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Application of pulse shape discrimination in Si detector for fission fragment angular distribution measurements

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Abstract. Pulse shape discrimination (PSD) with totally depleted transmission type Si surface barrier detector in reverse mount has been investigated to identify fission fragments in the presence of elastic background in heavy ion-induced fission reactions by both numerical simulation and experimental studies. The PSD method is compared with the other conventional methods adopted to identify fission fragments with solid-state detectors such as ΔE–E telescope and single thin ΔE detector and the data for the ^{10}B + ^{232}Th fission reaction are presented. Results demonstrate the usefulness of a single transmission-type surface barrier detector for the identification of fission fragments and projectiles like heavy ions.

Keywords. Pulse shape discrimination; solid-state surface barrier detector; heavy ion-induced fission reaction studies.

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1. Introduction

It has been known for more than 40 years that the shape of the pulse collection in a solid-state detector following the interaction of charged particles can be used for particle identification [1]. Recently, it has been demonstrated by many authors [2–4], that the sensitivity of the pulse shape to density and length of the ionization track is further enhanced if the rear contact (reverse mount) of a totally depleted Si-detector is exposed to charged particle irradiation. Moreover, potentially improved capability has been also discussed using homogeneously neutron-transmutation doped (n-TD) silicon detector [5]. The sensitivity of the pulse shape in the solid-state detectors is essentially governed by two factors: (i) the plasma erosion time ($\tau_{\mathrm{pl}} \propto n_0(x)/F(x)$, where $n_0(x)$ is the carrier density and $F(x)$ is the field strength at penetration depth x); and (ii) the finite drift time of the charge carriers. As a result of both these effects, the charge-collection time increases monotonously with charge and mass number of the detected ion for a given incident energy. Hence a heavier ion generates a current signal of longer duration but smaller amplitude, which corresponds to a larger rise time of the charge signal. The above technique has been employed to discriminate light charged particles (α, proton and triton) in various experimental set-ups such as the 8πLP detector array [6] and the ISIS ΔE–E ball of EUROBALL [7].

In the case of heavy ion-induced fission studies using solid-state surface barrier detectors, it is often a problem to identify fission fragments in the presence of large elastic scattering background, if the energy loss of elastically scattered particles in the detector overlaps with the fission fragment energy spectrum. Because of this, very thin ΔE detectors are often used to identify fission fragments so that fission fragments completely stop inside the detector and the corresponding elastic energy loss is small enough to be well-separated from the fragment energy spectrum. Another frequently used technique is the ΔE–E telescope in anti-coincidence or veto mode to reject elastic products from fission fragments. It is difficult to separate fission fragments and elastically scattered particles produced in a nuclear reaction using a particular thickness ΔE detector or a fixed set of ΔE and E telescope over a wide range of beam energy, and projectile and target combinations.

Since there is a large difference in the length and density of ionization in the silicon detector for fission fragments and elastic products of similar energy, due to the difference in energy loss mechanism [8], this property can be exploited to identify fission fragments in the presence of large elastic scattering background. In the present work, we have investigated the feasibility of pulse shape discrimination (PSD) for the identification of fission fragments and projectile-like products in heavy ion-induced fission reactions.

2. Results of simulations

To demonstrate the feasibility of pulse shape discrimination for identification of fission fragments and elastically scattered heavy ions, we have carried out numerical simulations of the charge-collection process in a transmission-type surface barrier detector of thickness 150 μm for rear-side injection of the particles, following the procedure outlined in [3]. As a test case, we have taken an ion of mass $M = 120$ and charge $Z = 50$ to characterize the fission fragment and mass $M = 10$ and charge $Z = 5$ as the elastic particle in the numerical simulation.

Figure 1 shows the results of the calculation on the pulse shapes of current and charge signals for fission fragment $Z = 50$, $M = 120$ and ^{10}B ion at energy $E = 40$ MeV. As expected the fission fragment generates a current signal $i(t)$ of longer duration but smaller amplitude, which corresponds to a large rise time of the charge signal $Q(t)$ in comparison to ^{10}B signal. In order to characterize the pulse shape discrimination, we have defined a parameter t_{PSD}, the time difference between 90% and 10% of the charge signal $Q(t)$.

In figure 2, we plot t_{PSD} as a function of energy deposited in the detector for both fission fragments and ^{10}B ions. In terms of t_{PSD}, the fission fragments and ^{10}B ions are well-separated to be identified as two different groups. The difference in variation of t_{PSD} as a function of energy can be ascribed to the energy loss mechanism. This result motivated us to carry out experimental measurements to

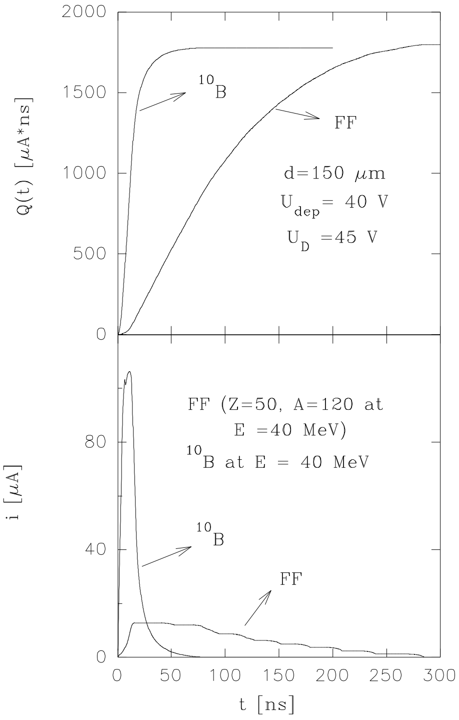

Figure 1. Pulse shapes of charge and current signals for fission fragments and ^{10}B ion obtained with a Si detector of thickness 150 μm for rear-side particle injection.

