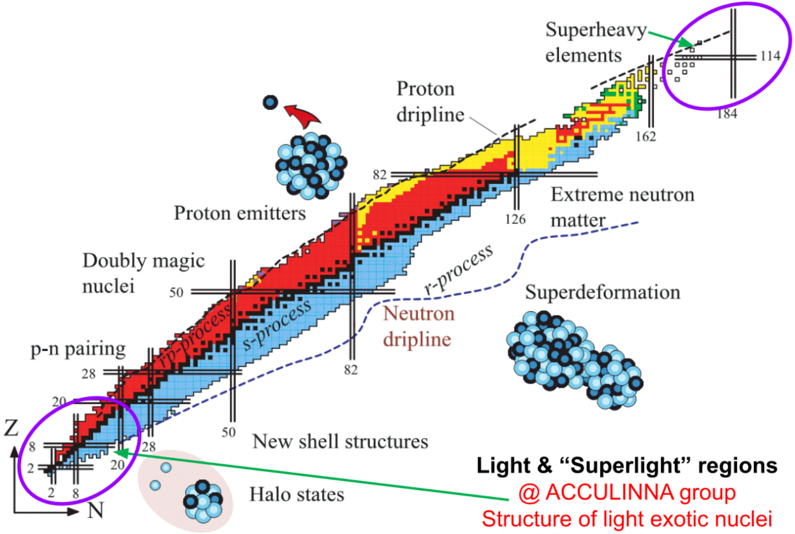
A MOdular NEutron Spectrometer (MONES) for studies with radioactive beams at ACCULINNA-2 fragment separator

Anh Mai

ACCULINNA group,
Flerov Laboratory of Nuclear Reactions

28^{th} International Scientific Conference of Young Scientists and Specialists
28 October - 01 November 2024, JINR

