Title

Note: Coincidence measurements of 3He and neutrons from a compact D-D neutron generator

Journal
Review of Scientific Instruments, 88(5)

ISSN
0034-6748

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Publication Date
2017-05-01

DOI
10.1063/1.4981896

Peer reviewed

^{3}He Tagging of 2.45 MeV Neutrons from DD Neutron Generator

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Tagging of neutrons (2.45MeV) with their associated ^{3}He particles from DD fusion reactions has been demonstrated in a compact neutron generator setup enabled by a high brightness, microwave-driven ion source with a high fraction of deuterons. Energy spectra with well separated peaks of the DD fusion reaction products ^{3}He, tritons, and protons were measured with a silicon PIN diode. The neutrons were detected using a liquid scintillator detector with pulse shape discrimination. By correlating the ^{3}He detection events with the neutron detection in time we demonstrated the tagging of emitted neutrons with ^{3}He particles detected with a Si PIN diode detector mounted inside the neutron generator vacuum vessel.

I. INTRODUCTION

Neutrons from DD and DT fusion reactions are widely used for material analysis and active nuclear interrogation [1]. Using a specially equipped DT neutron generator the kinematic correlation of a 14 MeV neutron with an associated 3.5 MeV alpha particle [2] can be exploited to perform associated particle imaging (API) [3]. By detecting the alpha particle with a fast position-sensitive alpha detector its trajectory and therefore the direction of the neutron can be determined and the time of the fusion reaction recorded. Several API techniques have been developed for a variety of applications. Isotopic measurements can be performed by detecting gammas from inelastic neutron scattering reactions in coincidence with the alpha particle and systems have been developed for contraband detection [4]. Other associated-particle techniques include transmission imaging where the transmitted neutron is detected in coincidence with the alpha particle to greatly reduce the scatter background, and induced-fission imaging for the characterization of special nuclear materials. Knowing the direction of the emitted neutrons can also be exploited to eliminate the background generated by neutrons reacting outside a selected region of interest and thus to increase sensitivity. Compact API neutron generators with excellent directional fidelity are needed for applications in treaty verification and safeguards. [5, 6]

DD fusion reactions produce 2.45 MeV neutrons via the D(d, n)^{3}He reaction. In a second reaction channel, protons and tritons are generated via the D(d,p)T reaction with a branching ratio of roughly 50% [2]. The DD neutrons can be tagged with the associated 0.82 MeV ^{3}He particle for DD-based API. Compared to DT operation, the DD neutron yield is ~100x lower but a DD-based API system would avoid the regulatory burden of tritium and offer better serviceability, increased safety, and much lower life cycle cost.

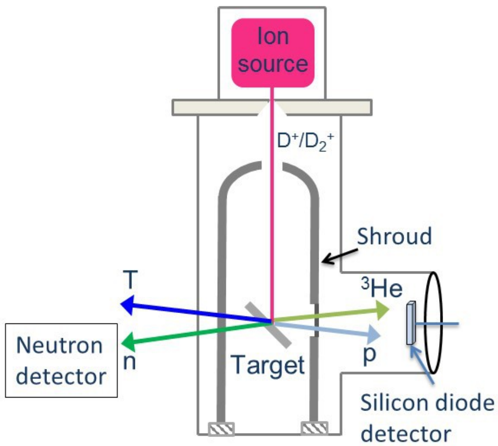
In addition to the applications mentioned above, low-angle inelastic scattering of mono-energetic neutrons from DD reactions can be utilized to calibrate the response of cryogenic noble gas detectors for dark matter experiments. Using tagged neutrons allows a reduction of the scattered neutron background and a forty times increase in useful event rate relative to the traditional elastic neutron scattering scheme. [7]

