

The γ - γ fast-timing technique and the EXILL&FATIMA campaign

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Abstract. At the Institut Laue-Langevin in Grenoble, germanium-gated γ - γ fast-timing lifetime measurements of nuclear excited states in neutron-rich nuclei have been performed within a prompt γ -ray spectroscopy experimental campaign. We report on results obtained from the cold-neutron induced fission of ^{235}U . The excited secondary fission products were stopped almost instantaneously within the thick target and the γ rays emitted were collected triggerlessly using the EXILL&FATIMA mixed array of HPGe and $\text{LaBr}_3(\text{Ce})$ detectors. Precise lifetimes could be determined by analysing the γ - γ time difference spectra using the generalized centroid difference method. This picosecond-sensitive method provides many advantages and is briefly explained. Still, the major source of systematic errors is related to the contribution of time-correlated Compton background. The EXILL&FATIMA results are discussed with respect to the typical energy-dependent timing behaviour of the background. According to the time response of the background, appropriate methods and a time correction for the sub-nanosecond regime are proposed.

1 Introduction

The γ - γ timing technique with very fast Ce-doped LaBr_3 scintillator detectors has become popular since the good relative energy resolution of 3.3% at 662 keV in some cases allows for clean separation

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of single γ rays to perform picosecond-sensitive γ - γ time-difference measurements [1]. Considering more complex γ -ray spectra, such as obtained in prompt-fission γ -ray spectroscopy, an additional selective trigger is needed to clean the LaBr_3 γ -ray spectra, where ideally only a few well-separated γ -ray peaks should be seen. The high-purity germanium (HPGe) detector is a good choice to select a γ ray of a specific nucleus, or a specific γ -ray cascade of a nucleus, in order to reduce the complexity of the coincident LaBr_3 γ -ray spectra. This was the basic idea of the EXILL&FATIMA campaign performed at the Institut Laue-Langevin of Grenoble, France. The mixed array consisted of 8 Compton-suppressed clover detectors (EXILL part), each made of 4 HPGe crystals, and 16 LaBr_3 detectors (FATIMA part) for HPGe-gated γ - γ fast timing [2]. This relatively large mixed array has been used in a 5 week experimental campaign to measure picosecond to nanosecond lifetimes of excited states produced by cold-neutron capture reactions [3], or in fission products by cold-neutron induced fission [4–9].

The EXILL&FATIMA mixed array was installed around a target that was exposed to a collimated cold-neutron beam with diameter of 1.2 cm and flux of $10^8/(\text{s}\times\text{cm}^2)$ [10]. Time-stamped data of the detected γ rays have been acquired triggerlessly using the standard digital pulse-shape algorithm. The fast-timing signals of the LaBr_3 detectors (anode pulse) were treated using conventional analogue electronics as described in Ref. [2]. Time-to-amplitude converters (TAC) were used to measure the time difference between two γ rays detected in a pair of LaBr_3 detectors. The pulse height of the TAC being proportional to the time difference was analysed digitally and also time-stamped to reconstruct the LaBr_3 - LaBr_3 -TAC correlations off-line. Time-difference spectra were generated using a relatively new approach called the generalized centroid difference method (see Section 2.1). This powerful method allows for picosecond-sensitive lifetime determination by reducing possible systematic errors to a minimum of about 3 ps [11]. The only serious systematic error that can be induced is related to the time-correlated Compton background which often lies underneath the two full-energy peaks (FEP) of the γ - γ cascade.

We present γ - γ fast-timing results of the prompt-fission γ -ray spectroscopy experiment on ^{235}U using the EXILL&FATIMA mixed array. Although a triggering γ ray was selected by the HPGe-clover detectors, a relatively low full-energy peak-to-background ratio is obtained, dependent on the fission yield and the relative intensities of the three γ rays. Another reason is that also γ rays and the corresponding Compton background of the complementary fission partners contribute to the coincidence spectra. Our aim is to show how the complex background affects the experimentally obtained γ - γ time distribution. An appropriate time correction for the contributions of the background lying underneath the two FEPs of the γ - γ cascade is proposed. Precise lifetimes of excited states in $^{94,98}\text{Sr}$ down to the limit of about 10 ps has been determined using the EXILL&FATIMA spectrometer with peak-to-background ratios down to 0.3.

