Fast Neutron Imaging for SNM Detection

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Special Nuclear Materials

- Terrorist threat
- Detection by fast neutron emissions
  - passive
  - active

intensities in (kg.s)$^{-1}$

<table>
<thead>
<tr>
<th>SNM</th>
<th>form</th>
<th>Gamma-rays</th>
<th>Neutrons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Energy</td>
<td>Intensity</td>
</tr>
<tr>
<td>Uranium</td>
<td>Highly enriched</td>
<td>1.001</td>
<td>$\leq 10^4$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.6</td>
<td>$2.7 \times 10^4$</td>
</tr>
<tr>
<td>Plutonium</td>
<td>Mixed Oxide</td>
<td>0.769</td>
<td>$10^5$</td>
</tr>
<tr>
<td></td>
<td>Weapons grade</td>
<td>0.769</td>
<td>$2.3 \times 10^5$</td>
</tr>
<tr>
<td>Californium 252</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Flux from 1 kg plutonium (WGP)

- Plutonium n-emission (n.kg\(^{-1}.s^{-1}\))

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Flux (n/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{236}\text{Pu})</td>
<td>3560</td>
</tr>
<tr>
<td>(^{238}\text{Pu})</td>
<td>2660</td>
</tr>
<tr>
<td>(^{240}\text{Pu})</td>
<td>920</td>
</tr>
<tr>
<td>(^{242}\text{Pu})</td>
<td>1790</td>
</tr>
<tr>
<td>(^{244}\text{Pu})</td>
<td>1870</td>
</tr>
</tbody>
</table>

- 1 kg WGP
  - 6\% \(^{240}\text{Pu}\) + 94\% \(^{239}\text{Pu}\)
  - \(6 \times 10^4\) n/s
  - at 7 m distance \(\frac{6 \times 10^4}{4\pi (700)^2} = 0.01\) n cm\(^{-2}\) s\(^{-1}\)
Neutron back ground

- Neutron back ground
  - cosmic
  - sun
  - earth crust
  - ship effect

- Flux
  - varies
    - in time -> solar activity
    - with height / location

- $10^{-3} \text{ n cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1}$
- for 1-10 MeV $0.01 \text{ n cm}^{-2} \text{ s}^{-1}$
- equal to Pu rate at 7 m!

Imaging

- Back ground reduction
  - angular resolution, say $10^\circ$
  - reduction factor
    \[
    \frac{\pi (r \tan 10^\circ)^2}{4\pi r^2} = \frac{\tan^2 10^\circ}{4} = \frac{1}{128}
    \]
  - now 1 kg WGP detectable up to 70 m distance above back ground

- Need direction sensitive detector for fast neutrons
Back ground from cargo

- Standard detection portals?
  - not direction sensitive

- Activity present in normal cargo
  - p.e. Tiles
    - filling fraction 10%
    - fraction K 1%
    - $^{40}$K fraction 0.012%
    - half life $10^9$ yr
    - decay by β-emission (80%)

\[6 \times 10^6 \text{ Bq}\]
Detection principle

- Two successive n-p elastic scattering
- Determine:
  - interaction positions
  - energy scattered neutron $E_{n'}$
  - direction scattered neutron
  - energy of the first recoil proton $p_1$
- Determine the incident neutron energy

$$E_n = E_{p_1} + E_{n'}$$

- Calculate scatter angle $\Theta$
- Construct cone

$$\Theta = \arcsin \sqrt{\frac{E_{p_1}}{E_n}}$$

Common direction on several cones points to the source
Existing systems

- P.E. Vanier et al
Existing systems

- Bravar et al.
Detector schematic

- Interaction positions
  - light distribution on PMTs
- Time difference $t_{p2} - t_{p1}$
  - scintillation light flash timing
- Energy first proton
  - light intensity
- Positions and time difference gives $E_n$, and direction scattered neutron
  - time differences $\sim$ ns
  - track lengths $\sim$ cm
- Fast scintillator necessary
Scintillation light pulses

**NE111**
- Decay: 1.4 ns
- 10200 photons/MeV

**LaBr like**
- Decay: 16 ns
- 80000 photons/MeV
Position determination

- Light intensity
  - \( \text{pos} \sim \frac{\text{intensity difference}}{\text{intensity sum}} \)
  - suppose linear relation
  - \( \sigma \) of 3 mm

- Time difference of light
  \[ t_{\text{right}} - t_{\text{left}} = \left( \frac{L + x}{c/n} - \frac{L - x}{c/n} \right) = \frac{2x}{c/n} = 0.1 \text{ [ns/cm]} \ x \]

- Anger principle
  - accuracy?
Experimental test
Energy response

- Background
  - No lead shield
- $^{252}\text{Cf}$ source
  - No lead shield
  - With lead shield
Scintillation light pulses

**BTP3_14**
3-bromo-p-terphenyl
rise: 0.18 ns, decay: 0.57 ns
3300 photons/MeV

**NE111**
decay: 1.4 ns
10200 photons/MeV
Sample pulse shapes
Direction determination

- Assume
  - time resolution 0.4 ns
  - position resolution 5 mm
  - energy resolution 16%

- Calculate (fully drawn lines)
  - scatter angle
  - 1σ error ~ 12°

- Disregard events (dashed lines)
  - $E_{p1} < 200$ keV
  - track length < 5 mm
  - time difference < 0.4 ns
  ⇒ offset
Efficiency

- n-p and n-C interactions
- n-C interactions
  - small light yield $\Rightarrow$ go undetected
  - but change n-direction
- only n-p interactions useable
  - for hydro-carbon scintillator (10 cm cube) $\Rightarrow$ 27% of all events

<table>
<thead>
<tr>
<th>first hit</th>
<th>fraction</th>
<th>second hit</th>
<th>fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td>55%</td>
<td>proton</td>
<td>27%</td>
</tr>
<tr>
<td>carbon-nucleus</td>
<td>32%</td>
<td>carbon-nucleus</td>
<td>28%</td>
</tr>
<tr>
<td>no hit</td>
<td>13%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- other scintillators?
Efficiency

- Simulation of 2.5 MeV neutrons in 10 cm$^3$ cube scintillator
  - $E_{p1}$ versus time difference $t_{p2}-t_{p1}$
  - theory: flat distribution of $E_p$
- Some events below detection limits
  - $t_{p2}-t_{p1}$ below time resolution
  - $E_{p1}$ below 200 keV limit
  - assuming
    - 200 keV lower energy limit
    - 0.4 ns time resolution
  - $\Rightarrow$ 70% detected
- Overall efficiency $0.7 \times 0.27 = 19\%$
TEUs
Application

- Port of Rotterdam
- Container stack
  - 50 x 50 m² ~ 2500/(2.5x12) ~ 80 TEUs
  - stacked 4 layers ⇒ over 300 containers

- 1 kg Pu, 10 cm³ cube detector at 25 m, rate:
  \[
  \frac{6 \times 10^4}{4\pi (2500)^2} \times 100 \text{ cm}^2 = 0.076 \text{ n/s}
  \]

- background rate:
  \[
  \frac{\pi (r \tan 12^\circ)^2}{4\pi r^2} \times 0.01 \times 100 \text{ cm}^2 = 0.011 \text{ n/s}
  \]

- in 10 minutes:
  ⇒ 90 Pu counts on a background of 14 counts
Thank you