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NArCoS

Geant4 simulations to study the efficiency and cross-talk probability in the new neutron correlator NArCoS

G. Santagati[1], **E.V. Pagano**[2], C. Boiano[3], G. Cardella[1], A. Castoldi[4,3], E. De Filippo[1], E. Geraci[5,1], B. Gnoffo[5,1], C. Guazzoni[4,3], G. Lanzalone[6,2], C. Maiolino[2], N. S. Martorana[1], A. Pagano[1], S. Pirrone[1], G. Politi[5,1], F. Risitano[7,1], F. Rizzo[5,2,8], P. Russotto[2], M. Trimarchi[7,1], and C. Zagami[5,2,8].

CHIRONE Coll.

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[6]Università di Enna "Kore", Enna, Italy
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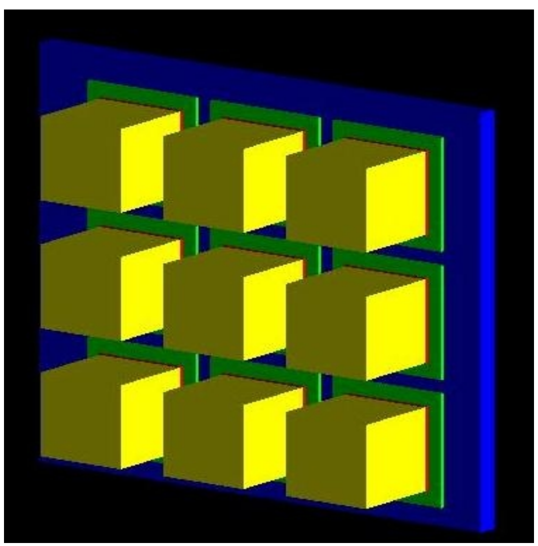
Supported by PRIN ANCHISE (2020H8YFRE)

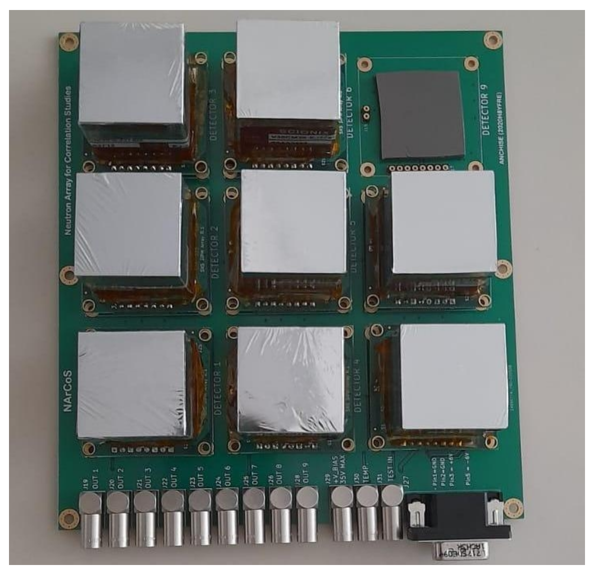
The CROSSTEST experiment

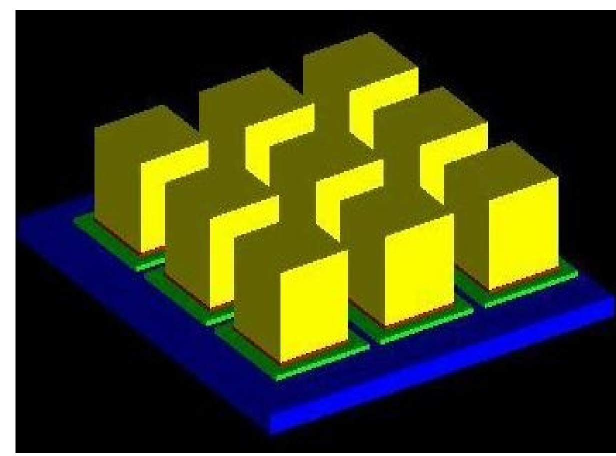
- Present calculations are preparatory for the CROSSTEST experiment
  Spokepersons: E.V. Pagano, T. Marchi, G. Politi, P. Russotto.

- Neutron beam from $p+{}^{7}Li \longrightarrow {}^{7}Be+n$ @ 5.5 MeV.

- Two different detector configurations will be tested:







Matrix configuration

Three-cluster configuration

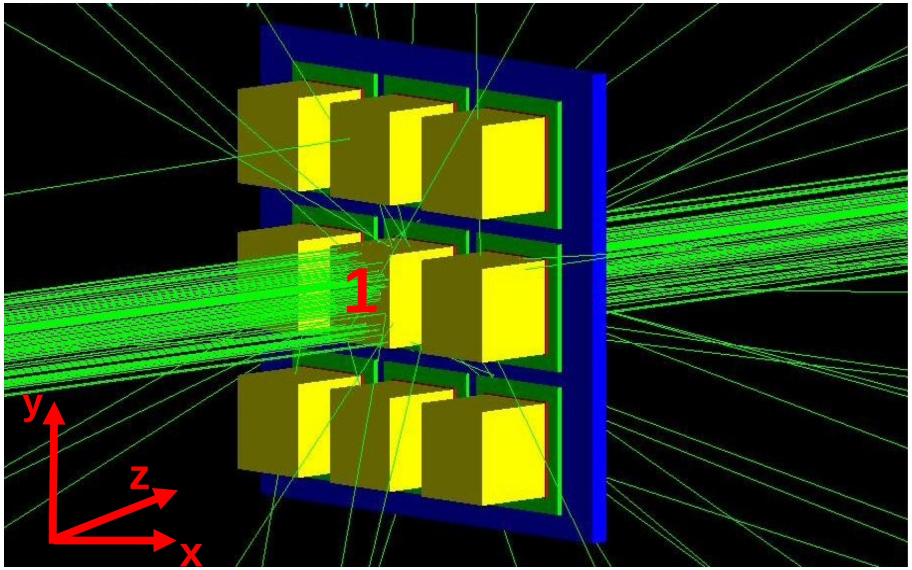
Matrix configuration: CT estimation

Cross-talk definition:

$$CT = Detected - \sum_{i=1}^{9} Cell_i$$

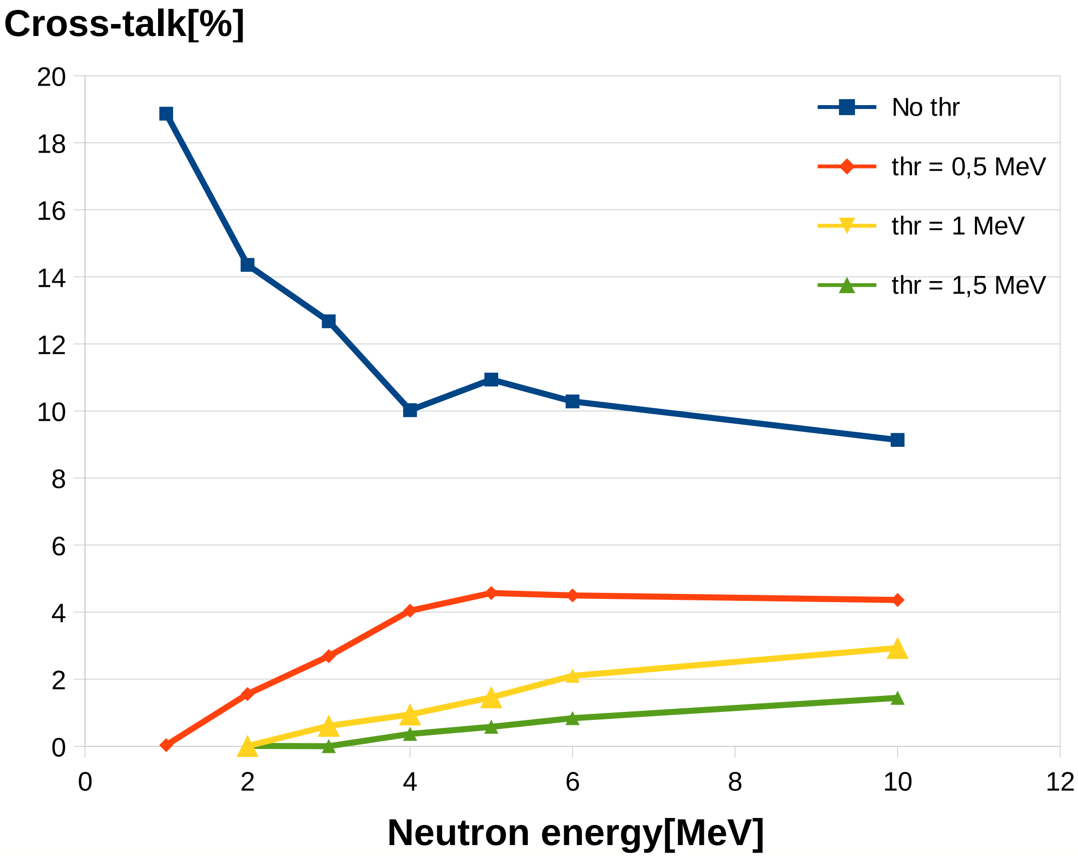
Detected := Integral of the number of particles detected by the whole Matrix detector configuration.

$Cell_i$:= Number of particles detected by one and only single detector cell i



Simulated beam:

- 10^5 neutrons in air configuration
- E_{inc} = {1,2,3,4,5,6,10} MeV
- Uniform distribution impinging on the central cell
- Cell detection thresholds: {0.0,0.5,1.0,1.5} MeV



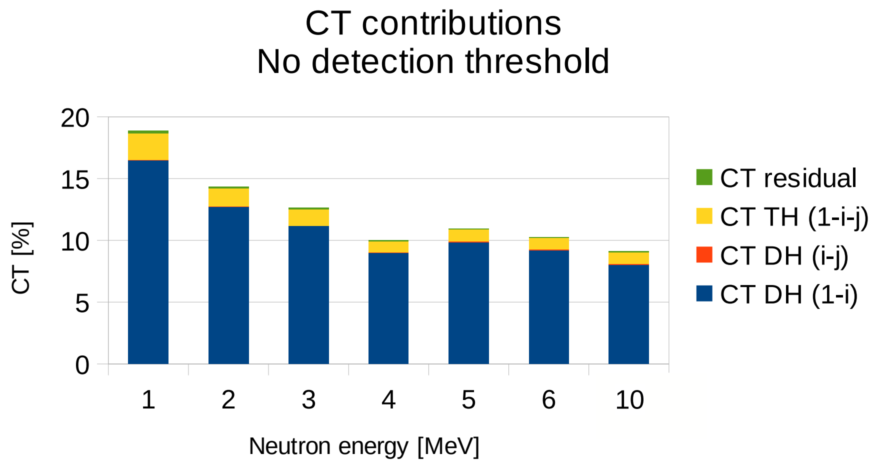
Matrix configuration: CT contributions

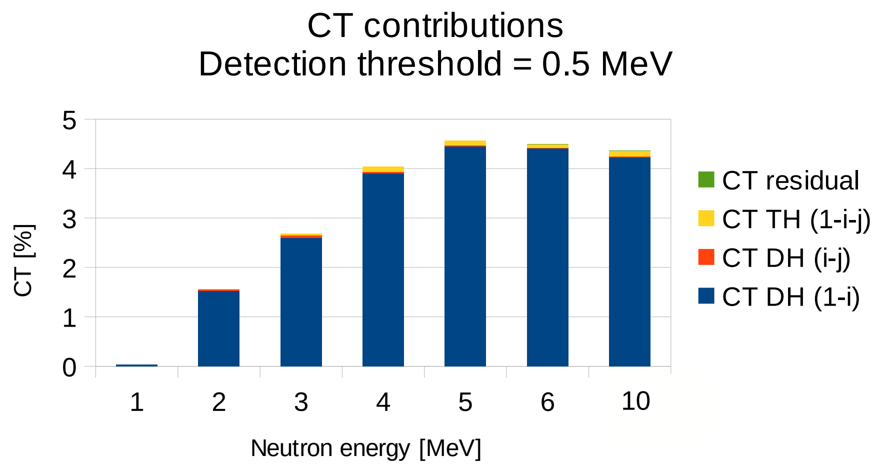
CT DH (1-i) := Double-hits cross-talk from cell 1 to cell i with i = {2,…,9}.

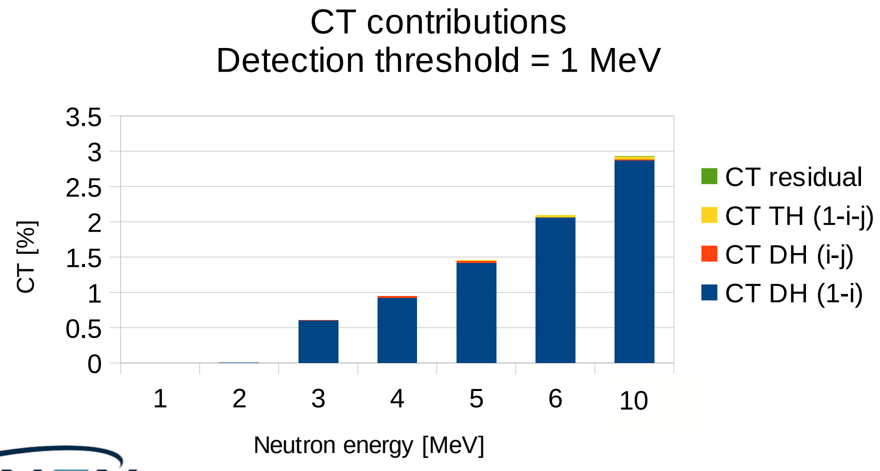
CT DH (i-j) := Double-hits cross-talk from cell i to cell j with i = {2,…,9} and j = {2,…,9} and i ≠ j.

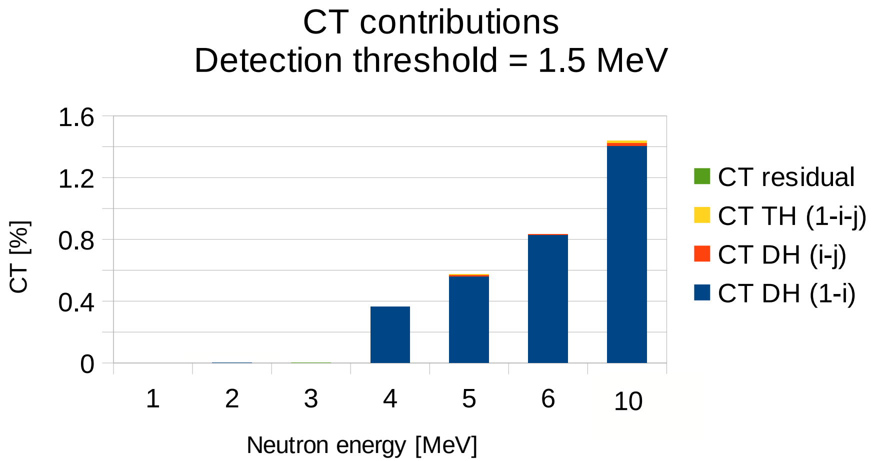
CT TH (1-i-j) := Triple-hits cross-talk from cell 1 to cell i to cell j, with i = {2,…,9} and j = {2,…,9} and i ≠ j.

CT residual := All other possible cross-talk combinations.



