Parity assignments to strong dipole excitations of ^{92}Zr and ^{96}Mo

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Parity quantum numbers for dipole-excited states of the nuclei ^{92}Zr and ^{96}Mo have been determined from azimuthal asymmetries of nuclear resonance fluorescence intensities induced with the linearly polarized photon beam of the HIγS facility at Duke University. This parity information is crucial for an interpretation of the investigated $J=1$ states as two-phonon excitations originating from inhomogeneous phonon coupling.

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I. INTRODUCTION

Multiphonon excitations of atomic nuclei are interesting collective structures of the nuclear many-body system. Their existence enables us to judge the capability of the corresponding phonon modes for acting as building blocks of nuclear structure. Possible deviations from harmonic phonon coupling occur due to the microscopic structure of the underlying phonon modes and can serve as a sensitive source of information on the formation of collectivity in the nuclear many-body system.

Of particular interest are multiphonon excitations originating from inhomogeneous phonon coupling—i.e., states formed from the coupling of different phonon modes. The classic example for inhomogeneous phonon coupling is the $2^+ \otimes 3^-$ quadrupole-octupole coupled (QOC) quintuplet of states with spin and parity quantum numbers $J^\pi = 1^-, \ldots, 5^-$ in even-even nuclei [1,2]. In heavy vibrational nuclei this multiplet lies close to the sum energy of the constituent one-phonon modes [3], typically at energies between 2 and 5 MeV. The 1^- member of this multiplet has been investigated in detail with various probes and its multiphonon character was identified in vibratorlike nuclei in the region of the $N=82$ neutron shell closure on the basis of absolute transition strengths (see, e.g., [4–7]). The QOC 1^- state decays predominantly to the 0^+ ground state with $E1$ transition rates of the order of 10^{-3} W.u. (Weisskopf units) and shows a collective $E2$ decay to the 3^- octupole vibration with $E2$ strengths in excess of 10 W.u. The QOC character of these 1^- states is also seen in the apparent correlation of the $E1$ transition rate of the two-phonon 1^- state to the ground state with the $E1$ transition rate between the 3^- and 2_1^+ constituent one-phonon states [8]. Data on QOC states are still rather sparse in the $A \approx 90$ mass region. Near the $N=50$ shell closure the QOC $E1$ strength is comparatively weak and anharmonicities can be large [9]. Therefore, structure assignments cannot be based on transition rates and decay behavior alone. Reliable parity information is crucial for an interpretation of dipole excitations in this mass region [9].

Another example of inhomogeneous phonon coupling in the valence space of heavy nuclei are two-phonon states with positive parity, resulting from the coupling of the isoscalar quadrupole excitation and the proton-neutron mixed-symmetry (MS) quadrupole excitation, the $2^+_{1,ms}$ state, of the valence shell. MS states are not fully symmetric with respect to the proton-neutron (pn) degree of freedom and are predicted in the pn version of the interacting boson model (IBM-2) [10–14]. The recent observation of multiphonon structures with predominantly mixed symmetry in nuclei of the $A \approx 90$ mass region [15–22] has demonstrated the fundamental role of the one-phonon $2^+_{1,ms}$ excitation as a building block of nuclear structure. Experimental signatures for MS states are strong $M1$ transitions to excited states with a higher proton-neutron symmetry. For example, the two-phonon 1^+ MS state with the structure $(2_1^+ \otimes 2^+_{1,ms})^{1^+}$ decays by relatively strong $M1$ transitions to pn symmetric two-phonon states and to the 0^+ ground state. The strength of the latter transition depends on the presence of ground-state correlations [23]. Microscopic models have recently been applied to the description of MS multiphonon states [19,24,25]. These calculations allowed sensitive tests of the model inputs and, more importantly, provided a microscopic understanding of the collective multiphonon structures. Systematic information on multiphonon states is desirable for the further development of our microscopic understanding of the formation of nuclear collectivity.

Recent investigations of low-spin structures in ^{92}Zr [19,22] and ^{96}Mo [26] yielded information on several dipole

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excitations of those nuclei from scattering of unpolarized bremstrahlung and inelastic neutron scattering. In ^{92}Zr, a total of five dipole excitations was observed in the energy range from 3.1 to 3.7 MeV. For some of these states, parities were tentatively assigned from an earlier $^{91}\mathrm{Zr}(d,p)^{92}\mathrm{Zr}$ experiment [27] or from the decay pattern observed with γ-ray spectroscopy in inelastic neutron scattering [22]. In the nucleus ^{96}Mo five strong dipole excitations were detected in the energy range between 2.7 and 3.9 MeV in a photon scattering experiment with bremsstrahlung performed at Stuttgart [26]; however, no parity information was available for these states. The lack of parity assignments hampers a reliable interpretation of the observed $J=1$ states because two-phonon dipole excitations with both parities are expected to occur in these nuclei at energies around 3.5 MeV. Therefore, definite parity assignments are crucial.

