Level lifetimes and the structure of ^{134}Xe from inelastic neutron scattering

E. E. Peters, A. Chakraborty, B. P. Crider, S. F. Ashley, E. Elhami, S. F. Hicks, A. Kumar, M. T. McEllistrem, S. Mukhopadhyay, J. N. Orce, F. M. Prados-Estévez, and S. W. Yates

Phys. Rev. C **96**, 014313 — Published 19 July 2017

DOI: 10.1103/PhysRevC.96.014313

Level lifetimes and the structure of ^{134}Xe from inelastic neutron scattering

E. E. Peters,[1] A. Chakraborty,[1, 2, *] B. P. Crider,[2, †] S. F. Ashley,[1, 2] E. Elhami,[2, ‡] S. F. Hicks,[3] A. Kumar,[2, 1, §] M. T. McEllistrem,[2] S. Mukhopadhyay,[1, 2] J. N. Orce,[2, ¶] F. M. Prados-Estévez,[1, 2] and S. W. Yates[1, 2]

[1]*Department of Chemistry, University of Kentucky, Lexington, Kentucky 40506-0055, USA*
[2]*Department of Physics & Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055, USA*
[3]*Department of Physics, University of Dallas, Irving, TX 75062, USA*

The level structure of ^{134}Xe was studied with the inelastic neutron scattering reaction followed by γ-ray detection. A number of level lifetimes were determined for the first time with the Doppler-shift attenuation method and the low-lying excited states were characterized. From this new spectroscopic information, the third excited state, a 0^+ level which had only been observed in a previous inelastic neutron scattering study, was verified. Reduced transition probabilities were calculated; comparisons were drawn with a vibrational description of the nucleus and found lacking. The 3^- octupole phonon has been confirmed, and the complete negative-parity multiplet resulting from the $\nu(1h_{11/2}2d_{3/2})$ configuration has also been tentatively identified for the first time in the $N = 80$ isotones.

I. INTRODUCTION

The stable isotopes of xenon span a transitional region that evolves from γ-soft structures for the lighter mass isotopes [1] to nearly spherical ^{136}Xe with a closed $N = 82$ neutron shell. The nature of this transition, which is gradual, is not well understood [2].

Recent computational studies within the interacting boson model [3–5] describe ^{134}Xe as "vibrational"; however, the detailed experimental data supporting this description are not available. For example, according to the most recent data compilation [6], the spin-parity of the second excited state is not firmly established and a putative 0^+ excitation, the third excited state, has been reported in inelastic neutron scattering (INS) but has not been observed with other reactions. One goal of the present investigation was to determine the properties of the lowest-lying states in ^{134}Xe and compare them to the predictions of the vibrational model.

Hughes et al. [7] pointed out in their work on ^{132}Te that the $\nu(1h_{11/2}2d_{3/2})$ configuration should result in a multiplet of negative-parity states, where a 7^- state is found lowest in energy, a 5^- state somewhat higher in energy, and the nearly degenerate 4^- and 6^- states highest in energy. In ^{132}Te, only the 5^- and 7^- states were identified [7] and a tentative 6^- state was later suggested by Biswas et al. [8]. A similar situation exists for ^{136}Ba [9], and ^{138}Ce [10] where the 5^- and 7^- states are known and candidates exist for the 6^- states, but in none of these $N = 80$ isotones has the entire multiplet been identified. In ^{134}Xe, only the 7^- state was known prior to this study [6].

Compared to other nuclei in this mass region, the level structure of ^{134}Xe is not well known. Much of this deficiency is doubtlessly a consequence of the fact that the required targets for many scattering and reaction methods are gases requiring high pressures or cryogenics. The most recent studies of the β^- decays of ^{134}I ($J^\pi = 4^+$, $T_{1/2} = 52.5$ min) and ^{134m}I (8^-, 3.52 min) were performed over forty years ago [11–14] and the EC decay of ^{134}Cs (4^+, 2.0652 years) populates only the first excited state of ^{134}Xe [15]. More recent studies include Coulomb excitation in inverse kinematics [16–18], photon scattering measurements on high-pressure gas targets [19], high-spin studies of states populated in multinucleon transfer reactions [20] and fission [21], and inelastic neutron scattering on natural [22] and enriched solid XeF_2 targets [23].

To provide detailed spectroscopic information on ^{134}Xe, we have studied this nucleus at the University of Kentucky Accelerator Laboratory (UKAL) using the INS reaction [2]. For these measurements, highly enriched xenon gas was converted to solid $^{134}XeF_2$ and γ-ray spectroscopic measurements were performed following INS with nearly monoenergetic neutrons. The excitation function and angular distribution measurements yielded branching ratios, multipole mixing ratios, and level lifetimes (from the Doppler-shift attenuation method [24]), which allowed the determination of reduced transition probabilities and provided insight into the structure of this nucleus.

II. EXPERIMENTS

The $(n, n'\gamma)$ experiments were performed at UKAL in a manner similar to those described earlier [2, 23]. Highly enriched (99.952% ^{134}Xe) xenon gas was converted to solid XeF_2, as described in Ref. [2], and 11.5077 g of $^{134}XeF_2$ was placed in a polytetrafluoroethylene vial with

---

* Present Address: Department of Physics, Siksha Bhavana, Visva-Bharati, Santiniketan 731 235, West Bengal, India
† Present Address: National Superconducting Cyclotron Laboratory (NSCL), Michigan State University, East Lansing, Michigan 48824, USA
‡ Present Address: Department of Physics, University of Winnipeg, Winnipeg, MB Canada R3B 2E9
§ Present Address: Department of Physics, Banaras Hindu University, Varanasi 221005 India
¶ Present Address: Department of Physics, University of the Western Cape, P/BX17, ZA-7535, South Africa

an inner diameter of 1.8 cm for the neutron irradiation.

