Instrumentation and Physics Cases for EURISOL- DF Scintillators

Franco Camera

University of Milano Statale, Department of Physics
INFN section of Milano

Outline:

- Old and New Scintillators, test, measurements and R&D:
  - $LaBr_3$:Ce, $LaBr_3$:Ce:Sr^+
  - Elpasolite - CLYC - CLLBC
  - $CeBr_3$, SrI_2 and GYGAG
- Some physics cases for EURISOL-DF
- Conclusions

Sorry in advance if I did not cite all the works and R&D activity which have been done so far

Important

In this talk we concentrate on scintillators. HPGe detector or in general solid state detectors will not be discussed. Semiconductor detectors have an energy resolution which will never be reached by scintillators (because of the energy gap, the conversion light-electrons, Fano factor, …)

First Generation 'old' scintillators

NaI ⇒ acceptable energy resolution, strong non linearity in energy, bad time resolution
BaF_2 ⇒ bad energy resolution, excellent time resolution
BGO ⇒ bad energy resolution, bad time resolution, excellent efficiency
CsI ⇒ good for the measurement of light charged particles

……

Second Generation 'almost new or new' scintillators

Lanthanum Halide ⇒ $LaBr_3$:Ce, $LaCl_3$:Ce
New Matherials: ⇒ SrI_2:Eu, $CeBr_3$
Elpasolide : ⇒ CLYC, CLLB, CLLBC, CLLC
Ceramic ⇒ GYGAG

……

Third Generation scintillators

Co Doped $LaBr_3$:Ce - Sr^{++}

Material	Light Yield [ph/MeV]	Emission λ_{max} [nm]	En. Res. at 662 keV [%]	Density $[g/cm^2]$	Pricipal decay time [ns]
NaI:Tl	38000	415	6-7	3.7	230
CsI:Tl	52000	540	6-7	4.5	1000
$LaBr_3$:Ce	63000	360	3	5.1	17
SrI_2:Eu	80000	480	3-4	4.6	1500
$CeBr_3$	45000	370	<5%	5.2	17
GYGAG:Ce	40000	540	<5%	5.8	250
CLYC:Ce	20000	390	4	3.3	1 CVL 50, ~1000

Now there are, in addition to the one listed above, some new materials (CLLB, CLLBC, LaBr3:Ce-Sr)

$LaBr_3$:Ce:Sr was borrowed from St.Gobain

Picture done in Milano

Lanthanum Halide: $LaBr_3$:Ce Detectors

It was discovered in 2001 in Delft
It is now a rather ‘known’ scintillator detector

- it is in Knoll book !

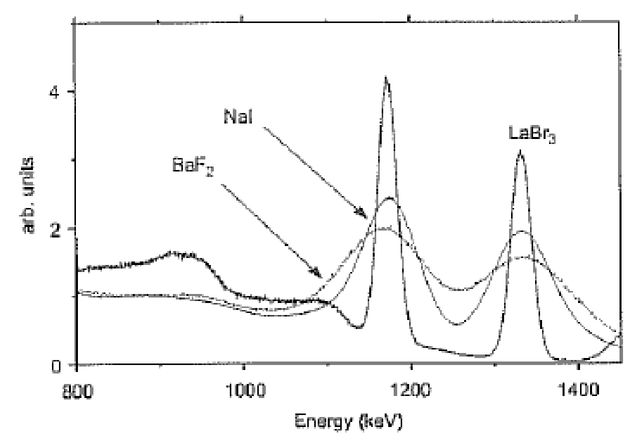


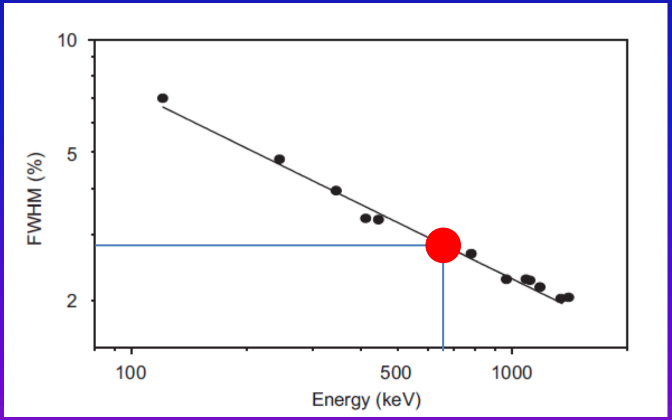
Figure 8.14 Comparison of the ^{60}Co pulse height spectrum measured with 1-inch × 1-inch $LaBr_3$, NaI, and BaF_2 (From Nicolini et al.[215]).

E.V.D. van Loef et al.
Appl. Phys. Lett. 79(2001)1573

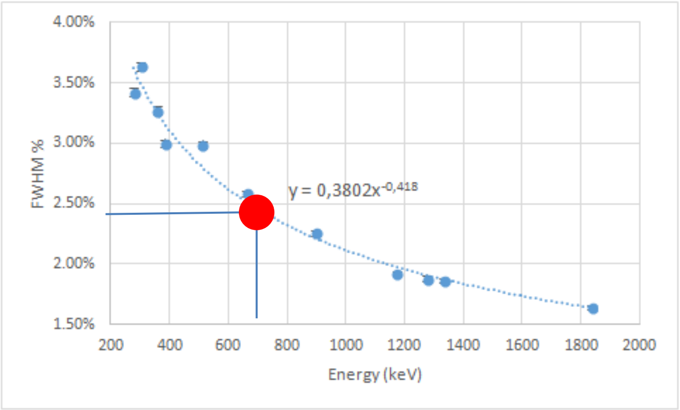
R. Nicolini et al.
NIM A582>(2007)554

Several arrays have been designed

- HECTOR$^+$
- FATIMA
- PARIS, CALIFA
- OSCAR
- ALBA
- $LaBr_3$:Ce in
  - ROSPHERE and ELI-NP
  - Darmstadt $LaBr_3$:Ce array
  - HIγS array
- ……..



$LaBr_3$:Ce
R. Nicolini et al. NIM A582(2007)554



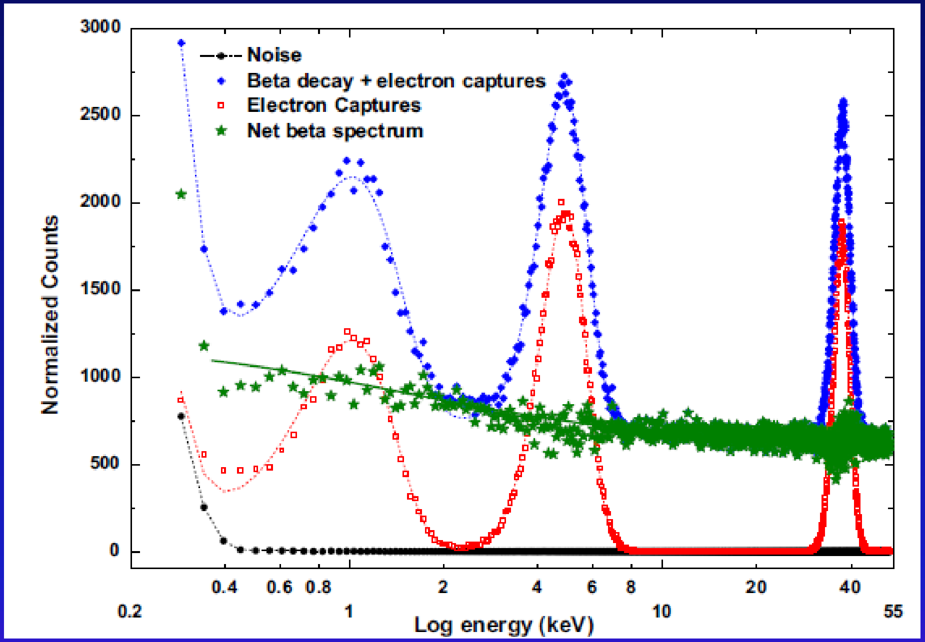
There is something new
Co-Doped $LaBr_3$:Ce
$LaBr_3$:Ce-Sr$^+$
B390 (St.Gobain)

Better energy Resolution
PSD Possible

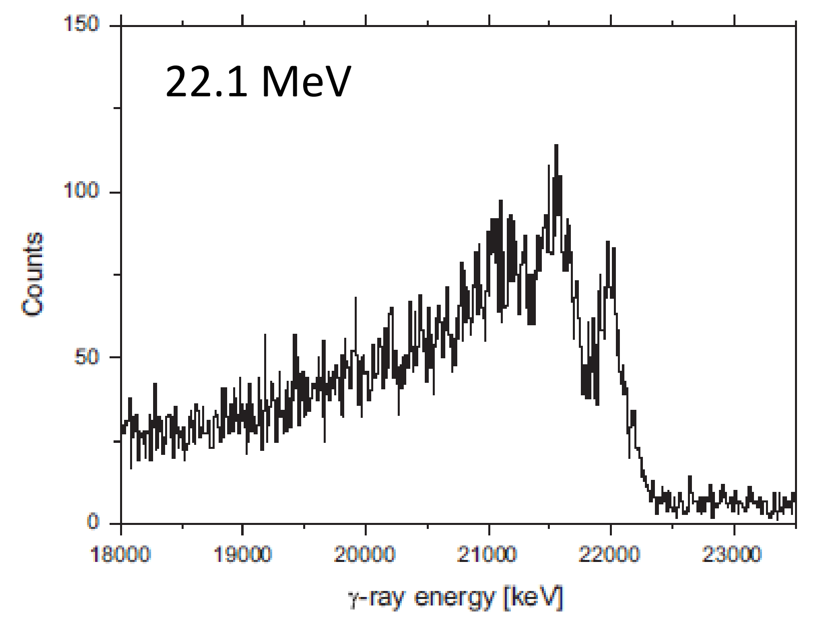
$LaBr_3$:Ce-Sr$^+$ - Thanks to St.Gobain which borrowed us a sample
G. Colombi – private communications

