Energy resolution and absolute detection efficiency for LSO crystals: a comparison between Monte Carlo simulation and experimental data

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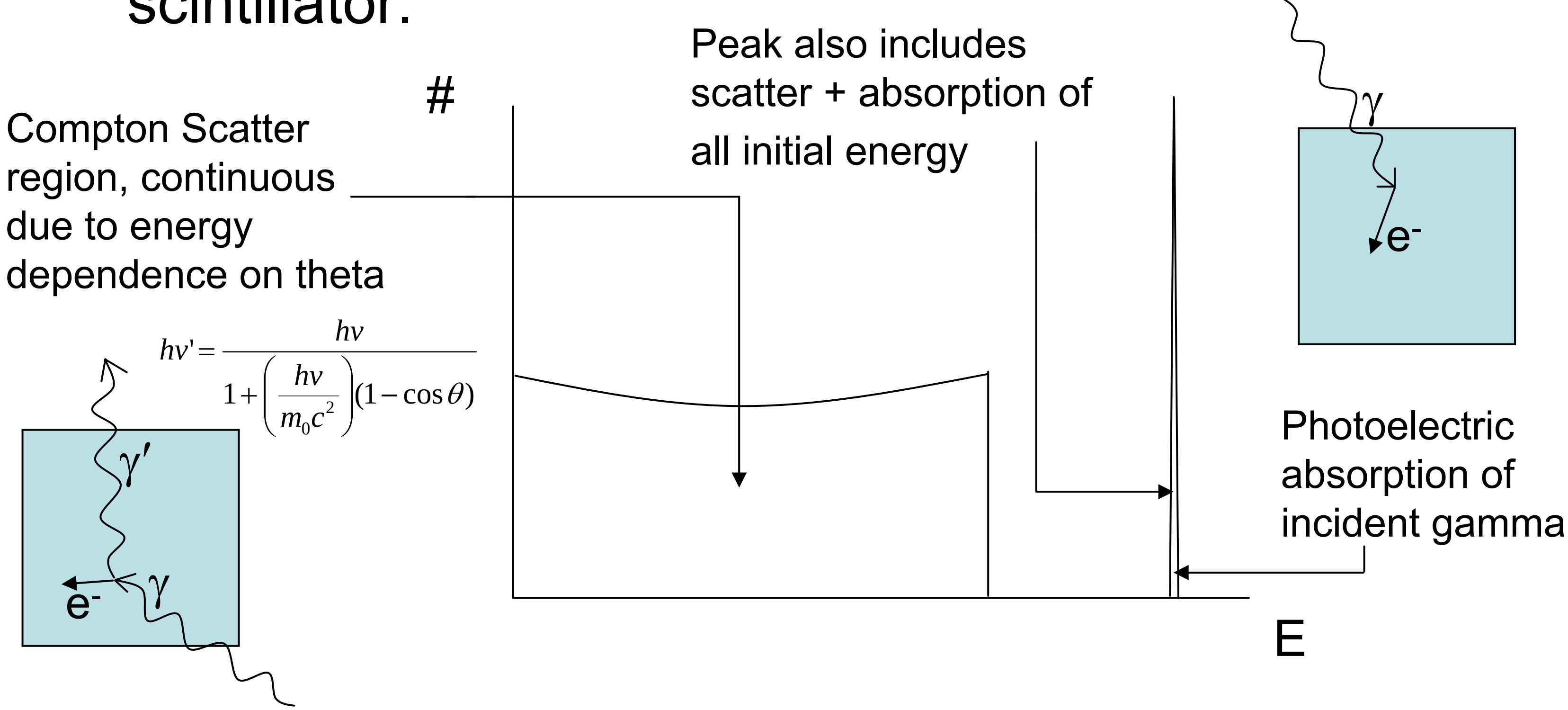
Basics of Radiation Spectroscopy with scintillators.

