Nuclear structure of $^{96,98}\text{Mo}$: shape coexistence and mixed-symmetry states

T. Thomas^{a,b,*}, V. Werner^{b,c}, J. Jolie^a, K. Nomura^{d,e}, T. Ahn^{b,f},
N. Cooper^b, H. Duckwitz^a, A. Fitzler^a, C. Fransen^a, A. Gade^{a,**},
M. Hinton^b, G. Ilie^b, K. Jessen^{a,* * *}, A. Linnemann^a, P. Petkov^{a,g,h},
N. Pietralla^c, D. Radeck^{a,* * * *}

^a*Institute for Nuclear Physics, University of Cologne, Zùlpicher StraÙe 77, D-50937 Kùln, Germany*

^b*WNSL, Yale University, P.O. Box 208120, New Haven, CT 06520-8120, USA*

^c*Institut für Kernphysik, TU Darmstadt, SchlossgartenstraÙe 9, 64289 Darmstadt, Germany*

^d*Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DSM-CNRS/IN2P3, Bd Henri Becquerel, BP 55027, F-14076 Caen Cedex 5, France*

^e*Physics Department, Faculty of Science, University of Zagreb, HR-10000 Zagreb, Croatia*

^f*Physics Department, University of Notre Dame, Notre Dame, IN 46556, USA*

^g*Bulgarian Academy of Science, Institute for Nuclear Research and Nuclear Energy, Tsarigradsko Chausse 72, 1784 Sofia, Bulgaria*

^h*Horia Hulubei - National Institute for Physics and Nuclear Engineering (IFIN-HH), RO-077125 Bucharest, Romania*

Abstract

Excited low-spin states in ^{96}Mo and ^{98}Mo have been studied in $\gamma\gamma$ angular correlation experiments in order to determine spins and multipole mixing ratios. Furthermore, from a Doppler lineshape analysis effective lifetimes τ in the femtosecond range were obtained. The experimental data show a complex spectrum due to configuration mixing, which is confirmed by Interacting Boson Model calculations based on a Skyrme energy density functional. The $M1$ -transition strengths of transitions depopulating excited 2^+ states to the first 2^+ state are discussed in terms of the proton-neutron mixed symmetry.

Key words: NUCLEAR REACTIONS $^{96}\text{Zr}(^3\text{He},3n)$, $E=18$ MeV; $^{96}\text{Zr}(\alpha,2n)$, $E=16$ MeV; measured E_γ , I_γ , $\gamma\gamma$ -coin, $\gamma(\theta)$ using OSIRIS and YRAST Ball spectrometer. ^{96}Mo , ^{98}Mo ; deduced levels, J , π , branching and mixing ratios, $B(E2)$ values. Interacting Boson Model, Skyrme energy density functional.

1. Introduction

The molybdenum isotopes have recently been a focus of nuclear structure research [1,2]. The challenge is to describe both, so-called mixed-symmetry states (MSSs) as found in $^{94,96}\text{Mo}$ [3–5] and shape coexistence in ^{98}Mo within a state-of-the-art nuclear structure model.

The mixed-symmetry states, including the scissors mode [6,7], as well as other phenomena of isovector-type such as giant dipole resonances [8] or pygmy resonances [9], involve the collective motion of neutrons against protons which essentially depend on the strength of the fundamental proton-neutron interaction. However, mixed-symmetry states are valence excitations and therefore observed at low energies usually similar to or lower than needed to break a proton or neutron pair. The Proton-Neutron Interacting Boson Model (denoted as IBM-2) [10,11] can describe the out-of-phase vibrations of valence neutrons and protons well. In that framework one can introduce the so-called F -spin in analogy to isospin, which is applied for proton and neutron bosons instead of particles. Hereby, the fully symmetric states are states with $F = F_{max} = (N_\pi + N_\nu)/2$, where N_π and N_ν are the numbers of proton and neutron bosons, respectively. The considered mixed-symmetry states are associated with the F -spin quantum number $F = F_{max} - 1$. A comprehensive review on the studies of F -spin in vibrational nuclei is given in Ref. [12].

Shape coexistence is associated with two or more configurations exhibiting distinguishable nuclear shapes and formed by the pure normal valence configuration and the normal $2p-2h$ (intruder) configuration [13,14]. In the $A=100$ mass region, several nuclei are known which have been discussed in the framework of shape coexistence [15–18]. In Ref. [1], evidence for two strongly mixed configurations was revealed for ^{98}Mo . In that case, the normal $2p-0h$ proton configuration is linked to a rather $U(5)$ vibrational structure and the intruder $4p-2h$ configuration constructed from excitation across the $Z=40$ sub-shell closure and resembles an $O(6)$ γ -soft structure. The level scheme was described by IBM-2 calculations based on a mean-field energy surface calculation with the Skyrme energy density functional [1]. The description of ^{98}Mo in the framework of shape coexistence is supported by two-proton separation energies of even-even nuclei in the $A = 100$ region. In fig. 1 the evolution of the two-proton separation energies for isotonic chains are shown. To specifically show the changes of two-proton separation energy in an isotonic chain, the energies are subtracted from the linear function $f(Z) = (65000 - 1200 * Z)$ MeV. Hereby the slope approximately reproduces the evolution of the $N = 52$ isotones for $Z \geq 40$. This way the drop of the separation energy due to sub-shell closures at $Z=38$ and $Z=40$ is observed. For ^{98}Mo and ^{100}Mo another drop of the normalized separation energy is observed and hints to coexisting shapes [14]. For ^{96}Mo the drop of the two-proton separation energy is not as significant, but might also be attributed to the effect of coexisting shapes.

* Corresponding author

** Present address: National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824 Michigan, USA

*** Present address: Physics Laboratory Courses, Ludwig-Maximilians-Universität München, Edmund-Rumpler-Straße 9, D-80939 München, Germany

**** Present address: PTB, Braunschweig, Germany

Fig. 1. (Color online) Normalized two-proton separation energies for isotonic chains in the $A = 100$ mass region normalized to the slope of the isotonic $N = 52$ chain. For more information see text.

In this article, we present the full evaluation of data on the $^{96,98}\text{Mo}$ isotopes, which was partially reported in [1] for ^{98}Mo but which includes new data from an in-beam experiment on ^{96}Mo .

The result is compared to schematic calculations employing configuration mixing and calculations using a single IBM-2 configuration with parameters based on a microscopic energy surface. Finally, we investigate the effect of shape coexistence on the signatures for mixed-symmetry states in $^{96,98}\text{Mo}$, i.e. strong $2_{ms}^+ \rightarrow 2_1^+$ M1 transitions.

2. Experimental results

To excite low-lying states in ^{96}Mo , an in-beam experiment was performed at the FN-Tandem accelerator of the Institute of Nuclear Physics, University of Cologne. The $(^3\text{He}, 3n)$ reaction was carried out at a beam energy of 18 MeV with 8 mg/cm² ^{96}Zr target enriched to a purity of 96%. For the detection of γ rays the OSIRIS-9 [19] cube spectrometer, equipped with nine HPGe-detectors in this experiment, six of which had additional Compton suppression shields, was used. During one week of measurement around 1.5 billion coincident $\gamma\gamma$ events were collected using 14-bit ADCs. Figure 2 shows a total projection of the $\gamma\gamma$ coincidence matrix, where the strongest lines in the spectrum belong to ^{96}Mo and states with spins $J \geq 8$ are weakly populated.

Another in-beam experiment was performed at the ESTU-Tandem accelerator at Wright Nuclear Structure Laboratory at Yale University to investigate the neighboring ^{98}Mo . Using an α beam accelerated to an energy of 16 MeV and a 1.25 mg/cm² thick ^{96}Zr target enriched to 57.36%, γ transitions emitted after the $(\alpha, 2n)$ reaction were detected by 10 Compton-suppressed Clover detectors mounted in the YRAST Ball array [20], and data was recorded using 12-bit ADCs. A more detailed discussion of this experiment and partial results are published in Ref. [1]. In the present work, the complete results of ^{98}Mo

Fig. 2. Total projection of the $\gamma\gamma$ coincidence data (up to 2000 keV) of the ^{96}Mo experiment. The strongest γ lines are observed at around 800 keV and belong to Yrast band transitions of ^{96}Mo .

will be discussed.

An important objective of these experiments was to measure multipole mixing ratios of decay transitions. Especially suited for this purpose are $\gamma\gamma$ angular correlations in in-beam experiments. For a $J_1 \xrightarrow{E_A, \delta_A} J_2 \xrightarrow{E_B, \delta_B} J_3$ cascade, as described in Refs. [21,22], different hypotheses for multipole mixing ratios δ and spin assignments can be tested. In order to perform a $\gamma\gamma$ angular correlation analysis, the data is sorted in correlation group matrices, which account for detector pairs at specific angles $\Theta_{1,2}$ with respect to the beam axis and a relative angle ϕ between the planes spanned by the corresponding detectors and the beam axis. For the OSIRIS setup nine correlation groups were used, while the YRAST Ball setup provided eleven correlation groups. Since neither of the used targets were pure, the different reaction channels could be used to cross check the results of the angular correlation analyses between both experiments.

Figures 3 and 4 show the angular correlations for the 778-719 keV $\gamma\gamma$ cascade in ^{96}Mo in the OSIRIS and the YRAST Ball setup respectively, comparing two possible $E2/M1$ mixing ratios measured also in a $(n, n'\gamma)$ experiment [5]. The data from ^{96}Mo in the YRAST Ball experiment stems from a side reaction, hence, statistics are lower. Note, the smaller δ_{719} value results from a least-squares fit while $\delta_{719} = +1.1$ (1) yields a second minimum in Ref. [5]. Clearly the $\delta = +0.40$ (3) assignment from the OSIRIS experiment agrees with the $\delta = +0.42$ (10) from the YRAST Ball experiment and the weighted average is adopted in table 1. Since $E2/M1$ mixing ratio δ_{719} determines the $E2$ transition strength between the second to the first 2^+ state, it gives insight to the phonon structure of ^{96}Mo and is discussed in section 3. The fit of the spin hypotheses to data was performed with the computer code CORLEONE [23,24]. All multipole mixing ratios determined by angular correlation analysis are listed in tables 1 and 2. For more

Fig. 3. (Color online) Comparison of two hypotheses $2 \xrightarrow{719, \delta_{719}} 2 \xrightarrow{778, \delta_{778}=0} 0$ with different $E2/M1$ mixing ratios δ_{719} (black solid and green dashed line) with relative intensities obtained from nine $\gamma\gamma$ angular correlation groups at the OSIRIS setup. The $E2/M1$ mixing ratio $\delta = +0.40$ (3) obtained from a least-squares fit is favored over $\delta = +1.1$ (1), one of two minima reported in Ref. [5]. The smaller $E2/M1$ mixing ratio $+0.34^{+0.90}_{-0.70}$ reported in Ref. [5] agrees with the present values from both experiments (see also Fig. 4).

details about angular correlation analyses using the OSIRIS or YRAST Ball setups, see Refs. [19] and [1,25], respectively. Furthermore, in figures 3,4,A.1-A.8 featuring angular correlations, multipole mixing ratios are given with errors derived from a least square fit of the data from this work, otherwise the multipole mixing ratio is fixed to the given value obtained from Nuclear Data Sheets (NDS) [26,27].

