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

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Abstract

The nucleus $^{94}$Mo was investigated using a powerful combination of $\gamma$-singles photon scattering experiments and $\gamma\gamma$-coincidence studies following the $\beta$-decay of $^{94m}$Tc. 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 $\gamma$ 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 Lo Iudice and Palumbo [2] predicting the scissors mode. Later on, Iachello predicted [3] enhanced M1 transitions between low-lying states within the proton-neutron (pn) version [1] 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 $F$. 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 $F_{\text{max}}$ and $F_{\text{max}} - 1$. 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 [4–8] 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:

$$
|2_1^+\rangle \propto Q_s |0_1^+\rangle \quad F = F_{\text{max}} \\
|2_2^+\rangle \propto (Q_s Q_\nu)^{(2)} |0_1^+\rangle \quad F = F_{\text{max}} \\
|2_{\text{ms}}^+\rangle \propto Q_m |0_1^+\rangle \quad F = F_{\text{max}} - 1 \\
|1_{\text{sc}}^+\rangle \propto (Q_s Q_m)^{(1)} |0_1^+\rangle \quad F = F_{\text{max}} - 1.
$$

Here, $Q_s = Q_s + Q_\nu$ is the symmetric sum of the proton and neutron boson quadrupole operators and $Q_m = Q_\pi/N_\pi - Q_\nu/N_\nu$ is the orthogonal linear combination with $\langle 0_1^+ | Q_s, Q_m | 0_1^+ \rangle = 0$. $N_\pi$ ($N_\nu$) 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 $1_{\text{sc}}^+$ 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 $F_{\text{max}}$ and $F_{\text{max}} - 1$ 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: $1_{\text{sc}}^+ \rightarrow 2_2^+$ and $2_{\text{ms}}^+ \rightarrow 2_1^+$.

In the early 1980ies Richter and co-workers discovered the MS $J^\pi = 1_{\text{sc}}^+$ state in electron scattering $(e,e')$ experiments [13] in Darmstadt. This discovery was supported by photon scattering $(\gamma,\gamma')$ experiments [14] in Stuttgart. Subsequent $(e,e')$ [15] and systematic $(\gamma,\gamma')$ 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. [10,20]). Further information about MS states was deduced from inelastic hadron scattering cross sections (e.g. [21]), from $E2/M1$ mixing ratios $\delta$ (e.g. [22,23]) and electron conversion coefficients measured in β-decay studies (e.g. [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 $1_{\text{sc}}^+ \rightarrow 2_1^+$ transition. This new information on MS
states was accessible due to the new and powerful combination of a \((\gamma,\gamma')\) experiment on \(^{94}\text{Mo}\) and a \(\gamma\gamma\)-coincidence measurement of transitions following the \(\beta\)-decay of \(^{94}\text{Tc}\) to \(^{94}\text{Mo}\). 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 \(\beta\)-decay enabling the measurement of small \(\gamma\) branches and multipole mixing ratios. In favored cases \(\beta\)-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 [13] in Stuttgart. For bremsstrahlung production we used electron beams with energies of \(E_e = 4.0\) MeV and \(E_e = 3.3\) MeV. Figure 2 shows the \((\gamma,\gamma')\) spectrum of \(^{94}\text{Mo}\) 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 \(^{94}\text{Mo}\). We measured the photon scattering cross sections \(I_{s,f} = g^2 \pi^2 \lambda^2 \Gamma_0 / \Gamma\), where \(g = (2J + 1)/(2J_0 + 1)\) is a statistical factor and \(\lambda = \hbar c/E_\gamma\) is the reduced wave length. \(\Gamma\) and \(\Gamma_0\) are the total level width and the partial decay width to the ground (final) state.

