Fast Neutron Imaging for SNM Detection

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Special Nuclear Materials

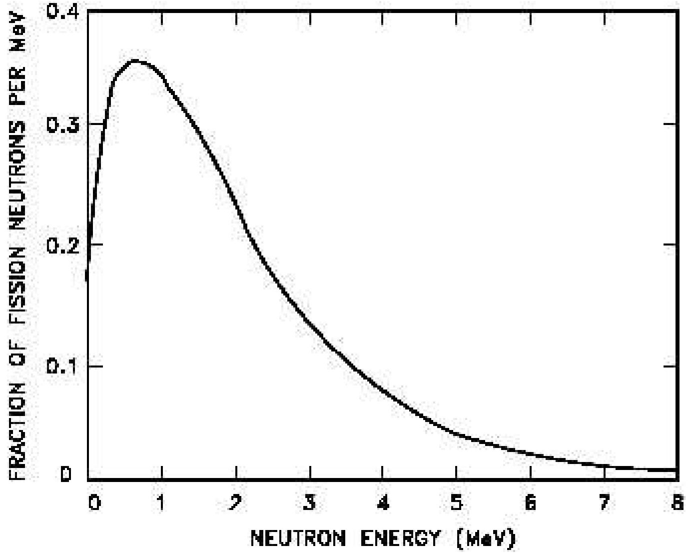
- Terrorist threat
- Detection by fast neutron emissions
  - passive
  - active

SNM	form	Gamma-rays		Neutrons	
		Energy	Intensity	Energy	Intensity
Uranium	Highly enriched	1.001	$\leq 10^4$	≈ 2	1
		2.6	2.7×10^4		
plutonium	Mixed Oxide	0.769	10^5	≈ 2	$\approx 5 \times 10^5$
	Weapons grade	0.769	2.3×10^5	≈ 2	$\approx 6 \times 10^4$
Californium 252					$\approx 2 \times 10^6$

Flux from 1 kg plutonium (WGP)

- Plutonium n-emission ($n.kg^{-1}.s^{-1}$)

^{236}Pu	3560
^{238}Pu	2660
^{240}Pu	920
^{242}Pu	1790
^{244}Pu	1870



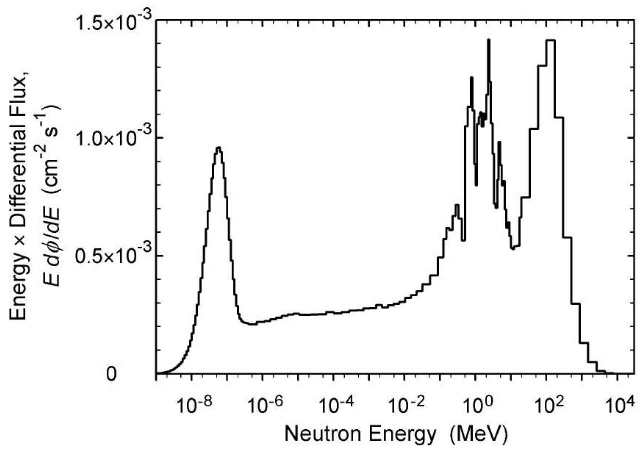
- 1 kg WGP
  - 6% ^{240}Pu + 94% ^{239}Pu
  - 6.10^4 n/s
  - at 7 m distance $\frac{6.10^4}{4\pi 700^2} = 0.01$ n cm^{-2} s^{-1}

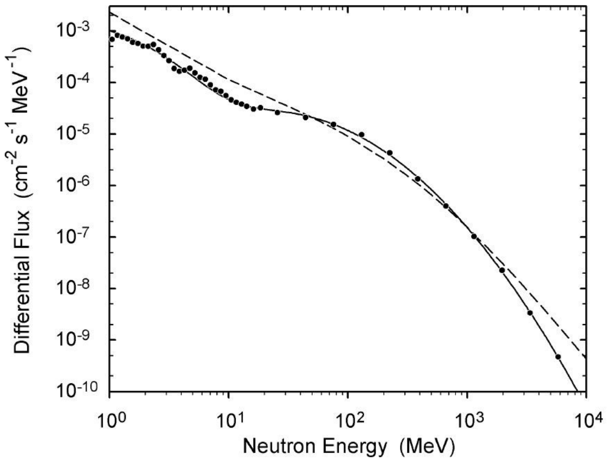
Neutron back ground

- Neutron back ground
  - cosmic
  - sun
  - earth crust

- Flux
  - varies
    - in time -> solar activity
    - with height / location

  - 10^{-3} n cm^{-2} s^{-1} MeV^{-1}
  - for 1-10 MeV 0.01 n cm^{-2} s^{-1}
  - equal to Pu rate at 7 m!





