Simulation of a tagged neutron inspection system prototype

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Abstract.

The illicit trafficking of explosive materials in cargo containers has become, in recent years, a serious problem. Currently used X-ray or γ-ray based systems provide only limited information about the elemental composition of the inspected cargo items. During the last years, a new neutron interrogation technique, named TNIS (Tagged Neutron Inspection System), has been developed, which should permit to determine the chemical composition of the suspect item by coincidence measurements between alpha particles and photons produced. A prototype of such a system for container inspection has been built, at the Institute Rudjer Boskovic (IRB) in Zagreb, Croatia, for the European Union 6FP EURITRACK project. We present the results of a detailed simulation of the IRB prototype performed with the MCNP Monte Carlo program and a comparison with beam attenuation calculations performed with GEANT3/MICAP. Detector signals, rates and signal over background ratios have been calculated for 100 kg of TNT explosive located inside a cargo container filled with a metallic matrix of density 0.2 g/cm^3. The case of an organic filling material is discussed too.

1. Introduction

The terrorist use of cargo containers has become, in recent years, a serious threat for civil populations. At present, control systems are largely based on X-ray or γ-ray radiography, which cannot give information on the chemical composition of the inspected items [1].

Recently, the EURITRACK project (EURopean Illicit Trafficking Countermeasures Kit) has been approved within the 6th Framework Program of the European Union "FP6-2004-IST-2 Proposal/Contract 511471". The project is aimed at developing a cargo inspection system to ascertain the presence or not of threat materials or smuggled goods without opening the cargo container. It is based on an innovative Tagged Neutron Inspection System (TNIS), which uses the Associated Particle Image (API) technique [1, 2, 3].
A prototype of a such system has been constructed at the Neutron Laboratory facility of the Institute Ruder Boskovic (IRB) in Zagreb, Croatia.

We report here the results of a detailed simulation of the IRB prototype performed with the MCNP Monte Carlo program [4] and a comparison with neutron beam attenuation calculations performed with GEANT3/MICAP [5]. We consider the case of 100 kg of TNT explosive located at the center of the cargo container and surrounded by a metallic or organic filling matrix. The metallic matrix is the demonstration case of the EURITRACK project and the organic matrix accounts for the large portion of containers filled with organic goods.

2. The TNIS measurement system
The inspection based on the TNIS system is performed only if a first level X-ray scanning of the cargo has individuated a suspect object.

In this case the container is irradiated with fan beams of 14 MeV neutrons produced by the deuterium-tritium reaction in a sealed tube neutron generator. The beam is tagged by detecting the associated alpha particle produced in the reaction with a segmented $\alpha$-particle detector (API technique) [2, 3]. The position of the alpha particle defines the neutron emission angle (because alpha and neutron are emitted almost back-to-back). Neutrons undergo inelastic scattering on chemical elements of the cargo with emission of gamma rays. The time delay between the hit in the alpha tracker and the detection of the gamma produced determines the depth of the neutron collision.

The analysis of the relative amounts of carbon, oxygen and nitrogen in the $\gamma$-ray spectrum makes possible to characterize the chemical composition of the inspected volume and to sort out explosive materials and drugs from benign materials [6].

The use of fan beams allows for the simultaneous measurement of gamma rays emitted also on neighbouring voxels, thus making possible the online subtraction of the background.

3. TNIS simulation with GEANT
A first Monte Carlo simulation of the TNIS set-up has been performed using simulation codes based on GEANT, version 3.21 [5]. In order to simulate the interactions of low energy neutrons (from 0.025 eV to 10 MeV) on different nuclei, a specific package of subprograms called MICAP (Monte Carlo Ionization Chamber Analysis Package) has been used.

We have studied the effects on the attenuation of the primary tagged neutron beam due to the presence of different filling materials inside the cargo container.

