(U) High Resolution Combined Neutron/X-ray Imaging Detector

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(U) Abstract: In recent years, scintillator fabrication, fiberoptic faceplates, and flat panel detectors have seen many advances. This paper summarizes progress on a novel scintillator designed and fabricated by Radiation Monitoring Devices in conjunction with research scientists at the United States Army. New advances in accelerator technology have now allowed for a rebirth in neutron radiography. Combined, Neutron and X-Radiography will allow engineers and scientists to ensure manufacturing excellence with unprecedented precision and accuracy.

(U) Research Innovation and Objective(s): A novel new scintillator has been fabricated and tested for neutron radiography. There are several desirable characteristics when developing a neutron detector. First, the scintillator must exhibit high light yield. Second, the detector must differentiate between neutron and gamma interactions. Lastly, the detector must be made into a large format in an economical way. [1]

(U) Impacts on Warfighter Mission: Radiographic inspection of munitions allows for the best equipment to be delivered to the warfighter in an expeditious manner. Advances in radiographic capabilities continues to ensure existing and new manufacturing techniques can be refined and perfected.

(U) Keywords: Non-Destructive Testing (NDT), Radiography, Neutron Radiography, X-Radiography, Thermal Neutrons, GEANT4, scintillator, neutron detector, Industrial Radiography, Modular Transfer Function (MTF)

1. (U) Introduction

(U) Industrial Radiography has been an indispensable tool for finding defects in manufactured items. Most military grade explosives are solid compounds which are manufactured in granular form. These granular compounds are then mixed with other explosives or inert additives. These final mixtures are then cast, pressed or extruded. Casting involves heating the explosive until it melts, pouring it into a container and leaving it to solidify by cooling. One disadvantage of casting is that cracks can occur when the composition solidifies upon cooling. Other manufacturing methods can suffer similar defects. [2]

(U) Neutron radiography can produce information that is complimentary to X-Radiography. Traditionally, X-rays have been the preferred method for finding subsurface defects due to the difficulty in generating neutrons. Neutron sources have been limited to nuclear reactors or national laboratories. Recently, new advances in accelerator technology have allowed neutrons to be more accessible for the purposes of nondestructive testing.

(U) X-Rays are attenuated based on a materials density. On the other hand, thermal neutron attenuation is not related to density. Many lighter elements absorb thermal neutrons. In addition to this, common metals appear transparent to thermal neutrons. When an insufficient flux of thermal neutrons exist, utilization of fast neutrons can be used, but this is still an active area of research.

(U) The need for efficient detectors with adequate spatial resolution becomes a real technological problem if neutron radiography of assets is to be performed. Due to the complimentary nature of X-Rays and neutrons, having one detector that can detect both modalities can be advantageous. The detection of neutrons requires a scintillator, fiberoptic faceplate, and a flat panel detector.

2. (U) Theory and Method

(U) At the heart of the detector is the scintillator. Lithium and Gadolinium isotopes are popular for use in thermal neutron scintillators due to their high thermal cross section. Although Gadolinium has one of the highest known cross sections, it also has several key drawbacks for use in radiographic applications. On the other hand, thermal neutrons interacting with lithium produce charged particles that can be readily absorbed in solid material. This makes lithium more advantageous for our purposes. The novel scintillator is the synthesis of a Lithium and Sodium Iodide thin film. The thin film is synthesized by crystallizing sodium and lithium iodides which possess similar crystal structure with a low lattice mismatch. The vapor is deposited in a microcolumnar form whose importance will become apparent. [3]

(U) A fiberoptic faceplate is used to separate the scintillator from the flat panel detector. The fiberoptic plate prevents direct bombardment of the flat panel detector with neutrons. The fiberoptic faceplate must also transport the light from the scintillator to the flat panel detector.