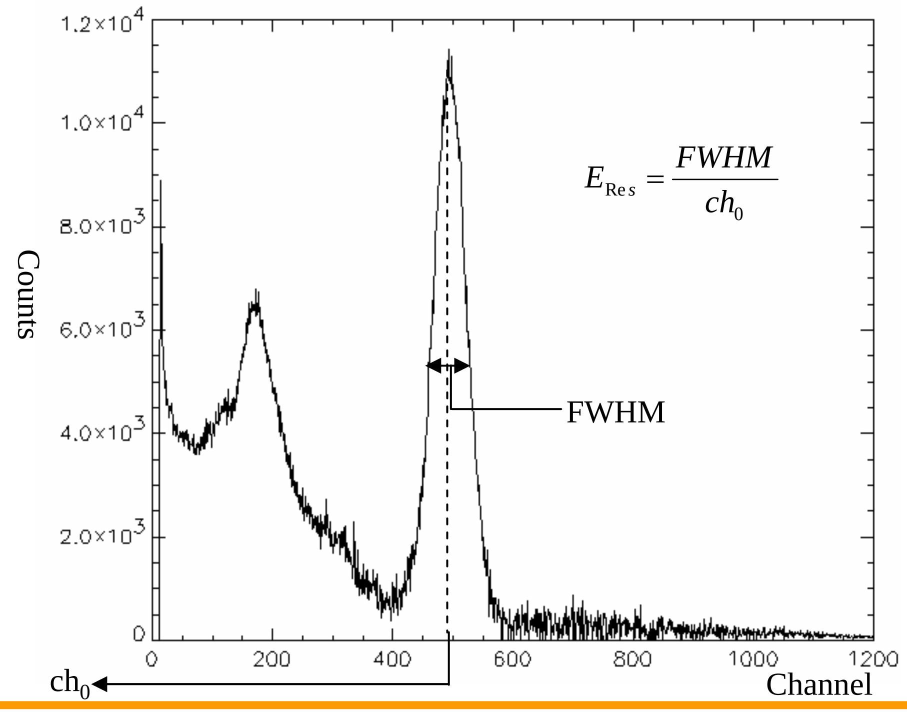
- **<u>Ideal Energy Spectrum</u>**
  - Photoelectric effect and Compton scattering seen in spectrum’s structure as energy deposited in the scintillator.



Basics of Radiation Spectroscopy with scintillators.

- **<u>Departure from Ideal Energy Spectrum</u>**

  - Interaction effects from ideal energy spectrum “blur” due to physical effects such as transport efficiency, non proportional effects, statistical effects and electrical effects.
  - Measure of “blurring” of the full energy peak is done with the energy resolution of the of the scintillator.



Introduction

Monte Carlo simulations of Positron Emission Tomographs (PET) often overestimate the experimental sensitivity, and blurring functions are also needed to properly represent spatial and energy resolution.