Fast neutrons were produced by bombarding tritium gas with accelerated protons, i.e., the $^{3}H(p,n)^{3}He$ reaction, from the UKAL 7 MV Van de Graaff accelerator. The resulting nearly monoenergetic ($\Delta E_n = 60$ keV) neutrons were scattered from the xenon difluoride sample, and the emitted γ rays were detected in a high-purity germanium (HPGe) detector surrounded by an annular bismuth germanate (BGO) detector which served for Compton suppression and as an active shield. Excitation functions were performed by varying the neutron energy in 100 keV steps from 1.5 to 3.5 MeV and observing the γ-ray yields, which permitted the placement of γ rays in the level scheme. Angular distributions were performed by varying the detection angle in the range from 40° to 150° while holding the incident neutron energy constant at 1.9, 2.2, 2.7, and 3.5 MeV. In addition to providing information about the multipolarity of the transitions in ^{134}Xe, the angular distribution data provided nuclear level lifetimes from a few fs to about 2 ps through the Doppler-shift attenuation method [24]. The lifetimes are extracted from the slope of the linear fit to the γ-ray energy as a function of the cosine of the angle of detection according to the equation

$$E_{\gamma}(\theta) = E_0\Big[1 + F(\tau)\frac{v_{c.m.}}{c} cos\ \theta\Big], \quad (1)$$

where $E_{\gamma}(\theta)$ is the γ-ray energy as a function of the detection angle with respect to the direction of the incident neutrons, E_0 is the energy of the γ ray emitted by the nucleus at rest, $F(\tau)$ is the experimental attenuation factor, which describes the slowing-down process of the recoiling nucleus within the material, $v_{c.m.}$ is the recoil velocity of the center-of-mass, and c is the speed of light [24].

III. RESULTS

A summary of the data for levels in ^{134}Xe from the current experiments is provided in Table I. Comments on some of the levels to which these measurements have contributed uniquely are provided.

TABLE I: Data extracted from the present $(n, n'\gamma)$ experiments for ^{134}Xe. When two mixing ratios are possible, the solution with the lowest χ^2 value is listed first. The final column is the reduced transition probability for either $M1$ or $E1$ multipolarity as appropriate.

E_{level} (keV)	E_{γ} (keV)	J_i^{π}	J_f^{π}	B.R.	$\bar{F}(\tau)$	τ (fs)	δ or multipolarity	B(E2) (W.u.)	B(M1)/B(E1) (μ_N^2)/(mW.u.)
847.085(8)	847.082(10)	2_1^+	0_1^+	1		2300^{+2100}_{-800}	E2	20(10)	
1613.807(10)	766.727(15)	2_2^+	2_1^+	0.501(9)	0.056(13)	1260^{+390}_{-240}	-0.99^{+13}_{-26}	14.9^{+81}_{-53}	0.025(11)
							-2.37^{+74}_{-71}	25.5^{+86}_{-91}	0.0076^{+96}_{-40}
	1613.801(14)		0_1^+	0.499(9)			E2	0.72^{+19}_{-18}	
1636.163(21)	789.078(19)	0_2^+	2_1^+	1		> 1200	E2	< 55	
1731.221(10)	884.131(7)	4_1^+	2_1^+	1		> 1700	E2	< 22	
1919.754(13)	188.524(34)	4_2^+	4_1^+	0.033(3)		> 850			
	1072.674(14)		2_1^+	0.967(15)			E2	< 16	
1947.164(12)	1100.086(12)	2_3^+	2_1^+	0.866(5)	0.377(15)	127^{+9}_{-8}	-0.055^{+39}_{-40}	0.26^{+56}_{-24}	0.290(22)
							$+2.86^{+39}_{-34}$	75.6^{+76}_{-75}	0.032^{+11}_{-8}
	1947.145(23)		0_1^+	0.134(5)			E2	0.755^{+81}_{-76}	
1965.46(18)	234.24(18)	7_1^-	4_1^+	1			E3		
2082.175(21)	162.4 [a]	5_1^-	4_2^+	0.27(10)			E1		
	350.953(18)		4_1^+	0.73(22)			E1		
2116.585(10)	1269.500(6)	2_4^+	2_1^+	0.911(6)	0.089(17)	750^{+190}_{-130}	-0.98^{+13}_{-19}	3.6^{+16}_{-12}	0.0172^{+67}_{-59}
							-2.43^{+61}_{-65}	6.3(18)	0.0049^{+47}_{-24}
	2116.598(40)		0_1^+	0.089(6)			E2	0.056^{+16}_{-14}	
2136.654(13)	405.433(9)	6_1^+	4_1^+	1			E2		
2234.334(25)	152.159(15)	(6^-)	5_1^-	1					
2262.373(13)	1415.284(12)	2_5^+	2_1^+	0.542(14)	0.249(19)	222^{+23}_{-21}	$+0.066^{+60}_{-50}$	0.04^{+11}_{-3}	0.0458^{+65}_{-60}
							$+2.02^{+29}_{-26}$	6.5^{+13}_{-11}	0.0091^{+38}_{-27}
	2262.404(31)		0_1^+	0.458(14)			E2	0.75^{+10}_{-9}	
2293.69(10)	1446.60(10)	(3,4)	2_1^+	1					
2301.8 [b]	570.6	(3,4)	4_1^+						
	1454.7		2_1^+						
2353.034(13)	433.300(17)	(4^-)	4_2^+	0.256(7)	0.074(29)	990^{+760}_{-310}	E1		1.22^{+62}_{-56}
	621.807(9)		4_1^+	0.744(7)			E1		1.16^{+55}_{-51}
2389.374(63)	1542.290(63)	(0^+)	2_1^+	1		> 950	(E2)	< 3	
2408.582(16)	488.777(36)	(5^+)	4_2^+	0.129(15)					
	677.368(14)		4_1^+	0.871(40)					
2440.447(18)	1593.362(16)	(0^+)	2_1^+	1	0.247(29)	221^{+37}_{-30}	(E2)	8.8^{+14}_{-13}	

TABLE I: (Continued.)

