10-03571

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Intended for: 18th Topical conference on High Temperature Plasma Diagnostics, Wildwood, NJ, May 16-20, 2010 and the Review of Scientific Instruments

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Form 836 (7/06)

A capture-gated neutron calorimeter using plastic scintillators and ^{3}He drift tubes

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(Dated: 16 April 2010)

A segmented neutron calorimeter using nine 4"x4"x48" plastic scintillators and sixteen 2"-diameter 48"-long 200-mbar-^{3}He drift tubes is described. The correlated scintillator and neutron-capture events provide a means for n/γ discrimination, critical to the neutron calorimetry when the γ background is substantial and the γ signals are comparable in amplitude to the neutron signals. A single-cell prototype was constructed and tested. It can distinguish between a ^{17}N source and a ^{252}Cf source when the γ and the thermal neutron background are sufficiently small. The design and construction of the nine-cell segmented detector assembly follow the same principle. By recording the signals from individual scintillators, additional γ-subtraction schemes, such as through the time-of-flight between two scintillators, may also be used. The variations of the light outputs from different parts of a scintillator bar are less than 10%.

Keywords: Fast neutron calorimeter, segmented detector, low-pressure ^{3}He detector, γ-subtraction

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I. INTRODUCTION

Excluding pair-production, a free neutron can only come from a nucleus. When the neutron emission is isotropic, neutron (kinetic) energy is one of the most important measure of the nuclear process. Neutrons from the DD fusion have a characteristic energy of 2.45 MeV, from the DT fusion 14.1 MeV. Neutrons from the ^{17}N β-delayed decay have three characteristic energies at 1.70 MeV (7%), 1.17 MeV (50%), and 0.383 MeV (37%) respectively.[1,2] The neutron energies from ^{235}U, ^{252}Cf, or other fission processes are continuous, at least for low-resolution instruments. In particular, measurement of the neutron energy spectrum can be used to identify the nuclear precursors involved. This is not always possible or simple, since neutrons can lose their energies to the ambient nuclei through collisions, a process usually known as neutron moderation. On average, the neutron energy loss after n elastic collisions with nucleii of mass A is given by $E_n = E_0 \exp(-n\xi)$,[3] with $\xi = 1 - \frac{(A-1)^2}{2A} \ln \frac{A+1}{A-1}$. For proton recoil, $\xi = 1$. For large A, carbon for example, $\xi \sim \frac{2}{A}$. In a common plastic with a hydrogen density of 5.17×10^{22} cm^{-3}, the mean free path of a 1 MeV neutron due to collisions with hydrogen atoms alone is about 4.5 cm, and 10.5 cm for 4 MeV neutrons.

We describe a segmented neutron calorimeter using nine plastic scintillators and sixteen low-pressure (0.2 bar of ^{3}He and a total gas pressure of 1 bar) ^{3}He drift tubes. Fast neutrons deposit their kinetic energies in the plastic through one or more proton recoils. Thermalized fast neutrons are then detected by the drift tubes through the capture reaction ^{3}He(n,p)T. The Poisson-distributed neutron-capture signals are on average delayed by about 20 μs (fast neutron thermalization time) from the scintillator pulses. Although plastic scintillators have lower energy resolution than magnetic or electrostatic spectrometers,[4] the combination of energy proportionality (nonlinear, unfortunately), high efficiency, nanosec pulse duration, plus compactness, low cost and non-toxicity, makes scintillators attractive for calorimetry of fast neutrons.[5–7] Fast neutrons produce recoil protons in plastic scintillators due to elastic (n,p) collisions, which is isotropic in the center-of-mass frame for neutron energies $\lesssim$ 10 MeV.[3,8,9] Above 10 MeV, the (n,p) scattering becomes increasingly anisotropic (for example, showing nuclear spin and neutron-spin dependence). In contrast, for (n,D) and (n,α) scattering, the angular distribution of scattered neutrons becomes anisotropic at energies as low as 100 keV.

In the lab frame, denote the recoil proton scattering angle with respect to the incidental

neutron direction as θ, the residue neutron energy (E_n) is given by $E_n = E_0 \sin^2\theta$, and the recoil proton has $E_p = E_0 \cos^2\theta$, with E_0 being the incidental neutron energy. The angular distribution of the recoil proton is given by $\frac{dn}{d\Omega} = \frac{\cos\theta}{4\pi}$ for $0 \leq \theta \leq \frac{\pi}{2}$, and zero for $\theta \geq \frac{\pi}{2}$.