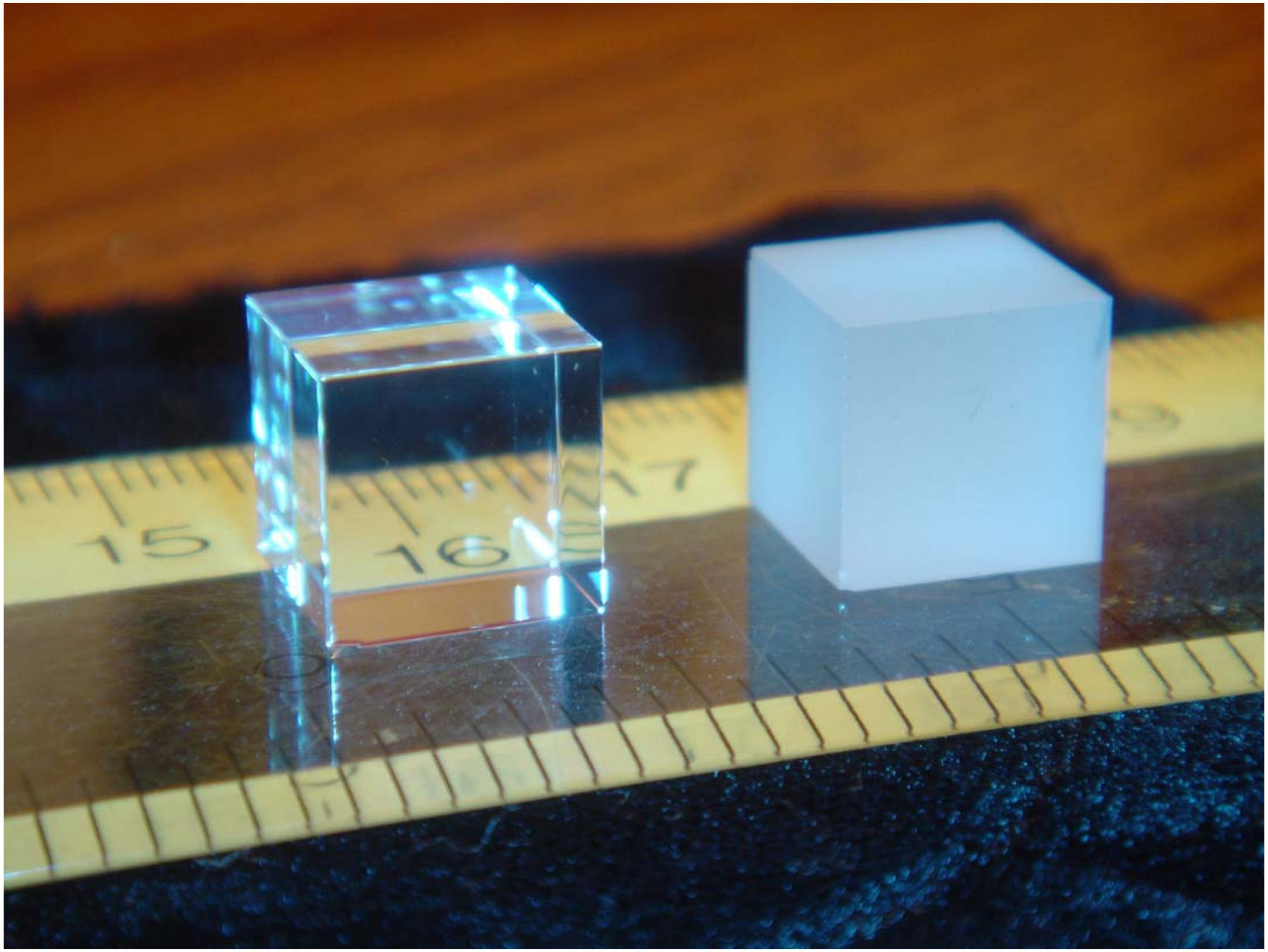
In order to understand and overcome these issues, we introduced in the Monte Carlo simulation light yield non-proportionality and transport of optical photons in scintillating material, in addition