E_{level} (keV)	E_γ (keV)	J_i^π	J_f^π	B.R.	$\bar{F}(\tau)$	τ (fs)	δ or multipolarity	B(E2) (W.u.)	B(M1)/B(E1) (μ_N^2)/(mW.u.)
2485.612(16)	871.793(16)	2^+	2_2^+	0.286(24)	0.190(25)	335^{+61}_{-48}		33.9^{+90}_{-76} [c]	
	1638.569(34)		2_1^+	0.464(28)			$+2.458^{+79}_{-57}$	2.02^{+64}_{-56}	0.0025^{+23}_{-13}
							-0.01^{+11}_{-10}	0.0003^{+350}_{-3}	0.0179^{+43}_{-38}
	2485.653(60)		0_1^+	0.250(21)			E2	0.158^{+42}_{-36}	
2502.336(14)	771.103(14)	(3)	4_1^+	0.518(25)	0.161(76)	370^{+390}_{-140}			
	888.514(22)		2_2^+	0.269(19)					
	1655.314(27)		2_1^+	0.213(18)					
2547.694(25)	627.934(22)	5^+	4_2^+	0.826(17)					
	816.599(95)		4_1^+	0.174(17)					
2580.279(21)	1733.194(19)	(0^+)	2_1^+	1	0.413(31)	115^{+15}_{-13}	(E2)	11.1^{+14}_{-13}	
2588.560(18)	857.327(20)	(4^+)	4_1^+	0.493(11)		> 800	-0.25^{+11}_{-11}	< 2	< 0.05
							$+1.76^{+55}_{-38}$	< 20	< 0.01
	974.780(31)		2_2^+	0.328(10)			(E2)	< 9	
	1741.489(68)		2_1^+	0.179(8)			(E2)	< 0.3	
2653.942(25)	1806.857(24)		2_1^+	0.455(8)			-0.72^{+21}_{-49}	0.72^{+78}_{-37}	0.0128^{+58}_{-63}
2751.413(57)	1904.176(16)	1	2_1^+	0.092(10)	0.737(41)	30(6)			
	2751.436(61)		0_1^+	0.908(10)					
2770.029(34)	1922.946(33)	$1,2^+$	2_1^+	0.948(10)	0.094(43)	740^{+680}_{-260}			
	2769.63(53)		0_1^+	0.052(10)					
2772.966(38)	1159.178(41)		2_2^+	0.611(20)	0.26(10)	220^{+190}_{-80}			
	1925.792(89)		2_1^+	0.389(20)					
2867.187(21)	920.044(37)	3_1^-	2_3^+	0.193(8)	0.214(39)	283^{+78}_{-54}	E1		0.326^{+94}_{-81}
	1253.410(30)		2_2^+	0.394(10)			E1		0.263^{+70}_{-62}
	2020.039(36)		2_1^+	0.413(10)			E1		0.066^{+18}_{-16}
2881.168(40)	2034.023(47)	2^+	2_1^+	0.447(20)	0.487(37)	84^{+13}_{-11}	-0.46^{+16}_{-20}	0.54^{+62}_{-32}	0.0296^{+99}_{-93}
	2881.315(73)		0_1^+	0.553(20)			E2	0.66^{+13}_{-11}	
2912.480(78)	2065.377(80)	$1,2^+$	2_1^+	0.868(21)	0.21(11)	290^{+360}_{-120}			
	2912.785(3)		0_1^+	0.132(21)					
2973.236(94)	2973.236(94)	$1,2^+$	0_1^+	1	0.125(78)	500^{+1000}_{-200}			
3007.948(84)	2160.863(84)		2_1^+	1	0.34(11)	100^{+100}_{-50}			
3053.269(78)	2206.16(11)	2^+	2_1^+	0.423(29)	0.304(67)	176^{+68}_{-44}	$+0.3^{+21}_{-3}$	0.06^{+110}_{-6}	0.012^{+6}_{-11}
							+1.2(13)	0.56^{+58}_{-56}	0.005^{+13}_{-4}
	3053.29(11)		0_1^+	0.577(29)			E2	0.248^{+99}_{-78}	
3074.48(25)	2227.40(25)		2_1^+	1					
3134.61(15)	2287.52(15)		2_1^+	1	0.77(19)	25^{+34}_{-21}			
3159.40(12)	2312.31(12)		2_1^+	1					
3219.537(78)	2372.416(84)	2^+	2_1^+	0.751(27)	0.571(72)	59^{+19}_{-15}	$+5^{+16}_{-2}$	3.3^{+15}_{-11}	0.0023^{+72}_{-22}
							-0.19^{+16}_{-17}	0.12^{+42}_{-12}	0.052^{+23}_{-17}
	3219.74(20)		0_1^+	0.249(27)			E2	0.24^{+12}_{-8}	
3251.03(25)	2403.95(25)		2_1^+	1					
3254.79(20)	2407.70(20)		2_1^+	1					
3265.66(13)	2418.58(13)		2_1^+	1	0.64(16)	44^{+38}_{-24}			

[a] E_γ determined from level energy differences due to background contamination.
[b] E_γ of the 570.6 keV branch determined from level energy differences due to background contamination. The 1454.7 keV branch is also contaminated by a ^{19}F γ ray, thus the branching ratios could not be determined.
[c] Calculated assuming pure $E2$ multipolarity.