The OSIRIS and the YRAST Ball experiments allowed the determination of lifetimes of excited states using the Doppler-Shift Attenuation Method (DSAM) ([28] and references therein). Although the covered solid angle of a clover detector of YRAST Ball was larger than that of a single-crystal detector of OSIRIS-9, and the resolution of the YRAST Ball ADCs was lower, line shifts were sufficient to determine lifetimes in both experiments. The incoming beam particle transfers its momentum to the compound nucleus. Then, excited nuclei recoil in the target. The recoiling nuclei are stopped while emitting γ radiation. The radiation is detected Doppler-shifted in forward and backward angles. By simulating the stopping process of the excited nucleus in the target, a determination of lifetimes in the fs range is possible. For the simulation, both the nuclear and electronic stopping power in the target and backing material were considered, as well as the beam energy, the recoil energy, the lifetime τ of the state and the angle of the detected γ ray with respect to the beam axis. For the ^{98}Mo experiment also partial recoil into vacuum due to the relatively thin target was included in the simulation. By means of a lineshape analysis, a theoretical lineshape was fitted with a least squares fit to the experimental data using the lifetime as a free fit parameter. Figures 5, 6, A.9, and A.10 show the application of line shape analyses to the data from the OSIRIS and the YRAST Ball experiments, respectively. All γ transitions were analysed in coincidence with transitions

Fig. 4. (Color online) Comparison of theoretical angular correlations of the $2_{719}^{+} \rightarrow 2_{778}^{+} \rightarrow 0$ hypothesis with relative intensities obtained from eleven correlation groups at the YRAST Ball setup for the 778-719 keV $\gamma\gamma$ coincidence. The $E2/M1$ mixing ratio $\delta = +0.42$ (10) (black solid) obtained from a least square fit is favored over $\delta = +1.1$ (1) (green dashed line) reported in Ref. [5]. For more information see Fig. 3.

below the decay of interest. Due to possible delayed side feeding, the level lifetimes can be overestimated with this method. Thus, the determined mean lifetimes, e.g., $\tau_{OSIRIS} = 0.29$ (5) ps of the $J^{\pi} = 2_4^{+}$ state at 2095 keV in ^{96}Mo and $\tau_{YRAST} = 0.25$ (5) ps of the $J^{\pi} = 2_7^{+}$ state at 2700 keV in ^{98}Mo , are effective lifetimes τ_{eff} only, hence, upper limits of the actual mean lifetimes. In fact, the comparison between the lifetime of the 2095 keV state from the present work and the one obtained in a $(n,n'\gamma)$ experiment [5], where side feeding can be excluded, provide a scale for the delay $\frac{\tau_{OSIRIS,eff}}{\tau_{[5]}}$ of ≈ 2 . This corresponds to a similar delay from unseen feeding for the neighboring ^{94}Mo which was measured in a similar setup (Ref [4]). The lifetimes of the 2095 keV state in ^{96}Mo and the 2700 keV state in ^{98}Mo are of interest especially in the context of mixed-symmetry states and is discussed in section 4.

In the following sections the complete results obtained from the $\gamma\gamma$ analyzes of both in-beam experiments, ^{96}Mo and ^{98}Mo , are given. First, some states conflicting with previous data in ^{96}Mo and ^{98}Mo are discussed, followed by tables 1 and 2 with all experimental results.

2.1. Results for ^{96}Mo :

1497.88 (9) keV, 2^{+} . In addition to the $2_2^{+} \xrightarrow{1497} 0_1^{+}$ and $2_2^{+} \xrightarrow{719} 2_1^{+}$ transitions, a $2_2^{+} \xrightarrow{349} 0_2^{+}$ would be expected at 349.9 keV. Due to multiple transitions with energies

Fig. 5. (Color online) Determination of the effective lifetime by analyzing the line shape of the 1317 keV transition depopulating a 2^+ state at 2095 keV in ^{96}Mo measured with the OSIRIS setup. Coincidence spectra with a gate set on the 778 keV transition for two different angles are shown. The black solid line represents the simulated line shape at forward (a) and backward (b) angle. The determined effective mean lifetime is $\tau = 0.29$ (5) ps.

close to 350 keV, it is not possible to confirm such a transition, thus an upper limit of the expected relative γ intensity is given.

1625.92 (9) keV, 2^+ . For the 847.68 (12) keV transition conflicting literature values of $E2/M1$ mixing ratios, $\delta(2_3^+ \xrightarrow{847} 2_1^+) = -1.05_{-10}^{+9}$, -0.6 (5), -6.9_{-21}^{+12} , exist, where the first value was measured in a (n, γ) [29] experiment and the latter two originate from Ref. [5]. Evaluation of the angular correlation of the 847-778 $\gamma\gamma$ cascade reveals a rather strong M1 admixture with $\delta_{847} = -0.12$ (5) (see Figure A.1), which agrees with the smaller $E2/M1$ mixing ratio given in Ref. [5]. In order to determine the $E2/M1$ mixing ratio, the two peaks at 847.68 (12) keV and 849.99 (9) ($4_1^+ \rightarrow 2_1^+$) keV have to be discriminated, which is impossible for NaI(Tl) detectors employed in Ref. [29] but possible in this experiment due to the superior resolution of the HPGe detectors. Figures A.1 shows that the $\delta_{847} = -0.12$ (5) assignment is clearly favored.

1978.43 (10) keV, 3^+ . The angular correlation analysis of the depopulating transition

Fig. 6. (Color online) Determination of the effective lifetime by analyzing the line shape of the 1913 keV transition depopulating a (2^+) state at 2700 keV in ^{98}Mo measured with the YRAST Ball setup. Coincidence spectra with a gate set on the 787 keV transition for two different angles are shown. The black solid line represents the simulated line shape at forward (a) and backward (b) angle. The determined effective mean lifetime is $\tau = 0.25 (5)$ ps.

at 480.55 (9) keV clearly shows that the $E2/M1$ mixing ratio $\delta_{480} = -18^{+10}_{-65}$ is favored (see Figure A.2) over the assignment of $\delta_{480} = -0.12 (4)$ reported in Ref. [5]. A rather pure E2 characteristic for the 480 keV transition is also supported by the angular correlation of the 1498-480 keV cascade. On the other hand, for the other depopulating transition to the 2^+_1 at 1200.39 (7) keV a smaller $E2/M1$ mixing with $\delta_{1200} = +0.34(4)$ was determined (see Figure A.3) than in Ref. [5].

2219.46 (9) keV, 4^+ . The branching ratios from this work for the transitions depopulating this state mostly agree with values reported in Ref. [5]. However the relative γ intensity of the 241.36 (20) keV transition seems to be overestimated in Ref. [29], which might originate from a doublet with a 241.33 keV transition depopulating a state at 1869.64 (6) keV and which cannot be distinguished in the singles spectrum used in Ref. [29]. The coincidence technique employed in this work allows to determine the branching ratio and avoids any contribution of the contaminating 241.33 keV

transition.

2594.39 (12) keV, 3^+ . The analysis of the branching ratios of the depopulating transitions yields different results than given in [5]. One reason might be that the coincidence technique together with the superior absolute efficiency of the OSIRIS setup allows a better discrimination of the 966 keV and 968 keV peaks compared to the one detector used in Ref. [5].

2818.67 (35) keV, 4^+ . The angular correlation analysis of the 1190-849 keV $\gamma\gamma$ cascade suggests a spin for the state with either $J_{2818} = 4, 5, 6$, but the spin assignment $J_{2818} = 5, 6$, assuming only dipole and quadrupole transitions, can be ruled out due to the depopulating 1320.9 (5) keV transition to the $J^\pi = 2^+$ state reported in Ref. [29].

2875.35 (12) keV, $6, 7^+$. Using the angular correlation analysis of the $J \xrightarrow{434} 6 \xrightarrow{812} 4$ cascade the spin of this state could be limited to $J = 6, 7$. The corresponding multipole mixing ratios to the spin assignment are $\delta_{434, J=6} = +0.12$ (7) and $\delta_{434, J=7} = +1.8$ (2) respectively.

3416.32 (14) keV, 5^+ . The Doppler shift observed for the 975 keV transition and the angular correlation analysis shows different decay characteristics than the depopulating transitions of the $J^\pi = 4^+$ state at 3416.82 (13) keV observed in Ref. [5]. This suggests a new state at 3416.32 keV.

Table 1: Results of this work on ^{96}Mo . States discussed in section 2.1 are labeled with a sharp sign ($\#$). Newly observed states are labeled with an asterisk ($*$) and newly observed transitions with a dagger ($\dagger$). Furthermore, γ intensities I_γ of transitions that are listed in NDS [26] but are not observed due to the sensitivity limit of the detector system or background are labeled with a dash ($-$). If a value is adopted from NDS it is labeled with a double asterisk ($**$). If a spin assignment of a state due to angular correlation analysis is not unique, those spins are labeled with a double-dagger ($\ddagger$). Lifetimes obtained in the present work are effective values, hence, upper limits for the mean lifetimes, and are marked with a superscript eff . If an angular correlation analysis is not feasible but selection rules suggest the multipole characteristic of the γ transition, the multipolarity is given in parentheses.

E_{level} (keV)	J_{initial}^π	$\tau(\text{ps})$	$E_\gamma(\text{keV})$	$I_{\gamma, \text{exp}}$	δ_{exp}	$E_{\text{final}}(\text{keV})$	J_{final}^π
0.0	0^+	stable					
778.23 (6)	2^+	5.29 (9)**	778.23 (6)	100	E2	0.0	0^+
1147.96 (10)	0^+	88 (12)**	369.73 (8)	100	E2	778.23 (6)	2^+
1497.88 (9) $\#$	2^+	1.13 (10)**	(349.9)	<2.3	(E2)	1147.96 (10)	0^+
			719.55 (7)	100	+0.40 (4)	778.23 (6)	2^+
			1497.97 (9)	39.9 (8)	E2	0.0	0^+
1625.92 (9) $\#$	2^+	$>1.30^{**}$	128.0 (4)**	<0.9		1497.88 (9)	2^+
			477.61 (25) $\dagger$	1.7 (4)	E2	1147.96 (10)	0^+
			847.68 (12)	100	-0.12 (5)	778.23 (6)	2^+

E_{level} (keV)	J_{initial}^{π}	$\tau(\text{ps})$	$E_{\gamma}(\text{keV})$	$I_{\gamma,\text{exp}}$	δ_{exp}	$E_{\text{final}}(\text{keV})$	J_{final}^{π}
			1626.00 (22)	6.4 (17)	E2	0.0	0^{+}
1628.22 (8)	4^{+}	$1.73 (29)^{**}$	849.99 (6)	100	-0.01 (2)	778.23 (6)	2^{+}
1869.64 (6)	4^{+}	$9.23^{+40}_{-22},^{**}$	241.33 (7)	9.0 (5)	$+0.5^{+1.2}_{-0.6}$	1628.22 (8)	4^{+}
			(243.6)	< 0.6		1625.92 (9)	2^{+}
			371.71 (7)	6.3 (6)	-0.05 (6)	1497.88 (9)	2^{+}
			1091.50 (6)	100	-0.03 (3)	778.23 (6)	2^{+}
1978.43 (10) [#]	3^{+}	$>3.30^{**}$	108.94 (11)	-		1869.64 (6)	4^{+}
			349.96 (8)	4.9 (2)	+0.22 (10)	1628.22 (8)	4^{+}
			352.54 (10)	4.4 (2)	$+4^{+15}_{-2}$	1625.92 (9)	2^{+}
			480.55 (9)	30.8 (4)	-18^{+10}_{-65}	1497.88 (9)	2^{+}
			1200.39 (7)	100	+0.34 (4)	778.23 (6)	2^{+}
2095.86 (11)	2^{+}	$0.29 (5)^{\text{eff}}$	(597)	<4.7		1497.88 (9)	2^{+}
			947.41 (32)	1.8 (5)	(E2)	1147.96 (10)	0^{+}
			1317.63 (9)	100	-0.01 (9)	778.23 (6)	2^{+}
			2095.59 (10) ^{**}	-	(E2)	0.0	0^{+}
2219.46 (9) [#]	4^{+}	$>0.55^{**}$	241.36 (20)	14.7 (8)		1978.43 (10)	3^{+}
			349.65 (16)	88.5 (37)	+0.09 (13)	1869.64 (6)	4^{+}
			591.21 (9)	96.7 (39)	+0.84 (23)	1628.22 (8)	4^{+}
			593.42 (18)	46.0 (35)	-0.05 (10)	1625.92 (9)	2^{+}
			721.57 (12)	100	+0.04 (5)	1497.88 (9)	2^{+}
			1441.10 (16)	43.5 (22)	+0.03 (5)	778.23 (6)	2^{+}
2234.70 (8)	3^{-}	$>0.40^{**}$	365.01 (17)	10.0 (7)	-0.10 (20)	1869.64 (6)	4^{+}
			608.70 (8)	100	-0.09 (12)	1625.92 (9)	2^{+}
			736.92 (8)	94.0 (38)	+0.03 (5)	1497.88 (9)	2^{+}
			1456.25 (9) ^{**}	-		778.23 (6)	2^{+}
2426.51 (29)	$2^{+},^{**}$	$0.27^{+6}_{-4},^{**}$	447.62 (10) ^{**}	-		1978.43 (10)	3^{+}
			800.27 (10) ^{**}	<45.2		1625.92 (9)	2^{+}
			928.25 (10) ^{**}	-		1497.88 (9)	2^{+}
			1648.00 (28)	100		778.23 (6)	2^{+}
			2426.28 (10) ^{**}	-		0.0	0^{+}

