A Large Surface Neutron and Photon Detector for Civil Security Applications

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Motivation

• The security of ports and transportation is of utmost importance for the development of economy and the security of a nation.

• Among the necessary actions to ensure the security of ports and borders, the inspection of cargo containers is one of the most time consuming and expensive procedures: over 9 million containers passed through Italian ports in 2008.

• Potential threats are the smuggling of radioactive materials and in particular of special nuclear materials (SNM) such as highly enriched uranium (HEU) or weapon-grade plutonium.

• New techniques for the inspections of cargo containers should be fast, allow the detection and identification of dangerous materials, and be non-invasive, to reduce the costs and shipping delays.

We propose to use a large surface neutron detector based on plastic scintillator to identify the presence of fissile or fertile material inside a container.
Existing Systems

- **Active Interrogation Systems**: use external radiation sources (neutrons or photons) to induce reactions as fission, photo-fission, nuclear resonance fluorescence, ...
  - Pro: high induced reaction rate results in high sensitivity
  - Con: safety issues in usage of radiation sources, dose limits in public areas, irradiation limits on inspected items (food, ..)

- **Passive Systems**: rely on detection of intrinsic radiation emitted by the material, such as neutrons from spontaneous fission or (α,n) reactions or characteristic photon lines
  - Pro: ideal for usage in public areas
  - Con: effectiveness depends on SNM type and presence of shields; low spontaneous fission rate of HEU requires large surface detectors

- Existing systems employ scintillators for gamma detection and 3He tubes for neutron detection

*The proposed detector can be used both in passive and active systems for simultaneous detection of neutrons and photons with large acceptance*
Detector Layout

- Matrix of plastic scintillator bars (16 x 4 bars of 200 cm x 6 cm x 6 cm)
- Bars wrapped in Mylar foils with Gadolinium coating for neutron capture
- 3 mm Lead foils between the scintillator planes to increase photon absorption
- Scintillator light read on both ends by 2” PMTs

Total surface of ~ 2 m²
The inspection system will consist of two detectors mounted few meters a part to form a portal.

Thanks to the modularity of the detector, the system can be optimized for the specific application by modifying the number of scintillator bars.
GEANT4 Simulation

Full simulations of detector response to neutrons and photons with GEANT4 (v.4.9.2)

Photon and neutron energy distribution generated according to typical fission spectra

Step-by-step tracking of particles through the detector

Simulations results were used to optimize the relevant parameters as the detector dimension, number of scintillator bars, gadolinium foils thickness, readout, ...
**GEANT 4 Simulation**

**Photons:**
interact primarily through Compton scattering
⇒ **few hits in the entire detector**

**Neutrons:**
scatter elastically on the hydrogen in the scintillators, till captured by the Gadolinium producing a photon cascade (total energy released ~ 8 MeV)
⇒ **several hits in the detector**
Simulations of scintillation light transmission and collection using effective parameters:

- scintillation light yield $N = 1600 \times$ optical photons/MeV
- attenuation length: $\lambda = 2 \times m$
- light collection surface: 2" pmt
- QE = 15%

One hit in a bar is reconstructed if a signal greater than 4 p.e. is detected by both PMTs, corresponding to a 150keV threshold

* very conservative values have been used in the assumption a first prototype may be built with low cost/low performance material
The segmentation of the detector allows to determine the particle impact point on the detector surface.

Neutrons release more energy than photons because of the gamma cascade emitted by the Gd upon capture.

The hit multiplicity (number of bars involved in one event) is higher for neutrons allowing for n/\gamma discrimination.
Detection Efficiency

The hit multiplicity allows to distinguish neutrons from photons

For example, requiring multiplicity $N_{hit} > 3$, the detection efficiency for neutrons is 28% and for photons 0.17%, with a rejection factor of 165

The multiplicity cuts can be applied in the software analysis allowing to use the device both to detect neutrons and photons

<table>
<thead>
<tr>
<th>Threshold ($N_{phef}$)</th>
<th>$N_{hit}$</th>
<th>$\text{Eff}_n$ (%)</th>
<th>$\text{Eff}_\gamma$ (%)</th>
<th>R</th>
</tr>
</thead>
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<tr>
<td>4</td>
<td>&gt; 0</td>
<td>87</td>
<td>66</td>
<td>1.3</td>
</tr>
<tr>
<td>4</td>
<td>&gt; 1</td>
<td>55</td>
<td>16</td>
<td>3.4</td>
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<tr>
<td>4</td>
<td>&gt; 3</td>
<td>28</td>
<td>0.17</td>
<td>165</td>
</tr>
</tbody>
</table>
Detection Efficiency

