Mixed-symmetry octupole and hexadecapole excitations in the $N = 52$ isotones

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(Dated: February 24, 2015)

Background: Experiments with mixed proton-neutron symmetry have been previously observed in the $N = 52$ isotones. Besides the well-established quadrupole mixed-symmetry states (MSS), octupole and hexadecapole MSS have been recently proposed for the nuclei $^{92,94}$Zr and $^{94}$Mo.

Purpose: The heaviest stable $N = 52$ isotope $^{96}$Ru was investigated to study the evolution of octupole and hexadecapole MSS with increasing proton number.

Methods: Two inelastic proton-scattering experiments on $^{96}$Ru were performed to extract branching ratios, multipole mixing ratios, and level lifetimes. From the combined data, absolute transition strengths were calculated.

Results: Strong $M1$ transitions between the lowest-lying $3^-$ and $4^+$ states were observed, providing evidence for a one-phonon mixed-symmetry character of the $3^-_{2s}$ and $4^+_{2s}$ states.

Conclusions: $sdg$-IBM-2 calculations were performed for $^{96}$Ru. The results are in excellent agreement with the experimental data, pointing out a one-phonon hexadecapole mixed-symmetry character of the $4^+_{2s}$ state. The $\langle 3^- |M1|3^-_{2s}\rangle$ matrix element is found to scale with the $\langle 2^+_{2s} |M1|2^+_{ms}\rangle$ matrix element.

Introduction. Protons and neutrons are the building blocks of atomic nuclei, which feature collective excitations which are symmetric or not symmetric with respect to the proton-neutron degree of freedom [1]. Excitations resulting from the antisymmetric coupling of proton and neutron eigenstates are usually referred to as mixed-symmetry states (MSS), whereas the symmetric coupling results in fully-symmetric states (FSS) [2].

Mixed-symmetry quadrupole excitations are predicted within the $sd$ proton-neutron version of the interacting boson model ($sd$-IBM-2) [3,4], where $s$- and $d$-bosons are obtained by coupling protons and neutrons to pairs with angular momentum $L = 0$ and $L = 2$, respectively. In the IBM-2, MSS and FSS can be distinguished by their $F$-spin quantum number [4,5], which is the bosonic analog of isospin for fermions. Strong $F$-vector ($\Delta F = 1$) M1 transitions from MSS to their symmetric counterparts are predicted by the model. In the IBM-1, where proton and neutron bosons are not distinguished, M1 transitions with a one-body M1 transition operator are forbidden. Thus, M1 transitions serve as a key signature for MSS [7,8].

Recently, the strong $M1$ transition between the lowest-lying $4^+$ states of $^{94}$Mo was successfully reproduced within the $sdg$-IBM-2 without abandoning the description of quadrupole MSS [20], suggesting the strong $M1$ transition to result from MS and FS one-phonon hexadecapole components in the $4^+_{2s}$ and $4^+_{1s}$ states, respec-
tively. Additional evidence for this interpretation is provided by shell-model calculations for $^{92}$Zr and $^{94}$Mo \cite{12 13 22}, indicating dominant $\nu = 2, j = 4$ configurations for the lowest-lying $4^+$ states. These are by definition identified with $g$-bosons in the IBM; here, $\nu$ denotes the seniority.

The study in Ref. \cite{20} was based on the only experimentally known case at that time. The intention of the present work is to show, that the case of $^{94}$Mo is not exceptional, but that the presence of hexadecapole components in the wave functions of low-lying $4^+$ states in near-spherical nuclei is a general phenomenon. For this purpose, we have studied the heaviest stable $N = 52$ isotope $^{96}$Ru in two proton-scattering experiments. In addition, the structure of the low-lying $4^+$ states was investigated in the framework of $sdg$-IBM-2 calculations. Details on the experimental aspects will be given in a more extensive article.

Experiments. To identify MSS based on absolute transition strength, two inelastic proton scattering experiments were performed. The first one at the Wright Nuclear Structure Laboratory (WNSL) at Yale University, USA, the second one at the Institute for Nuclear Physics at the University of Cologne, Germany.

