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Evolution of the mixed-symmetry $2^+_{1,\mathrm{ms}}$ quadrupole-phonon excitation from spherical to γ-soft Xe nuclei

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Low-lying collective states of ^{130,132}Xe have been investigated by γ-ray spectroscopy following ^{12}C(Xe,Xe*)^{12}C projectile Coulomb excitation. The one-phonon $2^+_{1,\mathrm{ms}}$ states have been identified: the 2^+_4 state at 2150 keV with $B(M1; 2^+_4 \to 2^+_1) = 0.15(4)\mu_N^2$ in ^{130}Xe and the 2^+_3 state at 1985 keV with $B(M1; 2^+_3 \to 2^+_1) = 0.22(6)\mu_N^2$ in ^{132}Xe. The evolution of the one-phonon $2^+_{1,\mathrm{ms}}$ states in the even-even stable xenon isotopic chain from the vibrators near $N = 82$ to the γ-soft nuclei toward midshell is discussed.

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I. INTRODUCTION

The emergence of collective motion from the underlying fermionic single-particle degrees of freedom is a key feature of the nuclear system. The strong correlations between like particles (pairing), and the correlations between protons and neutrons are essential for the development of collectivity. Low-lying collective excitations can usually be interpreted in terms of valence excitations of fermion pairs. In the framework of the interacting boson model (IBM), such pairs of fermions are treated as bosons. This approximation is frequently used as most of the dynamics of heavier nuclei still lie beyond the scope of full microscopic shell-model or Hartree-Fock calculations.

The lowest collective states always involve coherent motion of the protons and neutrons. More subtle couplings can produce new and interesting modes of excitation, the so-called mixed symmetry states (MSSs). This special class of states (i.e., out-of-phase vibrations of protons against neutrons) emerge in the proton-neutron version of the IBM (IBM-2). The excitation energy and collectivity of these states are important for understanding proton-neutron correlations. In the framework of the IBM-2, MSSs are defined in terms of the F-spin quantum number [1,2] with $F = F_{\max} - 1$, where $F_{\max} = (N_\pi + N_\nu)/2$ is the maximum value of F with $N_\pi (N_\nu)$ being the number of proton (neutron) bosons. The three dynamical symmetries of the IBM [1]—U(5) for vibrating nuclei [3], SU(3) for axially deformed nuclei [4], and O(6) for γ-soft nuclei [5]—provide structural benchmarks for the description of nuclear quadrupole collectivity. The properties of MSSs are analytically known for all these symmetries, but their evolution from one symmetry to another is still poorly understood. In vibrational nuclei, the lowest lying MSS is the one-quadrupole phonon MSS labeled as $2^+_{1,\mathrm{ms}}$ and characterized by a weakly collective $E2$ transition probability to the ground state and a large $M1$ transition to the 2^+_1 state [2]. Hitherto discovered MSSs have been reviewed in Ref. [6].

The low-lying collective quadrupole states of the Xe-Ba-Ce mass region have been numerically investigated by Puddu *et al.* [7] within the IBM-2. It turns out that the even-A $_{54}$Xe isotopes exhibit a structural change from a U(5)-like behavior toward a O(6)-like pattern as the number of neutron-hole pairs increases away from the $N = 82$ closed shell. This was later supported further by Casten and von Brentano [8], even though deviations from the O(6) symmetry can be found [9]. Thus, stable Xe isotopes offer a possibility to study the evolution of the MSS on the transitional path from a vibrational structure toward a deformed one with pronounced fluctuations in triaxiality. Such information does not exist up to now. In this work, we report on the identification of the $2^+_{1,\mathrm{ms}}$ states in ^{130}Xe and ^{132}Xe obtained by measuring absolute $M1$ transition strengths using Coulomb excitation (CE). The $2^+_{1,\mathrm{ms}}$ states are already known in ^{128}Xe [10,11] and ^{134}Xe [12]. By combining the results of the present work with those from Refs. [9,11–14], it is now possible for the first time to follow the evolution of the $2^+_{1,\mathrm{ms}}$ state along the U(5) to O(6)-like path for a specific isotopic chain: $^{124-134}$Xe. It is the purpose of this article to show how the excitation energy and the observed $M1$ decay strength of the $2^+_{1,\mathrm{ms}}$ state evolve along the chain of Xe isotopes ($Z = 54$) from spherical vibrational nuclei ($N \sim 80$) to more deformed, γ-soft shapes ($N \sim 70$).

