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**Ground-state and pairing-vibrational bands with equal quadrupole collectivity in  $^{124}\text{Xe}$** 

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The nuclear structure of  $^{124}\text{Xe}$  has been investigated via measurements of the  $\beta^+/\text{EC}$  decay of  $^{124}\text{Cs}$  with the  $8\pi\gamma$ -ray spectrometer at the TRIUMF-ISAC facility. The data collected have enabled branching ratio measurements of weak, low-energy transitions from highly excited states, and the  $2^+ \rightarrow 0^+$  in-band transitions have been observed. Combining these results with those from a previous Coulomb excitation study,  $B(E2; 2_3^+ \rightarrow 0_2^+) = 78(13)$  W.u. and  $B(E2; 2_4^+ \rightarrow 0_3^+) = 53(12)$  W.u. were determined. The  $0_3^+$  state, in particular, is interpreted as the main fragment of the proton-pairing vibrational band identified in a previous  $^{122}\text{Te}(^3\text{He},n)^{124}\text{Xe}$  measurement, and has quadrupole collectivity equal to, within uncertainty, that of the ground-state band.

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**I. INTRODUCTION**

Nuclei in the  $Z > 50$ ,  $N < 82$  region (i.e., “northwest” of  $^{132}\text{Sn}$ ) display a remarkably smooth evolution of their properties. As highlighted by Rowe and Wood [1], this region is unsurpassed in the smoothness of the trends in the first  $2^+$  energy and  $B(E2; 2_1^+ \rightarrow 0_1^+)$  values, with no abrupt changes observed. It is thus an ideal region in which to explore the development of collectivity progressing away from the doubly-magic  $^{132}\text{Sn}$  towards the well-deformed mid-shell. This region is also the focus of many searches for a possible neutrinoless double- $\beta$ -decay mode  $0\nu\beta\beta$ . Observation of this process would reveal the nature of the neutrino as a Majorana particle, while a measurement of the rate would provide information on the Majorana mass of the neutrino provided that the nuclear-structure-dependent matrix element is known

[2]. Some of the most promising candidates in which to pursue observation of the  $0\nu\beta\beta$  process include  $^{130}\text{Te}$  (see, e.g., Ref. [3]),  $^{136}\text{Xe}$  (see, e.g., Ref. [4]), and  $^{124}\text{Sn}$  [2], and for the double-electron-capture  $0\nu\text{ECEC}$  mode,  $^{124}\text{Xe}$  [5,6].

Motivated by the need to evaluate the nuclear matrix elements for the  $0\nu\beta\beta$  mode, there has been a renewed interest in using transfer reactions to probe the occupancies and correlations of the protons and neutrons involved [7]. Especially important are the results of two-nucleon transfer (TNT) experiments on even-even nuclei where the transfer strength is shared by the ground and excited  $0^+$  states indicating a departure from BCS-type wave functions [7]. Strong transitions observed in TNT reactions to excited  $0^+$  states can arise from gaps in the single-particle spectrum leading to pairing vibrations, shape coexistence, and pairing isomers. In the absence of other complementary data, the observation of strong TNT transitions alone is insufficient information to determine the nature of the  $0^+$  wave function. In the Cd region, there is convincing evidence, including strong enhancements in the  $(^3\text{He}, n)$  two-proton transfer cross sections to excited  $0^+$  states [8], that the shape-coexisting intruder bands are based on proton  $2p$ - $2h$  excitations (resulting in a  $2p$ - $4h$  configuration) across the  $Z = 50$  closed shell. The interaction of the additional proton 2 valence particles and 2 valence holes with the neutrons in the open  $50$ – $82$  shell and the gain in the correlation energy results in the appearance of the deformed rotational-like band in the low-excitation energy region [9–12]. Thus, the shape-coexisting states in the near- to mid-shell Cd isotopes are the main fragments of the proton-pairing vibrational states.