A. Level Discussions

847.1 keV 2^+ state. The energy of this state was measured with high precision for the first time. The lifetime of this state exhibits large uncertainties, but is consistent with the value of Jakob et al., 3000(200) fs [16].

1613.8 keV 2^+ state. While the spin-parity of this level is given in the Nuclear Data Sheets (NDS) [6] as $(2)^+$, our measurements, as well as those of other recent publications, e.g., Ref. [18], remove the uncertainty of the spin of this state. Moreover, the angular distribution of the γ ray to the ground state is consistent with the 2^+ assignment. The level lifetime determined by Ahn et al. [18] ($\tau = 1270(60)$ fs) is in excellent agreement with our value (see Table I); however, the mixing ratio ($\delta = -1.5(2)$) is not. Our measurement is consistent though with that determined by Gualda et al. [14], −2.4(2).

1636.2 keV 0^+ state. This state, observed previously only in $(n, n'\gamma)$ experiments on XeF_2 of natural abundance [22], is clearly identified and placed from the present measurements based on the observed 1.7 MeV threshold (see Fig. 1). As expected, the angular distribution of the 789.1 keV γ ray is isotropic (see Fig. 2b), and the yield of this state is consistent with the 0^+ assignment. Unfortunately, the lifetime of this level is too long for a determination with our DSAM technique, and only a limit is given.

1731.2 keV 4^+ state. From our measurements, we were only able to establish a limit on the level lifetime of $>$ 1700 fs. Jakob et al. [16] determined a value of 3200(200) fs, with which we are consistent.

1919.8 keV 4^+ state. Although assigned a spin-parity of 3^+ [6], the present measurements are consistent with a 4^+ assignment, which is supported by each of the angular distribution measurements (see Fig. 2c). The population of this state in Coulomb excitation [18] also supports its assignment as a natural-parity state.

1947.2 keV 2^+ state. This level, first placed by McGrath et al. [22], was assigned as the 2^+ mixed-symmetry state in ^{134}Xe by Ahn et al. [18]. Its properties, as determined in our measurements, are consistent with the assignment of this level as the mixed-symmetry state. Ahn's level lifetime of 124(7) fs is in excellent agreement with our determination. While our measured mixing ratio is not within error of Ahn's value, 0.08(20), the resulting $B(M1)$ of 0.30(2) μ_N^2 is.

1965.5 keV 7^- state. Although not in our prompt spectra, the 234.2 keV γ ray was observed in the delayed spectra, consistent with its previously determined lifetime of 420(25) ms.

2082.2 keV 5^- state. This state was previously observed only in the $(n, n'\gamma)$ measurements on natural xenon [22], but the 351 and 162 keV γ rays were observed in two β decay experiments [11, 13]. We refute, however, the existence of the reported 468.2 keV γ ray [22]. From the previous INS experiments [22], the level was assigned as (4^+), but the present measurements favor a 5^- assignment (see Fig. 2a).

2116.6 keV 2^+ state. This state was observed previously in the $(n, n'\gamma)$ measurements on natural xenon [22] and in Coulomb excitation [18]. The present data, including an observed ground-state transition, lead to a firm assignment of 2^+.

2136.7 keV 6^+ state. This state was well characterized in the study of the 5 μs 10^+ isomer of ^{134}Xe by Genevey et al. [25]. Only the 405.4 keV γ ray depopulates this level. We find no evidence of the 217 keV γ ray used to establish a doublet of levels in the NDS [6].

(2207.9 keV level). No evidence for a level at this energy, which was observed only by McGrath et al. [22], was found.

2234.0 keV (6^-) state. The 152.2 keV γ ray was previously observed in INS [22] and was placed as a transition from a new 2560.6 keV level. We, however, observe the 152.2 keV γ ray to have a threshold of 2.4 MeV, which invalidates that placement. Based on the excitation function, the γ ray seems to feed the 5^- state and we thus establish the 2234.0 keV level. From the angular distribution and absence of other transitions to low-spin states, we assign a tentative spin and parity of 6^-.

2262.4 keV 2^+ state. Our data, including the level lifetime, branching ratios, and mixing ratios, are in agreement with those provided by Ahn et al. [18] from Coulomb excitation ($\tau = 250(10)$ fs and $\delta = 0.14(2)$ or 1.6(1)).

(2272.0 keV level.) We find no evidence for the reported 135.4 keV γ ray [6], and we observe the 540.8-keV γ ray to have a 2.7-MeV threshold, which is inconsistent with a 2.3 MeV state. No placement of the 541 keV γ ray is proposed from this work.

2353.0 keV (4^-) state. The angular distributions of both the 433.3 and 621.9 keV γ rays suggest that these are transitions between spin 4 states, and the minimum χ^2 value for the mixing ratio determination is zero, implying pure multipolarity. We, therefore, propose the level as a tentative 4^- state.

(2372 keV level.) This level was identified in (γ, γ') experiments [19], but we observe the γ ray to have a 3.4 MeV threshold, which means it is not be a ground-state transition, but rather one to the 2_1^+ state, which establishes a 3219.5 keV level.

(2417.4 keV level.) The only reference for the existence of this level is based on a 1570.3 keV γ ray observed in $(n, n'\gamma)$ measurements on natural xenon [22]. We, however, do not observe this γ ray and refute the existence of the level.

Few higher-lying levels above 2.4 MeV have firm spin-parity assignments, but one is deserving of comment. The 2867.2 keV $(4)^+$ level is shown in the Nuclear Data Sheets [6] to decay by nine γ rays. In their Coulomb excitation study, Ahn et al. [18] observed only three γ rays and suggested that this level may be the octupole phonon; however, they could not assign a definite spin. We observe the same three γ rays seen by Ahn et al. [18], but no others. Moreover, these γ rays display angular distributions consistent with electric dipole (E1) transitions. Combining these recent data, we find the 3^- assignment to be reasonable.

