Eur. Phys. J. A **13**, 99–103 (2002)

THE EUROPEAN PHYSICAL JOURNAL A

Proton-neutron structure of collective excitations in ^{94}Mo

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Received: 1 May 2001

Abstract. Resulting wave functions of low-lying $J^\pi = 2^+$ states from a recent shell model calculation for the near-spherical nucleus ^{94}Mo are analyzed with respect to their collectivity and the proton-neutron degree of freedom. The analysis uses the Q-phonon scheme applied to the shell model and it supports the mixed-symmetry interpretation of the interacting boson model for the multiphonon structure observed recently in ^{94}Mo by means of γ-ray spectroscopy. Simple operators are obtained which generate major parts of the symmetric- and mixed-symmetry 2^+ states in ^{94}Mo when applied to the calculated ground state.

PACS. 21.60.Cs Shell model – 21.10.Re Collective levels – 23.20.Js Multipole matrix elements – 27.60.+j $90 \leq A \leq 149$

1 Introduction

One of the fundamental aspects of nuclear-structure physics is the understanding of collective quantum phenomena, such as deformation or phonon excitation, and the role played by the proton-neutron degree of freedom in their formation. This aspect deals with the many-body property of the nucleus. It is natural to address this subject in the frameworks of microscopic many-body approaches like the nuclear shell model. Big progress was recently made in the shell model description of collective phenomena. However, nuclear shell model calculations still suffer often from too large dimension or the resulting shell model wave functions can be highly complex and difficult to interpret preventing us from deeper insight in the underlying physics if there were no guidelines from simplifying or more schematic models. Therefore, the radical truncation of the fermionic shell model space suggested in the Interacting Boson Model (IBM) [1,2] remains one of the powerful and simultaneously simple tools for the analysis of the collective phenomena.

The proton-neutron (pn) version of IBM (the IBM-2) predicted [3,4] a class of collective nuclear states which are not fully symmetric with respect to the pn degree of freedom. According to the algebraical IBM approach, the pn symmetry of an IBM-2 wave function can be quantified by the F-spin quantum number [2,5]. F-spin is the isospin for elementary proton and neutron bosons. IBM-2 wave functions with non-maximum F-spin quantum number, $F < F_{\mathrm{max}} = (N_\pi + N_\nu)/2$, contain at least one pair of proton and neutron bosons, which is not symmetric under an exchange of nucleon labels. Such states are called mixed-symmetry (MS) states. The MS quadrupole excitation represents the building block of MS structures in the framework of the *sd*-IBM-2. IBM Hamiltonians with $O(5)$ symmetry (or those where the dominant part has $O(5)$ symmetry) support vibrational features. The corresponding excitation spectra are particularly simple to interpret in terms of quadrupole phonon (Q-phonon) excitations [6–13]. The Q-phonon scheme can help to at least qualitatively understand MS structures, too [14]. 2^+_{ms} states with the properties of the fundamental MS one Q-phonon excitation were identified in some nuclei [15,16]. Figure 1 shows their excitation energies in all cases where the MS assignment is based on measured absolute transition strengths. The 2^+_{ms} states are observed at rather constant energies close to 2 MeV [16]. Another example of a MS state is given by the (generally fragmented) 1^+ scissors mode [17] first discovered in deformed nuclei [18]. Due to recent increase of the experimental sensitivity, photon scattering investigations of the scissors mode could be extended to γ-soft [19,20] and near-spherical nuclei [21,22]. In contrast to early perceptions the excitation energy of the scissors mode was found [23,24] to be almost constant, too.

In this contribution we apply the Q-phonon scheme in the framework of the fermionic shell model in order to investigate whether and how far the shell model agrees with the existence of MS states predicted by the IBM. We do this in a comparably small shell model configurational space which corresponds to almost the smallest possible number of proton and neutron bosons needed to construct symmetric and MS phonons. One of the best examples where both the shell model and IBM-2 approaches