However, detecting the ^{3}He particle with its relatively low kinetic energy of 0.82 MeV at 90-degree emission angle is more difficult than detecting 14 MeV alpha particles from DT reactions. The alternative reaction channel that produces 3.02 MeV protons and 1.01 MeV tritons [2] must also be considered. These additional particles increase the accidental coincidence rates. This increase could be avoided with an energy discriminating associated particle detector, but this is generally not essential. In the pioneering experiments by Hsu and Robson [6], a thin plastic scintillator (NE102) was used to detect ^{3}He particles. But due to the limited energy resolution of the scintillator, ^{3}He events could not be reliably distinguished from triton events without use of time-of-flight coincidences with associated neutrons. Silicon diode particle detectors, which have been widely used for the detection of light ions at MeV energies, including those from DD fusion reactions [8, 9], are an alternative.

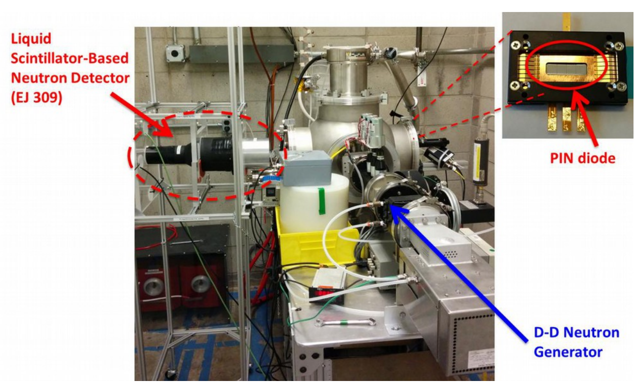
In this article, we demonstrate coincidence measurements of DD neutrons and ^{3}He ions in a table-top pumped neutron generator setup where a high brightness, microwave driven ion source is combined with a neutron production target, a silicon PIN diode detector [10] and a fast neutron detector.

II. EXPERIMENTAL SETUP

Figure 1(a) shows the schematic of the experimental setup for tagging neutrons with the associated ^{3}He particles, i.e., detecting neutrons and ^{3}He particles in coincidence. For generating neutrons (and associated particles) a permanent magnet microwave (2.45 GHz) ion source [11] was operated at ground potential, while the neutron production target was biased at -25 kV. The target shroud was biased at -2 kV relative to the target to prevent secondary electrons from the target to stream back into the ion source. A current of positive deuterium ions with a density of up to 95 mA/cm^2 and an atomic ion fraction over 90% is extracted from the ion source. This high beam current yielded sufficient neutron production for the experiments reported here at the low D^+ kinetic energy of 25 keV where the DD cross section is greatly reduce compared to the typical neutron generator energies for 100 keV or higher. The generator was operated at this low acceleration voltage to reduce the background from secondary electrons and x-rays in the Si-diode detector as further discussed in section III. While improvements can be made to allow operation at much higher voltages, it should be noted that a modest neutron yields of ~10^5 n/s is sufficient for, e.g., detector calibrations. Operation at higher neutron yields, well in excess of 10^7 n/s is possible with operation of a high atomic fraction ion source at current levels in the 100 μA range and ~100 kV acceleration voltage.



(a)



(b)

FIG.1 (a) Schematic drawing of ^{3}He tagging experimental setup; and (b) photograph of the experimental setup. The distance from the target to the PIN diode was 21 cm.

The neutron production target consisted of a 0.5 mm thick titanium layer bonded to the end of a water-cooled copper rod. The surface of the neutron production target was oriented 45° with respect to the incident beam, facing the silicon PIN diode [10] used for ^{3}He detection. Deuterium ions were extracted from an aperture with a diameter of 1 mm and accelerated onto the Ti target. The silicon detector with active area of 3 mm × 12 mm was placed in the vacuum chamber of the neutron generator at 90° to view the target through an opening in the shroud. A Si PIN diode with a 200 Å thick phosphorous doped polysilicon back-side contact and a 200 Å thick aluminum layer deposited on top of the polysilicon in order to reduce their response to stray light was chosen to allow ions to penetrate into the active silicon. Energy losses in this combined back-side structure are very small, about 80 eV for 25 keV electrons and about 11 keV for 0.82 MeV ^{3}He ions.