IV. DISCUSSION

It has been suggested that ^{134}Xe can be described as vibrational [3–5]. The $N = 80$ isotone ^{136}Ba has been studied with the $(n, n'\gamma)$ reaction in our laboratory [26], and the transition strengths of the two-phonon states were found to be consistent with the vibrational picture and candidates were proposed for three-phonon excitations. In spite of the new information provided by the present study, it remains difficult to evaluate the vibrational structure of ^{134}Xe, as can be seen in Fig. 4. The $B(E2; 2_2^+ \rightarrow 2_1^+)$ of 14.9^{+81}_{-53} or 25.5^{+86}_{-91} *W.u.*, depend-

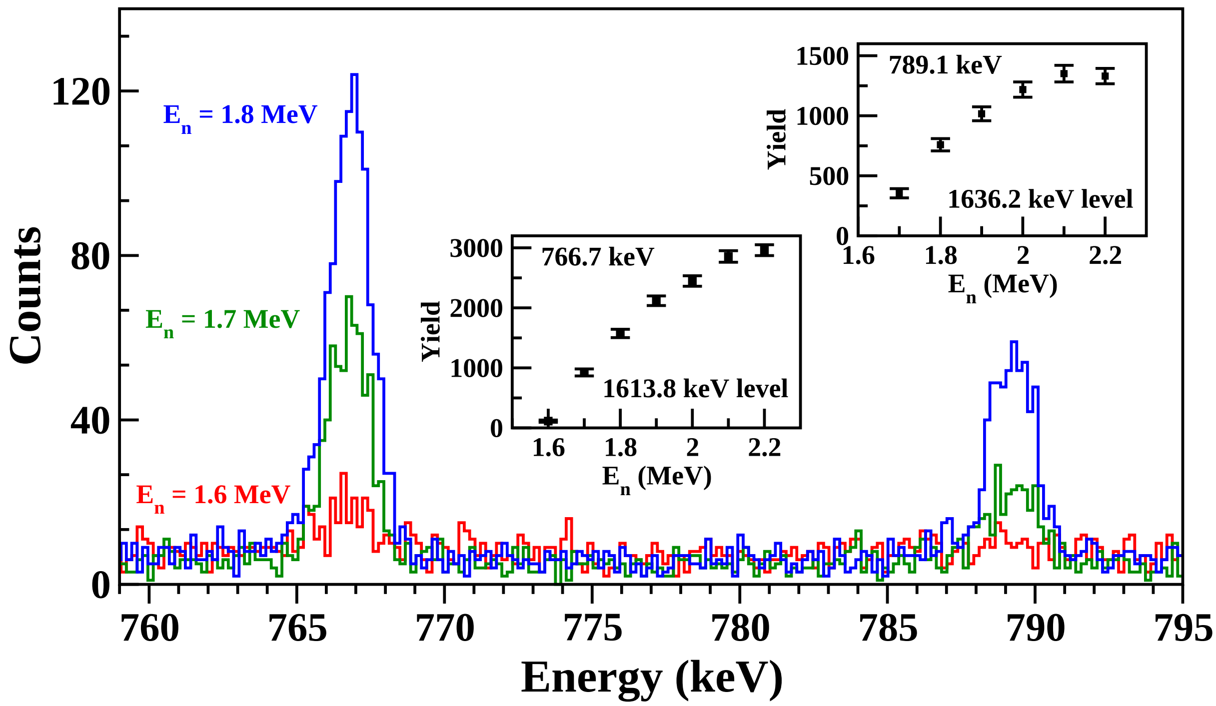

FIG. 1. Portion of the excitation function spectra for incident neutron energies of 1.6, 1.7, and 1.8 MeV showing the 766.7 keV γ ray from the 1613.8 keV 2_2^+ state and the 789.1 keV γ from the 1636.2 keV 0_2^+ state. The γ-ray excitation functions are shown as insets.

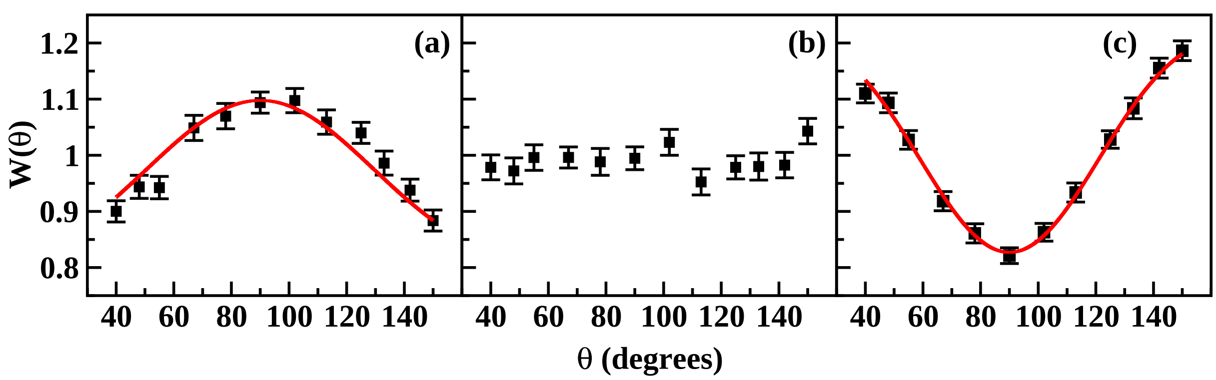

FIG. 2. γ-ray angular distributions measured at $E_n = 2.7$ MeV for (a) the 351.0 keV $5_1^- \to 4_1^+$ transition from the 2082.2 keV state, (b) the 789.1 keV $0_2^+ \to 2_1^+$ transition from the 1636.2 keV state, and (c) the 1072.7 keV $4_2^+ \to 2_1^+$ transition from the 1919.8 keV state. The experimental data are shown as points with error bars and Legendre polynomial fits to the data are shown as solid lines.

ing on which mixing ratio is chosen, is large; however, the $B(E2; 4_1^+ \to 2_1^+)$ is smaller than $B(E2; 2_1^+ \to 0_1^+)$. Moreover, it was not possible to obtain the lifetime of the newly confirmed 0_2^+ state. We also could not identify good candidates for three-phonon states. Thus a vibrational descripton of ^{134}Xe does not appear to be appropriate.

