Status of analysis of neutron data obtained with the compact TOF neutron spectrometer

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Motivation:

Study of neutron emission in collisions of heavy nuclei at energies of several GeV per nucleon.

Such data have a great interest for the development of theoretical models and codes.

Aim of the Neutron spectrometer in BM@N experiment:

Study of energy spectra of neutrons at large angles, in the region of fragmentation of target spectator, with beams of heavy nuclei of Nuclotron in energy range of 2 – 4 GeV/nucleon.

The event-by-event data analysis with selection on the collision centrality is applied.

Requirements to the neutron spectrometer

Requirement	Method
Energy range of neutrons: 2 – 200 MeV	TOF method, energy resolution $\Delta E/E$ <20% at E = 200 MeV
Operation into BM@N magnet with B = 0.9 T	Application of SiPMs in scintillation detectors
Strong suppression of γ-ray background	Pulse shape discrimination with stilbene detectors
Suppression of charged particles	Scintillation veto-detectors
Reduction of neutron background	Measurements with small flight path L < 50 cm

Task for BM@N run 2022-23 with Xe-ion beam

To prove that we are able to get reliable data on neutron spectra in energy interval 2 – 200 MeV in experimental conditions of the BM@N setup

BM@N Run 2022-2023 with Xe ions

Beam: Beam of ^{124}Xe ions in vacuum beam pipe
Typical beam intensity: $n \times 10^5$ ions/spill
Spill duration: 2 – 3 s.
Beam energy: 3.8 GeV/nucleon

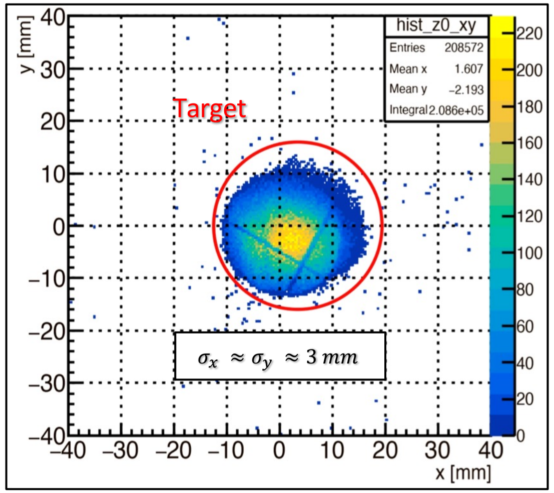
Target: CsJ (2%)
$n = 3{,}64 * 10^{21}$ nuclei/cm^2

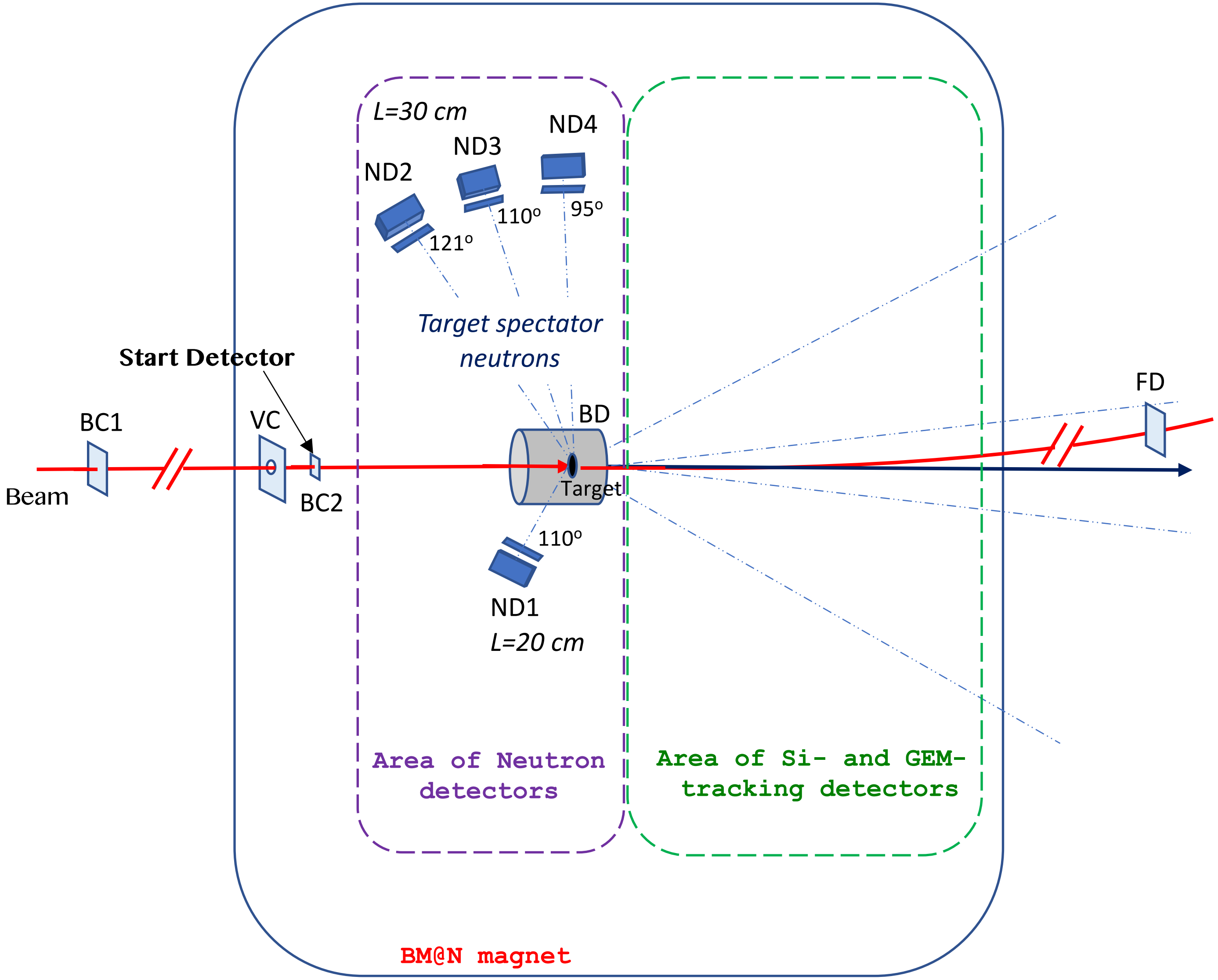
Trigger for data taking:

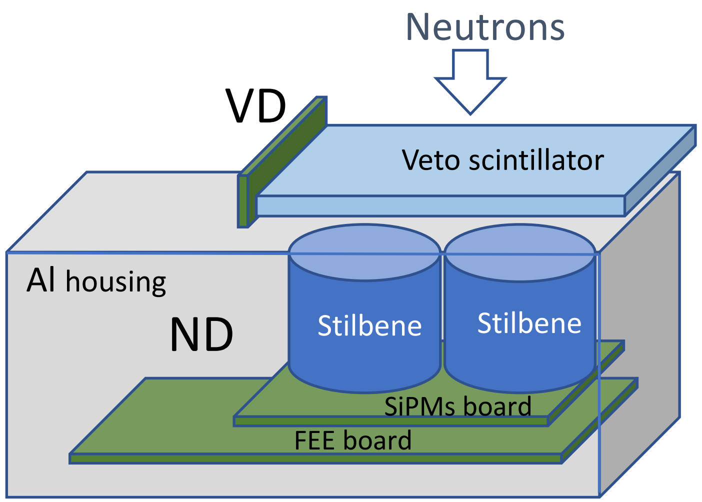
Beam trigger (BT) = BC1 * VC(veto) * BC2

