IDENTIFICATION OF MIXED-SYMMETRY STATES IN ^{94}Mo*

C. Fransen, P. von Brentano, A. Gade, V. Werner

Institut für Kernphysik, Universität zu Köln
50937 Köln, Germany

N. Pietralla

A. W. Wright Nuclear Structure Laboratory, Yale University
New Haven, Connecticut 06520-8124, USA

U. Kneissl and H.H. Pitz

Institut für Strahlenphysik, Universität Stuttgart
70569 Stuttgart, Germany

(Received October 31, 2000)

The nucleus ^{94}Mo was investigated using a powerful combination of a photon scattering experiment, an off-beam $\gamma\gamma$ coincidence study following the β^+ decay of ^{94m}Tc, and the fusion-evaporation reaction $^{91}\mathrm{Zr}(\alpha,n)^{94}$Mo. We identified the one-phonon 2^+ Mixed-Symmetry (MS) state and two-phonon MS states in the nucleus ^{94}Mo from the measurement of absolute M1 and E2 transition strengths. These strengths were determined from photon scattering cross sections, Doppler shifts, branching ratios, and E2/M1 mixing ratios. The experimental results are in reasonable agreement with the interacting boson model.

PACS numbers: 21.10.Re, 21.10.Tg, 23.20.Js, 27.60.+j

In most low-lying collective states in heavy nuclei protons and neutrons move in phase. However, the proton–neutron version of the Interacting Boson Model (IBM–2) predicts [1] a class of low-lying states, which contain antisymmetric parts with respect to the proton–neutron degree of freedom. These states are called Mixed-Symmetry (MS) states. From the IBM–2 we expect the following signatures of MS states, which are accessible to

* Presented at the XXXV Zakopane School of Physics "Trends in Nuclear Physics", Zakopane, Poland, September 5–13, 2000.

γ spectroscopy: low excitation energy, weakly collective E2 transitions to the symmetric states, and strong M1 transitions to symmetric states with matrix elements of the order $|\langle J^f_{\rm sym} \parallel {\rm M1} \parallel J^i_{\rm MS}\rangle| \approx 1\mu_N$. Since the low-lying symmetric states decay predominantly by collective E2 transitions, large M1 matrix elements are the key signatures for MS states. One example is the 1^+ MS state, which is called scissors mode due to its geometrical picture in deformed nuclei [2]. It was investigated extensively during the last 15 years in electron scattering [3] and in systematic photon scattering experiments mostly in the rare earth region [4]. This enabled systematic studies of the scissors mode [5–7] including data for weakly deformed nuclei.

The lowest 2^+ MS state is interpreted as the MS one-phonon excitation, which results from an antisymmetric coupling of a proton and a neutron quadrupole excitation. It is orthogonal to the symmetric 2^+_1 state. There are few data about this fundamental $2^+_{\rm MS}$ state: In some weakly deformed nuclei $J^\pi = 2^+$ MS states were identified from lifetime measurements [8–10]. Other MS states are basically unknown. In a vibrator like nucleus we expect the existance of a quintuplet of MS states with the structure $(2^+_1 \otimes 2^+_{\rm MS})^{(0^+,\ldots,4^+)}$, if the boson space is large enough. The scissors mode is the 1^+ member of this multiplet. The present work deals with the identification of the one-phonon $2^+_{\rm MS}$ state and two two-phonon MS states in ^{94}Mo. The 3^+ MS state was observed for the first time.