M.S. Gordon et al., IEEE TNS 51, no:6 (2004)

Imaging

- Back ground reduction
  - angular resolution, say 10°
    - reduction factor

$$\frac{\pi\left(r\tan 10^\circ\right)^2}{4\pi r^2} = \frac{\tan^2 10^\circ}{4} = \frac{1}{128}$$

  - now 1 kg WGP detectable up to 70 m distance above back ground

- Need direction sensitive detector for fast neutrons

Back ground from cargo

- Standard detection portals?
  - not direction sensitive

- Activity present in normal cargo
  - p.e. Tiles
    - filling fraction 10%
    - fraction K 1%
    - ^{40}K fraction 0.012%
    - half life 10^9 yr

    } $6x10^6$ Bq

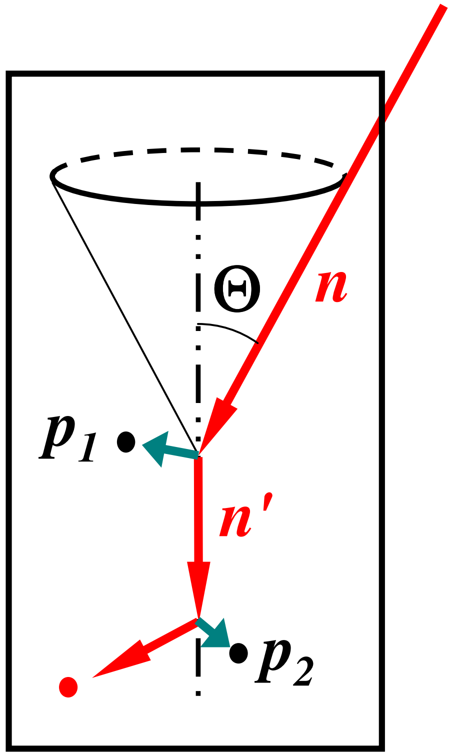
  - decay by β-emission (80%)

Detection principle

- One large organic scintillator
- Two successive n-p elastic scattering
- Determine:
  - interaction positions
  - energy scattered neutron $E_{n'}$
  - direction scattered neutron
  - energy of the first recoil proton p_1
- Determine the incident neutron energy

$$E_n = E_{p1} + E_{n'}$$

- Calculate scatter angle Θ $\quad \Theta = \arcsin\sqrt{\frac{E_{p1}}{E_n}}$
- Construct cone