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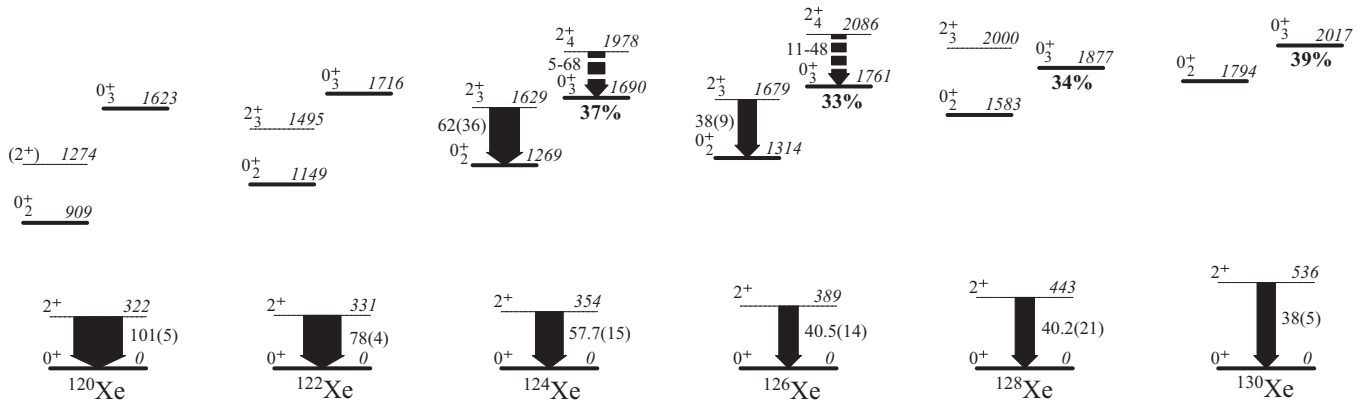


FIG. 1. Systematics of the low-lying  $0^+$  states in the  $^{120}\text{Xe} - ^{130}\text{Xe}$  isotopes. Absolute in-band  $B(E2; 2^+ \rightarrow 0^+)$  values are shown, where known [16–18], in W.u. with uncertainties in parentheses. The possible ranges of values for the  $0^+_3$  bands in  $^{124}\text{Xe}$  and  $^{126}\text{Xe}$  were derived from Coulomb excitation analyses [17,18] for these unobserved transitions. For  $^{124-130}\text{Xe}$ , the values of the ratio of the  $(^3\text{He}, n)$  cross section attributed to the  $0^+_3$  state to that of the ground state are written below the  $0^+_3$  levels in percentages [15,19].

The  $(^3\text{He}, n)$  reaction on the tin isotopes [13] also showed enhancements to excited  $0^+$  states in the Te isotopes, but unlike the mid-shell Cd isotopes, to date there has been no convincing evidence of a shape-coexisting band based on these  $0^+$  states. [Rotational bands have been observed in the lighter-mass Te isotopes (see, e.g., Ref. [14]), but none extended down to a  $0^+$  band head.] The  $\text{Te}(^3\text{He}, n)$  two-proton transfer reactions populating the Xe isotopes [15] also located the low-lying fragment of the proton-pairing vibration, with a  $0^+$  state between 1.65 MeV ( $^{124}\text{Xe}$ ) and 2.1 MeV ( $^{130}\text{Xe}$ ) populated with approximately 1/3 of the ground-state strength. Figure 1 summarizes the systematics of the low-lying excited  $0^+$  states in the  $^{120}\text{Xe} - ^{130}\text{Xe}$  isotopic chain. The in-band  $B(E2; 2^+ \rightarrow 0^+)$  values, in W.u., are shown where known [16–18]. Displayed under the  $0^+_3$  levels are the  $(^3\text{He}, n)$  cross sections [15] relative to that of the ground state [19]. As Fig. 1 shows, the  $B(E2; 2^+ \rightarrow 0^+)$  values in the pairing-vibrational band in  $^{124}, ^{126}\text{Xe}$  have such large uncertainties that their degree of quadrupole collectivity is difficult to assess.

Recently, the stable Xe isotopes have been the subject of detailed Coulomb excitation studies [17,18,20,21] with beams of the Xe isotopes bombarding a  $^{12}\text{C}$  target and the resulting de-excitation  $\gamma$  rays detected using the GAMMASPHERE array. These experiments provided a wealth of information on matrix elements, and allowed detailed tests of nuclear structure models [17,18,20] and the elucidation of the evolution of mixed-symmetry states [21]. The study [17] of  $^{124}\text{Xe}$ , in particular, provided numerous  $B(E2)$  transition strengths for off-yrast, low-spin states. The results were compared with interacting boson model, (IBM) calculations and indicated that  $^{124}\text{Xe}$  badly breaks  $O(6)$ , but preserves  $O(5)$  symmetry [17].

