Transition Rates between Mixed Symmetry States: First Measurement in ^{94}Mo

N. Pietralla,[1] C. Fransen,[1] D. Belic,[2] P. von Brentano,[1] C. Frießner,[1] U. Kneissl,[2] A. Linnemann,[1] A. Nord,[2]
H. H. Pitz,[2] T. Otsuka,[3] I. Schneider,[1] V. Werner,[1] and I. Wiedenhöver[1,*]

[1]*Institut für Kernphysik, Universität zu Köln, 50937 Köln, Germany*
[2]*Institut für Strahlenphysik, Universität Stuttgart, 70569 Stuttgart, Germany*
[3]*Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
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The nucleus ^{94}Mo was investigated using a powerful combination of γ-singles photon scattering experiments and $\gamma\gamma$-coincidence studies following the β decay of ^{94}Tc^m. The data survey short-lived $J^\pi = 1^+, 2^+$ states and include branching ratios, $E2/M1$ mixing ratios, lifetimes, and transition strengths. The proton-neutron mixed-symmetry (MS) 1^+ scissors mode and the 2^+ MS state are identified from $M1$ strengths. A γ transition between MS states was observed and its rate was measured. Nine $M1$ and $E2$ strengths involving MS states agree with the O(6) limit of the interacting boson model-2 using the proton boson $E2$ charge as the only free parameter.

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Enhanced magnetic dipole $(M1)$ γ transitions between low-lying states of heavy nuclei are of great interest [1]. Investigations were influenced by LoIudice and Palumbo [2] predicting the scissors mode. Later, Iachello predicted [3] enhanced $M1$ transitions between low-lying states within the proton-neutron (pn) version [4] of the interacting boson model (IBM-2). According to the IBM-2 approach, an enhanced $M1$ strength is a general feature of a pn degree of freedom. The pn symmetry of an IBM-2 wave function is quantified by the F-spin quantum number [5]. F spin is the isospin for the elementary proton and neutron bosons. The IBM-2 predicts enhanced $M1$ transitions between states with F-spin quantum numbers $F_{\max}$ and $F_{\max} - 1$. The latter are not fully symmetric with respect to the pn degree of freedom and are called mixed-symmetry (MS) states.

The recently proposed Q-phonon scheme [6–8] is an approximate scheme in the IBM. In this scheme the wave functions of the lowest symmetric and MS [9–11] states are approximated by simple expressions involving the proton and neutron quadrupole operators:

$$|2_1^+\rangle \propto Q_s|0_1^+\rangle, \qquad F = F_{\max}, \qquad (1)$$

$$|2_2^+\rangle \propto (Q_s Q_s)^{(2)}|0_1^+\rangle, \qquad F = F_{\max}, \qquad (2)$$

$$|2_{\rm ms}^+\rangle \propto Q_{\rm m}|0_1^+\rangle, \qquad F = F_{\max} - 1, \qquad (3)$$

$$|1_{\rm sc}^+\rangle \propto (Q_s Q_{\rm m})^{(1)}|0_1^+\rangle, \qquad F = F_{\max} - 1. \qquad (4)$$

Here, $Q_s = Q_\pi + Q_\nu$ is the symmetric sum of the proton and neutron boson quadrupole operators and $Q_{\rm m} = Q_\pi/N_\pi - Q_\nu/N_\nu$ is the orthogonal linear combination with $\langle 0_1^+|Q_s \cdot Q_{\rm m}|0_1^+\rangle = 0$. N_π (N_ν) denotes the number of proton (neutron) bosons. The Q-phonon scheme generalizes the bosonic phonon concept in vibrators. In contrast to that, the Q operators do not have to obey the boson commutation relation. Furthermore, the Q operators are applied to the true ground state, which can be correlated. The lowest 2^+ MS state is interpreted as the MS one-Q-phonon excitation, which is orthogonal to the symmetric one-Q-phonon excitation, the 2_1^+ state. The $1_{\rm sc}^+$ state is a MS two-Q-phonon state. The two-Q-phonon structure can be tested by measuring $E2$ strengths of decay transitions from the MS 1^+ and 2^+ states. Enhanced $M1$ transitions between states with F-spin quantum numbers $F_{\max}$ and $F_{\max} - 1$ are expected to have matrix elements of the order of $1\mu_N$. In γ-soft nuclei, one expects [12], for instance, the following enhanced $M1$ transitions: $1_{\rm sc}^+ \to 2_2^+$ and $2_{\rm ms}^+ \to 2_1^+$.