Below, we first describe a single-cell prototype with one plastic scintillator and a ^{3}He drift tube. The energy response of the detector to neutrons is calibrated using a time-of-flight technique. The measured neutron energy spectrum from a ^{17}N source is compared with that from a ^{252}Cf fission source. Afterwards, we describe the design and construction of the nine-cell segmented calorimeter, followed by a discussion and some data on its neutron detection efficiency, neutron/γ discrimination, and energy response.

II. A PROTOTYPE CHARACTERIZATION

The single-cell prototype has an external plastic dimension of 5"x5"x16 3/8" with a 2"-diameter hole carved out in the center to hold the ^{3}He drift tube. The ^{3}He pressure is at 1 bar, five times the amount of ^{3}He used in the nine-cell segmented detector. First, the energy response to the recoil protons is calibrated using a time-of-flight (ToF) technique. The result is shown in Fig. 1. The neutrons are produced by the LANSCE 800 MeV pulsed proton beams hitting a carbon target at a frequency between 1-10 Hz. The number of protons per pulse is between 10^4 to 10^5. The low intensity proton beam is ideal for the calibration, since the total number of particles (neutrons, together with pions and γ's) produced at the distance of 21 m away is slightly less than one particle per pulse. The linearity of the scintillator response to γ-ray is checked with a ^{137}Cs source and a ^{60}Co source.

In Fig. 1, the data are compared with three models, Gooding & Pugh[10,11] in green, Cecil *et al.*[12] in red, and Aksoy *et al.*[13] in blue. Within the accuracy of the measurement, all three models fit the data quite well, except probably for the last point, which favors the Gooding & Pugh model and the Aksoy *et al.*'s model. We use the Gooding & Pugh model for our calibration.

The normalized recoil proton energy spectrum from a ^{17}N source is shown in Fig. 2. The ^{17}N's are produced by the 800 MeV proton beams hitting an ^{18}O-enriched water target through the knock-off process ^{18}O(p, 2p)^{17}N. Since Compton-scattered γ signals have comparable amplitudes as the MeV neutron signals, it is essential to have a reliable recipe for n/γ discrimination. Here the neutron capture by ^{3}He is used as the 'gate'. The reduction

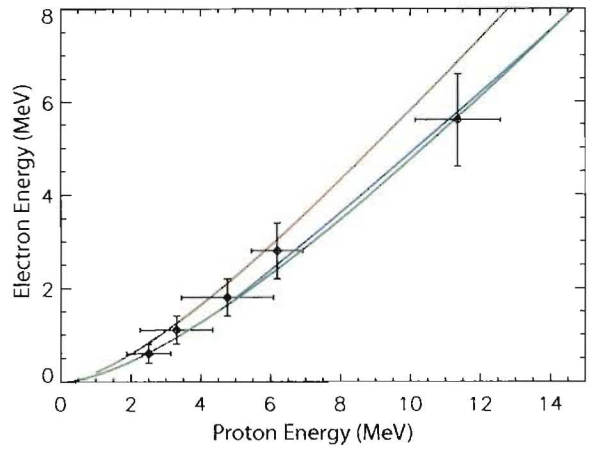

FIG. 1. ToF energy calibration of the scintillator energy reponse to protons. The three solid lines correspond to three models presented previously. More details in the text.

of the neutron detection efficiency comes from two causes as a result. They are the escape of the thermal or faster neutrons from the detector (never captured by ^{3}He) and the neutron capture by ^{1}H in the plastic. A third cause, insufficient neutron energy deposition in the plastic is intrinsic to the scintillator, and therefore independent of the γ-discrimination scheme. Meanwhile, a γ signal could be mistaken for a neutron signal if the γ signal happens to coincide with a ^{3}He capture. Both the high γ ray background and thermal neutron background increase the probability of the random coincidences, the rate of which is given by $f_\gamma f_n T$. In other words, the background rates, f_n, $f_\gamma = \nu_\gamma \epsilon_\gamma \Omega_\gamma$, the product of the source rate ν_γ, detector efficiency ϵ_γ and the solid angle Ω_γ(similarly for f_n), should be kept below 1- 10 kHz, determined by the neutron thermalization time in the plastic.