The high flux of quasimonochromatic polarized photons produced [28–31] through the Compton backscattering of intracavity photons of a storage-ring-driven free electron laser can be used to determine parity quantum numbers of dipole-excited states with a new degree of accuracy [30–33]. The azimuthal asymmetry of γ rays resulting from nuclear resonance fluorescence (NRF) about the axis of the polarized photon beam is sensitive to the radiation character of the induced dipole transitions. In order to make unambiguous parity assignments to dipole excitations we have studied azimuthal asymmetries of NRF γ rays in the nuclides ^{92}Zr and ^{96}Mo using a completely polarized, quasimonochromatic photon beam.

II. EXPERIMENTS

A. Method

The measurements were performed at the High Intensity γ-ray Source (HIγS) of the Duke Free Electron Laser Laboratory (DFELL). Here we give only a brief sketch of the photon beam production; details can be found in Ref. [30]. The HIγS facility produces a nearly monoenergetic, 100% linearly polarized photon beam from the backscattering of photons in the optical cavity of the storage-ring-driven free electron laser on the relativistic electrons in the storage ring with energies in the GeV range. The Compton scattering process boosts the free electron laser photons from the eV energy range by six orders of magnitude to the MeV range in the laboratory system. Relativistic kinematics provides for a narrow forward cone of the Compton radiation. A selection of backscattering processes close to 180°, and thus an energy selection, is done with a primary collimator on the photon beam axis located 60 m behind the photon-electron collision point. We have used a collimator with an inner diameter of 25.4 mm, resulting in a typical energy resolution of about 3%. Pure 180° backscattering preserves the polarization of the initial laser photons. After on-axis collimation, the resulting photon beam is completely polarized with a degree of polarization in excess of 99% [34].

A large high-purity germanium (HPGe) γ-ray detector with an efficiency of 123% relative to a 7.6 cm$\times$7.6 cm NaI detector was used to monitor the energy profile of the beam during the beam-tuning procedure. This beam monitor was positioned along the beam axis, 6 m behind the target position. The intensity of the photon beam was tuned to less than 5000 photons per second in order to be counted by the HPGe detector. During the experiments, the typical intensity of the beam on target was of the order of 10^6 photons per second. Details about the free electron laser and the production of the polarized photon beam can be found elsewhere, e.g., in Ref. [30].

Parities of dipole excited states are determined from the azimuthal asymmetry of the corresponding NRF intensity. The angular distribution of a polarized photon beam resonantly scattered from a nuclear state can be written in terms of an angular correlation function $W(\theta,\phi)$ [35], where ϕ is the azimuthal angle between the polarization plane of the beam and the direction of the scattered γ ray and θ is the polar scattering angle. The azimuthal scattering asymmetry (analyzing power) perpendicular to the beam axis—i.e., $\theta=90°$—is given by

$$\Sigma(90°) = \frac{W(90°,0°) - W(90°,90°)}{W(90°,0°) + W(90°,90°)}. \tag{1}$$

The angular correlation function for a $0^+ \rightarrow 1^\pi \rightarrow 0^+$ photon scattering reaction on an even-even nucleus with a totally linearly polarized photon beam is given by [32,35]

$$W(\theta,\phi) = 1 + \frac{1}{2}\left[P_2(\cos\theta) + \frac{1}{2}\pi\cos(2\phi)P_2^{(2)}(\cos\theta)\right]. \tag{2}$$

$P_2^{(2)}$ is the unnormalized associated Legendre polynomial of second order and π is the parity quantum number of the dipole excited state. In this situation the analyzing power is maximum with values of $\Sigma(90°)$ equal to +1 for a $J^\pi=1^+$ state and -1 for a $J^\pi=1^-$ state. Measurement of the sign of the azimuthal scattering asymmetry is sufficient for making unambiguous parity assignments.

Relative NRF intensities were measured with an array of high-resolution HPGe γ-ray detectors. The target was surrounded by four detectors with relative efficiencies of 60% at mean scattering angles of $\langle\theta\rangle=90°$ and $\langle\phi\rangle=0°$, 90°, 180°, and 270°, respectively. The detectors were located about 10 cm from the beam axis. Further details of this setup are presented in Refs. [32,33].