II. EXPERIMENT

The experiments were performed at Argonne National Laboratory. The superconducting ATLAS accelerator provided beams of ^{130,132}Xe ions with energies of 409 and 414 MeV, respectively. These energies correspond to ~82% of the Coulomb barrier for the reactions of ^{130,132}Xe ions on a ^{12}C target. The beam intensities were ~1 pnA. The beams were pulsed (12 MHz) and impinged on a natural ^{12}C target of 1 mg/cm^2. Emitted γ rays were detected by the Gammasphere array, which consisted of 98 high-purity Compton-suppressed germanium detectors arranged in

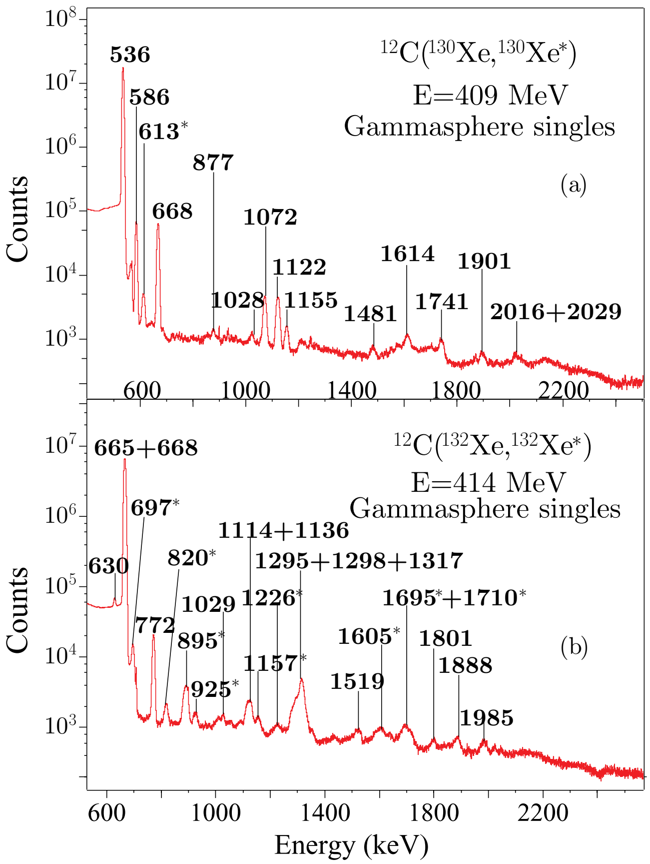

FIG. 1. (Color online) Background-subtracted and Doppler-corrected total singles γ-ray spectra for ^{130}Xe (a) and ^{132}Xe (b). The asterisks show peaks coming from impurities of the beam.

16 rings [15,16]. The event trigger was defined by detection of a single γ ray, but higher multiplicity events were recorded as well. The average trigger readout rate was 12 000 events/s (with a readout dead time of $\sim$30%). This count rate compares with a "beam-off" rate of 600 events/s. Doppler correction [recoiling velocity $\beta = 6.4(2)\%$, $\beta = 6.3(2)\%$ for ^{130,132}Xe, respectively] and time random-background subtraction were applied. The dominant part of the "beam-off" count rate came from natural radioactivity. This background was identified and subtracted by selecting events with times between the beam bursts, scaled to eliminate the 1461-keV decay from ^{40}K. The singles spectra are displayed in Fig. 1. Unfortunately, the ^{132}Xe-ion beam was slightly contaminated with a ^{37}Cl impurity owing to the close A/q ratio of both species in the 25$^+$ (Xe), 7$^+$ (Cl) charge states. Therefore, the γ-ray spectra contain lines (labeled with $*$ in Fig. 1) related to reaction products from beam impurities. The intensities of the Xe lines interfering with these lines were deduced through their previously known branching ratios [17,18] with respect to other γ-ray lines that were visible in the spectra without contamination. The total number of events was 9.2×10^8 for a running time of $\sim$24 h for ^{130}Xe, and 4.7×10^8 events were recorded in $\sim$13 h for ^{132}Xe. Only about 1% of the data are events with γ-ray fold higher than 1, emphasizing the "single-step" CE optimization of this experiment. However, these coincident events proved important in confirming the decay scheme and intensity balances.

