Pulse-Shape Discrimination Properties of the BC-501A and BC-537 Liquid Scintillators for the Neutron Detector Array NEDA

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INTRODUCTION

In heavy-ion induced fusion-evaporation reactions for γ-ray spectroscopy studies of heavy proton-rich nuclei, reactions with evaporation of up to three neutrons are of interest. Since these reactions have a very small cross-section, that rapidly decreases with the number of evaporated neutrons, high-efficiency neutron detectors are needed for reaction-channel selection. One current neutron-detector array of this kind is the Neutron Wall \cite{1,2}, located at GANIL. The Neutron Wall has an efficiency, for single neutron detection, of 20-30\% in symmetric fusion-evaporation reactions, for neutron energies up to about 10 MeV. At the radioactive ion-beam facilities the experiments will be carried out on weak reaction channels in a high γ-ray background, which put higher requirements on the detection efficiency, including the selection of neutron events with the correct multiplicity and rejection of background γ-rays. Thus, a new neutron detector array named NEDA is currently in its design phase \cite{3,4}. One of the key aspects for an optimal design of NEDA is the choice of scintillator. Previous arrays, like the Neutron Wall, have used a hydrogen-based liquid scintillator of the type BC-501A, while other neutron detector arrays that are currently being designed, like the DESCANT array at TRIUMF, are planned to contain the deuterated liquid scintillator BC-537. In this work, the pulse-shape discrimination properties of BC-501A and BC-537 are compared for possible use in the future NEDA array.

EXPERIMENTAL SET-UP

In this work, four detectors, two of each type, of cylindrical shape with a size of 5'' × 5'' were studied. The detectors were coupled to 10-stage photomultiplier tubes, with a 5'' diameter of the type Philips XP4512B with voltage dividers VD105K. These are the same photomultiplier tubes that are used in the Neutron Wall detector array \cite{1}. Each detector was contained in an aluminium housing with a thickness of 2 mm. A 3'' × 3'' BaF$_2$ detector was also used as time reference for time-of-flight measurements. The data sets were collected using two neutron detectors and one BaF$_2$ detector, triggered by a coincidence between the BaF$_2$ detector and at least one neutron detector.

A digitizer was used for digitizing the waveforms from the detectors. This was a STRUCK SIS3350 unit which has four channels, with a sampling frequency of 500 MS/s and a bit resolution of 12 bits \cite{5}. This sampling frequency and bit resolution has been shown to be sufficient for pulse-shape analysis of the signals from liquid scintillator detector \cite{6}. The analogue pulse-shape discrimination was carried out using a BARTEK NDE202 unit, the same unit that is currently used in the Neutron Wall detector array \cite{1}. The digitizer communicated with the data acquisition system via a VME controller, using an optical link.

Data were collected using several γ-ray calibration sources and a $^{252}$Cf neutron source, with a measured activity of 2.75 MBq as of 25 April 2010, which means an activity of approximately 1.9 MBq at the time of the experiment.

PULSE-SHAPE DISCRIMINATION

Several sophisticated methods for digital pulse-shape discrimination in BC-501A have been developed by various research groups. All these methods have yielded good results regarding the discrimination of neutrons and γ rays. Pulse-shape discrimination of a deuterated liquid scintillator has been studied in Ref. \cite{7}. However, in that work the detectors filled with different scintillators were of different size, and worked in a different energy range. Therefore, it is difficult to draw conclusions from that work on how the performances of the two different scintillators differ.

Three methods were used to evaluate the neutron-γ discrimination capabilities of the two scintillators. These were the digital implementation of the charge-comparison method and the integrated rise-time method, as described in Ref. \cite{6}, and artificial neural networks, as described in Ref. \cite{8}. The fast component of the charge comparison method was chosen to be 12 sampling points, which is the time range 0–24 ns relative to the trigger. The slow component was defined as starting after 24 ns relative to the trigger and have a variable length, extending to the maximum value of the integral. The integrated rise-time was extracted from the difference between the position in time of the 10\% and 75\% values of the total height of the integrated pulse.

A feed-forward neural network was created based on the ROOT TMultiLayerPerceptron class \cite{9}. It was designed with
75 input nodes, corresponding to the first 75 sampling points after the leading-edge discriminator in the waveform, two hidden layers of 20 and 5 nodes, respectively, and one output node where the value 0 corresponds to a \( \gamma \) ray and the value 1 corresponds to a neutron. The network was trained using the Broyden-Fletcher-Goldfarb-Shanno [10–13] method. In Ref. [8], the network was trained using data with 300 Ms/s in a time window between 0 and 237 ns (71 sampling points used as input nodes). As we used in this experiment 500 Ms/s sampling frequency, the time window was limited to between 0 and 150 ns (75 input nodes) in order to keep the size of the network small.

Neutrons and \( \gamma \) rays were identified using two-dimensional cuts in total charge (measured deposited energy) versus time-of-flight and total charge versus analogue pulse-shape discrimination parameter. These cuts were used both for training of the artificial neural network, as well as evaluating the performances of the different discrimination methods. Two different limits were defined, one limit containing 75\% of the neutrons in the selection and one 95\% of the neutrons in the selection. The misidentification error, \( \epsilon_{\gamma} \), was then defined as the fraction of \( \gamma \) rays that was present within the neutron limit. The results are shown in figure 1.

The results show that BC-501A performs better than BC-537 over most of the energy range. This might result from the fact that, for the same energy, BC-501A gives larger light output than BC-537. The improvement in discrimination between neutrons and \( \gamma \) rays using artificial neural networks are also consistent with the results in Ref. [8] both for BC-501A and for BC-537. It is worth to point out that the artificial neural network in this work uses only 150 ns of the pulse length, while the charge comparison, for example, uses 500 ns of the pulse length. Thus, it is expected that the artificial neural network would give even better results if the number of input nodes is increased from 75 to 250.