to the conventional electromagnetic interaction.

The simulation results were compared with fundamental experiments on single LSO crystals and blocks.

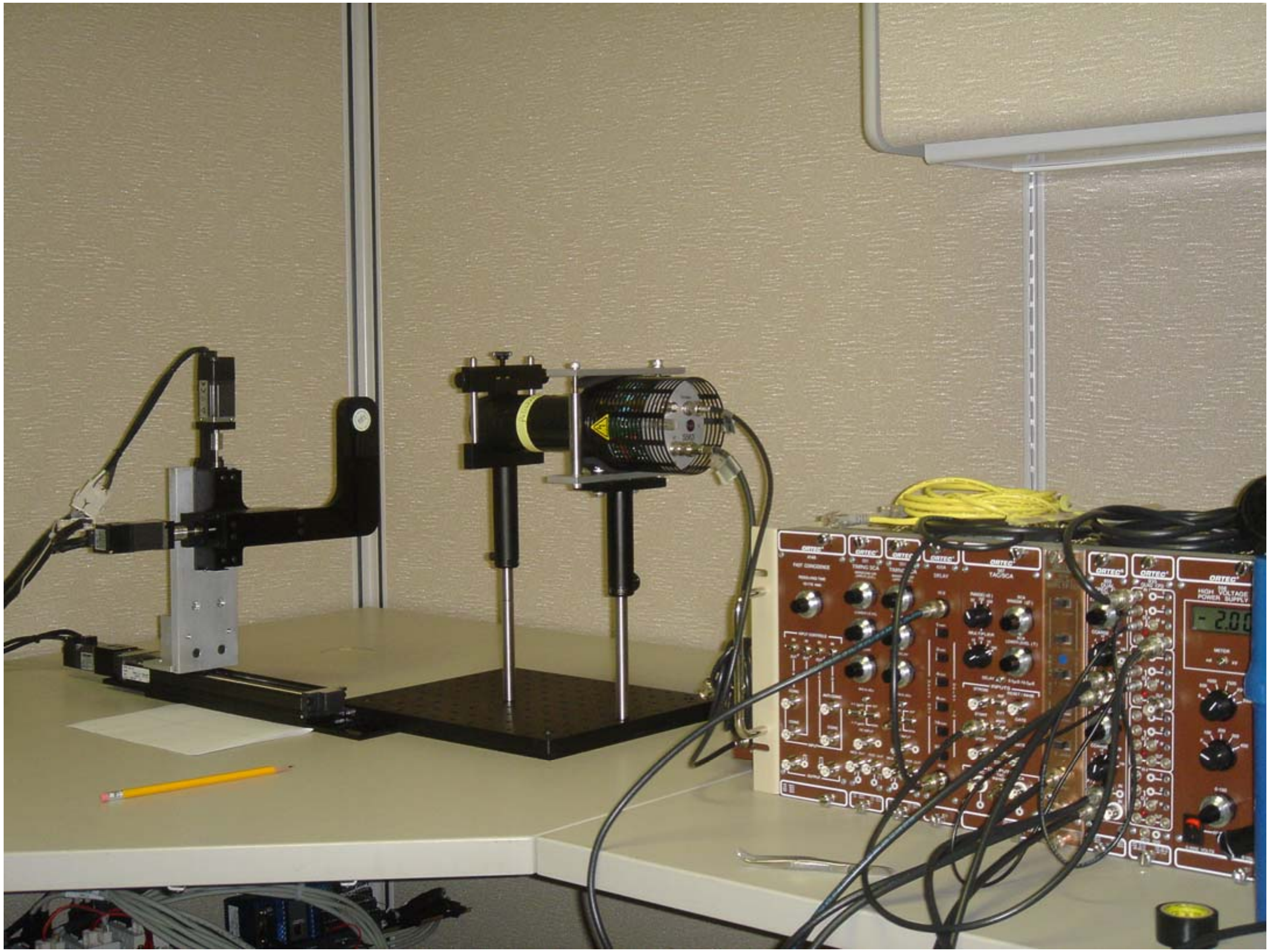
The simulation code used was Geant4.

