Ultra-fast timing detectors to probe exotic properties of nuclei using RIB facility

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Abstract

Recently, the facilities of radioactive ion beam (RIB) combined with advanced detector systems provide us unique opportunity to probe the exotic properties of the nuclei with unusual neutron-to-proton ratio. In this article, a study of characterization of different types of ultra-fast timing detectors: a special type of gas detector (multi-strip multi-gap resistive plate chamber, MMRPC) (σ <100 ps), scintillators array (viz., LaBr3:Ce) (timing resolution (σ <250 ps) are being presented. A brief discussion on usage of these different types of ultra-fast timing detector systems at radioactive ion beam facilities is also included.

1 Introduction

In recent decades, the-state-of-art ultra-fast timing detectors have evolved very rapidly toward ever-higher performance. These detectors have few key characteristics that enable their application to expand our knowledge on basic and applied sciences with unique dimensions. The fast rise time (<10 ns) pulses due to response of the detector allow high-resolution measurements in the time-domain. Moreover, due to the simplicity of detector construction, easy to handle and long time performance reliability, researchers are attracted for various utilization of these types detectors. In this article, studies of the response of different types of ultra-fast timing detector systems for detecting particles and γ-rays are presented. These different types of ultra fast timing detectors are special type of gas detector (multi-strip multi-gap resistive plate chamber, MMRPC) and scintillators (viz., LaBr3:Ce). Different types of scintillator detectors are commercially available and detector response mechanism is similar. Though depending upon light output and its decay constant, the utilities are different for optimum uses. Ultra fast timing plastic scintillators array are used in many large-scale experiments for charge, time of flight and position measurements of charged particles or nuclei. These detectors are also used for

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detecting neutrons. Due to fast decay time and high light output inorganic scintillators, like $\text{LaBr}_3$ etc. are very useful for detecting $\gamma$-rays with good timing and energy resolution. A brief discussion on usage of these detectors for studying the properties of the exotic nuclei is also included.

