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PANDORA, a large volume low-energy neutron detector with real-time neutron–gamma discrimination

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ABSTRACT

The PANDORA (Particle Analyzer Neutron Detector Of Real-time Acquisition) system, which was developed for use in inverse kinematics experiments with unstable isotope beams, is a neutron detector based on a plastic scintillator coupled to a digital readout. PANDORA can be used for any reaction study involving the emission of low energy neutrons (100 keV–10 MeV) where background suppression and an increased signal-to-noise ratio are crucial. The digital readout system provides an opportunity for pulse shape discrimination (PSD) of the detected particles as well as intelligent triggering based on PSD. The figure of merit results of PANDORA are compared to the data in literature. Using PANDORA, 91 ± 1% of all detected neutrons can be separated, while 91 ± 1% of the detected gamma rays can be excluded, reducing the gamma ray background by one order of magnitude.

1. Introduction

Recent nuclear physics studies are increasingly focused on the region far from the valley of stability, leading to an increase in the intensity of available exotic isotopes. This advancement makes it possible to investigate phenomena with low cross sections, such as inelastic scattering and charge-exchange reactions. Because the cross sections of the charge-exchange reactions are very low, it is crucial to efficiently tag these reaction channels and to minimize contaminant events from other reaction channels with larger cross-sections (e.g., elastic scattering and knockout reactions).

The (p,n) charge-exchange reactions at intermediate energies (200–300 MeV/nucleon) are a powerful tool to study the spin–isospin excitations of nuclei. The technique of inverse kinematics [1,2] enables the (p,n) reactions on exotic nuclei with a high luminosity to be studied. In this technique, neutron detectors are used to measure the time-of-flight (ToF) of low-energy recoil neutrons from a few hundred keV to a few MeV produced from the (p,n) reaction. This methodology has been successfully applied to study the Gamow–Teller strength distribution from ^{56}Ni [2,3] and ^{132}Sn [4] isotopes.

The first generation of neutron detectors designed for these measurements, such as LENDA [5,6] at NSCL/MSU,[1] WINDS [7] at RIKEN RIBF[2] and ELENS [8] (ATOMKI[3]), provide good setups, but they cannot distinguish between neutrons and gamma rays. The prompt gammas can partly be excluded by the gating of the ToF online. However, the random gamma background, which mainly arises from the environment, cannot be distinguished. Previously, the reported random gamma + neutron event rate (after eliminating the prompt gamma contribution) was about 2 kHz, whereas the rate of the (p,n) reaction events was a few Hz using about 70 plastic scintillator bars and a 10^4 particle/s secondary beam intensity [4]. For future experiments with higher beam intensities, this background event will lead to higher trigger rates that cannot be handled with data acquisition systems (DAQ), suppressing the lifetime of DAQs. A clear tagging of low-energy recoil neutrons in real-time (i.e. prior to recording the event data by online neutron–gamma discrimination) may solve this problem.

Our work focuses on the development of PANDORA (Particle Analyzer Neutron Detector Of Real-time Acquisition) as an upgrade of the WINDS detector. PANDORA is based on a plastic scintillator, which is sensitive to the differences between neutrons and gamma rays. Our main goals are:

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- To reduce the trigger rate in online data processing by one order of magnitude. This can be achieved by removing the background due to gamma rays, which will lead to a smaller data size and the capability to handle high intensity beams.
- To improve the separation of neutrons and the gamma ray background in offline analysis. This can be realized using a new parameter from the pulse shape discrimination (PSD) method and a ToF method.

Since the beginning of neutron detection, organic liquid scintillators have been used to distinguish neutrons from gamma rays and other (charged) particles. In organic liquid scintillators, the amount of the emitted photons depends on the kind of incident particle. Neutrons and gamma rays can be distinguished by their pulse shapes because their signals in the tail region differ [9]. On the other hand, plastic scintillators have their own practical merits: easier handling, segmentation, and low cost. However, standard plastic scintillators do not have a PSD capability. Therefore, plastic scintillators with PSD capabilities had been long sought after [10]. Recently, Zaitseva and her collaborators [11] introduced a plastic material with an efficient PSD comparable to that of commonly used organic liquid scintillators. The composition of this scintillator (EJ-299-33 and EJ-299-34) is based on a combination of the polyvinyltoluene matrix loaded with fluorescent compounds, 2,5-diphenyloxazole and 9,10-diphenylanthracene, which are used as primary and secondary solvents, respectively.

The light collection and neutron–gamma discrimination abilities of EJ-299-33 have been previously discussed [12,13]. Compared to a conventional cylindrical shape with a size of a few cm, the above counters are limited and can be read from only one side. To overcome this issue, we use a 30-cm bar-type detector with readouts on both sides since it matches the time- and spatial-resolutions necessary in the experimental setup for an inverse (p, n) reaction. To obtain a larger counter, we chose EJ-299-34 as the scintillator material. Although its PSD properties are reported to be slightly worse than those of EJ-299-33 [14], it is a harder plastic and easier to machine and polish to a high tolerance.

