Soreq NRC

# Dual-Purpose Ion-Accelerator

## for Explosives- & SNM-Detection in Massive Cargo

PTB

**W H Y ?**

**BECAUSE SINGLE-NUCLEAR-PROBE SYSTEMS**
**INADEQUATELY COVER BROAD THREAT SPECTRUM**

↓↓

**MULTI-PROBE SYSTEMS**
**(VERSATILE ACCELERATORS)**

→
→

**AN EXAMPLE**
**(THIS PRESENTATION)**

# Dual-Purpose Ion-Accelerator

## for Explosives- & SNM-Detection in Massive Cargo

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**Concept: Nuclear-Reaction-based Inspection System**

$^{13}C(p,\gamma)$ $E_p$=1.75 MeV — and, alternately — $^{11}B(d,n+\gamma)$ $E_d$= 3 - 6 MeV

***DETECTING:***

**Nitrogen-rich Explosives**
(including sheet)
*via*
**$\gamma$-Resonance Absorption (GRA)**
*(this Talk)*

**all Explosives**
(including TATP)
*via*
**Fast-N Resonance Radiography (FNRR)**
*(David Vartsky, SM/EN-14, tomorrow 08:30)*

***AND:***

**SNM**
(1st-Level System)
*via*
**Dual-Energy $\gamma$-Radiography**
*(this Talk)*

*ALSO*
(2nd-Level System)
*via*
**Active Fission Signatures**
*(A. Hunt, AT/INT-01, Monday)*

**PROBLEM: HOW ARE ACCELERATOR REQUIREMENTS BEST MET?**

# Dual-Purpose Ion-Accelerator

## for Explosives- & SNM-Detection in Massive Cargo

**A SOLUTION: Mass-2 beam @ E = 3.5 MeV**

*2 × GRA Resonance-energy*

*alternating*

**DEGR:** pulsed d-beam *on* $^{11}B$ target

*with*

**GRA** cw $H_2^+$-beam *on* $^{13}C$ target

### Topics Addressed

- DEGR: salient features
- GRA: " "
- Missing Info
- New Data
- Accelerator Specs (combined system)

# DETECTING Special Nuclear Materials (SNM) CONCEALED within CARGO CONTAINERS

**PROPOSED METHOD:** DUAL-ENERGY $\gamma$-RADIOGRAPHY **DEGR**

**DETECTION LIMIT:** our goal: ~20 g (1 $cm^3$)

**APPLICATION SCENARIO:** Interdict assembly of Improvised Nuclear Device (IND), smuggled in piecemeal

Reaction of choice: $^{11}B(d,n\gamma)^{12}C^*$ (4.43 & 15.09 MeV)

**UPDATED STATUS:**

a) Physics (Dec. 2003): Fully-developed

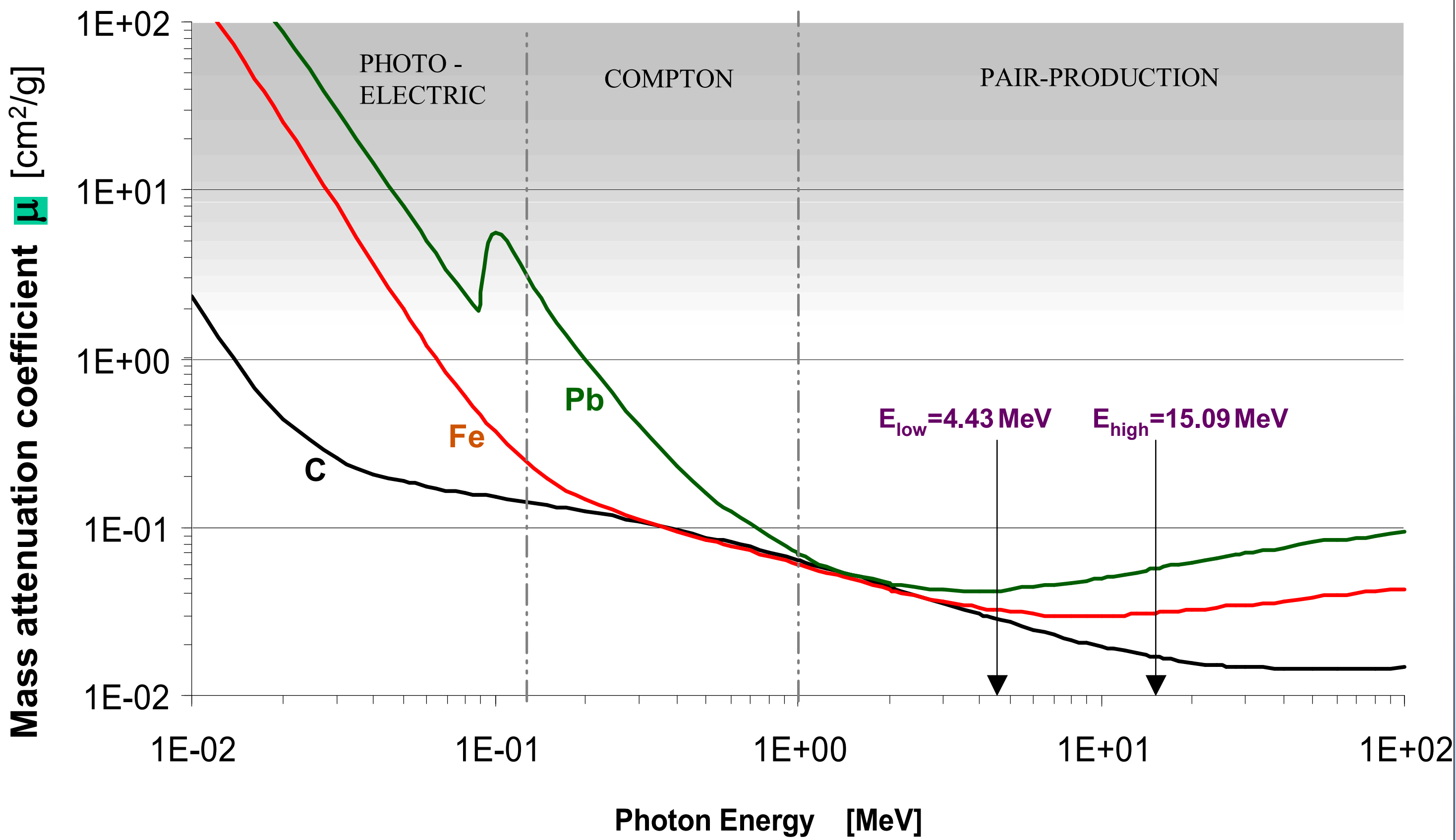
b) 1st Exp't (Dec. 2006): Sensitivities confirmed

