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Neutron detector array at IUAC: Design features and instrumentation developments

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Abstract. The characteristics and performance of the newly commissioned neutron detector array at IUAC are described. The array consists of 100 BC501 liquid scintillators mounted in a semi-spherical geometry and are kept at a distance of 175 cm from the reaction point. Each detector is a $5'' \times 5''$ cylindrical cell coupled to $5''$ diameter photomultiplier tube (PMT). Signal processing is realized using custom-designed home-made integrated electronic modules which perform neutron–gamma discrimination using zero cross timing and time-of-flight (TOF) technique. Compact custom-built high voltage power supply developed using DC–DC converters are used to bias the detector. The neutrons are recorded in coincidence with fission fragments which are detected using multi-wire proportional counters mounted inside a 1 m diameter SS target chamber. The detectors and electronics have been tested off-line using radioactive sources and the results are presented.

Keywords. Fusion–fission reactions; instrumentation; scintillation detectors.

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1. Introduction

The study of fission dynamics in heavy nuclei using ion-induced nuclear reactions has been a topic of great research interest for many years. In recent years, it has been experimentally proved that, competition from quasifission is a dominant process in heavy systems, thereby hindering the formation of superheavy systems in complete fusion reactions. Near the Coulomb barrier energies, fusion–fission and quasifission exhibit their own characteristic reaction times, that can be probed by measuring the prescission component of neutron and charged particle multiplicities [1–3]. Contrary to the standard statistical model predictions, an excess of prescission multiplicities has been measured in many fusion–fission reactions. Over the years, the measurement of prescission and postscission neutron multiplicities in coincidence with fission fragment has been used as a powerful tool to study the dynamics of the fissioning system and a large number of such experiments have been performed [4–7]. These experimental results provide evidence to the hindrance of fusion–fission process.

At Inter University Accelerator Centre (IUAC), New Delhi, studies on fusion–fission dynamics around Coulomb barrier energy regime has been carried out using heavy-ion beams from the Tandem plus LINAC accelerator facilities. Using DC and pulsed beams, we have performed a number of experiments probing the fusion–fission dynamics in the large scattering chamber and neutron detector array facility. The scattering chamber facility consists of a 1.5 m diameter vacuum chamber and a pair of multiwire proportional counter (MWPC) time-of-flight (TOF) spectrometer for the measurement of fission fragment mass. The neutron detector array consists of 24 liquid scintillators (at a flight path of 2 m) and MWPCs for the detection of fission fragments. These facilities have been used for many experiments to measure the fission fragment mass distribution, angular distribution and extraction of pre- and postscission neutron multiplicities [8–13]. The observed excess of prescission multiplicities has been explained by including the effect of dissipation on the collective flow of nuclear matter through fission barrier. By measuring total neutron multiplicity for three isotopes across a major closed shell, the influence of shell closure on fission observable has been explored recently [11]. In order to distinguish the time-scale of different dynamical processes in fission, it is also necessary to experimentally extract the correlation between the pre- and postscission multiplicities and their evolution with the excitation of the parent nucleus. The prescission neutron multiplicity has a strong correlation with the evolution of the composite system in the nuclear deformation space [14]. Clearly, more experiments are needed, especially in neutron–neutron correlations and multiplicity distribution measurements. To enhance further studies in this field, a bigger neutron detector array has been planned and a large array consisting 100 neutron detectors is currently being commissioned at IUAC. The array uses liquid scintillators and conventional pulse shape discrimination (PSD) technique to discriminate the neutrons from γ-rays. The energy of the neutrons will be measured by TOF method. This detector array is a national facility being built as a collaboration of IUAC, other institutes and participating universities with the support from the Department of Science and Technology, Government of India. The design features and the technical developments are discussed in this paper.

