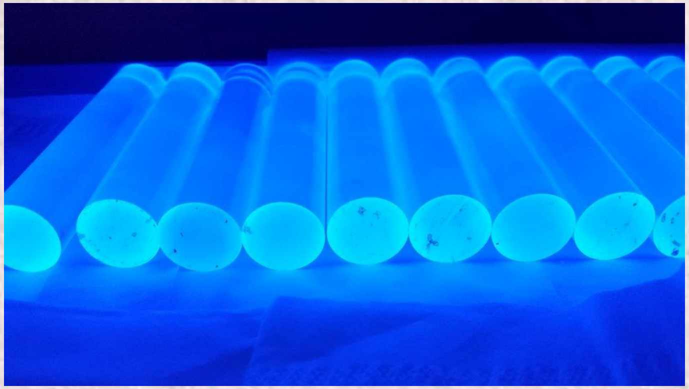
Production and testing of commercial scintillators



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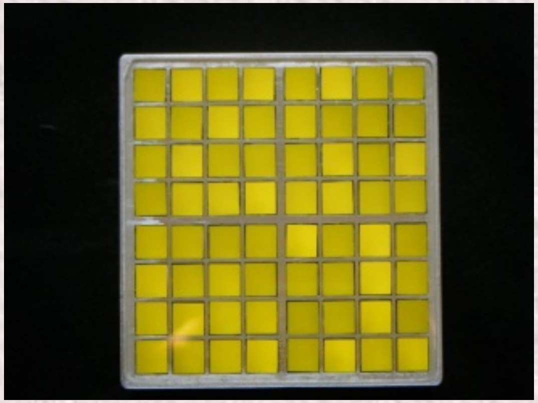
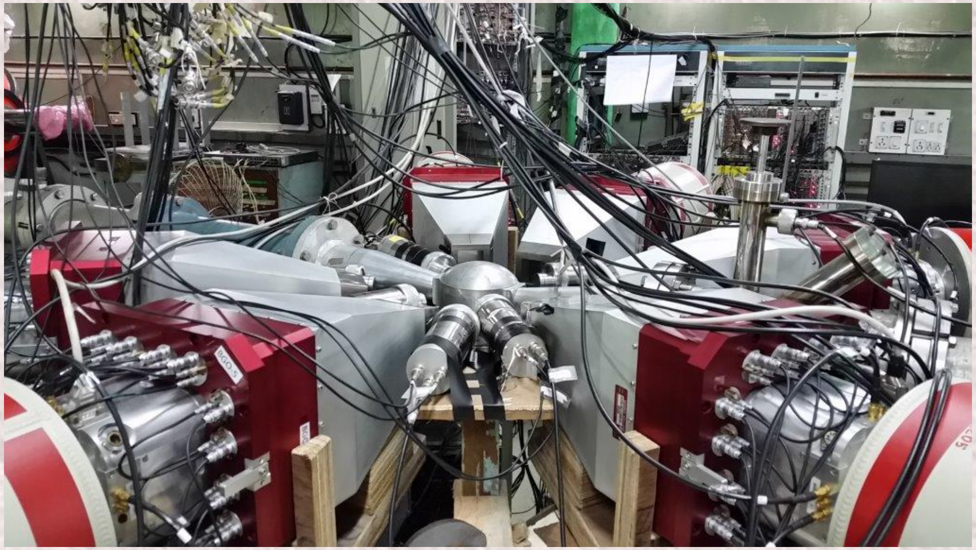




scintillation detectors from an industrial point of view :

Aim : to be able to produce larger quantities of devices with well defined specifications against affordable cost

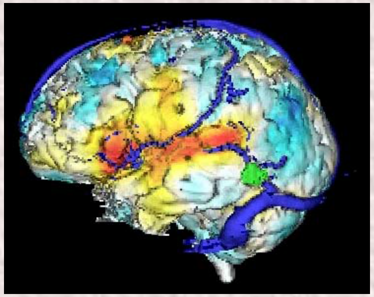
Requirements → Why new materials ?

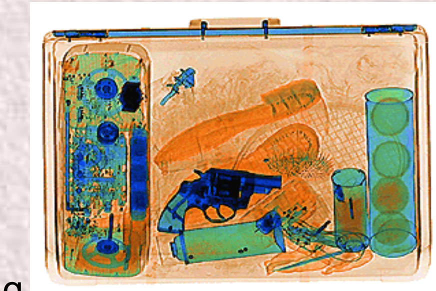
- Newer scintillation crystals, requirements
- To what level are new materials applied at this moment ?

  Inorganics / Organics

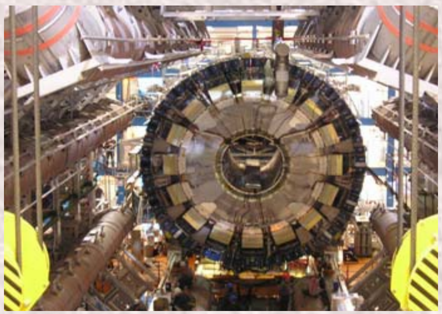
- Challenges and hurdles when going to large(r) scale production
- Advances in crystal readout : SiPms and actual applications
- A few examples

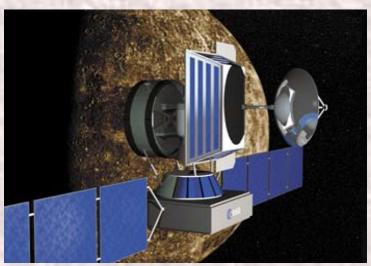
Scintillation detectors : standard tools in many disciplines



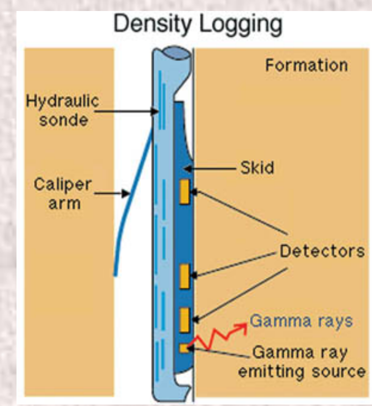


- Medical (SPECT/PET/CT) : Imaging, density
- Health Physics : Dose (particles, photons, neutrons)
- Security (finding/identifying sources) : spectroscopy
- High Energy Phyics (HEP) : particles, photons, imaging
- Nuclear Physice (high res.) Gamma rays spectr. Timing
- Geology: finding U, Th via spectroscopy,
- Mineral exploration (density, PNGA elemental analysis)
- Oil industry (density, well logging,)
- Space (gamma) spectroscopy, neutrons
- ……





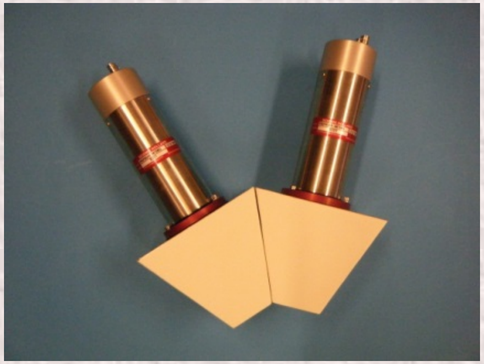
There is more around han 662 keV energy resolution

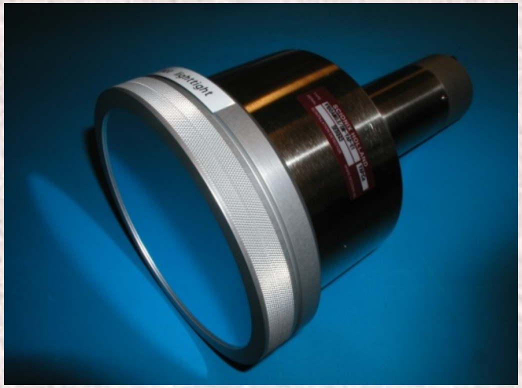


EACH DISCIPLINE has a vastly different specifications, definition of "better scintillators" depends on application !

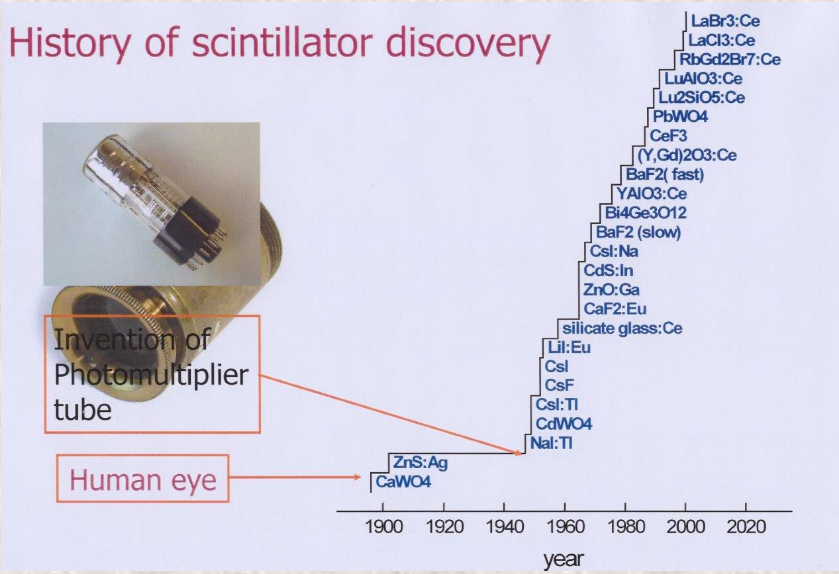
Advantages of scintillators :

- large efficiency (density up to approx. 9 g / cc)
- inorganic crystals possible with large Z (La, Ce, Cs, Bi,Cd)
- speed (ns-microseconds)
- special shapes possible
- usually no cooling needed (unlike HpGe)
- can be relatively inexpensive (compete γ- ray spectr). < 4k€





Some crystals easy machinable
(soft) like CsI(Tl)



PLUS e.g.

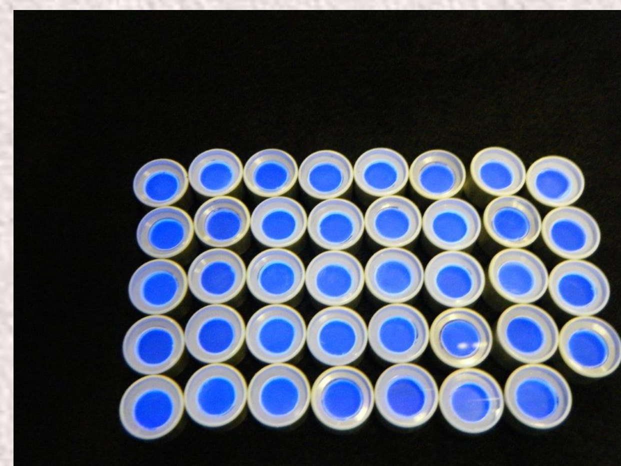
CLYC (Ce)
SrI_2(Eu)
$CeBr_3$
CLLB + other epasolites
GAGG:Ce family
La:GPS (Ce)

and others…

Last 10- odd years <u>many</u> new (in)organic scintillation materials were discovered/published , most of them have not made it (yet) into industrial production…

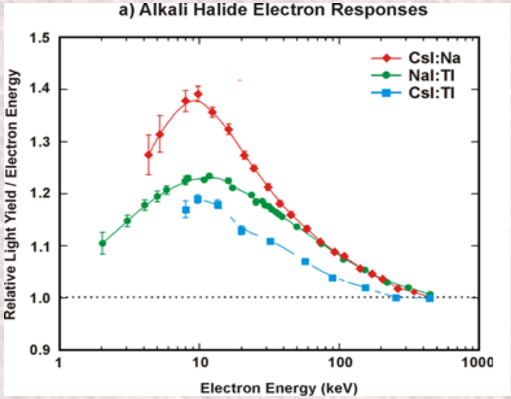
Q. What do we mean with novel/better scintillators ?

Q. What do we really need ?



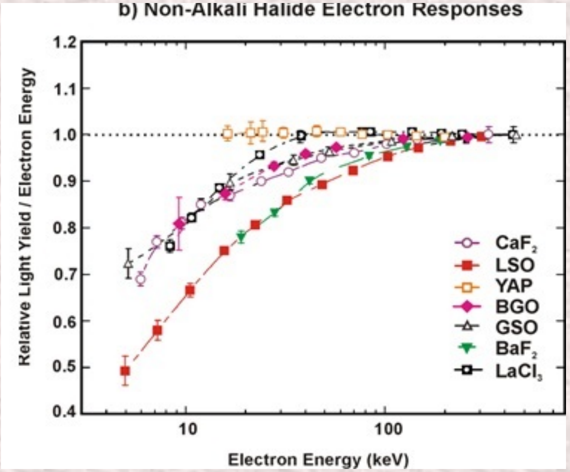
It all depends on application !

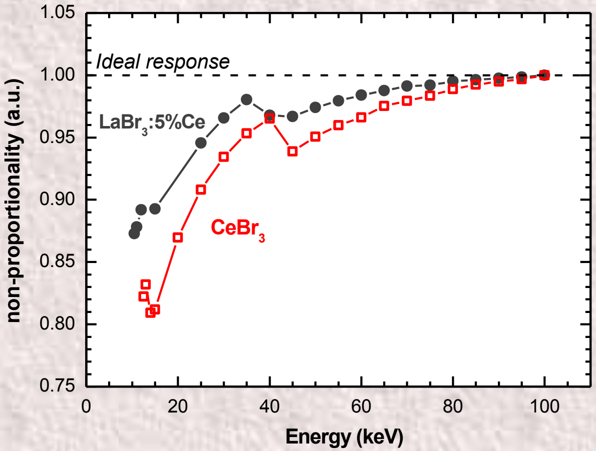
scintillator research very much focused on **improved energy resolution for 662 keV gammas** pushed by security needs…..



This has led to discovery/ development of proportional crystals :

$LaBr_3$:Ce, $CeBr_3$, SrI_2(Eu), GAGG (Ce), CLYC(Ce) etc.