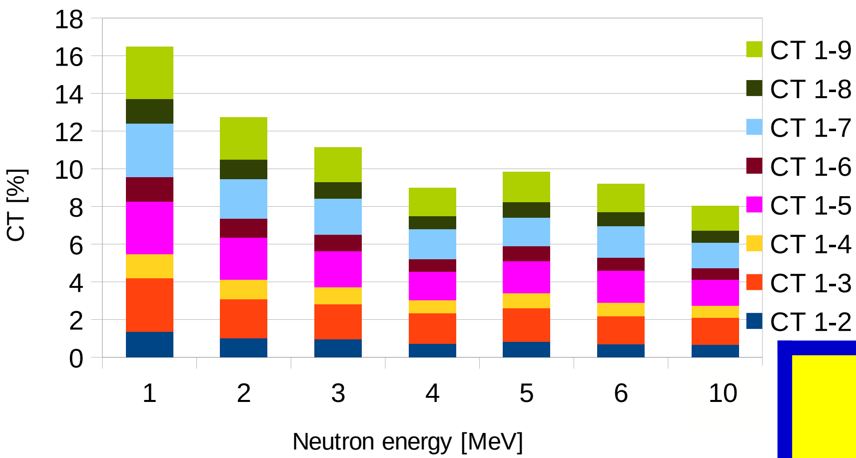




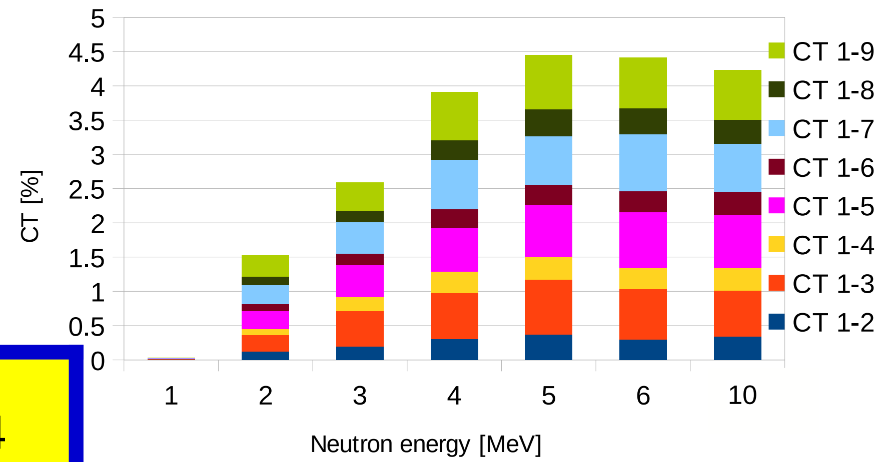


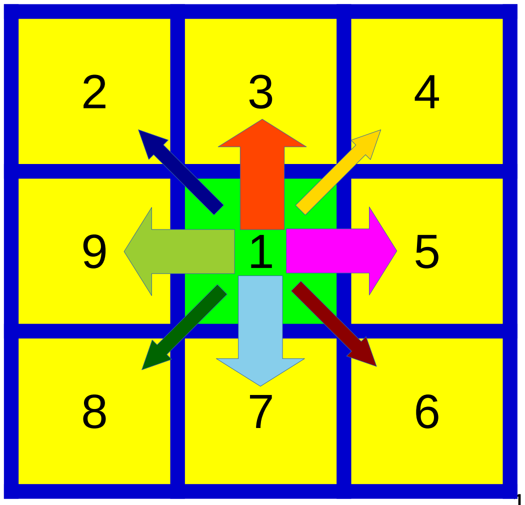
Matrix configuration: DH CT distributions

CT DH (1-i) distributions
No detection threshold

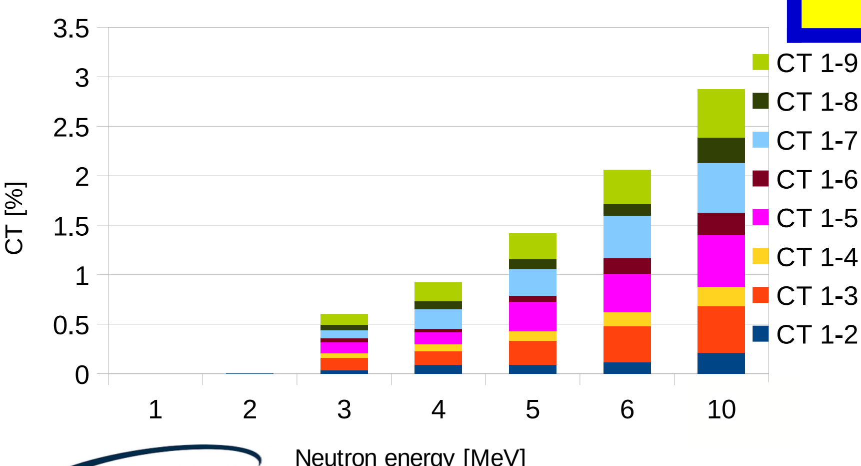


CT DH (1-i) distributions
Detection threshold=0.5 MeV

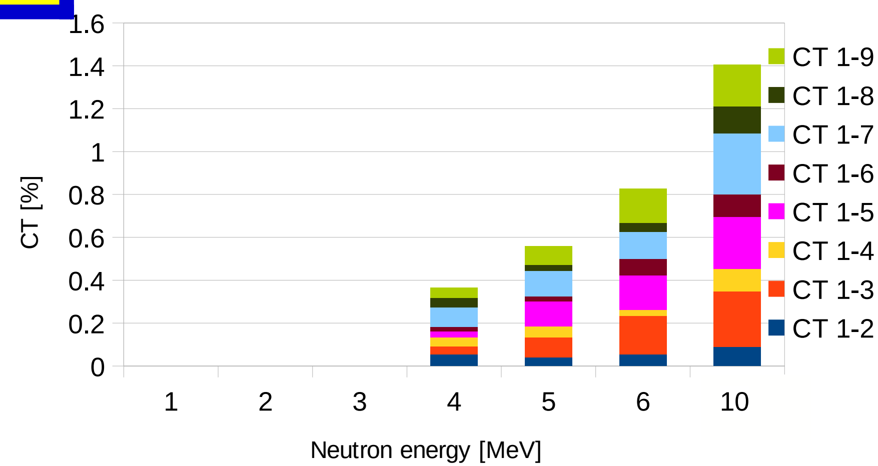




CT DH (1-i) distributions
Detection threshold= 1 MeV



CT DH (1-i) distributions
Detection threshold= 1.5 MeV



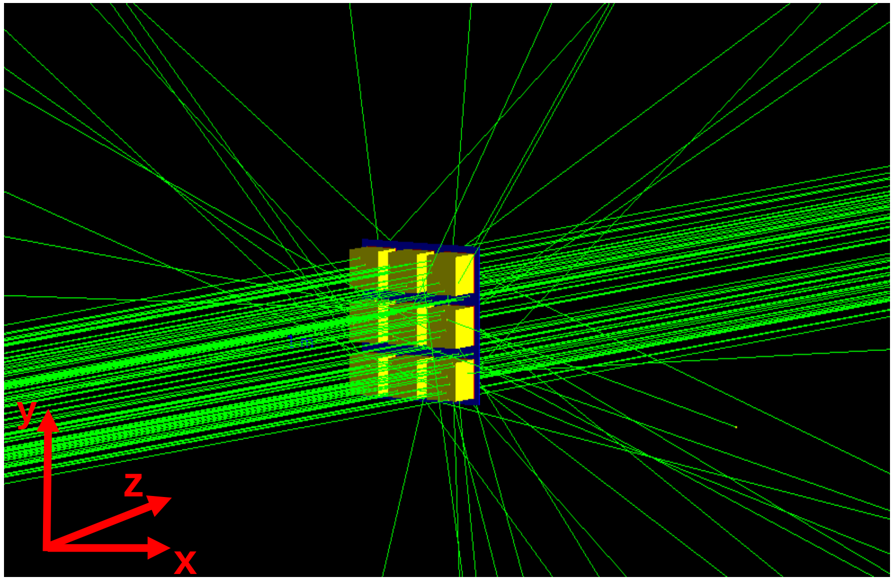
Matrix configuration: Efficiency estimation

Detection efficiency definition:

Efficiency = Detected / Total

Detected:= Integral of the number of particles detected by the whole Matrix detector configuration.

Total:= Number of neutrons simulated impinging on the entire Matrix detector configuration surface.



Simulated beam:

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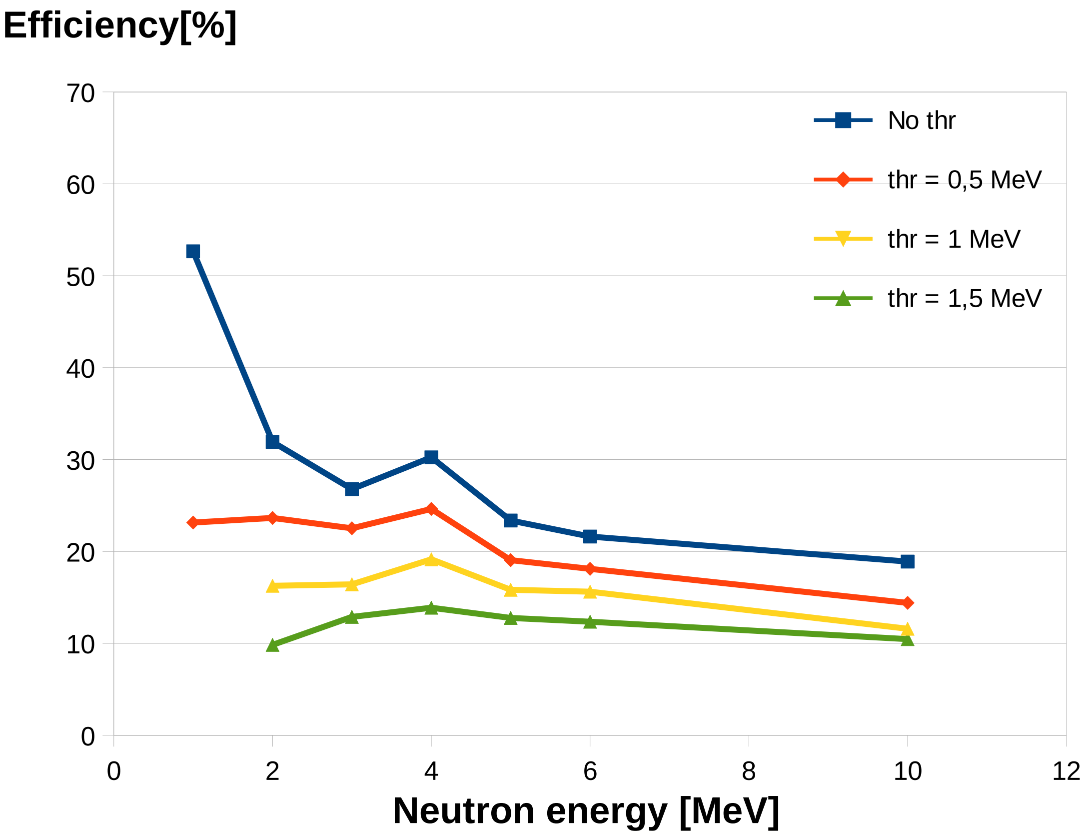


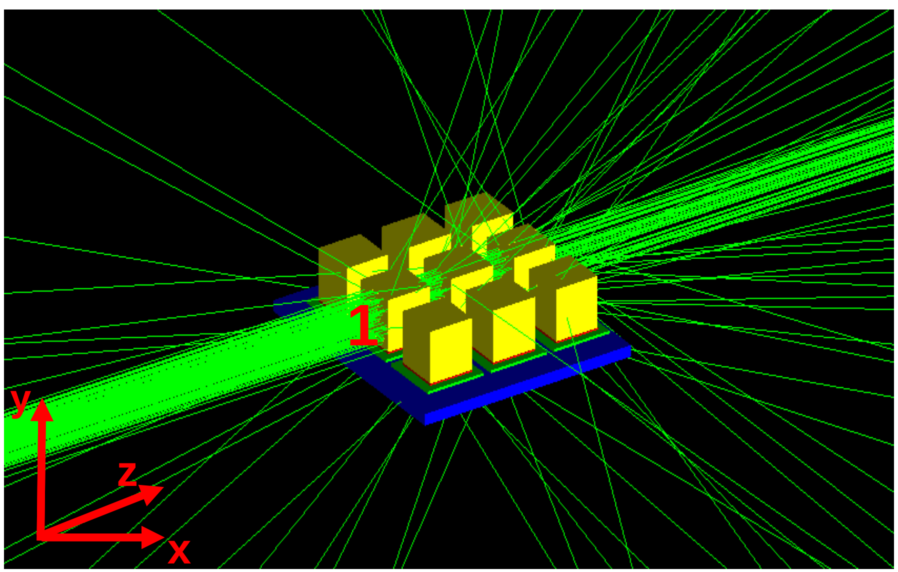
Three-cluster configuration: CT estimation

Cross-talk definition:

$$\mathbf{CT = Detected - \sum_{i=1}^{9} Cell_i}$$

Detected:= Integral of the number of particles detected by the whole three-cluster detector configuration.

$Cell_i$:= Number of particles detected by one and only single detector cell i



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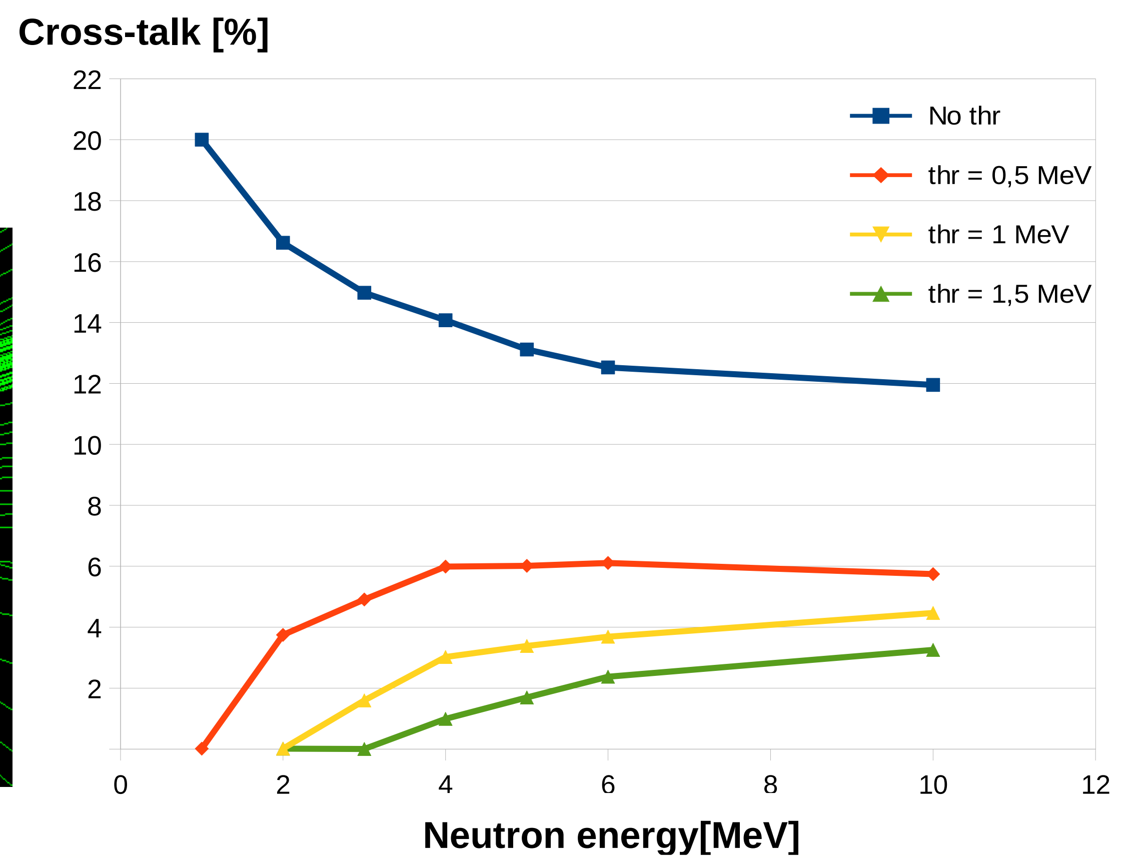
- Uniform distribution impinging on the central cell
- Cell detection thresholds {0.0,0.5,1.0,1.5} MeV