Decay intensity ratios \(\Gamma_f/\Gamma\) were measured for low-spin states in \(^{94}\text{Mo}\) in a study of \(\gamma\)-rays following the \(\beta\)-decay of the \(J^\pi = (2)^+\) low-spin isomer, \(^{94}\text{mTc}\). We produced \(^{94}\text{mTc}\) nuclei in the center of the Cologne coincidence cube spectrometer using the reaction \(^{94}\text{Mo}(p,n)^{94}\text{Tc}\) at an energy of \(E_p = 13\) MeV. The beam was periodically switched on for 5 seconds to create activity and switched off for 5 seconds to observe singles \(\gamma\) spectra and \(\gamma\gamma\)-coincidences of transitions following the \(\beta\)-decays. The singles spectrum between 1.9 MeV and 3.3 MeV is displayed in Fig. 2 on the left. The high counting rate, the low background in this off-beam measurement and the isotropy of the \(\gamma\) radiation after \(\beta\)-decay enabled us to precisely determine the intensity ratios \(\Gamma_f/\Gamma\). From our \(\gamma\gamma\)-coincidence data, we could place a 1062 keV transition in the level scheme of \(^{94}\text{Mo}\). The right part of Fig. 2 shows the 1062 keV transition in the background-subtracted \(\gamma\) spectrum, which we observed in coincidence with the \(2^+_3 \rightarrow 2^+_2\) transition. The 1062 keV transition populates the \(2^+_1\) state at 2067 keV directly from the \(1^+_1\) state at 3129 keV. This transition is interpreted below as the \(1^+_1 \rightarrow 2^+\) 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 \(\Gamma_0/\Gamma\) from the \(\beta\)-decay experiment, we determined partial decay widths \(\Gamma_f\), total level widths \(\Gamma = \sum \Gamma_f\), lifetimes \(\tau = \hbar / \Gamma = 1 / \sum w_f\), and transition rates \(w\)). The transition rates enable an unique identification of short-lived collective states. For the most intense \(\gamma\) transitions we could determine \(E2/M1\) 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 \(2^+_1\) states the \(E2\) excitation strengths have been taken from [25,27]; all other data are from this work. The total \(M1\) strength from the ground state to the \(1^+\) states at 3129 keV 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 formulae [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 $3.2-3.5\text{ MeV}$ with a total excitation strength of $B(M1) \uparrow \approx 0.55 \mu_N^2$. The extrapolation of the 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 $2^+_1$ state amounts to 10% of the $0^+_1 \to 2^+_1$ strength. This is one 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 $0^+_1 \to 2^+_1$ $E2$ transition suggests that the $2^+_1$ state is a one-$Q$-phonon excitation, in agreement with Eq. (3). Part c) of Fig. 3 shows the $M1$ transition strengths of the four lowest non-yrast $2^+$ states to the $2^+_1$ state. Only the $2^+_2$ state decays via an enhanced $M1$ transition to the $2^+_1$ state. The enhanced $2^+_1 \to 2^+_1 M1$ transition and the weakly-collective $2^+_1 \to 0^+_1 E2$ transition agree with the MS interpretation for the $2^+_1$ state.

The $1^+_1$ state and the $2^+_1$ 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. 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 boson. We reduced the number of parameters in the transition operators further 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 $L_\pi$ and $Q_\pi$ 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 $e_\pi = 9 \text{ efm}^2$ the only adjustable parameter for the description of absolute $M1$ and $E2$ transition strengths. Table I summarizes the relevant spectroscopic information in comparison to the IBM-2 values in the O(6) dynamical symmetry limit. The data, including 9 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 $e_\pi$ as the only free parameter.

For $\gamma$-soft nuclei $M1$ transitions obey selection rules [24] with respect to the $d$-parity quantum number $\pi_d = (-1)^{n_\pi}$, i.e., the number of $Q$-phonons $n_Q$ modulo two does not change. According to Eqs. (1-4) the $M1$ transition from the $1^+_1$ state to the $2^+_1$ state is

\[1^+_1 \to 2^+_1 \Rightarrow T(M1) = \sqrt{3/4\pi}g_\pi L_\pi, \quad T(E2) = e_\pi Q_\pi.\]

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.