The γ background from the random coincidences between a scintillator pulse and a ^{3}He signal is subtracted in Fig. 2. The time delay (t) between a scintillator signal due to proton recoils and its corresponding ^{3}He-capture signal should obey the Poisson distribution, $N = N_0 \exp(-t/\tau_0)$, with $\tau_0 \sim 20$ μs being the neutron thermalization time. The time delay is measured using a time-to-amplitude converter (TAC) unit. For a sufficient number of counts, the random coincidences show up as a flat distribution cross the whole TAC spectrum. The corresponding γ energy spectrum should be TAC-independent. The 'pure' γ energy distribution (neglecting the cosmic and charged particle background) therefore corresponds to the part of the TAC spectrum with time-delays longer than a few times τ_0. We use $t \geq 600$ μs here based on the measured TAC spectrum. In comparison with the ^{18}O spectrum,

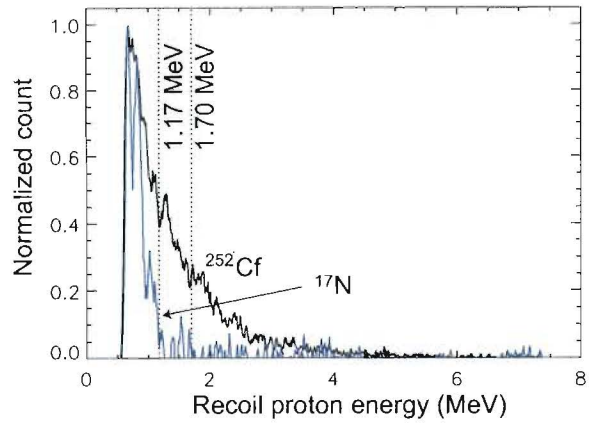

FIG. 2. The normalized recoil proton energy distribution from a ^{17}N (blue) compared with the spectrum from a ^{252}Cf source. The two characteristic energies for β-delayed neutron emissions of ^{17}N are also marked. The third energy at 0.383 MeV is off the scale because of the energy cut near 0.5 MeV.

the spectrum from a ^{252}Cf source is also shown in Fig. 2 by using the same γ-spectrum-subtraction scheme. The observations are consistent with the expected responses of the two sources, although the statistics from the ^{17}N measurement could improve with more counts.

III. THE SEGMENTED CALORIMETER

With similar considerations to γ-subtraction as the single-cell prototype, we are building a segmented detector consisting of a 3×3 array of plastic scintillators and a 4×4 array of ^{3}He drift tubes, Fig. 3. Each scintillator bar, using the generic plastic type EJ200 from Eljen Technology, is a 4" $\times$ 4" $\times$ 48" cube with corners carved out to accommodate the 48" long drift tubes with a diameter of 2". The construction and performances of the 200 mbar ^{3}He drift tubes were described previously.[14] Each scintillator bar has two photomultiplier tubes (PMTs), one at each end, to achieve more uniform response along its length by summing up the two PMT responses. The scintillator pulse rise time is about 7 ns. We plan to cover the detector array with borated blankets to reduce the false coincidences from the thermal neutron background.

The energy resolution is mainly determined by two factors. The variation of light output for the same amount of recoil proton energy and the position-dependent light transmission to PMT's. The PMT gain stability and the additional amplifier, if used, can also affect the

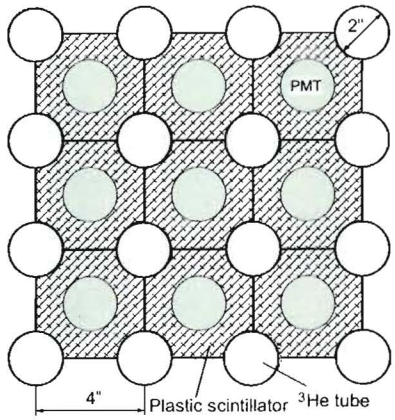

FIG. 3. A schematic design (end view) of the nine-plastic-cell segmented calorimeter with sixteen ^{3}He drift tubes at the corners of the plastic scintillator cubes.

energy resolution. The overall response as a function of the position along the scintillator length have been measured using the Compton edge of a ^{137}Cs source. An example is given in Fig. 4. Less than 10% variation is seen for both the arithmetic and the geometrical mean. Both averaging methods give comparable results.

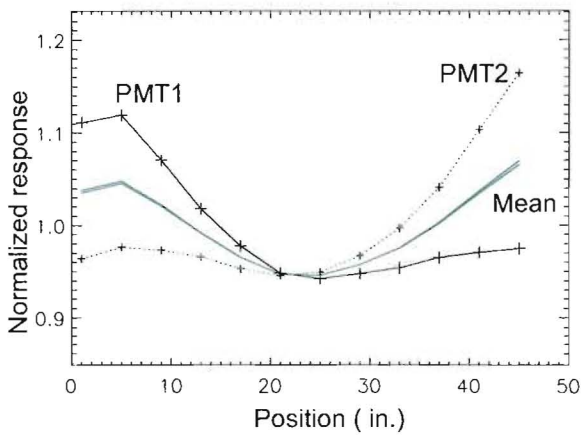

FIG. 4. The position-dependent responses of the two PMT's of a 4" × 4" × 48" scintillator bar to the Compton edge of a ^{137}Cs source. The arithmetic mean response is shown in blue, the geometrical mean in green.