E_{level} (keV)	J_{initial}^{π}	$\tau(\text{ps})$	$E_{\gamma}(\text{keV})$	$I_{\gamma,\text{exp}}$	δ_{exp}	$E_{\text{final}}(\text{keV})$	J_{final}^{π}
2438.47 (6)	5^{+}	$>0.20^{**}$	219.05 (9)	6.4 (9)		2219.46 (9)	4^{+}
			459.91 (7)	44.4 (29)	+0.05 (13)	1978.43 (10)	3^{+}
			568.82 (6)	100	-0.15	1869.64 (6)	4^{+}
					or -3.6		
			810.18 (36)	16.3 (34)		1628.22 (8)	4^{+}
2440.80 (10)	6^{+}	$>0.30^{**}$	812.58 (6)	100	-0.02 (3)	1628.22 (8)	4^{+}
2481.28 (10)	$2,3,4^{\ddagger\ddagger}$	$>1.46^{**}$	611.30 (20)	17.1 (37)		1869.64 (6)	4^{+}
			853.09 (8)	100		1628.22 (8)	4^{+}
			983.1 (2)**	-		1497.88 (9)	2^{+}
			1703.24 (39)	33.9 (79)		778.23 (6)	2^{+}
2501.69 (23)	$1,2^{\ddagger\ddagger}$	$0.139 (19)^{**}$	875.61 (10)**	-		1625.92 (9)	2^{+}
			1003.69 (10)**	-		1497.88 (9)	2^{+}
			1353.73 (21)	100		1147.96 (10)	0^{+}
			1723.29 (10)**	-		778.23 (6)	2^{+}
			2501.84 (10)**	-		0.0	0^{+}
2540.78 (32)	$(3)^{+,**}$	$0.100 (14)^{**}$	914.53 (9)**	-		1625.92 (9)	2^{+}
			1042.62 (9)**	-		1497.88 (9)	2^{+}
			1762.55 (32)	100		778.23 (6)	2^{+}
2594.39 [#] (12)	$3^{+,**}$	$1.2_{-6}^{+62,**}$	374.9 (2)**	-		2219.46 (9)	4^{+}
			615.66 (23)	74 (13)		1978.43 (10)	3^{+}
			966.38 (31)	36.5 (69)		1628.22 (8)	4^{+}
			968.37 (19)	100		1625.92 (9)	2^{+}
			1096.31 (26)	63 (12)		1497.88 (9)	2^{+}
			1816.21 (33)	26.4 (55)		778.23 (6)	2^{+}
2625.32 (20)	4^{+}	$0.72_{-29}^{+115,**}$	405.9 (3)**	-		2219.46 (9)	4^{+}
			1847.09 (19)	100		778.23 (6)	2^{+}
2734.68 (12)	5^{+}	$>0.36^{**}$	293.9 (4)**	-		2440.80 (10)	6^{+}
			864.93 (10)	63.9 (12)	+0.05 (6)	1869.64 (6)	4^{+}
			1106.59 (7)	100	-0.02 (3)	1628.22 (8)	4^{+}
			1109.1 (5)**	-		1625.92 (9)	2^{+}

E_{level} (keV)	J_{initial}^{π}	$\tau(\text{ps})$	$E_{\gamma}(\text{keV})$	$I_{\gamma,\text{exp}}$	δ_{exp}	$E_{\text{final}}(\text{keV})$	J_{final}^{π}
2736.27 (21)	$3^{+,**}$	$0.175^{+26}_{-25},**$	1238.50 (27)	75 (10)		1497.88 (9)	2^{+}
			1957.89 (32)	100	+0.14 (25)	778.23 (6)	2^{+}
2755.31 (33)	$6^{+,**}$	$>0.280^{**}$	314.17 (9)	20.1 (8)	+0.19 (14)	2440.80 (10)	6^{+}
			316.52 (19)	14.0 (7)		2438.47 (6)	5^{+}
			535.78 (8)**	-		2438.47 (6)	5^{+}
			885.4 (2)**	-		1869.64 (6)	4^{+}
			1127.09 (7)	100	-0.03 (5)	1628.22 (8)	4^{+}
2806.42 (24)	$(1)^{**}$	$0.164^{+30}_{-26},**$	1180.42 (10)**	-		1625.92 (9)	2^{+}
			1308.39 (10)**	-		1497.88 (9)	2^{+}
			1658.46 (22)	100		1147.96 (10)	0^{+}
2818.67 (35)	4^{+}	$0.22 (3)^{\text{eff}}$	1190.45 (34)	100	-0.08 (15)	1628.22 (8)	4^{+}
			1320.9 (5)**	-		1497.88 (9)	2^{+}
2875.35 (12) [#]	$6, 7^{+}$		120.34 (18)	2.9 (6)		2755.31 (33)	$6^{+,**}$
			434.55 (7)	100	+0.12 (7)	2440.80 (10)	6^{+}
					or +1.8 (2)		
2975.70 (14)	5^{+}		434.6 (2)**	-		2540.78 (32)	$(3)^{+,**}$
			740.78 (12)	46.0 (57)		2234.70 (8)	3^{-}
			755.6 (2)**	-		2219.46 (9)	4^{+}
			997.15 (22)	53.1 (72)	(E2)	1978.43 (10)	3^{+}
			1347.54 (15)	100	$+1.5^{+4.1}_{-0.9}$	1628.22 (8)	4^{+}
2978.51 (11)	8^{+}		223.31 (9)	2.1 (4)	(E2)	2755.31 (33)	$6^{+,**}$
			537.70 (7)	100	(E2)	2440.80 (10)	6^{+}
3014.43 (20)*	$5^{(+)}$		279.53 (9) [†]	77.7 (35)		2734.68 (12)	5^{+}
			1386.39 (11) [†]	100	+0.02 (7)	1628.22 (8)	4^{+}
3030.83 (12)*			592.43 (10) [†]	100		2438.47 (6)	5^{+}
3143.32 (34)*			388.01 (10) [†]	100		2755.31 (33)	$6^{+,**}$
3370.29 (12)	8^{+}		391.59 (13)	6.1 (2)	-0.04 (38)	2978.51 (11)	8^{+}
			929.49 (7)	100	-0.01 (3)	2440.80 (10)	6^{+}
3416.32 (14)*, [#]	5^{+}	$0.31 (6)^{\text{eff}}$	975.52 (10)	100	-0.34 (5)	2440.80 (10)	6^{+}
3445.96 (12)	6^{+}		1007.49 (10)	100	+0.35 (8)	2438.47 (6)	5^{+}

E_{level} (keV)	J_{initial}^{π}	$\tau(\text{ps})$	$E_{\gamma}(\text{keV})$	$I_{\gamma,\text{exp}}$	δ_{exp}	$E_{\text{final}}(\text{keV})$	J_{final}^{π}
3473.14 (10)	7^{+}		738.39 (7)	78.6 (19)	+0.04 (5)	2734.68 (12)	5^{+}
			1032.42 (12)	100	-0.02 (4)	2440.80 (10)	6^{+}
3597.08 (16)			862.40 (10) [†]	100		2734.68 (12)	5^{+}
3710.73 (16)*			732.22 (11)	100		2978.51 (11)	8^{+}
3787.26 (13)	10^{+}		808.75 (7)	100	(E2)	2978.51 (11)	8^{+}
3804.55 (39)*			434.26 (37) [†]	100		3370.29 (12)	8^{+}
3916.20 (15)	$7^{+}, 9^{\ddagger\ddagger}$		545.91 (9)	100		3370.29 (12)	8^{+}
4533.33 (17)	$9^{+}, 11^{\ddagger\ddagger}$		746.07 (11)	100		3787.26 (13)	10^{+}
4795.38 (26)	11^{**}		879.18 (21)	100		3916.20 (15)	$7^{+}, 9^{\ddagger\ddagger}$

Table 2: Results of this work on ^{98}Mo . States discussed in section 2.2 are labeled with a sharp sign (#). Newly observed states are labeled with an asterisk (*) and newly observed transitions with a dagger (†). Furthermore, γ intensities I_{γ} of transitions that are listed in NDS [27] but are not observed due to the sensitivity limit of the detector system or background are labeled with a dash (–). If a value is adopted from NDS it is labeled with a double asterisk (**). If a spin assignment of a state due to angular correlation analysis is not unique, those spins are labeled with a double-dagger (‡‡). Lifetimes obtained in the present work are effective values, hence, upper limits for the mean lifetimes, and are marked with a superscript ^{eff}. If an angular correlation analysis is not feasible but selection rules suggest the multipole characteristic of the γ transition, the multipolarity is given in parentheses.

E_{level} (keV)	J_{initial}^{π}	$\tau(\text{ps})$	$E_{\gamma}(\text{keV})$	$I_{\gamma,\text{exp}}$	δ_{exp}	$E_{\text{final}}(\text{keV})$	J_{final}^{π}
734.75 (4)	0^{+}	31.45 (130)**					
787.26 (15)	2^{+}	5.08 (9)**	(52.6)**	–		734.75 (4)	0^{+}
			787.26 (15)	100	+0.0	0.0	0^{+}
1432.18 (12) [#]	2^{+}	2.21 (23)**	644.70 (15)	100	+1.67 (25)	787.26 (15)	2^{+}
			697.10 (46)	5.8 (7)	(E2)	734.75 (4)	0^{+}
			1432.29 (20)	81.5 (16)	+0.0	0.0	0^{+}
1509.74 (21)	4^{+}	3.65 (7)**	(78.0)**	–		1509.74 (21)	4^{+}
			722.48 (15)	100	+0.02 (3)	787.26 (15)	2^{+}
1758.32 (12)	2^{+}	2.05 (9)**	248.5**	–		1509.74 (21)	2^{+}
			326.05 (25)	7.0 (3)	-0.17 (22)	1432.18 (12)	2^{+}