As shown in Fig. 1, in  $^{124}\text{Xe}$  there were two key transitions for which the matrix elements could not be accurately determined: the  $2^+_3 \rightarrow 0^+_2$  and the  $2^+_4 \rightarrow 0^+_3$  transitions. These transitions represent the in-band decays and an accurate measurement of their  $B(E2)$  values is crucial in determining the quadrupole collectivity of the bands. The 289-keV  $2^+_4 \rightarrow 0^+_3$  transition, in fact, has never been observed in any experiment to date for  $^{124}\text{Xe}$ , but its existence was hypothesized using  $\gamma$ -ray yields of other observed decay branches [17]. Observation of

these missing transitions and measurements of their  $B(E2)$  values would provide the information needed to further investigate the structure of this nucleus. Experiments utilizing  $\beta$  decay are ideal to search for such weak  $\gamma$ -decay branches that are often unobserved with other experimental techniques.

## II. EXPERIMENTAL DETAILS

An experiment to observe low-energy, weak decay branches in  $^{124}\text{Xe}$  was performed at the Isotope Separator and Accelerator (ISAC) facility at TRIUMF in Vancouver, Canada. A 25- $\mu\text{A}$  beam of 500-MeV protons from the TRIUMF main cyclotron bombarded a thick tantalum production target, inducing spallation reactions. The reaction products diffused through the target and were surface ionized and mass separated to produce a beam containing  $9.8 \times 10^7$  ions/s  $^{124}\text{Cs}$  ( $J^\pi = 1^+$ ,  $T_{1/2} = 30.8$  s) and  $2.6 \times 10^6$  ions/s  $^{124}\text{Cs}^m$  ( $J^\pi = (7)^+$ ,  $T_{1/2} = 6.3$  s). The beam was implanted into a movable mylar-backed FeO tape in the center of the  $8\pi$   $\gamma$ -ray spectrometer—an array of 20 Compton-suppressed high-purity germanium detectors in a truncated icosahedral arrangement [22]. The tape system was operated in a cycling mode. Singles  $\gamma$ -ray and  $\gamma$ - $\gamma$  coincidence data were collected during the implantation and decay period, after which the implantation site was transported behind a thick lead wall to remove any long-lived sources from the focal volume of the  $8\pi$  array. The following cycle times were implemented: 5 s of implantation and 6 s of decay for 8 hours; 1 s of implantation and 12 s of decay for 8 hours; and 300 s of implantation and 45 s of decay for 35 hours. Calibration measurements using sources of  $^{152}\text{Eu}$ ,  $^{56}\text{Co}$ ,  $^{60}\text{Co}$ , and  $^{133}\text{Ba}$  were performed immediately following the experiment. The data were sorted into a time-random background-subtracted  $\gamma$ - $\gamma$  coincidence matrix containing approximately  $4.5 \times 10^8$  events and analyzed with the RADWARE package of programs [23].

The analysis procedure was outlined in Ref. [24,25]. Briefly, all branching ratios were determined by analyzing coincidence-gated  $\gamma$ -ray spectra, generally by taking the coincidence gate from below. The number of counts in

a coincidence peak,  $N_c$ , is given by

$$N_c = \mathcal{N} I_\gamma^f \epsilon_\gamma^f \text{BR}_\gamma^d \epsilon_\gamma^d \epsilon_c \eta(\theta_{fd}), \quad (1)$$