The experimental relative photon scattering intensities in the (horizontal) polarization plane of the photon beam, $I_\parallel = I(\langle\phi\rangle=0°)+I(\langle\phi\rangle=180°)$, and perpendicular to it, $I_\perp = I(\langle\phi\rangle=90°)+I(\langle\phi\rangle=270°)$, were determined by fitting peak areas, subtracting the local background in the summed spectra of the corresponding two detectors, and correcting for the relative detector efficiencies. A ^{56}Co radioactive source, mounted at the position of the target, was used to determine these efficiencies.

The experimental asymmetries

$$\epsilon = \frac{I_\parallel - I_\perp}{I_\parallel + I_\perp} \tag{3}$$

are proportional to the analyzing powers

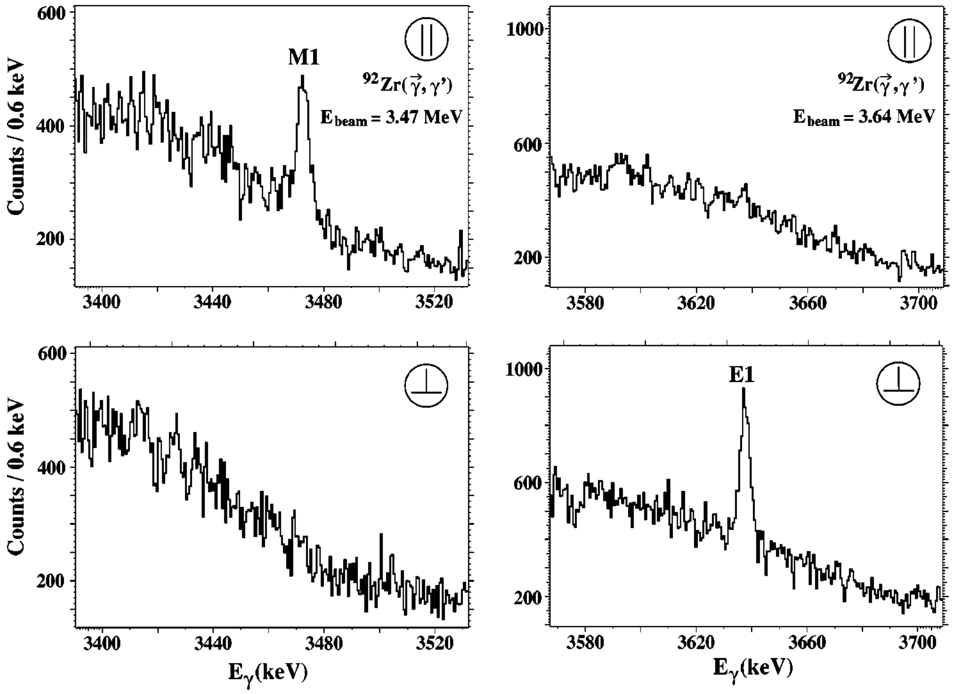

FIG. 1. Summed photon scattering spectra from ^{92}Zr for detectors parallel to the polarization plane of the incident polarized photon beam from the Duke Free Electron Laser (‖) and vertical to it (⊥) for beam energies of 3.47 (left part) and 3.64 MeV (right part). The 3472-keV transition was clearly identified as an $M1$ transition; the 3638-keV decay is an $E1$ transition.

$$\epsilon = q\Sigma, \tag{4}$$

where q denotes the polarization sensitivity of the setup. As a result of the finite size of the detectors and target, each detector is sensitive to a finite range of angles around the mean observation angles $\langle\theta\rangle$ and $\langle\phi\rangle$. Consequently, the sensitivity q of the setup is less than 100%. A numerical simulation yielded a sensitivity of $q=0.76(1)$, which is consistent with our previous measurements [32,33] within the experimental uncertainties. For the specific purpose of making parity assignments to dipole excitations, additional corrections for these finite-size effects are unnecessary.

B. Data

1. ^{92}Zr

Incident photon beam energies of 3.47 and 3.64 MeV were used on a ^{92}Zr target. The target was a 41.1415-g metallic Zr cylinder, with a diameter of 2 cm and a length of 2 cm, which was enriched in ^{92}Zr to 95.16%. Dominant dipole excitations of ^{92}Zr at 3472 and 3638 keV were recently identified in photon scattering experiments with unpolarized bremsstrahlung [19] and inelastic neutron scattering [22]; however, unambiguous parity assignments were not available. Figure 1 shows portions of the photon scattering spectra of the detectors parallel to the (horizontal) polarization plane of the HIγS photon beam (‖) and perpendicular to it (⊥) with the two different incident photon energies. Clear signals of the dipole excitations under investigation are visible in only one of the two spectra. The radiation character of each of the corresponding dipole transitions is obvious. Experimental asymmetries and parity assignments are given in Table I.

