Contrabands detection with a low energy electron linac driven photoneutron source

Yigang Yang

Tsinghua University, Beijing, China

yangyigang@mail.tsinghua.edu.cn
1. Research motivation

2. e-LINAC based contrabands detection

3. Summary
MV X-ray images

\[ \ln \left( \frac{I_0}{I_D} \right) = N \cdot \sigma \cdot D = \mu_m \cdot t_m \propto t_m \]

constant in MeV region
In the traditional MV X-ray imaging system, mass-thickness is the only acquired information, which is not enough to indicate the existence of contrabands.

- Explosives, Drugs, and Special Nuclear Materials

- Fusion of different technologies is needed to locate and identify various contrabands from different aspects.

- Integrating different physics within one system can reduce the system complexity.
Outline

1. Research motivation

2. e-LINAC based contrabands detection
   ① High-Z materials detection with photons
   ② High-Z materials detection with photoneutrons
   ③ Explosives or Drugs detection

3. Summary
Dual-energy X-ray imaging

\[ \mu/\rho - \text{cm}^2/\text{g} \]

\[ E_1 \quad E_2 \]

\[ R = \ln T_H / \ln T_L \]

PE, Al, Fe, Pb
Scattering X-ray analysis

- CsI array for X-ray imaging
- 14bit 120MHz ADC
- Algorithm to reconstruct scattering spectra
- 3inch LaBr3 (Ce)
- Lead target
- 7 MeV e−
- Incident photon
- Scattered photon
- Transmitted photon
- Inspected matter
- Scattered photoelectron
- K X-ray
- Bremsstrahlung photon
- Photoelectric absorption
- Recoiled electron is scattered by coulomb field
- Compton scattering photon
- Bremsstrahlung photon
- Pair production
- Positron annihilation
- Rayleigh scattering
- Energy (MeV)
- Zn, Sn, W, Gd, Pb

Count rate vs. Energy (MeV) for different materials.
by analyzing the scattering X-ray spectra, Z information can be acquired

Outline

1. Research motivation

2. e-LINAC based contrabands detection
   ① High-Z materials detection with photons
   ② High-Z materials detection with photoneutrons
   ③ Explosives or Drugs detection

3. Summary
Fermion and neutral particle

- **Neutron:**
  - Neutral particle: *Penetrating capability*
  - Fermion: *Pauli exclusion principle* → *Nuclei Structure* → *gamma-rays with characteristic energies*

- **More information about contrabands can be provided by neutron related reactions.**
Why e-linac driven neutron source?

- Neutron flux: $\sim 10^{10}-15$ n/s
- Life-span: “∞”
- Deployable: Relocatable
- Operation cost: Low
- Fixed cost: ~1 M$
photoatomic or photonuclear reactions

- **Photoatomic Reactions**
  - Pe, Rayleigh, Compton, PP

- **Photonuclear Reactions**
  - $\gamma$, fission
  - $\gamma$, n

**Cross Sections (Barns)**

**Energy of Photons (MeV)**

- 238 U
- 9 Be
- 2 H

Graphs showing cross sections for different energies and elements.
Photons → Neutrons

Angular distribution of X-ray

X-ray detector array

- photoneutron yield of e-LINAC
  - 7MeV/100W : $10^{10}$ n/s
  - 10MeV/20kW : $6.7 \times 10^{12}$ n/s

$\gamma + D \rightarrow p + n$

$\gamma + ^9 Be \rightarrow 2\alpha + n$
PhotoNeutron X-ray Radiography (PNXR)

$L = 5.3 \, m$

7MeV $e^-$ pulse

MV X-ray pulse

20kg $D_2O$

$\theta = 17.8^\circ$

Neutron collimator

incident X-ray

Neutron collimator

photoneutron pulse

$\gamma$-ray

$\gamma$-ray

penetrated X-ray

CsI(Tl) detector

$1\, mm \, Cd$

Multi-Channel Scaler

$^3He$ with polyethylene or boron doped polyethylene

inspected materials

$7MeV$ X-ray attenuation

Photoneutron attenuation

Mass thickness (g/cm$^2$)

