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EXPLOSIVES DETECTION PERFORMANCE OF γ-RAYS INTERROGATION FOR ROBOTS AND VEHICLES

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ABSTRACT: The performance of a explosives detection system based on the pulsed fast/thermal neutron analysis technique was assessed using Monte Carlo simulations. The aim was to develop and implement simulation methods, to support and advance the data analysis techniques of the characteristic γ-ray spectra, potentially leading to elemental characterization of innocuous objects using the full spectrum analysis (FSA) approach. Several different neutron based techniques are being studied for the detection of contraband substances in luggage and cargo containers. The pulsed neutron generator is easy to transport and radiation protection is only needed during analysis time. This paper discusses accelerator requirements for fast neutron transmission spectroscopy (FNTS), pulsed fast neutron analysis (PFNA), pulsed thermal neutron analysis (PTNA), fast neutron scattering analysis (FNSA), delayed fission analysis (DFA).

Keywords: Neutron technologies, Fast Neutron Transmission Spectroscopy, Nuclear Reaction Energetic – Q values

1. INTRODUCTION

The explosives detection field has seen enormous growth, fueled by the threat of terrorism and the emphasis on homeland security. Explosives detection is a non-destructive inspection process to determine whether a container contains explosive material. Safety and liability have always been a major concern to the industrial community, it is a significant step forward in terms of user safety and handling to have an electrical neutron source which can be switched. Enhancing a robot with explosive detection capabilities will keep personnel out of harm's way. Neutron induced gamma spectroscopy is used for the detection of explosives and Chemical Warfare Agents (CWAs) in ammunition such as bombs and shells without container opening with the risk of CWAs emission. Neutron technologies are based on the interactions of neutrons with nuclei, and the gamma rays (γ-rays) released by the interactions are used to identify the nuclei in the objects being inspected. They do not detect explosives directly; instead they detect them indirectly from the concentration distributions of elements commonly found in explosives, such as nitrogen, oxygen and carbon. Strong radiation is involved during the inspection and, therefore, the applications of these technologies do not include searching the human body.

2. TECHNIQUES USED FOR DETECTION OF EXPLOSIVES BASED ON NEUTRON TECHNOLOGIES

A neutron is one of the subatomic particles inside a nucleus. There are few detection methods that are based on neutron technologies, including: Thermal Neutron Activation (TNA), Fast Neutron Activation (FNA), Pulsed Fast/ Thermal Neutron Activation (PFTNA), Fast Neutron Scattering Analysis (FNSA), and Delayed Fission Analysis (DFA). These are discussed from References [1], [2].

Thermal neutron activation (sometimes also called thermal neutron analysis) is an explosives detection method based on the characteristic emission of gamma rays in the object of concern. Thermal neutron activation is a bulk detection technique in which an item or area to be screened for explosives is exposed to a low-energy stream of neutrons. The thermal neutron interacts with the nucleus of matter under inspection and the neutron is absorbed and results in the emission of a high-energy gamma ray. Nitrogen nuclei have a strong interaction with thermal neutrons unlike carbon and oxygen, which have weaker interactions. The nitrogen nuclei emit gamma rays of a characteristic energy of 10.8 MeV. Detection of any emitted 10.8 MeV gamma rays indicates that the material contains nitrogen. Many explosives are nitrogen-containing compounds; therefore, this technique can be used to identify materials that contain nitrogen, which also have a high probability of being explosives. The neutrons used in a thermal neutron activation system are provided by either a radioactive isotope or by an electronic neutron generator.

Fast neutron activation techniques use fast neutrons (rather than thermal neutrons, which are highly penetrating) to interact with nuclei of interest. The neutrons interact with the nuclei of the various chemical elements in the object, emitting characteristic gamma rays, which acts like an elemental fingerprint. Fast neutron activation is a bulk detection technique in which an item or area to be screened for explosives is exposed to a high-energy stream of

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neutrons. The fast neutron interacts with the nucleus of matter under inspection and the neutron is absorbed and results in the emission of a high-energy gamma ray. Gamma ray emission occurs for carbon, nitrogen and oxygen. The technique is able to determine the type of substance under analysis. The neutron source used in a fast neutron activation system is provided by an electronic neutron generator.

Pulsed fast neutron activation (also called pulsed fast neutron analysis) is a technique where fast neutrons are pulsed at the nuclei of interest. The characteristic gamma ray emission is collected. Pulsed fast neutron activation yields information on several elements including carbon, hydrogen, nitrogen, and oxygen. Using very short fast neutron pulses (on the order of nanoseconds), the location of the detected material can be determined. Pulsed fast neutron activation is a highly specific technology for the identification of various substances. The high-energy neutron source used in a fast pulsed neutron activation system is provided by an electronic neutron generator. Advantages of pulsed fast neutron activation are:

- Information is gathered on elements besides nitrogen, such as carbon and oxygen, which helps in explosives-like material determination.
- This technique has good neutron penetration and can be used on large cargo containers.
- Three-dimensional location information can be determined in the object of concern.

