Development of a TOF neutron spectrometer in the BM@N experiment

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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.

At present, there are only a few experiments studied the neutron production in AA- collisions in the energy region above several hundred MeV per nucleon.

Au (0.8 GeV/u) + Au	R. Madey et al. (1988, 1990)
Ne (0.79 GeV/u) + Pb	A. Baldwin et al. (1992)
Bi (1 GeV/u) + Pb	M. Pachr et al. & A. Kugler et al. (1994)
He–Xe (0.23–0.6 GeV/u) + A	D. Satoh et al. (2011)
C (2 GeV/u) + A	V. Yurevich et al. (2012)

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.

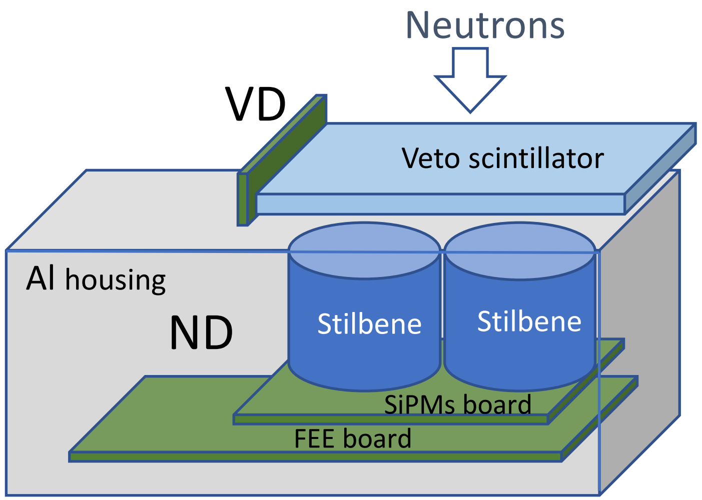
Requirements to the neutron spectrometer

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

Neutron Detectors



Scheme of neutron detector

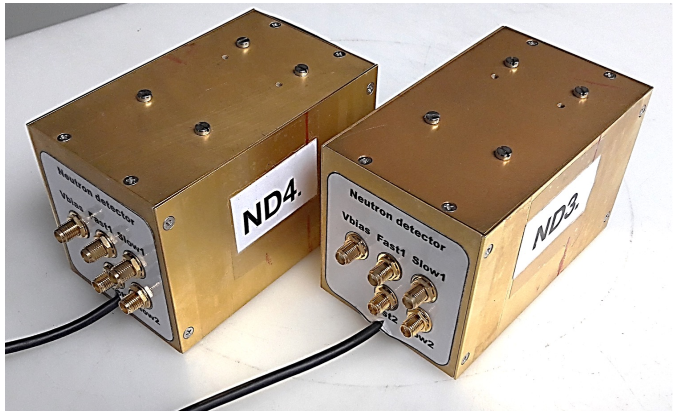
Stilbene crystal from Inrad Optics (USA)
(1”diam. × 1”)

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

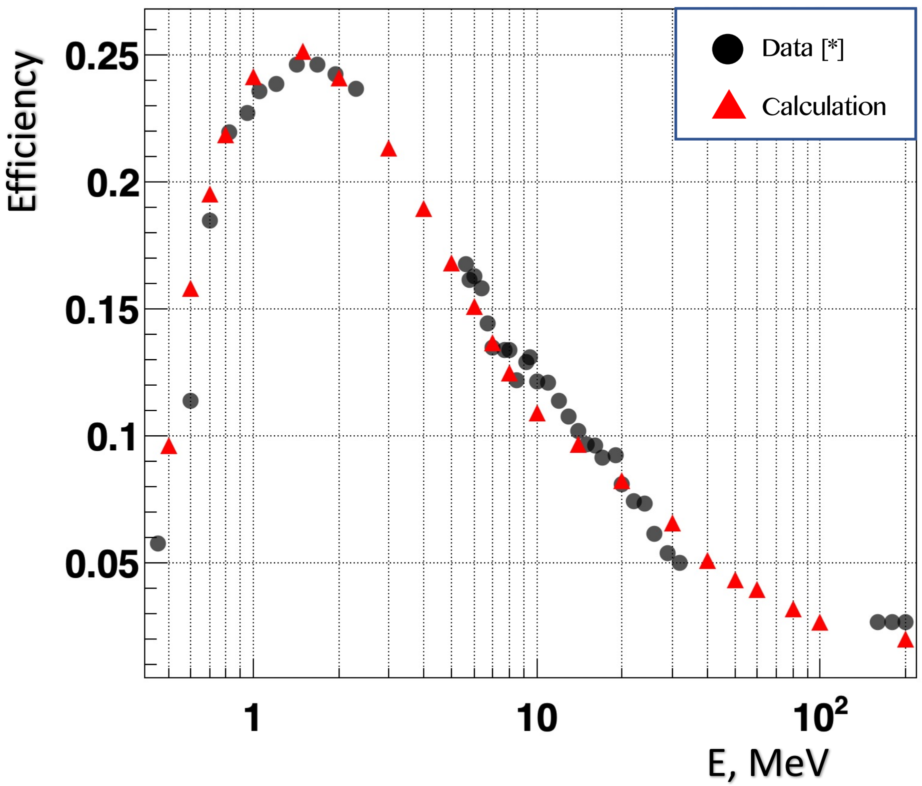
Readout Electronics – **TQDC16VS** module
Each channel consists of:

1. TDC with 25 ps binning
2. pulse-shaper and digitizer with 8 ns binning



Neutron Detectors

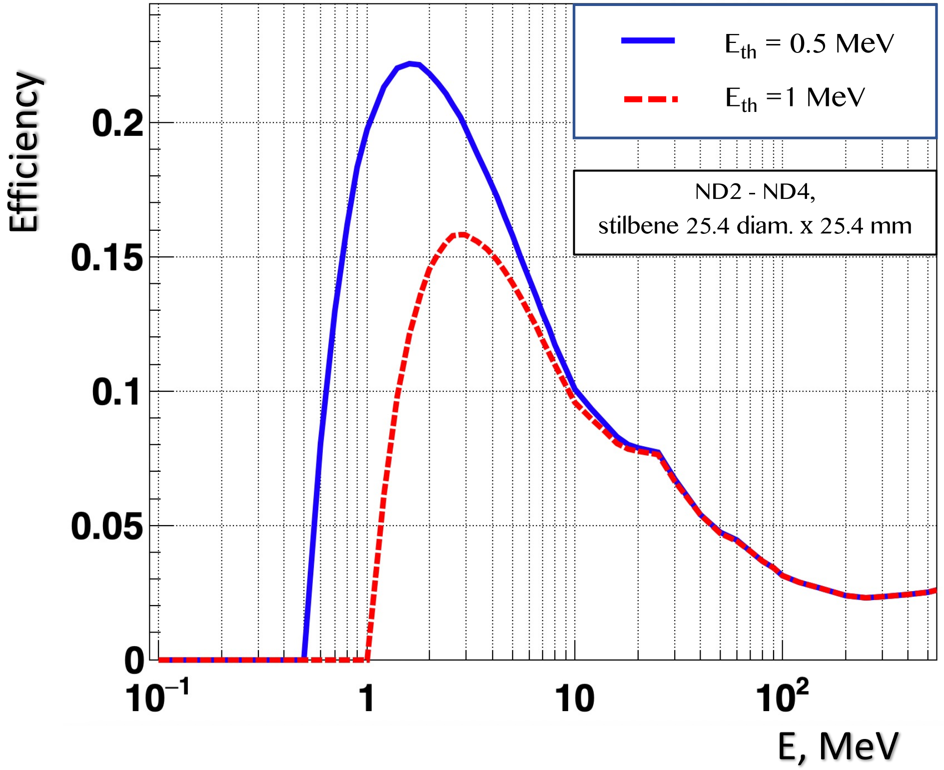
Neutron detection efficiency



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

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

E_{th}=0.45 MeV



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

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

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

BM@N Run 2022-2023 with Xe ions

Beam: Beam of ^{124}Xe ions in vacuum beam pipe
Typical beam intensity: $n\times10^5$ ions/spill
Spill duration: 2 – 3 s.
Beam energy: 3.8 GeV/nucleon

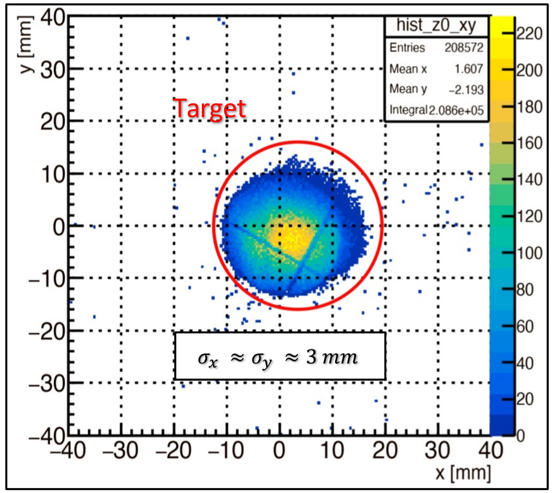
Target: CsJ (2%)
$n =$ 3,64 $*10^{21}$ nuclei/cm^2

