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Picosecond resolution on relativistic heavy ions' time-of-flight measurement

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ABSTRACT

We developed a time-of-flight measurement system for relativistic heavy ions with a requested resolution of 40 ps Full Width Half Maximum. Such a resolution is mandatory to assign the correct mass number to every fission fragment, identified using the $B\rho-\mathrm{ToF}-\Delta E$ method with the recoil spectrometer designed for the SOFIA experiment—which hold very recently at GSI. To achieve such a performance, fast plastic scintillators read-out by dedicated photomultiplier tubes were chosen among other possible options. We have led several test-measurements from 2009 to 2011, in order to investigate: the effect of the addition of a quenching molecule in the scintillator's matrix, the influence of the detector's size and the impact of the photomultiplier tube. The contribution of the dedicated electronics is also characterized. Time-of-flight measurements were performed realized with electron pulses and relativistic heavy ions, respectively provided by the LASER driven electron–accelerator (ELSA) at CEA–DAM Ile-de-France and by the SIS18/FRS facility at GSI. The reported results exhibit a time resolution better than 20 ps Full Width Half Maximum reached with the last prototype at GSI with an Uranium beam. These results confirm that the SOFIA experiment should enable the measurement of the relativistic fission fragments' time-of-flight with the requested resolution.

1. Introduction

Time-of-flight (ToF) techniques are widely used in nuclear and particle physics experiments. In particular, they enable the measurement of nuclei's lifetime [1,2]. However, as far as nuclear physics experiments at relativistic energies are concerned, most of them require to identify the nuclei mass number. The $B\rho-\mathrm{ToF}-\Delta E$ method is commonly used for this identification. Nuclei are deflected in a magnetic field, where their trajectories are tracked. Tracking and time measurements are undertaken, and the associated resolutions govern the feasibility of the ions' identification using the spectrometer [3].

Nowadays, tracking detectors reach resolutions of some tens of micrometers [4–7]. Consequently, the velocity resolution is usually limited by the performance of the time measurement, which is presently, at best, of about 100 ps Full Width Half Maximum (FWHM). Continuous efforts are therefore dedicated to improving the resolution of the time-of-flight measurement as stressed by the emergence of the Resistive Plate Chambers (RPCs) [8–10], Multi Gap RPCs (MRPC) [11–13] or Cherenkov-light based detectors [14,15], which typically reach 30–50 ps Root Mean Square (RMS) time resolution.

Motivated by those considerations, the present paper describes the design of the ToF system for the SOFIA (Studies On FIssion with Aladin) fission experiment performed in August 2012 at GSI (Helmholtzzentrum für Schwerionenforschung mbH) in reverse kinematics. The identification of the ions' mass number over the full fission fragments' mass range in the SOFIA experiment requires a ToF resolution better than 40 ps FWHM.

Some considerations on the technological choice for the ToF set-up are presented in the second part. Then, the plastic scintillators' properties are detailed and the electronics contribution to the ToF resolution is shown. The fourth section presents the results of ToF measurements performed using the electron beam from the ELSA accelerator located at CEA–DAM Ile-de-France. Finally, actual ToF measurements performed at GSI with relativistic heavy ions, are reported.

2. Choice of the detector's technology

This study is in line with the SOFIA experiment, which deals with the fission of relativistic actinide beams in reverse kinematics. A 650 A.MeV actinide beam impinges on a heavy nucleus' target leading to the Coulomb-excitation (coulex) induced fission of the projectiles [16]. Both fission fragments are emitted forward

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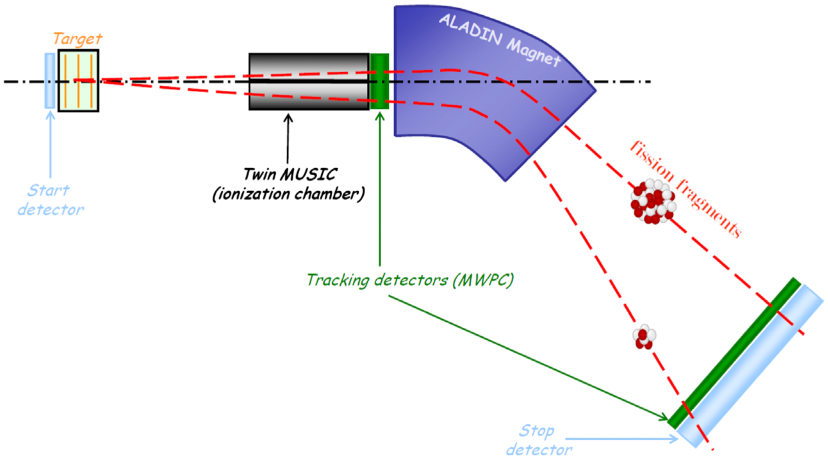

