Nuclear Photo-Science and Applications with T-Rex Sources


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Nuclear Photo-Science & Applications with T-REX Sources

- Motivation
- Nuclear Resonance Fluorescence
- Compton scattering
- Electron beam technology
- Laser technology
- LLNL’s T-REX source
- Nuclear applications

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Team

PI: Chris Barty (NIF/PS&A)
Co-PIs: Dennis McNabb (PAT), Page Stoutland (NAI), Jason Pruett (PAT), Fred Hartemann (PAT), Ed Hartouni (PAT)
Participants: Gerry Anderson (EE), Scott Anderson (PAT), Peter Barnes (PAT), Bob Berry (NTED), Shawn Betts (NIF/PS&A), Ray Beach (NIF/PS&A), Jason Burke (PAT), John Crane (NIF/PS&A), Jay Dawson (NIF/PS&A), Chris Ebbers (NIF/PS&A), Dave Gibson (PAT), Chris Hagmann (PAT), Jose Hernandez (NIF/PS&A), Micah Johnson (PAT), Igor Jovanovic (NIF/PS&A), Jenn Klay (PAT), Rick Norman (PAT), Craig Siders (NIF/PS&A), Miro Shverdin (NIF/PS&A), Ron Soltz (PAT), Aaron M. Tremaine (PAT)
Collaborators: Bill Bertozzi (MIT), Alan W. Hunt (Idaho State University), Chan Joshi (UCLA), Ed Morse (UC Berkeley), Jamie Rosenzweig (UCLA), James Trebes (DNT), Arthur Kerman (MIT)
Motivation: Mission-Driven R&D

T-REX R&D is mission-driven:

- Homeland Security top priority list includes the development of novel imaging technologies for fast, accurate, & reliable cargo container screening.
- Inverse density radiography (DNT)
- Flash MeV radiography (NIF)
Motivation: The Cargo Container Problem

Worldwide sea-faring cargo container traffic: 48,000,000/year
3 containers shipped/received every 2 seconds!
5 kg of concealed SNM = a very bad day!
Current inspection techniques are inadequate:

- Weight/manifest
- Radiation Counters
- Radiography
Nuclear Resonance Fluorescence

Incident photon

Fluorescent photon

Dipole mode
NRF Lines

Numerous lines in high-Z elements, at penetrating wavelengths
Doppler-broadened to ~ 1 eV

Strong MeV line in $^{235}\text{U}$
NRF in Practice: FINDER

Nuclear Resonance Flourescence (NRF)

T-Rex gamma source
Thomson-Radiated Extreme X-rays

$\Delta E/E = 10^{-3}$

0.5 - 2.5 MeV tunable

Open the container

Pass
FINDER NRF signature would be unmistakable…

… but how can we detect such a narrow notch?
"Bertozzi’s Trick"

![Diagram showing the setup for Bertozzi's Trick]

- **Source** positioned near the **Cargo Container**.
- **Detector Array** placed at a distance from the **Reference Target**.
- A graph showing the peak on-axis brightness as a function of X-ray energy (MeV).
- Two intensity plots: (a) showing an intensity peak at 1 MeV and (b) showing an intensity peak at 2 MeV.
Isotopic Imaging Requires Novel $\gamma$-Ray Sources

To become a practical technology, isotopic imaging using nuclear resonance fluorescence (NRF) requires the development of very bright, nearly monochromatic photon sources operating in the MeV range.

For NRF detection of a 1 cm$^2$ target located 10 m away, with high confidence ($6\sigma$), and a short acquisition time (s), one requires:

- **Photon energy**: 1 – 5 MeV (good transparency, strong NRF lines)
- **Beam divergence**: < 1 mrad (good pixel resolution)
- **Av. spectral brightness**: $10^{10}$ photons/0.1% bandwidth/s/mrad$^2$
Energetic Photon Sources

High-energy (MeV) photons are deeply penetrating
Flux & brightness required for imaging applications are high
No ideal light source for detection:

- X-ray laser (keV)
- X-ray FEL (10 keV)
- Synchrotron (100 keV)
- Laser-driven (116 keV U)
- Bremsstrahlung ($\Delta \omega_x/\omega_x$), dose
- Radioactive (weak)
Compton Scattering

Compton scattered photon energy scales as $\gamma^2$

MeV photons can be produced with laser & modest e-beam energies (~100’s MeV)

