Uniform properties of $J^{\pi}=1^{-}$ two-phonon states in the semimagic even-even tin isotopes ^{116,118,120,122,124}Sn

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Systematic nuclear resonance fluorescence experiments including model-independent parity determinations provided clear evidence for strong, isolated $E1$ excitations at excitation energies of 3.3–3.5 MeV in the spherical, semimagic nuclei ^{116,118,120,122,124}Sn. The corresponding $J^{\pi}=1^{-}$ states are interpreted as two-phonon excitations $(2^{+}\otimes 3^{-})$. The excitation energies $E_x(1^{-})$ *and* reduced excitation probabilities $B(E1)\uparrow$ are nearly constant in the entire isotopic chain $A=116$–124. The results are described in the framework of quasiparticle-phonon-model calculations. [S0556-2813(99)00704-9]

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I. INTRODUCTION

Low-lying natural parity excitations of heavy nuclei have long been described in terms of phonons in collective [1], algebraic [2], and microscopic models [3]. The low-lying β and γ vibrations of deformed nuclei fall into this category as well as the lowest 2^{+} and 3^{-} states of spherical nuclei. In this phonon picture, one naturally expects to observe multiphonon excitations built upon these states. However, if one attempts to construct multiphonon wave functions, the underlying single particle degrees of freedom become more and more important, leading to significant anharmonicities. It is therefore of great interest to study multiphonon excitations in order to learn about the interplay of collective and single particle degrees of freedom in complex multinucleon systems.

So far, multiplets built from multiple quadrupole excitations are rather commonly observed experimentally in spherical vibrator nuclei (see, e.g., [1,4]). There is also some, however, sparser evidence for two-phonon double-γ-vibrational excitations in deformed nuclei [5,6]. Direct evidence for a double octupole phonon multiplet is still rare and mainly indirect [7,8].

In this article we focus on the mixed quadrupole-octupole two-phonon states $(2^{+}\otimes 3^{-})$. This multiplet consists of five states with spin and parity $1^{-}, \ldots, 5^{-}$. While experimental studies of the entire multiplet have been successful in only a few cases [9,10], the 1^{-} member of that multiplet can ideally be investigated in (γ,γ') studies and has been identified in a large number of spherical nuclei near the shell closure $N=82$ [11,12]. Although these states have been predicted to have a two-phonon character for a long time [13,14], an experimental proof was given only recently by measuring the decay strengths from the two-phonon to the one-phonon states [15,16].

Two-phonon excitations of that kind should be a rather common excitation mode in spherical nuclei near shell closures. Indeed, in the semimagic Sn isotopes ^{116,124}Sn ($Z=50$) the strong $E1$ excitations were recently observed in photon scattering experiments performed by our collaboration [17] which were interpreted as excitations to the spin-1 member of the $2^{+}\otimes 3^{-}$ quintuplet. Candidates for similar excitations later on were observed also in the neighboring nuclei ^{122,126,130}Te ($Z=52$) [18].

The aim of the present work, including model-independent parity assignments, was to study systematically the mass dependence of these two-phonon excitations in semimagic isotopes covering a broad mass range. The Sn isotopic chain represents the most favorable, even unique case. The Sn isotopes exhibit very constant excitation energies of the low-lying collective excitations in the entire mass range from $A=100$ to 130, in contrast to the $N=82$ isotones [11]. Furthermore, there exist seven stable even-even Sn isotopes which are known to be of spherical shape [19,20]. Five even Sn isotopes have sufficient natural abundances to get enriched target quantities of some grams, allowing the application of the very sensitive, spin selective nuclear resonance fluorescence technique (NRF) [21].

II. EXPERIMENTAL METHOD

The NRF method has proved to represent the outstanding tool to study low-lying dipole excitations in heavy nuclei. The intensity of the scattered photons is proportional to the ratio of the partial and total widths Γ_0^2/Γ from which the interesting reduced transition probabilities $B(E1)\uparrow$ or $B(M1)\uparrow$ can be deduced. The measured angular correlations allow to determine unambiguously the spins of the excited states. Polarization observables (the linear polarization of the scattered photons or the analyzing power when using linearly