Fast Interaction Trigger (IT) = BT* FD($A<A_{beam}$) * BD(N>3)

Hits of Xe ions in the target position obtained with forward Si tracker

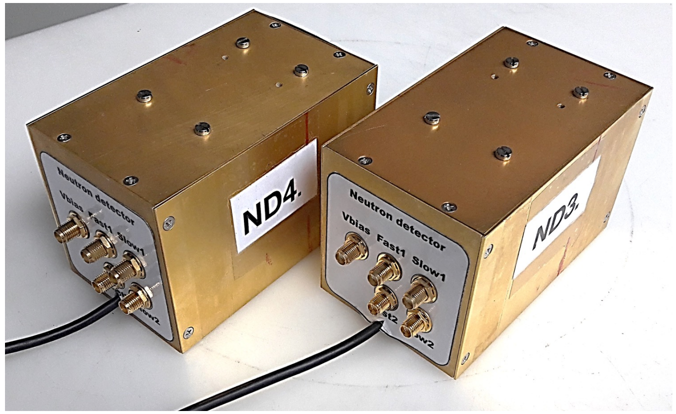






Neutron Detectors

(Stop pulse)

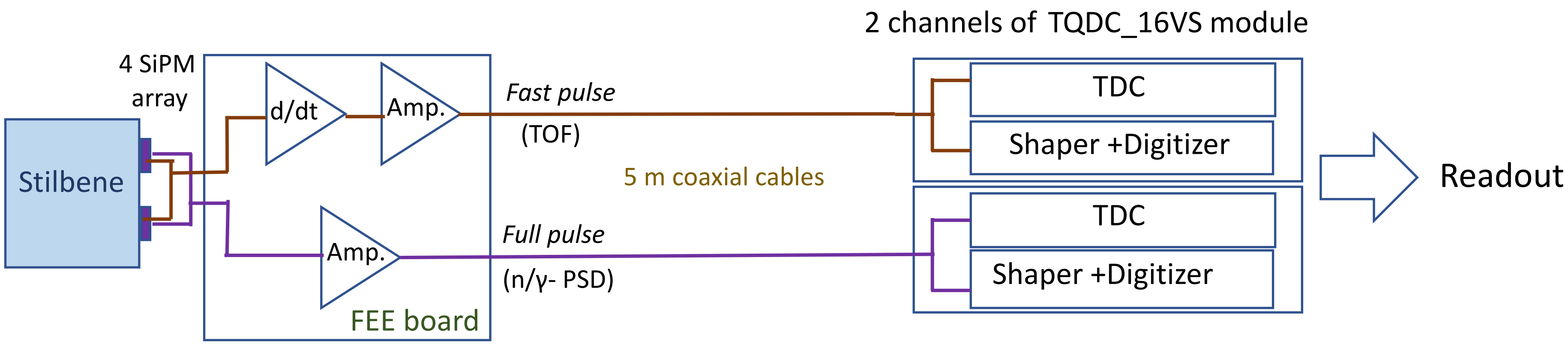


Stilbene crystal from Inrad Optics (USA)
(1"diam. × 1")

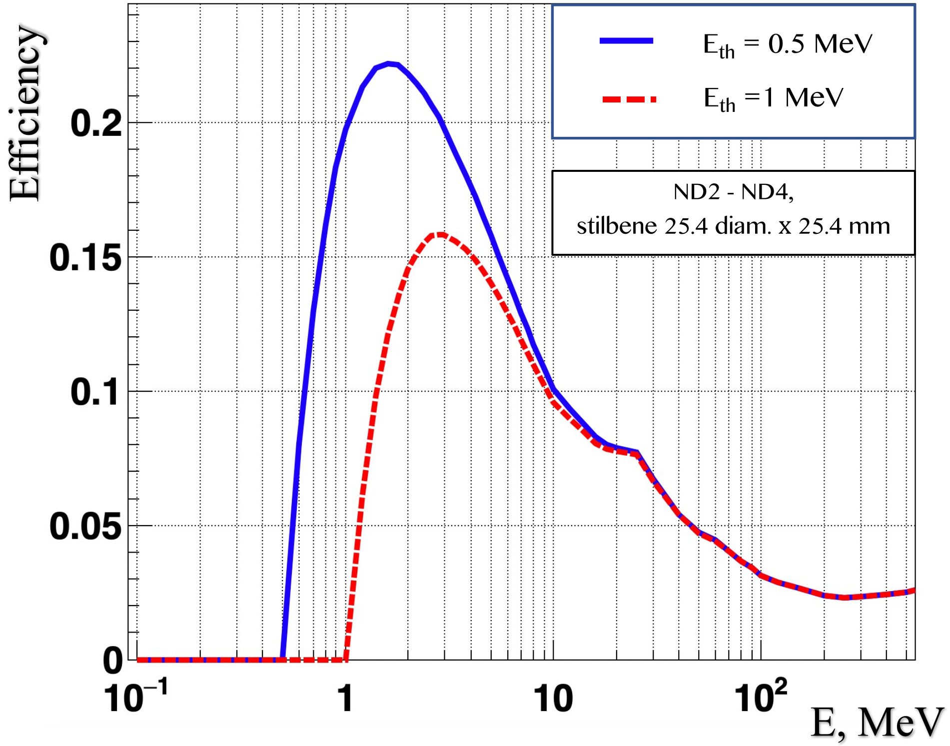
Scintillation photons are detected with SiPMs 6 x 6 mm^2 , J ser. SensL :