2. ^{96}Mo

The dipole excitation strength distribution in ^{96}Mo has recently been studied with unpolarized bremsstrahlung up to 4 MeV at Stuttgart [26]. Dominant dipole excitations have been observed at 2795, 3300, 3425, 3600, and 3895 keV. Since parity information was unavailable in this earlier work, a reliable interpretation of the observations was impossible. For parity assignments to the dominant dipole excitations of ^{96}Mo, we used photon beam energies of 2.80, 3.30, 3.43, 3.60, and 3.90 MeV on a ^{96}Mo target. The Mo target consisted of 40.0545 g of Mo powder, enriched in ^{96}Mo to 96.69%, contained in a thin-walled plastic cylinder, 5.2 cm long with a 26 mm inner diameter, with its axis oriented along the beam direction.

Clear signals have been obtained for all five dipole excitations under investigation. Figure 2 shows parts of the photon scattering spectra of the detectors parallel to the polarization plane of the HIγS photon beam (‖) and perpendicular to it (⊥) at incident photon energies of 3.43 and 3.90 MeV,

TABLE I. Measured asymmetries ϵ and parity quantum number assignments for $J=1$ states in ^{92}Zr and ^{96}Mo. The asymmetries are not corrected for the finite size of the detectors or attenuation effects.

	E_x(keV)	ϵ	J^π
^{92}Zr	3471.9	0.94(3)	1^+
	3638.1	−0.87(3)	1^-
^{96}Mo	2794.5	0.68(15)	1^+
	3300.1	0.93(3)	1^+
	3424.8	0.76(4)	1^+
	3599.7	−0.81(6)	1^-
	3895.3	−0.91(3)	1^-

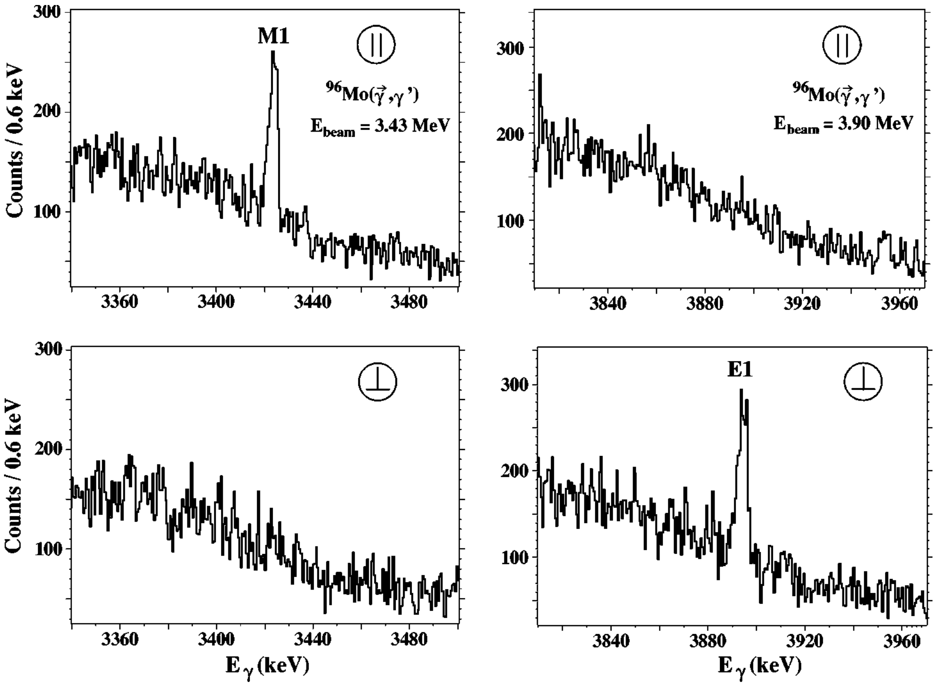

FIG. 2. Summed photon scattering spectra from ^{96}Mo (see Fig. 1) for beam energies of 3.43 (left) and 3.90 keV (right) proving that the 3425-keV transition has $M1$ character and the 3895-keV decay has $E1$ character.

respectively. Unambiguous parity assignments were possible in all cases.