Based on transition strengths from Coulomb excitation measurements, the major fragment of the 2^+ mixed-symmetry state in ^{134}Xe was identified at 1947.2 keV [18]. Our extracted level lifetime (see Fig. 3) and γ-ray branching ratios for this state, as well as the multipole mixing ratio for the $2_3^+ \to 2_1^+$ transition, are in good agreement with the results reported by Ahn et al. [18], and we confirm this identification. As expected, the $B(M1; 2_3^+ \to 2_1^+) = 0.290(22)\ \mu_N^2$ is large, while the $B(E2; 2_3^+ \to 0_1^+) = 0.755^{+81}_{-76}\ W.u.$ is small. The energy of the state fits well in the level systematics of mixed-symmetry states in this region.

The 3^- octupole phonon has not been definitively iden-

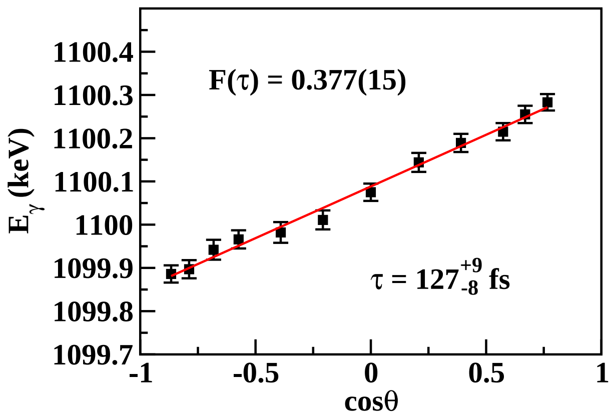

FIG. 3. Doppler-shift attentuation data for the determination of the lifetime of the 1947.2 keV level from the 1100.1 keV γ ray.

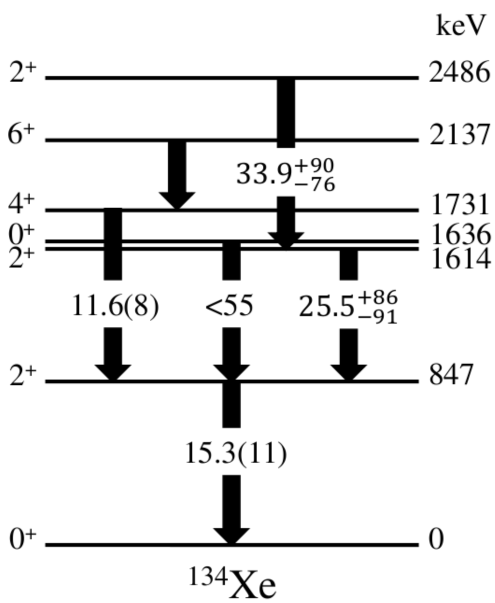

FIG. 4. Transitions and $B(E2)$s in *W.u.* relevant to a potential vibrational description of ^{134}Xe. The values for the $2^+_1 \rightarrow 0^+_1$ and $4^+_1 \rightarrow 2^+_1$ transitions are taken from Ref. [6].

tified in ^{134}Xe, but Mueller et al. [17] suggest that it should occur at an energy of about 2.70 MeV based on an empirical formula they derive from the systematic occurrence of the octupole phonon in this region. As noted previously, Ahn et al. [18] suggest the 2867.2 keV level as a candidate for the octupole phonon and note that its energy lies between the 3^- states found in the neighboring even-even Xe isotopes, i.e., 2469 keV in ^{132}Xe and 3275 keV in ^{136}Xe. Based on our angular distribution data, we confirm that the 2867.2 keV level is indeed a 3^- state.

Finally, we note that the 5^- and 7^- levels occur systematically throughout this mass region as demonstrated in Fig. 5. While the 7^- state in ^{134}Xe was already known, we identify the 5^- state for the first time in these measurements. The $\nu(1h_{11/2}2d_{3/2})$ configuration should result in a multiplet of negative-parity states, a 7^- state, 5^- state, and nearly degenerate 4^- and 6^- states in order of increasing energy. These neutron excitations appear to be exhibited in ^{134}Xe; a 7^- state is present at 1965.5 keV, a 5^- state at 2082.2 keV, a (6^-) state at 2234.3 keV, and a (4^-) state at 2353.0 keV. Shell model calculations by Jakob et al. [16] indicate that the $\nu(2d_{3/2})$ orbital plays a larger role than the $\nu(3s_{1/2})$ orbital in ^{134}Xe, which is in agreement with our observations.

V. CONCLUSIONS

The inelastic neutron scattering reaction has been employed to study the level structure of ^{134}Xe. Many level lifetimes were measured for the first time with the Doppler-shift attenuation method and the low-lying excited states were characterized. The third excited state, a 0^+ level which had only been observed in a previous inelastic neutron scattering study, was confirmed, as was the identification of the 2^+ mixed-symmetry state and the 3^- octupole phonon in ^{134}Xe. Finally, candidates for the complete negative-parity multiplet arising from the $\nu(1h_{11/2}2d_{3/2})$ configuration have also been proposed for the first time in the $N = 80$ isotones.

