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DESCANT and β-delayed neutron measurements at TRIUMF

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Abstract. The DESCANT array (**De**uterated **Sc**intillator **A**rray for **N**eutron **T**agging) consists of up to 70 detectors, each filled with approximately 2 liters of deuterated benzene. This scintillator material offers pulse-shape discrimination (PSD) capabilities to distinguish between neutrons and γ-rays interacting with the scintillator material. In addition, the anisotropic nature of $n-d$ scattering allows for the determination of the neutron energy spectrum directly from the pulse height spectrum, complementing the traditional time-of-flight (ToF) information. DESCANT can be coupled either to the TIGRESS (**T**RIUMF-**IS**AC **G**amma-**R**ay **E**scape **S**uppressed **S**pectrometer) γ-ray spectrometer [1] located in the ISAC-II [2] hall of TRIUMF for in-beam experiments, or to the GRIFFIN (**G**amma-**R**ay **I**nfrastructure **F**or **F**undamental **I**nvestigations of **N**uclei) γ-ray spectrometer [3] located in the ISAC-I hall of TRIUMF for decay spectroscopy experiments.

1 Introduction

Spectroscopy following β-decay is an important tool in studying radioactive isotopes. In a β^+/β^--decay, one can observe, besides the β-particles, γ-rays and conversion electrons from the de-excitation of the daughter nuclei. The new GRIFFIN array [3] and its ancillary detectors provide a state-of-the-art spectrometer for detecting all these emitted particles. In cases where the Q-value of the reaction is larger than the one-neutron-separation energy, S_n, however, β-delayed neutron emission can occur ($1n$-branch). The probability of the emission of a neutron increases with the $Q - S_n$ value. In cases where the Q-value of the reaction is even larger, the emission of two, three, or even four neutrons is also possible. These β-delayed neutrons play an important role in the stable operation of nuclear reactors, contribute to the decay heat of spent nuclear fuel, influence the abundance pattern of the astrophysical r-process, and yield information about the nuclear structure of the daughter nuclei.

Despite the importance of β-delayed neutron data, only about 50 % of the $1n$ branching ratios have been measured, and many fewer of the $2n$, $3n$, or $4n$ branching ratios [4]. Due to the intrinsic difficulty of measuring these branching ratios, the available data can differ up to an order of magnitude between different measurements. The new DESCANT array will provide a high efficiency to detect β-delayed neutrons, contributing to our understanding of this important process, and its coupling to GRIFFIN will enable n-γ coincidence studies.

2 DESCANT

The DESCANT array can be mounted on the downstream side of either the TIGRESS or GRIFFIN HPGe detector arrays, replacing four clover detectors of that lamp shade, see figure 1. In order to achieve a close packed coverage of 1.08π steradian (covering $\vartheta = 6.2 dash 65.5°$), the DESCANT detectors have five different irregular hexagonal shapes. The different shapes are color coded as can be see in figure 2. The white, red, and blue detectors are similar in size and use the same fast 5-inch photomultiplier tubes (PMTs) from Hamamatsu (model R1250), whereas the smaller green and yellow detectors (which are mirrors of each other) use fast 3-inch PMTs from Electron Tubes.

The detectors are mounted with their front face 50 cm from the center of the GRIFFIN or TIGRESS array and

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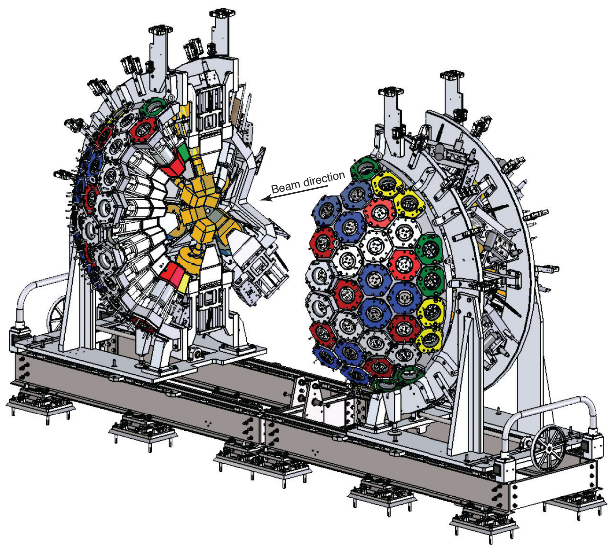

Figure 1. Schematic view of DESCANT (white, blue, red, green, and yellow detectors) coupled to the GRIFFIN or TIGRESS spectrometer (orange detectors).