In the early 1980s, Richter and co-workers discovered the MS $J^\pi = 1_{\rm sc}^+$ state in electron scattering (e, e') experiments [13] in Darmstadt. This discovery was supported by photon scattering (γ, γ') experiments [14] in Stuttgart. Subsequent (e, e') [1] and systematic (γ, γ') experiments [15] accumulated knowledge about the 1^+ scissors mode. This enabled systematic studies of the $M1$ excitation strength [16,17] and the excitation energy [18,19] of the 1^+ scissors mode, including information on weakly deformed nuclei. Knowledge about other MS states is sparser. In some weakly deformed nuclei $J^\pi = 2^+$ MS states were identified from lifetime measurements (e.g., Refs. [10,20]). Further information about MS states was deduced from inelastic hadron scattering cross sections (e.g., Ref. [21]), from $E2/M1$ mixing ratios δ (e.g., Refs. [22,23]) and electron conversion coefficients measured in β-decay studies (e.g., Ref. [24]).

In this Letter we report on the identification of the 2^+ MS state *and* the 1^+ MS state in ^{94}Mo. We identify the MS states from measured $M1$ strengths. We discuss the decays of the observed MS states including the first measurement of a transition rate between MS states and the first $E2$ strength of the $1_{\rm sc}^+ \to 2_1^+$ transition. This new information on MS states was accessible due to the new and powerful combination of a (γ, γ') experiment on ^{94}Mo and a $\gamma\gamma$-coincidence measurement of transitions following the β decay of ^{94}Tc to ^{94}Mo. Thereby, we combine the capability of two experimental techniques: (a) the singles spectroscopy by resonant photon scattering providing lifetime and spin information, and (b) the clean off-beam spectroscopy of $\gamma\gamma$ coincidences of transitions following β decay, enabling the measurement of small γ branches and multipole mixing ratios. In favored cases β decay strongly populates highly excited low-spin states among which we identify MS states. From this new combination of techniques we obtain a richness of information on absolute transition strengths from MS states, which gives a new quality to the investigation of MS states.

The photon scattering experiments were performed at the Dynamitron accelerator [15] in Stuttgart. For bremsstrahlung production we used electron beams with energies of $E_e = 4.0$ MeV and $E_e = 3.3$ MeV. Figure 1 shows the (γ, γ') spectrum off ^{94}Mo taken at incident photon energies $E_\gamma < 3.3$ MeV. The 1^+ state at 3129 keV with lifetime $\tau = 10(1)$ fs and the 2_3^+ state at 2067 keV with $\tau = 60(9)$ fs are strongly excited. Below we interpret these states as the main fragments of the 1^+ scissors mode and the 2^+ MS state in ^{94}Mo. We measured the photon scattering cross sections $I_{s,f} = g\pi^2 \lambda\!\!\!^{-2} \Gamma_0 \Gamma_f / \Gamma$, where $g = (2J + 1)/(2J_0 + 1)$ is a statistical factor and $\lambda\!\!\!^{-} = \hbar c / E_\gamma$ is the reduced wavelength. Γ and Γ_0 (Γ_f) are the total level width and the partial decay width to the ground (final) state.