E_{level} (keV)	J_{initial}^{π}	$\tau(\text{ps})$	$E_{\gamma}(\text{keV})$	$I_{\gamma,\text{exp}}$	δ_{exp}	$E_{\text{final}}(\text{keV})$	J_{final}^{π}
1962.81 (20)	0^{+}	93.8 (101)**	971.03 (16)	65.9 (10)	-0.97 (14)	787.26 (15)	2^{+}
			1023.61 (16)	100	+0.0	734.75 (4)	0^{+}
			1758.64 (14)**	—		0.0	0^{+}
			530.61 (30)	39.1 (29)	(E2)	1432.18 (12)	2^{+}
			1175.57 (20)	100	+0.0	787.26 (15)	2^{+}
2017.36 (16)	3^{-}	93.8 (101)**	258.96 (26)	22.0 (19)	+0.01 (6)	1758.32 (12)	2^{+}
			507.8 (2)	—		1509.74 (21)	4^{+}
			1230.04 (15)	100	-0.04 (7)	787.26 (15)	2^{+}
			2018.01 (53)	16.2 (17)	(E3)	0.0	0^{+}
			1250.00 (19)	100	+0.0	787.26 (15)	2^{+}
2037.26 (14)	$0^{(+)}$	93.8 (101)**	594.65 (12)**	—		1509.74 (21)	4^{+}
			672.50 (17)	78.9 (28)	$+6.7^{+3.4}_{-1.7}$	1432.18 (12)	2^{+}
			1317.37 (17)	100	$+2.9^{+0.6}_{-0.5}$	787.26 (15)	2^{+}
			448.2 (2)**	—		1758.32 (12)	2^{+}
			1419.48 (22)	100	-0.33 (11)	787.26 (15)	2^{+}
2206.74 (26)	2^{+}	0.30 (7) ^{eff}	206.3 (5)**	—		2017.36 (16)	3^{-}
			465.5 (2)**	—		1758.32 (12)	2^{+}
			713.80 (16)	100	+1.13 (17)	1509.74 (21)	4^{+}
			791.58 (17)	82.9 (36)	+0.07 (8)	1432.18 (12)	2^{+}
			1436.68 (25)	23.4 (19)	-0.03 (7)	787.26 (15)	2^{+}
2223.74 (14)	4^{+}	0.30 (7) ^{eff}	900.85 (21)	100	$-0.15^{+0.19}_{-0.20}$	1432.18 (12)	2^{+}
			109.48 (44)	10.9 (44)		2223.74 (14)	4^{+}
			575.06 (10)**	—		1758.32 (12)	2^{+}
			823.33 (16)	77.4 (47)	-0.388 (7)	1509.74 (21)	4^{+}
			1546.30 (22)	100	-0.04 (4)	787.26 (15)	2^{+}
2333.03 (24) [#]	2^{+}	0.50 (17) ^{eff}	833.52 (15)	100	-0.01 (7)	1509.74 (21)	4^{+}
			986.34 (27)	100	+0.01 (7)	1432.18 (12)	2^{+}
			1631.26 (50)	96.5 (59)		787.26 (15)	2^{+}
			195.66 (10)**	—		2223.74 (14)	4^{+}
			314.9 (2)**	—		2104.66 (15)	3^{+}
2333.32 (17) [#]	4^{+}	0.50 (17) ^{eff}	971.03 (16)	65.9 (10)	-0.97 (14)	787.26 (15)	2^{+}
			1023.61 (16)	100	+0.0	734.75 (4)	0^{+}
			1758.64 (14)**	—		0.0	0^{+}
			530.61 (30)	39.1 (29)	(E2)	1432.18 (12)	2^{+}
			1175.57 (20)	100	+0.0	787.26 (15)	2^{+}
2343.26 (26)	6^{+}	7.50 (29)**	258.96 (26)	22.0 (19)	+0.01 (6)	1758.32 (12)	2^{+}
			507.8 (2)	—		1509.74 (21)	4^{+}
			1230.04 (15)	100	-0.04 (7)	787.26 (15)	2^{+}
			2018.01 (53)	16.2 (17)	(E3)	0.0	0^{+}
			1250.00 (19)	100	+0.0	787.26 (15)	2^{+}
2418.52 (29) [#]	$2^{(+)}$	7.50 (29)**	594.65 (12)**	—		1509.74 (21)	4^{+}
			672.50 (17)	78.9 (28)	$+6.7^{+3.4}_{-1.7}$	1432.18 (12)	2^{+}
			1317.37 (17)	100	$+2.9^{+0.6}_{-0.5}$	787.26 (15)	2^{+}
			448.2 (2)**	—		1758.32 (12)	2^{+}
			1419.48 (22)	100	-0.33 (11)	787.26 (15)	2^{+}
2419.48 (18) [#]	4^{+}	7.50 (29)**	206.3 (5)**	—		2017.36 (16)	3^{-}
			465.5 (2)**	—		1758.32 (12)	2^{+}
			713.80 (16)	100	+1.13 (17)	1509.74 (21)	4^{+}
			791.58 (17)	82.9 (36)	+0.07 (8)	1432.18 (12)	2^{+}
			1436.68 (25)	23.4 (19)	-0.03 (7)	787.26 (15)	2^{+}

E_{level} (keV)	J_{initial}^{π}	$\tau(\text{ps})$	$E_{\gamma}(\text{keV})$	$I_{\gamma,\text{exp}}$	δ_{exp}	$E_{\text{final}}(\text{keV})$	J_{final}^{π}
2485.47 (21)	3^{+}		402.33 (39)	10.0 (14)	(E1)	2017.36 (16)	3^{-}
			661.16 (40)	17.8 (13)	+0.09 (10)	1758.32 (12)	2^{+}
			909.52 (17)	100	-0.64 (10)	1509.74 (21)	4^{+}
			987.48 (10)**	—		1432.81 (12)	2^{+}
			1632.46 (33)	40.5 (16)	(E2)	787.26 (15)	2^{+}
			151.9 (2)**	—		2333.32 (17)	4^{+}
			380.05 (43)	21.8 (17)		2104.66 (15)	3^{+}
			467.0 (9)**	—		2104.66 (15)	3^{+}
			726.83	< 4.6		1758.32 (12)	2^{+}
			975.25 (32)	35.9 (17)	$-0.89^{+0.62}_{-1.60}$	1509.74 (21)	4^{+}
			1053.04 (26)	55.2 (27)	$-0.97^{+0.27}_{-0.36}$	1432.18 (12)	2^{+}
			1698.49 (26)	100	-0.52 (13)	787.26 (15)	2^{+}
			86.51 (32)	8.2 (44)		2419.48 (18)	4^{+}
			162.53 (15)**	—		2343.26 (26)	6^{+}
2506.10 (16) [#]	5^{+}		172.89 (16)	73.6 (32)	+0.05 (11)	2333.32 (17)	4^{+}
			282.52 (10)**	—		2223.72 (14)	4^{+}
			299.6 (2)**	—		2206.74 (26)	2^{+}
			996.33 (16)	100	-0.96 (10)	1509.74 (21)	4^{+}
			2525.50 (29)	2^{**}	0.47 (6) ^{eff}	1093.32 (26)	100
2562.41 (23)	2		544.52 (39)	7.4 (9)		2017.36 (16)	3^{-}
			803.6 (5)**	—		1758.32 (12)	2^{+}
			1775.37 (23)	100	+0.05 (7)	787.26 (15)	2^{+}
2572.83 (17)	3		239.2 (2)**	—		2333.32 (17)	4^{+}
			555.07 (35)	47.0 (66)		2017.36 (16)	3^{-}
			814.46 (26)	49.6 (27)	+0.10 (10)	1758.32 (12)	2^{+}
			1140.83 (47)	29.1 (34)		1432.18 (12)	2^{+}
2574.35 (16)	4^{+}		1785.90 (24)	100	+0.01 (6)	787.26 (15)	2^{+}
			350.81 (18)	100	-0.13 (24)	2223.74 (14)	4^{+}
			557.08 (39)	19.9 (56)	(E1)	2017.36 (16)	3^{-}
			1064.27 (18)	90.9 (40)	$-2.69^{+0.75}_{-1.47}$	1509.74 (21)	4^{+}

E_{level} (keV)	J_{initial}^{π}	$\tau(\text{ps})$	$E_{\gamma}(\text{keV})$	$I_{\gamma,\text{exp}}$	δ_{exp}	$E_{\text{final}}(\text{keV})$	J_{final}^{π}
2612.21 (46)	$0^{(+)}$		1824.95 (44)	100	+0.0	787.26 (15)	2^{+}
2619.99 (28)	3^{+}		1187.50 (43)	9.7 (7)	$+0.95^{+0.98}_{-0.50}$	1432.18 (12)	2^{+}
			1832.93 (33)	100	-0.54 (13)	787.26 (15)	2^{+}
			1886.3 (7)**	—		734.75 (4)	0^{+}
2620.56 (17)	5^{-}		603.25 (17)	63.3 (12)	-0.08 (11)	2017.36 (16)	3^{-}
			1110.75 (16)	100	-0.05 (10)	1509.74 (21)	4^{+}
2678.49 (20)	6^{+}		172.47 (26)	3.6 (5)		2506.10 (16)	5^{+}
			335.15 (16)	52.8 (8)	-0.01 (10)	2343.26 (26)	6^{+}
			345.258 (20)**	—		2333.32 (17)	4^{+}
			445.04 (10)**	—		2223.74 (14)	4^{+}
			1168.81 (16)	100	+0.01 (4)	1509.74 (21)	4^{+}
2700.86 (36) [#]	$(2^{+})^{**}$	$0.25 (5)^{\text{eff}}$	493.4 (6)**	—		2206.74 (26)	2^{+}
			1913.60 (33)	100	-0.14 (14)	787.26 (15)	2^{+}
2733.27 (36) [#]	$(2^{+})^{**}$		1946.01 (33)	100	-0.09 (15)	787.26 (15)	2^{+}
2768.46 (35)	4^{+}		1981.20 (32)	100	+0.01 (11)	787.26 (15)	2^{+}
2795.37 (18)	4^{-}		778.01 (20) [†]	37.7 (31)	-0.37 (15)	2017.36 (16)	3^{-}
			1285.63 (16)	100	-0.02 (3)	1509.74 (21)	4^{+}
2812.72 (42) [#]	$1^{+}, 2^{+}, 3^{+}, \ddagger$		2025.46 (39) [†]	100	$-4.4^{+2.2}_{-56.7}$	787.26 (15)	2^{+}
2836.33 (16)	6^{+}		157.87 (16)	100		2678.49 (20)	6^{+}
			330.18 (23)	23.3 (56)	-0.24 (6)	2506.10 (16)	5^{+}
			493.09 (20)	23.0 (56)	-0.29 (15)	2343.26 (26)	6^{+}
			1326.7	—		1509.74 (21)	4^{+}
2853.71 (31)	$8^{+}, 7^{+}, 6^{+}, 5^{+}, \ddagger$		510.45 (16)	100		2343.26 (26)	6^{+}
2871.00 (43) ^{*,#}	$2^{+}, 3^{\ddagger}$	< 0.50	2083.74 (40) [†]	100	$+0.06(10)$ or $-3.7^{+1.5}_{-5.8}$	787.26 (15)	2^{+}
2896.58 (21) [*]	5^{+}		791.83 (28) [†]	100	(E2)	2104.66 (15)	3^{+}
			1386.84 (19) [†]	96.0 (35)	$+3.2^{+0.8}_{-0.5}$	1509.74 (21)	4^{+}
2905.07 (74)	$(4^{+})^{**}$	$0.22 (2)^{\text{eff}}$	2117.81 (72) [†]	100		787.26 (15)	2^{+}
2916.29 (47)	(2^{+})	$0.11^{+9}_{-6} \text{ eff}$	2129.03 (45)	100	$-0.71^{+0.37}_{-0.57}$	787.26 (15)	2^{+}
2962.58 (45)	$(2^{+}, 3, 4^{+})$		944.39 (44)	18.5 (47)		2017.36 (16)	3^{-}

