Università degli studi di Ferrara
Master's degree in physics

Time and charge response of linear alkylbenzene scintillators for JUNO experiment

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Academic Year 2013-2014

Summary

Scientific framework

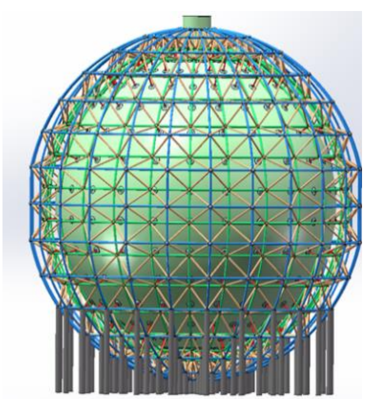
- JUNO experiment: main features and scientific goals.
- Basics of scintillation processes in linear alkylbenzene (LAB)

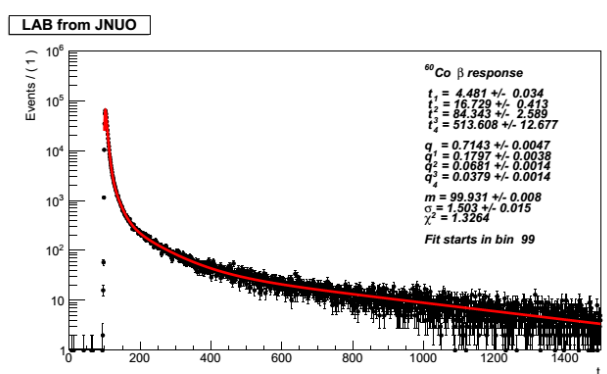
Time response

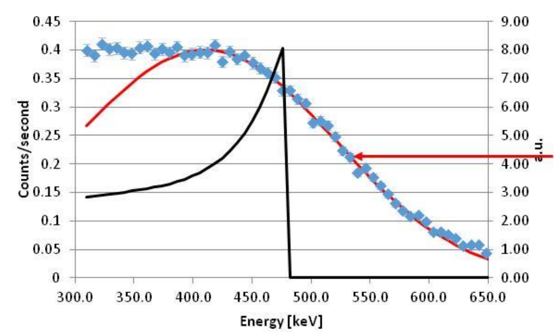
- Experimental setup
- Results of the measurements
- Analysis of data for estimating light emissions in function of time

Charge response

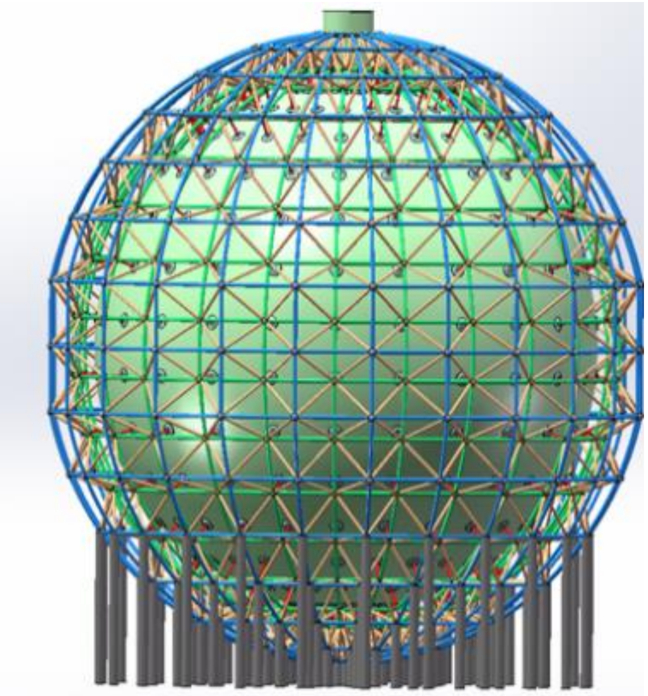
- Experimental setup
- Energy calibration based on analytical approach
- Light yield for different liquid scintillators







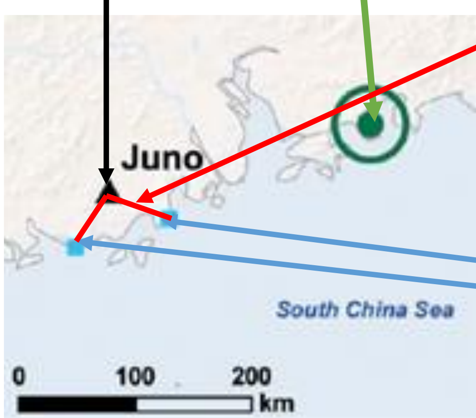
JUNO detector



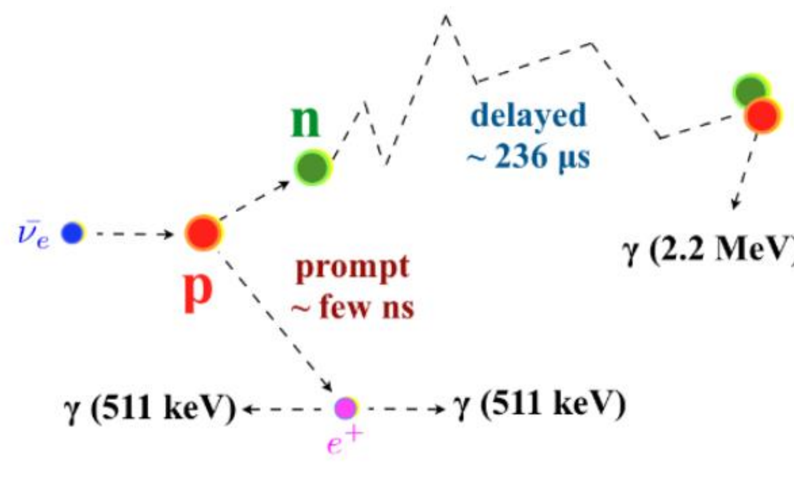
- JUNO (Jiangmen Underground Neutrino Observatory) is a reactor anti-*ν* detection experiment using a spherical detector loaded with 20 ktons of LAB based organic liquid scintillator.
- Inverse β decay is the main reaction used for detecting anti-*ν*.
- Anti-*ν* from reactors interact with protons through inverse β decay.

Position of Daya Bay

Baselines (distance from reactors) approximately 53 km



2 nuclear power plants (under construction) with a total of 10 reactors

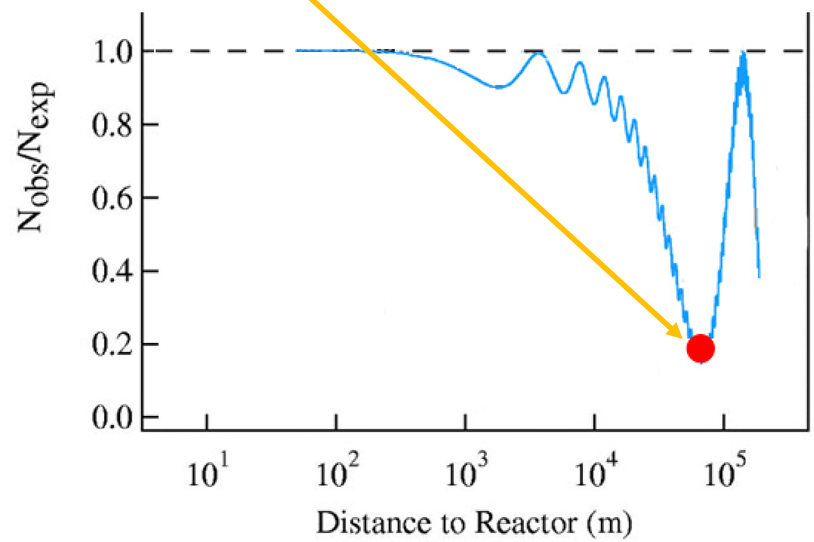


JUNO: scientific motivations

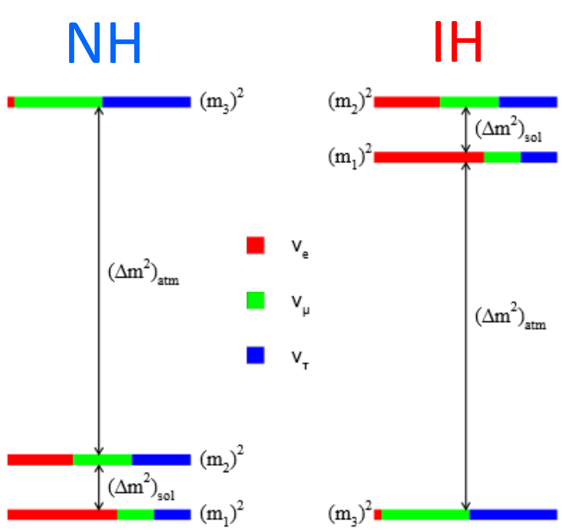
Scientific goals

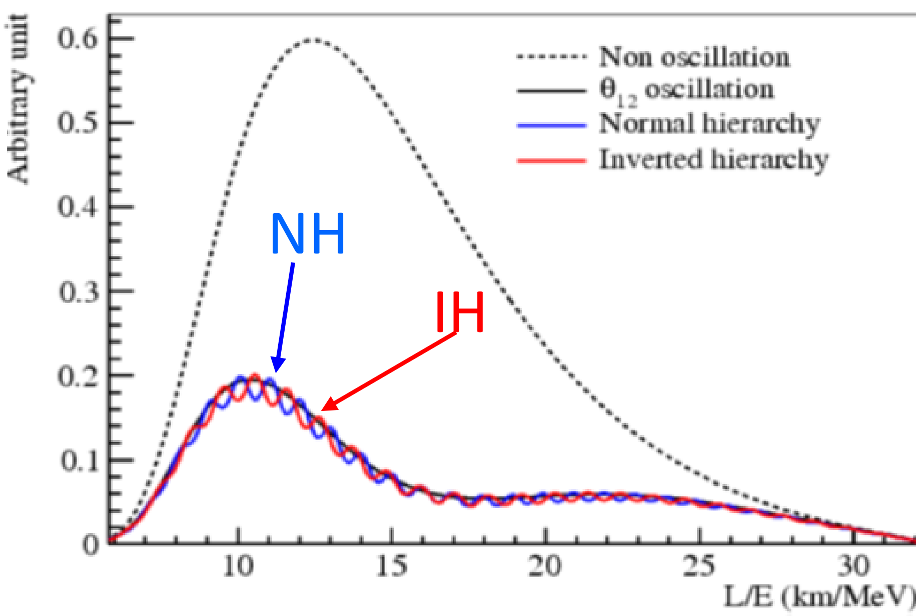
- Determination of mass hierarchy
- Precision measurement of oscillation mixing parameters
- Supernovae neutrino
- Geo-neutrino
- Sterile neutrino
- Atmospheric neutrinos
- Exotic searches

The baseline minimizes the destructive interference of anti-ν oscillations.

