GAMMA RESONANCE AND FISSION TECHNOLOGY (GRFT)
FOR DETECTION OF EXPLOSIVE AND NUCLEAR MATERIALS IN CARGO

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Objective

BULK ANALYSIS

Trace Analysis

X-Ray
- Standard Transmission
- Computed Tomography
- Dual Energy
- Diffraction
- Backscatter

Neutrons
- Thermal Neutron Analysis
- Pulsed Fast Neutron Analysis
- Associated Alpha Particle Time of Flight
- Neutron Backscatter
- Pulsed Fast Thermal Neutron Analysis

Other Nuclear
- Gamma Backscatter
- Gamma Transmission
- Gamma Resonance Technology

Electromagnetic
- Nuclear Magnetic Resonance NMR
- Nuclear Quadrupole Resonance NQR
To present a system that is capable of detecting a variety of illicit materials and is adaptable to diverse detection requirements.

- NRD - Non-Resonance Detectors
- RD - Resonance Detectors
- ND - Neutron Detectors
- NFD - Nuclear Fluorescence Detectors
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**Presentation Outline**

- Principles
- System Components
  - Accelerator
  - Targets
  - Detectors
- Applications
- Results
- Summary
1) **GRT** - is based on resonance interaction of gamma radiation with a specific nuclear level in the nucleus of an element of interest; N, O, Cl. This differs from the photoelectric, Compton, and pair production that are atomic reactions.

2) **PHOTO-FISSION** - is a process in which gamma rays above a threshold energy induce fission in nuclear materials producing prompt and delayed neutrons.
Resonance cross section is given by the Breit-Wigner formula:

$$\sigma_{abi} = \pi \lambda^2 g \frac{\Gamma_a \Gamma}{(E - E_R^b)^2 + \Gamma^2/4}$$

where $g$ is a statistical factor given by:

$$g = \frac{2J + 1}{(2s + 1)(2i + 1)}$$
The angular correlation is maximum at 90° that needs to be considered when optimizing a stand off system based on nuclear fluorescence.
GRFT Fluorescence Process

The process of the conventional- and nuclear resonance- attenuation of gamma radiation in presence and absence of nitrogenous material.

At 10 MeV the total attenuation in N is about 0.5 barns/atom. The resonance attenuation is about 2 barns/atom.
Brookhaven National Laboratory

GRFT System Main Components

Resonance Gamma Beam

Proton Accelerator

~2 MeV, 10 mA

(p,γ) ⇒ E

4π

Target

Recoil Doppler

E_{γ} = (E - E^2/Mc^2)(1 + (v/c)cosα)

E_{γ} ~10 MeV

Detectors

Inspected Object

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A new single stage proton accelerator is chosen to replace the tandem accelerator

1) It is an intense electrostatic electron accelerator converted to accelerate protons and will be procured from a commercial supplier as a turn key unit.

2) Uses a reliable Insulated Core Transformer (ICT) power supply designed for 100 kW. Single unit can feed several accelerators. About 250 units have been deployed.

3) Electron Cyclotron Resonance (ECR) reliable ion source for currents above 10 mA, no filaments, long life, very low maintenance.

4) The system is simple to operate, can be computerized, no skilled operator required, one or more units can be supplied within short time.
Two compact accelerators (can be expanded to four) attached to a single power supply occupy a very small footprint. With a flexible cable they can be placed in any arbitrary configuration.
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**Accelerator Configurations**

- **Alpha System**
- **Beta System**
GRFT Applications
13C Target has been constructed and heat tested for 10 mA
By using different target material or a combination of materials elements other than nitrogen can also be investigated.

Layered Targets

- CS$_2$ – Enriched in $^{13}$C and $^{34}$S for detection of N and Cl.
- BN (Boron Nitrate enriched with $^{13}$C) $^{13}$C; $^{11}$B; $^{15}$N; with $E_p$ @ 1.75; 1.1; 0.6; MeV respectively, we can measure N; C; and O, simultaneously.

