dependence of the calculated excitation energies of the indicated levels, when the remaining Hamiltonian parameters are taken as in Ref. [1]. In (b) the 3^+_2 level has been assumed to be the level at 2131 keV, but its spin value in [8] is only restricted to the range 2–3. (c) As in (a),(b), but for ξ_3 dependence of the excitation energies of the indicated levels.

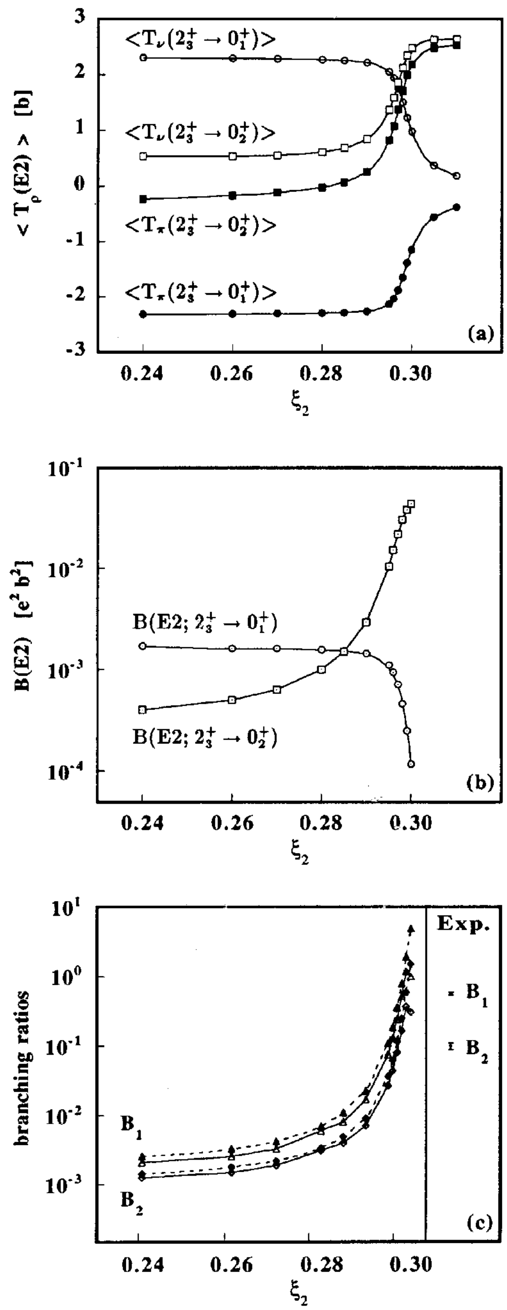

FIG. 3. Calculated ξ_2 dependence of (a) proton and neutron boson reduced $E2$ transition matrix elements $\langle T_\rho(E2)\rangle$ for the indicated transitions (positive sign is arbitrarily assigned to $\langle T_\nu\rangle$), (b) reduced $E2$ transition probabilities $B(E2)$, and (c) the branching ratios $B_1 = W_\gamma(2^+_3 \to 0^+_2)/W_\gamma(2^+_3 \to 0^+_1)$, $B_2 = W_\gamma(2^+_3 \to 4^+_1)/W_\gamma(2^+_3 \to 0^+_1)$ for two values of the difference of the adopted quadrupole effective charges (see text for details). On the right-hand side, the corresponding experimental branching ratios (present work) are reported.

transitions from the 2099-keV level (as well as to the $2^+_1 \to 0^+_1$ transition) is consistent with a constant value when evaluated in several spectra recorded at different times. The decay to the 4^+_1 level rules out the spin $J=1$, thereby leading to the assignment $J^\pi = 2^+$ as the only acceptable one.

2516.8-keV level. Contrary to what reported in [8], this level has definitely negative parity as follows from the $E1$ multipolarity of the transition to the 1865-keV, 2^+ level. The spin range $J=1,2,3$, implied by the value of α_K, is restricted to the first two values because of the logft value of the β^- decay from the ground state of ^{100}Tc [8].

