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Contraband Detection using Materials Identification by Resonance Attenuation (MIRA)

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Abstract

There currently exists a large gap between the capabilities of fieldable screening technologies and the threat portfolio faced at airport and border crossings. We seek to fill this gap with the Material Identification by Resonance Attenuation (MIRA) detector system, which has the potential to simultaneously identify and image a wide range of materials including illicit drugs, explosives, and special nuclear material without the use of a complex accelerator. MIRA is a combination of two fast neutron analysis techniques, elastic scattering analysis and neutron resonance attenuation, which allow for elemental and mass characterization along with 3D imaging. We have previously demonstrated material identification by neutron resonance attenuation with a 2-unit system. A current deployment of a six-unit system will soon demonstrate 3D imaging in addition to material identification with both Resonance Attenuation and Elastic Scattering Analysis.

1. Introduction

Since the late 1980's, renewed interest in screening capabilities has resulted in significant investment in Thermal Neutron Analysis (TNA) and Fast Neutron Analysis (FNA), which probe not just the electronic structure of matter as x-ray based devices do, but probe nuclear structure: x-ray devices are only sensitive to variations in density, and thus do not provide effective material identification for light elements. In TNA, gamma particles resulting from a handful of thermal neutron capture reactions in materials of interest (Hydrogen and Nitrogen) are used as a means of identification. FNA is a far more powerful technique, and measures either the gamma rays from nuclei activated by a neutron beam, or the energy of an attenuated neutron beam. Several groups have demonstrated 2D elemental imaging capabilities using Pulsed Fast Neutron Analysis (PFNA), however the majority of them require complex optics and employ the Time-of-Flight (TOF) technique combined with sophisticated high-flux, pulsed accelerator technology to determine neutron energies [1–4] (and see [5] for a review). MIRA does not require a pulsed source, using almost exclusive commercial off-the-shelf (COTS) components. It has the potential to address the threat portfolio composed of illicit drugs, explosives, and special nuclear material (SNM), along with 3D imaging of baggage.

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Several groups have demonstrated impressive imaging capabilities with the FNA techniques. The TRION (Time-Resolved Integrative Optical Neutron) detector [1, 2] uses Pulsed Fast Neutron Transmission Spectroscopy (PFNTS), employing a 1-2 MHz deuteron beam with 1-2 ns bursts on a Beryllium-9 target. TOF is used to determine the energy of individual neutrons, ranging from 1-10 MeV, impinging on system of optics coupled to a scintillator screen. The scintillation light is focused onto a gated image intensifier, pre-programmed to open and close its shutter to allow light caused by neutrons with a given TOF (or energy) to pass. A cooled CCD camera integrates images from multiple bursts for a specific acquisition time ranging from tens of seconds to several minutes. The second iteration of this technique incorporates several image intensifiers to allow the acquisition of multiple neutron energies in one dataset. The TRION detector has successfully demonstrated 2D imaging and some elemental analysis, however the technique intrinsically depends on a cyclotron for the pulsed neutron source. In addition, the gated optical setup limits the neutron energies that can be measured simultaneously. It is not clear from the literature what acquisition time is required.

G. Chen and R. Lanza have developed a device similar to TRION [3], however their method does not require TOF to determine the neutron energy. By accelerating deuterium or protons onto a deuterium or Lithium target, neutrons are produced with energies dependent on the angle between the beam and detectors: data acquired at various angles images an object with different energies. Data is acquired using an optical setup similar to TRION, however without gating. This method requires multiple viewing angles to image over a range of neutron energies, rather than a simultaneous measurement of all neutron energies. It is also not capable of imaging in 3D, since both the object and detector rotate in tandem with the neutron source.

The CSIRO/NUTECH detector [4] uses 14.1 MeV neutrons from a (d-T) source in combination with 6/3 MeV x-rays form a linear accelerator to determine both the average material density and composition of materials. The ratio of neutron and x-ray penetration, R, is indicative of the material present, and impressive 2D images have been obtained with conveyor belt speeds of 1-2 m/min. However for both illicit drugs and explosives, the discrimination parameter R has a significant overlap with common materials, causing a high false alarm rate.