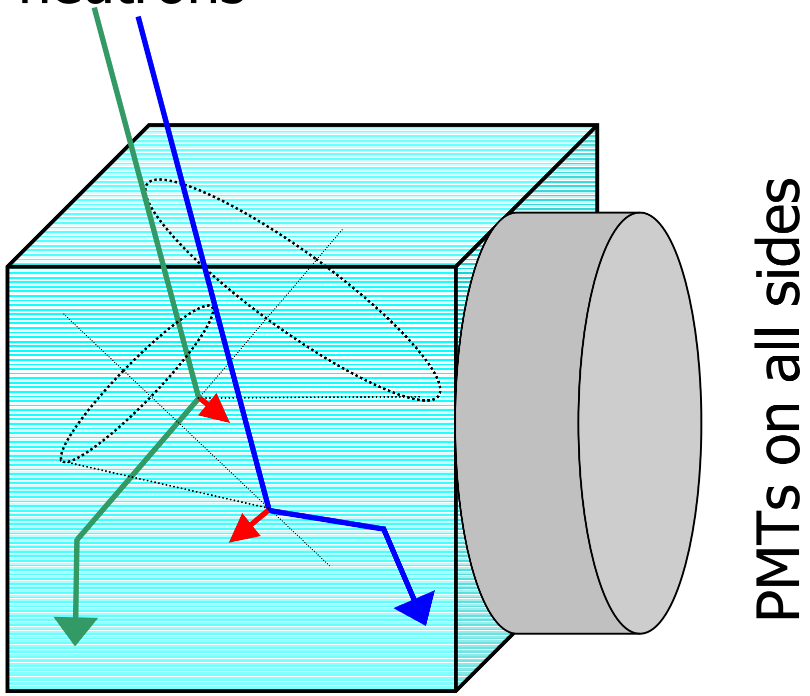


Common direction on several cones points to the source

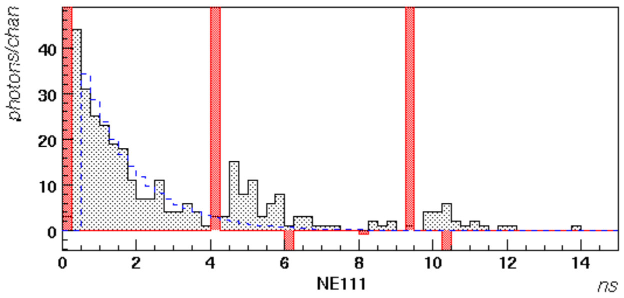
Detector schematic

- Interaction positions
  - light distribution on PMTs
- Time difference t_{p2}-t_{p1}
  - scintillation light flash timing
- Energy first proton
  - light intensity

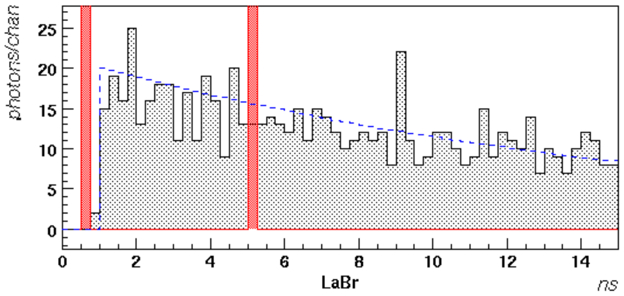
- Positions and time difference gives E_n, and direction scattered neutron
  - time differences ~ ns
  - track lengths ~ cm
- Fast scintillator necessary