3070.0-keV level. This level has definitely negative parity as follows from $E2$ or $M1$ multipolarity of the 600-keV

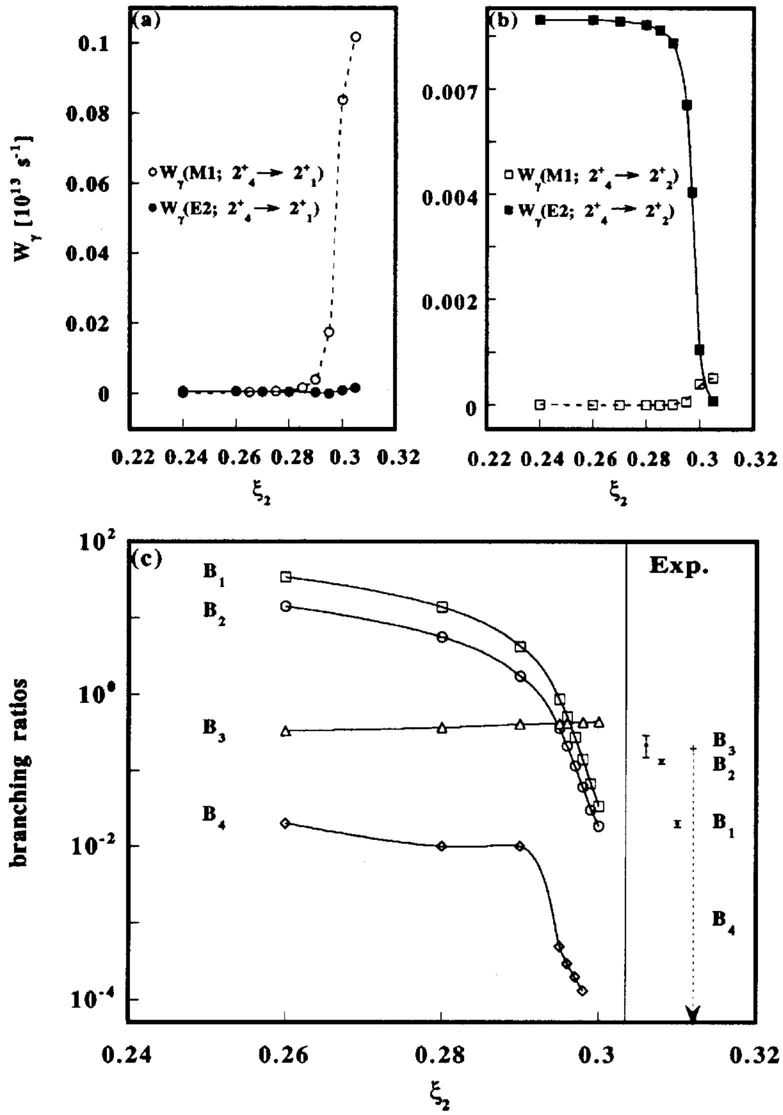

FIG. 4. (a) ξ_2 dependence of the calculated absolute $M1$ and $E2$ transition rates for the $2_4^+\rightarrow 2_1^+$ transition. For the effective neutron and proton boson charges and g factors the values of [1] have been used. (b) As in part (a), but for the $2_4^+\rightarrow 2_2^+$ transition. (c) ξ_2 dependence of the calculated branching ratios $B_1=W_\gamma(2_4^+\rightarrow 4_1^+)/W_\gamma(2_4^+\rightarrow 2_1^+)$, $B_2=W_\gamma(2_4^+\rightarrow 2_2^+)/W_\gamma(2_4^+\rightarrow 2_1^+)$, $B_3=W_\gamma(3_1^+\rightarrow 2_2^+)/W_\gamma(3_1^+\rightarrow 2_1^+)$, and $B_4=W_\gamma(2_4^+\rightarrow 2_3^+)/W_\gamma(2_4^+\rightarrow 2_1^+)$. Experimental values for B_1, B_2 (present work), and B_3, [8] together with the upper limit for B_4 (present work), are reported on the right-hand side.

transition to the 2469-keV, 2^- level. The presence of a gamma transition to the 0_1^+ state [8] rules out spins 0 and 4, whereas spin 3 is excluded by the same argument adopted for the 2516.8-keV level.