III. RESULTS

All the γ transitions observed in these experiments and the corresponding intensities agree with literature values reported in Refs. [17–19]; the present results are summarized in Tables I and II. Note that for ^{130}Xe, a state at 2017 keV is reported in Ref. [17] as a 0^+ state. This assignment was originally proposed by Hopke *et al.* [20], who observed transitions to the 2_1^+ ($E_\gamma = 1481$ keV) and to the 2_2^+ (894 keV) levels with a branching ratio of $I_{1481}/I_{894} = 0.06(1)$ from γ-ray spectroscopy following electron capture from the 1^+ ground state of ^{130}Cs (also confirmed in Ref. [21]). In Ref. [22], the observed branching ratio [$I_{1481}/I_{894} = 3.8(11)$ from the neutron capture reaction ^{129}Xe(n,γ)] differs strongly from the one measured in [20] and this led the authors to suggest that the 1481-keV line in their data was a doublet. They also proposed possible spin values of 0, 1, or 2 for a state at about 2017 keV. Owing to the high sensitivity of our experiment, we have observed a γ transition to the ground state that rules out a 0^+ assignment. Furthermore, this level was populated via CE. At energies of about 2 MeV, for low-spin states decaying to the 0^+ ground state, a one-step $E2$ excitation is more probable than an $E1$ (leading to a 1^- level) or $M1$ (generating a 1^+ state) excitation. This strongly suggests a $J^\pi = 2^+$ assignment for the 2016-keV level. This may give rise to a concern about how much of the intensity of the 1481-keV transition seen in the present measurement originates from the decay of the 0_2^+ state rather than from the 2_3^+ level. This issue can be addressed by combining the I_{1481}/I_{894} branching ratio just mentioned [20] with the nonobservation of the 894-keV γ-ray in the present experiment to conclude that the contribution from the 0_2^+ state can be safely neglected in the present analysis.

The γ-ray intensities have been normalized to the $2_1^+ \rightarrow 0_1^+$ transition, which dominates the spectrum by three orders of magnitude. Population yields for each state have been deduced from γ-singles and $\gamma\gamma$-coincidence data. Contributions from electron conversion decays to the population of the levels are small in comparison to the systematic errors ($<$1.5%, [23]) and have been neglected. The intensities of known transitions, unobserved in the present study, (e.g., owing to their low energy or the presence of contamination), have been adopted from Refs. [17] and [18].

The observed relative yields measure the CE cross sections relative to that for the 2_1^+ state. The multiple CE code CLX, based on the Winther–De Boer theory [24], has been used to determine the set of matrix elements required to reproduce the observed relative cross sections. The previously measured $B(E2; 2_1^+ \rightarrow 0_1^+)$ value [25] sets the absolute scale. The energy loss of the beam in the target (about 40 MeV) was taken into account. The unknown quadrupole moments of excited states were allowed to vary between the extreme rotational limits, adding uncertainties to the deduced matrix elements of about 3% on average. The input matrix elements in CLX were also constrained by the known branching and multipole mixing ratios. The resulting $B(E2)$ transition strengths are given in Tables I and II. For the 4^+ states, no $E4$ transitions from the

TABLE I. Transitions strengths of the low-lying Coulomb excited states of ^{130}Xe.

E_{level} (keV)	J^π	E_γ (keV)	I_γ	J^π_{final}	δ[a]	σ	$B(E2)$[b] W.u.
536	2_1^+	536	10^6	0_1^+		+	33.2(26)[c]
1122	2_2^+	586	3973(28)	2_1^+	+3.75(12)	−	44.3(81)
		1122	681(6)	0_1^+		+	0.28(5)
1204	4_1^+	82[d]		2_2^+		−	
		668	4835(34)	2_1^+		+	46.4(46)
1590	0_2^+[e]	469[f]	18.6(24)	2_2^+		−	256(118)
		1053[g]	15(15)	2_1^+		+	3.6(38)
1632	3_1^+	428[g]	1.04(23)	4_1^+		−	⩽53(21)[h]
		510[f]	10.6(20)	2_2^+		+	⩽226(40)[h]
		1096[g]	6.9(13)	2_1^+	$+1.3^{+3.8}_{-0.8}$	−	1.2(26)
1808	4_2^+	603[f]	18.8(16)	4_1^+		+	⩽25.6(45)[h]
		686[f]	23.8(19)	2_2^+		−	23.2(44)
		1272[f]	20.1(25)	2_1^+		−	0.74(14)
1944	6_1^+	739[f]	16.4(18)	4_1^+		+	69(9)
2016	2_3^+[i]	1481	70.6(33)	2_1^+		−	⩽0.86(21)[h]
							$B(M1) \leqslant 0.005(2)$
		2016	42.1(21)	0_1^+		−	0.11(2)
2059	$5^{(-)}$	855[f]	17.9(20)	4_1^+			
2081	4_3^+	877	46.6(10)	4_1^+		−	⩽247(43)[h]
		1546[g]	5.6(10)	2_1^+		+	1.74(43)
2150	2_4^+	1028[f]	14.1(24)	2_2^+	+0.18(35)[j]	+	0.55(16)
							$B(M1) = 0.05(2)$
		1614	154(5)	2_1^+	−0.08(14)[j]	−	0.13(47)
							$B(M1) = 0.15(4)$
		2150[g]	7.2(5)	0_1^+		−	0.24(7)
2278	3_1^-	260[f]		2_3^+			
		1072	461(20)	4_1^+			
		1155	130(7)	2_2^+			
		1741	124(5)	2_1^+			
		2278		0_1^+		+	$B(E3) = 0.023(9)$[k]
2437		1901[f]	64.7(33)	2_1^+			
2565		2029[f]	54.6(33)	2_1^+			

[a] Mixing ratios are taken from Ref. [17].

