Development of the calibration system of the STEREO experiment and search for sterile neutrinos at ILL

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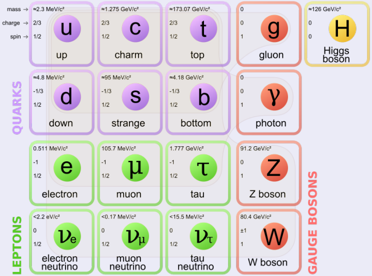
Outlook

1. Introduction
   - Neutrino physics
   - The STEREO experiment
2. STEREO Calibration
   - Energy scale calibration
   - Neutron capture efficiency
   - Non-uniformity in the detector response
3. Results and conclusions

Neutrino physics:

Neutrinos in the standard model



- No electric charge
- Tiny mass (<1 eV)
- Electroweak and gravitational interaction only
  $\Rightarrow \sigma \sim 10^{-3} fb = 10^{-42} cm^2$

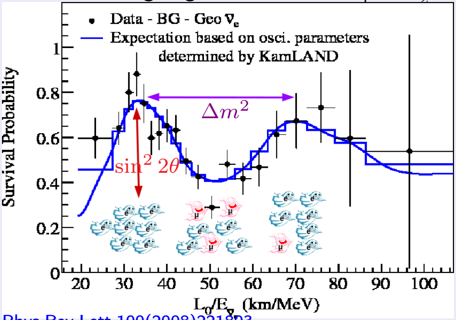
Neutrino oscillation

- Neutrinos **oscillate** during their propagation.
- **Flavor eigenstates** $\Rightarrow$ linear mixing of **mass eigenstates**.

$$|\nu_\alpha\rangle = \sum_{k=1,2} U_{\alpha k} |\nu_k\rangle$$

$$P_{(\nu_x \to \nu_y)} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

with θ mixing angle and $\Delta m^2 = m_1^2 - m_2^2$



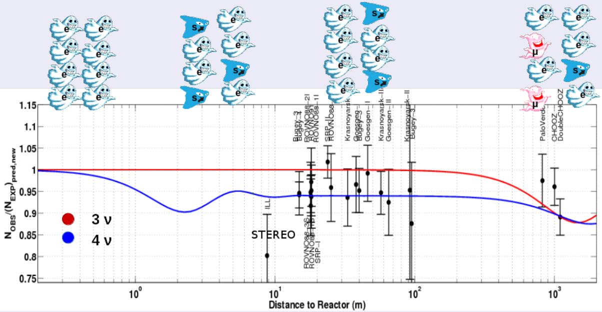
Phys.Rev.Lett.100(2008)221803

Are there more than 3 neutrinos?

$\rightarrow$ STEREO

The reactor antineutrino anomaly

Reactor antineutrino anomaly



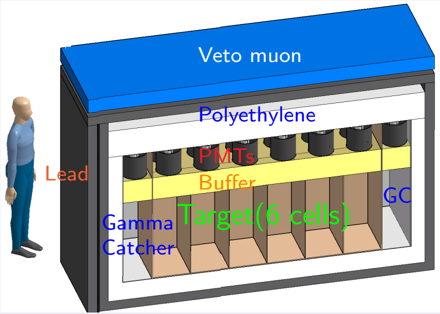
New estimation on the number of neutrino interactions expected in short baseline neutrino experiments→ deficit of 6% (Phys.Rev.D83(2011)073006)

A possible **interpretation** of this deficit ⇒ oscillation into a **4th neutrino** (**sterile neutrino**).
⇒ $\Delta m^2_{new} \sim 1eV^2$ and $\sin^2(2\theta_{new}) \sim 0.12$

The STEREO's aim is to **confirm or reject** the existence of a **light sterile neutrino state**, looking for an oscillation at short distance.