Table I summarizes the experimental asymmetries and parity quantum number assignments for $J=1$ states of ^{92}Zr and ^{96}Mo. These results are consistent with $\Sigma(90°)=\pm1$, respectively, when finite geometry and background uncertainties are taken into account.

III. DISCUSSION

A. ^{92}Zr

Positive parity was assigned to the $J=1$ state at 3472 keV in the nucleus ^{92}Zr, whereas the $J=1$ state at 3638 keV was clearly identified as having negative parity. The unambiguous $J^\pi=1^+$ assignment for the level at 3472 keV confirms the recent interpretation [19] of that state as the dominant fragment of the low-energy $M1$ excitation strength distribution. That discussion was based on an earlier, tentative parity assignment from a transfer reaction [27] and on the result of a shell-model calculation. The $J^\pi=1^+$ assignment is now unambiguous for the 3472-keV state.

The significance of our parity assignments is obvious from Fig. 3. Since the strong dipole excitations at 3472 and 3638 keV have almost identical reduced dipole decay widths to the ground state, a misinterpretation due to erroneous parity assignment for one of these states would have resulted in an error of about 100% in the total dipole strength of a given radiation character. Our negative-parity assignment for the level at 3638 keV proves that this state does not contribute to the $M1$ excitation strength distribution and, consequently, the previous comparison [19] of the calculated $M1$ strength distribution in the shell model for ^{92}Zr with the data has been justified. Some of the present authors [19] previously interpreted the 1_1^+ state at 3472 keV as being the main fragment of a two-phonon state with predominantly mixed-symmetry character, an interpretation which was recently supported by microscopic calculatons [36] in terms of the quasiparticle phonon model (QPM). Figure 3 also illustrates that besides the two dipole excitations at 3472 and 3638 keV and the weak $J^\pi=1^{(-)}$ state at 3371 keV discussed below, no further

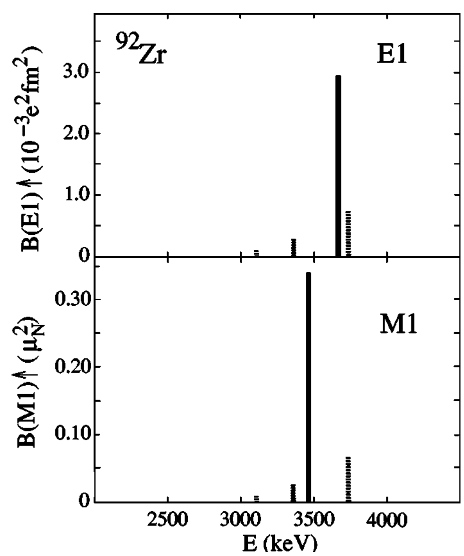

FIG. 3. Dipole excitation strength distribution in ^{92}Zr. The upper panel depicts the $E1$ excitation strengths of the 1^- states, the lower panel the $M1$ strengths of the 1^+ states. These values were calculated using the data from the neutron scattering experiment [22] and the parity quantum numbers from this work for the $J=1$ states at 3472 and 3638 keV. Parity quantum numbers have not been assigned to the $J=1$ levels at 3125, 3371, and 3697 keV, which have been included as dashed lines in both the $E1$ and $M1$ strength distributions, in order to demonstrate their small contribution to the dipole excitation strength distribution of either character. For easier comparison, the $E1$ and $M1$ strengths are displayed in the same scale ($11.058\times10^{-3}e^2$ fm^2 correspond to $1\mu_N^2$ in Gauss units).

strong dipole excitations were observed in ^{92}Zr below 4 MeV. Furthermore, an identification of the 1^- level at 3638 keV with the spin-strength-dominated $1^+_{2,\mathrm{theo}}$ state of the QPM (see Table IV of Ref. [36]) is invalid because of the discrepancy in parities.

The unambiguous negative-parity assignment for the level at 3638 keV is even more interesting for the characterization of the electric dipole excitation strength distribution in ^{92}Zr. An interpretation of this level as a fragment of a QOC two-phonon state with the structure $(2^+_1 \otimes 3^-_1)$ is improbable. Its excitation energy exceeds the sum energy of the 2^+_1 and 3^-_1 states of $E(2^+_1+3^-_1)=3274$ keV by about 400 keV. The corresponding energy anharmonicity

$$e \equiv \frac{E(1^-) - [E(2^+_1) + E(3^-_1)]}{E(2^+_1) + E(3^-_1)} = +0.111 \tag{5}$$

exceeds by a factor of 3 even the atypical positive anharmonicity $e=+0.038$ observed recently for the nucleus ^{88}Sr in this mass region [9]. Collective one-phonon annihilating decay transitions to the 2^+_1 and 3^-_1 states, which would uniquely identify a QOC 1^- state, were not observed. However, such relatively low-energy transitions have considerably smaller intensity than the competing $E1$ transition to the ground state and are thus not easy to detect. The sensitivity of the recent $(n,n'\gamma)$ measurement allows us to determine an upper limit of $B(E2;1^-_{3638}\to 3^-_1)<20$ W.u. [22] which still does not rule out the collective two-phonon interpretation.

