Threat Materials: Detection and Characterization

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Threat Materials

Threat to Public Health, Wealth, Safety and Security.

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.

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.

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/m^3 (higher than most organics & polymers, lower than most metals).

Effective Atomic Number: close to that of H_2O.

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 γ (11%); β (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).

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.

Vapor Emission

Unique Nuclear Mass: peculiar molecular composition.

Volatile molecules.

Sniffers: Biological (canis).

Ion Mobility spectrometry:

- Mass of vapor molecule by measuring velocity of ion when accelerated at a constant voltage.
- Ionization facilitated by a small source of beta particles, ^{63}Ni.

Electron-capture Device: Affinity of Nitrogen to absorbing electrons.

Chromatography:

- Heating of sample wipe.
- Emerging gases injected into an ion exchange column, aided by a carrier gas.
- Gases emerge from this separation column at different times, depending on their ionic properties.

Artificial Nose.

Vapor detection:

- Effective, but too sensitive to residual amounts.
- Affected by environmental conditions: dust, humidity and temperature.
- Some plastic explosives have a very low vapor pressure.
- Tight sealing can also reduce detectability.

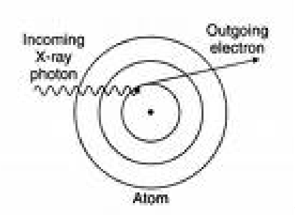
Vapor Emission

Which one is more cost effective?

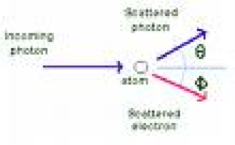
Vapor Emission: Body Scanner

Air Shower Portal

X-ray or Gamma-Ray Photons ($\approx$ 60 keV $\rightarrow$ 1.3 MeV)



$\tau_{atom} \propto \frac{Z^n}{E^m}$ Dominant at low E.



$\sigma_{atom} \propto \frac{Z}{E}$ Dominant at higher E.

Attenuation of X-ray & Gamma-Ray Photons

$$
\begin{aligned}
\mu &= N_{atom}(\tau_{atom} + \sigma_{atom}) = \frac{\rho}{Au}(\tau_{atom} + \sigma_{atom}) \\
&\propto \frac{\rho}{Au}\left(\frac{Z^n}{E^m} + \frac{Z}{E}\right) \\
&\propto \frac{\rho}{u}\frac{Z}{A}\left(\frac{Z^{n-1}}{E^m} + \frac{1}{E}\right); \frac{Z}{A} \approx \frac{1}{2} \\
&\propto \rho \text{ at high } E; \qquad \propto \rho Z^{n-1} \text{ at low } E
\end{aligned}
$$

Explosives: $\rho >$ most organics and polymers, $Z \approx H_2O$.

μ at high E: mass density, ρ.

μ at low E: combination of ρ and atomic number, Z^{n-1}.

μ at low E / μ at high E: Z^{n-1}.

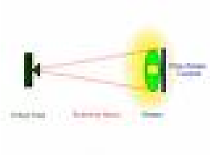
Dual E: ρ & Z^{n-1} separately.

Scattering/Transmission: ρ and ρ & Z^{n-1} separately.

How to measure μ of of X-ray or Gamma-Ray Photons

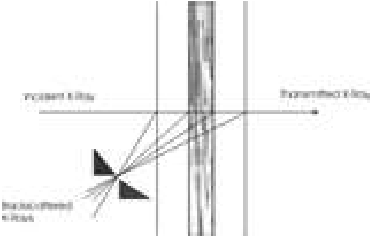
Transmission Radiography:

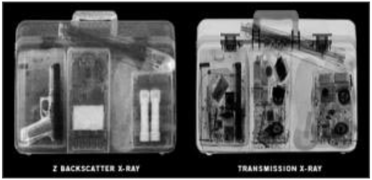
$$I(x) = I_0 \exp(-\mu x)$$



Luggage (X-ray) & Cargo (Gamma-ray) Radiography

Compton Scattering (Incoherent) $\rightarrow \rho$

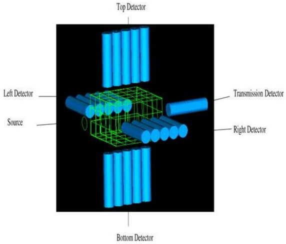


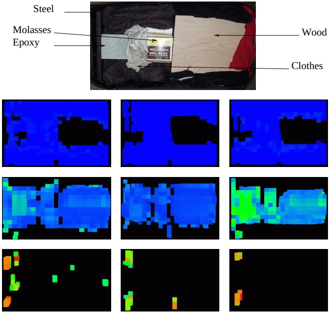


X-ray Backsatter Bodyscanner

One-Side Exposure: 3D - 3 Paramters

UNB-LTMD: ρ (from Compton Scattring), $\mu(E_{incident})$, $\mu(E_{scatter})$.

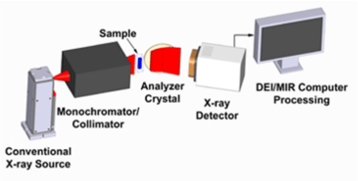


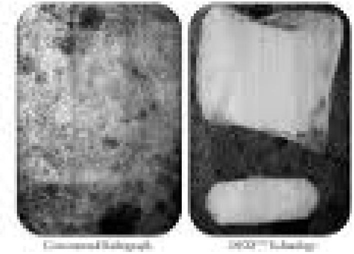


Crystalline Structure

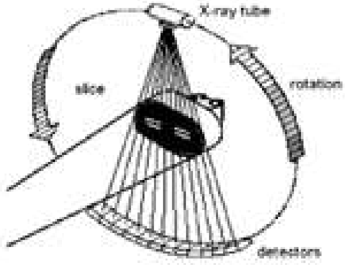
X-ray Coherent Scattering (Diffraction)

Low Energy X-rays → Diffraction Patterns → Characterize Crystals.
Diffraction Enhances X-ray Imaging (DEXI).





Computed Tomography

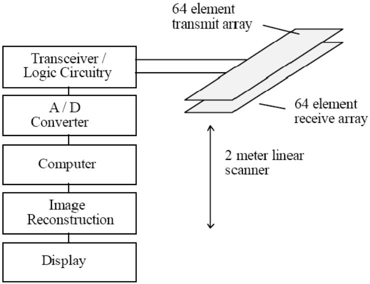


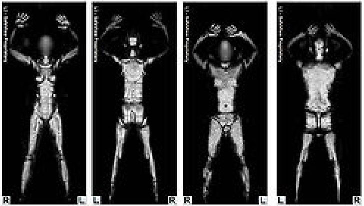
Molecular Structure

Micro (1 m - 1 mm, 300 MHz - 300 GHz) & Millimeter (27 - 33 GHz) Waves

- Determine dielectric properties.
- Mircowave transmission, refraction and reflections are affected.
- Microwave strongly absorbed by water and entirely reflected by metals.
- Lower-energy electromagnetic waves have wavelengths comparable to lattice pitch (can detect structure of crystallized explosives).
- Millimeter waves, used in body scanners for surface imaging to detect material concealed under clothing: two antennas simultaneously rotate around the body and cover its surface from all directions.

Millimeter EM waves Bodyscanner





Crystal Structure

Nuclear Quadruple & Magnetic Resonance (NQR & NMR)

- ^{14}N spin $> \frac{1}{2} = 1 \rightarrow$ a nuclear electric quadrupole moment affects electric field of the surrounding electrons.
- RF pulses to detect the presence of nitrogen in explosives.
- Produces an electric quadrupole coupling, with a resonance when valence electrons align with ^{14}N spins.
- Crystal structure determines the energy associated with this alignment, specific signature.
- NQR signal is weak, difficult to analyze, affected by metal.
- Nuclear magnetic resonance (NMR), similar principle but an external magnetic field is applied.
    - Interaction between magnetic moment of nuclei and the external field results in a resonance.
    - Energy of RF pulse, with a frequency appropriate to type of nuclei and molecular structure, is absorbed.
    - ^{1}H-^{14}N nuclear-dipole-moment cross coupling in explosive materials enables their detection with NMR.

