Production of an Associated Particle Neutron Generator with ZnO:Ga Alpha-Detector

D.S. Koltick, S.Z. Kane, J.T. Mihalczo, S.M. McConchie, E.K. Mace, M. Lvovsky

Abstract — An associated particle neutron generator (APNG) capable of 10^9 neutrons per second has been operated with an alpha particle detector made of a ZnO:Ga phosphor with decay time of approximately 1 ns. Fast 14.1 MeV neutrons and 3.5 MeV alpha particles are produced through deuterium-tritium (DT) fusion reactions and travel in opposite directions to conserve momentum. The neutron generator provides high rate capability, excellent subnanosecond time resolution (< 0.7 ns), and a large solid angle with acceptance of 8%. The alpha detector was found to have a detection efficiency of 88% using a Burle 8850 bialkali photocathode. The DT beam spot diameter was measured down to 2.1 mm with the possibility of achieving 1 mm if desired. An opaque aperture was placed on the alpha detector and the neutron beam was obstructed using various amounts of lead shielding in an effort to study the generator's imaging contrast capability for neutron radiography. The alpha detector can be pixilated using a multianode photomultiplier tube to deliver imaging capability and to enhance the signal to noise ratio. Due to its ability to suppress background, the developed APNG is to be used to search cargo containers for illicit special nuclear materials, using as a trigger prompt fission gamma rays in coincidence with an alpha particle within a 10 ns gate.

Index Terms **— active neutron interrogation, associated particle neutron generator, zinc oxide**

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I. Introduction

ACTIVE neutron-induced and photo-induced interrogation techniques are currently being investigated for the purpose of identifying special nuclear materials [1], radiologicals, explosives [2], and chemical warfare agents [3] in various sealed forms of containment. An associated particle neutron generator allows the electronic collimation of the nearly isotropic distribution of neutrons that are emitted through DT reactions occurring at the generator's target. The resulting cone of 14.1 MeV "tagged" neutrons [4] is used as a non-intrusive interrogation source. Knowing the time and position of the alpha particle, the direction of the tagged neutron is known [4]. Furthermore, the time of interaction of the neutron can be calculated using the prompt gamma ray detection timing information [4]. This tracking information can be used to gate the gamma ray detectors to reduce background and to perform imaging of the sample [4]. The APNG maximum flux output is ~10^9 neutrons per second and has an adjustable focus. The beam spot size varies from 7 mm to 1 mm using a voltage adjustment. The small spot size is used to achieve greater imaging resolution. Lastly, the APNG is a neutron source that can be conveniently switched on and off.

II. Description of the Alpha Detector

The produced 6.6 cm active diameter alpha detector was made using inorganic ZnO:Ga phosphor prepared by W. Lehmann [5]. A schematic depiction of the alpha detector is shown in Figure 1. First, a process of elutriation was used to eliminate the largest particles from the mix. Next, Lexel Imaging deposited the ZnO:Ga powder on a fiber optics faceplate by gravitational settling using potassium silicate as a binder and strontium acetate as an electrolyte, in proprietary proportions. The effective density of the phosphor is approximately 6 mg per cm^2. Next, a layer of organic lacquer was applied followed by a micron thick aluminum coating, by evaporation in vacuum. The aluminum coating renders the alpha detector insensitive to deuterium and tritium ions. Charged particles simply bleed off the aluminum coating, thereby preventing undesired charge build-up. Finally, the plate was baked in air up to 400° C in order to eliminate the organic matter.

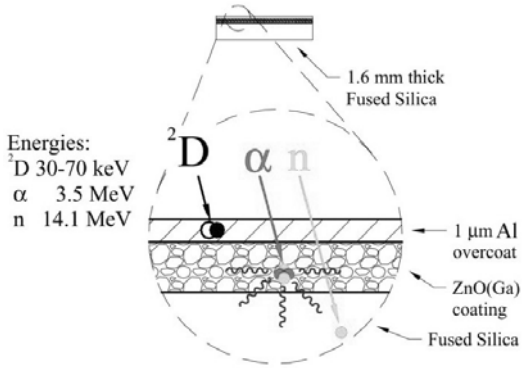

Fig. 1. Schematic depiction of ZnO:Ga alpha detector. A 1 μm thick aluminum coating is used to allow charged particles to bleed off, thereby preventing undesired charge build up.

