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Study of mixed-symmetry excitations in ^{96}Ru via inelastic proton-scattering

A Hennig[1], M Spieker[1], V Werner[2,3], T Ahn[2,4], V Anagnostatou[2,5], N Cooper[2], V Derya[1], M Elvers[1,2], J Endres[1], P Goddard[2,5], A Heinz[2,6], R O Hughes[2,7], G Ilie[2,8], M N Mineva[9], S G Pickstone[1], P Petkov[1,9], D Radeck[1,2], T Ross[5,7], D Savran[10,11], and A Zilges[1]

[1] Institut für Kernphysik, Universität zu Köln, D-50937 Köln, Germany
[2] Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520, USA
[3] Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany
[4] National Superconducting Cyclotron Laboratory NSCL, Michigan State University, East Lansing, Michigan 48824, USA
[5] Department of Physics, University of Surrey, Guildford, GU2 7XH, UK
[6] Fundamental Fysik, Chalmers Tekniska Högskola, SE-41296 Göteborg, Sweden
[7] University of Richmond, Richmond, Virginia 23173, USA
[8] National Institute for Physics and Nuclear Engineering, Bucharest-Magurele, RO-77125, Romania
[9] Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, BG-1784 Sofia, Bulgaria
[10] ExtreMe Matter Institute EMMI and Research Division, GSI, D-64291 Darmstadt, Germany
[11] Frankfurt Institute for Advanced Studies FIAS, D-60438 Frankfurt a.M., Germany

E-mail: hennig@ikp.uni-koeln.de

Abstract. Mixed-symmetry states of octupole ($L = 3$) and hexadecapole ($L = 4$) character have been recently proposed in the $N = 52$ isotones ^{92}Zr and ^{94}Mo, based on strong $M1$ transitions to the lowest-lying 3^- and 4^+ states, respectively. In order to investigate similar excitations in the heaviest stable $N = 52$ isotone ^{96}Ru, two inelastic proton-scattering experiments have been performed at the Wright Nuclear Structure Laboratory (WNSL), Yale University, USA and the Institute for Nuclear Physics, University of Cologne, Germany. From the combined data of both experiments, absolute $E1$, $M1$, and $E2$ transition strengths were extracted, allowing for the identification of candidates for MS octupole and hexadecapole states. The structure of the low-lying 4^+ states is investigated by means of *sdg*-IBM-2 calculations.

1. Introduction

The atomic nucleus is a two-component system composed of protons and neutrons. Excitations of the atomic nucleus, which are symmetric and antisymmetric under pairwise exchange of protons and neutrons are denoted as fully-symmetric (FSS) and mixed-symmetry states (MSS), respectively [1, 2]. MSSs are predicted in the proton-neutron version of the interacting boson model (IBM-2) [3, 4, 5, 6] and can be distinguished from FSSs by their F-spin quantum number, which is the bosonic analog of isospin for fermions [4, 5]. An experimental signature of MSSs are strong $M1$ transitions with matrix elements in the order of 1 μ_{N} to their symmetric counterparts [7, 8].

Mixed-symmetry states have been extensively studied in the $N = 52$ isotones, two neutrons away from the $N = 50$ shell closure (see [8] and references therein). Besides the fundamental one-phonon mixed-symmetry quadrupole excitation 2^+_{ms}, members of the two-phonon $(2^+_{\mathrm{ms}} \otimes 2^+_{\mathrm{s}})$ quintuplet have been identified in ^{92}Zr, ^{94}Mo, and ^{96}Ru as well. The existence of mixed-symmetry states of higher-order multipolarity, namely of octupole ($L = 3$) and hexadecapole ($L = 4$) character, has been recently proposed for the nuclei ^{92}Zr and ^{94}Mo, based on the observation of strong $M1$ transitions to the lowest-lying 3^- and 4^+ states, respectively [9, 10, 11].

Mixed-symmetry octupole excitations have been predicted in the $U_{\pi\nu}(1) \otimes U_{\pi\nu}(5) \otimes U_{\pi\nu}(7)$ dynamical-symmetry limit of the *sdf*-IBM-2 [9]. Along with the $M1$ fingerprint, $E1$ transitions to the 2^+_{s} states are predicted by the model in agreement with the two-body character of the $E1$ operator [12]. In addition, a strong $E1$ transition to the 2^+_{ms} state has been observed in the case of ^{94}Mo. The strong $M1$ transition strength between the lowest-lying 4^+ states in ^{94}Mo has been recently described by introducing g-boson excitations in IBM-2 calculations [11]. This suggests a MS and FS one-phonon hexadecapole admixture in the 4^+_2 and 4^+_1 states, respectively. Additional evidence for this interpretation was provided by shell-model calculations predicting dominant $\sigma = 2$, $j = 4$ configurations for the lowest-lying 4^+ states [13], which are by definition g-boson excitations in the IBM language. Here, σ denotes the seniority.