(U) A Varex Imaging PaxScan 2530HE/4343HE digital imaging receptor amorphous silicon (a-Si:H) was used as for the flat panel detector. This detector has a pixel size of 139 microns. Conservative assumptions were used to calculate SNR values for single thermal neutron detection. The a-Si:H receptor coupled to the LNI scintillator via the fiberoptic can result in detecting single thermal neutrons with an SNR of 4.7:1. [3]

(U) While this detector is developed for nondestructive inspections using thermal neutrons, the basic design is such that the detector can be easily be re-configured to facilitate fast neutron and high energy X-ray imaging. [1]

2.1 (U) Sctintillators

(U) For high resolution thermal neutron imaging Radiation Monitoring Devices, (RMD) has developed the microcolumnar $Li_xNa_{1-x}I:Eu$ (LNI) thermal neutron scintillator, which contains 50% ^6Li by weight. [1,3,5] Theoretical neutron absorption efficiencies, shown in figure 1, were obtained for thermal neutrons at 0.0254 eV. With its high ^6Li content LNI offers the highest efficiency for thermal neutrons.

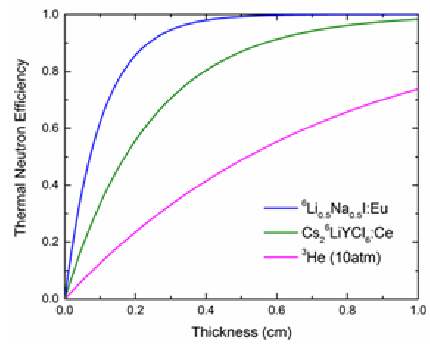

Figure 1. Theoretical detection efficiency curves of various thermal neutron detectors.

(U) Microcolumnar structure promotes light channeling within the scintillator column due to total internal reflections and therefore prevents lateral spread of light in the scintillator film which reduces spatial resolution, figure 2.

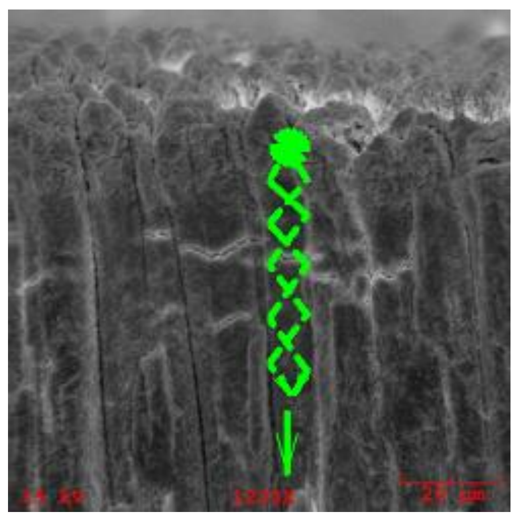

Figure 2: Scanning Electron Micrograph of LNI scintillator

(U) This novel scintillator allows high resolution thermal neutron imaging due to its microcolumnar structure and high detection efficiency (>80% for 1 mm thick screen) due to its high ^6Li content. LNI is the only microcolumnar scintillator developed to date for thermal neutron imaging and is commercially available from RMD. The scintillator was evaluated with a fiberoptic coupled electron-multiplying charge coupled device (EMCCD) camera. The performance of the scintillator and EMCCD camera was evaluated by obtaining an image of a Gd resolution mask. A source of neutrons was provided by the beamline CG1a at a high flux isotope reactor.

(U) To demonstrate the versatility of the LNI detector, a series of X-Ray images were also taken. Film thickness was 375 microns deposited on a fiber optic faceplate. Next, this was coupled to a photometric CCD with a refractive index matching fluid. A commercial X-Ray generator was used a source to detector distance of 45 cm with 70 kVp at 10 mA. [3]

(U) For fast neutron/X-ray detection we rely on yet another microcolumnar scintillator which is unique to RMD. In this instance CsI:Tl is deposited in a microcolumnar form using thermal vapor deposition. The scintillator is then coated with a plastic converter which absorbs fast neutrons. Recoiled protons generated by the fast neutron interaction in plastic are absorbed in the CsI:Tl layer which produces scintillation light. The light is channeled through the CsI:Tl microcolumns to the underlying flat panel readout to produce a high resolution fast neutron image.