Fig. 1. Layout for the SOFIA experiment. The fission of a relativistic actinide occurs in the target. Both fission fragments are emitted forward (dashed red lines). They cross an ionization chamber and a first tracking detector before being deflected in the ALADIN magnet and passing through a second tracking detector. The time-of-flight is measured between a start detector located upstream the target and a stop detector, which is the last detector of the experimental set-up. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

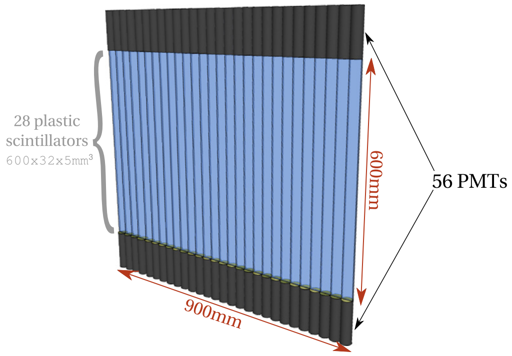

Fig. 2. Layout for the stop ToF wall detector. The wall is made of 28 plastic scintillator blades read-out by a photomultiplier at each end. The dimensions of a single blade, $600 \times 32 \times 5\ \mathrm{mm}^3$, as well as the PMT types have been chosen to optimize the time resolution.

within a 40 mrad emission angle. Due to the center of mass boost, all fission fragments (FFs) exhibit a kinetic energy close to the actinide beam energy. Their identification is completed using the Bρ–ToF–ΔE method. A layout of the SOFIA experiment is shown in Fig. 1. Besides the ToF set-up, the various detectors are dedicated to the energy loss (MUSIC) and to the tracking of the FF through the set-up.

As far as the ToF measurement is concerned, the start detector stands right upstream the target, while the stop ToF wall stands at the very end of the setup. On the one hand, the secondary actinide beam spot size is about 20 mm diameter, requiring a small-sized start detector. On the other hand, the stop detector dimensions are related to the fission fragments' dispersion in the dipole. Thus, a $600 \times 900\ \mathrm{mm}^2$ active surface is needed to cover the full space occupancy of the fission fragments. A scheme of the stop detector is given in Fig. 2.

2.1. Detector's options

The substantial size of the stop detector greatly limits the technological choice for the ToF wall. Only two kinds of detectors were considered: RPCs (Resistive Plate Chambers) or MRPCs (Multigap RPCs) on the one side, and plastic scintillator wall on the other side. While RPCs provide excellent timing results for MIPs (Minimum Ionizing Particles) or light ion measurements [17,18], plastic scintillators read-out by photomultiplier tubes (PMTs) are particularly efficient for relativistic heavy ion experiments.

Indeed, the amount of light produced in the scintillator increases as the square of the nuclear charge of the detected ions. Taking into account the enormous amount of energy deposited by relativistic fission fragments in matter, and in light of the encouraging results of Nishimura et al. [19], plastic scintillators read-out by PMTs were retained as the only option to investigate.

2.2. Time resolution considerations

The time resolution obtained with plastic scintillators and PMTs is affected both by the PMT characteristics and by the scintillator's light production properties. In addition, the absorption wavelength range of the PMT's photocathode has to match the emission wavelength range of the scintillating material.

As far as the PMT is concerned, the time resolution $\mathcal{R}_{PMT}$ is defined as

$$\mathcal{R}_{PMT} \propto TTS/\sqrt{N_{p.e.}},$$

where TTS stands for Transit Time Spread (TTS) and $N_{p.e.}$ is the number of photoelectrons produced at the photocathode.

The latter expression assumes that all electrons reach the photocathode at the very same instant. While the TTS is an intrinsic characteristic of the PMT, the $N_{p.e.}$ depends on the quantum efficiency (Q.E.) of the photocathode for a given light input:

$$N_{p.e.} \propto Q.E. \times E_{\gamma},$$

where E_{γ} represents the total photon energy at the photocathode.

The recently developed MicroChannel Plate based Photomultiplier Tubes (MCP-PMTs) typically feature shorter TTS than dynode-based PMTs. However these fast-timing MCP-PMTs are significantly more costly than the best standard PMTs and are, mechanically speaking, not suited to the integration in a ToF wall. Therefore, only dynode-based PMTs are considered here. To our knowledge, the PMT with the shortest TTS is the Hamamatsu H6533, followed by the Hamamatsu H10580.

Regarding the $N_{p.e.}$ optimization, the quantum efficiency is a characteristic of the photocathode. The latter is available embedded with a "Super Bialkali" photocathode as an option [20]. The "Super Bialkali" is characterized by a better quantum efficiency than the standard bialkali. Thus, part of the loss due to