[b] $B(E2)$ values are given in W.u. [1 W.u. $(E2) = 0.003912\ e^2\ \mathrm{b}^2$], $B(M1)$ values are given in μ_N^2, and $B(E3)\uparrow$ values are given in $e^2\ \mathrm{b}^3$.

[c] From Ref. [25].

[d] This transition is not observed. In contrast to the situation in Ref. [9], this transition is not relevant for the population of the 4_1^+ state.

[e] Spin and parity of this level are unknown. We assumed a 0^+ state.

[f] These transitions were detectable only in coincidence spectra.

[g] These transitions are not observed in our experiment, but they are included in the calculations for the CE cross sections. Their intensities are deduced from the previously known branching ratios of Ref. [25].

[h] This is the upper value for $B(E2)$ since the multipole mixing ratio δ was unknown; the quoted value is obtained by assuming a pure $E2$ transition.

[i] This level has been assumed to be a 2^+ state. For more details, see text.

[j] From Ref. [21].

[k] In Ref. [19], a $B(E3)\uparrow = 0.033(9)\ e^2\ \mathrm{b}^3$ value is reported.

ground state were included. The choice of signs of the matrix elements is not always unique in a fit to multistep CE processes. However, constraints come from the requirement that the relative phases must be "quantum mechanically coherent" as outlined by Wu *et al.* [26]. Quantum mechanical coherence was checked through a comparison with an IBM calculation. The signs of the $E2$ matrix elements (σ) chosen in this way are also included in Tables I and II for clarity. We note that our results are in good agreement with the previously known $B(E3)\uparrow$ [19] (Tables I and II) and $B(M1)$ values [10,27] (Table III).

TABLE II. Transitions strengths of the low-lying Coulomb excited states of ^{132}Xe.

E_{level} (keV)	J^{π}	E_{γ} (keV)	I_{γ}	J^{π}_{final}	δ[a]	σ	$B(E2)$[b] W.u.
667	2_1^+	667	10^6	0_1^+		+	23.0(15)[c]
1297	2_2^+	630	2026(19)	2_1^+	+4.07(16)	−	29.4(46)
		1297[d]	136(12)	0_1^+		+	0.056(7)
1440	4_1^+	142[e]		2_2^+		−	
		772	3427(26)	2_1^+		+	29.5(45)
1803	3_1^+	363[f]	10.6(40)	4_1^+	+1.10(20)	−	
		505[f]	114(42)	2_2^+	+7.5(6)	+	
		1136[g]	72(26)	2_1^+	+0.34(2)	−	[h]
1963	4_2^+	522[g]	115(15)	4_1^+	−0.09(1)	−	
		665[i]		2_2^+		−	
		1295[d]	13.5(19)	2_1^+		−	
1985	2_3^+	1317	1695(31)	2_1^+	−0.16(5)	−	1.14(73)
							$B(M1) = 0.22(6)$
		1985	192(5)	0_1^+		−	0.67(18)
2187	2_4^+	889[d]	81(23)	2_2^+		+	$\leqslant$32(13)[j]
		1519	132(7)	2_1^+		−	$\leqslant$3.1(9)[j]
		2187[f]	45(12)	0_1^+		−	0.20(3)
2468	3_1^-	483[f]	189(13)	2_3^+			
		1028	138(7)	4_1^+	−0.071(11)		
		1171[f]	75(7)	2_2^+			
		1801	108(4)	2_1^+			
		2468		0_1^+		+	$B(E3) = 0.029(9)$[k]
2555	2_5^+[l]	570	119(17)	2_3^+	$+0.7^{4}_{3}$	+	
		1114[d]	95(16)	4_1^+		+	
		1887	151(10)	2_1^+		+	

[a] Mixing ratios are taken from Ref. [18].

[b] $B(E2)$ values are given in W.u. [1 W.u.$(E2) = 0.003\,992\ e^2\ \text{b}^2$], $B(M1)$ values are given in μ_N^2, and $B(E3)\uparrow$ values are given in $e^2\ \text{b}^3$.