c) 2nd Exp't (Dec. 2007): Measured Yield = $f(E_{beam})$

d) Patents: IL-2003; PCT-2005; U.S.-2008

# Dual-Energy γ-Radiography (DEGR)

**Radiation fraction transmitted through absorber = $e^{-\mu \cdot \rho \cdot x}$**



# DEGR: Single-View & Few-View



Transmission ratio through absorber: $e^{-\Delta\mu\cdot\rho\cdot x}$

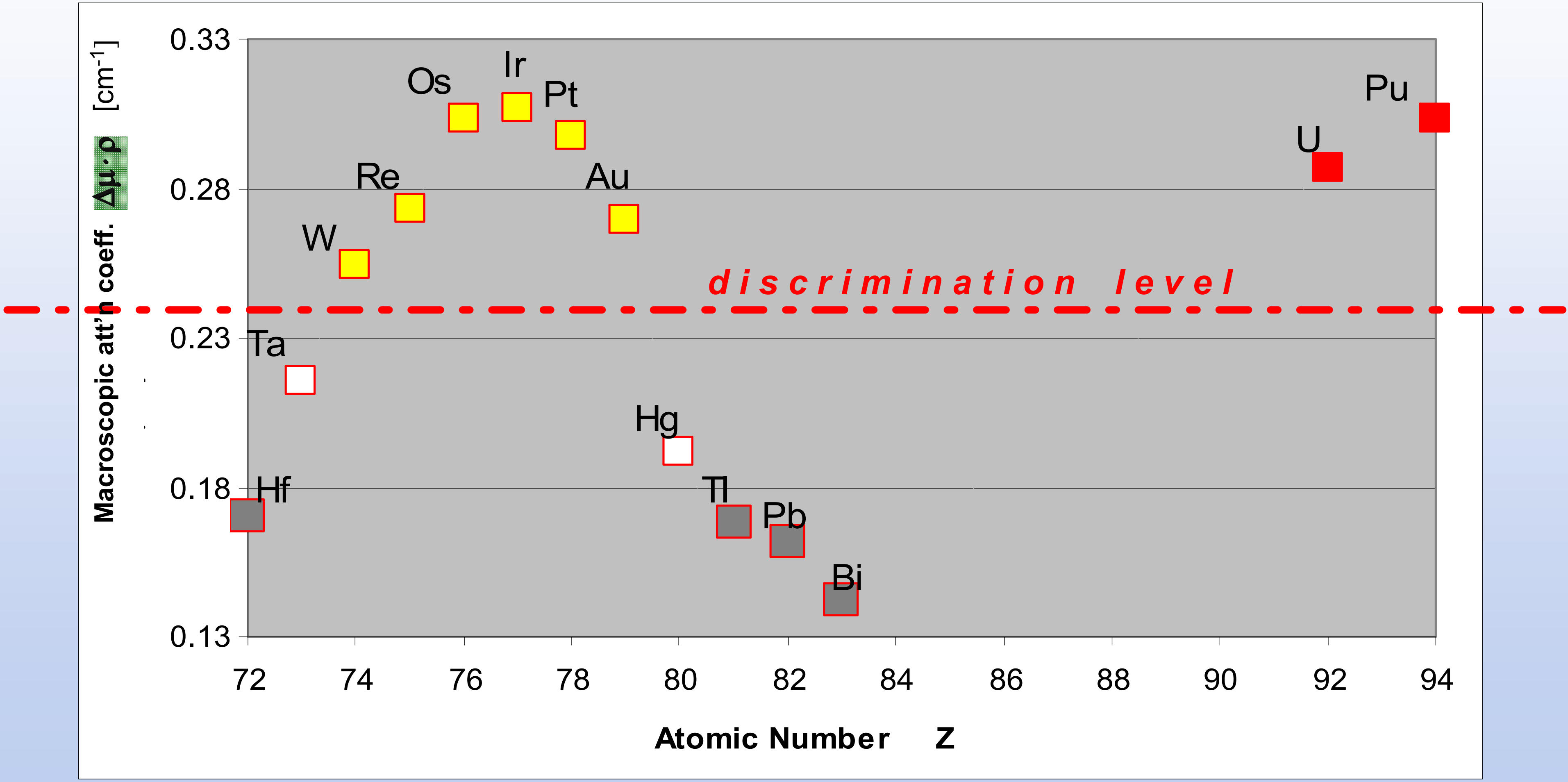
**Single-View:**

Only gross Z-discrimination: inadequate
(false alarms)

**Few-Views:**

Macroscopic Attenuation Coefficient $\Delta\mu\cdot\rho$: adequate

# Absorber-Density
## (few-view reconstruction)



# X-RAY & γ-RAY DUAL-E SOURCES: pro’s & con’s

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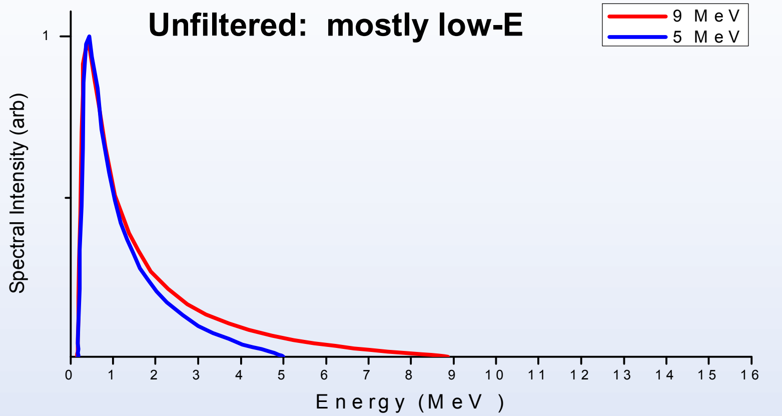
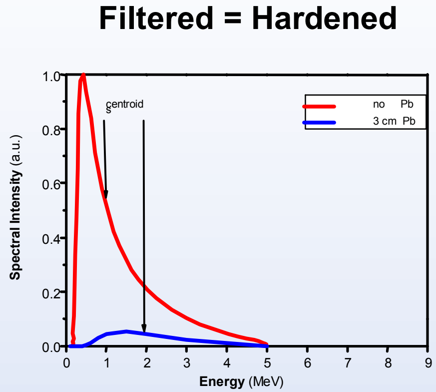
## Continuous

### X-rays

(Bremsstrahlung – electron beams)

**much higher yield (×100)**
**(but only ×5 after appropriate filtering)**



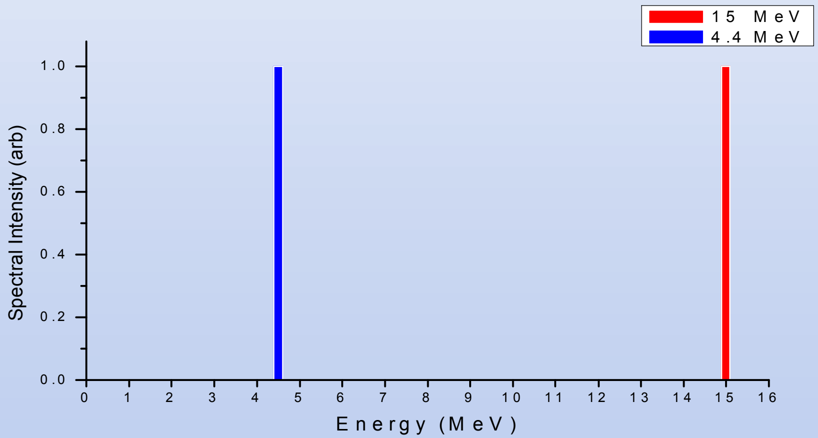




## Discrete

### γ-rays (+ fast-n)

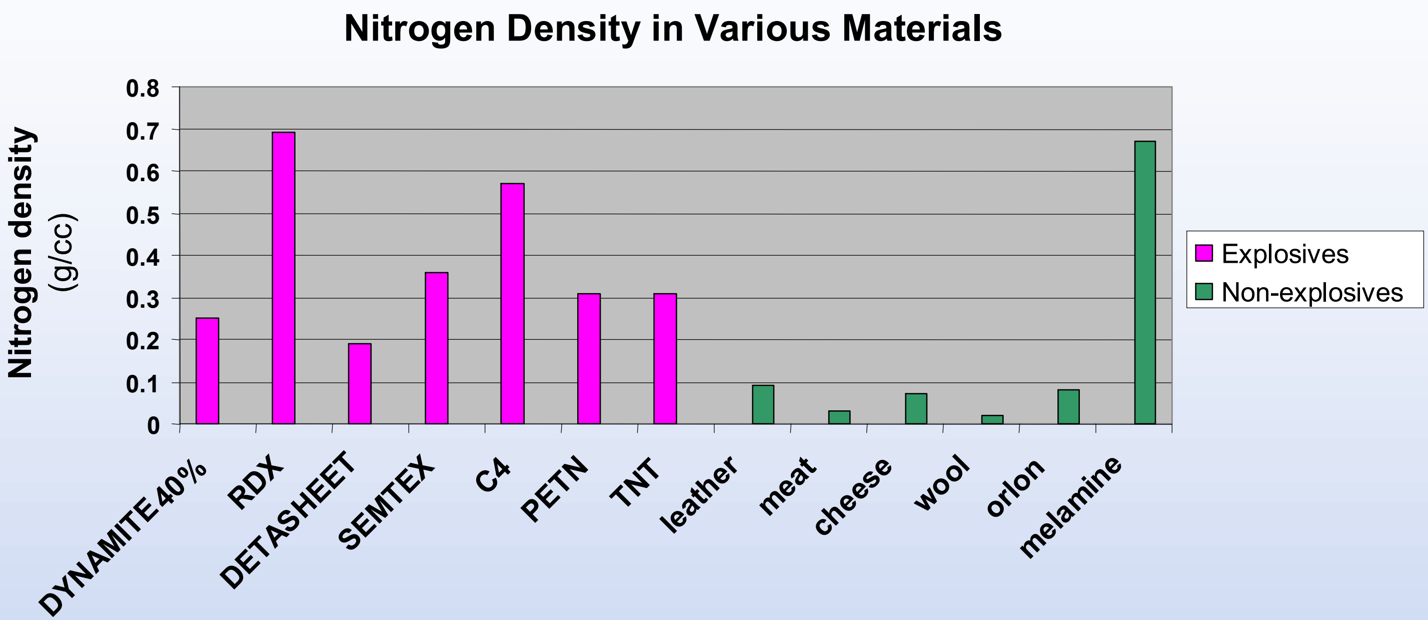
(nuclear reaction – ion beams)