Compton scattering source brightness scales as $\gamma^2$

X-ray phase space ~ e-beam phase space; $(\gamma/\varepsilon)^2$

Small cross-section: $8\pi r_0^2/3$

Requires high electron and photon densities at focus

Compton formula: 4-momentum conservation

$\hbar \omega_x \approx \hbar \omega_0 4\gamma^2$

Thomson scattering is the recoil-free limit of Compton scattering
E-beam parameters:

- E-beam energy: 235 MeV
- Bunch charge: 1 nC
- Energy spread: 0.1%
- Emittance: 1 mm.mrad
- Bunch duration: 3 ps

Laser parameters:

- Laser pulse energy: 5 J
- Laser pulse duration: 5 ps
- Wavelength: 532 nm
- Spot size: 20 μm

Above 1 MeV, the peak brightness of T-REX sources is > 15 order of magnitudes larger than that of a 3rd-generation synchrotron.
FINER with T-REX Advantages

Photon energy range near absorption minimum (MeV)
Large NRF cross-section (deep notch) relative to atomic processes
Low false positive/negative rates
Highly accurate; very high-resolution (µm)
Isotopic imaging (!)
Low dose

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Detecting clandestine material with nuclear resonance fluorescence

J. Pratt, D. P. McNab, C. A. Hogmann, F. V. Hartmann, and C. P. J. Barty
Lawrence Livermore National Laboratory, 7000 E. Avenue, Livermore, California 94551
(Received 1 November 2005; accepted 6 April 2006; published online 18 June 2006)

We study the performance of a class of interrogation systems that exploit nuclear resonance fluorescence (NRF) to detect specific isotopes. In these systems the presence of a particular nuclide is inferred by observing the preferential attenuation of photons that strongly excite an electromagnetic transition in that nuclide. Estimates for the false positive/negative error rates, radiological dose, and detection sensitivity associated with discovering clandestine material embedded in cargo are presented. The relation between performance of the detection system and properties of the beam of interrogating photons is also considered. Bright gamma-ray sources with high energy and angular resolution, such as those based on Thomson backscattering of laser light, are found to be associated with uniquely low radiological dose, scan times, and error rates. For this reason a consideration of NRF-based interrogation systems may provide insight for efforts in light source development for applications related to national security and industry. © 2006 American Institute of Physics. [DOI: 10.1063/1.2200905]
The specific application we target has strong implications in terms of source parameters.

Requires high average brightness

High-quality, bright electron beam

- Beer can UV, 8 ps
- High-charge gun (nC)
- Very low emittance

Low linac noise (dump, dark current, etc.)

Need sufficient electron beam energy
680 keV T-REX Source for $^{238}$U Demonstration

**E-beam parameters:**
- E-beam energy: 112 MeV
- Bunch charge: 0.3 nC
- Energy spread: 0.1%
- Emittance: 2 mm.mrad
- Bunch duration: 8 ps

**Laser parameters:**
- Laser pulse energy: 0.5 J
- Laser pulse duration: 5 ps
- Wavelength: 355 nm
- Spot size: 20 μm
## LLNL/UCLA Gun Design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient</td>
<td>120 MV/m</td>
</tr>
<tr>
<td>Emittance</td>
<td>0.7 mm.mrad</td>
</tr>
<tr>
<td>Charge</td>
<td>1 nC</td>
</tr>
<tr>
<td>Energy</td>
<td>6 MeV</td>
</tr>
<tr>
<td>Energy spread</td>
<td>0.17%</td>
</tr>
</tbody>
</table>

![BNL Image](image1.png)  
![3-D model of LLNL/UCLA RF gun](image2.png)
Cold tests have been performed successfully

Key upgrades include:

- Wider frequency separation between the 0 and $\pi$-modes
- No tuners (to allow high-gradient operation > 120 MV/m)
- No 70° laser input windows (fully symmetrized half cell)
- Solenoidal magnetic field symmetrized up to quadrupole
Low-Energy Beamline

- Fully emittance-compensated setup
- Precision diagnostics included
- Optimized gun/linac interface
- UHV for photocathode lifetime
- Symmetrized beamline for CSR
- Symmetrized UV coupling box
Sputtered Mg Photocathode Enables Fiber-Based UV Laser

2 μm of Mg is sputtered on a 1 cm diameter spot on the polished Cu back plane of the photoinjector. A 2 mm diameter UV laser strikes the Mg spot, generating photoelectrons.