2 Multi-strip multi-gap Resistive Plate Chamber (MMRPC) developed at SINP, Kolkata

Three decades ago the Resistive Plate Chamber (RPC) \cite{1,2} was invented to overcome several problems of parallel plate chambers. The working principle is similar to a gas detector in avalanche or streamer mode with modification due to resistive plate cathode. The electrodes of RPCs are made of resistive material like Bakelite or glass. This has the effect that only a limited part of the electrode is discharged during the passage of an ionizing particle with subsequent avalanches or streamers, while the rest of the electrode remains unchanged. To improve timing resolution, Multi-gap Resistive Plate Chamber \cite{3,4} (MRPC) is an intelligent modification of a RPC by increasing the electric field across the gas gap and the thickness of the gas gaps are reduced by inserting (electrostatically) floating glasses between anode and cathode. Moreover, via segmentation of readout board, high granularity can be achieved for a single MMRPC detector. Thus the MRPCs have high granularity, high-resolution inexpensive TOF system (compared to standard scintillator with PMTs). This includes both fundamental research in particle physics\cite{5}, astrophysics, cosmology, nuclear physics\cite{6}, and applied research in medical imaging (cost effective Positron Emission Tomography)\cite{7,8}, security purpose like cosmic muon tomography, climate change etc. But, utilization of such detector in low-energy nuclear physics study is scarce. To explore new applications, a prototype detector was developed at SINP, Kolkata \cite{9,10}. The prototype is a double stack glass MMRPC of size $40 \text{ cm} \times 20 \text{ cm}$ with segmented anode strips (Figure 1-left). The cathode plates were made by introducing a thin layer of conducting material on $1 \text{ mm}$ thick float glass. Negative high voltage was supplied to the cathode while the anodes were kept at ground potential. A non-flammable gas mixture of 89% $\text{R134a (C}_2\text{H}_2\text{F}_4)$, 4.0% Sulfur Hexaflu-
oride (SF$_6$) and 7.0% Isobutane (C$_2$H$_{10}$) was kept in flow mode at atmospheric pressure throughout the volume of the detector. The detailed response of the developed detector for detecting cosmic muons and γ-rays from radioactive source had been studied [9]. For response of non-charged particle the charged clouds are produced in the counting gas via indirect processes and hence, the response time of the MMRPC for the neutrons and γ-rays is worse in comparison to minimum ionizing particles (MIPs). The response of the MMRPC to cosmic muons and γ-rays using radioactive source (60Co) have been studied in coincidence with fast scintillator, cerium doped Lanthanum bromide (LaBr$_3$:Ce) scintillators. The measured time resolution of the MMRPC for γ-rays is $\sim$270 ps which is much worse in comparison to high energy cosmic muons (150 ps) as shown in Figure 4 (bottom-right) of Ref. [9]. Subsequently, a more detailed study of the MMRPC detector was performed using a pulsed electron beam (pulse width < 10 ps) of 29 MeV at the ELBE facility [10]. A sufficiently long plateau has been observed ($\sim$ 95%) as shown in Figure 1-middle. The time resolution of MMRPC improves with increasing negative bias voltage and reaches an optimum at 7.5 kV which is considered as the operating voltage. Figure 2 (top-left) and (bottom-left) show the time against deposited charge in a single strip of the MMRPC detector before and after slew correction, respectively. The measured time resolution ($\sigma$) of the MMRPC for events hitting only a single strip after slew correction is 90±1 ps. The measured position resolution of the MMRPC along and across the strip are 2.8±0.6 cm and 0.58 cm, respectively. Figure 3 shows the reconstructed image of electron beam spot in the XY-plane of the MMRPC detector. The advantage of the detector is fast timing response along with position resolution. Other practical advantages of MMRPCs are simple and easy of construction, operated in atmospheric gas pressure, working condition independent of temperature, negligible distortion in presence of magnetic field, cost-effective and possibility of utilization in large scale. The major limitation of this type of detector is lack of high event rate capability. As shown in the Figure 1-right, the efficiency and timing resolution of the developed detector became worse with increasing events rate. Considering above-mentioned advantages and limitations, these type of excellent detectors can be used as a TOF for relativistic energy neutrons [11, 12, 13, 14], protons [15], fragments/light charged particles [16], and electrons [10] as reaction products. Detailed simulation work for response of MMRPC detector to detect low energy neutron has been reported by a number of research groups [13]. We are planning to study the neutron response using 14 MeV neutron generator [17] with a modification of MMRPC. Now, few examples for utility of MMRPC to study exotic nuclei is being discussed. The study of exotic heavy nuclei (A > 50) via invariant mass analysis is restricted due to limitation of acceptance of the neutrons detection in the setup at various RIB facilities. Plastic scintillator based neutron detector of larger dimension for better acceptance becomes commercially inviable. The low cost MMRPC based large area neutron detector can be the alternative to provide neutron detection with good time and position resolution. Study of the exotic nuclei beyond drip line by proton knockout of neutron-rich nuclei is an excellent tool. But the measurements may be affected due to reaction product of other channels. The tagging of knockout proton using this detector may solve the problem and provide valuable information about the unbound nuclei.
Figure 2: Time distribution of MMRPC before (top-left) and after (bottom-left) slew correction, against the deposited charge on a strip for the events hitting only one strip at a time. (top-right) Time of MMRPC (before slew correction) and (bottom-right) the same after slew correction.

Figure 3: Reconstructed image of electron beam spot at ELBE, obtained by present developed detector via timing measurement.