E_{level} (keV)	J_{initial}^{π}	$\tau(\text{ps})$	$E_{\gamma}(\text{keV})$	$I_{\gamma,\text{exp}}$	δ_{exp}	$E_{\text{final}}(\text{keV})$	J_{final}^{π}
			1452.69 (42)	100		1509.74 (21)	4^{+}
			2176.41 (47) [†]	82.5 (141)		787.26 (15)	2^{+}
2976.70 (32)	$4^{+,\ddagger\ddagger}$	0.64 (33) ^{eff}	557.1 (4)**	—		1419.48 (18)	4^{+}
			753.19 (14)**	—		2223.74 (14)	4^{+}
			1466.96 (24)	100	+0.05 (17)	1509.74 (21)	4^{+}
			2189.4 (5)**	—		787.26 (15)	2^{+}
3019.73 (18)	5^{-}		399.43 (18)	100	+0.06 (15)	2620.56 (17)	5^{-}
			676.66(26)	33.5 (24)	-0.01 (10)	2343.26 (26)	6^{+}
			1002.85 (31)	24.4 (10)	+0.03 (5)	2017.36 (16)	3^{-}
			1510.4**	—		1509.74 (21)	4^{+}
3021.39 (40)	$(5^{-},**)$		688.23 (10)**	—		2333.03 (24)	2^{+}
			797.88 (10)**	—		2223.74 (14)	4^{+}
			815.5 (3)**	—		2206.74 (26)	2^{+}
			917.05 (13)**	—		2104.66 (15)	3^{+}
			1004.31 (10)**	—		2017.36 (16)	3^{-}
			1263.36 (11)**	—		1758.32 (12)	2^{+}
			1511.65 (34)	100		1509.74 (21)	4^{+}
			1589.62 (10)**	—		1432.18 (12)	2^{+}
			2234.31 (10)**	—		787.26 (15)	2^{+}
3025.93 (33)*	5^{+}		1516.19 (25) [†]	100	+0.27 (6)	1509.74 (21)	4^{+}
3050.21 (35)	$(4^{+})^{**}$	0.18 (3) ^{eff}	544.5 (4)**	—		2506.10 (16)	5^{+}
			631.4 (2)**	—		2419.48 (18)	4^{+}
			717.5 (3)**	—		2333.03 (24)	$2^{(+)}$
			1540.47 (52)	100	-0.20 (27)	1509.74 (21)	4^{+}
			1618.75 (11)**	—		1432.18 (12)	2^{+}
			2263.0 (2)**	—		787.26 (15)	2^{+}
3067.34 (24)	$4^{-},5$		446.78 (17)	100		2620.56 (17)	5^{-}
3095.74 (19)	7^{-}		475.23 (17)	100	+0.01 (3)	2620.56 (17)	5^{-}
			752.41 (16)	81.2 (16)	-0.01 (4)	2343.26 (26)	6^{+}
3108.99 (21)	$2^{+},4^{\ddagger\ddagger}$		1091.52 (20)	100		2017.36 (16)	3^{-}

E_{level} (keV)	J_{initial}^{π}	$\tau(\text{ps})$	$E_{\gamma}(\text{keV})$	$I_{\gamma,\text{exp}}$	δ_{exp}	$E_{\text{final}}(\text{keV})$	J_{final}^{π}
			1599.50 (33)	24.2 (37)		1509.74 (21)	4^{+}
3210.45 (34)	$(4^{+})^{**}$		1193.09 (30)	100		2017.36 (16)	3^{-}
3228.71 (29)	$5^{+}, 6^{+}, 7^{+}, 8^{+}, \ddagger\ddagger$	0.22 (3) ^{eff}	885.48 (21)	100		2343.26 (26)	6^{+}
			1718.80 (55)	<23.8		1509.74 (21)	4^{+}
3271.24 (31)	$8^{+}, 7^{+}, 6^{+}, \ddagger\ddagger$		927.95 (17)	100		2343.26 (26)	6^{+}
3323.12 (21)*	$7^{(-)}$		227.37 (18) [†]	100	-0.08 (10)	3095.74 (19)	7^{-}
			979.87 (23) [†]	99.9 (66)	(E1)	2343.26 (26)	6^{+}
3556.67 (46)*		0.24 (7) ^{eff}	1213.41 (38) [†]	100		2343.26 (26)	6^{+}

2.2. Results for ^{98}Mo :

1432.18 (12) keV, 2^{+} . For the depopulating 644 keV transition conflicting multipole mixing ratios are reported. A $(n, n'\gamma)$ experiment [30] yielded two competing values, +1.70 (16) and +0.13 (4) (less likely according to Ref. [30]). The Coulomb excitation experiment by M. Zielinska *et al.* [31], however, resulted in a multipole mixing ratio $\delta = +0.27$ (2), and a (n, γ) experiment [32] determined a value of 0.58 (5). The different multipole mixing ratios are tested in the angular correlation analysis shown in figure A.4. Clearly a multipole mixing ratio of $\delta_{644} = +1.67$ (25) is favored and is in good agreement with one of the multipole mixing ratios from the previous $(n, n'\gamma)$ experiments. Note, that in a neutron capture experiment the angular correlation function for a sequence of γ cascades depends only on the angle between the γ rays. In the present in-beam experiment the multi-detector setup and the given beam quantization axis allow to use 11 correlation groups for the angular correlation analysis. Furthermore, a large $E2$ component of the 644 keV $2_2^{+} \rightarrow 2_1^{+}$ transition is supported by the angular correlation analysis using the OSIRIS setup ($\delta_{\text{Osiris}, 644} = +3.2_{-1.4}^{+4.6}$).

2333.03 (24) and 2333.32 (17) keV, 2^{+} and 4^{+} . Using $\gamma\gamma$ coincidences of the 172.89 (16) keV transition which feeds the state at 2333.32 keV, a γ line at 900.85 keV cannot be detected. This agrees with data from a β decay experiment [30], where a depopulating transition at 900.85 keV was not observed with the relative γ intensity reported in Ref. [27]. The 900.85 keV transition also exhibits a Doppler shift in detectors positioned in forward and backward direction which is not observed for the other transitions given in NDS, thus establishing that at 2333 keV in fact two states can be placed as previously proposed in proton and deuteron inelastic scattering experiments [33]. Thus, in the present work the 2333.03 and 2333.32 keV state can be confirmed by independent gates. Additionally, using the angular correlation analyses (see figures A.7 and A.8) the spins $J = 2$ and $J = 4$ for the 2333.03 keV state and for the 2333.32 keV state is obtained, respectively. Note, the positive parity of the $J = 2$ state is adopted from Ref. [34].

2418.52 (29) keV, 2^{-} . The two states at 2418.52 (29) keV and 2419.48 (18) keV are difficult to disentangle. But the coincidence spectrum of the observed 86.51 (32) keV transition depopulating the 2506.10 (16) keV state (see discussion of that state) allows

to solely observe γ decays from the state at 2419.48 keV, since a transition with an E3 multipole characteristic is unlikely to be observed. From the coincidence spectrum from the 86 keV transition we can infer that a hypothetical contribution of a 987.48 keV transition depopulating the state at 2419.48 keV to the 986.34 keV transition depopulating the state at 2418.52 keV is negligible.

2419.48 (18) keV, 4^+ . In previous β decay and (p, t) experiments [30,35] a spin of 3^- was assigned to the 2419 keV state while in a $(\text{pol } t, p)$ reaction [34] the spin 2 was determined for this state. Figure A.5 shows the comparison of the three possible spin hypothesis with data and a spin of 4^+ is favored. The new spin assignment is confirmed by the angular correlation analysis of the $\gamma\gamma$ cascade 661-1023. Note, the $(\text{pol } t, p)$ experiment might have observed the state at 2418 keV instead, (see discussion to the 2418 keV state) which revealed a spin of 2.

2485.47 (21) keV, 3^+ . The relative intensity of the 726.83 (11) keV transition reported in Ref. [30] cannot be confirmed, as no such γ line is observed in coincidence with the 1023 keV transition. At this energy the sensitivity is such that peaks with a relative γ intensity greater than 4.6% with respect to the 1698.49 keV transition depopulating this state would be observed.

2506.10 (16) keV, 5^+ . The angular correlation analysis of the 722-996 keV $\gamma\gamma$ cascade (see Figure A.6) clearly favors the spin assignment 5^+ for the 2506 keV state, while the tentative spin assignment of $J = (3)$ and $J = (3^-, 4^+)$ reported in Ref. [35] and in Ref. [30], respectively, is rejected.

2700.86 (36) keV, (2^+) . The angular correlation analysis favors a spin assignment of 2^+ for this state, however a spin assignment of 1^+ or 3^+ cannot be fully rejected. The δ_{1913} value given in Table 2 is for a presumed spin 2^+ adopted from literature [27]. The $E2/M1$ mixing ratio for other spin hypotheses are $\delta_{1^+ \rightarrow 2_1^+} = -0.45$ (10) and $\delta_{3^+ \rightarrow 2_1^+} = +0.34$ (9).

2733.27 (36) keV, (2^+) . The angular correlation analysis yields a possible spin assignment of 2^+ , 3^+ for this state. The δ_{1946} value given in Table 2 is for a presumed spin 2^+ adopted from the compiled data [27]. If the spin of the 2733 keV state is 3^+ , the associated multipole mixing ratio is $\delta_{1946} = 0.27$ (10) for the 1946.01 (33) keV transition to the 2_1^+ .

2812.72 (42) keV, $1^+, 2^+, 3^+$. The angular correlation analysis of the 2025-787 keV $\gamma\gamma$ cascade yields a possible spin of $J = 1, 2, 3$. However, if the spin assignment of 2 reported in an inelastic scattering experiment Ref. [33] is correct, the multipole mixing would be $\delta_{2025} = -4_{-57}^{+2}$.

2871.00 (43) keV, $2^+, 3$. The angular correlation analysis of the 2083-787 keV $\gamma\gamma$ cascade yields two possible spins, a $J^\pi = 2^+$ state with an associated multipole mixing ratio $\delta_{2083} = -3.7_{-5.8}^{+1.5}$ or a state with spin $J = 3$ with an associated multipole mixing ratio $\delta_{2083} = -0.06$ (10). In the coincidence spectra a Doppler shift is clearly observed, albeit the statistics are not sufficient for a line shape analysis. Thus, for the lifetime of this state an upper limit of $\tau_{eff} < 0.50$ ps is given, which is derived from the calculated mean stopping time.

3095.74 (19) keV, 7^- . The depopulating 752 keV transition is observed with a smaller branching ratio than reported in Ref [30]. However, in that publication another γ decay with the same energy is observed to depopulate the state at 2976 keV (which was not observed in our data). If the given γ intensities were swapped for both transitions, the

Fig. 7. (Color online) Low-lying states from experiment [26,27] are plotted for different molybdenum isotopes. To provide a better overview, off-Yrast states are shown in red.

newly calculated branching ratio from the β decay experiment would fit to our data. Note, from a previous (α , 2n) experiment [36] the relative intensity was also reported to be much stronger with respect to the depopulating 475.23 keV transition.

3. Test for shape coexistence in ^{96}Mo

A previous phenomenological IBM-2 fit by Sambataro and Mólnar [37] suggested that a good description of low-lying structure in ^{96}Mo , including its first excited 0^+ state, was obtained by invoking configuration mixing. In fact, several observables strongly point towards shape coexistence. The evolution of low-lying states is plotted in Fig. 7 as functions of mass. It is striking that while the excitation energy of the second 0^+ state drops steeply from ^{94}Mo to ^{98}Mo , the states within the Yrast band remain approximately constant. On the other hand, the second excited 0^+ and 2^+ states (labeled in red) decrease in energy for ^{96}Mo and show a local maximal separation in energy for ^{98}Mo . These features together with other observables such as γ transitions depopulating 1^+ states with equal strengths to both 0^+ states [38] in ^{98}Mo are well described by shape coexistence [1,37].

To test whether a single configuration is sufficient for the understanding of the low-lying states in ^{96}Mo or an explicit inclusion of shape coexistence is needed for the description of ^{96}Mo , theoretical calculations are performed in terms of the method of Ref. [39]. The basic idea of the method is that the parameters of the IBM-2 Hamiltonian are obtained by the mapping from the microscopic mean-field deformation energy surface onto the expectation value of the equivalent IBM Hamiltonian in the boson condensate state [40] (for details, see Refs. [39,41]). The resultant Hamiltonian is used to calculate energy levels and wave functions of excited states. Recently, the method of [39] has been extended to

Fig. 8. (Color online) Contour plots of the microscopic energy surfaces in (β, γ) plane of $^{94-100}\text{Mo}$ (a-d). The color code ranges from 0 (mean-field minimum) to 2 MeV, and the minima are identified by the solid white circles. The Skyrme SLy6 functional is used.

include the mixing of the different configurations associated with the different intrinsic shapes [42].