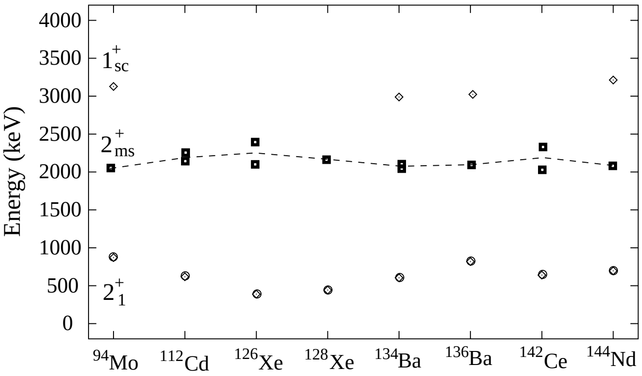

Fig. 1. Excitation energies of one-Q-phonon MS 2^+ states in vibrational nuclei. The filled squares connected with the dashed line correspond to the (mean) excitation energy of the one-Q-phonon MS 2^+ states. In some nuclei the one-Q-phonon MS 2^+ state is fragmented. For comparison, the excitation energies of the 2^+_1 state (circles) and the center of gravity of the low-lying $M1$ excitation strength (energy of the 1^+ scissors mode, diamonds) are shown, too. The data are taken from refs. [21–23,25–30].

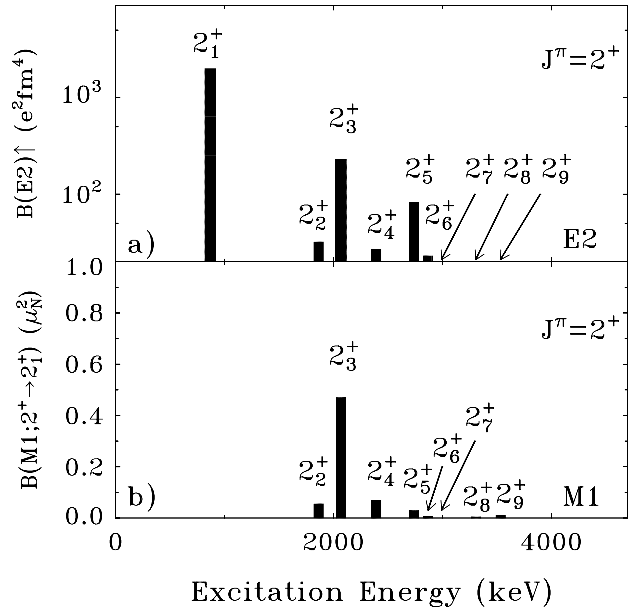

Fig. 2. Top: Experimental $B(E2; 0^+ \rightarrow 2^+_i)$ values for ^{94}Mo. Bottom: Experimental $B(M1; 2^+_i \rightarrow 2^+_1)$ values. The strong $2^+_3 \rightarrow 2^+_1$ $M1$ transition indicates the MS one-Q-phonon nature of the 2^+_3 state in ^{94}Mo (from ref. [35]).

can be applied to study symmetric and MS Q-phonon excitations is the near-spherical nucleus ^{94}Mo. Most importantly, the recently obtained data on ^{94}Mo represent at present the most complete data set on electromagnetic transition strengths from MS states.

In the next section we briefly review recent experiments [22,31] on MS states in ^{94}Mo. In sect. 3 we will make an attempt to interpret the observed MS structures in terms of Q-phonons using the results of a recent shell model calculation [32] for ^{94}Mo.

2 Multiphonon states in ^{94}Mo

The low-spin level scheme of the near-spherical nucleus ^{94}Mo has been investigated by γ-ray spectroscopy using the photon scattering technique, the (α,n) light-ion fusion evaporation, and β-decay reactions as populating mechanisms. Combining the complementary information of these experiments, we obtain a new richness of nuclear-structure data, which enable us to identify MS multiphonon structures from absolute $M1$ and $E2$ transition strengths [22, 31].

Photon scattering ^{94}Mo(γ,γ') experiments have been performed at the bremsstrahlung facility of the Stuttgart Dynamitron accelerator [33] of the Institut für Strahlenphysik, Universität Stuttgart. Continuous-energy photon beams with maximum energies of 3.3 MeV and 4.0 MeV were used to measure the ground-state excitation width $\Gamma_0 \propto B(\Pi\lambda; 0^+_1 \rightarrow J^\pi)$ of the $1^+_{1,2}$ states, of the 1^-_1 state, and of the $2^+_{3,4,5}$ states, with excitation energies between 2.0 MeV and 3.5 MeV [34].

