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A CsI(Tl) detector array for the measurement of light charged particles in heavy-ion reactions

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ABSTRACT

An array of eight CsI(Tl) detectors has been set up to measure the light charged particles in nuclear reactions using heavy ions from the Pelletron Linac Facility, Mumbai. The energy response of CsI(Tl) detector to α-particles from 5 to 40 MeV is measured using radioactive sources and the ^{12}C(^{12}C, α) reaction populating discrete states in ^{20}Ne. The energy non-linearity and the count rate effect on the pulse shape discrimination property have also been measured and observed the deterioration of pulse shape discrimination with higher count rate.

1. Introduction

CsI(Tl) scintillation detectors have been widely used for both γ-ray and charged-particle spectroscopy. These detectors have higher density and contain elements of higher atomic number than NaI(Tl) detectors. CsI(Tl) detectors therefore have a higher γ-ray absorption efficiency than NaI(Tl) detectors. The scintillation light of the CsI(Tl) detector is composed of two components, a fast component with decay time of ~0.6 μs and a slower one with decay time of ~3.5 μs [1,2]. The intensity of these components as well as the decay time vary for various exciting particles. Exploiting these properties, CsI(Tl) is used to identify the particles that caused the scintillation. Many techniques such as charge comparison [3], zero cross over time (ZCT) [4,5] and ballistic deficit [6] are used for the charged-particles identification. In addition to the techniques mentioned above, the FPGA-based digital signal processing has also been employed for the particle identification using pulse shape analysis [7]. In the charge comparison method, the ratio of integrated charge of linear signal for a short time (few hundreds of ns) to long time (few thousands of ns) window provides the identification of charged particles. The amplitude degradation at the output of a pulse shaping circuit due to the finite rise time of the input pulse is used for the particle identification in the ballistic deficit method. The zero crossover time of the amplified bipolar signal with respect to the fast timing is used for the particle identification in the ZCT technique. The CsI(Tl) detectors have been incorporated in many large solid angle coverage arrays for the measurement of charged particles in heavy-ion induced reactions [8,9]. These detectors have been used to measure both mass and charge of the particles either in pulse shape analysis and ΔE-E techniques with plastic or silicon detector used as a ΔE detector [10–12].

An array of CsI(Tl) detectors was assembled to make measurements related to the damping of the shell effect on the nuclear level density in the ^{208}Pb region. This involved populating ^{208}Pb at excitation energies of 5–20 MeV using the ^{205}Tl(^{7}Li, α)^{208}Pb* reaction and measuring neutrons in a 1 m × 1 m plastic detector array using the time of flight method. The transfer-fusion reaction similar to the measurement [13] was used to populate a range of excitation energies in ^{207}Pb. As a result, the parameter corresponding to the damping of the shell effect in the Ignatyuk–Reisdorf formulation of the level density could be measured confirming a prediction of V. S. Ramamurthy, S.K. Kataria, and S. S. Kapoor [14].

The measurement required the detection of the alpha particles, whose angular distribution at a ^{7}Li energy close to the Coulomb barrier on ^{205}Tl is backward peaked, with as large an efficiency as possible viz. about 1 sr. A close packed array of detectors with good particle discrimination capability was required. While silicon detector telescopes could be used, the CsI(Tl) array had the advantage of being low-cost, readily available and adequate. The CsI(Tl) detector array is used for alpha particle measurement in the transfer reaction. As the ejectile alpha peaks at grazing angles, the solid angle coverage of 1 sr is adequate to perform the measurement. Since the alpha particles have fairly broad energy distribution, the requirements on the CsI(Tl) detectors are not stringent in terms of energy resolution and this is only used for putting

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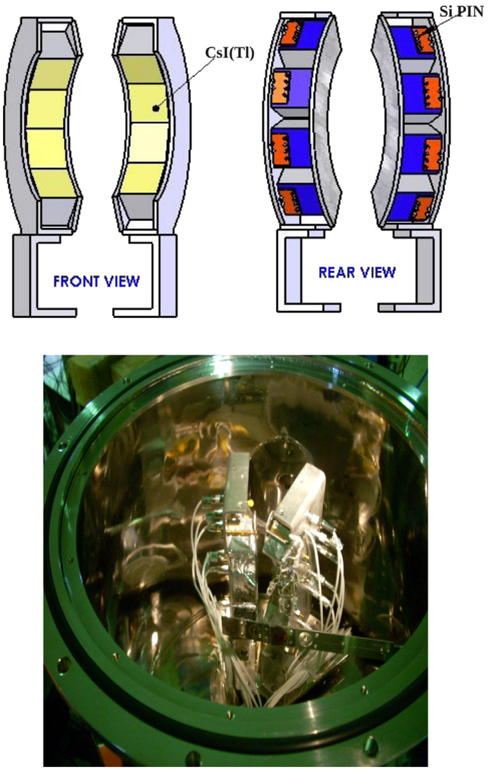