2 On the γ - γ fast-timing technique

The γ - γ timing technique provides a direct method to determine lifetimes of nuclear excited states by means of electronic time-difference measurements between the two signals generated by the full-energy peak (FEP) events of a $\gamma_{\text{feeder}}\text{-}\gamma_{\text{decay}}$ cascade which connects an excited state. This γ - γ timing technique is widely used with high-resolution HPGe detectors [12], however, it has a lower limit of about 100 ps or more due to the bad time resolution of semi-conductor detectors. The γ -ray timing limit can be reduced to a few ps using very-fast inorganic scintillators, such as BaF_2 [13, 14]. Due to the relatively bad energy resolution of about 9%, the BaF_2 are typically used for β - γ timing experiments in low-multiplicity β^- -decay studies. Using very-fast LaBr_3 detectors with good energy resolution of 3.3% at 662 keV, the γ - γ timing technique can be applied with a limit of a few ps. To achieve this limit, the well-known centroid-shift method is used. It takes into account that the delayed

time distribution consists of a convolution of the prompt response function (PRF) of the set-up $P(t)$ with an exponential decay as:

$$D(t) = \int_{-\infty}^t P(t - t_0)e^{-\lambda t} dt \quad \text{with} \quad \lambda = \frac{1}{\tau}, \quad (1)$$

where λ and τ are the transition probability and the mean lifetime of the nuclear excited state, and t_0 is the centroid of the PRF. The centroid (centre of gravity) of an experimental time-difference distribution is determined as the first moment of the distribution and can be expressed in terms of experimental time channels as:

$$C^D = \frac{\sum_{t=t-}^{t+} t \cdot n(t)}{\sum_{t=t-}^{t+} n(t)}. \quad (2)$$

Here, $n(t)$ is the number of counts in channel t and $t-$ and $t+$ correspond to the integration limits which should be set just at the beginning and the end of the time distribution. This is to avoid systematic errors related to the random coincidences on the left and the right of the time peak. In principle, the centroid-shift method is easy since the mean lifetime is directly obtained from the time shift between the centroids of the delayed and the prompt time distributions as:

$$\tau = C^D - C^P. \quad (3)$$

Consequently, precise knowledge on the energy-dependent time response of the set-up, i.e. the time walk of the centroid of the PRF, is required. Considering the γ - γ timing technique, the determination of the time walk becomes difficult due to the need of selecting two energy gates (narrow energy window) at different energies using two detectors, which in general have slightly different characteristics. Thus, the PRF centroid corresponds to the linear combination of the individual time responses of the two (start and stop) detectors, as:

$$C^P(E_{\text{start}}, E_{\text{stop}}) = T_d + T(E_{\text{start}}) + T(E_{\text{stop}}), \quad (4)$$

where T_d is related to the constant time delay that is introduced to the stop signal of a standard fast-timing electronics circuitry. Although possible, the determination of the time walk of an individual detector within a γ - γ fast-timing set-up is complicated by iterative shifts obtained when changing the two energy gates. In principle, this tedious work has to be done N times when considering a large fast-timing array with $N \gg 2$ detectors, whereby systematic errors can easily be introduced. A new simplified approach for large fast-timing arrays that reduces possible systematic errors was required.

2.1 The Generalized Centroid Difference method

We first consider the standard γ - γ fast-timing set-up consisting of two (start and stop) detectors. As both the start and the stop detectors see the same γ -ray source, two time distributions are obtained in the off-line analysis dependent on whether the decay transition of the excited state is selected by the stop detector (the delayed time distribution) or the start detector (anti-delayed), while the γ ray that feeds the excited state is selected by the other detector. The generalized centroid difference (GCD) method takes advantage of this fact by measuring the "centroid difference" as the relative time shift between the centroids of the delayed and the anti-delayed time distributions [11, 15]:

$$\Delta C(E_{\text{feeder}}, E_{\text{decay}}) = C^D(E_{\text{feeder}}, E_{\text{decay}}) - C^{AD}(E_{\text{decay}}, E_{\text{feeder}}). \quad (5)$$