Clean off-beam $\gamma\gamma$-coincidence spectroscopy of γ transitions between excited states of ^{94}Mo populated in the β-decay of the (2^+) low-spin isomer ^{94}Tc$^{\rm m}$ was done [22,35] with the Cologne cube spectrometer at the FN-Tandem accelerator of the Institut für Kernphysik, Universität zu Köln. The ^{94}Tc$^{\rm m}$ nuclei were produced with the low-angular momentum generating ^{94}Mo(p,n) reaction directly in the center of the spectrometer in a beam-pulsing mode. The high counting rate and the good definition of the beam spot and the well-collimated observation angles enable us to observe new γ-rays, to extract precise branching ratios from the high-statistics γ-singles data and many accurate multipole mixing ratios by analyzing the angular correlations of the $\gamma\gamma$-coincidences.

In-beam $\gamma\gamma$-coincidence spectroscopy experiments on ^{94}Mo were performed in Cologne with the Cologne cube spectrometer using the "cold" ^{91}Zr(α,n)^{94}Mo reaction close to the Coulomb barrier to populate low-spin states with high cross-section [31]. The complementary angular correlations of the $\gamma\gamma$-coincidences from the in-beam oriented states helped in some cases to decide on multipole mixing ratios which were ambiguous from the β-decay. The Doppler shifts observed for γ-transitions depopulating states of ^{94}Mo with a lifetime less than 1 ps enabled us to identify short-lived states in the term scheme of ^{94}Mo and to measure their lifetimes [31,35].

Combining the results from the three complementary experiments we obtain a panoply of absolute transition strengths some of which are displayed in fig. 2. In particular the measured $B(M1, 2^+_i \rightarrow 2^+_1)$ values indicate the 2^+_3 state at 2067.4(1) keV to be the one-phonon MS state. We stress that our knowledge [36,35] of the lifetimes of the first nine 2^+ states in ^{94}Mo enables us to unambiguously observe the concentration of the $2^+_i \rightarrow 2^+_1$ $M1$ strength in the 2^+_3 state with only little fragmentation. Moreover, the

2_3^+ state represents the strongest low-lying $E2$ excitation above the 2_1^+ which hints at its collective one-phonon character. Another argument in favor of the MS interpretation is the observation of $1_1^+, 3_2^+ \rightarrow 2_3^+$ transitions [22,31,34], in spite of their relatively low transition energies and the competing strong $M1$ decays of both states to lower-lying symmetric states. This fact agrees with the anticipated collective $E2$ decay rates from two-phonon MS states to the one-phonon MS state.

3 Q-phonons in the shell model

The Q-phonon scheme was originally formulated [6,7] in the framework of the interacting boson model. Simple operators were obtained which are able to generate to a good approximation the wave functions of excited yrast [8,9] and low-lying off-yrast [10] symmetric states when they are applied to the ground state. MS states in the IBM-2 can be approximated in the Q-phonon scheme, too [14]. The application of the Q-phonon scheme is, however, not limited to the IBM but is possible [11,13] also in other models, which are able to predict $E2$ transition rates. Usage of the Q-phonon scheme in the shell model is not yet reported in the literature.

In the F-spin limit of the IBM-2 Q-phonon operators for MS one-Q-phonon and two-Q-phonon states have already been formulated [14,16,21]. For instance in the $U(5)$ dynamical symmetry limit the wave functions of the one-phonon and two-phonon MS states are obtained by the expressions

$$|2^+_{\mathrm{ms}}, n_d = 1\rangle = \mathcal{N}_1 Q_m |0_1^+\rangle \,, \tag{1}$$

$$|L^+_{\mathrm{ms}}, n_d = 2\rangle = \mathcal{N}_L [Q_s \times Q_m]^{(L)} |0_1^+\rangle \,, \tag{2}$$

with $L = 0$–4. $Q_s = Q_\pi + Q_\nu$ denotes the symmetric linear combination of the proton and the neutron quadrupole operators in the IBM and $Q_m = Q_\pi/N_\pi - Q_\nu/N_\nu$ generates the orthogonal one-Q-phonon configuration with F-spin $F_{\mathrm{max}} - 1$.

In order to microscopically investigate the observed MS structures in ^{94}Mo we performed recently a realistic shell model calculation for ^{94}Mo [32]. We used the Surface Delta Interaction (SDI) as the residual interaction. The model space is chosen as 4 protons and 2 neutrons in the $(\pi 2p_{1/2}, \pi 1g_{9/2})$ and $(\nu 2d_{5/2}, \nu 3s_{1/2}, \nu 1g_{7/2}, \nu 2d_{3/2}, \nu 1h_{11/2})$ shell model orbitals outside of the $Z = 38$, $N = 50$ assumed inert core ^{88}Sr. The calculation yields a good overall reproduction of excitation energies of positive-parity states with spin quantum numbers $J \le 6$ as well as satisfactory agreement with measured $B(M1)$ and $B(E2)$ values (see for details [32]).