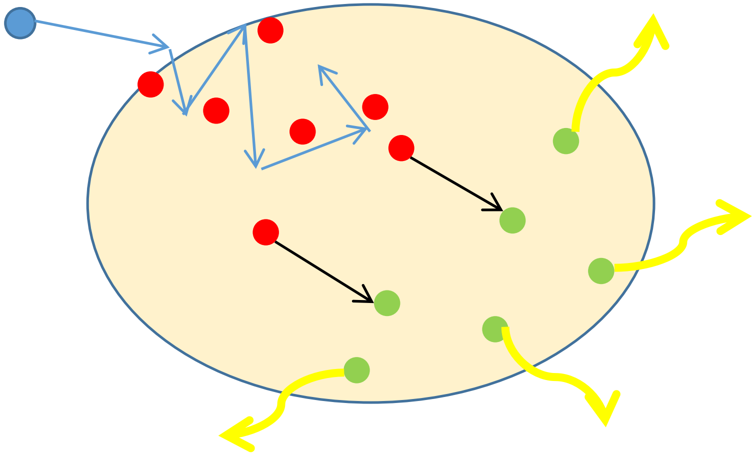


The goal is to distinguish between normal (NH) and inverted (IH) mass hierarchy.



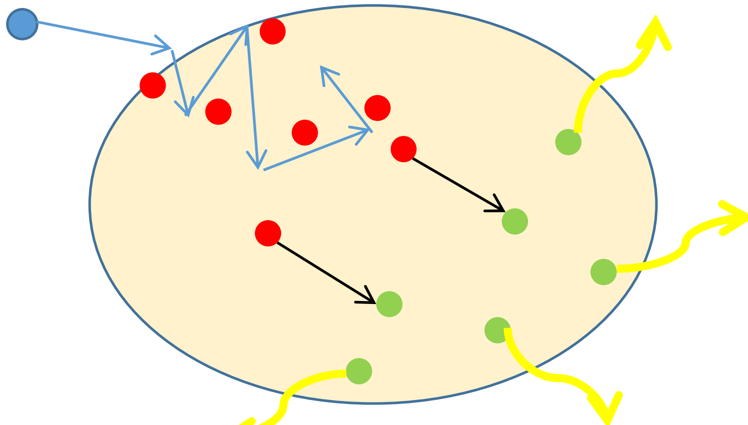


Excitations of organic liquid scintillators



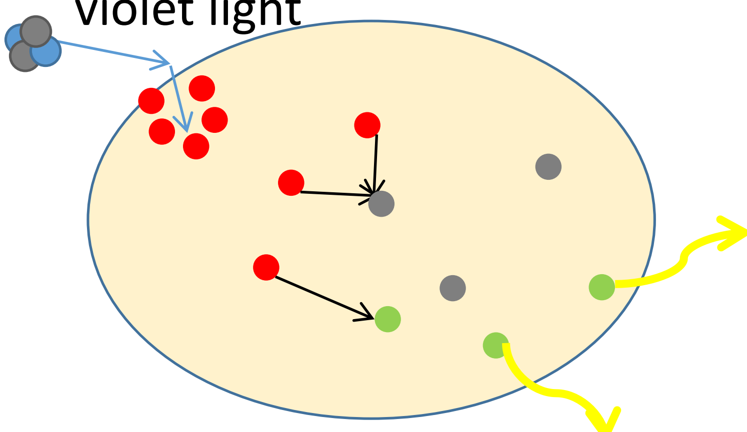
- Charged particle excites solvent molecules
- Solvent molecules transfer energy to the fluors
- Fluors decay emitting scintillation

Excitations of organic liquid scintillators

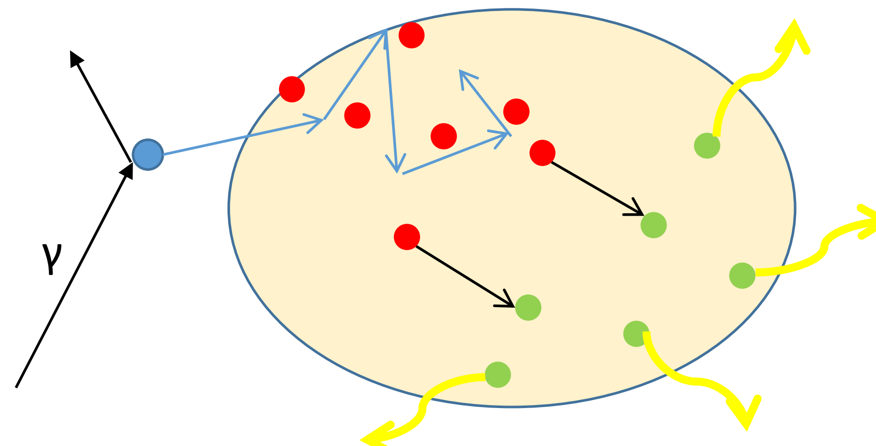


- Charged particle excites solvent molecules
- Solvent molecules transfer energy to the fluors
- Fluors decay emitting scintillation

- α particles produce dense ionization in solvent molecules which often recombine in triplet states and dimers
- Slower scintillation produces blue-violet light

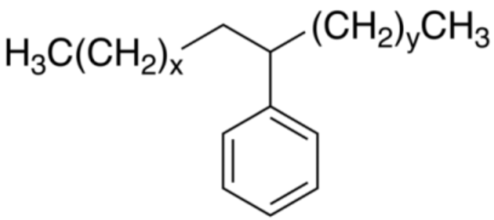


- photons scatter on electrons with Compton scattering
- Scattered electron excites solvent molecules



The solvent LAB and the fluors PPO and bis-MSB

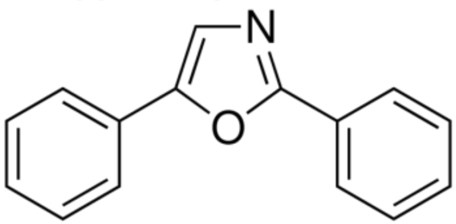
Linear alkylbenzene (LAB)



LAB is a solvent industrially produced for detergent products.

- ✓ environmental friendly
- ✓ high flash point (403 K)
- ✓ biodegradable
- ✓ easy to purify
- ✓ cheap
- ✘ new solvent in neutrino physics

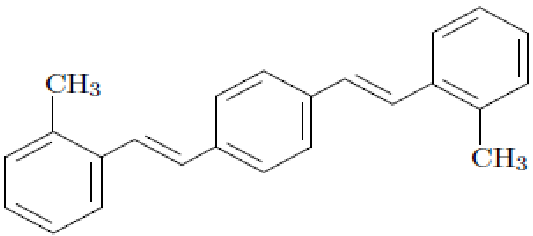
2.5-dyphenyloxazhole (PPO)



PPO is a primary fluor widely used in neutrino physics

- ✓ used in low concentrations (g/l)
- ✓ better known for neutrino physics
- ✘ expensive
- ✘ environment and health safety issues

