FAST TIMING MEASUREMENT USING AN $LaBr_3$(Ce) SCINTILLATOR DETECTOR ARRAY COUPLED WITH GAMMASPHERE*

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A fast-timing experiment was performed at the Argonne National Laboratory in December 2015 and January 2016, measuring decay radiation of fission products from a ^{252}Cf fission source. Details of the set-up, integration with Digital Gammasphere, and the data acquisition system are presented. The timing performance of the set-up, capable of measuring lifetimes from the nanosecond region down to tens of picoseconds, is discussed. First preliminary results from the fast-timing analysis of the fission fragment data are presented.

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1. Introduction

The fast timing method is a well-established tool for measuring lifetimes of excited nuclear states [1, 2]. Especially since γ–γ fast timing in the sub-nanosecond region has become feasible using $LaBr_3$(Ce) scintillators, many studies in different mass regions have employed this method, more and more also in studies of very exotic nuclei using radioactive beams (*e.g.* β–γ timing at RIKEN [3]) or neutron induced fission sources (*e.g.* FATIMA at EXILL [4]).

When employing methods like nuclear fission, which create an abundance of different isotopes, care has to be taken to select a particular isotope of interest. Especially in fast timing measurements using $LaBr_3$(Ce) detectors (LaBr) it is very important to have good isotope selection, in order to set clean energy gates. One way to achieve this is by coupling the fast timing detectors with a High-Purity Germanium (HPGe) detector array. The superior energy resolution of the HPGe detectors allows resolution of single transitions in a nucleus of interest. Coincident γ–γ events detected with the LaBr array can then be used to apply the fast timing technique. With its high efficiency, Gammasphere is ideal for this kind of task.

25 FATIMA detectors of the UK NuSTAR Collaboration [5, 6] composed the fast timing array in this experiment. The fast timing data acquisition system (DAQ) used is a compact and flexible system with sub-nanosecond timing based on semi-digital VME electronics. This experiment was also a first field test for this new DAQ system. There has been one experiment before, which used two LaBr detectors with Gammasphere [7]. However, this is the first measurement with a large fast timing array coupled with Digital Gammasphere. The focus of this article lies on the fast timing part of the set-up. For a detailed description of Gammasphere and the Digital Gammasphere (DGS) acquisition system, see [8, 9].

2. Fast timing array coupled with Gammasphere

The detector arrays were arranged in two hemispheres, see Fig. 1 (a). The ^{252}Cf fission source was placed at the focus of one hemisphere of the Gammasphere array (50 High-Purity Germanium (HPGe) detectors) which was coupled with a fast timing array, comprising 25 LaBr detectors.

Each FATIMA detector consists of a cylindrical $LaBr_3$(Ce) crystal (length 2 inches, diameter 1.5 inches) coupled with a Hamamatsu R9779 photo multiplier tube with eight dynodes. Each detector was equipped with a lead shield of 4 mm thickness around the crystal to avoid detecting γ rays scattered from neighbouring detectors.

The fast timing system and Digital Gammasphere each took data independently in their own data stream. DGS on its own accepted events of two γ rays in coincidence within 2 μs.

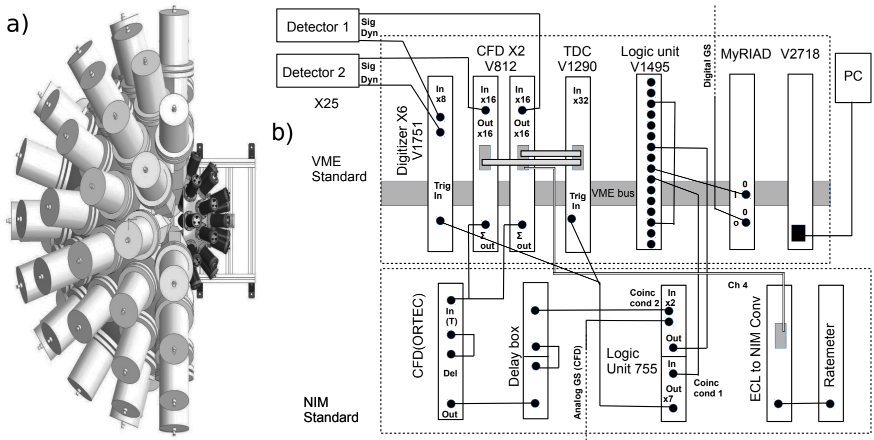

Fig. 1. (a) Top view drawing of the LaBr + Gammasphere array. (b) Schematic drawing of the fast timing data acquisition system. See the text for details.