Considering the anti-delayed time distribution as presented in Fig. 1, it is $\tau = C^P - C^{AD}$. Combining this with Eq. (3) and assuming that no time-correlated Compton background is present underneath the two FEPs of the γ - γ cascade, it follows:

$$\Delta C_{\text{FEP}}(E_{\text{feeder}}, E_{\text{decay}}) = \text{PRD}(E_{\text{feeder}}, E_{\text{decay}}) + 2\tau, \quad (6)$$

where $\text{PRD}(E_{\text{feeder}}, E_{\text{decay}}) = C^P(E_{\text{feeder}}, E_{\text{decay}}) - C^P(E_{\text{decay}}, E_{\text{feeder}})$ is the prompt response difference between the two PRFs obtained by inverting the energies of the $(E_{\text{start}}, E_{\text{stop}})$ gates and describes the linearly combined γ - γ time response of the two-detector timing system. Eqs. (5) and (6) are generalized for an N -detector timing system that provides $N(N - 1)/2$ combinations of unique detector pairs, by assuming that the individual detector time responses differ only slightly (e.g. by using the same timing settings [11, 16]). The data delivered by the fast-timing array are simply superimposed only by distinguishing between the start and the stop signals in order to generate the two independent delayed and anti-delayed time distributions of the whole array. To improve the time resolution of the fast-timing array, the $N(N - 1)/2$ time-difference spectra only need to be time matched using (energy- and time-independent) constant shift values [11].

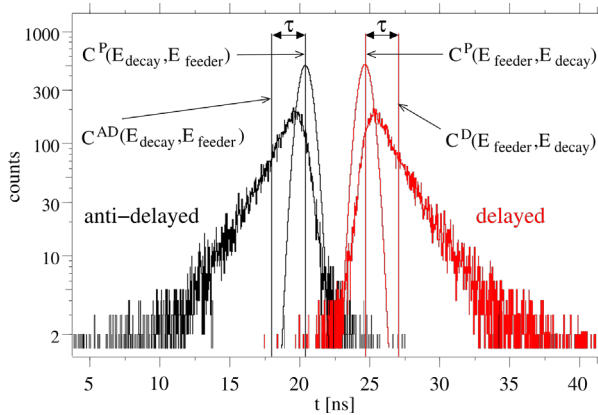


Figure 1. Illustration of the basic centroid-shift method and the extended GCD method. In γ - γ timing experiments, two time distributions are obtained by inverting the two energies of the $(E_{\text{start}}, E_{\text{stop}})$ gates. The measurement of the centroid difference, $\Delta C = C^D - C^{AD}$, cancels the possible systematic errors related to electronic time drifts and to timing asymmetries (different time response and time resolution of individual detectors leading to asymmetric PRFs) [15].

The major task of the GCD method is to precisely determine the energy dependency of the PRD. One can show that for a given reference energy, e.g. $E_{\text{ref.}} = E_{\text{decay}}$, the PRD is a smooth function of the energy. Also, the PRD curve in the energy representation, $\text{PRD}(E_\gamma)$, does not change its shape using different reference energies. Only a parallel shift is observed related to the γ - γ time walk, thus the PRD itself [11, 16]. Therefore, it is very useful to transform the experimentally obtained PRD into the (PRD, E_γ) representation, e.g. $\text{PRD}(E_{\text{feeder}}, E_{\text{decay}}) = \text{PRD}_{\text{decay}}(E_{\text{feeder}})$. The GCD method is mirror symmetric and accordingly, an additional data point is given at the reference energy, i.e. $\text{PRD}_{\text{decay}}(E_{\text{decay}}) = 0$ [16]. In other words, the PRD curve crosses or touches the energy axis at the reference energy. This means that for any energy combination of a γ - γ cascade, the corresponding PRD is obtained from the PRD curve and is given by the relative difference of the PRD between the

two γ -ray energies as [11, 15]:

$$\text{PRD}(E_{\text{feeder}}, E_{\text{decay}}) = \text{PRD}_{\text{decay}}(E_{\text{feeder}}) - \text{PRD}_{\text{decay}}(E_{\text{decay}}). \quad (7)$$

A high-precision PRD calibration procedure has been introduced using the standard ^{152}Eu γ -ray source, as described in Ref. [16]. ^{152}Eu provides more than 10 different γ - γ cascades in the region of 40 to 1408 keV. Most of the γ - γ cascades are free of background contributions, meaning that no Compton background is seen underneath the FEP in the coincidence spectra obtained for certain reference energies. Also the fast lifetimes ($\tau < 100$ ps) of the intermediate states are known with precision of about 1 ps. As a result of these properties, PRD uncertainties in the range of 3-6 ps (2σ standard deviation) can be obtained over the total dynamic range.