[c] From Ref. [25].

[d] These transitions are doublets; the respective individual intensities have been separated through the known branching ratios from Ref. [18].

[e] This transition is not observed. In contrast to the situation in Ref. [9], this transition is not relevant for the population of the 4_1^+ state.

[f] These transitions are not observed in our experiment, but they are included in the calculations for the CE cross sections. Their intensities are deduced from the previously known branching ratios of Ref. [18].

[g] These transitions were detectable only in coincidence spectra.

[h] The population of the 3_1^+ state is unknown since we could not quantify the feeding from the 4_2^+ state through the 159-keV line.

[i] This transition is a doublet with the $2_1^+ \to 0_1^+$ transition. Since its branching ratio is unknown, it was not possible to establish the yield of the 4_2^+ state.

[j] This is the upper limit for the $B(E2)$ value since the multipole mixing ratio δ was unknown; the quoted value is obtained by assuming a pure $E2$ transition.

[k] In Ref. [19], a $B(E3)\uparrow = 0.016(6)\ e^2\ \text{b}^3$ value is reported.

[l] The spin of this state is not well known: $J = 2^+$ or 3. The $B(E2)$ values were not measured because the branching ratio to the ground state transition is unknown.

IV. DISCUSSION

In ^{130}Xe and ^{132}Xe, a single 2^+ state dominates the $2_i^+ \to 2_1^+$ $M1$ strength distribution up to our sensitivity limit at about 2.2 MeV. These are the 2_4^+ state in ^{130}Xe at 2150 keV [$B(M1; 2^+_{1,\text{ms}} \to 2_1^+) = 0.15(4)\mu_N^2$] and the 2_3^+ level in ^{132}Xe at 1985 keV [$B(M1; 2^+_{1,\text{ms}} \to 2_1^+) = 0.22(6)\mu_N^2$]. Other $B(M1; 2_i^+ \to 2_1^+)$ values are negligible in comparison. We, therefore, assign predominant mixed-symmetry character to these 2^+ excitations. The MSSs of ^{130,132}Xe combined with the results for ^{134}Xe [12], ^{128}Xe [11], ^{126}Xe [13,14], and ^{124}Xe [9] provide first information on the evolution of the $2^+_{1,\text{ms}}$ state along the Xe isotopic chain, as shown in Fig. 2(b) and Table III. In ^{128,134}Xe, the observed $B(M1; 2^+_{1,\text{ms}} \to 2_1^+)$ strength is concentrated in a single state as well. Note that no MSSs have been observed in ^{124}Xe and ^{126}Xe below about 2.2 MeV with the same technique [9,14]. However, in ^{126}Xe, significantly lower $B(M1; 2^+_{1,\text{ms}} \to 2_1^+)$ values have

TABLE III. Absolute strengths $B(M1; 2^+_{1,\mathrm{ms}} \rightarrow 2^+_1)$ of the MSSs found in the even-even Xe isotopes.

Isotope	N_ν	MSS	Energy (keV)	$B(M1; 2^+_{i,\mathrm{ms}} \rightarrow 2^+_1)$ (μ_N^2)		Ref.
				This work	Literature	
^{124}Xe	6			no MSS below 2.3 MeV[a]		
^{126}Xe	5			no MSS below 2.1 MeV[b]		
^{128}Xe	4	2^+_4	2127	0.04(1)[c]	0.07(2)	[10]
^{130}Xe	3	2^+_4	2150	0.15(4)		
^{132}Xe	2	2^+_3	1986	0.22(6)	0.29[d]	[27]
^{134}Xe	1	2^+_3	1947	0.30(2)		[12]

[a] From Ref. [9].

[b] From Ref. [14].

[c] From Ref. [11].

[d] No uncertainty is given in Ref. [27].

been found for the 2^+_4 state at 2064 keV and the (2^+) level at 2359 keV [13]. This would imply a weighted averaged $2^+_{1,\mathrm{ms}}$ state lying above 2225 keV.

Figure 2(a) indicates that the detected $2^+_{1,\mathrm{ms}} \rightarrow 2^+_1$ $M1$ strength decreases as the number of valence neutron pairs (N_ν) increases, that is, with increasing collectivity. Simultaneously, the excitation energy of the state of dominant mixed-symmetry character increases with increasing collectivity (N_ν). The same effect was observed for the two-quadrupole phonon $1^+_{1,\mathrm{ms}}$ states [28]. At this point, the following issue arises: Does the collective $2^+_{1,\mathrm{ms}}$ state rise in energy beyond our sensitivity limit and fragment by mixing with many other levels, or does it just disappear as a collective mode? Both hypotheses could explain the observed experimental behavior. In the first case, it is possible that only the lowest fragment of the MSS is observed and that this level does not necessarily carry the largest part of the total $M1$ strength. In the second, the states with mixed-symmetry character at the U(5) limit gradually lose their isovector character toward midshell and the $M1$ strength finally disappears. This scenario would require an as yet unknown mechanism. The former case, however, can be discussed in the framework of a simple two-state mixing model.