(U) In yet another variation we have synthesized a so-called embedded scintillator by infusing ZnS:Cu particles in a plastic matrix, figure 5. The distribution and concentration of ZnS:Cu is manipulated in such a way that the scintillator responds to both X-rays and fast neutrons, and produces high resolution images.

2.2 (U) Simulations

(U) In order to predict the performance of scintillators, we ran preliminary GENAT4 models to determine the optimal thicknesses and compositions. In the case of layered scintillators there is a tradeoff between the plastic layer thickness and detection of the recoil protons in the scintillator. The optimal plastic thickness is where the probability for proton transport into the scintillator reaches a plateau. Simulations for 2.45 MeV DD neutrons and 14.1 MeV DT neutrons show that the optimal thicknesses of plastic for these energies are ~1 mm and 3 mm respectively. We refer the reader to figure 4 for a neutron radiograph. The simulations also predicted the energy distribution of protons crossing into the CsI:Tl scintillator, the average energy of which is 1.117 MeV and 7.526 MeV for DD and DT neutrons respectively. Figure 3 contains some of the critical data obtained from the simulations.

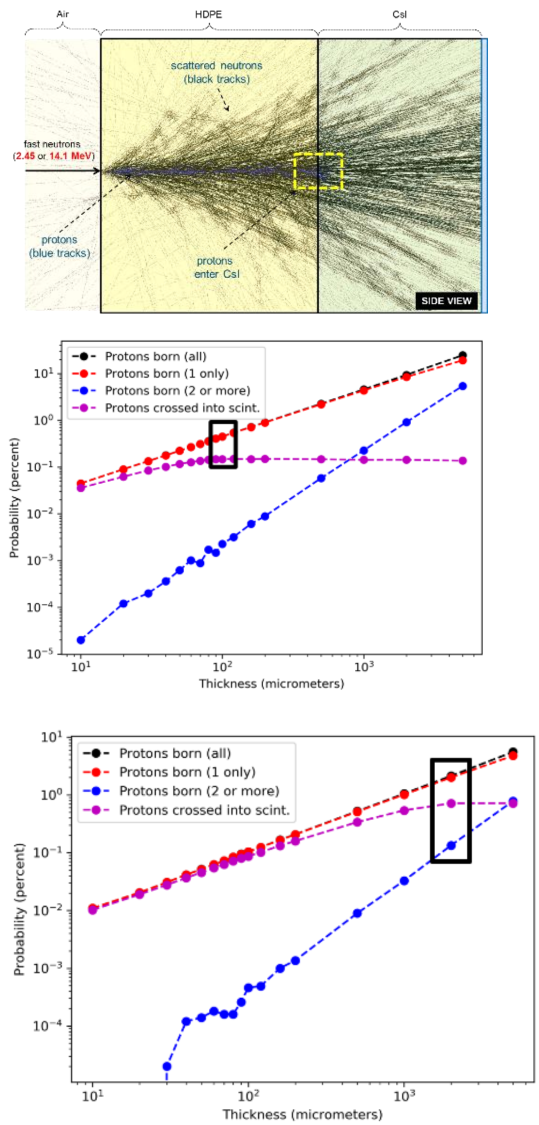

Figure 3. (Left) Modeling geometry showing the HDPE (polymer) layer in association with CsI scintillator. Both 2.45 MeV and 14.1 MeV fast neutrons from DD and DT generators respectively were assumed to impinge upon the HDPE and were simulated to track the secondary proton range. The optimum thickness of HDPE is where the probability for proton transport into the scintillator reaches a plateau, i.e. this is the best tradeoff between HDPE thickness and detection efficiency. (Right) The data encapsulated by the dark squares indicates the optimum HDPE thickness.