However, scattered deuterons and electrons accelerated from the vicinity of the target shroud can reach the Si detector. In order to prevent these particles from reaching the diode and causing a high background signal, the silicon diode was covered by a 0.5-μm-thick Au foil. A liquid scintillator neutron detector (EJ 309) was located on the opposite side (270° to the beam direction) of the silicon PIN diode. A photograph of the experimental setup including the neutron generator, silicon PIN diode, and liquid scintillator neutron detector is shown in Figure 1(b).

The signal processing electronics is shown in the block illustration of Figure 2.

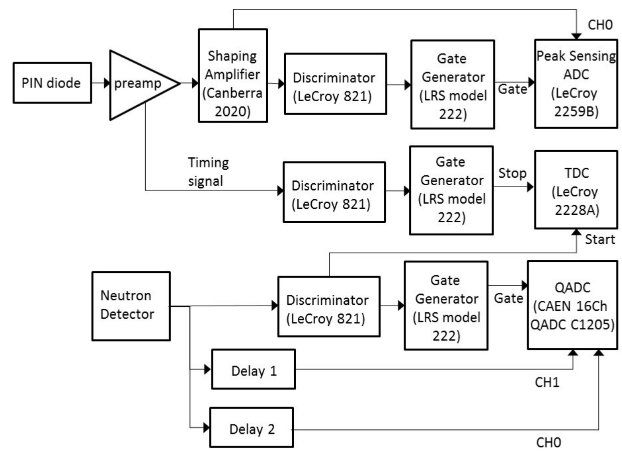


FIG.2 Block diagram of the measurement and data. The preamplifier model was an Ortec 142AH.

III. RESULTS

The energy spectrum measured by the silicon PIN diode with its ^{3}He, proton and triton peaks is shown in Figure 3. The energy of proton, triton and ^{3}He particles produced in DD reaction are 3.02 MeV, 1.01 MeV, and 0.82 MeV, respectively. Based on SRIM [12] calculations, energy losses of protons, tritons, and ^{3}He in the 0.5 μm gold foil are approximately 102 keV, 159 keV, and 360 keV respectively. Po-210, which emits alpha particles with a characteristic energy of around 5.3 MeV, was used to calibrate the energy spectrum of the silicon PIN diode. The FWHM of the 5.3 MeV Po-210 peak was approximately 8 keV indicating the detector resolution. While the ^{3}He, proton and triton peaks in Figure 3 are well resolved, the ^{3}He peak is not well separated from the broad detector noise peak. The peaks in the spectrum have a FWHM of ~120 keV, much broader the Po-210 peak. Several factors contributed to the peak width: a) when operated inside the neutron generator, the electronic noise was higher than for the calibration measurement, b) energy straggling in the Au foil in front of the detector, and c) the main contributor to the noise and the peak broadening was likely a high x-ray rate due to accelerated electrons impinging on the Au protection foil. In the experimental setup, the ion source was at ground and the neutron production target was biased at negative potential. Secondary electrons leaking out from the suppressor could thus be accelerated towards the silicon diode at ground potential and generated x-rays in the Au protection foil. This needs to be further investigated and the experimental setup improved to reduce the noise. Electrons from the target shroud could be better screened or the target could be put on ground potential (and the ion source on high voltage) to prevent electrons from being accelerated towards the detector.