In the following, we will shortly discuss the dipole excitation known [37] at 3371 keV. However, as a result of its weak excitation strength from the ground state, it was not investigated in our experiments. Spin $J=1$ was confirmed by recent experiments ([19,22], and references therein). Negative parity was assigned to this state only tentatively [37],

If we assume this state to have positive parity, we see from Fig. 3 that it provides only a minor contribution to the total $M1$ strength in ^{92}Zr. Alternatively, the dipole excitation at 3371.4 keV could have negative parity. In this case it represents a candidate for the QOC 1^- state. Its excitation energy is rather close to the sum energy of the 2^+_1 and 3^-_1 states (3274 keV, $e=+0.030$) and the decay transition to the 2^+_1 state was observed with an $E1$ branching ratio of $R_{\mathrm{expt}}=2.66(3)$ [22]. From systematics [8], the $1^-_{\mathrm{QOC}}\to 0^+_1 E1$ transition is expected to be about as strong as the $3^-_1\to 2^+_1 E1$ transition. This was shown for several vibrational nuclei [8] and is a consequence of the fact that whereas the former transition results from the annihilation of both the quadrupole and octupole phonons, the latter one results from the annihilation of the octupole phonon and the creation of the quadrupole phonon. This simple scheme neglects, of course, the microscopic structure of the states involved. The $E1$ strengths from QOC 1^- states to the ground state and between the 3^-_1 states and 2^+_1 states were found to differ by less than a factor of 2 for several vibrational nuclei [8]. For the 3371-keV $1^{(-)}$ state of ^{92}Zr, however, an $E1$ ground-state decay strength of $B(E1;1^{(-)}\to 0^+_1)=0.10^{+0.01}_{-0.01}\times 10^{-3}e^2$ fm^2 and a $3^-_1\to 2^+_1$ transition strength of $B(E1;3^-_1\to 2^+_1)=0.39^{+0.05}_{-0.04}\times 10^{-3}e^2$ fm^2 were measured [22]. These transition strengths differ by a factor of 4, in disagreement with the typical behavior of QOC states. In addition, a strong $E1$ transition from the $1^{(-)}$ state at 3371 keV to the 0^+_2 state was detected with a transition strength of $B(E1;1^-\to 0^+_2)=1.10^{+0.14}_{-0.12}\times 10^{-3}e^2$ fm^2—i.e., more than an order of magnitude stronger than the ground-state transition strength. In a pure phonon coupling scheme this transition would correspond to the annihilation of the octupole phonon in the 1^-_{QOC} wave function and the creation of a quadrupole phonon in the two-phonon 0^+_2 wave function. This scheme would be identical to the $3^-_1\to 2^+_1$ transition if the two-phonon description of the 0^+_2 state were valid. Indeed, a microscopic analysis in the QPM framework [36] assigns pure QOC two-phonon character to the $1^{(-)}$ state at 3371 keV. Unfortunately, the structure of the dominant low-energy $E1$ excitation at 3638 keV has not been addressed in that publication because it was misinterpreted as an $M1$ excitation. The description of the octupole collectivity in Zr isotopes in terms of the shell model [38] may suggest strong single-particle effects on QOC structures in these nuclei.

A further $J=1$ excitation at 3697 keV with tentative positive parity [22] was not investigated in this work, too, due to its small dipole excitation strength (see Fig. 3).