3 Results of the EXILL&FATIMA campaign

In order to unambiguously disentangle the cascade of the nucleus of interest out of the rather complex prompt-fission γ -ray spectrum, triple Ge-LaBr₃-Ge and Ge-LaBr₃-LaBr₃ events are used in a first analysis to investigate for good Ge and LaBr₃ gates, i.e., narrow energy windows set on γ peaks which provide for clean coincidence spectra. Such an analysis for the 289-keV $4_1^+ \rightarrow 2_1^+$ and 433-keV $6_1^+ \rightarrow 4_1^+$ transitions in ^{98}Sr is illustrated in Fig. 2. The Ge-clover gate was set on the 144-keV $2_1^+ \rightarrow 0_1^+$ ground-state transition and the so-called reference LaBr₃ gate on one of the two other transitions of the triple γ -ray cascade. A relatively high Compton-background level is observed in this case, probably related to the relatively low fission yield of 0.81% [17] for ^{98}Sr in thermal-neutron induced fission of ^{235}U . Considering the doubly-gated LaBr₃ spectra presented in Fig. 2, single peaks are seen at the energies of the corresponding γ rays of ^{98}Sr . The doubly-gated Ge spectra indicate relatively clean γ -ray spectra, meaning that other FEPs close to the one of interest, e.g. in the range of ± 20 keV, are relatively small compared with the FEPs of interest and the background. These cannot be resolved by the LaBr₃ detectors, and thus could contaminate the peak seen in the LaBr₃ spectrum. In the next step of the analysis, two LaBr₃-TAC matrices $[(E_{\text{start}}, t)$ and $(E_{\text{stop}}, t)]$ with appropriate Ge-clover gate and a reference LaBr₃ gate are generated to produce γ - γ time-difference spectra.

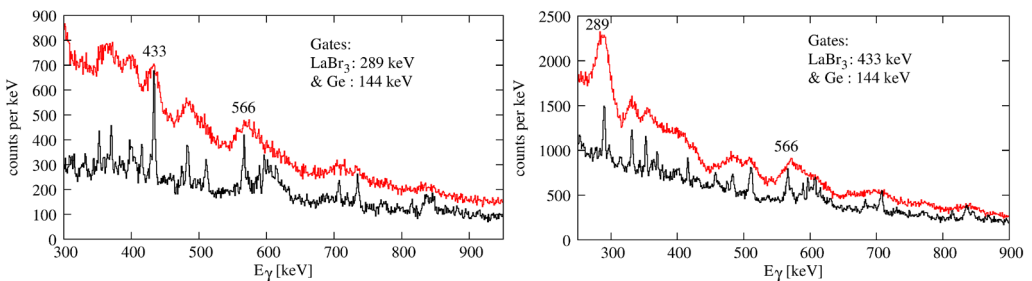


Figure 2. Doubly-gated coincidence γ -ray spectra of the EXILL&FATIMA campaign on ^{235}U generated to investigate the quality of the data for HPGe-gated γ - γ fast-timing of the 4_1^+ state in ^{98}Sr . The peak-to-background ratios (P/B) of the FEPs in the LaBr₃ spectra (shown in red) at 289 and 433 keV are both slightly smaller than 0.5.

