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FIND: Fluorescence Imaging in the Nuclear Domain

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March 11, 2005

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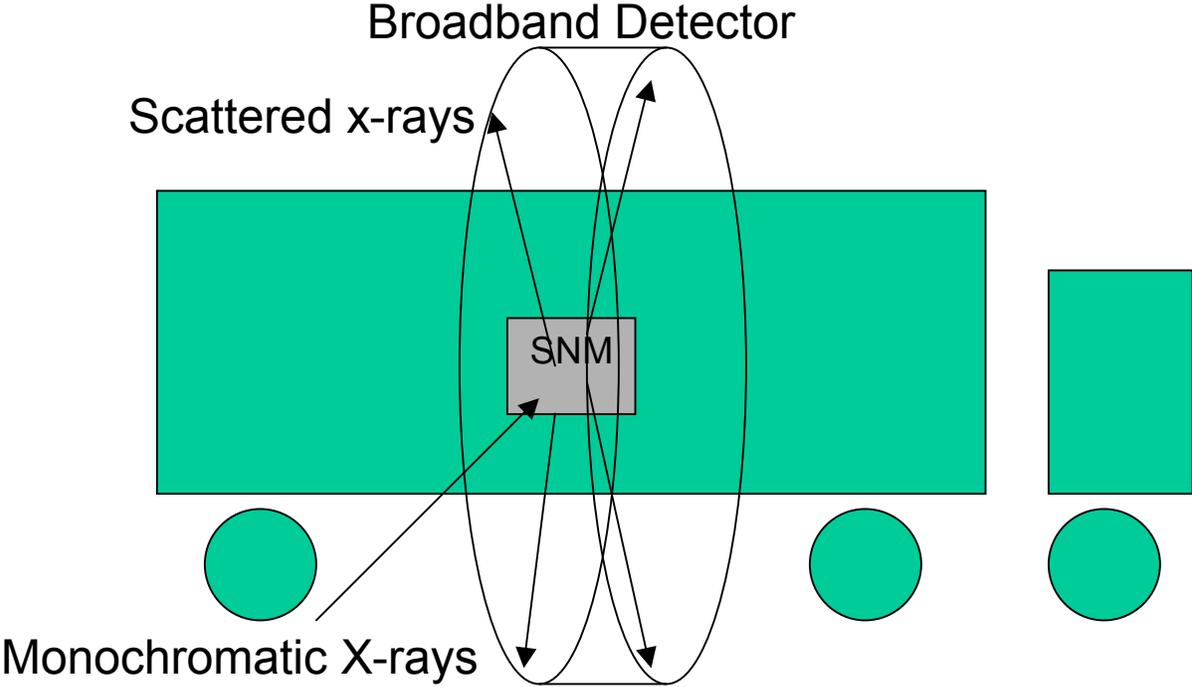
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This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

FIND: Fluorescence Imaging in the Nuclear Domain

Non-invasive detection and imaging of special nuclear materials
with Thomson-Radiated Extreme X-ray sources

C. P. J. Barty



FIND: Fluorescence Imaging in the Nuclear Domain
Chris Barty (NIF)

Summary:

This document examines the potential use of Thomson-Radiated Extreme X-ray (T-REX) sources for Fluorescence Imaging in the Nuclear Domain (FIND) of special nuclear materials. A back-of-the-envelope, relative comparison of T-REX sources vs. Bremsstrahlung sources for this application is presented. It is estimated that use of T-REX for FIND could be as much as 5×10^{12} more effective than the use of anode based sources. Furthermore it is estimated that illumination of samples of dimension 1 cm on a side could produce up to $\sim 10^9$ detectable photons per second.

Background:

Nuclear resonance fluorescence (NRF) is a well-established technique for the study of photo-allowed nuclear transitions. In this technique a sample is exposed to broadband radiation in the 100 keV to several MeV range. The radiation is most commonly generated by impinging energetic electrons of several MeV onto a metal target. The emitted Bremsstrahlung photons are collimated and illuminate the sample under test. Radiation that is resonant with allowed transitions of the nuclei is then re-radiated into 4π and detected by energy resolving detectors. Schematically this arrangement is shown in Figure 1.