where  $\mathcal{N}$  is an overall normalization factor for a particular data set,  $I_\gamma$  is the  $\gamma$ -ray intensity for the feeding  $f$  or draining  $d$  transition from a level,  $\text{BR}_\gamma^d$  is the branching ratio of the draining transition,  $\epsilon_\gamma$  is the  $\gamma$ -ray detection efficiency,  $\epsilon_c$  accounts for the deviation of the relative efficiency from that determined using singles analysis due to the coincidence condition, which in principle depends on both the feeding and draining  $\gamma$ -ray energies, and  $\eta(\theta_{fd})$  is the angular correlation correction factor for the particular pair of feeding and draining  $\gamma$  rays. Angular correlation effects are generally smaller than a few percent due to the symmetry of the  $8\pi$  spectrometer [26]. To account for such effects, in addition to the statistical uncertainties of the  $\gamma$ -ray peak areas, a 3% systematic uncertainty was added in quadrature to the relative intensities of the  $\gamma$  rays. The  $\gamma$ - $\gamma$  coincidence efficiency factor  $\epsilon_c$  is generally most affected by timing conditions placed on the data, and since these were very generous ( $|\Delta t_{\gamma\gamma}| \leq 200$  ns), it was assumed to be 1. The validity of this assumption was verified by branching ratios obtained using multiple gates and comparison with singles intensities [25]. To generate the coincidence spectra, generally the gate was taken on the strongest draining transition. Intensities were obtained by dividing the peak area by the  $\gamma$ -ray singles photopeak efficiencies of both the feeding and draining  $\gamma$  rays and the branching ratio of the draining  $\gamma$  ray. Branching ratios were then found by dividing the peak intensity by the total intensity out of the level of interest [24,25].

### III. RESULTS

Shown in Fig. 2 is a partial level scheme for  $^{124}\text{Xe}$  obtained from the current work, focusing on the decays of the  $2_3^+$  and  $2_4^+$  levels, and the results are listed in Table I. The coincidence spectrum of the 915-keV  $0_2^+ \rightarrow 2_1^+$   $\gamma$  ray, shown in Fig. 3, clearly displays the 360-keV  $2_3^+ \rightarrow 0_2^+$   $\gamma$  ray. The observed branch was 5.81(27)%, in agreement with the previously measured branch of 6.4(7)% [16], and the most

recent measurement in the Coulomb excitation experiment [17] of 8(4)%. Figure 4 displays a portion of the coincidence spectrum with the 1336-keV  $0_3^+ \rightarrow 2_1^+$   $\gamma$  ray, revealing the heretofore unobserved 289-keV transition from the 1979-keV  $2_4^+$  level. As can be seen, while the  $\gamma$ -ray peak is small, it is clearly present and the branching ratio extracted is 0.79(9)%.

### IV. INTERPRETATIONS

The  $B(E2)$  values for the transitions were obtained using ratios with previously measured  $B(E2)$  values for  $\gamma$  rays from the same level determined from Coulomb excitation [17] via

$$B(E2) = B(E2)_{ref} \frac{E_{\gamma_{ref}}^5}{E_\gamma^5} \frac{\text{BR}}{\text{BR}_{ref}}, \quad (2)$$

where the subscript *ref* denotes the reference transition, and BR refers to the branching ratio. While the modification of the branching ratios and the observation of additional transitions affect the Coulomb excitation yield, the population of any given level is largely determined by its direct feeding from the ground state, or in the case of levels with no measurable yield to ground state, from the  $2_1^+$  level. To verify this assumption, new calculations using the GOSIA code [27] were undertaken using the same assumptions as the original analysis [17] (since the system of equations is under-determined, the signs of the matrix elements were taken from an IBM calculation [17]) but with the newly extracted branching ratios. It was determined that the population of the  $2^+$  levels was not significantly affected by the new branching ratios, and therefore the direct  $B(E2; 0_1^+ \rightarrow 2^+)$  values from the original analysis [17] remained valid. The  $B(E2)$  value for the 360-keV  $2_3^+ \rightarrow 0_2^+$  transition was thus determined to be 78(13) W.u. and that of the 289-keV  $2_4^+ \rightarrow 0_3^+$  transition 53(12) W.u. These values agree with the previous values of 62(36) W.u. and 5–68 W.u., respectively, but are considerably more precise. The new values for the low-lying  $0^+$  and  $2^+$  levels are listed in Table I; the  $B(E2)$  transition used as the reference value in Eq. (2) is indicated by an asterisk under the present results.

