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# Lifetime measurements in exotic nuclei at Lohengrin

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**Summary.** — In this work, we present recent lifetime measurements in exotic nuclei performed at Institut Laue-Langevin in different $^{235}$U neutron-induced fission campaigns, using the Lohengrin spectrometer and a hybrid setup made of HPGe clover detectors and LaBr$_3$(Ce) scintillators. In particular, results on the neutron-rich $^{131}$Sb and $^{96}$Rb isotopes will be discussed, which have implications on the origin of collectivity around the doubly magic $^{132}$Sn nucleus and the shape-coexistence phenomenon around $N = 60$, respectively.

## 1. – Introduction

Lifetimes of nuclear excited states are key observables to study nuclear structure properties, such as the interplay between single-particle and collective degrees of freedom [1-3] and more complex phenomena as the coexistence of different shapes at similar excitation energies [4-7]. In this context, neutron-rich nuclei are particularly challenging

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to be accessed experimentally, and neutron-induced fission experiments offer a unique opportunity to explore exotic regions of the nuclide chart [8]. Although lifetimes can be successfully measured in fission experiments using prompt $\gamma$ rays [2, 8], the weakest channels would benefit from the selection and the identification in charge and mass of the fission fragments. This can be achieved with the Lohengrin spectrometer [9] at Institut Laue-Langevin, where the $\gamma$ decay of long-lived isomeric states can be measured at the focal plane of the mass separator.

## 2. – The experiments

The experiments were performed at Institut Laue-Langevin (ILL) by using the Lohengrin spectrometer [9], where the nuclei of interest are produced by thermal neutron-induced fission of a $^{235}$U target. Fission fragments are selected by combining magnetic and electric fields and are finally collimated to the focal plane of the spectrometer. Fission products are detected by an ionization chamber and their $\gamma$ decay by HPGe clover detectors and four $LaBr_3$(Ce) scintillators. The latter allow for the measurement of sub-nanosecond lifetimes using $\gamma$-ray fast-timing techniques [10]. Considering the time-of-flight of the ions of $\approx$2 $\mu$s, only $\gamma$ decays from long-lived isomeric states can be observed at the focal plane of the mass separator.

## 3. – Lifetime measurements in $^{131}$Sb and $^{96}$Rb

In one of the Lohengrin experiments, mass $A = 131$ nuclei were studied. The focus here was $^{131}$Sb, two neutron holes and one proton away from the doubly magic $^{132}$Sn nucleus [11]. Low-lying excited states were fed by the microsecond isomers at 2166, 1687, and 1676 keV, as shown in fig. 1. In this work, the lifetime of the $11/2^+$ state at 1226 keV was measured with the *Generalised Centroid Shift Method*, using the 450–1226 keV $\gamma$-ray cascade and accounting for the *Prompt Response Difference* (PRD) correction [10]. As an example, we report the antidelayed time distribution in the left panel of fig. 1, where the centroid position is marked by a vertical blue bar.

The background was treated as reported in [12] and the centroid positions of the different background components are also indicated in fig. 1 (see [11] for details). The

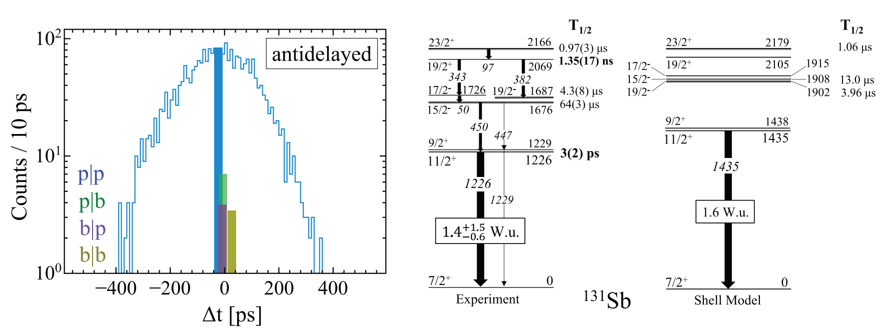


Fig. 1. – Left: antidelayed time distribution for the 450–1226 keV $\gamma$ cascade involving the $11/2^+$ state. Vertical bars represent the centroid positions of the peak and background components (see [11] for details). Right: comparison between the experimental level and decay scheme of $^{131}$Sb and the one obtained with shell-model calculations. The half life of the $11/2^+$ state and the corresponding $B(E2;\, 11/2^+ \to 7/2^+)$ value are also reported.