**much higher contrast (×5)**
**(independent of attenuation)**




**OVERALL: γ-rays win (discussed on Poster)**

# Nitrogen signature of explosives

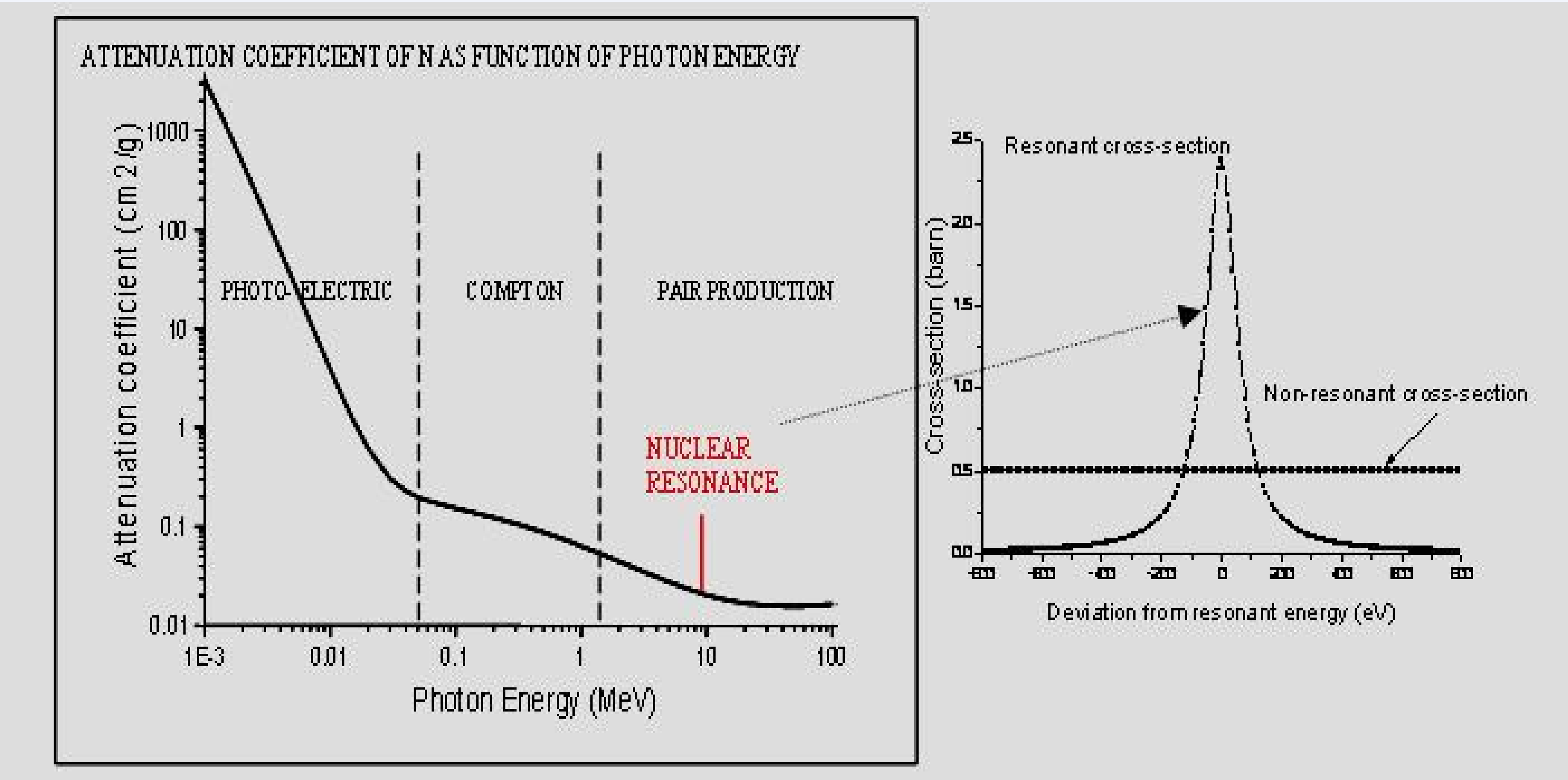



## GRA Detects

| | | |
|---|---|---|
| Military explosives | All | |
| Dynamites | All | |
| High explosives | All | |
| Liquid explosives | All except | **LOX1, LOX2** |
| Chlorates and Perchlorates | All except | Potassium perchlorate |
| Primary explosives | All except | non-nitrogenous TATP |

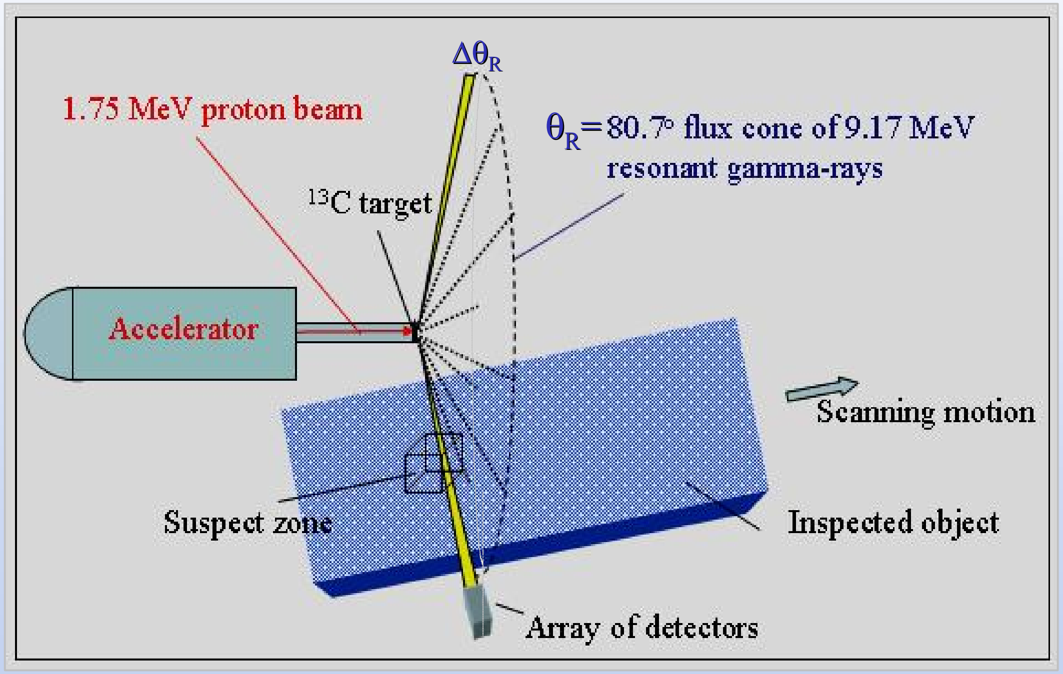
# GRA: Nitrogen-Specific Radiography

## UNDERLYING PRINCIPLE



# GRA: Inspection Configuration

## DICTATED BY PHYSICS



# GRA EXPLOSIVES DETECTION TEST

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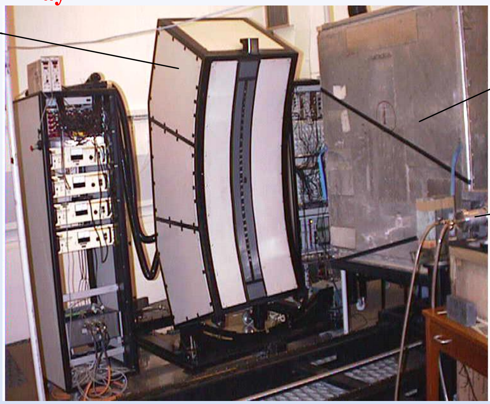
## (LD-3 Aviation Containers, Birmingham Univ. U.K., 1998)

60 Detector Array



LD-3 Container

Target

LD-3 container loaded with mixed cargo: canned food, chinaware, textiles, fertilizers etc.