2.3 (U) Resolution Measurements

(U) The spatial resolution was quantified in terms of presampling the modulation transfer function (MTF). [3] The modular transfer function is a measurement of the ability of an optical system to transfer contrast at a particular resolution from the object to an image. As line spacing decreases in the spatial domain, (the frequency increases in the frequency domain) it becomes difficult for the optical system to transfer this decrease in contast. Therefore, as the frequency increases, the MTF decreases. The modular transfer function is the discrete fourier transform of the line spread function. The line spread function is simply the image of a line. For radiography, the line spread function is usually obtained by using a narrow slit as the object. [7]

2.4 (U) Neutron Gamma Discrimination

(U) There are two main methods for neutron gamma discrimination. This is the pulse shape discrimination (PSD) and pulse-height discrimination (PHD). Both these methods can be employed with varying tradeoffs for the LNI scintillator. [3]

3. (U) Results & Discussion

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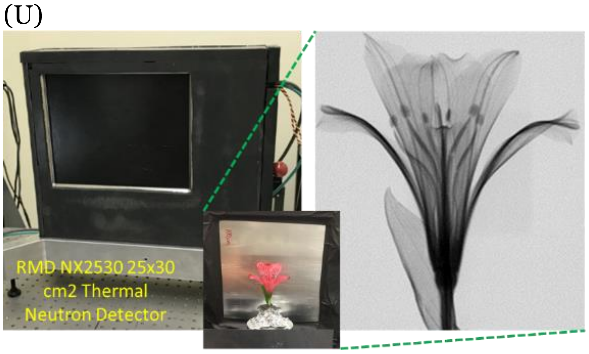

Figure 4: (Left) RMD NX2530 flat panel thermal neutron detector with 139 μm intrinsic resolution. (Right) Thermal neutron image of a lily flower taken using the NX2530 at ORNL HFIR beamline. The exposure was 15 seconds. As can be seen, this digital detector produces high quality radiographs.

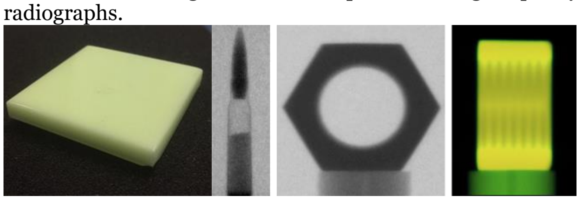

Figure 5: (Left) ZnS:Cu based fast neutron scintillator synthesized at RMD. (1) Projection radiograph of a .50-cal BMG cartridge, (2) Projection radiograph of a 3" stainless steel nut, and (3) a slice from 3D reconstructed image of the nut showing the inside threads. Neutron energy was 1-40 MeV and acquisition times were 20 second each.

(U) Per ASTM standard E 545-99, a beam purity indicator and a sensitivity indicator were used to evaluate image quality. The fabrication of these devices is detailed in ASTM E2003. For an 180 micron thick LNI scintillator, a category I image was obtained at the high flux isotope reactor at Oak Ridge National Laboratory. [3]

(U) Two different resolution mask phantoms were used to discern spatial resolution. The first phantom was a Boral sheet made with slit widths ranging from 1mm to 250 microns. A Line spread function (LSF) was extracted from the 250 micron slit and the full width at half maximum (FWHM) was calculated. Two different LNI scintillator thicknesses were evaluated (350 micron and 180 micron) with the Boral sheet analysis described above. The FWHM for both thicknesses will comparable despite the 2.5 difference in scintillator thickness. This demonstrates the superiority of the underlying microcolumnar structure of the LNI scintillator. The second resolution mask phantom was a gadolinium test phantom with 30 line groups each with 4 periods ranging from 0.25 lp/mm to 25 lp/mm corresponding to periods of 4 mm down to 0.04 mm. A 300 micron thick LNI scintillator exhibited a resolution of over 15 lp/mm at 10% contrast. [3]

(U) Figure 4 contains the image of the detector and an item to be imaged. A lily flower contains elements that attenuate thermal neutrons. The demonstration shows the potential of this detector to produce high quality radiographs. Figure 5 shows the fast neutron scintillator along with example radiographs.

4. (U) Conclusion

(U) We present a unique detector design that can simultaneously allow high resolution imaging using fast, and thermal neutrons and high energy X-rays. Scintillators are the heart of the detector and our preliminary data demonstrates efficacy of high resolution imaging using various radiation probes. The paper discussed the details of our design and the latest data, which should stimulate much interest.

5. (U) Future Work/Acknowledgements (optional)

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