In order to investigate MS states in ^{94}Mo we performed a new powerful combination of classical γ spectroscopic techniques. From a photon scattering experiment at the DYNAMITRON accelerator in Stuttgart done with bremsstrahlung we got photon scattering cross sections. A $\gamma\gamma$ coincidence study at the Cologne OSIRIS cube coincidence spectrometer following the β^+ decay of the $J^\pi = (2)^+$ isomer of ^{94}Tc yielded multipole-mixing ratios and exact values for branching ratios because of the very clean off-beam spectroscopy. From a combination with the results of the photon scattering experiment we obtained lifetimes of some dipole and quadrupole excited states. In $\gamma\gamma$ coincidence experiments with the fusion–evaporation reaction ^{91}Zr$(\alpha, n)^{94}$Mo at two different beam energies of $E_\alpha = 12$ MeV and 15 MeV we determined lifetimes of excited states using the Doppler shift attenuation method (DSAM) [11]. Moreover the level scheme of ^{94}Mo was expanded and we got multipolarities of transitions from the measurement of angular correlations. At 2067.4 keV we observed the 2^+_3 state. Our data [12] yielded detailed information about the decay properties of this state: It has a weakly collective E2 transition to the ground state with a decay transition strength of 1.8(2) W.u. The E2/M1 multipole mixing ratio $\delta = 0.15(4)$ gives evidence that the $2_3^+ \to 2_1^+$ transition has predominantly $M1$ character. The $2_3^+ \to 2_1^+$ M1 transition matrix element amounts to $1.5(1)\mu_N$. Our data [12] show that the 2_3^+ state is the only of the observed 2^+ states, which decays via an enhanced M1 transition to the 2_1^+ state. The enhanced $2_3^+ \to 2_1^+$ $M1$ transition and the weakly collective $2_3^+ \to 0_1^+$ transition agree with the MS interpretation of this state [12].

The 1_1^+ state was observed at 3128.6 keV. The decay transition strengths of this state give clear evidence for the interpretation of this state as the 1^+ MS two-phonon state, the scissors mode: We obtained a strong M1 transition to the symmetric two-phonon 2_2^+ state with a transition matrix element of $|\langle 2_2^+ \parallel \mathrm{M1} \parallel 1_1^+ \rangle| = 1.14(7)\mu_N$ as expected from the IBM–2 for a two-phonon MS state. A weakly collective E2 transition to the 2_1^+ with an E2 transition strength of $B(\mathrm{E2}; 1_1^+ \to 2_1^+) = 1.2(4)$ W.u. comparable to the $2_{\mathrm{MS}}^+ \to 0_1^+$ transition strength was determined. We got a strong $1_1^+ \to 2_{\mathrm{MS}}^+$ transition of $B(\mathrm{E2}; 1_1^+ \to 2_{\mathrm{MS}}^+) = 24.4(28)$ W.u., if pure E2 character is assumed. This value is in the same order of magnitude as the strength of the $2_1^+ \to 0_1^+$ decay [12]. The decay transitions of the 1^+ state are shown in Fig. 1 to visualize the two-phonon character. At 2965.4 keV the 3_2^+ state was observed. Fig. 1 represents the decay transitions of this state. All decays

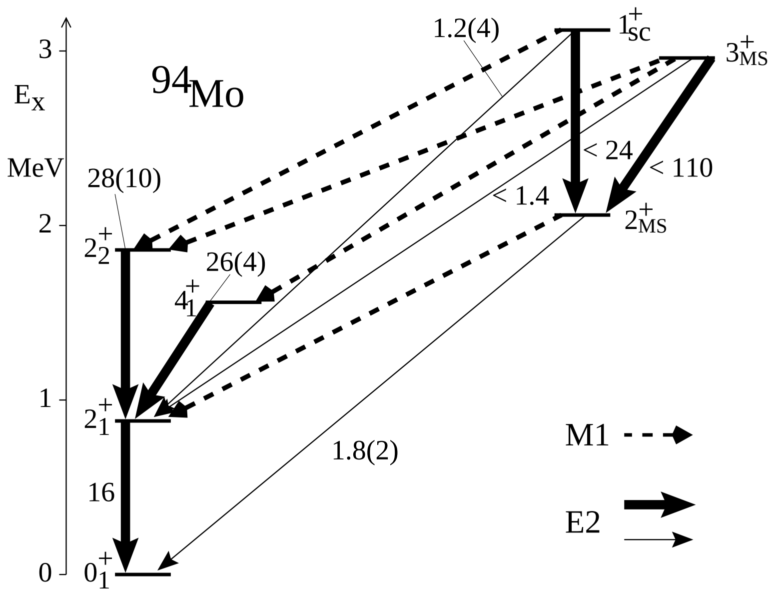

Fig. 1. Partial level scheme of ^{94}Mo (from [13]). The numbers denote B(E2) values in Weisskopf units. For B(M1) values see Table I.