The two fast-timing array time distributions of the 433-289-keV γ - γ cascade that connects the 4_1^+ state in ^{98}Sr are presented in Fig. 3. These were obtained using 6-keV wide gates set symmetrically

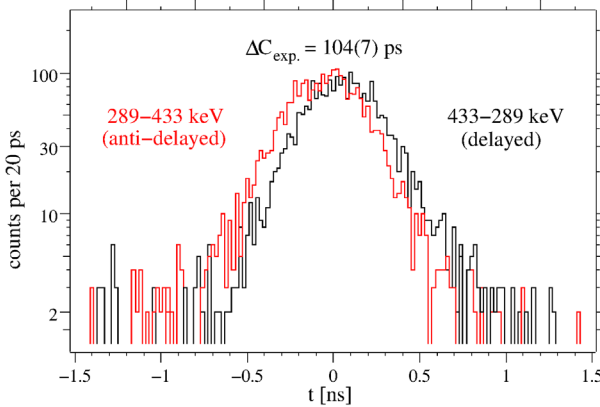


Figure 3. The delayed and anti-delayed time distributions related to the 4_1^+ state in ^{98}Sr obtained using the EXILL&FATIMA mixed array with Ge-clover gate on the 144-keV $2_1^+ \rightarrow 0_1^+$ ground-state transition and LaBr_3 gates as indicated. The FWHM of the total time spectra correspond to 453(6) ps. The lifetime of the 4_1^+ state in ^{98}Sr has been reported to be 115(9) ps, measured via HPGe-gated β^- - γ timing after the β^- decay of ^{98}Rb [13]. The time spectra include time-correlated background contributions and the experimental centroid difference, $\Delta C_{\text{exp.}}$, is corrected using Eq. (9).

around the maximum of the FEPs and include the contributions of the Compton background. According to the P/B ratios derived from Fig. 2, one can estimate the background contribution relative to the total time distribution to be about 65% in this case. A conventional "background subtraction" is not practicable since the total background time distribution, which may consist of up to three different components, cannot be measured directly. Assuming only one background component (BG), e.g. $\text{FEP}(E_{\text{feeder}})$ vs. $\text{BG}(E_{\text{decay}})$, the centroid, the full width at half maximum (FWHM) and the artificial slope of the background time spectrum are dependent on the energy [18]. Only the centroid, or the centroid difference of the background, ΔC_{BG} , can be interpolated precisely, as illustrated in Fig. 4. Assuming again only one background component, the following time correction is exact [2, 14]:

$$\Delta C_{\text{FEP}} = \Delta C_{\text{exp.}} + t_{\text{cor.}} \quad \text{with} \quad t_{\text{cor.}} = \frac{\Delta C_{\text{exp.}} - \Delta C_{\text{BG}}}{\text{P/B}}. \quad (8)$$

When Compton background is present underneath both the FEPs of the γ - γ cascade, the two related background time spectra are superimposed and therefore, the centroid difference related to FEP vs. FEP events only is expected to be well approximated using [9]:

$$\Delta C_{\text{FEP}} = \Delta C_{\text{exp.}} + \frac{t_{\text{cor.}}(E_{\text{feeder}}) + t_{\text{cor.}}(E_{\text{decay}})}{2}. \quad (9)$$

Let us briefly explain the background phenomenon and the correction procedure by looking on the results presented in Fig. 4. On the top are shown the LaBr_3 energy projections of the (E_γ, t) matrices obtained using the reference energies as indicated, e.g. $E_{\text{ref.}} = 289$ keV on the left. Several time distributions are generated by setting narrow gates on the background at different energies, as indicated by the red arrows. Centroids and relative centroid differences are determined and plotted against the corresponding energies. The background data then are fitted using a polynomial function. The results presented on bottom of Fig. 4 show the typical timing behaviour of the (Compton) background. For energies larger than about 500 keV, the background mainly consists of Compton events. A smoothly increasing non-linear time difference between the Compton and the FEP events (represented by the PRD curve) is observed. This has been explained to be related to a fast single-interaction Compton event in contrast to the multiple-Compton and final photoeffect interactions in the creation of the FEP [14, 18]. In addition, the shift at higher energies is partially dependent on the lifetime of the reference γ -ray, as can be seen in Fig. 4. Below about 500 keV, the time response of the background rapidly increases with decreasing energies and crosses the PRD curve at some energy, also dependent on the lifetime of the reference γ -ray. The "delayed" background is mainly related to the detection of:

"scattered" γ rays produced by Compton-scattering in the materials of the spectrometer and reaching the detector after the escape, such as the backscatter peak [14, 18]. Although, the time walk of the background around the corresponding FEP considerably differ in the two cases, the interpolated time responses of the two components are nearly the same. Using Eqs. (6) and (9) with $PRD = -41(7)$ ps, the results of the lifetime determination yields $\tau = 121(11)$ ps and is in excellent agreement with the value of $115(9)$ ps reported in Ref. [13]. The error follows from error propagation, whereby for each $t_{cor.}$, only the error of the determination of the time response of the background, as a one σ deviation, is taken into account.