The shell model supports the simple phonon picture: The calculation yields collective $E2$ transitions between two-phonon and one-phonon MS states, and weakly collective $E2$ transitions in cases which correspond to the annihilation of the MS quadrupole phonon Q_m [32]. Moreover, the collective $E2$ transitions, that correspond to the annihilation of the symmetric quadrupole phonon Q_s have almost pure isoscalar character, while a predominant isovector character is calculated [37] for the weakly collective $E2$ transitions, that correspond to the annihilation of the MS quadrupole phonon Q_m. These facts indicate already agreement of the shell model with the Q-phonon scheme for MS states. A quantitative statement about this agreement has to be obtained from a Q-phonon analysis of the shell model wave functions. A previous analysis of the leading seniority components supported the MS interpretation [32]. In the following, we report on our analysis of the shell model wave functions in terms of the Q-phonon scheme.

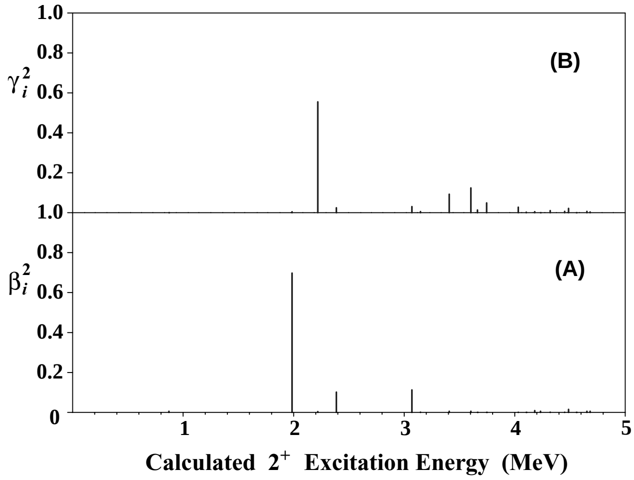

Fig. 3. (A) Overlaps $\beta_i^2 = \langle 2_i^+ | 2_{ss}^+ \rangle^2$ of the shell model 2^+ eigenstates with the symmetric two-Q-phonon configuration defined in eq. (6). (B) The corresponding quantity $\gamma_i^2 = \langle 2_i^+ | 2_m^+ \rangle^2$ for the MS one-Q-phonon configuration defined in eq. (7). Results are shown for the lowest 25 states.

We use the standard shell model quadrupole operators $Q_\rho^\mu = \sum r_{i,\rho}^2 Y_{2,\mu}(\theta_{i,\rho}, \phi_{i,\rho})$ with $\rho \in \{p, n\}$. The symmetric, isoscalar Q-phonon operator is defined [1] as

$$Q_s^\mu = Q_p^\mu + Q_n^\mu \,. \tag{3}$$

The corresponding symmetric one-Q-phonon configuration is

$$|2_s^+\rangle = \mathcal{N}_s Q_s |0_1^+\rangle = \sum_i \alpha_i |2_i^+\rangle, \tag{4}$$

where $\mathcal{N}_s$ is the normalization factor [8]

$$1/\mathcal{N}_s = \sqrt{\langle 0_1^+ \| (Q_s Q_s)^{(0)} \| 0_1^+ \rangle} \,.$$

The right-hand side of eq. (4) represents the expansion of the Q-phonon configuration in the basis of shell model eigenstates. The overlaps of the eigenstates with the symmetric one-Q-phonon configuration $|2_s^+\rangle$ are given by the squared amplitudes α_i^2. The amplitudes can be given explicitly [10] in terms of reduced matrix elements of the

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[1] Later, for the sake of simplicity and because of the use of reduced matrix elements, we will omit the index μ.

quadrupole operator Q_s

$$\alpha_i = \langle 2^+_i | 2^+_s \rangle = \mathcal{N}_s \langle 2^+_i \| Q_s \| 0^+_1 \rangle. \qquad (5)$$