Hereby, we first perform a set of constrained Hartree-Fock-BCS calculations using the Skyrme energy density functional [43,44] with SLy6 interaction [45] using the code `ev8` [46] to obtain the energy surface for a given nucleus. The constraint imposed here is for mass quadrupole moments, associated to the deformation parameters β and γ of the collective model [47]. The density-dependent pairing interaction is used for the pairing correlation in the BCS approximation, with its strength being the fixed value of $V_0=1000$ MeV fm³, and the Lipkin-Nogami prescription is taken for the treatment of the particle number. For a review on the self-consistent mean-field approach, the reader is referred to Ref. [48].

In Fig. 8 we show the energy surfaces for even-even $^{94-100}\text{Mo}$ nuclei, calculated by the constrained Hartree-Fock plus BCS method with the Skyrme SLy6 interaction. The energy surface for the ^{94}Mo nucleus exhibits a spherical shape, while the topology of the energy surface for ^{96}Mo is more flat in β direction and is rather elongated in the direction of γ deformation. As already discussed in [1], one can see clearly two minima for ^{98}Mo (c), one spherical and the other one more prolate. Although the energy surface for ^{96}Mo does not show two distinguishable minima, the minimum is much shallower than in ^{94}Mo and somewhat elongated in direction of the γ deformation. A very pronounced deformation characterized by a deep minimum is found for ^{100}Mo (d).

In the IBM-2 framework, ^{90}Zr is assumed to be the inert core. As the number of

proton (neutron) bosons is equal to that of pairs of valence protons (neutrons) outside of the $Z = 40$ ($N = 50$) shell closure [10], we have $N_\pi = 1$ proton and $N_\nu = 2, 3, 4$ and 5 neutron bosons for the $^{94-100}\text{Mo}$ nuclei, respectively. As assumed by Sambataro and Mólnar [37], we consider that the intruder configuration is associated to the $2p-2h$ proton excitation from the $N = 28-40$ pf shell to the $0g_{9/2}$ shell. Therefore, the normal ($0p-0h$) configuration is composed of $N_\pi = 1$ proton boson, while for the intruder ($2p-2h$) configuration $N_\pi = 3$. The Hamiltonian used for the configuration mixing can then be written as:

$$\hat{H} = \hat{\mathcal{P}}_1 \hat{H}_1 \hat{\mathcal{P}}_1 + \hat{\mathcal{P}}_3 (\hat{H}_3 + \Delta) \hat{\mathcal{P}}_3 + \hat{H}_{mix}, \quad (1)$$

where $\hat{H}_1$ ($\hat{H}_3$) and $\hat{\mathcal{P}}_1$ ($\hat{\mathcal{P}}_3$) represent the Hamiltonian of and the projection operator onto the normal $N_\pi = 1$ (intruder $N_\pi = 3$) configuration space, respectively. Δ specifies the energy difference between the eigenvalues of the two configurations.

The term H_{mix} in Eq. (1) stands for the interaction term mixing the two configurations:

$$\hat{H}_{mix} = \hat{\mathcal{P}}_3 (\omega_s s^\dagger \cdot s^\dagger + \omega_d d^\dagger \cdot d^\dagger) \hat{\mathcal{P}}_1 + H.C, \quad (2)$$

where $s^\dagger$ (s) and $d^\dagger$ (d) represent the creation (annihilation) operator of the s and d boson, respectively. For simplicity, the mixing strengths ω_s and ω_d set are equal to each other, $\omega_s = \omega_d \equiv \omega$. The following Hamiltonian is used for each configuration:

$$\hat{H}_i = \epsilon_{\nu,i} \hat{n}_{d\nu} + \epsilon_{\pi,i} \hat{n}_{d\pi} + \kappa_i \hat{Q}_\nu \cdot \hat{Q}_\pi + \hat{M}_{\pi\nu,i}, \quad (3)$$

where the first and the second terms in Eq. (3),

$$\hat{n}_{d\rho} = \sum_{\rho,m} d_{\rho,m}^\dagger d_{\rho,m}, \quad \rho = \nu, \pi, \quad (4)$$

stand for the neutron and proton boson number operators, respectively. ϵ_ρ is the single proton or neutron boson energy, and is assumed to be the same for protons and neutrons, $\epsilon_\nu = \epsilon_\pi \equiv \epsilon$. κ and χ_ρ stand for, respectively, the strength parameter for the quadrupole-quadrupole interaction and the parameter which determines whether the nucleus is prolate (if $\gamma = 0^\circ$ and $\chi_\pi + \chi_\nu < 0$) or oblate (if $\gamma = 60^\circ$ and $\chi_\pi + \chi_\nu > 0$). The third term in Eq. (3) is the quadrupole-quadrupole interaction between the proton and the neutron bosons, with the quadrupole operator $\hat{Q}_\rho$ being

$$\hat{Q}_\rho = [s_\rho^\dagger \tilde{d}_\rho + d_\rho^\dagger s_\rho]^{(2)} + \chi_\rho [d_\rho^\dagger \times \tilde{d}_\rho]^{(2)}. \quad (5)$$

The fourth term in Eq. (3) represents the so-called Majorana term which renders the symmetric states energetically favored:

$$\hat{M}_{\pi\nu} = \frac{1}{2} \xi_2 (d_\pi^\dagger s_\nu^\dagger - s_\pi^\dagger d_\nu^\dagger) \cdot (\tilde{d}_\pi s_\nu - s_\pi \tilde{d}_\nu) + \sum_{\lambda=1,3} \xi_\lambda (d_\pi^\dagger d_\nu^\dagger)^{(\lambda)} \cdot (d_\pi^\dagger d_\nu^\dagger)^{(\lambda)} \quad (6)$$

$\xi_{1,2,3}$ are the strength parameters, which are determined empirically so that the mixed-symmetry states do not appear in the low-energy region, typically below 2 MeV excitation from the ground state.

In the case of configuration mixing, the boson coherent state should be extended accordingly to the direct sum of the coherent states associated to the two configurations [49]. The energy surface of the IBM-2 with configuration mixing from Eq. (1) can be

defined as the lower eigenvalue of the 2×2 coherent-state matrix [49]. The parameters for the Hamiltonian of each configuration space are determined by associating the Hamiltonian with each mean-field minimum, and the energy offset Δ and the mixing parameter ω are determined so that the energy difference between the two mean-field minima and the barrier height for these minima, respectively, are reproduced [42]. Since the Majorana terms do not appear in the boson energy surface, provided that equal deformations between proton and neutron are assumed, the parameters which are to be extracted by mapping from the microscopic energy surface are ϵ , κ , χ_π , and χ_ν for both configurations, and the mixing strength ω and the energy offset Δ . The explicit form of each element of the coherent-state matrix is found in Ref. [50], where substituting $\kappa'_i = \kappa''_i = 0$ in Eq.(6) in Ref. [50] reduces to the formula used in the present study.

In applying the above method to ^{96}Mo , we encounter two major problems in the description of shape coexistence and mixed-symmetry states. First the parameters for the Majorana interaction cannot be determined by the mapping of the energy surface. The second problem is that only one minimum is predicted in the energy surface for ^{96}Mo (cf. Fig. 8(b)), which makes it difficult to fix the Hamiltonian for the intruder configuration. For these reasons, we determine some of the IBM-2 parameters for ^{96}Mo in phenomenological ways: (i) For the Majorana parameters, the values used by Sambataro and Molnár [37], $\xi_1 = \xi_3 = -0.07$ MeV and $\xi_2 = -0.24$ MeV for the normal configuration while $\xi_1 = \xi_2 = \xi_3 = 0$ MeV for the intruder configuration, are taken; (ii) for the intruder configuration, we use the same Hamiltonian the same mixing strength as in [1], but here the energy offset $\Delta = 2.0$ MeV is fixed so that the experimental energy level of the 0_2^+ intruder state is reproduced.

For comparison, we also perform the IBM-2 single configuration calculation on ^{96}Mo , where only the Hamiltonian for the $N_\pi = 1$ normal configuration is determined by the mapping procedure. Note that, in this calculation, the Majorana terms were not included.

The employed parameters for the IBM-2 plus configuration mixing are presented in Tab. 3. Similar parameter values are used for the normal configurations of ^{96}Mo and ^{98}Mo , except for the χ_π parameter. The sum $\chi_\pi + \chi_\nu$ measures the degree of γ softness. Indeed, the sum for the normal configuration is smaller in magnitude for ^{98}Mo than for ^{96}Mo in agreement with the energy surface in Fig. 8. The striking difference from the phenomenologically determined parameters used in [37] is that the κ parameter for both configurations in the present study is more than twice as large in magnitude than in [37], reflecting that the quadrupole deformation is quite prominent in the mean-field calculation.

We show the corresponding IBM-2 energy surfaces for $^{94,96,98}\text{Mo}$ nuclei in Fig. 9. The IBM-2 energy surfaces for $^{94,98}\text{Mo}$ are based on those parameters, all of which are determined from the mapping procedure, with the former being only with a single configuration. For ^{96}Mo , on the other hand, as described above, the intruder Hamiltonian is adopted from ^{98}Mo and the Δ parameter is fitted to the experimental 0_2^+ energy level. Even though not every detail of the microscopic energy surface is reproduced by the boson energy surface, the essential feature of the nucleon and boson energy surfaces are similar: The evolution of the minimum, that is, almost pure spherical configuration at ^{94}Mo , more β - and γ -soft structure in ^{96}Mo and the coexistence of the nearly spherical and γ -soft shapes in ^{98}Mo . We note that the second minimum in ^{98}Mo is on the prolate axis with $\beta \approx 0.2$ but is in the triaxial region $\beta \neq 0^\circ$ or 60° . The reason is that the present Hamiltonian is composed of only one- and two-body boson terms, and to

Fig. 9. (Color online) The IBM-2 energy surfaces in the (β, γ) plane for the ^{94}Mo (a), ^{96}Mo (b), ^{98}Mo (c), and ^{100}Mo (d) nuclei. The color code ranges from 0 to 2 MeV, and the minima are identified by the solid white circles.

reproduce the triaxial minimum, a three-body term becomes necessary [51]. The inclusion of the three-body term would improve the agreement of the quasi- γ band, but it is not particularly of relevance for the present study. Similar to the corresponding microscopic energy surface in Fig. 8, the mapped energy surface for ^{100}Mo exhibits a pronounced but γ -soft minimum, however, on oblate side as compared to ^{98}Mo .

Table 3

Parameters for the IBM-2 configuration mixing. For ^{98}Mo the parameters are derived from the mapped energy surface (see Fig. 9, while parameters used to describe the ^{96}Mo intruder states are based on ^{98}Mo but adjusted to reproduce the excitation energy of the second 0^+ . Note, $\xi_{1,2,3}$ values are adopted from Ref. [37]).

nucleus	configuration	ϵ (MeV)	κ (MeV)	χ_ν (MeV)	χ_π (MeV)	$\xi_1 = \xi_3$	ξ_2	ω	Δ (MeV)
^{96}Mo	normal	1.10	-0.368	-0.90	-0.50	-0.07	0.24	0.15	2.00
	intruder	0.70	-0.335	-0.85	0.43	0.00	0.00		
^{98}Mo	normal	1.05	-0.368	-0.80	0.18	-0.07	0.24	0.15	1.715
	intruder	0.70	-0.335	-0.85	0.43	0.00	0.00		

Beside level energies, transition strengths are important observables to obtain information on the wave functions of states. To obtain $B(M1)$ and $B(E2)$ values, the standard operators [11] are used:

Fig. 10. (Color online) Selected states of the low-energy level scheme of ^{96}Mo , observed in the experiment $^{96}\text{Zr}(^3\text{He},n)^{96}\text{Mo}$. The IBM-2 calculations with single (left-hand side) and configuration mixing (middle) are compared with the experimental energy spectra (right-hand side).

$$\hat{T}^{E2} = \sum_{\rho,i} \hat{P}_i e_{B,i}^\rho \hat{Q}_{\rho,i} \hat{P}_i, \quad (7)$$

and

$$\hat{T}^{M1} = \sqrt{\frac{3}{4\pi}} \sum_{\rho,i} \hat{P}_i g_{\rho,i} \hat{J}_{\rho,i} \hat{P}_i, \quad (8)$$

where $\hat{Q}_\rho$ is defined in Eq. 5, $\hat{J}_\rho = [d_\rho^\dagger \tilde{d}_\rho]^{(1)}$ and i corresponds to the normal $N_\pi = 1$ (intruder $N_\pi = 3$) configuration. The effective charges are set as $e_{B,1}^\pi = e_{B,1}^\nu = 0.106$ eb and $e_{B,3}^\pi = e_{B,3}^\nu = 0.106$ eb so that a good overall agreement is obtained for the E2 transition from the 2_1^+ to the ground state. On the other hand, free orbital effective g-factors $g_{\pi,1} = g_{\pi,3} = 1$ and $g_{\nu,1} = g_{\nu,3} = 0$ (in μ_N units) are employed. For the IBM-2 calculation with single configuration for ^{96}Mo , the effective charges for proton and neutron bosons are set to $e^\pi = e^\nu = 0.116$ eb in order to reproduce the $B(E2; 2_1^+ \rightarrow 0_1^+)$ value.

