$B(E2; 2_1^+ \rightarrow 0_1^+)$ value in ^{90}Kr

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A smooth onset of collectivity in ^{88,92,94,96}Kr has been determined from reported $B(E2; 2_1^+ \rightarrow 0_1^+)$ and $E(2_1^+)$ values. This is in contrast to the sudden onset in even-even Zr, Mo, and Sr isotopes. Our objective was to complete the systematics by determining the $B(E2; 2_1^+ \rightarrow 0_1^+)$ value in ^{90}Kr, which was produced by cold-neutron-induced fission of ^{235}U. The lifetime of the 2_1^+ state in ^{90}Kr was measured via the electronic γ-γ timing technique using the EXILL and FATIMA spectrometers. Based on the measured mean lifetime of $\tau = 15(10)$ ps, the $B(E2; 2_1^+ \rightarrow 0_1^+)$ value of 13^{+26}_{-5} W.u. in ^{90}Kr is determined for the first time and the smooth onset of deformation in the even-even Kr isotopes beyond neutron number $N = 50$ is confirmed.

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Introduction. Neutron-rich nuclei in the region around $Z = 40$ and $N = 60$ have been the focus of intensive investigation from both theoretical and experimental points of view for three decades [1–8]. A remarkable feature is the sudden onset of quadrupole deformation in the zirconium ($Z = 40$), molybdenum ($Z = 42$), and strontium ($Z = 38$) isotopic chains when going from neutron number $N = 58$ to $N = 60$. Whereas the even-even Zr, Mo, and Sr isotopes with neutron numbers $N \leqslant 58$ exhibit near-spherical ground-state shapes, those with $N \geqslant 60$ are strongly quadrupole deformed. This can be associated to a sudden disappearance of the $Z = 40$ subshell in the Zr, Mo, and Sr isotopes at $N = 60$ and illustrates the subtle interplay of single-particle and collective degrees of freedom [1].

The question of whether this sudden shape transition also occurs in the even-even Kr isotopes ($Z = 36$) was recently investigated in a series of Coulomb excitation experiments using the MINIBALL γ-ray array at the REX-ISOLDE facility [9–11]. Based on $B(E2; 2_1^+ \rightarrow 0_1^+)$ and $E(2_1^+)$ values, it was found that in ^{88,92,94,96}Kr, a smooth onset of deformation takes place, confirming what was inferred from recent mass and charge-radii measurements [12,13]. This was in agreement with theoretical predictions of neutron-proton interacting boson model calculations based on self-consistent mean-field calculations using the microscopic Gogny energy-density functional [10,11]. Only ^{90}Kr was not measured in this REX-ISOLDE campaign, in order to prevent long-lived β-decay contamination related to grand-daughter ^{90}Sr in the CD particle detector [9].

Here we report on the determination of the $B(E2; 2_1^+ \rightarrow 0_1^+)$ in ^{90}Kr after cold-neutron induced fission of ^{235}U at

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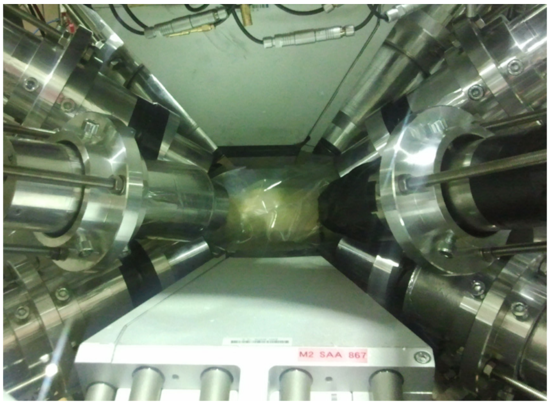

FIG. 1. (Color online) A portion of the EXILL and FATIMA spectrometer, which consisted of a ring of eight BGO Compton-suppressed EXOGAM Clovers (one removed for the photo), each made of four Ge crystals [18] and 16 $LaBr_3$(Ce) scintillator detectors.

the Institut Laue-Langevin (ILL) of Grenoble, France. The experiment was part of the EXILL and FATIMA campaign described in Ref. [14] and the lifetime of the 2_1^+ state in ^{90}Kr was measured via fast electronic timing with $LaBr_3$(Ce) detectors by using the generalized centroid difference (GCD) method [15].