Fig. 1. A schematic of the CsI(Tl) detector array (upper) and a photograph of the detectors mounted in a thin wall multi-purpose chamber (lower).

1.5 MeV gates resulting in corresponding excitation energy bins in the compound nucleus ^{208}Pb.

In this paper, we report on the characterization of the CsI(Tl) detector. The paper is organized mainly in four sections. The second section describes details of the detector array. In the next section the measured alpha particles in the ^{12}C(^{12}C, α)^{20}Ne reaction at E(^{12}C)=24, 30 and 40 MeV are presented. The subsequent section explains the count rate effect on the PSD in the ^{7}Li + ^{197}Au at E(^{7}Li)=30 MeV which is followed by a summary.

2. Description of CsI(Tl) detector array

An array of eight CsI(Tl) scintillators, each coupled to a Si(PIN) photodiode was assembled to detect the charged particles in the heavy-ion induced reaction at the Pelletron Linac Facility (PLF), Mumbai. Since the size of the photodiode is smaller than the CsI(Tl) crystal, a compact, closely packed configuration can be made. The detectors were grouped into two arrays, each consisting of four detectors and mounted in aluminium frames as shown in Fig. 1. Each group has a solid angle coverage of 1 sr and is placed either side of the beam. The CsI(Tl) detector array will be used for the measurement of charged particles by pulse shape discrimination in the reaction with weakly bound nuclei and also useful for the coincidence measurements involving neutrons and gamma rays [15,16]. The CsI(Tl) scintillators coupled to a Si(PIN) photodiode have been procured from M/s SCIONIX, Holland [17]. The active area of the CsI(Tl) is 25 × 25 mm^2 and the thickness is 10 mm. The coupling of Si-PIN photodiodes (Hamamatsu S3204-08) to the scintillators was done using a perspex light guide of dimension $25 \times 25 \times 15$ mm^3. The sensitive area of the photodiode is 18×18 mm^2. Some of its important features are good energy resolution, good stability, fast response, low capacitance and high quantum efficiency (85% at peak wavelength 540 nm). The signal readout was taken through a high gain (~9 V/pC) charge sensitive preamplifier mounted close to the Si-PIN photodiode for further processing. The preamplifier is vacuum compatible and has low power dissipation (~100 mW). The DC offset in the preamplifier signal output was eliminated by using a capacitor (~6 μF) and a battery was used to supply 12 V to preamplifier in order to reduce the pick-up problem and, thus, to improve the signal to noise ratio. A six-channel ZCT (Hex-ZCT) module was specially designed and fabricated for the CsI(Tl) detectors to identify particles using the ZCT technique [18]. The measured figure of merit (M), which is defined as the ratio of peak separation between two particles to the sum of their full widths at half maxima(FWHM), observed to be comparable with that obtained using a commercial module. The measured M depends on the particle types, dynamic energy range of the particles and the count rates.

The typical block diagram used for the measurement of the PSD and energy of the particles is shown in Fig. 2 and is similar to the existing procedure [5]. The preamplifier signal was split, one part fed to the constant fraction discriminator through the fast amplifier for the start time of a Time to Amplitude Converter(TAC) and the second to the amplifier for the measurement of energy and zero cross over time to stop of the TAC for pulse shape discrimination. The measured alpha