Decay intensity ratios Γ_f / Γ were measured for low-spin states in ^{94}Mo in a study of γ rays following the β decay of the $J^\pi = (2)^+$ low-spin isomer, ^{94}Tc^m. We produced ^{94}Tc^m nuclei in the center of the Cologne coincidence cube spectrometer using the reaction ^{94}Mo$(p, n)^{94}$Tc at an energy of $E_p = 13$ MeV. The beam was periodically switched on for 5 s to create activity and switched off for 5 s to observe singles γ spectra and $\gamma\gamma$ coincidences of transitions following the β decays. The singles spectrum between 1.9 and 3.3 MeV is displayed in the left-hand side of Fig. 2. The high counting rate, the low background in this off-beam measurement, and the isotropy of the γ radiation after β decay enabled us to precisely determine the intensity ratios Γ_f / Γ. From our $\gamma\gamma$-coincidence data, we could place a 1062 keV transition in the level scheme of ^{94}Mo. The right-hand side of Fig. 2 shows the 1062 keV transition in the background-subtracted γ spectrum, which we observed in coincidence with the $2_3^+ \to 2_1^+$ transition. The 1062 keV transition populates the 2_3^+ state at 2067 keV directly from the 1_1^+ state at 3129 keV. This transition is interpreted below as the $1_{\rm sc}^+ \to 2_{\rm ms}^+$ transition between MS states. This is the first identification of such a transition.

Combining the measured photon scattering cross sections $I_{s,f} \propto \Gamma_0 \Gamma_f / \Gamma$ and the decay intensity ratios Γ_0 / Γ from the β-decay experiment, we determined partial decay widths Γ_f, total level widths $\Gamma = \sum \Gamma_f$, lifetimes $\tau = \hbar / \Gamma = 1 / \sum w_f$, and transition rates $w_f = \Gamma_f / \hbar$. The transition rates enable a unique identification of short-lived collective states. For the most intense γ transitions, we determined the $E2/M1$ mixing ratios $\delta^2 = \Gamma_{f,E2} / \Gamma_{f,M1}$ from the measured $\gamma\gamma$-angular correlations. Details will be given in a subsequent full length article. The measured, partial, single-multipolarity decay widths $\Gamma_{f,\pi\lambda}$ are proportional to the reduced transition strengths $B(\pi\lambda)$.

Figure 3 shows measured $M1$ and $E2$ strengths which are relevant for the identification of 1^+ and 2^+ MS states. For the $2_{1,2}^+$ states the $E2$ excitation strengths have been taken from [26,27]; all other data are from this work. The total $M1$ strength from the ground state to the 1^+ states at 3129 and 3512 keV amounts to $\sum B(M1) \uparrow = 0.61(7) \mu_N^2$. The weighted average 1^+ energy lies at 3.2 MeV. These data fit well into the systematics of the 1^+ scissors mode observed so far: From the empirical formulas [16,18,19], extracted from data on the 1^+ scissors mode in the rare earth region, we expect the scissors mode in ^{94}Mo at an excitation energy of 3.2–3.5 MeV with a total excitation strength of $B(M1) \uparrow \approx 0.55 \mu_N^2$. The extrapolation of the

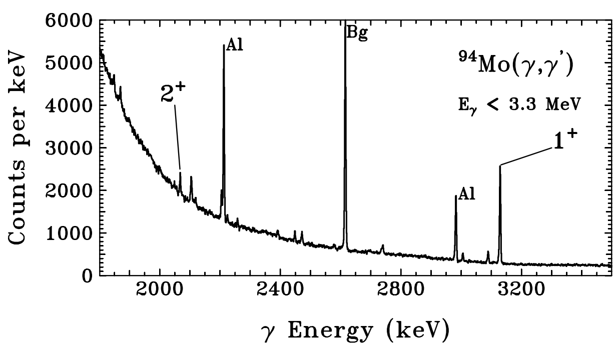

FIG. 1. Photon scattering spectrum off ^{94}Mo in the energy range of MS states. At 2067 and 3129 keV we observe ground state transitions of strongly excited 2^+ and 1^+ states. Photon scattering cross sections are measured relative to well known [25] cross sections in ^{27}Al, which is irradiated simultaneously (marked "Al"). "Bg" denotes background lines.