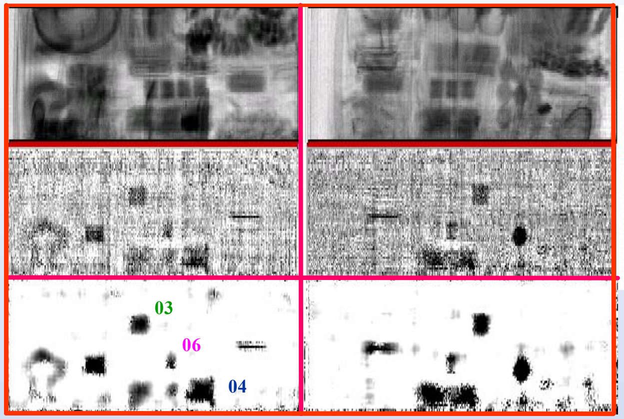
## MIXED CARGO

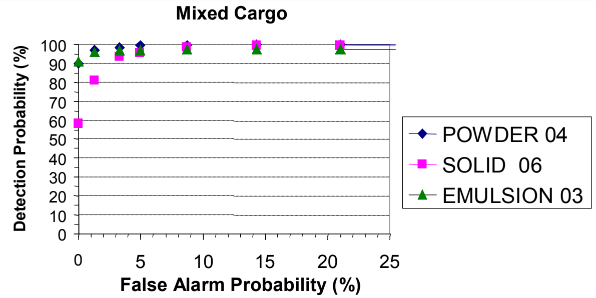
View #1 View #2 (@ 90° to #1)

Conventional radiograms (non-res. att'n) →

Nitrograms (show only nitrogenous objects) →

Image-processed Nitrograms →




ROC curves for three types of explosives inside a container loaded with mixed cargo

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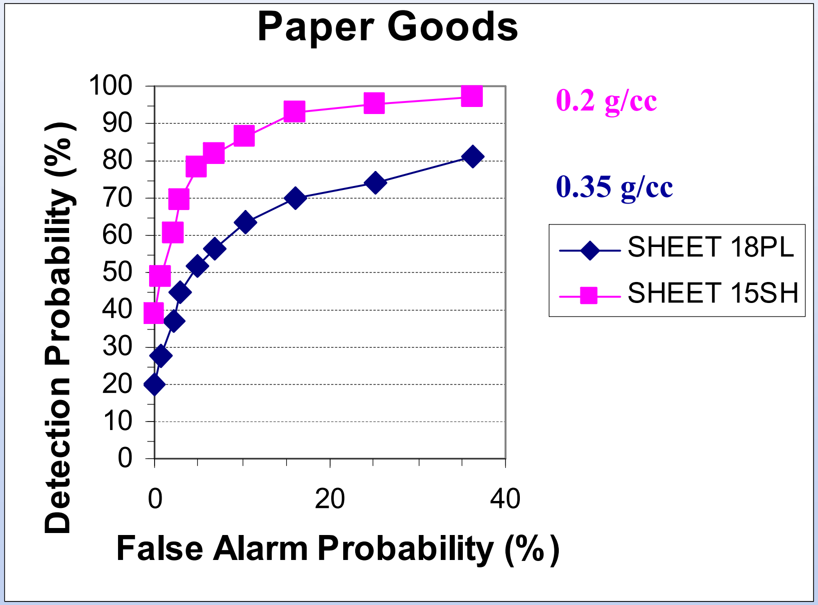
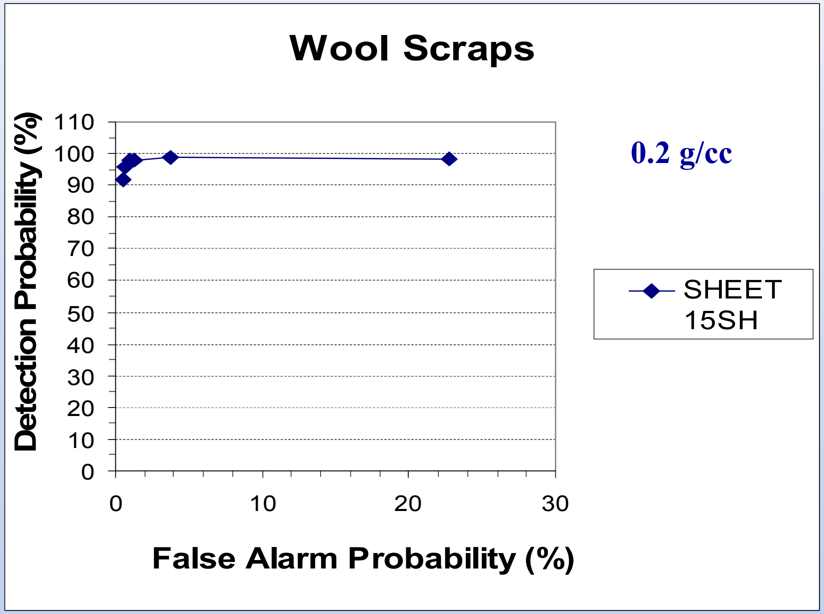
# GRA Results: LD-3 aviation container - 1998

## Detection of sheet explosives
### (two views only!!)



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# GRA: Salient Features

## Explosives Detection

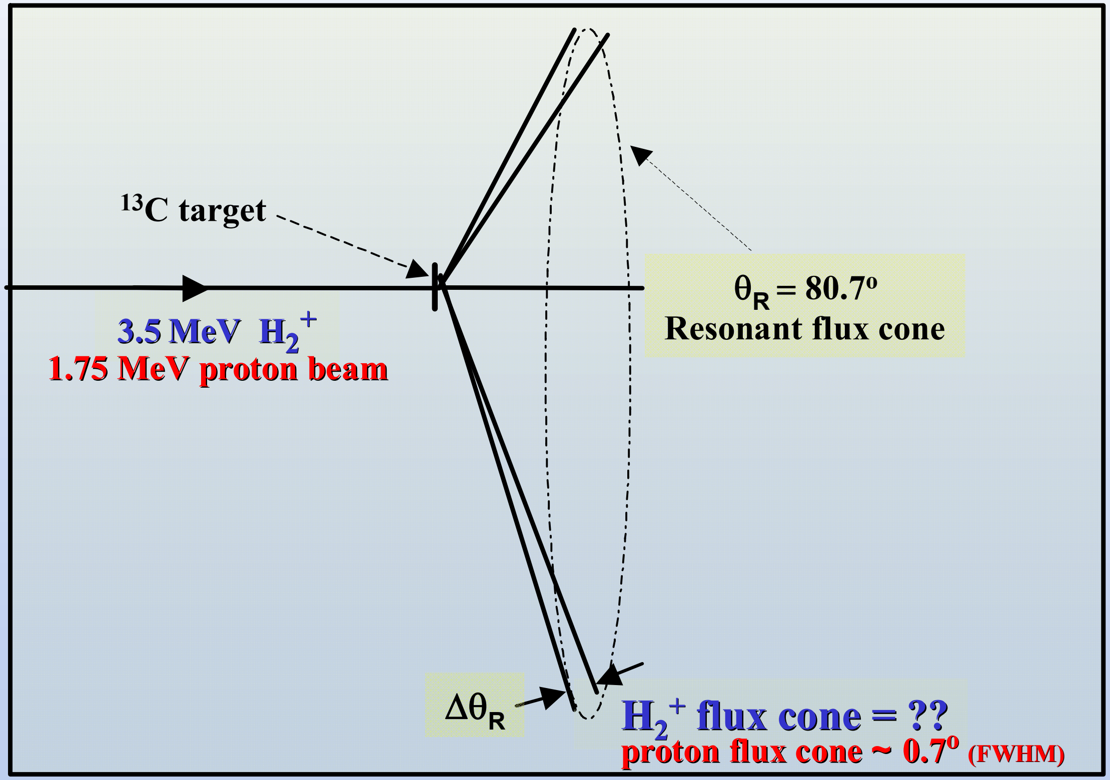
- Very high specificity: nitrogen density = best single explosives indicator
- Automatic detection (no operator intervention)
- Penetrability-Suitable for containers and trucks
- Ability to detect thin explosives sheets
- Very low radiation dose to the object and the vicinity