In the former, an 8.4 MeV proton beam, provided by the ESTU Tandem Accelerator, impinged on a 106 $\mu g/cm^2$ enriched $^{96}$Ru target, supported by a $^{12}$C backing with a thickness of 14 $\mu g/cm^2$. The scattered protons were detected using five silicon surface-barrier detectors, positioned predominantly at backward angles. For the $\gamma$-ray detection, eight BGO-shielded Clover-type HPGe detectors of the YRAST Ball spectrometer \cite{24} were used. Further information on the experimental setup can be found in Ref. \cite{24}. From the energy information of scattered protons, the excitation energy $E_x$ was deduced on an event-by-event basis. Thus, $\gamma$-decay branching ratios were extracted with high sensitivity from the acquired $p\gamma$ coincidence data by gating on a specific excitation energy \cite{25}. Spin quantum numbers and multipole mixing ratios were obtained by means of the $\gamma \gamma$ angular-correlation technique \cite{26}.

For the extraction of level lifetimes, a second proton-scattering experiment was performed at the Institute for Nuclear Physics at the University of Cologne. The same target was bombarded with a 7.0 MeV proton beam, provided by the 10 MV FN Tandem accelerator. For the coincident detection of the scattered protons and de-exciting $\gamma$-rays, the particle-detector array SONIC, equipped with six passivated implanted planar silicon (PIPS) detectors, was embedded within the $\gamma$-ray spectrometer HORUS. Nuclear level lifetimes were measured by means of the Doppler-shift attenuation method (DSAM) \cite{27, 28} using $p\gamma$ coincidence data \cite{29}. Peak centroids were extracted from $\gamma$-ray spectra that were gated on the excitation energy of the level of interest. This way, feeding from higher-lying states is eliminated. The stopping process of the recoil nuclei in the target and stopper material was modeled by means of a Monte-Carlo simulation \cite{30} using the computer code DSTOP96 \cite{28} which is based on the code DESASTOP \cite{31}. More detailed information on the experimental technique and the data analysis will be the subject of an upcoming publication. Absolute transition strengths were finally calculated from the combined experimental data of both experiments.

Mixed-symmetry octupole excitations. For the $J = 3$ state of $^{96}$Ru at 3076 keV, a negative parity has been previously assigned based on the observation of a $\gamma$ decay to the $5^-$ state at 2588 keV \cite{32}. As in \cite{13}, this $\gamma$ decay was not confirmed in the present experiments. However, since the $3m_\pi$ candidates of $^{94}$Mo (3011 keV) and $^{92}$Zr (3040 keV) have been observed at similar excitation energies, a negative parity was assigned tentatively. With this assumption, an $M1$ transition strength of $B(M1) = 0.14(4) \mu N^2$ was obtained for the $3^2(\rightarrow) \rightarrow 3^1$ transition.

As expected for collective excitations, the $3_2^- \rightarrow 3_1^-$ $M1$ matrix element scales with the one for the $2_2^+ \rightarrow 2_1^+$ transition for several nuclei in the $A \approx 100$ mass region \cite{19}, in particular also for the $N = 52$ isotones $^{92}$Zr and $^{94}$Mo. With the bare $g$ factors ($g_\pi = 1$ and $g_\rho = 0$), a value of $\sqrt{14/5} \approx 1.67$ is predicted in the $U_{\pi\nu}(5) \otimes U_{\pi\nu}(7)$ limit of the $sdg$-IBM-2 for the ratio of the matrix elements \cite{18}. The experimental ratios are close to unity but stay rather constant \cite{19}. Only the value for $^{96}$Mo deviates from the others by a factor of 2. From our new data, we calculated a ratio of $\langle 3^-_2 ||M1||3^+_1 \rangle / \langle 2^+_2 ||M1||2^-_1 \rangle = 0.53(9)$ for $^{96}$Ru, close to the value for $^{96}$Mo. The deviation of the ratio for $^{96}$Ru compared to the values for the other $N = 52$ isotones might result from the more $O(6)$-like structure of $^{96}$Ru compared to, e.g., $^{94}$Mo (see below).