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 using also a vanishing effective quadrupole neutron boson charge $e_\nu = 0$ and a comparably large effective quadrupole proton boson charge $e_\pi = 15.6 \text{ efm}^2$. 

\[1\text{We use the Ginocchio sum rule for } B(M1) \text{ strength [28] and the total strength } \sum B(M1) \uparrow = 0.61(7) \mu_N^2 \text{ which we observed below 4 MeV and we derive a fraction of } 42(5)% d\text{-bosons in the IBM-2 ground state wave function of } ^{94}\text{Mo. This large } d\text{-boson content rules out the U(5) dynamical symmetry limit (no } d\text{-boson in the ground state) for an adequate IBM-2 description of } ^{94}\text{Mo and favors the O(6) limit, which predicts a fraction of } 33% d\text{-bosons in the IBM-2 ground state of } ^{94}\text{Mo.}\n\]

\[2\text{In a recent numerical IBM-2 calculation [10] for symmetric and mixed-symmetry states in the } (N_\nu = 1)\text{-nucleus } ^{136}\text{Ba good agreement between theoretical and experimental } E2 \text{ transition strengths was obtained by using also a vanishing effective quadrupole neutron boson charge } e_\nu = 0 \text{ and a comparably large effective quadrupole proton boson charge } e_\pi = 15.6 \text{ efm}^2.\]
\textit{d}-parity-forbidden \cite{28} while the $1^+_1 \to 2^+_2$ \textit{M1} transition is allowed. The measured ratio of the corresponding \textit{M1} strengths is 0.02, confirming the \textit{d}-parity selection rule. A dominant \textit{E2} character of the $1^+_\text{sc} \to 2^+_1$ transition in $\gamma$-soft nuclei was previously assumed for the interpretation of data for the nuclei $^{196}\text{Pt}$ \cite{30} and $^{134}\text{Ba}$ \cite{31}. Our measurement supports the earlier assumptions.

Of particular interest is the comparison of the \textit{E2} strengths, which are interpreted in the $Q$-phonon scheme as the annihilation of the MS $Q$-phonon, $Q_m$. According to Eqs. (4,5) the MS $Q$-phonon, $Q_m$, is annihilated in both the weakly collective \textit{E2} transitions $2^+_\text{ms} \to 0^+_1$ and $1^+\text{sc} \to 2^+_1$, respectively. The ratio of the measured $B(E2)$ values is

\begin{equation}
\frac{B(E2; 1^+_1 \to 2^+_1)}{B(E2; 2^+_3 \to 0^+_1)} = 0.7(3) .
\end{equation}

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 ($Q_m$) $Q$-phonon operators. Analogously, one expects from Eqs. (1,4) collective \textit{E2} strengths for the $1^+\text{sc} \to 2^+_\text{ms}$ and the $2^+_1 \to 0^+_1$ transitions. In the present paper the transition rate of the $1^+\text{sc} \to 2^+_\text{ms}$ transition was measured. This represents the first measurement of a transition rate between two MS states. Due to the too weak intensity of the $1^+_1 \to 2^+_3$ transition the $E2/M1$ mixing ratio could not be measured. From the \textit{d}-parity selection rules we expect a dominant \textit{E2} character of the $1^+\text{sc} \to 2^+_\text{ms}$ transition. Assuming a vanishing \textit{M1} contribution, the ratio of the energy-reduced transition rates

\begin{equation}
\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) .
\end{equation}

equals the corresponding $B(E2)$ ratio. We find indeed a collective \textit{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 $^{94}\text{Mo}$. The weakly collective \textit{E2} transition from the $1^+_1$ state to the $2^+_1$ state and the probable collective \textit{E2} transition to the $2^+_\text{ms}$ state represent – besides the large \textit{M1} transition strengths – new and independent observables for the collectivity of the $1^+$ scissors mode. It is interesting, that these observables are deduced from \textit{E2} properties, which are considered to be well described by the IBM.

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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 $e_\pi = 9\text{fm}^2$ only.

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

$^a$from references [26,27]

$^b$assuming pure $E2$ character, the value is 620(70) $e^2\text{fm}^4$
FIG. 1. Photon scattering spectrum off $^{94}\text{Mo}$ in the energy range of MS states. At 2067 keV 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 $^{27}\text{Al}$ cross sections in $^{27}\text{Al}$, which is irradiated simultaneously (marked "Al"). "Bg" denote background lines.

FIG. 2. Left: Part of the observed spectrum of $\gamma$-rays following the $\beta$-decay of the $J^\pi = (2)^+$ low-spin isomer of $^{94}\text{Tc}$ populated in the $^{94}\text{Mo}(p, n)$ 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 $2^+_3 \rightarrow 2^+_1$ 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. Part a) and b) display the $M1$ and the $E2$ excitation strength distributions versus the excitation energies of the $1^+$ and $2^+$ states. Part 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.