Crystals and geometry

- Crystal size : LSO 1cc cube, saw cut.
- Reflectant : Teflon sheet over crystal and tube
- Light guide : no, crystal directly on PMT with optical grease
- PMT : XP2020Q (Photonics)
- Source : ^{137}Cs (0.404 MBq, 662 keV γ) at 20 cm from the detector



Polished and saw cut LSO crystals

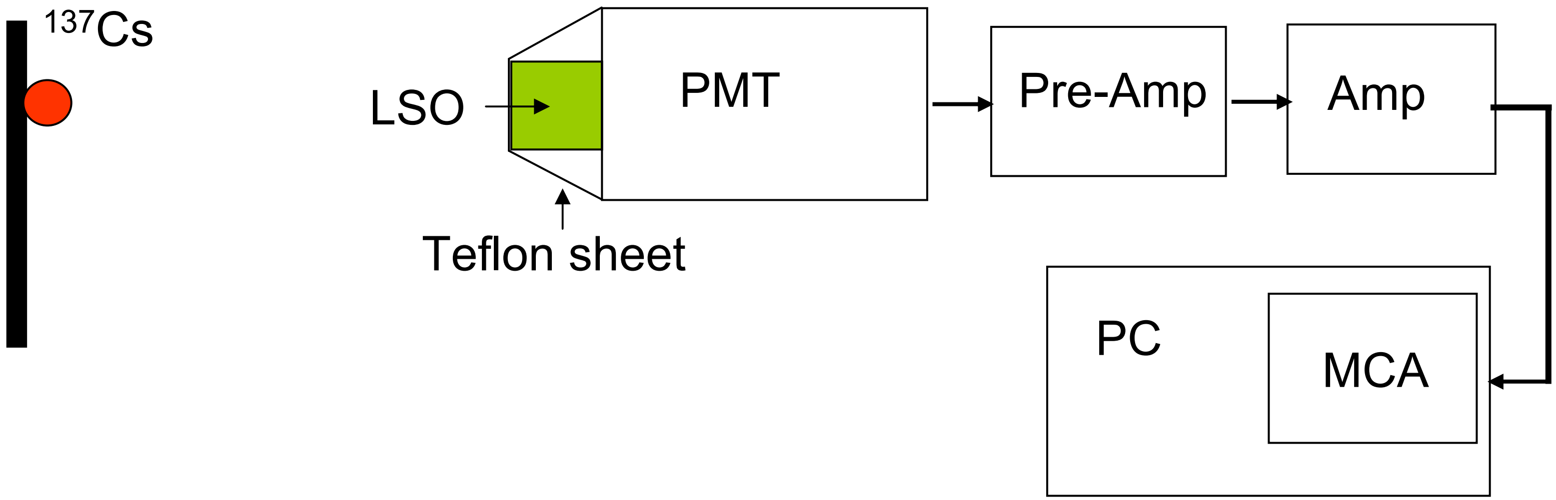


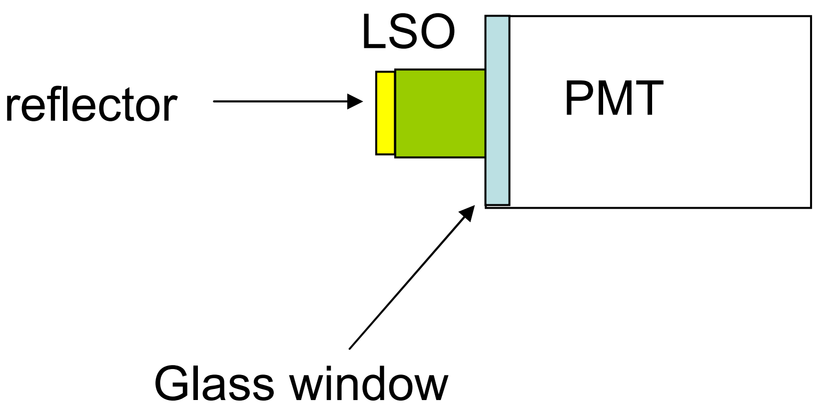
Experimental set-up

Electronics set-up

- High Voltage : Ortec 556 with -2000V
- Pre-Amplifier : Ortec Model 113, input capacitance 20pF
- Amplifier : Ortec 855 Dual Spec Amp with x25 gain
- MCA : Ortec Maestro 32MCB25
- Acquisition time : 24 hours (and 24h background subtraction)

Experimental set-up

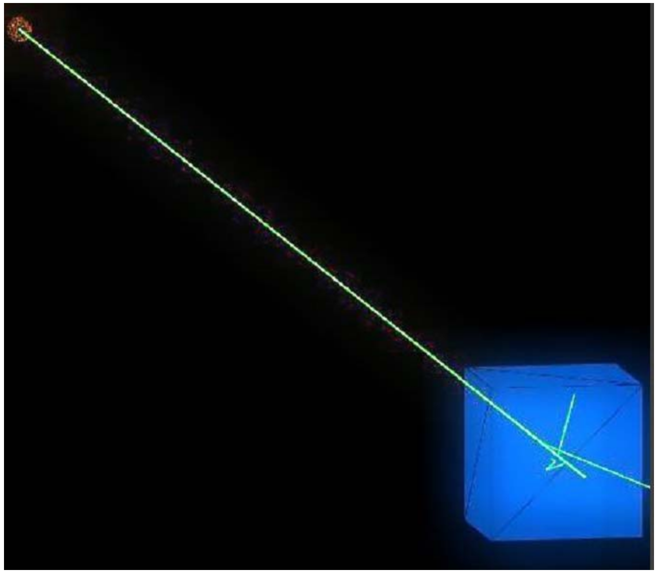




Simulation detail

Simulation performed with GEANT4

- Geant4 Low Energy Library is used
- Source was a ^{137}Cs point source in vacuum with $4*\pi$ emission of a 662 keV Gamma
- Energy deposit in LSO is scored
- Non proportionality is applied to modify the number of light photons emitted (below 1 MeV E_{dep})