Experimental description. Prompt-fission γ-ray spectroscopy experiments using a highly segmented mixed array of Ge and Ce-doped $LaBr_3$ detectors have been performed at the ILL within the EXILL and FATIMA campaign of 2013. Part of the HPGe high-resolution EXILL (EXOGAM at ILL) spectrometer was combined with a large fast-timing array of $LaBr_3$ detectors (FATIMA). As shown in Fig. 1, the detectors were placed around a fission target with thick backings used in order to stop the fission fragments within the target in $\lesssim$ 1 ps. We report on results obtained from the fission of ^{235}U induced by an intense cold-neutron beam from the collimated neutron guide PF1B [16,17] of the ILL reactor. In the off-line analysis, prompt γ-ray cascades from the nuclei of interest were selected via triple (Ge-$LaBr_3$-$LaBr_3$) or quadruple (Ge-Ge-$LaBr_3$-$LaBr_3$) coincidences. Such coincidence conditions are necessary, as over 100 different nuclear species are strongly produced in fission, into states at high spins (up to $20\hbar$ and more) with resulting high γ-ray multiplicity. Here the good energy resolution of the Ge detectors (EXILL part) allows for precise selection of a cascade, while the excellent timing performance of the $LaBr_3$ detectors is used for electronic time-difference measurements in the ps-ns region between the γ rays feeding and decaying from an excited state (FATIMA part). The analog electronics fast-timing circuitry used for picosecond sensitive lifetime measurements is described in Ref. [15]. The FWHM of the combined FATIMA prompt response function of the EXILL and FATIMA setup was measured to be 500–270 ps for the energy region of 0.1—6.8 MeV [14].

According to the GCD method, the mean lifetime τ is derived from the simple superposition of the $N(N-1)/2$ unique time-difference spectra of the N detector timing system [14,15]. Two independent FATIMA time spectra are obtained depending on whether the decay transition provided a stop signal (the "delayed time spectrum") or a start signal ("antidelayed") as described in more detail in Ref. [14]. Assuming no background contributions, the measurement of the time shift between the centroids (first moment of a time distribution) of the delayed and the antidelayed time spectra of a γ-γ cascade provides the centroid difference and corresponds to [14,15]

$$\overline{\Delta C} = \overline{C}_{\text{delayed}} - \overline{C}_{\text{anti-delayed}} = \overline{\text{PRD}} + 2\tau, \tag{1}$$

where $\overline{\text{PRD}} = \overline{\text{PRD}}(E_{\text{feeder}}) - \overline{\text{PRD}}(E_{\text{decay}})$ is the mean prompt response difference and describes the linearly combined γ-γ time-walk (physical zero-time vs. energy) characteristics of the complete fast-timing array. Using a standard ^{152}Eu source and the neutron-capture reaction ^{48}Ti$(n,\gamma)^{49}$Ti, the mean PRD curve of the FATIMA plus the electronics setup of the EXILL and FATIMA spectrometers was calibrated for the energy region of 0.04-6.8 MeV with an overall precision of δPRD = 10 ps, as reported in Ref. [14].

Results and discussion. The aim of the EXILL and FATIMA campaign was to use the EXILL array as a high-resolution γ-ray selector in order to provide relatively clean $LaBr_3$ coincidence spectra with few γ rays and resulting low Compton background. For the case of ^{90}Kr, the cleanest and most significant result was obtained using an EXILL (Ge) gate on the 199-keV ground-state transition in the complementary fission partner ^{144}Ba. As shown in Fig. 2, the triple coincidence spectra in coincidence with the 199-keV transition in ^{144}Ba measured in the Ge and the 707-keV $2_1^+ \rightarrow 0_1^+$ transition in ^{90}Kr (in $LaBr_3$) provide a significant peak at 1123 keV corresponding to the energy of a transition feeding the 2_1^+ state in ^{90}Kr [19]. Most importantly, no γ rays can be observed in the vicinity ($\pm$30 keV) of the 1123-keV peak. The same result was obtained when checking the 707-keV $2_1^+ \rightarrow 0_1^+$ transition in ^{90}Kr (with Ge gate on 199 keV and $LaBr_3$ gate