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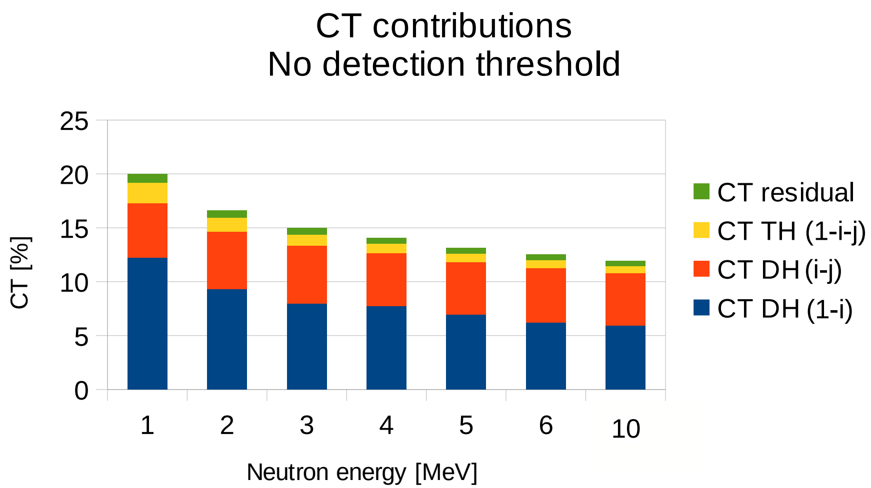
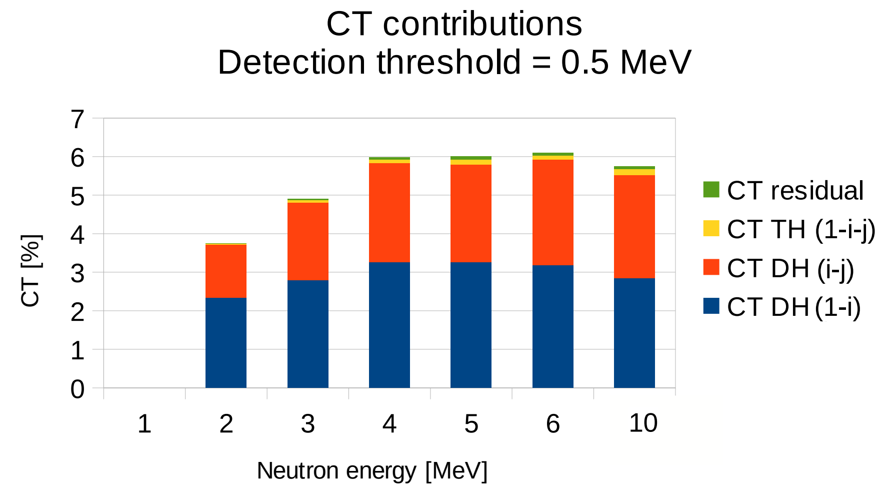
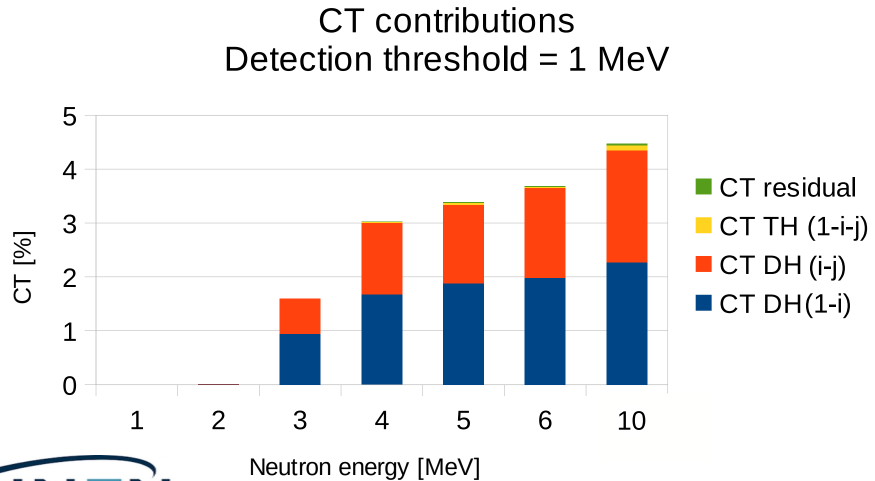
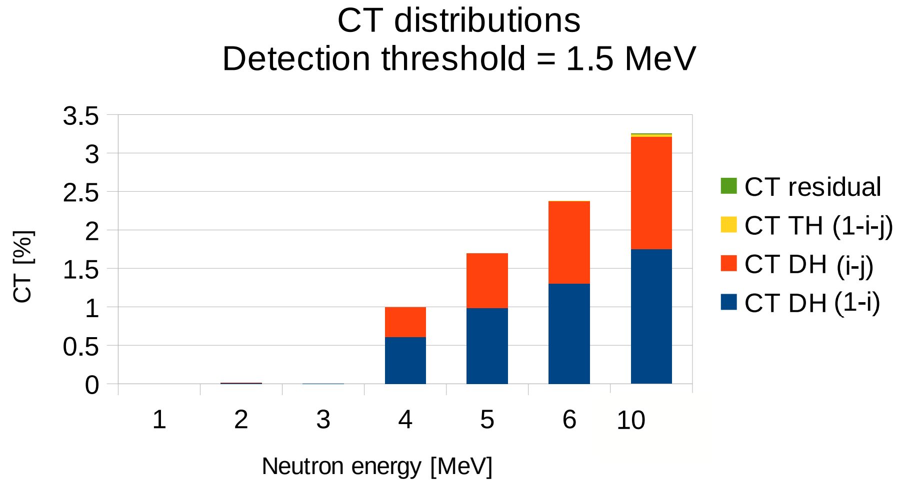
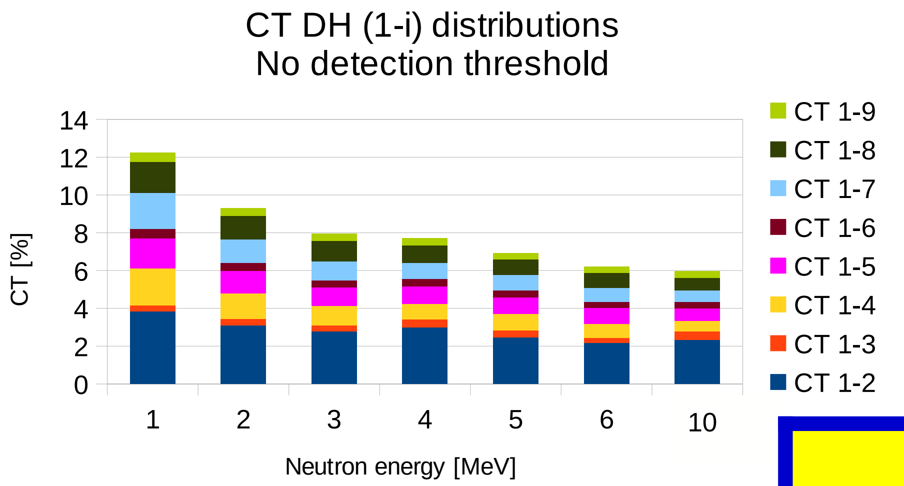


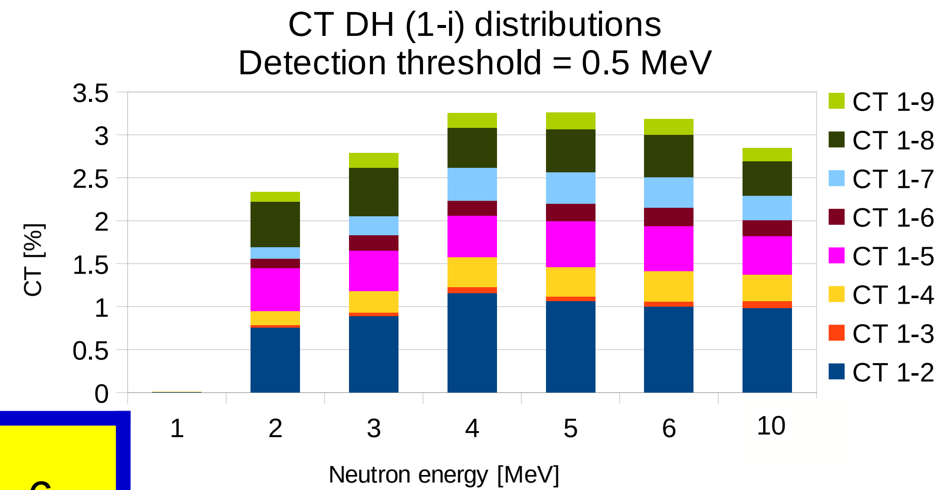


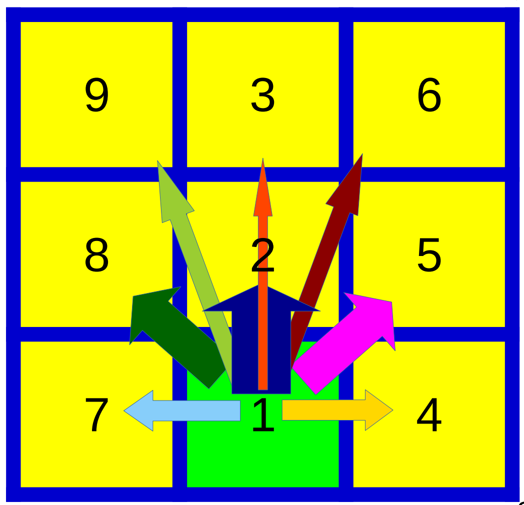


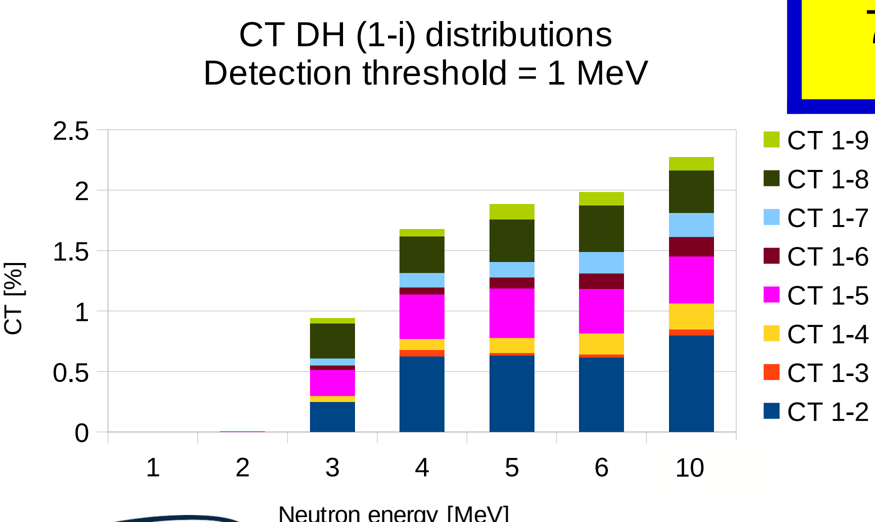


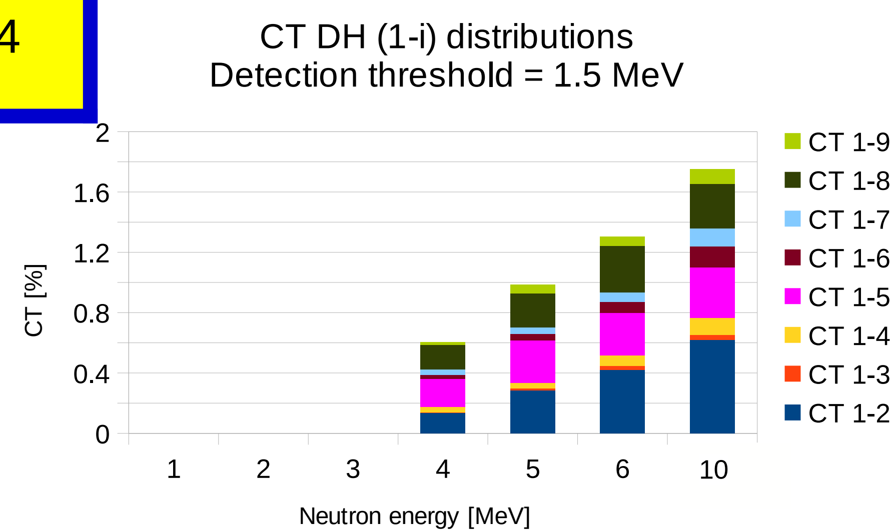
Three-cluster conf.: CT DH (1-i) distributions



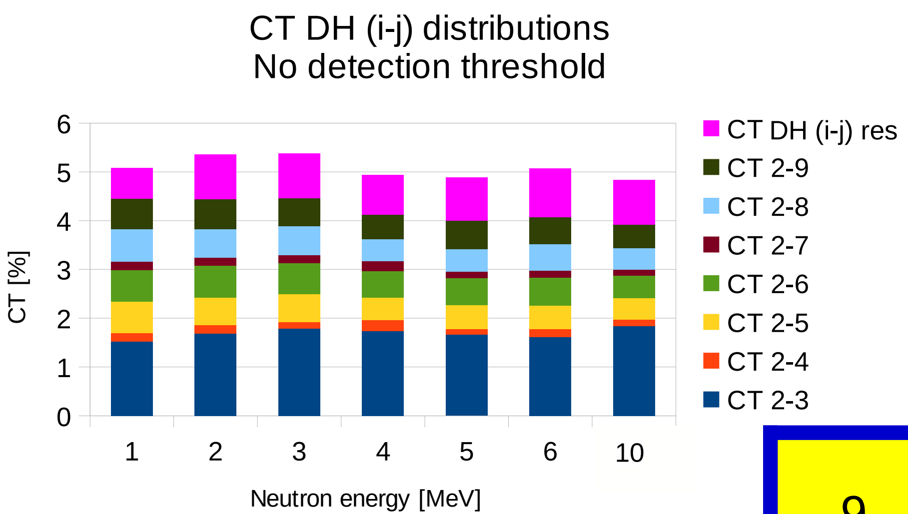


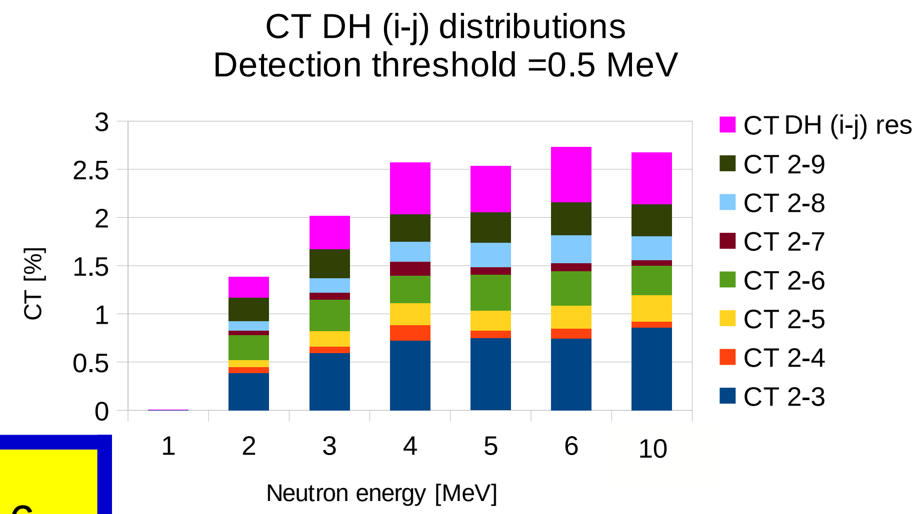


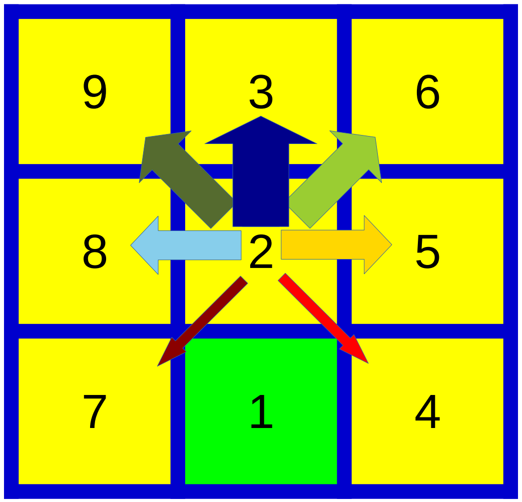


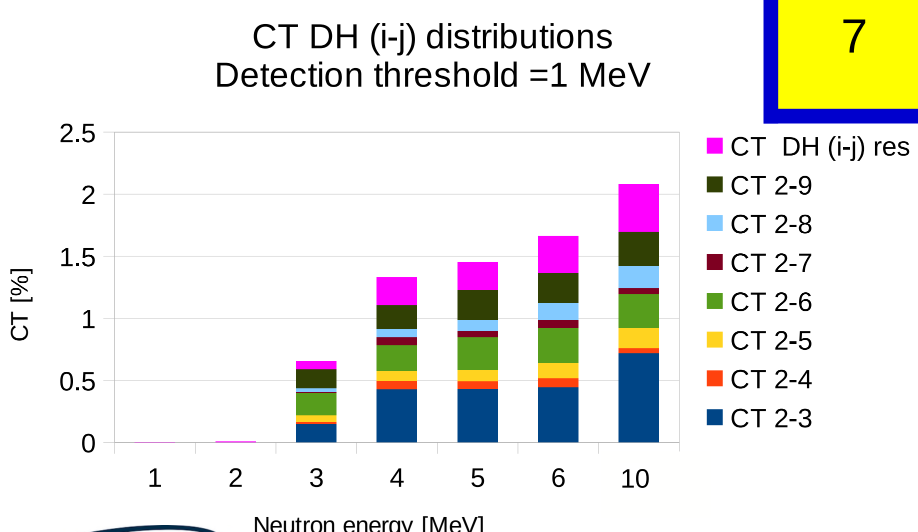


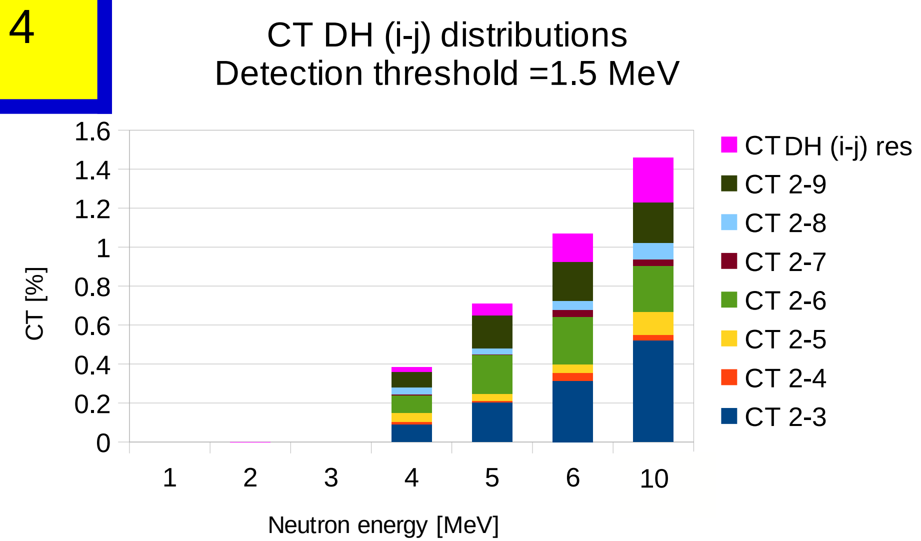
Three-cluster conf.: CT DH (2-i) distributions











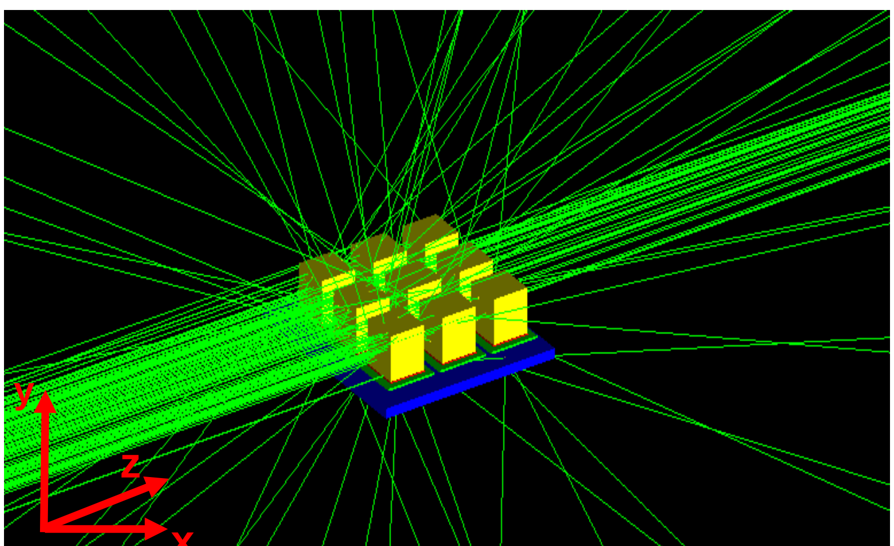
Three-cluster configuration: Efficiency estimation

Detection efficiency definition:

Efficiency = Detected / Total

Detected:= Integral of the number of particles detected by the whole three-cluster detector configuration

Total:= Number of neutrons simulated impinging on the entire three-cluster detector configuration surface.