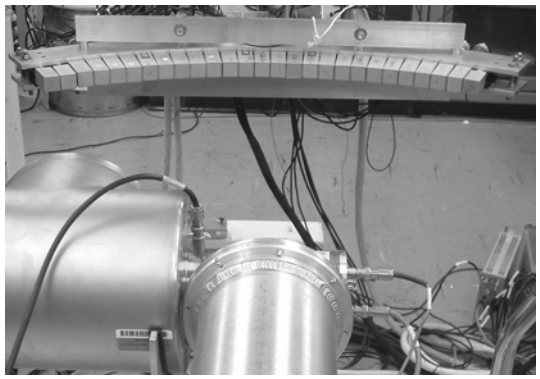

Fig. 2. The DT beam spot diameter measurement set up utilizes twenty four 2.5 x 2.5 x 15.2 cm^3 thick fast plastic scintillators on an arc 85 cm from the target spot.

III. Measurement of the DT Beam Diameter at Target

The diameter of the DT beam spot on the target was determined using an array of twenty-four 2.5 × 2.5 × 15.2 cm^3 thick fast plastic neutron scintillators on an arc 85 cm from the target spot, as shown in Figure 2. The number of alpha-neutron coincidences in a particular neutron detector is proportional to the number of DT reactions in the target. Hence, from the FWHM of the distribution of relative alpha-neutron coincident counts with neutron detector position, the beam spot diameter was first determined at the plane of neutron detectors. Then, it was geometrically projected onto the target plane in order to obtain the DT beam spot diameter at the target.

The thresholds on the neutron scintillators were set at 1 MeV while the threshold on the alpha detector was set slightly above noise. The pulse signals from the alpha detector and plastic scintillators were passed through constant fraction discriminators (Ortec CFD 935). The CFD logic gates were then put into the Nuclear Materials Identification System (NMIS) processor [6] at ORNL to obtain alpha-neutron coincidences. The NMIS processor acquires data in 10 channels synchronously sampling detector signals at a rate of 1 GHz in all input channels.

As seen in Figure 3, the DT beam spot diameter ranged from 7.2 mm to 2.1 mm for focus voltages between 2.5 kV to 11.3 kV, respectively. A beam diameter of 1 mm is achievable

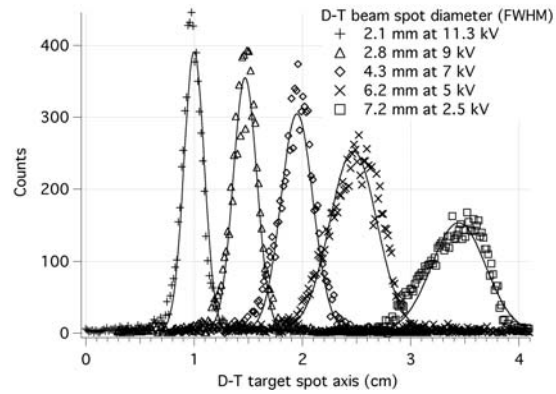

Fig. 3. Measured DT beam spot diameter (FWHM) as a function of focus voltage.

if an upper limit restriction on the focus voltage is removed from the generator's control panel. The restriction was placed by Thermo Fischer Scientific to prevent burning of the DT target.

The measurements were performed at a flux of ~10^5-10^6 neutrons per second. Furthermore, a 1 mm diameter opaque circular aperture was placed on the alpha detector to lower the count rate as to not overflow the NMIS processor.

IV. Measurement of Alpha Detection Efficiency

The alpha detector's efficiency was measured using two 10 × 10 × 10 cm^3 fast plastic scintillation neutron detectors in an alpha-neutron coincidence set up shown in Figure 4. The first neutron detector is placed 50 cm from the alpha detector's face and the second is 50 cm from the first detector and at an angle of 45° from the alpha detector's line of sight. These detectors identify a subset of direct 14.1 MeV neutrons, which elastically scatter off a single hydrogen nucleus in the