3.1. Simulation of the TNIS geometry
The simulation of the TNIS geometry is shown in figure 1.

The tritium target is placed inside a vacuum chamber at the position (0, 0, 127 cm) of a Cartesian coordinate system with x-axis along the deuteron beam direction and y-axis along the produced neutron beam. The target has a typical diameter of 2.5 cm and is rotated by 45° with respect to the deuteron beam direction. The vacuum reaction chamber is a 1 mm thick stainless steel cylinder having a diameter large enough to contain the target and the $\alpha$-particle detector matrix. The $\alpha$-particle tracking system consists of an 8×8 matrix of 6×6 mm$^2$ YAP:Ce scintillators coupled with a multianode photomultiplier tube and is placed inside the reaction chamber in the (x, z) plane, at a distance of 15 cm from the T-target.

The cargo container is simulated by a 4 mm thick iron box of 400×250×240 cm$^3$. The first wall of the container is at 30 cm from the T-target. A hypothetical large area (300×300 cm$^2$) position-sensitive surface is placed at different distances from the T-target in order to study the characteristics of the tagged neutron beam. The container may be filled with different materials.
3.2. Results

To study the effect of the filling material on the primary tagged neutron beam, the neutron position-sensitive surface has been placed at 90, 150, 210 and 285 cm from the T-target. The position at 150 cm corresponds roughly to the middle of the container, the one at 285 cm to the second wall of the container.

For each position the number of "unperturbed" neutrons, defined by the condition of having energy $E_n > 13.6$ MeV, hitting a given area of the surface, has been determined. The definition of unperturbed neutrons is used to evaluate the fraction of the tagged neutron beam that is hitting a given target, without suffering from previous scattering interactions. The unperturbed neutrons are directly correlated with the associated $\alpha$-particle detected in the $\alpha$-tracker, therefore the flight direction and time of flight of the neutron from the T-target can be correctly reconstructed.

The calculations have been initially performed with the container filled with an iron-based material, having density $\rho = 0.1, 0.2, 0.5$ and 1.0 g/cm$^3$. The same calculations have been repeated in the case of a cargo container filled with an averaged organic matrix of composition $C_{2.6}H_{5.05}N_{0.55}O_{1.6}$ and density $\rho = 0.5$ g/cm$^3$.

The results are reported in table 1 for each of the filling materials. We may note that the higher the density the lower is the number of unperturbed neutrons that can scan the whole container. For example, in the case of an iron load with $\rho = 0.5$ g/cm$^3$, only 8% of the initial tagged neutron beam will be transmitted without interaction through the cargo container. In the organic material, the primary beam intensity is reduced to about 1% of the initial value already in the middle of the container. In the latter case, the use of the neutron tagged beam to explore in depth the cargo container asks for a specific TNIS design (see later).

4. Simulation of the IRB set-up with MCNP

The IRB prototype has been simulated using MCNP Monte Carlo program, version 4c [4].

The neutron generator of the TNIS prototype at IRB is composed of a deuteron beam of 150 keV, from a 300 keV electrostatic accelerator, hitting a tritium target and an alpha particle tracker based on a matrix of YAP:Ce detectors.
Table 1. Percentages of unperturbed neutrons at different distances from the tritium target, relative to the initial tagged neutron beam, calculated with GEANT Monte Carlo program for an iron-based filling material at different densities and for an average organic matrix.

| T-target container distance with air | Fe 0.1 g/cm³ | Fe 0.2 g/cm³ | Fe 0.5 g/cm³ | Fe 1.0 g/cm³ | org. 0.5 g/cm³ |
|-------------------------------------|--------------|--------------|--------------|--------------|----------------|
| 90                                  | 91%          | 74%          | 61%          | 36%          | 18%            | 8.0%           |
| 150                                 | 92%          | 68%          | 51%          | 22%          | 6.0%           | 0.8%           |
| 210                                 | 90%          | 63%          | 43%          | 14%          | 2.0%           | 0.1%           |
| 285                                 | 87%          | 54%          | 33%          | 8.0%         | 0.7%           | –              |

4.1. Simulation of the IRB geometry

The simulation of the set-up is built in a three-dimensional space using a (x, y, z) Cartesian coordinate system, centred in the middle of the container, as shown in figure 2.

The T-target is simulated by a copper cylinder of radius 3.5 mm and 0.3 mm thick, its axis being directed at 53.3° with respect to the y beam reference axis.