Lanthanum Halide: $LaBr_3$:Ce Detectors

$LaBr_3$:Ce detectors provide, at the same time, clean spectroscopic information from a few tens of keV up to tens of MeV, being furthermore able to clearly separate the full energy peak from the first escape one. This is particularly true for large volume detectors which have Full Energy Peak efficiency for high energy γ-rays



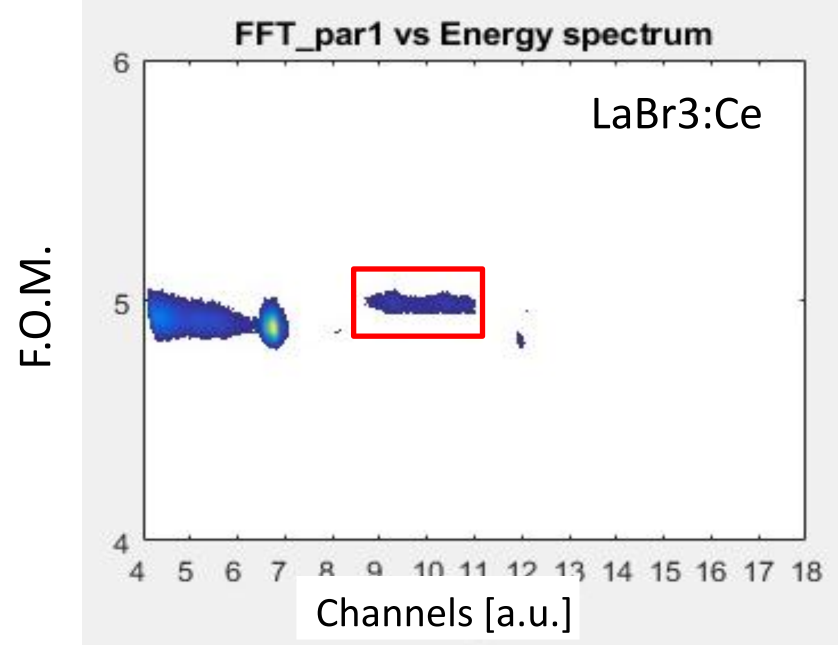
3”x3” LaBr3:Ce
F.G.A. Quarati et al. Appl. Rad. and Iso. 108(2016)30

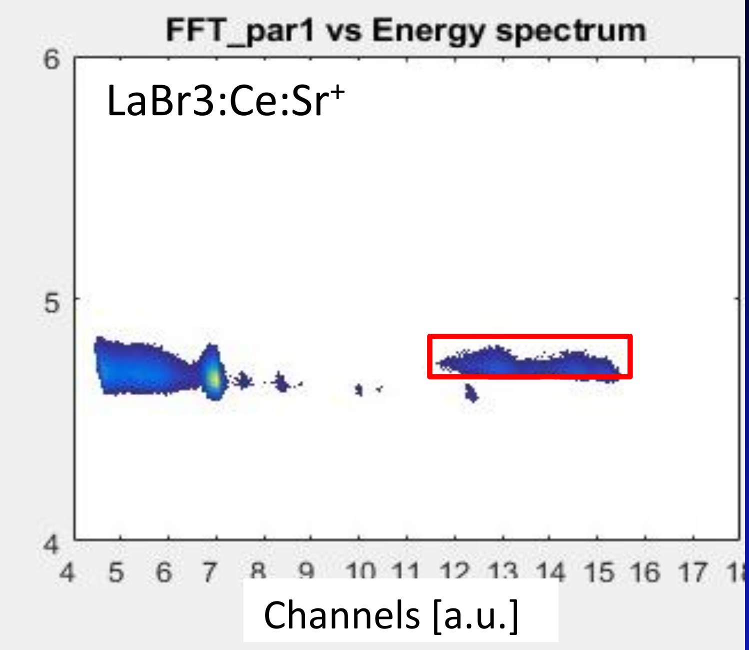


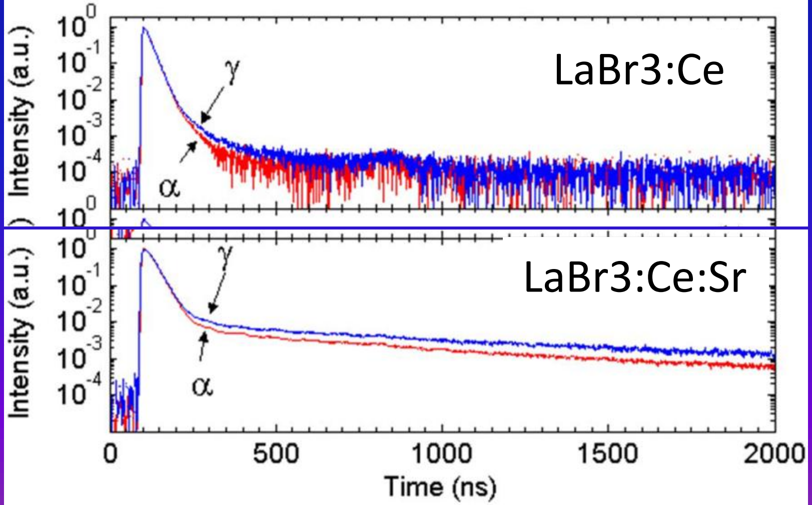
3.5” x 8” LaBr3:Ce
A. Giaz et alk et al. NIM A 729(2013)910

PMT non linearity and in-homogeneity in large volume crystals might limit the energy resolution to 0.5-1%. Intrinsic $LaBr_3$:Ce non linearity may affect energy resolution for $E_\gamma < 100$ keV

R&D on $LaBr_3$:Ce Detectors + Co-Doped PSD Properties







Thanks to St.Gobain -

In LaBr3:Ce and LaBr3:Ce:Sr^+ PSD might be capable to discriminate alpha internal background (especially for LaBr3:Ce:Sr^+)

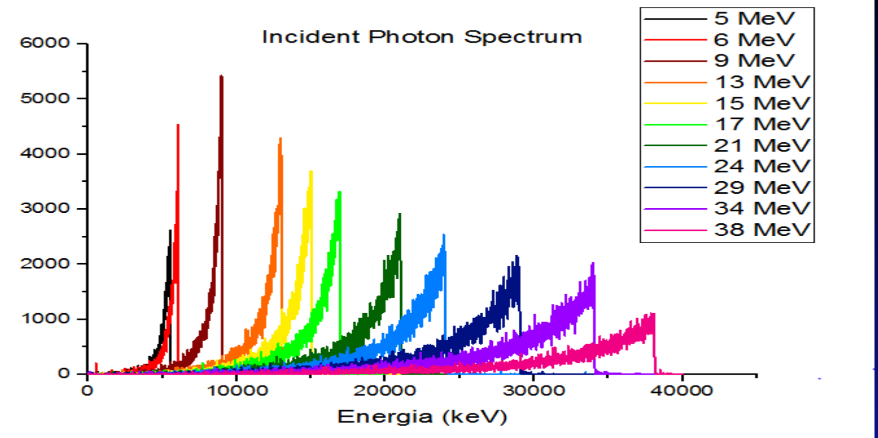
- F.Crespi et al. NIMA 602(2009)520
- Yang et al IEEE-TNS 63(2016)416
- G.Colombi, S.Capra e G.Gosta
  private communications

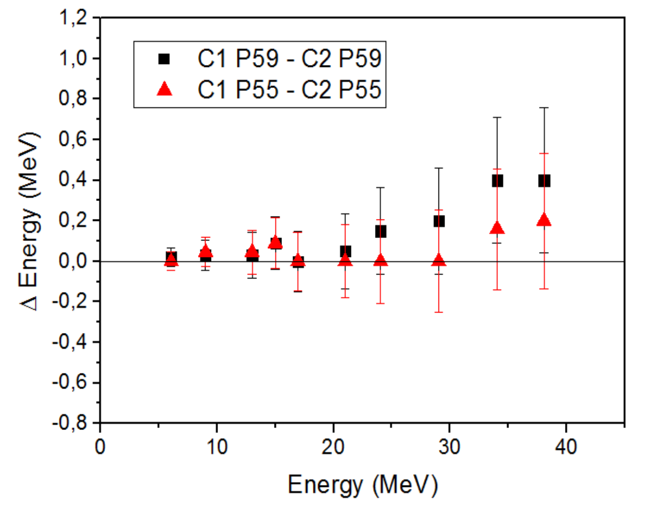
R&D on Lanthanum Halide: $LaBr_3$:Ce Detectors