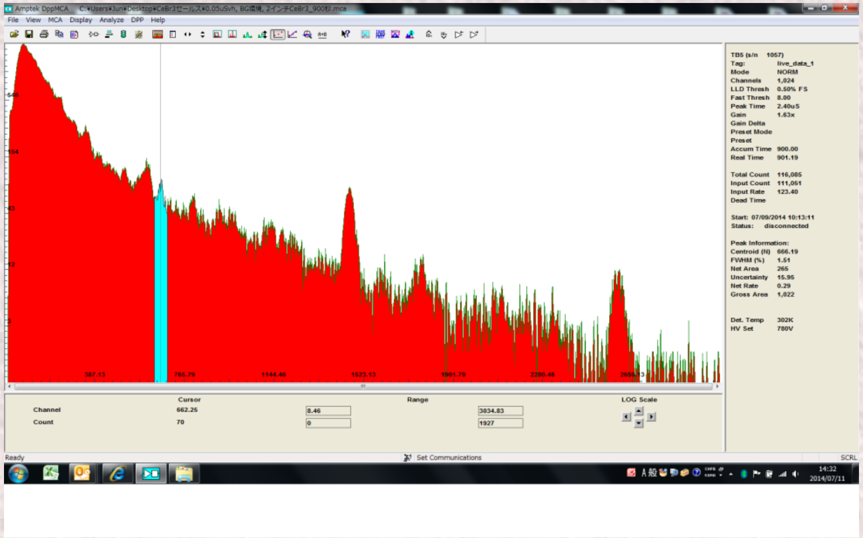


Of course we would in general prefer : fast, bright, crystals BUT ..this is not always needed.

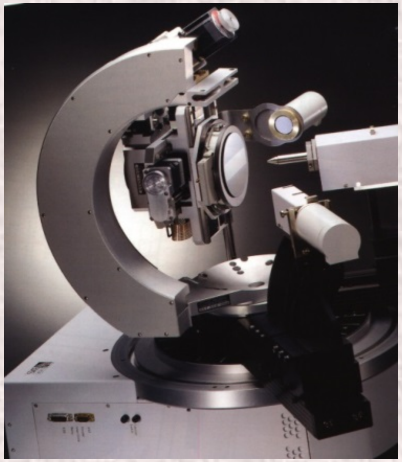
Some other things we would like to see e.g. :

Environmental (gammas < 2.6 MeV)

~3-4 % energy resolution @ 662 keV as $LaBr_3$:Ce BUT low background as $CeBr_3$



Problem : cost !



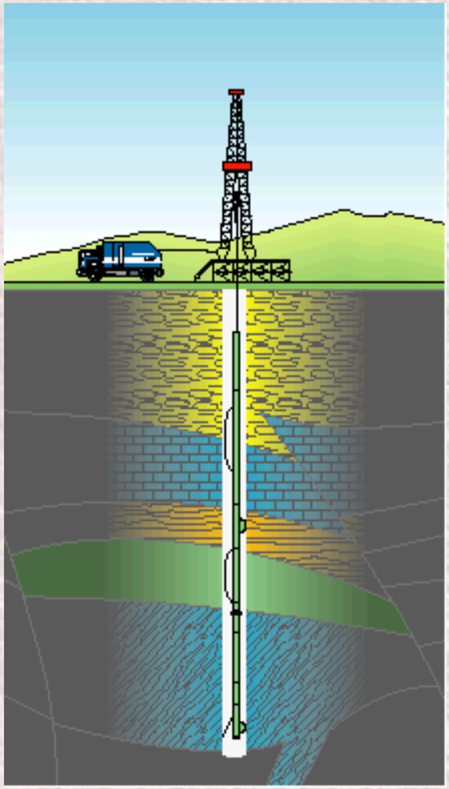
e.g. In **X-ray spectroscopy** we really need fast (tens of ns) bright (> NaI(Tl)) crystals at < 10 keV energy to allow quicker analysis Requested count rate MHz. $CeBr_3$ but high LO at low energies

Oil Industry :

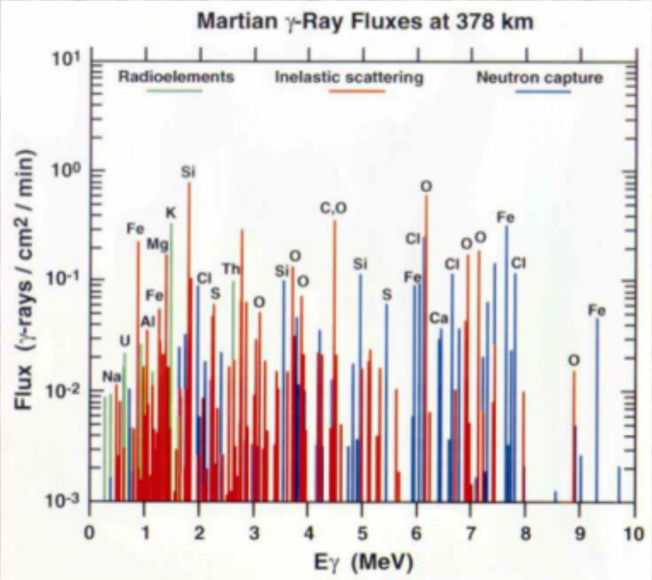
Porosity, saturation , densiry, multi phase flow

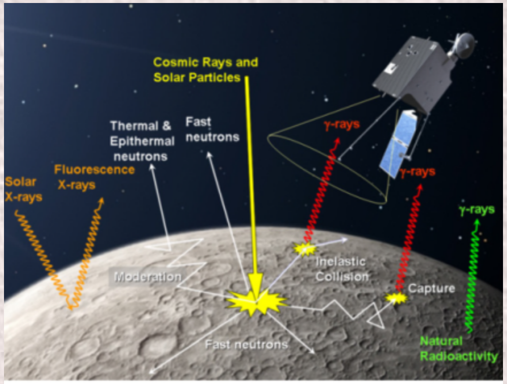
- Fast, High T high resolution crystals : $LaBr_3$:Ce, $CeBr_3$ O.K.

But also (fast) plastics able to operate (longtime) at 100 degrees C (MHz counting). Not available…



Space : High resolution low background (k-40)
< 30 MeV, $CeBr_3$ O.K.





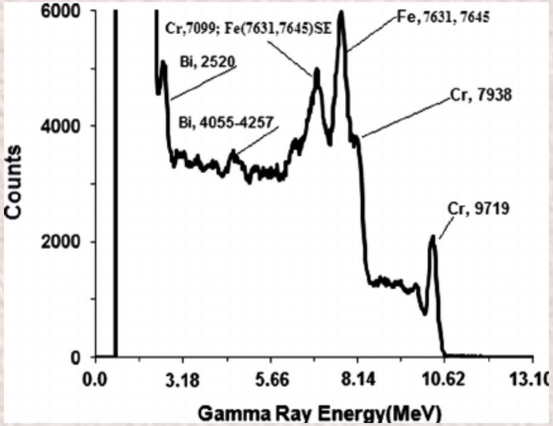
High Cost not real issue..

Mineral exploration using PNGA
(coal analysis, cement)

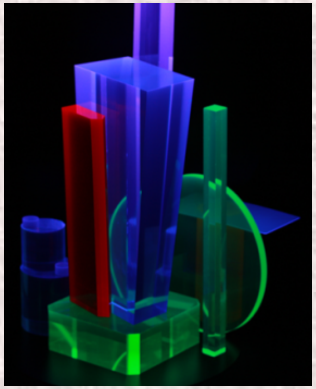
- many kg crystals needed (> 5 kg per system)

- better energy resolution at 5 - 10 MeV, large Z required (comparable to BGO)

- $LaBr_3$ / $CeBr_3$ too expensive !



High on the wish list also :



- organic scintillators with spectroscopic capability (W, Bi) under development
- Plastics with Neutron/ gamma capability (Li doped) idem

NEW materials imply new challenges

$$\left(\frac{\Delta E}{E}\right)^2 = \underbrace{\left(\frac{\Delta E}{E}\right)^2_{sci,\,intr}}_{1} + \underbrace{\left(\frac{\Delta E}{E}\right)^2_{stat,\,N}}_{2} + \underbrace{\left(\frac{\Delta E}{E}\right)^2_{PMT,\,sci}}_{3}$$

WHY ?

For example

- Ideal (super) energy resolution is only achieved under optimum circumstances (maximum <u>photoelectron detection</u> and optimum homogeneity (items 1 and 3 in equation)

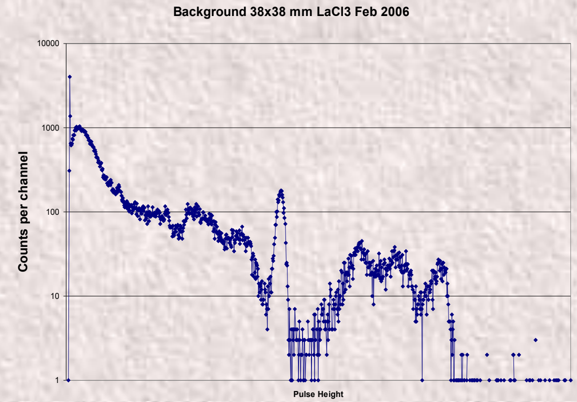
This all imposes :
- selected QE or special high Cb cathode
- PMT same size or larger than crystal
- suitable glass or quartz windows needed

i.e "Ideal" configuration for light detection is needed.

Not all crystal / readout configurations are possible to retain high resolution

For SiPm readout same : number of primary charge cariers needs to be optimised

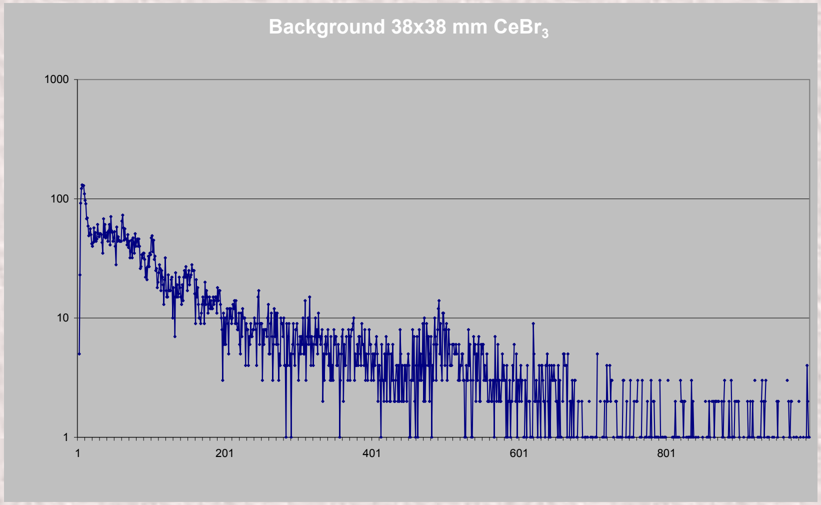
Where are we with application of “new” materials ?



$LaBr_3$:Ce: Mature material used on extensive scale

High price prevents large scale us
La-138 background is disadvantage

$CeBr_3$:



Absence of slow components allows use at MHz spectroscopy in plasma experiments

At high Multi (5-10 MeV) gamma energies resolution $CeBr_3$ only slightly worse than $LaBr_3$:Ce.

No beta background, very small alpha background (< 0.001 c/s/cc)

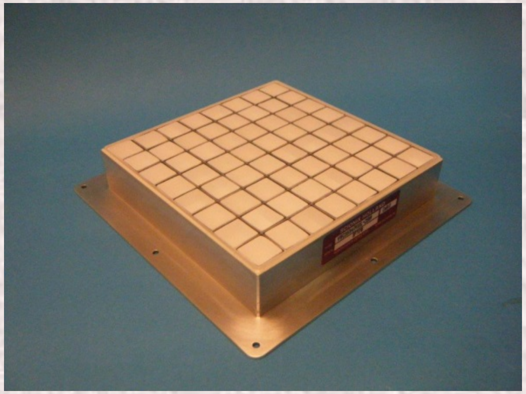
Rel. high cost (yield)

CeBr$_3$ used in : Space applications (resolution)

Plasma Physics (speed)

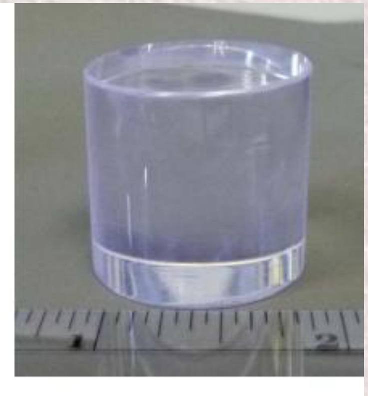
PALS (time resolution)

Environmental (resolution / background)



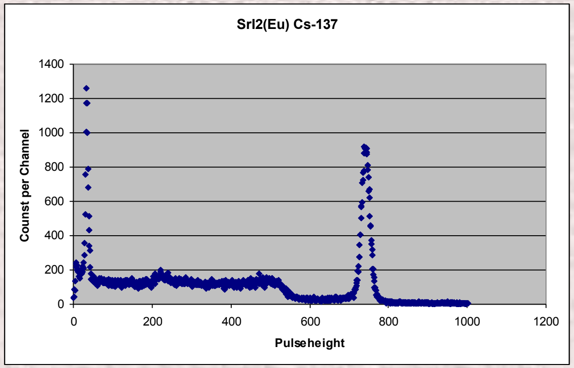
Time resolution comparable 127 / 119 ps Ackermann et al. (NIM A 786, 2015) 5-11 : energy resolution 5 % instead of 10 % @ 511 keV.

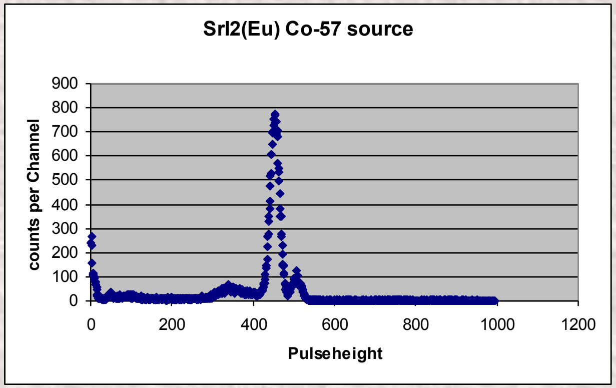
SrI$_2$(Eu) **:** very bright, proportional



small Stokes shift --→ self absorption
---- > larger crystals worse E-resolution !