To study possible mixed-symmetry octupole and hexadecapole states in the heaviest stable $N = 52$ isotone ^{96}Ru, two proton-scattering experiments have been performed. A possible one-phonon hexadecapole admixture in the lowest-lying 4^+ states was investigated in the scope of *sdg*-IBM-2 calculations.

2. Experiments

For the determination of absolute transition strengths, spins and parities of excited states, γ-decay branching ratios, multipole mixing ratios δ, and nuclear level lifetimes τ have to be determined experimentally. For this purpose, the nucleus ^{96}Ru has been studied in two proton-scattering experiments.

One experiment was performed at the WNSL at Yale University. A proton beam with an energy of $E_p = 8.4$ MeV, provided by the ESTU Tandem accelerator, was impinged on an enriched ^{96}Ru target with a thickness of 106 μg/cm^2, mounted on a ^{12}C backing with a thickness of 14 μg/cm^2. To measure the energy of the scattered protons, the target chamber was equipped with five silicon surface-barrier detectors mounted at predominantly backward angles with respect to the beam axis. The de-exciting γ-rays were detected with the YRAST ball array [14], equipped with eight BGO-shielded Clover detectors. $\gamma\gamma$ and pγ coincidence data were acquired in this experiment. Further details on the experimental setup can be found in [15]. From the energy of the scattered protons, the excitation energy of the ^{96}Ru target nuclei was calculated. Gating on the excitation energy in the proton spectra, γ-decay branching ratios were extracted with high sensitivity from the pγ coincidence data. Spin quantum numbers and multipole mixing ratios were determined from the $\gamma\gamma$ coincidence data by means of the $\gamma\gamma$ angular-correlation technique (see e.g., [16, 17]).

The lifetimes of MSSs are expected to be in the sub-picosecond range [8]. Thus, the Doppler-shift attenuation method (DSAM) [18, 19] was applied in a second proton-scattering experiment taking advantage of pγ coincidence data [20]. The same target as used for the prior experiment was bombarded with a proton beam with an energy of $E_p = 7.0$ MeV, provided by the 10 MV Tandem accelerator at the Institute for Nuclear Physics at the University of Cologne. The scattered protons were detected with the new particle detector array SONIC (**S**ilic**ON** **I**dentification **C**hamber), which was equipped with six PIPS silicon particle detectors. SONIC was constructed such that it can be embedded within the existing γ-ray spectrometer HORUS,