Although each of these techniques has been successful in imaging (although primarily in 2D) for certain threat portfolios, MIRA has the potential to achieve 3D imaging and address the entirety of the threat portfolio covered by illicit drugs and explosives with COTS components.

2. Material Identification and Imaging with Neutron Attenuation

2.1. What is MIRA

Material Identification by Resonance Attenuation is a FNA technique that measures the energy dependent attenuation of 1-10 MeV neutrons as they pass through a sample of interest. Elemental information can be determined from the neutron absorption resonances unique to each element. Figure 1, left, shows the spectrum of neutron interaction cross sections for Hydrogen, Carbon, Nitrogen, and Oxygen from the ENDF/B-VII.0 database [6]. Given sufficient energy resolution, the unique resonances in the energy attenuation for each sample can be used to categorize a wide

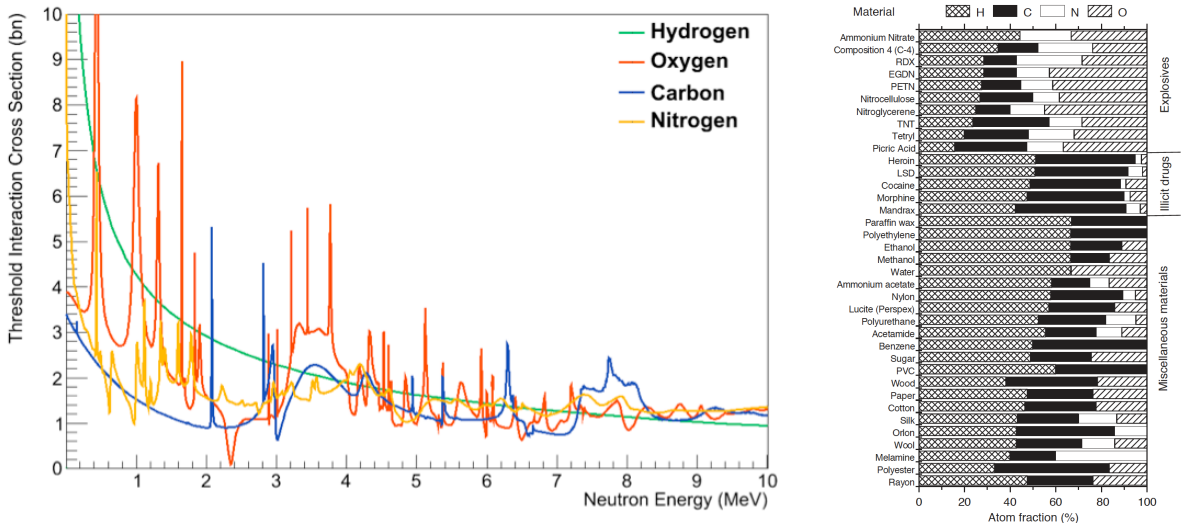

Figure 1: Left: The total neutron interaction cross section spectra for Hydrogen, Carbon, Nitrogen, and Oxygen, from ENDF/B-VII.0 [6]. Right: the atomic fraction of several materials, taken from [5].

range of materials. This serves as a powerful discrimination technique between explosives, illicit drugs, and other materials. Figure 1, right, shows the atomic fraction of Hydrogen, Carbon, Nitrogen, and Oxygen for several materials of interest along with common benign materials. Many conventional explosives, for example, are characterized by their relatively high Nitrogen and Oxygen content. Although the focus is on these four elements, in principle other elements can be used for more detailed material identification.