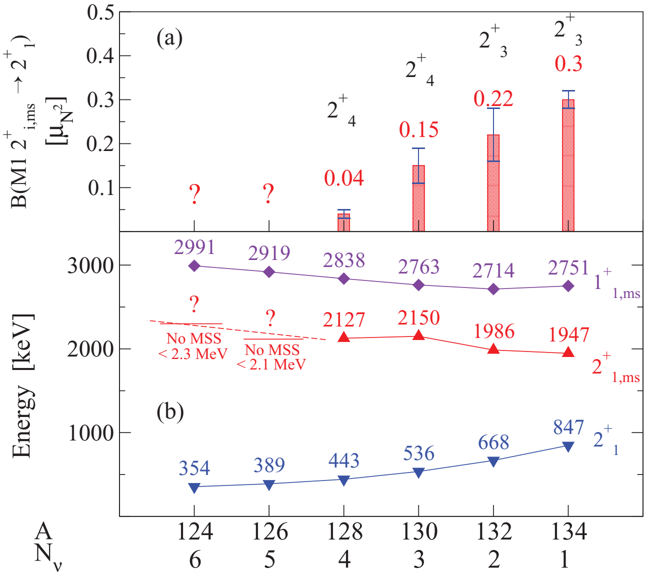

FIG. 2. (Color online) The evolution of the $B(M1; 2^+_{1,\mathrm{ms}} \rightarrow 2^+_1)$ strength in μ_N^2 is presented at the top (a) for the six even-even stable Xe isotopes. The corresponding energy of the first one-quadrupole phonon $2^+_{1,\mathrm{ms}}$ state and the evolution of the excitation energy of the two-quadrupole phonon $1^+_{1,\mathrm{ms}}$ state investigated by von Garrel *et al.* [28] are given at the bottom (b).

According to the two-state mixing scheme outlined in Refs. [12,29], the observed 2^+_1 and $2^+_{1,\mathrm{ms}}$ states arise through the mixing of the unperturbed proton and neutron 2^+ configurations (where their energies are labeled here as ϵ_π and ϵ_ν, respectively) in which the proton-neutron coupling matrix element increases as a function of the product $N_\pi N_\nu$. This mixing originates from the proton-neutron quadrupole interaction and was parametrized in Ref. [29] as $V_{\pi\nu}(N_\pi, N_\nu) = \beta\sqrt{N_\pi N_\nu}$ $(N_\pi = 2$ in our case). For studying this two-state scheme over the Xe isotopic chain, the energies of the elementary proton (ϵ_π) and neutron (ϵ_ν) quadrupole excitations need to be known over this sequence of nuclei. The unperturbed proton energy ϵ_π for the Xe isotopic chain was chosen as the energy of the 2^+_1 state of the $N = 82$, semi-magic nucleus ^{136}Xe [i.e., $\epsilon_\pi = E_{2^+_1}(^{136}\mathrm{Xe}) = 1313$ keV]. However, the dependence of ϵ_ν on neutron number over the Xe isotopic sequence was taken into account by assuming that this variation follows the 2^+_1 energies in the nearby magic Sn isotopes (no valence protons; i.e., $N_\pi = 0$). The local evolution of the 2^+_1 state in the Sn chain for the same neutron numbers is slightly parabolic (diamonds in Fig. 3). Therefore, the unperturbed neutron energy (ϵ_ν) has been parametrized as $\epsilon_\nu = a + b(N_\nu - 1) + c(N_\nu - 1)^2$. The value of the parameter a is $a = \epsilon_\nu(N_\nu = 1) = E_{2^+_1}(^{130}\mathrm{Sn}) = 1221$ keV. From the two-state mixing scheme, the resulting energies of the one-phonon 2^+ states $(2^+_{1,\mathrm{ms}}, 2^+_1)$ can be expressed as

$$E(2^+_{1,\mathrm{ms}}, 2^+_1) = \frac{\epsilon_\pi + \epsilon_\nu}{2} \pm \sqrt{\frac{(\epsilon_\pi - \epsilon_\nu)^2}{4} + \beta^2 N_\pi N_\nu}, \qquad (1)$$

where + [−] apply to the $E(2^+_{1,\mathrm{ms}})$ and $E(2^+_1)$ energies, respectively. The values of parameters b, c, and β were derived simultaneously from a least-squares fit to the ten data points of Fig. 3. The fit yields the values $\beta = 0.319(1)$ MeV,