Figure 2. Photo of DESCANT detectors mounted on an assembly stand. The different colors of the detectors denote their different shapes.

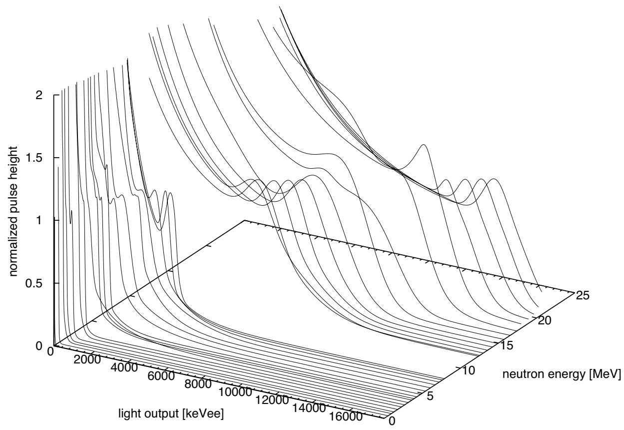

Figure 3. Pulse heights for monoenergetic neutrons with energies ranging from 60 keV to 20.7 MeV for a white DESCANT detector without any PSD applied. The individual spectra were scaled to roughly the same height. The gap between 7.9 MeV and 12.3 MeV is due to the maximum achievable neutron energy using the d(d, n)^{3}He reaction and the minimum energy achievable using the t(d, n)^{4}He reaction at the accelerator laboratory of the University of Kentucky.

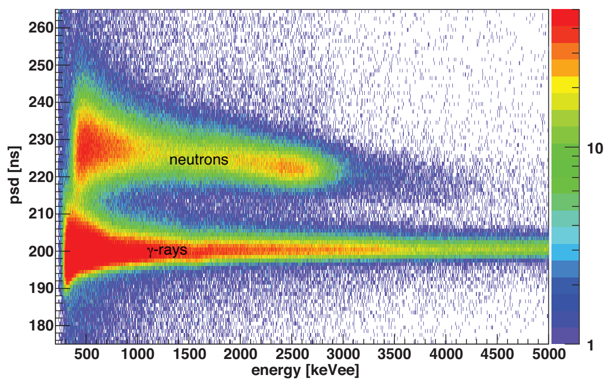

Figure 5. Pulse-shape discrimination employing analogue time to zero-crossover vs. pulse height for 5 MeV neutrons in a white DESCANT detector.

are 15 cm thick. This $\Delta L/L$ of 30 % limits the energy resolution achievable via the time-of-flight (ToF) technique; however the anisotropic nature of the $n-d$ scattering will allow the determination of the neutron energy spectrum directly from the pulse height spectrum [5]. This unfolding technique will work best for high neutron energies where the background from other neutron energies is low.

In order to be able to use the unfolding technique, the detector response has to be well known. To this effect, the pulse height spectra for a white and a green DESCANT detector were measured for monoenergetic neutrons with 75 different energies ranging from 60 keV to 20.7 MeV at the accelerator laboratory of the University of Kentucky. The quasi monoenergetic neutrons were produced via the t(p, n)^{3He} reaction for neutron energies up to 5 MeV, the d(d, n)^{3He} reaction for neutron energies up to 8 MeV, and the t(d, n)^{4}He reaction for neutron energies from 12.3 MeV to 20.7 MeV. Figure 3 shows an overview of pulse height spectra for the white DESCANT detector, whereas figure 4 shows two example spectra taken at 60 keV and 20.7 MeV neutron energy. One can clearly see the peak-like structure corresponding to the increased back-scattering cross section in the $n-d$ scattering.