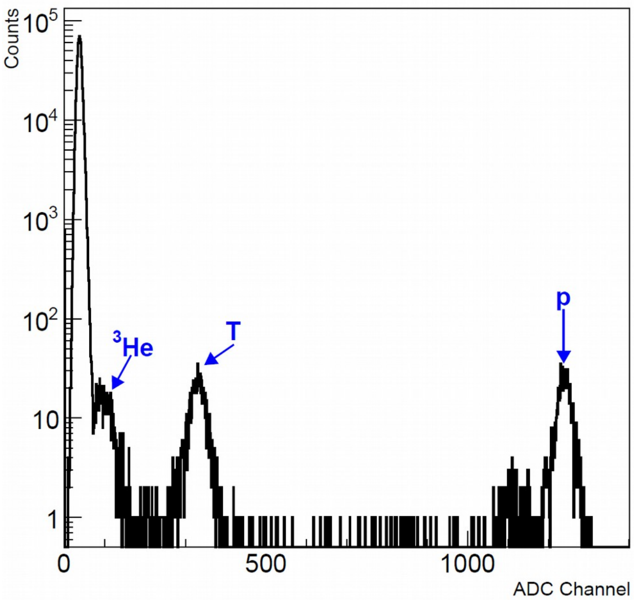
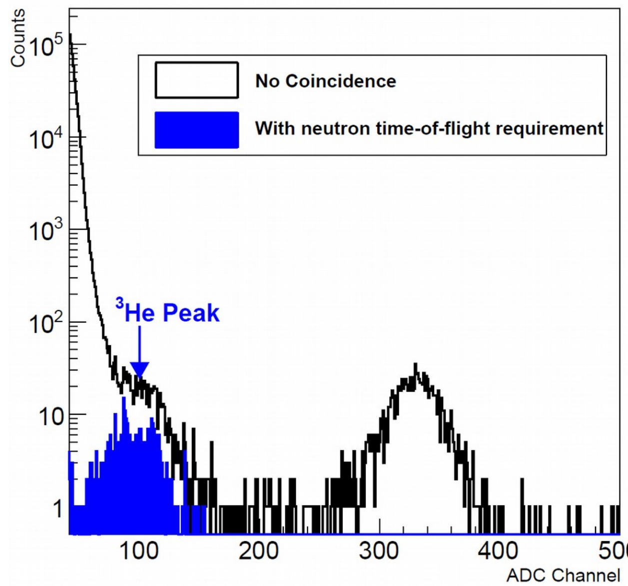


FIG.3 Energy spectrum measured with the silicon PIN diode showing the ^{3}He, triton and proton peaks.

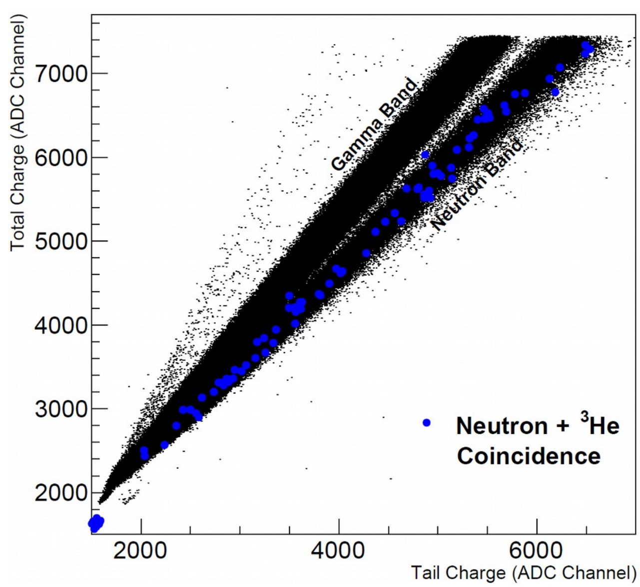
Figure 4 (a) shows the measured Si-diode energy spectrum and (b) the pulse shape discrimination plot for the neutron and gamma events recorded by the liquid scintillator detector. The blue part in the energy spectrum shows the ^{3}He events measured in coincidence with a DD neutron; and the blue dots in (b) represent the neutron events coincident with ^{3}He particles detected by the silicon diode.