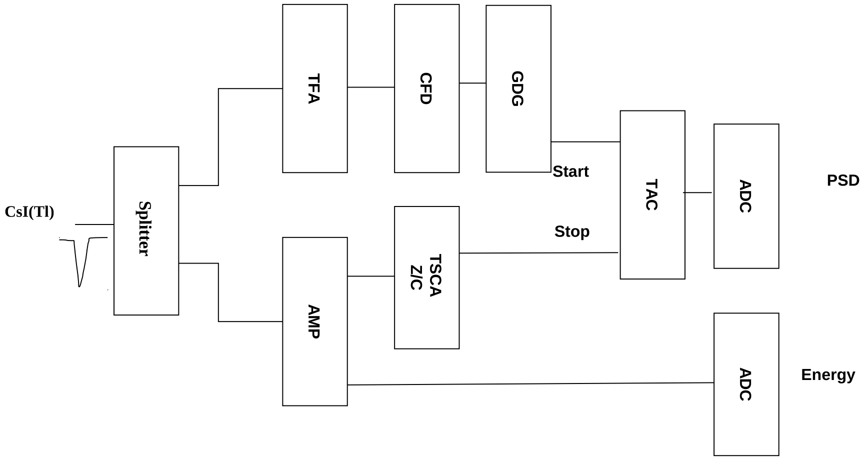

Fig. 2. Basic electronic block diagram for the PSD using laboratory made Zero Cross over module(Hex-ZCT). The electronic modules includes, TFA: Time filtered amplifier, AMP: Spectroscopic amplifier, CFD: Constant fraction discrimination, TSCA: Timing single channel analyzer/Hex-ZCT, TAC: Time to amplitude converter, GDG: Gate and delay generator and ADC: Analogue to digital converter.

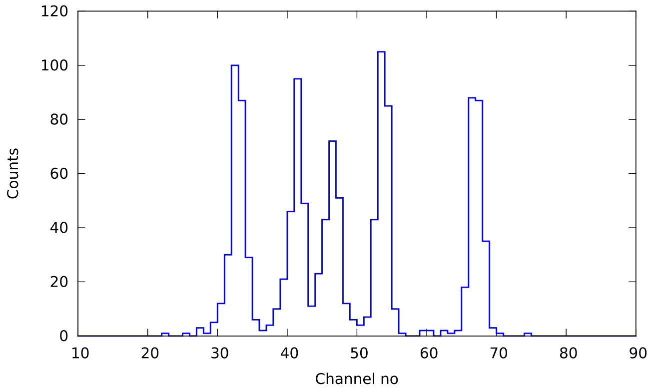

Fig. 3. Typical alpha spectrum of the CsI detector using ^{229}Th source. The peaks corresponds to the alpha particles with energies 4.9, 5.8, 6.3, 7.1 and 8.4 MeV.

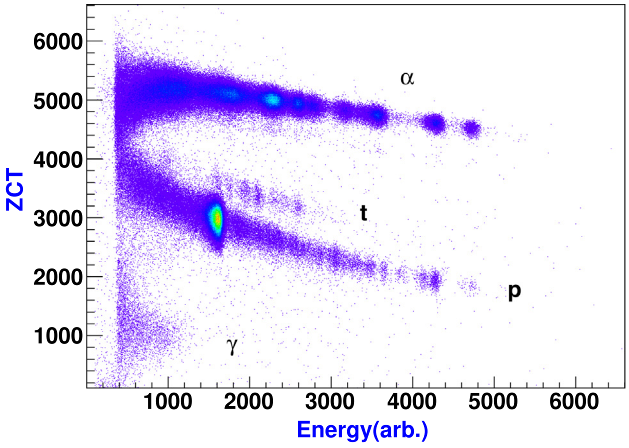

Fig. 4. A 2D spectrum between the ZCT and the energy of CsI(Tl) detector which shows the particles emitted in the ^{12}C + ^{12}C reaction are well separated by the pulse shape discrimination technique.

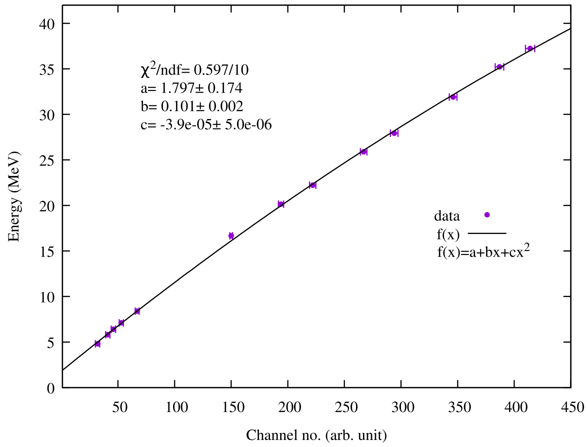

Fig. 5. Measured calibration curve for alpha particles up to ~ 40 MeV.

spectrum for the ^{229}Th source is shown in Fig. 3. The typical energy resolution of these detectors is about 6% at ~5 MeV for alpha particles.