Although explosives discrimination based on elemental composition has been demonstrated by others (see for example, [3]), what makes MIRA unique is that it simultaneously down-scatters and time tags neutrons in detectors oriented between the generator and sample, allowing for TOF measurements without pulsed neutron beams. The 14.1 MeV neutrons from a (d-T) source are down scattered in energy by an amount dependent on the angle, θ, of the scattered neutron:

$$E_i = \frac{14.1\ \mathrm{MeV}}{1 + \tan^2\theta}. \tag{1}$$

The neutron energy incident on the sample, E_i spans a range from 1-10 MeV depending on the scattering angle, i.e. multiple energies interrogate the sample simultaneously, vastly improving the required scan time for each sample. Figure 6, left, shows the path of a down-scattered neutron. This energy is measured by:

$$E_i = \frac{m}{2}\left(\frac{d}{t}\right)^2, \tag{2}$$

where d is the distance between two detectors on either side of the object to be interrogated, t is the time-of-flight, and m is the mass of the neutron. The difference between the energy spectrum with and without a sample present

Sample	Hydrogen (M/cc)			Carbon (M/cc)			Nitrogen (M/cc)			Oxygen (M/cc)		
	exp.	mea.	% err.	exp.	mea.	% err.	exp.	mea.	% err.	exp.	mea.	% err.
HDPE	0.23	0.23	0	0.11	0.09	18	0.00	0.00	0	0.00	0.00	0
Water	0.22	0.22	0	0.00	0.04	100	0.00	0.02	100	0.11	0.10	9
Ammonium Nitrate	0.06	0.08	33	0.00	0.00	0	0.03	0.03	0	0.05	0.04	25

Table 1: The expected and measured molar concentrations for three samples from a 2-unit test, taken from [7]. It should be noted that the water sample was not pure: impurities were expected but not quantified.

provides a measure of the energy-dependent attenuation attributed to the presence of the sample. Because this method relies on measuring the resonant attenuation as a function of transmitted energy, it is critical for the detection system to have excellent energy resolution. The error on the measured energy is a function of the timing and spatial widths:

$$\sigma_{E_i} = \sqrt{\left(\frac{\partial E_i}{\partial d}\right)^2 \sigma_d^2 + \left(\frac{\partial E_i}{\partial t}\right)^2 \sigma_t^2} \tag{3}$$

$$= 2E_i\sqrt{\frac{\sigma_d^2}{d^2} + \frac{\sigma_t^2}{t^2}}. \tag{4}$$

Therefore, the timing and spatial resolution of the neutron detectors are directly related to the energy resolution that can be obtained. In addition, Equation 1 can be used to measure the energy or to constrain the TOF to a range corresponding to the expected energies in order to reduce accidental backgrounds. If one determines the energy via Equation 1, the error is given by

$$\sigma_{E_i} = \sqrt{\left(\frac{\partial E_i}{\partial \theta}\right)^2 \sigma_\theta^2 + \left(\frac{\partial E_i}{\partial \alpha}\right)^2 \sigma_\alpha^2} \tag{5}$$

$$= 2\sqrt{2}E_i\tan\theta\sqrt{\left(\frac{z}{x^2+z^2}\right)^2 \sigma_x^2 + \left(\frac{-x}{x^2+z^2}\right)^2 \sigma_z^2 + \sigma_\alpha^2}, \tag{6}$$

where α is the angle defined by the angular extent of the (d-T) generator's emission region, and z and x are the coordinates of the second detector in reference to the first detector.

This technique was previously demonstrated with a 2-unit device [7] after which the criticality of the spatial and timing resolution was realized. Data was taken with no sample present, with a 4 inch water sample, a 2 inch HDPE sample, and a 2 inch Ammonium Nitrate sample. The difference between the empty dataset and each sample, such as those shown in Figure 2, is used in a χ^2 minimization to determine the elemental densities. The results are summarized in Table 1, and demonstrate overall determination of the molar concentrations for the four elements of interest. The six unit device is expected to be superior due to the improved timing resolution of the detection units, directly affecting the energy resolution.