VULNERABILITY: NON-NITROGENOUS EXPLOSIVES

# Missing Information

## for Dual-Purpose DEGR / GRA System

**GRA emission-linewidth with $H_2^+$ beam**




$H_2^+$ Coulomb-Explosion effects

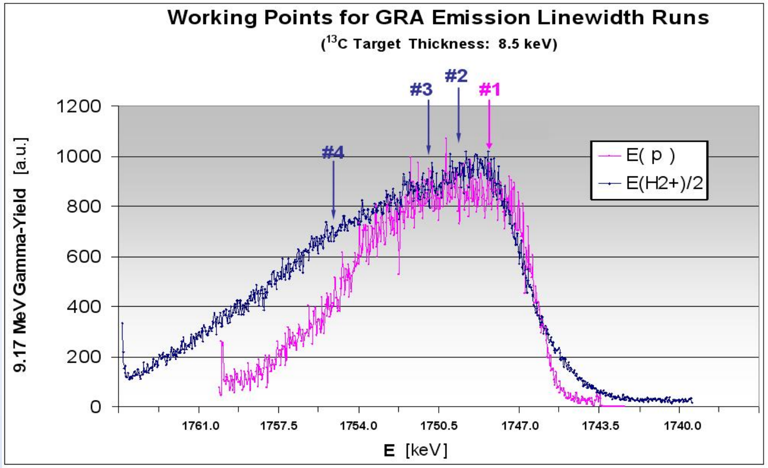
could broaden the line up to

$\Delta\theta_R \leq 2^o$

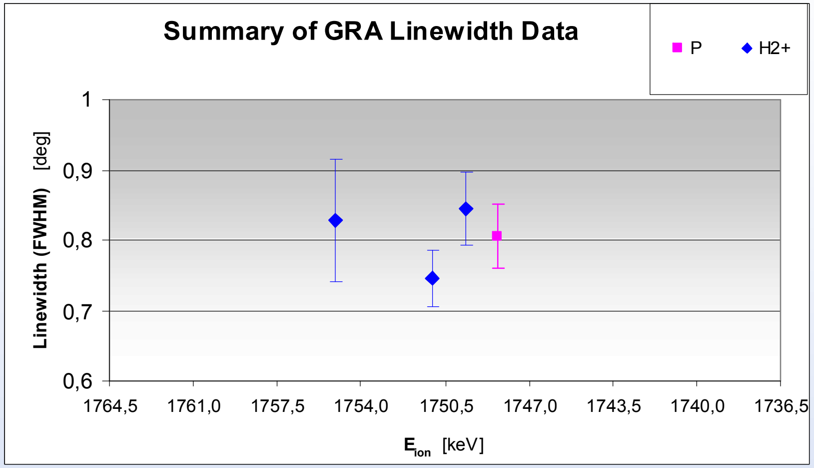
much poorer GRA spatial resolution

(crucial for sheet detection)

# GRA emission-linewidth:
## measurements with $H_2^+$ & proton beams




**1st Experiment**: 9.17 MeV γ-excitation curves mapped out with NaI detector, for proton & $H_2^+$ beams (fixed VDG energy, varying target voltage)




**2nd Expt**: emission-linewidth determined from angular distrib. of photo-protons produced in a nitrogen-rich liquid scintillator via $^{14}N(\gamma,p)$ resonant absorption reaction

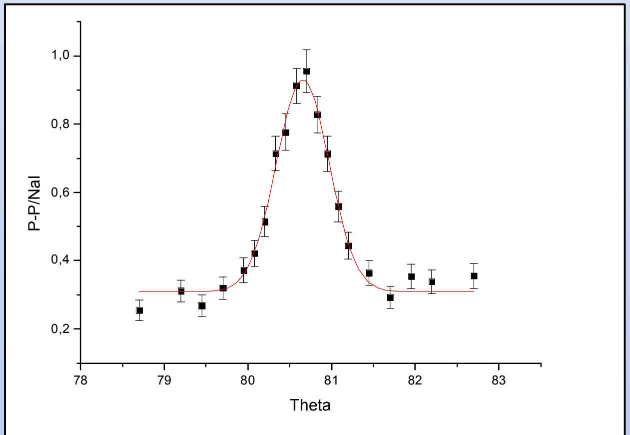



Photo-proton angular distrib. of Run #3

**Conclusion**: no appreciable effect over $\Delta E(H_2^+)$ ~8 keV. So, E-resolution of $H_2^+$ beam could be ~15 keV (not stringent!!)

# Accelerator Specs: combined DEGR / GRA system

- Beam Species: Mass-2 ions ($H_2^+$ & d)
- Energy Resolution 15 keV (FWTM)
- Beam Current 3 mA $H_2^+$ (cw) *and, alternately*

- Ion Energy 3.5 MeV
- Energy Variability ±20 keV
- Beam Current 0.2 mA d (pulsed)

# FINALLY

**A FOND THOUGHT FOR THE IAEA STAFF**

**WHO ARE TAKING SUCH WONDERFUL CARE OF US**

**Ladies: if only I were thirty years younger…**

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# Our Collaboration

PTB

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# THANKS FOR YOUR ATTENTION!

* on Sabbatical leave at PTB-Braunschweig

# Slides for contingencies

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# DEGR: ATTENUATION / TRANSMISSION

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**Transmission fraction** through two absorbers with atomic numbers $Z_a$ , $Z_b$ is:

$$T(E_\gamma) = e^{-(\mu_a \cdot \rho_a \cdot x_a + \mu_b \cdot \rho_b \cdot x_b)}$$

where $\mu$, $\rho$, & $x$ are the ***mass attenuation coefficient***, ***density*** & ***thickness***, respectively

($\mu$ are characteristic and known functions of $Z$ & $E_\gamma$)

