Lifetime measurement around ^{132}Sn with the ν-Ball array

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Abstract. Neutron-rich nuclei were studied after fast neutron-induced fission of ^{238}U and ^{232}Th at the ALTO facility in Orsay, France. The neutrons were produced with the LICORNE directional neutron source using a pulsed ^{7}Li beam provided by the Tandem accelerator. The actinide targets were surrounded by the ν-Ball array to measure the de-excitation of fission fragments. The ν-Ball array is a hybrid spectrometer which consists of HPGe detectors (equipped with BGO shielding) and LaBr$_3$(Ce) scintillation detectors allowing for high-resolution γ-ray spectroscopy and lifetime measurements in the ns/sub-ns range. This contribution presents preliminary results on ^{134}Te and ^{137}I populated in the ^{238}U(n,f) reaction.

1. Introduction

The study of nuclei around the doubly magic ^{132}Sn provides one of the best testing grounds for nuclear structure studies far away from the valley of stability. With the improvement of experimental facilities, nuclei with large N/Z ratios become more accessible. Experimental information on these nuclei allow to trace the evolution of shell structure and the development of collectivity with increasing neutron number. The region in the vicinity of ^{132}Sn is of particular importance to determine and test two-body matrix elements for the proton-neutron interaction and offers a key input to state-of-the-art nuclear theories. Furthermore, the structure of nuclei around ^{132}Sn plays an important role in the astrophysical r-process waiting point nuclei close to $N = 82$ and is therefore relevant for the modeling of nucleosynthesis.

Indicators for collectivity in even-even nuclei are, for example, the energy of the 2_1^+ state, the $R_{4/2} = E_x(4_1^+)/E_x(2_1^+)$ ratio and the reduced transition probability of transitions connecting low-lying excited states. The latter can be deduced from measuring the lifetime of a particular

state or from Coulomb excitation measurements. This gives valuable information about the wave function and the degree of collectivity which is particularly unknown for large N/Z ratios. Beyond ^{132}Sn, single-particle and collective excitations are competing in the wave function of the excited states, resulting in high-energy μs-ns isomers as well as low-lying ns/sub-ns states. These lifetimes are accessible with electronic timing using fast scintillators.

2. Experimental Details

The experiment was carried out at the ALTO facility of the IPN Orsay in France. Fast neutrons were produced with the LICORNE neutron source [1] using a p(^{7}Li,^{7}Be)n reaction with a ^{7}Li beam provided by the 13 MV Tandem accelerator. The primary beam was pulsed with a 400 ns repetition time and a 2 ns pulse width. The neutrons were kinematically focused on actinide targets (either ^{238}U or ^{232}Th) to induce the fission reactions.

The de-excitation of the resulting fission fragments via γ-rays was measured with the ν-Ball array [2]. This hybrid spectrometer consisted of 24 HPGe Clover type and 10 HPGe coaxial type detectors, all with BGO Compton shielding. Additionally, 20 LaBr$_3$(Ce) detectors were used for lifetime measurements of excited states in the ns/sub-ns range. Figure 1 shows a schematic description of the experiment including the fast neutron production target and the different detector types arranged in a total of four rings around the target position.
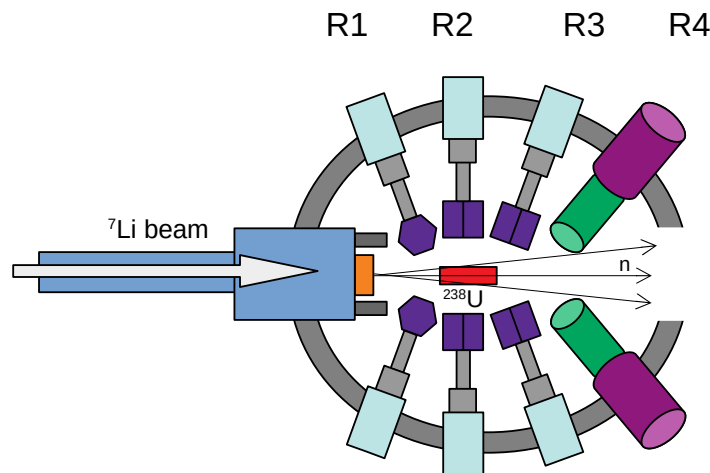

Figure 1. Simplified schematic representation of the experimental setup. The ^{7}Li beam from the Tandem accelerator hits the hydrogen target (orange) and produces neutrons which impinge onto the fissile targets (red). The different detector rings (R1-4) consisting of HPGe (purple) and LaBr$_3$(Ce) detectors (green) are placed symmetrically around the target at a distance of about 15 cm.