Hexadecapole excitations. For the $J = 4$ state of $^{96}$Ru at $E_x = 2462$ keV, a positive parity was assigned because of a newly observed $\gamma$-decay to the $2_1^+$ state. A lifetime of $\tau = 140^{+30}_{-40}$ fs has been previously reported for this state \cite{32}, characterized by large uncertainties in the determination of the Doppler-shift attenuation factor. From our present analysis a lifetime of $\tau = 72(5)$ fs was extracted. Figure 1 shows the centroid energy of the $E_y = 944$ keV $4_2^+ \rightarrow 4_1^+$ $\gamma$-transition as a function of $\cos(\theta)$, where $\theta$ is the angle between the initial direction of motion of the recoil nucleus and the direction of the $\gamma$-ray emission. For the transition to the $4_2^+$ state, an $M1$ transition strength of $0.90(18)$ $\mu N^2$ was derived, which is even stronger than the $M1$ strength of the $2_2^+ \rightarrow 2_1^+$ transition \cite{11}. The $M1$ strength between the lowest-lying $4^+$ states of $^{94}$Mo is of comparable size \cite{13}. Hence, the $4_2^+$ state is a likely candidate to show one-phonon hexadecapole MS contri-
symmetry features. Motivated by this work, we chose the description of the well established quadrupole mixed-

TABLE I. sdg-IBM-2 parameters obtained from the parameter scan for $^{96}$Ru compared with the parameters obtained for 94Mo [20]. $e_{B_r}$ is quoted in units of $\sqrt{W \pi}$. $g_{p,\pi}$ is quoted in units of $\mu_N$. See also [20] for details.

| Parameter | $^{96}$Ru | $^{94}$Mo |
|-----------|-----------|-----------|
| $c$       | 5.58      | 3.53      |
| $\zeta$   | 0.78      | 0.64      |
| $\alpha$  | 1.1       | 1.4       |
| $\beta$   | 1.5       | 1.86      |
| $\lambda_{sd}$ | 0.026 | 0.05 |
| $\lambda_{sg}$ | 0.018 | 0.016 |
| $e_{B_r}$ | 2.26      | 1.83      |
| $g_{\pi}$ | 1.34      | 1.44      |

with respect to $^{100}$Sn as inert core, resulting in $N_\pi = 3$ and $N_\nu = 1$.

To reduce the number of parameters, the proton $g$-factors $g_{d_\pi}$ and $g_{g_\pi}$ were set equal and the neutron effective charges $e_{B_\pi}$ and $g$ factors $g_{d_\nu}$ and $g_{g_\nu}$ were set to zero, as were the parameters $\chi_{d_\pi}$ and $\chi_{g_\pi}$. To fix the remaining five free parameters of the Hamiltonian, a parameter scan was performed to optimize the calculation to reproduce the energy of the $2^+_1$ state, the $R_{2/1}$ ratio, the $B(E2; 4^+_1 \rightarrow 2^+_1)/B(E2; 2^+_1 \rightarrow 0^+_1)$ ratio, the energy of the known one-phonon quadrupole MSS, which is the $2^+_1$ state of $^{96}$Ru [11], and the $B(M1; 4^+_1 \rightarrow 2^+_1)/B(M1; 2^+_1 \rightarrow 2^+_1)$ ratio.

The effective charges $e_{B_\pi}$ set the scale for $E2$ transitions and were fixed to reproduce the $B(E2; 2^+_1 \rightarrow 0^+_1)$ value. The $g$ factor $g_\pi = g_{d_\pi} = g_{g_\pi}$ was fixed to describe the $B(M1; 2^+_1 \rightarrow 2^+_1)$ value. The obtained parameters are quoted in Table I and are similar to those obtained for 94Mo [20]. The larger value of $\zeta = 0.78$ for $^{96}$Ru indicates a more $O(6)$-like structure compared to 94Mo. Only little difference is found for the excitation energies of the $d$ and $g$ bosons for $^{96}$Ru, governed by the parameter $\alpha$.