Main areas of interest at FLNR at nuclide chart



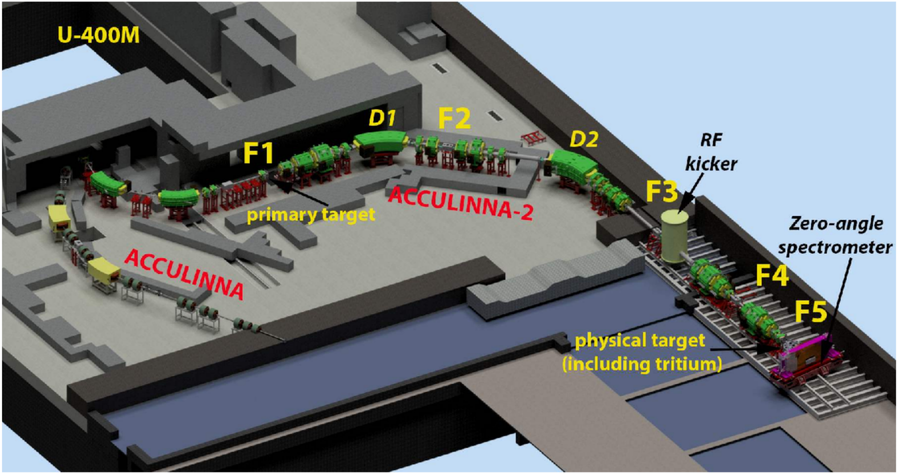
Light & "Superlight" regions

@ ACCULINNA group

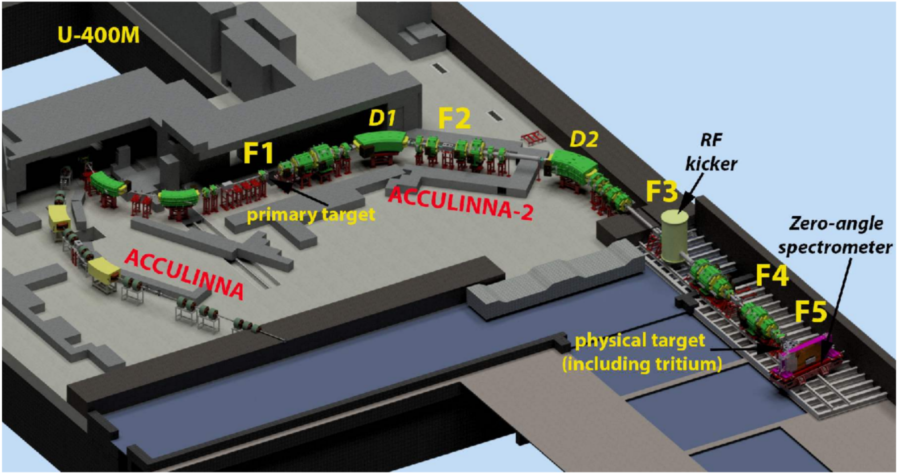
Structure of light exotic nuclei

^{10}Li, $^{5-7}$H and $^{7-9}$He isotopes

Beam production @ ACCULINNA-2



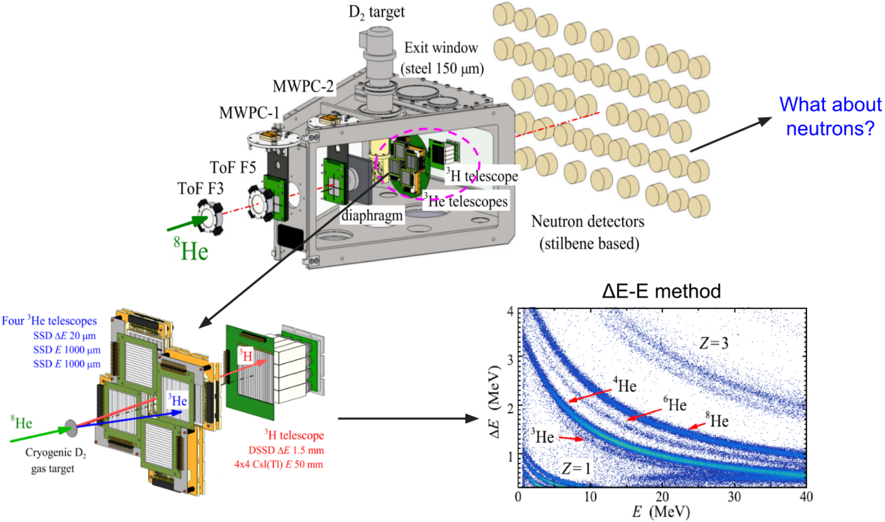
Beam production @ ACCULINNA-2



$^{11}B^{5+}$ @ 32 AMeV + 1 mm ^{9}Be → ACCULINNA-2 →∼ 90% and 10^5 pps ^{8}He @ 26 AMeV

Reaction chamber @ final focal plane F5

$$^{8}\mathrm{He} + \mathrm{d} \rightarrow {}^{3}\mathrm{He} + {}^{7}\mathrm{H} \rightarrow {}^{3}\mathrm{H} + 4\mathrm{n}$$

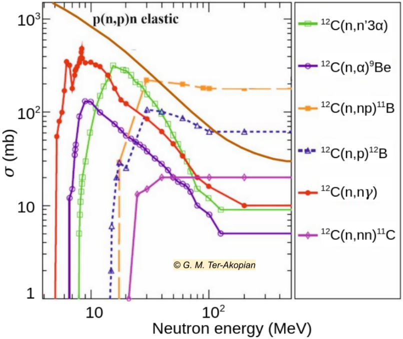


Reaction chamber in the experiment

Neutron detection

Neutron-matter interaction cross-sections

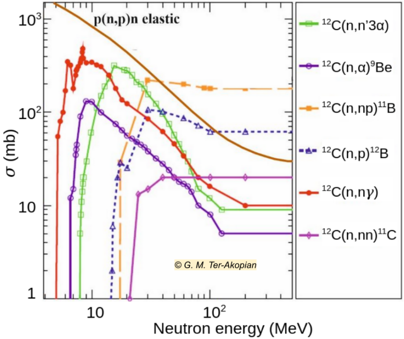
in accordance with different neutron energies



Neutron detection

Neutron-matter interaction cross-sections

in accordance with different neutron energies



The characteristics of some common organic scintillators.

Formula	Density (g/cm^3)	Decay time(ns)	Wavelength (nm)	Light output relatively %
Anthracene $C_{14}H_{10}$ [1]	1.25	30	445	100
Stilbene $C_{14}H_{12}$ [1]	1.16	6	410	56
Liquid BC501A (or NE213) [2]	0.901	3.2	425	78
Plastic EJ276 (or EJ299-33A) [3]	1.896	13	425	56

[1] R.K. Svenk (1956), Usp. Fiz. Nauk, vol. 58, no. 3, p. 519.
[2] http://www.eljentechnology.com/products/plastic-scintillators/ej-299-33a-ej-299-34.
[3] https://www.crystals.saint-gobain.com/sites/hps-mac3-cma-crystals/files/2021-09/BC501-501A-519-Data-Sheet.pdf.

