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Illicit substance detection using fast-neutron interrogation systems

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ABSTRACT

Fast-neutron interrogation techniques are of interest for detecting illicit substances such as explosives and drugs because of their ability to identify light elements such as carbon, nitrogen, and oxygen, which are the primary constituents of these materials. Two particular techniques, Fast-Neutron Transmission Spectroscopy and Pulsed Fast-Neutron Analysis, are discussed. Examples of modeling studies are provided which illustrate the applications of these two techniques.

1. INTRODUCTION

Fast-neutron interrogation techniques are being studied for the detection of illicit substances (e.g., explosives and drugs) in luggage and cargo containers. X-ray techniques are often unable to detect these substances. Fast-neutron based techniques are attractive because they offer the possibility of determining the densities of light elements such as carbon, nitrogen, and oxygen within a volume element. Illicit substances are composed primarily of these elements, and are characterized by elemental densities and density ratios which are different from most other substances likely to be found in legitimate cargo.

This paper discusses two different fast-neutron based techniques. The first is based on measuring the neutron spectrum from a distributed energy neutron source after the neutrons pass through the items to be interrogated. The transmission spectrum depends on the neutron total cross sections of the elements in the sample. The basic technique was first examined^{1,2} for bulk material analysis. The technique is best suited for examination of luggage or small containers for which the transmission ratio is greater than about 0.01.

The second technique is based on detecting gamma rays from fast-neutron interactions with the material being interrogated. The characteristic gamma rays emitted from the material allow one to determine the elemental densities within a given volume. Several variations³⁻⁶ of this technique have been proposed. We discuss the technique referred to as the Pulsed Fast Neutron Analysis (PFNA) technique³ being developed by Science Applications International Corporation. Pulsed monoenergetic neutrons are used. Neutron energies greater than 6.5 MeV are required to detect carbon and oxygen. Incident neutron collimation and timing are used to determine the elements in a particular volume. This technique is suitable for examination of large containers because of the good penetration of the fast neutrons and the low attenuation of the high-energy gamma rays.

2. FAST-NEUTRON TRANSMISSION SPECTROSCOPY

Fast-Neutron Transmission Spectroscopy (FNTS) uses standard time-of-flight (TOF) techniques to measure the energy spectrum of neutrons emitted from a collimated continuum source before and after transmission through an interrogated sample. The Monte Carlo radiation transport code MCNP⁷ was used to simulate transmission experiments assuming a collimated parallel neutron beam irradiating the interrogated object. The neutron source used is the zero-degree neutron energy spectrum from the $^9\text{Be}(d,n)$ reaction at $E_d = 5 \text{ MeV}$.⁸ This deuteron energy results in a source with high neutron yield in the range 1-4 MeV, which contains many resolved resonances for the light elements. The source-detector distance is 5 m, with source and detector timing widths of 2 nsec. Analog transport is used (i.e., no variance reduction) so that each neutron from the source represents one neutron from a real source. In this way we can achieve errors of the proper magnitude and variation across energy phase space, which is important in evaluating analysis and decision-making algorithms that use the data. The number of neutron histories run is chosen to simulate a one-second exposure for a maximum count rate of $10^5/\text{s}$ in a detector.

Transmission data are analyzed in the time domain using standard nuclear techniques to determine the areal density (nuclei per cm^2) of various elements along the line-of-sight through the sample. This unfolding includes errors both in counting statistics

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and in the elemental cross sections. The cross sections used in the unfolding are obtained by simulating transmission experiments for pure elements, and inverting the transmission results to get the cross sections. The elements which have been used in unfolding are: elements which are present in most conventional high explosives [H C N O]; elements which are present in many non-nitrogen-based explosives [F Na Si Cl K]; other elements which one might expect to find inside luggage [Al Si Fe Cu]; and a fictitious element X, which is meant to account for elements that are not explicitly included. The element X is presently assigned a flat cross section. Unfolding has been performed to date with the ten-elements sets [H C N O F Al Si Cl Fe Cu] and [H C N O F Na Si Cl K X] and the five-element set [H C N O X].

A representative transmission spectrum, for a 3-cm thickness of the high explosive RDX, is shown in Figure 1(a). The unfolding routine propagates errors throughout the calculation, so that the areal densities, or normalized areal densities, are presented with errors and correlations as shown in Figure 1(b). Here the + sign signifies the true solution, the filled diamond shows the unfolded solution, and the ellipse shows the locus of points (called the $1-\sigma$ ellipse) which lie one standard deviation away from the solution. The unfolded solution is stable over repeated independent calculations for a given thickness and over a range of thicknesses. Transmission results were obtained for various explosives and benign materials to test the algorithm's ability to unfold accurately the areal densities of a variety of elements. A variety of materials has been simulated, singly or in combination, to include such materials such as ABS plastic, water, melamine, polyurethane, plexiglas, cloth, salt, sugar, glass, and various explosives. A sampling of results from such simulations are shown in Figure 2. The areal densities calculated for a given material or combination of materials are quite good, as long as the constituent elements are represented in the cross-section matrix used in the unfolding.