The pulse-shape discrimination capabilities of the DESCANT detectors have been tested with the monoenergetic neutrons as well. Figure 5 shows the results of the analogue time to zero-crossover method vs. the pulse height of the signal. One can clearly distinguish the neutrons from the γ-rays in this two dimensional plot. Since the scintillation light created by the neutrons has a stronger tail component, the zero-crossover signal (which is in effect the time the integrated signal reaches 50% of it's full

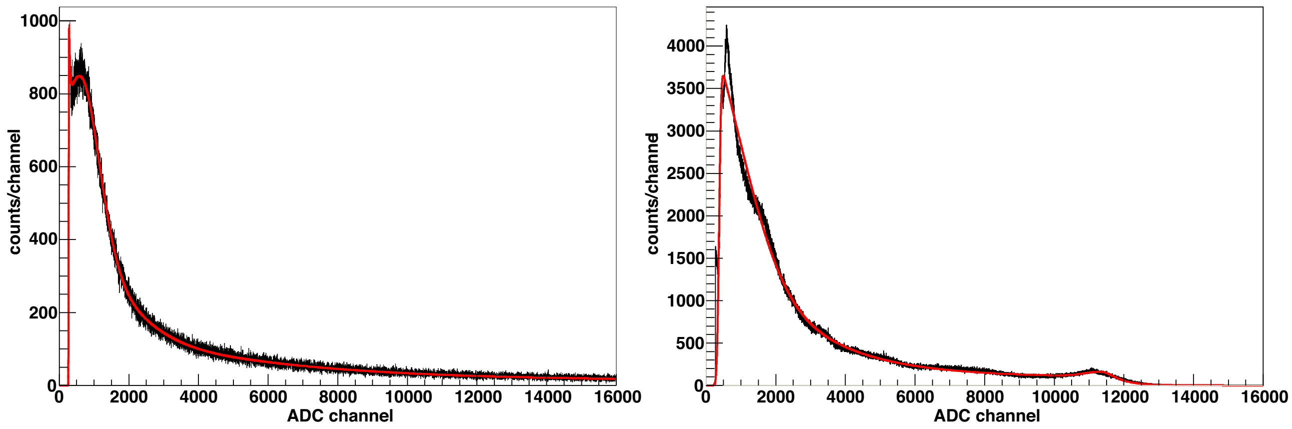

Figure 4. Pulse heights for monoenergetic neutrons with energies of 60 keV (left panel) and 20.7 MeV (right panel) for a white DESCANT detector. Fits of the spectra are shown in red.

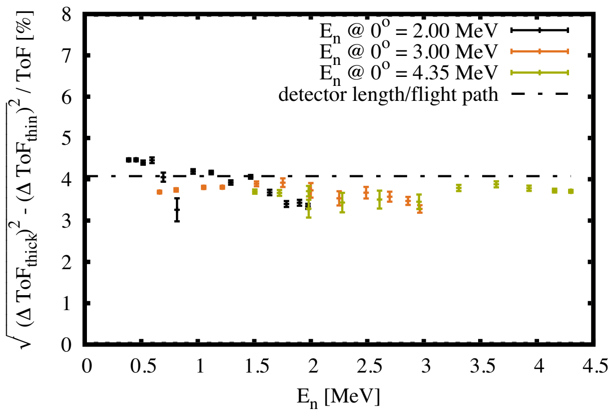

Figure 6. Time-of-flight width measured with a white DESCANT detector, corrected for the intrinsic time distribution of the neutrons by subtracting the ToF width measured with a one-inch thick test can filled with deuterated benzene.