Fast neutron scattering analysis (FNSA) is an alternative approach in which neutrons scattered out of the interrogated material are detected. The type, amount and positions of the nuclides responsible for the scattering are determined from measurements of the dependence of scattered neutron intensity and energy on scattering angle and the incident neutron energy.

Delayed fission analysis (DFA), after all neutrons in the pulsed beam have thermalized and been absorbed, the continued emission of neutrons and gamma-rays by the interrogated object are a signature of the presence of fissile material. This is clear indicator for special nuclear materials, in particular weapons grade uranium, which is difficult to detect by other methods.

Pulsed fast/thermal neutron activation technique uses both fast neutron and thermal neutrons. Neutrons are pulsed at the nuclei of interest and characteristic gamma ray emission is collected. In the period after the fast neutron pulse has ended, some of the fast neutrons remaining within the object thermalize and are captured by elements such as H, N, Cl and Fe. The prompt capture gamma-rays are detected by the same detectors and the events stored separately from the inelastic scattering spectrum. By combining fast inelastic neutron scattering, thermal neutron capture and delayed activation analysis, a large number of elements contained in an object can be measured. Pulsed fast/thermal neutron activation yields information on several elements including carbon, hydrogen, nitrogen, and oxygen.

3. FAST NEUTRON TRANSMISSION SPECTROSCOPY (FNTS)

Fast-Neutron Transmission Spectroscopy (FNTS) uses standard time-of-flight techniques to measure the energy spectrum of neutrons emitted from a collimated ^{9}Be (d, n) continuum source before and after transmission through the sample [Reference 8]. An unfolding algorithm determines the areal densities (density integrated along the line of sight, with units of number density per cm2), and the uncertainties, of the various elements present in the sample. Projection data from several angles are then reconstructed to provide two-dimensional images, one for each element, of a slice through the sample. The elemental reconstructions are then combined and processed through a detection algorithm. Only a few projections and coarse resolution are used to minimize interrogation time while still obtaining a reconstruction that provides enough separation between objects to maximize the success rate of an explosive detection algorithm. The use of this method as applied to explosive detection is discussed in Reference [6].

The accelerator requirements for FNTS system involve tradeoffs between many parameters, including: The accelerator energy (size), the time available for sample examination, maximum allowable detector count rates, spatial resolution required for adequate explosive detection, and neutron yield and spectrum versus deuteron energy. There are also limits on how well elemental densities can be determined at lower deuteron energies. In general, one would like to have a high detector count rate as possible to minimize sample irradiation time, consistent with acceptable errors due to dead time and spectral distortion. This limits the detector count rate to about one-tenth of the accelerator pulse repetition rate. Given a detector count rate, one can then determine the required neutron source rate from the left-hand-side of

$$R/(\langle T\rangle \langle \varepsilon\rangle) = \text{source } n/s = S_n \, \Delta\Omega \, I_p \, \tau_p f \qquad (1)$$

Where R = maximum detector count rate

$\langle T\rangle$ = average transmission

$\langle e\rangle$ = average detector efficiency

S_n = zero-degree neutron emission (n/sr-s-μA)

$\Delta\Omega$ = detector solid angle (sr)

I_p = peak current (μA)

τ_p = pulse time width (s)

f = accelerator pulse repetition rate ($1/s$)

The right-hand-side of Eqn. [1] can then be used to determine the required accelerator current once the deuteron energy, pulse width, and pulse repetition rate have been chosen. A typical time-of-flight system would have a flight path of 5 m, limiting f to $10^6/s$ (to avoid wrap-around), thus making $R = 10^5/s$. If the required spatial resolution inside the interrogated object is 2 cm, the detector size would be 4 cm if the object is placed midway between source and detector. The required accelerator current as a function of deuteron energy is shown in Table 1 for transmission through 3 cm of RDX high explosive. While lower deuteron energies would lead to a smaller accelerator and thus smaller system footprint, the declining neutron yield means that more current is required.