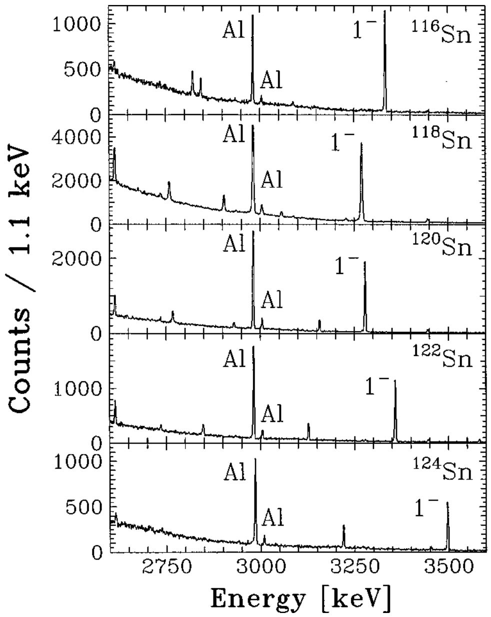

FIG. 1. NRF spectra for ^{118,120,122}Sn together with the data from our previous study on ^{116,124}Sn [17]. The peaks marked by ''1^-'' correspond to the two-phonon excitations. Peaks labeled by ''Al'' stem from transitions in ^{27}Al, used for the photon flux calibration [26]. The bremsstrahlung endpoint energy in all measurements was 4.1 MeV.

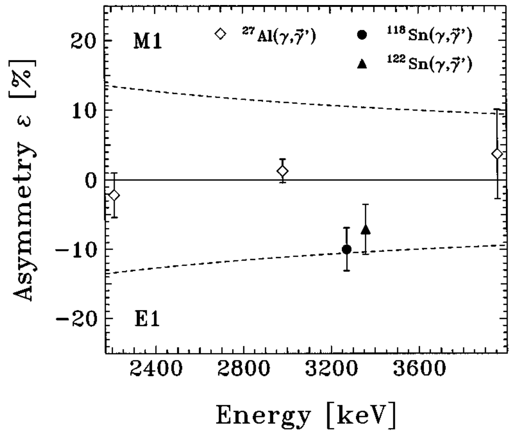

FIG. 2. Azimuthal asymmetries ε measured by the Compton polarimeter. Solid symbols correspond to the $E1$ two-phonon excitations in ^{118,122}Sn; open symbols correspond to the unpolarized transitions in ^{27}Al, which are used in addition for the absolute photon flux calibration [26].

polarized photons in the entrance channel) provide model-independent parity assignments (see Refs. [21,22]).

The present NRF experiments were performed at the well-established bremsstrahlung facility of the Stuttgart high-current 4.3 MV Dynamitron accelerator [21] (maximum dc electron current 4 mA, typical current ≈ 0.5 mA). The excellent quality of the bremsstrahlung beam allowed us to run NRF experiments at two different setups simultaneously. At the first NRF site the scattered photons are detected by three carefully shielded Ge(HP) γ spectrometers (efficiencies ϵ: 100%, 100%, and 22% relative to a $3'' \times 3''$ NaI/Tl detector) placed at scattering angles of 90°, 127°, and 150° with respect to the incident beam. At the second site two sectored single crystal Ge Compton polarimeters ($\epsilon = 25\%$ and 60%) [23,24], installed at slightly backward angles of $\approx 95°$, measured the linear polarization of the resonantly scattered photons, providing the parity information. An additional Ge γ detector ($\epsilon = 38\%$) allowed the measurement of angular distributions at this second site too and hence the simultaneous investigation of a second isotope. In all measurements targets of high enrichments ($\geqslant 96\%$) were used. Typical target quantities were 2.5–3.3 g for the angular correlation measurements, whereas 4.5 g (^{122}Sn) and 6.5 g (^{118}Sn) were used in the polarization measurements, respectively. For further experimental details see, e.g., Refs. [21,24,25].