The definite identification of the 2_3^+ and 2_4^+ states at 1865 and 2099 keV, respectively, is quite important in clarifying the nature of the lowest MS states (see below). In Table II the measured intensities of the transitions deexciting these levels are reported together with those given in [8], from which, in some cases, they differ considerably. For example, in the present work, no decay from the 2_4^+ level to the 2_3^+ and 3_1^+ levels has been detected while, in addition to the already mentioned transition to the 4_1^+ level, a transition having energy of 968.8(3) keV, which matches with a transition to the 1130.5-keV, 0_2^+ level, has been observed. Also, in this case it has been checked that its intensity ratio with respect to other transitions from the ^{100}Rh decay was constant in time.

We observe that our assignment of spins 3 and 2 to the 1881- and 2099-keV levels is at variance with those chosen (in the absence of definite experimental information) for these states by Kern *et al.* [4] in their analysis of the excitation energy pattern of nuclei exhibiting U(5) dynamical symmetry in the framework of the IBM-1.

We now consider, in relation to our previous work on MS states in ruthenium isotopes [1], some detailed decay properties of the 2_3^+, 2_4^+, and 3_1^+ states in ^{100}Ru, with particular emphasis on their dependence on the values of the parameters ξ_2 and ξ_3 in the Majorana term of the IBM-2 Hamiltonian [2]. As is well known, the Majorana parameters are of crucial importance in determining the energies of MS states, while they hardly influence those of FS states, at least in a situation close to one of the limits of the IBM-2. In the discussion below no mention is made of the ξ_1 parameter as the excitation energies of the levels considered in this work are essentially not affected by the value of ξ_1, when this is varied over quite a large range [1]. The excitation energies of the lowest-lying 2^+ and 3^+ states (calculated by means of the NPBOS code [11]) are reported as a function of ξ_2 and ξ_3 in Fig. 2. It is seen that, in particular ranges of these parameters, the excitation energy of several levels changes rapidly, implying a strong MS component in their wave functions. Instead, the 2_1^+ state maintains its excitation energy, hence the $1d$-boson FS character, over the whole range