The sdg-IBM-2 with the chosen Hamiltonian and parameters is a simplified approach. A more sophisticated description has to include for example non-vanishing parameters $\chi_{d,\nu}^\rho$ to allow $SU(3)$ contributions. However, the choice of $\chi_{d,\nu}^\rho \neq \chi_{d,\nu}^\rho$ would result in a breaking of $F$-spin symmetry, which was avoided to maintain a clear distinction between MSS and FSS. In addition, the chosen Hamiltonian conserves $d$-parity [34].

The calculated level scheme is in good agreement with the data, as shown in Fig. 2. In particular, the excitation energies of the $4^+_1 \rightarrow 2^+_1$ states are well reproduced. Only for the excitation energies of the $2^+_1$ and $2^+_2$ states significant deviations from the experimental values were obtained.

The experimental and calculated level energies as well as the $M1$ and $E2$ transition strengths are compiled in Table I. As for the level scheme, the transition strengths are in overall agreement. Only the transitions depopulating the $3^+_2$ states are predicted too strong by about one
order of magnitude. For transitions which are forbidden for the applied Hamiltonian, only small transition strengths are observed experimentally. Of particular interest for the investigation of hexadecapole components in the $4^{-}_{1,2}$ states is the $4^{-}_{2} \rightarrow 4^{-}_{1}$ M1 transition. The IBM predicts a transition strength of 1.13 $\mu^2_N$ which is close to the experimental value of 0.90(18) $\mu^2_N$. No other $4^+$ state is found to show enhanced M1 transitions to the $4^+_{1}$ state in the calculations. Also the $4^+_{2} \rightarrow 2^+_{1}$ E2 transition strength is reproduced by the model. The predicted E2 branching with sizable strength of 10.5 W.u. to the $2^+_3$ state is way below the experimental sensitivity limit.

The predicted $F$-spin quantum numbers are shown in Table I as well. $F$-spin quantum numbers of $F_{\text{max}} - 1$ are obtained for the $2^+_3$, $1^+_2$, $3^+_2$, and $4^+_2$ states. From their decay properties, the $2^+_3$ state and the $1^+_2$ and $3^+_2$ states can be identified as the experimentally known one- and two-phonon quadrupole MSS, respectively [11,13]. They will be discussed in an upcoming publication. A mixed-symmetry character is also predicted for the $4^+_2$ state. A variation of the strength parameters $\lambda_{sd}$ and $\lambda_{sg}$ revealed, that the $4^+_2$ state is most sensitive to the $\tilde{M}_{sg}$ operator. Thus a one-phonon mixed-symmetry hexadecapole character is obtained for the $4^+_2$ state. In contrast, a fully-symmetric character is predicted for the $4^+_{1}$ state based on the calculated $F$-spin quantum number.

To quantify the amount of M1 strength of the $4^+_{2} \rightarrow 4^+_{1}$ transition related to the $g$- and $d$-boson parts of the M1 operator, the $\langle 4^+_{1} | M_1 | 4^+_{2} \rangle$ matrix element was recalculated with the values $g_d = 0$ and $g_g = 0$, respectively. The respective other value was kept at the value obtained from the parameter scan. With a contribution of 83% the $\langle 4^+_{1} | M_1 | 4^+_{2} \rangle$ matrix element is dominated by the $g$-boson part of the M1 operator, while only 17% is related to the $d$-boson part.

