National Centre
for Nuclear Research
Świerk

# Organic and inorganic scintillators for Neutron Detection

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A He-3 world crisis triggered a development of new techniques of neutron detection to replace commonly used He-3 detectors, so important in homeland security applications.

The demand of He-3 in USA in 2010 was estimated to be about 65 $m^3$, whereas the supply was dramatically lower of about 20 $m^3$ per year.

It triggered, in the recent years, intensive studies to find alternative detectors, particularly new scintillators.

Below, I will review our activity addressed to the new organic scintillators, in fast neutron detection, and some inorganic scintillators for thermal neutrons detection.

**My talk is based mostly on the earlier studies adressed too:**

- NORDBALL neutron wall
- French-Belgian DEMON arrangement
- EUROBALL neutron wall
- NEDA arrangement

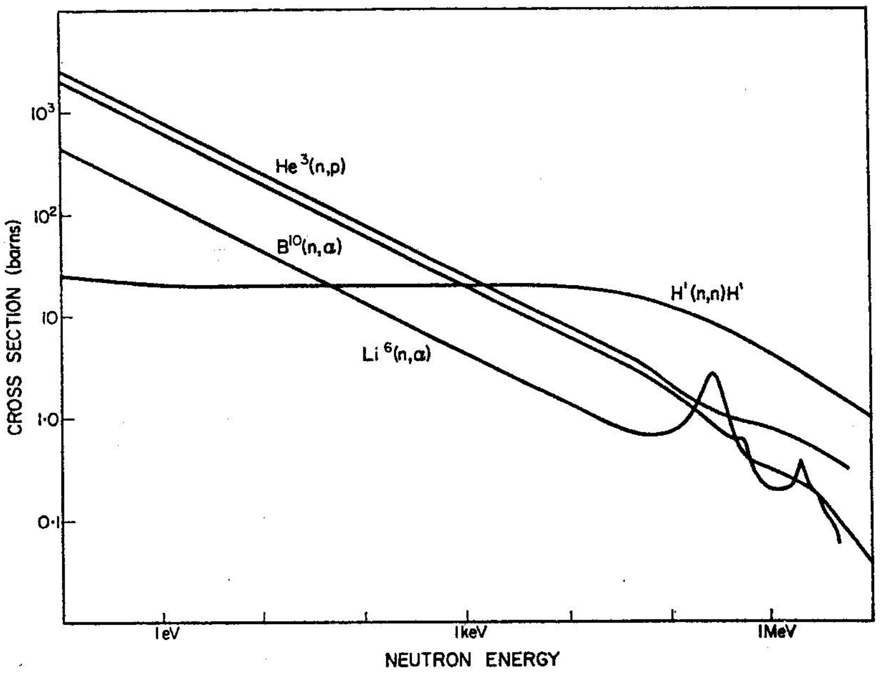
and the present studies, carried out by our group at Świerk in Poland, addressed mainly to the homeland security, see for example, J. Iwanowska's PhD thesis:

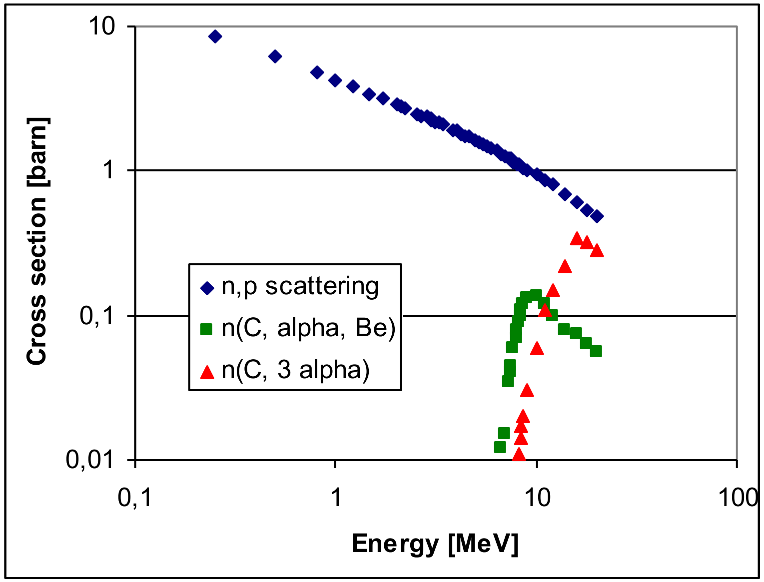
http://www.ncbj.gov.pl/en/dokument/comparative-studies-neutron-detectors-crisis-3he-supply

# Advantages of organic scintillators in neutron detection

- large cross-section for n,p elastic scattering
- possible large volume – high detection efficiency
- fast output pulse of detectors
- high time resolution in time-of-flight experiments
- good gamma ray discrimination by PSD methods
- high counting rate capability

# Detection efficiency



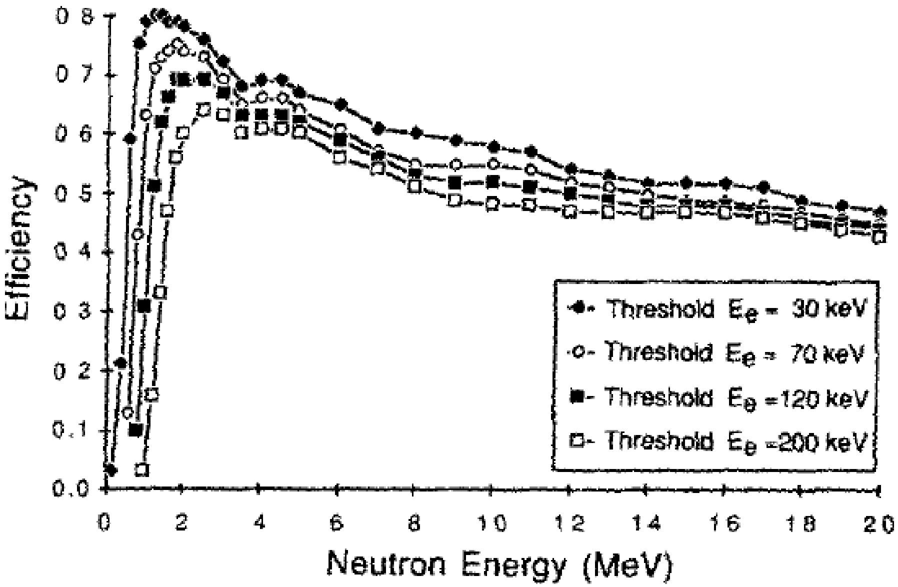




Cross section of n,p scattering in comparison to other reactions involved in the neutron detection

Different reaction channels responsible for neutron detection with energy up to 20 MeV

# Detection efficiency-BC501A liquid scintillator

- number of H atoms: $5x10^{22}$ atoms/$cm^3$
- number of C atoms : $4x10^{22}$ atoms/$cm^3$
- continuous spectrum of recoil protons
- detection efficiency controlled by a low energy threshold




BC501A detector of NORDBALL
Volume 3.3 l,
detection efficiency for Am-Be neutrons:
**about 60%.**



S.E. Arnell, et al., NIM A300(1991)303

# Liquid scintillators in neutron detection, B-10 loaded liquids

- Fast neutrons:

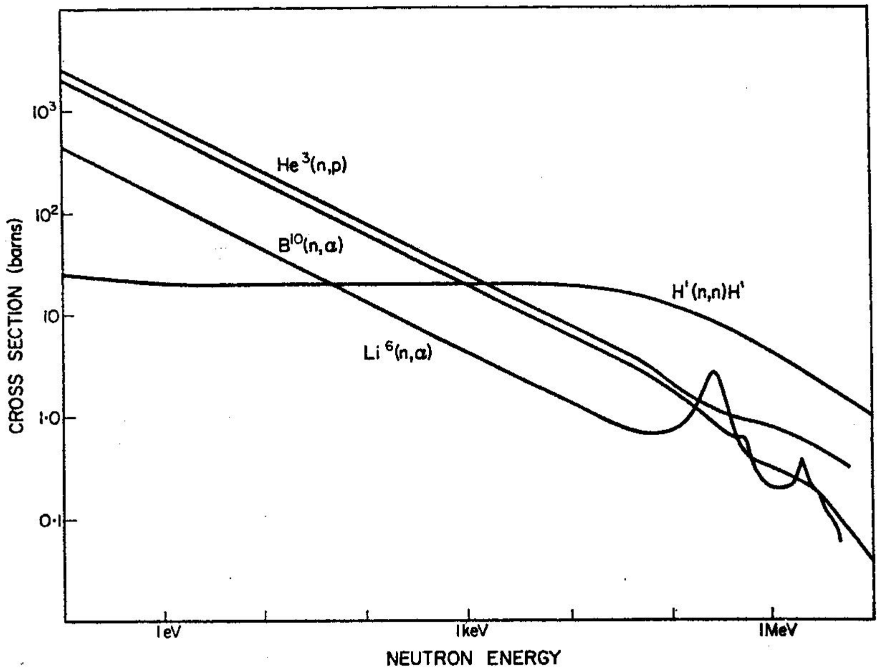
  n,p scattering

- Thermal neutrons:

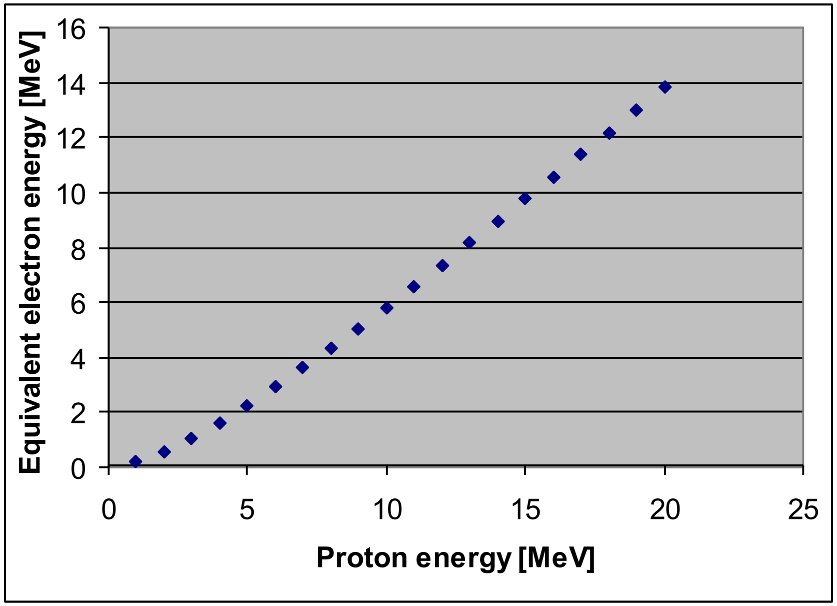
  $^{10}$B loaded – neutron detection via (n,$\alpha$) reaction

  Q = 2.3 MeV

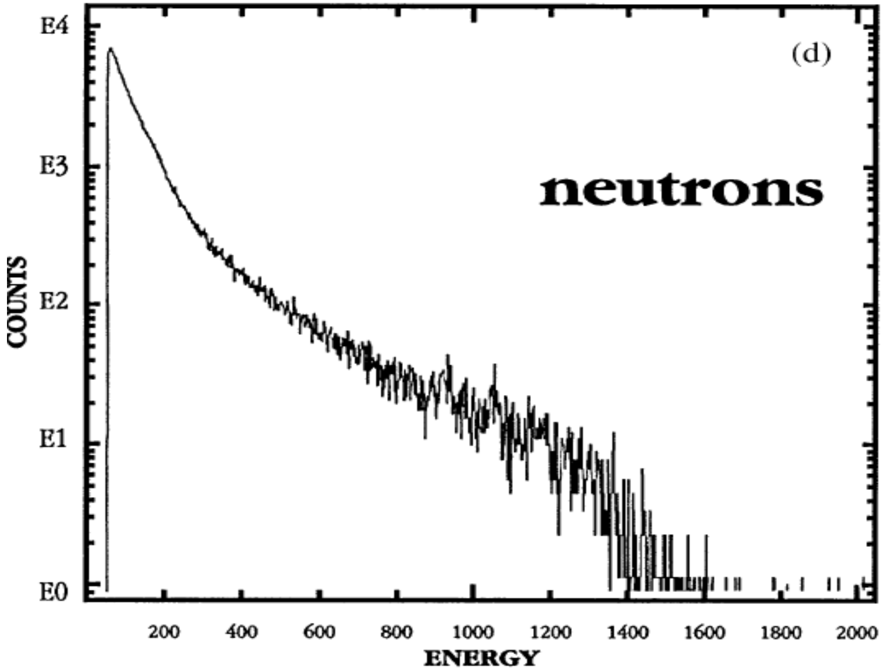
$$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{4}_{2}He + ^{7}_{3}Li + \gamma(480\,keV)$$



# Energy spectra of neutrons



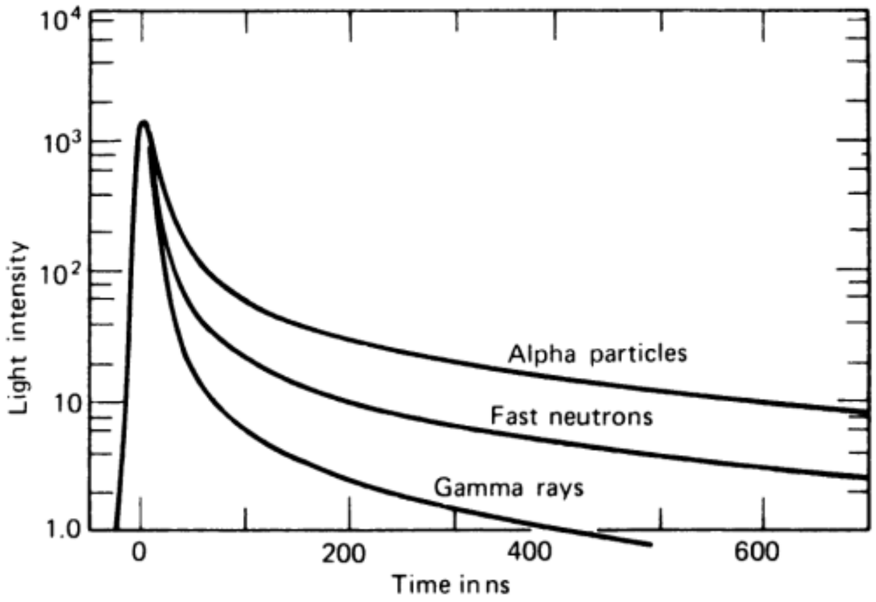

Equivalent electron energy corresponding to given energy of recoil protons (NE213/BC501A)




Spectrum of recoil protons from $^{246,248}$Cm, in BC501A scintillator of EUROBALL neutron wall

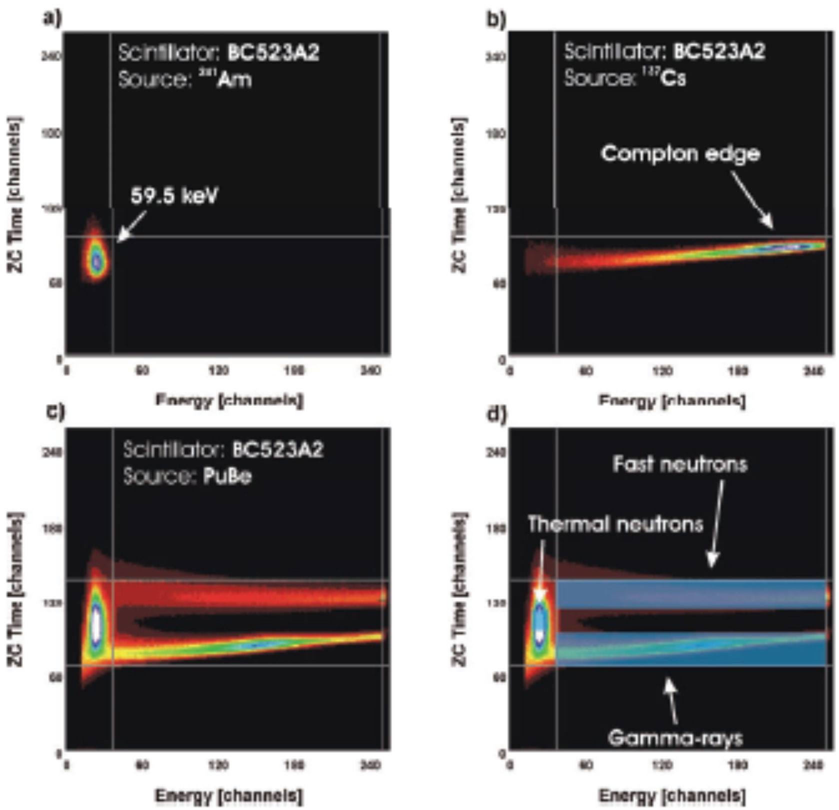
# Neutron and gamma ray detection

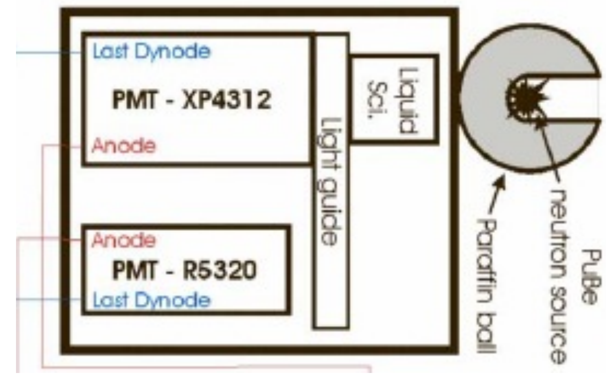
- large cross-section for Compton scattering in organic scintillators
  - 0.72 MeV – 20 barns
  - 2.2 MeV – 10 barns
- **n-gamma discrimination**

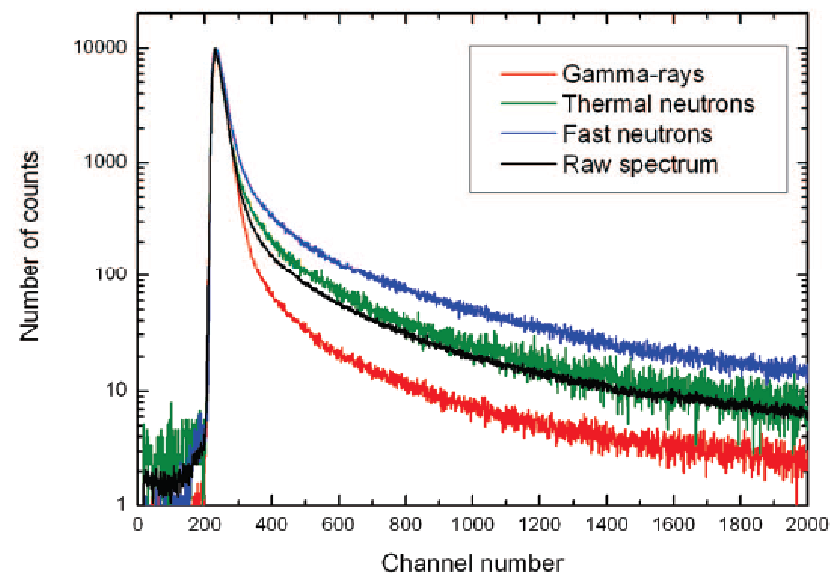



Schematical presentation of light pulses due to gamma rays, fast neutrons and alpha particles

# Light pulses due to gamma rays and neutrons in $^{10}B$ loaded BC523A liquid




T. Szczesniak, et al., TNS 57(2010)3846

# Decay components of light pulses due to gamma and neutrons

Fitting parameters of the three components calculated
for the tested classic liquid scintillators

| scintillator | particle | Fast component | | Medium component | | Long component | |
|---|---|---|---|---|---|---|---|
| | | decay constant (ns) | % | decay constant (ns) | % | decay constant (ns) | % |
| BC501A | gamma | 3.9 ± 0.4 | 85 | 27 ± 3 | 9 | 240 ± 20 | 6 |
| | fast n | 5.3 ± 0.5 | 43 | 40 ± 4 | 29 | 280 ± 30 | 28 |
| EJ301 | gamma | 4.1 ± 0.4 | 88 | 20 ± 2 | 7 | 110 ± 10 | 5 |
| | fast n | 5.4 ± 0.5 | 54 | 41 ± 4 | 28 | 250 ± 30 | 19 |
| EJ309 | gamma | 3.8 ± 0.4 | 81 | 30 ± 3 | 11 | 170 ± 20 | 8 |
| | fast n | 4.8 ± 0.5 | 46 | 38 ± 4 | 32 | 240 ± 20 | 22 |

T. Szczesniak, et al., TNS 57(2010)3846

# Organic scintillators

- 1960 – stilbene

- Liquid scintillators
- NE213 BC501A EJ301
- EJ309 – high flash liquid
- BC523A, EJ301B, EJ309B – boron loaded liquids