III. RESULTS

In Fig. 1 the very clean (γ,γ') spectra for ^{118,120,122}Sn are depicted together with our previously taken data for ^{116,124}Sn [17]. The spectra are dominated by the strong 1^- two-phonon excitations. All angular correlation measurements clearly identified the strong excitation around 3.3–3.5 MeV in each isotope as a dipole transition. For two of the dipole excitations (in ^{118,122}Sn) the negative parity could be established exemplarily by the present linear polarization measurements using the Compton polarimeters. This is shown in Fig. 2 where the measured azimuthal asymmetries ε are plotted versus the excitation energy. The data for the two-phonon excitations in ^{118,122}Sn (solid symbols) are in agreement with the negative value of ε as expected for $E1$ transitions (lower dashed line) and are more than three standard deviations off from the $M1$ expectation (positive ε values). The asymmetries for the nearly unpolarized ^{27}Al transitions agree with zero within their error bars, demonstrating the nearly complete symmetry of the polarimeter. In addition, negative parities for the two-phonon excitations in ^{116,124}Sn could be assigned from the feeding corrected analyzing powers measured in photon scattering experiments [17] using partially linearly polarized bremsstrahlung at the Gent facility [27]. Figure 3 summarizes the results for the two-phonon excitations obtained in the Stuttgart NRF experiments. For all investigated Sn isotopes all quantities are remarkably constant: the energies of the one-phonon excitations $E_x(2^+)$ and $E_x(3^-)$, the two-phonon excitations $E_x(1^-)$, *and* the absolute excitation strengths $B(E1,0^+ \rightarrow 1^-)$. Such a behavior is expected for collective modes in nuclei of an isotopic chain without changes of the nuclear shapes.

IV. DISCUSSION AND COMPARISON WITH QPM CALCULATIONS

In the following discussion we restrict ourselves to the strong $E1$ transitions interpreted as two-phonon excitations. The corresponding 1^- states have been detected already in a comprehensive $(n,n'\gamma)$ study on the even Sn isotopes by Govor *et al.* [28,29]. However, the lifetimes of these 1^- states are too short, corresponding to the enhanced $B(E1)\uparrow$ values, to be measured with some precision by Doppler shift methods in $(n,n'\gamma)$ reactions. The observed excitation energies $E_x(1^-)$ are very close to the sum of the one-phonon excitation energies $E_x(2^+)$ and $E_x(3^-)$ corresponding to a nearly completely harmonic coupling of the quadrupole and

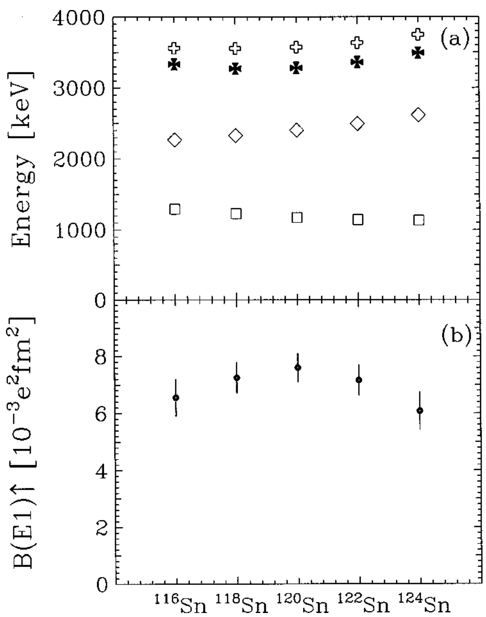

FIG. 3. (a) Energies of the 2_1^+ (open squares), 3_1^- (open diamonds) one-phonon states, and the 1^- (solid crosses) two-phonon states in ^{116,118,120,122,124}Sn compared to the sum energies $E_x(2^+)+E_x(3^-)$ (open crosses). (b) Experimental $B(E1)\uparrow$ values for the $E1$ two-phonon excitations.

octupole vibrations. This nearly perfect correlation between the one-phonon sum energies and the two-phonon energies $E_x(1^-)$ is demonstrated in the upper panel of Fig. 3. The two-phonon anharmonicities are small and result in a minor lowering of the 1^- two-phonon states. The energy ratio $R_E=[E_x(1^-)]/[E_x(2^+)+E_x(3^-)]$ is about 92.6% and very constant in the entire isotopic chain with fluctuations of only 1% (see Table I). The measured $B(E1)\uparrow$ values also are nearly constant with a flat maximum for ^{120}Sn. The absolute values of $6–8\times10^{-3}$ $e^2\,\mathrm{fm}^2$ are at least one order of magnitude larger than for other $E1$ transitions in neighboring nuclei.