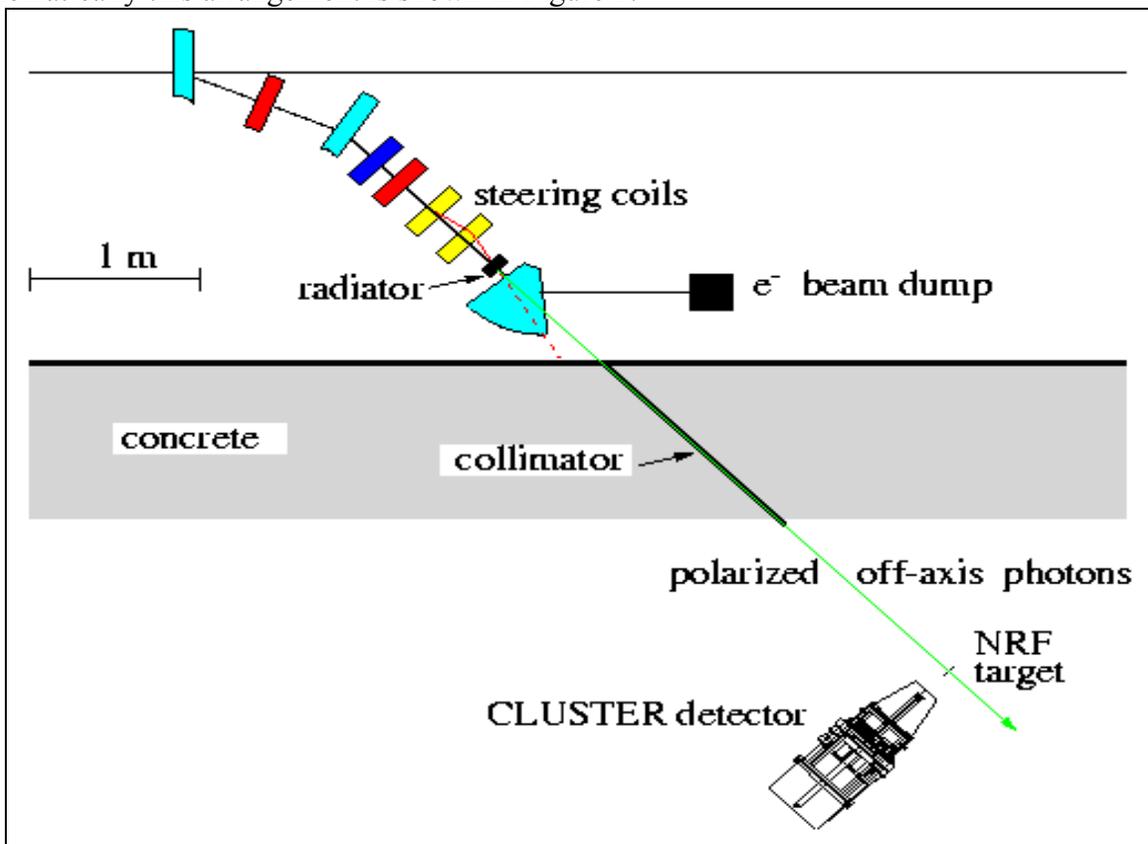


Figure 1. schematic of nuclear resonance fluorescence experiments ELBE (figure copied without permission from <http://www.fz-rossendorf.de/pls/rois/Cms?pOid=10568&pNid=0>)

A typical NRF spectrum is shown in Figure 2.