The hit multiplicity allows to distinguish neutrons from photon

For example, requiring multiplicity $N_{hit} > 3$, the detection efficiency for neutrons is 28% and for photons 0.17%, with a rejection factor of 165

The multiplicity cuts can be applied in the software analysis allowing to use the device for simultaneous detection of neutrons and photons

<table>
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<tr>
<th>Threshold ($N_{phel}$)</th>
<th>$N_{hit}$</th>
<th>$E_{Eff}$ (%$n$)</th>
<th>$E_{Eff}$ (%$\gamma$)</th>
<th>$R$</th>
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<tbody>
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<td>$&gt; 0$</td>
<td>85</td>
<td>44</td>
<td>1.9</td>
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<td>$&gt; 2$</td>
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<td>0.69</td>
<td>49</td>
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<tr>
<td><strong>$&gt; 3$</strong></td>
<td></td>
<td><strong>19</strong></td>
<td><strong>0.04</strong></td>
<td><strong>475</strong></td>
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</table>

The separation between neutrons and photons can be further increased inserting lead foils (3 mm) between the scintillator planes
The results of GEANT4 simulations for neutron transport and interaction were tested by comparing with MCNPX.

Transport and interaction of 1 MeV neutrons in plastic scintillator was simulated.

Neutron flux and energy spectrum was evaluated on different surfaces in the scintillator volume.

Good agreement between MCNPX and GEANT4 is found.
GEANT4 Validation

Good agreement between GEANT4 and MCNPX both in terms of integrated flux and energy spectrum

![Graphs showing the comparison between GEANT4 and MCNPX simulations](image-url)
Applications

Detection of SNM by measuring neutron rates by spontaneous fission

Two detectors located at 2 m from the source

1 Kg of Weapon-Grade Plutonium ⇒ 6.7 x 10⁴ counts/min

10 Kg of Highly Enriched Uranium ⇒ 20 counts/min

Use of neutron/photon detector in active interrogation system

Bremsstrahlung Photons produced by a few MeV electron linac can induce photofission reactions.

Measure of induced photon and neutrons rate below and above fission threshold would allow the detection of fertile material
**Background Sources**

**Cosmic rays:** can be easily discriminated because of the **large deposited energy** (a charged particle crossing the plastic scintillator releases 2 MeV/cm) and **event topology** (a charge particle passing through the detector would create a hit in each bar along the path).

**Spallation neutrons:** neutrons produced by cosmic rays that interacts with the surrounding material. Most problematic type of background since it is correlated with the presence of the container. Neutron/photon ratio can be used to reduce this contribution. Simulation of this background to provide a quantitative estimate of the resulting rate are in progress.

**Environmental background:** radiation emitted by other sources. Can be measured and subtracted from the final rate.
Detector Prototype

- Measurement of the response of a single bar
- Comparison of different plastic scintillator
- Measure of the detection efficiency as a function of the deposited energy
- Measure of environmental background rates
Summary

• We have developed the conceptual design of a large surface neutron and photon detector based on plastic scintillator to be used as radiation portal monitor

• The long experience with this technology from particle and nuclear physics application ensure the stability and reliance of this detector

• Simulations of the detector response show that high efficiency for simultaneous detection of photons and neutrons can be achieved

• Neutron/photon discrimination can be achieved at the level software analysis exploiting the different event topology

• First estimates of the expected rates indicate good sensitivity to the presence of SNMs with short time measurements (minutes)

• First prototype of the detector has been assembled and will be used for first measurements of the system response and validation of the simulation results
Neutron Cross Sections

Neutron Capture Cross Section from ENDF/B-VII.0 Library

Incident energy (MeV)

Neutron Capture Cross Section from ENDF/B-VII.0 Library

Incident energy (MeV)
Detector Response

The thickness of the Gadolinium Oxide coating was chosen based on the results of simulations.

In the limit of 0 thickness, neutrons are captured by hydrogen with the emission of a 2.2 MeV photon.