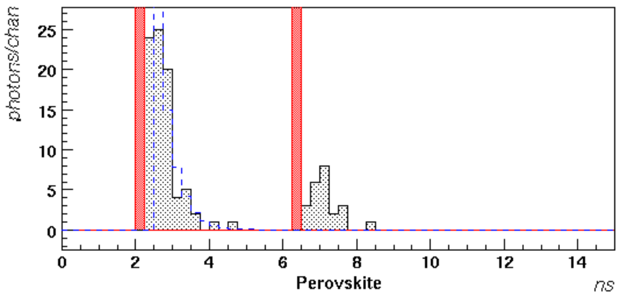
Scintillation light pulses



NE111
decay: 1.4 ns
10200 photons/MeV



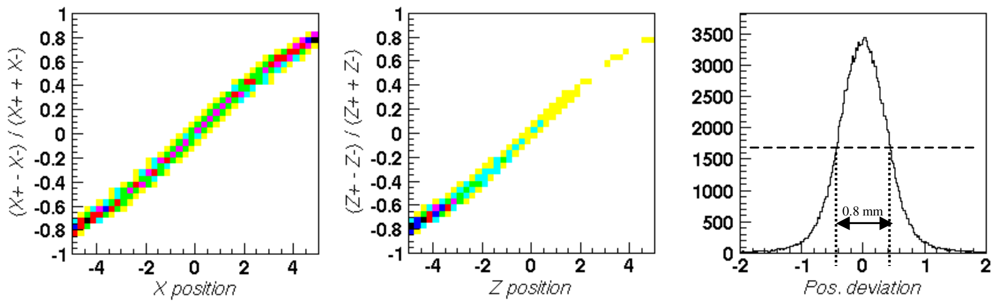
LaBr like
decay 16 ns
80000 photons/MeV



Perovskite
decay: 0.4 ns
4000 photons/MeV

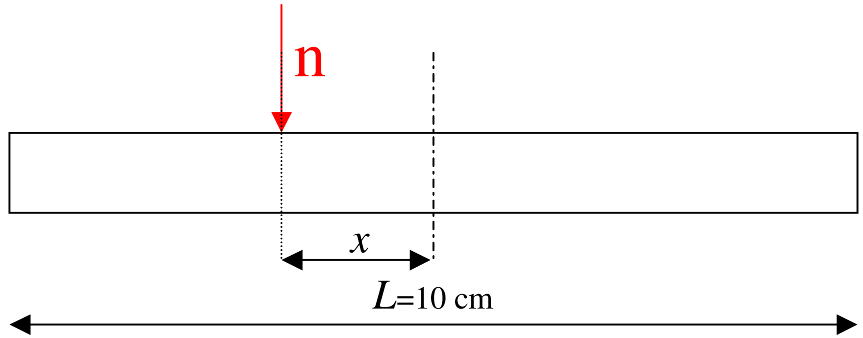
Position determination

- Light intensity
  - pos ~ $\frac{\text{intensity difference}}{\text{intensity sum}}$
  - suppose linear relation
  - σ of 3 mm



- Time difference of light

$$t_{right} - t_{left} = {(L+x)}/{c/n} - {(L-x)}/{c/n}$$
$$= {2x}/{c/n} = 0.1\,[\text{ns/cm}]\; x$$

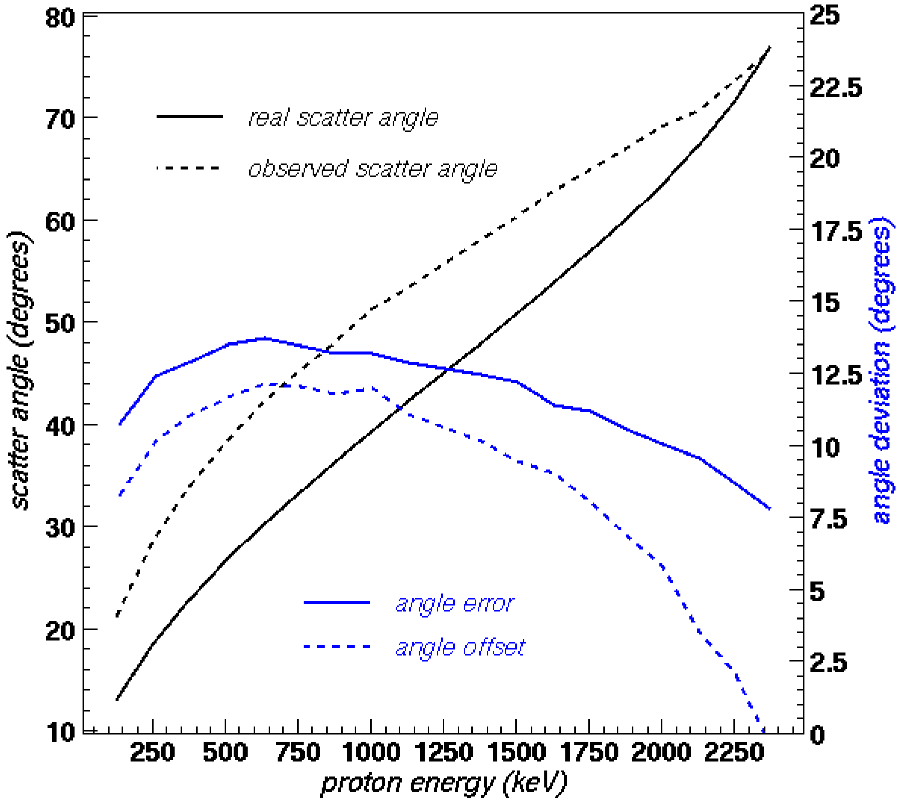


- Anger principle
  - accuracy ?

Direction determination

- Assume
  - time resolution 0.4 ns
  - position resolution 5 mm
  - energy resolution 16%
- Calculate (fully drawn lines)
  - scatter angle
  - 1 σ error ~ 12°
- Disregard events (dashed lines)
  - E_{p1} < 200 keV
  - track length < 5 mm
  - time difference < 0.4 ns

  ⇒ offset



Efficiency

- n-p and n-C interactions
- n-C interactions
  - small light yield $\Rightarrow$ go undetected
  - but change n-direction
- only n-p interactions useable
  - for hydro-carbon scintillator (10 cm cube) $\Rightarrow$ 27% of all events

