MeV Photons for Detection and Characterization of Concealed Threat Materials

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Threat Materials


**Explosives:** in luggage or cargo, ammunition, buried landmines and UXO’s.

**Narcotics:** cocaine, heroine, marijuana.

**Contraband:** weapons, cash, tobacco.

**Contaminating:** chemical and biological.

**Nuclear/Radioactive:** radioisotopes (dirty bomb), enriched uranium, plutonium.

**Depriving:** loss of coolant in a reactor, LDL in blood.
The Context: Crime in a Box


- More than 420 M sea containers move around the globe every year, transporting 90% of the World’s cargo.
- Karachi port (2008): illicit chemicals were intercepted, including 14,000 kg of acetic anhydride, a precursor to heroin, and 4,500 kg of acetyl chloride used to convert morphine into heroin, about 8 tons of marijuana.
- Ecuador (2005-2008): contraband electrical items, whiskey and vodka, valued at US$1.5M.
- Port Tema, Ghana (in 1 month): three stolen luxury cars in containers from Spain, declared as personal effects.
- “Inspectors often risk their lives as traffickers stop at nothing to disguise their contraband and sometimes use dangerous cover loads such as potentially radioactive scrap metal to conceal heroin and cocaine.”
Detection Challenges

- Obscured, Concealed, Hidden, Smuggled, Secreted.
- No particular geometric shape (or have a common shape).
- Detection Technology: Fast, reliable (low false alarm rate), Foolproof, simple and inexpensive.
- Need to determine peculiar distinguishing features.
- Need to find a way to detect these features.
Explosives
Characteristics

**Explosion:** rapid decomposition, release a substantial amount of energy.
Most are nitrogen-based (but some are not).

**Bonding Agent:** Nitrogen, attaches itself to the other elements (high specific power).

**Fuel:** Hydrogen and/or Carbon.

**Oxidation:** of fuel, need Oxygen.

**Detonator:** needed to trigger a high explosive.
Explosives
Detection Parameters

**Detonator:** a low explosive within a metallic tube or a shell, ignited by an electrically heated wire or a fuse.
- Common metal detectors.
- Plastic explosives contain no detonators.

**Four basic elements:** N, O, H, and C.
- Common elements in innocuous materials.
- Difficult to determine all simultaneously.
- Particular chemical & crystalline structure.

**Relative Elemental Content:** O/N, C/N and/or H/N ratios.
- Unique indicators.
- Difficult to determine.

**Mass Density:** 1300 to 1800 kg/m³ (higher than most organics & polymers, lower than most metals).

**Effective Atomic Number:** close to that of H₂O.
Illicit Drugs

Characteristics

**Hard drugs:** heroine and cocaine.
- Rich in H, C, O, Cl, and to a lesser extent, N.
- Much denser than most organics and polymers.
- Cl is a good thermal-neutron absorber.

**Recreational drugs:** marijuana, tobacco.
- Leafy, low density.
- Rich in potassium
- Illicit Drugs: naturally radioactive, $1.46$ MeV
  $\gamma$ (11%); $\beta$ (89%), $E_{max} = 1.312$ MeV.
- Illicit Drugs gamma-ray used to passively detect marijuana in large quantities concealed in shipment containers.
- Beta particles are detectable with contamination detectors (paper-cased postal parcels).
Nuclear Materials

**Fissile:** $^{239}$Pu, $^{233}$U, enriched, natural uranium, $^{237}$Np (can undergo fission) and its presence is indicative of the presence of U and/or Pu.

**Fertile:** Depleted uranium, thorium.

- Mainly alpha emitters, but also decay by spontaneous fission but at very low level.
- Fission produces neutrons and gamma-rays, detectable.
- Neutron emission is mostly indicative of the presence of a nuclear material.
- Alpha particles produce neutrons when interacting with surrounding metal or ceramic.
- Large-angle Coulomb deflection of cosmic-ray muons by the large Z-number of nuclear materials.
Non-Nuclear Radioactive Material

**Medical Isotopes:** $^{18}$F, $^{67}$Ga, $^{99m}$Tc, $^{111}$In, $^{123}$I, $^{125}$I, $^{131}$I, $^{133}$Xe, $^{201}$Tl, $^{51}$Cr and $^{103}$Pd.

**Industrial Isotopes:** $^{57}$Co, $^{60}$Co, $^{75}$Se, $^{90}$Sr, $^{133}$Ba, $^{137}$Cs, $^{192}$Ir, $^{241}$Am and $^{152}$Eu,

**Natural Isotopes:** $^{40}$K (fertilizer, kitty litter, tiles, ceramics, some plant vegetation), $^{226}$Ra (from uranium decay) and its daughters, $^{232}$Th and its decay products, and $^{238}$U in natural uranium (in colored glass and in Fiesta ware).
Biological and Chemical Threats

**Biological:** anthrax, ricin, viruses, bacteria and toxins.
- Detection requires some form of assaying using techniques commonly employed in food, clinical and environmental testing.
- Detectable by molecular recognition.