The data was acquired in a triggerless mode using the digital acquisition system FASTER developed at LPC Caen [3]. In total, data was taken for two weeks with the ^{238}U target (81 g) with an average beam current $I_{av} \approx 20$ nA at a neutron energy of $E_n = 1.7$ MeV and three weeks with the ^{232}Th target (129 g) at $I_{av} \approx 100$ nA and $E_n = 1.7$ MeV. In the following, only data from the ^{238}U experiment will be presented.

Due to the lack of trigger, the first step in the analysis is to build events from the raw data. The following trigger conditions were accepted in the offline analysis: 1) two HPGe hits (after addback and Compton suppression) within one beam period or 2) two LaBr$_3$(Ce) hits in a 15 ns window around the prompt peak. Delayed ($t > 400$ ns) events are recorded in the successive

pulses after a fission event up to 2800 ns. In addition, the total energy deposit was measured with the help of the BGO detectors, allowing for further selection of fission events such as high multiplicity and high energy events [4].

3. Results

In the following, a few selected preliminary results from the ^{238}U(n,f) reaction will be presented. These include an example illustrating the advantage of a pulsed beam with a 400 ns repetition time. Further results combining HPGe and LaBr$_3$(Ce) coincidence events will be shown.

3.1. Isomers in ^{134}Te

The beam pulsing of the Tandem accelerator allows multiple repetitions of the isomeric production, and thus, its identification if it is comparable to the isomeric half-life. The used repetition rate of 400 ns was particularly suitable for the 6^+ isomer in ^{134}Te with a half-life of 164.1(9) ns [5]. Therefore, this nucleus provides one of the best test cases for a prompt-delayed coincidence analysis using this setup. In the analysis, a prompt window of $0 < t_{HPGe} \leq 100$ ns and a delayed window of $100 > t_{HPGe} \leq 400$ ns is used.
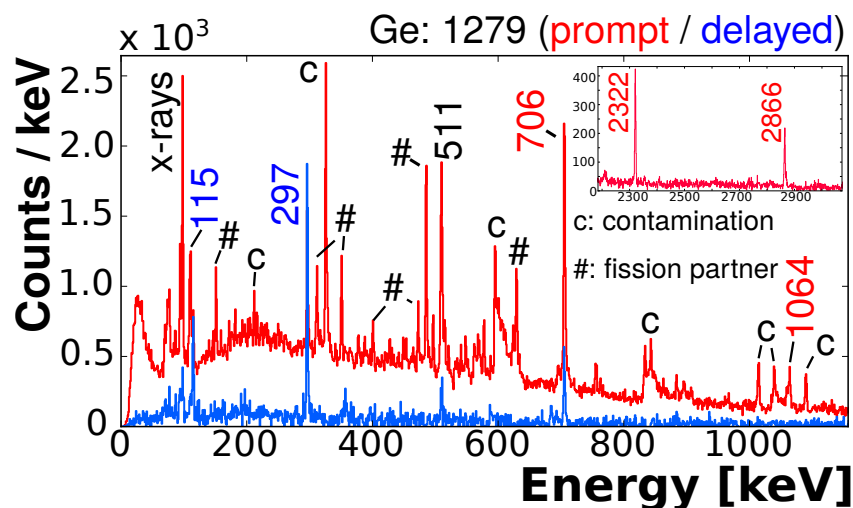

Figure 2. Red: Prompt (0-100 ns) γ-ray HPGe spectrum with a delayed gate on the 1279 keV $2_1^+ \rightarrow 0_1^+$ transition in ^{134}Te. Blue: same as red but delayed γ-rays (100-400 ns).