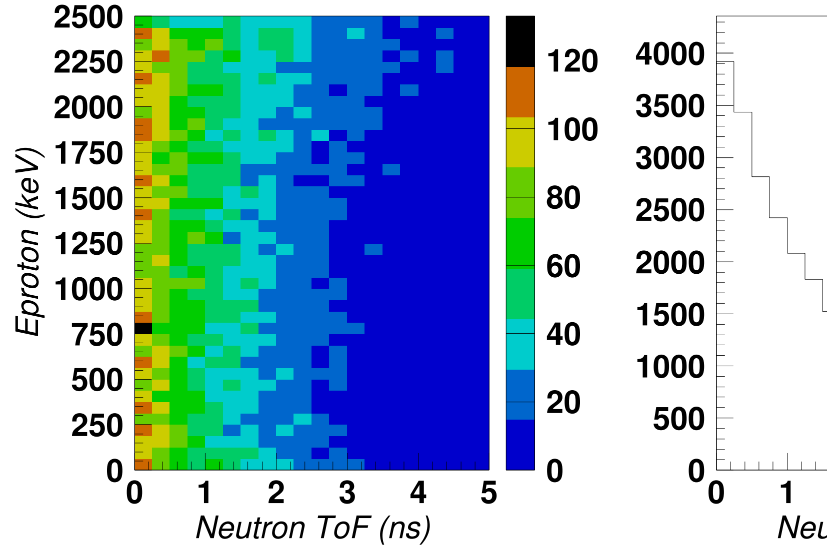
first hit	fraction	second hit	fraction
proton	55%	proton	27%
		carbon-nucleus	28%
carbon-nucleus	32%	proton	
		carbon-nucleus	
no hit	13%		

33% for perovskite $(n\text{-}C_6H_{13}NH_3)_2PbI_4$

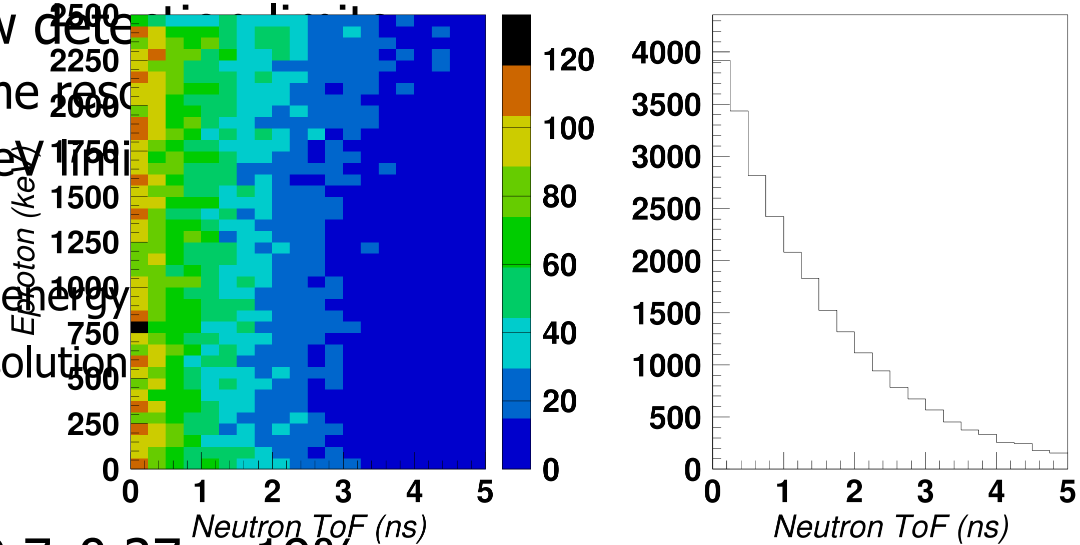
- other scintillators?