The newly-determined in-band  $B(E2)$  values reveal that the excited  $K^\pi = 0^+$  bands have considerably more quadrupole

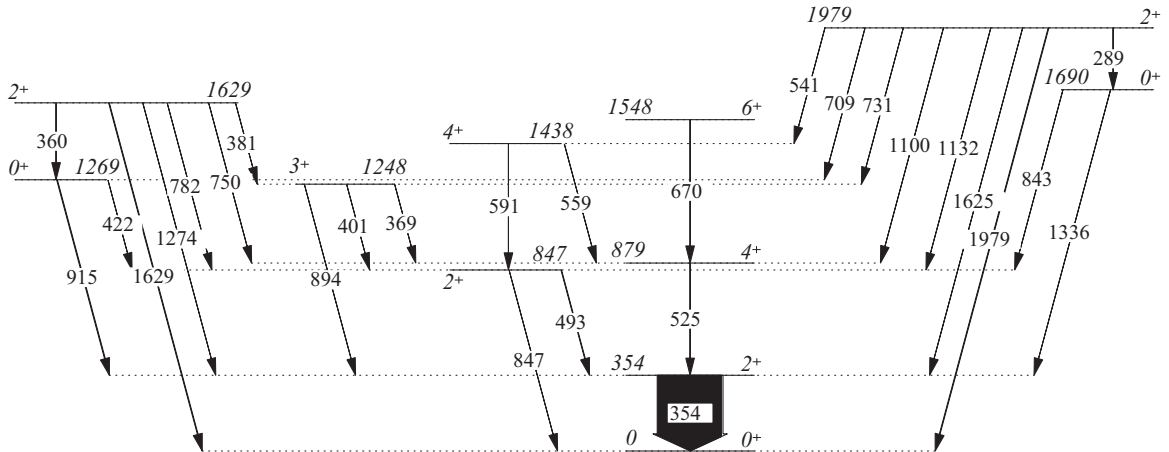


FIG. 2. Partial level scheme observed in the  $\beta^+/\text{EC}$  decay of  $^{124}\text{Cs}$ . Levels are labeled with their energies in keV and their  $J^\pi$  values. The transitions are labeled with their energies in keV, with arrow widths proportional to the observed intensity.

TABLE I. Experimental data for the low-lying “ $K^\pi = 0^+$ ” bands in  $^{124}\text{Xe}$ . The previous results are those from Ref. [17]. Energies are given in keV and  $B(E2)$  values in W.u. (uncertainties are given in parentheses) with those indicated by an asterisk used as the reference transition in Eq. (2). The rightmost columns are predictions using the IBM [17], and the DPPQ model [28].

State	Experimental						Theoretical			
	$E_{ex}$	$I_i^\pi \rightarrow I_f^\pi$	Previous		Present		IBM		DPPQ	
			BR	$B(E2)$	BR	$B(E2)$	$E_{ex}$	$B(E2)$	$E_{ex}$	$B(E2)$
$2_1^+$	354	$2_1^+ \rightarrow 0_1^+$	1.0	57.7(15)	1.0		354		355	62
$2_2^+$	847	$2_2^+ \rightarrow 2_1^+$	0.750(2)	64(5)	0.774(12)	74(7)	811	61	1097	45
		$2_2^+ \rightarrow 0_1^+$	0.250(2)	1.45(12)	0.226(12)	*		1.47		0.03
$0_2^+$	1269	$0_2^+ \rightarrow 2_2^+$	0.122(12)	87(21)	0.098(4)	68(16)	1104	76	1099	82
		$0_2^+ \rightarrow 2_1^+$	0.878(12)	13.2(31)	0.902(4)	*		16		57
$2_3^+$	1629	$2_3^+ \rightarrow 0_2^+$	0.081(40)	62(36)	0.0581(27)	78(13)	1693	36	1708	52
		$2_3^+ \rightarrow 3_1^+$			0.0340(17)	34(6) <sup>a</sup>				
		$2_3^+ \rightarrow 4_1^+$	0.151(8)	5.6(8)	0.119(5)	4.0(7)		4.5		21
		$2_3^+ \rightarrow 2_2^+$	0.119(7)	3.5(7)	0.114(5)	3.1(5)		1		17
		$2_3^+ \rightarrow 2_1^+$	0.235(13)	0.61(7)	0.225(9)	0.54(9)		0.02		0.03
		$2_3^+ \rightarrow 0_1^+$	0.415(19)	0.315(49)	0.450(17)	*		0.07		0.04
		$2_3^+ \rightarrow 2_1^+$	0.138(19)	18.5(17)	0.072(4)	9.2(14)	1570	15		44
$0_3^+$	1690	$0_3^+ \rightarrow 2_1^+$	0.862(19)	11.9(17)	0.928(4)	*		13		2.2
		$0_3^+ \rightarrow 2_2^+$								
$2_4^+$	1979	$2_4^+ \rightarrow 0_3^+$		5–68	0.0079(9)	53(12)	2146	33		49
		$2_4^+ \rightarrow 4_2^+$			0.0048(4)	1.4(3)				
		$2_4^+ \rightarrow 0_2^+$			0.0147(13)	1.12(23)				
		$2_4^+ \rightarrow 3_1^+$			0.0138(12)	0.90(19) <sup>a</sup>				
		$2_4^+ \rightarrow 4_1^+$	0.183(34)	1.47(38)	0.262(9)	2.2(4)		6.4		1.4
		$2_4^+ \rightarrow 2_2^+$	0.38(5)	2.7(8)	0.361(11)	2.6(5)		4.4		3.3
		$2_4^+ \rightarrow 2_1^+$	0.183(45)	0.21(7)	0.090(5)	0.11(2)		0.15		0.05
		$2_4^+ \rightarrow 0_1^+$	0.25(5)	0.11(2)	0.245(9)	*		0.10		0.03