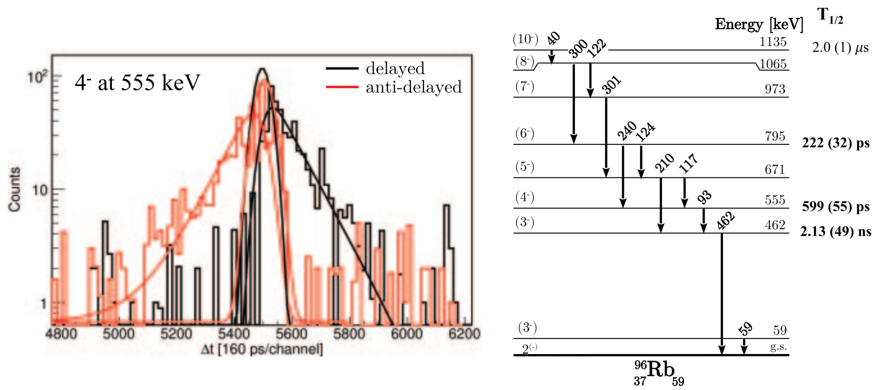


Fig. 2. – Left: delayed (black) and antidelayed (red) time distributions for the 240–93 keV $\gamma$-ray cascade involving the $4^-$ state at 555 keV in $^{96}$Rb. The fitting curves are also shown. Right: level and decay scheme of $^{96}$Rb as observed in this work. Measured lifetimes are reported in bold.

result obtained for the $11/2^+$ state was $T_{1/2} = 3(2)$ ps, which provides the first lifetime measurement for the $11/2^+$ state in neutron-rich Sb isotopes, at the limits of applicability of the fast-timing techniques. The corresponding $B(E2;\, 11/2^+ \to 7/2^+\ \text{(gs)})$ is $1.4^{+1.4}_{-0.6}$ W.u., indicating a non-collective nature of this state, consistent with the $B(E2;\, 2^+ \to 0^+)$ of the $^{130}$Sn core of 1.18 (26) W.u. This suggests that the addition of a proton does not induce any extra quadrupole collectivity, in contrast to the neighbouring $^{129}$Sb nucleus where the $B(E2;\, 11/2^+ \to 7/2^+\ \text{(gs)})$ was found to exceed the $B(E2)$ of the $^{130}$Sn core [13]. Results have been compared with realistic, large-scale shell model calculations, using the two-body effective interaction obtained with many-body perturbation theory from the CD-Bonn nucleon-nucleon potential (see [14] and references therein). This approach was successfully employed to describe $(n,\gamma)$ data in the Pb region [15, 16]. The results are presented in fig. 1 (right), compared with the experimental ones. The level scheme of $^{131}$Sb is well reproduced as well as the $B(E2;\, 11/2^+ \to 7/2^+\ \text{(gs)})$ value. Shell-model predictions suggest the wave function of the $11/2^+$ state to be dominated by the almost-pure $2^+(^{130}\text{Sn}) \otimes \pi g_{7/2}$, core-proton coupled configuration. On the other hand, the same calculations for $^{129}$Sb show a larger fragmentation of the $11/2^+$ state wave function, therefore the gain in quadrupole collectivity, not observed in $^{131}$Sb, can be ascribed to coherent proton-neutron correlations when more neutrons are removed from the $N = 82$ shell closures.

In a different experiment, mass $A = 96$ nuclei were studied. We present here the preliminary results for the neutron-rich, odd-odd $^{96}$Rb nucleus [17], located at the borders of the well-known island of large ground-state deformations at $N = 60$ [18, 19]. Three lifetimes were extracted using the *Decay Slope Method*, as they happened to be of the order of hundreds of picoseconds or more. They are all fed by the $10^-$, 2 $\mu$s isomer and belong to a rotational band, possibly built on the $3^-$ state at 462 keV [20].

For the $6^-$ state at 795 keV the result is $T_{1/2} = 222$ (32) ps, which enables to obtain $B(E2;\, 6^- \to 4^-) = 64.3(96)^{+6.4}_{-5.4}$ W.u. for the 240 keV, intra-band transition. This corresponds to a large quadrupole deformation parameter $\beta_2 = 0.40(3)^{+2}_{-3}$, consistent with the one proposed by [20], thus supporting the rotational character of the band. The lifetime of the $4^-$ state at 555 keV was also measured, using the 240–93 keV $\gamma$-ray cascade. The results for the delayed and antidelayed time distributions are shown in the left panel of fig. 2 in black and red, respectively. The result is $T_{1/2} = 599$ (55) ps, which allowed us to extract $B(E2;\, 4^- \to 2^-\ (\mathrm{gs})) = 0.042(9)^{+3}_{-2}$ W.u. for the 555 keV transitions connecting the deformed band to the near-spherical ground state. This $E2$ decay turned out to be rather hindered, well below 1 W.u., indicating a retardation caused by the shape change, as observed in the Ni region [6, 7], providing a first evidence for shape coexistence in the $^{96}$Rb nucleus. Finally, the lifetime of the $3^-$ state at 462 keV was also measured, yielding $T_{1/2} = 2.13$ (49) ns. The isomeric character of this state supports the shape coexistence scenario and its possible band-head nature. The results obtained in this work are summarized in the right panel of fig. 2.

## 4. – Conclusions

In conclusion, lifetime measurements in the neutron-rich $^{131}$Sb and $^{96}$Rb nuclei were presented, shedding lights on the emergence of collectivity around $^{132}$Sn and shape coexistence around $N = 60$, respectively. The experiments performed at the Lohengrin spectrometer of Institut Laue-Langevin, combining the detection of fission fragments with $\gamma$-ray measurements, allowed accessing peculiar states in these exotic nuclei, which would be otherwise hard to reach in prompt fission or experiments with accelerated beams.

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