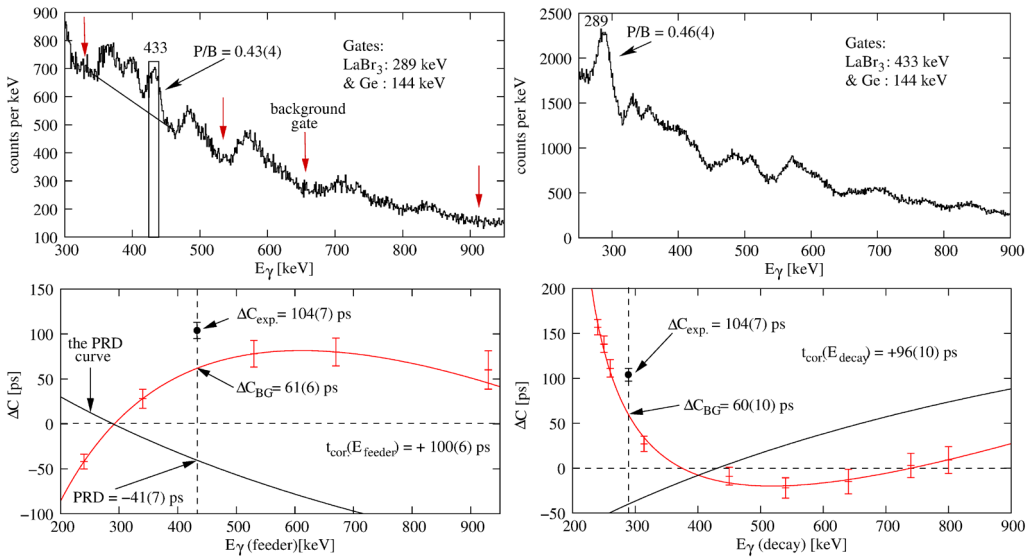


Figure 4. The top figures show $LaBr_3$ projections using gates as indicated. The red arrows indicate the positions where narrow gates were set to produce background time spectra. The solid black curve in the bottom figure represents the FEP vs. FEP time-walk characteristics of the fast-timing array and was determined using the ^{152}Eu γ -ray source. Note that Eq. (5) has been used to measure the centroid differences in the two cases shown on the left and the right. Therefore, the PRD curve is inverted for the case $E_{ref.} = E_{feeder}$. The PRD curve is adjusted in parallel to cross the energy axis at the corresponding reference energy. More details are given in the text.

The case presented in Fig. 4 and discussed before is quite exceptional. In the more general case, the time responses of the two background components are different. This is illustrated by the lifetime determination of the 2_1^+ state in ^{94}Sr presented in Figs. 5 and 6. Here, very clean $LaBr_3$ coincidence spectra have been obtained with relatively good peak-to-background ratios, probably related to the high fission yield of 4.51% [17] in thermal-neutron induced fission of ^{235}U . Using Eqs. (6) and (9) with $PRD = -54(7)$ ps, the results of the lifetime determination here is $\tau = 10(5)$ ps. This again is in excellent agreement with the value of $10(4)$ ps reported in Ref. [14] and indicate that the proposed time correction given by Eq. (9) is a good approximation.

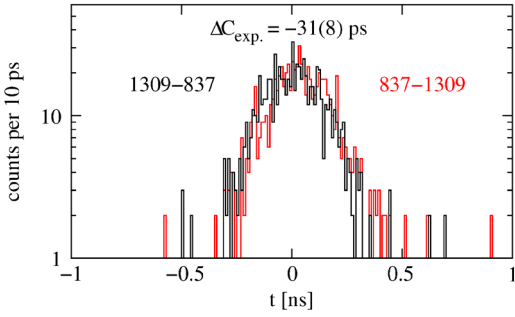


Figure 5. The two experimental EXILL&FATIMA time distributions of the 837-1309-keV γ - γ cascade in ^{94}Sr including background contributions. The Ge-clover gate is set on the 1010 keV $6_1^+ \rightarrow 4_1^+$ γ -ray transition. The FWHM of the time spectra correspond to 304(5) ps. The known lifetime of the 2_1^+ state at 837 keV corresponding to 10(4) ps was measured via HPGe-gated β - γ timing after β^- decay of ^{94}Rb [14].