Although the energy of the 1_1^- state is very close to the sum of the energies of the 2_1^+ and 3_1^- states, the only unambiguous identification of this 1^- level as a member of the two-phonon multiplet $(2^+\otimes3^-)$ would be a direct measurement of its $E2$ and $E3$ decay transitions into the 3_1^- and 2_1^+ one-phonon states. Unfortunately, because of background and transition intensity considerations, this is not possible in the present experiment. A reasonable theoretical description of the experimental data (excitation energy and decay properties) may provide confidence in a theoretically predicted structure of the 1_1^- state. In fact, the direct decay of the two-phonon state into the ground state is a ''forbidden'' transition [31] and, thus, rather sensitive to the details of the calculations. The model to be used should prove its ability to describe multiphonon configurations. Also, as shown by Heyde and De Coster [17,32] one-particle–one-hole $(1p\text{-}1h)$ admixtures, at the low-energy tail of the giant dipole resonance (GDR), into the low-lying two-phonon 1^- states appreciably change their decay properties to the ground state, indicating that the GDR phonons should be included in the model space.

One of the models satisfying these demands is the quasiparticle-phonon model (QPM). It has been already used to interpret the observed enhanced $E1$ strengths in the $N=82$ isotones [31,33]. We apply it here for an explanation of our actual experimental results concerning the properties of

TABLE I. Properties of the low-lying 2^+, 3^-, and 1^- levels in the even-even, stable Sn isotopes. Excitation energies E_x and reduced transition probabilities $B(E\lambda)$ are compared with the results of present QPM calculations, given in brackets [ ].

	^{116}Sn	^{118}Sn	^{120}Sn	^{122}Sn	^{124}Sn
$E_x(2^+)$	1.294	1.230	1.171	1.141	1.132
(MeV)	[1.31]	[1.23]	[1.14]	[1.13]	[1.11]
$B(E2,0^+\to2^+)$ [a]	0.195(10)	0.217(5)	0.200(3)	0.194(11)	0.166(4)
(10^4 $e^2\,\mathrm{fm}^4$)	[0.20]	[0.20]	[0.20]	[0.18]	[0.17]
$E_x(3^-)$	2.266	2.325	2.401	2.493	2.614
(MeV)	[2.25]	[2.35]	[2.42]	[2.49]	[2.65]
$B(E3,0^+\to3^-)$ [b]	0.127(17)	0.115(10)	0.115(15)	0.092(10)	0.073(10)
(10^6 $e^2\,\mathrm{fm}^6$)	[0.12]	[0.12]	[0.12]	[0.089]	[0.074]
$B(E1,3^-\to2^+)$ [a]	$1.67^{+0.41}_{-0.75}$	$2.28^{+0.34}_{-0.43}$	2.02(17)	2.24(14)	2.02(16)
(10^{-3} $e^2\,\mathrm{fm}^2$)	[2.0]	[2.0]	[1.8]	[1.2]	[0.95]
$E_x(1^-)$	3.334	3.271	3.279	3.359	3.490
(MeV)	[3.35]	[3.29]	[3.32]	[3.42]	[3.57]
$R_E=[E_x(1^-)]/[E_x(2^+)+E_x(3^-)]$	0.937	0.920	0.918	0.924	0.932
$B(E1,0^+\to1^-)$	6.55(65) [d]	7.20(54) [c]	7.60 (51) [c]	7.16 (54) [c]	6.08(66) [d]
(10^{-3} $e^2\,\mathrm{fm}^2$)	[8.2]	[8.6]	[7.2]	[4.9]	[3.5]

[a]From Ref. [28].
[b]From Ref. [30].
[c]Present work.
[d]From our previous measurements [17].

the low-lying states in the even-even Sn isotopes. The wave functions describing these states include one-, two-, and three-phonon configurations. First, a phonon basis was constructed by solving the quasiparticle random-phase approximation (RPA) equations for natural parity states ($J^{\pi}=1^{-}$, 2^{+}, 3^{-}, and 4^{+}) with a model Hamiltonian which included an average field for protons and neutrons, a monopole pairing for neutrons, and a residual interaction in a separable form. For all Sn isotopes, the same average field was used while the strength of the monopole pairing decreases in accordance with a $1/A$ dependence. The strength of the residual interaction for the $J^{\pi}=2^{+}$ and 3^{-} levels was adjusted for each nucleus in order to reproduce the experimental excitation energies and $B(E\lambda)$ values of the 2_1^+ and 3_1^- states. For the dipole strength, conditions were imposed to exclude the spurious center of mass motion and to achieve the correct position of the GDR. Once the one-phonon basis was obtained, the model Hamiltonian was diagonalized on a basis of states for which a coupling between one- and many-phonon configurations was taken into account. The coupling matrix elements were calculated microscopically within the QPM without any free parameter. Multiphonon components of the wave functions are built of phonons of different multipolarity and parity and different RPA root numbers, which finally couple to the same J^{π} as the one-phonon components. Since experimental data were only available up to an excitation energy of 4 MeV, we included in our calculation scheme only one- and many-phonon configurations below 5.5 MeV. For the 1^{-} states, we took all the one-phonon 1^{-} configurations up to 20 MeV into account to include the GDR polarization effect on the properties of the $(2_1^+\otimes 3_1^-)_{1^-}$ state on a microscopic footing. This avoids a phenomenologic renormalization of the effective charges.