3. Response of CsI(Tl) detector to α-particles

The amount of light produced by a CsI(Tl) scintillators depends on the energy, charge and mass of the particle interacting with the scintillator. The light output of the scintillator is related to the stopping power (energy loss per unit length) of the particle in the crystal and is described by the Birks relation [1]. It is a non-linear function of the energy of the alpha particles. Thus, in order to use these detectors for alpha spectroscopy, it is necessary to measure the light output over a wide energy range for alpha particles. The non-linearity of the light output of the CsI(Tl) detector in the energy region from ~5 to 40 MeV has been measured for α-particles. The alpha response from ~5 to 8 MeV was measured using a ^{229}Th source and is shown in Fig. 3. The response at higher energies was measured with alpha particles from the ^{12}C(^{12}C, α)^{20}Ne reaction populating discrete states in ^{20}Ne.

The experiment was carried out to measure alpha particles in (^{12}C, α) reaction at 24, 30 and 40 MeV ^{12}C beam using the Mumbai PLF . The carbon target backed by 42.4 mg/cm^2 thick Ta foils was mounted 9.5 cm upstream of the centre of the reaction chamber and the detectors were placed at 4.5 cm from the centre. The detectors were brought to 0° to reduce the kinematic energy spread and alpha particles were detected by the ZCT technique. A 2D spectrum between ZCT and energy of the particles for this reaction is shown in Fig. 4. The gamma rays, proton, triton and alpha particles were clearly identified. The value of figure of merit for gamma ray and alpha discrimination is found to be $M_{\gamma\alpha}$ = 2.5 ($M_{p\alpha}$ = 2.1 for proton and alpha particles). The value of $M_{\gamma\alpha}$ is comparable to that found in the literature [5]. The projected alpha energy spectra were corrected for the energy loss in the Ta foil using the energy loss of alpha particles in Ta calculated using SRIM [19]. The measured energy calibration for alpha particles is shown in Fig. 5. It can be seen from the figure that the calibration is not linear over the full energy range and can be fit to a polynomial function of light output [20]. This nonlinear behaviour of energy calibration is useful for alpha spectroscopy with CsI(Tl) detector.

4. Effect of count rate on pulse shape discrimination

An experiment was performed to study the count rate effect on the PSD in the CsI(Tl) detectors at the Mumbai Pelletron Linac Facility. The beam of ^{7}Li at 30 MeV from the Pelletron bombarded a self-supported ^{197}Au target and the beam current was varied from 4 enA-24 enA. The parameters, energy and ZCT were recorded in an event-by-event mode with the LAMPS data acquisition system [21]. Fig. 6(a) shows that the particles from proton to ^{7}Li are well separated in a 2D figure between energy and ZCT. The discrimination between alpha and ^{7}Li deteriorates with increasing count rate as shown in Fig. 6(a)–(d). Quantitatively, the extracted figure of merit (M) obtained from the projected ZCT spectrum decreases with increasing count rate, M = 0.75 at a count rate of 1.6 kHz while M = 0.4 at a count rate of 9.2 kHz. As reported by Winyard et al., the figure of merit M = 0.75 at a count rate of 1.6 kHz indicates the particle discrimination for alpha and ^{7}Li is more than 92% while M = 0.69 at a count rate of 3.5 kHz, the discrimination is between 70%–92% and the discrimination is 100% if M>1.5. The effect of count rate on the figure of merit for the alpha and ^{7}Li separation is shown in Fig. 7. This effect is due to the fact that the zero cross over time deteriorates with high count rates due to pile-up events. However at the counting rates experienced during the experiment, the discrimination between the alpha particles and ^{7}Li elastics was adequate. Moreover, a small leakage of ^{7}Li in the alpha gate led to a slight increase in random coincidences which were, in any case, estimated and subtracted.

