Development of a fast-timing LaBr$_3$(Ce) array for NuSTAR

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Abstract.

The development of a new fragment separator (Super-FRS) at the future Facility for Anti-proton and Ion Research (FAIR) will allow the study of proton- and neutron-rich short-lived nuclei. As one of the nine proposed set-ups established under the NuSTAR international collaboration, the DESPEC group plan to develop a new fast-timing array to be located at the focal point of the separator, which will use LaBr$_3$(Ce) scintillators to measure the half-lives of excited states in these exotic nuclei. In order to optimise the efficiency of the array while maintaining the intrinsically good timing properties of the detectors, Monte-Carlo simulations will be carried out for 1, 1.5 and 2" cylindrical and 1x1.5x1.5" conical detectors. These simulations will inform the final design of the array based on the criteria of efficiency as a function of γ-ray energy, and timing performance. The simulations will be validated by comparing them with the results of an experiment at Bucharest, where sub-nanosecond lifetime measurements were successfully performed for excited states in ^{138}Ce. The results of the simulations will dictate the final design, and how it will be used in future experimental conditions.

1. Motivation

The development of a new synchrotron and an in-flight separator (Super-FRS) at FAIR will deliver rare isotopes of all elements up to uranium and will allow the study of very short-lived nuclei at the extremes of existence. The NuSTAR (Nuclear STructure, Astrophysics and Reactions) international collaboration was established to develop and equip this facility with nine ambitious experimental set-ups, which include the HIgh-resolution in-flight SPECtroscopy and DEcay SPECtroscopy (HISPEC/DESPEC) set-ups. These set-ups aim to obtain more information on the behaviour of nucleon-nucleon interactions in both proton- and neutron-rich nuclei. In particular for neutron-rich nuclei, the combination of a higher primary beam intensity and the Super-FRS will allow access to nuclei along the r-process path, where the β-decay half-life, the neutron branching ratios and the neutron separation energy can be measured. In order to accurately determine these, an optimal set-up of charged particle, γ-ray and neutron detectors will be needed.

2. Decay Spectroscopy and the Fast-Timing Array

Decay spectroscopy uses a "stopped beam" set-up, which involves the implantation of the ions from the separator into an "active catcher", which is usually an array of highly segmented double

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sided silicon strip detectors (DSSSDs). Ions are implanted into one of these detectors at the stopping plane, where they de-excite, releasing energy in the form of γ-rays and βs. The high pixellation of the detectors allows the correlation of the time and position of the initial pulse from the implantation of the heavy ion, with the signal produced in the same detector from the subsequent β decay. It is envisaged that the Advanced Implantation Detector Array, (AIDA[1]) will be used. The fast-timing array and AIDA set-ups could be complemented by the addition of several neutron detectors, such as the MOdular Neutron SpectromeTER (MONSTER), for studies of neutron-rich nuclei.

In the past 10 to 15 years, there has been a flurry of development of highly efficient scintillators for γ-ray spectroscopy. One of the most notable candidates to emerge is lanthanum bromide (LaBr$_3$(Ce)), in which LaBr$_3$ crystals are doped with Ce^{3+} to produce luminescence in the blue/UV part of the electromagnetic spectrum ($\lambda_{max} = 380$ nm)[2], making it compatible with most modern day photo-multiplier tubes (PMTs). The timing response of LaBr$_3$(Ce) is exceptionally good ($\sim$250 ps FWHM at 600 keV for a 30 mm crystal[3]), and it has an energy resolution of ~ 2.9 % at 662 keV[2], one of the best energy resolutions obtainable with current inorganic scintillators. In addition to this, the stopping power of the detector is notably good due to its high density (5.07 g/cm^3[2]). Therefore, LaBr$_3$(Ce) detectors can be developed to measure sub-nanosecond fast-timing due to their fast response. Their energy resolution is better than older scintillators, such as BaF$_2$, resulting in a better peak-to-Compton ratio, which will aid in applying clean gates to the transitions of interest.
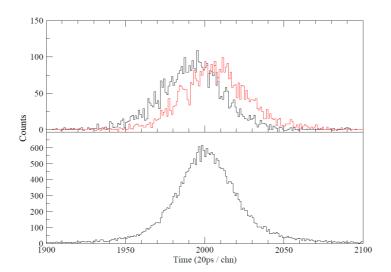
2.1. Fast-Timing LaBr$_3$(Ce) Array