By applying the coincidence requirement between the neutron detector and the silicon diode timing signals, associated n-^{3}He pairs could be cleanly identified. The neutron detector signals are separated into "gamma-like" and "neutron-like" events based on pulse shape discrimination [13] as shown in Figure 4(b). The total charge measured by the photomultiplier tube (PMT) of the neutron detector (vertical axis) is plotted against the measured charged in the tail of the PMT signal (horizontal axis). Overlaid on the plot are events that have been tagged as n-^{3}He pairs using time-of-flight coincidence (blue dots). This demonstrates that the counts in the lowest energy peak are ^{3}He events and indicates the possibility of DD API or neutron tagging.

The counts seen in the low energy region (< 100 channel), in both Figure 3 and 4 (a), were background counts from electronic noise and likely x-rays generated due to accelerated electrons impinging on the Au protection foil. In the experiment, the acceleration voltage in the neutron generator was kept at 25 kV to minimize this background. While the neutron yield is drastically reduced at this low deuterium beam energy [2], we were able to compensate by increasing the ion current from our high-brightness ion source [11]. Typically, the acceleration voltage for deuterium ions in a compact neutron generator is about 100 to 160 kV for neutron yields of about 10^8 n/s/mA with a beam of atomic deuterium ions [1]. The background problem due to accelerated secondary electrons can be eliminated by holding the neutron production target at ground potential, i.e., at the same potential as the alpha detector [14]. In such an arrangement, a 0.62 µm-thick gold foil can be used to stop scattered deuterons (100 keV) from reaching the silicon detector. The energy loss for 820 keV ^{3}He in a 0.62-µm-thick gold foil is about 420 keV and a ~395 keV ^{3}He could be detected well above the (in this case much lower) noise with a thin entrance contact of a silicon diode such as used here.



(a)



(b)

FIG.4 Measurement of DD neutrons and ^{3}He coincident events. (a) silicon diode energy spectrum with (blue) and without (black) neutron coincidence requirement (low energy section of spectrum in figure 3); and (b) measured neutron events with (blue) and without (black) ^{3}He coincidence requirement.

IV. SUMMARY and OUTLOOK

A proof-of-principle experiment of tagging DD neutrons (2.45MeV) with their associated ^{3}He particles has been performed in a compact neutron generator setup. By using a silicon PIN diode with high energy resolution and thin entrance dead-layer, energy spectra showing well separated peaks of ^{3}He, triton, and proton particles from DD fusion reactions were collected. Compact integration and high neutron yield for a given acceleration voltage is enabled by a high brightness, microwave driven ion source with a high atomic fraction of deuterium ions.

In these initial experiments the acceleration voltage had to be kept very low to limit the x-ray noise in the silicon detector. This noise could be reduced by better electron screening. In addition, by detecting the ^{3}He ions at a more forward angle where the ^{3}He energy is higher, e.g., 1.06 MeV at 60° [8], the ^{3}He peak can be further separated from the noise. As discussed above the x-ray noise can be completely avoided by operating the ion source on high voltage and the target at ground potential.

In further developments, the neutron intensity can be increased by orders of magnitude and the deuterium ion beam spot, i.e., the neutron production area, can be reduced down to 1 mm^2 for DD API with excellent angular resolution. A compact DD neutron generator equipped with a position sensitive Si diode detector offers the potential for API without the need to handle tritium and its regulatory burden. Furthermore, these experiments are a first step towards neutron generators equipped with fast 2-dimensional Si detector arrays that could greatly enhance DT API capabilities and enable DD tagged neutron measurements.

V. ACKNOWLEDGEMENT

The authors would like to thank Erik Brubaker (Sandia National Laboratory) for providing the neutron detector and Cory Lee, Takeshi Katavanagi, Steve Wilde, Joseph Wallig, Peter Kozy, William Waldron (Lawrence Berkeley National Laboratory) for their technical support. This work was preformed under the auspices of the U.S. Department of Energy, NNSA Office of Nonproliferation and Verification Research and Development by the Lawrence Berkeley Laboratory under contract No. DE-AC02-05CH11231.

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