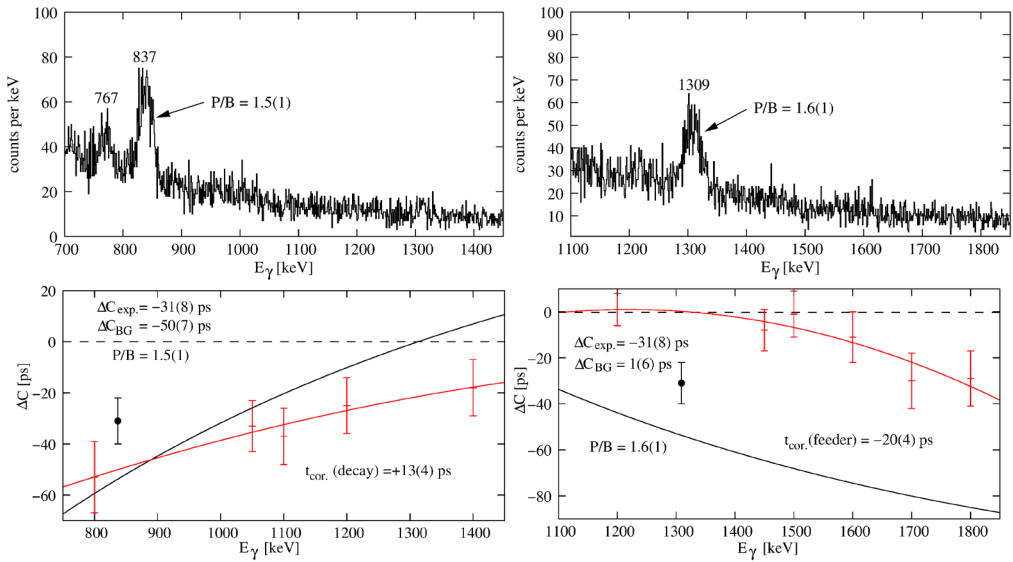


Figure 6. Analysis of the time responses of the two background components of the 837-1309-keV γ - γ cascade in ^{94}Sr . In this case, the time shifts of the two components relative to the total centroid difference, which include all the background components, are in opposite directions. The resulting mean correction according to Eq. (9) is just $-3(4)$ ps and with PRD = $-54(7)$ ps, the lifetime result of the 2_1^+ state in ^{94}Sr yields $\tau = 10(5)$ ps.

Finally, we would like to discuss cases where the lifetime is larger than about 1 ns, such as the 4.01(12) ns lifetime of the 2_1^+ state in ^{98}Sr [13]. The doubly-gated EXILL&FATIMA coincidence spectra showing the quality of the FEP of the 144-keV $2_1^+ \rightarrow 0_1^+$ γ -ray transition and the resulting time distribution are presented in Fig. 7. For comparison, an appropriate background time distribution is also presented. Firstly, the total time spectrum clearly shows two decay components. Especially the long component in the semi-logarithmic plot shows an extremely straight decay with very small fluctuations, as expected for a statistical distribution. The fast component is related to the detection of background events, as indicated by the background time distribution obtained by setting a 5-keV wide gate in the background at 180 keV, just above the FEP of the decay γ ray. Indeed, this approximated background time distribution includes contributions of FEP(E_{feeder}) vs. BG($E \approx E_{\text{decay}}$) and possible BG(E_{feeder}) vs. BG($E \approx E_{\text{decay}}$) events. This particularly means that the long decay component of the total time distribution is due FEP detection of the decay γ ray only. The approximated background

time spectrum also shows that after the artificial decay of the time-correlated background, only more uniformly distributed random coincidences are seen. In general, the time-correlated background is relatively fast compared with the FEP time response, as illustrated by the results presented in this work. In cases where the time spectrum shows two decay components, the lifetime related to the long component is directly obtained using the slope method. Only the level of the random coincidences needs to be determined from the total time spectrum for being used as a constant to fit the data after the fast component using:

$$ae^{-\lambda(t-t_0)} + b, \tag{10}$$

where a is related to the statistics and b is the random background level. The fit of the slope of the long decay in the time range of 28-40 ns yields a lifetime of 4.0(1) ns, which exactly corresponds to the high-precision value obtained using the HPGe-gated β^- - γ timing technique [13].