The beam is uniformly distributed in a cone with the axis directed along the y axis in order to simulate the tagged neutron beam, but may also be isotropically distributed over $4\pi$ to simulate the uncorrelated background. The source is surrounded by a cylindrical vacuum reaction chamber of radius 10 cm and is placed 127 cm above the soil, in order to align the tagged neutron beam cone with the TNT target.

A section of the cargo container is simulated by a 2 mm thick iron box with dimensions $200 \times 240 \times 235$ cm³ and opened at the two ends, the first wall of the container being 50 cm from the T-target. Ribs profiles of the container lateral walls are also simulated.

The target is made up by a block of 100 kg of TNT explosive ($\rho = 1.5$ g/cm³), with a surface of $40 \times 40$ cm² totally lighted by the beam spot of opening $\Delta \Omega = 37$ msr. The TNT target is surrounded either by a metallic or organic matrix that fill all the remaining cargo volume. The metallic matrix is composed of 0.2 cm thick iron boxes $66 \times 60 \times 50$ cm³ ($66 \times 60 \times 35$ cm³ for the higher layer), filled with bundles of iron wire of density $\rho = 0.2$ g/cm³; the organic matrix consists of panels made of dry (10% water) spruce wood with density $\rho = 0.5$ g/cm³.

Three detector arrays have been simulated. The "reflection array" is simulated by a 5”×5” NaI(Tl) γ-ray detector, placed below the neutron source on an aluminium stand and surrounded by composite iron and lead shadow bars to shield from the direct neutrons and photons emitted by the neutron source. The "transmission array" is simulated by a 4”×2” CH₂ neutron detector (used as beam attenuation monitor) placed along the collimated beam line after the cargo and a 5”×5” inch NaI(Tl) γ-ray detector, placed below the neutron detector. The two detectors are positioned on a stand very similar to the reflection one and surrounded by lead shadow bars. The reflection/transmission arrays are 40 cm away from the container walls. The "top array" is made up of a 5”×5” NaI(Tl) γ-ray detector, surrounded by lead shadow bars, and is vertically aligned with the TNT target.

4.2. MCNP results

To evaluate the signal count rates and the signal over background ratio in the gamma detectors, MCNP provides a number of estimators, named "tallies", with different physical meaning.

A tally of type F1, called "surface current tally", gives the number of particles crossing (entering or exiting) a surface. No account is given for the neutron or photon interactions inside the detector material. Tallies of type F1 are useful to evaluate currents in different positions.
Table 2. Percentages of unperturbed neutrons at different distances from the tritium target, relative to the initial tagged neutron beam, calculated with MCNP Monte Carlo program for an iron-based filling material at different densities.

| T-target container distance with air | Fe 0.1 g/cm³ | Fe 0.2 g/cm³ | Fe 0.5 g/cm³ | Fe 1.0 g/cm³ |
|-------------------------------------|--------------|--------------|--------------|--------------|
| 90                                 | 94%          | 85%          | 77%          | 57%          | 34%          |
| 150                                | 93%          | 77%          | 62%          | 33%          | 11%          |
| 210                                | 93%          | 68%          | 50%          | 19%          | 3.5%         |
| 285                                | 89%          | 59%          | 38%          | 10%          | 1.0%         |

and are typically used for transmission calculations.

To obtain the number of interactions of photons in the $\gamma$-ray detector an F4 tally on photons can be used. The F4 tally computes the average particle flux in a cell by summing track lengths for all particle tracks in that cell. When multiplied by the specific photon cross sections that dominate in the investigated energy range (Compton scattering and pair production) it provides the number of primary photon interactions in the detector volume. The obtained value is normalized by source particle, so giving the probability to have such an interaction, whatever the total deposited energy in the detector may be. In this way we account for photon primary collisions in the detector material. Furthermore, this technique takes also into account direct neutron collisions in the detector material that generate photons inside the detector.

Finally, the F5 + F8 tally method is a statistically very efficient approach to estimate the gamma signal in a physical detector. An F5 "point detector tally" gives a deterministic estimate of the photon flux at a given point in space, accounting for all possible interactions of the source particle along the path from the source to the detector. This flux is given in input to a second step to eventually produce a final F8 "pulse height tally" in the detector. This tally gives the energy distribution of pulses created by photon interactions in the cell that models the physical detector, normalized by source particle.