Efficiency

- Simulation of 2.5 MeV neutrons in10 cm^3 cube scintillator
  - E_{p1} versus time difference t_{p2}-t_{p1}
  - theory: flat distribution of E_p

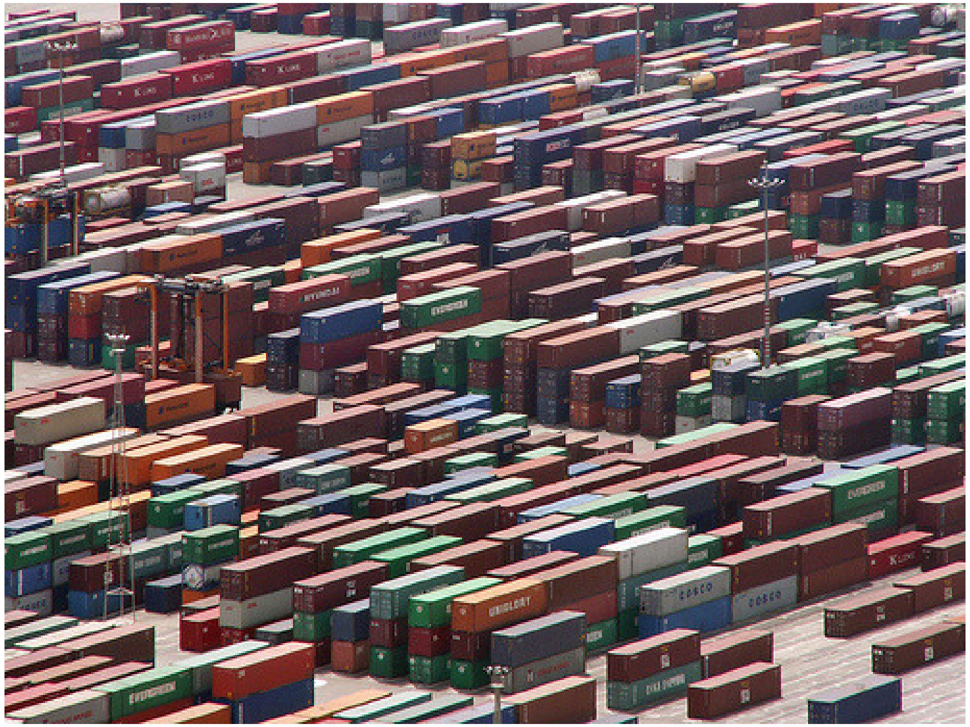


- Some events below dete
  - t_{p2}-t_{p1} below time reso
  - E_{p1} below 200 keV limi
  - assuming
    - 200 keV lower energy
    - 0.4 ns time resolution
  - $\Rightarrow$ 70% detected



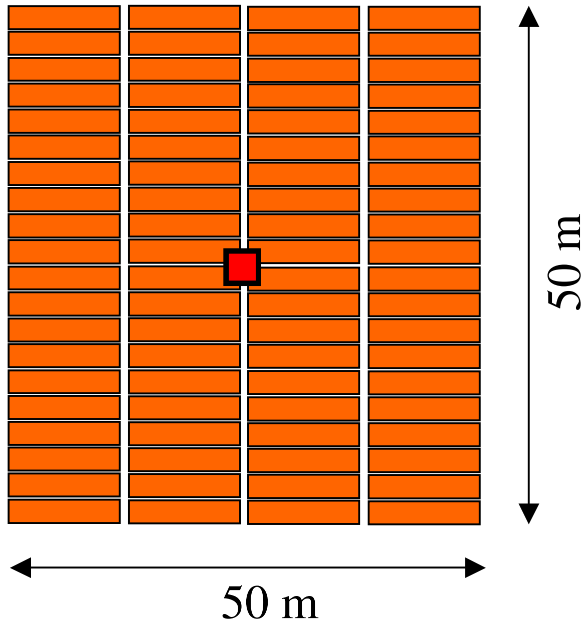
- Overall efficiency 0.7x0.27 = 19%

TEUs



Application

- Port of Rotterdam
- Container stack
  - 50 x 50 m2 ~ 2500/(2.5x12) ~ 80 TEUs
  - stacked 4 layers ⇒ over 300 containers



  - 1 kg Pu, 10 cm^3 cube detector at 25 m, rate:

$$\frac{6.10^4}{4\pi(2500)^2} 100\ \mathrm{cm}^2 = 0.076\ \mathrm{n/s}$$

  - back ground rate:

$$\frac{\pi\left(r \tan 12^\circ\right)^2}{4\pi r^2} 0.01 \times 100\ \mathrm{cm}^2 = 0.011\ \mathrm{n/s}$$

  - in 10 minutes:

⇒ 90 Pu counts on a background of 14 counts