2. Large neutron detector array at IUAC

The National Array of Neutron Detectors (NAND) at IUAC consists of 100 neutron detectors installed on a fixed radius semisphere configuration. Each neutron detector is made of $5'' \times 5''$ cylindrical cell filled with organic liquid scintillator type BC501A (M/s Saint-Gobain) and coupled to a $5''$ photomultiplier tube (PMT Model Hamamatsu R4144). The detectors are mounted on a geodesic dome structure at a radial distance of 175 cm from

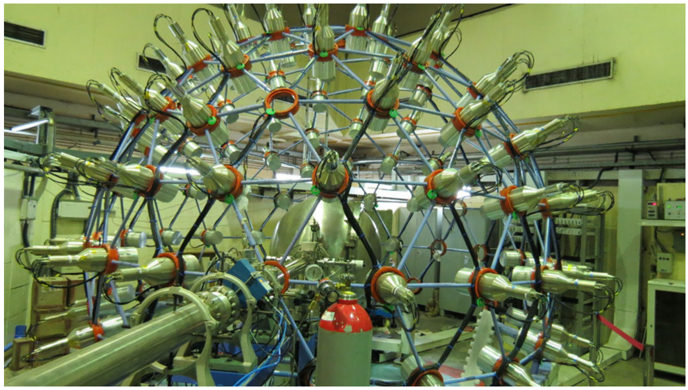


Figure 1. The detector array installed in the beam line.

the target. The mechanical structure has been built based on the design of geodome using metallic (mild steel) hubs and links. The dome truncated 80 cm above the floor level has 111 vertices with circular hubs attached to each vertex and 100 detectors are distributed among these hubs. These hubs form eight rings on the structure, the lowest ring being 15° below the reaction plane. The mechanical structure has been built using very less material to reduce the chances of neutron scattering. The total solid angle coverage of the neutron detector array in this geometry is 3.3% of 4π. A spherical vacuum chamber of 100 cm diameter has been installed at the centre of the array to house the targets, fission fragment detectors and other ancillary charged particle detectors. The vacuum chamber is made of 4 mm thick steel and has a target ladder with linear and rotary movements. The detector array is installed on a dedicated beam line of LINAC accelerator facilities at beam hall II. The centre of the target chamber is located 1.4 m above the ground level. The dome structure with detector mounted is shown in figure 1. Currently, all detectors have been mounted on the structure and aligned with respect to the beam line. Electronics for the operation of 50 detectors have been completed.

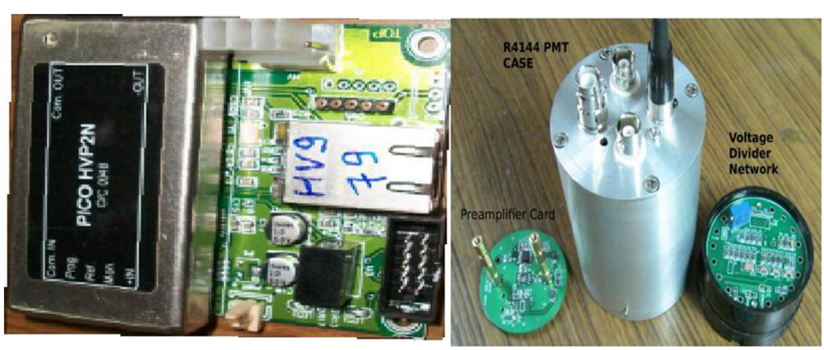
3. Instrumentation for neutron detector array

3.1 *Pulse shape discrimination*

The liquid scintillator used in the array is sensitive to both neutrons and γ-rays and they need to be discriminated. The required n–γ discrimination is achieved by pulse shape analysis of the detector signals and in our set-up it is accomplished electronically by the conventional zero-cross timing technique. It has been reported earlier [15] that the BC501A liquid scintillator detector coupled to a 5″ PMT shows good timing and PSD properties yielding good n–γ separation. In the present set-up, the signal processing and pulse shape analysis are performed using standard analog NIM electronics and data read-out using VME data acquisition system. The anode signal from PMT is used for timing as well as PSD whereas the dynode signal is used for light output (energy) information. For this purpose, custom-made PSD electronic modules have been built to process signal from each detector. This module contains the integrated electronics for n–γ discrimination, TOF and light output [16]. It is a single-width NIM module having two independent channels that can accept and process signals from two detectors. From each detector, the anode and dynode (through a charge-sensitive preamplifier) signals are fed to the inputs of the PSD module which process them and provides three output signals, namely, the light output (energy deposited), constant fraction timing and a time to amplitude signal corresponding to zero-crossing time distribution for n–γ separation. Other logic signals and monitoring signals are also provided on its front panel. Currently, a total of 50 channels of PSD modules have been fabricated, installed in the set-up and their performance evaluated using standard radioactive source data.