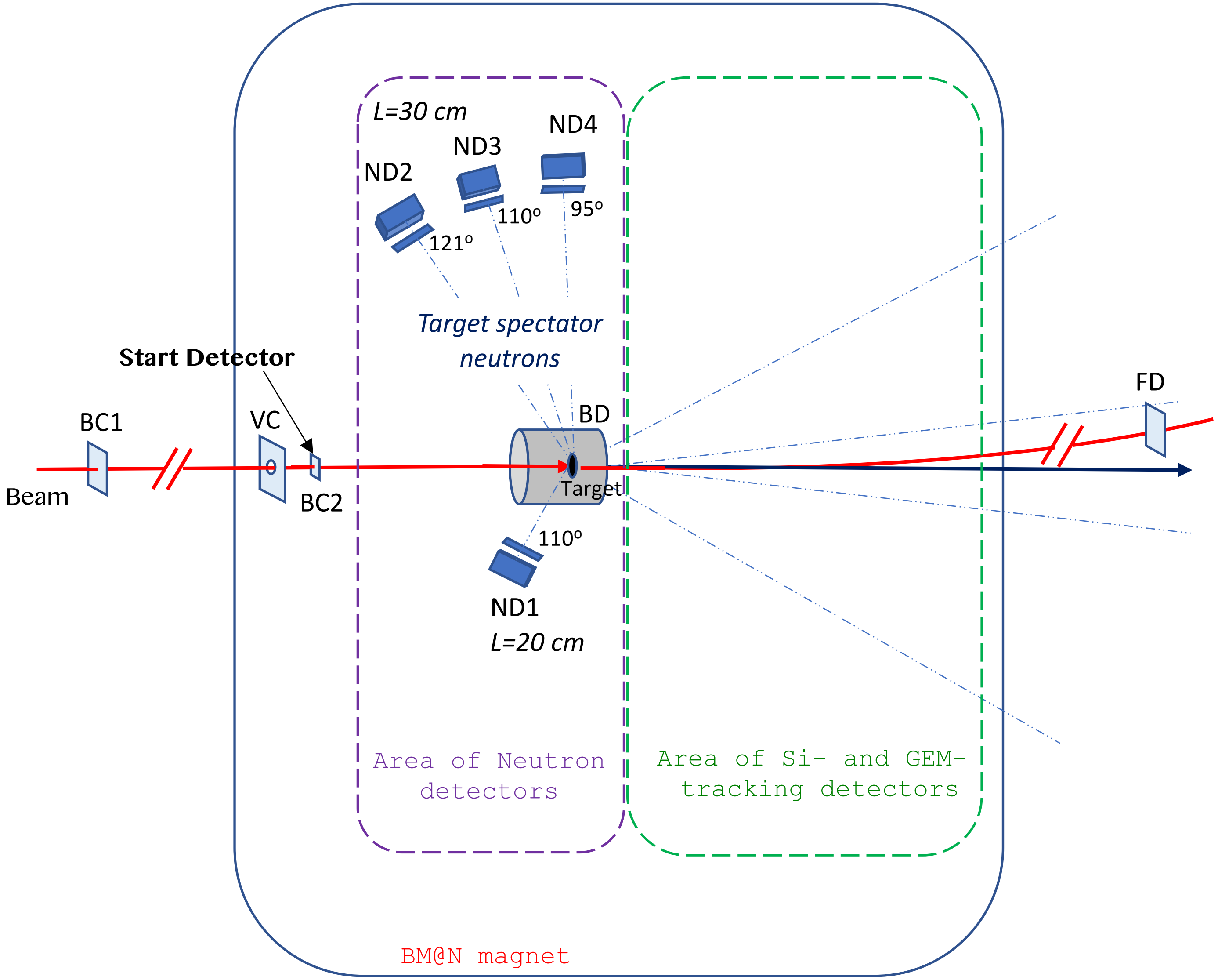
Trigger for data taking:

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

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

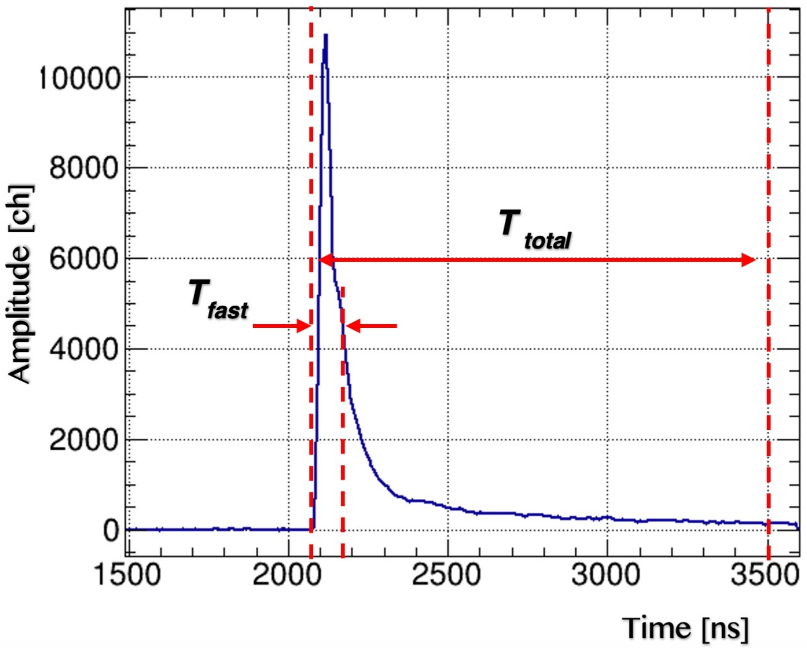
Hits of Xe ions in the target position obtained with forward Si tracker