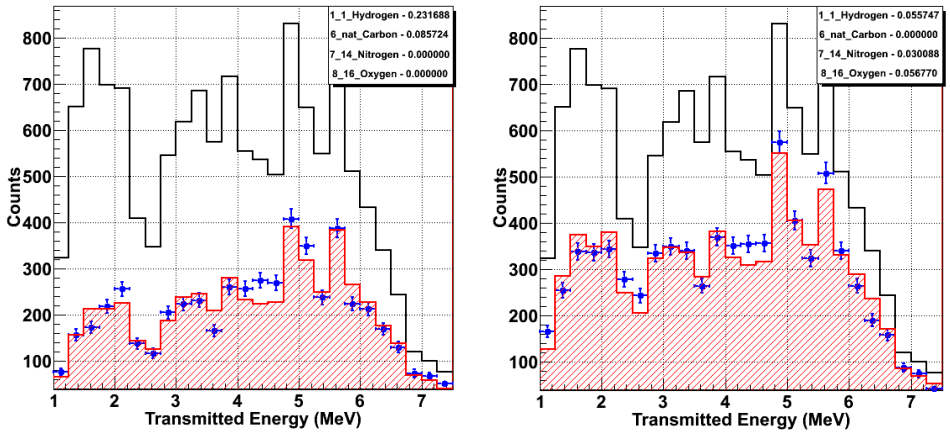

Figure 2: The transmitted energy distribution for no sample present (solid black) and target material (blue dots) for 2 inches of HDPE (left) and 2 inches of Ammonium Nitrate (right). The filled red curve is created by attenuating the black curve according to known cross sections. The amount of each element in units of moles/cc from a Minuit fit is shown in the upper right text box. Taken from [7].

2.2. Detector Development

Since our 2-unit feasibility demonstration, our focus has been on obtaining neutron detectors with the best possible position and timing resolution, while simultaneously eliminating excess scattering material. Each detector unit, shown in Figure 3, consists of a 2 inch block of plastic scintillator and seven 3 inch photomultiplier tubes (PMTs) inside a hexagonal Aluminum cover. The sides of the scintillator block are coated with black absorbing paint and the face is coated with a white reflective material to increase the total light collected. The scintillator is EJ-200, chosen for its high light output and fast response, and the PMTs are Electron Tubes model 9812KB, also chosen for their fast and linear response. The scintillator is coupled to the PMTs with a 3/8 inch acrylic light guide. At the top of each unit is an LED calibration board with 13 LEDs for position reconstruction calibrations. Each PMT is digitized by Struck SIS3320 eight-channel 250 MHz digitizers.

The position resolution of the units is calculated using the method described in [8]. The results from a ^{60}Co source, in which the source is positioned 2 cm from the center of the unit and collimated perpendicular to the PMT faces, is shown in Figure 4. The results demonstrate a spatial resolution of $\sim$0.4 cm (σ). In order to determine the timing resolution, the response to muons propagating perpendicularly to the PMT faces is used: the units were separated by approximately 1.5 meters vertically, and the coincidence of the two units was used as a trigger. The resulting timing response is shown in Figure 4, right. A TOF FWHM of $\sim$1 ns is measured, corresponding to an uncertainty of $\sim$0.3 ns (σ) for each block.

The detector units are arranged cylindrically around a sample of interest, with a radius of approximately 50 cm: for the six-unit prototype device described here, all units are in the same plane as the sample. The layout is shown in Figure 6. A Thermo MP320 Deuterium-Tritium neutron source is situated outside of the radius of the units, approximately

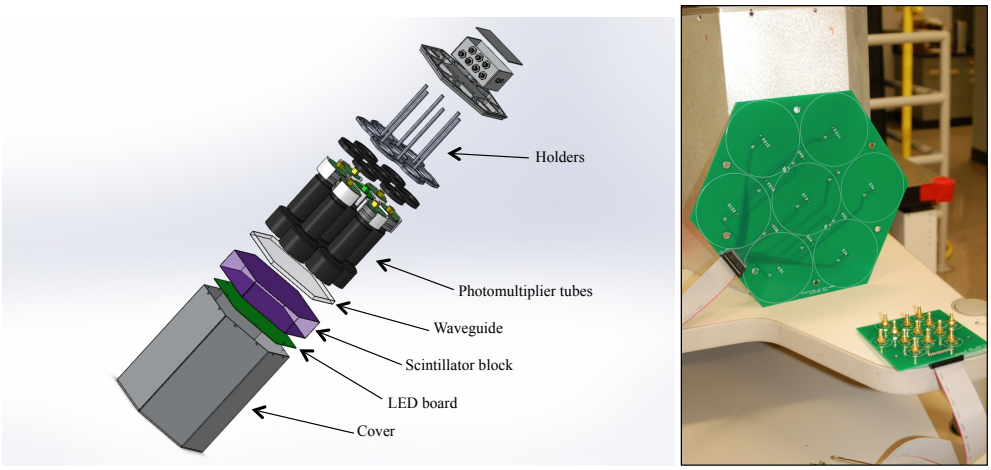

Figure 3: The detector units for MIRA, left, consisting of seven PMTs and a 2 inch block of EJ-200 plastic scintillator. The right picture shows the LED calibration board situated in front of the scintillator.