A schematic picture of the LaBr DAQ system is shown in Fig. 1 (b). The signal from the eighth dynode of the LaBr detectors was directly fed into V1751 digitizers (1 GS/s, 10 bit resolution) and provided the energy information. The anode signal was directly fed into V812 CFD modules. The constant fraction delay was set to 8 ns. The output was then sent to V1290 TDC modules which provided the time information (25 ps/chn). In order to correlate the energy and time data, an event-based data acquisition is controlled by a V1495 logic unit. In stand-alone operation, the trigger for a fast timing event is formed by at least 2 LaBr detectors within 200 ns, using the CFD multiplicity output. The event-based readout system currently leads to a large read-out dead-time of the order of 300 μs. Due to this fact, an additional coincidence with a Gammasphere detector was imposed on the fast timing event trigger to ensure at least one DGS coincidence for each trigger. The coincidence width for this was set to 500 ns.

The integration of the two DAQ systems was accomplished by introducing a MyRIAD module [10] into the fast timing part. This module was connected to the Digital Gammasphere DAQ by a bidirectional optical fiber to synchronize its clock with the Digital Gammasphere DAQ master clock and to send triggers to Digital Gammasphere. The fast timing trigger described above was fed into to MyRIAD module, where a time stamp was generated and stored for the event. This time stamp from the MyRIAD clock, which was synchronized with the DGS clock, was later used to merge the two data streams. The fast timing trigger was also sent to the DGS DAQ where it triggered a readout (width of 2 μs). This ensured readout of single γ events in DGS which were in coincidence with a fast timing trigger, but not with a multiplicity-two trigger of DGS itself.

3. Experiment and state of analysis

First several tests were made with the sources ^{152}Eu, ^{60}Co, ^{88}Y, and ^{166}Ho to verify the proper working of the fast timing part, the integration with DGS, and for calibration. The relative energy resolution of the LaBr array was found to be around 3.7% at 660 keV. The full energy peak singles efficiency of the 25 detectors, which were positioned 12.4 cm away from the source, was about 2.5% at 1 MeV and about 5% at 500 keV. For the 50 DGS detectors, this was about 5% and 8% respectively. Figure 2 (c) shows the prompt response distribution of the full array for a prompt cascade in ^{88}Sr (^{88}Y source). The width of a prompt distribution is a measure of the timing resolution of the set-up. The result of FWHM = 343 ps is slightly worse but comparable to what is found in similar experiments for these γ energies, *e.g.* FATIMA at EXILL [4]. A test with a ^{166}Ho source, decaying to ^{166}Er, showed the capabilities of the fast timing set-up. In the ground state band of ^{166}Er, according to the NNDC data base [11], the half lives of the first 2^+, 4^+ and 6^+ are 1815(23) ps, 118(4) ps, and 15.0(8) ps. We measured the 2^+ half life with a slope fit, obtaining 1851(30) ps, which agrees well with the adopted NNDC value. Half lives in the picosecond region were measured