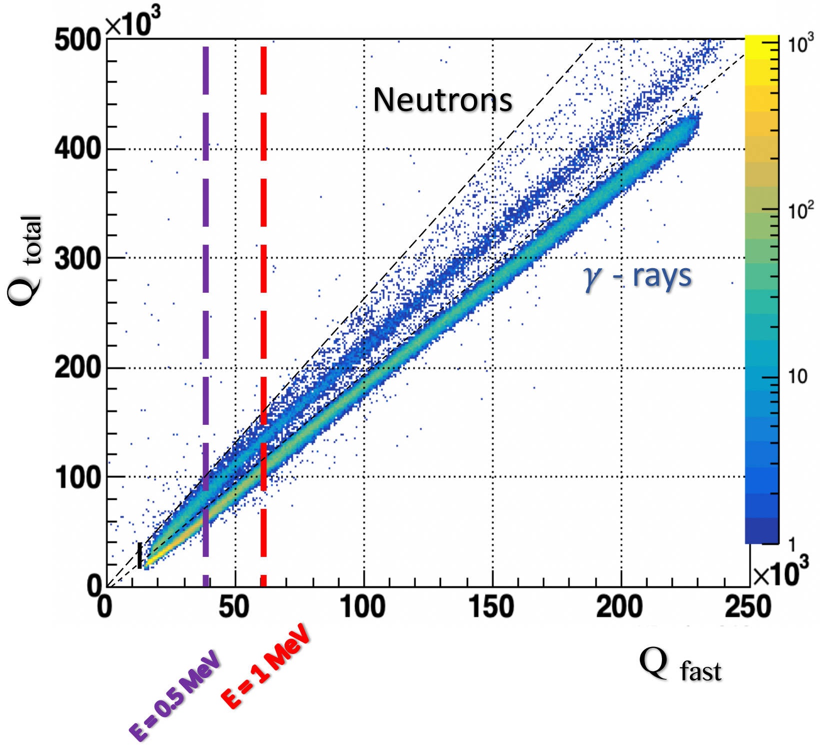


Pulse Shape Discrimination and Suppression of Background

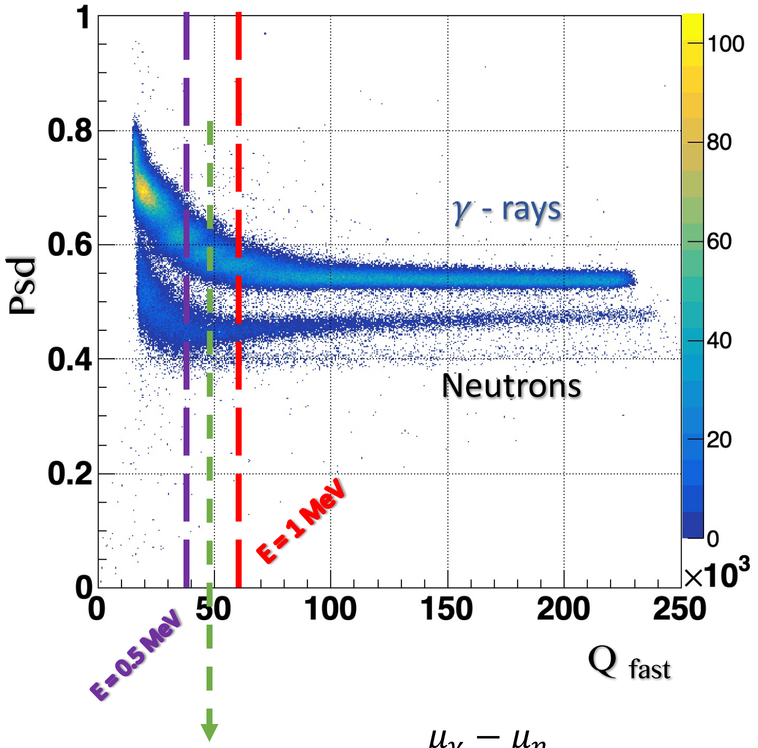
Waveform of Nd4 detector (TQDC)



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]

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

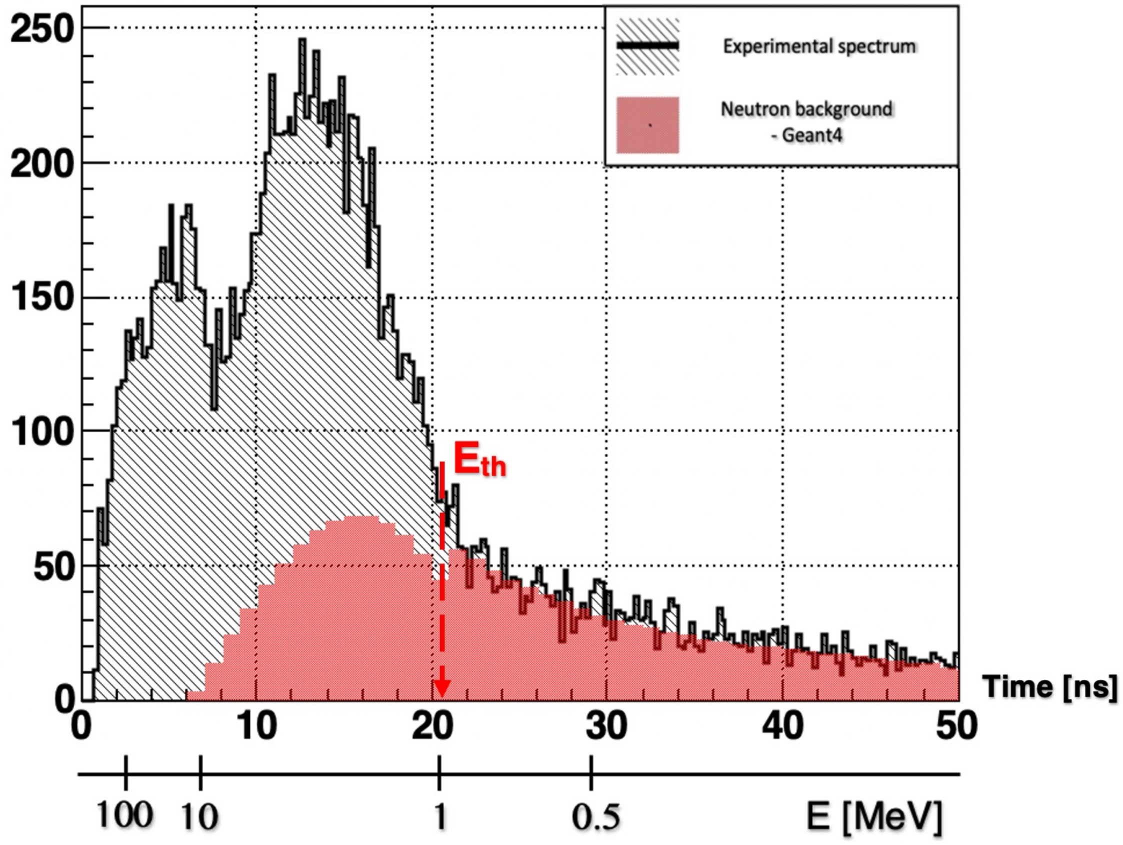
T_{total} = 1,5 μs. : time window for charge integration Q_{total}