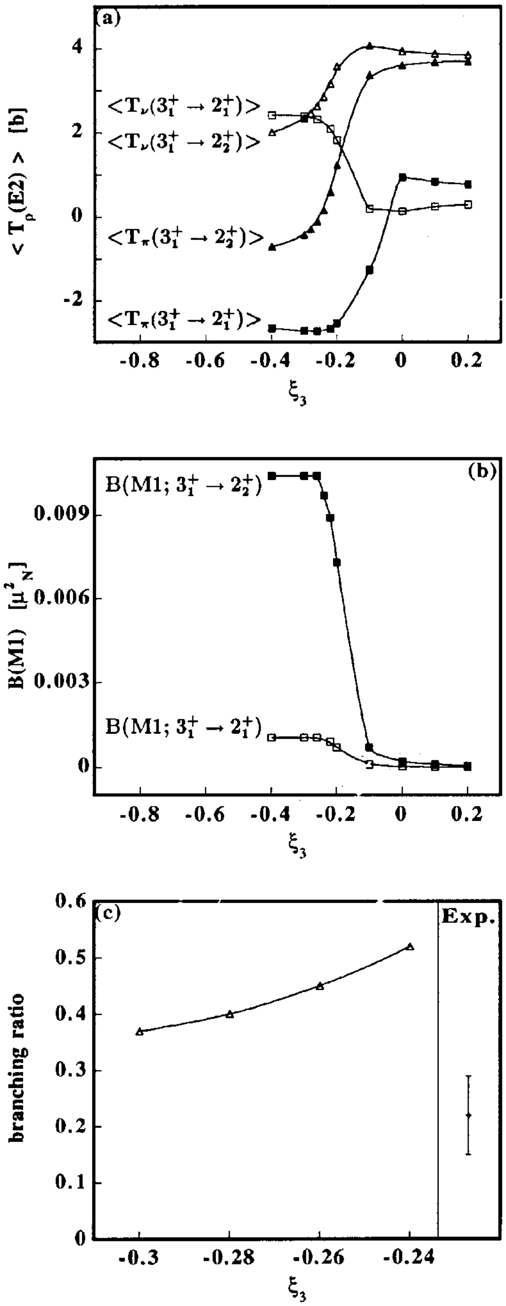

FIG. 5. Calculated ξ_3 dependence of (a) proton and neutron reduced $E2$ matrix elements for the indicated transitions (positive sign is arbitrarily assigned to $\langle T_\nu \rangle$), (b) reduced $M1$ transition probabilities $B(M1)$, and (c) the branching ratio $W_\gamma(3_1^+ \to 2_2^+)/W_\gamma(3_1^+ \to 2_1^+)$. The experimental value [8] is shown on the right-hand side.

considered for ξ_2 and ξ_3. The comparison of experimental and theoretical excitation energies in Fig. 2(a) shows that the only possibility, in the framework of the IBM-2, to account for the presence of a doublet of $J^\pi = 2^+$ levels around 2 MeV, is to adopt for ξ_2 a value in the range 0.25–0.4 MeV. A similar situation is expected for the $J^\pi = 3^+$ levels when their excitation energies are studied as a function of ξ_2 [Fig. 2(b)] and ξ_3 [Fig. 2(c)], even though the uncertain identification of the 3_2^+ level does not allow one to draw any definite conclusion. It must be stressed that the properties relevant to the $2_3^+, 2_4^+$ states do not depend sensitively on the parameters ξ_3 of the Majorana term.

More detailed information on the viable values for the parameters ξ_2, ξ_3 can be derived from a comparison of experimental values and model predictions for transitions deexciting the states here considered. Since no absolute values for $E2$ and $M1$ transition probabilities are known, the comparison is restricted to branching ratios. Particularly interesting is the case of the 2_3^+ and 2_4^+ states. For $\xi_2 = 0.295$ MeV (the value adopted in [1]), these states are still considerably pure, their strongest component being the $1d$ and $3d$ bosons, respectively. This value of ξ_2 is close to the one ($\xi_2 \sim 0.3$ MeV) for which level crossing occurs and FS and MS properties are exchanged by members of the doublet. As a consequence, in a very restricted range of values of this parameter, the electromagnetic properties of the two states show a large variation as illustrated in Figs. 3 and 4. It is to be noted that the small $B(E2)$ value of the $2_3^+ \to 0_1^+$ transition for ξ_2 in the range 0.24–0.28 MeV [Fig. 3(b)] results from the opposite sign and almost equal magnitude of the relevant reduced transition matrix elements $\langle T_\rho(E2) \rangle$ ($\rho = \nu, \pi$ for neutron and proton bosons, respectively), as expected [12] for a transition between predominantly MS and FS states [see Fig. 3(a)]. This gives rise to a sizable cancellation due to the similar values adopted in [1] for the quadrupole effective charges ($e_\nu = 0.12$ eb, $e_\pi = 0.08$ eb). Instead, for $\xi_2 > 0.3$ MeV, the $B(E2)$ drops rapidly since the $3d$-boson component in the wave function of the 2_3^+ state becomes the strongest one, so that the transition to the ground state is strictly forbidden due to the d-boson number selection rule for the $E2$ transition ($\Delta n_d = 0, \pm 1$). On the other hand, no such selection rule is operating in the case of the $2_3^+ \to 0_2^+$ transition since the 0_2^+ state maintains (as the 2_2^+ and 4_1^+ states) its $2d$-boson FS character over the whole range $0.24 < \xi_2 < 0.31$ MeV. The small values of the corresponding $B(E2)$ for $\xi_2 < 0.28$ MeV are essentially due to the smallness of the relevant T_ν and T_π. Similar arguments hold for the $2_3^+ \to 4_1^+$ transition. The high sensitivity to the ξ_2 value of the branching ratios is shown in Fig. 3(c). The trend is not affected by the precise values of the adopted effective charges; indeed, the dashed and solid curves for each branching ratio correspond to values of the difference $|e_\nu - e_\pi|$ varied by $\pm 10\%$ with respect to the value given in [1].