are consistent with the interpretation of this state as a two-phonon MS state: Our data yield strong M1 transitions to the symmetric two-phonon states with M1 matrix elements of the order of one nuclear magneton giving evidence for the MS interpretation: $|\langle 4_1^+ \parallel \mathrm{M1} \parallel 3_2^+\rangle| = 0.72^{+0.19}_{-0.10}\,\mu_N$ and $|\langle 2_2^+ \parallel \mathrm{M1} \parallel 3_2^+\rangle| = 1.30^{+0.33}_{-0.21}\,\mu_N$. The E2 transition to the 2_1^+ state may be weakly collective with a transition strength of about one Weisskopf unit. The $3_2^+ \rightarrow 2_{\mathrm{MS}}^+$ transition is consistent with a collective E2 strength with tens of Weisskopf units. The uncertainties of the mixing ratios in both cases prevent definite numbers. Table I shows a comparison of the measured M1

TABLE I

Comparison of analytical IBM–2 predictions using the core ^{100}Sn with $N_\pi = 4$ for M1 strengths (in μ_N^2) of MS states with experimental data on ^{94}Mo. Orbital values, $g_\pi = 1\,\mu_N$ and $g_\nu = 0\,\mu_N$, are used for the boson g-factors.

Observable	U(5)	O(6)	Experimental	Ref.
$B(\mathrm{M1}; 1_{\mathrm{MS}}^+ \rightarrow 0_1^+)$	0	0.16	0.16(1)	[12]
$B(\mathrm{M1}; 1_{\mathrm{MS}}^+ \rightarrow 2_2^+)$	0.33	0.36	0.43(5)	[12]
$B(\mathrm{M1}; 2_{\mathrm{MS}}^+ \rightarrow 2_1^+)$	0.23	0.30	0.48(6)	[12]
$B(\mathrm{M1}; 3_{\mathrm{MS}}^+ \rightarrow 2_2^+)$	0.16	0.18	$0.24^{+0.14}_{-0.07}$	[13]
$B(\mathrm{M1}; 3_{\mathrm{MS}}^+ \rightarrow 4_1^+)$	0.12	0.13	$0.074^{+0.044}_{-0.019}$	[13]

transition strengths of MS states in ^{94}Mo with the results of theoretical calculations in the U(5) and O(6) limit of the IBM–2. The good agreement gives clear evidence for the MS interpretation of the corresponding states. Due to the $1_1^+ \rightarrow 0_1^+$ strength U(5) symmetry has at least to be broken.

This work was supported by the DFG under Grants No. Br 799/9-1, No. Pi 393/1-1, and No. Kn 154/30.

REFERENCES

[1] F. Iachello, *Phys. Rev. Lett.* **53**, 1427 (1984).
[2] N. Lo Iudice, F. Palumbo, *Phys. Rev. Lett.* **41**, 1532 (1978).
[3] A. Richter, *Prog. Part. Nucl. Phys.* **34**, 261 (1995).
[4] U. Kneissl, H.H. Pitz, A. Zilges, *Prog. Part. Nucl. Phys.* **37**, 349 (1996).
[5] N. Pietralla *et al.*, *Phys. Rev.* **C52**, R2317 (1995).

[6] N. Pietralla *et al., Phys. Rev.***C58**, 184 (1998).
[7] J. Enders *et al., Phys. Rev.* **C59**, R1851 (1999).
[8] P. von Brentano *et al.*, Proc. Int. Conf. on Nuclear Structure, Gatlinburg, Tennessee, USA, 1998 (*AIP*, 1998) and refs. therein.
[9] N. Pietralla *et al., Phys. Rev.* **C58**, 796 (1998).
[10] P.E. Garrett *et al., Phys. Rev.* **C54**, 2259 (1996).
[11] P. Petkov *et al., Nucl. Phys.* **A640**, 293 (1998).
[12] N. Pietralla, C. Fransen *et al., Phys. Rev. Lett.* **83**, 1303 (1999).
[13] N. Pietralla, C. Fransen *et al., Phys. Rev. Lett.* **84**, 3775 (2000).