[1] Nature, Sci. Rep. V.11 (2021) 3826

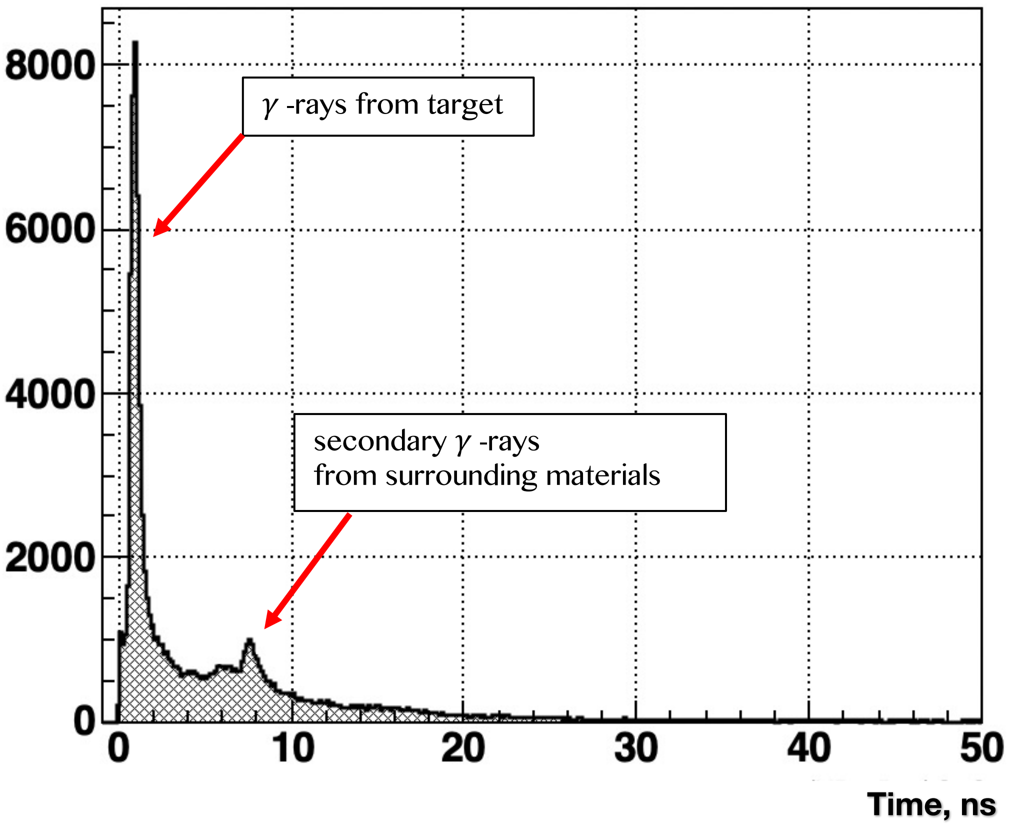
[2] IEEE Trans. Nucl. Sci. V.61 (2014) 2410

Analysis of Results

TOF spectrum of neutrons



TOF spectrum of γ-rays



Time and Energy Resolution

Time resolution

$\sigma_{ND4-BC2}$	σ_{BC2}	σ_{ND4}
117 ps	38 ps	110 ps

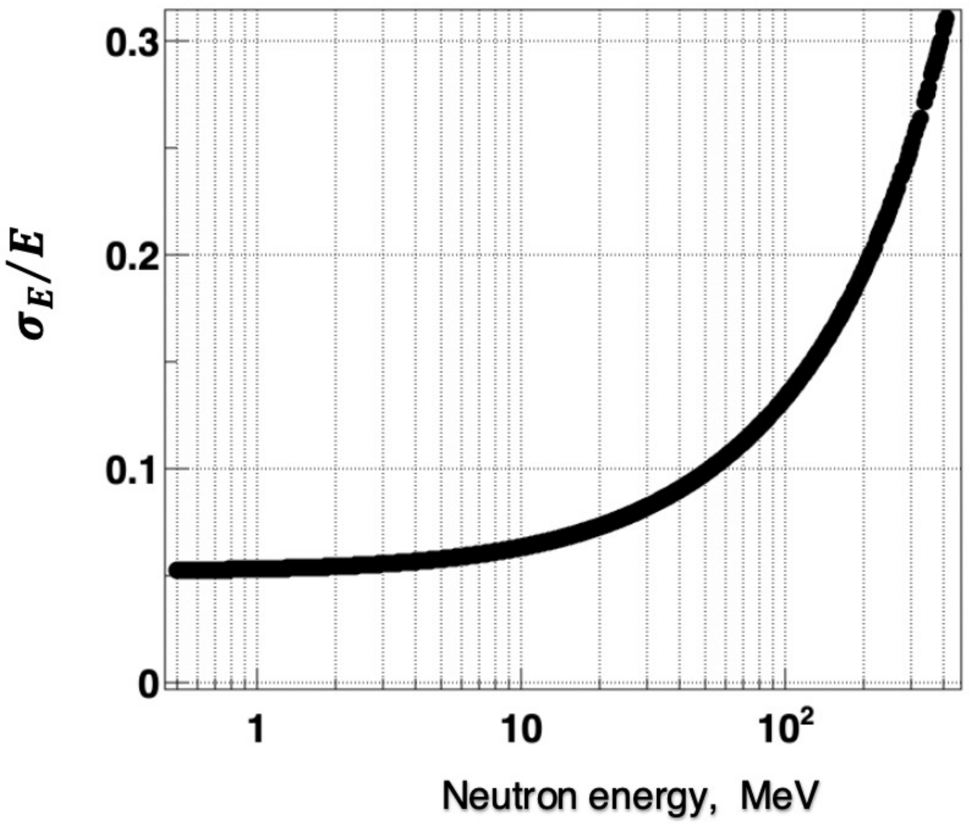
$$\frac{\sigma_E}{E} = \gamma(\gamma+1)\left[\left(\frac{\sigma_l}{l}\right)^2 + \left(\frac{\sigma_t}{t}\right)^2\right]^{1/2}$$