The STEREO detector

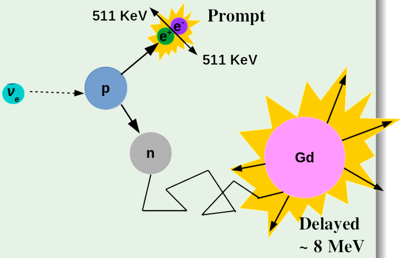
STEREO at ILL



- 2.3 m^3 liquid scintillator doped with Gd (Target)
- 6 cells X length 37 cm
- Small detection volumes $\Rightarrow$ Leak of gammas $\Rightarrow$ Extra 30 cm of non-Gd doped Liquid Scintillator (Gamma Catcher)
- Reactor core at Institut Laue-Langevin (ILL) at Grenoble, very compact ($\phi = 37$ cm)
- Detector center placed ~ 10 m away of the reactor core

Experimental signature:

IBD: $\overline{\nu_e} + p \rightarrow e^+ + n$

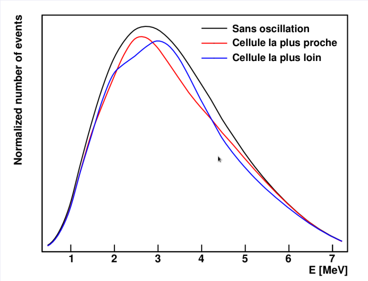


Coincidence of e^+ (*prompt*) and **n capture** on Gd (*delayed*, $\sim 20\mu$s later)

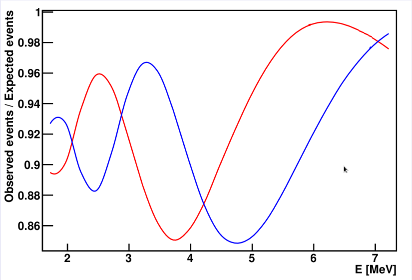
Looking for a new oscillation with STEREO

$$P\left(\overline{\nu_e} \rightarrow \overline{\nu_s}\right) = \sin^2(2\theta_s)\sin^2\left(1.27\frac{\Delta m_s^2 L}{E_{\overline{\nu_e}}}\right)$$

Spectra deformation

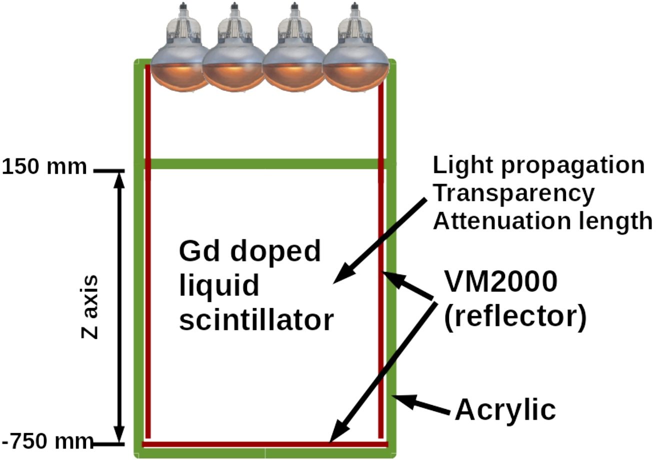


Ratio oscillated / non-oscillated



A new oscillation would modify the energy spectra of reactor neutrinos
The oscillation phase depends on the distance
$\Rightarrow$ Energy calibration: vital !

A cell in STEREO



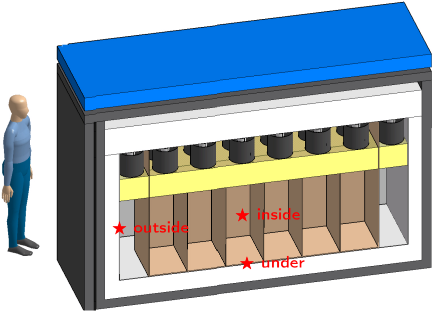
Calibration goals

- Calibrate the absolute energy scale better than 2% in each cell
- Calibrate neutron capture efficiency
- Study and characterize the non-uniformity in the detector response (ex: dependence of the energy response with the distance to PMTs)