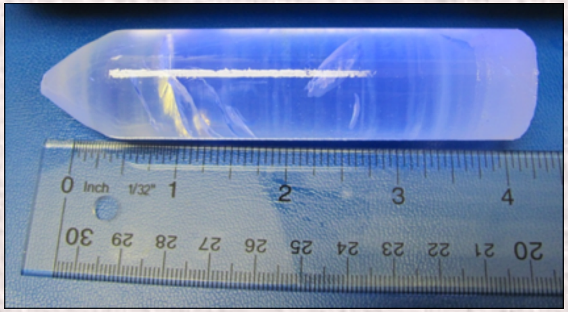
Recently some very encouraging data were published though





light yield very high **! → very good resolution at 100 keV**

Radiopure



Energy resolution approx. 3.5 % FWHM @ 662 keV

Price relatively high = drawback

Hardly used (yet) in commercial products

This crystal may find interesting applications in low background high resolution spectroscopy at low gamma ray energies !

More crystals of this "family" under development like

$KCaI_3$(Eu)
$KCa_{0.8}Sr_{0.2}I_3$(Eu)

Contain a lot of K-40 but crystals can be grown very fast (cost) (University of Tennessee)

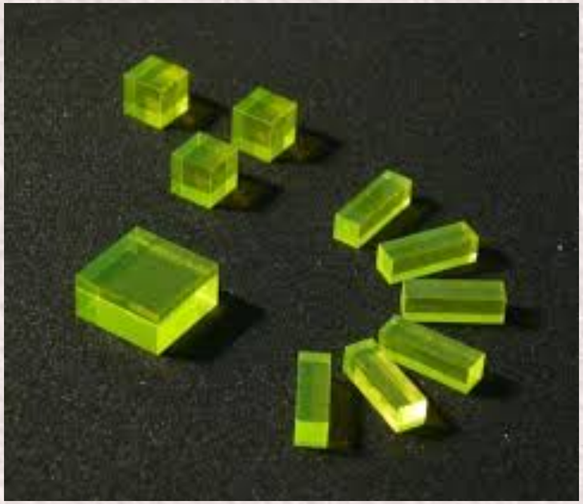
E-res 3.5 – 4.0 % @ 662 keV

GAGG ($Gd_3Al_2Ga_2O_{12}$) Ce

- 6.6 g/cc
- 520 nm max emission
- 56000 photons / MeV

Proportional, not hygrsoscopic

FIRST non hygroscopic High LO crystal



Proportional, FIRST non hygroscopic High LO crystal

High melting point (1850 ^{o}C) → cost

Not used frequently yet

SiPm readout ? Special applications ?

No new generation scintillator will be the "ideal" material = illusion

Often bottom line is COST = growing yield

(material cost is seldom the real issue**)**

"Tuning" proportionality remains hot topic

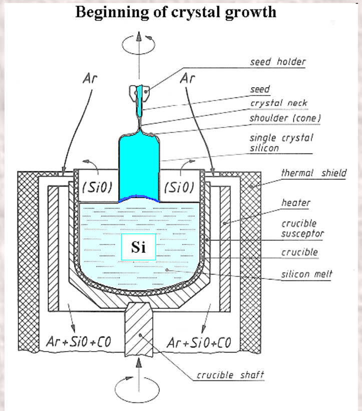
Important factors for Industrial use are ?

- what is the cost ?
- can larger crystals be grown at usable size ?
- is the (superior) performance justified by the price ?

Crystal grown on Industrial scale remains a multiparameter system of which not all parameters can be always controlled 100 % :

- purity of materials (sub ppm) → Background/absorption
- temperature during growth → Inhomogeneities in dopant/cracks

growing one crystal ←→ growing 100 crystals



Too tight specifications leads to (sometimes unaffordable) high cost !

Price idea :	NaI(Tl) detector	76 x 76 mm	:	2 k€	5 $ / cc
	BGO detector	76 x 76 mm	:	5-6 k€	20 $ / cc
	$LaBr_3/CeBr_3$	76 x 76 mm	:	35 k€	100 $ / cc

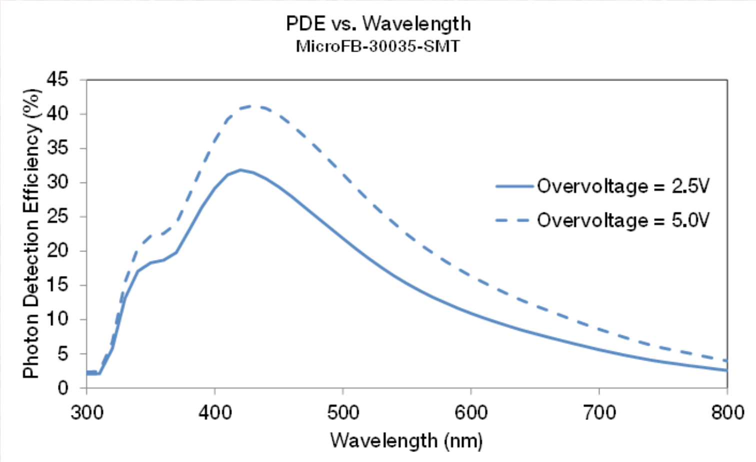
For many applications standard inexpensive scintillators like e.g. NaI(Tl) / or standard plastic scintilators are 100 % sufficient and will not be replaced by novel scintillators due to low price of existing materials.

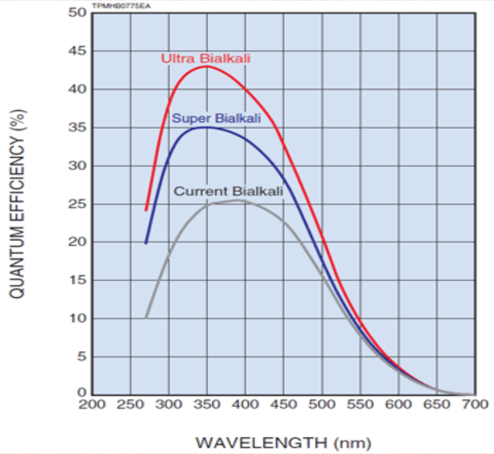
ADVANCES in scintillation light detection

Range of possibilities for readout of scintillation light :

- **PMTs**
- **(PIN) Diodes**
- **Avalanche Photodiodes (APDs)**
- **(Drift Diodes)**
- **(EM) CCDs**
- **Si-PMs (MPPCs)**

The use of silicon technology allows higher wavelength emitting scintillators; PMTs dictated an emission in the 400 nm region.





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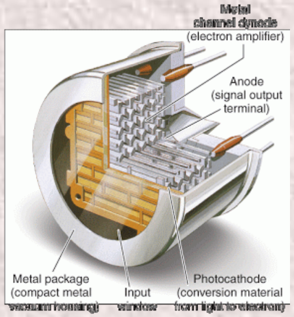
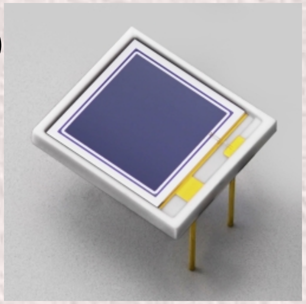


PMTs

- Made of glass (fragile + K-40 background)
- Large signals, good S/N ratio, fast (ns)
- Large dimension, low price per cm^2
- Sensitive to B fields
- Existing old technology (vacuum tubes)

PIN diodes

- No amplification (small signals)
- Maximum cm size
- Stable (temperature)



CCDs :

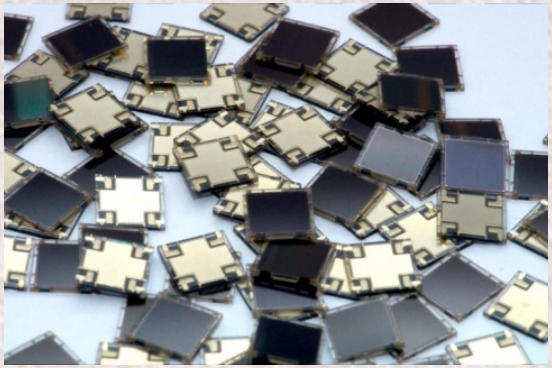
- DC measurement mostly
- Imaging
- For higher radiation fields

APDs

- Amplification 100-1000
- rather Unstable (temp)
- rel expensive, small (max 10x10mm)

Drift diodes (for light detection)

- small (not often used)
- still rel. expensive

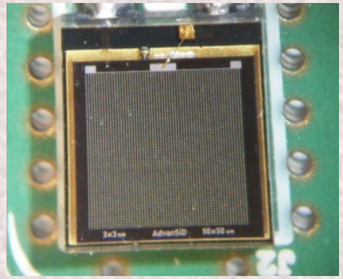


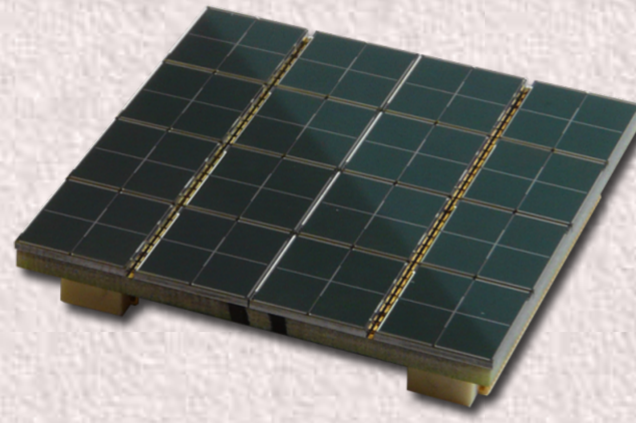
Silicon Photomultipliers (SiPMs, MPPCs)

Large improvement of SiPms since 1.5 year does open up many possibities :

- Higher PDE

- Lower noise





PRO’s

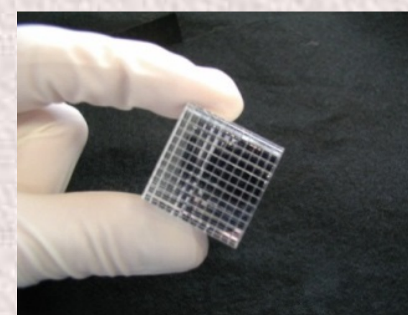
- Large gains (10^6), fast
- Affordable cost (6x6 mm< 50-100 €)
  (mass production process)
- Higher basic QE than PMTs : Si
- Low voltage (30-70 V) e.g. ATEX

CON’s

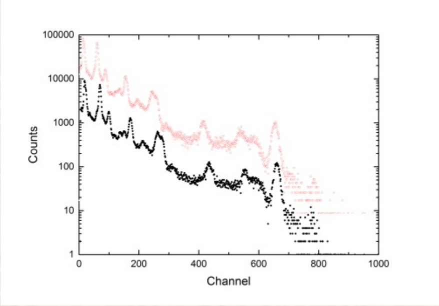
- high price per cm^2
- filling factor
- pixel saturation easy (fast bright scintillators !)
- temperature dependent gain rel. large (+-1% / ^oC)

Readout of crystal pixels with SiPm obvious :

Med. Imaging
(WLS) Fibers



Issues with SiPms : **A. Saturation / alinearity**



Alinearity effects

- The higher the amount of pixels, the less problems with saturation. When all pixels fire = end of story

  Typical pixel size 35 micron = 19.000 pixels on 6x6 mm

- the slower the scintillator, the more pixels can recover
- to some level, energy calibration can be a solution

B. Limitation due to PDS / filling factor

- typical PDE for 6x6 mm is currently 52 % (more than UBA cathode)

C. Temperature behaviour

- Gain drift (typical -1.5 % per degree C)
- increase of noise

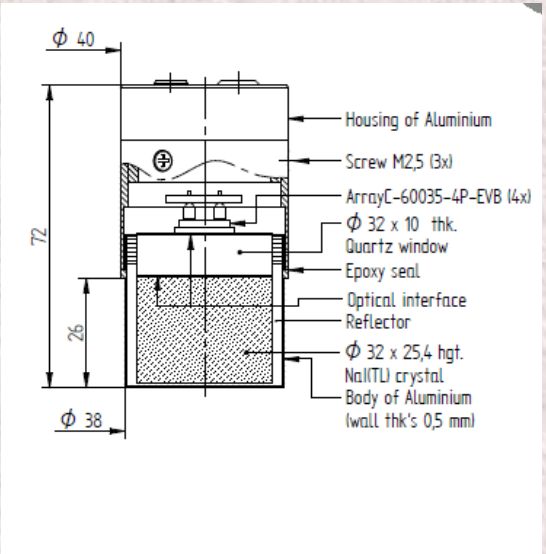
D. Cost Since SiPm price per cm^2 is much higher than that of PMTs (100 € / cm^2) compared to approx. 10 € / cm^2, 100 % scintillator coverage is not cost effective for larger crystals.