ACKNOWLEDGMENTS

This material is based upon work supported by the U.S. National Science Foundation under Grant No. PHY-1606890. We wish to thank H. E. Baber for his valuable contributions to these measurements.

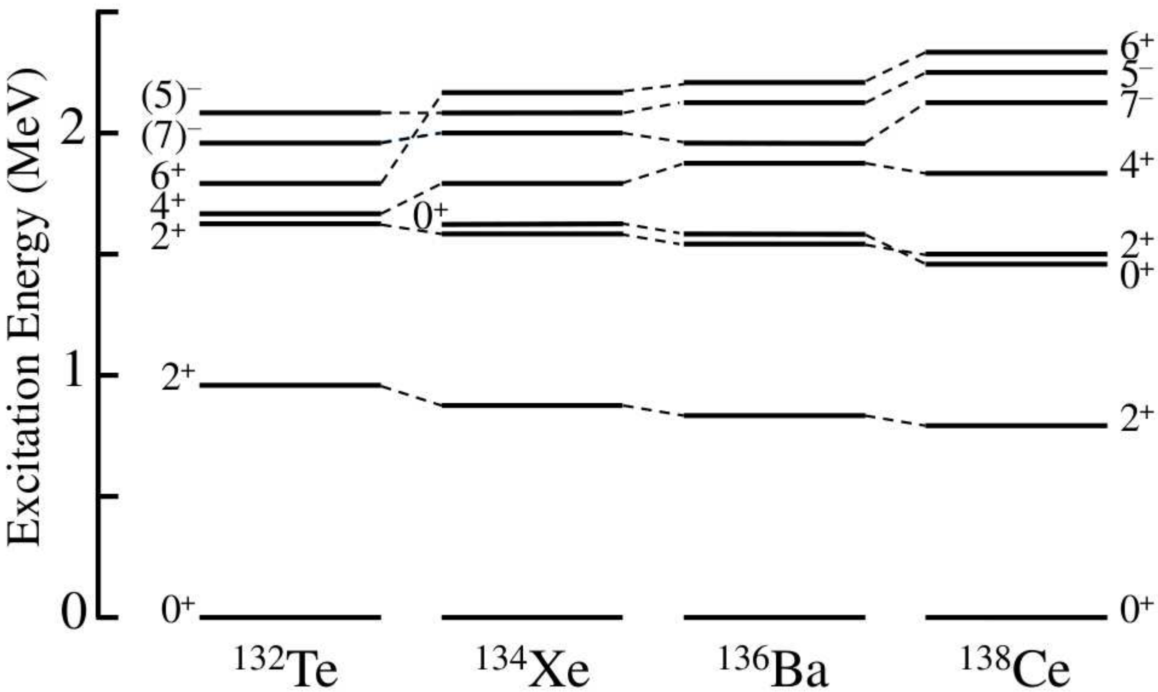

FIG. 5. Systematics of the $N = 80$ isotones in the vicinity of ^{134}Xe [9, 10, 27].

[1] A. J. Radich, P. E. Garrett, J. M. Allmond, C. Andreoiu, G. C. Ball, L. Bianco, V. Bildstein, S. Chagnon-Lessard, D. S. Cross, G. A. Demand, A. Diaz Varela, R. Dunlop, P. Finlay, A. B. Garnsworthy, G. Hackman, B. Hadinia, B. Jigmeddorj, A. T. Laffoley, K. G. Leach, J. Michetti-Wilson, J. N. Orce, M. M. Rajabali, E. T. Rand, K. Starosta, C. S. Sumithrarachchi, C. E. Svensson, S. Triambak, Z. M. Wang, J. L. Wood, J. Wong, S. J. Williams, and S. W. Yates, Phys. Rev. C **91**, 044320 (2015).

[2] E. E. Peters, T. J. Ross, S. F. Ashley, A. Chakraborty, B. P. Crider, M. D. Hennek, S. H. Liu, M. T. McEllistrem, S. Mukhopadhyay, F. M. Prados-Estévez, A. P. D. Ramirez, J. S. Thrasher, and S. W. Yates, Phys. Rev. C **94**, 024313 (2016).

[3] S. A. Eid and S. M. Diab, Prog. Phys. **1**, 54 (2012).

[4] M. A. Jafarizadeh, N. Fouladi, and H. Sabri, Braz. J. Phys. **43**, 34 (2013).

[5] D.-L. Zhang and B.-G. Ding, Commun. Theor. Phys. **60**, 581 (2013).

[6] A. Sonzogni, Nuclear Data Sheets **103**, 1 (2004).

[7] R. O. Hughes, N. V. Zamfir, R. F. Casten, D. C. Radford, C. J. Barton, C. Baktash, M. A. Caprio, A. Galindo-Uribarri, C. J. Gross, P. A. Hausladen, E. A. McCutchan, J. J. Ressler, D. Shapira, D. W. Stracener, and C.-H. Yu, Phys. Rev. C **69**, 051303 (2004).

[8] S. Biswas, R. Palit, A. Navin, M. Rejmund, A. Bisoi, M. S. Sarkar, S. Sarkar, S. Bhattacharyya, D. C. Biswas, M. Caamaño, M. P. Carpenter, D. Choudhury, E. Clément, L. S. Danu, O. Delaune, F. Farget, G. de France, S. S. Hota, B. Jacquot, A. Lemasson, S. Mukhopadhyay, V. Nanal, R. G. Pillay, S. Saha, J. Sethi, P. Singh, P. C. Srivastava, and S. K. Tandel, Phys. Rev. C **93**, 034324 (2016).