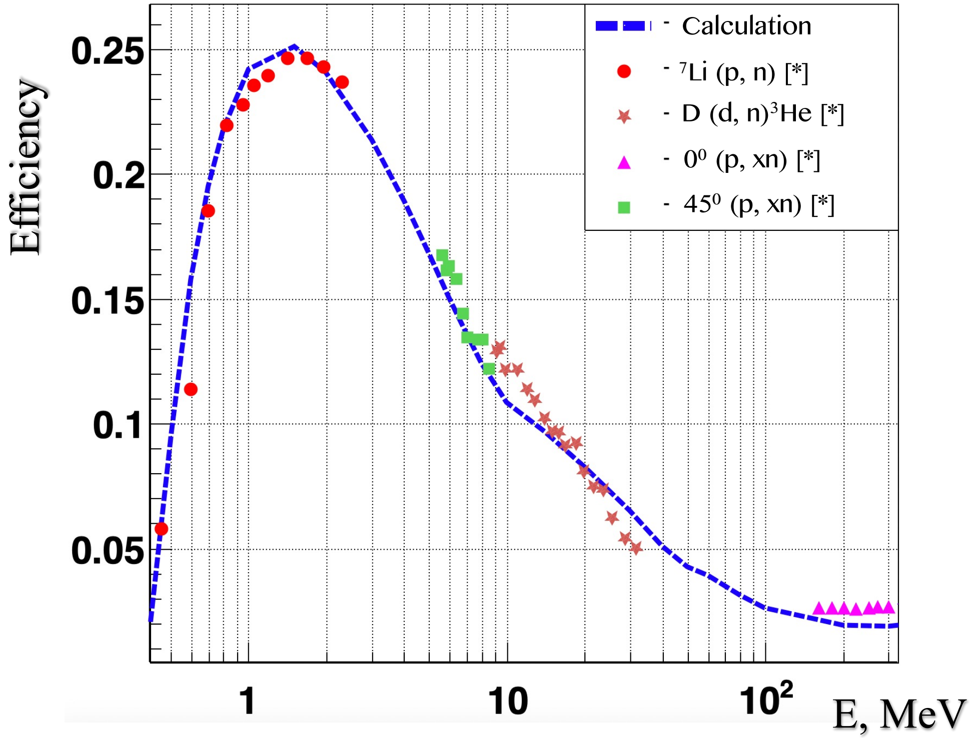
- 4 SiPMs – coupled with stilbene crystal
- 2 SiPMs – coupled with Veto-scintillator

Electronics chain



Neutron detection efficiency





$$\varepsilon = \left(1 - e^{-\Sigma h}\right)\left[\frac{\Sigma_H}{\Sigma}\left(1 - \frac{B_H}{E}\right) + \frac{\Sigma_C}{\Sigma}\left(1 - \frac{B_C}{E - E_H + E_0}\right)^{\alpha}\right]$$

$\Sigma = \Sigma_c + \Sigma_H = n_C\,\sigma_{ch}(nC) + n_H\,\sigma(np)$

σ_{ch}(nC) – cross section of ch. particle production in reactions with carbon nuclei

σ(np) - cross-section of np scattering

h – the thickness of the stilbene crystal

B_c – the threshold for reactions with carbon

B_h – the threshold for recoil protons in np scattering

[*] S.D. Howe et al., NIM in Phys. Res. 227 (1984) 565.

Detector: NE-213 Diam.=51mm, H=25mm

E_{th}=0.45 MeV

TOF neutron spectrometers at accelerators in energy range from units to hundreds MeV

Beam	Detectors (cm)	$E_{min.}$ (MeV)	L (м)	σ_t (ps)	σ_t /L (ps/m)	n/γ	Year
p, C Synchrophasotron JINR	Stilbene ∅5×5	2	1.2	500	417	Yes	**2006**
p Synchrotron (ITEP)	Plast. scintillator ∅20×20	7.5	1.5	~500	333	No	**1982**
p Synchrotron (ITEP)	Liquid scintillator ∅12.7×15.2	2.5	2, 3	670	~270	Yes	**2005**
Heavy Ions BEVALAC	NE-102 101.6×25.4×10.2	150	4 - 14	~1000	250 - 140	No	**1990**
p LAMPF	BC-418 ∅5.08×5.08, ∅5.08×2.54	0.4	29-50	~1000	34 - 20	No	**1992**
p PS KEK	NE-213 ∅5.08×5.08, ∅12.7×12.7	1 3	0.75 1.3	500	666 - 385	Yes	**1995**
p SATURNE	NE-213 ∅12.7×5.1 NE-213 ∅16×20	2 4	~8.5	2000 1500	235 - 176	Yes	**1999**
Heavy Ions HIMAC	NE-213 ∅12.7×12.7	5	3 - 5	1000	333 - 200	Yes	**2001**
Heavy Ions Nuclotron (JINR)	**Stilbene ∅2.5×2.5**	**1**	**0.3**	**110**	**367**	**Yes**	**2023**

Compact geometry

The best resolution!

Data analysis

Runs: $7579 \leftrightarrow 7982$

Number of runs (IT): **138**

Data acquisition time : **86** hours

Conditions used for event selection

Fast Interaction Trigger (IT) = BT* FD(A<A_{beam}) * BD(N>3)

Off-line B/A protection

Neutron event statistics

ND4 (95^0): **28600**

ND2 (121^0): **18500**

Corrections

DAQ busy correction

Time – pulse height correction to improve time resolution

Efficiency of neutron detectors

Selection of neutron events using pulse shape analysis

Neutron background contribution

Neutron production double-differential cross section

$$\frac{d^2\sigma}{dEd\Omega} = \frac{\Delta N}{\Delta E \cdot \Delta\Omega \cdot \varepsilon(E) \cdot n \cdot I \cdot k_1 \cdot k_2}$$

ΔN - the number of detected neutrons;

ΔE - the energy bin width;

$\Delta\Omega$ - the solid angle for each neutron detector;

$\varepsilon(E)$ - the neutron detection efficiency;

I - the number of beam particles on the target;

n - the number of target nuclei per 1 cm^2

k_1 - the correction factor taking into account dead time of DAQ .

k_2 - the correction factor taking into account B/A protection time of 1.5 μs

Time and Energy Resolution

Time resolution

Neutron detector	σ_{TOF}	σ_t	σ_{T0}
ND4	117 ps	110 ps	38 ps
ND2	120 ps	114 ps	

TQDC16VS module, TDC with 25- ps binning

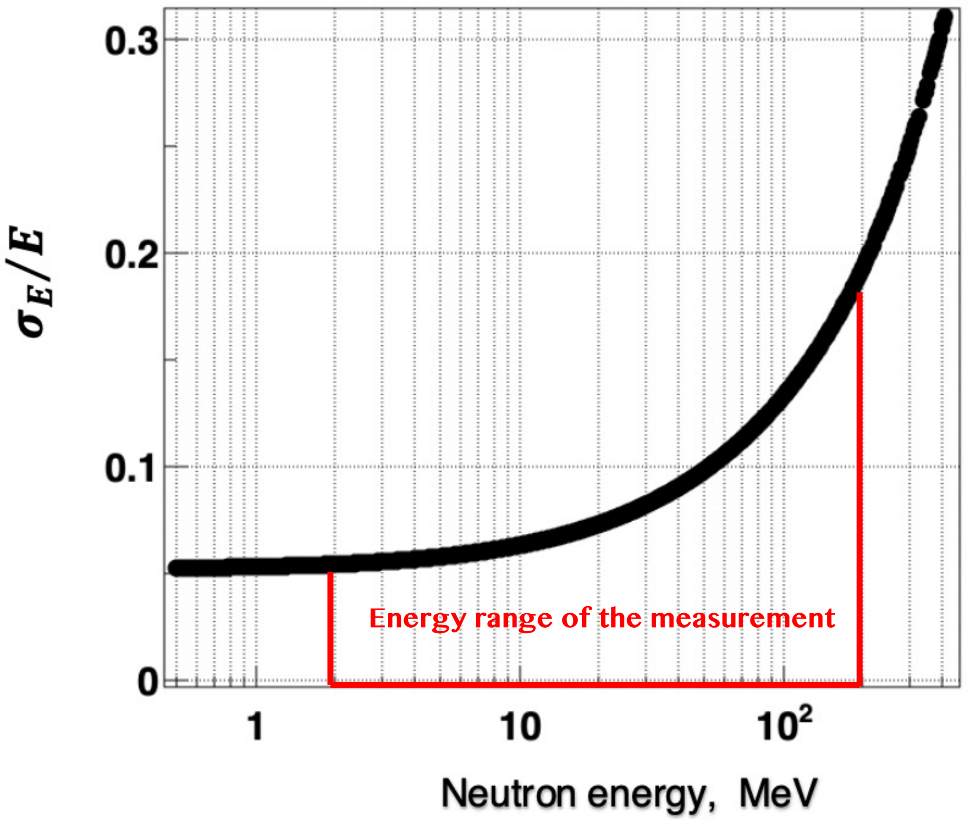
$$\frac{\sigma_E}{E} = \gamma(\gamma+1)\left[\left(\frac{\sigma_l}{l}\right)^2 + \left(\frac{\sigma_t}{t}\right)^2\right]^{1/2}$$