B. ^{96}Mo

In ^{96}Mo, we expect collective characteristics comparable to those in the neighboring ^{94}Mo, where clear evidence for both the one-phonon $2^+_{1,ms}$ state and members of the expected two-phonon multiplet of MS states has been previously found [15–17,21]. A total of three $J^\pi=1^+$ states were identified in ^{96}Mo. Information on radiative widths and decay branching ratios is available for these states from a bremsstrahlung photon scattering experiment [26]. This, along with the parity assignments of the present work, makes it possible to estimate the absolute transition strengths for the ground-state decays. The lowest $J^\pi=1^+$ state[1] at an excitation energy of 2795 keV was reported [26] to have an elastic resonant photon scattering cross section of $I_{s,0}=7.5(9)$ eV b corresponding to an effective ground-state decay width of $\Gamma_0^2/\Gamma=5.1(6)$ meV. A decay branch to the 2^+_1 state with a branching ratio of $\Gamma_1/\Gamma_0=0.18(5)$ has been observed. Other branches with lower transition energies were not observed. However, one should keep in mind that low-energy decay branches with intensities lower than the ground-state decay might escape observation because of the increasing background toward low energy. Under the assumption of no further decays—i.e., $\Gamma=\Gamma_0+\Gamma_1=\Gamma_0(1+\Gamma_1/\Gamma_0)=1.18\ \Gamma_0$—we deduce a ground-state transition width of $\Gamma_0=6.0(8)$ meV which corresponds to an $M1$ excitation strength of $B(M1;0^+_1\to 1^+)=0.071(10)\mu_N^2$. The photon scattering cross sections for the 1^+ states at 3300 and 3425 keV amount to $I_{s,0}=15.1(6)$ and 35.8(13) eV b corresponding to values of $\Gamma_0^2/\Gamma=14.3(6)$ and 36.4(13) meV, respectively. This converts together with the observed [26] decay branches of Γ_1/Γ_0

[1]This state was misinterpreted as a 1^- state in a recent compilation of QOC 1^- structures [4] based on strength and energy arguments [26].

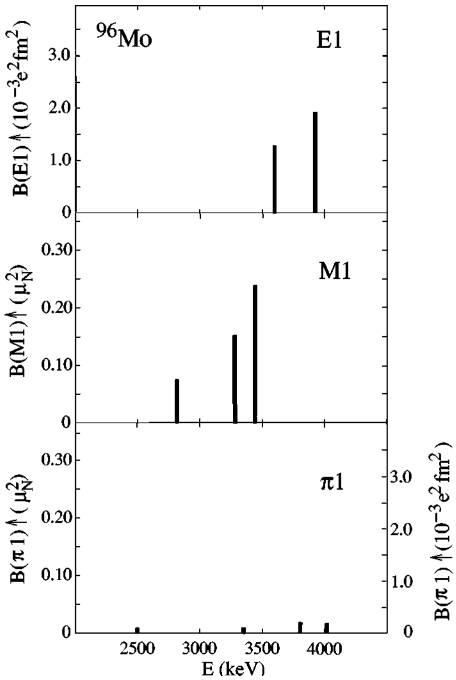

FIG. 4. Dipole excitation strength distribution for the observed $J=1$ states in ^{96}Mo. The upper panel shows the $E1$ excitation strengths of the 1^- states, the middle one the $M1$ strengths of the 1^+ states, and the lower panel the dipole excitation strengths for the states with unknown parity both in μ_N^2 and $10^{-3}e^2$ fm^2. The parity quantum numbers are from this work; the transition strengths were determined with data from [19]. Similar to Fig. 3 the $E1$ and $M1$ strengths are displayed in the same scale.

$=0.47(6)$ and 0.038(7) into ground-state decay widths of $\Gamma_0=21.0(12)$ and 37.8(14) meV or values for the $M1$ excitation strengths of $B(M1;0_1^+\rightarrow 1_2^+)=0.152(9)\mu_N^2$ and $B(M1;0_1^+\rightarrow 1_3^+)=0.243(9)\mu_N^2$. The $M1$ excitation strength distribution is shown in the middle panel of Fig. 4.

The summed $M1$ excitation strength of the three observed 1^+ states is $\Sigma B(M1;0_1^+\rightarrow 1_{1,2,3}^+)=0.47(2)\mu_N^2$ and is comparable to the summed $M1$ excitation strength in the nucleus ^{94}Mo of $\Sigma B(M1;0_1^+\rightarrow 1^+)=0.67(7)\mu_N^2$ in the energy range around 3.2 MeV [15,21]. These $M1$ excitations in ^{94}Mo exhibit characteristics of the two-phonon 1^+ MS state resulting from the coupling of the one-phonon symmetric and mixed-symmetry quadrupole excitations of the ground state [15,21]. Since the measured values for the total $M1$ excitation strengths are similar for ^{94}Mo and ^{96}Mo, we interpret the observed 1^+ excitations in ^{96}Mo as fragments of the 1^+ member of the mixed-symmetry two-phonon multiplet of that nucleus. The center of gravity of the observed $M1$ excitation strength distribution of ^{96}Mo lies at 3.29 MeV, very close to the value (3.2 MeV [21]) observed in ^{94}Mo.