A new, modular, high-efficiency array will be designed, which will use the well established method of "ultra fast-timing"[4], exploiting the timing properties intrinsically found in LaBr$_3$(Ce) detectors. The timing of these detectors depends on the concentration of the cerium dopant. Typically, the decay time is between 15 and 23 ns, with the quickest times attributed to the highest concentration of Ce^{3+}[5]. Measurements made using the ultra fast-timing method are usually performed via triple β-γ-γ coincidences, and via γ-γ coincidences for long-lived isomeric states[6]. The lifetime of states can be measured by taking the time difference between several transitions above and below the level of interest. In cases where the lifetime is too short to see the anticipated exponential decay, the centroid shift method will be used. This method enhances the sensitivity of measurements in the 100 ps range as shown in fig. 1[7], and measures the lifetime from the relative shift between the centroids of the forward and backward time spectra by slicing a LaBr$_3$(Ce)-LaBr$_3$(Ce)-Δt matrix. This centroid shift method will measure lifetimes with precision down to tens of picoseconds. Half-lives of ~ 50 ps can be obtained by the method of deconvolution of the slope, where high precision results can be obtained based on a relatively small number of events (as low as 1-5 particles/s for exotic nuclei)[4]. However, it is anticipated that initial measurements will be made with beam intensities down to 10-20 particles/s at the stopper plane.

3. Geant4 Simulations

Geant4 simulations will determine the optimal distribution of detectors around the implantation point of the fast-timing array. After determining the optimal size, shape, and arrangement of LaBr$_3$(Ce) detectors through simulations and experimental tests, construction and testing can commence.

Simulations have been performed to compare the performance of cylindrical crystals of size 1"x1"x1", 1.5"x1.5"x1.5", and 2"x2"x2" with 1"x1.5"x1.5" conical detectors. Initially, the simulations focused on just the performance of the crystals without their insulation, housing and shielding, examining the full-energy peak (FEP) efficiency. A beam of γ-ray events was projected onto the face of each crystal, ensuring full solid angle coverage of each detector face.

Figure 1. Timing spectra from a recent measurement of the lifetime of the 14^+ level in ^{138}Ce. The top panel shows the two time difference spectra between 254 and 338 keV γ-rays, obtained by swapping the start and stop conditions. The bottom panel shows the time distribution of a prompt distribution of transitions of the same energies. The half-life for the 14^+ level was found to be ~ 70 ps [7].

A "smearing factor", or σ was added to the simulation code to imitate the observed energy resolutions from previous experiments. For energies between 2 and 11 MeV, this energy response exhibits a profile as shown in Ciemala et al.[8].

The initial simulations with these individual segments indicate that the efficiencies of the 2" and 1.5" cylindrical detectors are better than the 1"x1.5"x1.5" conical detectors. This is expected since the cylindrical detectors are larger, and thus cover more of the solid angle if placed at the same distance from the source.
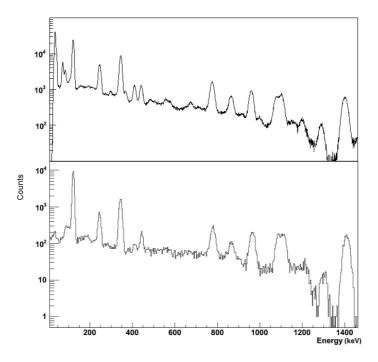
On-going comparisons between simulations and experimental work are essential in developing the simulation package, as is testing the detectors currently available within the collaboration. An opportunity to test the fast-timing method with LaBr$_3$(Ce) detectors occurred, where three 2" cylindrical detectors, three 1.5" cylindrical detectors and two 1"x1.5"x1.5" conical detectors were used to measure the lifetimes of states in ^{138}Ce, ^{136}Ba and ^{188}W. An approximate set-up of the array was generated in Geant4, and a number of events (equivalent to several hours of acquired calibration data) were generated to simulate what was observed during the experiment. Fig. 2 shows that the simulated ^{152}Eu energy spectra for the detectors defined in the simulations are consistent with the data from the actual experiment. Calibration measurements with the array of 8 LaBr$_3$(Ce) detectors and a ^{137}Cs source revealed an efficiency of ~ 1.5 % for the entire array at 662 keV. This is in good agreement with the value of 1.2% from the simulations.

3.1. A Test Case: Lifetime Measurements in ^{132}Te.
Following the successful experiment in Bucharest, a test case to use the fast-timing method with these detectors has been proposed. Using the ^{130}Te(^{7}Li,αp)^{132}Te reaction at a beam energy of 22 MeV (~ 2 MeV above the Coulomb barrier), a pulsed beam will be used to study levels below the isomeric ($T_{1/2} = 145(8)$ ns) $I^\pi = 6^+$ state out of beam. The lifetime of the 4^+ level was calculated to have a half-life of ~ 90 ps [9].