The present work is devoted to presenting the neutron–gamma discrimination capability of PANDORA and the experimental results obtained using the prototype. We report the design and construction of the detector (Section 2) and the digital data acquisition system (Section 3). The setup to test the response of PANDORA is described in Section 4. The results of our measurements and the efficiency of the online neutron separation together with the first on-beam experiment are explained in Sections 5 and 6 respectively. The conclusion follows in Section 7.

2. Description of PANDORA's detector

PANDORA consists of a plastic scintillator bar with dimensions of $2.5 \times 5 \times 30$ cm^3 coupled to a photomultiplier tube (PMT) on each end. The detector is designed to measure neutron energies using the ToF technique in the kinetic-energy region from around 100 keV to a few MeV. To measure the neutron kinetic energy with an energy resolution of $\sim 5\%$ ΔE/E for neutron energies below 5 MeV, a ToF resolution better than 0.6 ns (FWHM) and an angular resolution below $1.5°$ are required. Fig. 1 depicts one bar.

The fast plastic scintillator bars are EJ-299-34 produced by Eljen Technology [14]. This is the largest existing sample of EJ-299-34. The manufacturer quotes a light yield of 8600 photons/MeV (at 1 MeV$_{ee}$) and an emission spectrum dominated by wavelengths around 420–425 nm. According to the manufacturer, the mean decay times of the first three components of the light created in EJ-299-34 are 13 ns, 35 ns, and 270 ns for gamma rays and 13 ns, 50 ns, and 460 ns for neutrons (i.e. the relative contribution from the slow component is enhanced in neutron signals). Iwanowska-Hanke et al. [15] reported shorter decay times for both.

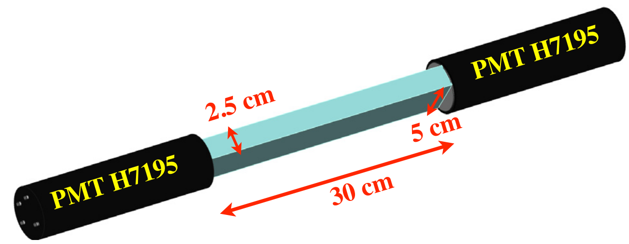

Fig. 1. Sketch of one PANDORA detector bar.

The PANDORA scintillator bar is wrapped with two layers of reflective aluminized Mylar foil, a layer of aluminum foil, and black insulating tape to ensure proper light propagation through the bar as well as light-tightness.

The PANDORA photomultiplier tubes are 51-mm-diameter-type Hamamatsu H7195 [16] tubes due to their high photoelectron gain of 3×10^6 and low anode dark current (below 10 nA). The PMTs are coupled to the plastic scintillator using EJ-500 colorless epoxy optical cement [17] with a refractive index at 1.57.

Using the time and optional pulse-height information from the two PMTs [5], the timing of a neutron hit as well as the hit position along the longest side can be determined.

3. Digital data acquisition system

PANDORA employs a digital data acquisition system. The detector signals from the anode output of both PMTs are read-out with a 14-bit 500 MSample/s flash ADC (FADC) waveform digitizer CAEN V1730, which operates with a 2-V full-scale range. The sampling clock of the module (one sample corresponds to a 2-ns time step) is adequate to digitize the signals, where information critical for particle identification is situated in the long tail. A CAEN A3818A optical link is installed for fast communications between the digitizer and the PC of the digital data acquisition system. CAEN's Digital Pulse Processing for the Pulse Shape Discrimination (DPP-PSD) firmware [18] is installed on the field programmable gate arrays (FPGAs) of the digitizer.

The system uses a charge comparison method [19,20] to identify particles. Fig. 2 overviews the principle of the charge comparison method. Neutron–gamma discrimination is possible in real-time by digital signal processing based on integrated charge measurements over two different time regions of the input pulses.

The pulse shape discrimination parameter is defined as

$$\mathrm{PSD} = \frac{Q_{Long} - Q_{Short}}{Q_{Long}}, \quad (1)$$

where Q_{Long} is the charge integrated in the long gate. Typically, it contains all charges in the signal. Q_{Short} is the charge integrated in the short gate at the beginning of the signal. Different studies report that the long gate varies between 400–500 ns, while the short gate is between 25–50 ns [21,22].

This framework allows the task-oriented configuration of the digitizer and data reduction by programming the onboard FPGA chips for a certain goal, providing an online list of:

- Coarse time stamp related to the event.
- Parameters (extracted in EXTRAS [23]) related to the calculation of the fine time stamp (on the order of tens of ps).
- Q_{Long}.
- Q_{Short}.

To maximize the particle identification with respect to better separation, the PSD parameters and high voltages of PMTs are tuned in a