Similar considerations apply to absolute $E2$ transition probabilities $W_\gamma(E2)$, relevant to the $2_4^+ \to 2_1^+$ and $2_4^+ \to 2_2^+$ transitions, displayed in Figs. 4(a) and 4(b) as a function of ξ_2. In the same figure the absolute $M1$ transition probabilities are also reported. Their trend is related to the d-boson number selection rules for $M1$ transitions ($\Delta n_d = 0$). It is interesting to observe how the relative importance of $M1$ and $E2$ contributions rapidly varies as the structure of the 2_4^+ state changes from a dominant $3d$-boson FS character to a dominant $1d$-boson MS character. In Fig. 4(c) the experimental values of the branching ratios from the 2_4^+ state are compared to the corresponding theoretical values calculated as a function of ξ_2. The branching ratio $W_\gamma(3_1^+ \to 2_2^+)/W_\gamma(3_1^+ \to 2_1^+)$ is reported in the same figure; it appears to be almost constant over the restricted range of ξ_2 considered since the predicted level crossing of the 3_1^+ and 3_2^+ doublet occurs for values of $\xi_2 > 0.3$ MeV [see Fig. 2(b)].

The comparisons given in Figs. 3(c) and 4(c) suggest for the Majorana parameter ξ_2 a value slightly larger than that reported in [1]. This implies that the 2_3^+ state would share to a larger extent its MS character with the 2_4^+ state.

We now study the dependence on the parameter ξ_3 of the $3_1^+ \rightarrow 2_1^+$ and $3_1^+ \rightarrow 2_2^+$ transitions (Fig. 5). The $\langle T_\rho(E2) \rangle$ and the $M1$ reduced transition probabilities $B(M1)$ are shown in Figs. 5(a) and 5(b). For the reduced $E2$ transition matrix element, cancellation effects and d-boson number selection rule play the same role as in Fig. 3(a). As long as the 3_1^+ state maintains its $2d$-boson MS character ($\xi_3 < -0.2$ MeV), the $M1$ component of the transition to the 2_2^+ state proceeds unhindered, whereas it drops rapidly as the 3_1^+ state acquires a $3d$-boson character. As to the $M1$ component of the $3_1^+ \rightarrow 2_1^+$ transition, it would be completely forbidden in the exact U(5) limit and only acquires a value significantly different from zero for $\xi_3 < -0.2$ MeV, due to the small admixture of components with the same number of d bosons in the two states. The sensitivity of the calculated branching ratio $W_\gamma(3_1^+ \rightarrow 2_2^+)/W_\gamma(3_1^+ \rightarrow 2_1^+)$ for values of ξ_3 around the one adopted in [1] ($\xi_3 = -0.27$ MeV) is seen to be rather weak [Fig. 5(c)]. This is due to the fact that level crossing of the 3_1^+ and 3_2^+ states occurs for much larger values of ξ_3 (i.e., $\xi_3 \sim -0.18$ MeV).

To summarize, the new information given in the present work on the 2_3^+, 2_4^+, and 3_1^+ levels in ^{100}Ru supports our previous interpretation of the character of these states.

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