In Fig. 10 we compare the predicted states both with (the level scheme in the middle) and without (on the left-hand side) configuration mixing. The states drawn in blue in the configuration mixing calculation represent mixed-symmetry states and will be discussed in more detail in section 4. Considering that only Δ is adjusted, compared to

Table 4

Theoretical $E2$ transition strengths (in W.u.) from the single IBM-2 configuration (fifth column, “ $B(E2)_{\text{single}}$ ”) and mixing IBM-2 configurations (sixth column, “ $B(E2)_{\text{mixed}}$ ”) compared to experimental values given in table 1. Transitions given in parentage are upper limits for relative intensities and not yet observed. States in bold are predicted to be of intruder nature in theory.

E_{level} (keV)	J_I^π	E_γ (keV)	J_F^π	$B(E2)_{\text{single}}$	$B(E2)_{\text{mixed}}$	$B(E2)_{\text{exp}}$
778.23	2_1^+	778.23	0_1^+	20.6	20	20.7 (4)
1147.96	0_2^+	369.73	2_1^+	8.5	6	51 (7)
1497.88	2_2^+	(349)	0_2^+	5.4	32	<93.2
		719.55	2_1^+	1.1	0	13.9 (28)
		1497.97	0_1^+	1.9	0.1	$1.0_{-0.1}^{+0.2}$
1628.22	4_1^+	849.99	2_1^+	24	25	41 (7)
1869.64	4_2^+	241.33	4_1^+	1.4	1.5	0.2 (1)
		(243.6)	2_3^+	2.0	1	<32
		371.71	2_2^+	45	37	26 (11)
		1091.5	2_1^+	0.54	0.04	2 (1)

the configuration mixing in ^{98}Mo , the improvement of the calculated states is remarkable, reproducing the ordering of the first and second $0^+, 2^+$, and first 4^+ states. However some problems remain in the current calculation for configuration mixing. For transitions between low-lying excited $J^\pi=2^+$ states considerable M1 admixture is observed, specifically $B(M1, 2_2^+ \xrightarrow{719, \text{exp}} 2_1^+) = 0.082_{-7}^{+8} \mu_N^2$ and $B(M1, 2_3^+ \xrightarrow{847, \text{exp}} 2_1^+) < 0.067 \mu_N^2$ (values were calculated with data from this work and lifetimes adopted from [26]). While in the simple phonon picture no M1 strength is expected for transitions between fully symmetric states, in the calculation, the M1 strengths are predicted to be $B(M1, 2_2^+ \xrightarrow{719, \text{theo}} 2_1^+) = 0.004 \mu_N^2$ and $B(M1, 2_3^+ \xrightarrow{847, \text{theo}} 2_1^+) = 0.055 \mu_N^2$. Since the calculated $B(M1(719))$ value is too small, certain modification to the parameters, i.e., increase of the mixing interaction ω , may be necessary to improve the agreement in the ^{96}Mo nucleus. This is also evident from the comparison of calculated and observed $B(E2)$ values given in Table 4. While most values are reproduced, the $B(E2)$ strength of the $0_2^+ \xrightarrow{369} 2_1^+$ transition is predicted to be too weak. This may be because the wave functions of the 2_1^+ and the 0_2^+ states are composed almost purely of the normal and the intruder configurations, respectively. Specifically, the lower-energy states for ^{96}Mo are predicted to be rather weakly mixed. In particular, a stronger contribution of a vibrational-like normal configuration to the second 0^+ state would lead to a stronger $E2$ transition to the first 2^+ state. Also the $4_1^+ \rightarrow 2_1^+$ $E2$ transition is somewhat underpredicted, and the ratio $B_{4/2} = B(E2; 4_1^+ \rightarrow 2_1^+)/B(E2; 2_1^+ \rightarrow 0_1^+)$ is predicted to be only 1.25, much lower than the geometrical limit of 2, which is very close to experiment. A stronger mixing of a deformed structure into the 4_1^+ wave function would likely lead to an enhanced $E2$ strength. The low $B_{4/2}$ ratio, however, can rather be attributed to the limited model space, which suppresses $E2$ transition strengths for higher-lying states. Note, that even in a single IBM-1 space with 3 bosons, the U(5) $B_{4/2}$ ratio amounts to only 4/3. The geometrical limit of $B_{4/2} = 2$ is reached only in the large-N limit [11]. In spite of the fact that intricacies of the level

scheme or transition strengths are not yet fully described, our calculation obtains a reasonably good description of the low lying states in ^{96}Mo . This shows the significance of introducing configuration mixing, especially in order to reproduce the low-lying second 0^+ state .

4. One phonon mixed-symmetry states in the molybdenum isotopes

The $O(6)$ -like and $U(5)$ -like features of the unmixed configurations for the IBM-2 calculations not only break the $O(5)$ symmetry rather weakly, but the F -spin quantum number is approximately preserved. This can be tested by projecting the wave function of a state to the $F = F_{max}$. Here, we define the ratio R_F to quantify the amount of mixed-symmetry character:

$$R_F = \frac{\langle \hat{F} \cdot \hat{F} \rangle}{F_{max}(F_{max} + 1)}, \quad (9)$$

where the numerator stands for the expectation value of the F -spin operator squared:

$$\hat{F} = \hat{F}_+ \cdot \hat{F}_- + F_z^2 - F_z \quad (10)$$

where

$$\hat{F}_+ = (\hat{F}_-)^{\dagger} = s_{\pi}^{\dagger} \cdot s_{\nu} + d_{\pi}^{\dagger} \cdot \tilde{d}_{\nu} \quad \text{and} \quad F_z = (N_{\pi} - N_{\nu})/2. \quad (11)$$

If the R_F ratio for a state is small, the state has mixed-symmetry character. While low-lying states associated with fully symmetric states have more than $R_F = 90\%$, we find for mixed-symmetry states $R_F < 50\%$ (see table 5). Since the selection rule for $M1$ transition between mixed-symmetry states and fully symmetric states still apply, namely that both states must have the same τ quantum numbers, one can still search for strong $M1$ transitions to the first excited 2^+ state.

The ^{94}Mo nucleus is well known for having mixed-symmetry character [4]. Also, in ^{96}Mo one and two mixed-symmetry phonon states are observed [5]. In Fig. 11, the $M1$ strength of 2^+ states to the first excited 2^+ state are plotted against the level energy of the depopulating transition for $^{94-98}\text{Mo}$. A state carrying the largest portion of this $M1$ strength is located at about 2100 keV for all three cases, however, the absolute $M1$ strengths vary strongly. The mixed symmetry states associated to the normal configuration are predicted at 2335 keV, well below the mixed-symmetry state associated with the intruder configuration at 3236 keV. This energy gap between the configurations is roughly the same value as the shift between the configurations Δ . Due to the large energy gap, the one phonon mixed-symmetry state is almost unmixed with 86.7 % contribution of the normal configuration to the wave function. The calculated $B(E2)$ and $B(M1)$ values agree with the experimental values and confirm the preservation of F -spin in ^{96}Mo (see table 5).

However, in ^{98}Mo the basic conditions are different. The energy gap Δ between the configurations is much smaller than in the neighboring ^{96}Mo . Thus, the calculation predicts one-phonon mixed-symmetry states, which are strongly mixed and in the unperturbed configurations close in energy (≈ 200 keV). The one-phonon mixed-symmetry state from the intruder configuration has a large $M1$ strength to the 2_1^+ state, while the

Table 5

Calculated and experimental $B(E2)$ and $B(M1)$ values for ^{96}Mo are shown for the one phonon mixed-symmetry state and the next 2^+ . The lifetimes are adopted from [5] and the remaining values necessary for the calculation of transition strength are taken from this experiment. The exception are those values labeled with ** which are adopted from NDS [26].

$E_{\text{level},i}$ (keV)	$J_i \xrightarrow{E(\text{keV})} J_f$	$R_{F,i}$ (%)	$R_{F,f}$ (%)	$B(M1)_{\text{theo}}$ (μ_N^2)	$B(M1)_{\text{exp}}$ (μ_N^2)
2095	$2_4^+ \xrightarrow{1317} 2_1^+$	42	98	0.24	0.17 (2)
2095	$2_4^+ \xrightarrow{597} 2_2^+$	42	95	0	<0.08
2426	$2_5^+ \xrightarrow{1648} 2_1^+$	80	98	0.02	0.0056^{+19}_{-21} **
2426	$2_5^+ \xrightarrow{928} 2_2^+$	80	95	0.06	0.0003 (3)**
$B(E2)_{\text{theo}}$ (W.u.) $B(E2)_{\text{exp}}$ (W.u.)					
2095	$2_4^+ \xrightarrow{2095} 0_1^+$	42	98	0	0.081 (11)
2095	$2_4^+ \xrightarrow{1317} 2_1^+$	42	98	1	0
2095	$2_4^+ \xrightarrow{947} 0_2^+$	42	94	0	5.0^{+22}_{-17}
2095	$2_4^+ \xrightarrow{597} 2_2^+$	42	95	0	0
2426	$2_5^+ \xrightarrow{1648} 2_1^+$	80	98	0	2.9^{+8}_{-9} **
2426	$2_5^+ \xrightarrow{928} 2_2^+$	80	95	21	6.1^{+11}_{-14} **

mixed-symmetry state belonging to the normal configuration decays strongly with large $M1$ strength to the 2_2^+ state. Our in-beam experiment revealed two candidates for the one phonon mixed-symmetry states of either configuration. The candidates are shown in table 6, which compares calculated and experimental values. Note, that in the case of the $2_{7,9}^+$ states the parity could not be determined, as small $M1/E2$ mixing ratios could also indicate $E1$ transitions. It is assumed, that these states are of positive parity, however, as the depopulating transition only feed positive parity states. One of the obvious shortcomings of the IBM-2 configuration mixing calculation is the over prediction of the $B(M1, 2_{ms}^+ \rightarrow 2_1^+)$ strength in ^{98}Mo compared to data. There are two possible explanations: either, the strongest fragment of the one-phonon mixed-symmetry state has not been populated, which we find rather unlikely with respect to the sensitivity of this experiment, or it is strongly fragmented, so that we miss the remaining $M1$ strength, or in fact the degree of deformation of the ground state (intruder) configuration is underestimated by the model. In the latter case, for a more deformed configuration, one would expect the 2_{ms}^+ state to rise in energy and to fragment leading to weaker $M1$ strength to the 2_1^+ state.