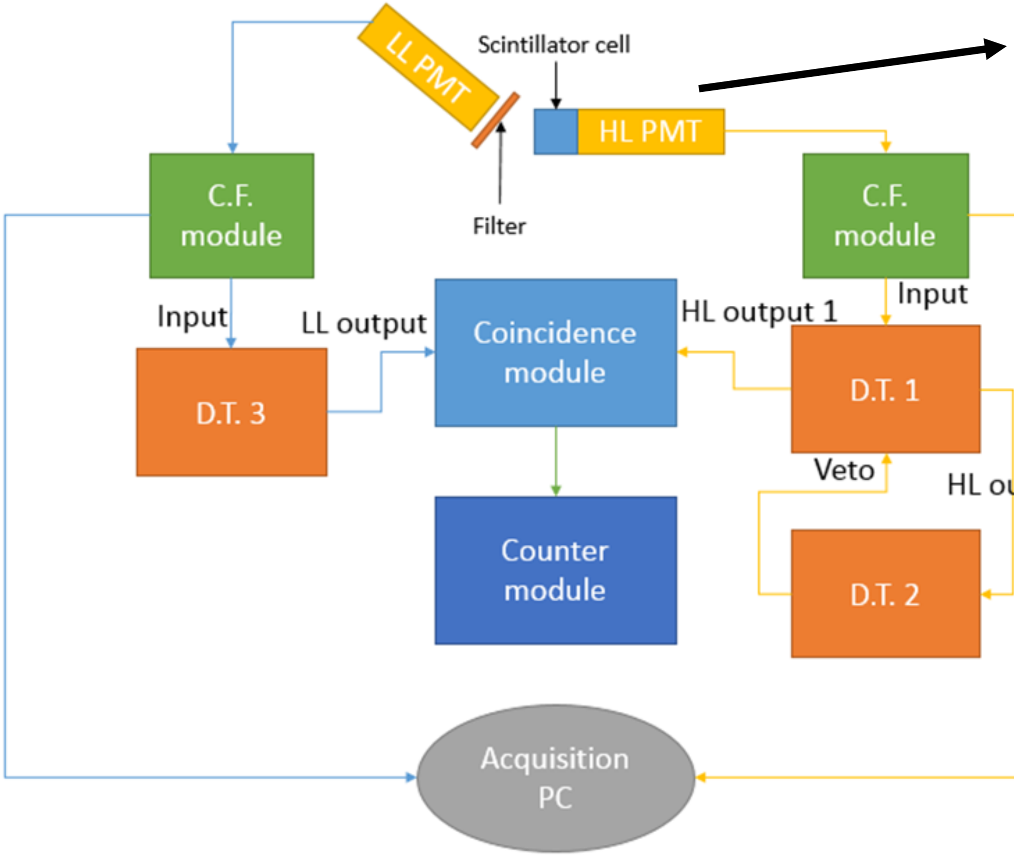
1,4-bis-(2-methylstyryl)-benzene (bis-MSB)

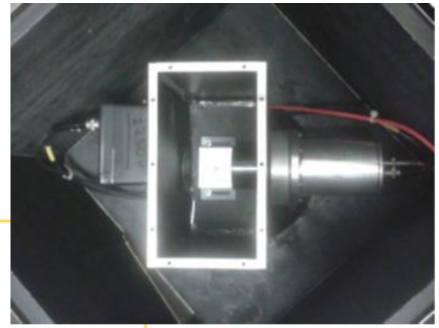


bis-MSB is a secondary fluor used as wavelength shifter

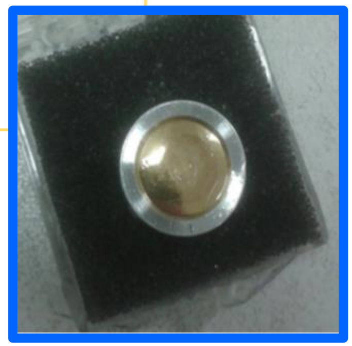
- ✓ used in very low concentrations (mg/l)
- ✓ fast decay time (1.5 ns)
- ✓ higher quantum efficiency (96%)
- ✘ expensive
- ✘ environment and health safety issues

Time response experimental setup





- Single photo-electron method for pulse shape reconstruction
- Acquisition software uses inverted logic to minimize dead time



α particles source ^{244}Cm

$E_{\alpha 1}$= 5.80 MeV
$I_{\alpha 1}$ = 76.4%

$E_{\alpha 2}$= 5.76 MeV
$I_{\alpha 2}$ = 23.6%

γ particles source ^{60}Co

$E_{\gamma 1}$= 1.17 MeV
$I_{\gamma 1}$ = 100%

$E_{\gamma 2}$= 1.33 MeV
$I_{\gamma 2}$ = 100%

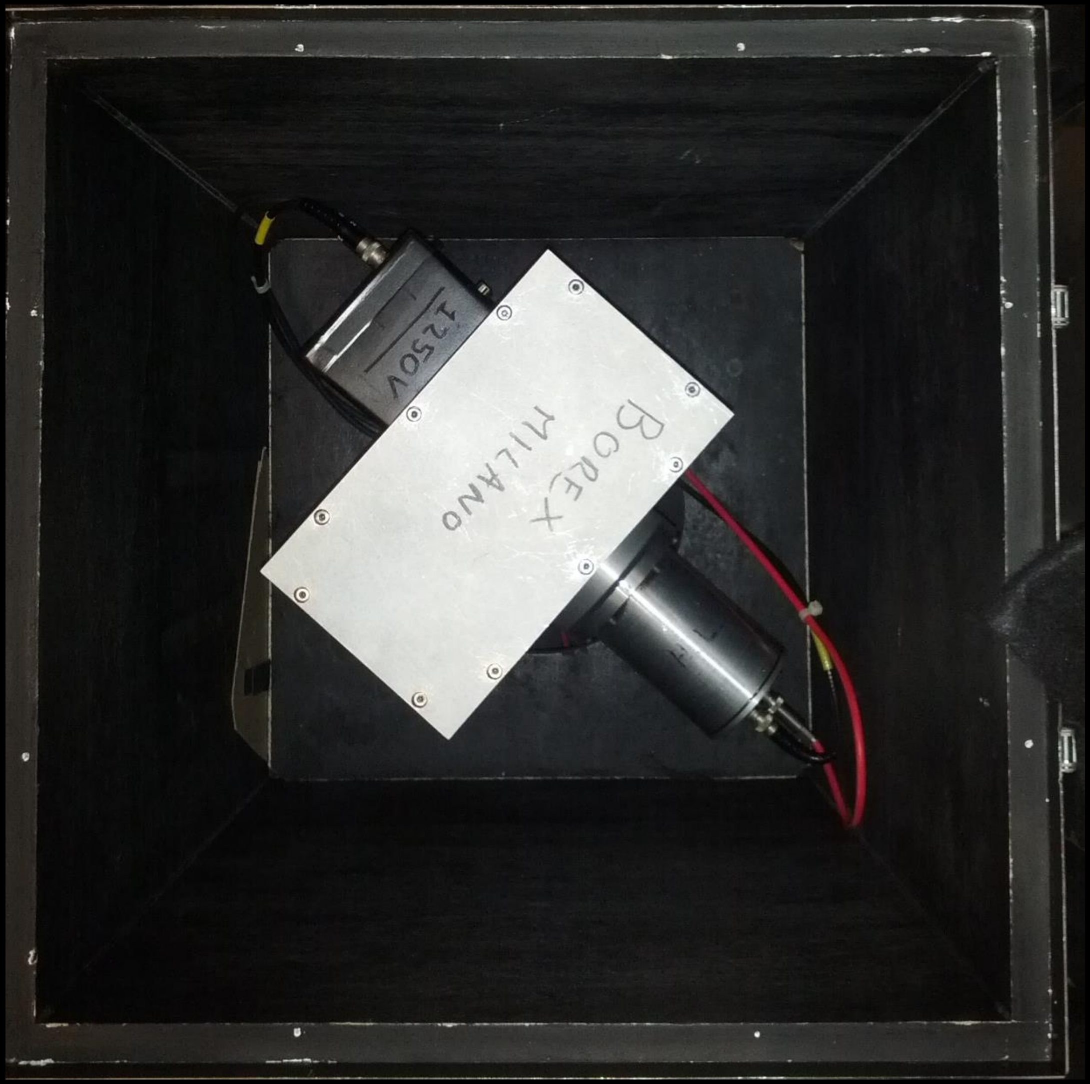
- HL PMT = High Level photomultiplier tube
- LL PMT = Low Level photomultiplier tube
- C.F. = constant fraction module
- D.T. = dual timer module
- E = energy of the emitted particle
- I_x = relative intensity of emission of particle x