**Transmission Ratio** at two $\gamma$-energies $E_{\gamma_1}$ & $E_{\gamma_2}$ is thus:

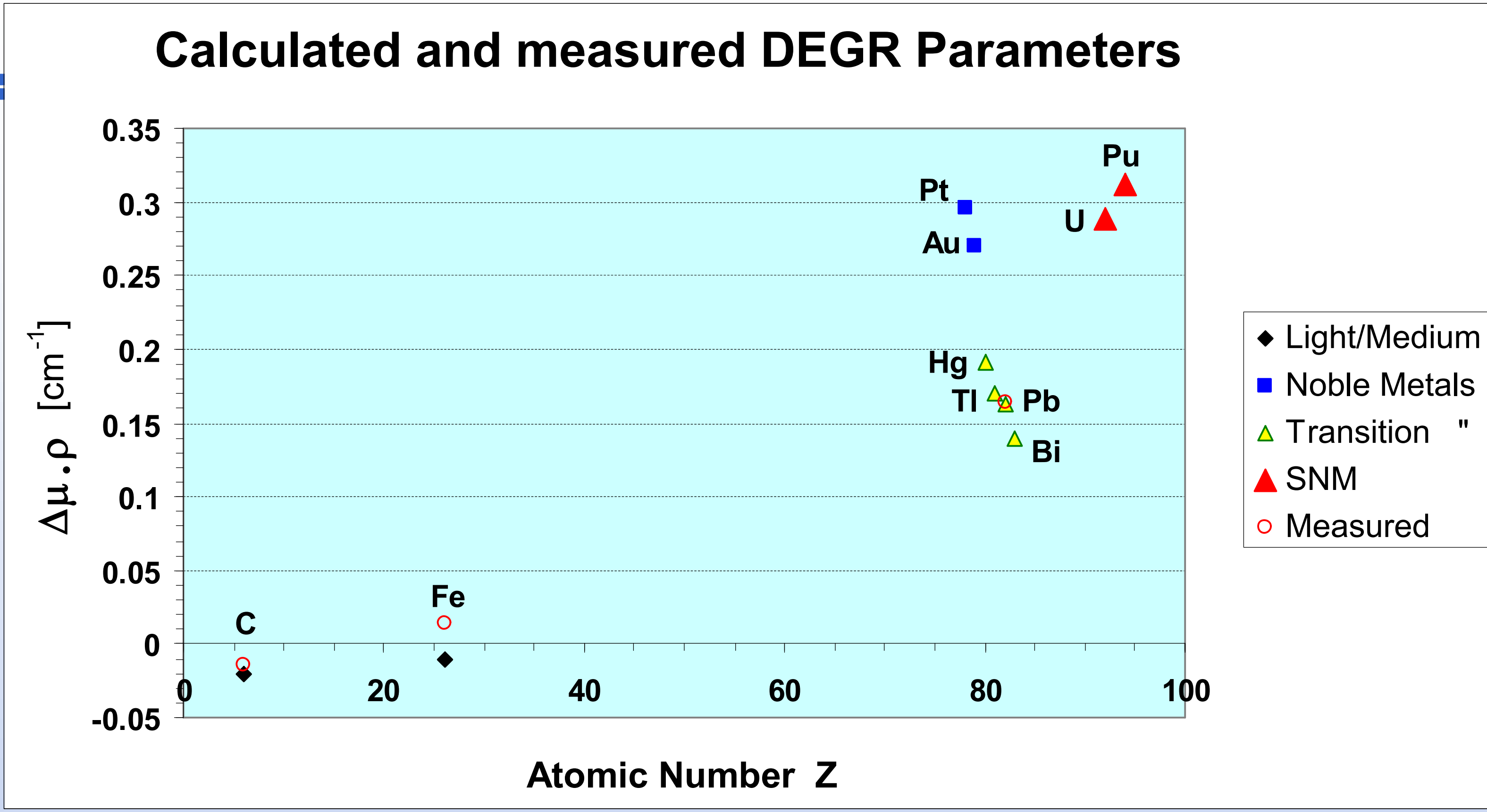
$$T(E_{\gamma_1}) / T(E_{\gamma_2}) = e^{-(\Delta\mu_a \cdot \rho_a \cdot x_a + \Delta\mu_b \cdot \rho_b \cdot x_b)}$$

**High sensitivity** to detect **a** (threat object) against background of **b** (benign item) requires:

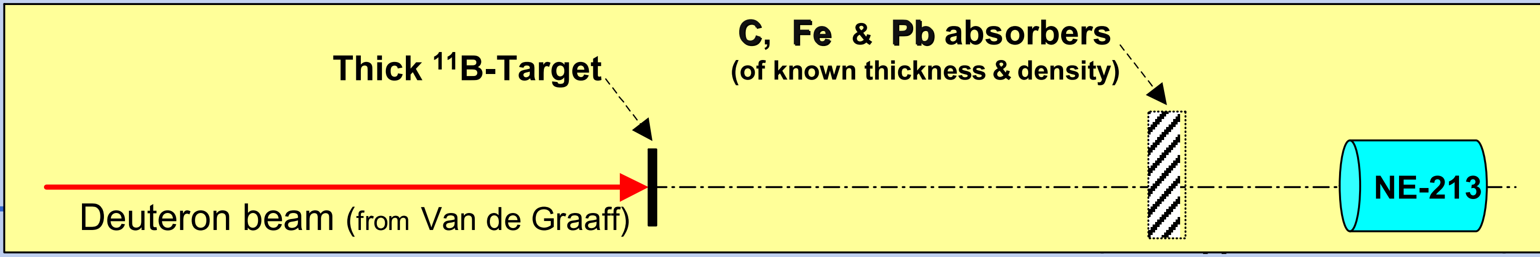
$$|\Delta\mu_a| = \textit{maximal} \quad \& \quad |\Delta\mu_b| = \textit{minimal}$$

Clearly, the effect of **b** is eliminated ***only if*** $\Delta\mu_b = 0$ or $\Delta\mu_b \cdot \rho_b \cdot x_b$ is known

# DEGR data (4.43 & 15.11 MeV)




**Nota Bene:** This was ***not*** a few-view imaging exp't. $\Delta\mu\cdot\rho$ values were derived from ***measured attenuations*** and ***known absorber thicknesses***



# METHODOLOGY of SNM DETECTION



1. DISTINCTION between HIGH-Z & LOW / MEDIUM-Z

   via DEGR TRANSMISSION RADIOGRAPHY

*and*

2. DISTINCTION among HIGH-Z ITEMS of DIFFERENT DENSITY

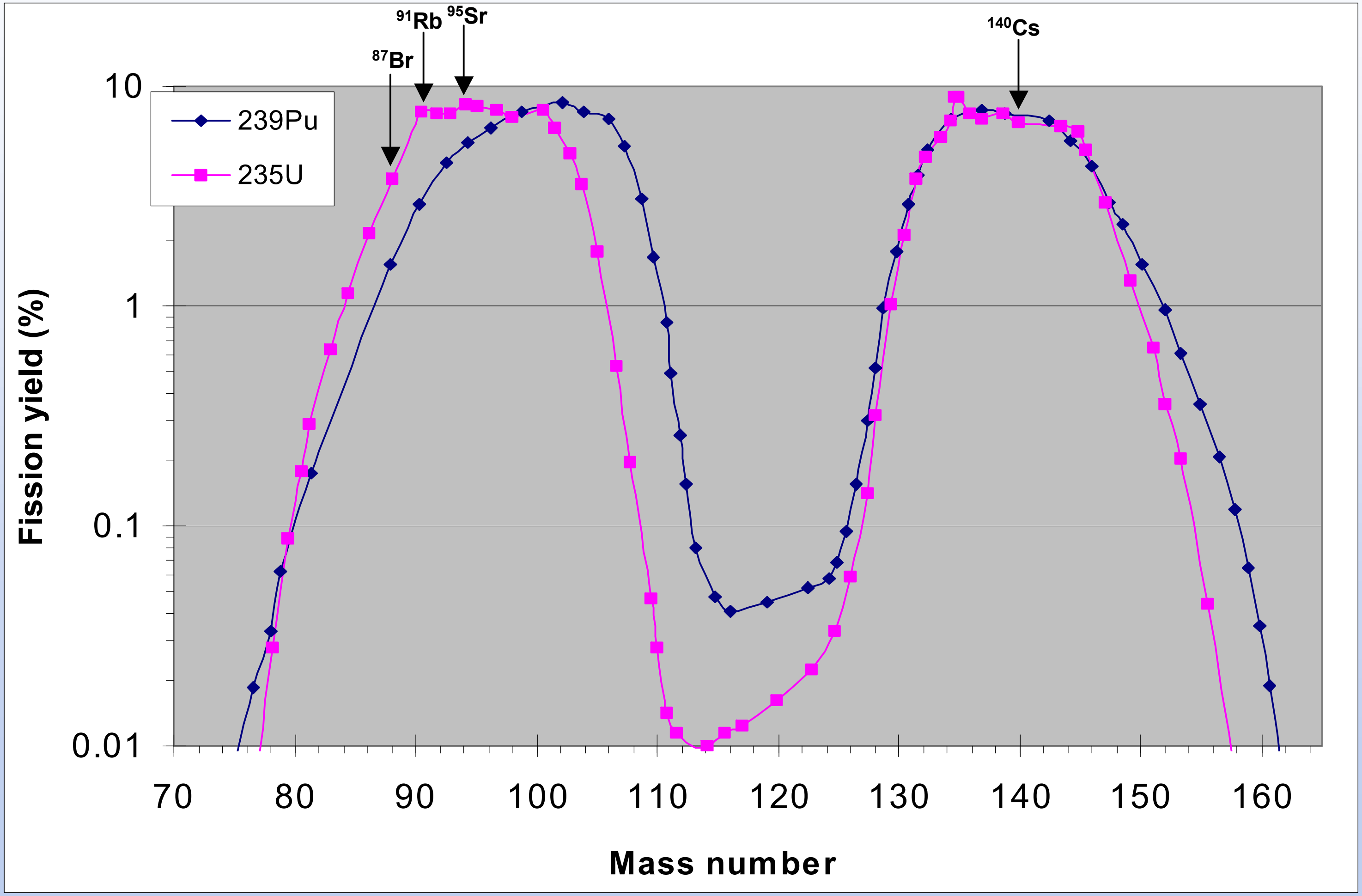
   via FEW-VIEW SPATIAL-RECONSTRUCTION

3. DISTINCTION between $^{235}U$ & $^{239}Pu$

   via $n_{th}$-induced FISSION-PRODUCT γ-SPECTROSCOPY (LLNL method)