γ – the Lorentz factor

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

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

Energy resolution



Example of Neutron Energy Spectrum

^{124}Xe + CsI collisions

Beam energy – 3.8 GeV/nucleon;

Trigger – Interaction Trigger (IT) ;

Detector – ND4;

Angle – 95^0

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

ΔN - the number of detected neutrons;

ΔE - the energy bin width;

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

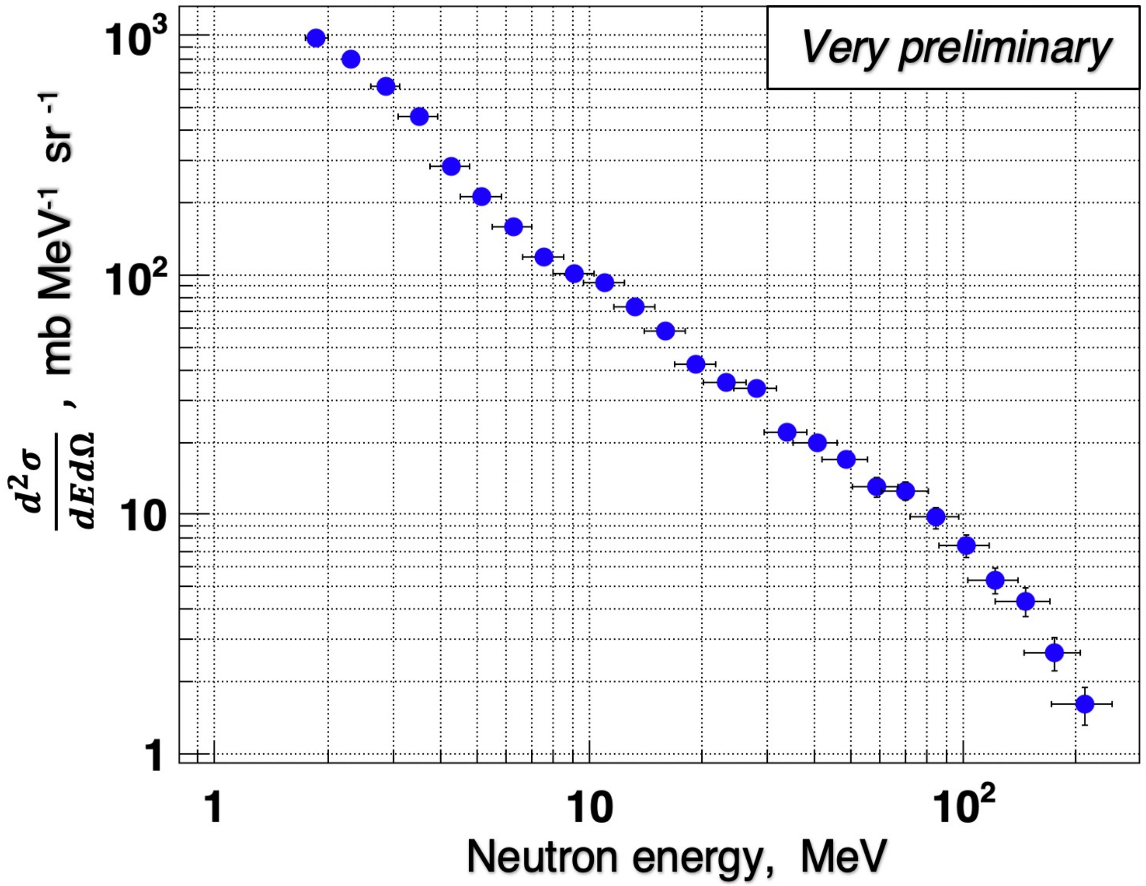
$\varepsilon(E)$ - the neutron detection efficiency;

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



$I \cdot k_1 \cdot k_2 = 9.1 * 10^8$ ions

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, which allows fully suppress the gamma-ray background