Uncollimated geometries have also been studied to investigate the effects of small-angle scattering within the sample. The primary effect is spectral distortion, since neutrons arriving at any given time may have different energies. The cases modeled involved broad-beam irradiation of samples which were viewed by an uncollimated detector. Scattered neutrons were only a few percent of the total, so that the unfolded areal densities were little affected. These results suggest that multiple scattering within the sample is not important, and that scattering effects may be dominated by surrounding materials (walls, detector shielding, source collimators, etc.). One reason to use ratios of areal densities to determine the presence of explosives is that, since the effect of scattered neutrons is to create an apparently larger density, this effect might be reduced or eliminated by taking ratios of two quantities which are both increased by scattering.

Figure 1. (a) Sample transmission energy spectrum for fast-neutron transmission through 3 cm of the high explosive RDX. (b) Unfolded solution for 3-cm thick RDX in terms of normalized nitrogen and oxygen densities.

Figure 2. Solutions from fast-neutron transmission unfolding in terms of normalized nitrogen and oxygen densities for a variety of explosive and benign materials.

3. PULSED FAST-NEUTRON ANALYSIS

The results from computer simulations of PFNA systems are quite sensitive to the exact details of the source and detector characteristics, geometry, and container contents. However, many basic physics questions can be addressed using simple models. These questions include: Do regions of contraband give signals which are distinguishable from background? What sort of signal-to-noise ratios can one expect? What are the time and spatial dependencies and dynamic range of the detected signals? What physics issues are raised by neutron and gamma ray scattering?

The basic geometry of a PFNA system is shown in Figure 3. A short ($\sim$ nsec) burst of collimated, monoenergetic neutrons is incident on the container and interacts with the material inside the container to create inelastic-scatter gamma rays. The minimum neutron energy required to excite inelastic levels is 4.44 MeV for carbon and 6.13 MeV for oxygen. These gamma rays are then observed by detectors arranged around the sides and back of the container. The point at which the gamma ray was created is determined by measuring the time between the source neutron burst and the time at which the gamma ray is detected. The interaction location is determined using the equation $t = z/v_n + r/v_\gamma$, where t is the total flight times of the neutron and gamma ray, z is the depth at which the interaction occurs, r is the flight path length for the gamma ray to a given detector, and v_n and $v_\gamma = c$ are the neutron and gamma ray velocities, respectively. An analytic representation of this signal can be obtained for any detector location by treating the container depth as a discrete variable z_i , and calculating the expected signal S_i at time t_i .

$$t_i = z_i/v_n + r_i/v_\gamma \quad S_i = \phi_0 \exp[-\lambda z_i] (N_i \sigma) (A_d/4\pi r_i^2) \exp[-\mu r_i] \quad (1)$$

where ϕ_0 is the neutron flux at the container front face, λ = the attenuation constant for neutron flux, N_i = the number of target nuclei, σ = the inelastic scatter cross section, A_d = the detector area, and μ = the gamma ray attenuation constant.

MCNP has been used to model a typical PFNA system to estimate the signal at various detector locations for a uniform container loading of 0.5 g/cm³ of sugar. For these models, variance reduction techniques such as exponential transform and weight window are employed to adequately determine the neutron interaction and gamma-ray transport deep inside the container. A calculation of the gamma-ray signal from $^{12}\text{C}(n,n1)$ (i.e., the first excited state gamma ray from ^{12}C) is shown in

Figure 3. Schematic of the geometry of a typical Pulsed Fast-Neutron Analysis system.

Figure 4, along with the analytic signal prediction discussed above. One can see that the MCNP simulation shows less attenuation as a function of time (distance into container) than the analytic prediction. This greater number of counts seen in the MCNP simulation is directly attributed to gamma rays caused by neutrons which have scattered away from their initial direction into the container. These gamma rays are created in regions off the beam axis, and thus do not follow the time-space correlation of an ideal neutron. This can be directly shown by tabulating the gamma rays generated inside a 10-cm radius cylinder which is coaxial with the beam axis, and following these gamma rays to the detector. This is equivalent to using collimated detectors to look only along the beam axis. One finds that the gamma rays generated inside this cylinder compare quite well with the analytic signal prediction.

Detection of drug contraband is often accomplished by using the fact that drugs are relatively rich in carbon and poor in oxygen compared to most substances. Thus detection based on the ratio of concentrations C/O (or C^2/O) has been suggested as a detection parameter. Figure 5 shows this detection parameter as a function of depth for the MCNP simulation discussed above

Figure 4. Comparison of predicted $^{12}\text{C}(n,n1)$ signal from analytic model vs. MCNP simulation.

(sugar at 0.5 g/cm^3). The true C/O ratio is unity. Densities are unfolded from the simulated signal using a model similar to the analytic signal prediction model above. The increase in C/O with depth for uncollimated detectors is due to the detection of gamma rays which are due to neutrons which have scattered away from the incident beam axis. This scattering effect is stronger in carbon than in oxygen because the lower threshold energy for inelastic events in carbon allows neutrons to scatter more times before losing enough energy to pass beneath the threshold. The ratio C/O departs most significantly from unity in the back half of the container; thus this technique may be useful only in the front half for this example, making it necessary to irradiate from both sides.

Figure 5. Variation of detection parameter C/O with depth into container (0.5 g/cm^3 sugar) from MCNP simulation.

4. CONCLUDING REMARKS

Nuclear techniques are very promising for nondestructive examination of luggage and cargo containers. Both analytic models and Monte Carlo simulations provide an insight into the physics of these examination processes, indicate limitations of candidate systems, and offer clues for system optimization.

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