Energy scale calibration

Energy scale calibration with γ sources

Position of sources



Energy reconstruction

$PMT_i = q_i$ integrated charge

$Qtot = \Sigma_i^n \frac{q_i}{g_i}$; with g_i PMT gain

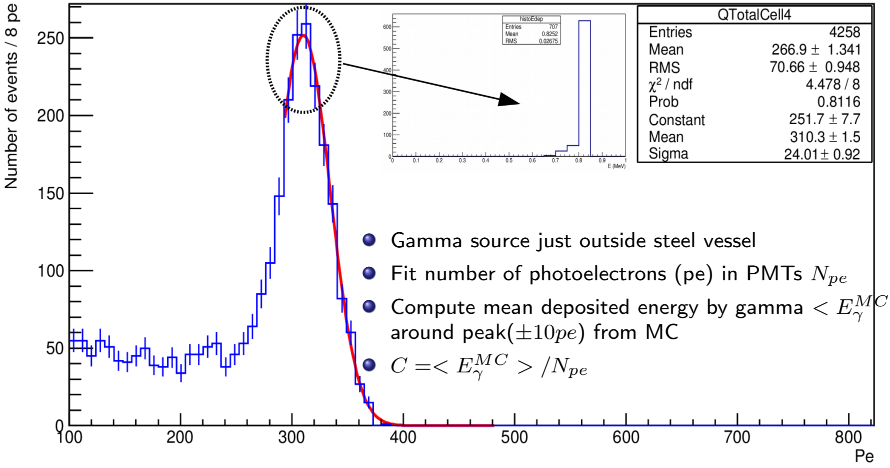
$E_{rec} = Qtot(pe) \times C^{e^+} (MeV/pe)$

and

$E_{rec}^{\overline{\nu_e}} = E_{rec}^{e+} + 0.79 MeV$

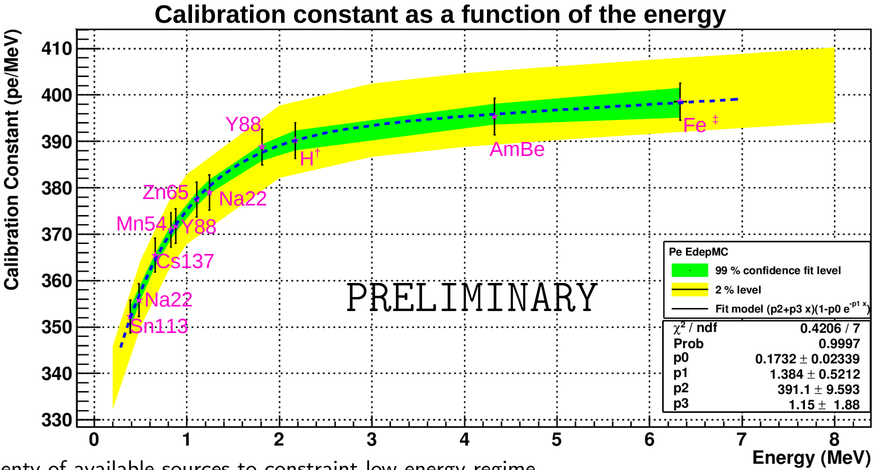
- γ lines from radioactive sources give absolute energy scale reference
- Small detection volume $\Rightarrow$ energy leaks and Compton scattering of γ $\Rightarrow$ account for using MC
- Need to compare energy spectrum of different cells $\Rightarrow$ calibration of each independently

^{54}Mn (0.834 MeV) **outside detector** (γ go through 10 mm steel and GC)



- Gamma source just outside steel vessel
- Fit number of photoelectrons (pe) in PMTs N_{pe}
- Compute mean deposited energy by gamma $< E_\gamma^{MC} >$ around peak($\pm 10pe$) from MC
- $C =< E_\gamma^{MC} > / N_{pe}$

STEREO calibration curve: Evis 2-8 MeV



Plenty of available sources to constraint low energy regime

Lacking sources above 4.4 MeV ⇒ **solution found at HE, 7.6 MeV from n capture on Fe**

Energy scale calibration: PRELIMINARY summary

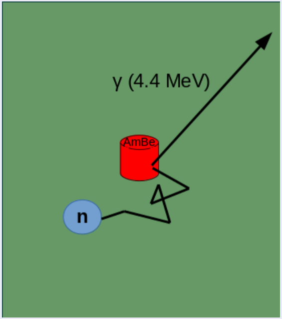
Source	Energy (MeV)	Constant (pe/MeV)	Stat error (%)	Sys error (%)
^{22}Na	0.511	238	0.8	0.9
^{137}Cs	0.66	256	0.7	0.9
^{54}Mn	0.83	260	0.5	0.8
^{65}Zn	1.12	266	0.4	0.5
^{22}Na	1.27	268	0.6	0.8
$AmBe$	4.44	290	0.3	0.9
H^*	2.22	284	0.5	0.8
Fe^*	6.5±0.06†	291	0.4	1.1