Spring-8 - New Subaru

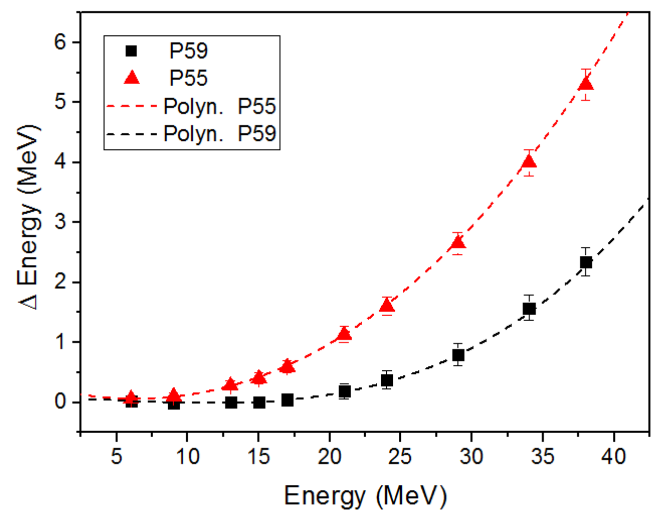
NewSUBARU :

- laser Compton scattering (LCS)
- E_{e-} = 0.5 - 1.5 GeV.
- Laser Nd(w): YVO_4 with wavelength 1064 nm
- 'Almost'-monocromatic gamma-rays





Two 3.5” x 8” crystals have the same response (within the error bars) for high energy g-rays



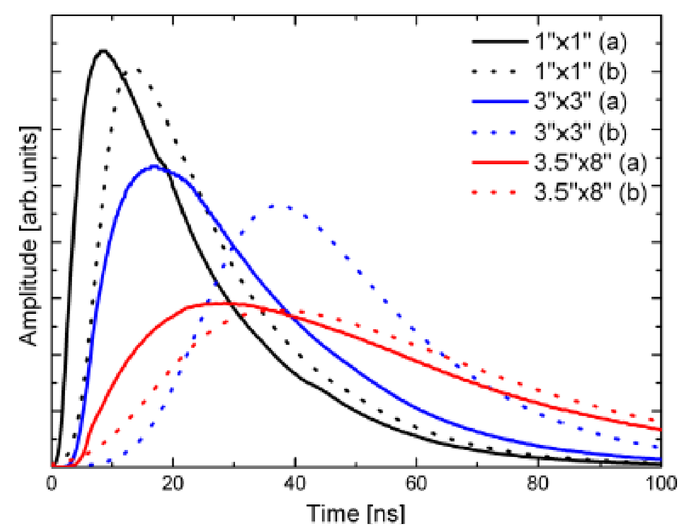
Two PMTs (same model, same production run) have different responses.

A shift of 10.2 MeV makes the two NON- linearity curves overlap

Simulation nicely reproduces measured spectra

G.Gosta et al NIMA 879(2018)92

R&D on Lanthanum Halide: $LaBr_3$:Ce Detectors



A.Giaz et al. NIM-A729(2013)910–921

a – detector size –Hamamatsu H6533 PMT (0.7 ns risetime)
b – PMT induced effect

In general, the larger is the PMT the 'slower' is its time response.

$LaBr_3$:Ce (whatever is the size) has a time resolution < 2 ns

Extremely fast timing (FWHM < 300 ps) might be very difficult to achieve with large volume (i.e. 3" x 3") $LaBr_3$:Ce

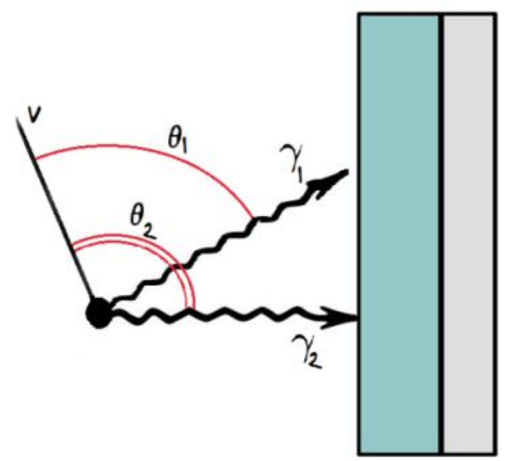
Small $LaBr_3$:Ce Detectors $\Rightarrow$ excellent time performances

- They can be used for lifetime measurement
  - ΔT = 50 ps
  - See N. Marginean et al. Eur. Phys. J. A 46, 329–336 (2010)
  - A very fast tube is needed (XP20D0) - M. Moszynski et al. A 567 (2006) 31–3
  - Energy resolution is not optimized (3.6% at 511 keV)

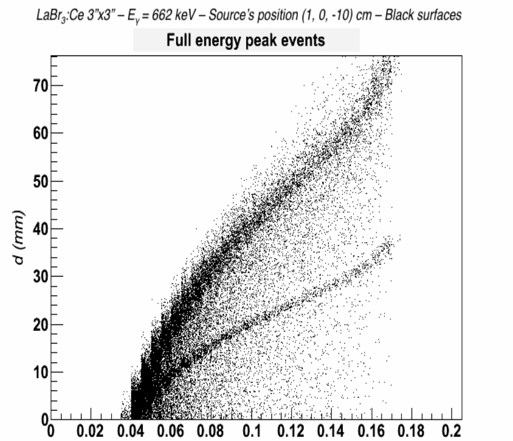
- Fast Timing It is a very powerful technique applied in several experiment in ROSPHERE, FATIMA array was designed for that. The important aspect is an highly tuned and well maintained array of small $LaBr_3$:Ce

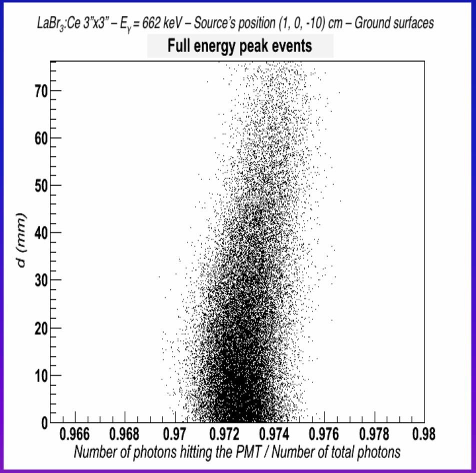
R&D on Position Sensitivity in $LaBr_3$:Ce

Position sensitivity in thick continuous crystals with diffusive surfaces is not for medical application but – for example – for doppler broadening correction



- Multiple interation points $\Rightarrow$ Multiple light sources
- Large volume crystals $\Rightarrow$ Transport of scintillation light from sources to photocathode
- Diffusive surfaces $\Rightarrow$ it is the major issue
  - to have good energy resolution one need to collect all the scintillation photons, namely to collect the reflected light (it does not carry position infomation)

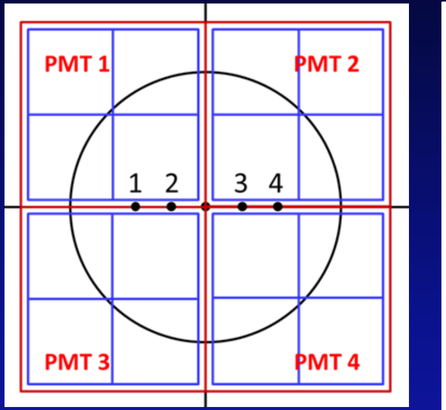


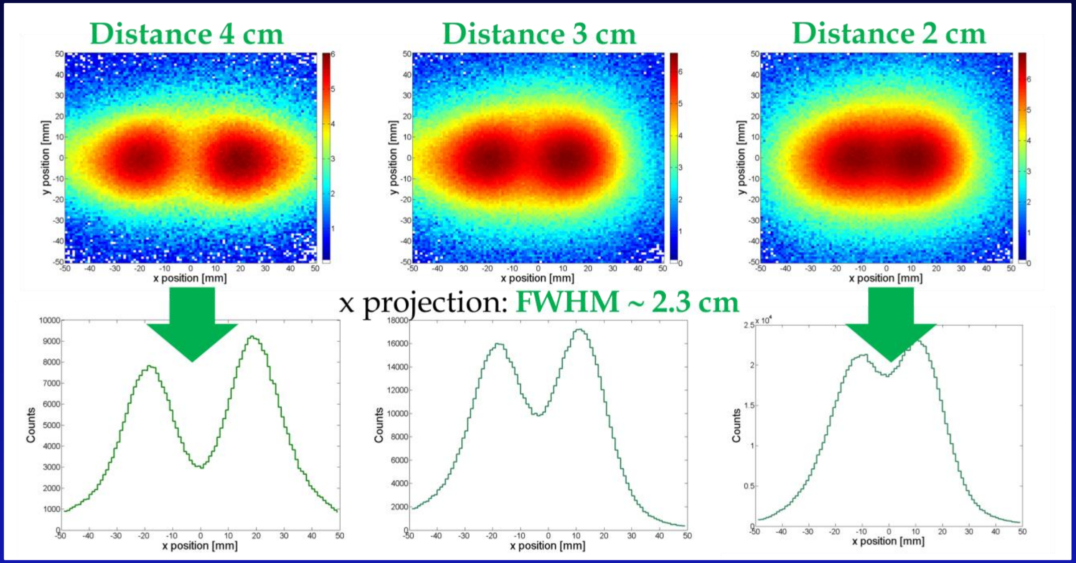


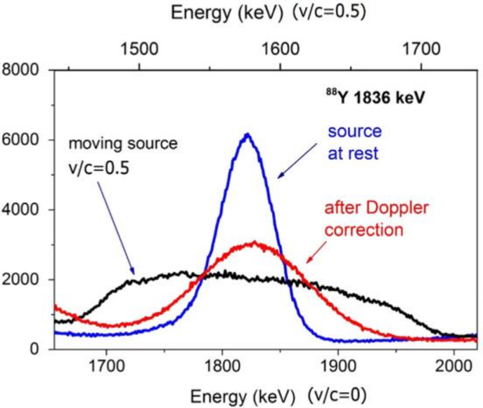
This simulation shows that in a 3"x3" LaBr3 detector only 5% of the scintillation light is directly collected, the rest was reflected at least one time

Position Sensitivity (3”x3” LaBr$_3$:Ce)

The resolution in position is such that two events 4 cm distant are rather clearly separated.