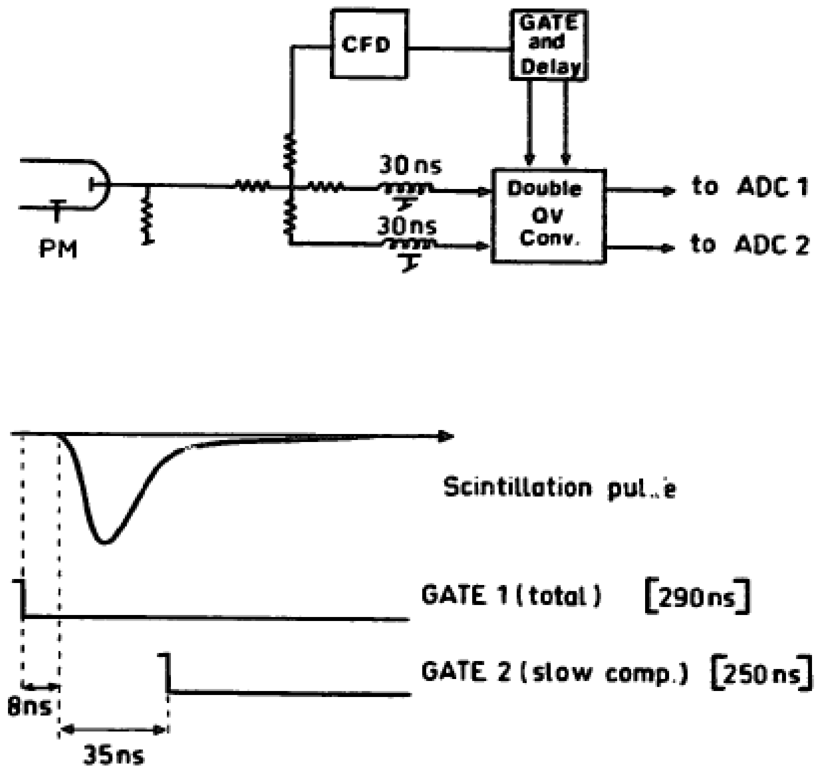
- Composite crystals – mixture of stilbene or *p*-terphenyl and resin – Nikolay Galunov – Kharkov

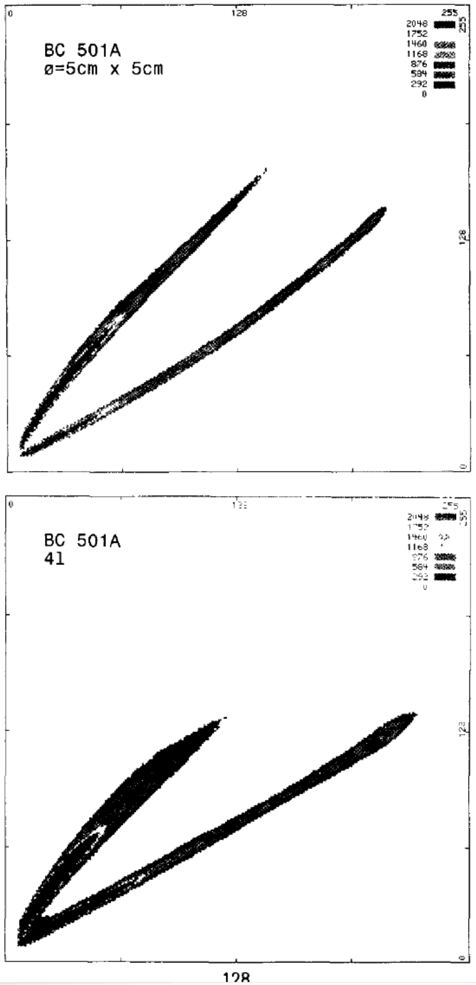
- Plastics:

  - Lawrence Livermore Laboratory, USA– Natalia Zaitseva - Eljen Technology/ Scionix
  - Amcrys H, Ukraine
  - Saclay, France

- New stilbene – Natalia Zaitseva - Inrad Optics

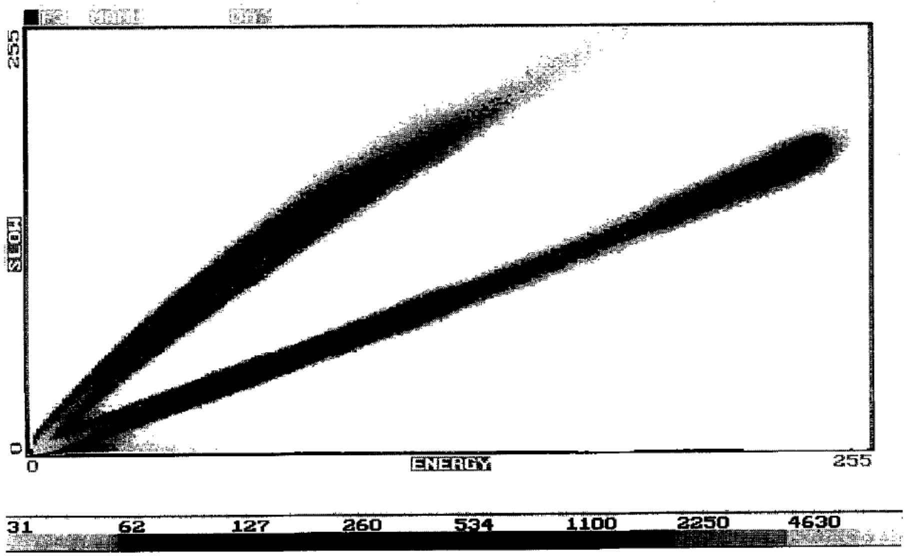
# Charge comparison method



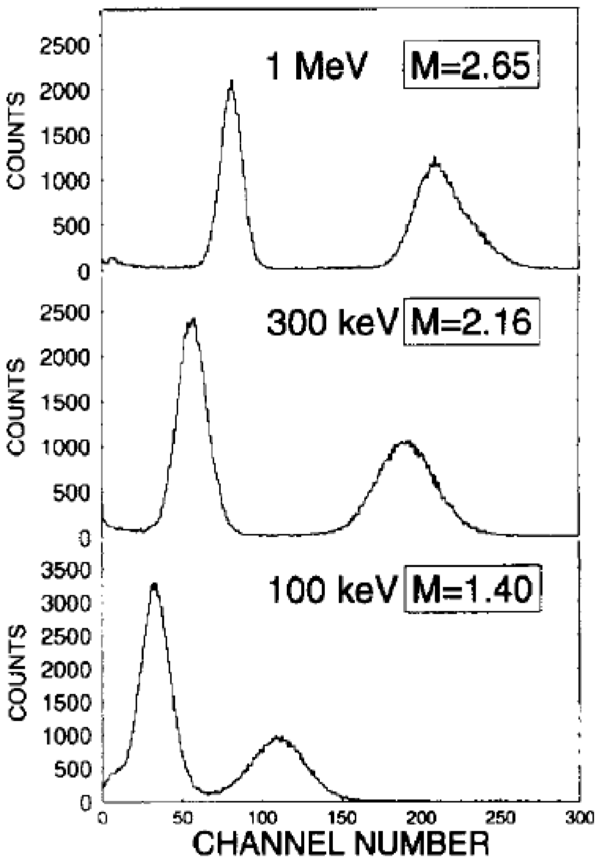




M. Moszynski, et al., NIM A350(1994)226

# Charge comparison method




∅5” × 5” BC501A at XP45212B,
Am-Be source, PHE number = 2300 phe/MeV



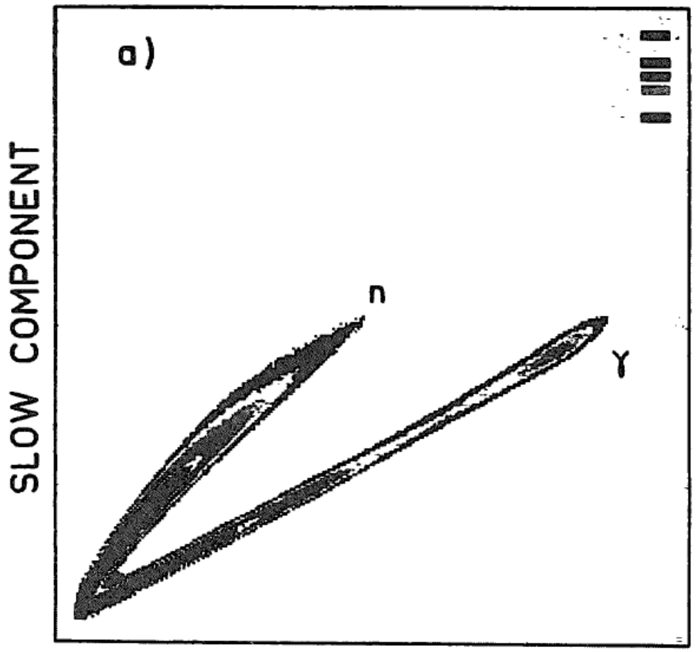

n – gamma dicrimination at different energy gates



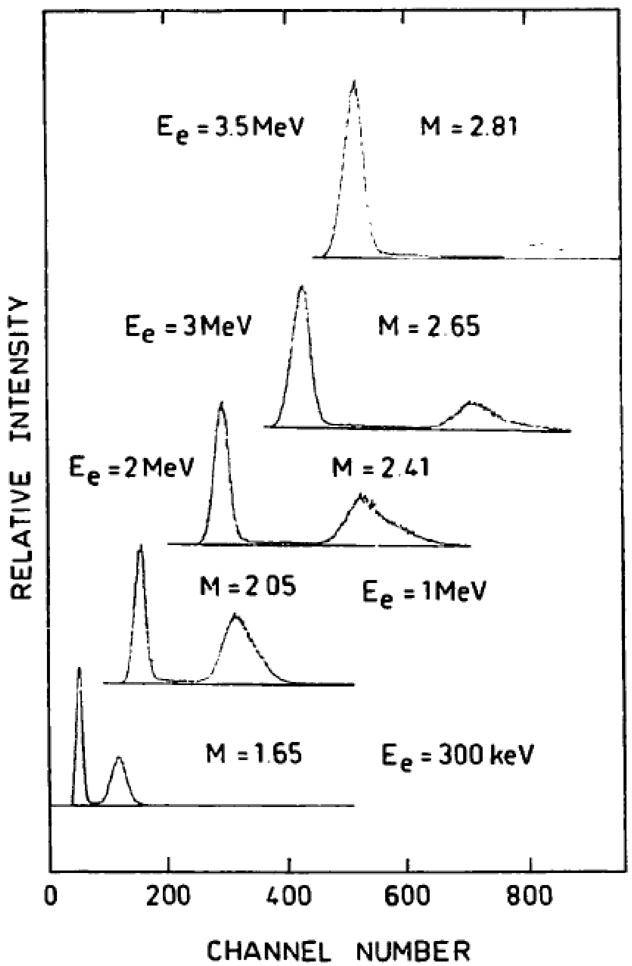
D. Wolski, et al., NIM A360(1995)584

# Charge comparison - optimization

Demon detector:
BC501A Ø16 cm x 20 cm
at XP45212B PMT



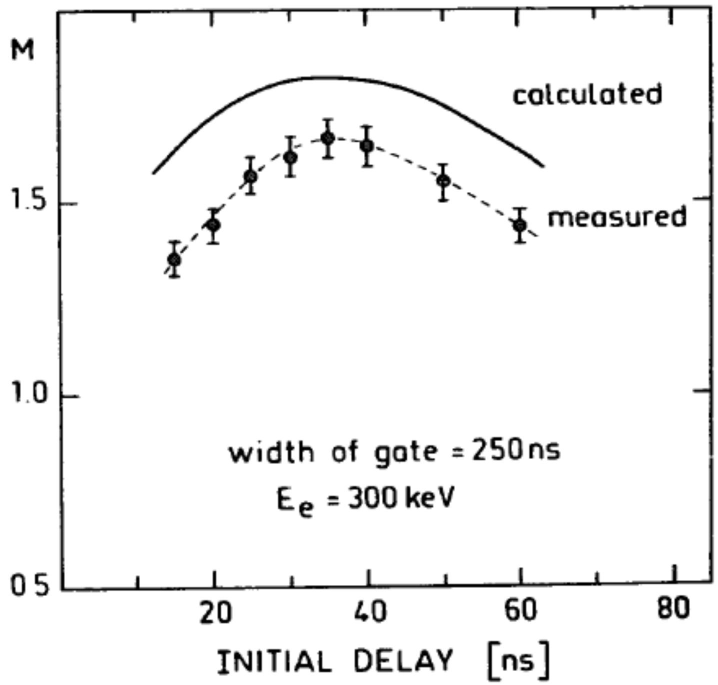

$N_{phe}$ = 1100 phe/$MeV_{ee}$

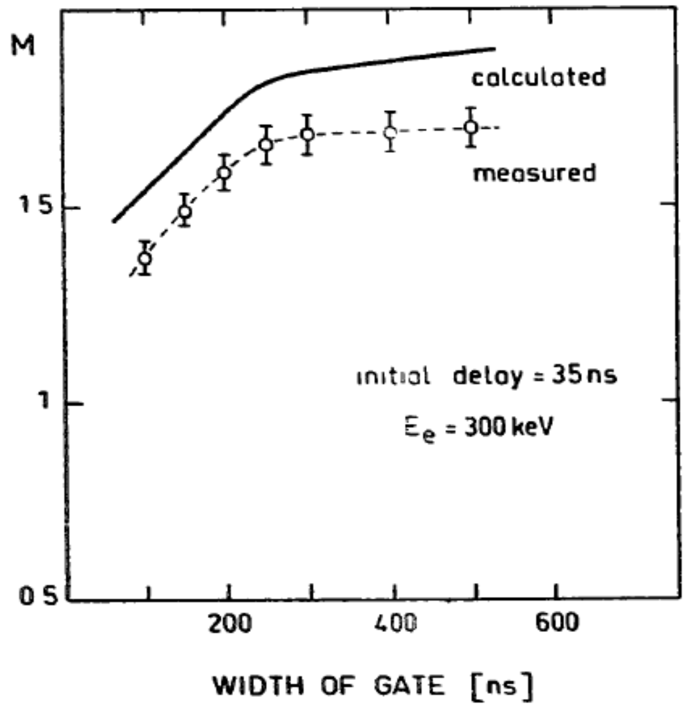



M. Moszynski, et al., NIM A317(1992)262

# Charge comparison - optimization

Demon detector:
BC501A Ø16 cm x 20 cm
at XP45212B PMT

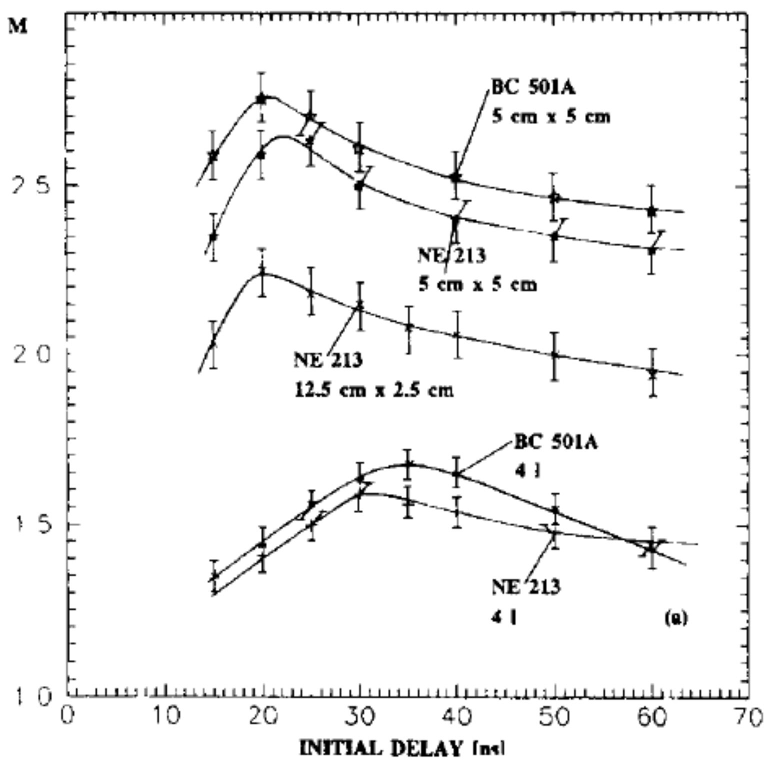


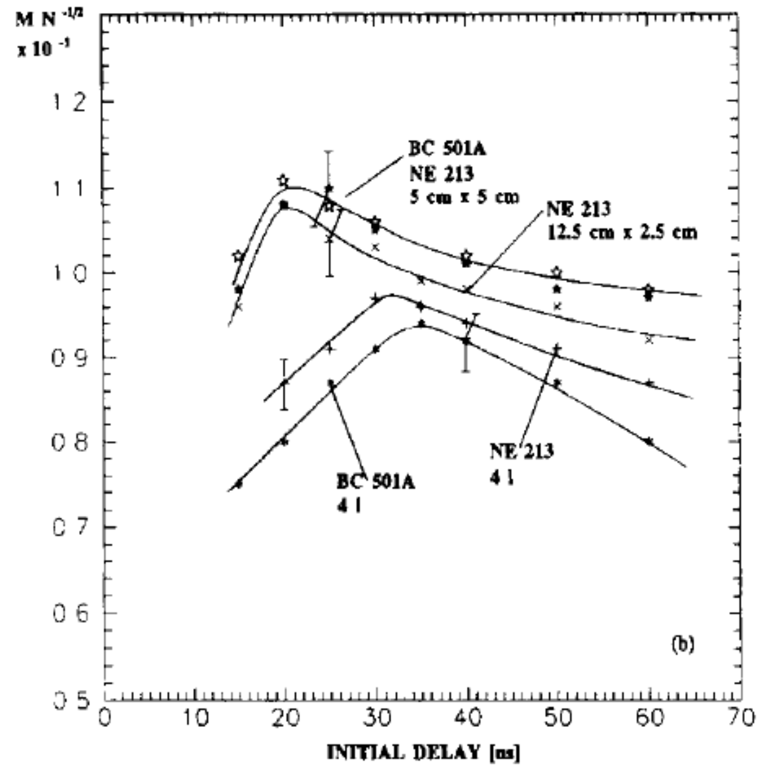

PHE number = 1090±50 phe/$MeV_{ee}$

M. Moszynski, et al., NIM A317(1992)262

# Charge comparison - optimization




M factor at 300 $keV_{ee}$

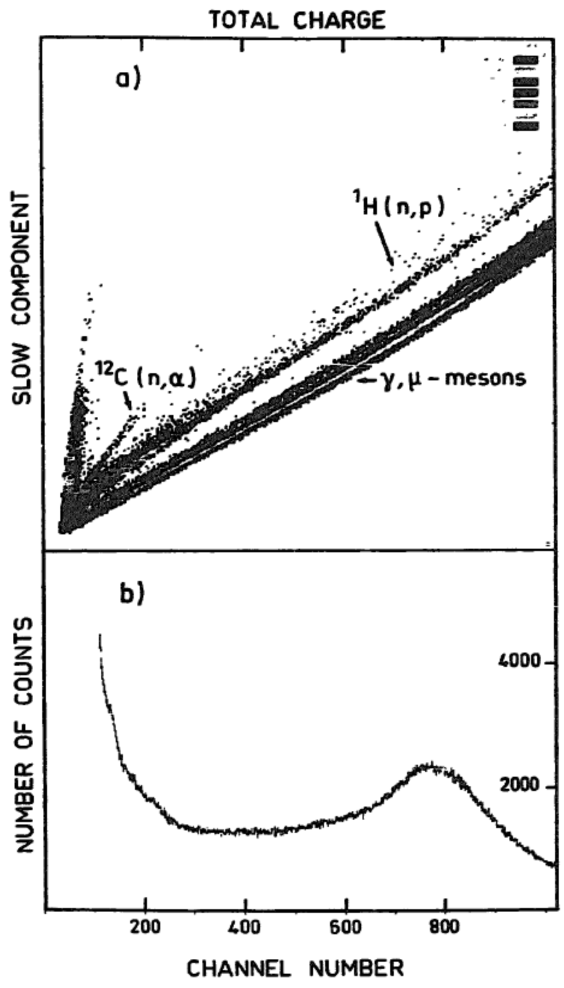



M factor normalized to the PHE number

M. Moszynski, et al., NIM A350(1994)226

# Atmospheric neutrons

- Detector BC501A, ∅16 cm x 20 cm
- Test in the laboratory in Strasbourg,
- Energy of neutrons up to 50 MeV
- Intensity of about 0.1-0.3% in relation to meson component
- Energy spectrum of mesons, straggling peak at about 30 MeV




M. Moszynski, et al., NIM A317(1992)262

# Detection of high energy neutrons

Monoenergetic neutrons of **56 MeV** detected in BC501A:

A – gamma rays

B – protons, not fully stopped

C – recoil protons

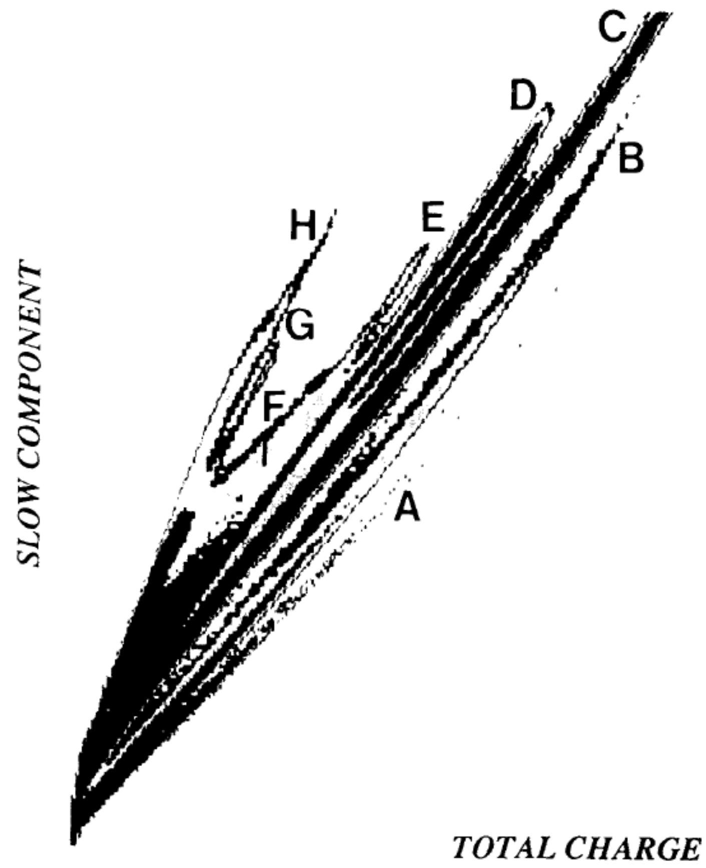
D – Deuterons

E – Tritons

F – Tritons and alphas

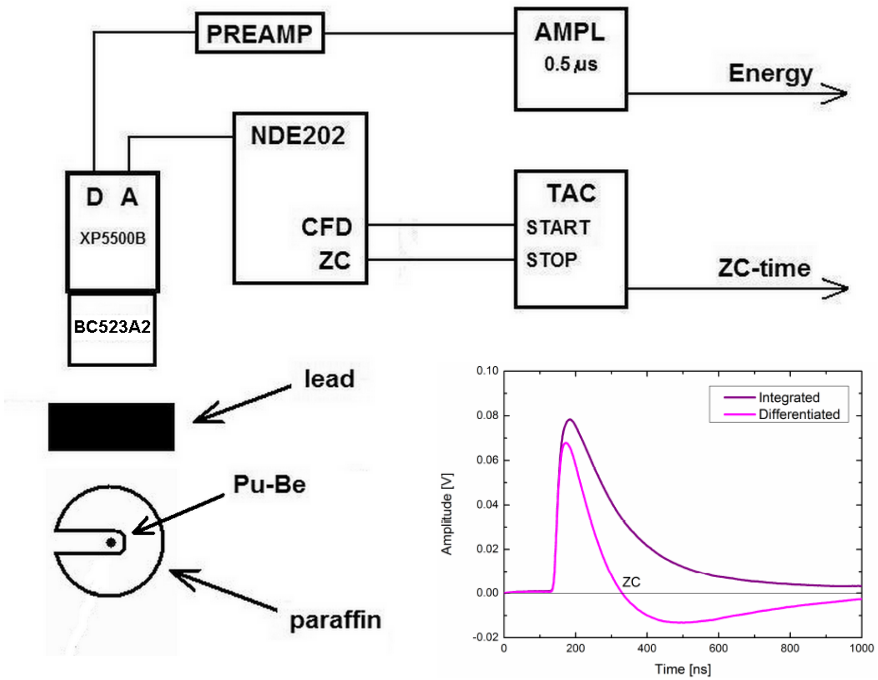
G – $^{3}$He

H – alpha particles

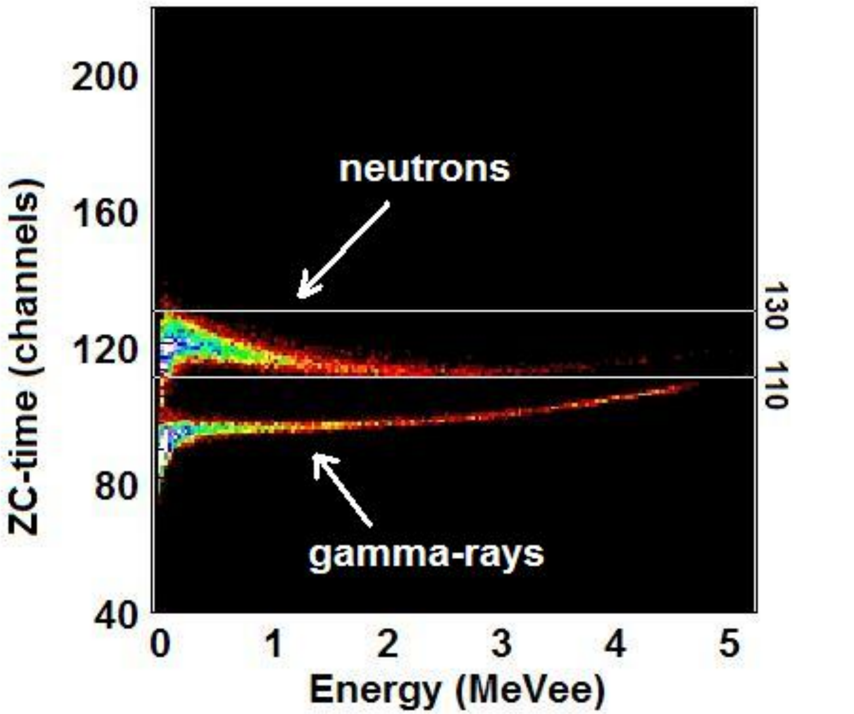



M. Moszynski, et al., NIM A343(1994)563

# Pulse shape discrimination by Z/C method

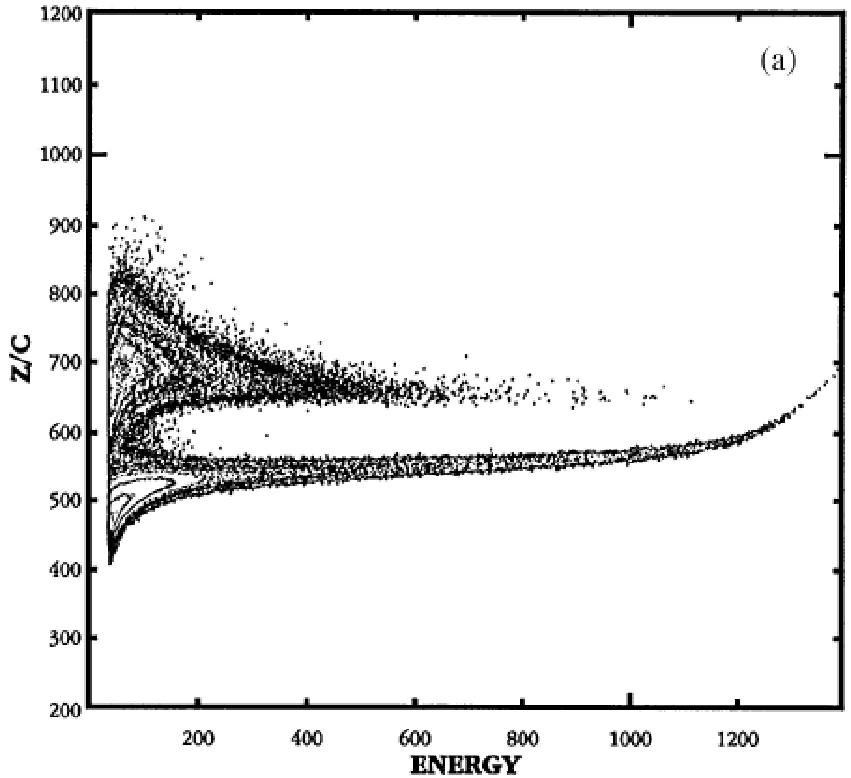



The experimental set up.
PSD by Z/C method.
Liquid scintillators coupled to slow XP5500 or XP53X2 PMTs with high quantum efficiency of about 35%!!!

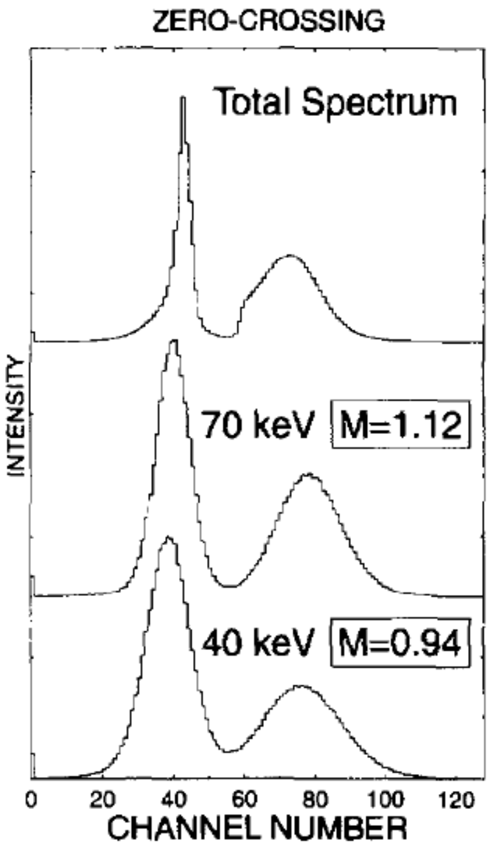



A 2D plot of ZC time vs. pulse height measured with an unloaded EJ309 under irradiation of a Pu-Be source

# Pulse shape discrimination by Z/C method



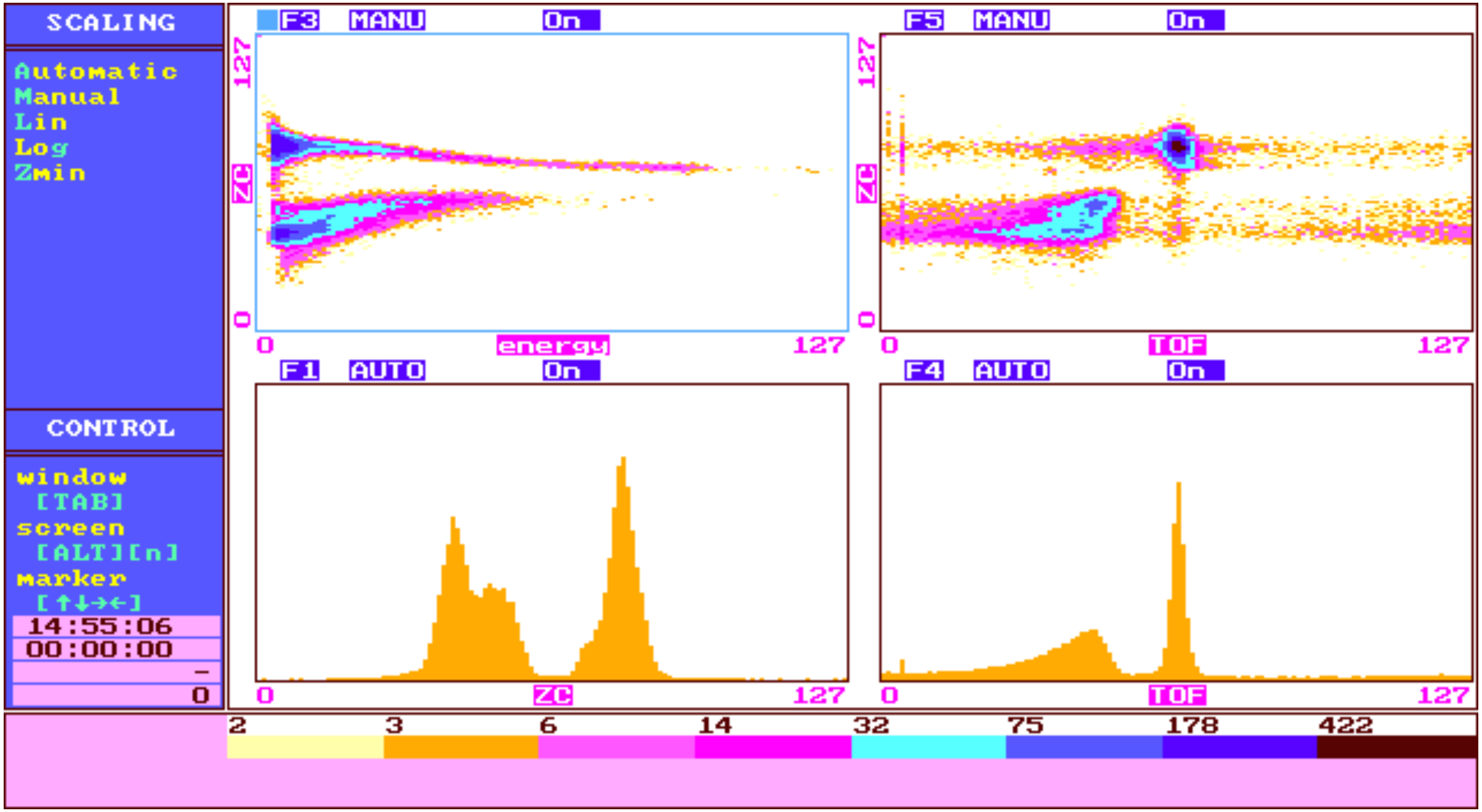

EUROBALL BC501A detector




5”x5” BC501A detector

Ö. Skeppsted, et al., NIM A421(1999)531

# Pulse shape discrimination by Z/C method

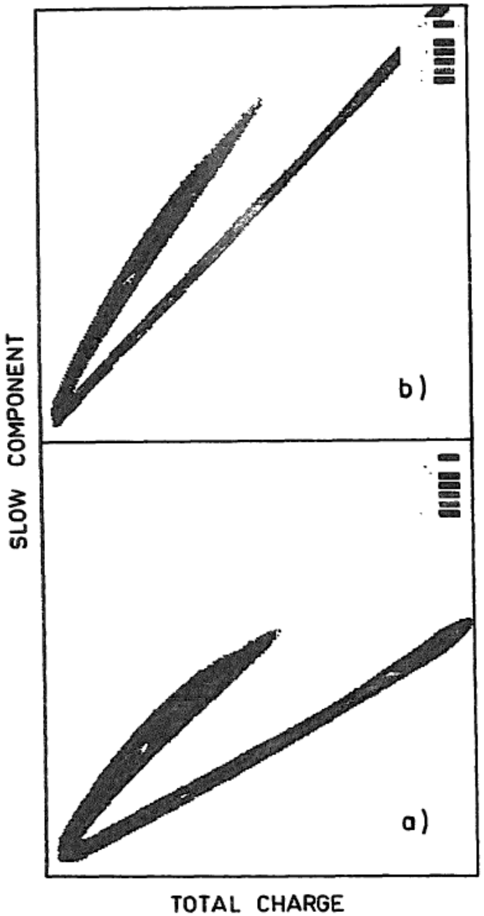


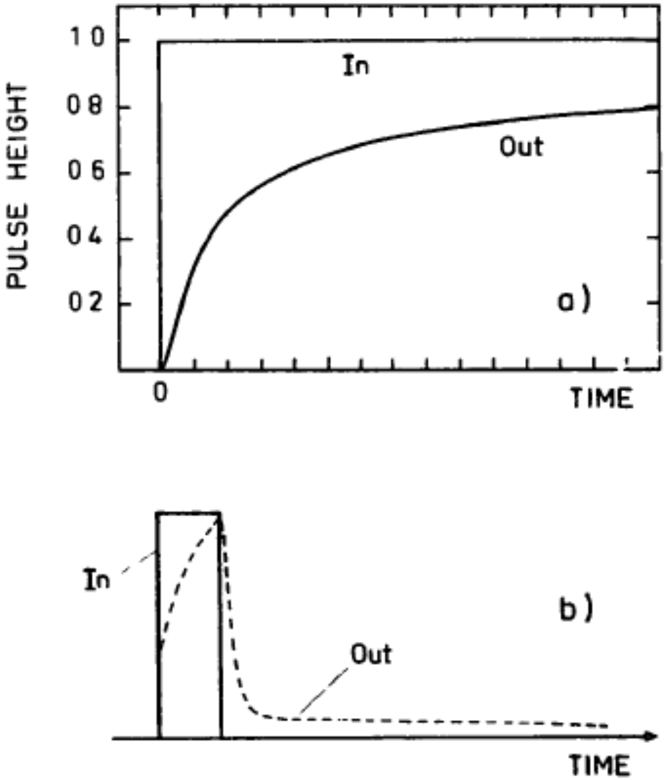

5"x5" BC501A, XP4512B PMT, EUROBALL neutron electronics, Pu-Be source

# Input cable length effect

40 m cable

2 m cable



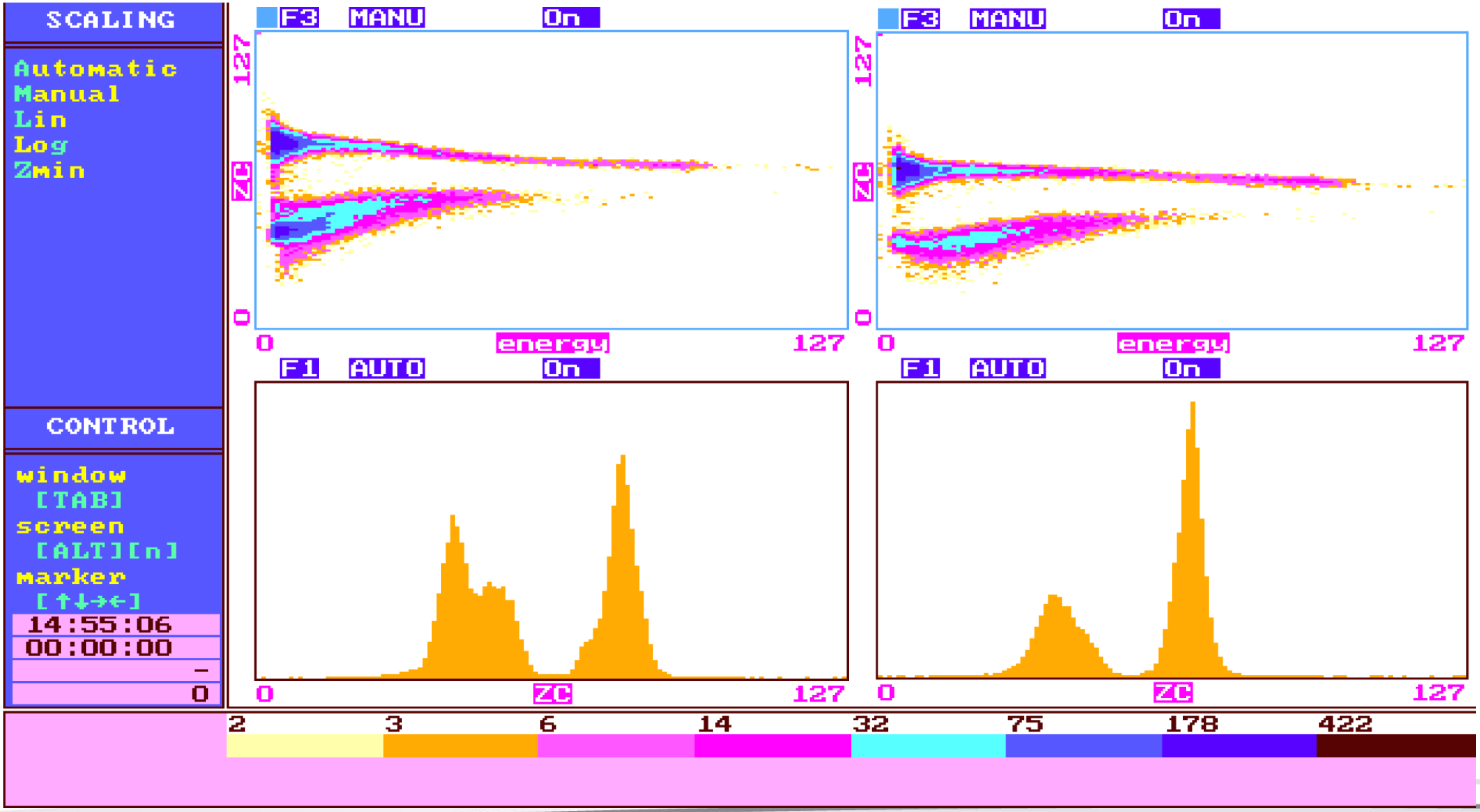

Distortion introduced by a long delay cable on the input pulse of the step function form (a), and on the short rectangular pulse (b).