[9] A. Sonzogni, Nuclear Data Sheets **95**, 837 (2002).

[10] A. Sonzogni, Nuclear Data Sheets **98**, 515 (2003).

[11] W. G. Winn and D. G. Sarantites, Phys. Rev. **184**, 1188 (1969).

[12] E. Takekoshi, H. Umezawa, and T. Suzuki, Nuclear Physics A **133**, 493 (1969).

[13] E. Achterberg, E. Y. de Aisenberg, F. C. Iglesias, A. E. Jech, J. A. Moragues, D. Otero, M. L. Pérez, A. N. Proto, J. J. Rossi, W. Scheuer, and J. F. Suárez, Phys. Rev. C **4**, 188 (1971).

[14] J. Gualda, R. Saxena, and F. Zawislak, Nuclear Physics A **234**, 357 (1974).

[15] J. R. Van Hise, D. C. Camp, and R. A. Meyer, Z. Phys. A **274**, 383 (1975).

[16] G. Jakob, N. Benczer-Koller, G. Kumbartzki, J. Holden, T. J. Mertzimekis, K.-H. Speidel, R. Ernst, A. E. Stuchbery, A. Pakou, P. Maier-Komor, A. Macchiavelli, M. McMahan, L. Phair, and I. Y. Lee, Phys. Rev. C **65**, 024316 (2002).

[17] W. F. Mueller, M. P. Carpenter, J. A. Church, D. C. Dinca, A. Gade, T. Glasmacher, D. T. Henderson, Z. Hu, R. V. F. Janssens, A. F. Lisetskiy, C. J. Lister, E. F. Moore, T. O. Pennington, B. C. Perry, I. Wiedenhöver, K. L. Yurkewicz, V. G. Zelevinsky, and H. Zwahlen, Phys. Rev. C **73**, 014316 (2006).

[18] T. Ahn, L. Coquard, N. Pietralla, G. Rainovski, A. Costin, R. Janssens, C. Lister, M. Carpenter, S. Zhu, and K. Heyde, Physics Letters B **679**, 19 (2009).

[19] H. von Garrel, P. von Brentano, C. Fransen, G. Friessner, N. Hollmann, J. Jolie, F. Käppeler, L. Käubler, U. Kneissl, C. Kohstall, L. Kostov, A. Linnemann, D. Mücher, N. Pietralla, H. H. Pitz, G. Rusev, M. Scheck, K. D. Schilling, C. Scholl, R. Schwengner, F. Stedile, S. Walter, V. Werner, and K. Wisshak, Phys. Rev. C **73**, 054315 (2006).

[20] A. Vogt, B. Birkenbach, P. Reiter, A. Blazhev, M. Siciliano, J. J. Valiente-Dobón, C. Wheldon, D. Bazzacco, M. Bowry, A. Bracco, B. Bruyneel, R. S. Chakrawarthy, R. Chapman, D. Cline, L. Corradi, F. C. L. Crespi, M. Cromaz, G. de Angelis, J. Eberth, P. Fallon, E. Farnea, E. Fioretto, S. J. Freeman, A. Gadea, K. Geibel, W. Gelletly, A. Gengelbach, A. Giaz, A. Görgen, A. Gottardo, A. B. Hayes, H. Hess, H. Hua, P. R. John, J. Jolie, A. Jungclaus, W. Korten, I. Y. Lee, S. Leoni, X. Liang, S. Lunardi, A. O. Macchiavelli, R. Menegazzo, D. Mengoni, C. Michelagnoli, T. Mijatović, G. Montagnoli, D. Montanari, D. Napoli, C. J. Pearson, L. Pellegri, Z. Podolyák, G. Pollarolo, A. Pullia, F. Radeck, F. Recchia, P. H. Regan, E. Şahin, F. Scarlassara, G. Sletten, J. F. Smith, P.-A. Söderström, A. M. Stefanini, T. Steinbach, O. Stezowski, S. Szilner, B. Szpak, R. Teng, C. Ur, V. Vandone, D. Ward, D. D. Warner, A. Wiens, and C. Y. Wu, Phys. Rev. C **93**, 054325 (2016).

[21] A. Shrivastava, M. Caamaño, M. Rejmund, A. Navin, F. Rejmund, K. H. Schmidt, A. Lemasson, C. Schmitt, L. Gaudefroy, K. Sieja, L. Audouin, C. O. Bacri, G. Barreau, J. Benlliure, E. Casarejos, X. Derkx, B. Fernández-Domínguez, C. Golabek, B. Jurado, T. Roger, and J. Taieb, Phys. Rev. C **80**, 051305 (2009).

[22] C. A. McGrath, M. F. Villani, D. P. Diprete, P. E. Garrett, M. Yeh, and S. W. Yates, Proc. 9th Intern. Symposium on Capture Gamma-Ray Spectroscopy and Related Topics (Budapest, Hungary, October 1996) **1**, 299 (1997).

[23] E. E. Peters, T. J. Ross, S. H. Liu, M. T. McEllistrem, and S. W. Yates, Phys. Rev. C **95**, 014325 (2017).

[24] T. Belgya, G. Molnár, and S. W. Yates, Nucl. Phys. A **607**, 43 (1996).

[25] J. Genevey, J. A. Pinston, C. Foin, M. Rejmund, R. F. Casten, H. Faust, and S. Oberstedt, Phys. Rev. C **63**, 054315 (2001).

[26] S. Mukhopadhyay, M. Scheck, B. Crider, S. N. Choudry, E. Elhami, E. Peters, M. T. McEllistrem, J. N. Orce, and S. W. Yates, Phys. Rev. C **78**, 034317 (2008).

[27] A. Sonzogni, Nuclear Data Sheets **95**, 837 (2002).