12 Segments – instead of 256 segments

- gain matching is complex

Distance d = 20 cm

The authors mimic a v/c = 0.5% source of 1836 keV

- No doppler broadening correction FWHM ~ 250 keV
- With doppler broadening correction FWHM ~ 100 keV
- Source at rest ~ 50 keV

N.Blasi et al. NIM A 839(2016)23

Therefore:

$LaBr_3$:Ce (and probably Co-Doped $LaBr_3$:Ce:Sr) Detectors

- They can do, in a much better way, the work of NaI scintillators
  - large volumes (we have 9x20 cm crystals)
  - good energy resolution (at low and high γ-ray energy)
  - very fast (fast signals and excellent time resolution)

- But
  - Weak PSD properties
  - No neutron spectroscopy is possible
  - ‘strong’ internal activity

Elpasolite scintillators: CLYC, CLLC, CLLB and CLLBC

- The elpasolite crystals were discovered approximately 10 years ago.
- Excellent performances in terms of **gamma and neutron detection**.

They are Gamma and Neutron detectors:

- High **energy and time resolution**
- Neutron-gamma PSD capability
- High **linearity**

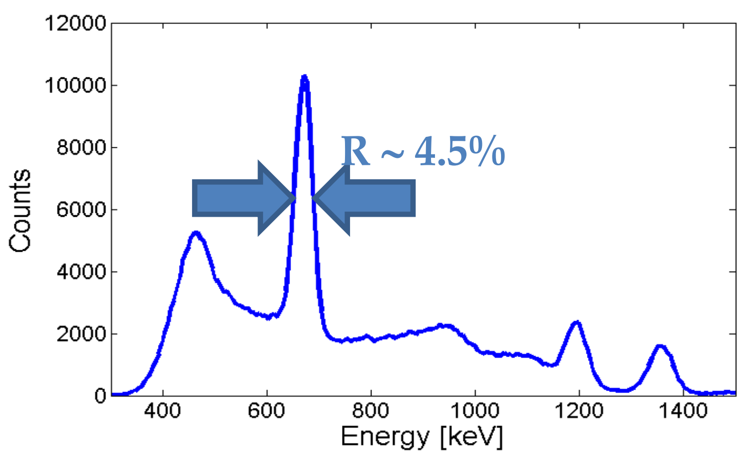
CLYC is commercially available up to 3″ x 3″

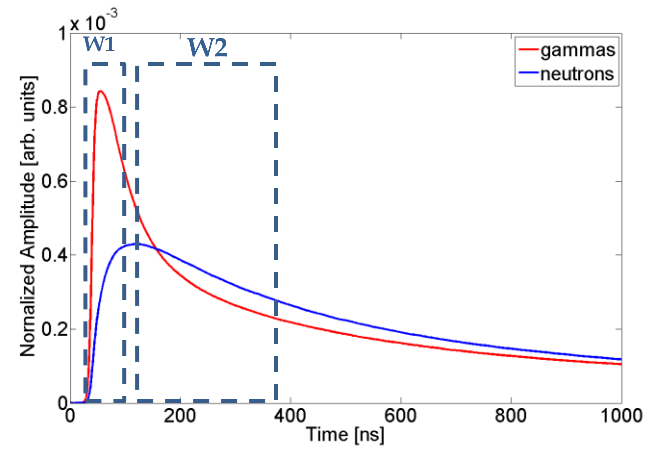
CLLB is commercially available up to 1.5 “ x 1.5″

CLLBC is commercially available up to 1“ x 1″

	CLYC	**CLLC**	**CLLB**	CLLBC
Density [g/cm^2]	3.3	3.5	4.2	4.2
Emission [nm]	290 CVL 390 Ce$^+$	290 CVL 400 Ce$^+$	410 Ce$^+$	410 nn
Decay Time [ns]	1 CVL 50,~1000	1 CVL 60, ≤ 400	55, ≤ 270	
Light yield [ph/MeV]	20000	35000	45000	45000
Light yield [n/MeV]	70000	110000		140000
En. Res. at 662 keV [%]	4	3.4	2.9	3.3%
PSD	Excellent	Excellent	Possible	Yes

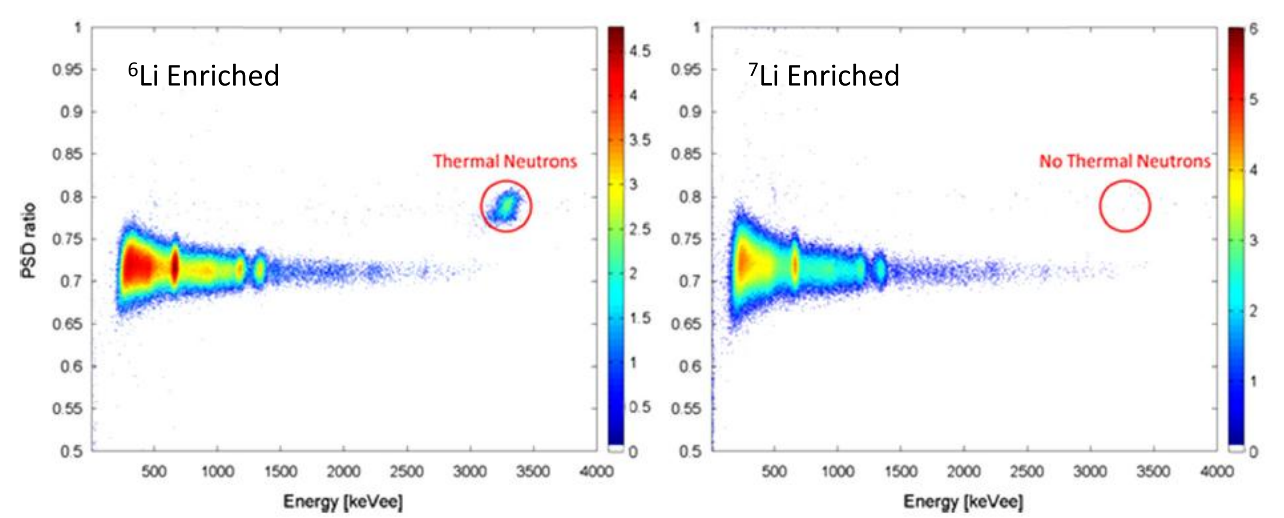
CLYC ($Cs_2LiYCl_6:Ce^{3+}$) scintillator





Good resolution:
Better than NaI
Worst than $LaBr_3$

PSD
Possible



Thermal Neutrons:

✓ ^{6}Li (n,α)t
- Q-value = 4.78 MeV

Fast Neutrons

✓ ^{35}Cl(n,p)^{35}S
- Q-value = 0.6 MeV

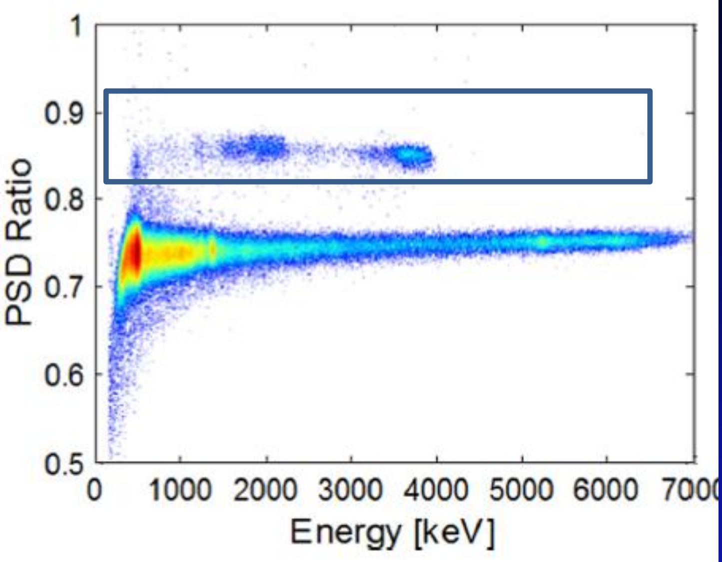
✓ ^{35}Cl(n,α)^{32}P
- Q-value = 0.9 MeV