M. Moszynski, et al., NIM A317(1992)262

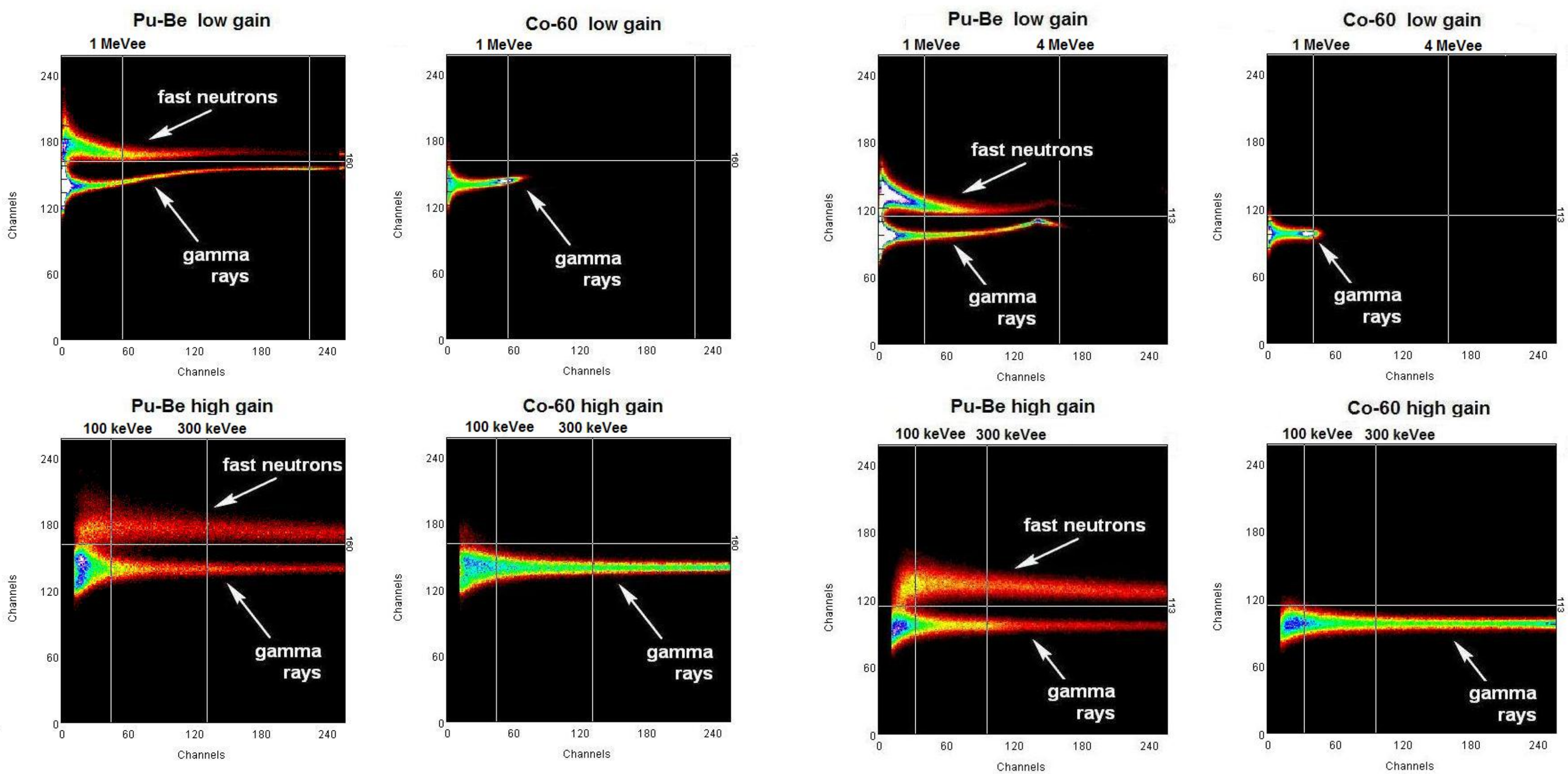
# Input cable length effect

2 m cable

25 m cable



# PMT comparison

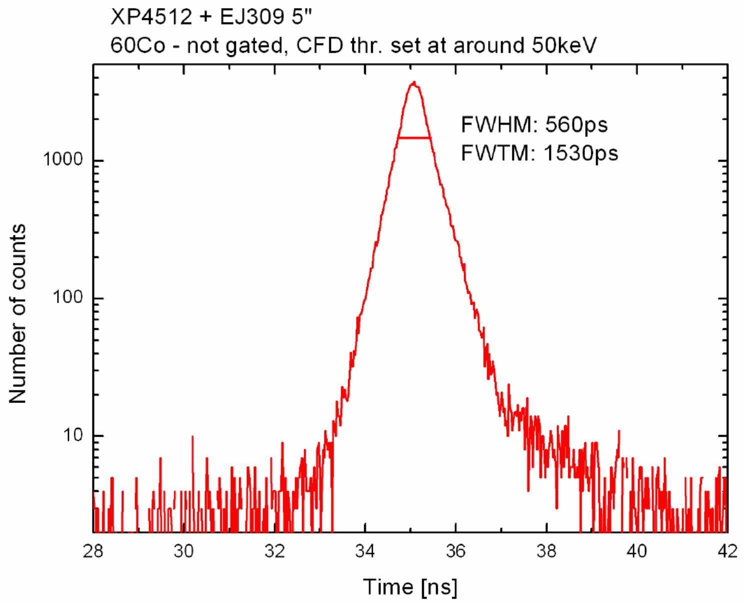


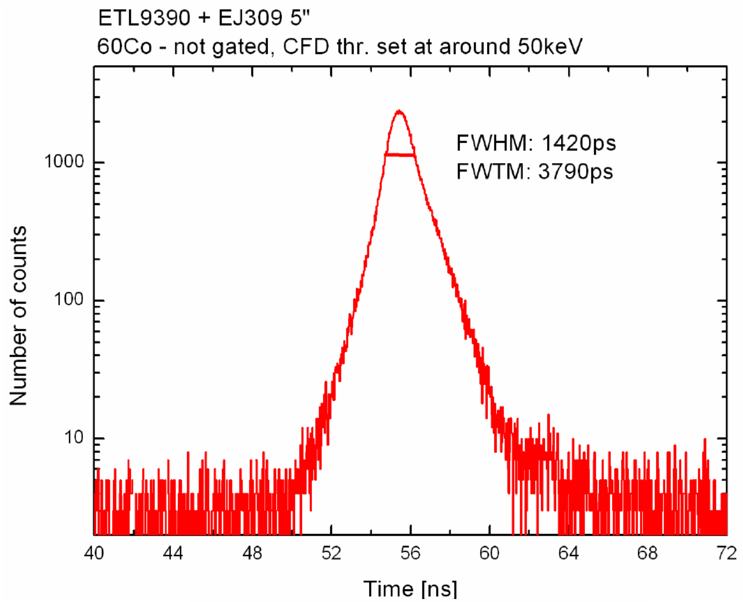

**XP4512B**,
PHE number = 1500±50 phe/MeV

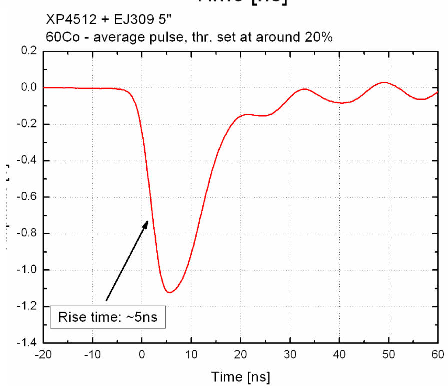
**ETL9390**,
PHE number = 3200±100 phe/MeV

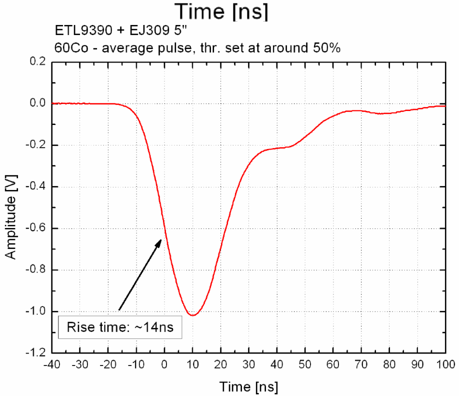
**L. Swiderski, et al., unpublished data**

# PMT comparison - timing




**T. Szczesniak, et al., unpublished data**

# New organic scintillators

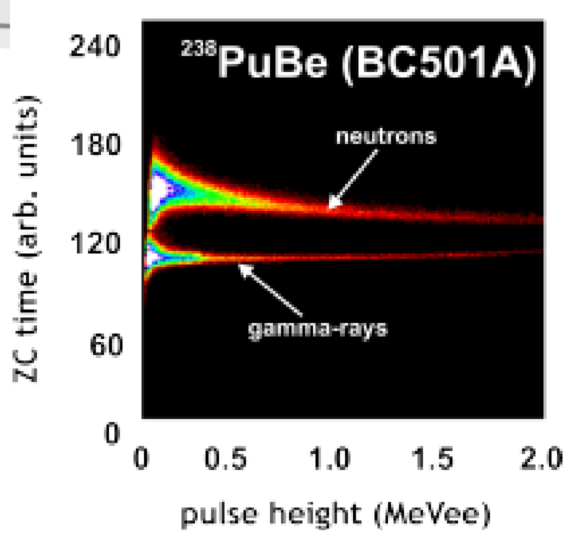
| Scintillator | $^{10}$B loaded | Flash Point | Density [g/cm$^3$] | H:C Ratio | Light Yield[a)] [phe/MeV] |
|---|---|---|---|---|---|
| **BC501A** | NO | 24 °C | 0.87 | 1.21 | 1620 |
| **EJ301** | NO | 26 °C | 0.87 | 1.21 | 2540 |
| **EJ309** | NO | 144 °C | 0.96 | 1.25 | 2600 |
| **BC523A** | YES, 4.4% | -8 °C | 0.92 | 1.74 | 1540 |
| **BC523A2** | YES, 2% | -8 °C | 0.92 | not known | 2450 |
| **EJ339A2** | YES, 2.5% | -8 °C | 0.92 | 1.49 | 2190 |
| **EJ309B5** | YES, 4.6% | 144 °C | 0.96 | 1.31 | 1850 |

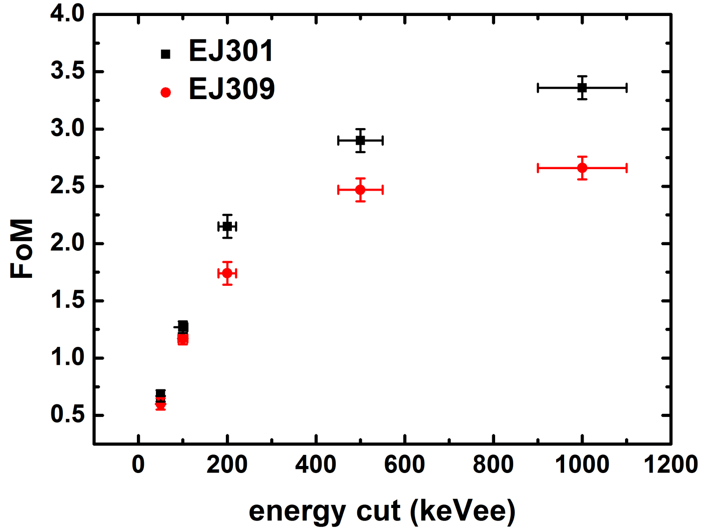
BC*** – scintillators of Saint-Gobain Crystals
EJ*** - scintillators of Eljen/Scionix
2” x 2” liquid cells at XP5500 PMT, QE = 35%
BC501A and BC523A – old!!!

# EJ309 vs EJ301 liquid scintillators

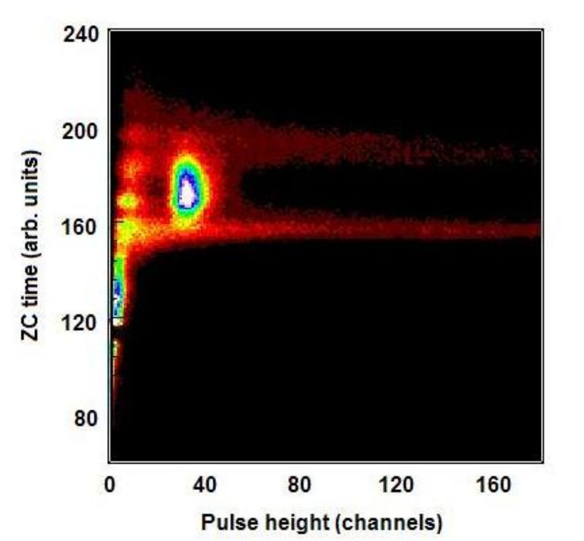
- EJ301 – BC501A – NE213
  xylene-based liquid scintillator, low flash point at 20˚C, toxic, light output – 12000 ph/MeV

- EJ309
  inorganic solvent, high flash point of 144 ˚C, low vapor pressure, low chemical toxicity, light output – 12300 ph/MeV, Slightly poorer n/gamma PSD

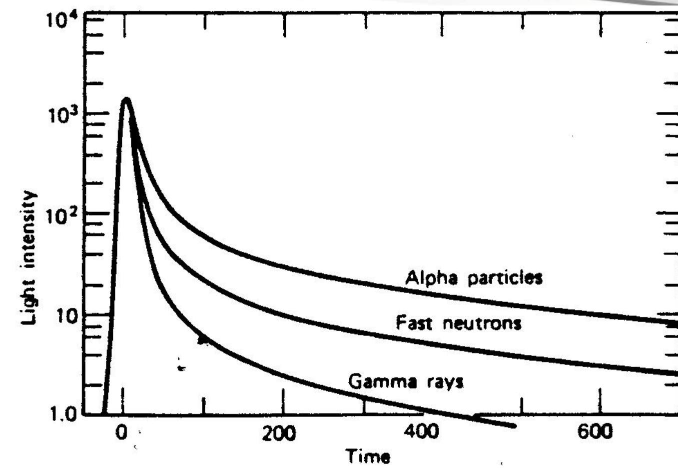


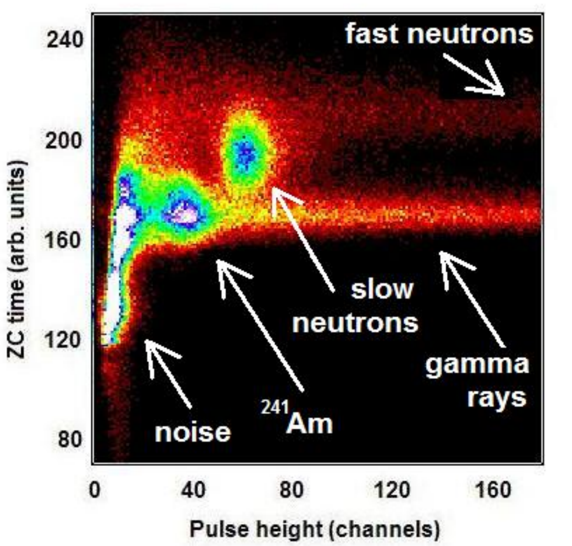



# n/γ discrimination with B-10 loaded liquid scintillators

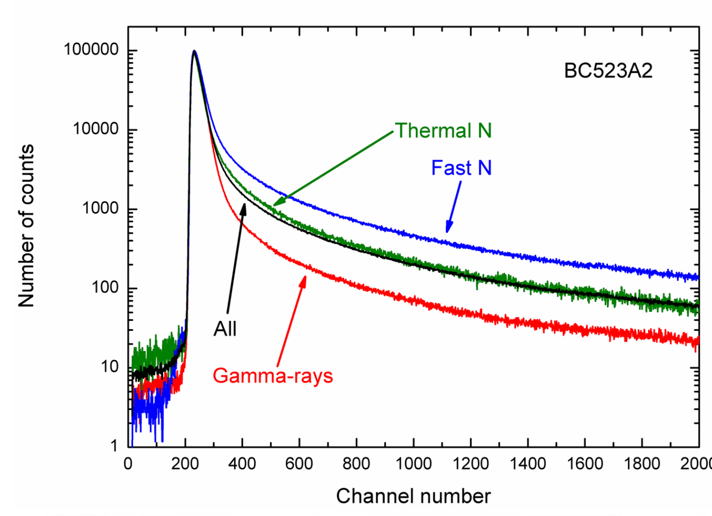



BC523A2



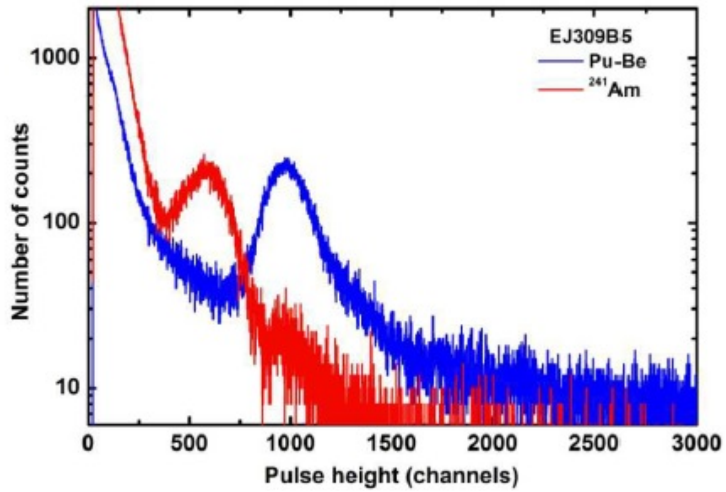



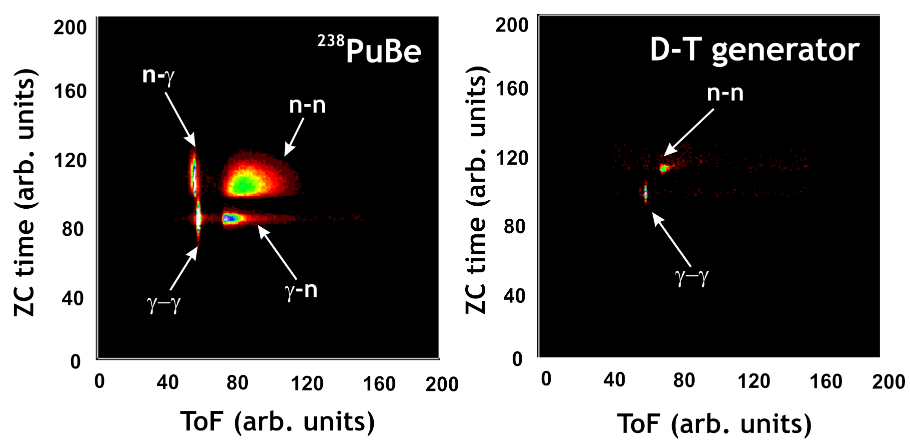

EJ309B5

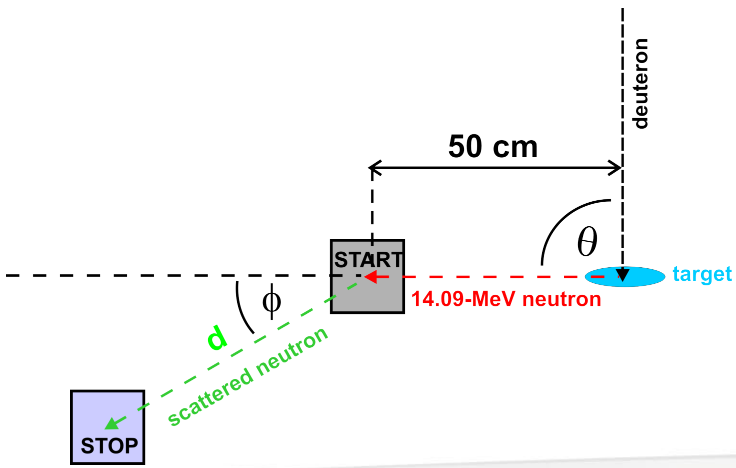


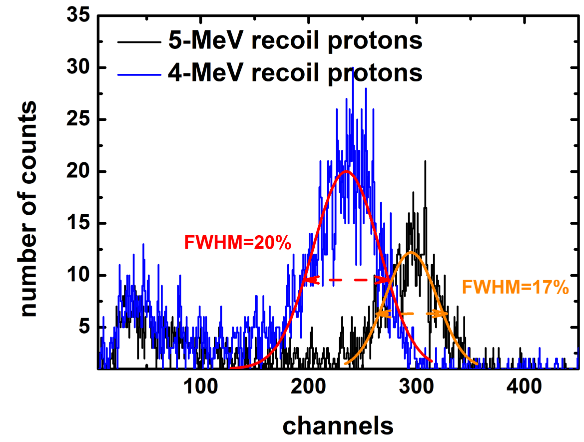

L. Swiderski, et al., TNS 57(2010)375

# EJ309 vs. EJ301 calibration



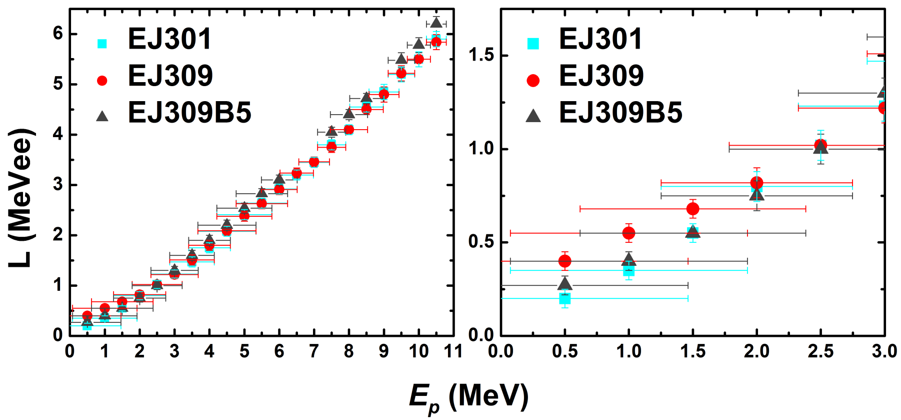



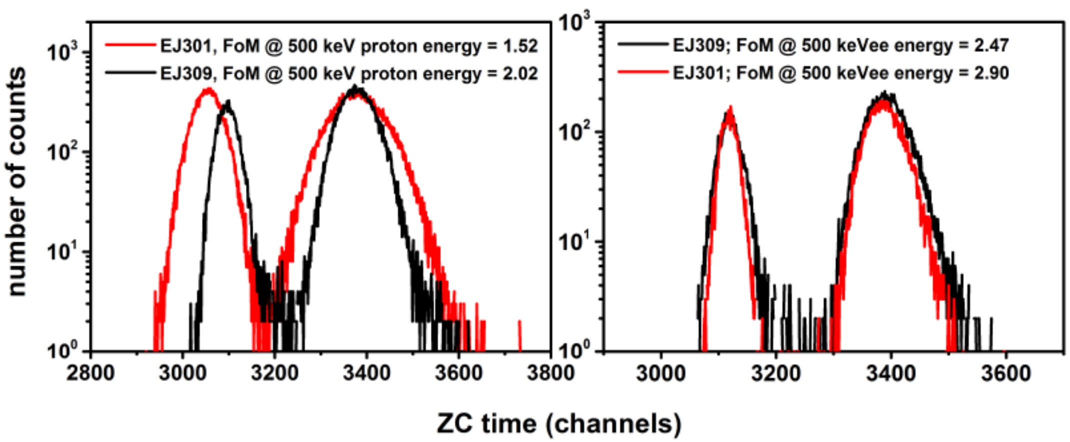




J. Iwanowska, et al., NIM A781(2015)44

# EJ309 vs. EJ301 calibration




- Calibration curves of the light output vs recoil proton energy as measured with EJ301, EJ309 and EJ309B5.
- Note a largest light output of EJ309 at low energies reflecting a weaker quenching of light due to protons.