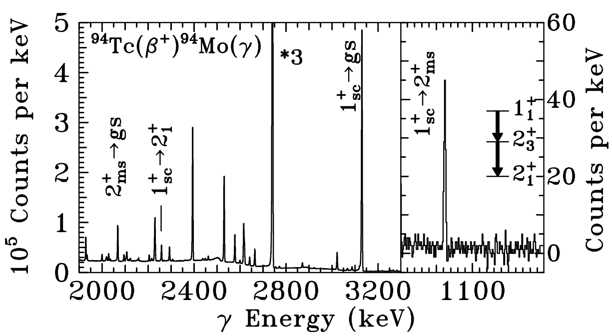

FIG. 2. Left: part of the observed spectrum of γ rays following the β decay of the $J^\pi = (2)^+$ low-spin isomer of ^{94}Tc populated in the ^{94}Mo(p, n) reaction. High statistics and low background enable us to observe weak decay branches and to measure $\gamma\gamma$ coincidences for decays of MS states. Right: part of the $\gamma\gamma$-coincidence spectrum gated with the $2_3^+ \to 2_1^+$ transition. The coincident observation of the 1062 keV line establishes the population of the 2_3^+ state at 2067 keV from the 1_1^+ state at 3129 keV.

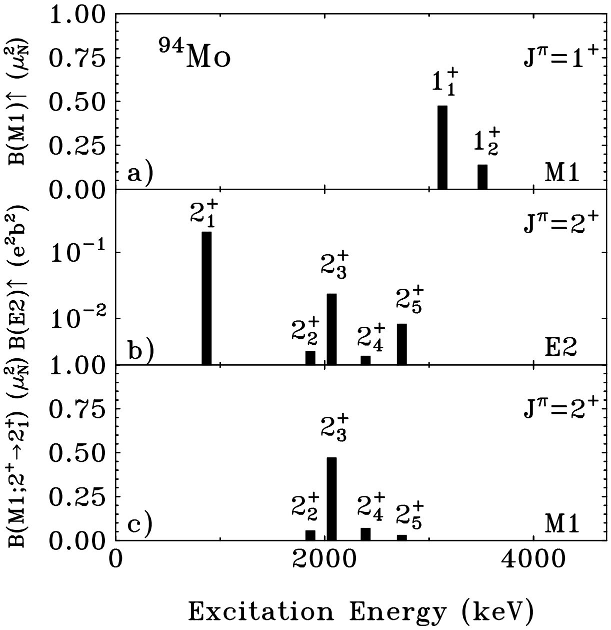

FIG. 3. Measured $M1$ and $E2$ transition strengths relevant for the identification of 1^+ and 2^+ MS states in ^{94}Mo. Panels (a) and (b) display the $M1$ and $E2$ excitation strength distributions versus the excitation energies of the 1^+ and 2^+ states. Panel (c) shows the $B(M1; 2^+ \rightarrow 2_1^+)$ values for the four lowest non-yrast 2^+ states. The 1_1^+ state is the main fragment of the scissors mode. The 2_3^+ state is the main fragment of the 2^+ MS state.

empirical formulae agree with our observations. This is a strong argument that the 1_1^+ state is the main fragment of the scissors mode (1^+ MS state) in ^{94}Mo.

The $E2$ strength distribution, shown in Fig. 3b, is dominated by the 2_1^+ state, which is the pn symmetric one-Q-phonon excitation. The $E2$ excitation strength of the 2_3^+ state amounts to 10% of the $0_1^+ \rightarrow 2_1^+$ strength. This is 1 order of magnitude more than the $E2$ excitation strength to the 2_2^+ state, which is a symmetric two-Q-phonon state. The weakly collective $0_1^+ \rightarrow 2_3^+$ $E2$ transition suggests that the 2_3^+ state is a one-Q-phonon excitation, in agreement with Eq. (3). Figure 3c shows the $M1$ transition strengths of the four lowest non-yrast 2^+ states to the 2_1^+ state. Only the 2_3^+ state decays via an enhanced $M1$ transition to the 2_1^+ state. The enhanced $2_3^+ \rightarrow 2_1^+$ $M1$ transition and the weakly collective $2_3^+ \rightarrow 0_1^+$ $E2$ transition agree with the MS interpretation for the 2_3^+ state.

The 1_1^+ state and the 2_3^+ state can be described quantitatively as MS states in IBM-2. In order to reduce the number of free parameters, we compare the measured transition strengths to the predictions of the O(6) dynamical symmetry.