Simulated beam:

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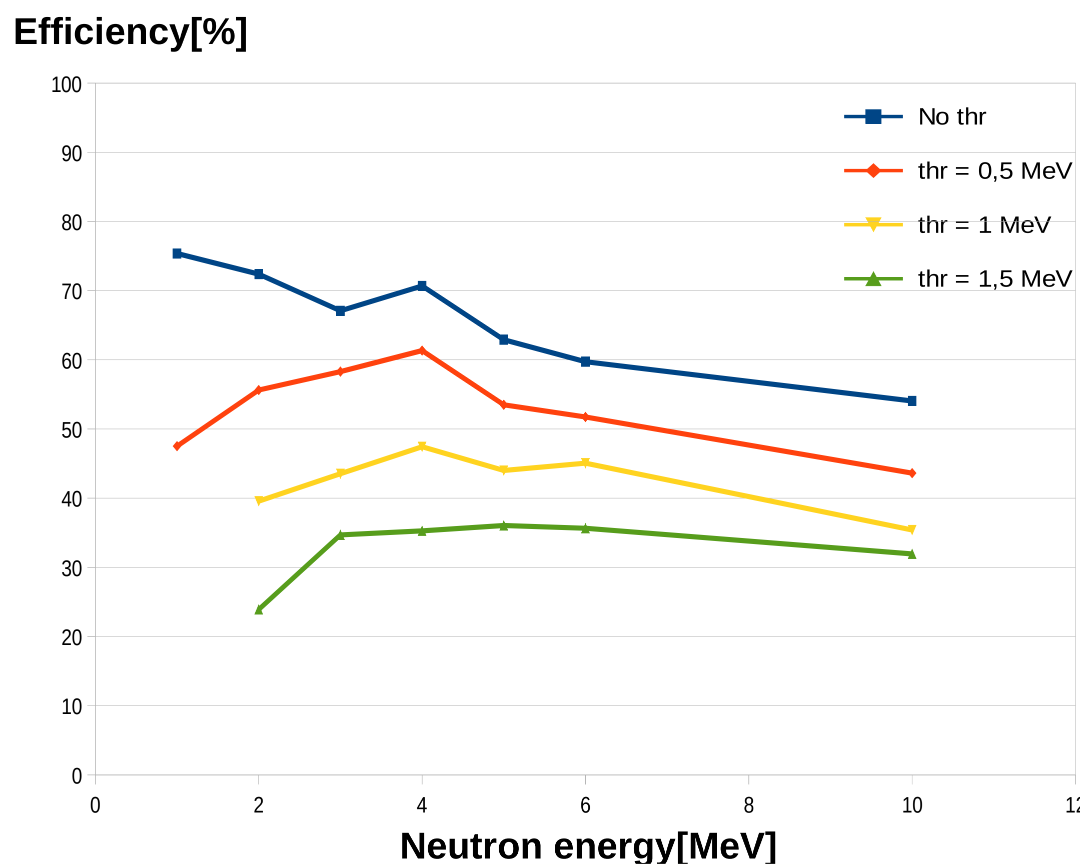
- E_{inc} = {1,2,3,4,5,6,10} MeV
- Uniform distribution impinging on the entire three-cluster surface
- Cells detection thresholds: {0.0,0.5,1.0,1.5} MeV



Future calculations

- Particle tracking code implementation (event by event information).
- Volume and edge effects estimations.
- Mechanical structure effects.
- Background estimation (Cosmic-Rays and environmental contributions)
- Extension to higher energy neutron distributions.
- Attenuator material (or veto detectors) between cells (possible solution for charged particles cross-talk).
- Final detector configuration (64 elementary cells).

Conclusions & Outlook

According to the simulations

- Due to high cross-talk probabilities it is not possible to work with very low detection thresholds.

- Reasonable cross-talk probabilities (~1-4%) in both geometrical configurations were found with 1-1.5 MeV detection thresholds.

- Higher detection efficiency (~33-40%) were found for the three-cluster configuration respect to the matrix configuration (~11-15%) with 1-1.5 MeV detection threshold.

✓ A prototype test will be performed at the end of November 2023 at LNL using a neutron beam and the experimental results will be compared with simulations.

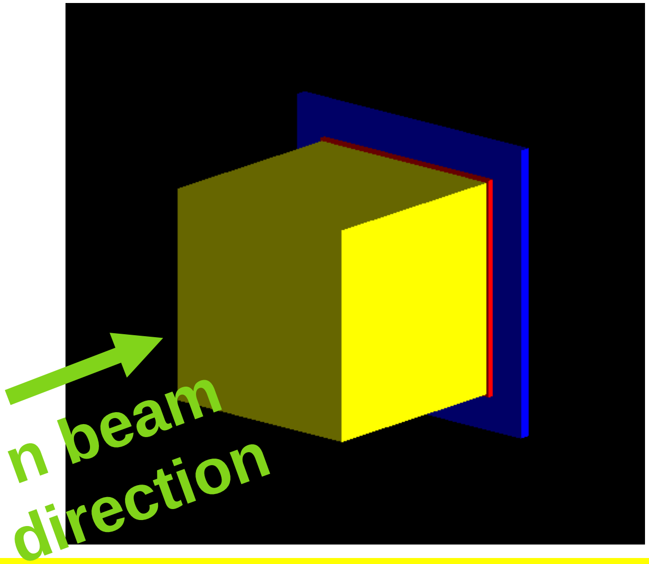
Thanks for your attention!

NArCoS

EJ276-G elementary cell

Each elementary cell of EJ276G (3x3x3 cm^3) is equipped with a matrix of 25 SiPM (6x6 mm^2) of 30 μm of thickness (≈ 40k microcells).

The SiPM matrix is coupled with the plastic having theirs PAC and bias/temperature compensation circuit



EJ276-G scintillator cell dimension:

- 3x3x3 cm^3

SiPM matrix chip dimension:

- 30.7 x 30.7 x 0.96 mm^3

PCB board dimension:

- 40.8 x 40.8 x 1.6 mm^3

- GEANT4 Libraries used: QGSP_BIC_HP

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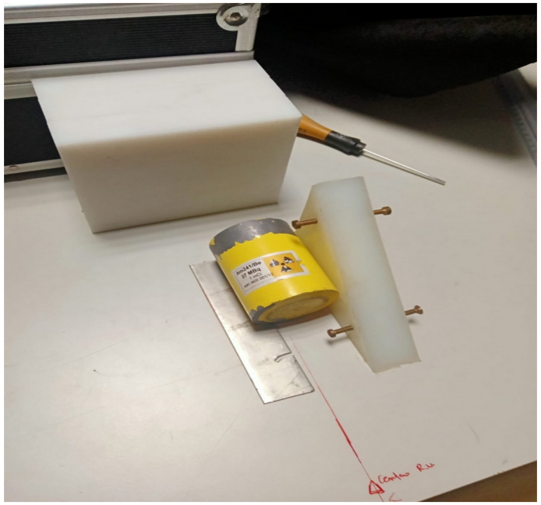
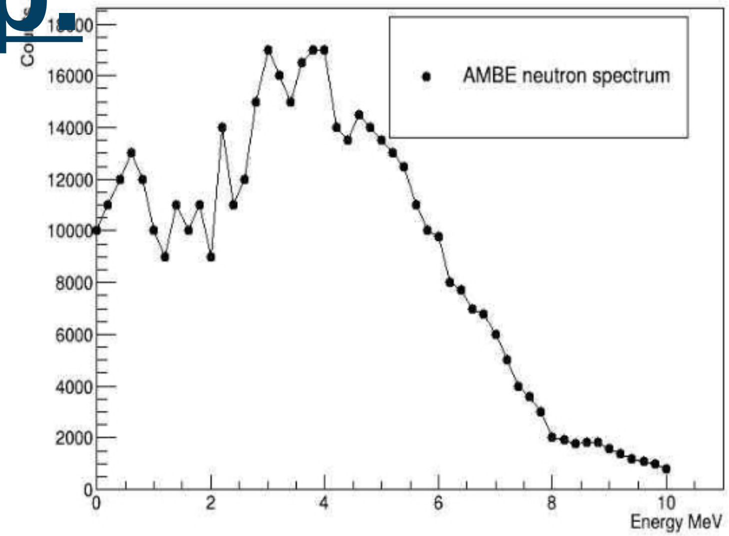
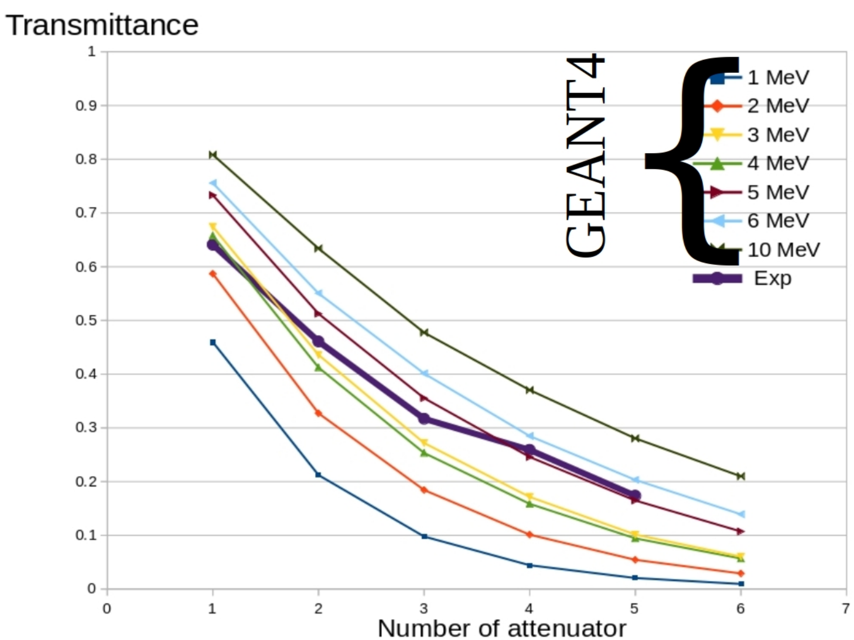
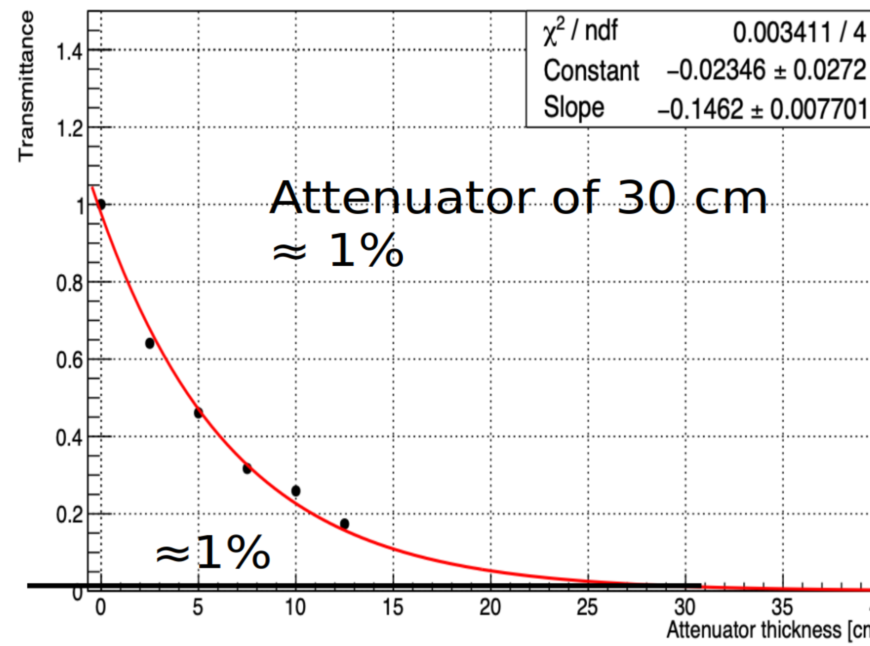
Attenuation study for the CROSSTEST exp.









Physics cases and application

Energy of interest: 2 MeV ≤ E_n ≤ 50 MeV (having particular attention for Fermi energy regime)

Nuclear fundamental physics

In medium nuclear interaction
Intensity interferometry (HBT effect)
n-n, n-p, n-LCP, n-IMF, n-TLF, n-PLF
Studies on nuclear symmetry energy (EOS) and its dependence on the nuclear density
Neutron stars
Reaction mechanism
Reaction times
Clustering and nuclear structure of unbound exotic nuclei
Validation of nuclear dynamics model (BUU,QMD)
Measurements of the neutron signal in the n-rich RIBs (SPES, SPIRAL2, FRIB, FAIR)

Some applications

Radioprotection
Measurement of neutron flux (single measurement, cross section)
Validation of MC based code(GEANT4, MCNPX)
Homeland security

Purpose of the project: fundamental nuclear physics examples

Intensity interferometry (HBT effect)

Correlation functions $$1 + R(q) = C\frac{Y_{Coinc}(q)}{Y_{Uncor}(q)}$$

Space-time characterization of the emitting source

N. Colonna et al., PRL **75**, 23 (1995) 4190-4193

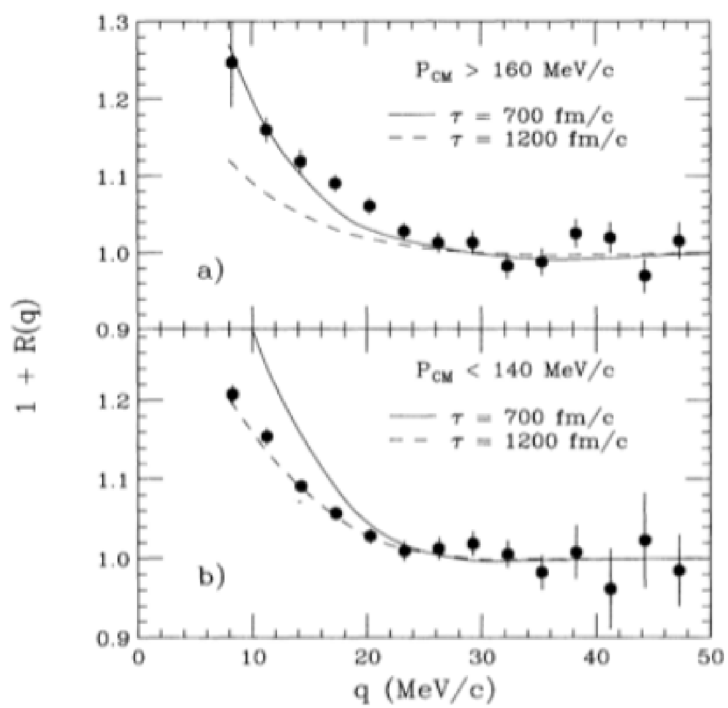


FIG. 3. Angle-integrated correlation functions for two cuts on the total neutron pair momentum in the compound nucleus frame. The solid and dashed curves are results of theoretical calculations with the indicated emission time scales.