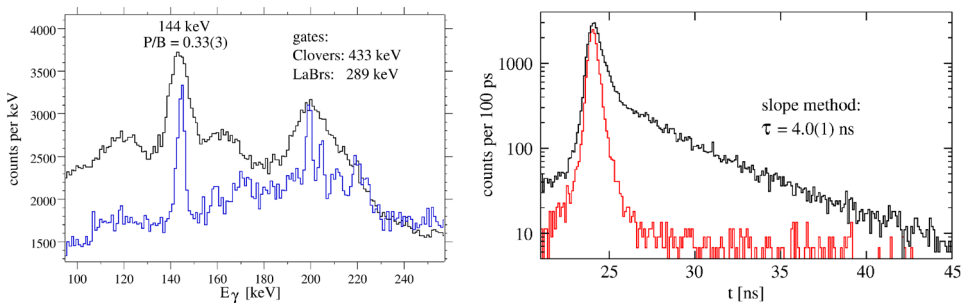


Figure 7. On the left: The EXILL&FATIMA coincidence spectra obtained using gates as indicated. The FEP at 144 keV belongs to the $2_1^+ \rightarrow 0_1^+$ γ -ray transition in ^{98}Sr . On the right: The total time distribution of the 289-144 keV γ - γ cascade in ^{98}Sr (with Ge-clover gate on 433 keV). The indicated lifetime of the 2_1^+ state was directly extracted from the total time spectrum using the slope method. The approximated background time spectrum shown in red is for comparison and discussion. As obtained using a 5-keV wide gate at 180 keV in combination with $E_{\text{ref.}} = 289$ keV, the FWHM of the background time distribution is 614(8) ps and the apparent slope corresponds to an artificial lifetime of about 250 ps.

4 Conclusion and outlook

This work reports on the latest developments and findings in the γ - γ fast-timing technique using arrays with many $\text{LaBr}_3(\text{Ce})$ detectors. These have been introduced to the EXILL&FATIMA campaign to perform HPGe-gated γ - γ fast-timing of nuclear excited states in neutron-rich nuclei via prompt γ -ray spectroscopy of fission products. 16 almost equal $\text{LaBr}_3(\text{Ce})$ detectors were used and the most precise generalized centroid difference method was employed to generate and analyse the γ - γ time distributions of the fast-timing array. High-quality data have been acquired, meaning that optimal energy and time resolutions of 3.3% and about 350 ps at 662 keV and also good statistics have been delivered. Three exemplary results are shown to illustrate the high sensitivity of the method. The energy-dependent time response of the experimental Compton background has been measured and shown to differ non-linearly from the time response related to the full-energy peak events. While the Compton events are relatively fast, the low-energy background includes delayed background from the detection of scattered γ rays with typical artificial lifetime of 0.2-0.4 ns at 100 keV, dependent on the set-up geometry and detector shielding. For the sub-nanosecond regime, a time correction is proposed

which takes advantage of the ability to precisely measure the time response (the centroid difference) and the peak-to-background ratios of the two background components. The slope method is recommended for the nanosecond regime, where, dependent on the energy, 2-4 ns after the maximum of the total time spectrum, the time-correlated background has "decayed" and thus do not play a role. The results of three lifetime measurements, corresponding to 10(5) ps, 121(11) ps and 4.0(1) ns, have been obtained without any manipulation of the time-difference spectra and agree with the precisely known literature values within the statistical errors. The results also show that a reduction of the complexity of the γ -ray spectrum is crucial for lifetime determination via prompt γ -ray spectroscopy of fission products. An additional unambiguous trigger, e.g. by ion identification with FIPPS, the new Fission Product Prompt γ -ray Spectrometer at ILL, should improve the quality of the coincidence spectra and thus the peak-to-background ratio.

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