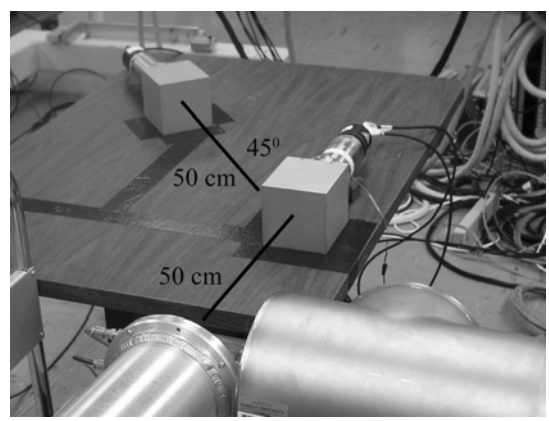

Fig. 4. Experimental set up to identify a subset of direct 14.1 MeV neutrons, which single scatter elastically off the near neutron detector into the far neutron detector, to determine the detection efficiency of the alpha detector.

near detector into the far detector in coincidence with an alpha particle. The alpha efficiency is determined as the fraction of these neutrons to 14.1 MeV neutrons which single scatter in the near detector into the far detector out of coincidence with the alpha detector [7]. The coincidence set up is necessary as the neutron detectors are sensitive to neutrons scattering off the floor and walls, as well as neutron-induced gamma rays from the environment.

As in the case of the DT beam spot diameter measurements, an opaque circular aperture was used to reduce the active area of the alpha detector. The pulse signals from the alpha detector and the neutron detectors were passed through constant fraction discriminators (Ortec CFD 935). The CFD logic gates were put into the NMIS processor, which was utilized to construct neutron time of flight spectra (TOF) between the near and far neutron detectors with and without alpha coincidence.

The energy of the scattered neutron is the product of the initial energy and the cosine squared of the scattering angle [7]. Thus, because the second detector is set at an angle of 45° from the line of sight of the alpha detector, direct 14.1 MeV neutrons depart from the first detector with 7 MeV.

Figure 5 shows neutron TOF spectra between the neutron detectors. The circle (square) data points correspond to neutron scatters that are in (out of) coincidence with the alpha detector. Positive times correspond to detector-detector coincidences where the first interaction was in the near detector. The peak at approximately 15 ns, labeled as (d), corresponds to direct 14.1 MeV neutrons that interact in the near detector first by single scatter off hydrogen and are later detected in the far detector [7]. The out of coincidence TOF spectrum has been scaled up to the in coincidence TOF spectrum so as to match the peaks in region (d). From the scaling factor, the alpha efficiency was determined to be 88%.

The in and out of coincidence TOF spectra reveal several

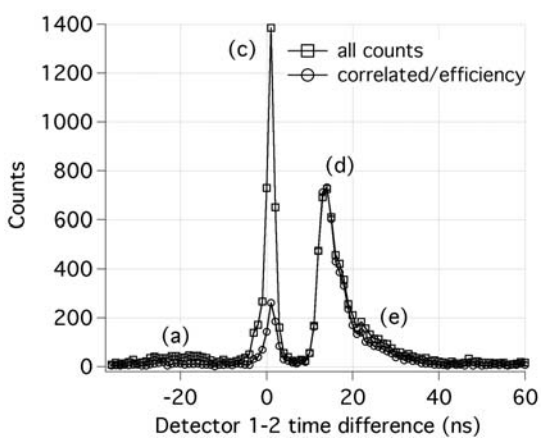

Fig. 5. Neutron time of flight between detectors with (circle) and without (square) alpha coincidence.

interesting features [7]: (a) neutrons interacting with the far detector first, (b) gamma rays originating in or interacting with the far detector first, (c) gamma rays originating in or interacting with the near detector first, (d) 14.1 MeV neutrons interacting in the near detector first by a single scatter off hydrogen and being detected later in the far detector, and (e) neutron scattering multiple times in or before the near detector.

V. Estimation of Alpha Detector Time Resolution

An 18 × 18 × 2 cm^3 plastic scintillation detector was placed 10 cm from the face of the alpha detector. Using a TDS 3032B 300 MHz Tektronix oscilloscope, the combined time resolution of the alpha-neutron detectors was determined to be approximately 0.7 ns, as shown in Figure 6. Therefore, the time resolution of the alpha detector is less than 0.7 ns.