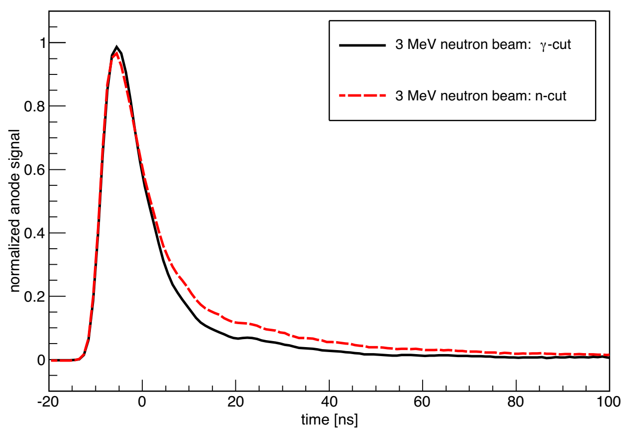

Figure 7. Waveform of the anode signal of a white DESCANT detector in response to γ-rays (solid black curve) and neutrons (dashed red curve).

height) comes at a later time. This can also be verified by comparing the PSD signal with the time-of-flight. The PSD in figure 5 has a figure-of-merit of 1.3, i.e. the separation of the neutron and γ-ray peaks is a factor 1.3 larger than the sum of their full-width-half-maxima.

The ToF resolution in these measurements is dominated by the energy distribution of the neutrons due to the straggling of the protons in the entrance foil of the tritium gas chamber, straggling in the chamber itself, as well as the changing kinematics within the opening angle of the detector. To exclude all these factors the ToF width as determined with a one-inch thick test can (filled also with deuterated benzene) was subtracted from those measured with the white DESCANT detector. The result fits very well the expected width due to the larger size of the detector (15 cm compared to 1 inch), as can be seen in figure 6.

3 Digital Readout

The anode signals of the DESCANT detectors are read out via custom-built fast sampling analog-to-digital converters (ADCs). Two interleaved ADCs running at a maximum frequency of 500 MHz, each consisting of two interleaved 250 MHz ADCs on one chip, are used. In the current configuration, the two ADCs are set up to run at a combined frequency of 800 MHz and the Cyclone IV field-programmable gate array (FPGA) from Altera used to process the data from the ADCs is run at 100 MHz. This requires that the FPGA processes eight data streams in parallel, requiring more resources from the FPGA and thus constraining the algorithms that can be used in the processing of the data.

In the current version of the firmware, a moving window algorithm (MWD) is implemented to determine the baseline of the signal in order to correct for any offset on the signal. The pulse height is determined by integrating the anode signal with the use of another moving window and correcting the result by the determined baseline. For coincidence timing and energy determination via the ToF method, a modified constant fraction discriminator (CFD) algorithm was implemented that allows the user to change the delay and attenuation factor used.

The pulse-shape discrimination abilities of the scintillator depend on the different response to recoiling electrons (from Compton scattered γ-rays) and recoiling deuterons (from scattered neutrons). The latter create tracks of much higher excitation density in the scintillator material, leading to a different ratio between the fast and slow component of the scintillation light, as can be seen in figure 7.

For the on-board pulse-shape discrimination, three different algorithms are being employed:

- charge-charge comparison (CC) in which a short integration of the peak is compared with a long integration of the tail of the signal,
- time to zero-crossover method (T_{ZC}) in which the time between the start of the signal (as determined by the CFD algorithm) and the moment the integrated signal reaches 50 % or more (the exact number is user determined) of its maximum amplitude (determined via another instance of the CFD algorithm), and the
- pulse gradient analysis (PGA) technique, which compares the difference between one sample at the peak of the (normalized) waveform with one sample of the tail of the waveform.

4 Summary & Outlook

The DESCANT neutron detector array, coupled to the HPGe GRIFFIN array, will enable high efficiency studies of β-delayed neutrons, which play an important role in astrophysics, reactor safety, stockpile stewardship, and nuclear physics. The 70 detectors, filled with $\approx 2\,l$ of deuterated benzene each, are read out via fast sampling ADCs with on-board algorithms to determine the timing, pulse heights, and pulse-shape discrimination. A white DESCANT detector has been tested with monoenergetic neutrons, measuring the pulse height, time-of-flight, and pulse-shape discrimination at neutron energies ranging from 60 keV to 20.7 MeV. From the same data neutron detection efficiencies can be determined, the analysis of which is in process. A green DESCANT detectors has been tested in the same setup simultaneously with the white Detector. The data from these two detectors will be used to verify the results of a Geant4 [6] simulation. DESCANT coupled to GRIFFIN will be commissioned in 2015.

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