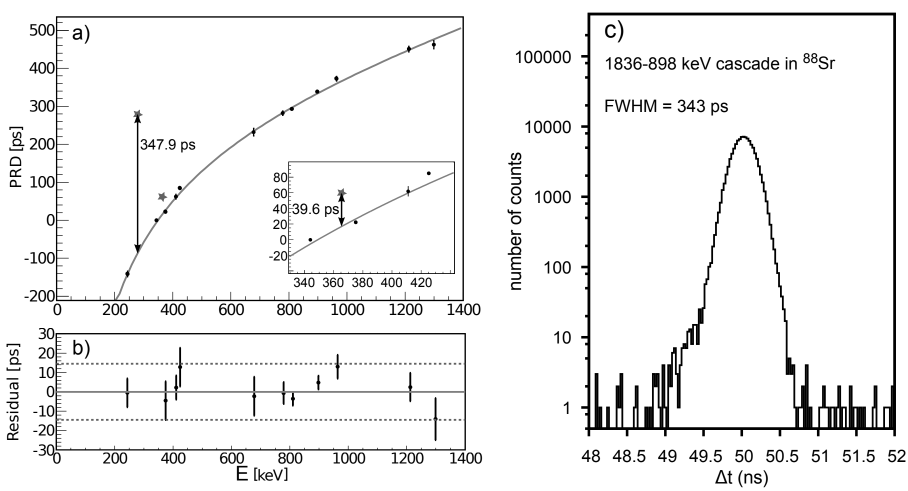

Fig. 2. (a) Prompt response difference (PRD) of the fast timing array for the experiment at ANL, measured with transitions from the sources ^{152}Eu, ^{60}Co, and ^{88}Y (black dots). The fitted function [12] is shown as a solid line. The delayed centroid difference values for the $6^+ \rightarrow 4^+ \rightarrow 2^+$ and the $8^+ \rightarrow 6^+ \rightarrow 4^+$ cascade (inlay) in the ground state band of ^{166}Er are shown as grey stars. (b) Residual of the PRD fit function and the data points used for the fit. (c) Coincidence time spectrum of a prompt cascade measured with an ^{88}Y source.

using the generalized centroid difference method (GCD) [12]. This method is a refinement of the centroid shift method [1]. For the GCD method, the difference of the centroid positions of the delayed (decay transition gated on stop detector) and anti-delayed (decay transition gated on start detector) time distributions is measured. This value is then two times the lifetime plus a time walk value. The time walk of the system, depending on the energy of the start and stop transition, is obtained by measuring the prompt response difference (PRD) for the energy range of interest. For this experiment, the PRD was measured using the sources ^{152}Eu, ^{60}Co, and ^{88}Y, see Fig. 2 (a). For the accuracy of the PRD, we adopt a value of 15 ps, see Fig. 2 (b). This results in a lower measuring limit of $\tau > 8$ ps ($T_{1/2} > 6$ ps) for the setup.

The measured centroid difference values for the $6^+ \to 4^+ \to 2^+$ and $8^+ \to 6^+ \to 4^+$ cascade in the ^{166}Er ground state band are shown in Fig. 2 (a). These yield the half lives $T_{1/2,4^+} = 121(14)$ ps and $T_{1/2,6^+} = 14(8)$ ps respectively, both being consistent with the literature values cited above. These results demonstrate the general capability of the fast timing system to measure half lives from the ns region down to about 10 ps.

The ^{252}Cf source was mounted on 18.12.2015 and data were taken for about five weeks. A typical LaBr singles rate was 2.7 kHz. The DGS double coincidence rate was about 13.5 kHz. Here, we show first preliminary results for one of the stronger fission products, ^{100}Zr. Figure 3 (a) shows an LaBr and DGS spectrum, both in triple coincidence with the $6^+ \to 4^+$ transition in ^{100}Zr and the $2^+ \to 0^+$ transition in the fission partner ^{148}Ce. The result is a quite clean spectrum showing only transitions in the ground state band of ^{100}Zr and ^{148}Ce. Note that due to the trigger condition on the fast timing DAQ part, the LaBr spectra are additionally a double LaBr event projection. Figure 3 (b) shows the delayed coincidence time spectrum of the $4^+ \to 2^+ \to 0^+$ cascade in ^{100}Zr. These spectra were produced with only one DGS coincidence condition on the $6^+ \to 4^+$ transition in ^{100}Zr. Background was then subtracted from the resulting time distributions to get the shown time spectra. Please note that these results are, therefore, only to be taken as a first measure of the capabilities of the set-up, especially the cited accuracies are not final. This is mainly the case because the background subtraction is not straightforward in this case and possible systematic errors were not taken into account. Still it was possible to reproduce the literature value from the nuclear data sheets [13] within the uncertainty, see Fig. 3 (b). Also, two different analysis methods, the fit of a convolution and the GCD method, yield consistent results.