[We use the Ginocchio sum rule for $B(M1)$ strength [28] and the total strength $\sum B(M1) \uparrow = 0.61(7)\mu_N^2$, which we observed below 4 MeV, and we derive a fraction of 42(5)% d bosons in the IBM-2 ground state wave function of ^{94}Mo. This large d-boson content rules out the U(5) dynamical symmetry limit (no d boson in the ground state) for an adequate IBM-2 description of ^{94}Mo and favors the O(6) limit, which predicts a fraction of 33% d bosons in the IBM-2 ground state of ^{94}Mo.]

These predictions are independent of any Hamiltonian parameters and are simple analytical expressions [12], which involve the boson numbers and the parameters of the transition operators, only. We consider the doubly closed shell nucleus ^{100}Sn as the core and, consequently, use $N_\pi = 4$ proton bosons and $N_\nu = 1$ neutron bosons. We further reduced the number of parameters in the transition operators by restricting them to the proton parts alone: $T(M1) = \sqrt{3/4\pi}\, g_\pi L_\pi$ and $T(E2) = e_\pi Q_\pi$. Here L_π and Q_π are the standard proton angular momentum operator and the proton quadrupole operator in the O(6) limit ($\chi_\pi = 0$). Moreover, we must assume the orbital value $g_\pi = 1\mu_N$ for the proton boson g factor, leaving the effective quadrupole boson charge $e_\pi = 9e$ fm^2 the only adjustable parameter for the description of absolute $M1$ and $E2$ transition strengths.

[In a recent numerical IBM-2 calculation [10] for symmetric and mixed-symmetry states in the ($N_\nu = 1$)-nucleus ^{136}Ba, good agreement between theoretical and experimental $E2$ transition strengths was obtained by also using a vanishing effective quadrupole neutron boson charge $e_\nu = 0$ and a comparably large effective quadrupole proton boson charge $e_\pi = 15.6e$ fm^2.]

Table I summarizes the relevant spectroscopic information in comparison to the IBM-2 values in the O(6) dynamical symmetry limit. The data, including nine transition strengths from the 1^+ and 2^+ MS states, are in reasonable agreement with the O(6) limit of the IBM-2 using the effective proton boson quadrupole charge e_π as the only free parameter.

For γ-soft nuclei, $M1$ transitions obey selection rules [29] with respect to the d-parity quantum number $\pi_d = (-1)^{n_Q}$, i.e., the number of Q phonons n_Q modulo 2 does not change. According to Eqs. (1)–(4), the $M1$ transition from the 1_1^+ state to the 2_1^+ state is d-parity forbidden [29], while the $1_1^+ \rightarrow 2_2^+$ $M1$ transition is allowed. The measured ratio of the corresponding $M1$ strengths is 0.02, confirming the d-parity selection rule. A dominant $E2$ character of the $1_{sc}^+ \rightarrow 2_1^+$ transition in γ-soft nuclei was previously assumed for the interpretation of data for the nuclei ^{196}Pt [30] and ^{134}Ba [31]. Our measurement supports the earlier assumptions.

Of particular interest is the comparison of the $E2$ strengths, which are interpreted in the Q-phonon scheme as the annihilation of the MS Q-phonon, Q_m. According to Eqs. (3) and (4), the MS Q-phonon, Q_m, is annihilated in both the weakly collective $E2$ transitions $2_{ms}^+ \rightarrow 0_1^+$ and $1_{sc}^+ \rightarrow 2_1^+$, respectively. The ratio of the measured $B(E2)$ values is

$$\frac{B(E2; 1_1^+ \rightarrow 2_1^+)}{B(E2; 2_3^+ \rightarrow 0_1^+)} = 0.7(3)\,. \qquad (5)$$

TABLE I. Comparison of measured transition strengths to the prediction of the O(6) limit of the IBM-2, where the 1_1^+, 2_3^+ states have MS. The IBM-2 reproduces the dominant $E2$ character of the $1^+ \to 2_1^+$ transition. Many transition strengths and the transition rate w between the MS states are reproduced on an absolute scale using one free parameter $e_\pi = 9e$ fm^2 only.