The $d$- and $g$-boson contents of the low-lying, positive-
state. However, a similar $E^+$ strength is enhanced compared to, e.g., that of the $4^+$ state. For the chosen parameter of $\frac{\sqrt{8}}{3}$ strength low-spin states are shown in Fig. 3. With a value of 23%, the largest $g$-boson content is obtained for the $4^+_2$ state, supporting the one-phonon hexadecapole assignment. A similar $g$-boson contribution is predicted for the $3^+_2$ state. This can be explained assuming a dominant $(g'd^3)^{(3)}$ structure. In this case the $E2$ transition to the $2^+_1$ state would be forbidden by $d$-parity selection rules. This is supported by the calculation and is in remarkable agreement with the data (see Table II). Also for the $4^+_1$ state a large $g$-boson content is obtained which is considerably enhanced compared to, e.g., the $2^+_2$ state, which is known to be the $2^+$ member of the $(2^+_2 \otimes 2^+_2)$ triplet. In addition to the $g$-boson content, a $d$-boson contribution of about 30% is predicted by the IBM for the $4^+_1$ state. For the chosen parameter of $\beta$, a mixing of the one-phonon $g$-boson excitation with two-phonon $d$-boson excitations is allowed, which is also different multipolarities for the nuclei $^{92,94}$Zr and $^{96}$Ru. While for the quadrupole states an increase of $M1$ strength is observed with increasing proton number, the $M1$ strength decreases from $^{94}$Mo to $^{96}$Ru for higher multipolarities. It has to be mentioned, that the decrease might be related to a possible fragmentation of the one-phonon octupole and hexadecapole mixed-symmetry states which can not be excluded on the basis of the present experimental data.

The trend for the quadrupole states agrees with shell-model calculations, predicting a maximum $M1$ strength for $^{96}$Ru, based on the concept of configuration isospin polarization (CIP) [33]. Unfortunately, no results on $4^+$ states were reported in Ref. [33]. The decrease of the $M1$ strengths for the $4^+$ states with increasing proton number is not reproduced by the IBM, which predicts a parity low-spin states are shown in Fig. 3. With a value of 23%, the largest $g$-boson content is obtained for the $4^+_2$ state, supporting the one-phonon hexadecapole assignment. A similar $g$-boson contribution is predicted for the $3^+_2$ state. This can be explained assuming a dominant $(g'd^3)^{(3)}$ structure. In this case the $E2$ transition to the $2^+_1$ state would be forbidden by $d$-parity selection rules. This is supported by the calculation and is in remarkable agreement with the data (see Table II). Also for the $4^+_1$ state a large $g$-boson content is obtained which is considerably enhanced compared to, e.g., the $2^+_2$ state, which is known to be the $2^+$ member of the $(2^+_2 \otimes 2^+_2)$ triplet. In addition to the $g$-boson content, a $d$-boson contribution of about 30% is predicted by the IBM for the $4^+_1$ state. For the chosen parameter of $\beta$, a mixing of the one-phonon $g$-boson excitation with two-phonon $d$-boson excitations is allowed, which is also different multipolarities for the nuclei $^{92,94}$Zr and $^{96}$Ru. While for the quadrupole states an increase of $M1$ strength is observed with increasing proton number, the $M1$ strength decreases from $^{94}$Mo to $^{96}$Ru for higher multipolarities. It has to be mentioned, that the decrease might be related to a possible fragmentation of the one-phonon octupole and hexadecapole mixed-symmetry states which can not be excluded on the basis of the present experimental data.

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similar trend as for the quadrupole states.

Summary. The observation of strong M1 transitions in $^{96}$Ru between the lowest-lying 3$^-$ and 4$^+$ states provides experimental evidence for one-phonon mixed-symmetry octupole and hexadecapole components in the wavefunctions of the 3$^-$ and 4$^+$ states, respectively. The interpretation on the latter is supported by sdg-IBM-2 calculations. Together with the results of Ref. [20], the new data on $^{96}$Ru suggest that the presence of hexadecapole components in the wave functions of low-lying 4$^+$ states is a general phenomenon in near spherical nuclei.

Acknowledgments. The authors thank R. Casperson and S. Heinz for support with the IBM calculations and A. Poves for useful discussions. Furthermore, we highly acknowledge the support of the accelerator staff at WNSL, Yale and IKP, Cologne during the beam times. This work is supported by the DFG under grant No. ZI 510/4-2 and grant No. SFB 634, the U.S. Department of Energy grant No. DE-FG02-01ER40609, and the BMBF grant No. 05P12RDFN8. P.P. is grateful for the financial support of the Bulgarian Science Fund under contract DFNI-E 01/2. D.R. and D.S. acknowledge the German Academic Exchange Service (DAAD) for financial support. S.G.P. and M.S. are supported by the Bonn-Cologne Graduate School of Physics and Astronomy.

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