My experiences in Milano Lab

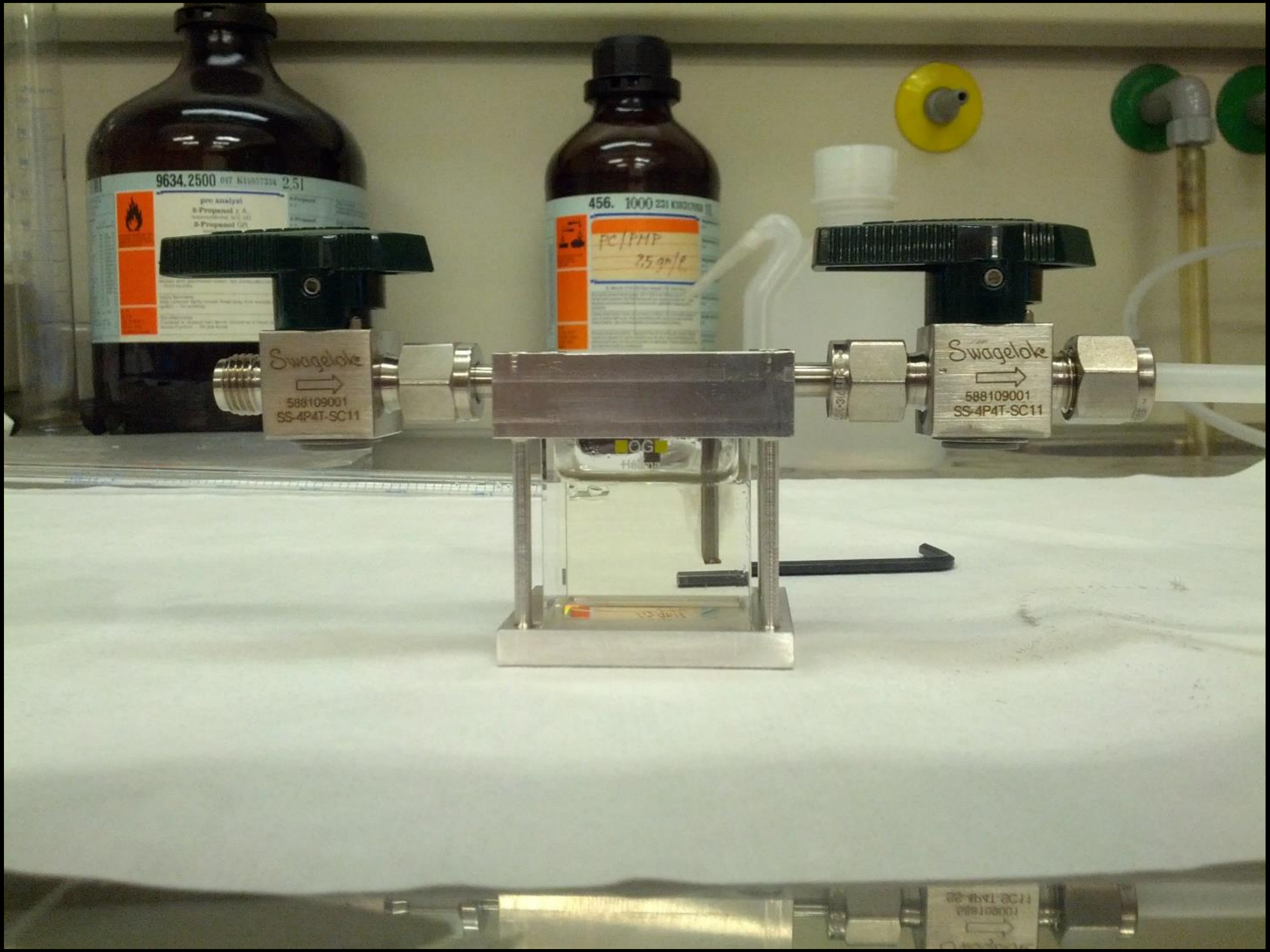
Time measurement experimental setup

My experiences in Milano Lab

Time measurement setup PMTs



My experiences in Milano Lab



Scintillator vial during nitrogen bubbling

My experiences in Milano Lab

Scintillator samples

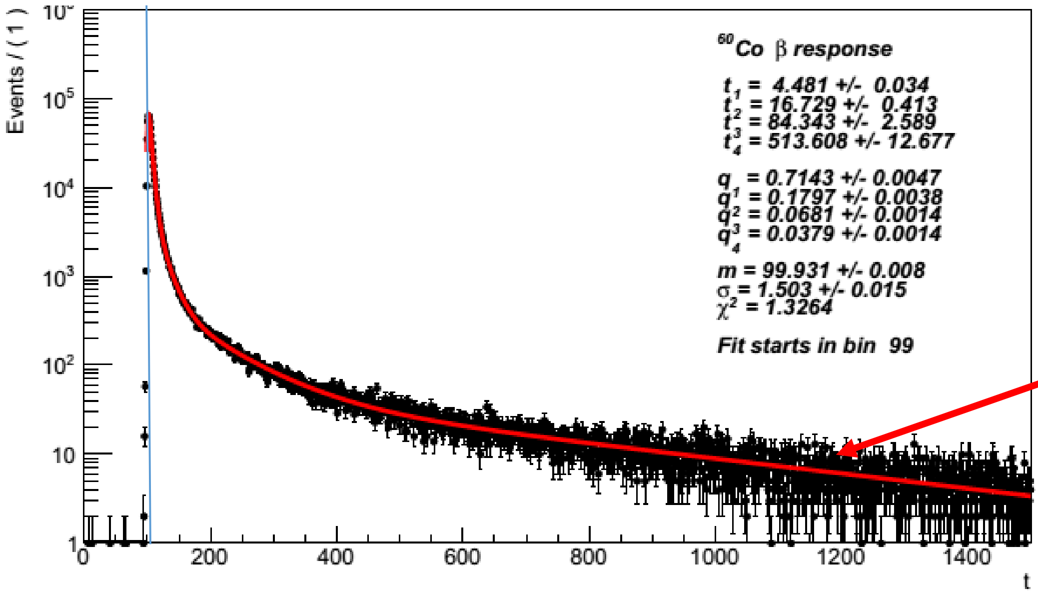
Measurements performed at Milano University

Producer	Fluor 1	Fluor 2	Distillation
Chinese	PPO (3 g/l)	bis-MSB (15 mg/l)	-
Petresa	PPO (3 g/l)	-	-
Helm	PPO (3 g/l)	-	-
	PPO (3 g/l)	-	2° fraction
	PPO (3 g/l)	-	3° fraction
Sasol	PPO (3 g/l)	-	-
	PPO (3 g/l)	bis-MSB (15 mg/l)	-
	PPO (3 g/l)	-	1°+2° fraction mix

- Chinese: chinese LAB scintillator (also referred as JUNO in some plots)
- Petresa: LAB produced by Cepsa (Spanish company)
- Helm: LAB produced by Helm AG (Hamburg company)
- Sasol: LAB produced by the SASol (South African Solvent)
- Distillation is used to remove radioactive and chemical impurities in the scintillator in order to have a better transparency to scintillation light and a lower radioactive background.
- Measurements were made at INFN laboratory in University of Milan in two months: July 2014 and October 2014
- Duration of measurements:
    - α excitation measurements lasted approximately 1 day
    - β excitation measurements lasted approximately 2 days

Time response fit functions

Chinese LAB sample



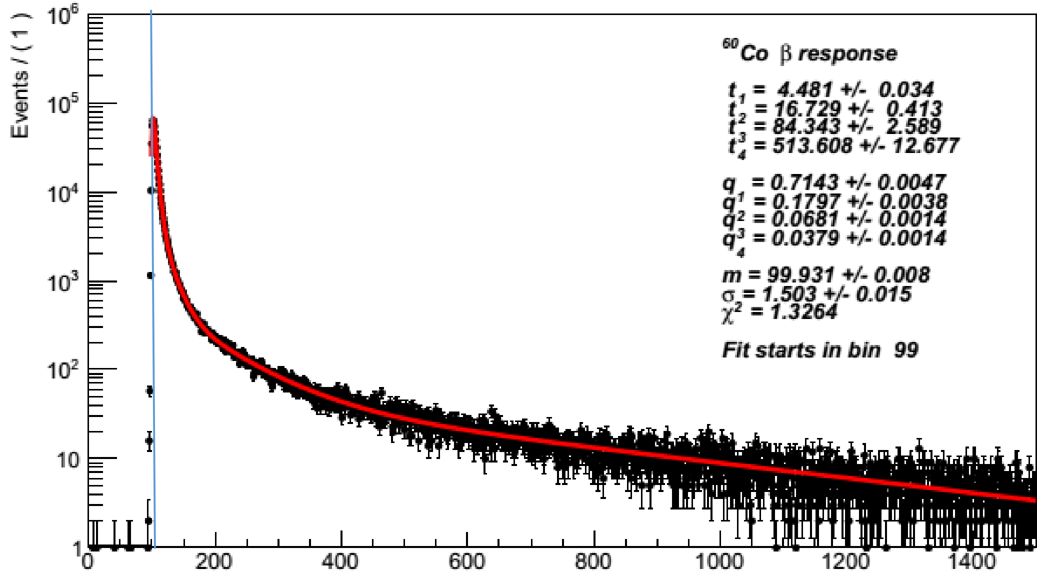
P(t) = emission probability function (pulse shape)

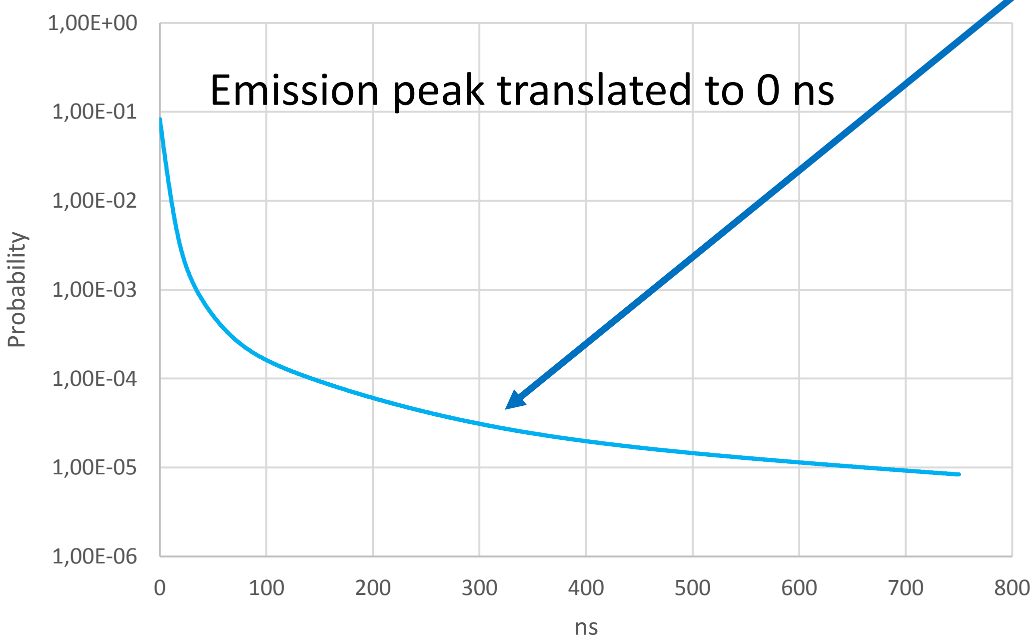
$$P(t) = R(m;\sigma)\sum_i \frac{q_i}{\tau_i} e^{-\frac{t}{\tau_i}}$$

- R(m;σ) = Gaussian resolution response
- q_i = amplitude of i-th exponential
- τ_i = exponential time constant
- Fits done with 4 exponentials