Table 1
Deuteron Current Required for a Neutron Count Rate of 10^5/s in a 4-cm Detector as a Function of Deuteron Energy (for 5 m Flight Path, $f = 10^6$/s, and $<\square> = 0.15$)

Ed (MeV)	*Yn (n/sr - □ C)*[a]	*<Id> (□ A)*[b]	*Ip (mA)*[c]
2.6	$2.62.10^8$	120	60
3.0	$4.35.\ 10^8$	69	35
3.4	$6.41.\ 10^8$	45	22
3.8	$8.83.10^8$	31	16
4.2	$1.17.10^9$	24	12
4.6	$1.50.10^9$	18	9.1
5.0	$1.87.10^9$	15	7.3
5.4	$2.31.\ 10^9$	12	5.9
5.8	$2.80.\ 10^9$	9.6	4.8
6.2	$3.35.\ 10^9$	7.9	4.0
6.6	3.97. 109	6.6	3.3
7.0	4.66. 109	5.6	2.8

a. Neutron yield data from Reference [8]

b. Average deuteron current

c. Peak deuteron current (2 ns pulse at 106 repetition rate)

4. PARTICLES ACCELERATOR NEUTRON GENERATOR

Particle accelerators are the source of neutrons for industry. Pulsed fast neutron analysis technique uses nsec pulses of monoenergetic neutrons produced by accelerating deuterons onto a deuterium gas target. The neutron beam is scanned vertically across the cargo container by a movable collimator. Scanning along the length of the container is accomplished by moving the container horizontally. Depth information is obtained using time-of-flight between the accelerator pulse and the arrival of a gamma ray in NaI detectors located outside the container.

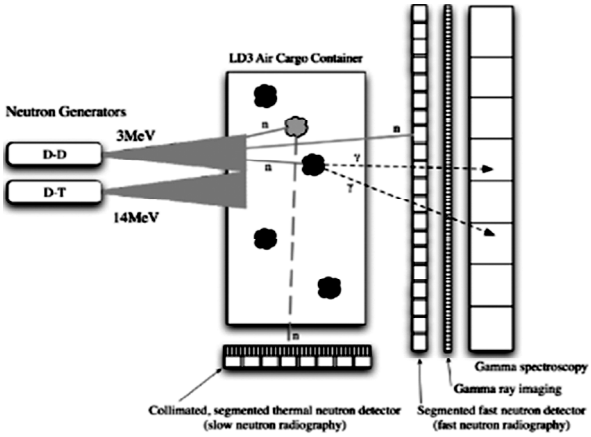

Figure 1: Neutron Generators

Since the neutrons produced have velocities of about 4 cm/ns, the accelerator pulse must be at most a few ns if the voxel depth (thickness) is to be about 10 cm. The 4.44-MeV gamma from the first excited state in 12C and the 6.13-MeV gamma ray from the second excited state in 16O are used to generate a qualifier that indicates the presence of contraband [From References (5,9)]. The signal obtained from this technique depends sensitively on the incident neutron energy used, as can be seen in Figure 2. Neutron energies greater than 6.5 MeV are required to detect 16O, with the optimum energy being between 8.2 and 8.25 MeV (requiring deuteron energy of about 5.0 MeV). However, since the inelastic scattering cross sections vary rapidly in this energy range, the energy stability of the accelerator and the pulse-forming network which generates the nsec-width pulses must create an energy variation of less than 10 keV.

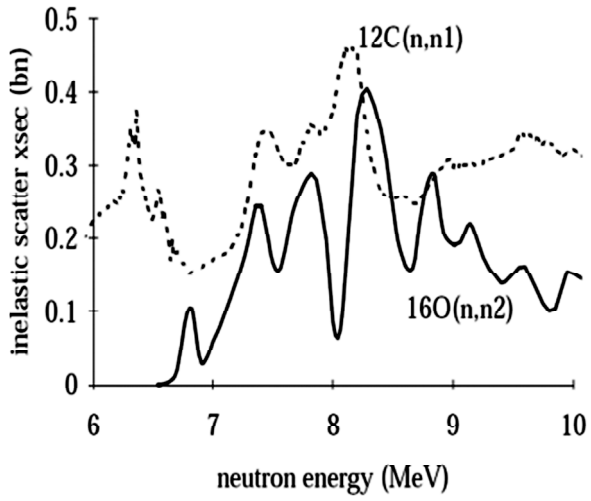

Figure 2: Inelastic Scattering Cross Sections for the First Excited State in Carbon and Second Excited State in Oxygen

Eqn [1] can be rewritten for PFNA in the form

$$R = \{<T_n><T_\square>\}\ [S_n\ I_p\ \tau_p f \Delta\Omega_n]\ \{S_\square\ \Omega_\square\}\ <\varepsilon_\square>$$

Eqn. [2]

where $S_\square$ = gamma source (gammas/*sr-n*)

$\Omega_\square$ = detector solid angle from gamma source

$<T_\square>$ = average gamma transmission to detector

This is the same as Eqn. [1], with the factor $\{S_\square \Omega_\square\}<T_\square>$ added to account for the production and transport of gamma rays.