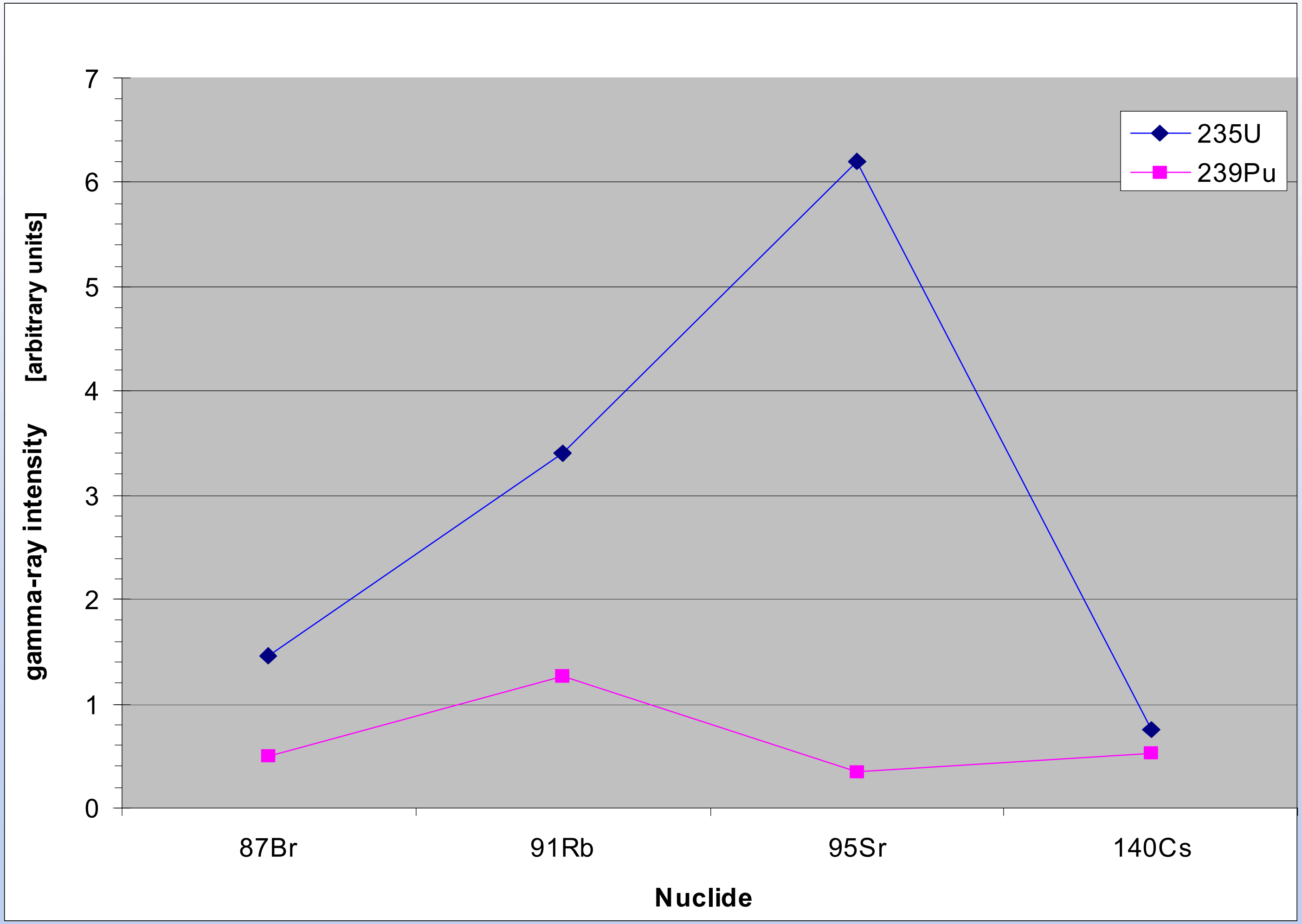
   using the same neutron source: $^{11}B(d,n)$ (see below)