Mass thickness (g/cm$^2$)
Fused X-ray image and Photoneutron image

\[ V(t) = \frac{\ln\left(\frac{I_n(t)}{I_n(0)}\right)}{\ln\left(\frac{I_X(t)}{I_X(0)}\right)} = \frac{\mu_n(t) \times t}{\mu_X(t) \times t} = \frac{\mu_n(t)}{\mu_X(t)} \frac{\sigma_n(E_n(t))}{\sigma_X(E_X(t))} \]

- DU
- Plywood
- Melamine
- Urea
- Sugar
- Paper
- Cloth
- Al
- Fe
- Cu
- Pb
Background line
Existence of fissionable material is confirmed

<table>
<thead>
<tr>
<th>delayed neutrons of U²³⁵</th>
<th>Group</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>T₁/₂(s)</td>
<td></td>
<td>55.72±1.28</td>
<td>22.72±0.71</td>
<td>6.22±0.23</td>
<td>2.30±0.09</td>
<td>0.610±0.083</td>
<td>0.230±0.025</td>
</tr>
</tbody>
</table>

Isotopes identification through photoneutron resonant attenuation

![Graphs showing transmission versus energy for various elements such as Ag, Ho, Er, Sb, W, Ta, Nd, and Tb.](image)
Steps for locating and identifying SNMs

1. Inspected by X-ray and photoneutron penetration
   - If yes, proceed to Beta-delayed neutron analysis
   - If no, clear and go-ahead

2. Heavy metal?
   - If yes, proceed to Neutron count
   - If no, clear and go-ahead

3. Neutron count
   - If > threshold, proceed to Neutron resonance analysis
   - If no, clear and go-ahead

4. Neutron resonance analysis
   - If 235U abundance > 93%, identified as SNM
   - If no, depleted or low enriched Uranium

---

Yigang Yang*, Zhi Zhang, Huaibi Chen, Yulan Li, Yuanjing Li. “Identification of high-Z materials with photoneutrons driven by a low-energy electron linear accelerator”. IEEE Transactions on Nuclear Science (accepted on Dec. 12, 2016, in press DOI: 10.1109/TNS.2016.2638451)
Outline

1. Research motivation

2. e-LINAC based contrabands detection
   ① High-Z materials detection with photons
   ② High-Z materials detection with photoneutrons
   ③ Explosives or Drugs detection

3. Summary
(n, γ) analysis for explosives or drugs

\[ \tau = \frac{1}{N\sigma_0 v_0} \]

The \(^{10}\text{BF}_3\) counter is blinded by the X-ray pulse within this time duration

Fusion of X-ray image and elemental concentration distribution

Drugs or explosives detection system
3. Summary

- An e-LINAC can produce both X-rays and photoneutrons.

- Properties of the photoneutron source:
  ① High neutron yield
  ② Long life-span & Robustness
  ③ Relocatable and suitable for the field use
  ④ Pulsed mode, enabling the energy selective methods

- The philosophy of “one-source, two-radiation, multi-physics” can be supported by the e-LINAC driven photoneutron source to enhance the contrabands detection capability.
“one-source, two-radiation, multi-physics” for the contrabands detection

Atomic number analysis by analyzing the scattered MV X-ray spectrum

Photoneutron production

Photoneutron resonant analysis

Photoneutron and X-ray radiography

Photoneutron-induced gamma-ray analysis

Beta-delayed neutron measurement

MV X-ray imaging for the mass-thickness measurement or dual energy inspection

\[ E_n = 200\text{eV} \quad \text{and} \quad E_n = 0.16\text{eV} \]
Thanks for your attention

&

Questions please
1. Research motivation

- In the traditional MV X-ray imaging system, mass-thickness is the only acquired information, which is not enough to indicate the existence of contrabands.
  - Explosives, Drugs, and Special Nuclear Materials
- Fusion of different technologies is needed to locate and identify various contrabands from different aspects.
- Integrating different physics within one system can reduce the system complexity.