These systems vary in size and diversity, and they include large installations such as the Spallation Neutron Source, and smaller photoneutron sources.

Binding energy,

$E = mc^2$; mass and energy are equivalent

c = velocity of light = 2.99792×10^{10}cm/s

1 amu = 1.660×10^{-24}g

$E = (1.660 \times 10^{-24}\text{g})\ (2.99792 \times 10^{10}\text{cm/s})^2$

$= 1.492 \times 10^{-3}$erg

1 eV = 1.602×10^{-12}erg

$\therefore$ 1 amu = 931.5 MeV

Alternatively one may say that $c^2 = 931.494$ MeV/u

Mass Defect = Δ ; This is sometimes called the Mass Excess.

$\Delta = (M - A)c^2$; units of Δ in MeV

Or

$M = A + \Delta/c^2$; Units of M in amu abbreviated u

Example:

$$M(^4He) = 4.002603\ u$$

$\Delta = (M–A)c^2 = (4.002603 - 4)u(931.494\ \text{MeV/u}) = 2.425$ MeV

Nuclear Reaction Energetics - Q values

Q is the energy RELEASED in a nuclear reaction, that is when two nuclei collide.

i.e., for $A + B \rightarrow C + D + Q$

$Q = \Sigma\,\Delta$ (reac tan *ts*) $- \Sigma\,\Delta$ (products)

Q = + $\rightarrow$ EXOTHERMIC

Q = – $\rightarrow$ ENDOTHERMIC

A negative Q value can always be overcome by accelerating one of the reactants and converting kinetic energy to mass energy.

Among the various light-ion accelerators, compact devices designed as hermetic, sealed tubes that use deuterium-deuterium (D–D) and deuterium-tritium (D–T) reactions have found the most widespread use in industry.

$$D + 2H \rightarrow 3He + n + Q = 3.270\ \text{MeV}$$

These accelerators generate neutrons of ~2.5 and ~14.1 MeV, respectively. Thousands of such small, relatively inexpensive systems have been built over the past five decades, and the number and variety of their applications are growing steadily [From Reference (6)]. The basic design of a modern compact accelerator neutron generator does not vary much from those of other particle accelerators. It consists of a source to generate positively charged ions; one or more structures to accelerate the ions (usually up to ~110 kV); a metal hydride target loaded with either deuterium, tritium, or a mixture of the two; and a gas-control reservoir, also made of a metal hydride material. The most common ion source used in neutron generators is a cold-cathode, or Penning ion source, which is a derivative of the Penning trap used in Penning ion gauges.

Example: Fusion power utilizes the following reaction

$^2H + {}^3H \rightarrow {}^4He + {}^1n + Q$

$Q = \Delta(^2H) + \Delta(3H) - \Delta n - \Delta(^4\text{He})$

$Q = 13.136 + 14.950 - 8.071 - 2.425$

Q = 17.590 MeV

The reaction can be as below,

$$D + 3H \rightarrow 4\text{He} + \text{n} + \text{Q} = 17.590\ \text{MeV}$$

When a 122-mm projectile filled with high explosives is examined with a pulsed neutron generator, a gamma-ray spectrum taken during a neutron pulse (blue) reveals characteristic carbon, nitrogen, and oxygen peaks, while a gamma-ray spectrum taken between pulses (red) reveals hydrogen and iron peaks, as can be seen in Figure 3[Reference 4].

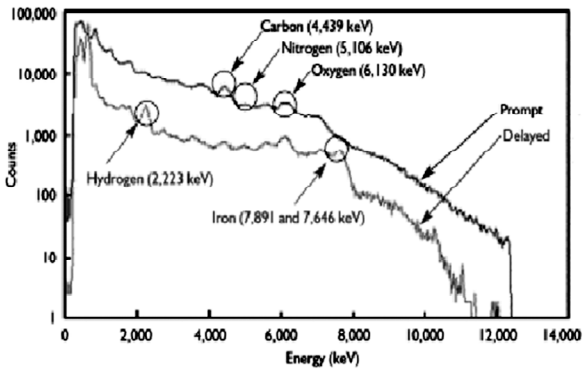

Figure 3: 122-mm Projectile Filled with High Explosives is Examined with a Pulsed Neutron Generator

5. CONCLUSION

The accelerator requirements for FNTS are determined primarily by detector count rates and not by fundamental accelerator limits. The main requirement for accelerator

designers is to reduce size and cost. For PFNA and 17-MeV neutron interrogation methods, the gamma-ray count rates are directly proportional to the accelerator current. These techniques could make use of increased accelerator current. This can be accomplished either by inserting the entire system onto the robotic platform, vehicles, or by attaching the sensor head to a robotic arm, where actual explosives detection takes place.

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