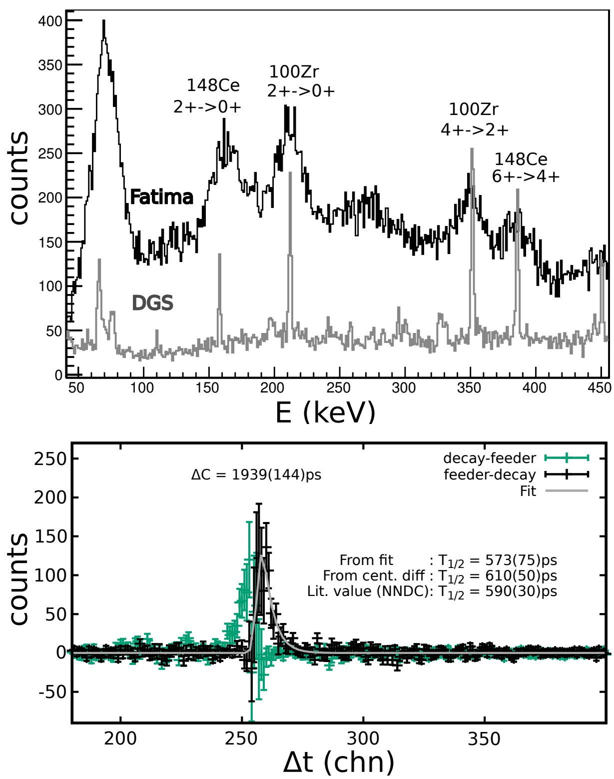

Fig. 3. (a) Coincidence γ-ray spectrum of Digital Gammasphere (DGS) (grey) and LaBr (black). The coincidence condition is a double gate on DGS with the $6^+ \to 4^+$ in ^{100}Zr (497 keV) and the $4^+ \to 2^+$ transition in the fission partner ^{148}Ce (294 keV). (b) Delayed LaBr coincidence time spectra of the $4^+ \to 2^+ \to 0^+$ cascade in ^{100}Zr with a selection gate on the $6^+ \to 4^+$ transition in DGS. Background was subtracted from these spectra. The grey line shows a fit to the data of a convolution of an exponential decay with a Gauss-shaped prompt response distribution.

4. Conclusion

In conclusion, the fast timing part of the experiment produced reliable results in the source measurements. Coupling with Digital Gammasphere was done successfully using the MyRIAD interface. The data have been successfully merged and are in progress of being analysed by the collaboration. It is expected to get results for more weakly produced isotopes by combining statistics from several DGS coincidence conditions.

In general, it can be said that the coupling of an LaBr array with Gammasphere is very fruitful. Not only fast timing in the sub-nanosecond region is feasible with this kind of experiment. At the same time, the LaBr detectors can potentially be used for spectroscopy of low-energy transitions, *e.g.* isomers, for which the Gammasphere detector efficiency is very low.

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REFERENCES

[1] H. Mach, R.L. Gill, M. Moszyński, *Nucl. Instrum. Methods Phys. Res. A* **280**, 49 (1989).

[2] P.J. Nolan *et al.*, *Rep. Prog. Phys.* **42**, 1 (1979).

[3] F. Browne *et al.*, *Acta Phys. Pol. B* **46**, 721 (2015).

[4] J.-M. Régis *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **763**, 210 (2014).

[5] S. Lalkovski *et al.*, *Acta Phys. Pol. B* **47**, 637 (2015).

[6] Zs. Podolyak *et al.*, *Rad. Phys. Chem.* **95**, 14 (2014).

[7] S. Zhu *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **652**, 231 (2011).

[8] I-Y. Lee *et al.*, *Nucl. Phys A* **520**, 641c (1990).

[9] T.J. Anderson *et al.*, *IEEE Nuclear Science Symposium and Medical Imaging Conference* **(NSS/MIC)**, 6551368 (2012).

[10] T.J. Anderson, MyRIAD user manual, ANL, 2015.

[11] C.M. Baglin, *Nucl. Data Sheets* **109**, 1103 (2008).

[12] J.-M. Régis *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **726**, 191 (2013).

[13] B. Singh, *Nucl. Data Sheets* **109**, 297 (2008).