γ – the Lorentz factor

$\frac{\sigma_t}{t}$ – the time resolution

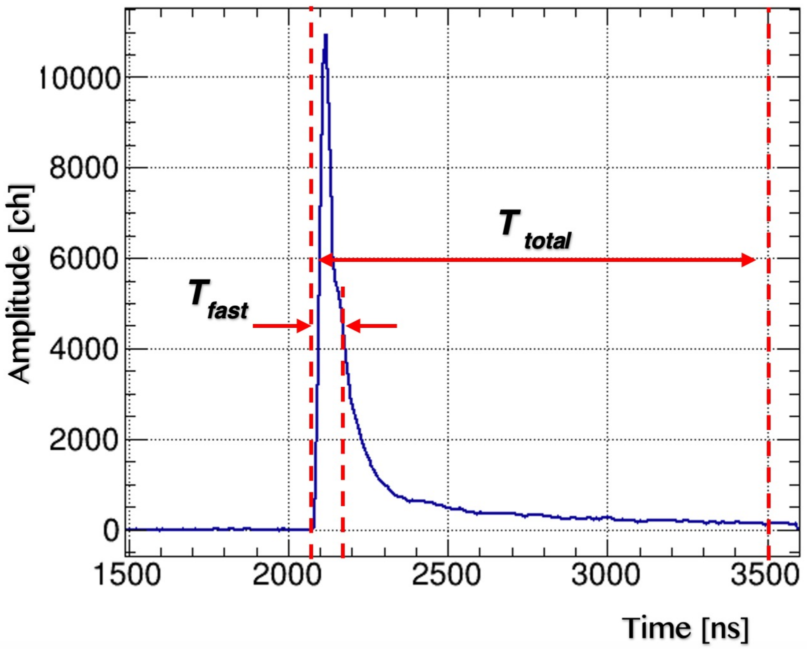
$\frac{\sigma_l}{l}$ – the uncertainty of flight path

Energy resolution

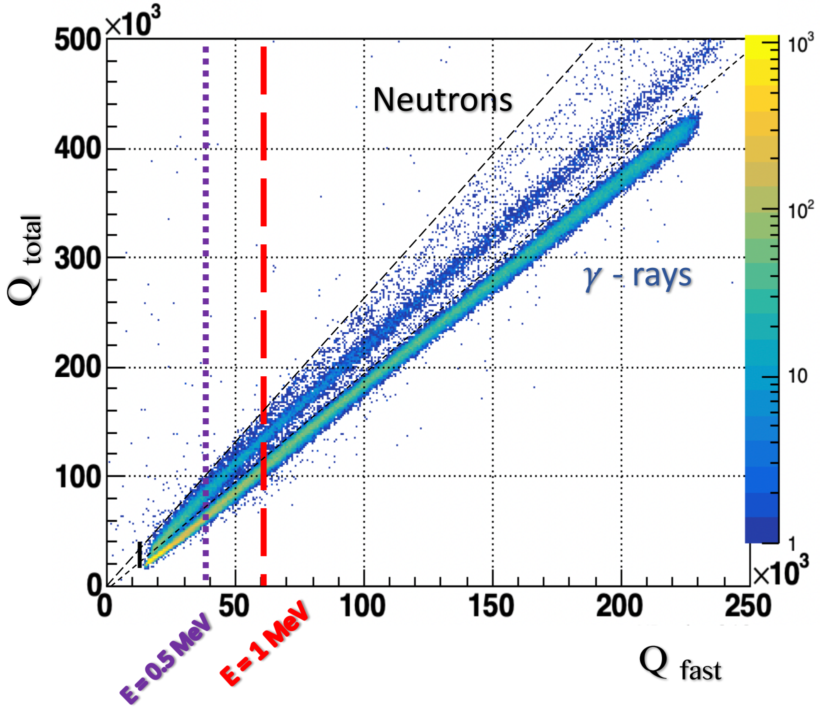


Pulse Shape Discrimination and Suppression of Background

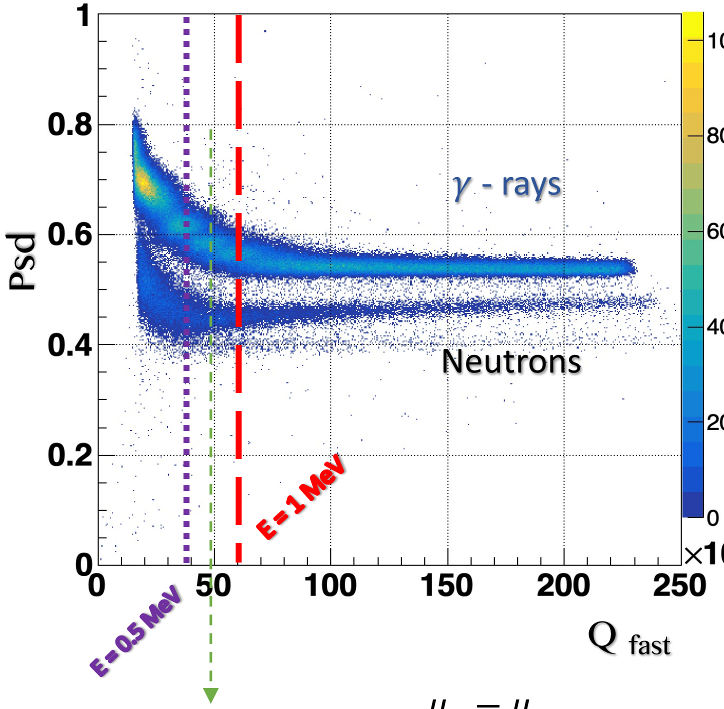
Waveform of Nd4 detector (TQDC)



n/γ - pulse shape discrimination



$$Psd\ parameter = 1 - \frac{Q_{total} - Q_{fast}}{Q_{total}}$$



$$FOM = \frac{\mu_\gamma - \mu_n}{FWHM_\gamma - FWHM_n}$$

$FOM \approx$ 2.87 (This work)