R. Ghetti et al., PRL **87**, 10 (2001)

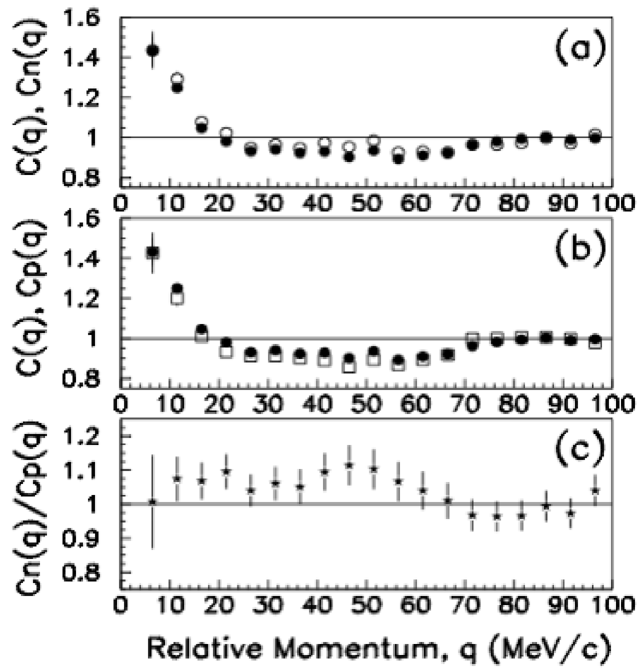
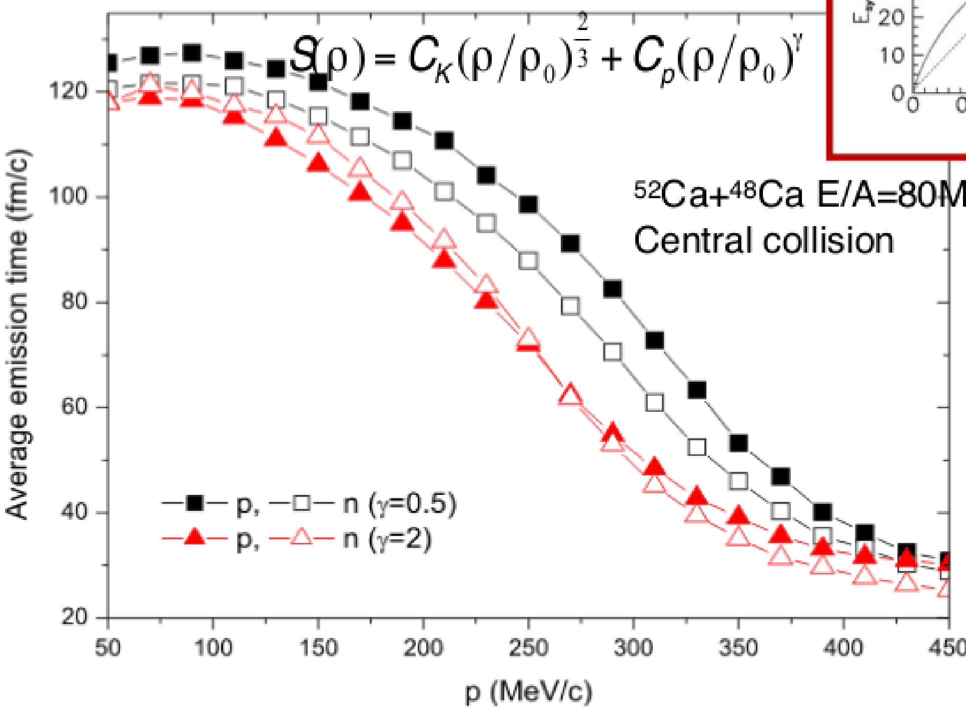


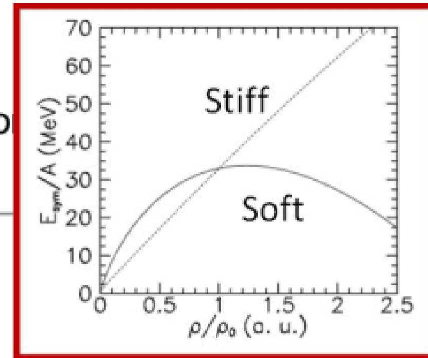
FIG. 2. Experimental ungated np correlation function $C(q)$, from the $E/A = 45$ MeV ^{58}Ni + ^{27}Al reaction [solid dots in panels (a),(b)] compared to panel (a), open circles: $C_n(q)$, constructed from pairs of type $E_n > E_p$, and panel (b), open squares: $C_p(q)$, constructed from pairs of type $E_n < E_p$. The ratio C_n/C_p is shown in panel (c).

Purpose of the project: fundamental nuclear physics examples

Correlation functio

$$S(\rho) = C_K(\rho/\rho_0)^{\frac{2}{3}} + C_p(\rho/\rho_0)^{\gamma}$$





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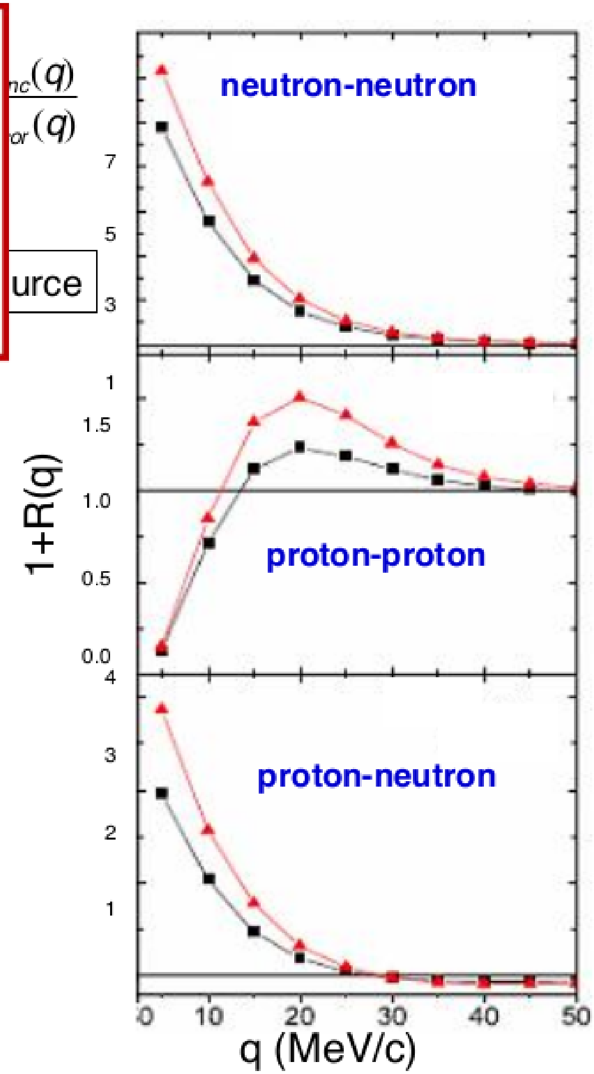

Lie-Wen Chen et al., PRL (2003); PRC(2005)

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Purpose of the project application examples

Anti-cancer therapy:
Risk of secondary radio-induced cancers

In proton therapy, in particular in the pediatric one (but not only), the "damage" caused from the neutron to the healthy cells is one of the principal causes of the so called " secondary radio-induced tumors" in particular if there are used degraders or collimators (passive technique)[1].

[1] Hall, E. J (2006) Intensity-modulated radiation therapy, protons, and the risk of second cancers.
Int J Radiat Oncol Biol Phys 65: 1-7.

Validation of Monte Carlo codes

Measurement of cross sections ($d^2\sigma/d\theta dE$) have a huge interest for the validations of Monte Carlo code like GEANT4 in particular for neutrons in the Fermi energy regime

Neutron Camera

Possible device for homeland security and health safety to be installed in airports, ports, etc...

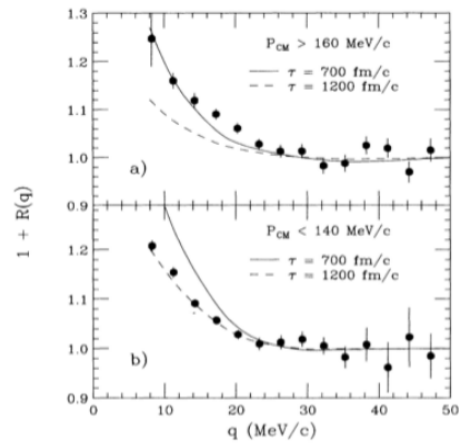
Purpose of the project: fundamental nuclear physics examples

Intensity interferometry (HBT effect)

Correlation functions $$1 + R(q) = C\frac{Y_{Coinc}(q)}{Y_{Uncor}(q)}$$

Space-time characterization of the emitting source

N. Colonna et al., PRL **75**, 23 (1995) 4190-4193



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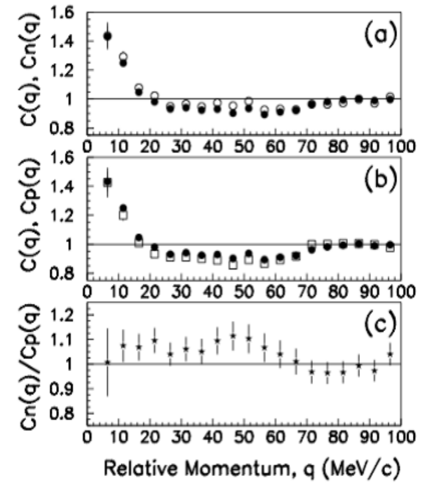

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Correlation functio

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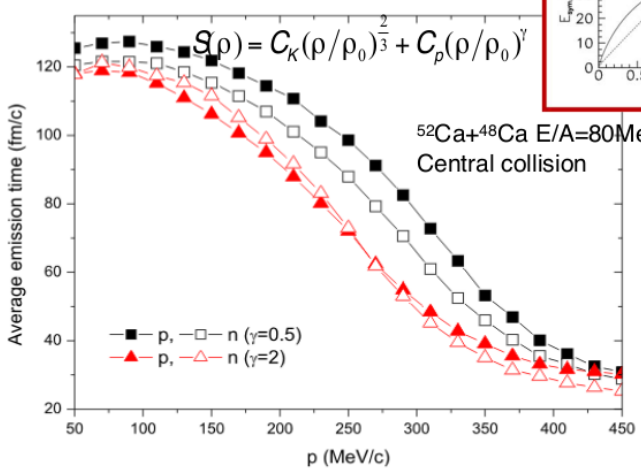
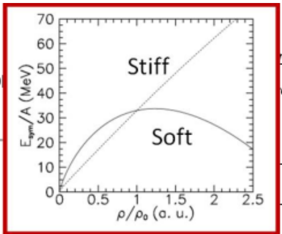


$^{52}Ca + ^{48}Ca$ E/A=80MeV
Central collision



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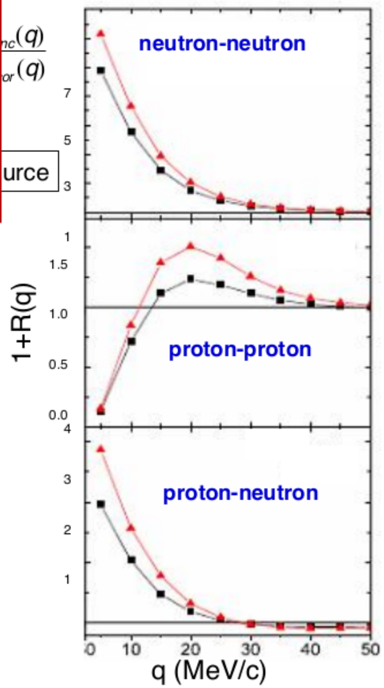


Lie-Wen Chen et al., PRL (2003); PRC(2005)

Cross-talk

È un problema poco rilevante in misure in singola mentre non si può sottovalutare per misure in coincidenza e soprattutto a piccoli impulsi relativi!

N. Colonna et al., NIM A 381 (1996) 472-480

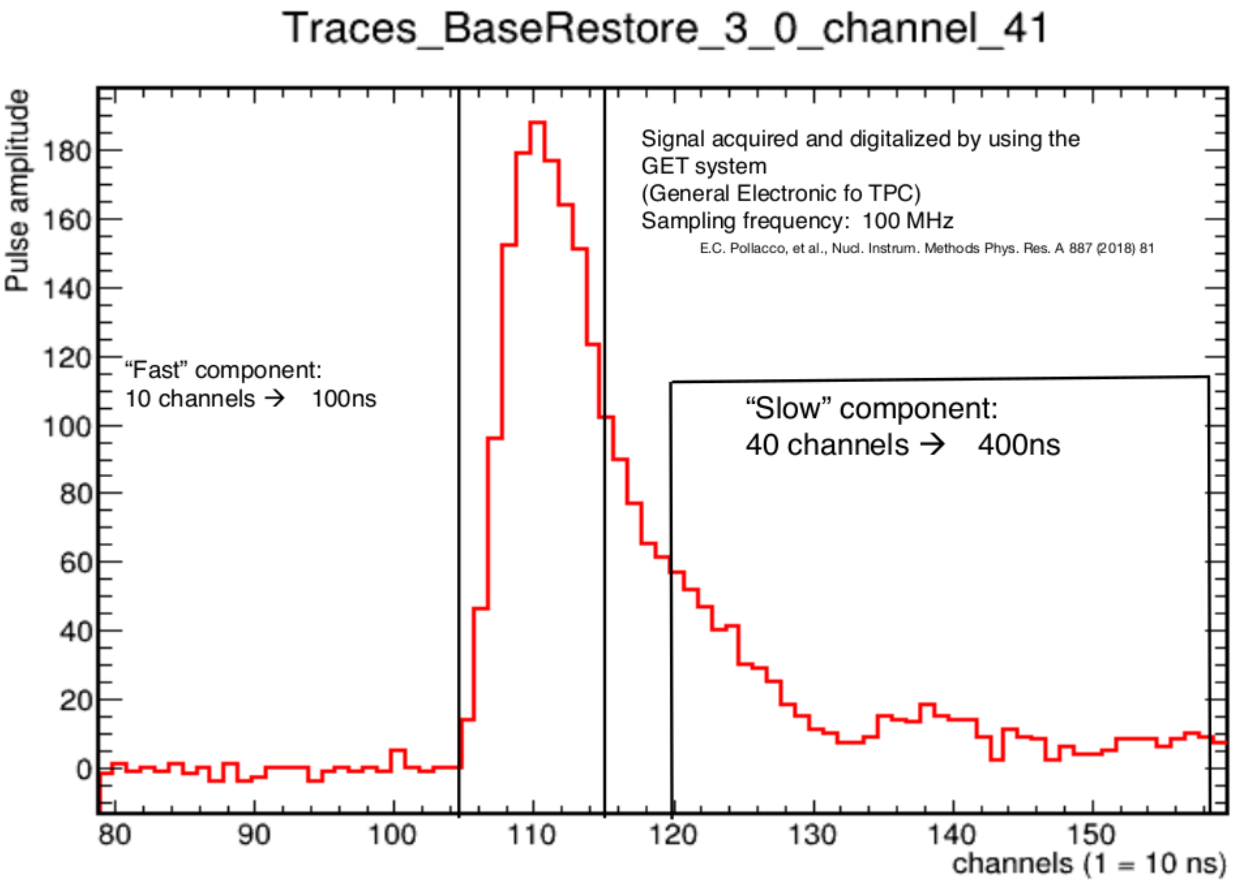
$$E_{diff} = E_1 - \frac{1}{2} m (d_{\min} / \Delta t)^2$$

L'energia minima che dovrebbe possedere il neutrone scatterato dal primo detector per raggiungere il secondo detector nel tempo Δt

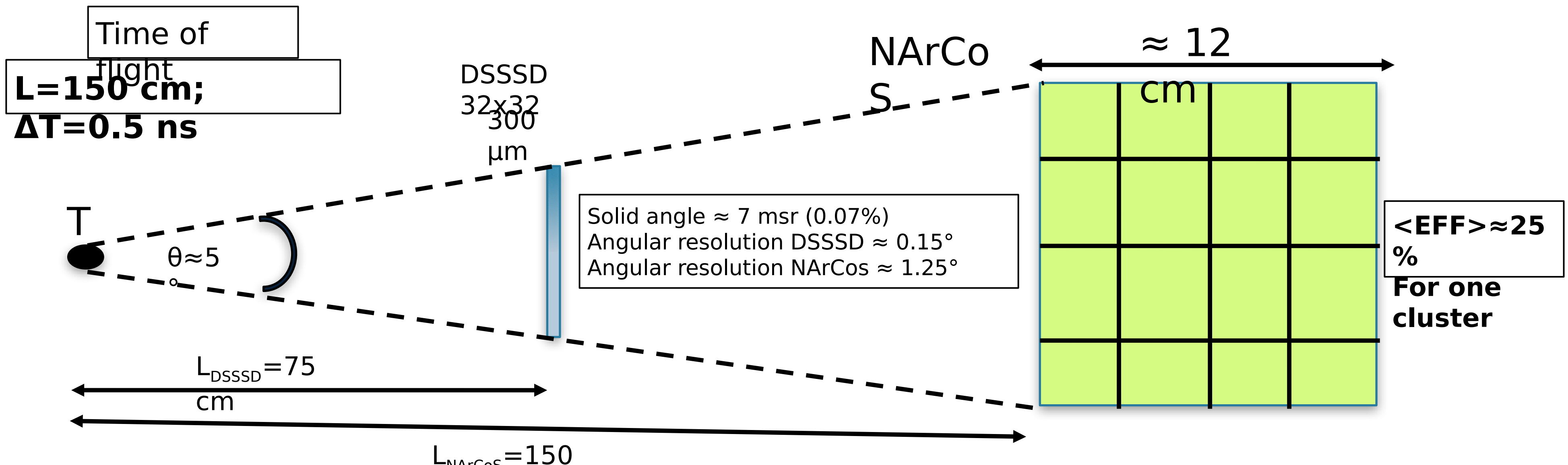
E_1 è lenergia del neutroni più veloce
D_{min} è la minima distanza tra due rivelatori colpiti
Δt è la differenza temporale tra i due rivelatori colpiti
E_{diff} rappresenta l'energia persa dal neutrone le primo detector