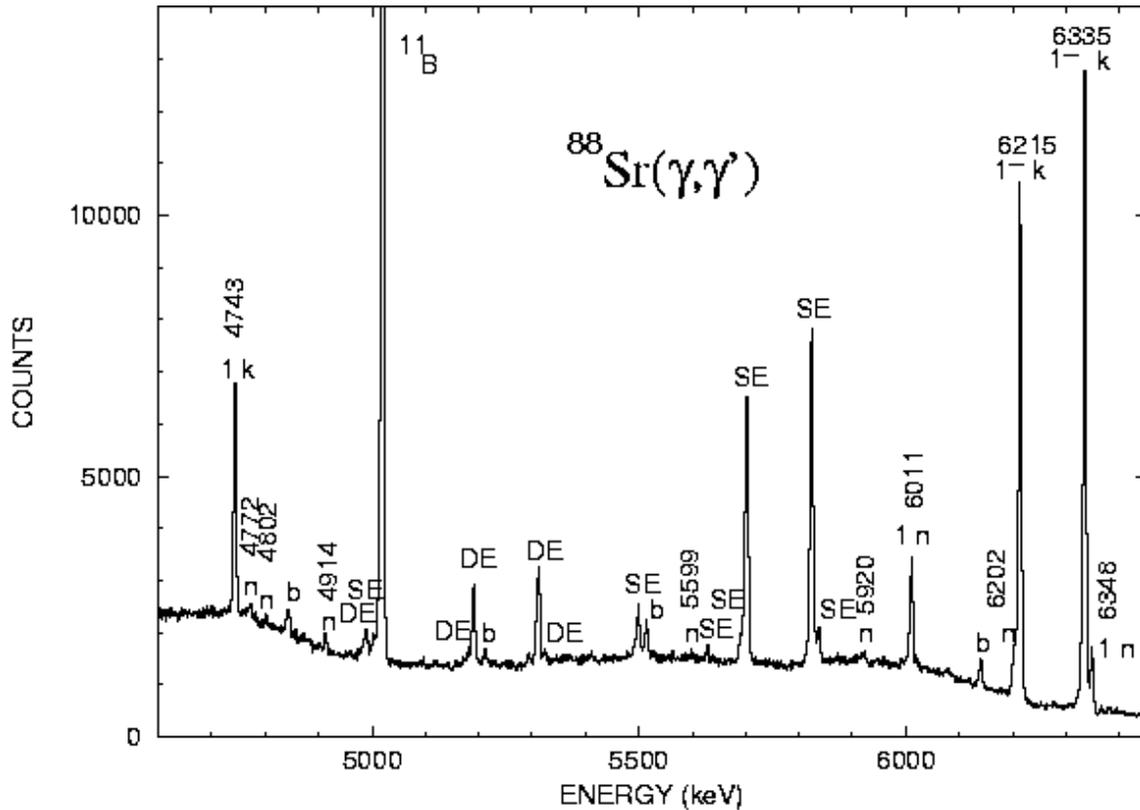


Figure 2. portion of the gamma NRF spectra of ^{88}Sr . (figure copied without permission from <http://www.fz-rossendorf.de/pls/rois/Cms?pOid=10568&pNid=0>)

The use of nuclear resonance fluorescence (NRF) to detect and characterize hidden materials has been proposed by Prof. Bertozzi of the MIT Bates Linear Accelerator Center (see Figure 3). With a collimated x-ray source it will be possible to not only detect and characterize material with NRF but also to image. We will refer to the overall imaging technique as Fluorescence Imaging in the Nuclear Domain or FIND.

The use of Thomson-Radiated Extreme X-ray (T-REX) sources (a full description of T-REX can be found in the white paper C. Barty and F. Hartemann) for FIND has significant advantages that are primarily the result of the tremendous spectral brightness of the T-REX source relative to anode based machines. The Bertozzi proposal suggests use of a common electron driven Bremsstrahlung x-ray source as the illuminator and requires high resolution Ge-detectors as analyzers. Specific details of the Bertozzi proposal are not available but from his poster and the description of NRF experiments at the ELBE facility in Europe it is possible to make the following back of the envelope comparison of FIND with T-REX as the illuminator and FIND with anode illumination.

Let us consider the task of detecting a 1 cm cubed volume of special nuclear material. From a descriptions of European experimental arrangements for nuclear resonance fluorescence studies, one learns that the collimated output of a high flux anode based machine into a sample area of approximately 20 cm in diameter is approximately 10^7 photons/MeV/sec. (For info on



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Material Identification & Object Imaging

using Nuclear Resonance Fluorescence

Materials:
 Explosives • Nuclear materials • Drugs • Chemicals • Toxic compounds

Containers:
 Substances • Tubes • Containers containers • Boxes of wood, iron, aluminum, etc.