- Sources that can be used to calibrate the energy scale in the STEREO experiment. * represents n capture
- † the mean energy of γ's from n capture on Fe is polluted with γ's from n captures on Gd and others materials, which gives 6.5 MeV

Neutron capture efficiency

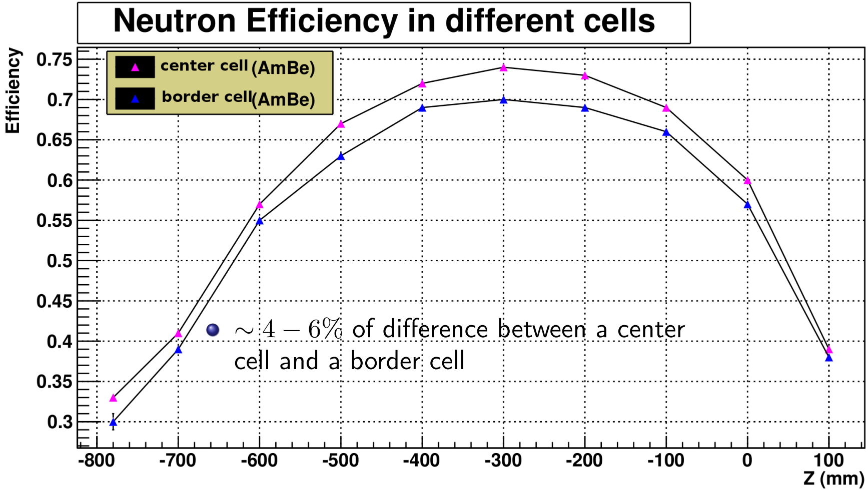
Neutron capture efficiency using AmBe

How to define the neutron efficiency ?



- Difficult to know n emission rate from source at 2-3% level ⇒ Use AmBe source, where 4.4 MeV γ always emitted with n
- Search for n capture on Gd (delayed) in Δt[2,50] μs after 4.4 MeV γ (prompt)
- $\Rightarrow \epsilon_n = \dfrac{N(\text{prompt\&delayed})}{N(\text{prompt})}$

Absolute n detection efficiency

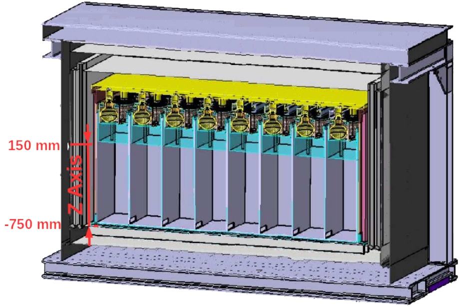


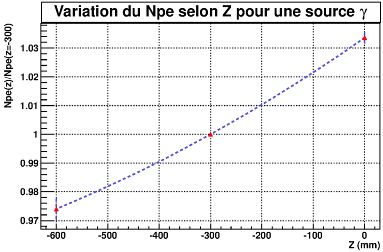
- $\sim 4-6\%$ of difference between a center cell and a border cell

To compare and measure the absolute n capture efficiency in different cell positions ⇒ n source inside liquid scintillator

Non-uniformity

Non uniformity in the light detection

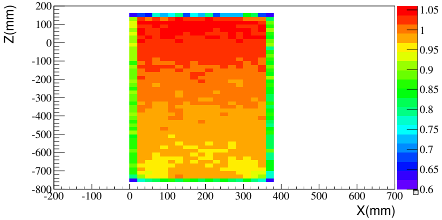




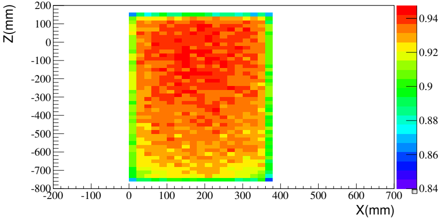
PMTs only in one side ⇒ **calibration of light detection as function of Z crucial!**

$$E_{rec}/E_{depTOTAL}$$

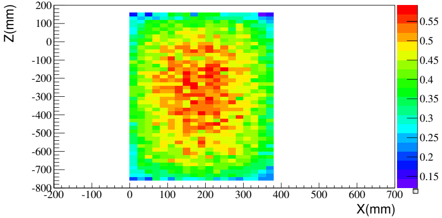
3 MeV e^-



3 MeV e^+



3 MeV γ's



Three effects:

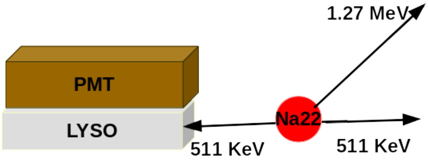
1. Gamma leakage (geometric)
2. Z dependence of calibration constant
3. Light leaks

Non uniformity in Z with a Na-22 source

- Study of response in Z with Na-22 source outside steel vessel
- Na-22→ 2γ(511 KeV back to back)+1γ(1.27 MeV).
- Energy deposited in a large interval in Z ⇒ need of collimation

Scintillator crystal

5x5x20 mm^3

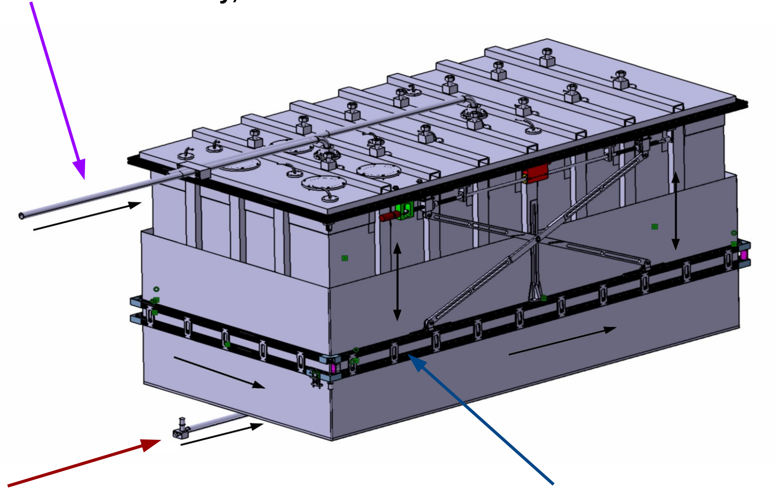


∼10 mm between source and crystal

> Trigger ⇔ accept **preferentially** gammas in **one direction**
> **Second possibility studied:** Passive collimation using a cylinder of lead or tungsten

STEREO calibration system

n absolute efficiency, etc



n efficiency intercalibration

Energy scale calibration, cells non uniformity

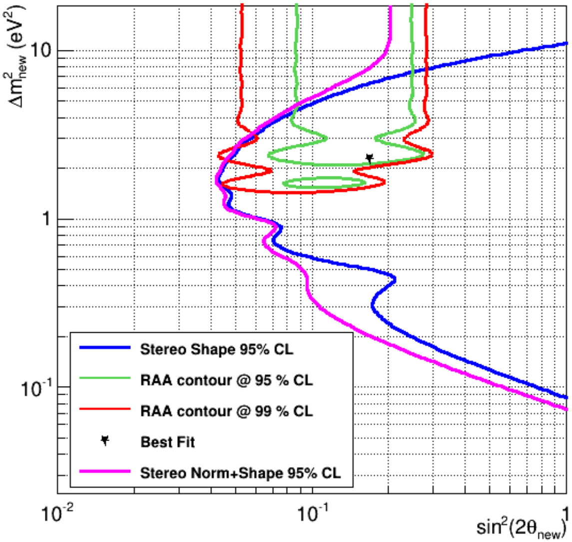
Conclusions

Calibration with radioactive sources has been studied with simulations

- Calibration with gamma sources from outside detector validated
- Can monitor z-dependence response using Na-22 device
- Calibration curve: plenty of sources at low energy, possible solution at higher energy (n capture on Fe)
- Defined procedure to measure n capture efficiency in a cell