Figure 2 shows prompt and delayed γ-rays measured with the HPGe detectors after applying a delayed HPGe gate on the 1279 keV $2_1^+ \rightarrow 0_1^+$ transition below the isomer in ^{134}Te. As it can be seen, the prompt γ-ray spectrum is dominated by contaminants from inelastic neutron scattering on Ge or from the ^{7}Li beam reactions. Prompt transitions above the 6^+ isomer are labeled with their respective energy and are identified up to about 7 MeV excitation energy. While the prompt HPGe spectrum shows many transitions, the delayed γ-ray spectrum has very little background and both delayed transitions belonging to the isomer (115 and 297 keV) are very clean, demonstrating the lifetime sensitivity of this experimental setup.

The half-life can be measured by projecting the HPGe time distribution of the 1279 keV γ-ray. Due to the large amount of background, a first HPGe gate was set on 297 keV to cleanly select the nucleus and a second gate on 1279 keV to measure its time distribution. The time distribution is shown in Fig. 3. It is fitted with an exponential decay and resulted in $T_{1/2} = 165(10)$ ns which is consistent with the literature value [5]. This value can be used to
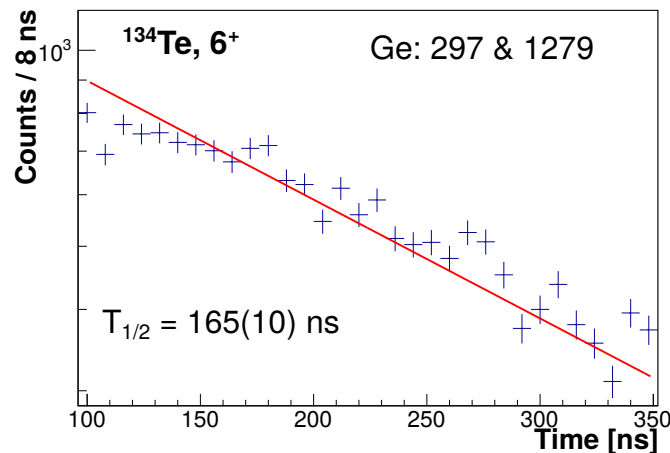
Figure 3. HPGe time distribution of the 1279 keV transition with an additional HPGe gate on 297 keV.

determine the $B(E2 : 6_1^+ \rightarrow 4_1^+)$ reduced transition probability which amounts to 1.9(1) W.u., a typical value for (semi-)magic nuclei, especially around ^{132}Sn.

3.2. Sub-ns lifetime measurement around ^{132}Sn
In order to measure lifetimes in the sub-ns range, HPGe-LaBr$_3$(Ce)-LaBr$_3$(Ce) triple coincidences are needed. In the analysis, a clean HPGe gate is used to select a cascade of interest. Then, a symmetric LaBr$_3$(Ce) E_1-E_2-ΔT cube is produced. To measure the lifetime of a particular state, the time difference between the γ-ray feeding and depopulating that state has to be measured. The time distribution can be expressed as a convolution of the prompt response function (PRF) of the detector system, and an exponential decay [7]:

$$D(t) = \frac{1}{\tau} N_0 \int_{-\infty}^{t} PRF(t') e^{\frac{t-t'}{\tau}} dt', \tag{1}$$

where $D(t)$ is the so-called delayed time distribution, N_0 the number of γ-rays feeding and depopulating the state with lifetime τ. The PRF is an energy-dependent Gaussian distribution. If its width is small compared to the lifetime of interest, an exponential tail can be observed which corresponds to the decay of the state.

This technique requires low background which is not the case in prompt γ-ray fission experiments due to the large number of fragments produced. Using one of the key features of the ν-Ball array, the measurement of total event multiplicities and energy released, constraints for specific isotopes can be applied. In the following, we will consider ^{137}I as an example.