HOWEVER : p.e. statistics not always that important (e.g. with alkali halides)

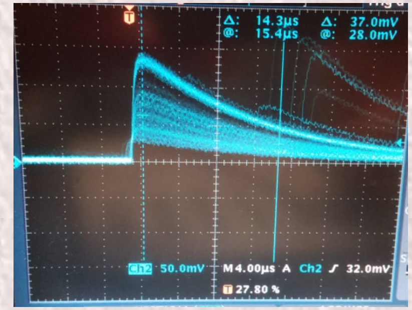
→ Counting applications are fine

All parameters are totally different then with classic PMT readout

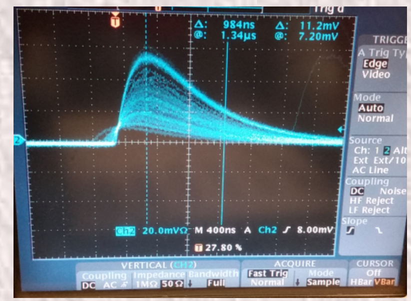
In many applications (especially with non proportional crystals), coverage of only a part of the scintillator with SiPm is sufficient for desired performance



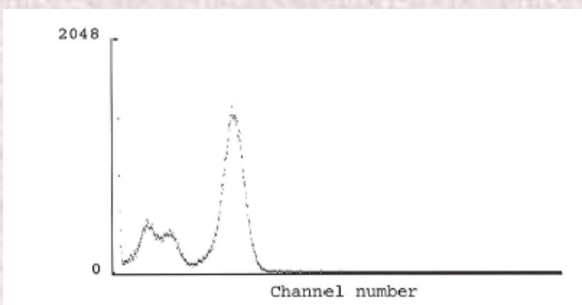
NaI(Tl)

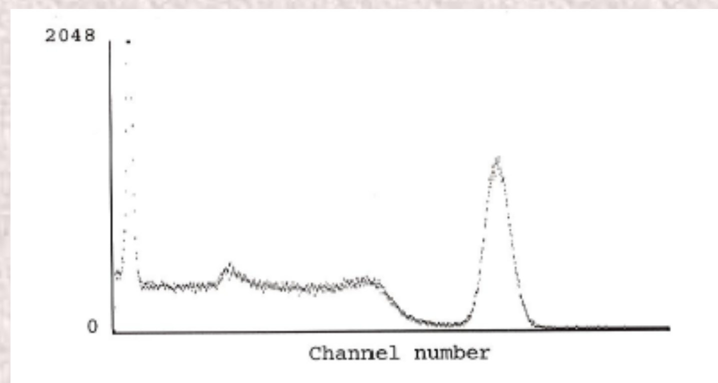


1 MΩ



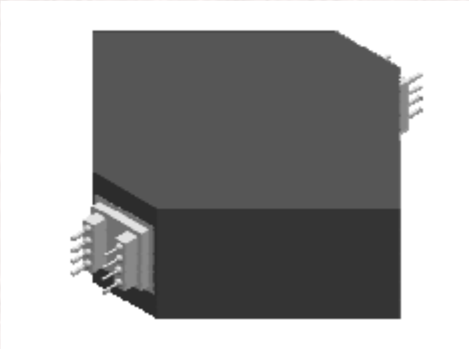
50 Ω



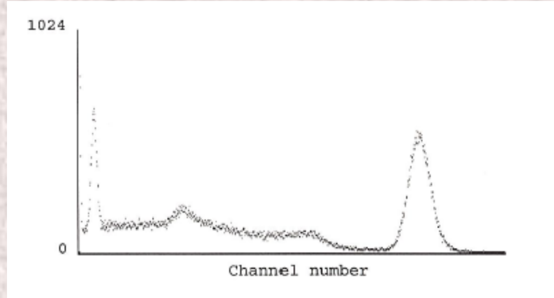


Am-241 20 % @ 59.5 keV

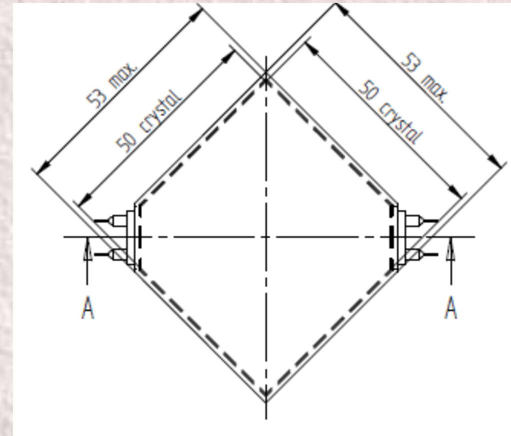
7.5 % resolution @ 662 keV

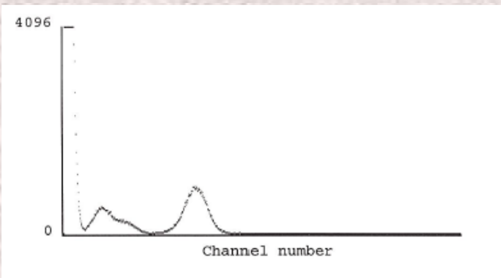


CsI(Tl)



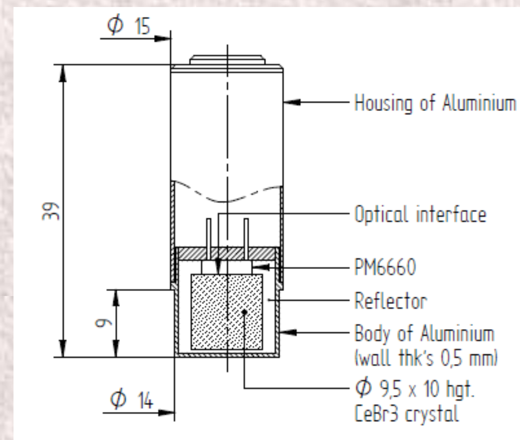
Cs-137 (7.4 %)

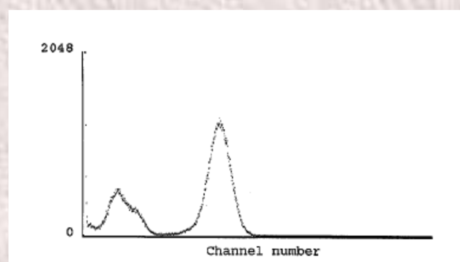




241-Am 20 % @ 59.5 keV

Miniature CeBr3

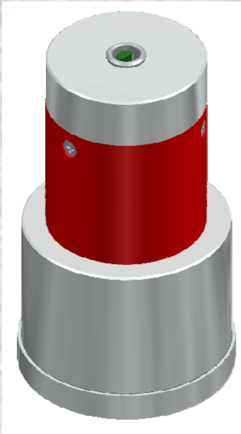


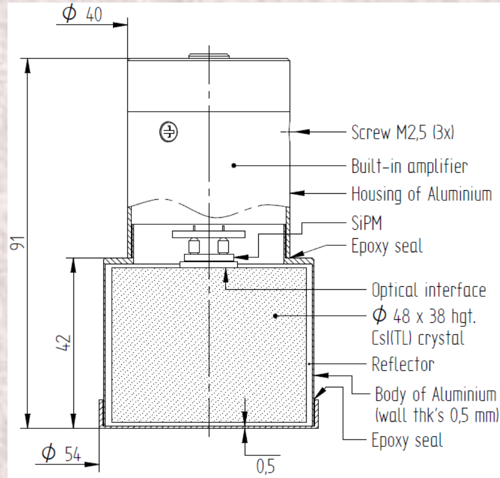


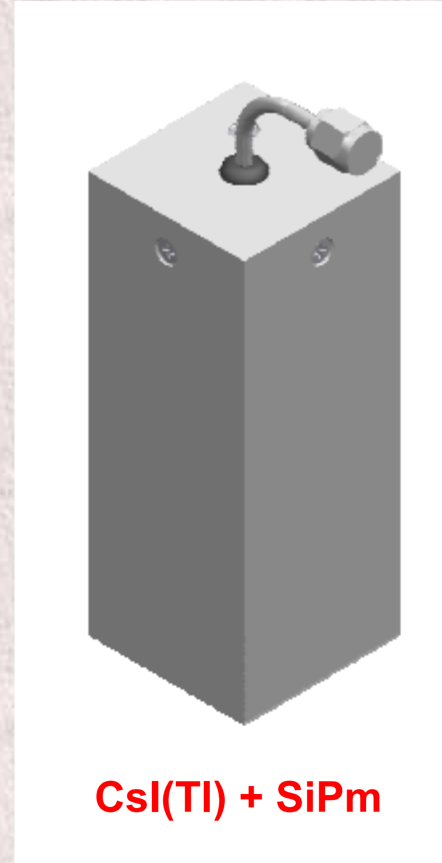
4.3 % @ 662 keV

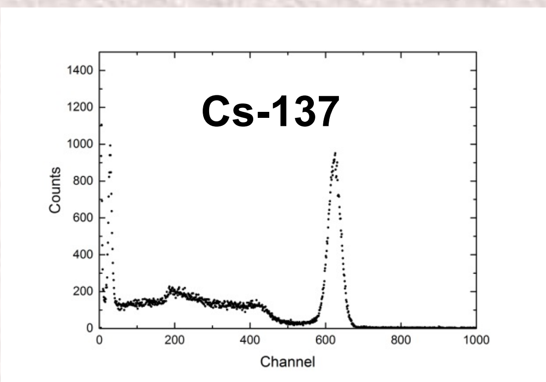
18.7 % @ 59.5 keV

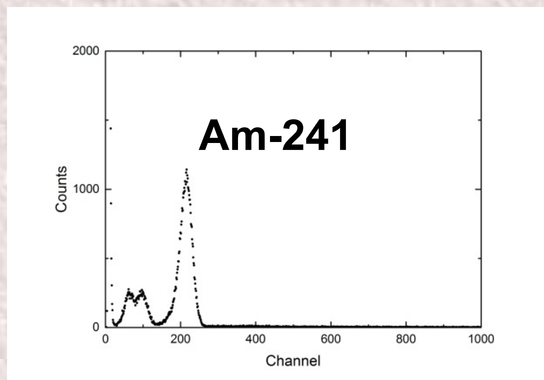
48x38 mm CsI(Tl) **7.4 % FWHM @ 662 keV**









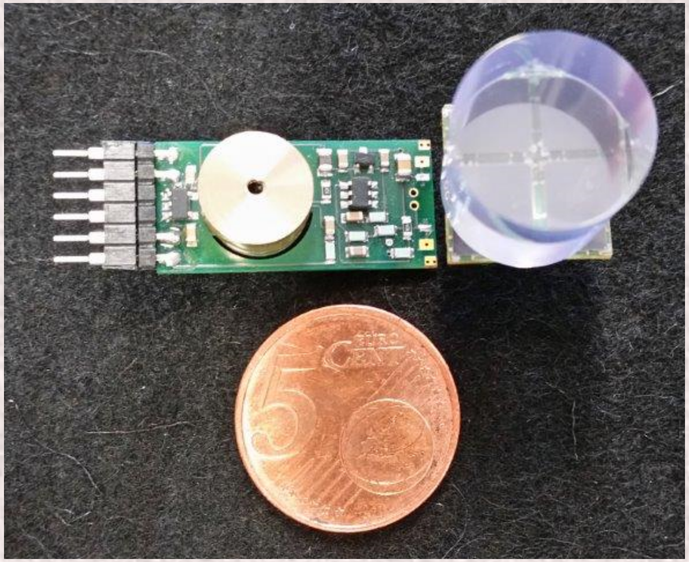


28x28x52 mm CsI(Tl)
< 7.0 % FWHM @ 662 keV

When problems of saturation and temperature drift are overcome, current generation of Sipms are now usuable for numerous applications

Counting (e.g. densitometry) and limited spectroscopic applications wil be first

With little extra space, first order temperature compensated bias generator / preamplifier add a lot of functionality



Mechanical ruggedness of SiPms needs some attention

When using coincidence techniques also large volume plastic scintillators can be read out with arrays of SiPms (work in progress)

Detection of Neutrons :

- Physics (e.g. particle Physics, HEP)
- Security (SNM e.g. Pu, U)
- Health Physics (dosimetry, often non spectrometric)

Neutron energy : Thermalised 0.025 eV – MeVs

(fast neutrons > 50 keV)

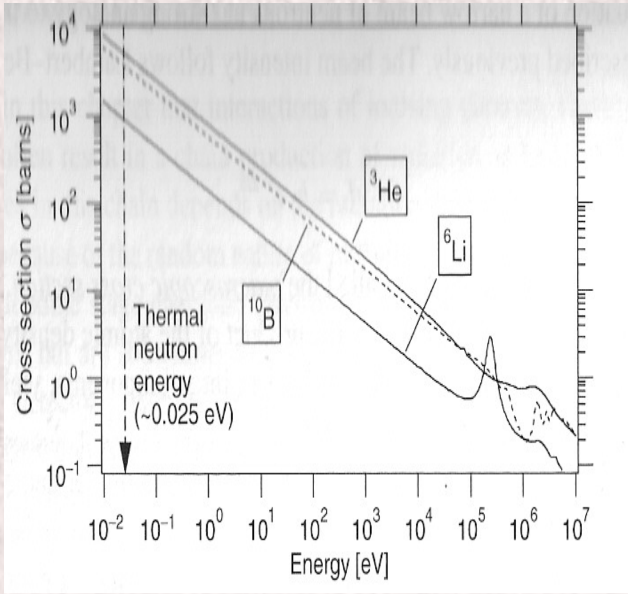
Interaction with Nucleus of absorber : A. Scattering or

B. Nuclear reactions

- **Elastic scattering (protons)**
- **Inelastic scattering + prompt gammas**

Nuclear Reactions e.g. : $^{10}B(n\ \alpha)\ ^{7}Li$, $^{3}He(n\ p)^{3}H$, $^{6}Li(n\ \gamma)\ ^{3}H$,

$^{157}Gd(n\ \gamma)\ ^{158}Gd$



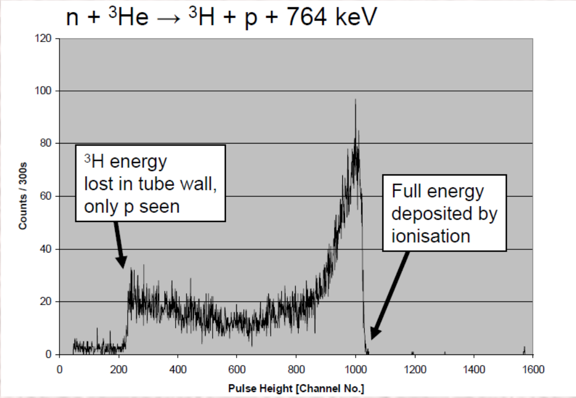
Most common detection method for neutrons

1. ^{3}He- tubes (pressurised)

   very unproblematic detector :

Easy to operate (no special electronics needed)

- gamma / neutron rejection > 10^6
- No serious safety issues
- Large sizes possible (meters long)



World wide structural He-3 shortage → availability / cost problems

possible alternative : Detection of neutrons with scintillators :

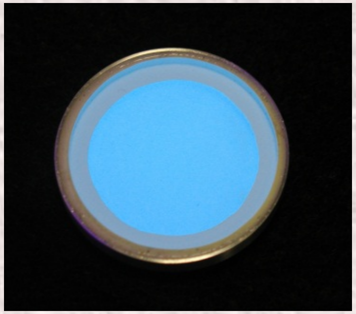
A. Thermal neutrons via nuclear reactions on Li, B or Gd in the material.

B. Fast neutrons via elastic (recoil) scattering in proton containing materials (organic scintillators)

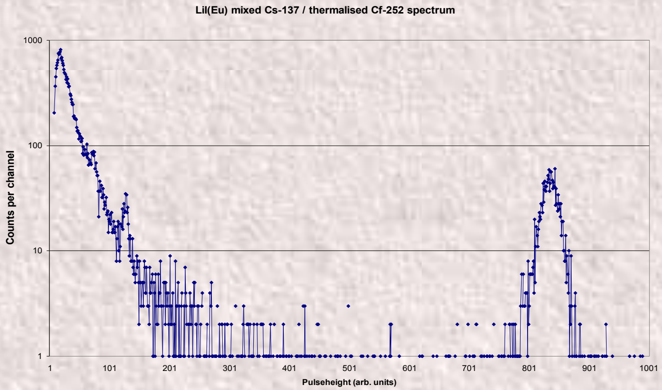
Usually , neutrons associated with gammas, both will interact with most scintillators but :

Neutron + ^{6}Li → alpha + Triton (4.78 MeV total)

(particles !) → Peak at e.g. > 4 MeV (In LiI(Eu))



LiI(Eu) scintillator



Neutron / gamma separation possible via Pulse height.