$E_{p/\alpha}=(E_n + Q)\, q_{p/\alpha} \Rightarrow$ Fast n spectroscopy

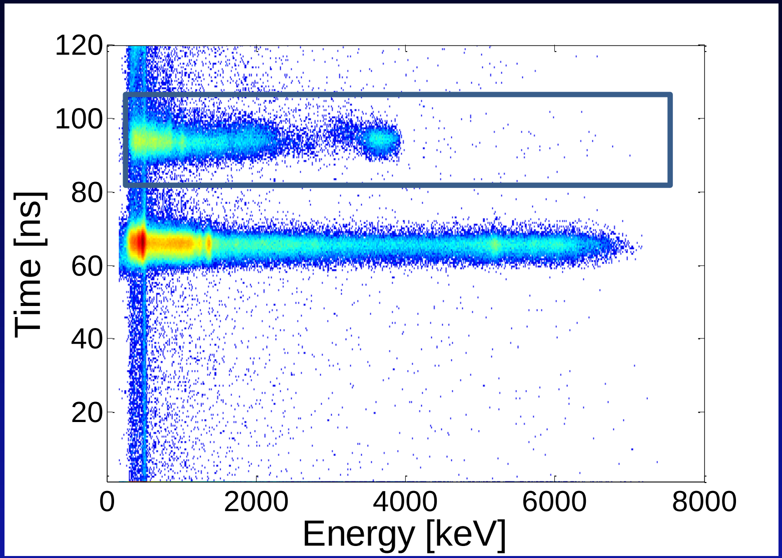
$E_n < 6$ MeV not to have 3 body channels

A.Giaz et al. NIM A825(2016)51 and A.Giaz et al. NIM A810(2016)132

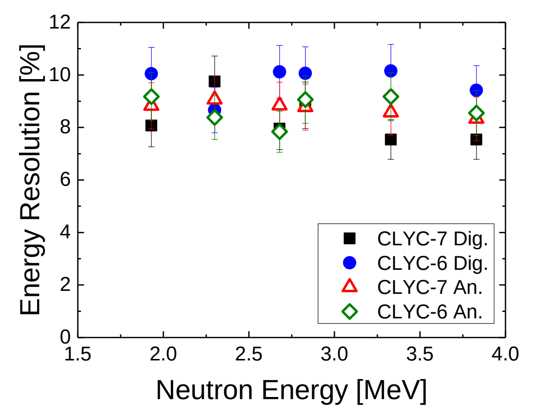
Fast Neutron Spectroscopy

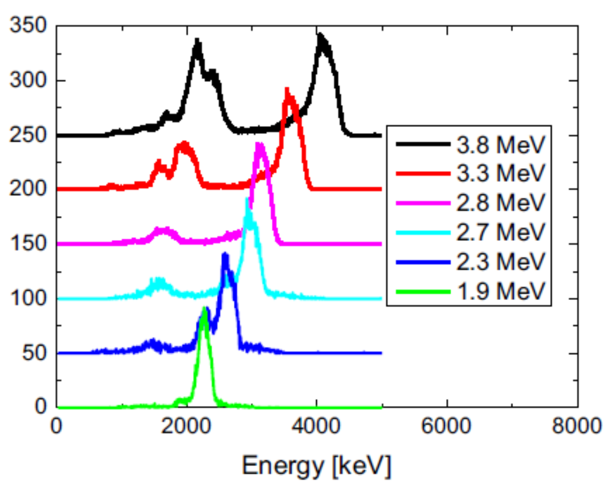


PSD Ratio vs Energy in CLYC (keVee)



TOF vs Energy in CLYC (keVee)