Previous "two neutron transfer" reactions with ^{7}Li reveal that the maximum spin that is likely to be populated is six. Thus it is anticipated that for ^{132}Te, the 7^- will be very weakly
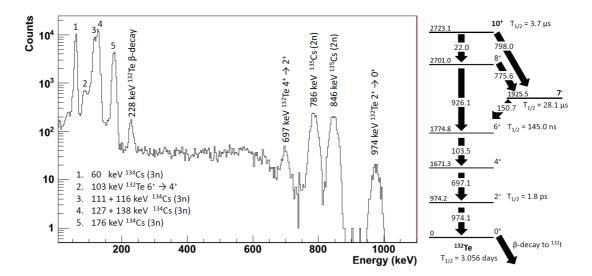
Figure 2. A comparison of the energy spectra from the simulations and calibration tests. In the top panel, a calibrated ^{152}Eu spectrum from the experiments performed in Bucharest, with the response of the 2" cylindrical LaBr$_3$ detectors is shown. The bottom panel shows a simulated ^{152}Eu spectrum of the same set-up with Geant4.

populated, and the 10^+ will not be populated at all. The pulsed beam will be used to isolate the decay from this 6^+ level, resulting in clean out-of-beam spectra. A 1-2 ns pulsed beam with a 200 ns interval will be used, and the DAQ trigger will be set to register when two LaBr$_3$(Ce) detectors fire within a time interval of 40-180 ns after the beam pulse.

Measuring the time difference between the $6^+ \rightarrow 4^+$ (103 keV), $4^+ \rightarrow 2^+$ (697 keV), and $2^+ \rightarrow 0^+$ (974 keV) transitions will allow us to deduce the lifetime of the 4^+ state with reasonable accuracy. The lifetime will be measured using the centroid shift method, where in order to make an accurate centroid shift measurement at the ~ 100 ps level, 10^4 counts are required in the resulting LaBr$_3$(Ce) singles spectrum. The efficiency of the initial Bucharest fast-timing array is expected to be increased by the addition of 4 detectors, including three 1.5"x1.5" detectors provided by the DESPEC collaboration. This will increase the expected coincidence efficiency to 0.04% at 662 keV.

Simulations of the initial fast-timing set-up were performed to look at the FEP efficiencies and singles spectra. The simulations include the internal conversion of the E1 $7^- \rightarrow 6^+$ ($\alpha = 0.62(9)$), and more importantly, the E2 $6^+ \rightarrow 4^+$ ($\alpha = 1.504(21)$) transitions [10]. The internal conversion of the M1 $3^+ \rightarrow 4^+$ transition in ^{132}I was also included ($\alpha = 5.62(8)$) [10]. The results of these simulations are shown in fig. 3. The spectrum was generated with the existing array of 8 LaBr$_3$(Ce) detectors, and includes the β decay to ^{132}I, and the fusion evaporation channels ^{135,134}Cs. These channels have been included in the simulations with relative populations based on their anticipated cross-sections (^{132}Te ~ 1 mb, ^{135}Cs ~ 9 mb, and ^{134}Cs ~ 90 mb[11]). Fig. 3 also demonstrates the cleanliness of the spectrum acquired with the pulsed beam set-up, where the $4^+ \rightarrow 2^+$ (697 keV) and $2^+ \rightarrow 0^+$ (974 keV) transitions in ^{132}Te are clearly visible. The $6^+ \rightarrow 4^+$ transition (103 keV) is obscured in the singles spectrum, but will be clean in the coincidence

Figure 3. The simulated ^{132}Te out-of-beam singles energy spectrum. The ^{132}Te decay scheme of the levels that are likely to be populated in this experiment is shown in the right panel.

matrix.

4. Summary and Future Work

The development of a new fast-timing array to complement the new in-flight separator (Super-FRS) at FAIR has been discussed. Its role will be to study half-lives in exotic nuclei in regions previously unattainable with the current set-up at the Gesellschaft für SchwerIonenforschung (GSI), in a range between several tens of picoseconds to several nanoseconds, with relatively low statistics. Currently, one of the main questions the collaboration need to consider is how the efficiency can be maximised, whilst maintaining the excellent timing properties of the LaBr$_3$(Ce) crystals. This has been examined with a series of Monte-Carlo simulations using the Geant4 program to determine the size and shape of the crystals, and how they should be distributed around the implantation point. A ^{152}Eu source was used to compare the efficiency between the three 1.5" and three 2" cylindrical detectors, and the two 1"x1.5"x1.5" conical detectors, where the conical detectors were observed to be worse than the cylindrical detectors due to the smaller solid angle coverage.

Maximising the solid angle coverage by introducing more detectors in the simulations will provide greater insight into the overall efficiency the array can achieve. The simulations will be developed to investigate the relationship between the interactions in adjacent detectors and clustering, and how these can be improved with reconstruction algorithms and add-back techniques to determine the increase in efficiency for higher energy transitions. On-going comparisons between acquired experimental data and simulations will further developments of the simulation package, and aid in the refinement of future test cases.

5. Acknowledgments

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