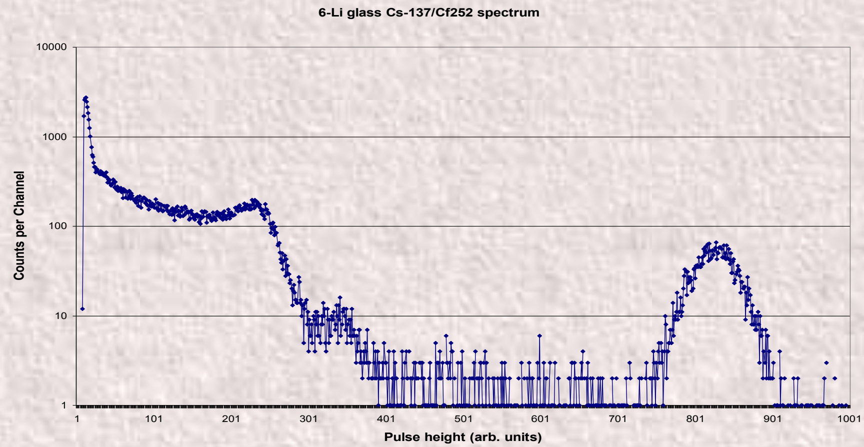
3 mm LiI(Eu) absorbs 95 % of thermal neutrons

However LiI(Eu) 96 % enriched is a relative expensive material that cannot be made in large sizes.

The ^{6}LiI(Eu) alternative is an excellent solution for hand held instruments and dosimeters but is not an option for e.g. radiation portals

Alternative ^{6}Li containing scintillators

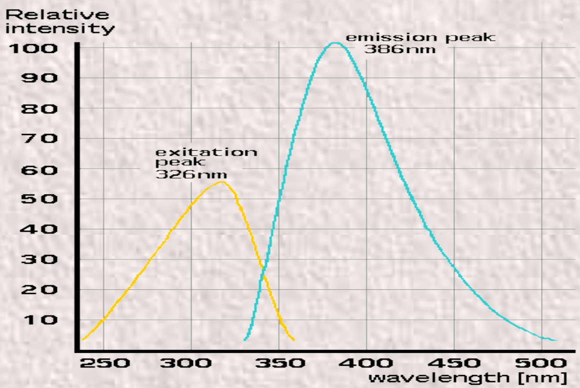
- ^{6}Li Loaded glass scintillator (Ce doped)
- Low neutron peak location (approx. 1.8 MeV) implying more problem with gamma rejection
- no large lengths possible (self absorption)



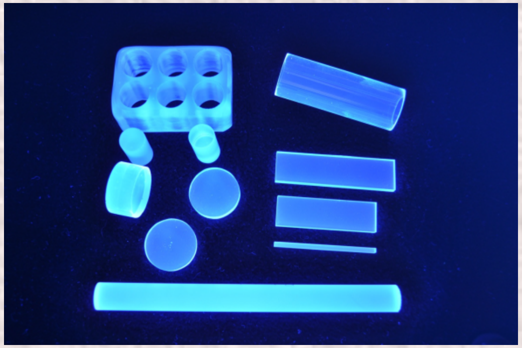
Neutron / gamma spectrum 6-Li glass

An alternative if gamma flux is low and of low energy and if time resolution is an issue

(scintillation is fast, 60 ns decay time)



90 % thermal neutron abs. in 1.5 mm



6-Li glass can be made in large sizes but cost is an issue

Cs_2LiYCl_6:Ce (CLYC)

(density 3.3 g / cc)

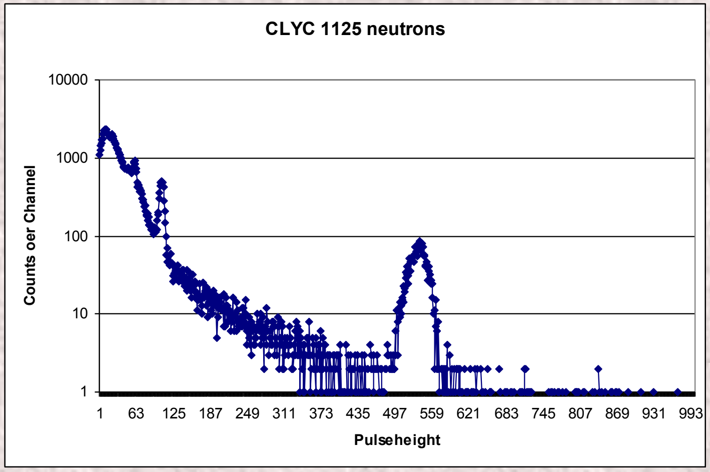
Proportional crystal :

Energy resolution approx. < 4-5 % (662 keV)

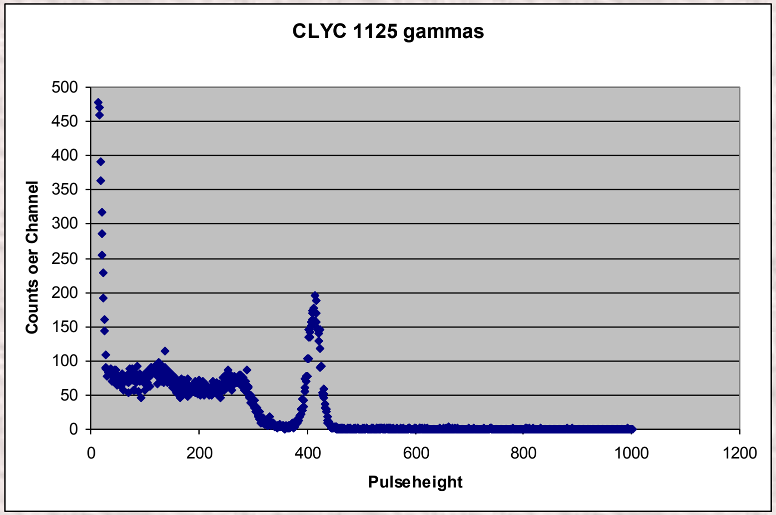
Neutron peak at 3.3 MeV

Fast neutron spectr. possible

12.7 mm needed for 90 % thermal neutron abs.



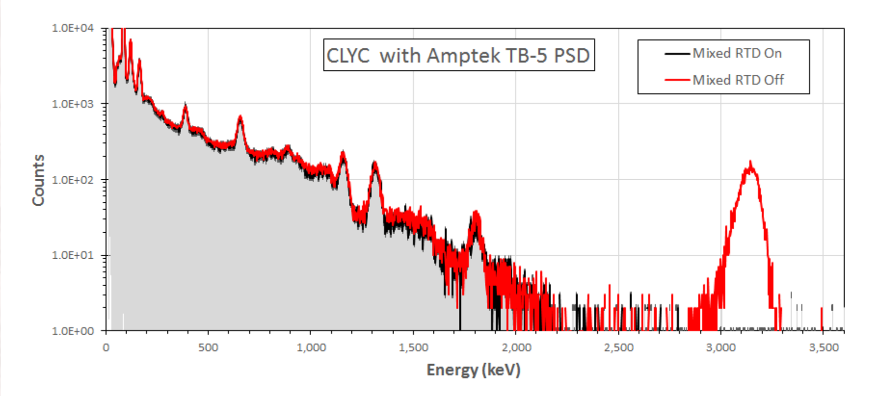
Cf-252 + Cs-137 spectrum in 1”x1”CLYC



Resolution approx. 4.5 % @ 662 keV

Problems :

- Cost (still) high
- Light output low
- Slow components



Gamma rejection with e.g. AMPTEK TB-5

Neutrons no fast (CVL) component : Neutron / gamma discrimination possible using PHA and PSD

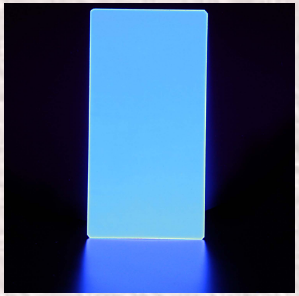
Digital electronics allows neutron gamma disc. based on PSD

CLYC used in identifiers more frequently. Cost prevent a wide scale use and replacement of LiI(Eu).

To achieve best energy resolution large (digital) shaping times are needed (? 4 µs)

CLYC ideal for small identifiers and PRDs

Large area neutron detection

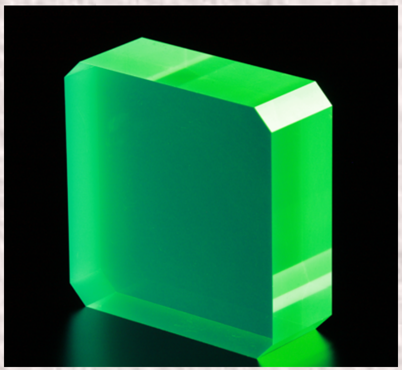


Screens of pressed powders 6-LiF and ZnS(Ag) : EJ 426
(cross section of 941 barns for 0.025 eV neutrons**)**

- 0.3 or 0.5 mm thick possible

Detection Properties of Some EJ-426 Screens

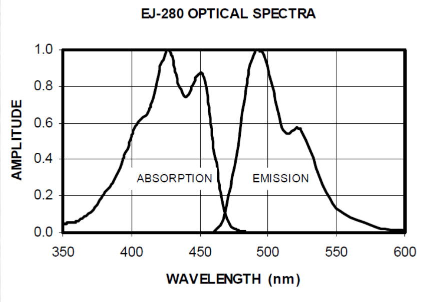
Screen Type	^{6}LiF:ZnS Mass Ratio	^{6}Li Density atoms/cc	Theoretical N_{TH} Efficiency 0.32mm Thick	0.5mm Thick
EJ-426-0	1:3	1.14×10^{22}	0.29	0.41
EJ-426HD2	1:2	1.63×10^{22}	0.39	0.53



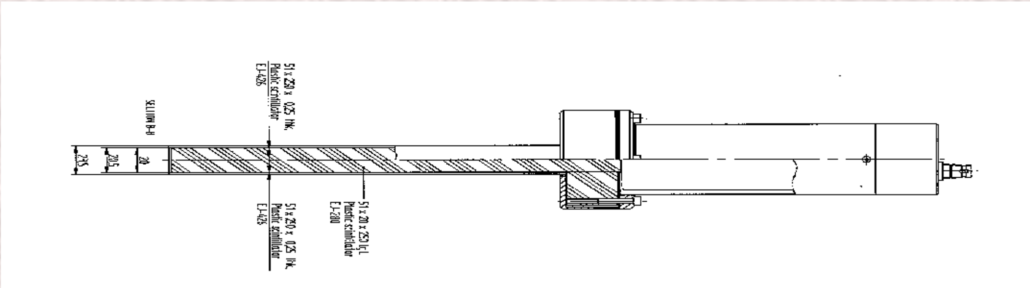
Problem is to get the light out (due to self absorption in powders)

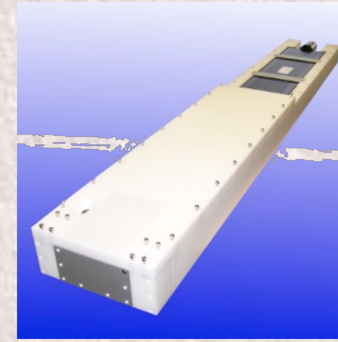
Wavelength shifting (fibers) e.g. **EJ 260** for large areas needed

- Due to non neglible gamma interaction in ZnS(Ag), PSD needed to obtain He-3 comparable neutron / Gamma discrimination

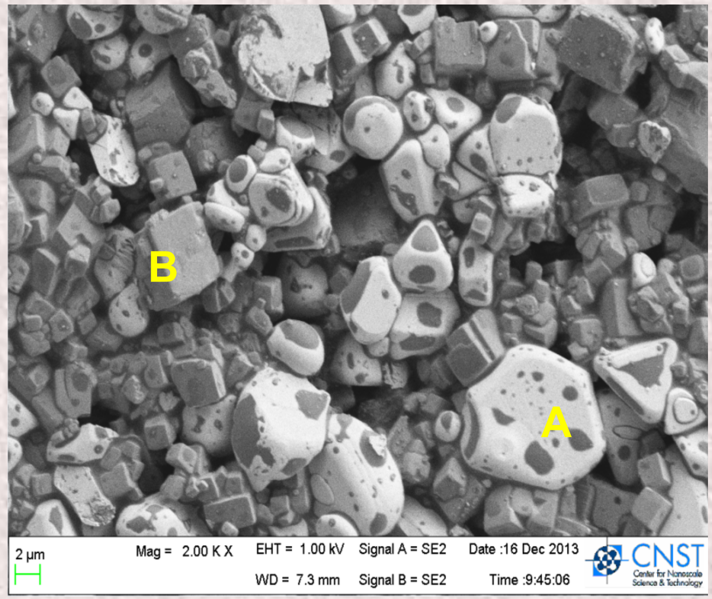


Commerical products available to replace He-3 in panels





System may be furher optimized via grain size, binder etc. (ongoing R+D)

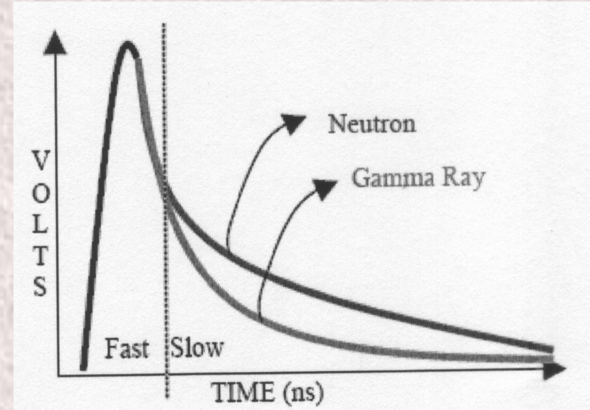


A- ZnS(Ag) grain B- LiF grain

D. Boron Loaded scintillators : No inorganics known except for Li Borate glasses with low light output

The other alternative :

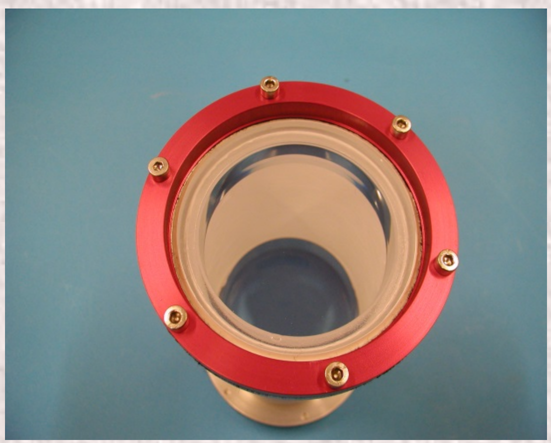
ORGANIC / Liquid scintillators

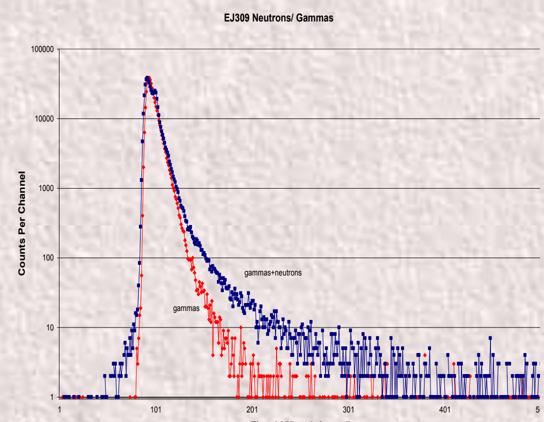


Some organic materials show <u>different pulse shape</u> for neutrons and gammas.