Elemental Analysis: Neutron Activation
N, O, C, H, Cl

Nitrogen-14: Thermal-neutrons $\rightarrow$ 10.83 MeV prompt gamma-rays.

Oxygen-16: Fast-neutrons ($> 5\ \mathrm{MeV}$ $\rightarrow$ 6.13) MeV gamma.

Carbon-12: Fast-neutrons ($> 5\ \mathrm{MeV}$ $\rightarrow$ 4.43) MeV gamma

Hydrogen: Thermal-neutrons $\rightarrow$ 2.22 MeV gamma.

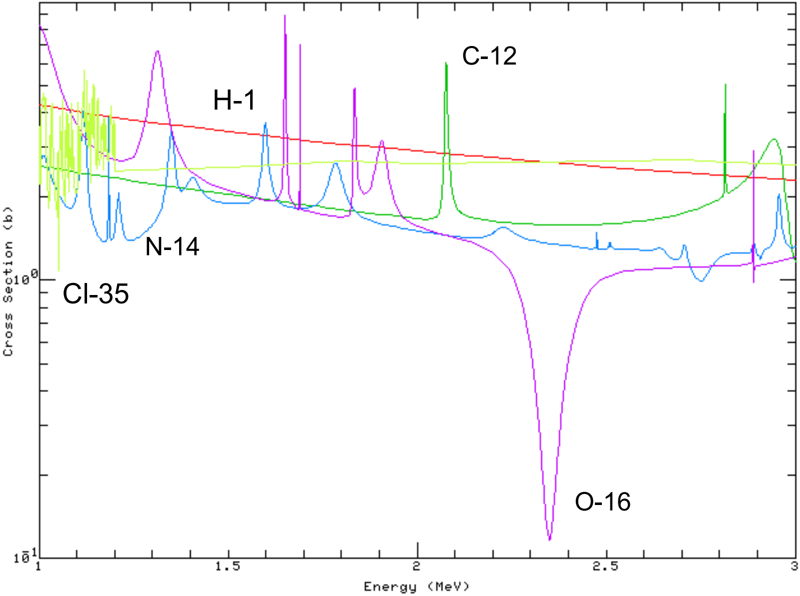
Chlorine-35: Thermal-neutrons $\rightarrow$ 517.07 MeV gamma.

Thermal Neutrons: not directly generated, bulky slowing-down material, self-attenuated, may leave undesirable secondary radiation.

Fast Neutrons: available generators, can also activate ^{14}N, slowed-down by ^{1}H, also residual activation.

Activation cross section are typically low $\rightarrow$ intense sources.

Elemental Analysis: Elastic-Scatter Resonances



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, ^{322}Th and its decay products, and ^{238}U in natural uranium (in colored glass and in Fiesta ware).

Radioactive Material Detection

- Detectable by their radiation emission, if penetrating (gamma rays & neutrons).
- Gamma and neutron emitters can be shielded, but no matter how well-shielded, some amount of radiation will penetrate through.
- Alpha and beta emitters are more difficult to directly detect.
    - Alpha particles produce neutrons when interacting with surrounding metal or ceramic.
    - β^- emitters: bremsstrahlung or heat imprint, gamma from daughter (Thermoelectric Generators: ^{90} Sr $\rightarrow$ ^{90}Yt $\rightarrow$ 2.18 MeV gamma)
    - β^+ emitters: detected by the 511 keV annihilation gamma.
    - Alpha and beta radiation may be detectable by contamination detectors.

Closing Comments

- Dealing with rare events.
- Even best of equipment will tend to have a positive-false alarm.
- Nature and type of threat are unpredictable.
- Slow detection systems are not suited everywhere.
- Efficient detection systems can come at the expense of reliability.
- Routine and predictable protocols are not desirable.
- Orthogonality of detection: more than one system each. based on different physics.

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