The observation of a collective $E2$ transition to the one-phonon $2_{1,ms}^+$ state from the annihilation of the symmetric quadrupole excitation, a weakly collective $E2$ transition to the 2_1^+ state from the annihilation of the mixed-symmetry quadrupole phonon from the 1^+ states, and strong $M1$ transitions to symmetric two-phonon states would allow a consistent assignment of the two-phonon MS character to the 1^+ states, as pointed out, e.g., in [22] and references therein. These branchings are expected to have intensities far below the sensitivity of the photon scattering experiments with bremsstrahlung. The search for these transitions and the determination of the corresponding transition strengths are thus of great interest. Besides the ground-state transitions, only decay transitions from the 1^+ states to the 2_1^+ state were observed in those photon scattering experiments [26]. If no further decays and, in addition, pure $E2$ radiation for these transitions are assumed, we determine for the $E2$ transition strengths the values $B(E2;1_1^+\rightarrow 2_1^+)=1.5(6)$ W.u., $B(E2;1_2^+\rightarrow 2_1^+)=4.6(8)$ W.u., and $B(E2;1_3^+\rightarrow 2_1^+)=0.53(11)$ W.u., respectively. These upper limits agree with a weakly collective $E2$ transition to the 2_1^+ state as expected for a two-phonon MS state.

1^- states were identified at excitation energies of 3600 and 3895 keV. The summed energy of the 2_1^+ and 3_1^- states is $E(2_1^+ + 3_1^-)=3012$ keV. In addition, no decay transitions to the 3_1^- state from either of these 1^- states were observed. But these transitions are expected for the decay of a QOC state. Thus, these states cannot be interpreted as harmonic QOC two-phonon 1^- states. This situation is very similar to the case of ^{92}Zr, discussed above, where the 1^- state that dominates the low-energy $E1$ strength distribution *is not* the QOC two-phonon state.

Besides the $J=1$ states discussed above with parity quantum numbers determined in this work, no further strong dipole excitations were observed in ^{96}Mo [26], as is shown in Fig. 4. The lower panel gives the excitation strength distribution of $J=1$ states where parity information is missing. These states are weakly excited from the ground state and do not contribute much to the total $E1$ and $M1$ strength, respectively.

It is surprising that in the investigated nuclei, ^{92}Zr and ^{96}Mo, the properties of QOC two-phonon 1^- states differ so much from the typical behavior observed in other mass regions with vibrational nuclei. The previous misinterpretation of the 1^+ state of ^{96}Mo at 2795 keV as the QOC 1^- state of this nucleus [4,26] demonstrates the necessity of our investigations. The low-energy $E1$ strength distributions in nuclei of the $A\approx 90$ mass region differ considerably from the systematic data for $E1$ excitations in vibratorlike nuclei close to the $N=82$ neutron shell closure [4,7]. Further microscopic investigations of the structure of the dipole excitations and QOC structures in these nuclei are of high interest.

IV. CONCLUSION

Parities of seven dipole excitations in ^{92}Zr and ^{96}Mo were determined unambiguously with the linearly polarized photon beams produced by the HIγS facility at the Duke Free Electron Laser Laboratory. It should be stressed that we were able to clearly assign parities to the essential fraction of the observed dipole excitations in these nuclei. In ^{92}Zr, a 1^+ state and a 1^- state were clearly identified. The decay transition strengths from the 1^+ state at 3472 keV are consistent with recent microscopic calculations [19,36]. In ^{96}Mo, positive parity was assigned to three $J=1$ states and negative parity to two dipole excitations. By comparison to results for the neighboring nucleus ^{94}Mo, the 1^+ states in ^{96}Mo represent good candidates for fragments of the 1^+ member of a multiplet of two-phonon mixed-symmetric excitations.

In contrast to the vast majority of heavy vibratorlike nuclei, those near the $N=50$ shell closure in the $A\approx 90$ mass region apparently exhibit low-energy $E1$ strength distributions that are not dominated by the quadrupole-octupole coupled 1^- state. The dominant low-energy $E1$ excitations have excitation energies more than 10% *higher* than the sum energy of the 2_1^+ and 3_1^- states. Microscopic calculations in the quasiparticle phonon model for ^{92}Zr assign two-phonon quadrupole-octupole coupled character to a much weaker $E1$ excitation close to the sum energy.

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