The nucleus ^{137}I has three valence protons and two valence neutrons outside the doubly magic ^{132}Sn core. Thus, studying this nucleus reveals key information on the proton-neutron interaction of few valence particles far off the valley of stability. Figure 4 shows a HK-Matrix for ^{137}I and ^{134}Te, i.e. the prompt total energy plotted against the total multiplicity gated on the lowest-lying transition in ^{137}I and ^{134}Te, respectively. The distribution pattern for ^{137}I shows a larger average multiplicity compared to ^{134}Te which reflects the odd-even nature of the nucleus. The prompt total energy is comparably high in both nuclei, despite the higher excitation energy states observed in ^{134}Te. This can be explained by the 6^+ isomer in ^{134}Te that is not taken into account in the prompt total energy. These hit patterns can be used for a 2D cut on multiplicity and total energy for each particular nucleus to improve the peak-to-background ratio.
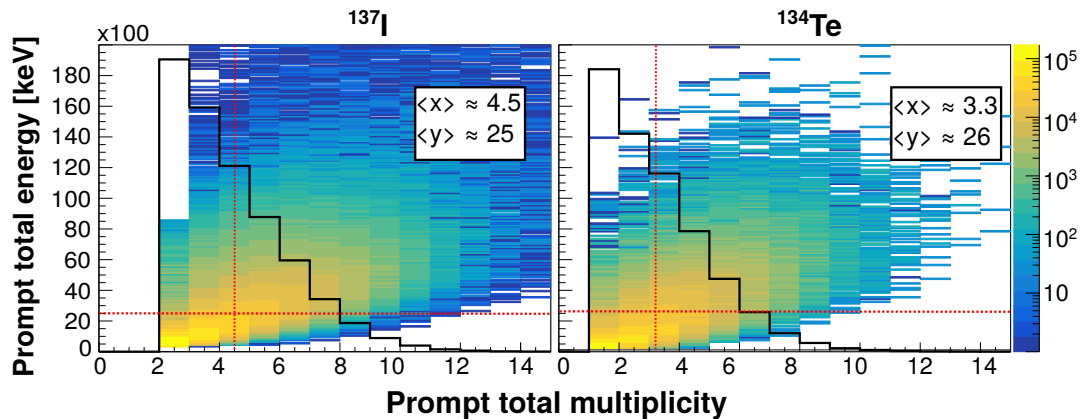
Figure 4. HK-Matrix gated on the 554 keV $9/2^+ \rightarrow (7/2^+)$ transition in ^{137}I (left) and the 1279 keV $2^+ \rightarrow 0^+$ transition in ^{134}Te (right). The plot shows the total prompt energy deposit in the array against the total number of prompt hits. The black solid line corresponds to the scaled multiplicity distribution (= x-axis projection). The average multiplicity and total energy are labeled and highlighted by the dashed red lines.

The transitions observed in ^{137}I from this experiment are shown in the level scheme of Fig. 5. For a clean identification of ^{137}I, a double HPGe gate on 554 keV $((9/2^+) \rightarrow (7/2^+))$ and 400 keV $((13/2^+) \rightarrow (9/2^+))$ is used. The resulting HPGe spectrum can be seen in Fig. 5(a). States up to $J^\pi = 23/2^+$ were observed.

Looking into HPGe-HPGe-LaBr$_3$(Ce) coincidences, a clean identification is also possible. Figure 5(b) shows a HPGe spectrum gated on either the 725 keV or 614 keV transition, to select ^{137}I and an additional LaBr$_3$(Ce) gate on the 554 keV transition. The desired 400 keV transition populating the $9/2^+$ state is clearly visible, showing the observation of this particular cascade also in the LaBr$_3$(Ce) detectors. Furthermore, instead of applying a LaBr$_3$(Ce) gate, a second HPGe gate on 400 keV is used to project out the LaBr$_3$(Ce) energy. This is shown in Fig. 5(c) where all transitions of interest are well visible. The next step is to use HPGe-LaBr$_3$(Ce)-LaBr$_3$(Ce) triple events and generate time difference spectra to determine the lifetime of this state. Such work is currently in progress and will be the subject of a forthcoming article [8].