3.2 *High voltage power supply*

Each detector requires high voltage applied to its PMT and the detectors are normally operated below −2000 V. High voltage is applied through a base which contains resistor divider network compatible to R4144 tube. Home-made voltage divider base is used which contains the voltage divider circuit as well as an integrated charge-sensitive preamplifier to collect the dynode signal. To take care of the large number of high voltage channels required for the full array, custom-built compact high voltage power supply has been developed at IUAC. High voltage upto −2000 V is generated using a compact DC–DC converter chip (PICO make [17]) mounted on an Ethernet control board that can be remote-controlled over a private local area network (LAN). The controller set the high voltage by connecting to the control pin of the chip via a 0–5 V programmable voltage through a digital-to-analog converter. Each board has its own unique MAC and IP address so that, each can be specifically selected at a time for read & write operations. A 24-channel power supply system, each channel having the converter chip and its Ethernet control board, has been assembled in a 2U box (19 rack mount) and tested successfully by biasing the detectors. A user-friendly graphical user interface using LabView framework has been developed to control high voltage over the network. A total of 60 channels of power supply has been fabricated using this technique. A single-channel power supply and PMT base are shown in figure 2.



(a) (b)

Figure 2. (**a**) A single-channel high voltage power supply and (**b**) PMT base with the voltage divider and the preamplifier.

3.3 *Fission fragment detector*

The fission fragments are detected in low-pressure MWPCs mounted inside the spherical vacuum chamber. The MWPC has been built based on the conventional design using three electrodes, a central cathode foil electrode sandwiched between two position sensing anode wire/strip frames [18]. The cathode frame is made of double-sided aluminized Mylar foil (2 μm thickness). The horizontal (X) position-sensing wire frame is made of 10 μm thin gold plated tungsten wires stretched (0.63 mm pitch) on to a printed circuit board (PCB). The vertical (Y) position-sensing frame is made of 2.5 mm strips on a PCB. The position information is derived using delay line chips. The electrodes are assembled inside a vacuum tight rectangular aluminium chamber having thin mylar foil window with an active area of 126 $\times$ 75 mm. The detector is normally operated with isobutane gas at a typical pressure of 2–3 Torr. The detectors mounted at a distance of 25 cm from the target spans the angular coverage of $\pm 14°$ in horizontal (X) plane and $\pm 8°$ in vertical (Y) plane, respectively. Fast rise time of about 3 ns and a position resolution about $\sim$1 mm have been observed with in-beam experiments. Two identical MWPCs are mounted at the folding angles so that the complimentary fission fragments are detected in coincidence. The detectors are mounted on arms that can be rotated and adjusted for linear displacement. To enhance the detection efficiency further, an array of four MWPCs can be used inside the chamber, that will cover a large solid angle for the detection of fission fragments.

3.4 *Data acquisition*

For in-beam experiments, there are three parameters from each neutron detector, viz., the light output, zero-cross timing (PSD) and the TOF which are to be recorded on event-by-event basis. Considering the signals from fission detectors and other ancillary detectors, the full array of 100 detectors will have more than 300 parameters to be collected on-line by the data acquisition system. Out of these signals, the TOF information and MWPC position delay line readout are digitized using time-to-digital converters (TDC) and the rest of the parameters by analog-to-digital converters (ADC). With the availability of modern high-density ADC/TDC modules in VME hardware, we have chosen to implement VME-based data acquisition system for collecting data from NAND array. The data acquisition system is implemented using a commercial controller based on VME to PCI optical link bridge (V2718 from M/s CAEN, Italy). The acquisition software is based on the latest version of LAMPS [19] developed for VME systems. A single crate VME system with LAMPS acquisition software has been tested by collecting random data for 350 parameters at the rate of 5000 events/s showing $\sim$20% dead time.

3.5 *Beam dump shielding*

The ion beam passing through the reaction target is stopped beyond the detector array on a beam dump located 4 m downstream from the target and this can initiate secondary radiations including fast neutrons from the dump. In order to limit these background radiations reaching the neutron detectors, proper shielding of the beam dump has been built using borated paraffin blocks and lead sheets surrounding the dump. To evaluate the neutron shielding effect on various materials, a detailed analysis of the material composition and geometry was performed by Monte-Carlo simulation using FLUKA particle transport and interaction code [20]. The optimum composition of the shielding material was chosen as 70% (mass fraction) of paraffin wax mixed with 30% of boric acid and the overall dimension of the shielding blocks was 120(l) × 80(h) × 80(w) cm^3. The blocks were fabricated at IUAC workshop by melting and mixing paraffin and boric acid powders under temperature-controlled environment.