The results of our calculations, given in brackets [ ], for some properties of the lowest 1^{-}, 2^{+}, and 3^{-} states in the even Sn isotopes are shown and compared with available experimental data in Table I. The agreement between calculated and experimental data in the first two rows is not surprising since the experimental information was used as input data to fit the parameters of the QPM model, as discussed above. In general, coupling matrix elements between one- and two-phonon configurations are not large in the semimagic Sn isotopes. As a result the 2_1^+ and 3_1^- states are practically pure one-phonon states with a contribution of the lowest one-phonon configurations of the order of 96–99 % in their wave functions. The last rows in Table I present the results of the calculations performed after all the model parameters were fixed. These results for the 1^{-} levels can be considered as a test of the QPM model.

Both transitions $3_1^-\rightarrow 2_1^+$ and $0_{\rm g.s.}^+\rightarrow 1_1^-$ are very weak compared to the collective one-phonon exchange transitions associated with the excitation of the GDR. The $E1$ transition $3_1^-\rightarrow 2_1^+$ occurs mainly via one-phonon components of these two states $\langle 2_1^+\|M(E1)\|3_1^-\rangle$, which is possible because of an internal fermion structure of the phonons. For the $E1$ transition $0_{\rm g.s.}^+\rightarrow 1_1^-$ we observe a destructive interference between an excitation of the main component of the 1_1^- state, the two-phonon configuration $(2_1^+\otimes 3_1^-)_{1^-}$ [with a weak matrix element $\langle(2_1^+\otimes 3_1^-)_{1^-}\|M(E1)\|\mathrm{g.s.}\rangle$], and a small admixture of the GDR in this state [with a large matrix element $\langle \mathrm{GDR}\|M(E1)\|\mathrm{g.s.}\rangle$]. As a result of this destructive interference we obtain transition probabilities in good agreement with the experimental findings. We concentrate now on the decreasing strength of both the $(0_{\rm g.s.}^+\rightarrow 1_1^-)$ and $(3_1^-\rightarrow 2_1^+)$ $E1$ transitions in our calculation for the two heaviest Sn isotopes (see Table I). This tendency seems not to be supported by the present experimental data. It occurs in the calculation due to the decreasing collectivity of the lowest 2^{+} and especially 3^{-} states. As discussed above, the strength of the residual interaction has been fitted to reproduce the experimental values of $B(E2, 0^{+}\rightarrow 2_1^+)$ and $B(E3, 0^{+}\rightarrow 3_1^-)$. Thus, the decreasing tendency in the $E1$ transition rates for ^{122}Sn and ^{124}Sn may be traced back to the decreasing tendency in the $B(E2)$ and $B(E3)$ values as reported in Refs. [28,30]. If in disagreement with Refs. [28,30] the $B(E2)$ and $B(E3)$ values for ^{122}Sn and ^{124}Sn would remain constant, like for the other Sn isotopes, the theory would also predict a constant behavior of the $B(E1, 3_1^-\rightarrow 2_1^+)$ and $B(E1, 0_{\rm g.s.}^+\rightarrow(2_1^+\otimes 3_1^-)_{1^-})$ transition rates for all isotopes under consideration. The predicted energy of the 1_1^- state would be even closer to its experimental value for the two heaviest isotopes because an increase of the collectivity of the 2_1^+ and 3_1^- phonons is followed by a decrease of their energies.

V. CONCLUSIONS

Strong $E1$ two-phonon excitations $(2^{+}\otimes 3^{-})$ in the semimagic $Z=50$ nuclei ^{116,118,120,122,124}Sn have been systematically observed using the NRF technique. The excitation energies are found close to the values $E(2_1^+)+E(3_1^-)$ expected for a harmonic coupling. The transition probabilities are constant in the whole investigated broad mass range. Calculations performed in the QPM framework support the interpretation of these states as two-phonon excitations $(2^{+}\otimes 3^{-})$.

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