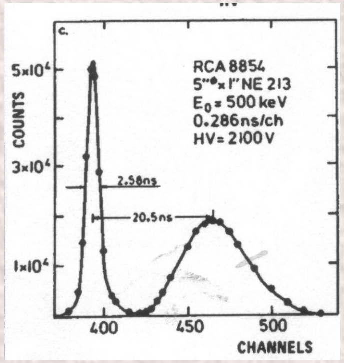
Liquid scintillators known since 1960's, most well known NE213(= EJ301 = BC501A), Xylene based.

Also organic crystals like **Stilbene**, **Anthracene** and **Para-terphenyl** are around for over 50 years. : "forgotten materials" untill recent !





Different ways to do neutron/gamma separation with PSD



1. QDC with 20 ns and 1 microseconds gate (or different)
2. Converts signals to time spectrum using a double delay line amplifier and CFDs (time spectrum shows two peaks)
3. Digitize the signal using wave form analyzer (500 Mhz to 1 GHz flash ADC)

Traditionally NIM electronics were used.

For many real field applications outside Physics this is very unpractical

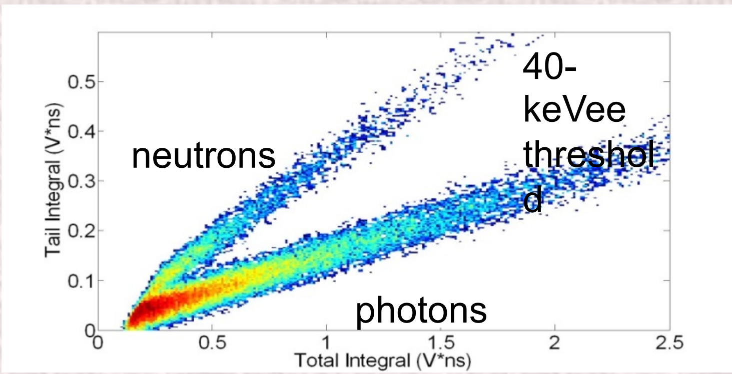
Other **disadvantages** of liquid scintillators :

- Expand with increasing temperature (expansion volume is needed)
- Many types EJ301, EJ315 are low flash point (flammable) and toxic materials (transport / safety / handling issues)

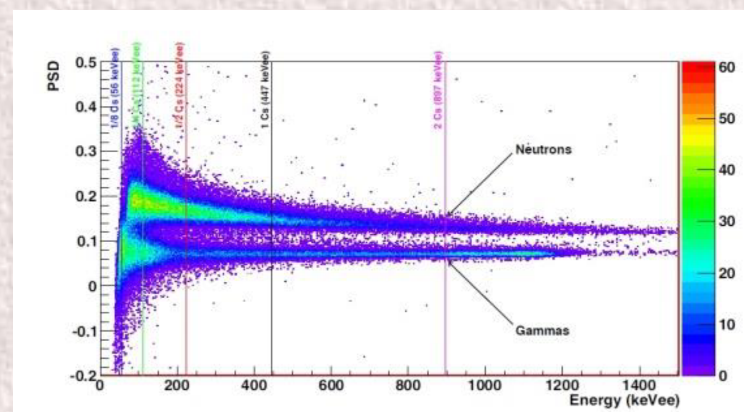
New developments :

- High flash point non toxic liquids
- New plastics with n-ɣ PSD
- FPGA based pulse digitizing techniques

open up applications



Advanced pulse sampling techniques using FPGAs allow on line 250 kHz throughput neutron / Gamma separation



For Physics appications multi-channel VMAE based fast digitizers are more frequently used

EJ301

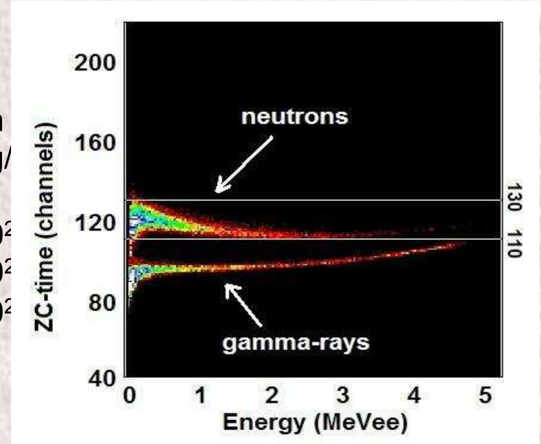
EJ301 is a scintillating liquid **equivalent to NE213 BC501A** specially designed for neutron / gamma discrimination.

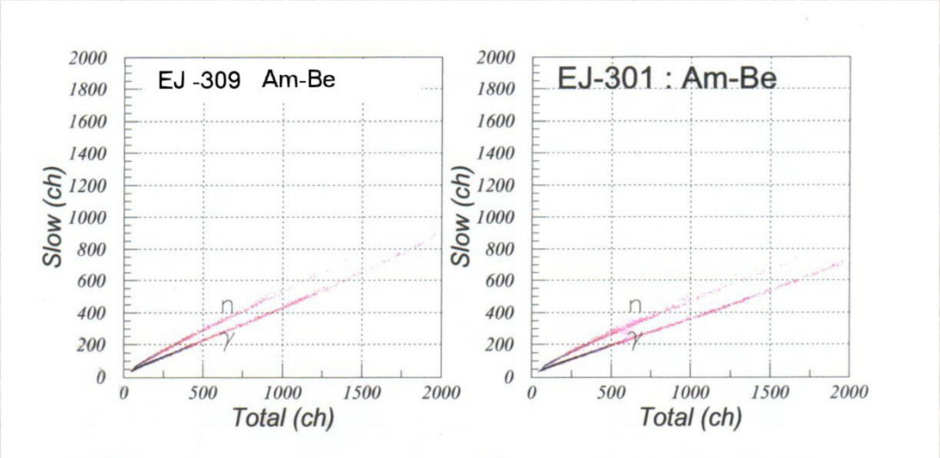
EJ309

EJ309 is a scintillating liquid especially designed for neutron discrimination It has a high flash point, low vapour pressure and no toxidity (biodegradable).

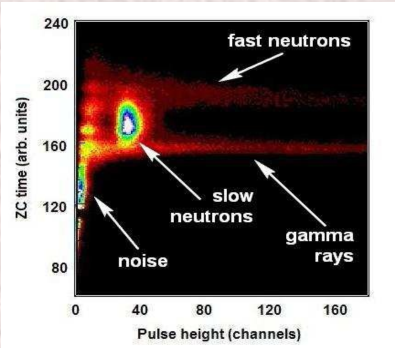
Properties :

Light output (rel. to antracene) :	78 %	75 %
Photon yield / MeV electrons :	12.000	11.500
Maximum of emission wavelength :	425 nm	424 nm
Density:	0.874 g/ cc	0.964 g/
H:C ratio:	1.21	1.25
No. C atoms per cc :	$4.0\ 10^{22}$	$5.46\ 10^{2}$
No. H atoms per cc :	$4.8 10^{22}$	$4.37\ 10^{2}$
No. electrons per cc :	$2.3\ 10^{23}$	$3.17\ 10^{2}$
Flash point :	26 ^{o}C	144 ^{o}C
Refractive index :	1.50	1.57
Decay time short component	3.2 ns	3.5 ns
Decay time long components	32.3, 270 ns ……	





When Liquid scintillators are Boron doped, the neutron sensitivity is increased

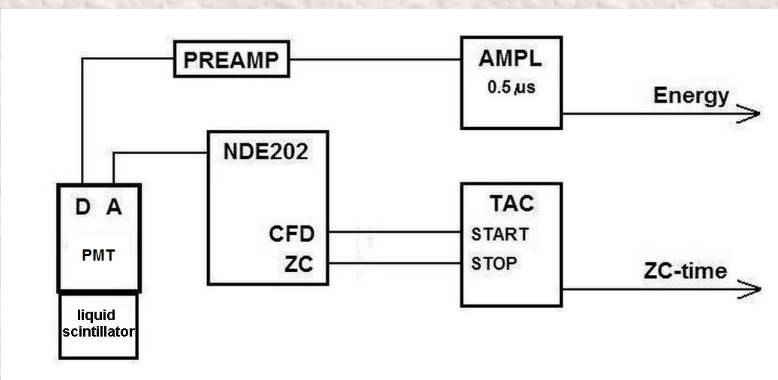


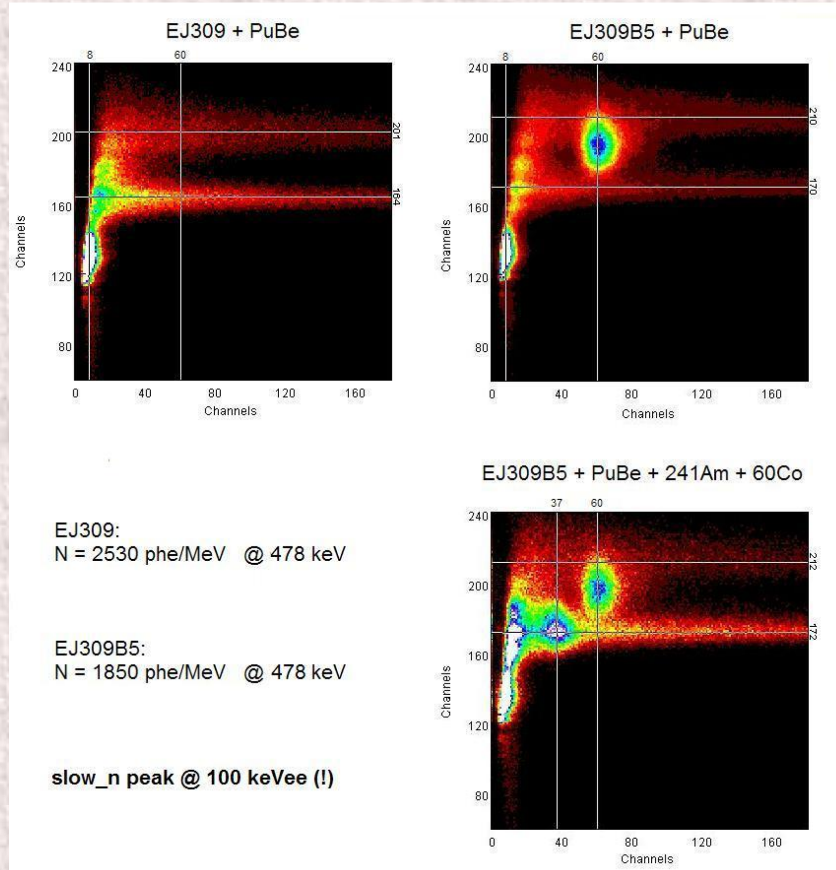
Boron peak at higher energies than with EJ301

(100 keV versus 60 keV)

Gammas, fast neutrons and slow neutrons can be separated by PSD

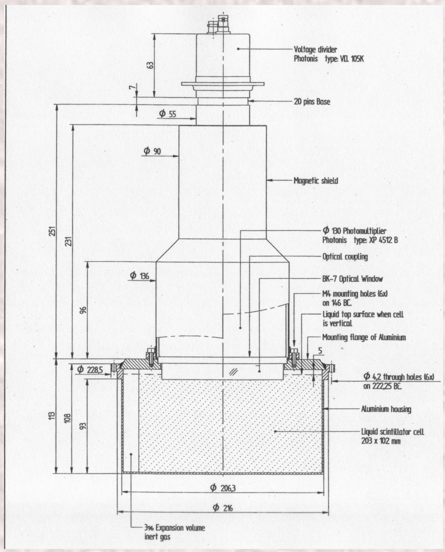
Courtesy Swiderski et al.