Time response fit functions

Chinese LAB sample





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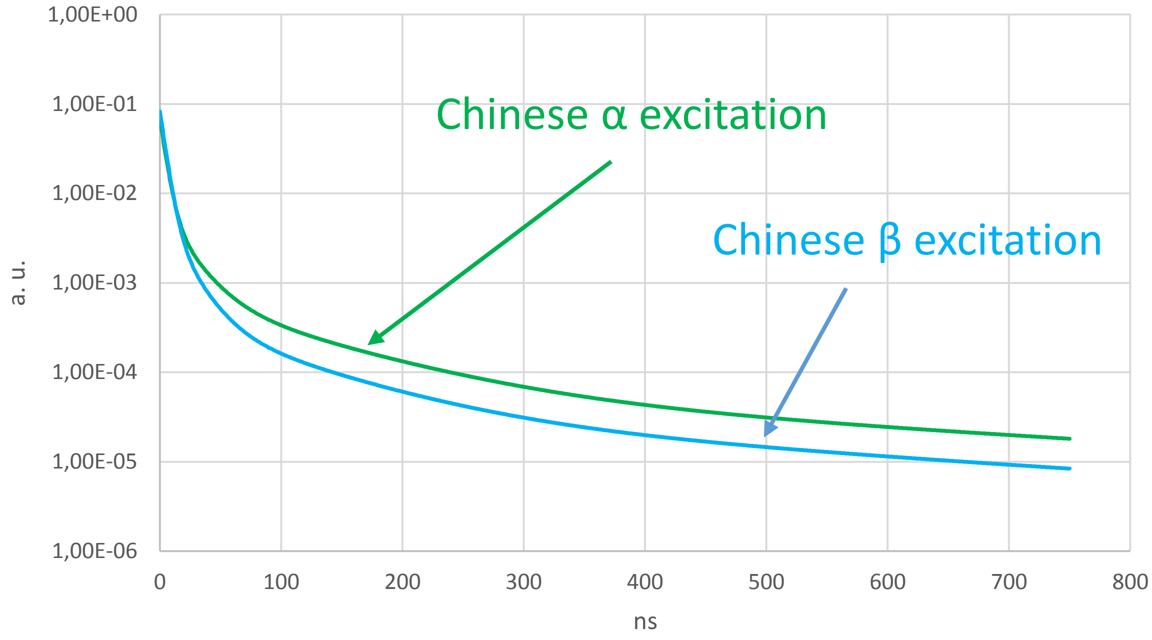
Time response fits: comparisons between α and β



α excitation properties

- Dimer and triplet states
- Slower scintillation

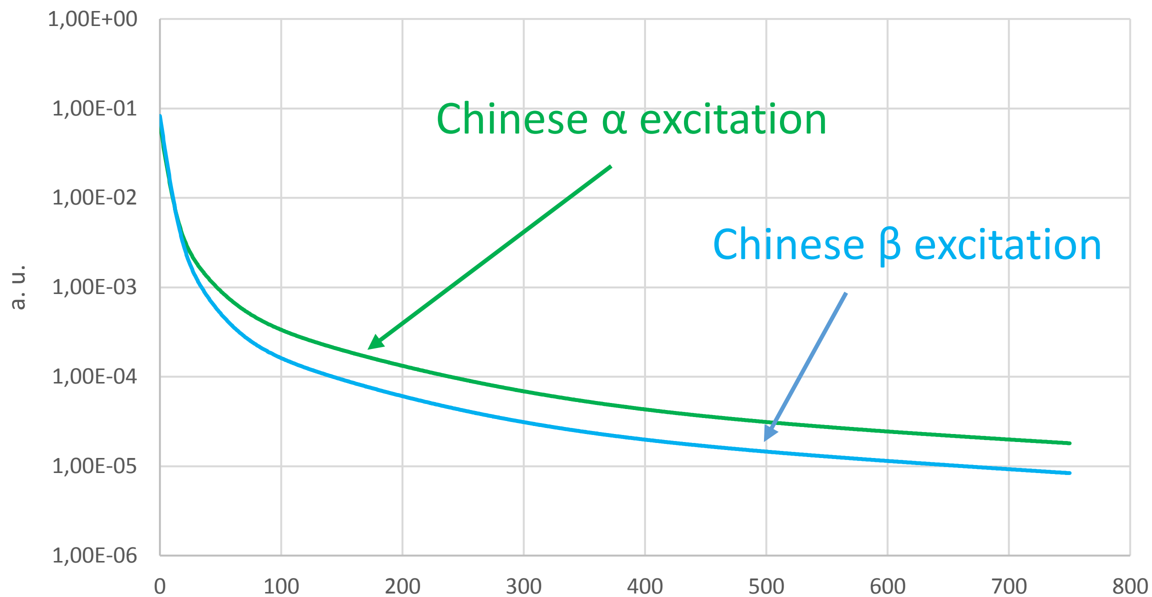
β excitation properties

- Lower ionization density
- Faster scintillation

Gatti's optimun method

$$D = \sqrt{N \int \frac{(f_\alpha(t) - f_\beta(t))^2}{f_\alpha(t) + f_\beta(t)} dt}$$

Time response fits: comparisons between α and β



α excitation properties

- Dimer and triplet states
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β excitation properties

- Lower ionization density
- <u>Faster scintillation</u>

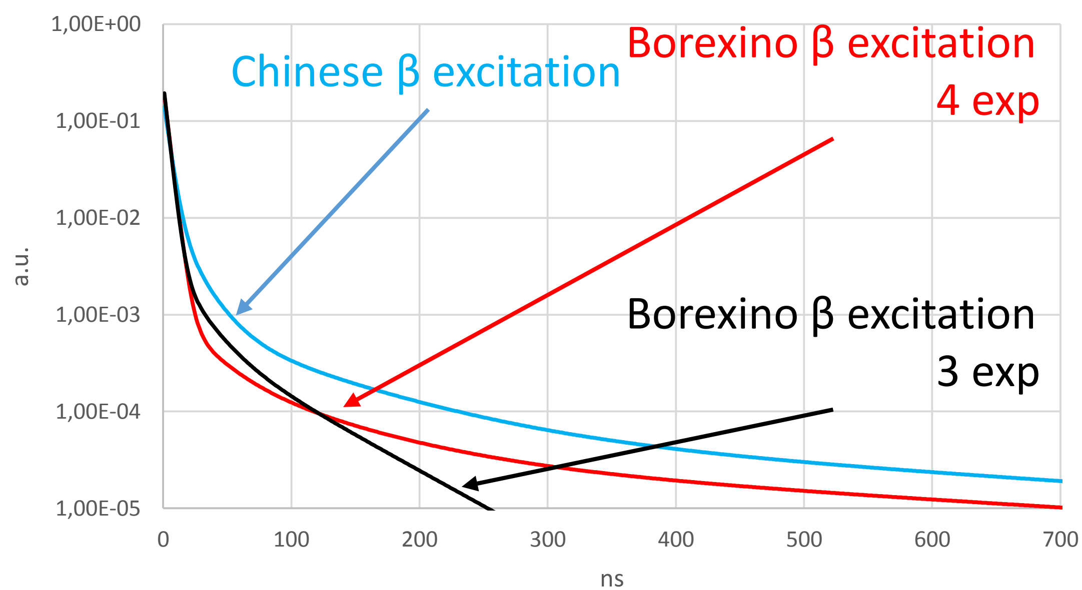
Gatti's optimun method

$$D = \sqrt{N \int \frac{(f_\alpha(t) - f_\beta(t))^2}{f_\alpha(t) + f_\beta(t)} dt}$$

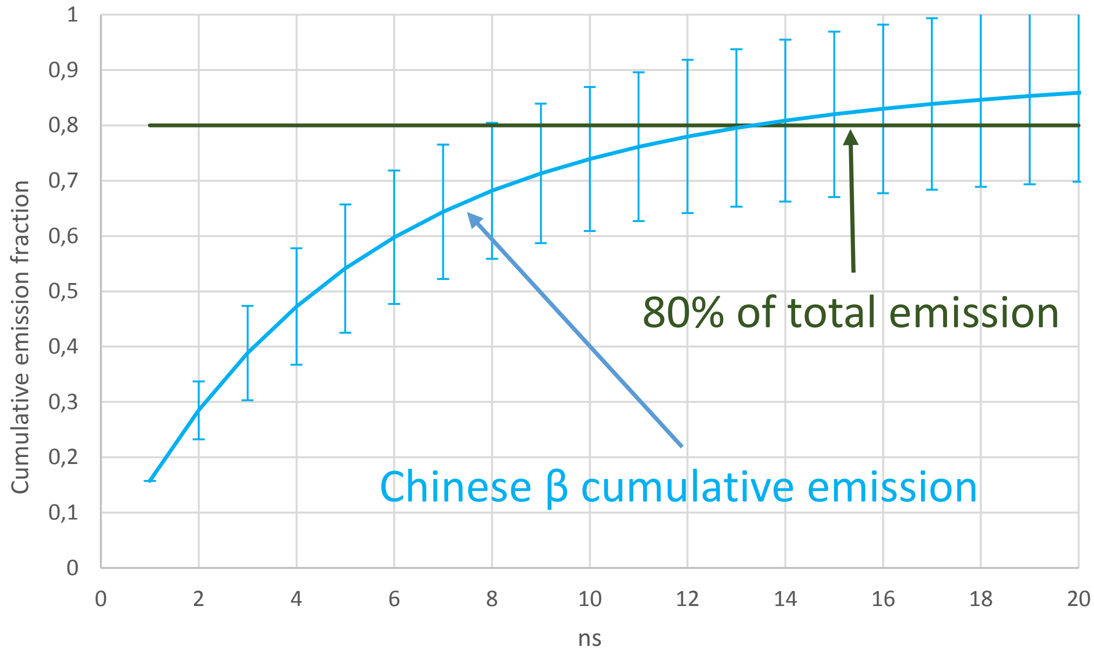
Time response fits: comparisons between LAB and Borexino PC

I compare the time response of LAB with the published data by Borexino.