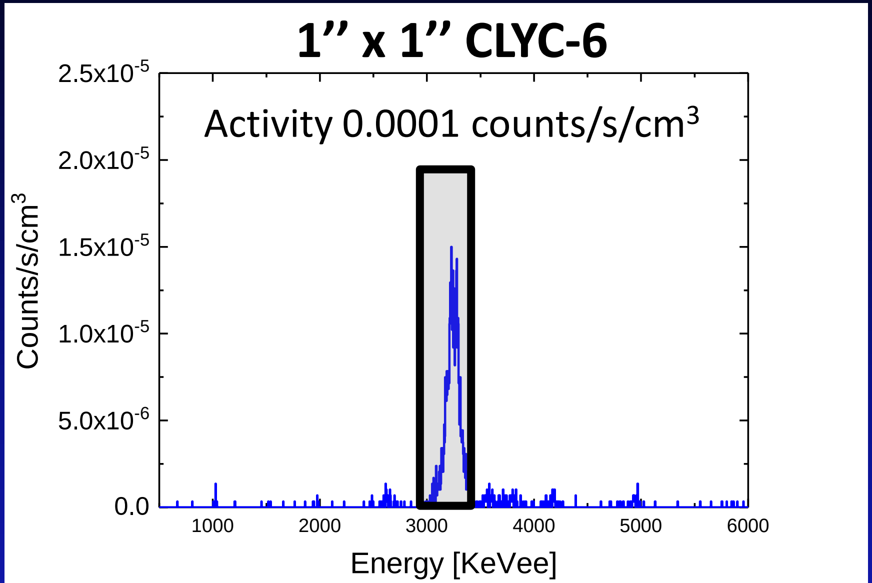




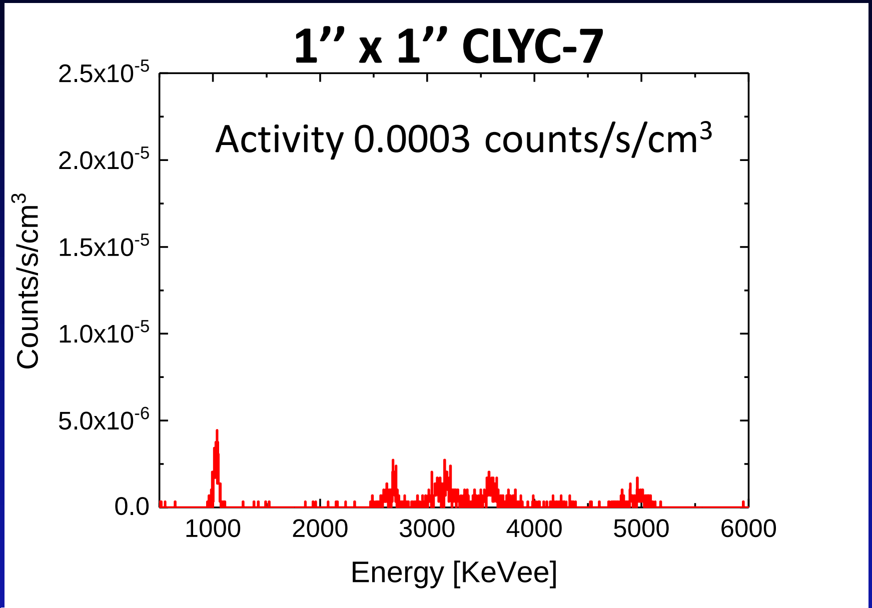
Energy spectra of Neutrons

A.Giaz et al. NIM A825(2016)51 e A.Giaz et al. NIM A810(2016)132

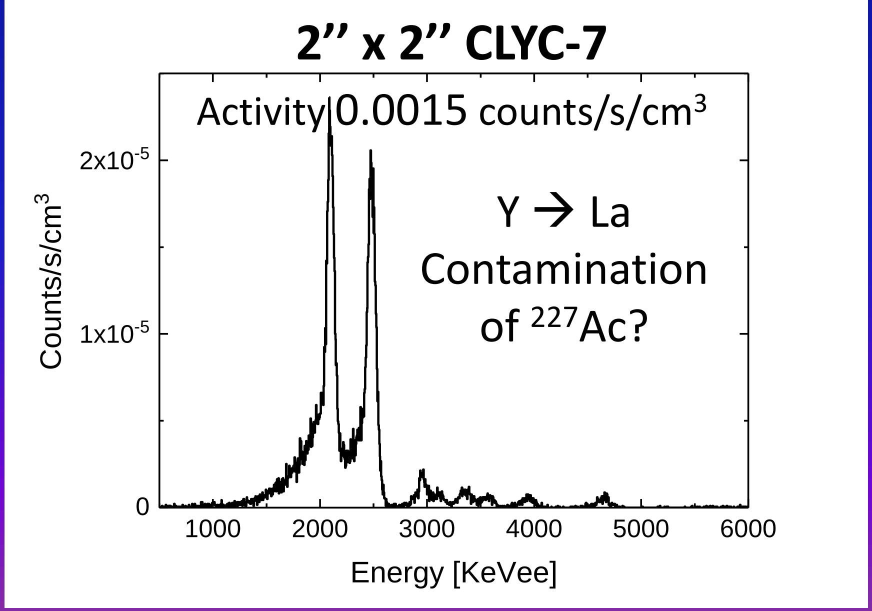
Particle internal activity


1” x 1” CLYC-6

Activity 0.0001 counts/s/cm^3

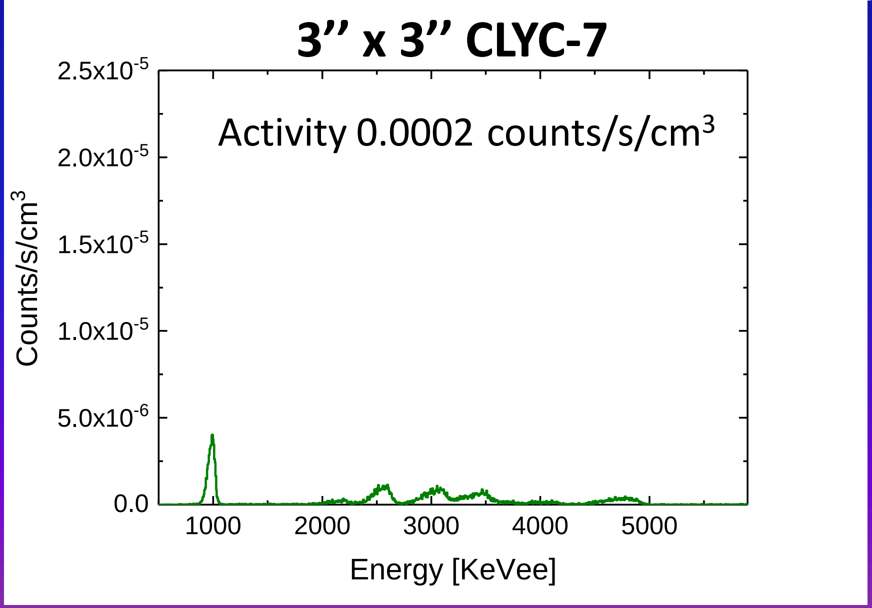

1” x 1” CLYC-7

Activity 0.0003 counts/s/cm^3


2” x 2” CLYC-7

Activity 0.0015 counts/s/cm^3

Y → La Contamination of ^{227}Ac?


3” x 3” CLYC-7

Activity 0.0002 counts/s/cm^3

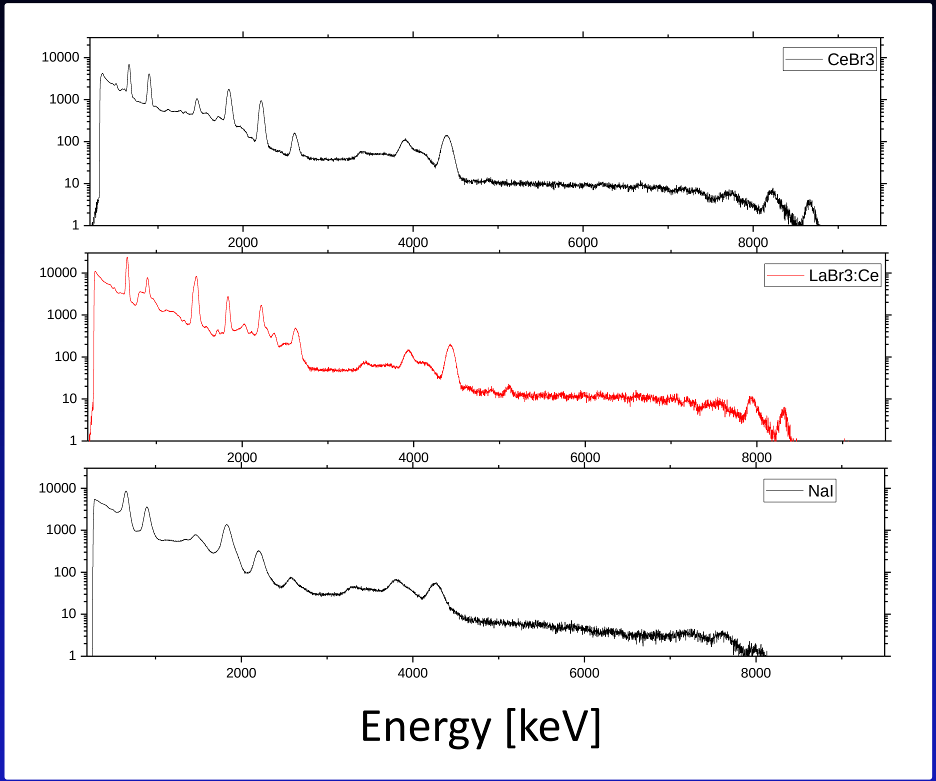
Therefore:

CLYC (and perhaps other ‘Elpasolite’) Detectors

- they can do the same work of $LaBr_3$:Ce
- $LaBr_3$:Ce can perform a little better job for γ-rays

- But
  - Strong PSD properties
  - CLYC-6 is sensitive mainly to thermal neutrons
  - CLYC-7 is sensitive only fast neutrons
    - neutron spectroscopy is possible
    - may be that CLYC could identify also p,D,T,alpha
  - Very weak internal activity

LaBr$_3$:Ce - CeBr$_3$ – NaI (3”x3”)

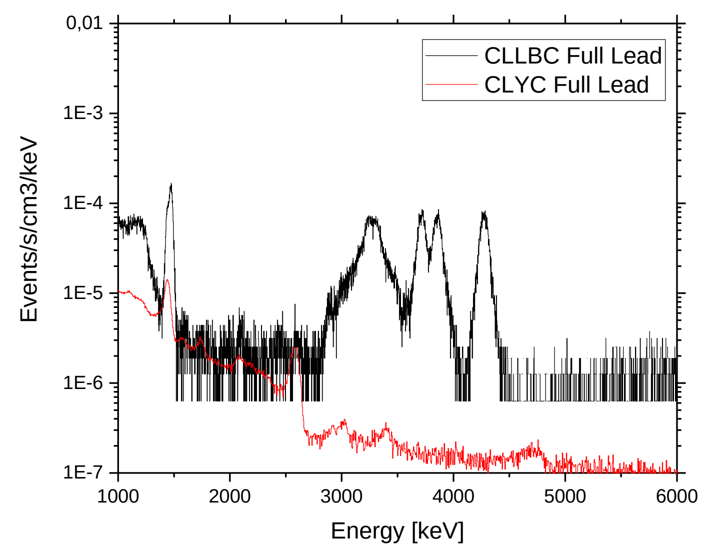


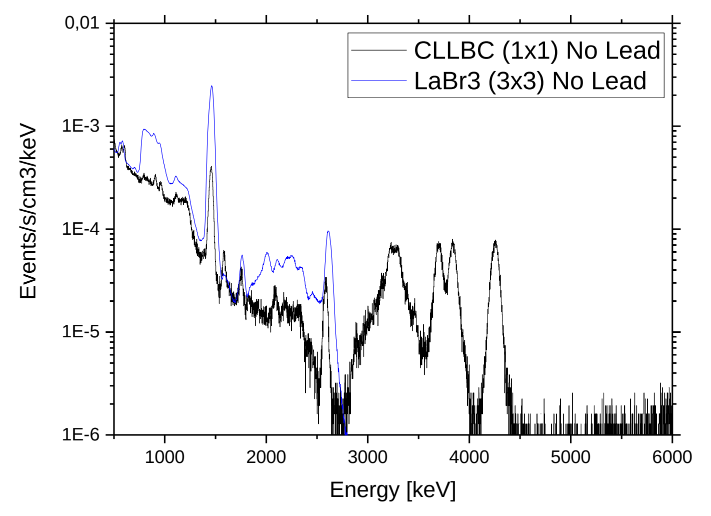
CeBr$_3$ has an energy resolution a little worser than LaBr$_3$:Ce but has no ^{138}La internal background

The internal radiation of CLLBC is comparable to that of LaBr$_3$:Ce

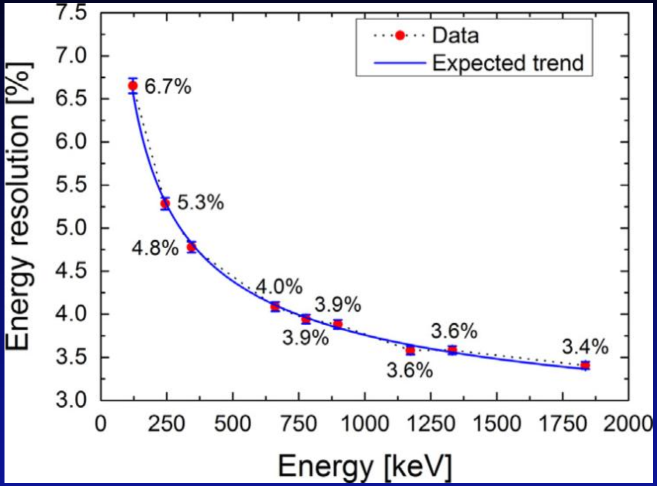
Internal radiation of CLYC is extremely low if compared to LaBr$_3$:Ce