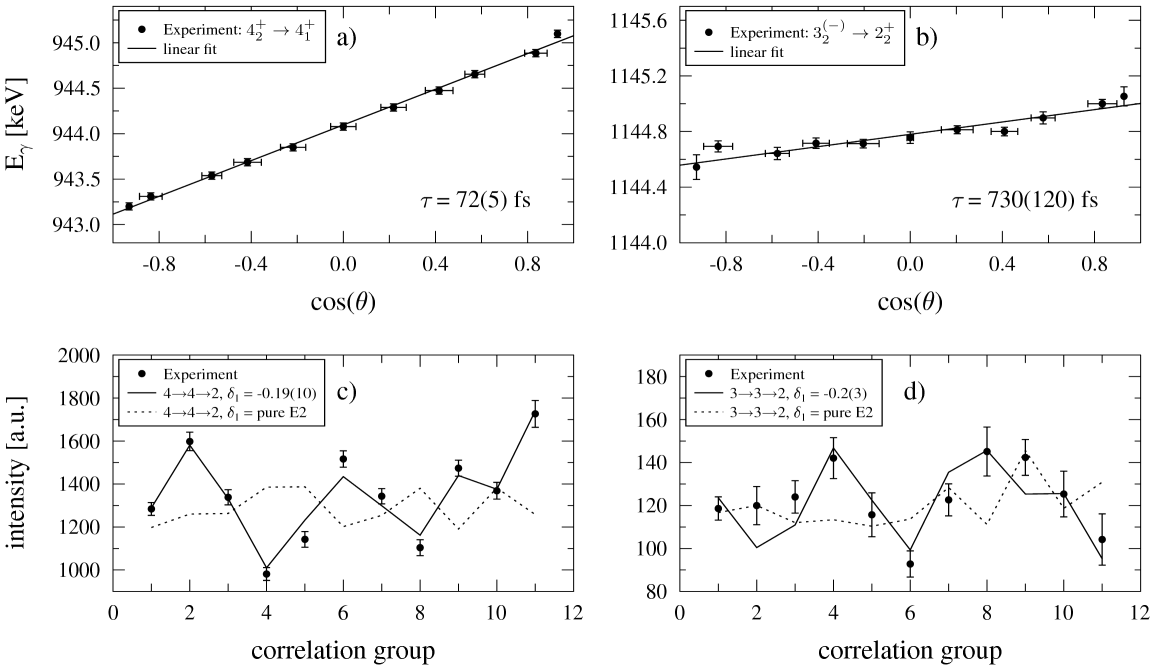

Figure 1. Experimental results for the identification of MS hexadecapole and MS octupole states. The upper panel shows the centroid shifts for γ-rays deexciting the 4^+_2 (a) and $3^{(-)}_2$ states (b) as a function of cos(θ). θ is the angle between the direction of the γ-ray emission and the direction of motion of the recoil nucleus. The lifetimes were extracted from the slope of a fit with a first order polynomial. The lower panel shows the extraction of multipole mixing ratios for the de-excitations of the MS hexadecapole (c) and MS octupole (d) candidates to their symmetric counterparts. Both transitions are of predominant $M1$ character (solid lines). Assuming a pure $E2$ character, the experimental data cannot be described at all.

which was equipped with 14 HPGe detectors for the detection of the de-exciting γ-rays.

Applying the DSAM technique to pγ coincidence data yields several advantages. Since the energy and the direction of the scattered particles are known, the velocity and the direction of the ^{96}Ru recoil nucleus can be calculated. Hence, the angle between the direction of the γ-ray emission and the direction of motion of the recoil nucleus can be extracted on an event-by-event basis. Furthermore, the centroid shift of the peaks in the γ-ray spectra can be determined from proton-gated spectra so that feeding from higher-lying states is eliminated. The slowing-down process of the ^{96}Ru recoil nuclei in the target and stopper material was modeled by means of the Monte-Carlo simulation program DSTOP96 [19] which is based on the code DESASTOP [21]. In total, the lifetimes of 30 excited states have been obtained, 24 of them for the first time. In the case of already existing lifetime data, our results are in excellent agreement with the previously measured ones [22, 23, 24].

3. Experimental results for mixed symmetry octupole and hexadecapole states

The experimental results for the identification of mixed-symmetry octupole and hexadecapole candidates are shown in Figure 1. The upper panel shows the centroid shift for de-exciting γ-rays of the 4^+_2 and $3^{(-)}_2$ states. Level lifetimes of $\tau = 72(5)$ fs and $\tau = 730(120)$ fs are obtained, respectively. In the lower panel, the results of the $\gamma\gamma$ angular-correlations are shown, from which the $E2/M1$ multipole mixing ratios are obtained. For the transitions to their symmetric counterparts, a dominant $M1$ character is deduced.

As pointed out in Sec. 1, a strong $M1$ transition to the symmetric octupole state along with an $E1$ transition to the symmetric one-phonon quadrupole state is predicted for the mixed-symmetry octupole state in the $U_{\pi\nu}(1) \otimes U_{\pi\nu}(5) \otimes U_{\pi\nu}(7)$ dynamical-symmetry limit of the *sdf*-IBM-2 [9]. In ^{96}Ru, the $3_2^{(-)}$ state is found at an excitation energy of $E_x = 3077$ keV, which is close to the excitation energies of the MS octupole states in ^{92}Zr (3040 keV) and ^{94}Mo (3011 keV) [10]. A sizeable $M1$ transition strength of $B(M1; 3_2^{(-)} \to 3_1^-) = 0.14(4)\ \mu_N^2$ is observed for the decay to the symmetric octupole state. Therefore, the $3_2^{(-)}$ state is a likely candidate for the one-phonon MS octupole state in ^{96}Ru. As for ^{94}Mo, a strong $E1$ transition with a strength of $B(E1) = 0.14(3)$ mW.u. is obtained for the decay to the $2^+_{\rm ms}$ state. However, only a weak $E1$ decay with a strength of 0.0017(4) mW.u. is observed for the $3_2^{(-)} \to 2_1^+$ transition.