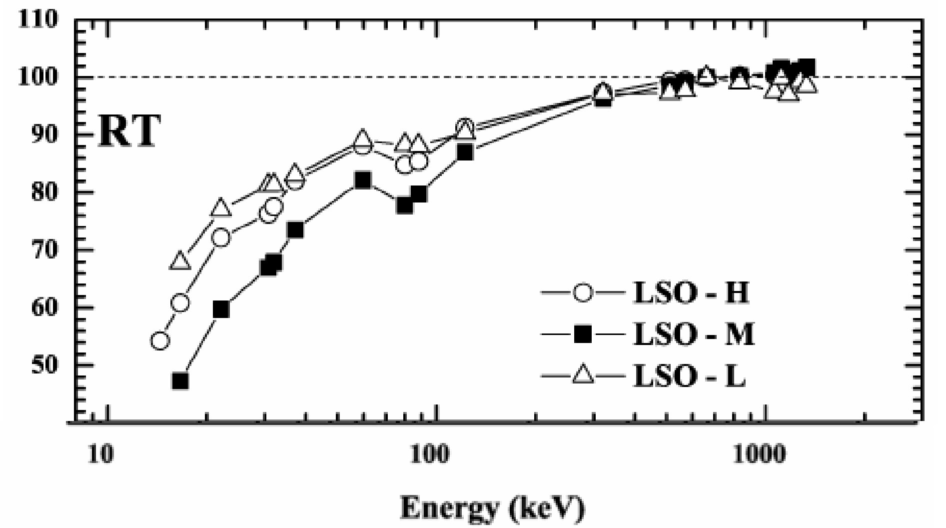
- Scintillation photons are generated and transported in the crystal

Non Proportionality

•At low energy (below 1 MeV) the number of scintillation photons is not proportional to the deposited energy

• We developed a model from experimental data [4] to decrease the effective deposited energy in LSO (eq.1)

•Effect is applied after the electromagnetic interaction and prior to the scintillation light transport



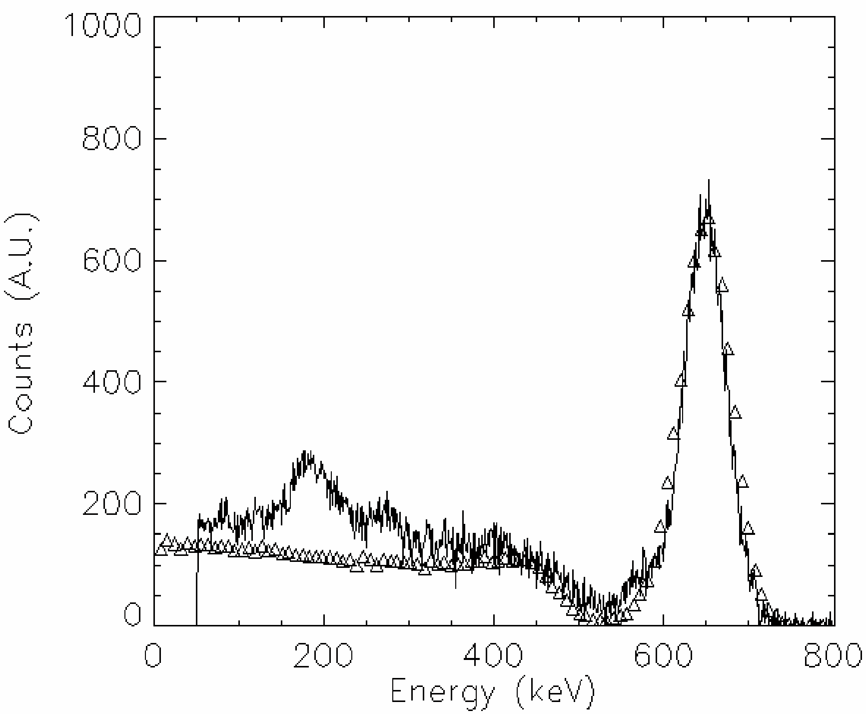
Eq.1 $$E_{eff} = E_{dep}(1 - e^{(-2.13 E_{dep}(MeV) - 0.625)})$$