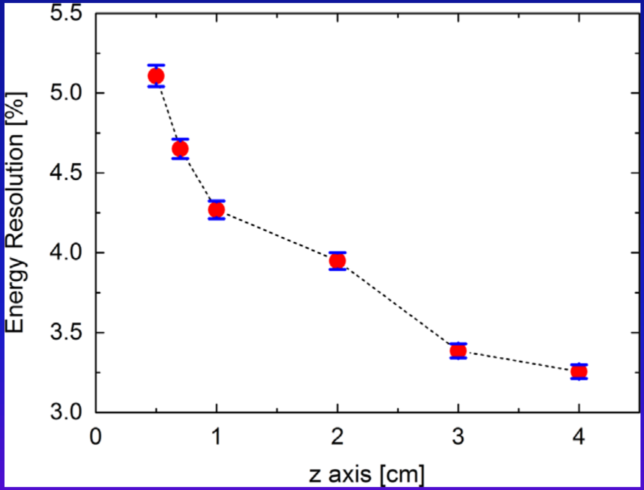
CLLBC scintillator





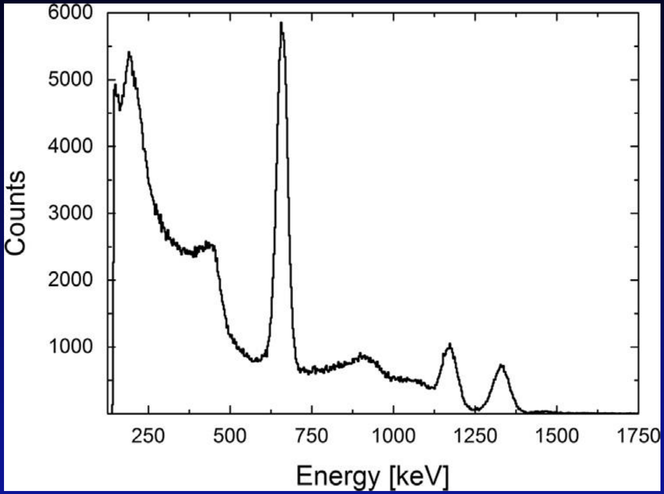
SrI$_2$

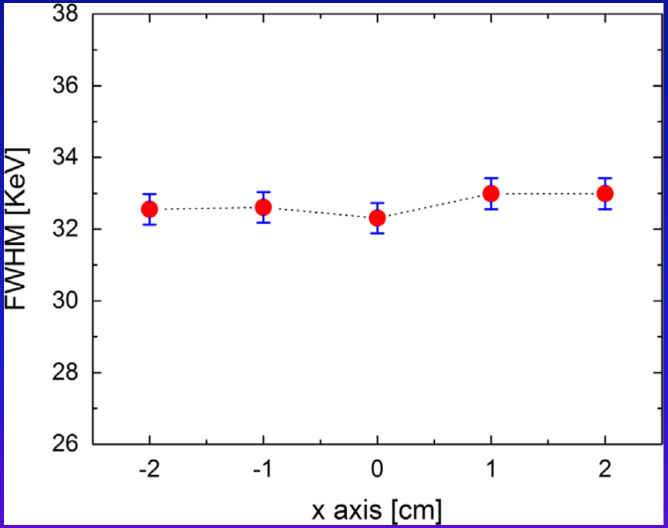




Strong Self-Absorption

GYGAG





It is a ceramic detector with a a strong afterglow
It emits in the yellow (530 nm) (Good for APD , …)

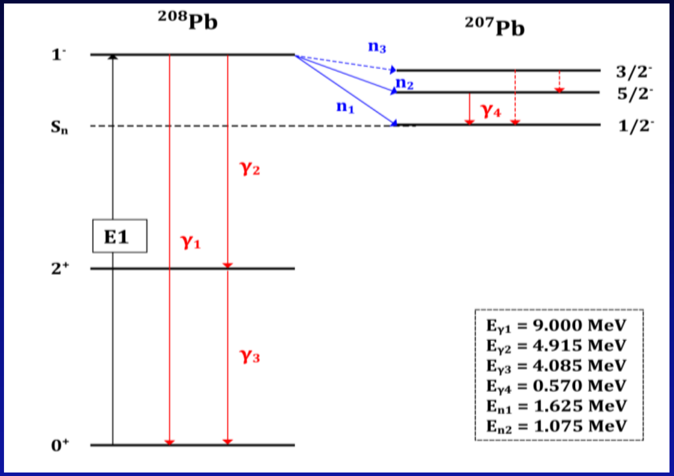
A.Giaz et al. NIM A804(2015)212

Scintillators should be used with HPGe or when HPGe cannot be used or/and when efficiency, timing and count rate is an important issue

- Large volumes are needed
  - high efficiency at high energy
  - large solid angles should be covered
  - ………………
- Nanosecond (or better) time resolution is needed
  - Large background
  - Lifetime measurements
  - Very fast beam repetition rate
  - ………………….
- Large count rate are expected
  - Several scintillators are very fast (in 200 ns the signal rise and fell)
  - Scintillators have always the same pulse shape
  - Pile up disentanglement
  - …………………………………..
- Good (not excellent) energy resolution is needed
  - Few gamma transitions are expected (at least separated
  - provide an efficient gate
  - Measurement of gamma transitions from states at energy higher than the particle binding energy
  - ……………………………
- Neutron Spectroscopy
- Total Price and detector maintenance is an issue
- ……………

Physics case: gamma and neutron decay of PDR and IVGDR

They are located higher than the particle binding energy

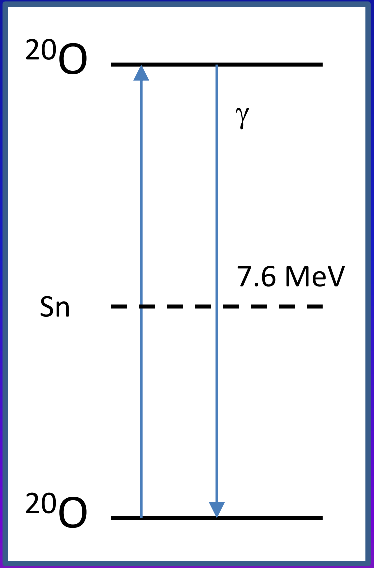


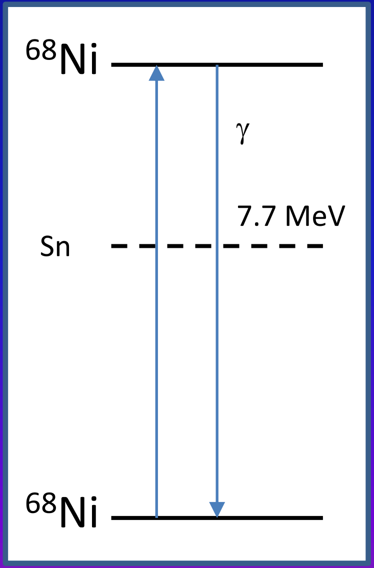
Measurement of high and low energy γ-rays
- Large efficiency
- branching ratio ~1%

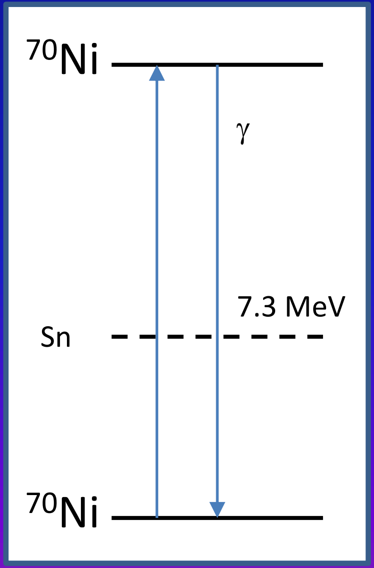
Neutron Spectroscopy

Coincidence Measurement

Large Background







Now are possible only PDR measurement on specific neutron rich nuclei

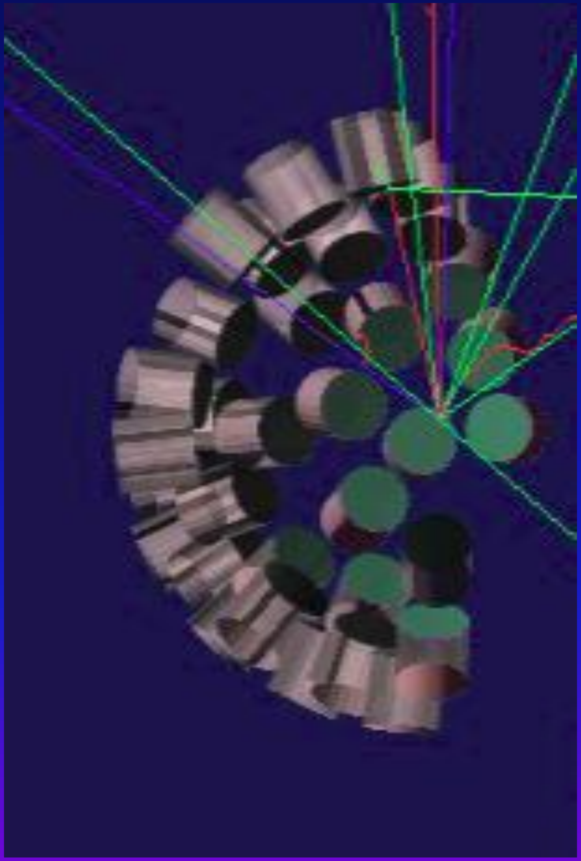
IV and IS probes

- Branching ratio measurement
- Wave Function of PDR
- Neutron skin

N.Nakatsuka et al. PLB 768(2017)387, O.Wieland et al submitted to PRL and M.Krzysiek et al private communications