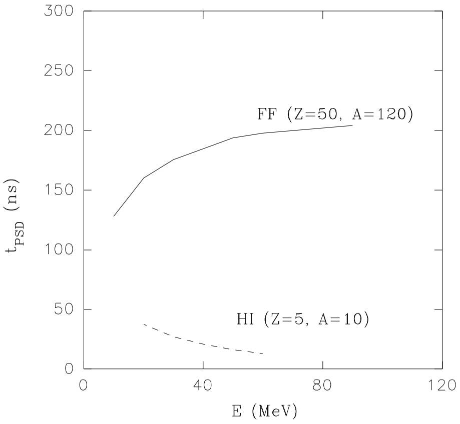

Figure 2. Simulation of the correlation between t_{PSD} (see text) vs. energy deposition in a 150 μm Si detector operated in the rear-side injection mode.

test the feasibility of identifying fission fragments in the presence of elastic scattered particles.

3. Experimental procedure

The measurements were carried out with the ^{10}B + ^{232}Th reaction at $E_{\mathrm{lab}} = 60$ and 64 MeV to produce the fission fragments and transfer products. A self-supporting 1.8 mg/cm^2 thick target of ^{232}Th was used to bombard with ^{10}B beam obtained from the 14 MV BARC-TIFR pelletron accelerator at Mumbai. A totally depleted transmission-type silicon surface barrier detector having a thickness of 150 μm (ORTEC TB-18-150-150) with the rear surface, i.e. Al ohmic contact side facing the target, was used to detect the fission fragments and transfer products. A charge-sensitive pre-amplifier (Tennelec TC-170) was used to derive pulse shape information. The linear signal from the pre-amplifier was further amplified by a timing filter amplifier (ORTEC TFA 474) to get leading edge time by means of leading edge discriminator, and by a linear amplifier (ORTEC 571) to get zero-cross-over time by means of zero-crossing discriminator. Time difference (t_{PSD}) between these two timing signals was recorded to represent the pulse shape. The energy deposition and the parameter (t_{PSD}) characterizing the pulse shape were recorded event-by-event.

In the same set-up a solid state ΔE (17 μm)–E (1 mm) telescope in anti-coincidence mode and a single thin ΔE (12 μm) detector were also used to identify fission fragments for comparison with the PSD results. A Si surface-barrier detector of thickness 500 μm was mounted at $\theta_{\mathrm{lab}} = 40°$ for use as the monitor detector to count the elastically scattered yields, providing a normalization for fission fragment angular distribution measurement.

4. Results and discussions

Figure 3 shows a typical two-dimensional spectrum of energy vs. zero-crossing time t_{PSD}, at a detector bias voltage of 40 V. As can be seen from the figure the fission fragments and projectile-like fragments (PLF) are well-identified as separate groups. The difference in variation of zero-cross-over time as a function of energy for the fission fragments and projectile-like fragments can be understood in terms of their energy loss mechanism as explained above. The energy loss is a function of the charge (Z) of the particle in the case of PLF as they are fully stripped of electrons at these energies. In the case of fission fragments, the energy loss is a function of the effective charge (Z_{eff}) of the fragments, which by itself depends on the velocity of the fission fragments. Hence, in the energy loss process, as the fragment energy decreases so also the effective charge of the fragments thereby reducing the differential energy loss as a function of range. This difference in energy loss mechanism gives a different variation in zero-cross-over time as a function of energy of fission fragment and PLF. The PSD spectra were also collected for various detector bias voltages to optimize the performance. It is observed that to obtain optimum PSD information, the detector must be operated with a bias voltage just sufficient to produce the full depletion.

4.1 *Identification of fission fragments using various methods*

The fission fragment energy spectra obtained at $\theta_{\mathrm{lab}} = 85°$ from ΔE (17 μm)–E (1 mm) telescope in anti-coincidence mode and in a single thin ΔE (12 μm) detector are shown in figure 4 for the ^{10}B + ^{232}Th reaction at $E_{\mathrm{lab}} = 60$ MeV. The figure also shows the fragment energy spectrum obtained from one-dimensional projection