Composite Target of $^{26}$Mg & $^{30}$Si

At $E_p$ 1.94 & 1.91 MeV respectively to detect $^{14}$N, $^{16}$O, and $^{35}$Cl

- $^{27}$Al @ $\sim$40 7.117 MeV $^{16}$O
- $^{26}$Mg (p,$\alpha$) & $^{30}$Si (p,$\alpha$) @ $\sim$117 9.082 MeV $^{35}$Cl
- $^{31}$P @ $\sim$86 9.173 MeV $^{14}$N
### GRFT Alternative Targets

<table>
<thead>
<tr>
<th>Element</th>
<th>Target</th>
<th>$E_p$ (MeV)</th>
<th>$\sigma$ abs (barns)</th>
<th>$E_{\gamma}$ (MeV)</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{14}\text{N}$</td>
<td>$^{13}\text{C}$</td>
<td>1.75</td>
<td>2.6</td>
<td>9.17</td>
<td>$^{13}\text{C}(p,\gamma)^{14}\text{N}$</td>
</tr>
<tr>
<td>$^{40}\text{Ca}$</td>
<td>$^{39}\text{K}$</td>
<td>2.04</td>
<td>5.0</td>
<td>10.32</td>
<td>$^{39}\text{K}(p,\gamma)^{40}\text{Ca}$</td>
</tr>
<tr>
<td>$^{35}\text{Cl}$</td>
<td>$^{34}\text{S}$</td>
<td>1.89</td>
<td>1.0</td>
<td>8.21</td>
<td>$^{34}\text{S}(p,\gamma)^{35}\text{Cl}$</td>
</tr>
<tr>
<td>$^{16}\text{O}$</td>
<td>$^{19}\text{F}$</td>
<td>2.6</td>
<td>2.4</td>
<td>6.92</td>
<td>$^{19}\text{F}(p,\gamma)^{1}\text{O}$</td>
</tr>
<tr>
<td>$^{12}\text{C}$</td>
<td>$^{15}\text{N}$</td>
<td>2.6</td>
<td>1.1</td>
<td>4.43</td>
<td>$^{15}\text{N}(p,\gamma)^{1}\text{C}$</td>
</tr>
</tbody>
</table>
NE – 213 Nitrogen Rich Liquid Scintillator
Organic Solvent + Primary Solute + Wavelength Shifter

\( \text{p-xylene} \) \( \text{naphtalene} \) \( \text{PPO+POPOP} \)

emiss. \( \sim 280\text{nm} \) emiss. \( \sim 330\text{nm} \) emiss. \( \sim 425\text{nm} \)

\( \gamma \text{ Beam (} \gamma, p \text{)} \)

Using pulse shape discrimination resonance detectors measure simultaneously total and nitrogen attenuation.
Two dimensional pulse height distribution from a resonance detector clearly separates proton pulses from electron pulses. Proton pulses at 1.5 MeV are produced in the detector by the inverse \((\gamma,p)\) reaction of the resonance radiation with the N in the detector.
**Detection Efficiency**

$$\text{eff}_R(E) = \frac{\mu_{\gamma p}(E) \rho_N}{\Sigma_T(E)} \left[1 - \exp(-\Sigma_T(E) d)\right]$$

**Detectors:**
- LANL – BGO, 50x29x90 mm$^3$
- TRIUMF – Segmented BGO, 50x50x50 mm$^3$ blocks 12x12 subvolumes 4x4x50 mm$^3$, 4 PMT
- SNRC – Resonance Detector
**GRFT Performance of the Detectors**

$$F.O.M = \mu_{\text{eff,N}} \cdot \Box N$$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Resonant Detector</th>
<th>Non-Resonant Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contrast_sensitivity</td>
<td>$\int_{-\infty}^{\infty} \mu_A(E) \Phi(E) \epsilon_{\text{eff}_R}(E) , dE$</td>
<td>$\int_{-\infty}^{\infty} \Phi(E) \epsilon_{\text{eff}_R}(E) , dE$</td>
</tr>
<tr>
<td>(thin absorber)</td>
<td>$\int_{-\infty}^{\infty} \Phi(E) , dE$</td>
<td>$\int_{-\infty}^{\infty} \Phi(E) , dE$</td>
</tr>
<tr>
<td>Number_of_detected_events</td>
<td>$\int_{-\infty}^{\infty} \Phi(E) , dE$</td>
<td>$\epsilon_{\text{eff}<em>{\text{NR}}} \int</em>{-\infty}^{\infty} \Phi(E) , dE$</td>
</tr>
</tbody>
</table>
Performance of the Resonance Detectors