4. Off-line source test results

All the 50 liquid scintillators have been tested for their performance characteristics using standard γ as well as neutron sources. For each detector, the nominal operating voltage was determined by keeping the anode signal at about 450 mV for 662 keV γ-rays from ^{137}Cs source. At this gain setting, neutrons can be detected in the dynamic range of 0.5–20 MeV with good timing and n–γ separation. The light output (the energy deposited) from the detector was calibrated and linearity tested using the Compton edges of γ-rays from ^{22}Na, ^{137}Cs and ^{60}Co sources. A typical light output spectrum for 662 keV γ-ray from ^{137}Cs source is shown in figure 3. The corresponding Compton edge is used to set the lower threshold for neutron detection.

The performance of the n–γ discrimination was tested using ^{252}Cf fission source which emit both neutrons and γ-rays. All the home-made PSD modules have been tested and tuned for the best n–γ separation. The performance of the module has been compared with other commercial PSD circuits and the n–γ discrimination is found to be as good as the other reported results. A one-dimensional histogram showing the n–γ discrimination corresponding to the energy threshold of 110 keV (recoil electron energy) is shown in figure 4. At a given energy threshold, the PSD performance is quoted using a figure-of-merit (FOM), defined as FOM $= S_{n\gamma}/(\delta_n + \delta_\gamma)$, where $S_{n\gamma}$ is the distance between neutron and γ-ray peaks and δ is the full-width at half-maximum (FWHM) of the peaks. In the present case, the typical FOM for the detector and electronics combination is found

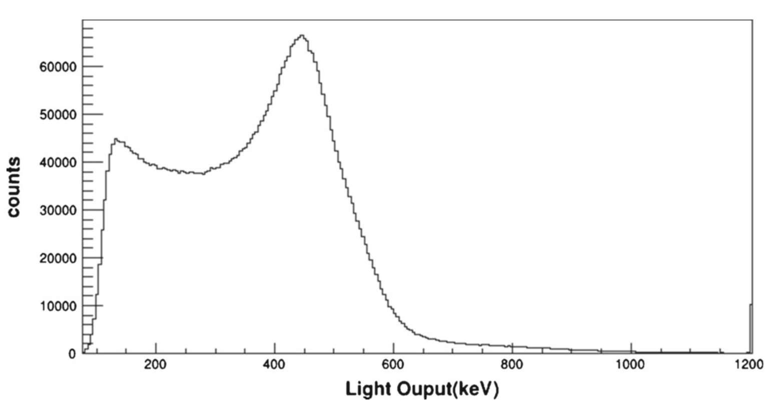


Figure 3. Light output from a 5″ × 5″ liquid scintillator detector irradiated by 662 keV γ-rays from ^{137}Cs source.

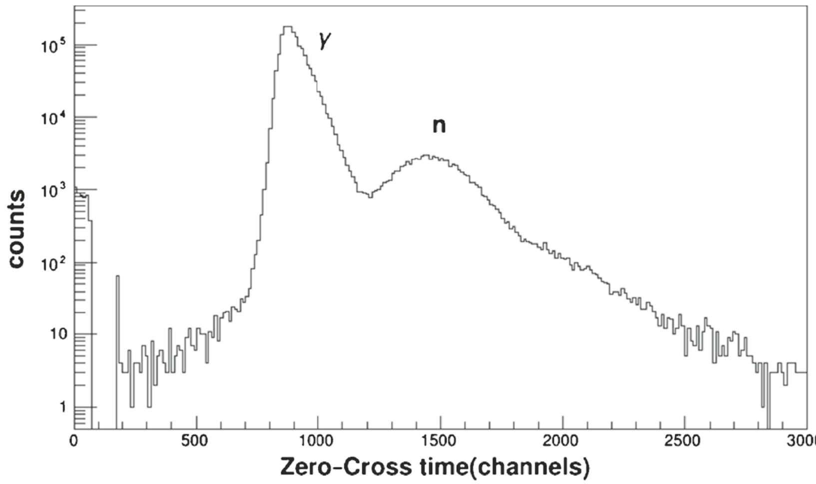


Figure 4. Neutron γ separation by zero-cross time distribution.

to be 1.4 at 110 keV. Figure 5 shows the two-dimensional histogram indicating zero-cross time distribution plotted against the light output for one detector. Distinct separation between neutron and γ events from ^{252}Cf source is clearly visible in the figure illustrating the PSD performance of the present set-up.