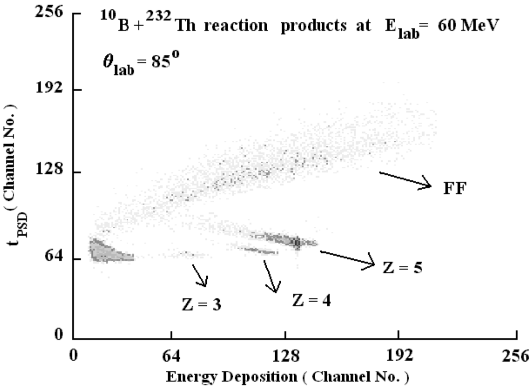

Figure 3. Typical zero-crossing time (t_{PSD}) vs. energy deposition plot for ^{10}B + ^{232}Th reaction at $\theta_{\mathrm{lab}} = 85^\circ$ and $E_{\mathrm{lab}} = 60$ MeV.

of PSD vs. energy plot (as shown in figure 3) after gating on fission fragments. It is seen that for ΔE–E and thin ΔE (12 μm) detectors, there is a rise in the yield at lower energy side of the fragment energy spectrum due to contributions from low-energy reaction products. But in the case of PSD detector this mixing due to low-energy reaction products could be completely eliminated from the fission fragment energy spectrum. The determination of fission fragment yield using ΔE–E and thin ΔE (12 μm) detector may have uncertainty in the yield due to mixing of low-energy reaction products in the case of heavy ion induced fusion–fission reactions. This mixing is more dominant as one goes below barrier energies. In such a scenario PSD method provides a better alternate technique to identify fission fragments in the presence of large background of low-energy reaction products.

4.2 *Fission fragment angular distribution measurement*

As a test experiment, we carried out fission fragment angular distribution measurements using the PSD detector in ^{10}B + ^{232}Th reaction in the angular range of $\theta_{\mathrm{lab}} = 90°$–$170°$ at $E_{\mathrm{lab}} = 64$ MeV. The fission fragment yields at various angles were obtained by adding events in the fission band by putting gate on two-dimensional plot of the zero-cross-over time and the energy of the detected products. The fragment angular distribution was obtained by normalizing the fission fragment yields at various angles by corresponding counts in the monitor detector. The fragment angular distribution so obtained is shown in figure 5. The results of the standard saddle point model (SSPM) [9] are also shown in figure 5. As expected, the experimental results are consistent with the model prediction. The fragment angular anisotropy determined from the present measurements is also in agreement with the earlier reported results on this system [10]. The present results demonstrate the usefulness of the PSD technique for fission fragment angular distribution measurements.

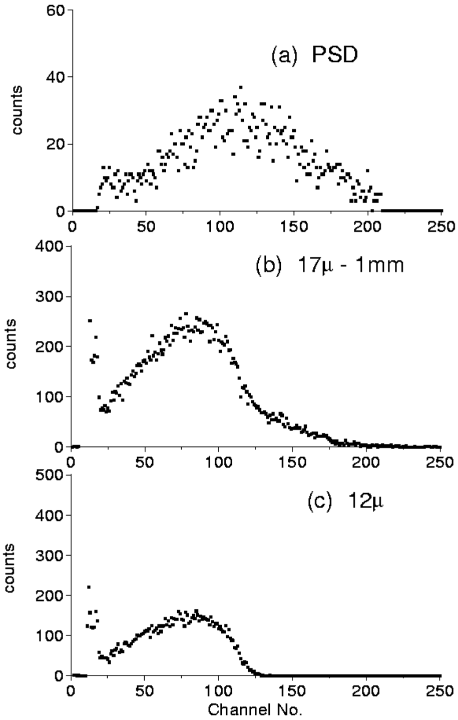

Figure 4. Comparison of fission fragment energy spectra obtained using (**a**) PSD, (**b**) ΔE–E and (**c**) thin ΔE techniques for ^{10}B + ^{232}Th at $\theta_{\rm lab} = 85°$ and $E_{\rm lab} = 60$ MeV.

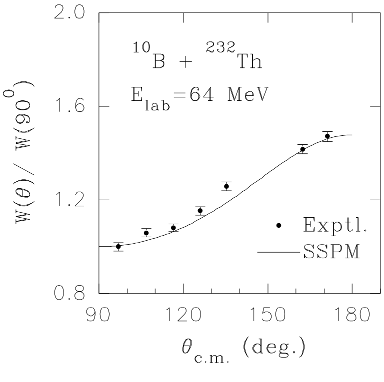

Figure 5. Fission fragment angular distribution for ^{10}B + ^{232}Th reaction at $E_{\rm lab} = 64$ MeV. The dots are the experimental points and solid line is the prediction of SSPM [7].

5. Conclusions

Simulations were carried out to calculate the pulse shapes of the charge collection in the surface barrier detectors for rear-side injection of fission fragments and projectile-like particles produced in heavy ion-induced fission reactions. It is shown that the pulse shape discrimination method can be used to separate the fission fragments and projectile-like fragments in heavy ion-induced reactions. Experiments results are presented to demonstrate the usefulness of the pulse shape discrimination method using a single surface barrier detector to discriminate fission fragments and heavy ions quite effectively when the detector is used in reverse mount. It is suggested that PSD technique can be used to measure the cross-sections and angular distributions of fission fragments for cases where the presence of large background of elastic events, introduces sizeable uncertainties in the measurement of cross-sections and angular distribution of fission fragments.

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