In operation, since the exact location of the thermalized neutron capture by ^{3}He is not critical, all of the ^{3}He drift tubes will be wired together in series and digitized by a single multi-channel analyzer (MCA). Each PMT will be digitizer separately, however. This will allow us to track multiple neutron-proton scattering events, and give us more coincidence

schemes for γ discrimination in addition to the one for the single cell unit. For example, we have a new scheme using two scintillators plus a ^{3}He. For 1 MeV neutrons, the neutron time-of-flight is about 7 ns for 10 cm, while it takes the Compton-scattered γ less than 1 ns to travel the same distance. It therefore may be possible to use the time-of-flight to distinguish scattered neutrons from scattered γ's, without the need for the ^{3}He signal. Furthermore, the time delays between the two PMT's at each end of a scintillator bar may allow us to locate each neutron-scattering position more precisely. The additional coincidence schemes require the recording the individual PMT signals separately. When a neutron deposits its energy in more than one scintillator and PMT, the energy responses from each scintillator and PMT also need calibration in order to obtain the sum correctly. We plan to use the ToF technique for this purpose in the near future. The performances of the detector using different coincidence schemes, such as the fast neutron efficiency, and n/γ discrimination are being studied using Monte Carlo simulations. The efficiency for 1 MeV neutrons is about 1%. Below, we describe the data acquisition system for the detector.

Each PMT output will be connected to a custom-built analog-to-digital converter (ADC) that is an upgraded version of a module[15] that was constructed for an experiment to measure the rate of muon capture on the proton.[16] The incoming signal will be continuously sampled with 12-bit resolution at a rate of up to 250 million samples per second by a Maxim MAX1215 flash ADC device. Each pair of flash ADCs is connected to a frontend Xilinx Spartan-3 (XC3S400-5C) field-programmable gate array (FPGA) that selects the samples of interest. Many variations on this filtering process are possible; it may be reconfigured by modifying the FPGA firmware or by downloading register settings from the host computer. The most commonly-used mode of operation is self-triggered: it selects "islands" of time corresponding to photomultiplier pulses, typically including about 32 samples from before and after the time at which the signal exceeds a programmed threshold value. In this mode, each group of four samples is tagged with a 28-bit timestamp that allows for 4.3 s of data collection between clock rollovers; all timing may be derived either from a 25 MHz ($\pm$ 30 ppm) crystal oscillator on the board or from an external clock input. Other modes of operation that have been demonstrated include an externally-triggered mode and a multichannel analyzer technique, where a histogram of pulse heights is collected and periodically transmitted.

There are only small buffer memories available on the board; the design philosophy is to stream data as quickly as possible over a 1000BASE-TX Gigabit Ethernet connection to

a host computer, where it can be archived and analyzed. Data that has been selected by the triggering logic passes through a first-in-first-out (FIFO) buffer in the 32 KiB internal block RAM on the frontend FPGA. It is transferred to the backend FPGA using a set of five differential pairs to minimize radiation of digital noise that might be picked up by the analog inputs. This process takes place at 25 MiB/s in the current system, but higher rates should be possible with additional firmware development. The backend FPGA collects data from the four frontend FPGAs, which together serve eight input channels; it divides the data into packets and generates appropriate headers and checksums for Ethernet transmission. A custom Ethernet-level protocol provides for reliable detection of lost packets, although retransmission is not possible. The physical layer of the Ethernet connection is implemented by a National Semiconductor DP83865 device.

ACKNOWLEDGMENTS

We wish to acknowledge the help from the Los Alamos LANSCE accelerator operations team. This work is supported by DTRA under the contract #IACRO_09-4559I.

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2010 May 14-04

Previously submitted ~ 30 Apr 2010

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PA Control Number: PA 10-297 17 May 10 — Suspense: ~~07~~ 16 May 2010

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1. Title: Capture-gated neutron calorimeter...plastic scintillators and 3He — Contract Number: IACRO 09-4559I

Originator: Dr. Z. Wang

2. Type of Material: ☒ Paper ☐ Presentation ☐ Abstract ☐ Other Summary

3. Overall Classification: ☐ Contractor ☒ Project Manager Unclassified

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4. Material to be: ☐ Presented ☒ Published — Date Required: ~~07~~ 16 May 2010

Name of Conference or Journal: 18th High-temperature Plasma Diagnostic Meeting, May2010, Wildwood, NJ

5. Remarks:

Presentation slides previously reviewed by LANL and cleared for unrestricted release, LA-UR-10-00627.

Presentation slides previously reviewed by DTRA and clear for public release, PA Control #10-235 PA 14 Apr.

Current manuscript reviewed by LANL and found unclassified with no mandatory FOUO.

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