**Chemical:** nerve choking, blister agents, and chemical toxins.
- Vapor emission.
- Chemical analysis on samples for molecular recognition.
## Cargo Containers

<table>
<thead>
<tr>
<th>Type</th>
<th>Size</th>
<th>Max Mass (kg)</th>
<th>Average Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sea Cargo:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard 20’</td>
<td>5.900 × 2.350 × 2.393</td>
<td>21,770</td>
<td>656</td>
</tr>
<tr>
<td>Platform 40’</td>
<td>12.19 × 2.5 × 1.95</td>
<td>39,200</td>
<td>660</td>
</tr>
<tr>
<td><strong>Air Freight:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main Deck Pallet</td>
<td>3.17 × 2.44 × 2.44</td>
<td>6,804</td>
<td>361</td>
</tr>
<tr>
<td>LD-11</td>
<td>3.17 × 1.52 × 1.62</td>
<td>3,176</td>
<td>400</td>
</tr>
<tr>
<td>Shipping Trailer</td>
<td>2.5 × 4.25 × 9.2</td>
<td>44,000</td>
<td>450</td>
</tr>
</tbody>
</table>
# Cargo Containers

- 300 s inspection time, false alarm < 1%
- Can contain high $Z$ material, machine parts and electronics.
- Penetration requires either high intense x-rays and/or high-energy X-rays in the MeV range.
- FDA requires photon energy < 10 MeV.

<table>
<thead>
<tr>
<th>Photon Source / (kg/m$^3$)</th>
<th>Attenuation Coefficient (m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Semtex (1,500)</td>
</tr>
<tr>
<td>200 keV</td>
<td>19.7</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>8.5</td>
</tr>
<tr>
<td>2-MeV</td>
<td>10.8</td>
</tr>
<tr>
<td>6-MeV</td>
<td>6.3</td>
</tr>
<tr>
<td>10-MeV</td>
<td>4.9</td>
</tr>
</tbody>
</table>

Runkle et al., NIMA A603 (2009) 510-528.
Positron Emission

- $^{14}\text{N}(\gamma,\text{n})^{13}\text{N}$ reaction.
- $^{13}\text{N} \frac{t_1}{2} = 600$ s.
- Two coincident 511 keV gamma rays, allowing PET.
- $E_{\text{threshold}} = 10.6$ MeV.
- Only Nitrogen is detected.
- $e^+$ can also be produced by other elements, e.g. Cu in electronic components (Cu has 20 times higher $\sigma$ than N).
- False negative can be reduced by the geometry of PET.
Resonance

- Nitrogen-specific radiograph from 9.17 MeV level of $^{14}$N.
- Resonance absorption with $\sigma = 2 \text{ b } ( > 10^3 \sigma_{e^+} \text{ of } ^{14}\text{N} (\gamma,\text{n}) ^{13}\text{N})$.
- Nitrogen specific.
- Difficult to detect these high-energy photons.
Photonuclear

- Photo-nuclear reactions with nitrogen, carbon, oxygen and chlorine.
- Thresholds energy around 5 to 10 MeV.
- Giant dipole resonances at 15 to 25 MeV.
- Cross-sections on the order of mb and nb.
- Reaction products promptly $\beta$-decay (ms), with end-point between 10 and 20 MeV: bremsstrahlung spectra detected.
- Elements can be differentiated by the $t_{\frac{1}{2}}$ of decays (differential die-away).
- Requires high energy photons: protons and neutron production between 17 and 45 MeV photons.
Nuclear Resonance Fluorescence

<table>
<thead>
<tr>
<th>Element</th>
<th>Excitation $E$ (MeV)</th>
<th>Emitted $E_\gamma$ (MeV)</th>
<th>Strength (eV b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}\text{C}$</td>
<td>4.44</td>
<td>4.44</td>
<td>10</td>
</tr>
<tr>
<td>$^{13}\text{C}$</td>
<td>3.09</td>
<td>3.085</td>
<td>220</td>
</tr>
<tr>
<td>3.68</td>
<td>3.685</td>
<td>230</td>
<td></td>
</tr>
<tr>
<td>$^{14}\text{N}$</td>
<td>2.31</td>
<td>2.31</td>
<td>1.6</td>
</tr>
<tr>
<td>3.95</td>
<td>2.31</td>
<td>7.7</td>
<td></td>
</tr>
<tr>
<td>4.91</td>
<td>4.91</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>7.03</td>
<td>7.03</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>$^{16}\text{O}$</td>
<td>6.92</td>
<td>6.92</td>
<td>39</td>
</tr>
<tr>
<td>7.12</td>
<td>7.12</td>
<td>13</td>
<td></td>
</tr>
</tbody>
</table>

Runkle et al., NIMA A603 (2009) 510-528
Nuclear Resonance Fluorescence: Cont.

NRF spectra: water, melamine and a simulant explosive; 8.3 MeV source (Bertozzi et al., NIM B 261 (2007) 331-336).
Nuclear Resonance Fluorescence: Cont.

- Emitted high $E_{\gamma}$, can penetrate through easily.
- Higher $\sigma$ than Compton and pair production.
- No activation products, unlike with neutrons.
- Cannot detect H.
- Can use a flat source.
- Can detect many elements.
Photofission

- Fissile material undergoes photofission with high-energy photons (> 2 MeV).
- Detect emitted neutrons and gammas.
- Pulsed (@ up to 500 Hz) 2-12 MeV photon sources.
- Advanced Research and Applications Corporation (ARACOR) (Sunnyvale, California) System: 6-MeV, 3 μA, up to 50 Hz.
Summary

Field-Application of MeV Photon Sources:

- **-ve** Regulatory constraint: 10 MeV maximum photon energy for use in public environment.

- **-ve** Regulatory constraint: Exposure to inspected object limited to 0.5 Gy per inspection.

- **+ve** Measurement and decision with in a few minutes, with low false alarm rate.

- **+ve** No disruption to containers’ trans-shipment.

- **+ve** Deep penetration.

- **+ve** Strong Signal.
Some Thoughts

- Regular x-rays can only show material hidden in what is supposed to be voided:

- Need data to characterize such material: resonance fluorescence, positron emission, dose deposited, etc.

- Development of field-deployable sources.