ZC time spectra for a 500 keV energy lost by protons and recoil electrons in EJ301 and EJ309.

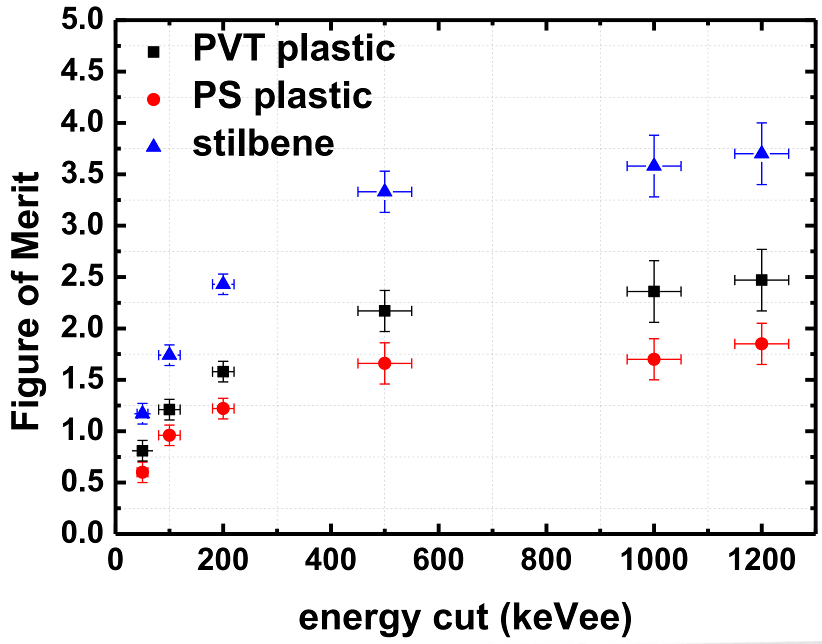


J. Iwanowska, et al., NIM A781(2015)44

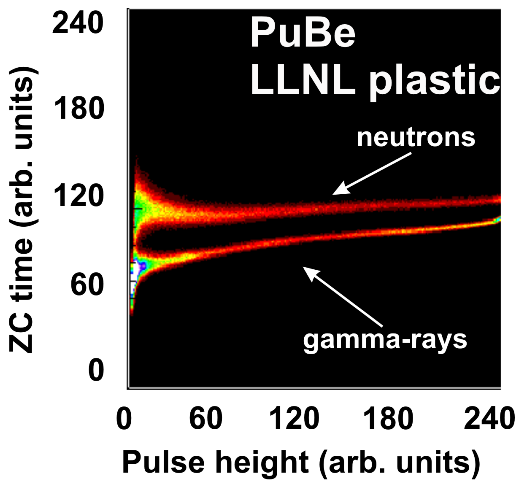
# Plastic scintillators – small samples

| sample | photoelectron yield (phe/MeV) |
|---|---|
| PVT plastic | 3800 ± 200 |
| PS plastic | 3100 ± 200 |
| stilbene | 4200 ± 200 |

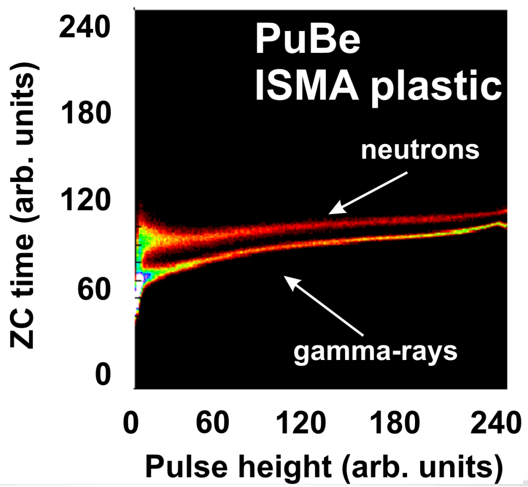
QE = 35%




A)



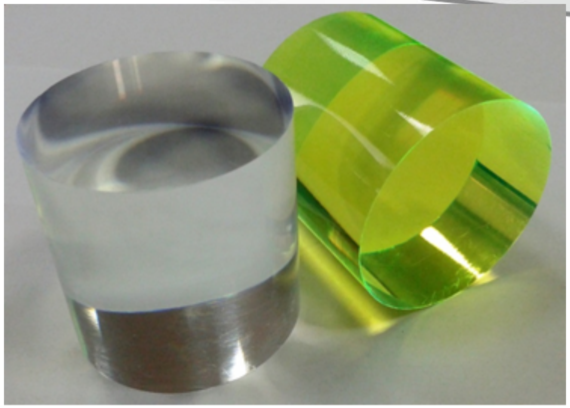

B)

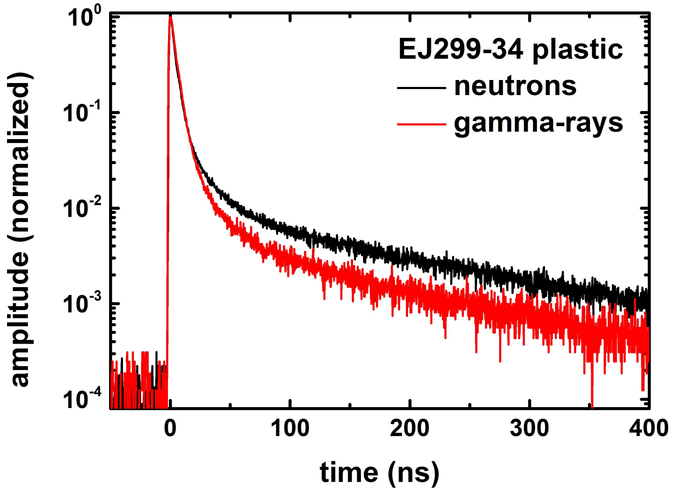



J. Iwanowska, et al., 2013 IEEE NSS Conf. Rec.

# Plastic scintillators – 2” x 2” samples

| scintillator | EJ299-33 | EJ309 |
|---|---|---|
| light Output, % Anthracene | 56 | 75 |
| scintillation Efficiency, photons/1 MeV e- | 8600 | 11500 |
| wavelength of maximum emission (nm) | 420 | 424 |
| number of H atoms per $cm^3$ | $5.13 \times 10^{22}$ | $5.46 \times 10^{22}$ |
| number of C atoms per $cm^3$ | $4.86 \times 10^{22}$ | $4.37 \times 10^{22}$ |
| number of electrons per $cm^3$ | $3.55 \times 10^{23}$ | $3.17 \times 10^{22}$ |
| density ($g/cm^3$) | 1.08 | 0.964 |

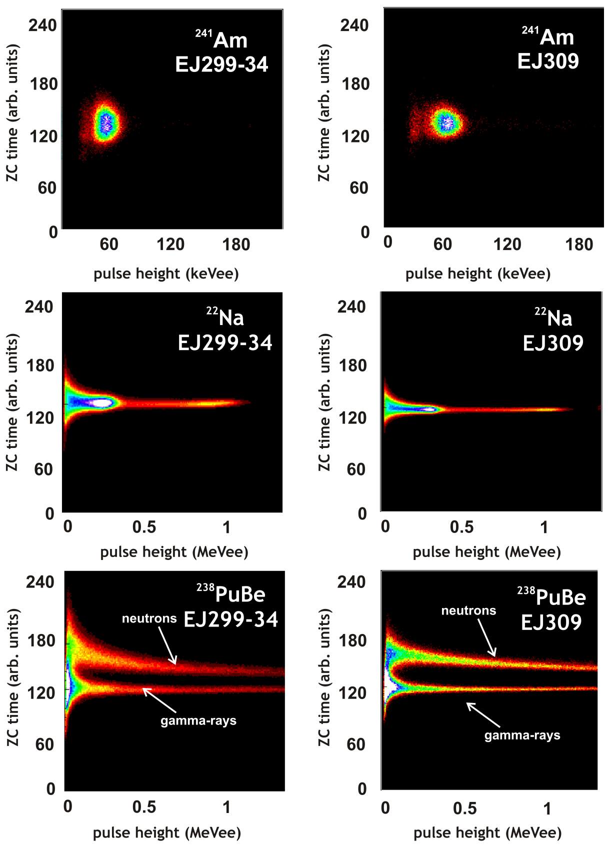


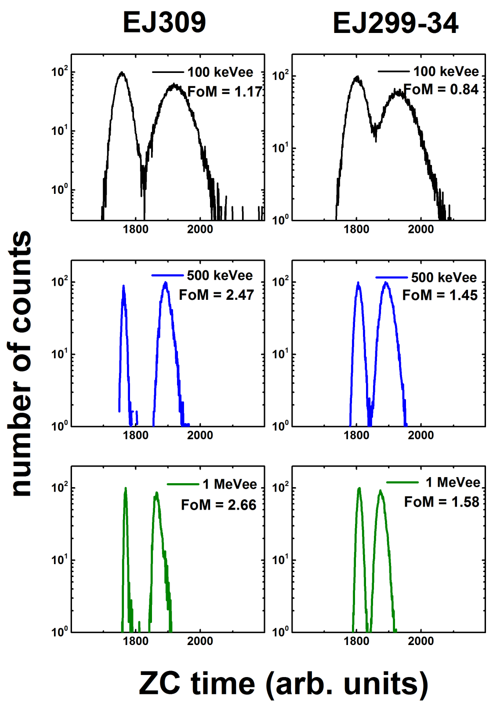


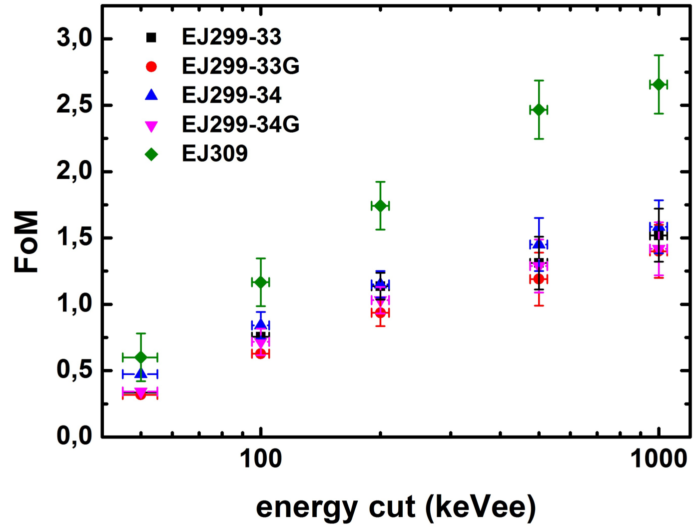

| scintillator | photoelectron yield (phe/MeV) |
|---|---|
| EJ309 | 2600 ± 50 |
| EJ299-34 | 2500 ± 50 |
| EJ299-34G | 2100 ± 50 |
| EJ299-33 | 1950 ± 30 |
| EJ299-33G | 1600 ± 30 |

J. Iwanowska, et al., JINST 9_06_P06014

# Plastic scintillators – 2” x 2” samples

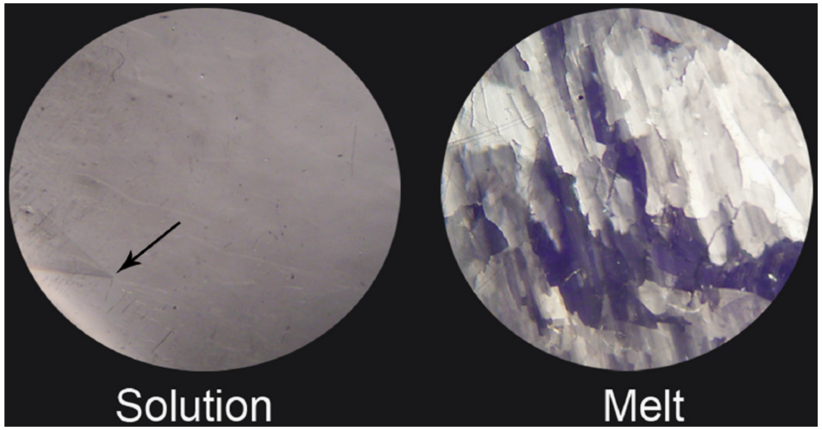


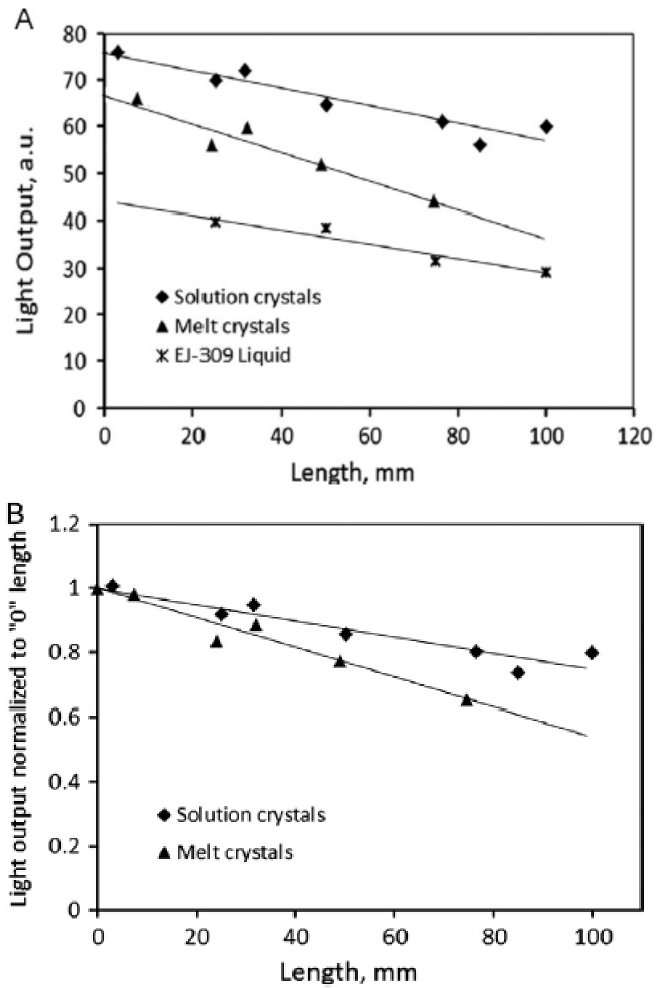




J. Iwanowska, et al., JINST 9_06_P06014

# New stilbene – grown from solution

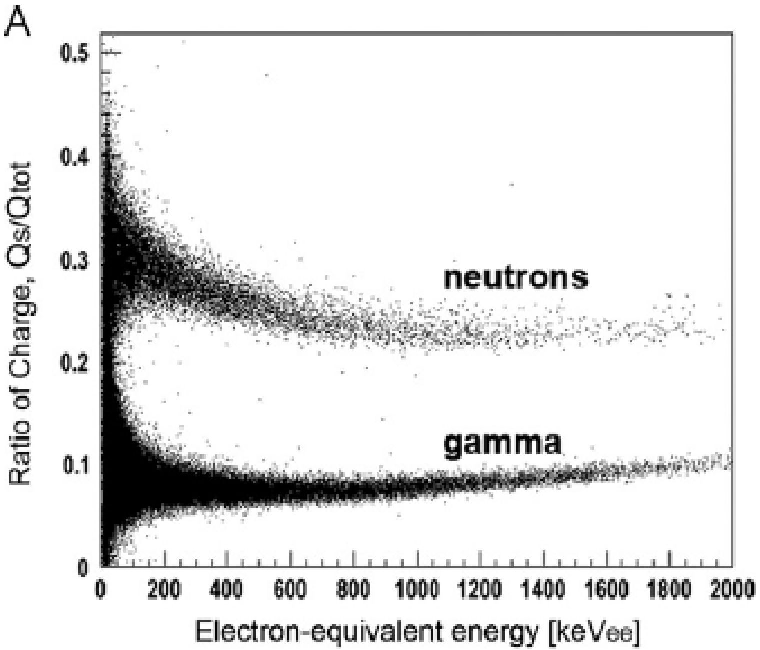


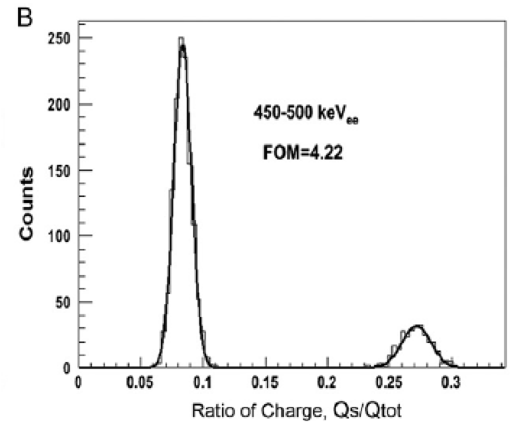

tested samples: ∅2”, height up to 4”