$FOM \approx$ 1.89 [1]

$FOM \approx$ 3.2 [2]

TQDC16VS module, a pulse-shaper and digitizer with 8- ns binning

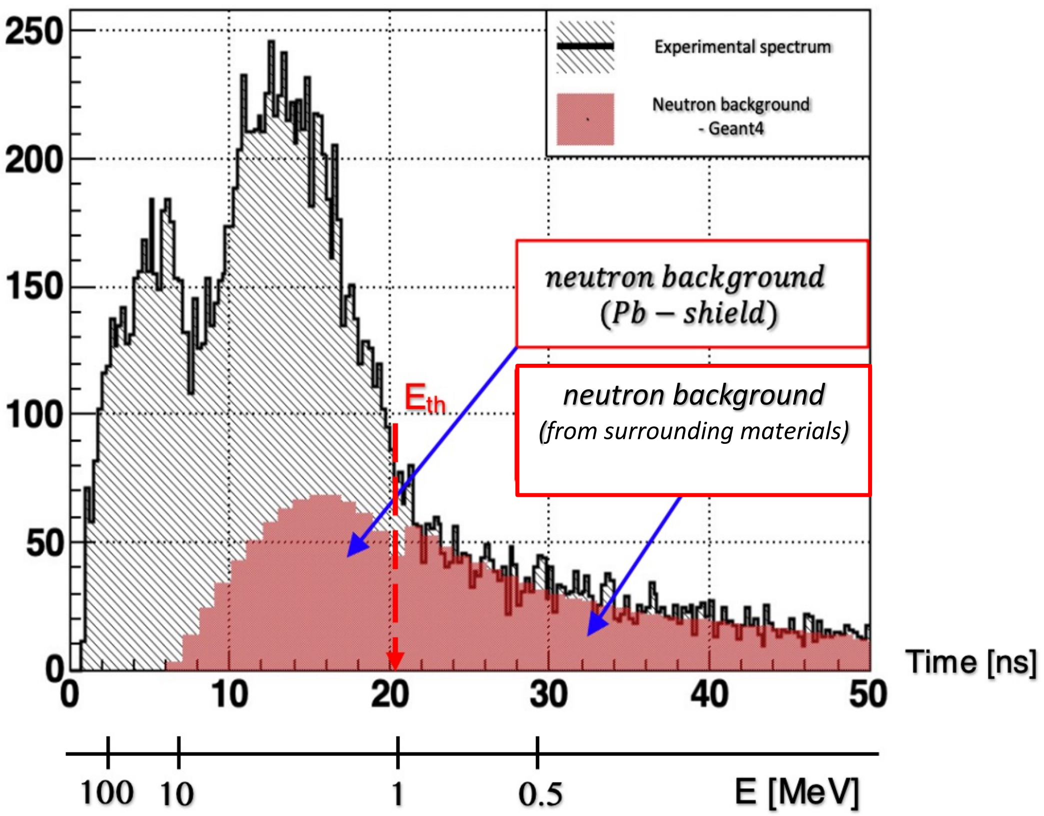
T_{fast} = 0.12 μs : time window for charge integration Q_{fast}

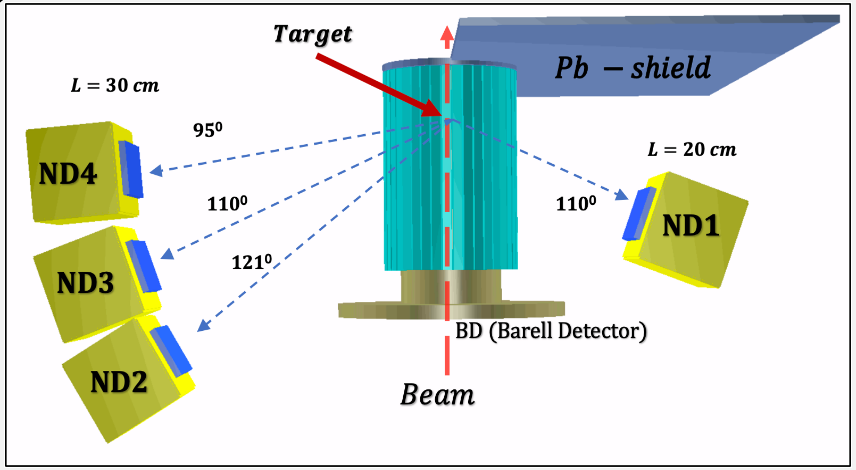
T_{total} = 1,5 μs. : time window for charge integration Q_{total}

[1] Nature, Sci. Rep. V.11 (2021) 3826
[2] IEEE Trans. Nucl. Sci. V.61 (2014) 2410