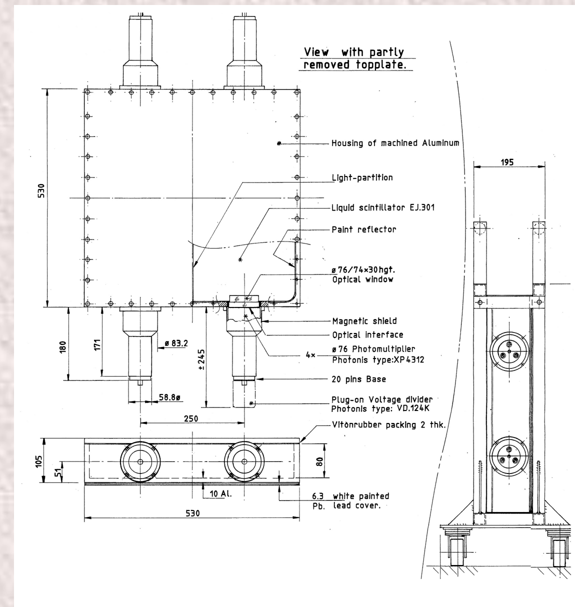




Design of Liquid cells for timing and PSD

General : Liquids expand (T) and expansion space has to be available (3-5 % for temp. range –20 – +50 ^{o}C) With properly designed so called dip-in windows optical interface between liquid and readout window can be guaranteed in all orentations





Larger sizes cells of different geometries also provide a good neutron / gamma PSD

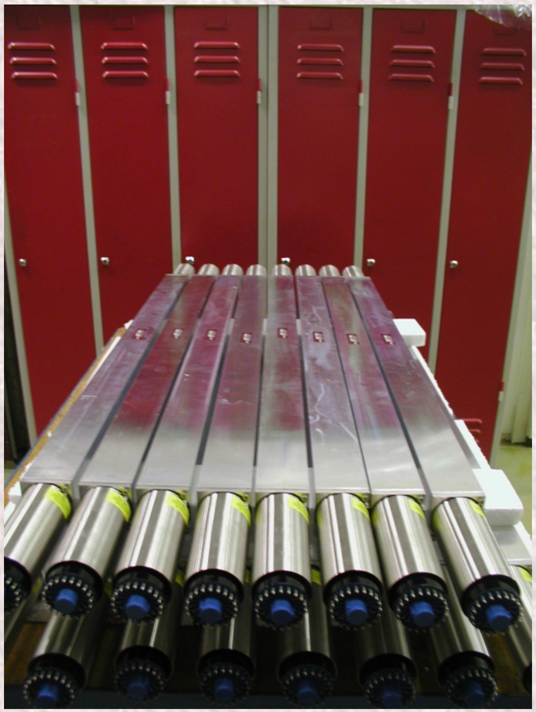
SOLUTIONS THAT WORK

HOWEVER :

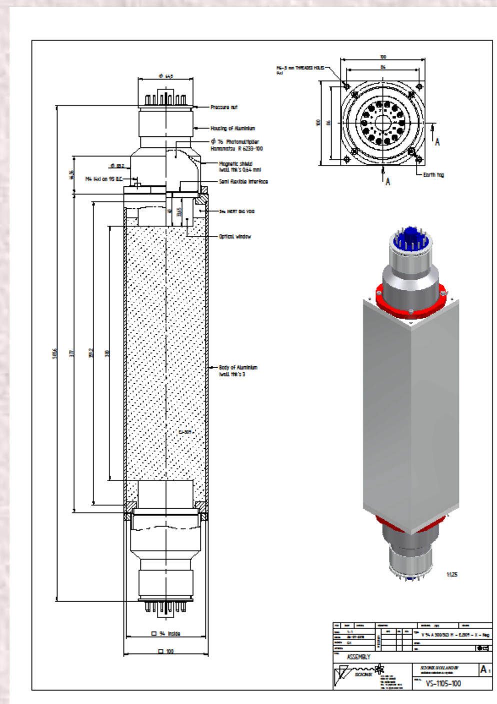
Neutron / Gamma PSD can be spoilt by a geometry where the light paths to the PMT are much different !

127 dia x 1000 mm X

a 1:1 plug-in replacement of He-3 tubes by long liquid cells is not possible !



54x54x1000 mm X



100x100x300 (2 PMTs)

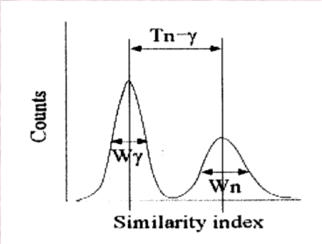
O.K.

Some recent tests on several liquid scintilallator assemblies :

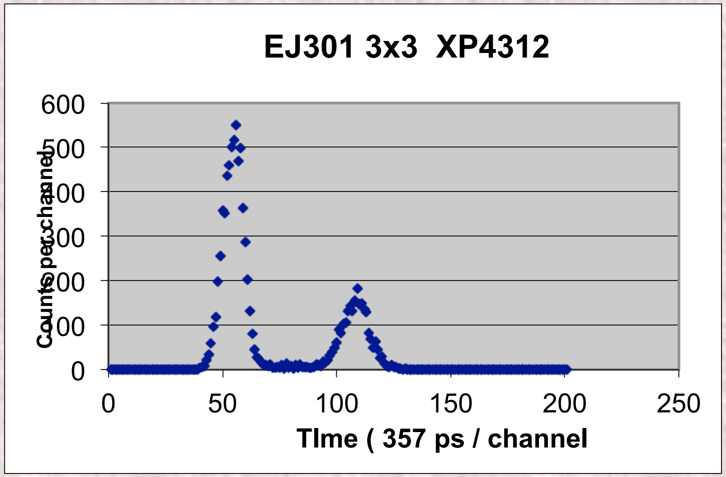
- **What is influence of PMT on PSD ?**
- **What is influence of shape / PMT size**

All tests with analog NDE 202, theshold 100 keV (el),
10 mm Pb shielded weak Cf-252 source

"3"x3" EJ301 2.1 ns rise time XP4312



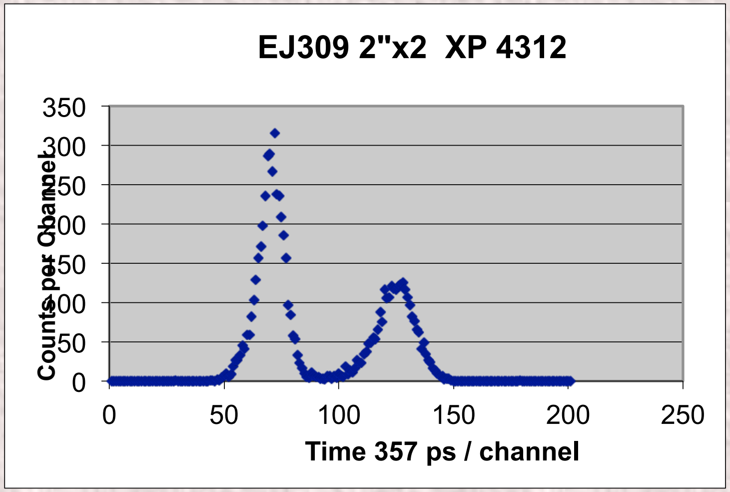
FOM = 2.2



2"x2"EJ309 2.1 ns rise time XP4312

$$FOM = \frac{T_{n-\gamma}}{W_n + W_\gamma}$$

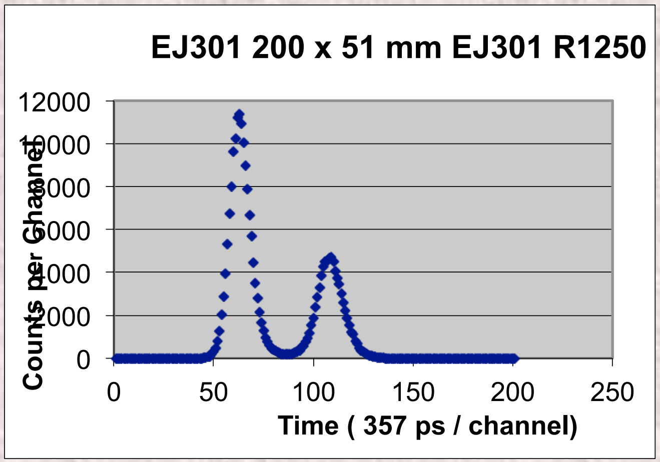
FOM = 1.9



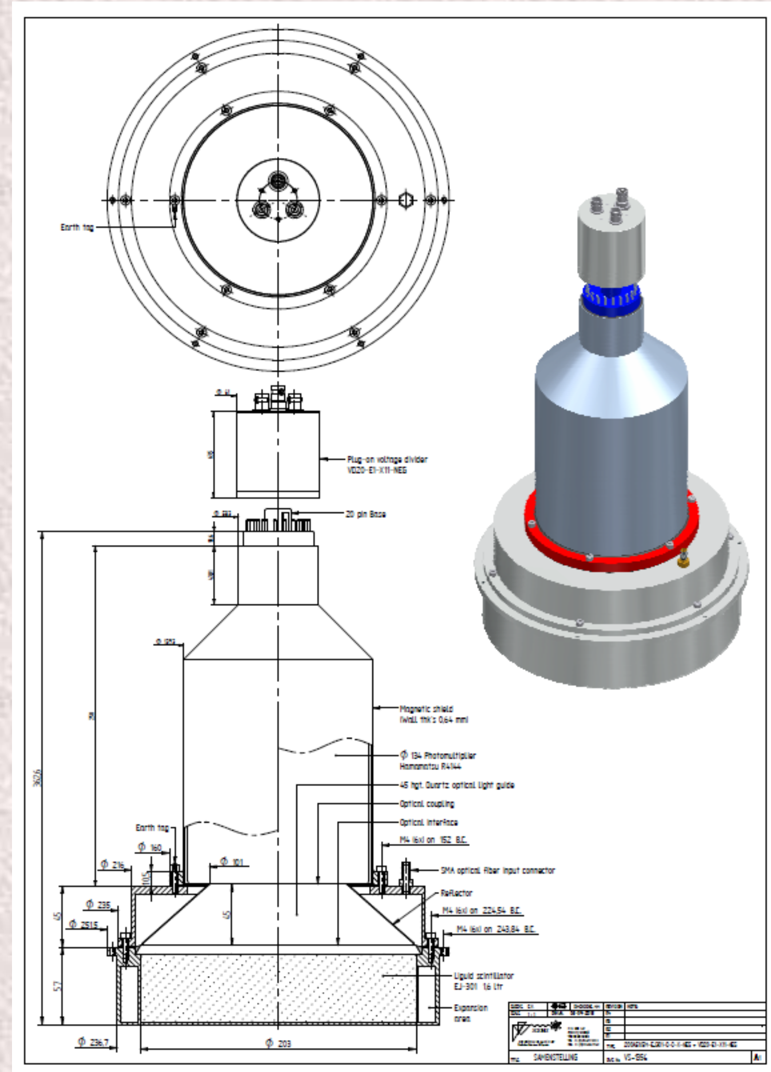
N-g PSD EJ301 better

Larger cells, smaller PMTs

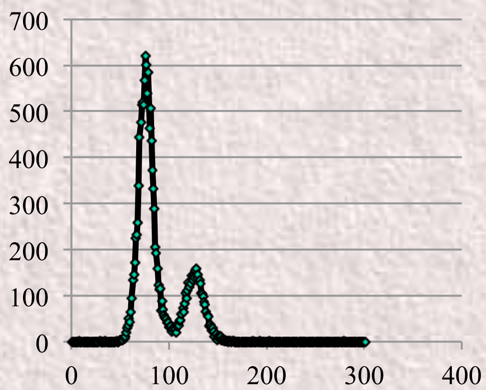
200x51 PMMA light guide R1250 PMT

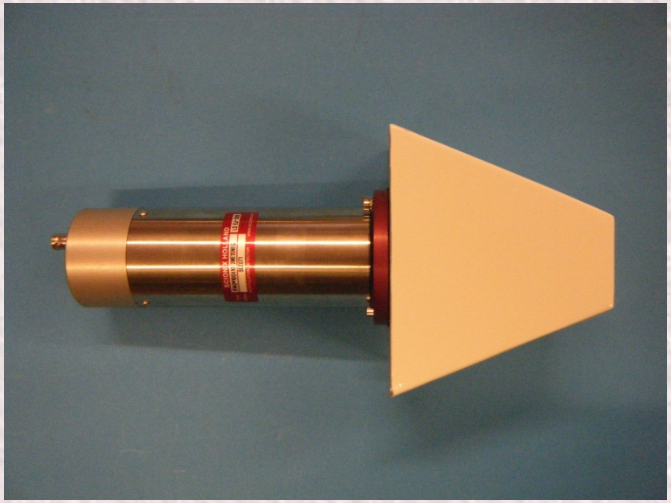


FOM = 1.88



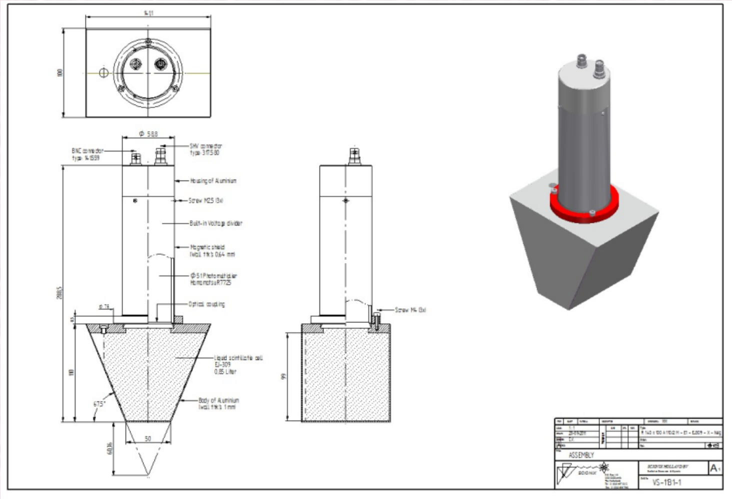
Pie shaped EJ309 cells 2 ns ET9214

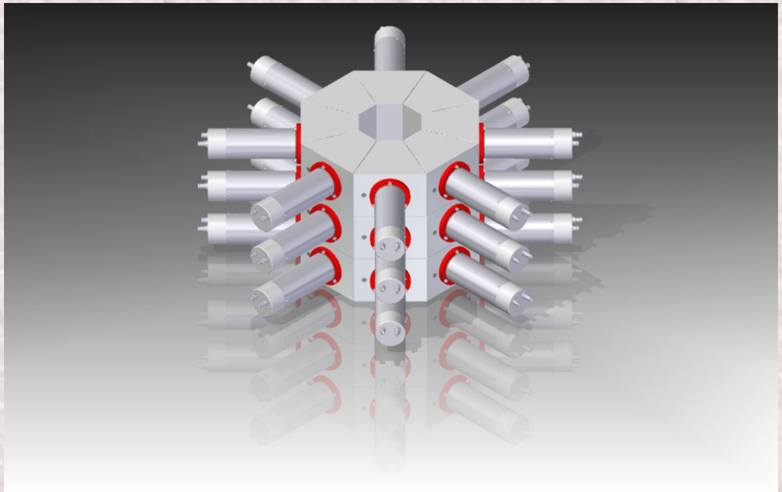




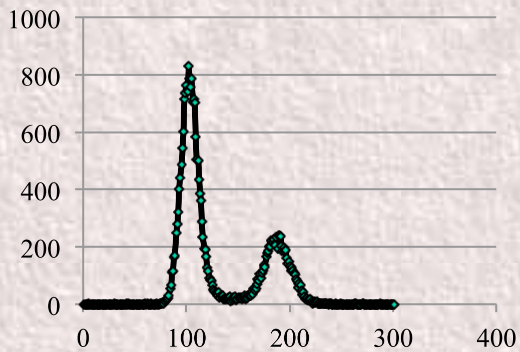
FOM = 1.22

Plutonium multiplicity counter (safeguards)