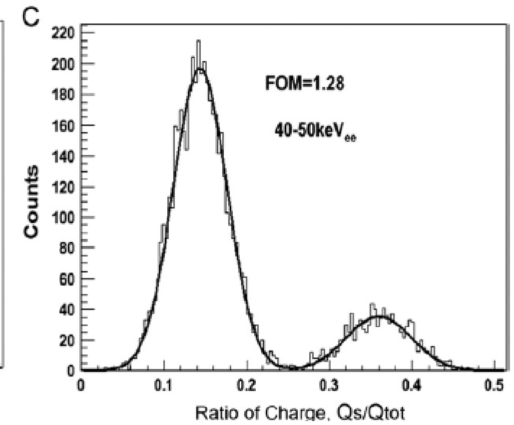


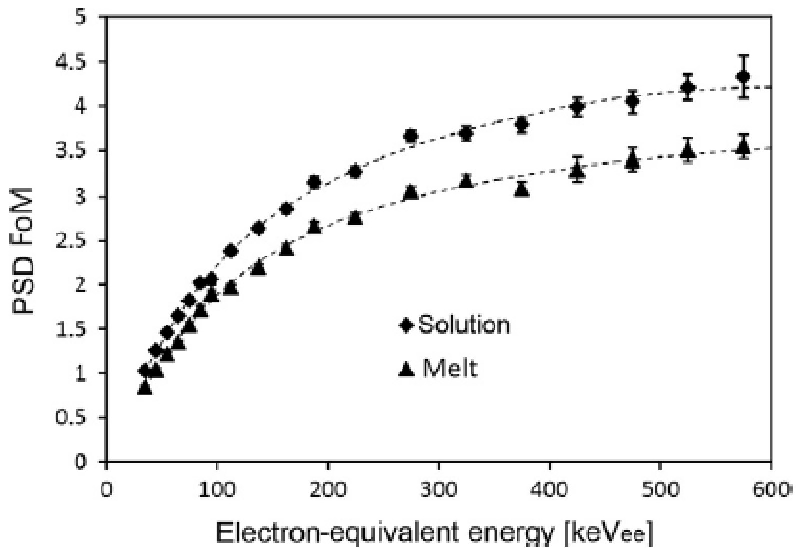

N. Zaitseva, et al., NIM A789 (2015) 8

# New stilbene – grown from solution



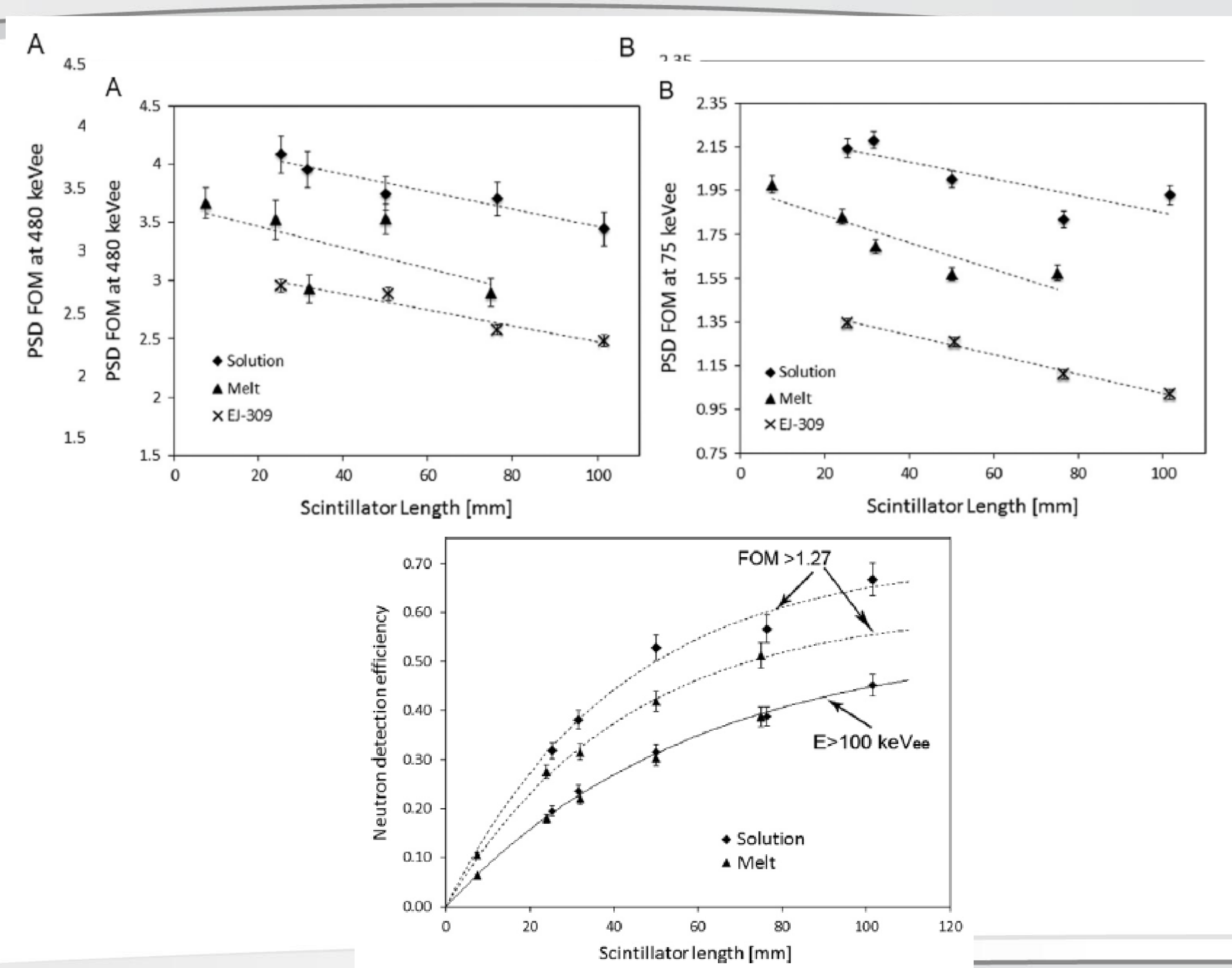



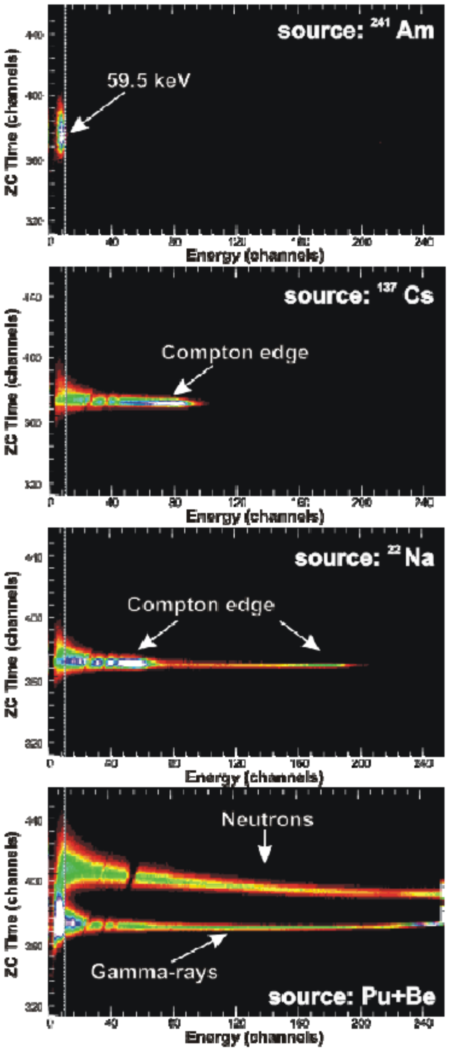

∅51 mm x 75 mm

N. Zaitseva, et al., NIM A789 (2015) 8

# New stilbene – grown from solution



# Stilbene and SiPMs in neutron detection

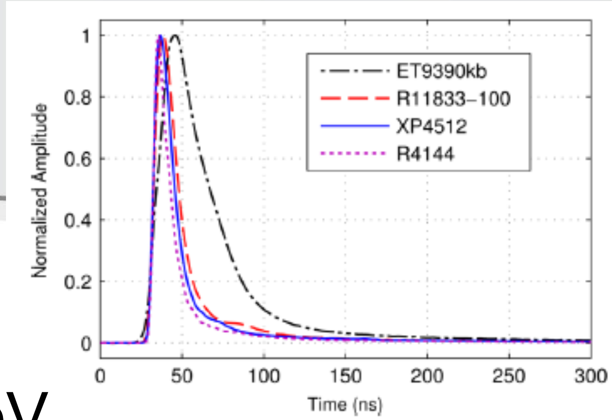



| Phe/MeV | 2240 ± 220 |
|---|---|
| FoM 100 keVee | 1.16 ± 0.06 |
| FoM 300 keVee | 2.13 ± 0.11 |
| FoM 500 keVee | 2.86 ± 0.14 |
| FoM 1 MeVee | 3.41 ± 0.17 |

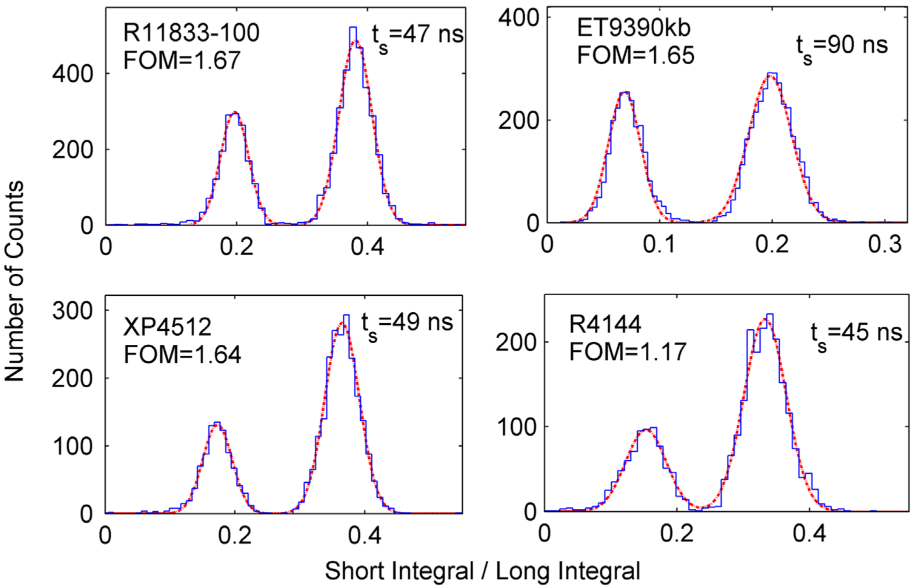
Stilbene: ∅25 mm × 25 mm
MPPC array 12 mm × 12 mm

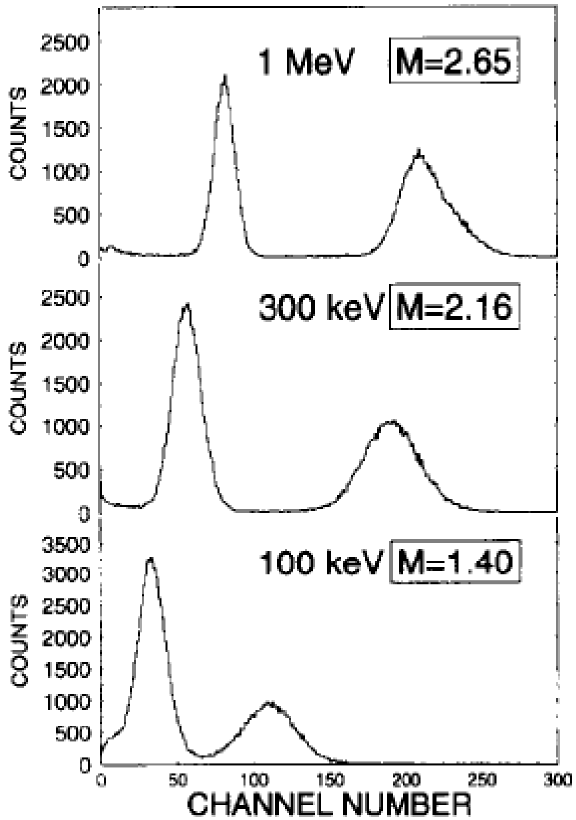
**M. Grodzicka, et al., 2014 IEEE NSS, Conf. Rec.**

# Analog vs. Digital PSD




300 keV




5” x 5” BC501A at XP4512B

ZC analog method

5” x 5” BC501A at different PMTs

Digital charge comparison method

X.L. Luo, et al., NIM A767(2014)83

D. Wolski, et al., NIM A360(1995)584

# Limitations of the digital method

Summary of FOM results for the digitizers under investigation.

| Digitizer model | ENOB for 1-V range | Sampling frequency (MHz) | $FOM_{FWHM}$ | $FOM_{valley}$ |
|---|---|---|---|---|
| V1720 | 9.14 | 250 | 1.26 | 1.06 |
| V1751 | 9.04 | 1000 | 1.33 | 1.17 |
| V1751 | 9.04 | 2000 | 1.33 | 1.34 |
| Pixie-400 | 10.2 | 400 | 1.46 | 3.00 |

Energy threshold = 80 keV

ENOB – effective number of bits

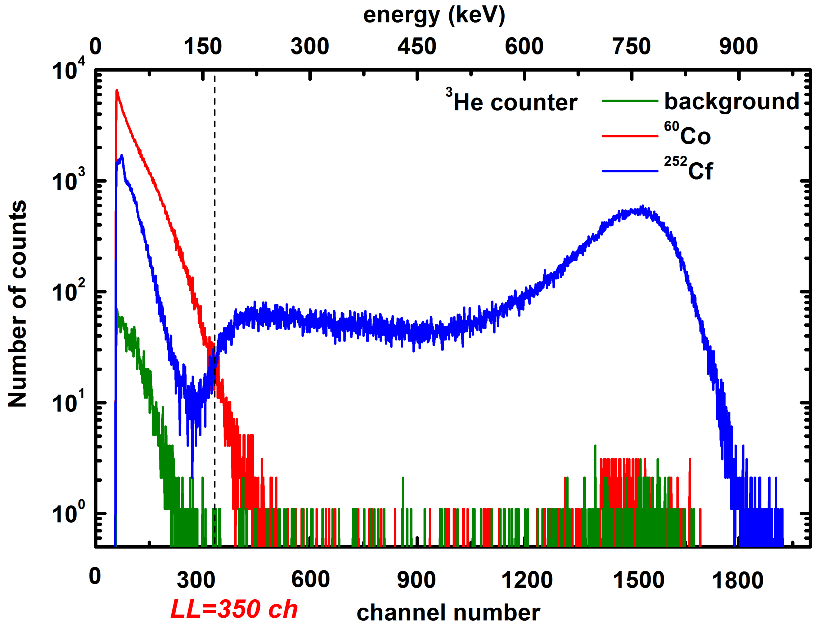


M. Flaska, et al.., NIM A729(2013)456

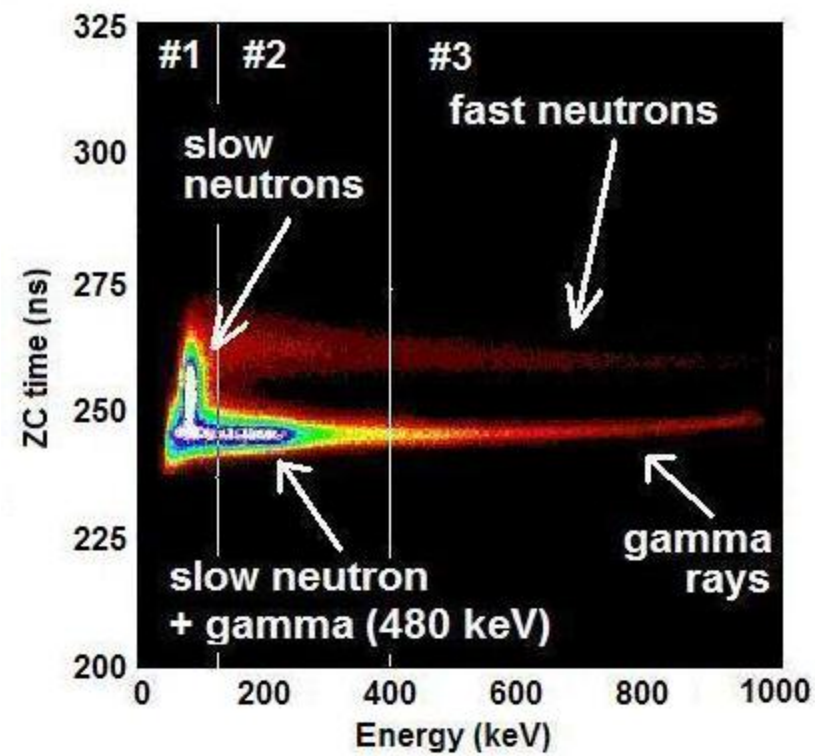
# Further questions

- Detection efficiency in comparison to He-3 detector
- Rejection of gamma rays in comparison to He-3 detector

# Detection efficiency




Energy spectra measured with He-3 counter under irradiation of a $^{60}$Co source, $^{252}$Cf and background.




A 2D plot of ZC time vs. energy from EJ309B5 irradiated with the $^{252}$Cf source.

L. Swiderski, et al., TNS 57(2010)2857

# Detection efficiency

| detector | Source moderator | B ($s^{-1}$) | G ($s^{-1}$) | N($s^{-1}$) | $\varepsilon_n$ | $\varepsilon_\gamma$ |
|---|---|---|---|---|---|---|
| He-3 | - | 0.55 | 0.59 | 12.8 | 0.20(2) | $<10^{-6}$ |
| He-3 | + | 0.55 | 0.59 | 13.0 | 0.23(3) | $<10^{-6}$ |
| EJ309B5 | - | 0.11 | 6.43 | 3.89 | 0.34(4) | $2.6(9)\times10^{-5}$ |
| EJ309B5 | + | 0.11 | 6.43 | 2.74 | 0.27(3) | $2.6(9)\times10^{-5}$ |

He-3 detector 2" diameter x 40" long

EJ309B5 3" x 3" liquid cell

L. Swiderski, et al., TNS 57(2010)2857

# Detection efficiency

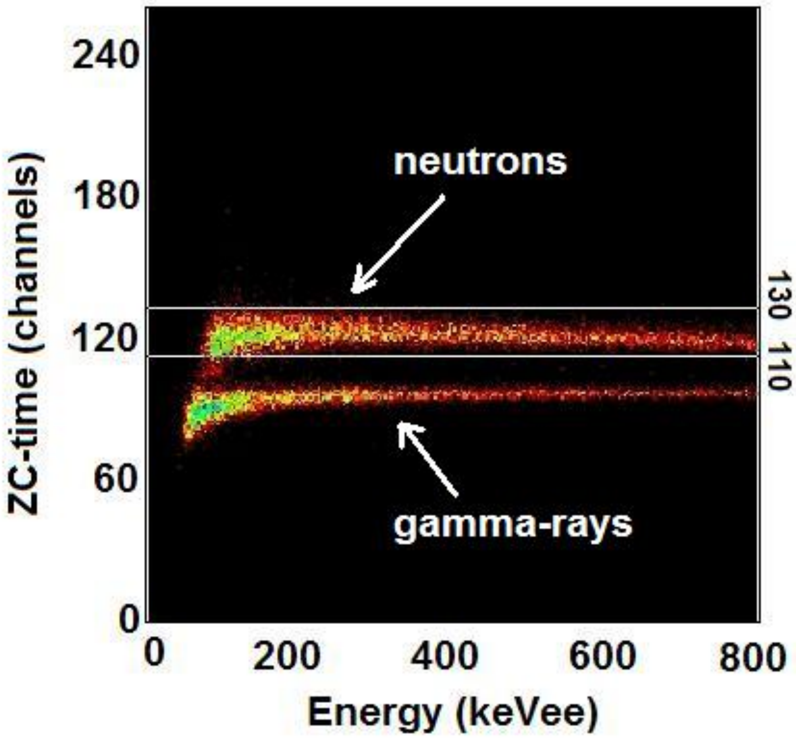
The improvement of performance of EJ309B5:

- **application of pile-up rejection circuit** in the n/γ discrimination electronics (to reduce γ-ray pile-ups)
- **increase of a lead shield** (to reduce γ-rays yield)
- **reduction of the detector size** (for further reduction of pile-ups of γ-rays from intense γ-ray sources)
- application of copper shield between the detector and lead shield (to reduce X-rays yield from lead)
- improved slow neutrons discrimination from γ-rays in low energy region (ROI #1).

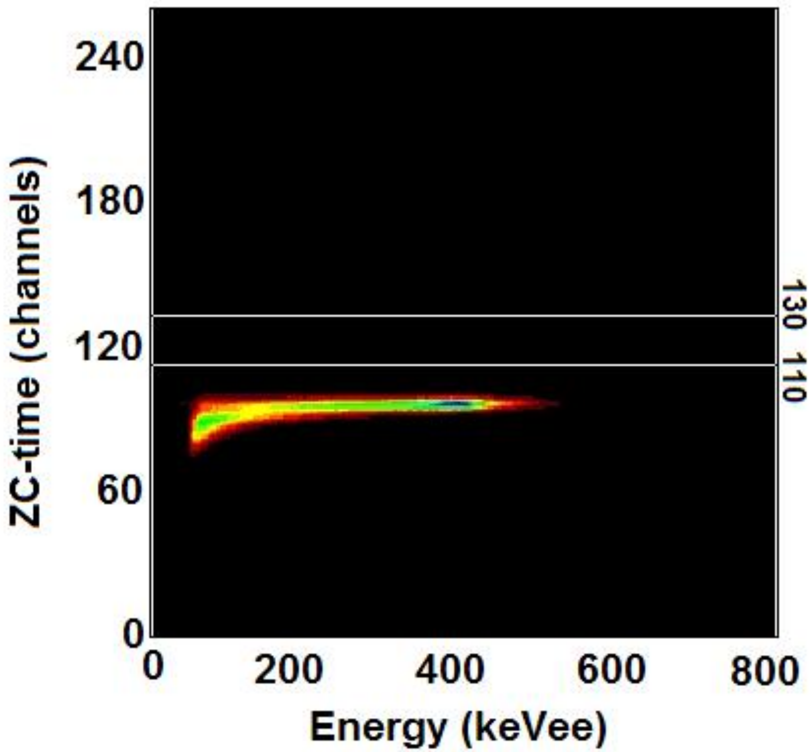
# Suppression of gamma-ray sensitivity in liquid scintillators

- 2” x 2” EJ309 liquid cell
- Z/C n-$\gamma$ PSD with pile up rejection
- a strong field of gamma radiation from $^{137}Cs$ source, yielding 10 mR/h at the detector, as proposed in Neutron Detector Gamma Insensitivity Criteria
- Different shielding of neutron detector
- A comparison to a 2” x 20” He-3 counter surrounded with polyethylene shield.