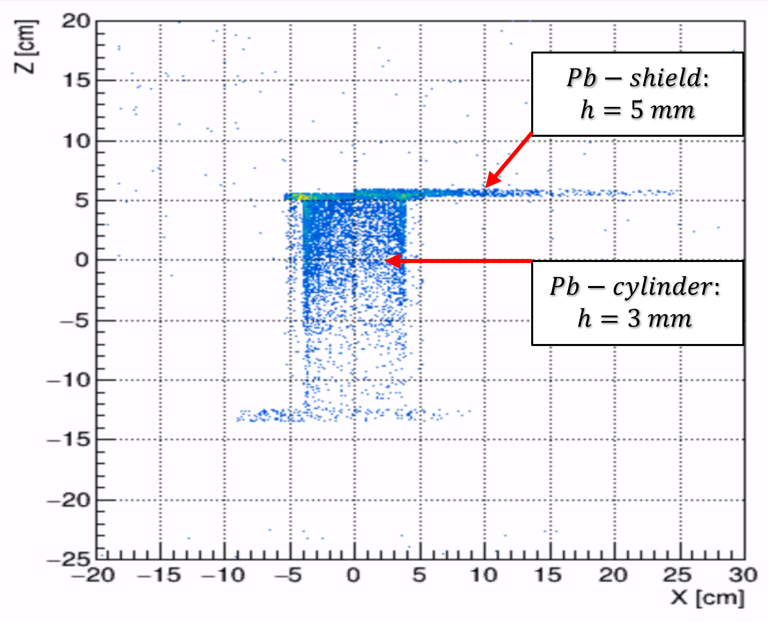
Neutron background conditions

TOF spectrum of neutrons





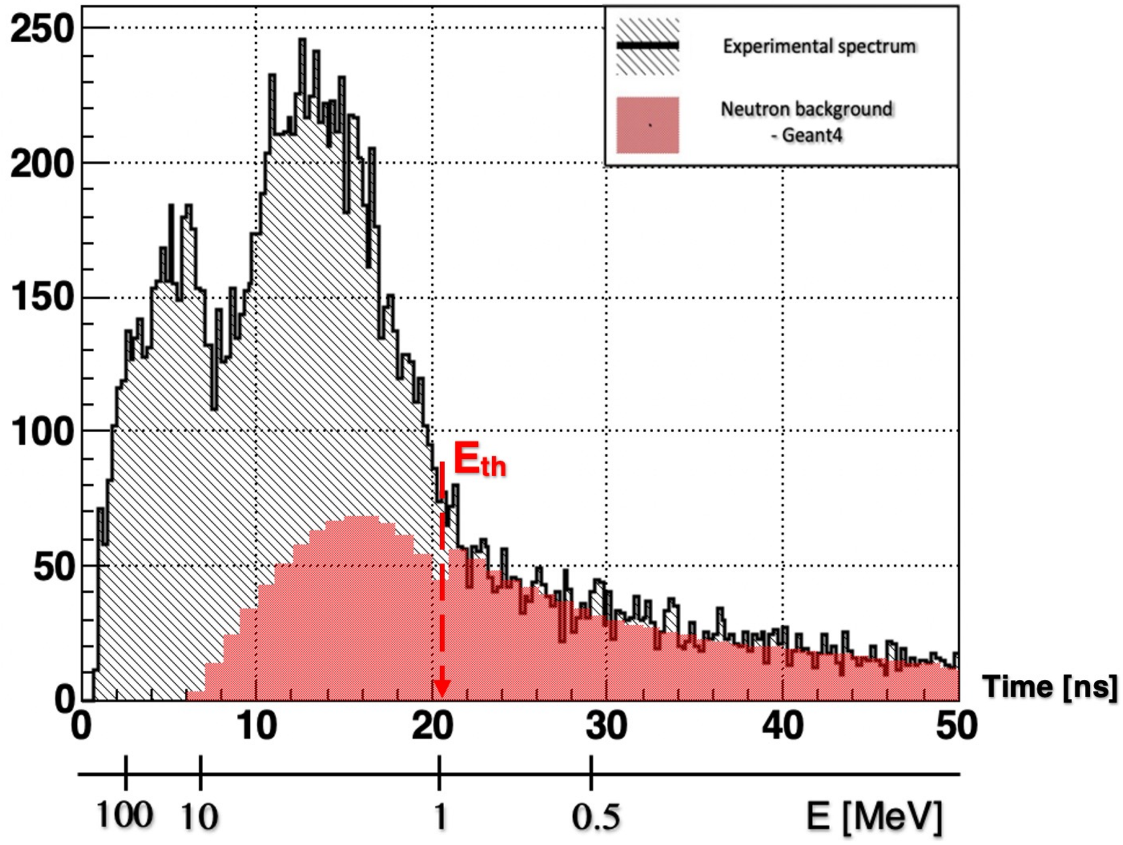
Background neutron vertices



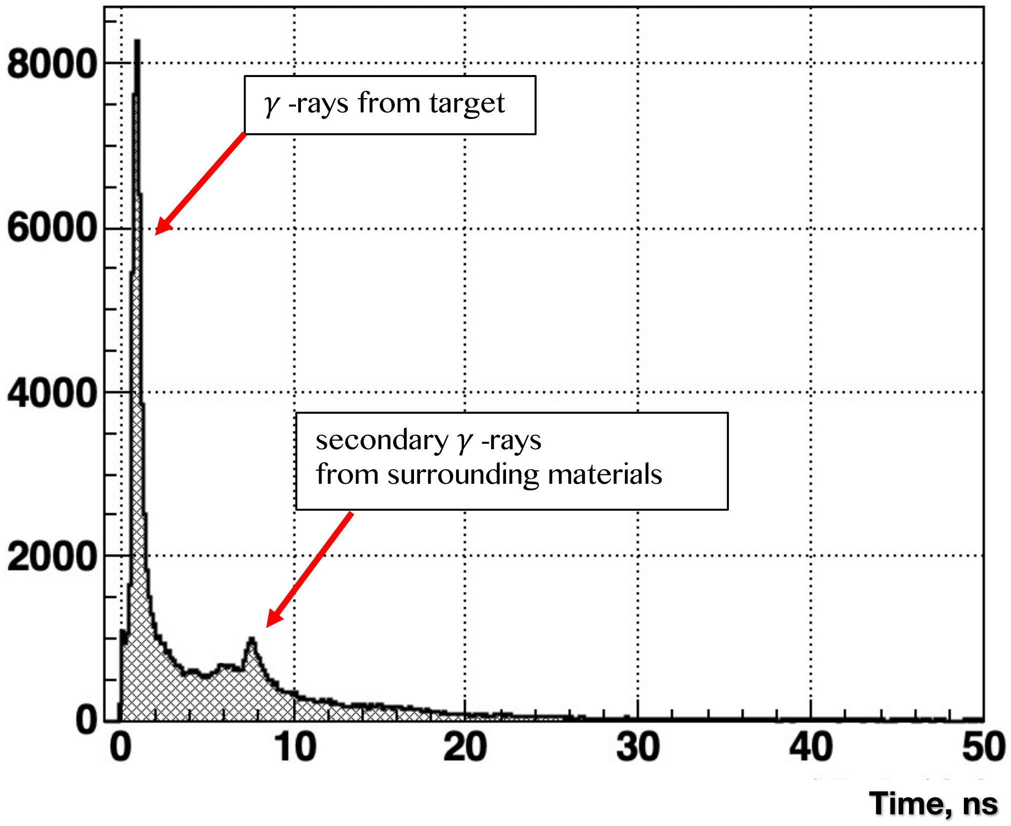
Geant4 (GNDL 4.7):
JEFF-3.3
JEFF-3.2
ENDF/B-VIII.0
ENDF/B-VII.1
BROND-3.1
JENDL-4.0u