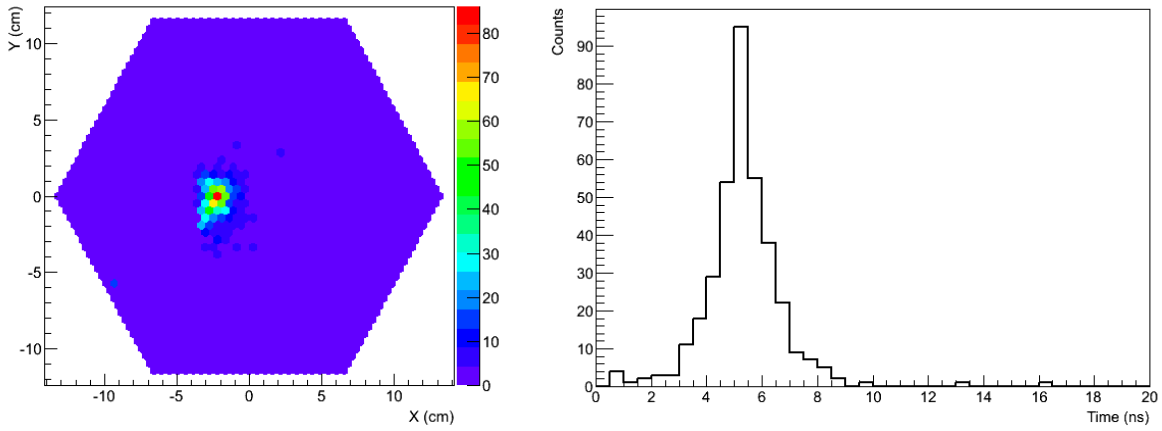

Figure 4: On the left is the result from a collimated ^{60}Co source positioned 2 cm from the center of the unit, perpendicular to the PMT faces. On the right, the timing resolution is shown.

one meter from the closest detectors. The neutrons are then down-scattered in one of the nearest three units ("near" units) to the 1-10 MeV range. The "far" units register these neutrons after having passed through the sample. The time between near and far hits is used to measure the transmitted neutron's energy. The trigger, also shown in Figure 6 is constructed from the 100 ns coincidence of any near unit with any far unit. Using Equation 4, the uncertainty in the energy of neutrons passing through a sample at 3 MeV is $\sim$2%: the timing resolution is the dominate factor contributing to the error. However, the geometrical constraints represented in Equation 6, which depend only on the spatial resolution and separation of the units, gives an uncertainty in energy of $\sim$1%.

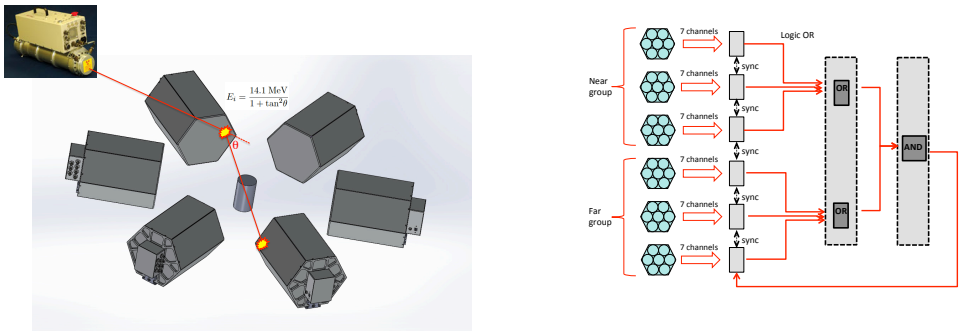

Figure 5: On the left is a rendering of the six-unit MIRA device. The (d-T) neutron generator is positioned outside of the radius subtended by the units. The units are classified into near and far groups, consisting of the units in which the first (near) and second (far) neutron interactions occur. Shown is a neutron down-scatter in a near unit and subsequent interaction in a far unit. On the right, the trigger scheme is shown: the 100 ns coincidence of the logical OR of the near and far units is the trigger condition.