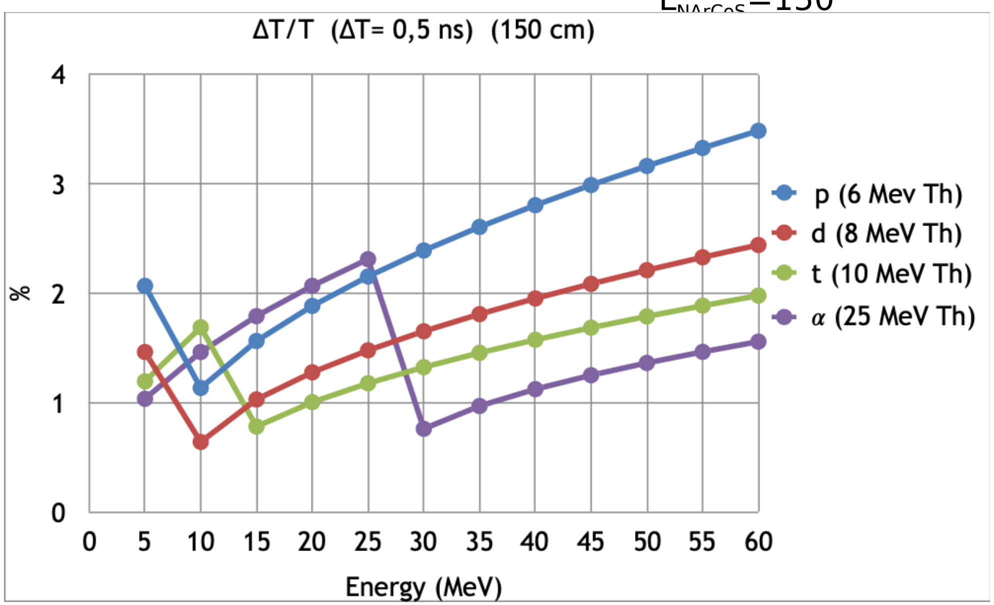
Se $E_{diff} < 0$ la coincidenza è reale
Se $E_{diff} > 0$ ulteriori analisi statistiche sono necessarie

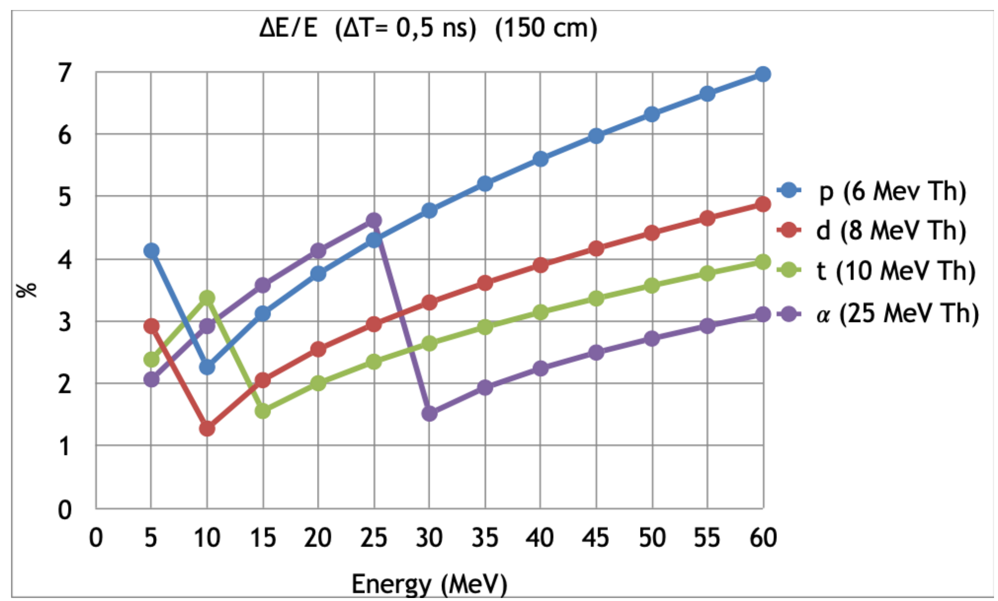
Digitalized signal



Expected performances







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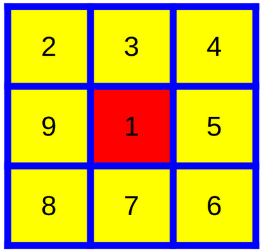
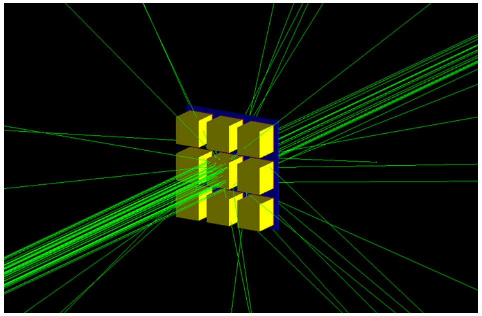
Matrix detector configuration

Typical numerical example:

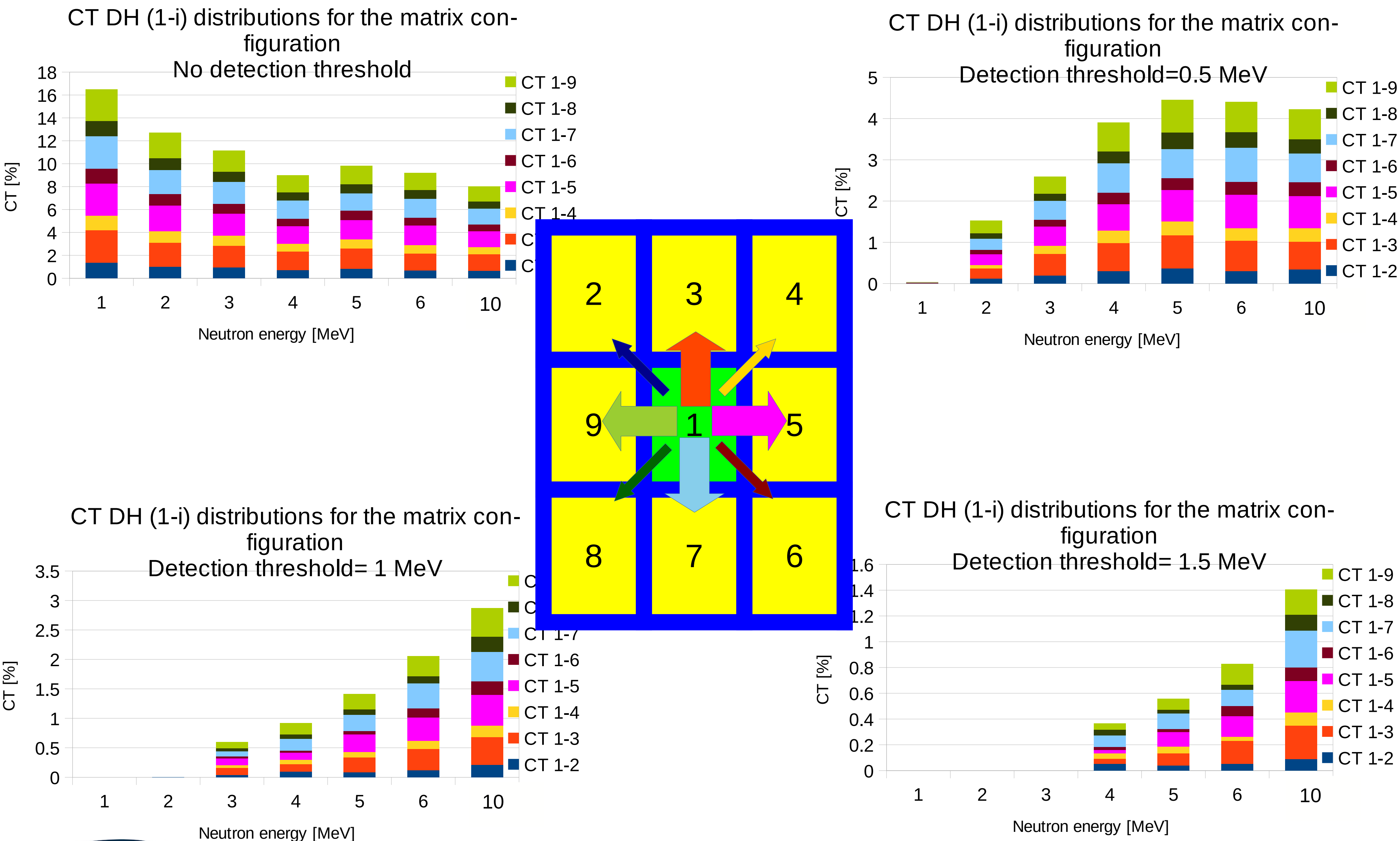
Cross-talk probability distributions for E_{inc} = 5 MeV





Threshold [MeV]	Tot	ID=1	CT 1-2	CT 1-3	CT 1-4	CT 1-5	CT 1-6	CT 1-7	CT 1-8	CT 1-9	CT [%] double hits from ID=1	CT [%] all other possible combinations	Total CT[%]
0.0	35588	30692	313	710	321	736	318	723	345	767	11.94	1.62	13.56
			0.88	1.99	0.91	2.07	0.89	2.03	0.97	2.15			
0.5	27139	25259	121	305	116	277	115	297	129	300	6.12	0.22	6.34
			0.45	1.12	0.43	1.02	0.42	1.09	0.47	1.11			
1.0	21987	20848	31	79	18	82	31	98	38	106	2.01	0.06	2.07
			0.14	0.36	0.08	0.37	0.14	0.41	0.09	0.42			
1.5	17574	16822	4	23	8	23	12	33	10	31	0.82	0.03	0.85
			0.02	0.13	0.05	0.13	0.07	0.19	0.06	0.18			

Matrix configuration: DH CT distribution



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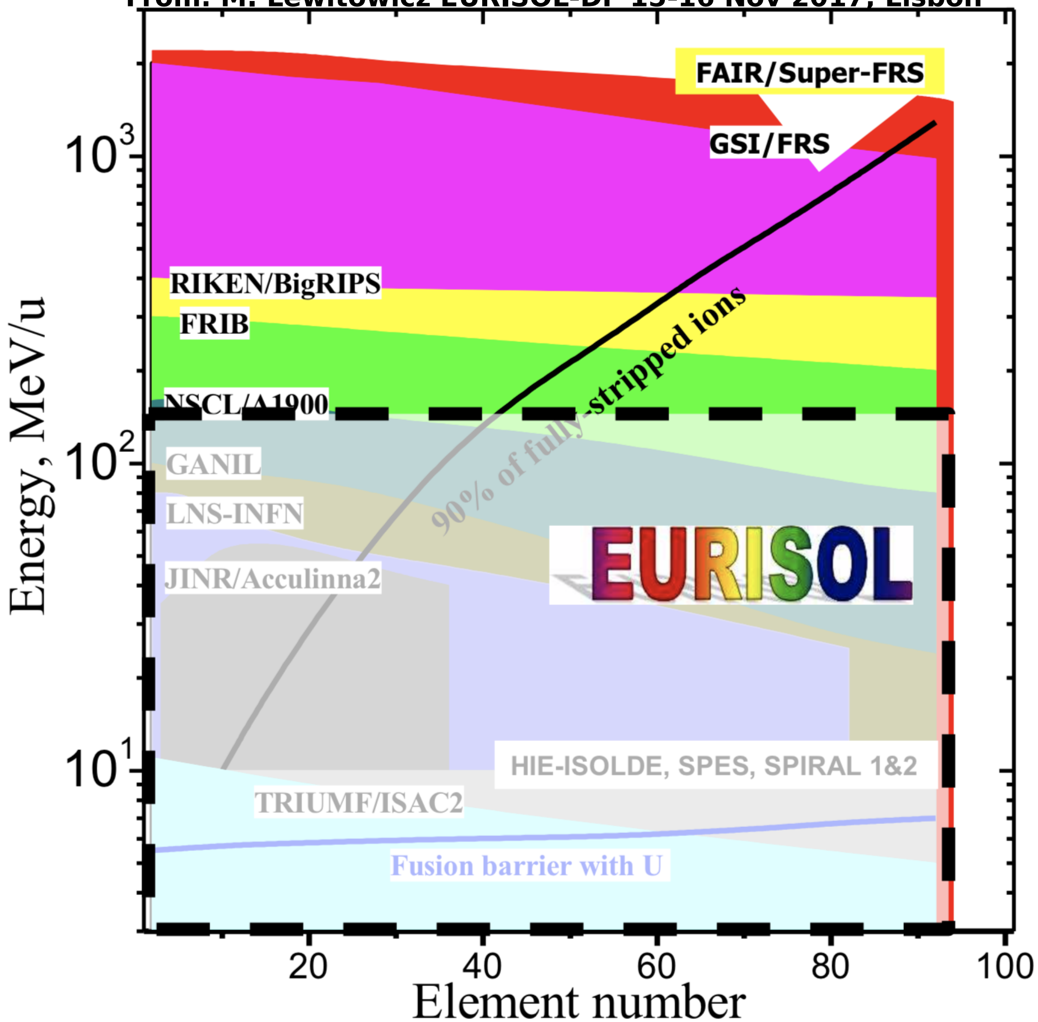
Project’s motivations

The advent of new facilities for Radioactive Ion Beams (RIBs), in particular for the n-rich ones, supports the idea of realizing a prototype able to detect charged particles and neutrons with high energy and angular resolution for reaction studies and applications.

“The RIBs are an important opportunity

(C. Horovitz)

From: M. Lewitowicz EURISOL-DF 15-16 Nov 2017, Lisbon

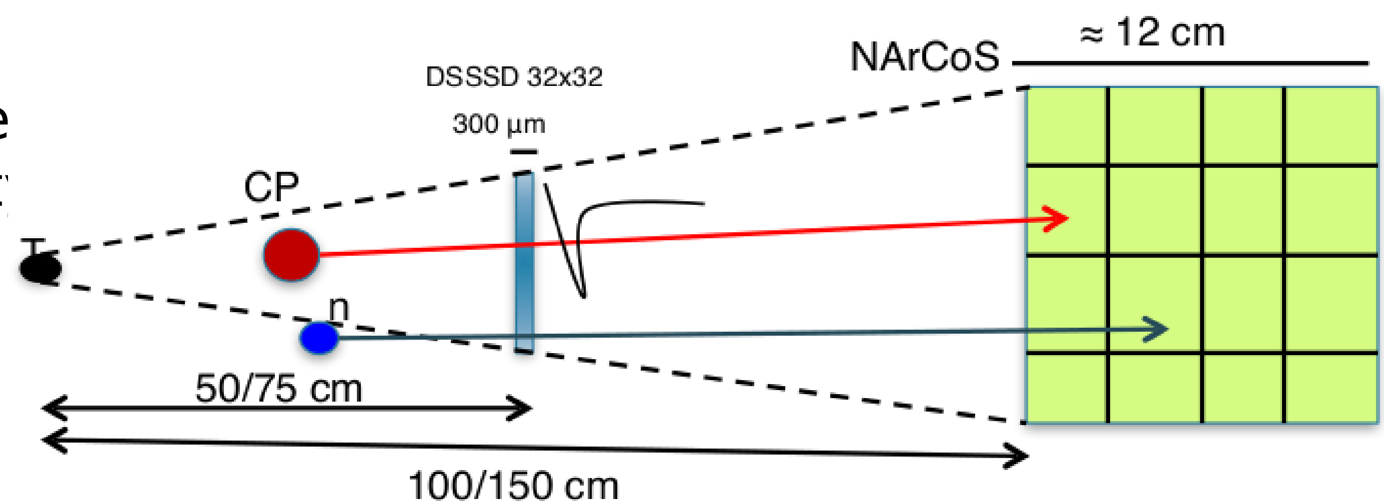


FRAISE@LNS

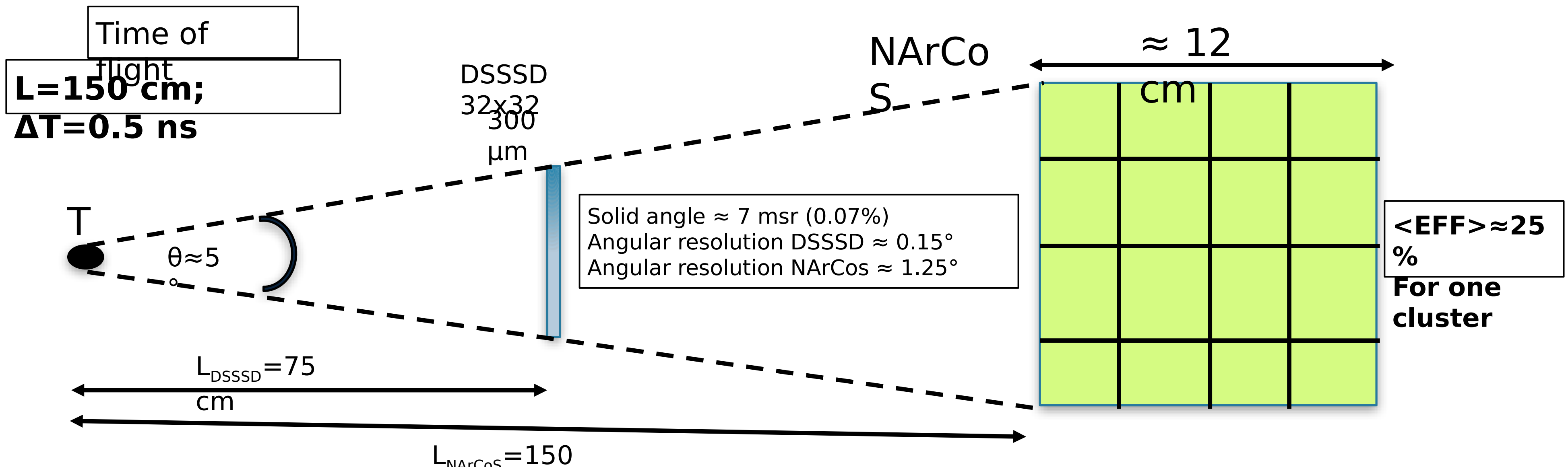
Idea

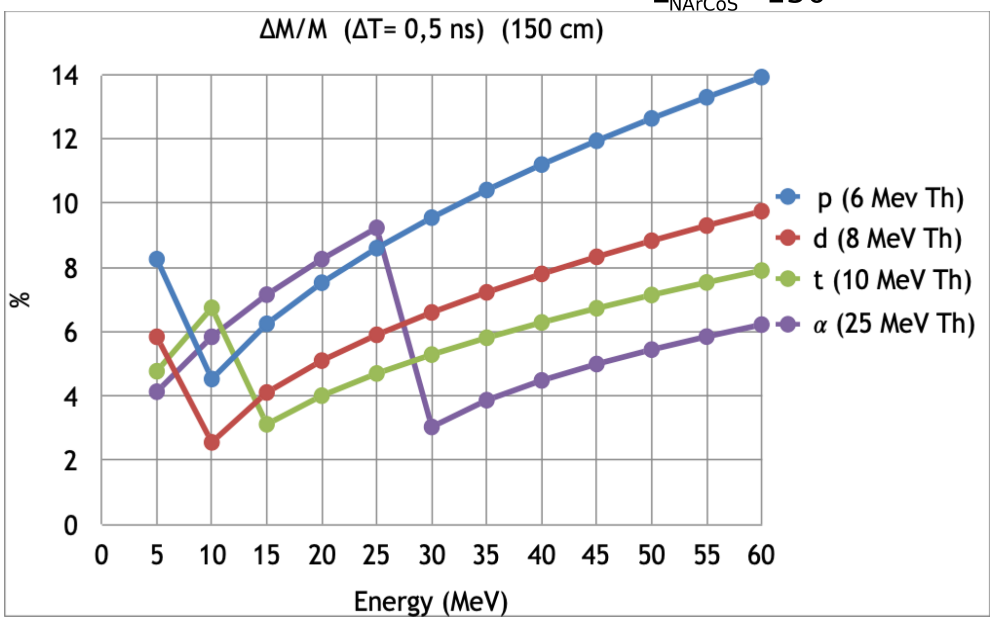
To realize a prototype of detector able to detect at the same time charged particles and neutrons with high energy and angular resolution for reaction studies and applications