5. Summary

An array of eight CsI(Tl) scintillators coupled to Si-PIN diodes with preamplifiers is setup to measure the light charged particle in the nuclear reaction using heavy ions from the PLF, Mumbai. The array is used for the study of shell effects through a transfer reaction populating the doubly closed shell nucleus ^{208}Pb and can also be used as an ancillary detector system for tagging on the light charged particle. The nonlinear alpha response of the detector using a ^{229}Th source and the ^{12}C(^{12}C, α) reaction up to 40 MeV is measured. The pulse shape

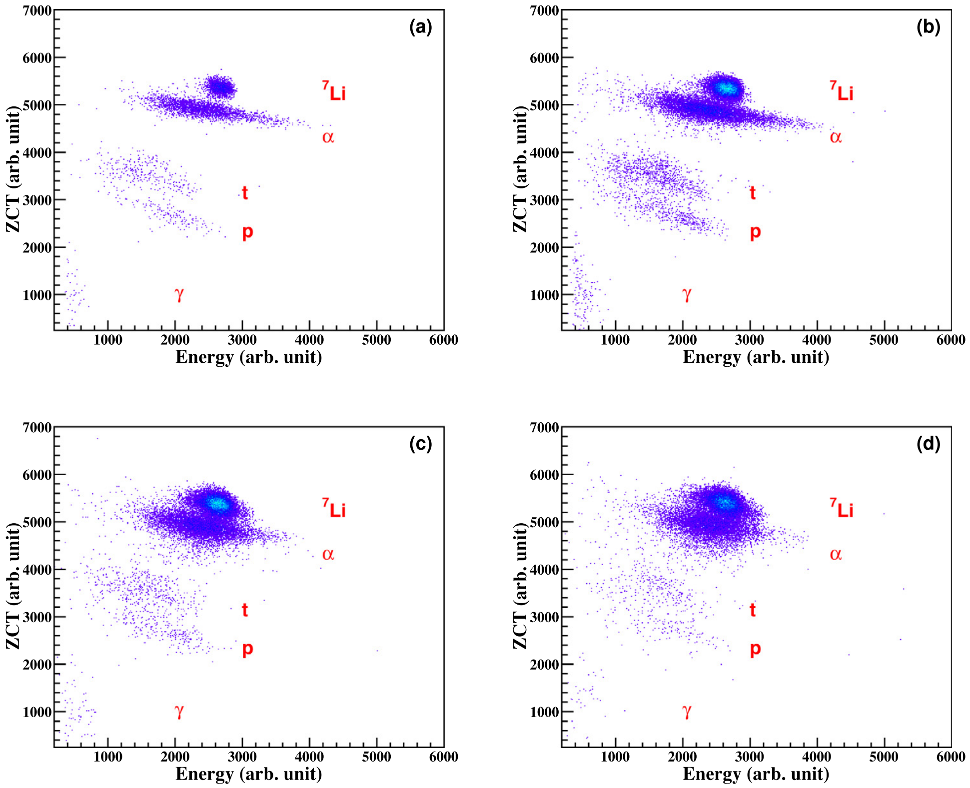

Fig. 6. Pulse shape discrimination spectra of CsI(Tl) detector for ^{7}Li + ^{197}Au reaction with increasing count rates:(a) 1.6 kHz, (b) 3.5 kHz, (c) 6.7 kHz and (d) 9.2 kHz.

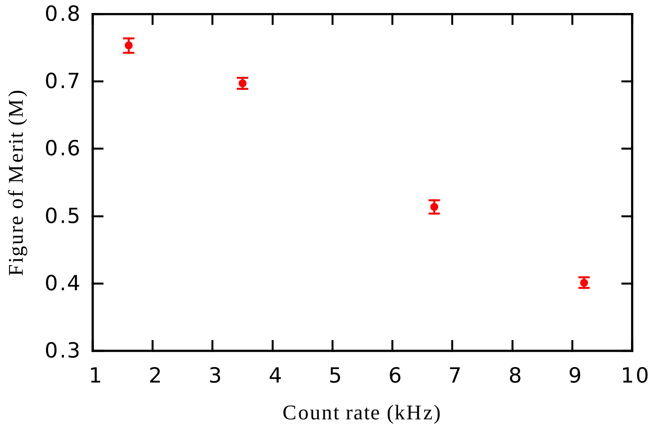

Fig. 7. Figure of merit as function of the count rate.

discrimination by ZCT method is used for the particle identification in the ^{7}Li induced reaction on a heavy target. It was observed that the PSD for heavy charged particles deteriorates with increasing count rates beyond ∼3 kHz.

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