We have calculated the overlaps of the lowest 25 shell model states $|2^+_i\rangle$ with the one-Q-phonon configuration $|2^+_s\rangle$. The 2^+_1 state exhausts 97% of the 2^+_s configuration, *i.e.*, it is an almost ideal symmetric one-Q-phonon state. In analogy to the Q-phonon scheme in the IBM the symmetric two-Q-phonon configuration must contain the operator $(Q_sQ_s)^{(2)}$ which has to be orthogonalized [10] to the one-phonon state

$$|2^+_{ss}\rangle = \mathcal{N}_{ss}[(Q_sQ_s)^{(2)} - vQ_s]|0^+_1\rangle = \sum_i \beta_i |2^+_i\rangle. \qquad (6)$$

From the orthogonality condition $\langle 2^+_s | 2^+_{ss}\rangle = 0$ we obtain [10] the constant $v = \mathcal{N}^2_s \langle 0^+_1 \| (Q_sQ_sQ_s)^{(0)} \| 0^+_1 \rangle$. The calculated overlaps $\beta^2_i = \langle 2^+_i | 2^+_{ss}\rangle^2$ are shown in fig. 3(A). The symmetric two-Q-phonon configuration is concentrated in the 2^+_2 state with an overlap of $\beta^2_2 = 70\%$ and little fragmentation mostly to the calculated 2^+_4 and 2^+_5 states. This agrees with a two-phonon interpretation of the 2^+_2 state in the shell model.

Analogously to the above procedure, we construct a MS one-Q-phonon configuration

$$|2^+_m\rangle = \mathcal{N}_m[Q_a - v_1Q_s - v_2(Q_sQ_s)^{(2)}|0^+_1\rangle \qquad (7)$$

$$= \sum_i \gamma_i |2^+_i\rangle, \qquad (8)$$

with the anti-symmetric isovector operator $Q_a = Q_p - Q_n$. The coefficients v_1 and v_2 are again obtained from the orthogonality conditions $\langle 2^+_m | 2^+_{ss}\rangle = 0$ and $\langle 2^+_m | 2^+_s\rangle = 0$. The calculated overlaps $\gamma^2_i = \langle 2^+_i | 2^+_m\rangle^2$ are shown in fig. 3(B). The MS one-Q-phonon configuration is concentrated in the 2^+_3 state with an overlap of $\gamma^2_3 = 56\%$ and some fragmentation. Most of the fragments are found to lie at higher energies with a maximum around 3.5 MeV and individually they contain less than 15% of the MS one-Q-phonon configuration. It is important to note also that according to this shell model calculation the symmetric one-phonon and, two-phonon states, and the MS one-phonon state are not mixed among themselves similarly to the situation in the vibrational F-spin limit of the IBM-2 and in the experiment. This is not a simple consequence of the orthogonalization of the Q-phonon configurations which are defined independently of the $2^+_{1,2,3}$ states. It is remarkable that the simple expressions from eqs. (6), (7) are able to generate a substantial part of the corresponding eigenstates in the shell model.

Comparing figs. 2 and 3(B), one can conclude about the remarkable correlation between the experimental $B(M1;\ 2^+_i \rightarrow 2^+_1)$ values[2] and the calculated overlaps of the MS one-Q-phonon configuration with various 2^+ states. The observed correlation strongly supports the IBM-2 picture despite that shell model $M1$ matrix elements contain substantial spin contributions.

4 Summary

The low-spin level scheme of the near-spherical nucleus ^{94}Mo was investigated by γ-ray spectroscopy. The $J^\pi = 2^+$ one-phonon mixed-symmetry state and $1^+, 3^+$ two-phonon mixed-symmetry states were identified from the measured $M1$ and $E2$ transition strengths. A realistic shell model calculation was performed using ^{88}Sr as the core and the residual Surface Delta Interaction. The shell model results are in good agreement with experimental data and support the mixed-symmetry interpretation for the observed multiphonon structure. The shell model wave functions are analyzed in terms of the Q-phonon scheme. The overlaps of shell model eigenstates with simple Q-phonon configurations are computed.

We are grateful to T. Otsuka for thorough discussions on the Q-phonon scheme for mixed-symmetry states. We thank D. Belic, U. Kneissl, A. Nord, and H.H. Pitz for the long-standing collaboration on the photon scattering experiments. We thank R.F. Casten, A. Dewald, A. Gelberg, J. Ginocchio, R.V. Jolos, F. Iachello, K.-H. Kim and V. Werner for stimulating and encouraging discussions. This work is supported by the Deutsche Forschungsgemeinschaft under Grants No. Br 799/9-1 and No. Pi 393/1-1 and by the US DOE under Contract No. DE-FG02-91ER-40609.

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