<sup>a</sup> $B(E2)$  calculated assuming a pure  $E2$  transition.

collectivity than previously thought. The  $0_2^+$  band has approximately twice the in-band  $B(E2)$  value predicted from the IBM calculations of Ref. [17] ( $78 \pm 13$  vs 36 W.u.), and also larger than predicted in recent dynamic-pairing plus quadrupole (DPPQ) model calculations [28], also listed in

Table I. The results for the  $0_3^+$  band further indicate that its quadrupole collectivity, as implied by the  $B(E2)$  value of  $53 \pm 12$  W.u., is similar to that of the ground-state band and considerably more than the IBM predictions (33 W.u.) [17], but in excellent agreement with the DPPQ model predictions [28].

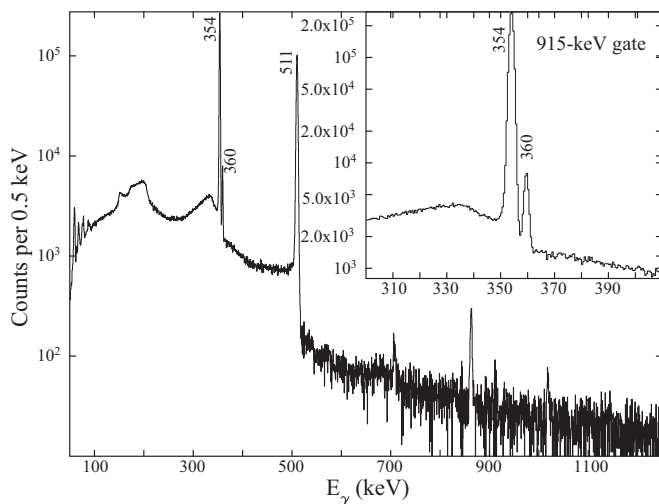


FIG. 3. Portion of the  $\gamma$ -ray coincidence spectrum gated on the 915-keV  $0_2^+ \rightarrow 2_1^+$   $\gamma$  ray showing the 360-keV  $\gamma$  ray from the 1629-keV level. The inset displays an expanded region of the spectrum centered near 350 keV.