In this work we have calculated the count rates on the top detector and we have compared the results obtained with the F4 and the F5 + F8 techniques.

5. Study of the beam attenuation

We have simulated, with MCNP, the attenuation of the tagged neutron beam due to the cargo filling materials with an approach similar to one we have used in the GEANT simulation, in order to compare the results produced by the two different Monte Carlo programs.

In table 2 the results obtained by MCNP are shown for a void container and an iron filling material at different densities. The comparison of table 2 and table 1 shows similar behaviours for the two calculations in the different filling conditions: the difference in absolute values is motivated by the different thickness of the container walls and by the different cargo depth used in the two simulations. In both cases, with an iron density of $\rho = 1.0$ g/cm³, which corresponds to scrap metal, the "unperturbed beam" surviving at the second wall of the cargo container is less than 1%.

6. Count rates for signal and background

To calculate the count rates for the signal on the top detector, we have calculated the $\gamma$-ray arrival time distribution in this detector with the tagged beam, using an F4 tally. We would like to stress that the time distribution provides information on the position of the different
materials encountered by the 14 MeV tagged neutrons. The unperturbed tagged beam has a velocity of about 4.5 cm/s. So, selecting a suitable time window $\Delta t$, it is possible to select the signal due to the photons coming from the tagged neutron interacting in the TNT volume.

In this time window, the $\gamma$-ray energy distributions have been calculated both with the F4 and F5 + F8 techniques. An energy window $\Delta E$ from 2 until 8 MeV has been adopted, in order to select the energy region where the $\gamma$ peaks from TNT elements are produced (mostly 4439 keV for carbon, 6130 keV for oxygen, 2313 keV and 5108 keV for nitrogen). With this procedure most background from the tagged neutrons interacting inside the filling matrix can be cut off, at least in the case of the metallic matrix.

The $\gamma$-ray energy distribution obtained in the previous condition gives the probability $P_S$ of having a signal mostly coming from the explosive. By multiplying this probability, integrated over the selected energy window, by the emission rate of the tagged beam, we can evaluate the count rate $R_S$, defined as the number of good coincidences per second:

$$R_S = I \times P_T \times P_S,$$

where $P_T = \Delta \Omega/(4\pi)$ is the trigger probability, $I = 10^8$ n/s is the neutron source intensity in the overall solid angle and $P_S = \Sigma_{\Delta E} P(E)$ is the probability of having a signal from the explosive, integrated over the selected energy window $\Delta E$.

In order to evaluate the random background from the anti-tagged beam (most of the neutrons), simulations have also been performed using neutrons emitted out of the tagged cone and the energy distribution has been calculated. In this case no time information is available.

To obtain the count rate for the random background $R_B$, representing the number of pulses (in the coincidence time window $\Delta t$) coming from neutrons emitted out of the tagged cone, we multiply the anti-tagged count rate, in the selected energy window, by the total fraction of time in which the signal time window $\Delta t$ is open (emission rate of the tagged beam multiplied by $\Delta t$):

$$R_B = I \times (1 - P_T) \times P_B \times (I \times P_T \times \Delta t)$$

where $P_B$ is the interaction probability for the anti-tagged beam, integrated over $\Delta E$.

The background coming from direct neutrons that interact in the detectors giving charged particles has been also estimated, using an F4 type tally on neutrons and setting proper cross sections for charged particle production. This contribution is of the order of few percent.

Finally, we have calculated the signal to noise ratio $R_S/R_B$ that will be compared with the experimental data.

### 6.1. The metallic matrix case

In this simulation the container has been filled with boxes of Fe-56 (density $\rho = 7.87$ g/cm$^3$) with dimensions 66×60×50 cm$^3$ (66×60×35 cm$^3$ for the higher layer), having 0.2 cm of thickness and including bundles of iron wire of density $\rho = 0.2$ g/cm$^3$.

