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Test of digital neutron–gamma discrimination with four different photomultiplier tubes for the NEutron Detector Array (NEDA)

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ABSTRACT

A comparative study of the neutron–γ discrimination performance of a liquid scintillator detector BC501A coupled to four different 5 in. photomultiplier tubes (ET9390kb, R11833-100, XP4512 and R4144) was carried out. Both the Charge Comparison method and the Integrated Rise-Time method were implemented digitally to discriminate between neutrons and γ rays emitted by a ^{252}Cf source. In both methods, the neutron–γ discrimination capabilities of the four photomultiplier tubes were quantitatively compared by evaluating their figure-of-merit values at different energy regions between 50 keVee and 1000 keVee. Additionally, the results were further verified qualitatively using time-of-flight to distinguish γ rays and neutrons. The results consistently show that photomultiplier tubes R11833-100 and ET9390kb generally perform best regarding neutron–γ discrimination with only slight differences in figure-of-merit values. This superiority can be explained by their relatively higher photoelectron yield, which indicates that a scintillator detector coupled to a photomultiplier tube with higher photoelectron yield tends to result in better neutron–γ discrimination performance. The results of this work will provide reference for the choice of photomultiplier tubes for future neutron detector arrays like NEDA.

1. Introduction

Since liquid scintillators, the most widely used detector materials for fast neutron detection, are sensitive to both neutrons and γ rays, the neutron–gamma (n–γ) discrimination is an essential requirement of fast neutron detection in radiation fields where neutrons and γ rays coexist [1]. Over the past few decades various n–γ discrimination methods have been developed based on the principle that the decay rate of the light output of a liquid scintillator depends on the radiation type. Among these methods, the most popular ones are conventional methods such as Charge Comparison (CC) method [2,3] and the Zero-Crossover (ZCO) method [4,5].

A lot of effort has recently been put into the development of n–γ discrimination, with focus on two aspects: the n–γ discrimination method itself and the scintillator material. On one hand, the availability of digital pulse-processing systems not only offers the feasibility of transforming the conventional n–γ discrimination methods into the digital framework, but also opens the possibility of proposing sophisticated n–γ discrimination algorithms. For instance, several original

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digital methods have yielded good results for n–γ discrimination such as the correlation method [6], pulse gradient analysis (PGA) [7–9], artificial neural networks [10–12], fuzzy *c*-mean algorithm [13,14], wavelet algorithm [15–17], and frequency gradient analysis (FGA) [18–21]. On the other hand, some research groups have demonstrated the possibility of manufacturing plastic scintillators with efficient pulse shape discrimination [22]. A new plastic scintillator EJ-299-33 capable of n–γ discrimination has been developed and commercialised very recently [23,24]. Although the n–γ discrimination quality of this plastic scintillator is currently poorer compared to that of liquid scintillators, the plastic scintillator has the advantage of removing the undesirable properties of a liquid scintillator, such as flammability, toxicity, and the necessity of an expansion volume [25].

However, it should be noted that regardless of the scintillator material and the algorithms used, n–γ discrimination would be impossible without a photomultiplier tube (PMT), which converts the light output of a scintillation pulse into a corresponding electrical signal. In this study, the principal task is to investigate the dependence of the n–γ discrimination performance of a liquid scintillator on the PMT type. This issue was evaluated in the context of the construction of the NEutron Detector Array (NEDA) [26–28]. The NEDA project addresses the design of a neutron detector array to be used as an ancillary device for large γ-ray arrays such as AGATA [29,30] using both intense stable as well as radioactive ion beams. The full version of NEDA will consist of around 350 identical hexagonal detectors, each containing about 3 l of liquid scintillator of type BC501A. The scintillators will be coupled to 5 in. PMTs for readout of the scintillation light and the signals will be digitised by electronic modules specifically designed for NEDA [31–33]. Modern neutron detector arrays, such as NEDA, combine two techniques for discrimination of neutrons and γ rays: pulse-shape analysis and time-of-flight (TOF). Both discrimination methods require excellent time resolution, thus, challenging the performance figures of the PMTs to be used. NEDA will consist of many closely packed liquid scintillators in order to achieve a high neutron detection efficiency. Nevertheless, only with an excellent n–γ discrimination performance, it is possible to identify weak reaction channels associated with emission of neutrons. Therefore, the n–γ discrimination performance of a BC501A liquid scintillator detector coupled to four different PMTs: ET9390kb, R11833-100, XP4512 and R4144 (see Table 1) has been tested carefully with the experimental set-up described in Section 2. The initial choice of the PMTs was restricted only to 5 in. PMTs that could meet our demands, such as fast timing, good linearity and large quantum efficiency. The results of n–γ discrimination and related properties of different PMTs are given and discussed in Section 3. Finally, the conclusions arising from this study are stated in Section 4.