- PC has a faster scintillation than LAB
- 3 exponentials fit derived from literature is less precise than a 4 exponentials fit



When does the LS release 80% of emission light?



- 80% of scintillation light is released in a time scale of tens of ns.
- Measuring the time response is important for the coupling with PMTs properties.
- Scintillation must not be too fast for the PMT to detect (longer than anode rise time), but fast enough to avoid overlapping with other independent events.

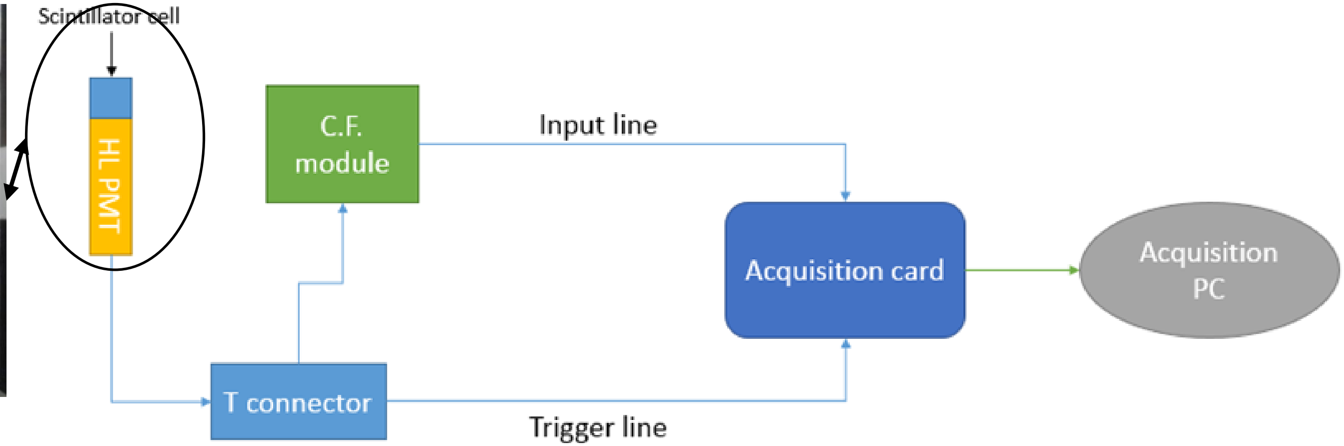
Source	Chinese [ns]	Petresa [ns]	Helm no-dist [ns]	Helm dist 2 [ns]	Helm dist 3 [ns]	Sasol no-dist [ns]	Sasol bis-MSB [ns]	Sasol dist [ns]
^{244}Cm	31	24	24	23	23	24	24	23
^{60}Co	13	11	11	10	10	11	11	10

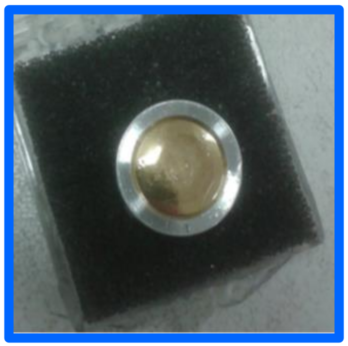
Slowest light emission

Fastest light emission

20'' PMT from Hamamatsu

Charge response experimental setup





α particles source ^{244}Cm

$E_{\alpha 1}$ = 5.80 MeV
$I_{\alpha 1}$ = 76.4%

$E_{\alpha 2}$ = 5.76 MeV
$I_{\alpha 2}$ = 23.6%

- Pulse shape integrated to obtain charge counts
- 256 charge bins
- PMT has similar response for PPO and bis-MSB

γ particles sources

^{137}Cs

E_{γ} = 0.66 MeV
I_{γ} = 99.4%

^{22}Na

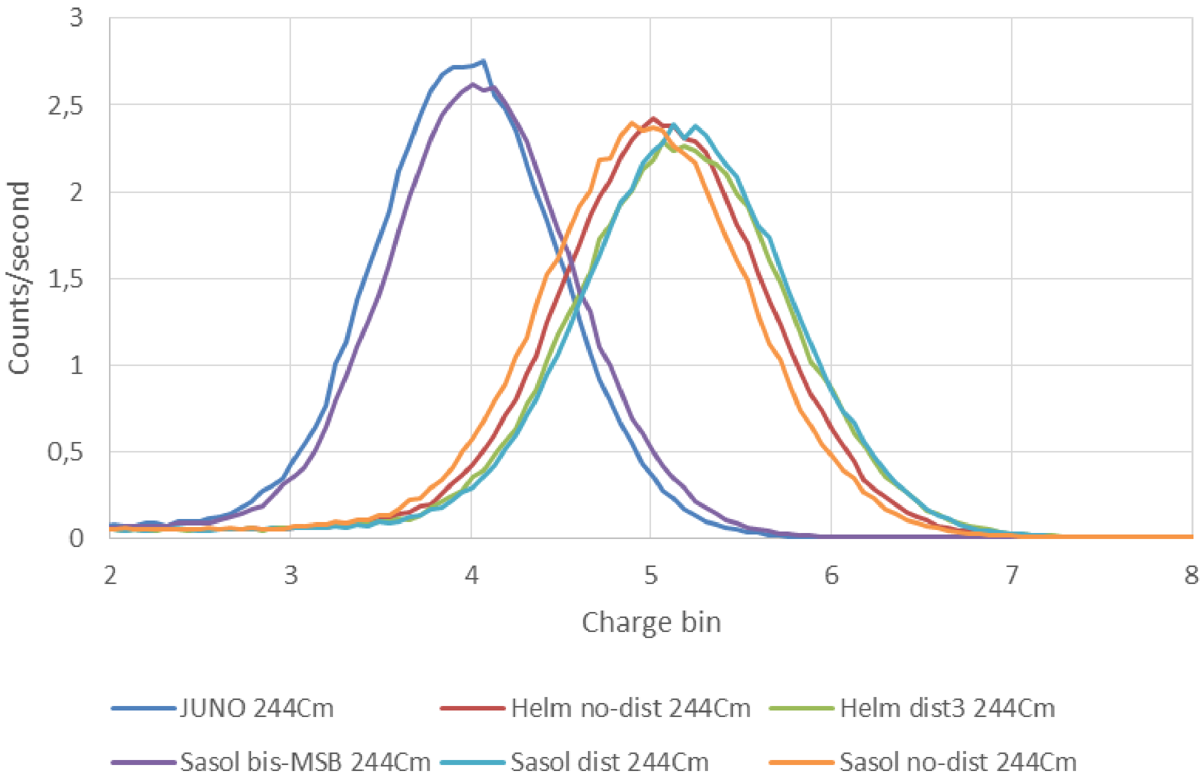
E_{γ} = 1.27 MeV
I_{γ} = 100%

$E_{\gamma\beta+}$ = 0.512 MeV
$I_{\gamma\beta+}$ = 89.84%

- HL PMT = High Level hotomultiplier tube
- C.F. = constant fraction module
- E = energy of the emitted particle
- I_x = relative intensity of emission of particle x

Measured LAB samples

Producer	Fluor 1	Fluor 2	Distillation
Chinese	PPO (3 g/l)	bis-MSB (15 mg/l)	-
Helm	PPO (3 g/l)	-	-
	PPO (3 g/l)	-	3° fraction
Sasol	PPO (3 g/l)	-	-
	PPO (3 g/l)	bis-MSB (15 mg/l)	-
	PPO (3 g/l)	-	1°+2° fraction mix



- Charge response for α particles excitation has a Gaussian shape.
- Different positions of the Gaussian functions are due to different quenching effects and energy transfer efficiency.
- Each measurement required a few hours