# Suppression of gamma-ray sensitivity in liquid scintillators



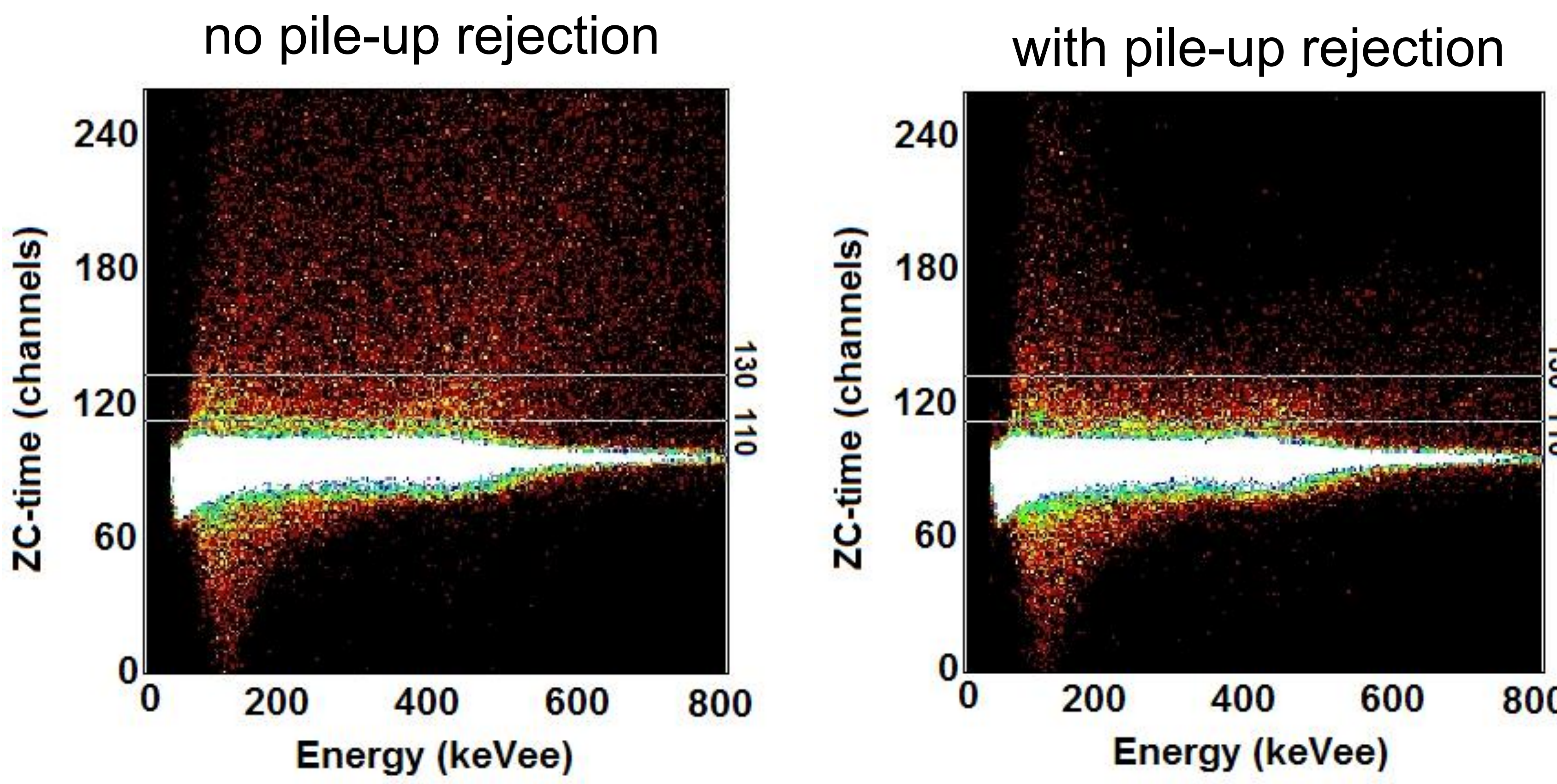

A 2D plot of ZC-time vs. Energy from EJ309 irradiated with the Pu-Be source.




EJ309 irradiated with the $^{137}Cs$ source.

L. Swiderski, et al., NIM A652(2011)330

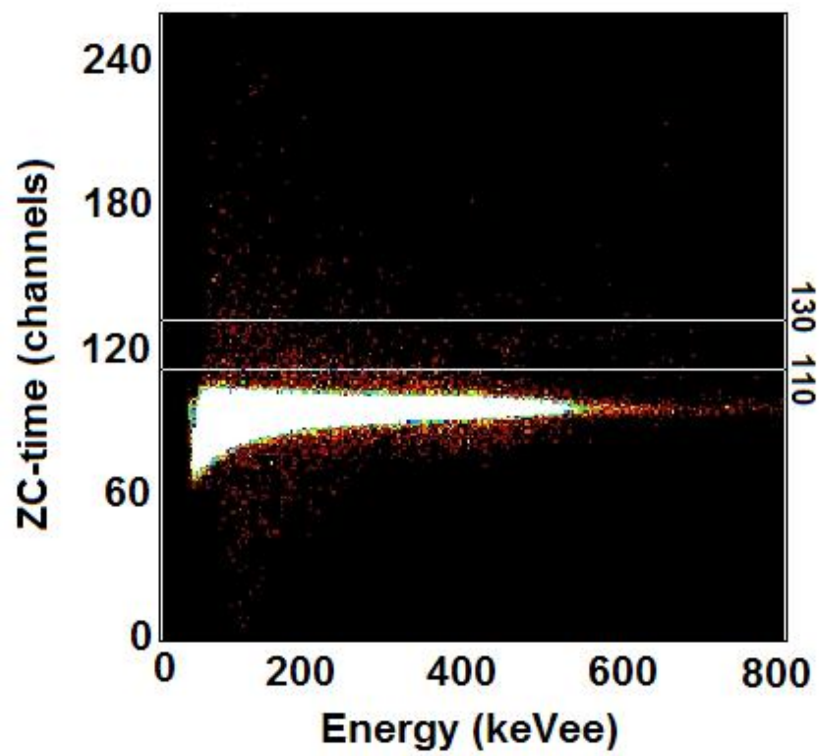
# Suppression of gamma-ray sensitivity in liquid scintillators




L. Swiderski, et al., NIM A652(2011)330

# Suppression of gamma-ray sensitivity in liquid scintillators

- Pile up rejection on
- The liquid cell shielded by lead and tin absorbers.






L. Swiderski, et al., NIM A652(2011)330

# Suppression of gamma-ray sensitivity in liquid scintillators

| Shield | No shield | Pb | Pb + Sn |
|---|---|---|---|
| Pb front | - | 50 mm | 50 mm |
| Pb side | - | 10 mm | 10 mm |
| Sn front | - | - | 7 mm |
| Sn side | - | - | 3.5 mm |
| $\gamma$-ray flux (kcps) | 41 | 6.8 | 4.6 |
| Relative neutron efficiency*) | 1.25 | 0.84 | 0.70 |
| intrinsic $\gamma$/neutron detection efficiency | $3.1x10^{-4}$ | $1.6x10^{-5}$ | $5.1x10^{-6}$ |

*) relative to the intrinsic neutron detection efficiency of a polyethylene moderated He-3 counter irradiated with a Pu-Be source in the same geometry

L. Swiderski, et al., NIM A652(2011)330

# First Conclusions

- A very efficient n/γ discrimination down to 20 $keV_{ee}$
- A high flash liquid scintillator showed an excellent n/γ discrimination capability
- A cheap solution due to PMT used in gamma spectrometry
- Unexpected quenching of slow component in the light pulses due to B events. Poor separation of thermal neutrons and gamma rays!!!
- Plastic scintillators with PSD capability still in the early phase of development

# First conclusions

- New stilbene, grown from solvent, is a very attractive proposition. However, it has to be cheaper!
- Digital vs. analog n/gamma pulse shape discrimination,
- Optimisation of PSD in digital method – a large number of bits to assure a high dynamic range of input pulse height – important for low energies,

# Inorganic scintillators in neutron detection

**Neutron capture reactions of $^{3}$He, $^{10}$B and $^{6}$Li**

- n + $^{3}$He (0%*) →p + $^{3}$H + 765keV

  σ =5333 barn @ 1.8 Å (~0.025 eV)

- n + $^{10}$B (20%*) →$^{7}$Li + $^{4}$He + 2.8 MeV 7%

  →$^{7}$Li + $^{4}$He + 2.3 MeV+ γ (0.5 MeV) 93%

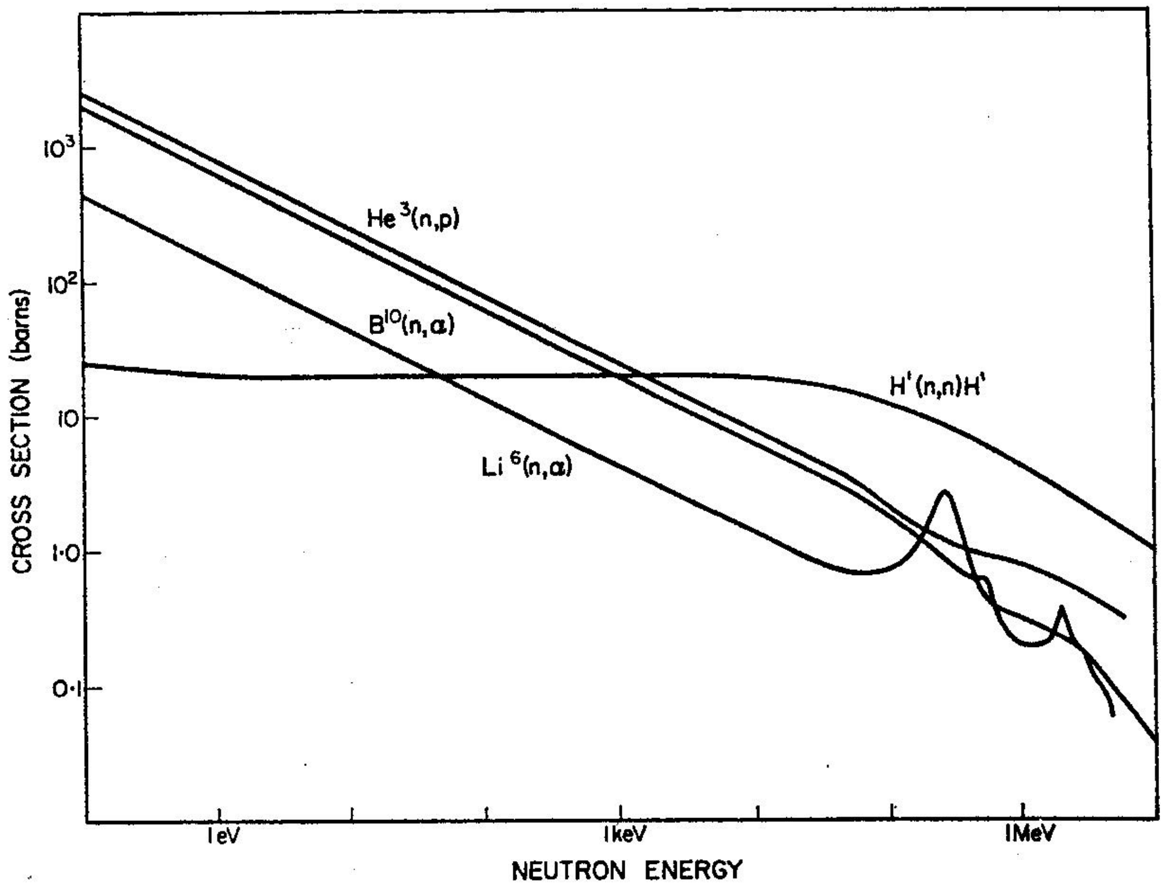
  σ = 3838 barn @1.8 Å

- n + $^{6}$Li (7.5%*) →$^{3}$H + $^{4}$He (4.8 MeV)

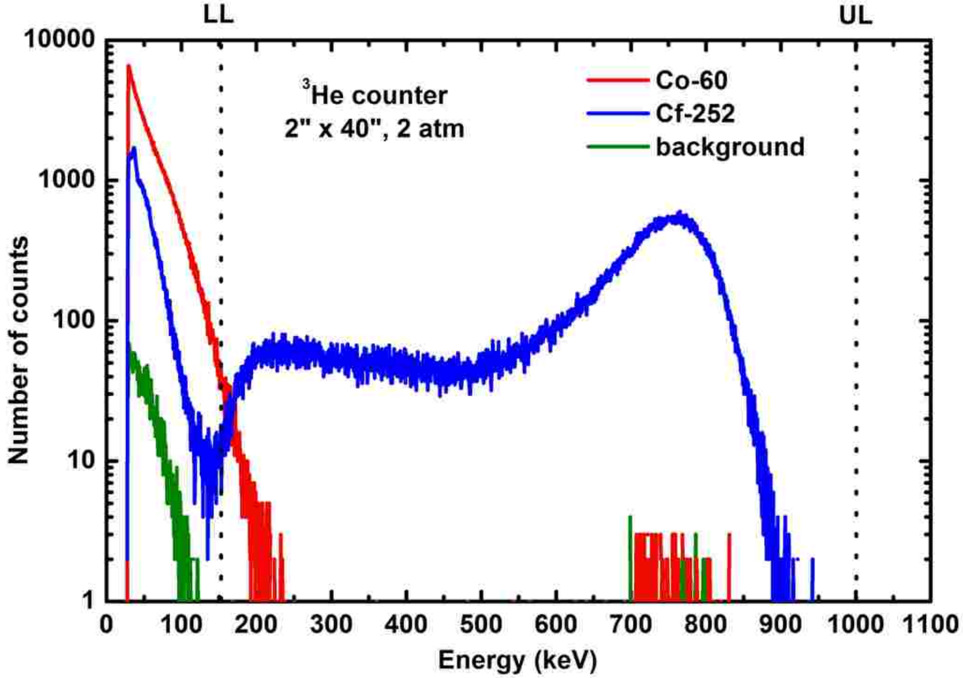
  σ = 941 barn @1.8 Å

C.W.E. Van Eijk, presented at SCINT, Giessen, Germany, 2011

# Inorganic scintillators in neutron detection



# He-3 detectors




Energy spectra measured with He-3 counter under irradiation by γ-rays of a $^{60}Co$ source, $^{252}Cf$ and background.

Note the best gamma rays suppression due to a low atomic number and density of He, enhanced by a good pulse height discrimination

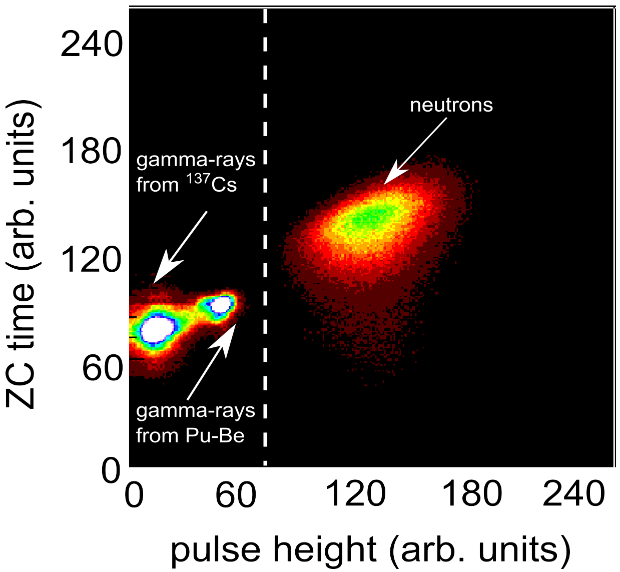
# Classical slow neutron detectors

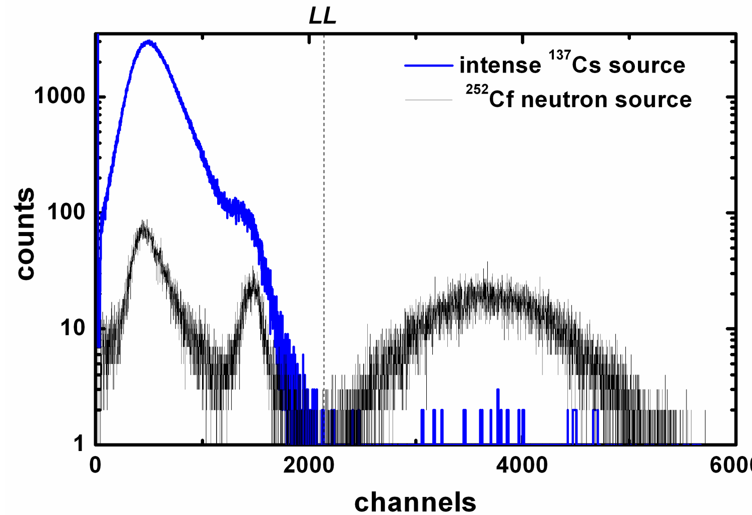
| crystal | Neutron light output (ph/n) | Decay | α/β ratio | PSD |
|---|---|---|---|---|
| $^{6}LiF/ZnS:Ag$ | 160,000 | 80 | 0.44 | + |
| $^{6}Li$-glass | ~7,000 | 70 | 0.35 | + |
| $^{6}LiI:Eu$ | 50,000 | 1,400 | 0.87 | - |

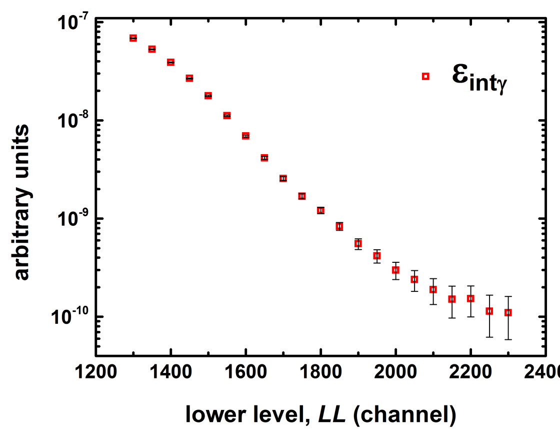
C.W.E. Van Eijk, presented at SCINT, Giessen, Germany, 2011

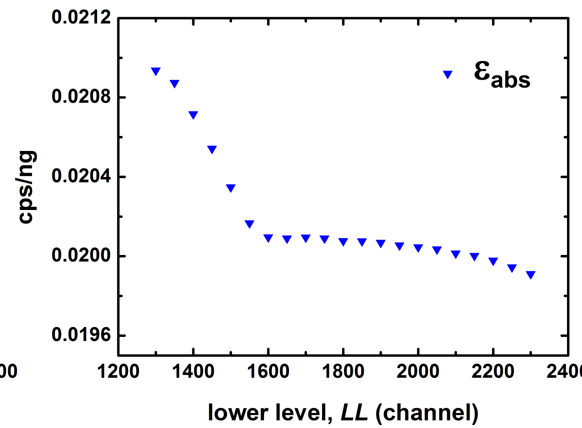
# $^{6}$LiF/ZnS:Ag screens

the screen with a light readout by scintillating fibers proposed by Saint Gobain for homeland security.