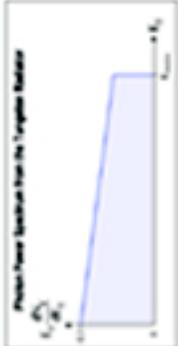
Advantages:
 Very penetrating • Suitable for small and large objects • Unambiguous identification of atomic species and quantitative mass determinations • Non-destructive

The Science

- Each nucleus has unique characteristic nuclear states. These states are very narrow in energy, and every state has a factor of an atomic unit width. They can be excited by the absorption of photons of the correct energy.
- After the excited state decays, the characteristic photons are emitted in all directions with respect to the incident beam, leading to unique photon energies of nuclear fluorescence.
- The excited photons can be detected by high-resolution solid state Ge detector spectrometers.
- Each nuclear species in the beam can be identified by the unique energy spectrum of the emitted photons.
- The probability of photo excitation by incident exciting photons are very high. Cross-sections are on the order of barns (1 barn = 10⁻²⁸ m²).
- The angular distribution of the photons is a function of the angle and depends on the angular momentum of the ground state, J_g , and of the excited state, J_e . (Detailed presentation is not included).
- Scattering of electrons backscattered (B) spectrum reduces photon energy below 4 MeV. This sets a minimal background from Compton scattering.
- Photon beam is continuously distributed up to the nuclear energy spectrum. Photons are emitted at all nuclear energies.
- The beam is stopped by the collimated photon beam and the subsequent use of the detectors.
- Scattered exciting photons can be used to excite Compton backscattered photons to further the absorption. In general, the absorption of scattered photons can be enhanced. The method of contrast detection is complementary to the detection of scattered photons.

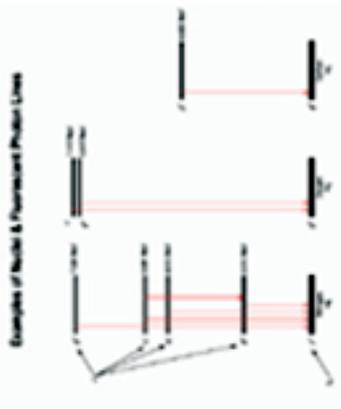
Realization

- Solid sources & well collimated
- System, hardware and software engineering required
- Activity safety measures for photon beam transport

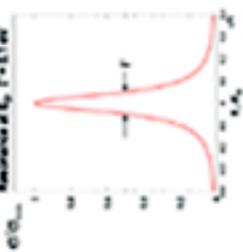


The techniques illustrated by this material are included in US Patent Numbers 5,400,852 and 5,105,489

Examples of Nuclear & Fluorescent Photon Lines



Resonance at E_0 , $\Gamma = 5.1$ eV



$\sigma \approx \frac{4\pi}{3} \left(\frac{E_0 - E_0'}{\Gamma} \right)^2 + \left(\frac{\Gamma}{2} \right)^2$

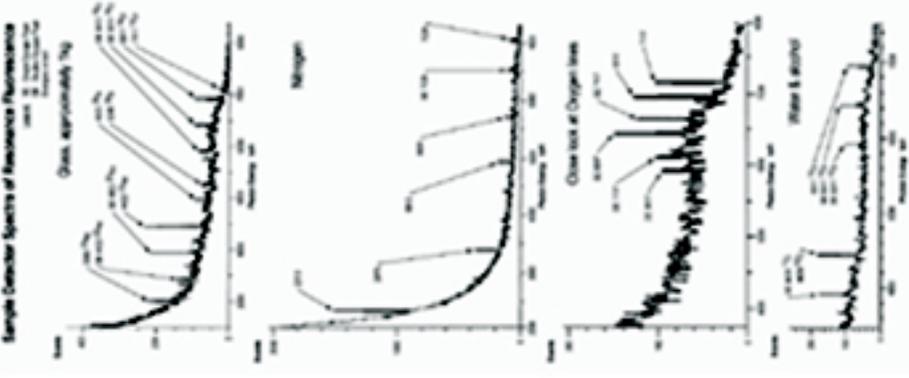
$G = \frac{2J_e + 1}{2J_g + 1} \lambda = \text{photo scattering}$