- As a result, a preliminary energy spectrum of neutrons was obtained in energy interval from 2 to 200 MeV. 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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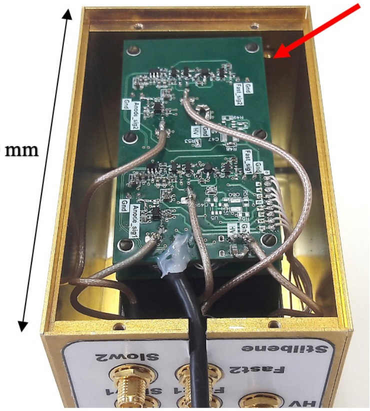
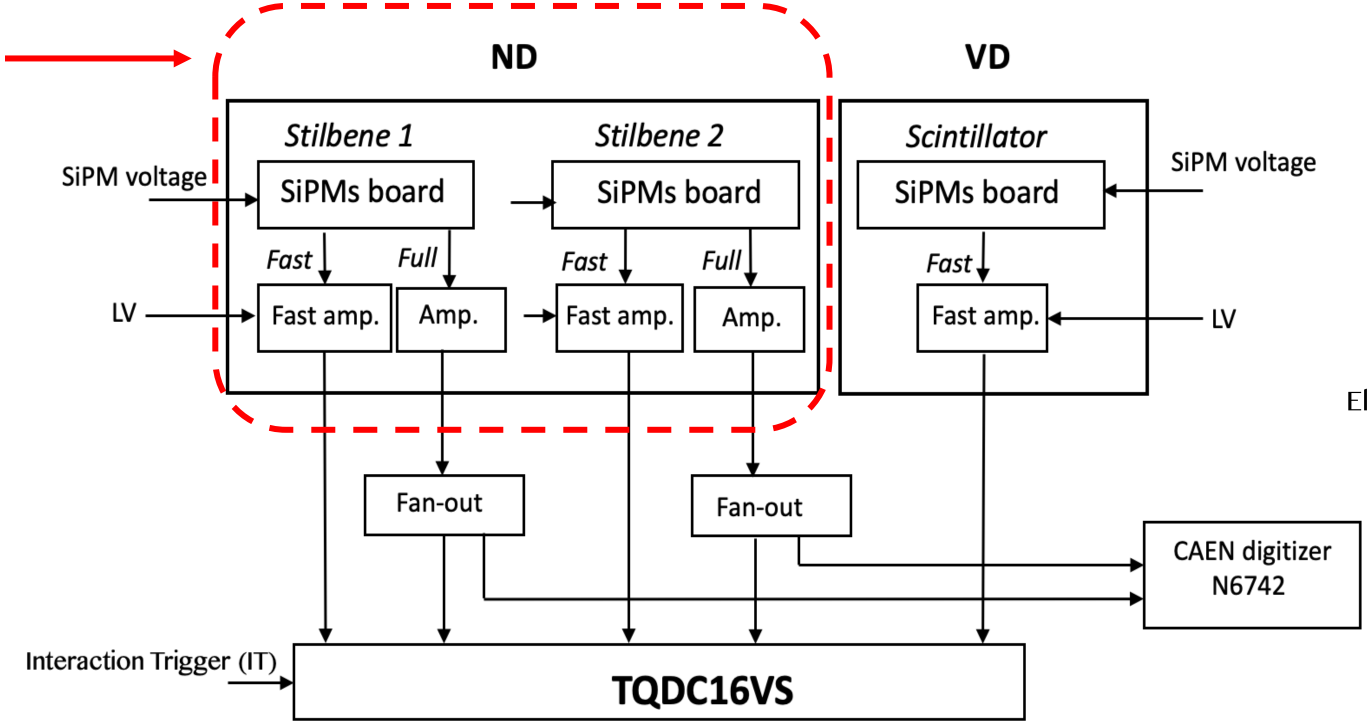
BM@N
Baryonic Matter at Nuclotron

Thank you
for your attention !

Backup slides

Electronics and DAQ





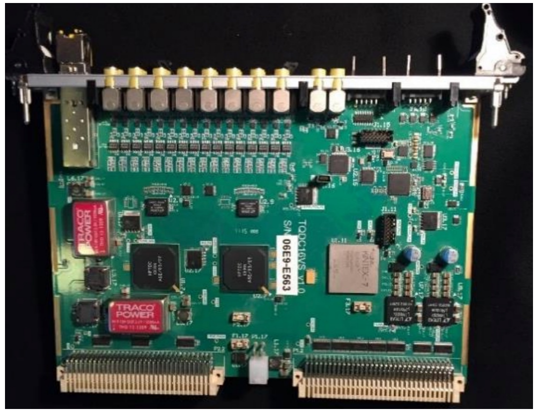
Electronics for control of the detector operation (**CAEN digitizer N6742** with 200ps binning)

Main readout electronics:

TQDC16VS (developed and produced at LHEP/JINR)