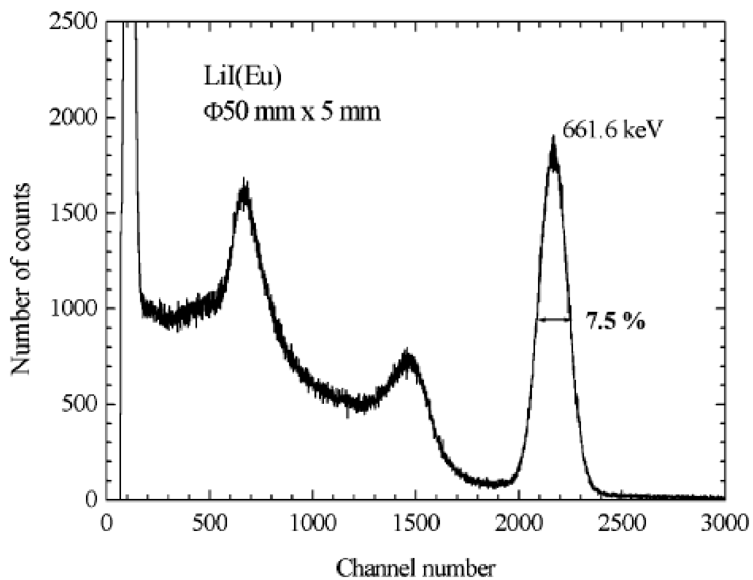



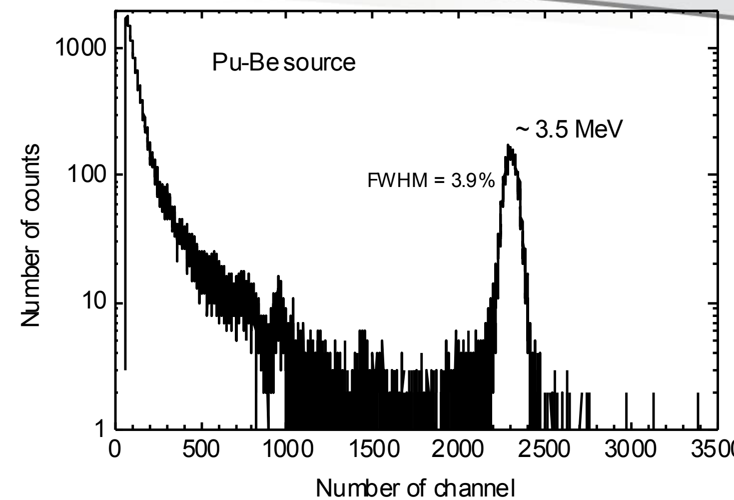



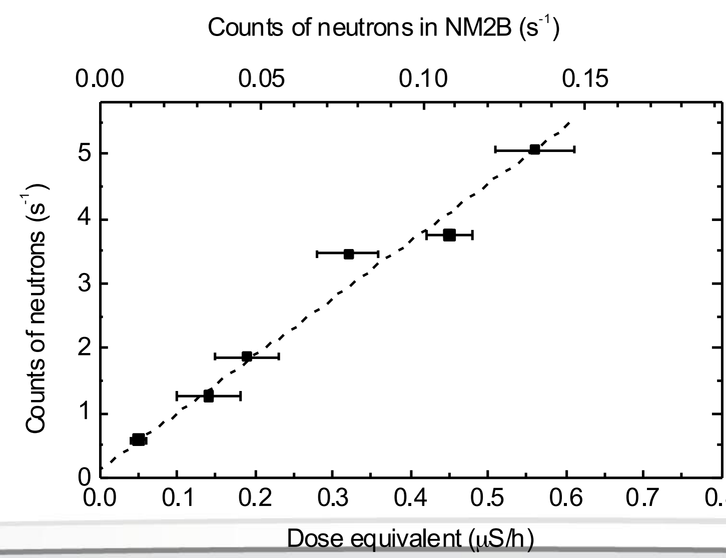



J. Iwanowska, et al.., 2011 IEEE NSS Conf. Rec.

# LiI:Eu




Light output 3000 phe/MeV (XP5200 PMT)

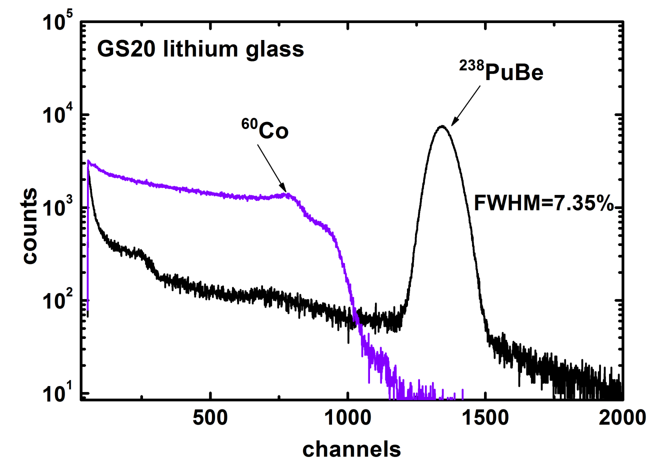
95% of thermal neutrons are stopped in 3 mm of LiI(Eu)

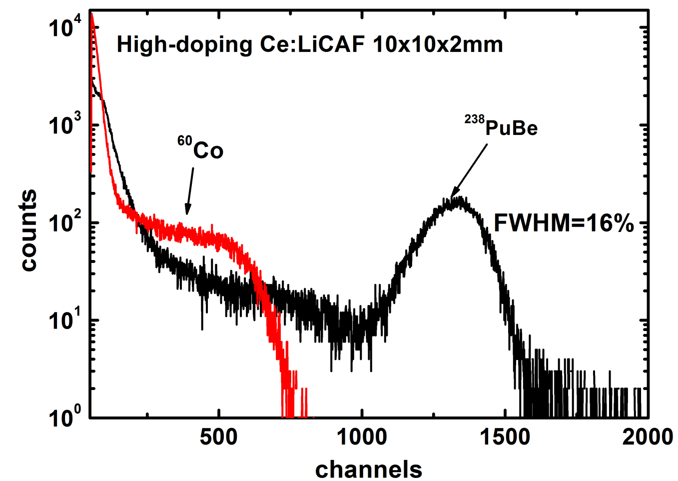
A. Syntfeld, et al., IEEE TNS, 52(2005)3151

# GS20 Li-glass and LiCAF:Ce ($LiCaAlF_6$:Ce)

| scintillator | Light output (phe/MeV) |
|---|---|
| GS20 | 1300 |
| LiCAF:Ce | ~200 |
| LiCAF:Eu | ~8100 |
| LiCAF:Eu (rubber) | ~5600 |

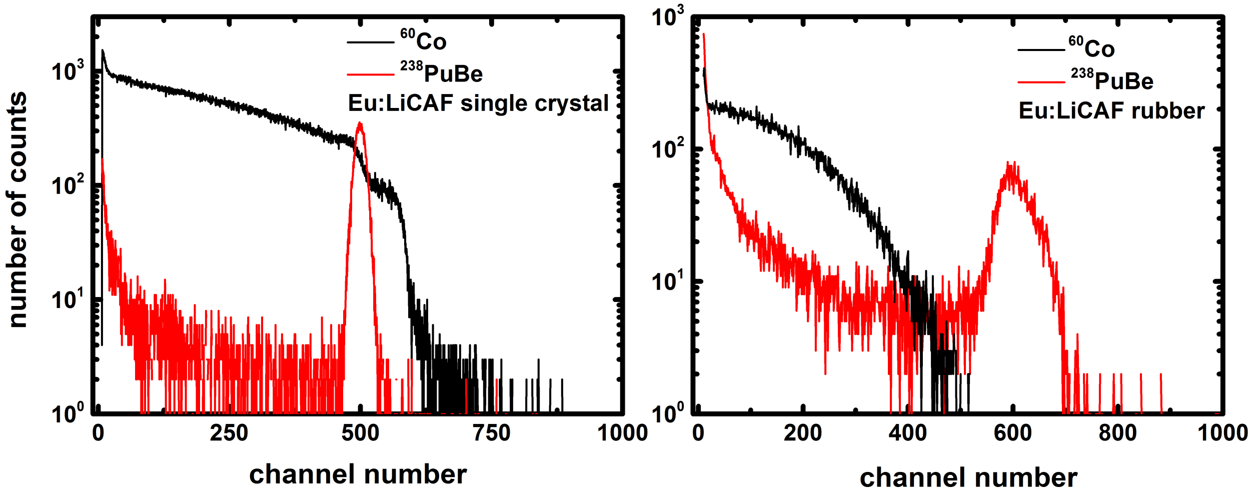
| scintillator | Number of $^6$Li atoms per cm$^3$ | Intrinsic thermal neutron efficiency |
|---|---|---|
| GS20 ∅50 x2 mm | ~$1{,}58\times10^{22}$ | 100% |
| High–doping Ce:LiCAF 10x10x2 mm | ~$0{,}5\times10^{22}$ | 35% |
| Low–doping Ce:LiCAF 10x10x2 mm | ~$0{,}5\times10^{22}$ | 32% |
| High–doping Ce:LiCAF ∅50.8x2mm | ~$1\times10^{22}$ | 82% |




J. Iwanowska, et al., NIM A652(2011)319

# LiCAF:Eu and LiCAF:Eu rubber

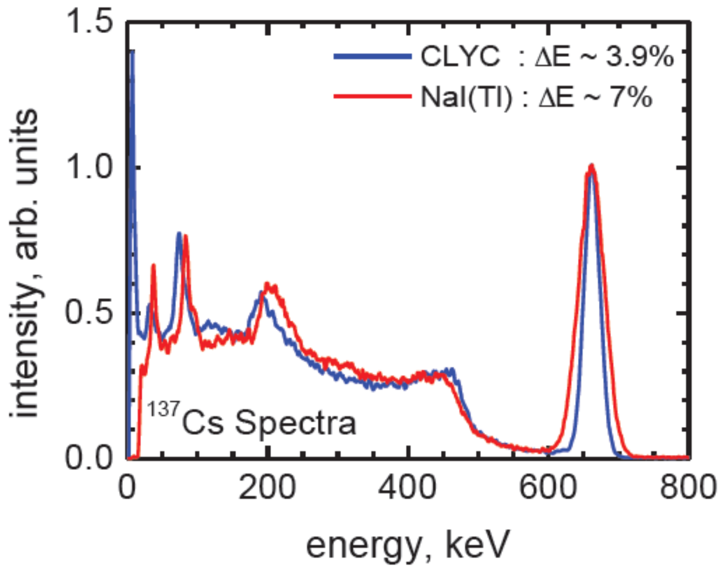


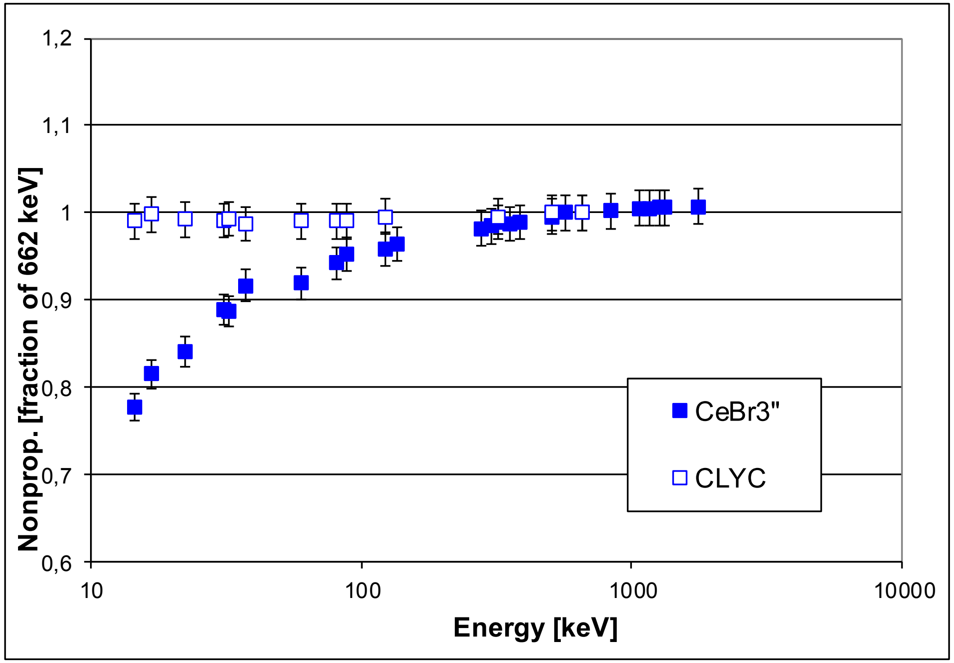

- A limited detection efficiency and pulse height of the gamma ray response is the effect of a small size of LiCAF grain. However, it is sufficient to stop alphas and tritons produced by neutron capture in Li-6.
- Detection efficiency of neutrons in the rubber is about 3 times lower than in the crystal, but gamma rays rejection is more efficient. In the test with 7 MBq Cs-137 source (10 mR/h dose) the intrinsic efficiency of crystal of $10^{-4}$ was reduced to $10^{-6}$ in the test with the rubber.



J. Iwanowska, et al., unpublished data

# CLYC scintillator ($Cs_2LiYCl_6:Ce$)



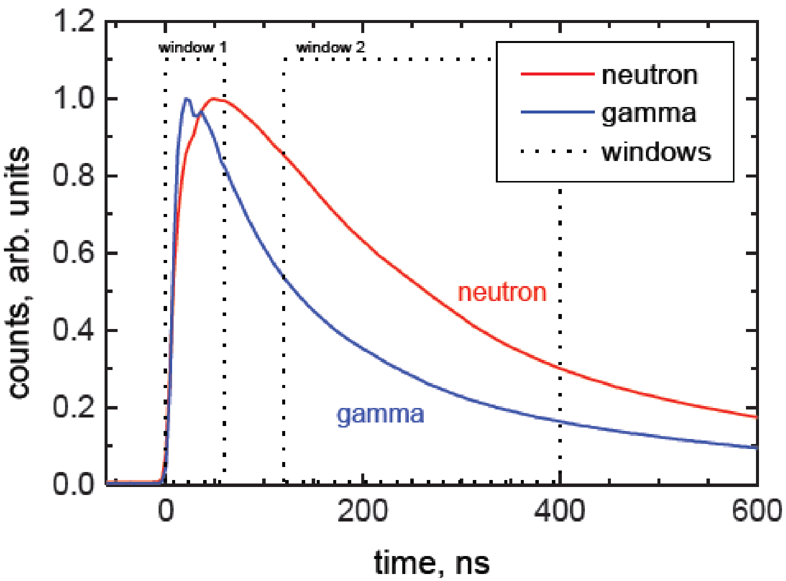



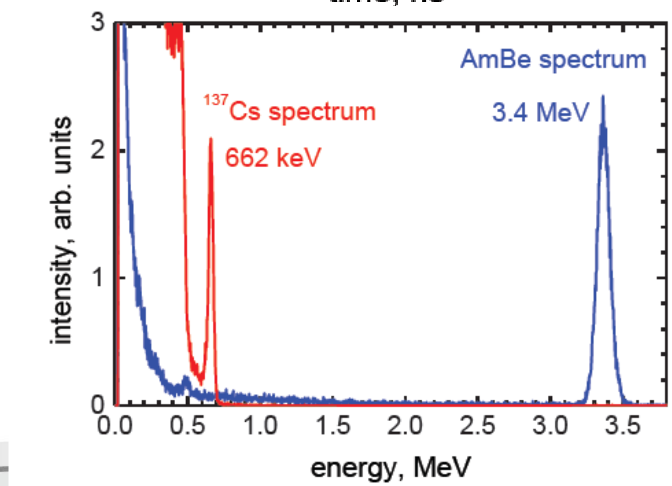

Light output 20,000 ph/MeV

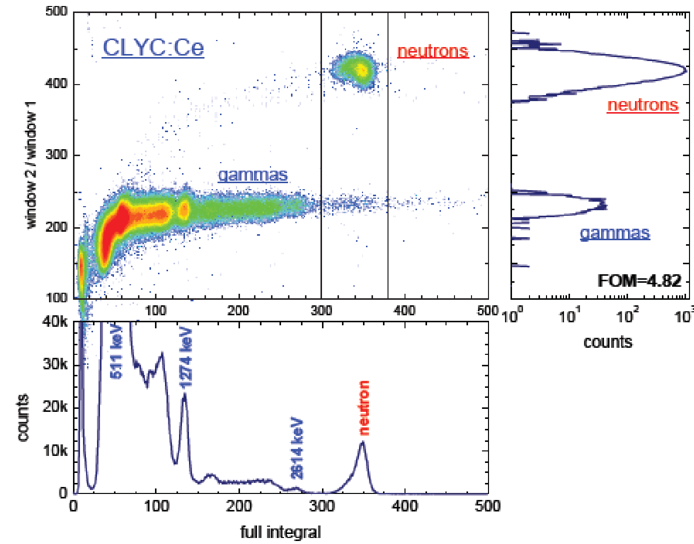
Measured at NCBJ

Following RMD data

# Thermal neutron detection in CLYC



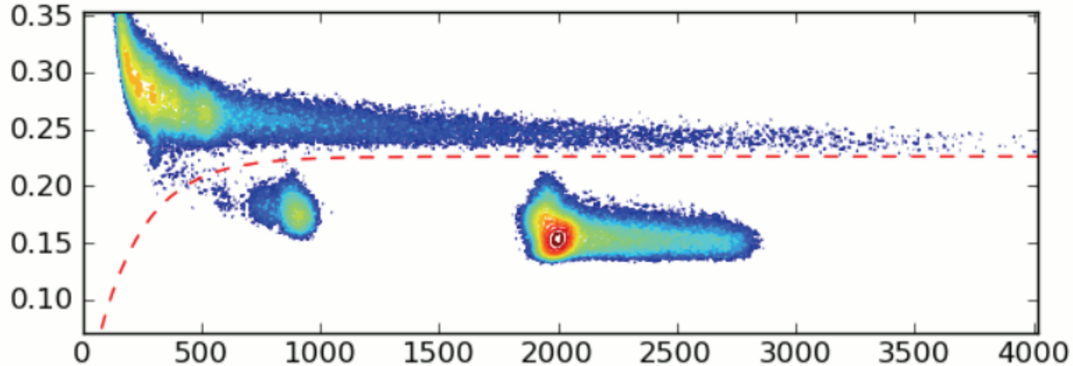




Thermal neutron detection:
$^{6}Li + {}^{1}n \rightarrow \alpha + {}^{3}H + 4.8$ MeV.

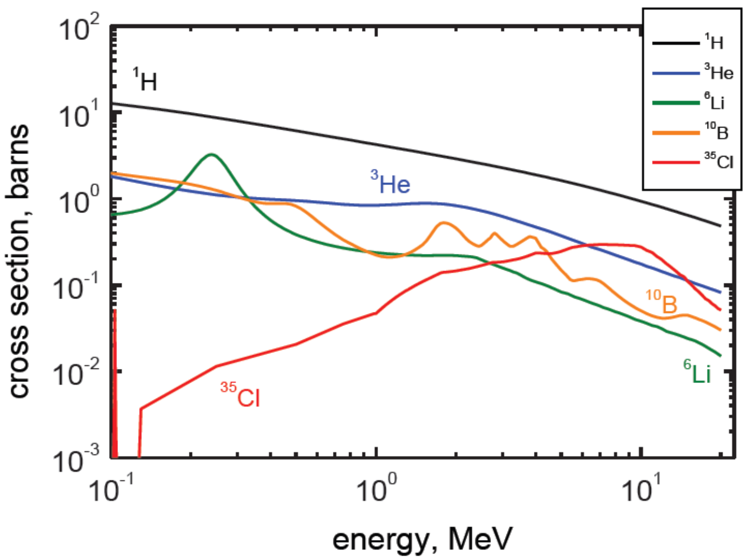
90% of thermal neutrons are stopped in 18.7 mm of CLYC

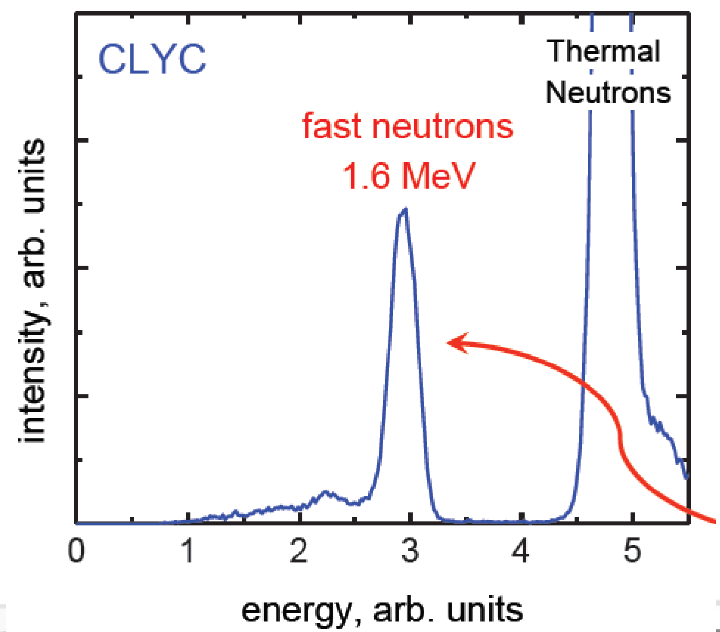
**J. Glodo, et al., presented at SORMA West, 2012**

# Fast neutron detection in CLYC




$^{35}Cl + {}^{1}n \rightarrow {}^{1}p + {}^{35}S$ + energy






**J. Glodo, et al., presented at SORMA West, 2012**

# Summary of new developments

- **Organic scintillators:**

  - EJ 309 high flash liquid
  - New stilbene – a very promising development, it has to be cheaper
  - Plastic scintillators – still in the development phase

  The most important application – physics, due to a good detection efficiency, a good n/gamma PSD and fast timing capabilities.

- Digital n/gamma PSD

# Summary of new developments

## Inorganic scintillators

- CLYC - good performance in thermal neutron detection and gamma spectrometry.
- LiCAF rubber – a very interesting proposition of detector with a good suppression of gamma rays.
- LiI:Eu - renaissance of the old scintillator

Applications: handheld monitors in the homeland security equipment.

# Border monitoring

$^{6}$LiF/ZnS:Ag screens:

This is one of the best proposition to replace He-3 detectors in the border monitoring