# Mass Distributions in $n_{th}$-induced Fission



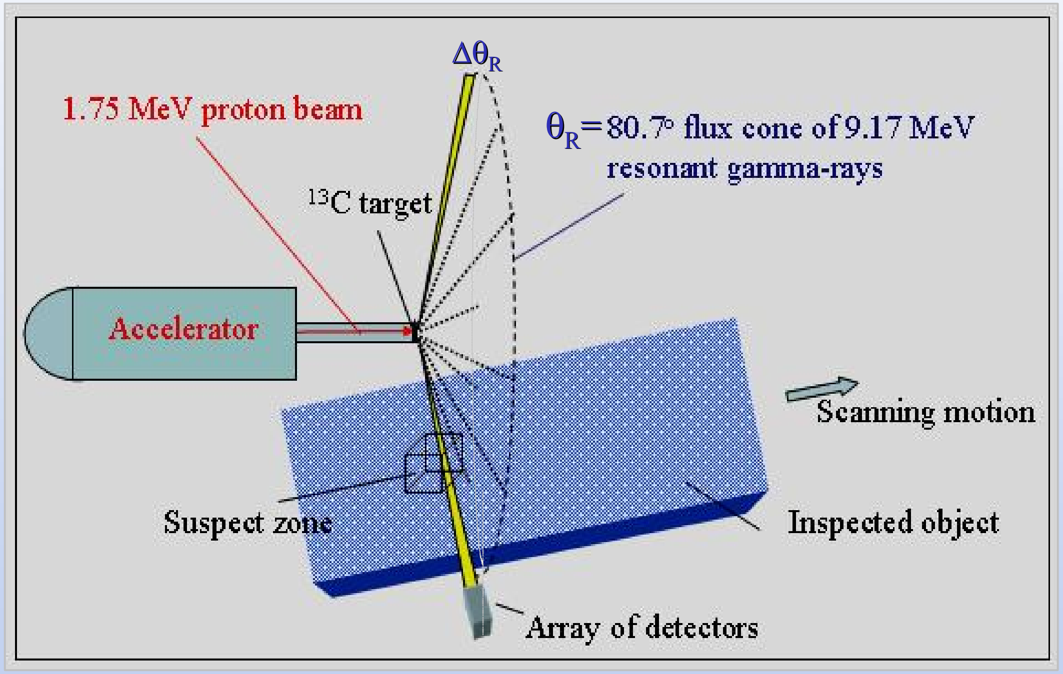
# Fission Radio-Isotope Yields

## (half-lives in 25-60s range: Slaughter et al, Livermore - 2005)



# GRA: Inspection Configuration

## DICTATED BY PHYSICS

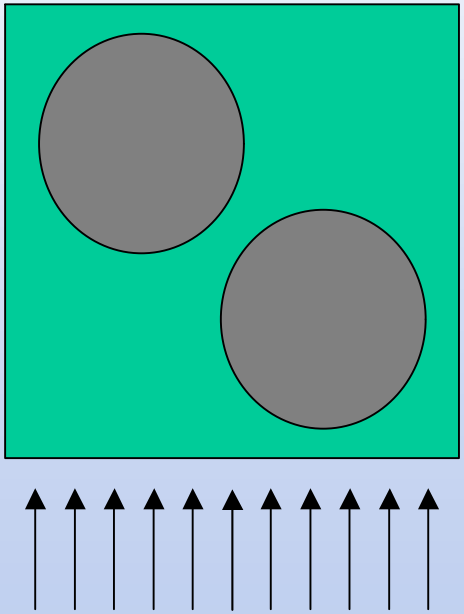



**Phenomenology *with* protons**

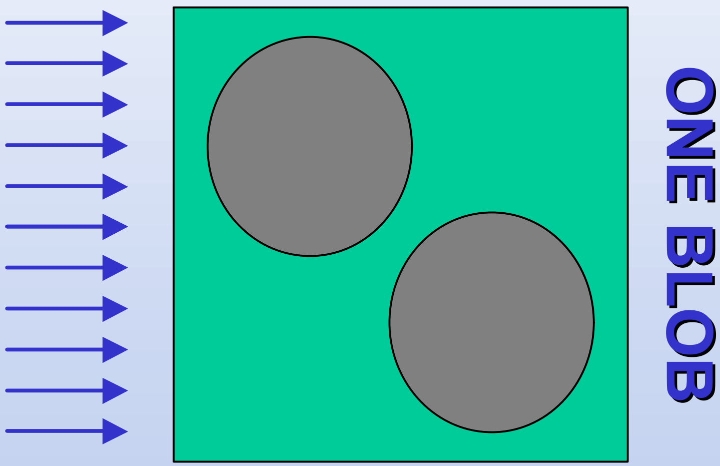
- Resonant $\gamma$-rays emitted at
  $\theta_R = 80.66^o$
  ($\Delta E_{doppler} = 2\times$ nucl.-recoil)
- 9.17 level-width $\Gamma_{tot}$ ~128 eV
- <u>But</u> 9.17 emission-line width is
  $\Gamma_{emission}$ ~520 eV ($\leftrightarrow \Delta\theta_R$ ~0.7°)

# Few-View Spatial-Reconstruction

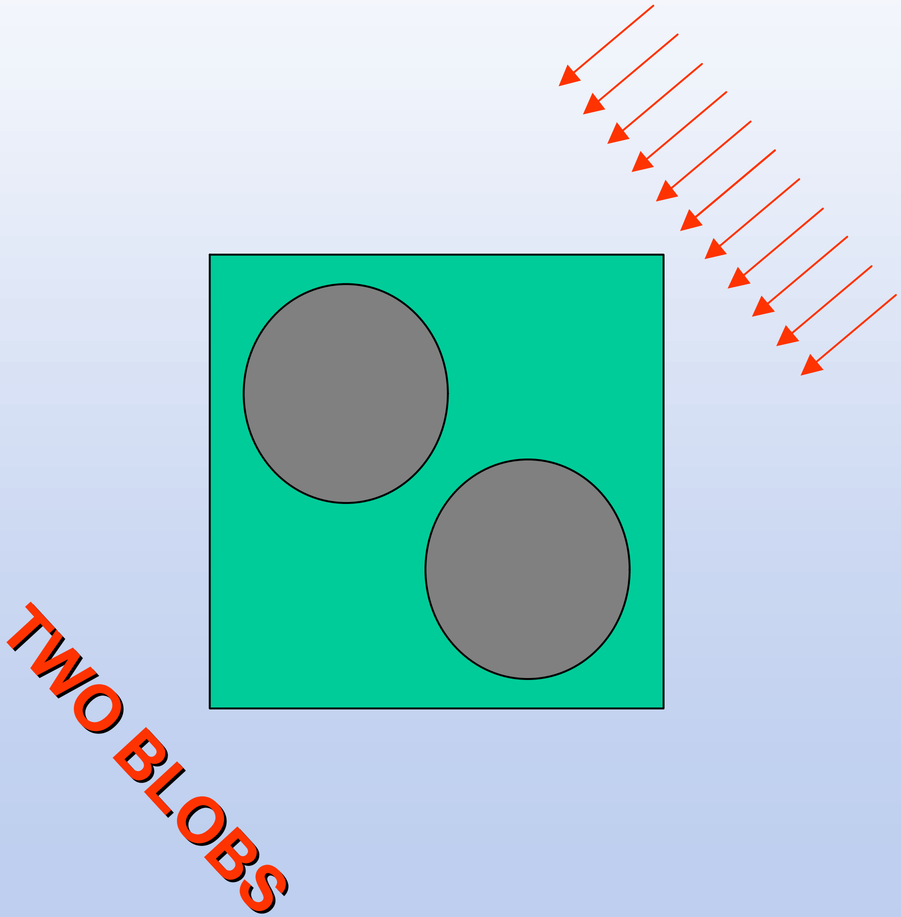
## ONE BLOB



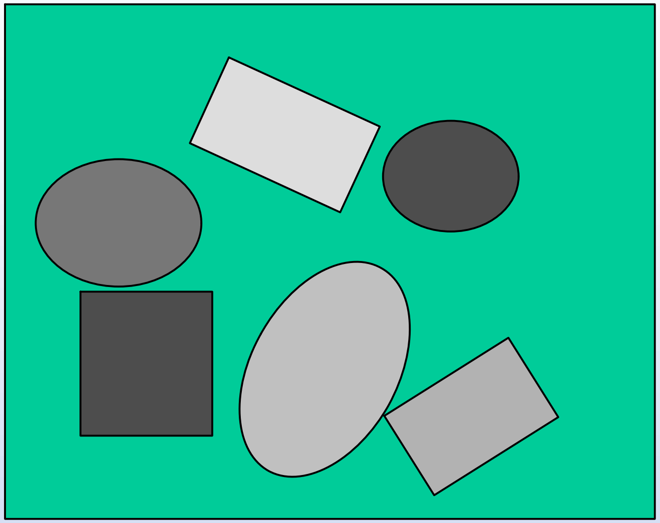
# Few-View Spatial-Reconstruction



# Few-View Spatial-Reconstruction



# Few-View
# Spatial Reconstruction



<u>CONCLUSION</u>: FIDELITY of SPATIAL-RECONSTRUCTION DEPENDS on:

- NUMBER OF VIEWS
- SPATIAL RESOLUTION
- IMAGE COMPLEXITY ( ↔ SPECIFICITY TO THREAT OBJECTS )

**DEGR ADVANTAGE: MINIMAL High-Z CLUTTER**

# A FOND THOUGHT FOR THE IAEA LADIES WHO ARE TAKING SUCH GOOD CARE OF US

**LECHEROUS OLD PHYSICIST, PROFESSOR HIGGINS, KEENLY OGLES SPRIGHTLY YOUNG IAEA STAFF MEMBER, LIZA DOOLITTLE, IN THE FOYER. SHE SMILES. HE APPROACHES.**

***HIGGINS:*** **„FAIR LADY, WOULD YOU LIKE TO SEE MY DUAL-PURPOSE ACCELERATOR?"**

***LIZA:*** **„OOOH, WOULDN'T THAT BE LOVERLY!"**

***HIGGINS:*** **„TELL ME, ARE YOU RHENIUM?"**

***LIZA:*** **„NO. ARE YOU ROPIUM?"**

***HIGGINS:*** **„NO. BUT AT PRESENT, GERMANIUM. SAY, DOESN'T LINE-BROADENING SCARE YOU?"**

***LIZA:*** **„NOT IF WE TWAIN STAY MAINLY IN THE PLANE."**

***HIGGINS:*** ***(TO HIMSELF):*** **I THINK SHE'S GOT IT. I THINK SHE'S GOT IT!** ***(ALOUD):*** **„BUT MY PROPOSAL IS STILL ONLY ON PAPER"**

***LIZA:*** **„NEVER MIND. I LOVE SPECIAL NUCLEAR MATERIALS LIKE YOU"**

***HIGGINS:*** **„BUT I HAVEN'T GONE CRITICAL FOR YEARS"**

***LIZA:*** **„NOT EVEN SUBCRITICAL?"**

***HIGGINS:*** **„MAINLY SELF-CRITICAL THESE DAYS ... BUT I STILL RESONATE OCCASIONALLY."**

***LIZA:*** **„WITH YOU, I COULD HAVE DANCED ALL NIGHT"**

***HIGGINS:*** **„DAMN, DAMN, DAMN! I'VE GROWN ACCUSTOMED TO YOUR FACE"**

***LIZA:*** **„JUST GET ME TO THE CHURCH ON TIME – I'M GETTING MARRIED IN THE MORNING"**