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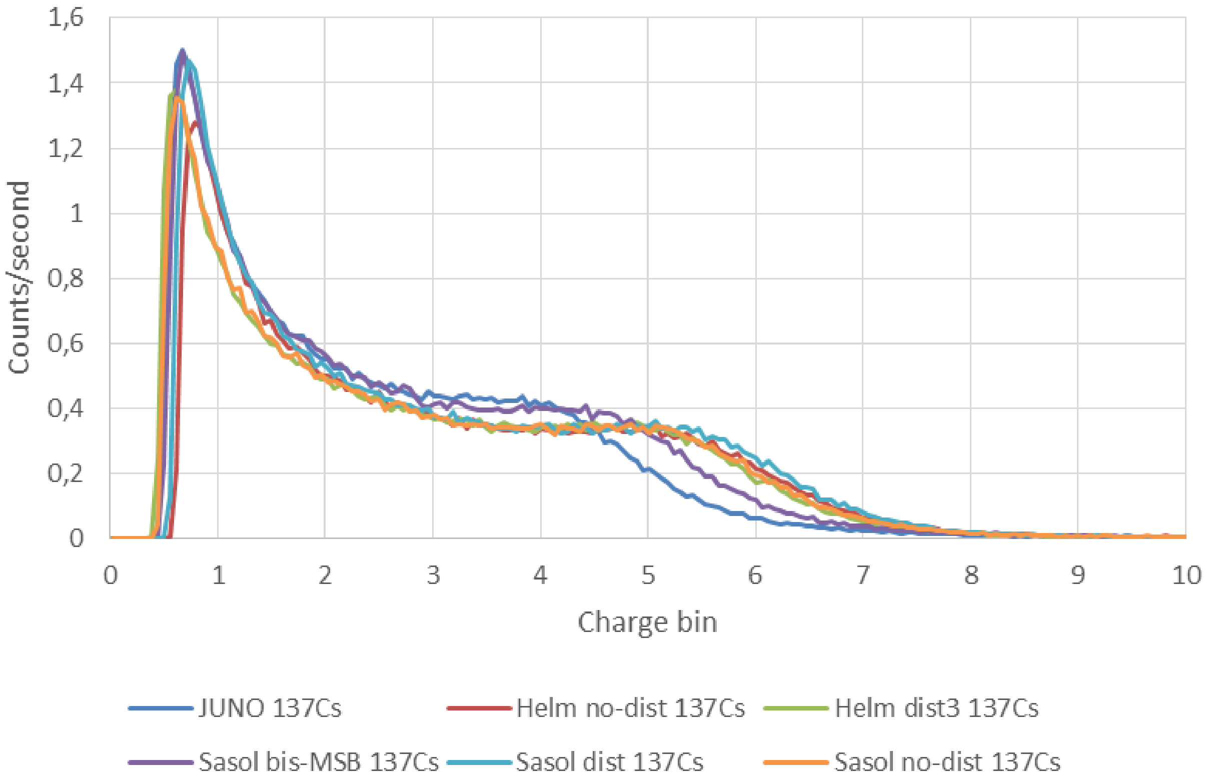

- Charge response for γ particles excitation has a Compton spectrum shape.
- Different positions of the Compton shouldersare due to different quenching effects and energy treansfer efficiency.
- Each measurement required 1 day

Measured LAB samples

Producer	Fluor 1	Fluor 2	Distillation
Chinese	PPO (3 g/l)	bis-MSB (15 mg/l)	-
Helm	PPO (3 g/l)	-	-
	PPO (3 g/l)	-	3° fraction
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	PPO (3 g/l)	bis-MSB (15 mg/l)	-
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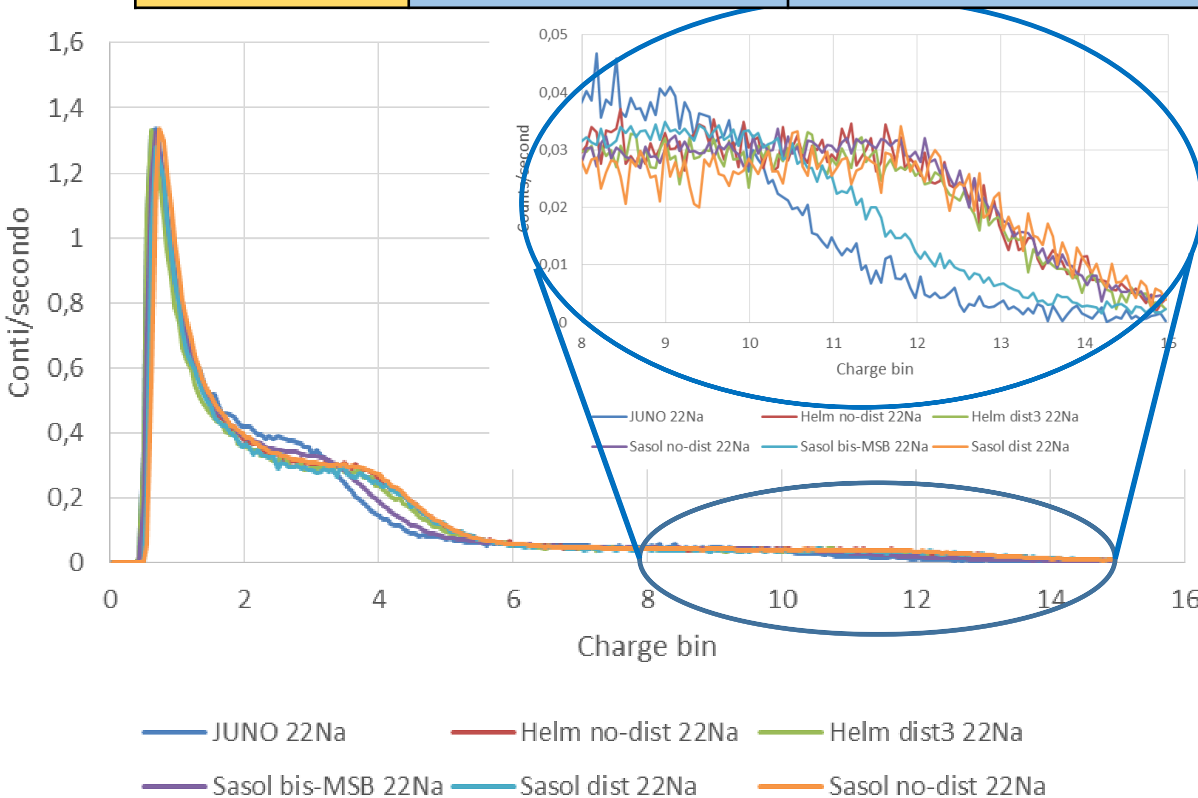
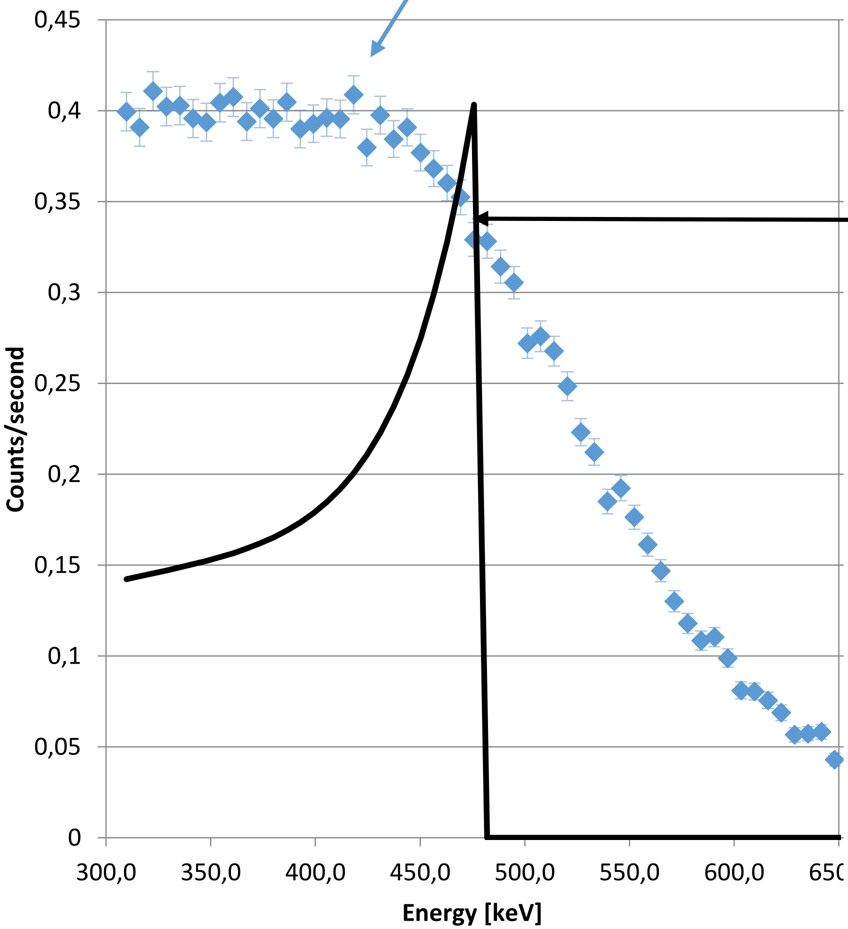


- ^{22}Na excites the scintillator with two γ.
- Low charge Compton shoulder is due to γ from β^+ annihilation.
- High charge Compton shoulder is due to γ from γ-decays.
- Every measurement required from 1 to 2 days

Energy calibration of Compton spectra

Chinese ^{137}Cs experimental data



Theoretical Compton spectrum obtained with Klein-Nishima formula:

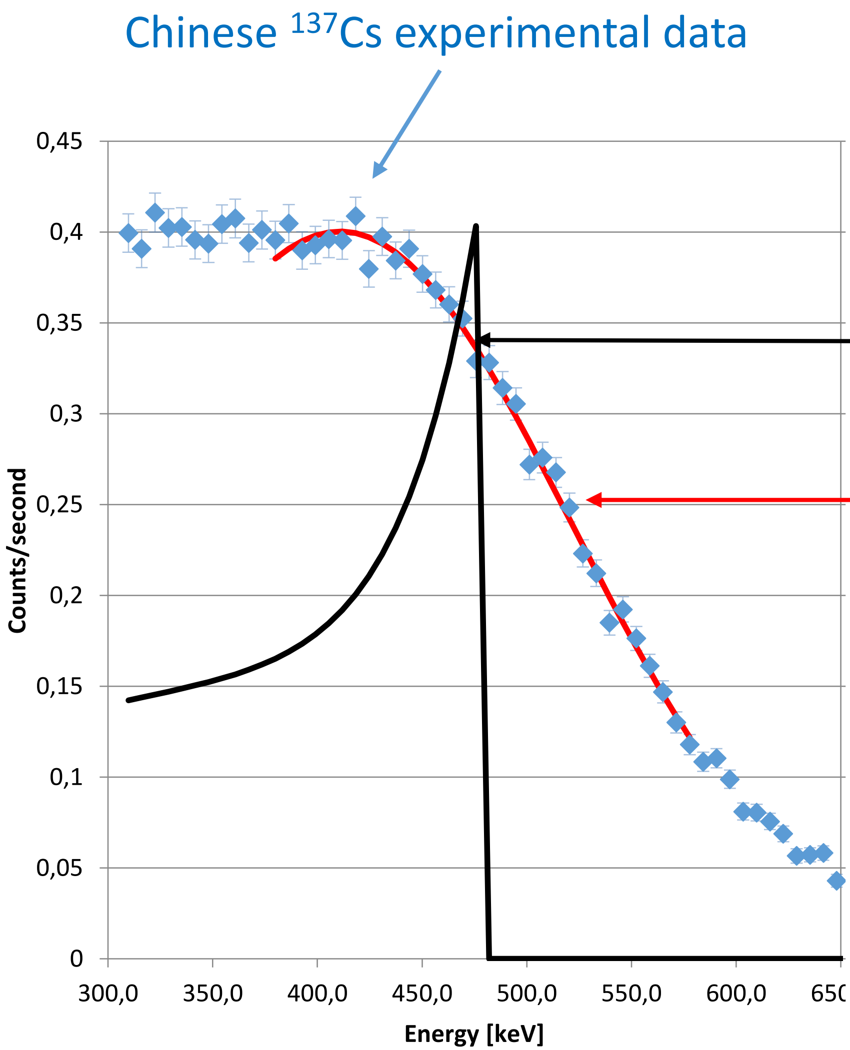
$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_e^2 \left(\frac{E'}{E}\right)^2 \left(\frac{E}{E'} + \frac{E'}{E} - sin^2\theta\right)$$

and scattered electron energy formula

$$E_e = E - E' = E - \frac{E}{1 + \frac{E}{m_e c^2}(1 - cos\theta)}$$

r_e = classical electron radius
E = initial energy of γ
E' = energy of scattered γ
E_e= energy of scatteres electron
θ = scattering angle
$m_e c^2$= electron rest energy

Energy calibration of Compton spectra



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Gaussian resolution

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Energy calibration of Compton spectra

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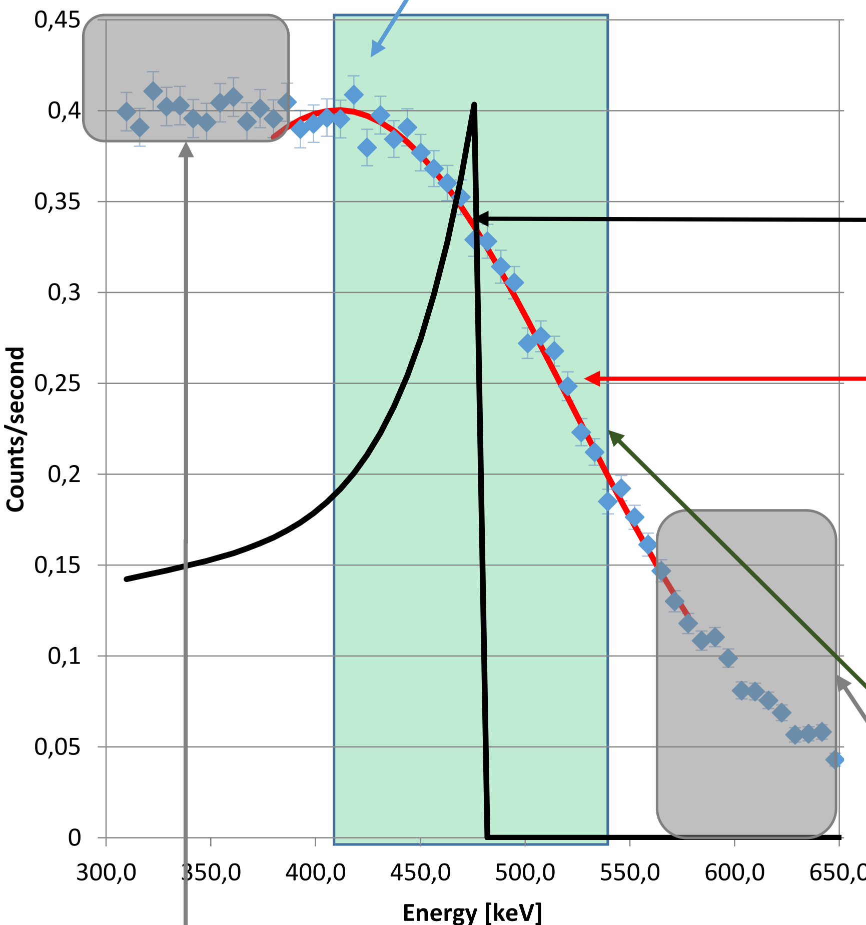

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$$E_e = E - E' = E - \frac{E}{1 + \frac{E}{m_e c^2}(1 - cos\theta)}$$

Gaussian resolution

r_e = classical electron radius
E = initial energy of γ
E’ = energy of scattered γ
E_e= energy of scatteres electron
θ = scattering angle
$m_e c^2$= electron rest energy

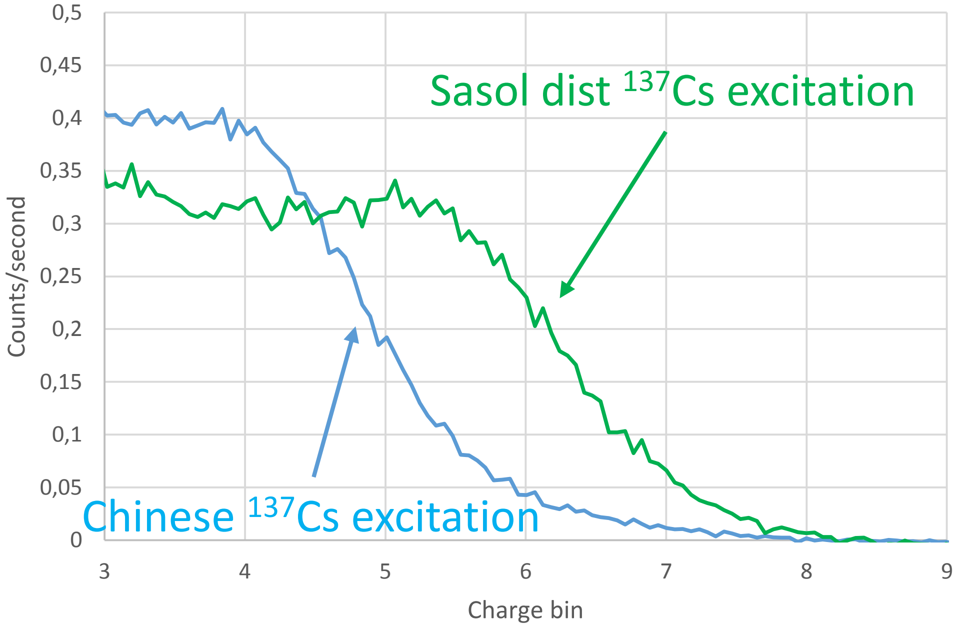
Fit from maximum to half maximum (the typical normalized χ^2 is < 2)

Detection efficiency not taken into account

Possible multiple Compton Scatterings

I observe a good agreement between analytical method of analysis with the Monte Carlo results (<7% difference)

Energy yield comparison



Sasol dist scintillator has the highest energy yield per scintillation

Chinese scintillator has the lowest energy yield per sicntillation

Scintillator	^{137}Cs [bin]	^{137}Cs E_m [keV]	^{22}Na [bin]	^{22}Na E_m [keV]
Chinese	4.38±0.03	357±5	9.74±0.07	797±12
Helm no-dist	5.82±0.04	475±7	12.97±0.08	1057±16
Helm dist	5.39±0.08	439±9	12.00±0.18	978±20
Sasol no-dist	5.58±0.08	455±9	12.42±0.18	1012±20
Sasol bis-MSB	4.83±0.03	393±6	10.75±0.06	876±13
Sasol dist	5.85±0.08	477±9	13.03±0.18	1062±20

Lowest energy yield

Highest energy yield

Compton shoulders positions computed with bin/energy conversion from ^{137}Cs excitations on distilled Sasol

Conclusions

Time response

- I measured the time response of 8 LAB samples in two months.
- I fitted all acquired data, the best performances come from all distilled LS.
- A function with 4 exponentials is better suited to fit long time scintillation than a 3 exponentials one.
- I quantified the separation between α and β response curves: best performance are for the distilled Helm sample (D = $0.219\sqrt{N}$).
- A comparison between PC (Borexino) and LAB shows that the best is PC.

Charge response

- I measured the charge response of 6 samples of LAB.
- I performed an energy calibration the α and β spectra.
- I developed an original analytical method for fitting the Compton edge of β excitation obtaining an excellent agreement with MC results (<7%).
- The Distilled Sasol sample shows the highest scintillation efficiency of the characterized samples.

Prospects

Since JUNO experiment is under construction (data taking will start on 2020) the results of this thesis are relevant for future strategy and technologic choices:

- A refined study of the optical and chemical properties of LAB is needed
- The scientific collaboration requires a characterization of long-time stability of LS
- The challenging energy resolution needs a refined estimation of the scintillation efficiency curve
- The measured time and charge data will be included in the Monte Carlo simulation codes
- The LAB performances studied in this thesis are fundamental for tuning the response of PMT which are still to be built

Thank you for the attention

PPO and bis-MSB spectra with PMT responsivity