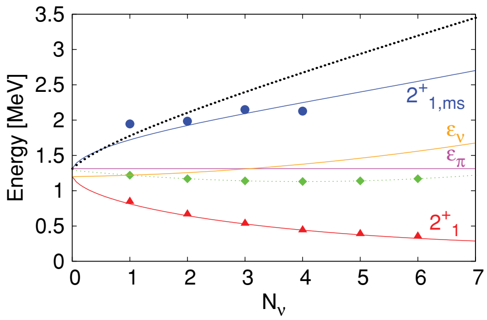

FIG. 3. (Color online) Fit of the experimental energies of the $2^+_{1,\mathrm{ms}}$ states (solid blue curve) and 2^+_1 states (solid red curve) in the $_{54}$Xe isotopes. The lines labeled ϵ_π and ϵ_ν represent the unperturbed energy of the proton and neutron states, respectively. The energies of the 2^+_1 states in the corresponding $Z = 50$ Sn isotopes are given as green diamonds. The black dashed line corresponds to the fit of the $2^+_{1,\mathrm{ms}}$ using the parameters [$\beta = 0.35(1)$ MeV, $b = 0.23(4)$ MeV] calculated via a two-state mixing in the $N = 80$ isotones [12].

$b = 0.028(4)$ MeV, and $c = 0.008(2)$ MeV and describes the data rather well.

In Ref. [12], a similar fit was carried out for the $N = 80$ isotones, including ^{134}Xe. The resulting proton-neutron interaction parameter was $\beta = 0.35(1)$ MeV. Since ^{134}Xe belongs to both chains ($N = 80$ and $Z = 54$), the same proton-neutron interaction parameter β should be expected, if the two-state mixing scheme holds true. Indeed, the values from our data, $\beta = 0.319(1)$ MeV, and from the $N = 80$ isotonic chain, $\beta = 0.35(1)$ MeV [12], coincide within 10%. The fact that they are not exactly equal in size may result from an oversimplification of the problem in the two-state mixing scheme or from insufficient sensitivity of our experiment to high-lying fragments of the $2^+_{1,\mathrm{ms}}$ excitation, located at energies above ~2.2 MeV. The $E(2^+_{1,\mathrm{ms}})$ values from Eq. (1) with the parameters proposed in Ref. [12] correspond to the dashed curve in Fig. 3. The difference between the two fitted curves for $E(2^+_{1,\mathrm{ms}})$ (dashed black and solid blue curves in Fig. 3) may suggest that, in lighter Xe isotopes, we have observed and included in our fit only the lowest fragment of the total $M1$ strength. There may be other fragments lying at higher energies (>~2.2 MeV) that were not observed. For example, if we assume that the main fragment of the $2^+_{1,\mathrm{ms}}$ state appears at energies as predicted by the dashed curve in Fig. 3 and that it decays to the ground state with a $B(E2)$ value of less than 0.6 W.u., the expected relative population to the 2^+_1 state (~8×10^{-5} average for $^{124-132}$Xe) is under the sensitivity limit of our experiments (~9×10^{-5} average for $^{124-132}$Xe) and no $2^+ \rightarrow 2^+_1$ $M1$ strength is observed above 2.2 MeV, in agreement with the data. An exception has to be mentioned for ^{128}Xe [11], where a 2^+ state at 2718 keV was observed with $B(E2; 2^+ \rightarrow 0^+_1) = 1.23(51)$ W.u., which could be the missing higher lying fragment suggested by Fig. 3 since a large upper limit of $B(M1; 2^+_{1,\mathrm{ms}} \rightarrow 2^+_1) \leqslant 0.19(5)\mu_N^2$ is in agreement with the data.

Another way to support the existence of higher lying fragments is the existence of the $1^+_{1,\mathrm{ms}}$ states [Fig. 2(b)]. In vibrational nuclei, the $2^+_{1,\mathrm{ms}}$ state is the lowest lying MSS and should, therefore, be located below the $1^+_{1,\mathrm{ms}}$ level. The $1^+_{1,\mathrm{ms}}$ states have been observed in the same Xe chain in nuclear resonance fluorescence experiments [28] and evolve from 2751 keV in ^{134}Xe to 2991 keV in ^{124}Xe. This observation supports the existence of higher lying missing fragments of the $2^+_{1,\mathrm{ms}}$ state in the energy region $\sim 2.2 < E < \sim 3$ MeV.