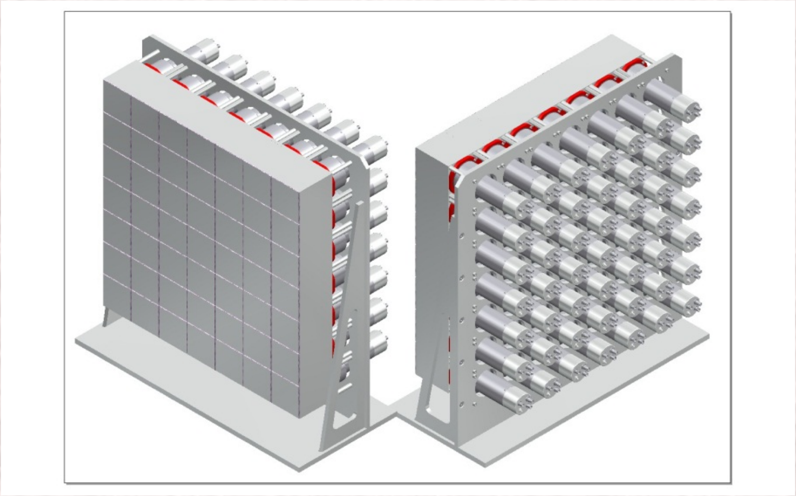


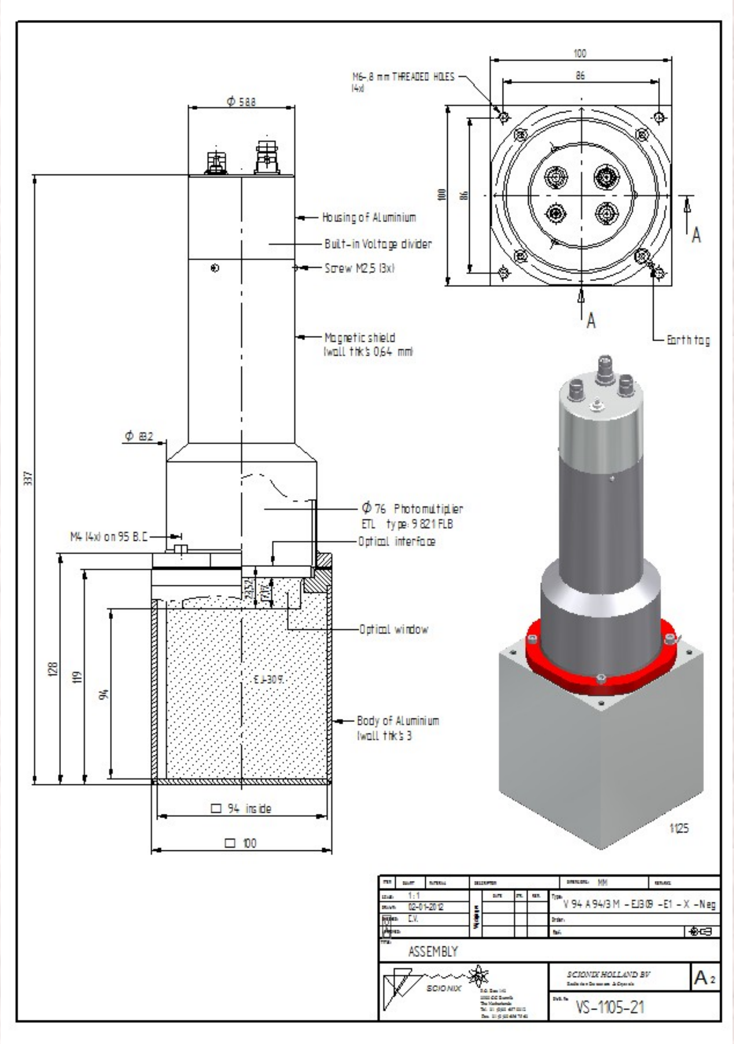


EJ309 94x94x94 mm
2.1 ns rise time ET 9821



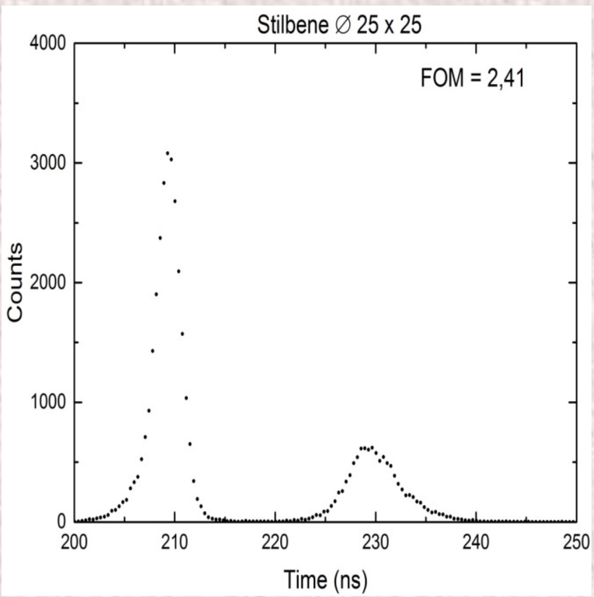
FOM = 1.75



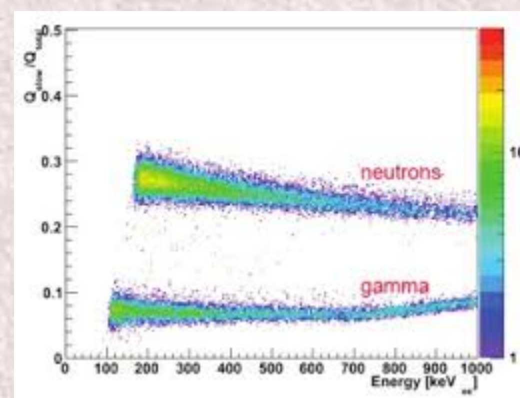


organic crystals like **Stilbene**, **Anthracene** and **Para-terphenyl** are around for over 50 years. : “forgotten materials” untill recent !

Recently renewed interest in organic crystals with PSD capability : Production on industrial scale (solution growth)



Solution grown Stilbene has almost 1.5 times more yield then bridgeman grown material (classic)

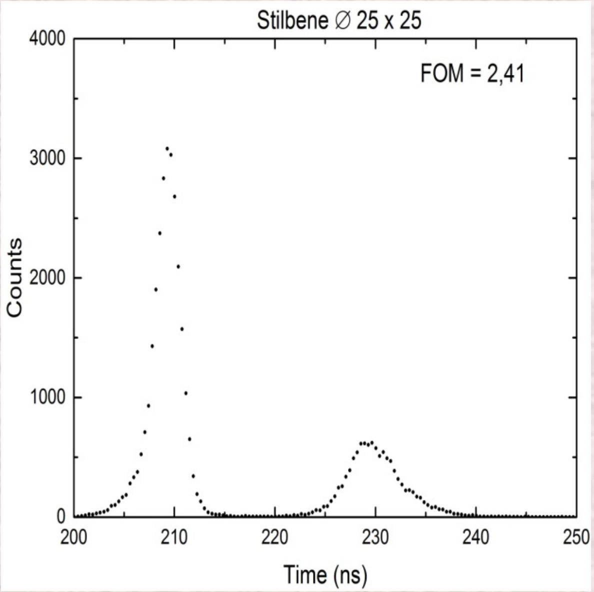


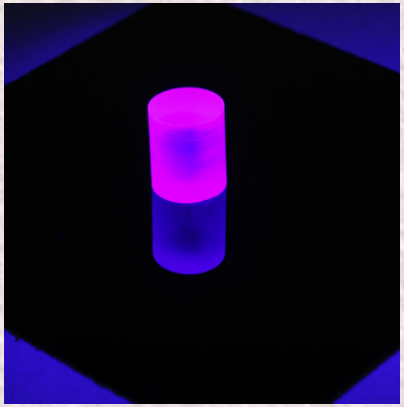
When price decreases promising material for neutron/gammma PSD with fast digitisers

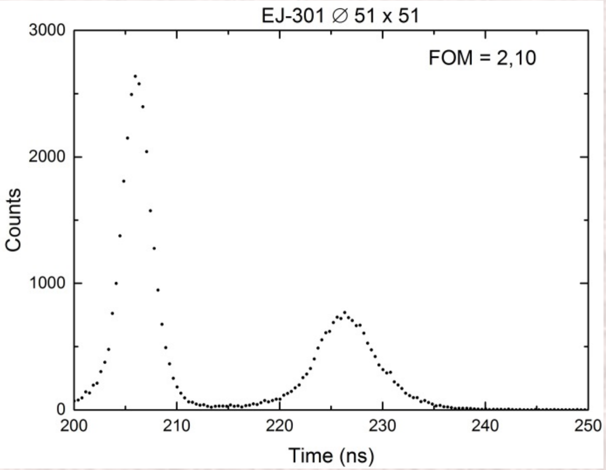
Some new data on Stilbene crystals

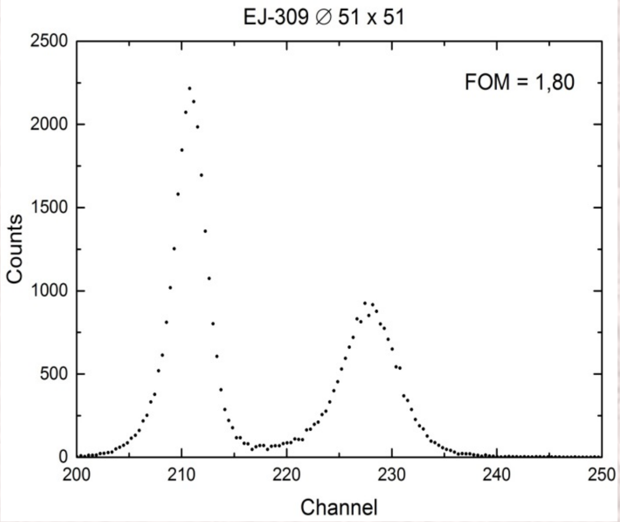
Recently renewed interest in organic crystals with PSD capability : Production on industrial scale (solution growth)

PSD superior to liquids





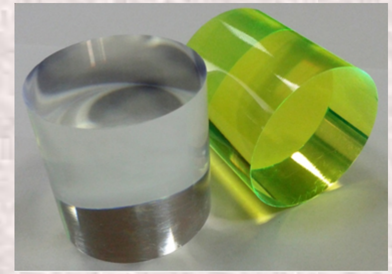




Stilbene remains rel. costly and toxic but other materials may follow….

Threshold in all cases 70 keV electron energy

EJ-299-33A PSD PLASTIC SCINTILLATOR

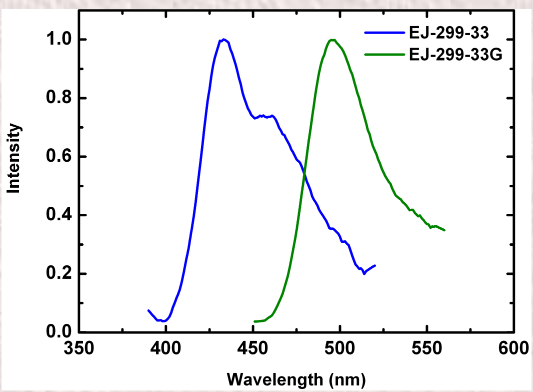


Physical and Scintillation Constants:

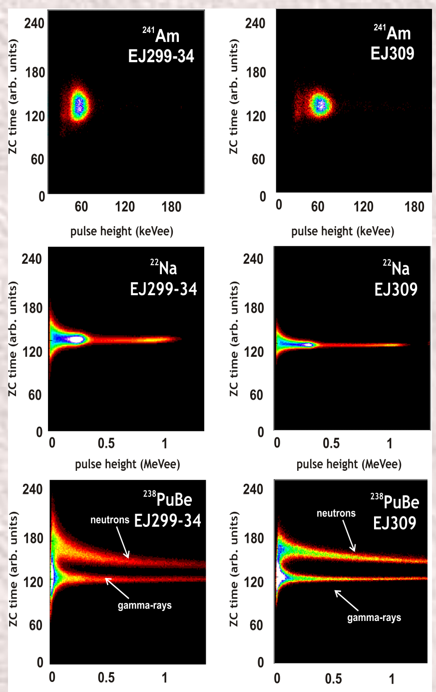
Light Output, % Anthracene 56
Scintillation Efficiency, photons/1 MeV e- 8,600
Wavelength of Max. Emission, nm 420
No. of H Atoms per cm^3, x 10^{22} 5.13
No. of C Atoms per cm^3, x 10^{22} 4.86
No. of Electrons per cm^3, x 10^{23} 3.55
Density, g/cc: 1.08

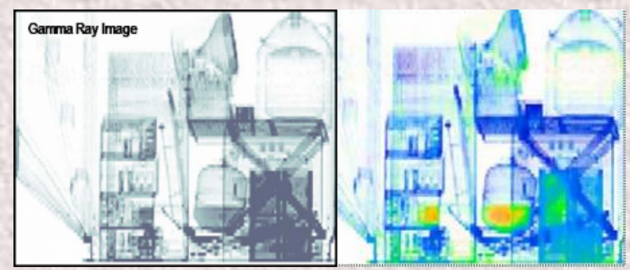
Decaytimes :

5 ns, 140 ns 150 ns (ratio diff. n-g)



Also green emitting version avaiable





Applied in neutron scanners

Very rapidly commercialised and widely used

Conclusions :

INORGANIC materials

1. Scintillator research flourishing ,many new materials developed, most of them not available commercially (yet). Cost remains issue
2. Li doped scintillators can replace He-3 tubes in some applications

ORGANIC materials

1. Since 50years organic scintillator research finally gets some interest !
   More new organic materials may follow coming years.
2. The current availability of high flash point non dangerous goods liquid scintillators opens up possibilities to use these detectors where was prohibitive in the past.
3. The current availability of digital techniques allows the construction of novel instruments for neutron / gamma discrimination in mixed neutron / gamma fields
4. Liquid scintillators can be a replacement for He-3 tubes in **some** applications
5. Novel plastic scintillators offer neutron gamma separation via PSD; neutron / gamma separation not as good as liquids for can be adequate.
6. Organic crystals like Stilbene are getting back in the picture