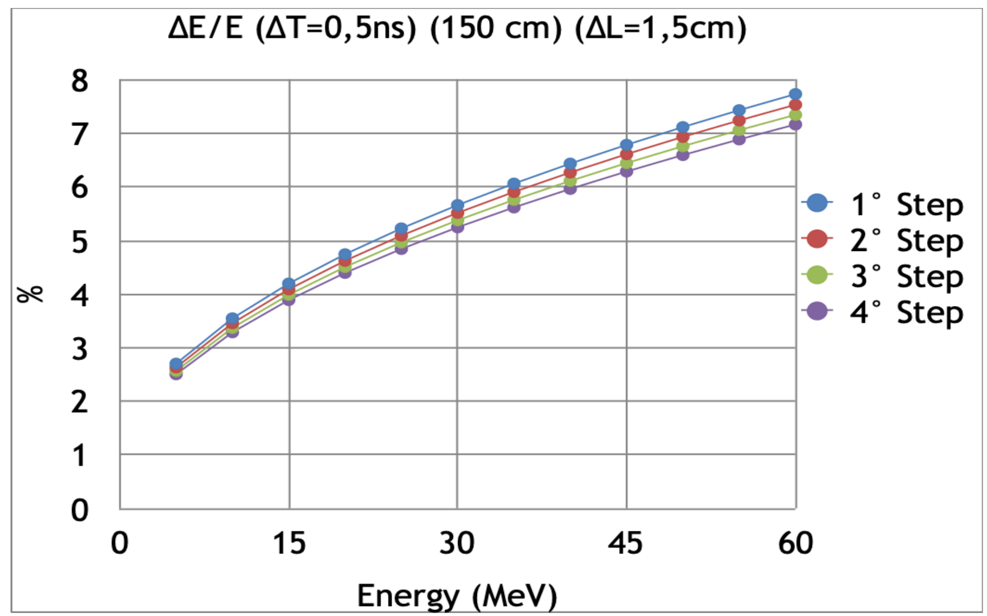
- Candidate: The plastic scintillator EJ276 Green Type (ex EJ299-33) (3x3x3cm^3)
- 1 cluster: 4 consecutively cubes -> 3x3x12 cm^3
- Reading the light signal: SiPM and digitalization
- Neutron detection efficiency ≈ 50% for the prototype (16 clusters)
- Modular, reconfigurable (in mechanic and electronic)
- Discrimi … rticles)
- Energy … 5m)
- TOF me … MCP (low intensit



Expected performances

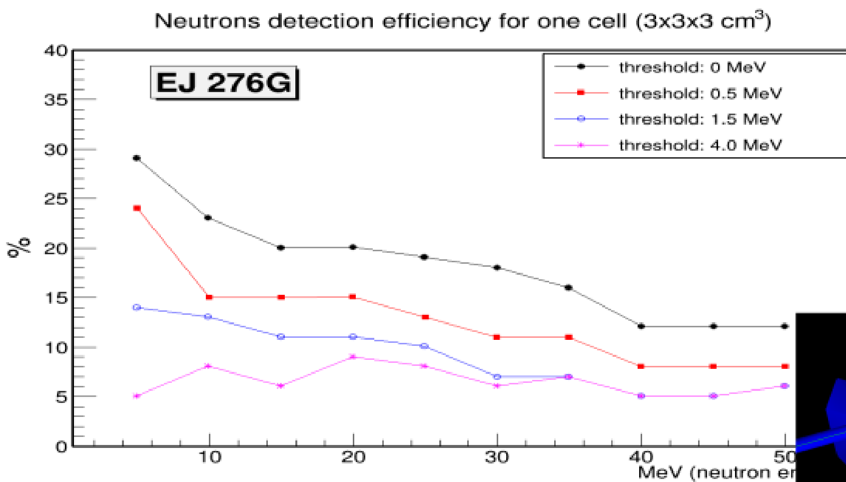


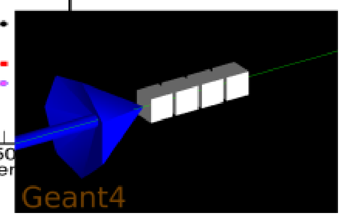




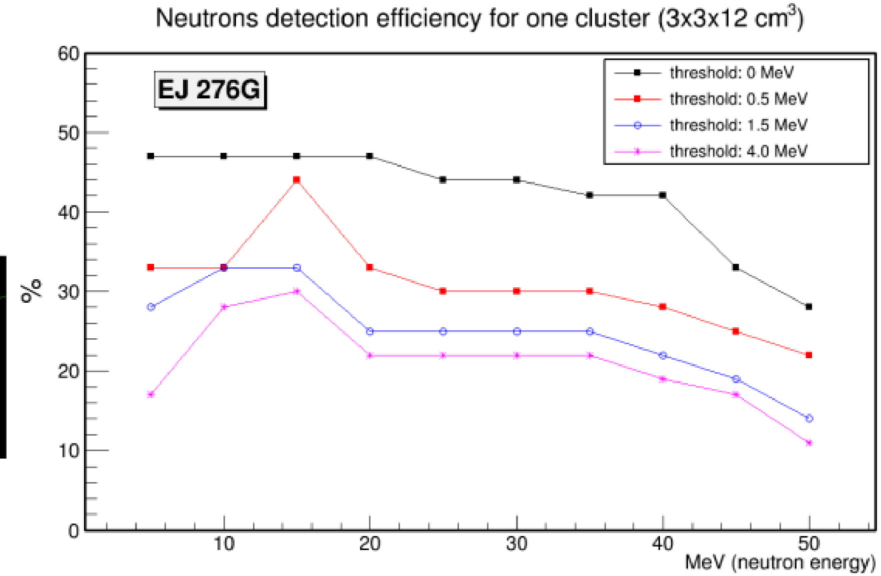
Expected performances

Mean value for one detection cell (3x3x3 cm^3) ≅ 9%

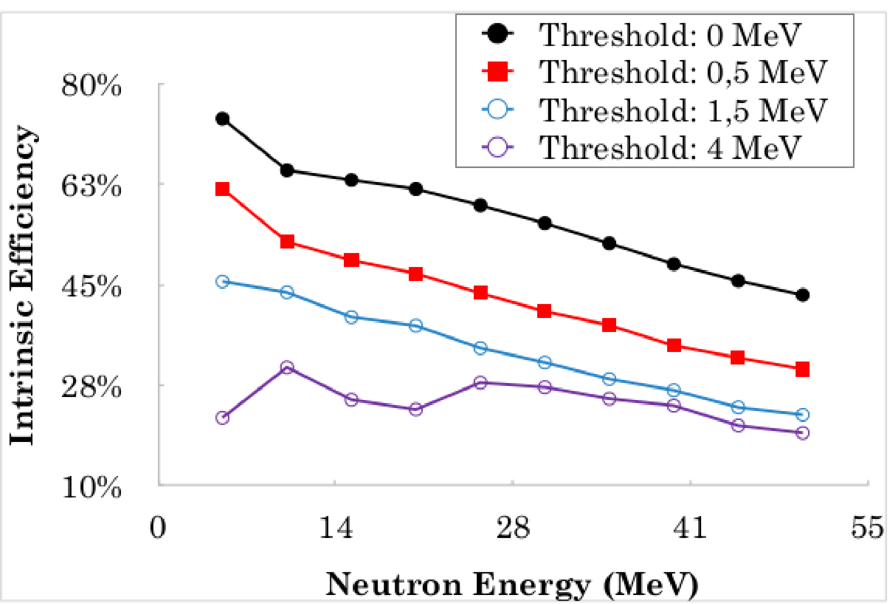




Mean value for one detection cluster (3x3x12 cm^3) ≅ 25%

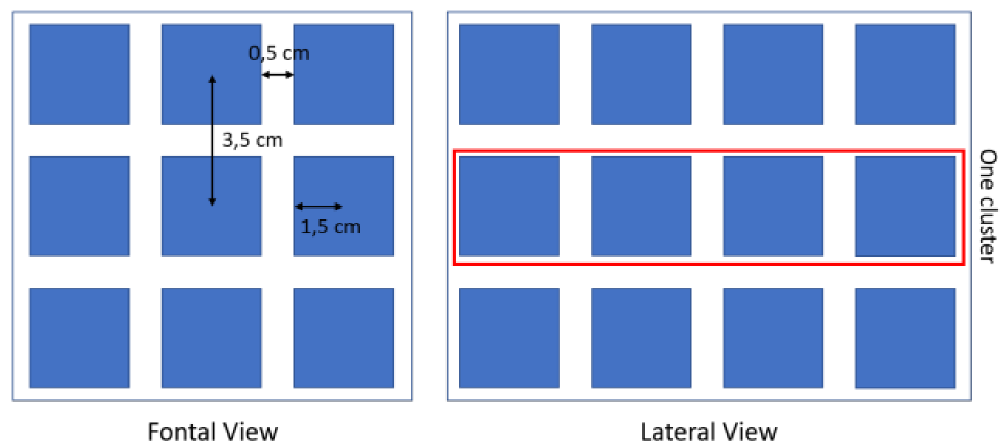


Mean value for a 36-cell array (9x9x12 cm^3) ≅ 33%



Scheme of Simulation Geometry:

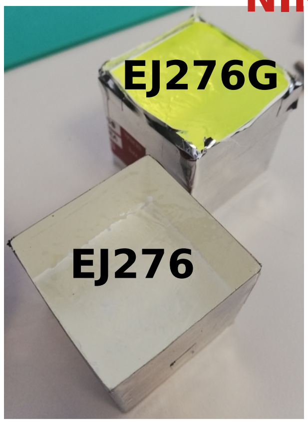
36 (3 x 3 x 4) cell array

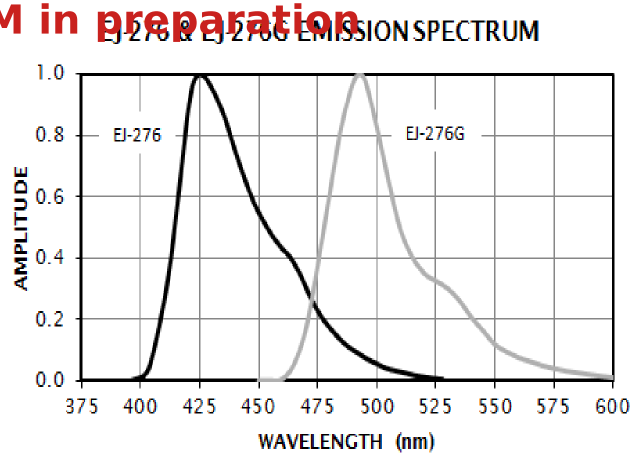


atest resuls: tests by using the SiPM

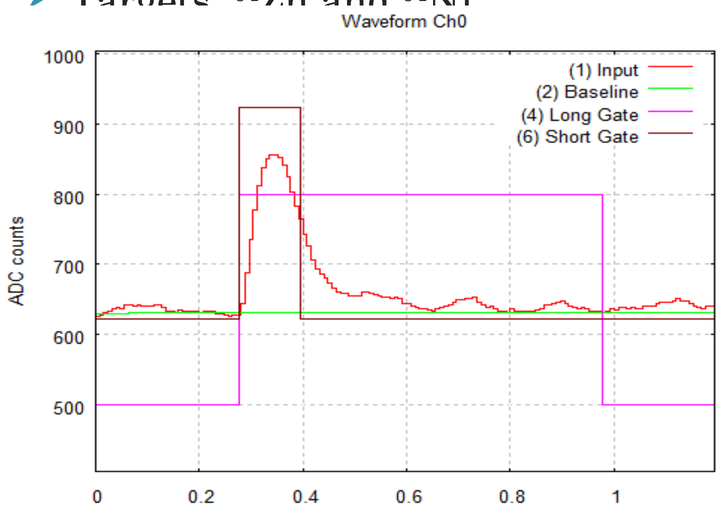
- **Detector Configurations:**
  - EJ-276G + PMT
  - EJ-276 + i-Spector
  - EJ-276G + i-Spector

E.V.Pagano, G. Politi, A. Simancas, G. Santagati et
NIM in preparation





- **Lab. measurements with radioactive sources:**
  - Vacuum Chamber
  - Pb shield
  - Gamma sources: ^{133}Ba, ^{137}Cs, ^{60}Co, ^{152}Eu
  - Alpha source: ^{241}Am
  - Digitizer from CAEN
- **Data analysis of heavy ion reactions:**
  - CHIMERA scattering chamber (LNS)
  - Detector at 11° in lab frame
  - Beam: ^{124}Sn at 20 MeV/A (CHIFAR experiment)
  - Targets: ^{64}Zn and ^{64}Ni



xample of signal and integration windows

i-Spector from CAEN (3x3 cm SiPM and electronics)