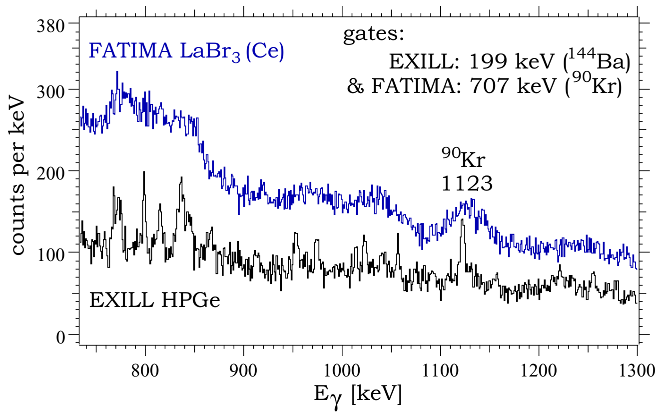

FIG. 2. (Color online) Double-gated triple coincidence spectra showing the cleanliness of the data in the region of the 1123-keV peak. The results are out of 8 TB of data digitally acquired trigger less from a 12 d measurement on cold-neutron induced fission of ^{235}U. For visibility, the EXILL coincidence spectrum is reduced by factor 3. The spectra are not background subtracted, as the Compton background is needed to derive its contribution to the time spectra presented in Fig. 3.

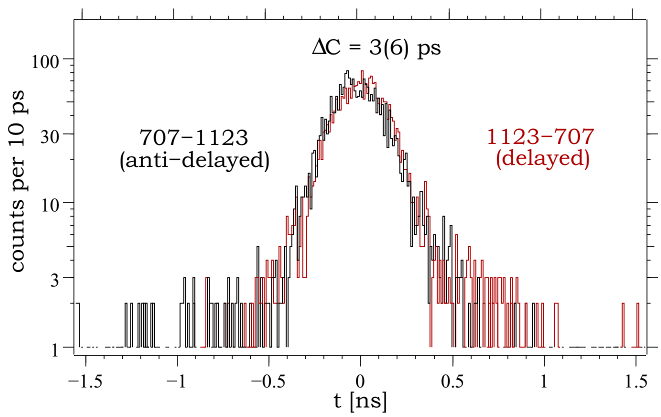

FIG. 3. (Color online) The two EXILL-gated FATIMA time spectra of the 1123–707 keV γ-γ cascade in ^{90}Kr. The result consists of the sum of spectra obtained using two different EXILL gates (199 keV and 331 keV in ^{144}Ba). The time spectra include large contributions of γ-Compton events, as can be deduced from Fig. 2.

on 1123 keV). Such checks are needed to ensure that no other γ rays contribute to the two FATIMA time spectra. Similar results were obtained using the 331-keV $4_1^+ \rightarrow 2_1^+$ transition in ^{144}Ba in the Ge detectors to trigger the 1123–707-keV cascade in the $LaBr_3$-$LaBr_3$ detectors.

To derive the lifetime of the 2_1^+ state from the measured centroid difference ΔC of the 1123–707 keV γ-γ cascade presented in Fig. 3, the (mean) PRD of this energy combination is required and a γ-Compton time-response correction has to be applied due to the significant Compton background contribution underneath the full-energy peak at 1123 keV (see Fig. 2). The γ-Compton time response $\Delta C_{\mathrm{Compton}}$ is extrapolated from the data of a set of time spectra generated using gates on the Compton background above 1123 keV, as illustrated in Fig. 4. Taking into account the peak-to-background ratio $\Pi = 0.36(3)$ of the 1123-keV peak in the FATIMA $LaBr_3$ coincidence spectrum shown in Fig. 2, the net centroid difference is derived from the time shift [here $-11(6)$ ps] between the measured centroid difference and the γ-Compton time response at 1123 keV using [14]:

$$\Delta C_{\mathrm{net}} = \Delta C + \frac{\Delta C - \Delta C_{\mathrm{Compton}}}{\Pi}. \tag{2}$$

By inserting the net centroid difference in Eq. (1) with PRD $= -58(10)$ ps, the mean lifetime of $\tau(2_1^+) = 15(10)$ ps follows. This translates into a $B(E2; 2_1^+ \rightarrow 0_1^+)$ value of 13_{-5}^{+26} W.u. which is compared with values of neighboring Kr isotopes in Table I.