2. Experiment

The measurements were carried out at INFN-LNL. The experimental set-up is illustrated in Fig. 1. All four tested PMTs have a diameter of 5 in. and are coupled to the same cylindrical cell containing BC501A scintillator liquid, 5 in. in diameter and 5 in. in depth. The BC501A detector was placed at 50 cm from a ^{252}Cf source to detect the neutrons. The activity of the source was about 2 MBq. The HV was set to get a signal amplitude of about 1 V/MeV for each PMT using a ^{60}Co source. All PMTs were shielded with μ-metal from magnetic fields. A lead brick with a thickness of 5 cm was put between the source and the BC501A detector. This shielding reduced the count rate due to γ rays without losing too many neutrons, thus keeping the count rate of the PMT at a reasonable value of around 2 kHz. In addition a cylindrical 1 in. by 1 in. BaF_2, mounted on a 2 in. PMT R2059, was placed as close as possible to the ^{252}Cf source for detection of γ rays, which provided a time reference for the TOF measurements. A time-to-amplitude (TAC) module was used to measure the time difference between the two detectors, using the coincidence signal (leading edge defined by the BC501A detector) as start and a delayed signal from the BaF_2 detector as stop. The threshold of the constant fraction discriminator (CFD) was set to approximately 30 keVee (keV electron equivalent). The counting rate of the BaF_2 detector was 200 kHz and the coincidence rate was 200 Hz. Signals from both detectors were digitised with a Struck SIS3350 digitiser [34] working at a 500 MHz sampling rate and with 12-bit resolution (effective number of bits $=9.2$). The analogue TAC and coincidence signals were also digitised by a Struck SIS3302 digitiser [35] with 100 MHz sampling rate and 16-bit resolution (effective number of bits ≈ 13). The data acquisition system was triggered by the coincidence signals [36]. In this study, the digital signals from the BC501A detector, together with the TOF information, were used for n–γ discrimination. For each PMT, a total of 100,000 pulse events were analysed in the present work. The total numbers of recorded sampling points were 496 and 488 for SIS3350 and SIS3302, respectively. The baseline shift was removed for each pulse by subtracting the average value of 70 sampling points in the pre-trigger range of the digitised waveform. A small amount of distorted pulses ($<1\%$ of the total), with heavily fluctuating baselines, were discarded.

3. Results and discussion

3.1. Digital CFD and average waveforms

Since the dynamic range of the scintillator pulse amplitude is quite large, a leading edge discriminator would cause a dependence of the trigger time on the pulse amplitude, an effect called time walk [1]. A CFD has been implemented digitally to generate, for each signal, a fixed time after the leading edge of the pulse has reached a constant fraction of the pulse amplitude [28]. The process involves taking the sum of the original signal attenuated to 20% and the delayed and inverted original signal, followed by extracting the point where this sum signal crosses the zero axis.

Table 1
The characteristics of the studied PMTs.

PMT	**ET9390kb**	**R11833-100**	**XP4512**	**R4144**
Manufacturer	ET Enterprises	Hamamatsu	Philips/Photonis	Hamamatsu
Photocathode material	Bialkali	Superbialkali	Bialkali	Bialkali
Photocathode diameter (in.)	5	5	5	5
Quantum efficiency (%)	28	35	24	22
Number of dynode stages	10	8	10	8
Anode pulse rise time (ns)[a]	5	4.3	2.5	1.5
Voltage divider	C636	E6316-01MOD2	VD123K (active)	E7693MOD2

[a] The given values are taken from the datasheets provided by the manufacturers. The anode pulse rise times of the PMTs measured in our experiment are considerably larger than these values, mainly because the PMTs are coupled to a large scintillator [28].