2.3. Imaging Capabilities

The six-unit test will for the first time demonstrate the imaging capabilities of the MIRA device. 2D imaging with neutrons alone has been demonstrated by others: the TRION detector [1, 2], for example, has demonstrated impressive multi-element images. 3D imaging with these devices, however, would involve rotating the sample with respect to the detector apparatus to provide multiple 2D maps. MIRA accomplishes 3D imaging with one scan due to the multiple scattering angles of the neutrons incident on the sample. Elemental 3D maps will be determined by measuring the complete energy dependent attenuation through every possible path between detector units. The total attenuation along each path is the product of attenuations through each voxel along the path in the interrogated object. By sampling every voxel multiple times by different paths at different angles, the energy (elemental) and position dependence can be deconvolved to construct an elemental density map of the target space. Only attenuation between pairs of near and far units is considered, and the robustness of the method considering scattering backgrounds and unknown elements within the sample and response space are currently undetermined.

2.4. Elastic Scattering Method

The six-unit test will be capable of material identification not just by the attenuated neutron signal, but by a direct measurement of the mass of the scattered nuclei within the sample. Assuming $m << M$[1], the energy lost by a neutron in an elastic scattering interaction is given by:

[1]For the special case of M=m (i.e. scattering on Hydrogen), the two particles scatter at right angles to each other and the energy loss $Q = E_0 \cos^2\phi$, or Equation 1.

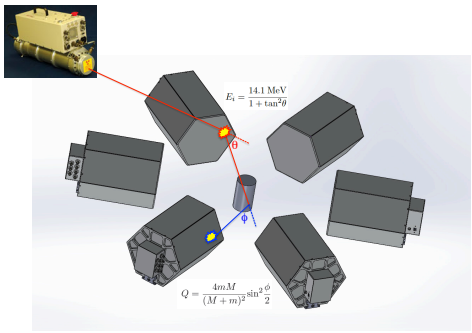

Figure 6: A rendering of the six-unit MIRA device, showing the neutron down-scatter in a near unit, elastic scattering in the sample, and detection in the far unit.

$$Q = \frac{4mM}{(M+m)^2}\sin^2\frac{\phi}{2}, \tag{7}$$

where M and m are the masses of the scattered nucleus and neutron respectively, and ϕ is the angle of the scattered neutron. A measurement of the neutron energy before and after a collision along with trajectory information uniquely determines the mass of the scattered nucleus:

$$M = \frac{2m}{Q}\sin^2\frac{\phi}{2}\left(1 \pm \sqrt{1 - \frac{Q}{\sin^2\frac{\phi}{2}}}\right) - m, \tag{8}$$

where $Q = E_i - E_f$. MIRA's geometry allows for such energy and trajectory measurements to be made so long as the sample is limited to approximately one scattering length of material, and adequate position and energy resolution of the neutron at all scattering locations can be realized. Again, the degree to which we can determine the mass of the scattered nuclei will depend on the resolution of the energy loss, which is dependent on the timing and spatial resolution. It should, however, be emphasized that this method adds an entirely new channel of information on the sample, and is likely to improve minimization routines.

3. Conclusions

The MIRA device is capable of determining the elemental composition of samples by both the energy-dependent resonant neutron attenuation and the elastic scattering of neutrons within the sample. The device is distinguished from other similar devices by its ability to measure the neutron attenuation signal from multiple energy neutrons and multiple scattering angles at the same time, drastically reducing the scan time necessary for each sample. A six-unit deployment of the MIRA device is currently underway, and is expected to have sufficient timing and spatial resolution to provide improved elemental characterization of samples along with 3D imaging. We will also determine to what extent the elastic scattering mode contributes to the determination of the sample contents.

Acknowledgements

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