Our final result includes a relatively large uncertainty due to large Compton background contribution and the PRD uncertainty of 10 ps, which includes possible systematic errors [14]. The $B(E2; 2_1^+ \rightarrow 0_1^+)$ value fits well into the trend of the even-even Kr isotopic chain. By adding neutrons to the $N = 50$ closed shell (^{86}Kr), the $B(E2; 2_1^+ \rightarrow 0_1^+)$ value smoothly increases and the $E(2_1^+)$ value decreases smoothly. These observations are in agreement with the results from mass and charge-radii measurements [12,13], indicating a smooth evolution of nuclear shape in Kr isotopes above $N = 50$. Our

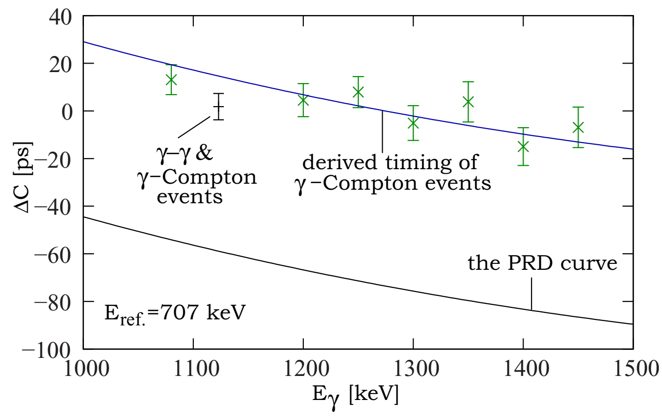

FIG. 4. (Color online) The centroid-difference diagram for the reference energy of 707 keV corresponding to the common gate of all time spectra. The presented PRD curve (time response of prompt full-energy γ-γ events) is adjusted by a parallel shift of the calibrated PRD curve to cross the energy axis at the reference energy. The result at 1123 keV, as obtained from Fig. 3, includes γ (707 keV) vs. Compton events. By fitting the data obtained by setting gates in the Compton background, the timing (time response) of the γ-Compton events is derived. The values needed for lifetime determination are inter- or extrapolated at 1123 keV, as explained in the text.

result also agrees with the microscopically founded neutron-proton interacting boson model calculations of Ref. [10] which reproduce well the observed trend, as illustrated in Table I.

Conclusion. The lifetime of the 2_1^+ state in ^{90}Kr has been measured for the first time via the Ge-gated γ-γ fast-timing technique in a cold-neutron induced prompt-fission γ-spectroscopy experiment on ^{235}U using the EXILL and FATIMA spectrometers. The extracted $B(E2; 2_1^+ \rightarrow 0_1^+)$ value of 13_{-5}^{+26} W.u. confirms the observations made in recent mass and charge-radii measurements. Accordingly, the now complete $B(E2; 2_1^+ \rightarrow 0_1^+)$ systematics indicate a smooth onset of a small quadrupole deformation in even-even Kr isotopes beyond $N = 50$.

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TABLE I. Comparison of experimental $E(2_1^+)$ and $B(E2; 2_1^+ \rightarrow 0_1^+)$ values of Kr isotopes with $N = 50$ to $N = 60$. The theoretical $B(E2)_{\mathrm{IBM-2}}$ values are taken from Ref. [10].

Nucleus	$E(2_1^+)$ [keV]	$B(E2; 2_1^+ \rightarrow 0_1^+)$ [W.u.]	Ref.	$B(E2)_{\mathrm{IBM-2}}$ [W.u.]
^{86}Kr	1565	8.7(5)	[20]	8.7
^{88}Kr	775	7.7(8)	[21]	10.1
^{90}Kr	707	13_{-5}^{+26}	this work	9.9
^{92}Kr	769	$13.6_{-3.3}^{+2.8}$	[11]	9.9
^{94}Kr	666	19.5(22)	[11]	18.5
^{96}Kr	554	$33.4_{-6.7}^{+7.4}$	[11]	36.6

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