V. SUMMARY

In summary, low-lying excited states in ^{130,132}Xe have been investigated with projectile CE and the $2^+_{1,\mathrm{ms}}$ levels have been identified. This allowed us to trace the evolution of this excitation along the Xe isotopic chain from the $N = 82$ neutron shell closure out toward midshell for the first time. We observe that the energy of the $2^+_{1,\mathrm{ms}}$ state increases and the $2^+_{1,\mathrm{ms}} \rightarrow 2^+_1$ $M1$ strength decreases as the number of valence neutron-hole pairs (N_ν) increases. The decrease and disappearance of the $M1$ strength can be explained by two different mechanisms: Either the $2^+_{1,\mathrm{ms}}$ state fragments on the path from vibrators to γ-unstable rotors and shifts to higher excitation energies or the $2^+_{1,\mathrm{ms}}$ state gradually loses its isovector character and disappears toward midshell. It remains a challenge to search for $M1$ transitions from higher lying states in these Xe isotopes to clarify which of the two mechanisms applies. We have discussed the former case by using a two-state mixing scheme that suggests that fragments of the $2^+_{1,\mathrm{ms}}$ state may occur at energies higher than 2.2 MeV in ^{124,126,128,130,132}Xe.

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[1] F. Iachello and A. Arima, *The Interacting Boson Model* (Cambridge University Press, Cambridge, UK, 1987).
[2] P. van Isacker, K. Heyde, J. Jolie, and A. Sevrin, Ann. Phys. (NY) **171**, 253 (1986).
[3] A. Arima and F. Iachello, Ann. Phys. (NY) **99**, 253 (1976).
[4] A. Arima and F. Iachello, Ann. Phys. (NY) **111**, 201 (1978).
[5] A. Arima and F. Iachello, Phys. Rev. Lett. **35**, 1069 (1975).

[6] N. Pietralla, P. von Brentano, and A. F. Lisetskiy, Prog. Part. Nucl. Phys. **60**, 225 (2008).
[7] G. Puddu, O. Scholten, and T. Otsuka, Nucl. Phys. A **348**, 109 (1980).
[8] R. F. Casten and P. von Brentano, Phys. Lett. B **152**, 22 (1985).
[9] G. Rainovski *et al.*, Phys. Lett. B **683**, 11 (2010).
[10] I. Wiedenhöver, A. Gelberg, T. Otsuka, N. Pietralla, J. Gableske, A. Dewald, and P. von Brentano, Phys. Rev. C **56**, R2354 (1997).
[11] L. Coquard *et al.*, Phys. Rev. C **80**, 061304(R) (2009).
[12] T. Ahn *et al.*, Phys. Lett. B **679**, 19 (2009).
[13] A. Gade *et al.*, Nucl. Phys. A **665**, 268 (2000).
[14] L. Coquard *et al.* (to be published).
[15] I. Lee, Nucl. Phys. A **520**, 641 (1990).
[16] P. Nolan, F. Beck, and D. Fossan, Annu. Rev. Nucl. Part. Sci. **44**, 561 (1994).
[17] B. Singh, Nucl. Data Sheets **93**, 33 (2001).
[18] Y. Khazov *et al.*, Nucl. Data Sheets **104**, 497 (2005).
[19] W. F. Mueller *et al.*, Phys. Rev. C **73**, 014316 (2006).
[20] P. G. Hopke *et al.*, Phys. Rev. C **8**, 745 (1973).
[21] L. Bettermann *et al.*, Phys. Rev. C **79**, 034315 (2009).
[22] W. Gelletly, W. R. Kane, and D. R. MacKenzie, Phys. Rev. C **9**, 2363 (1974).
[23] P. F. Mantica Jr., B. E. Zimmerman, W. B. Walters, J. Rikovska, and N. J. Stone, Phys. Rev. C **45**, 1586 (1992).
[24] K. Alder *et al.*, Rev. Mod. Phys. **28**, 432 (1956).
[25] S. Raman, C. W. Nestor, and P. Tikkanen, At. Data Nucl. Data Tables **78**, 1 (2001).
[26] C. Y. Wu *et al.*, Nucl. Phys. A **607**, 178 (1996).
[27] S. A. Hamada, W. D. Hamilton, and B. Moore, J. Phys. G **14**, 1237 (1988).
[28] H. von Garrel *et al.*, Phys. Rev. C **73**, 054315 (2006).
[29] K. Heyde and J. Sau, Phys. Rev. C **33**, 1050 (1986).