The 4_2^+ state is located at an excitation energy of $E_x = 2462$ keV. The newly observed γ-decay to the 2_1^+ state indicates a positive parity for this state. A strong $M1$ transition with a reduced transition strength of $B(M1; 4_2^+ \to 4_1^+) = 0.90(18)\ \mu_N^2$ is observed along with an $E2$ transition to the 2_1^+ state with a strength of $B(E2; 4_2^+ \to 2_1^+) = 1.52(19)$ W.u.. The observed $M1$ strength is even stronger than the one obtained for the $2^+_{\rm ms} \to 2^+_{\rm s}$ transition [22] and comparable to the $4_2^+ \to 4_1^+$ transition in ^{94}Mo [25]. Thus, the 4_2^+ state is a likely candidate to contain one-phonon hexadecapole MS contributions.

4. *sdg*-IBM-2 calculations

In order to investigate possible one-phonon symmetric and mixed-symmetric hexadecapole contributions in the 4_1^+ and 4_2^+ states, calculations in the framework of the *sdg*-IBM-2 have been performed. Recently, Casperson *et al.* were able to reproduce the strong $M1$ transition between the lowest-lying 4^+ states in ^{94}Mo by introducing g-boson excitations in the IBM-2 without deteriorating the description of the well established quadrupole mixed-symmetry features [11]. Motivated by this approach, we chose the same Hamiltonian for the description of ^{96}Ru:

$$\begin{aligned} \hat{H} &= c\Big((1-\zeta)(\hat{n}_{d_\pi} + \hat{n}_{d_\nu} + \alpha(\hat{n}_{g_\pi} + \hat{n}_{g_\nu})) - \frac{\zeta}{4N}(\hat{Q}_\pi + \hat{Q}_\nu)\cdot(\hat{Q}_\pi + \hat{Q}_\nu) \\ &\quad + \lambda_{sd}\hat{M}_{sd} + \lambda_{sg}\hat{M}_{sg}\Big) \end{aligned} \quad (1)$$

with the quadrupole operator for the proton and neutron bosons:

$$\hat{Q}_\rho = [s_\rho^\dagger \tilde{d}_\rho + d_\rho^\dagger \tilde{s}_\rho]^{(2)} + \beta[d_\rho^\dagger \tilde{g}_\rho + g_\rho^\dagger \tilde{d}_\rho]^{(2)} + \chi_d[d_\rho^\dagger \tilde{d}_\rho]^{(2)} + \chi_g[g_\rho^\dagger \tilde{g}_\rho]^{(2)} \quad (2)$$

with $\rho = \pi, \nu$. For details on the Hamiltonian and the transition operators, see Ref. [11]. The calculations were carried out with the program ArbModel [26]. The number of valence bosons ($N_\pi = 3$ and $N_\nu = 1$) were taken with respect to the doubly-magic nucleus ^{100}Sn. To reduce the number of free parameters, the proton g-factors g_{d_π} and g_{g_π} were chosen to be equal and the neutron effective charges and g-factors as well as the parameters χ_d and χ_g were set equal to zero. The remaining five parameters of the Hamiltonian were fitted to describe the energy of the 2_1^+ state, the $R_{4/2}$ ratio, the $B(E2; 4_1^+ \to 2_1^+)/B(E2; 2_1^+ \to 0_1^+)$ ratio, the energy of the 2_3^+ state, which is the one-phonon quadrupole MSS in ^{96}Ru, and the $B(M1; 4_2^+ \to 4_1^+)/B(M1; 2_3^+ \to 2_1^+)$ ratio. The proton effective charges and g-factors were fixed to reproduce the $B(E2; 2_1^+ \to 0_1^+)$ and $B(M1; 2_3^+ \to 2_1^+)$ strengths, respectively.

The results of the calculation in comparison to the experimental data are compiled in Table 1. The calculated level energies as well as the transition strengths are found in excellent agreement with the data. In particular, the strong $M1$ transition between the lowest-lying 4^+ states is reproduced by the IBM. The predicted value of 1.13 μ_N^2 is close to the experimental value of

Table 1. Results of the *sdg*-IBM-2 calculations in comparison to the data. The experimental and calculated level energies (columns 3 and 4) are given in units of MeV. Columns 5, 6, and 7 show the calculated *s*-, *d*-, and *g*-boson contents in the IBM wave functions. In the last columns, the reduced transition strengths are shown. $M1$ strengths are quoted in units of μ_N^2, $E2$, and $E4$ strengths are given in units of W.u., respectively. The calculated F-spin quantum number is quoted in column 2 as well. An F-spin quantum number of 2 corresponds to maximum F-spin.