Resonant and Non-resonant Contrast
Sensitivity Vs Emission Line Width

Ratio of Resonant to Non-resonant FOM vs Angular Aperture
Broad Beam Attenuation

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Nitrogen Total Effective Mass Attenuation Coefficient (Resonance plus Atomic)

$\mu_e = 0.074 \text{ cm}^2/\text{g}, \ 200\text{eV}$

$\mu_s = 0.022 \text{ cm}^2/\text{g}$

Broad Beam Transmission

Energy (MeV)

Transmission / Gamma

Incident Beam Width (eV)

Total Mass Attenuation (cm$^2$/g)
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**Broad Beam Attenuation**

- **Anode**
  - LLD
  - Int.
  - Amp.
  - Diff
  - Zero Crossover
  - Time LLD 150 to 300 nsec
  - Var. Delay
  - Delay
  - AND Start TAC
  - AND Stop TAC
  - AND Scaler p
  - AND Scaler, g

- **Proton E Window**
  - SCA
  - M.S.
  - AND
  - OR
  - AND
  - Board Select
  - All Energies
  - SCA Adj. LLD Adj. Delay On/Off Address Bus

- **Gamma LLD**
  - LLD
  - M.S.
  - Delay
  - Analog SW

Brookhaven National Laboratory
1. Simultaneous detection of the resonant and non-resonant attenuation.

2. No parallax resulting from two different paths at two angles.

3. Improved contrast due to resonance energy resolution of the detector.

4. Independent of the energy width of the incident beam

5. Ratio of the resonant to the non-resonant radiation independent of beam beam stability.

6. Liquid scintillator is a very cheap detection system.

7. Arbitrarily large detectors for remote detection can be easily constructed.
A configuration of a system in an airport feeding simultaneously two inspection stations for bags.

The same system can inspect small and large objects.

A possible configuration for scanning large containers.
Using four ramps may inspect simultaneously 40 foot container in about 3 to 4 minutes, stacked containers will double the capacity. (Times extrapolated from experiments)
Applications

Single system feeds simultaneously four inspection stations at one location.

Single system feeds alternatively three inspection locations.

Each detection station can process 1600 bags/hr, 24 LD-3 containers/hr, 4 conveyors simultaneously.
Nitrogenous and non-nitrogenous objects placed in a beam.

Experiments carried out by Nahal Soreq Group

Images:

Out of resonance

In resonance
Six explosives were hidden in a LD-3 container loaded with a mixed cargo.

Experiments carried out by Nahal Soreq Group

The gammagram (upper) and the nitrogram (lower) are created simultaneously. There is separation of the explosives from the remaining items.
Experimental Results

ROC curves, detection probability versus false alarm probability, were established
DP>90%, FAP<5%

Resonance Mass Attenuation ($\rho_{\text{Nres}}$) 0.052 cm$^2$/g

Resonance Count Rate (protons) 0.041 C/s
Non-Resonance Count Rate (electrons) 0.820 C/s

Since the detectors covered the entire width of the resonance beam these count rates are independent of the source distance.
**Gamma Resonance Counts**

\[ N_0 - kN_0 = n^{\varepsilon} = n\Delta N_0 \]

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**Scanning Time Estimates**

- **Gamma Resonance Counts**

\[ N' = kN_0 \]