The energy of neutrons is normally determined by the neutron TOF method. The performance of the detector and associated electronics for TOF were tested by off-line measurement, recording coincidence between neutrons and γ events from ^{252}Cf source. In the experimental set-up, a 1″ diameter BaF_2 timing detector was used as the start detector and one of the liquid scintillator as the stop detector. The detectors were separated by a distance of 85 cm from the source kept close to the BaF_2 detector. The coincidences between the two detectors were recorded on event-by-event basis using time-to-digital

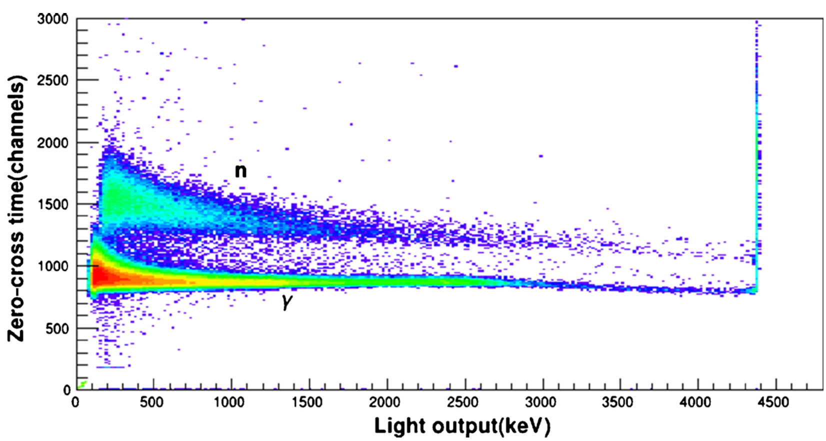


Figure 5. PSD (zero-cross time) plotted against light output.

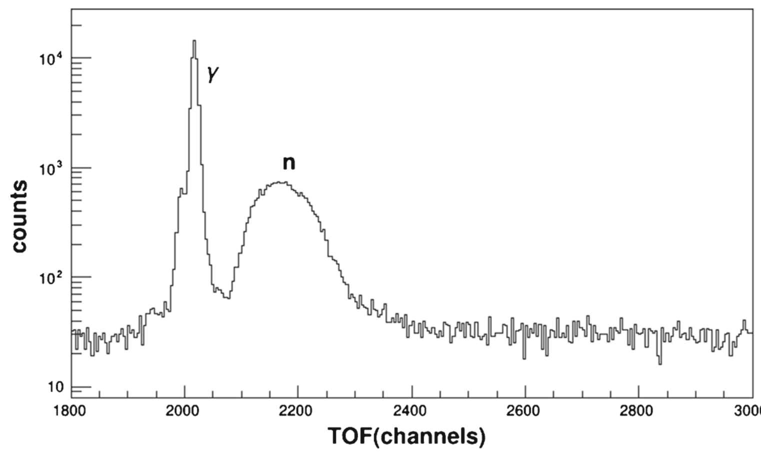


Figure 6. TOF spectrum showing separation of neutrons and γ-rays from ^{252}Cf source.

converter. Figure 6 displays the TOF spectrum at 85 cm showing good separation between neutrons and γ. The FWHM for the γ peak is found to be 2.2 ns.

In future, it is planned to test the performance of all the detectors, electronics set-up and data acquisition system for in-beam experiments using ion beams from accelerators. To study the response of the detector array, simulation using GEANT4 also will be performed.

5. Summary

A new facility for studying fusion–fission reactions around Coulomb barrier energy regime is being set-up at IUAC. The facility will have 100 liquid scintillators for the detection of neutrons and multiwire proportional counters for the detection of fission fragments. The detectors are mounted on a geodesic dome structure with a flight path of 175 cm from the target. A spherical 100 cm diameter vacuum chamber houses the targets and fission detectors. Signals from the detectors are processed using home-made electronic modules providing timing, energy and n–γ discrimination. High voltage for detectors are generated by compact DC–DC converters and multichannel high voltage system with remote controls over Ethernet has been fabricated and used in the set-up. All the 50 detectors in the first phase of the project have been tested for their performance using standard radioactive sources. The n–γ discrimination tests using custom-made PSD module showed good separation of neutron γ events with a figure-of-merit of 1.4 at the detection threshold of 110 keV. Further tests with in-beam experiments are planned.

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