3 Scintillators

3.1 LaBr$_3$(Ce)

Lanthanum Bromide, cerium doped, LaBr$_3$(Ce) is one of the new generation inorganic scintillator for detecting $\gamma$-rays which exhibit improved energy resolution, faster decay time, and temperature stability compared to available other inorganic scintillators; NaI, CsI etc. Figure 4-right shows the photograph of LaBr3 detector of six inches long crystal with fast PMTs. A detailed response of this types of detector with various dimensions and readout systems has been studied using using standard $\gamma$-ray sources ($^{60}$Co, $^{152}$Eu, $^{137}$Ba) and cosmic background [18, 9] at SINP laboratory. It has been observed that the energy response of $\gamma$-rays using this crystal is highly nonlinear (see figure 5) and the energy resolution is inversely proportional to the square root of the energy ($R(E) \propto 1/E^{1/2}$). Figure 5 [right] shows timing spectra ($t_1$-$t_2$) and inset shows the energy spectra of $^{60}$Co source. The dashes and solid line represents overall TAC (time-to-amplitude converter) and photo-peak projected TAC spectra. Measured time resolution is better for the smaller crystal (2.5 cm diameter and length) ($\sigma \sim 120$ ps)[9] compared to the larger crystal (7.6 cm dia and 15.6 cm length) ($\sigma \sim 225$ ps). Due to fast timing response compared to HpGe and NaI(Tl) detectors, the LaBr3 detectors are useful in the experiment that require good timing resolutions, such as lifetime measurements of isomeric states in the nuclei and one...
may pin down various structural properties of exotic nuclei [19]. This detector will be particularly useful for the measurement of lifetime which are not accessible by Doppler Shift Attenuation (DSA) and plunger method. Due to availability of larger dimensions of this type crystal, high energy $\gamma$-rays can be detected with better photo peak efficiency which may be helpful for measurements of the low cross section specific events of the nuclei. Study of the ground state configuration of the exotic nuclei by Coulomb breakup, knockout reaction at intermediate energy ($E > 100$ AMeV) are affected by identification of core excited states. This type of detectors with better energy resolution along with efficiency, may provide excellent solution. However, the plan of the experimental setup should be such that the Doppler broadening effect should not suppress the intrinsic detector resolution. Using this advanced detector, measurements of p-$\gamma$ branching ratio, relevant to nuclear astro-physics is another important utility.

### 3.2 Plastic scintillator

Plastic scintillator detectors are widely used for measurement of the time of flight and charges of high velocity particles in many experiments of nuclear [20] and high energy physics. In house facility at SINP offers us to measure various intrinsic properties of those detector like measurement of rise time, the optical attenuation length of the material [21] etc.. Figure 4-left shows the photographs of plastic scintillator array with equivalent size and granularity of the detection channels of our developed MMRPC. Though, this detector as TOF is expensive compared to MMRPC, but considering the capability of high events rates, these types of detectors are being used in wide range of experiment using exotic nuclei with high intensity. It would be interesting to explore composite detector TOF using MMRPC and plastic scintillator.
4 Applications of the ultra-fast timing detectors to the society

The applications of ultrafast technology, are wide in horizon. Here we are restricting our views with above-mentioned detectors. Use of cost-effective MRPCs in PET technology\textsuperscript{[7, 22, 23]} for medical imaging will be a great use of society. Positron Emission Tomography (PET) imaging technique is based on positron emitting radio-tracer and detecting the two back-to-back $\gamma$-rays emitted when the positron annihilates in the patients body. A line is drawn connecting the detected positions of the two $\gamma$-rays; thus an image can be constructed when many such lines have been recorded. If the time of arrival of the $\gamma$-rays in the detector can be measured (with precision), then the position of the positron annihilation can be localized along this line. This technique is known as TOF-PET and studies have shown that the resultant image becomes much clearer due to the reduction of the background. Muon tomography\textsuperscript{[8]} is a technique based on the measurement of multiple scattering of atmospheric cosmic muons. This is a promising technique for detecting and imaging heavily shielded high-Z nuclear materials\textsuperscript{[24]}. This technology will enables large-scale imaging of cargos, trucks etc. at border crossing or airport penetrating thick layers of steel.

5 Summary

Detailed response of different types of ultra-fast timing detectors; a special type of gas detector, MMRPC ($\sigma < 100$ ps), scintillators array (viz., $LaBr_3:Ce$) ($\sigma < 250$ ps) have been discussed. A wonderful, reconstructed image of the electron beam spot provide unique capability of imaging of the MMRPC which are almost two order of magnitude cheaper than scintillators. But due to limitation in rate handling capability, this detector can be used for detecting low rate reaction products. For larger rate handling capability, plastic scintillator are the unique for detecting purpose. Due to fast decay time and high light output inorganic scintillators, like $LaBr_3$ etc. are very useful for detecting $\gamma$-rays with good timing ($\sigma \sim 150\text{--}250$ ps) and energy resolution ($\Delta E/E \sim 3\%$)\textsuperscript{[18, 9, 19]}. We have studied the response of the charge particle of this type detector\textsuperscript{[9]}.

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