The current upper bound on the alpha detector's time

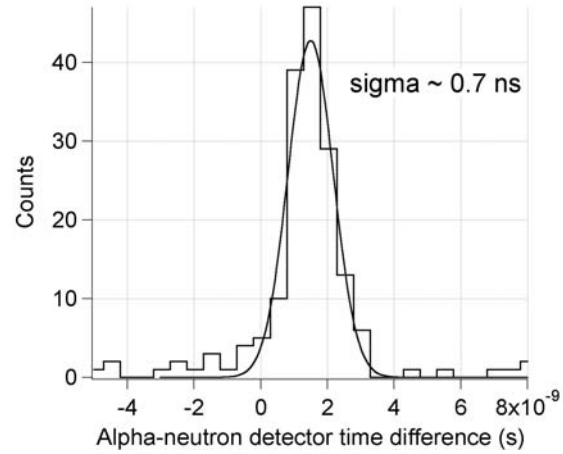

Fig. 6. Combined alpha detector and neutron scintillation detector time resolution of approximately 0.7 ns (FWHM).

resolution reflects the size of the neutron detector that was used. The time travel of the scintillation light in the neutron detector is predominantly being measured. Another measurement made with a smaller 5 × 3.8 × 5 cm^3 plastic detector gave the same result indicating that the limitations of the electronics used have been reached. However, the alpha detector has been shown capable of subnanosecond time resolution.

VI. Imaging Contrast for Neutron Radiography

The image contrast after which neutrons have passed through various thicknesses of lead was studied using the same set up as for the DT beam diameter measurement. An opaque

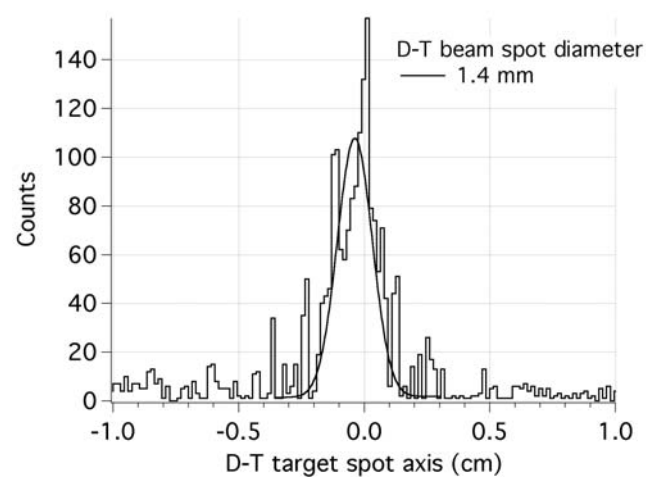

Fig. 7. DT beam spot diameter (FWHM) after passing through 25 cm of lead.

2 × 1 mm^2 aperture was placed on the alpha detector's active area. Figure 7 shows the image of the aperture after the neutron beam has passed through 25 cm of lead. For this measurement, the neutron generator's flux was increased slightly more than in previous measurements and for the given parameters the DT beam spot diameter was measured to be

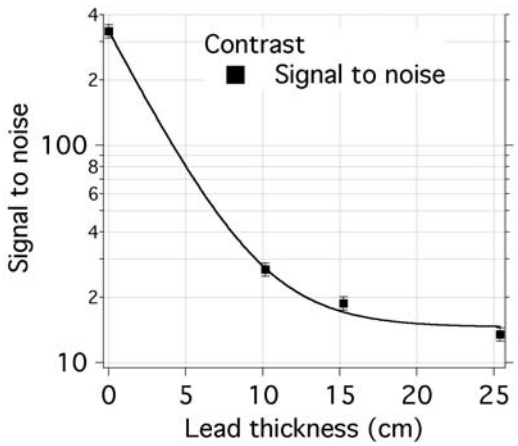

Fig. 8. Contrast as a function of lead thickness.

1.4 mm. Figure 8 shows the signal to noise ratio as a function of lead thickness. After 25 cm of lead, the signal to noise is still significant.

VII. Conclusion

An associated particle neutron generator has been developed and operated with a ZnO:Ga phosphor with nanosecond decay time. The generator was found to have an alpha detection efficiency of 88%. The beam spot size was measured to
2.1 mm with the possibility of achieving a 1 mm spot size if desired. The alpha detector was shown to have sub-nanosecond time resolution. The generator was also shown to have good image contrast after the neutron beam has passed through 25 cm of lead.

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