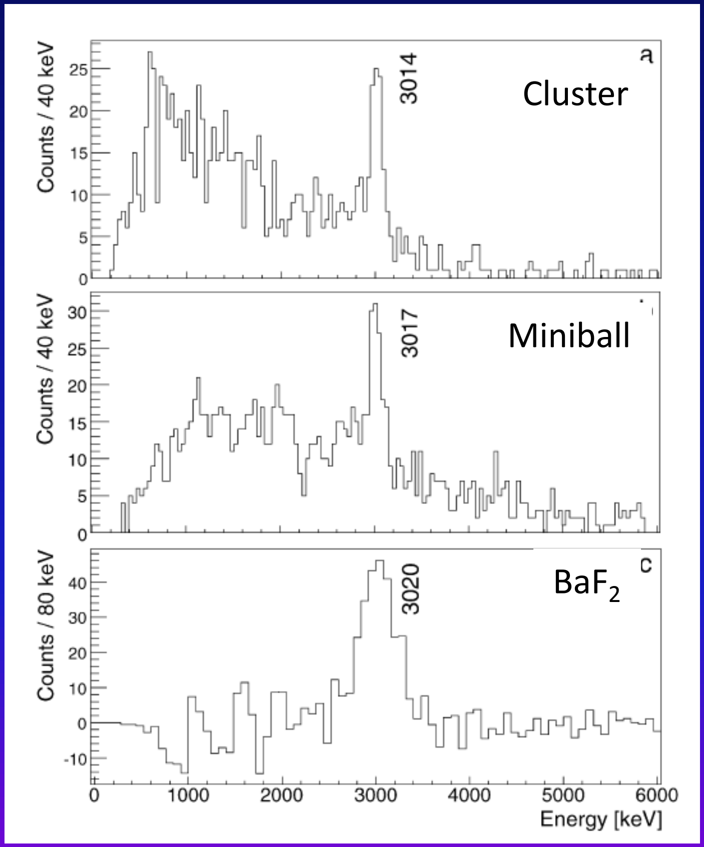
Physics case: Coulomb scattering reactions using radioactive beams

- extremely exotic nuclei
- nothing is known
- High efficiency and clean spectra are required
- Energy resolution is not mandatory



Beam

An example from the past (^{36}Ca)



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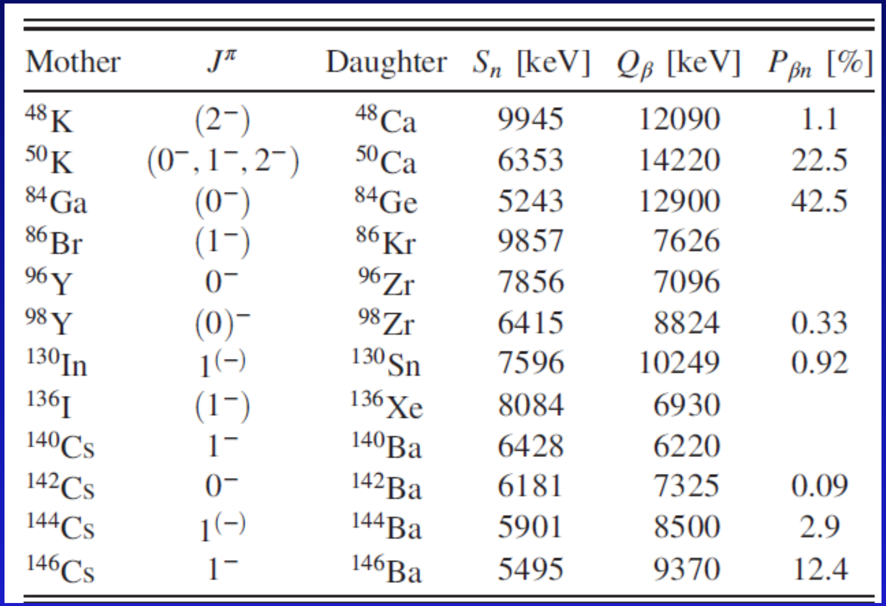
Physics case: Pygmy states populated through beta decay

- High Q Value ($Q_\beta > 7$ MeV)
- Good Selection rules to populate PDR using β decay



Mother	J^π	Daughter	S_n [keV]	Q_β [keV]	$P_{\beta n}$ [%]
^{48}K	(2^-)	^{48}Ca	9945	12090	1.1
^{50}K	$(0^-, 1^-, 2^-)$	^{50}Ca	6353	14220	22.5
^{84}Ga	(0^-)	^{84}Ge	5243	12900	42.5
^{86}Br	(1^-)	^{86}Kr	9857	7626	
^{96}Y	0^-	^{96}Zr	7856	7096	
^{98}Y	$(0)^-$	^{98}Zr	6415	8824	0.33
^{130}In	$1^{(-)}$	^{130}Sn	7596	10249	0.92
^{136}I	(1^-)	^{136}Xe	8084	6930	
^{140}Cs	1^-	^{140}Ba	6428	6220	
^{142}Cs	0^-	^{142}Ba	6181	7325	0.09
^{144}Cs	$1^{(-)}$	^{144}Ba	5901	8500	2.9
^{146}Cs	1^-	^{146}Ba	5495	9370	12.4

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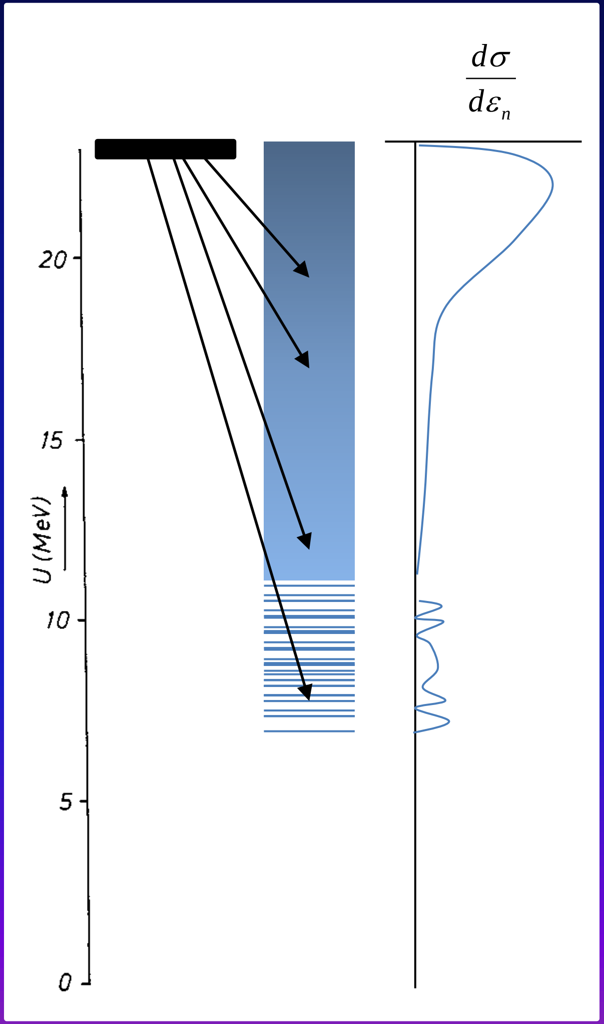
From the conclusion of the paper

" .. β decay populates level associated to the PDR but only a fraction of those ..... β decays represent an additional probe for PDR studies. "

Physics case:

Measurement of the nuclear level densities starting from the measurement of neutron evaporation spectra in exotic nuclei



Starting from the measurement of the neutron emission cross section and an analysis in the framework of statistical theory of nuclear reaction it is possible to measure the nuclear level density

Conclusions

- **In this talk we concentrate on scintillators.**

  Semiconductor detectors have an energy resolution which will never be reached by scintillators (because of the energy gap, the conversion light-electrons, Fano factor, …)

- **Scintillators should be used with HPGe or when HPGe cannot be used (when efficiency, timing and count rate is an important issue)**

  - Large volumes are needed
  - Nanosecond (or better) time resolution is needed
  - Large count rate are expected
  - Good (not excellent) energy resolution is needed
  - Neutron Spectroscopy
  - Total Price and detector maintenance is an issue

- **Scintillators world is rapidly evolving and several new materials arrived, arrive and will arrive on the market**

- **$LaBr_3$:Ce, CLLB, CLLB, CLYC, $CeBr_3$, CLLBC, $LaBr_3$:Ce:Sr^+**

- **There are some/several physics cases where one need the use of scintillators: for example**

  - Measurement of IVGDR and PDR gamma decay
  - Measurement of first excited states in very exotic nuclei
  - Measurement of PDR using large Q values beta decays
  - Measurement of Nuclear level density of exotic nuclei

Thank you for the attention

Misura di uno spettro continuo di neutroni

Spettro di neutroni continuo:

Sommo i contributi delle varie energie di neutroni monocromatici.

La somma della matrice tempo energia (con gate gate sui neutroni, usando PSD) mi mostra che è possibile separare i contributi delle due reazioni.

La regione individuata in rosso include il contributo della reazione $^{35}Cl(n,\alpha)^{32}P$, ma anche $^{35}Cl(n,p)^{35}S^*$ (Energia 1° stato eccitato = 1572 keV)