Interestingly, the calculated $M1$ strength connecting the higher-lying mixed-symmetry state, stemming from the near-spherical (normal) configuration, is very close to what we observe in experiment for two states centered at approximately 2.4 MeV (the 2333 keV and 2525 keV states in table 6). The combined $2_{ms}^+ \rightarrow 2_2^+$ $M1$ strength in ^{98}Mo would be similar to that of the near-spherical (normal) ground state configuration in ^{96}Mo . Inspecting Fig. 12, in this case our observations would reveal a decrease of the $2^+ \rightarrow 2^+$ $M1$ strength to the 2_1^+ state, as expected when its nature becomes more deformed, while the $M1$ strength into the 2_2^+ state rises in ^{98}Mo , since this state now carries the bulk of the near-spherical (normal) configuration. The $M1$ strengths from mixed-symmetry states are therefore suggested as an observable sensitive to the effects of shape coexistence

Fig. 11. (Color online) $M1$ strength of 2^+ states to the first excited 2^+ is plotted against excitation energy of the depopulating state. Top figure belongs to ^{94}Mo (a) and the values are adopted from Ref. [4], the middle figure (b) to ^{96}Mo and bottom figure (c) to ^{98}Mo .

and configuration crossing in such isotopic chains.

5. Two phonon mixed-symmetry states

In Refs. [5,52] also candidates for two phonon mixed-symmetry states have been identified, most importantly the 1^+ scissors mode. In table 7 we compare the ground-state $M1$ strengths of the lowest 1^+ states to our calculation. The experimentally observed fragmentation of $B(M1)$ strength is not reproduced by the model where the strength is

Table 6

Calculated and experimental $B(E2)$ and $B(M1)$ values for ^{98}Mo are shown for the one phonon mixed-symmetry state and the higher 2^+ states. Values necessary for the calculation of transition strength are taken from this experiment.

$E_{\text{level},i}$ (keV)	$J_i \xrightarrow{E(\text{keV})} J_f$	$R_{F,i}$ (%)	$R_{F,f}$ %	$B(M1)_{\text{theo}} (\mu_N^2)$	$B(M1)_{\text{exp}} (\mu_N^2)$
2206	$2_4^+ \xrightarrow{1419} 2_1^+$	79	97	0.011	0.059_{-6}^{+7}
2700	$(2_9^+) \xrightarrow{1913} 2_1^+$	57	97	0.13	0.031_{-6}^{+9}
2333	$2_5^+ \xrightarrow{900} 2_2^+$	54	94	0.021	0.153_{-41}^{+87}
2525	$2_7^{(+)} \xrightarrow{1093} 2_2^+$	46	94	0.27	0.094 (12)
<hr/>					
				$B(E2)_{\text{theo}}$ (W.u.)	$B(E2)_{\text{exp}}$ (W.u.)
2206	$2_4^+ \xrightarrow{1419} 2_1^+$	79	97	0.53	1.7 (2)
2700	$(2_9^+) \xrightarrow{1913} 2_1^+$	57	97	0.13	0.009 (2)
2333	$2_5^+ \xrightarrow{900} 2_2^+$	54	94	0.052	1.6_{-4}^{+9}
2525	$2_7^{(+)} \xrightarrow{1093} 2_2^+$	46	94	0.039	0.0043 (6)

Fig. 12. (Color online) $M1$ strength of 2^+ states to the first excited 2^+ shown in red and $M1$ strength of 2^+ states to the second excited 2^+ shown in blue.

concentrated in the first 1^+ state. Also the energy of this calculated state is significantly smaller than the centroid of the observed $B(M1)$ strength, although, close to the energy of the experimental 1^+ state. Hence, even the inclusion of an intruder configuration does not seem to yield sufficient fragmentation. This may be due to the choice of ξ_1 Majorana parameters, which would affect the energies of the calculated 1^+ configurations and the mixing between them. A reliable way to microscopically constrain the Majorana parameters yet needs to be found.

Experimentally [5], the 2^+ state at 2700 keV excitation energy and the 3^+ state at

2736 keV energy are candidates for mixed-symmetry two phonon states on the basis of their enhanced $M1$ transition strengths to the symmetric two-phonon 2^+ state. The corresponding $B(M1)$ values are included in table 7, and compared to the only 2^+ and 3^+ mixed-symmetry states from the calculation which show enhanced $M1$ transitions to the 2_2^+ state. The calculated $M1$ strengths, akin to that of the 1^+ state, do not fragment in the calculation. The calculated $B(M1)$ values reproduce the experimental ones well, however, a fragmentation of these states in experiment cannot be excluded.

Table 7

Calculated and experimental $B(E2)$ and $B(M1)$ values for ^{96}Mo are shown for the two phonon mixed-symmetry 1^+ , 2^+ and 3^+ states. Experimental values are taken from Refs. [5,52]

$J_i^+ \rightarrow J_f^+$	$E(J_i^+)_{\text{theo}}$ (keV)	$B(M1)_{\text{theo}}$ (μ_N^2)	$E(J_i^+)_{\text{exp}}$ (keV)	$B(M1)_{\text{exp}}$ (μ_N^2)
$1_1^+ \rightarrow 0_1^+$	2721	0.292	2794	$0.040^{+0.006}_{-0.005}$
$1_2^+ \rightarrow 0_1^+$	3468	0.0095	3300	$0.12^{+0.03}_{-0.02}$
$1_3^+ \rightarrow 0_1^+$	3789	0.0006	3424	$0.11^{+0.04}_{-0.03}$
$2_6^+ \rightarrow 2_2^+$	3237	0.307	2700	$0.10^{+0.02}_{-0.01}$
$3_3^+ \rightarrow 2_2^+$	3237	0.050	2736	0.06 (1)

6. Summary

Excited low-spin states in ^{96}Mo and ^{98}Mo have been studied in two separate $\gamma\gamma$ angular correlation experiments and allowed the determination of spins, multipole mixing ratios and effective lifetimes in the femto-second range. For ^{96}Mo spin assignments and lifetimes determined in a previous $(n,n'\gamma)$ experiment [5] were confirmed by our data. In some cases conflicting multipole mixing ratios could be resolved. For ^{98}Mo the complete analysis of the experiment YRAST Ball experiment [1] is presented and especially reveals previously unresolved doublet states at ≈ 2300 and ≈ 2400 keV. The results, obtained from the present in-beam experiments, point to shape coexistence in both ^{96}Mo and ^{98}Mo . The signatures for shape coexistence are rather evident in ^{98}Mo : the 0_2^+ state is the first excited state and our Skyrme mean-field calculation suggested that there are two distinct minima in the deformation energy surface. Thus, we introduced configuration mixing in the IBM calculation, that is, two independent Hamiltonians have been associated to different mean-field minima. The result of the IBM configuration mixing calculation compares well with the experimental data from spectroscopy of ^{98}Mo .

On the other hand, the present mean-field calculation did not predict any distinct second minimum in the energy surface for ^{96}Mo . We first carried out the IBM-2 calculation with only a single configuration, by mapping from the mean-field energy surface to the IBM-2 Hamiltonian with a single configuration, resulting in poor agreement of the calculated level scheme between theory and experiment. We also carried out a phenomenological IBM-2 configuration-mixing calculation for ^{96}Mo . The parameters for the unperturbed normal and intruder configurations and the mixing strength have been adopted from Ref. [1] and the Majorana parameters of the normal configuration have been adopted from Sambataro and Mólnar [37]. Solely the energy offset Δ has been adjusted to reproduce the experimental 0_2^+ energy in ^{96}Mo . With this phenomenological calculation, we have been able to reproduce basic features of ^{96}Mo . Due to configuration mixing, $M1$

strengths between the lowest 2^+ states are predicted in agreement with the experiment. Also, the corresponding IBM energy surface shows similarity to the microscopic energy surface. Furthermore, the agreement of the $M1$ strengths from the mixed-symmetry state to the first excited 2^+ state suggests, that F -spin and $O(5)$ quantum numbers are approximately preserved.

$M1$ strengths in ^{98}Mo are investigated as well in terms of one phonon mixed-symmetry states. Since Δ is very small, mixing between the one phonon mixed-symmetry states of both configurations occurs. Interestingly, the mixed-symmetry state of the near-spherical normal configuration seems to fragment into two states only, while the mixed-symmetry state of the intruder configuration seems to fragment strongly.

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Appendix $\gamma\gamma$ angular correlation and lifetime analysis

Fig. A.1. (Color online) Comparison of theoretical angular correlations with different spin hypotheses (black solid, green dashed line and blue dashed line) with relative intensities obtained from eleven correlation groups at the OSIRIS setup for the 778-847 keV $\gamma\gamma$ coincidence. Clearly the multipole mixing ratio $\delta = -0.12(5)$ is favored.

Fig. A.2. (Color online) The spin hypothesis $3 \xrightarrow{480, \delta_{480}} 2 \xrightarrow{719, \delta_{719} = -0.12} 2$ is compared to relative intensities obtained from nine correlation groups at the OSIRIS setup for the 719-480 keV $\gamma\gamma$ coincidences. Clearly the multipole mixing ratio $\delta_{480} = -17.8^{+10.3}_{-64.6}$ (black solid) obtained from a least-squares fit is favored to $\delta_{480} = -0.12$ (4) (green dashed line) reported in Ref. [5].

Fig. A.3. (Color online) Comparison of theoretical angular correlations $3 \xrightarrow{1200, \delta_{1200}} 2 \xrightarrow{778, \delta_{778}=+0.0}$ with relative intensities obtained from nine correlation groups at the OSIRIS setup. Clearly the multipole mixing ratio $\delta_{1200} = 0.34$ (4) (black solid line) is favored to the $E2/M1$ mixing ratio $\delta_{1200} = 0.89$ (10) reported in Ref. [5].

Fig. A.4. (Color online) The spin hypothesis $2 \xrightarrow{644, \delta_{644}} 2 \xrightarrow{787, \delta_{787}=+0.0} 0$ is compared to relative intensities obtained from eleven correlation groups at the YRAST Ball setup. Clearly the multipole mixing ratio $\delta_{644} = +1.67 (25)$ (black solid) obtained from a least-squares fit is favored to $\delta_{644} = +0.27 (2)$ (blue dashed line) reported in Ref. [31] and $\delta_{644} = +0.58 (5)$ (green dashed line) reported in Ref. [32].

Fig. A.5. (Color online) Three different spin hypotheses (black solid and green dashed line, and blue dashed line) were tested with data obtained at the Yrast Ball setup for the 722-909 keV $\gamma\gamma$ cascade. Clearly a spin of 4^+ with $E2/M1$ mixing ratio $\delta_{909} = -0.64$ (10) is favored.

Fig. A.6. (Color online) Three different spin hypotheses (black solid, green dashed line, and blue dashed line) were tested with data obtained at the YRAST Ball setup for the 722-909 keV $\gamma\gamma$ cascade. Clearly a spin of 5^+ with the multipole mixing ratio $\delta_{996} = -0.96$ (10) is favored.

Fig. A.7. (Color online) Three different spin hypotheses (black solid, green dashed line, and blue dashed line) were tested with data obtained at the YRAST Ball setup for the 1432-900 keV $\gamma\gamma$ cascade. A spin assignment $J = 2$ is favored for the state at 2333.03 (24) keV and is confirmed by the angular correlation analysis of the 644-900 keV $\gamma\gamma$ cascade.

Fig. A.8. (Color online) Three different spin hypotheses (black solid, green dashed line, and blue dashed line) were tested with data obtained at the YRAST Ball setup for the 787-1546 keV $\gamma\gamma$ cascade. A spin assignment $J = 4$ is clearly favored for the state at 2333.32 (17) keV and is confirmed by the angular correlation analysis of the 722-823 keV $\gamma\gamma$ cascade.

Fig. A.9. (Color online) Determination of the effective lifetimes from an analysis of the line shapes of the 1190 keV transition a) and the 975 keV transition b) in ^{96}Mo , and the 1419 keV c), 900 keV d), 1093 keV e), 1466 keV f), 1540 keV g), 885 keV h), and the 1213 keV i) in ^{98}Mo . Gates were set on the strongest deexciting transitions, akin to Figs. 5 and 6.

Fig. A.10. (Color online) Determination of the effective lifetimes from an analysis of the deconvoluted line shapes of the 2117 keV transition a) and the 2129 keV transition b) in ^{98}Mo . Gates were set on the strongest deexciting transitions, akin to Figs. 5 and 6.

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