50 μJ of UV light can be produced readily with custom LLNL fiber laser system.
LLNL Fiber Laser System

Modelocked pulses:

1 nJ
150 fs FTL
40.7785 MHz
Gun & UV Laser Integration

S-Band Gun
UV Pulse 5 ps, 100 μJ

Hyper-Michelson

Compressor
Chirp lines
LLNL Hyper-Michelson Pulse Stacker/Shaper
Emittance Optimization & Preservation
Solenoids and long steerers, which can induce emittance growth, will not be used.

Quadrupoles and short steerers will be used instead.
LLNL Drive Laser System

4-pass
40 μJ
6 mm diam, gain=15/pass

single-pass
190 mJ
12 mm diam, gain=20/pass

single-pass
340 mJ
12 mm diam, gain=20/pass

Input pulse:
energy = 40 μJ, bandwidth > 0.8 nm
Output pulse:
energy = 2.25 J, 10 dB bandwidth=0.25 nm, transform limited duration=10 ps

2.5J @1064nm
30 GW/cm²
10 ps

Type II
DQKD

1064 nm
532 nm

Type II
DQKD

5.2 cm
0.3 mm sapphire plates

Polarizer @35 deg

3.4 mm

3.2 mm

355 nm > 40% efficiency expected

HDC compressor
T-REX Interaction Region

Laser focusing box
E-beam dump
Capture Q-triplet
Interaction cube
150 MeV Dipole
Final focus Q-triplet
Laser re-circulation

1st Light: mid-FY07
Applications: Stockpile Surveillance

Isotopic imaging enables inverse density radiography
Applications: Waste Evaluation

Table 6-1: Historical Material Balance of Uranium-235 in HEU

<table>
<thead>
<tr>
<th>Material Balance Category</th>
<th>MTU-235</th>
<th>MTU-233</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquisitions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production from Uranium Enrichment Plants</td>
<td>889.2</td>
<td></td>
</tr>
<tr>
<td>Production from Mining</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Total Acquisitions</td>
<td>890.5</td>
<td></td>
</tr>
<tr>
<td>Removals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refurbished Plants</td>
<td>116.1</td>
<td></td>
</tr>
<tr>
<td>Nuclear Tests, Warfare Detonations, and Naval Reactor Use</td>
<td>11.1</td>
<td></td>
</tr>
<tr>
<td>Total Removals</td>
<td>127.2</td>
<td></td>
</tr>
<tr>
<td>Invanter Difference</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>Transfers to Foreign Countries</td>
<td>&lt;20,000</td>
<td></td>
</tr>
<tr>
<td>Down Blending</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Total Removals</td>
<td>25.8</td>
<td></td>
</tr>
<tr>
<td>Gross Total Removals</td>
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<td></td>
</tr>
<tr>
<td>Non-Classified Transactions</td>
<td>&lt;10,000</td>
<td></td>
</tr>
<tr>
<td>Classifiable Transactions</td>
<td>15.3</td>
<td></td>
</tr>
<tr>
<td>Calculated U.S. HEU Inventory</td>
<td>891.3</td>
<td></td>
</tr>
</tbody>
</table>


Defending against Corrosion

A Livermore-designed engineered barrier system for the proposed Yucca Mountain nuclear waste repository works with natural barriers to keep radioactive waste in its place.

The Safe Disposal of Nuclear Waste

Meeting environmental targets and standards that will protect the health and safety of future generations. The Livermore is developing a deep repository to sequester unused fuel and spent reactor. The performance and generation confidence that this process will provide future generations and their environment and the safe disposal of wastes of current and future use is no longer hazardous.
Applications: Nuclear Photo-Science

- Energy-recovery linacs
- Superconducting linacs
- Superconducting rf guns
- Tailor-aperture ceramic lasers
- Nonlinear trapping

kW-average $\gamma$-ray flux
- Isotopic imaging
- Inverse density radiography
- $\gamma$-induced fission
- Parity measurements
Conclusions

- There are a number of bright $\gamma$-ray missions within the DoE complex and beyond.
- T-REX sources will generate $\gamma$-rays with unprecedented brightness.
- LLNL’s laser and electron beam technology are key components for the development of T-REX sources.
- The future of T-REX sources is closely tied to advanced accelerators, as the $\gamma$-ray phase space maps onto the electron beam phase space.
- In particular, energy-recovery superconducting linacs, coupled to LLNL’s high average power lasers may yield a path to kW $\gamma$-ray beams.