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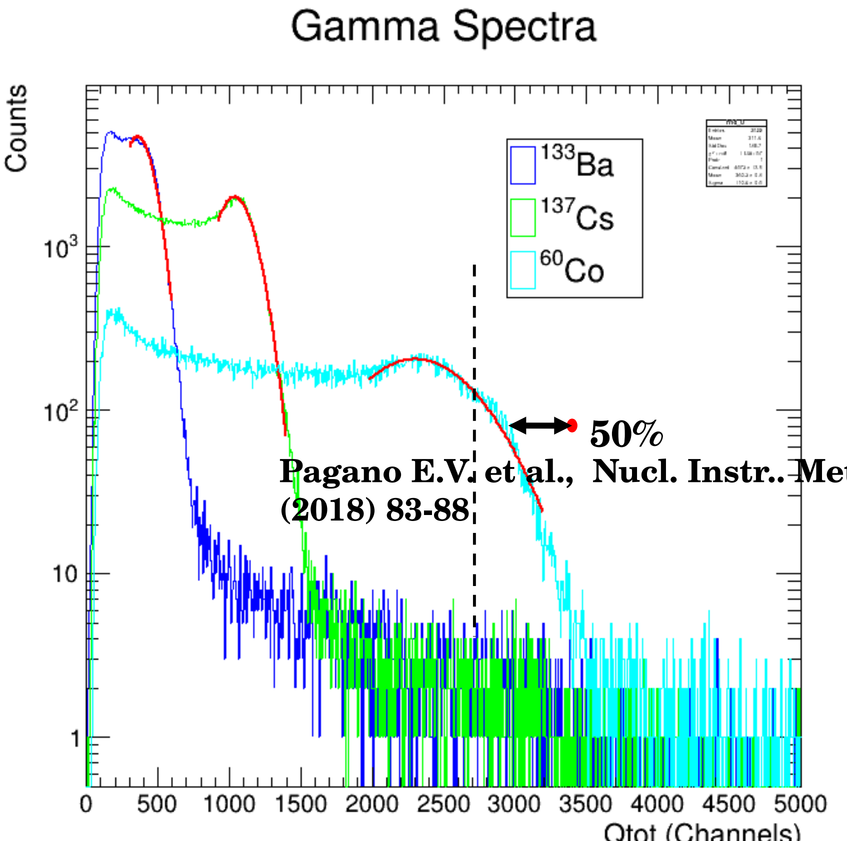
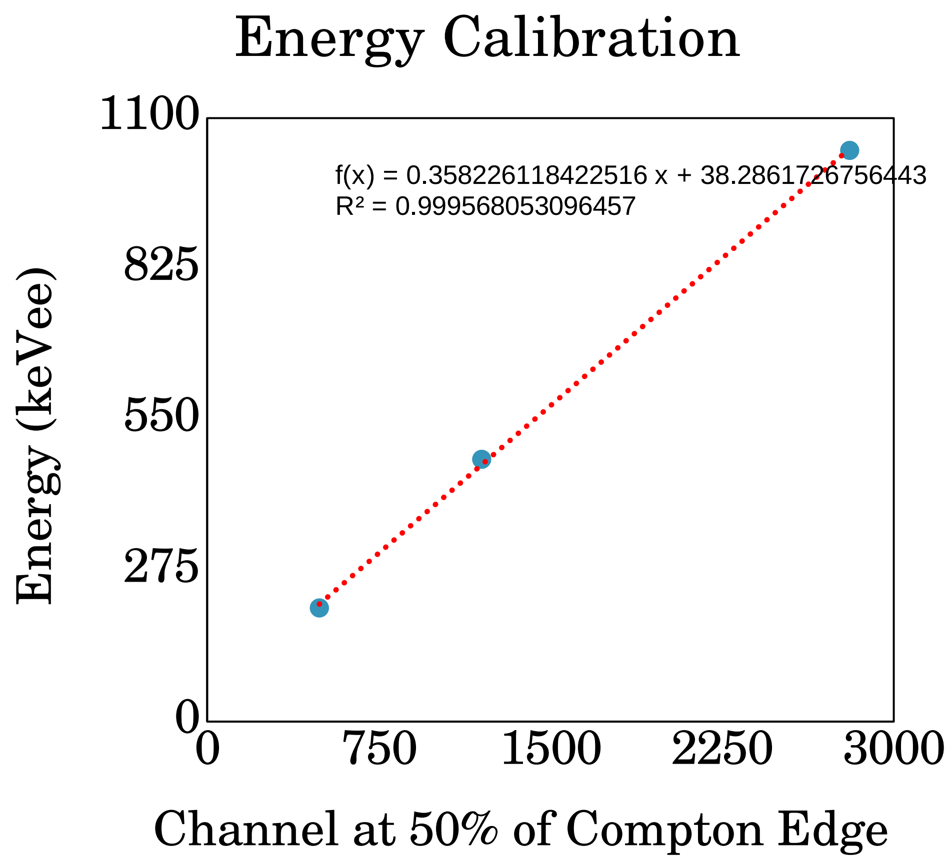
Gamma spectra



Pagano E.V. et al., Nucl. Instr.. Methods A, 889 (2018) 83-88

EJ-276G + i-Spector



PSD studies using sources

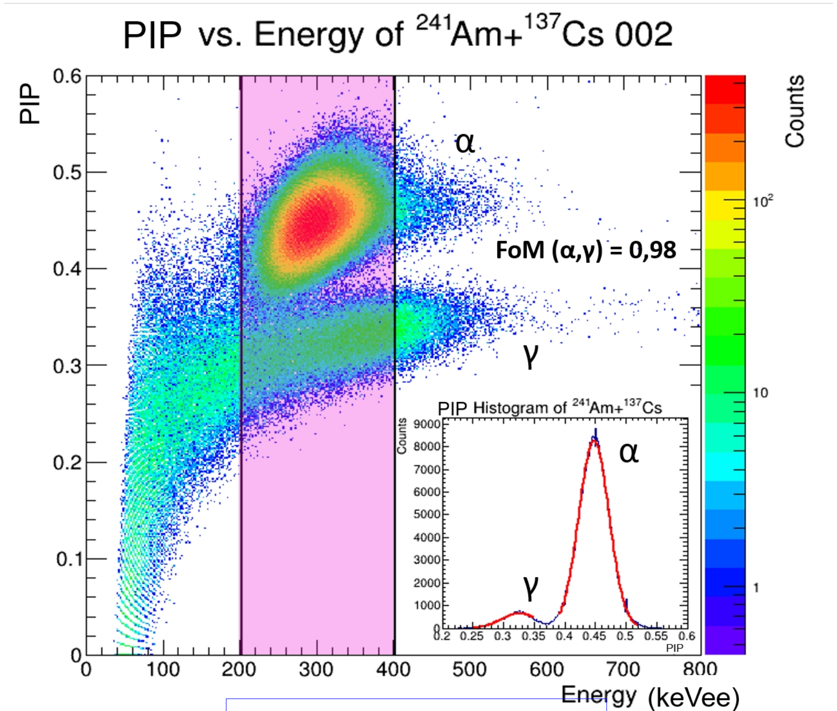
Test with radioactive sources (low background).

Sources ^{241}Am + ^{137}Cs. Setup: EJ276 + SiPM (I-spector). EJ276G + SiPM (I-spector)

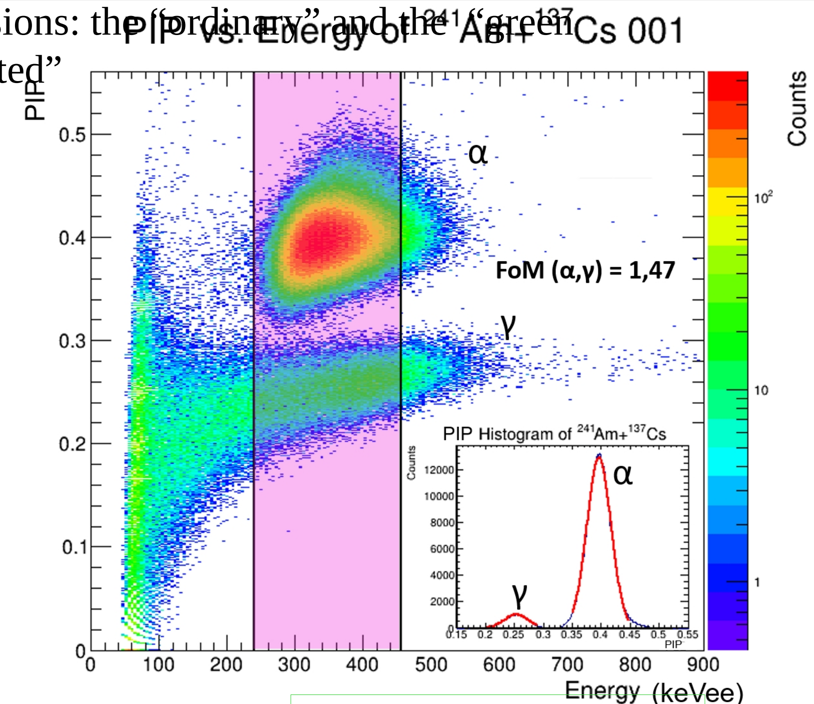
Comparison between the two plastic versions: the "ordinary" and the "green shifted"

Particle Identification Paramenter

$$PIP = 1 - \frac{Q_{fast}}{Q_{tot}} = \frac{Q_{slow}}{Q_{tot}}$$



EJ-276 + i-Spector



EJ-276G + i-Spector

Detector	FoM
i-Spector + EJ-276	0.98
i-Spector + EJ-276G	1.47
PMT + EJ-276G	1.03

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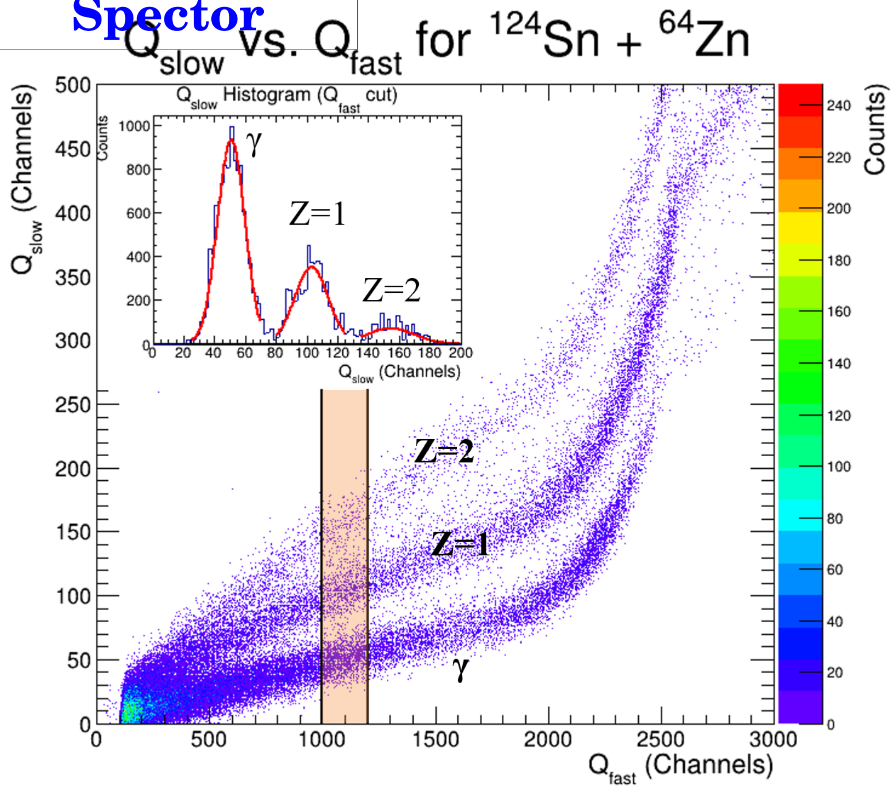
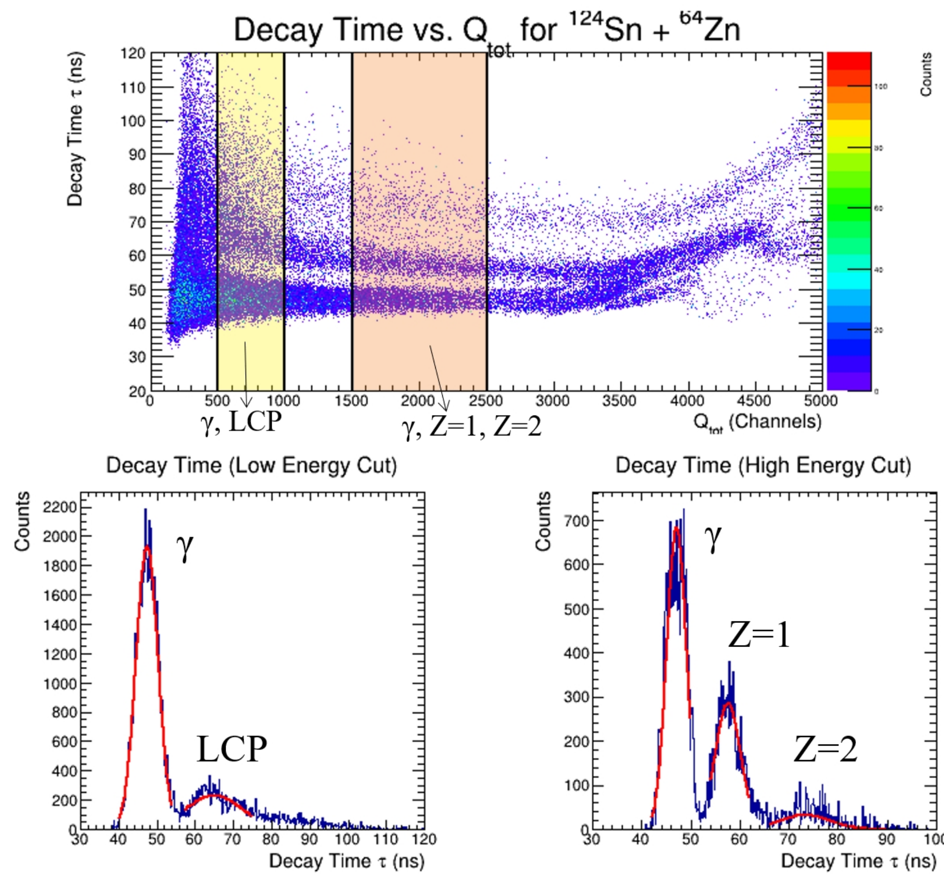
PSD studies using beams

AR exp @LNS (spokesperson:EVP, E. De Filippo, P. Russot

Test with beam (high background). Setup: EJ276 + PMT (1.6 kV) reaction ^{124}Sn + ^{64}Zn @ 20 AMeV

EJ-276 + i-Spector





PSD Method	FoM(γ, Z=1)	FoM(Z=1, Z=2)	FoM(γ, LCP)
Integration	1.08	0.78	-
[illegible]	0.95	0.87	0.71

LCP = Light Charged Particles
Neutrons included in Z=1

More information about the "Decay time" identification tech
E. V. Pagano et al. NIM A 905 (2018) 47-52

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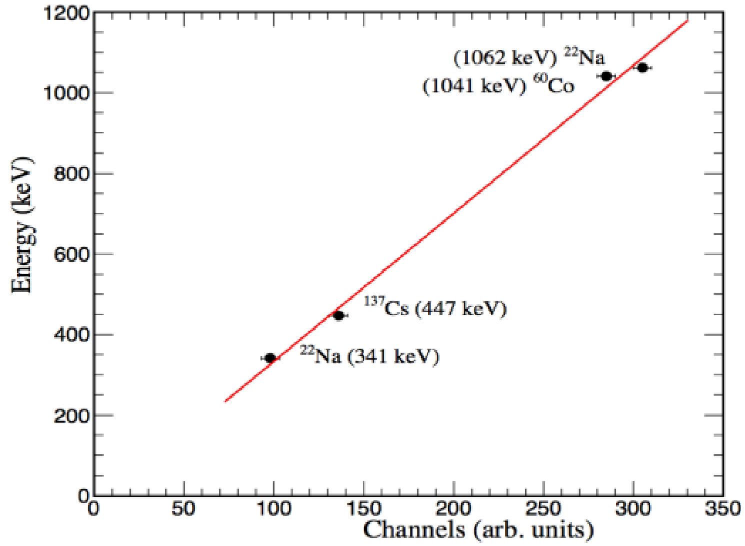
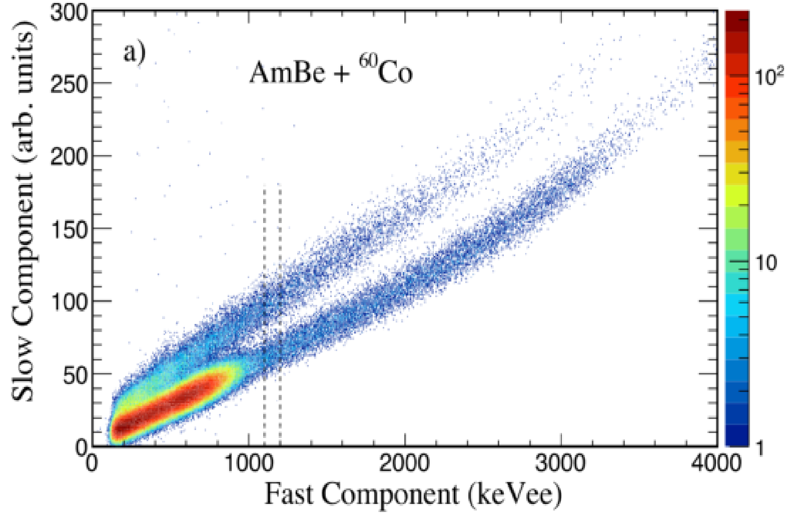
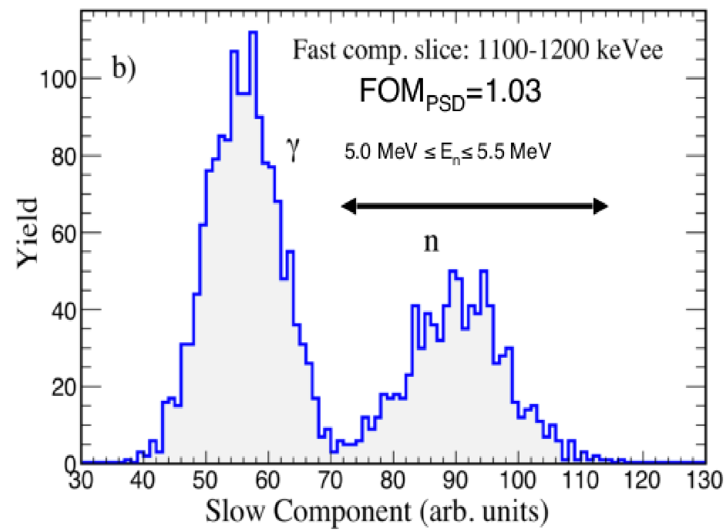
Some spectra with sources

E. V. Pagano et al. NIM A 889 (2018) 83-88







Detection threshold ≈ 0.7 MeV

Discrimination threshold ≈ 1.5 MeV (FOM_{PSD}=0.43)

$$L_{out} = A \cdot E_{dep} - B \cdot \left(1 - e^{-C \cdot E_{dep}}\right)$$

$A = 0.8 \quad MeVee \cdot MeV^{-1};$

$B = 3.9 \quad MeVee;$

$C = 0.19 \quad MeV^{-1};$

C. C. Lawrence et al., NIM A759 (2014) 16

me spectra: ^{24}Mg+^{90}Zr @71 MeV<E<81 MeV reactio

E. V. Pagano et al. NIM A 905 (2018) 47-52