4. Summary

In this work, we present first results from the ν-Ball fission campaign performed in 2018 in Orsay. The ν-Ball array is a hybrid spectrometer combining both excellent energy and time resolution for γ-ray spectroscopy and lifetime measurement. Two experiments were performed coupling the array to the LICORNE neutron source to study the de-excitation of neutron-rich fission fragments. Neutrons were produced with a pulsed ^{7}Li beam provided by the Tandem accelerator of the ALTO facility allowing both delayed and prompt-delayed coincidence technique to be applied. An example is shown for ^{134}Te to demonstrate the potential of the data. Furthermore, a clean identification of low-lying excited states in ^{137}I is shown which will allow the measurement of the lifetime of these states using the well established fast-timing technique. Only results from the ^{238}U(n,f) reaction are shown but these results will be verified by applying the same methods to the data obtained in the fission of ^{232}Th.
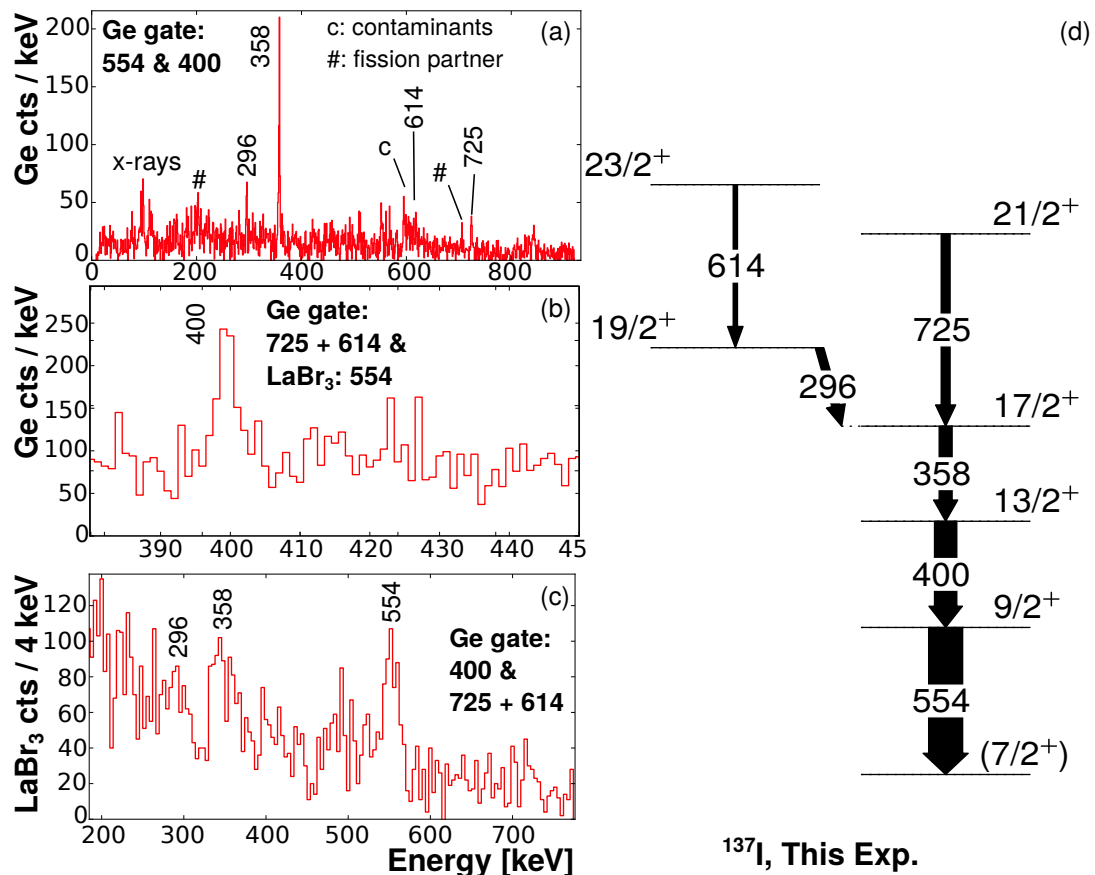
Figure 5. (a) HPGe spectrum gated 554 and 400 keV. (b) HPGe spectrum gated on 725 or 614 keV in the HPGe and on 554 keV in the LaBr$_3$(Ce) detectors. (c) LaBr$_3$(Ce) spectrum with a HPGe gate on 400 keV and on 725 or 614 keV. (d) Observed level scheme with intensities normalized to the $9/2^+ \rightarrow (7/2^+)$ transition.

5. References

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