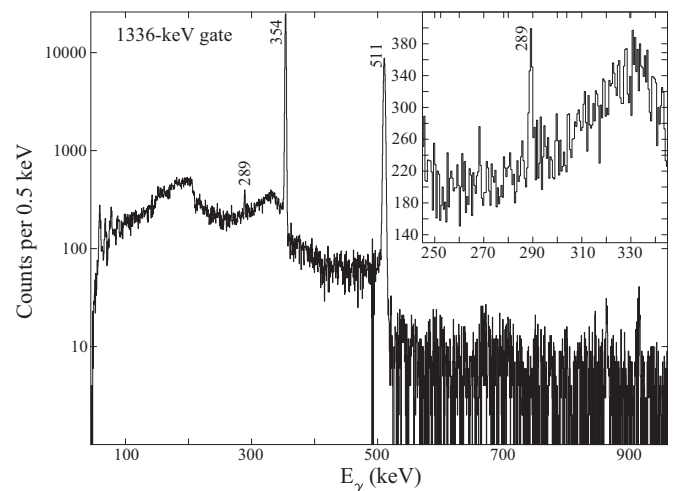


FIG. 4. Portion of the  $\gamma$ -ray coincidence spectrum gated on the 1336-keV  $0_3^+ \rightarrow 2_1^+$   $\gamma$  ray showing the 289-keV  $\gamma$  ray from the 1979-keV level. The inset displays an expanded region of the spectrum centered near 290 keV.



TABLE II. Values of  $\beta_0$  extracted using Eqs. (3) and (4). For comparison, the corresponding values from the IBM calculations [17] and DPPQ model [28] are listed.

	Expt.	IBM	DPPQ
$\beta(0_1^+)$	0.227(3)	0.224	0.231
$\beta(0_2^+)$	0.29(2)	0.217	0.406
$\beta(0_3^+)$	0.22(2)	0.182	0.286

Unfortunately, predictions of the two-proton transfer strength in the DPPQ model are unavailable.

With the increased precision for the  $B(E2)$  values for transitions involving the  $K^\pi = 0^+$  band heads, the Kumar-Cline sum rules [29] can be used to extract the rotationally-invariant  $E2$  moments via

$$\frac{1}{\sqrt{5}}Q^2 = \sum_i \langle 0 || \mathcal{M}(E2) || 2_i \rangle \langle 2_i || \mathcal{M}(E2) || 0 \rangle \begin{Bmatrix} 2 & 2 & 0 \\ 0 & 0 & 2 \end{Bmatrix} \quad (3)$$

where  $\mathcal{M}(E2)$  is the transition matrix element and  $\{\}$  is a  $6j$  symbol. While the sum extends over the complete set of  $2^+$  states, it generally is determined by a few key matrix elements. The  $Q^2$  invariant can be related to the  $\beta_0$  shape parameter within the axially-symmetric rotational model via

$$Q^2 = q_0^2 \beta_0^2 \quad (4)$$

with  $q_0 = \frac{3}{4\pi} Z R_0^2$  with  $R_0 = 1.2A^{1/3}$  fm. The values of  $\beta_0$  determined using the present data given in Table I are listed in Table II together with the values predicted by the IBM

[17] and DPPQ model [28]. In principle, the experimental values represent lower limits, but are unlikely to change significantly by extending the sum over more states. The conclusions reached regarding the degree of deformation of the  $0^+$  bands through the use of quadrupole invariants are consistent with the expectations from the magnitude of the in-band  $B(E2; 2^+ \rightarrow 0^+)$  values; the  $0_2^+$  band has significantly greater quadrupole collectivity than the ground state, and the  $0_3^+$  band has an equal degree within uncertainty.

## V. CONCLUSIONS

The observation of similar quadrupole collectivity for the low-lying fragment of the proton-pairing vibration as observed for the ground state in  $^{124}\text{Xe}$  provides a constraint on nuclear structure models used in this region. As shown in Table II, for the excited  $0^+$  states the IBM predicts that  $\beta_0$  decreases, whereas the DPPQ predicts an excessive deformation. (Models typically fit the  $B(E2; 2_1^+ \rightarrow 0_1^+)$  value, thus agreement for  $\beta(0_1^+)$  is to be expected.) The present work, which measured the branching ratios of  $\gamma$  rays, is insufficient to determine if the excited bands are prolate or oblate, only that the  $0_2^+$  band has a larger  $\beta_0$  value than the ground state, and that of the  $0_3^+$  band is essentially identical. Detailed spectroscopic measurements of this type are required for the heavier Xe and Te isotopes, especially for those used in experimental searches for neutrinoless double- $\beta$  decay.

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