		Energies		Boson numbers			Transition strengths			
Level	F	E_{exp}	E_{IBM}	$\langle n_s\rangle$	$\langle n_d\rangle$	$\langle n_g\rangle$	$J_i^\pi \to J_f^\pi$	$\pi\lambda$	$B(\pi\lambda)_{\text{exp}}$	$B(\pi\lambda)_{\text{IBM}}$
0_1^+	2	0.000	0.000	3.4	0.3	0.0	-	-	-	-
1_1^+	1	3.154	2.944	1.7	1.8	0.5	$1_1^+ \to 0_1^+$	$M1$	0.17(5)	0.13
2_1^+	2	0.832	0.832	2.6	1.3	0.1	$2_1^+ \to 0_1^+$	$E2$	18.1(5)	18.4
2_2^+	2	1.932	2.165	1.8	2.0	0.2	$2_2^+ \to 2_1^+$	$M1$	0.05(2)	0
							$2_2^+ \to 2_1^+$	$E2$	28(9)	24
2_3^+	1	2.283	2.322	2.5	1.2	0.3	$2_3^+ \to 2_1^+$	$M1$	0.69(14)	0.69
							$2_3^+ \to 0_1^+$	$E2$	1.36(19)	2.53
4_1^+	2	1.518	1.523	2.3	1.2	0.6	$4_1^+ \to 2_1^+$	$E2$	22.6(17)	25.6
							$4_1^+ \to 0_1^+$	$E4$	-	1.09
4_2^+	1	2.462	2.482	2.6	0.5	0.9	$4_2^+ \to 4_1^+$	$M1$	0.90(18)	1.13
							$4_2^+ \to 2_1^+$	$E2$	1.52(19)	1.44
							$4_2^+ \to 0_1^+$	$E4$	-	0.55

0.90(18) μ_N^2. In addition to the strong $M1$ transition, significant g-boson contributions are predicted for the 4_1^+ and 4_2^+ states. They are considerably enhanced compared to, e.g., the g-boson content of the 2_2^+ state, which is known to be the 2^+ member of the $(2_s^+ \otimes 2_s^+)$ two-phonon triplet [27]. The one-phonon hexadecapole admixture is furthermore reflected by the $E4$ transition strengths of the $4_{1,2}^+$ states to the ground-state. The $E4$ transition operator was defined in the same way as in Ref. [11]:

$$\hat{T}(E4) = e_{\pi 1}\left[s_\pi^\dagger \tilde{g}_\pi + g_\pi^\dagger \tilde{s}_\pi\right]^{(4)}. \tag{3}$$

Since no experimental $B(E4)$ values are known for ^{96}Ru, the parameter $e_{\pi 1}$ in Eq. (3) was arbitrarily set to 1 W.u.. Therefore, only relative $E4$ strengths can be compared in Table 1 unless experimental values for the $E4$ strengths become available, which may be accessible, e.g., in electron-scattering experiments. Table 1 also shows the calculated F-spin quantum numbers for excited states in ^{96}Ru. A mixed-symmetry character can be assigned to the 2_3^+ and the 1_1^+ state, which correspond to the one- and two-phonon quadrupole mixed-symmetry states, respectively [22, 23]. In addition, a mixed-symmetry character is also predicted for the 4_2^+ state. Thus, the IBM-2 calculations support the interpretation of the 4_1^+ and 4_2^+ states to show symmetric and mixed-symmetric one-phonon hexadecapole admixtures in their wave functions.

5. Summary

Mixed-symmetry states of octupole and hexadecapole character have been studied in two inelastic proton-scattering experiments. The 3_2^- and 4_2^+ states are likely candidates to show one-phonon mixed-symmetry octupole and hexadecapole contributions, based on strong $M1$ transitions to their symmetric counterparts. Calculations in the framework of the *sdg*-IBM-2 give further evidence for one-phonon hexadecapole components of symmetric and mixed-symmetric character in the 4_1^+ and 4_2^+ states, respectively.

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