In figure 3(a) the $\gamma$-ray time distribution for the tagged beam, on the top detector, is shown. The full line represents the photons from neutron interactions in a container with TNT target, while the dashed line corresponds to the case where TNT is replaced by an empty iron box. The peak corresponding to the signal is clearly seen and the time window chosen is $\Delta t = 7$ ns.

The $\gamma$-ray energy spectrum for the tagged beam in $\Delta t$ on the top detector, calculated with the F5 + F8 method, is shown in figure 3(b), full line. The peaks due to the neutron interactions in TNT elements are clearly seen.

The inelastic scattering interactions, within $\Delta t$, of the tagged neutrons on the matrix elements constitute most of the tagged background. In the case of the iron matrix, this contribution is small and the typical peaks are produced mostly out of the selected energy window.
Moreover, the tagged background due to the direct neutrons that interact inside the top detector is negligible; therefore, the F5 + F8 spectrum represents the best evaluation for the signal ($R_S = 6.4$ counts/s).

The energy spectrum due to the random background, calculated with the F5 + F8 method, is shown by a dashed line in figure 3(b). In this approach the background coming from gamma rays generated by interactions of direct anti-tagged neutrons is not accounted for; therefore uncorrelated background evaluation must be corrected using an F4 type tally. The amount of this correction depends on the distance detector-source and on the detector shielding. The estimated signal to noise ratio, once the correction for the random background due to direct neutrons has been made, results $R_S/R_B = 1.3$. This ratio will be compared with the experimental signal to noise ratio from the data that will be collected at IRB laboratory in Zagreb.

6.2. The organic matrix case
The organic matrix is composed by panels made of dry (10% water) spruce wood with composition $C_{3.8}H_{6.5}N_{0.13}O_{2.9}$ and density $\rho = 0.5$ g/cm$^3$.

If the TNT is surrounded by an organic matrix, the $\gamma$-ray signal from the time distribution in the top detector is much lower due to the beam attenuation and is hidden by the tagged neutron interactions in the matrix material (see figure 4(a)).

The $\gamma$-ray energy spectrum for the signal, calculated in the same time window of the metallic case, is shown as the full line in figure 4(b). In this case the tagged background due to the neutron interactions on the organic matrix, that contains the same TNT elements (C, H O and N), is undistinguishable from the signal. Analogously, the random background (dashed line in figure 4(b)) has the same behaviour of the signal.

So, to improve the signal to noise ratio evaluation we need more stringent features on the gamma detector geometry, in particular the use of passive lead collimators is needed [7].

7. Conclusions
The Tagged Neutron Inspection System (TNIS) is an innovative neutron interrogation technique that should allow the determination of the chemical composition of a suspect item hidden in
Figure 4. Organic matrix, top detector: (a) γ-ray time distribution for the tagged beam; (b) signal (full line) and random background (dashed line), calculated with the F5 + F8 method.

a cargo container by analysing the γ-ray spectra produced by inelastic scattering of a tagged neutron beam hitting the target.

A prototype of a TNIS system has been constructed at the IRB Neutron Laboratory in Zagreb, Croatia, in connection with the European Union EURITRACK project for container inspections. Detailed simulations of the IRB prototype have been performed with GEANT and MCNP Monte Carlo programs. The geometry of the TNIS has been described in detail and γ-ray time distributions and physical energy spectra have been calculated. Calculations of the neutron beam attenuation have been made with GEANT and MCNP in a similar geometrical lay-out and a comparison between the two different techniques has been presented. Count rates for signal and random background and signal to noise ratios have been produced for the top detector in the reference case of the EURITRACK project: 100 kg of TNT explosive located inside the cargo container filled with a metallic matrix of density 0.2 g/cm$^3$. The case of an organic filling material has also been discussed. In this situation the detection of the suspect object is more difficult, due to screening effect of the material surrounding the target, given the presence of the same elements (C, H O and N) in both materials and to the neutron beam attenuation. The inspection of the cargo filled with organic materials ask more stringent features on the gamma detector, in particular the use of collimators to improve the signal to noise ratio.

Experimental data will be collected at the end of year 2005 at the IRB Neutron Laboratory in Zagreb, Croatia. These data will allow the Monte Carlo calculations to be validated.

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