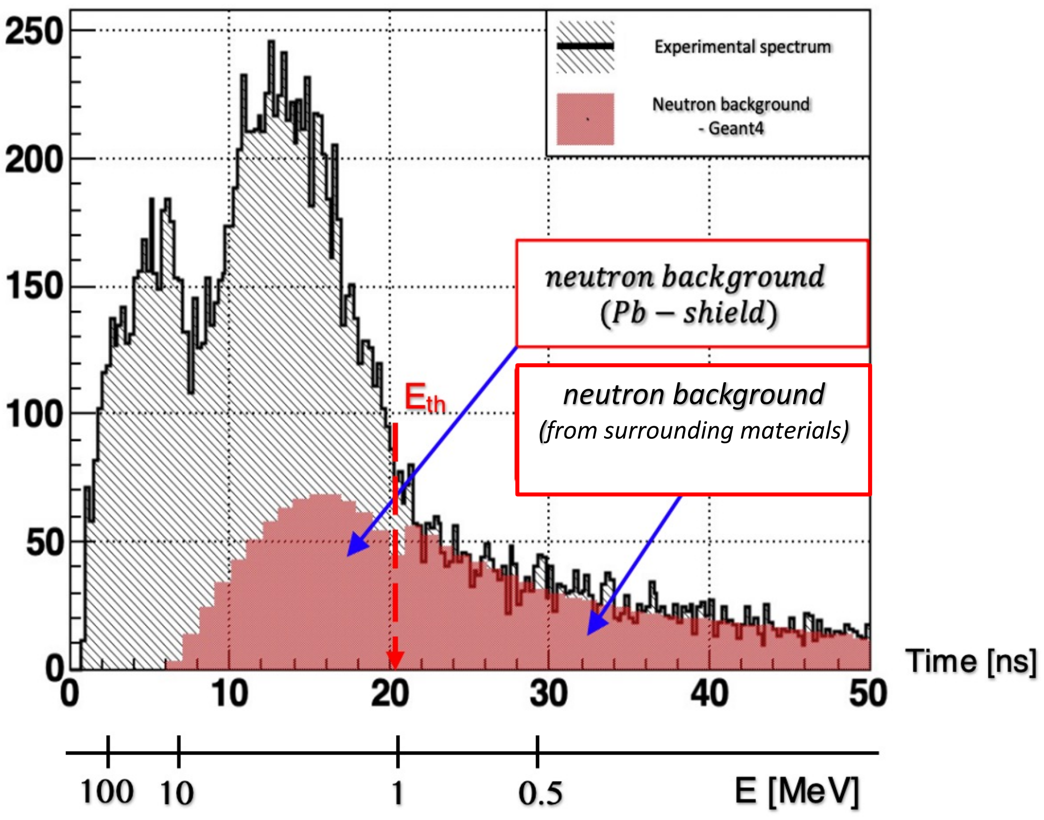
Characteristics of the **TQDC16VS** module:

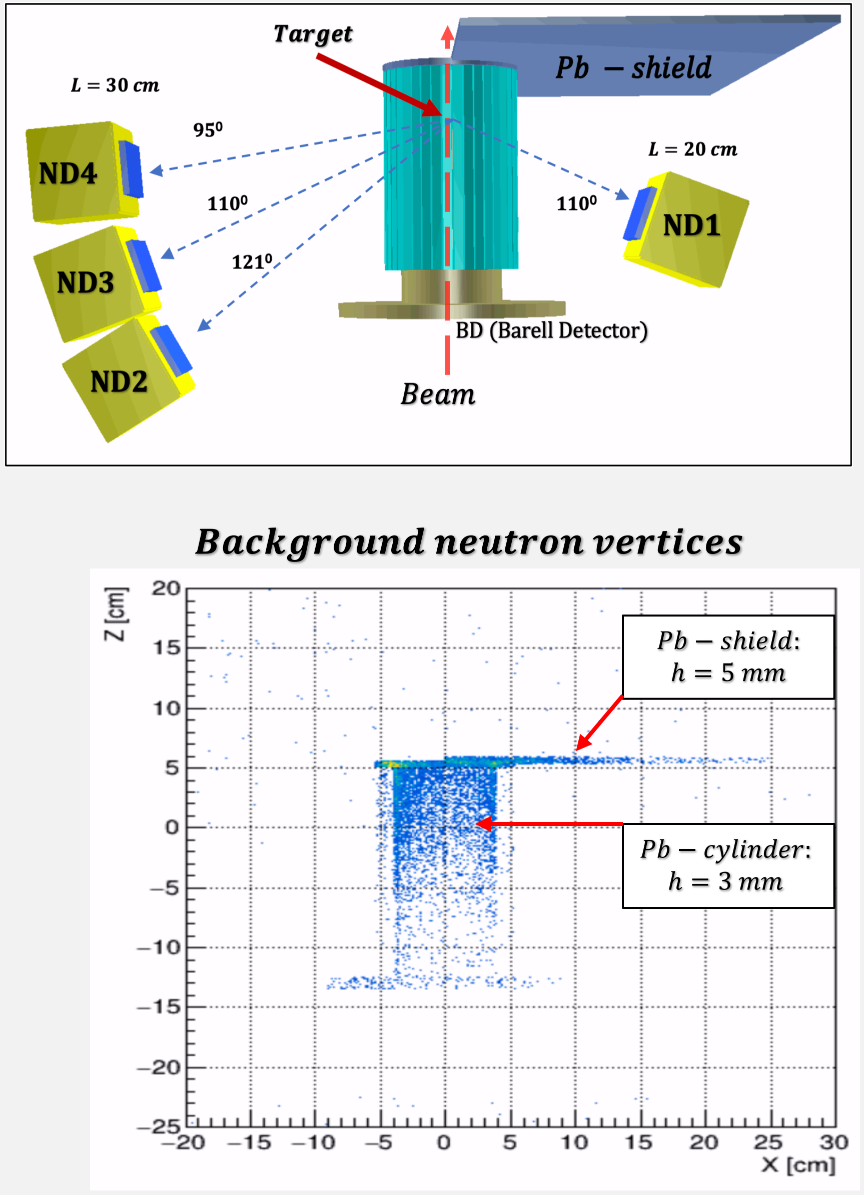
- 16 input channels,
- TDC with 25 ps time binning,
- Pulse height digitizer with 8-ns binning



Neutron background conditions

TOF spectrum of neutrons





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