Gamma Intensity

$\sigma_{\text{max}} \sim 3 \text{ barns}$

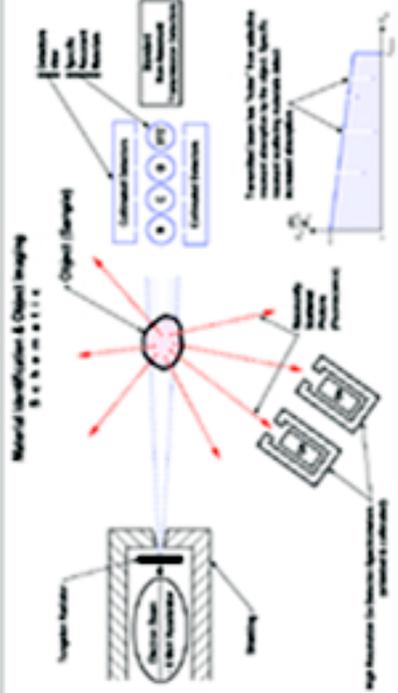
$\Gamma \sim 20 \text{ eV}$

Sample Detector Spectra of Resonance Fluorescence



Data, approximately 10g

Material Identification & Object Imaging



High Resolution Ge Detectors Spectrometers (p-n and Si) • Collimators

Figure 3. Bertozzi poster suggesting nuclear resonance fluorescence for material identification. This arrangement assumes use of a broadband Bremsstrahlung source.

the ELBE setup see <http://www.fz-rossendorf.de/pls/rois/Cms?pOid=10568&pNid=0>) In this arrangement the source is located about 3 meters from the interaction region. It is not possible to locate closer due to the shielding and collimation requirements of the source. The typical natural linewidth of nuclear resonances is of order femtoseconds ($\sim 0.1\text{eV}$) or fractionally $\sim 10^{-7}$ at 1 MeV. Doppler or other broadening may increase the linewidth an order of magnitude. One would thus expect of order 1 to 10 photons per transition per second. It is not clear from the web description of experiments what the data acquisition time is for NRF measurements is but the data is presented in terms of 100's to 1000's of counts per transition. If we consider a 1 cm sample size the flux illuminating our test sample is approximately 0.01 photons per second.

A Nd:YAG version of T-REX (see T-REX white paper) is predicted to produce $\sim 10^{12}$ photons per second with a fractional bandwidth of order 10^{-3} . Therefore a correctly tuned T-REX source would produce between $\sim 10^8$ to 10^9 (call it 5×10^8) photons/second within a transition bandwidth of the material of interest. Furthermore the emission cone angle of a T-REX source is $\sim 1/\gamma$ where γ is the normalized electron energy ($\gamma = 500$ in our example). Locating the source 5 meters from the sample allows ample shielding and produces a 1 cm diameter interaction region. T-REX would produce a useful flux onto the sample that is $\sim 5 \times 10^{10}$ times higher than that from an anode based source. Furthermore because energy-resolving detectors are not needed for FIND with T-REX, lower cost and/or higher efficiency detectors could be utilized. This potentially allows a much greater solid angle of detection. An additional increase in relative performance of FIND with T-REX by another 2 orders of magnitude is thus not unreasonable. In total T-REX could perform FIND with $> 10^{12}$ times higher signal rate.

It is interesting to note that the cross sections for NRF are large, of order 1 to 500 barns. A 1 cm cubed sample would thus scatter between 5% and 100% of the incident photons. For T-REX this would mean between 2.5×10^7 to 5×10^8 photons per second.

Atomic density of Plutonium = 4.88×10^{22} atoms per cc

Un-scattered fraction = $e^{-N\sigma L} = (5 \times 10^{22})(10^{-24})(1) = 0.95$ for 1 barn

or

Un-scattered fraction = $e^{-N\sigma L} = (5 \times 10^{22})(5 \times 10^{-22})(1) = 10^{-11}$ for 500 barns