Analysis of Results

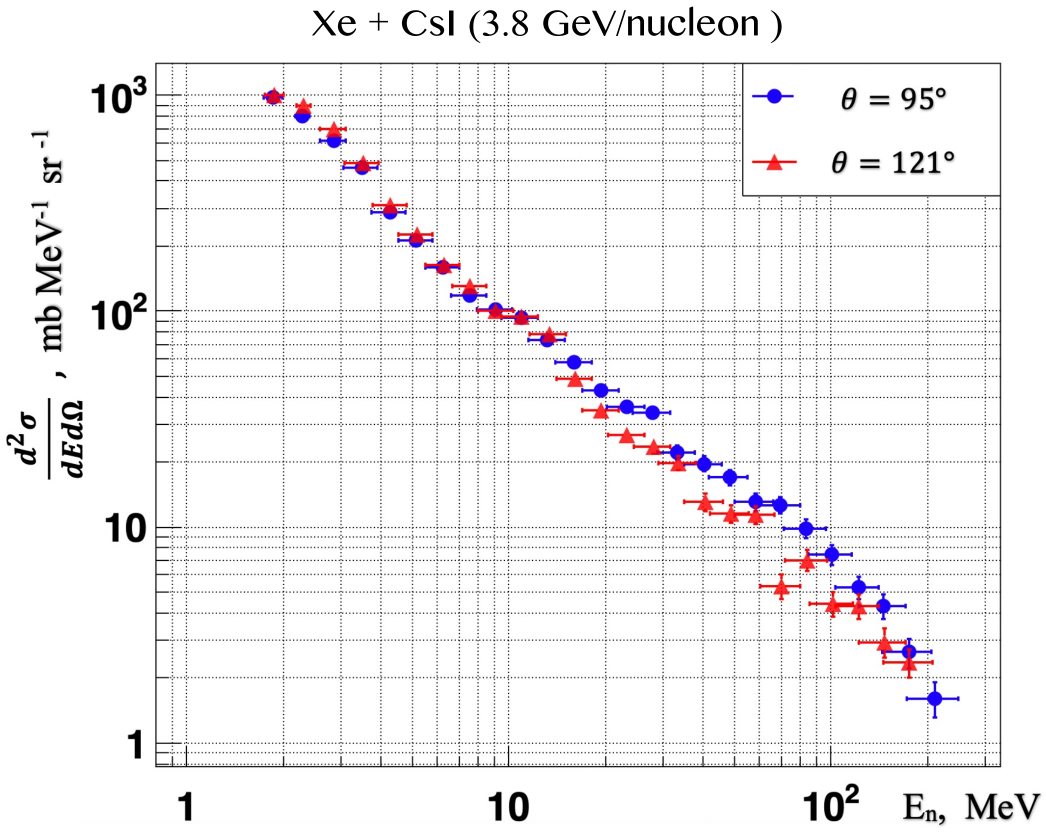
TOF spectrum of neutrons

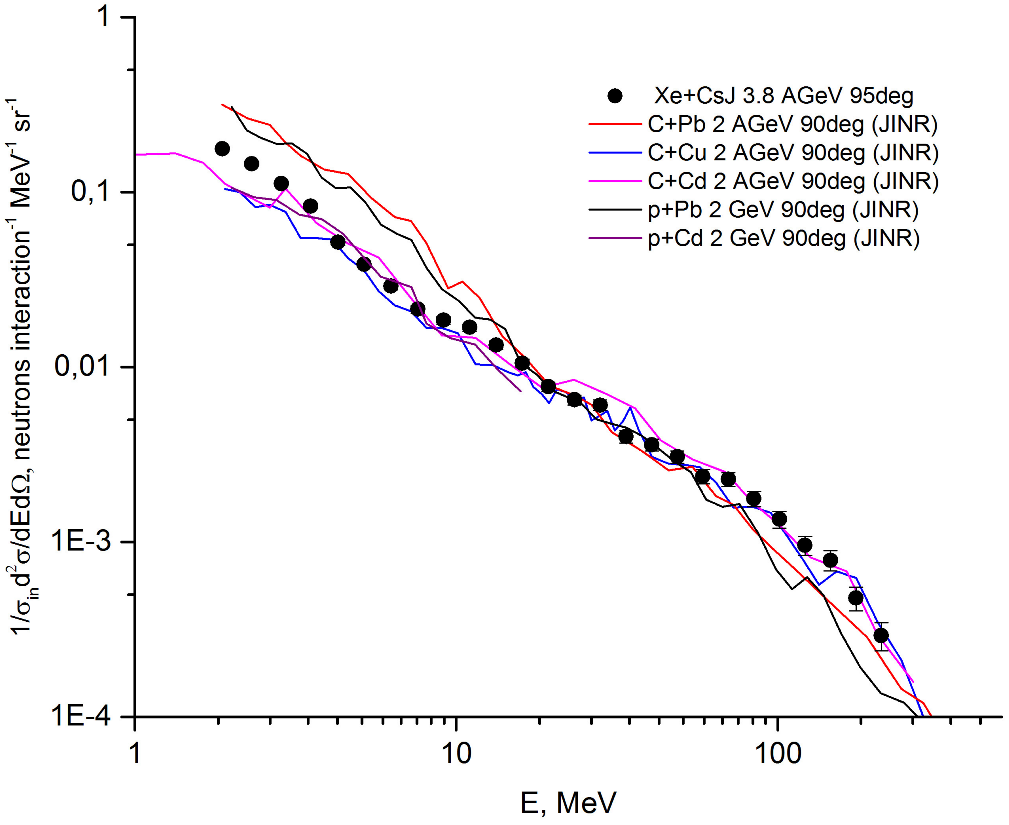


TOF spectrum of γ-rays

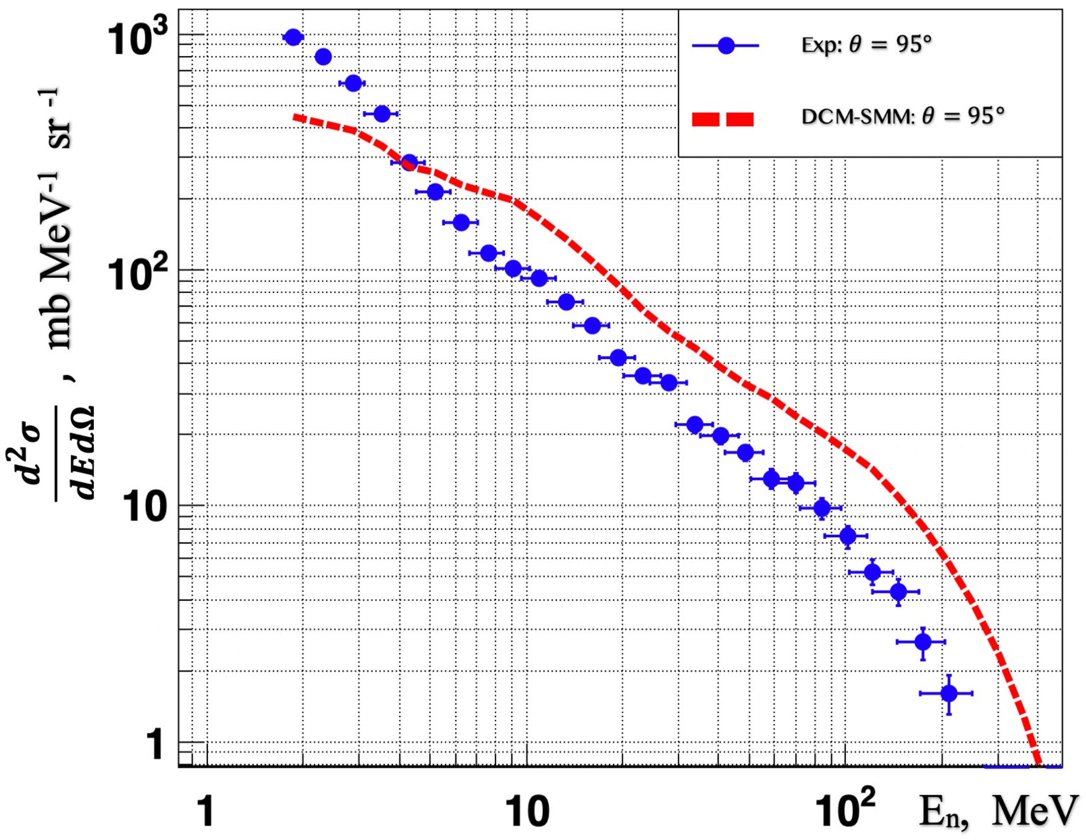


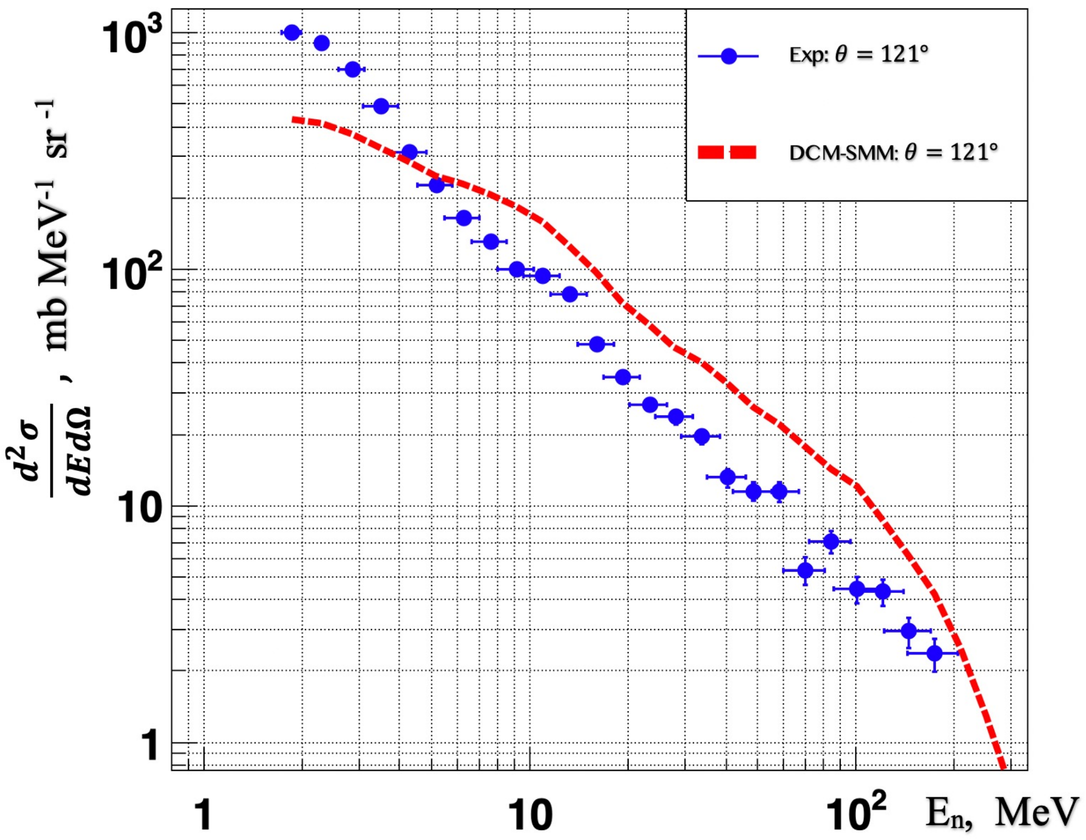
Preliminary results





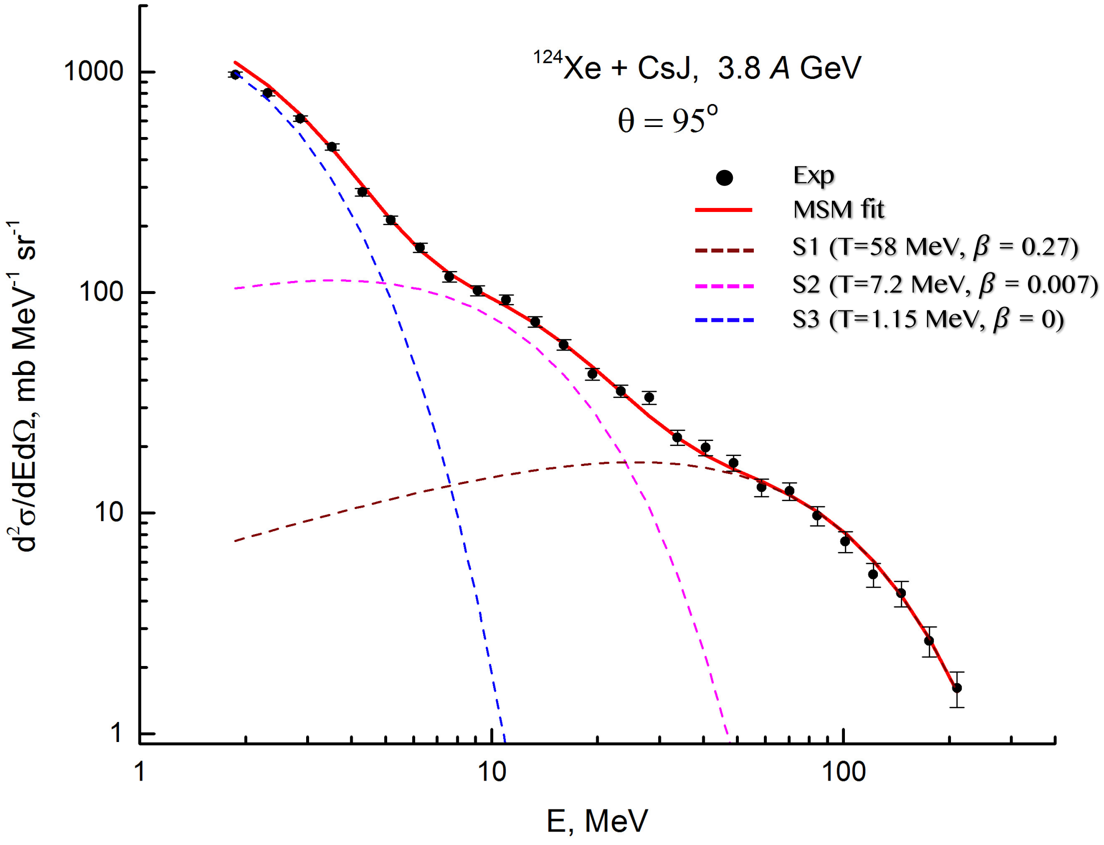
Preliminary results





Preliminary results

Moving Source Model with 3 sources of neutrons



S2 and **S3** – have very small velocities $v_{//}$ that corresponds to isotropic emission of neutrons from target spectator

S1 – has high temperature and velocity $v_{//} \approx 0.27c$ and describes a contribution from collision volume (participant region)

Mean multiplicity of neutrons from decay of the target spectator

$\langle \mathbf{M_n} \rangle = \langle M_n(S3) \rangle + \langle M_n(S2) \rangle = 9.0 + 3.9 =$ **12.9 neutrons**

Conclusion:

- The TOF neutron spectrometer with stilbene crystals and short flight path has been developed for measuring energy spectra of neutrons at large angles in the BM@N experiment
- It is shown importance of n/γ pulse shape discrimination for suppression of the γ –ray background
- As a result, preliminary energy spectra of neutrons were obtained in energy interval from 2 to 200 MeV and the analysis of data is continued
- The performed analysis proves that using the developed spectrometer we can obtain reliable neutron spectra in wide energy interval with good statistics
- Future plans - to use the spectrometer for study of neutron emission in BM@N runs with heavy ion beams

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Thank you
for your attention !