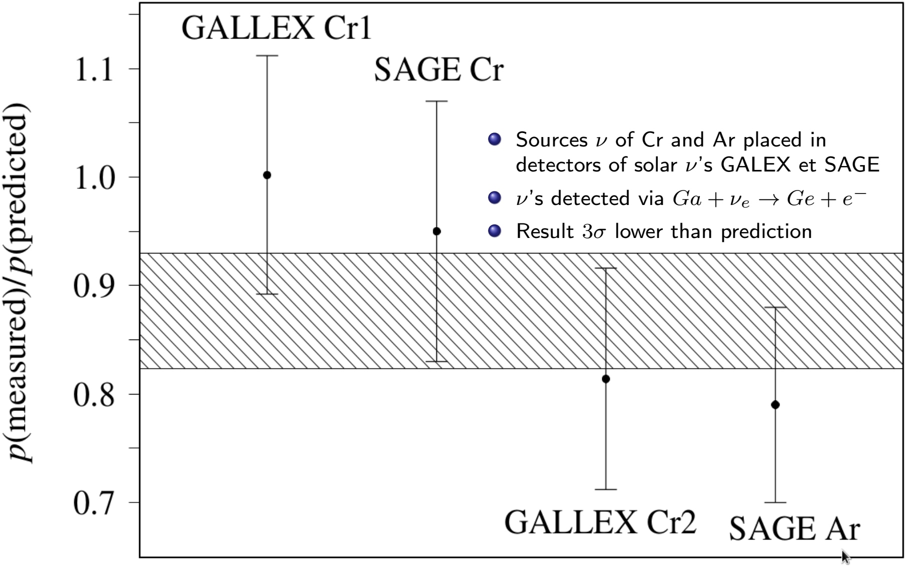
MERCI DE VOTRE ATTENTION

Exclusion contour



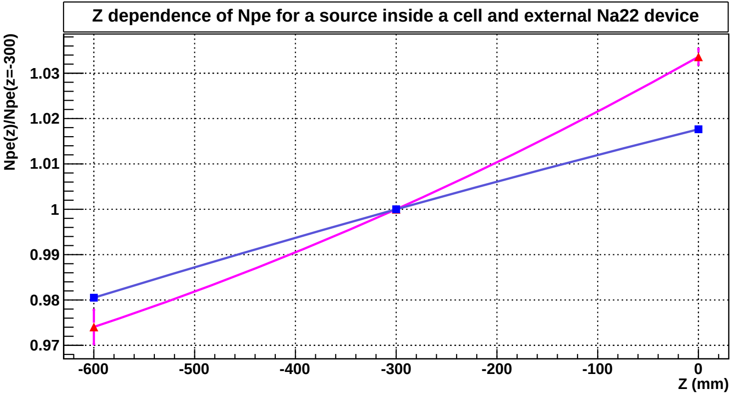
- 300 days
- Ep >2 MeV, Ed >5 MeV
- L0 = 10.0 m
- S/B = 1.5, 1/E + flat
- $\delta E_{scale} < 2\%$

Gallium anomaly



- Sources ν of Cr and Ar placed in detectors of solar ν's GALEX et SAGE
- ν's detected via $Ga + \nu_e \to Ge + e^-$
- Result 3σ lower than prediction

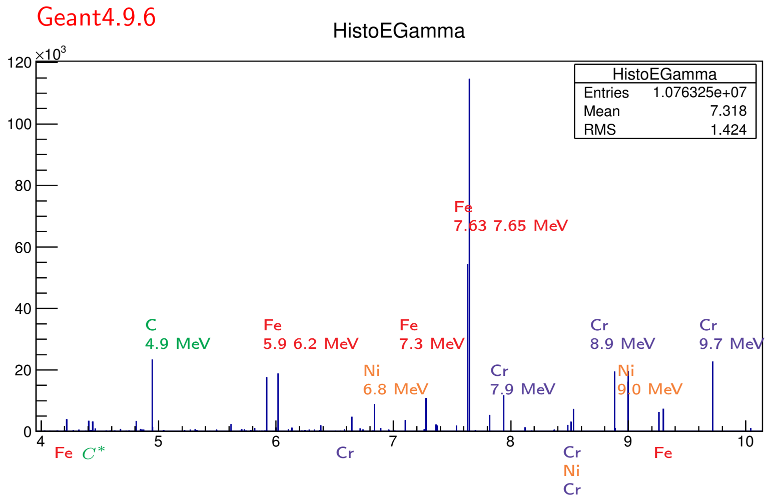
Z dependence



$\Delta N_{pe}^{Z} = 5.9\%$ over 60 cm with the **external Na22 device**

$\Delta N_{pe}^{Z} = 3.7\%$ over 60 cm with an **internal source**

Gammas from n captures: ^{252}Cf just outside steel vessel



At HE, spectrum is dominated by the two 7.6 MeV gammas from n captures on Fe