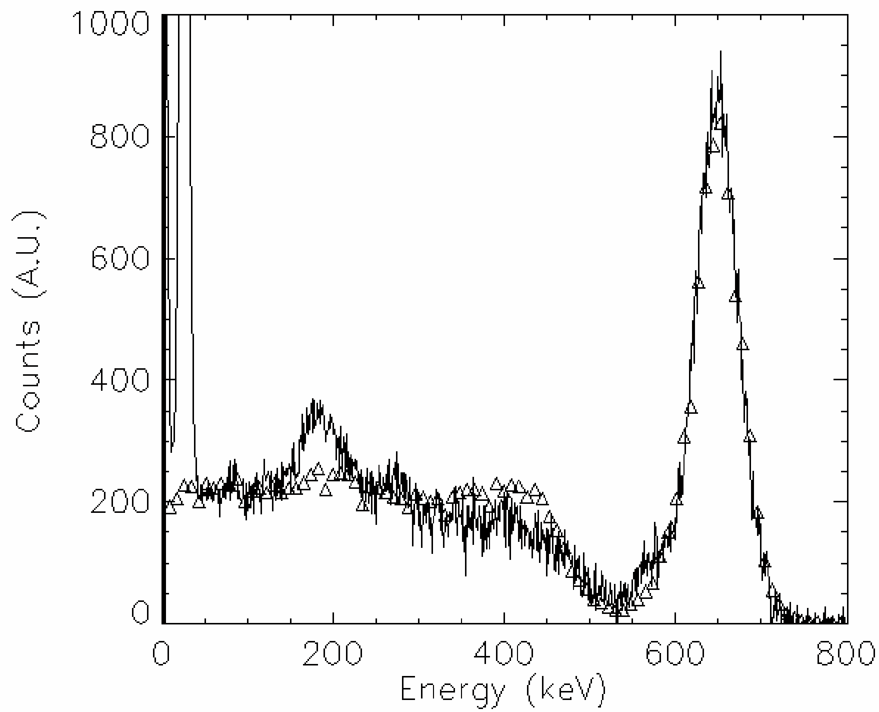
Optical photons transport

- We assumed 30000 scintillation photons per MeV and 25% PMT quantum efficiency
- The simulation components were the LSO crystal, a glass window of the PMT, the detecting photocathode of the PMT and some reflector.
- Surfaces of the crystal were modeled as a ground surface, index of refractions were $N_{LSO} = 1.8$ $N_{Window} = 1.45$
- When scintillation photons cross through the crystal surface, has probability of 0.99 to be reflected on reflector.
- Most scintillation photons undergo internal reflection due to mismatch of index of refractions. $N_{air} = 1.0$

Deposited energy spectra

•Experimental energy spectrum (solid line) from ^{137}Cs source with background subtracted, 24h acquisition, simulated spectrum (Δ).





Left plot has simulation with simulated EM processes only.

Right plot has simulation that includes Non-proportional effect and light transport.

Energy Resolution/Sensitivity

$E_{Resolution\ sim(w/LT\ \&\ NP)} = 10.48 \pm 0.04\%$

$E_{Resolution\ exp} = 10.2 \pm 0.4\%$

- Energy Resolution was obtained with a Gaussian fit of the curves between 540 keV and 775 keV, and defined as the FWHM of the Gaussian function.
- Separate simulations allowed to separate the contribution to the energy resolution of the non proportionality (5.2%) and optical transport (9.3%), assuming that:

$$E_{Resolution}^2 = E_{nonprop}^2 + E_{trans}^2$$

Sensitivity

$Sensitivity_{Sim} = (4.36 \pm 0.13)\ 10^{-5}$

$Sensitivity_{Exp} = (4.39 \pm 0.05)$ 10-5

- Sensitivity was computed adding detected events with energy from 540 keV to 775 keV divided by the total number of photons emitted from the source.
- Experimental emission of source was calculated with

Emission rate = activity(Ci) 3.7*10^{10}(counts/sec)* acquisition time(sec)* 0.851*

Timing Resolution

- Timing was simulated by tracking the path length and making the relationship of path length to transit time.
- The Timing resolution is the FWHM of the histogram of the difference of the start and stop signals.
- Simulated timing resolution only includes transit time of scintillation photons.

$$\text{Timing Resolution}_{\text{Exp (1cc)}} = 254 \pm 12 \text{ pSec}$$
$$\text{Timing Resolution}_{\text{Sim (1cc)}} = 52 \pm 7 \text{ pSec}$$
$$\text{Timing Resolution}_{\text{Exp (2cc)}} = 296 \pm 7 \text{ pSec}$$
$$\text{Timing Resolution}_{\text{Sim (2cc)}} = 108 \pm 4 \text{ pSec}$$

Conclusions

Introducing light yield non proportionality and optical transport in Monte Carlo simulation we could estimate energy resolution and absolute sensitivity that well agree with experimental data.

Information on the non proportionality of scintillating materials is available in literature and must be introduced in any simulation that aims to describe accurately detection of photons below 1MeV.

Proper modeling of optical transport properties of the scintillating crystals is a key element for the correctness of the simulation, and requires a considerable work of fine tuning and experimental testing.

This work will continue with simulation of crystals and blocks used in commercial PET scanners.

References

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