<table>
<thead>
<tr>
<th>Container</th>
<th>Explosive Dimensions cm</th>
<th>Explosive Mass g</th>
<th>Time/ Slice s</th>
<th>Scan Time min</th>
</tr>
</thead>
<tbody>
<tr>
<td>LD3*</td>
<td>20x20x0.5</td>
<td>300</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>LD3</td>
<td>5x5x5</td>
<td>190</td>
<td>1.4</td>
<td>1.75</td>
</tr>
<tr>
<td>C#</td>
<td>10x10x10</td>
<td>1500</td>
<td>1.8</td>
<td>3.66</td>
</tr>
</tbody>
</table>

**CR\textsubscript{p}** 200 C/s(5mA)

- * 153x156x163 cm\(^3\), Max. 1588 kg, ≤ 0.4 g/cc, Att. Factor 4
- # 8’x8’x20’, 246x246x610 cm\(^3\), Max. 20000 kg, ≤ 0.54 g/cc, Att. Factor 12
Photo-neutrons (\(\gamma, n\)) are produced with every material producing prompt neutrons.

Photo-fission (\(\gamma, \text{fission}\)) occurs only with fissile materials producing prompt and delayed neutrons.

Threshold energies in fissile materials

<table>
<thead>
<tr>
<th>Nuclear Isotope</th>
<th>((\gamma, n)) [MeV]</th>
<th>((\gamma, \text{fission})) [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>– Pu-239</td>
<td>5.6</td>
<td>5.6</td>
</tr>
<tr>
<td>– U-235</td>
<td>5.3</td>
<td>5.8</td>
</tr>
<tr>
<td>– U-238</td>
<td>6.1</td>
<td>5.8</td>
</tr>
<tr>
<td>– Th-232</td>
<td>6.4</td>
<td>6.0</td>
</tr>
</tbody>
</table>
GRFT  Photofission Proof-of-Principle

3He Neutron Detector

MCS

PC with Acquisition Program

Analysis Program

Accelerator Pulses

Nuclear material present

Region Of Interest

No nuclear material present

Time after pulse

Experiments carried at INEEL
Photofission Yield

\[ n = \int_{E_{\text{thres}}}^{E_{\text{max}}} (E,x)N(x,t) f(E) \, dE \]

![Graph showing cross-sections for different elements (U-235, U-238, Th-232, Pu-239) as a function of photon energy.](image-url)
\[ \ln \left( \frac{I}{I_0} \right)^L = \Sigma (\mu_i \rho_i L_i) \]

\[ \ln \left( \frac{I}{I_0} \right)^H = \Sigma (\mu_i \rho_i L_i) \]

Graph showing Total Mass Attenuation Coefficient in cm\(^2\)/g for different energies (1 MeV, 10 MeV, 5 MeV) against Atomic Number (z).
\[ \frac{I_L}{I_H} R = (\mu_H - \mu_L) \rho x \]

For:
- \( x = 0.1 \text{ cm}, R = 1.012, \)
- CR = 333 c/s 5 mA,
- @ 3\( \sigma \)

\[ I_L = \left( \frac{3}{1 - 1/R} \right)^2 \]

\( I_L = 253 \text{ counts. This will require 0.76 s.} \)
## GRFT  Air Attenuation for Remote, Stand Off

<table>
<thead>
<tr>
<th>Distance D (m)</th>
<th>Transmission in Air</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Off Resonance</td>
<td>On Resonance</td>
</tr>
<tr>
<td>10</td>
<td>97%</td>
<td>95%</td>
</tr>
<tr>
<td>50</td>
<td>88%</td>
<td>79%</td>
</tr>
<tr>
<td>100</td>
<td>77%</td>
<td>62%</td>
</tr>
<tr>
<td>200</td>
<td>60%</td>
<td>38%</td>
</tr>
<tr>
<td>300</td>
<td>46%</td>
<td>23%</td>
</tr>
</tbody>
</table>
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Site Development

BNL test site for container scanning system
GRFT Summary

- High detection probability (>90%) for explosives
- Low false alarm rate (<5%)
- High throughput
- Single source can feed multiple inspection stations
- Suitable for inspecting shipping containers
- Offers dual high energy gamma ray absorptiometry
- Capable of detecting fissile materials
- Elemental specificity 3-D imaging capability
- No residual activation or site contamination