Observable	Expt.	IBM-2
$B(M1;1_1^+ \to 0_1^+)$ (μ_N^2)	0.16(1)	0.16
$B(M1;1_1^+ \to 2_1^+)$ (μ_N^2)	0.007^{+6}_{-2}	0
$B(M1;1_1^+ \to 2_2^+)$ (μ_N^2)	0.43(5)	0.36
$B(M1;1_1^+ \to 2_3^+)$ (μ_N^2)	<0.05	0
$B(M1;2_2^+ \to 2_1^+)$ (μ_N^2)	0.06(2)	0
$B(M1;2_3^+ \to 2_1^+)$ (μ_N^2)	0.48(6)	0.30
$B(M1;2_4^+ \to 2_1^+)$ (μ_N^2)	0.07(2)	0
$B(M1;2_5^+ \to 2_1^+)$ (μ_N^2)	0.03(1)	0
$w(1_1^+ \to 2_3^+)$ (ps^{-1})	1.02(12)	0.92
$\frac{I_\gamma(E2)}{I_\gamma}(1^+ \to 2_1^+)$ (%)	60^{+12}_{-21}	100
$B(E2;0_1^+ \to 2_1^+)$ $(e^2$ fm$^4)$	2030(40)[a]	2333
$B(E2;0_1^+ \to 2_2^+)$ $(e^2$ fm$^4)$	32(7)[a]	0
$B(E2;0_1^+ \to 2_3^+)$ $(e^2$ fm$^4)$	230(30)	151
$B(E2;0_1^+ \to 2_4^+)$ $(e^2$ fm$^4)$	27(8)	0
$B(E2;0_1^+ \to 2_5^+)$ $(e^2$ fm$^4)$	83(10)	0
$B(E2;2_2^+ \to 2_1^+)$ $(e^2$ fm$^4)$	720(260)	592
$B(E2;4_1^+ \to 2_1^+)$ $(e^2$ fm$^4)$	670(100)[a]	592
$B(E2;2_3^+ \to 2_1^+)$ $(e^2$ fm$^4)$	<150	0
$B(E2;1_1^+ \to 2_1^+)$ $(e^2$ fm$^4)$	30(10)	49
$B(E2;1_1^+ \to 2_3^+)$ $(e^2$ fm$^4)$	<690[b]	556

[a]From Refs. [26,27].
[b]Assuming pure $E2$ character, the value is $620(70)e^2$ fm^4.

Within the error this $B(E2)$ ratio is one. We conclude, that the 1_1^+ state is a two-Q-phonon excitation of the ground state, built up by the coupling of the symmetric (Q_s) and the mixed-symmetric ($Q_{\rm m}$) Q-phonon operators. Analogously, one expects from Eqs. (1) and (4) collective $E2$ strengths for the $1_{\rm sc}^+ \to 2_{\rm ms}^+$ and the $2_1^+ \to 0_1^+$ transitions. In the present paper, the transition rate of the $1_{\rm sc}^+ \to 2_{\rm ms}^+$ transition is measured. This represents the first measurement of a transition rate between two MS states. Because of the too weak intensity of the $1_1^+ \to 2_3^+$ transition, the $E2/M1$ mixing ratio could not be measured. From the d-parity selection rules we expect a dominant $E2$ character of the $1_{\rm sc}^+ \to 2_{\rm ms}^+$ transition. Assuming a vanishing $M1$ contribution, the ratio of the energy-reduced transition rates

$$\frac{w_{1_1^+\to 2_3^+}/E_\gamma(1_1^+ \to 2_3^+)^5}{w_{2_1^+\to 0_1^+}/E_\gamma(2_1^+ \to 0_1^+)^5} = 1.5(2) \qquad (6)$$

equals the corresponding $B(E2)$ ratio. We find indeed a collective $E2$ strength, which is comparable to the collective $2_1^+ \to 0_1^+$ decay strength. This fact gives further support for the two-Q-phonon interpretation of the 1_1^+ state in ^{94}Mo. The weakly collective $E2$ transition from the 1_1^+ state to the 2_1^+ state and the probable collective $E2$ transition to the $2_{\rm ms}^+$ state represent—besides the large $M1$ transition strengths—new and independent observables for the collectivity of the 1^+ scissors mode. It is interesting that these observables are deduced from E2 properties, which are considered to be well described by the IBM.

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*Present address: Argonne National Laboratory, Argonne, Illinois 60439.

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