Stilbene based neutron spectrometer

Stilbene crystals:

- high luminescence efficiency
- fast response time

Stilbene based neutron spectrometer

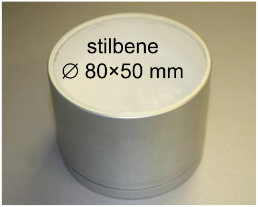
Stilbene crystals:

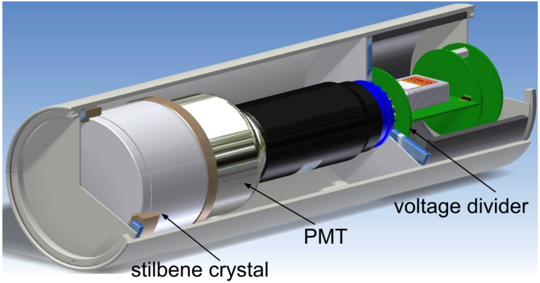
- high luminescence efficiency
- fast response time
- crystalline and solid
  $\rightarrow$ high durability,
  non-flammable
- greatly sensitive to neutrons
  $\rightarrow$ well-suited in our range
- excellent $n - \gamma$ discrimination

Stilbene based neutron spectrometer

Stilbene crystals:

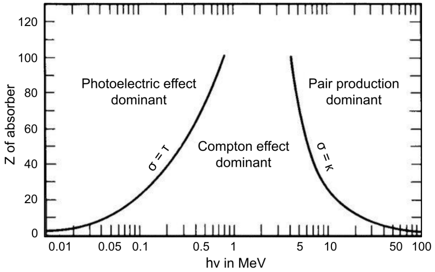
- high luminescence efficiency
- fast response time
- crystalline and solid
  $\rightarrow$ high durability,
  non-flammable
- greatly sensitive to neutrons
  $\rightarrow$ well-suited in our range
- excellent $n - \gamma$ discrimination





$\rightarrow$ Stilbene fit all qualifications and were implemented into MONES @ ACCULINNA-2.

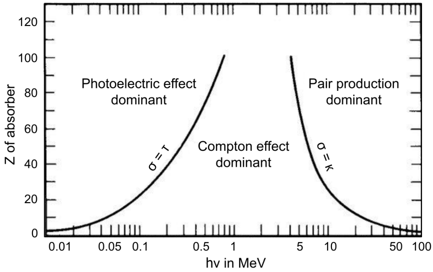
Energy calibration



The Compton edge energy E_{CE} is computed at a given gamma energy by the following,

$$E_{CE} = E_{\gamma}(1 - \frac{1}{1 + \frac{2E_{\gamma}}{m_e c^2}})$$

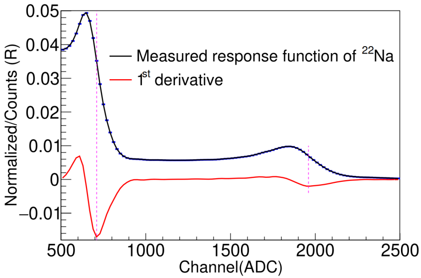
Energy calibration

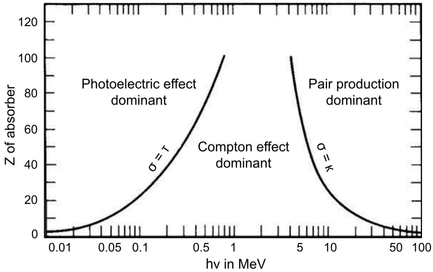


The Compton edge energy E_{CE} is computed at a given gamma energy by the following,

$$E_{CE} = E_\gamma \left(1 - \frac{1}{1 + \frac{2E_\gamma}{m_e c^2}}\right)$$

An example of Compton edge from stilbene scintillator using $^{22}\mathrm{Na}$

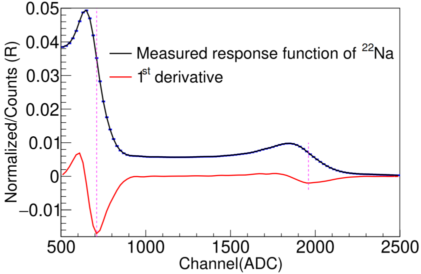


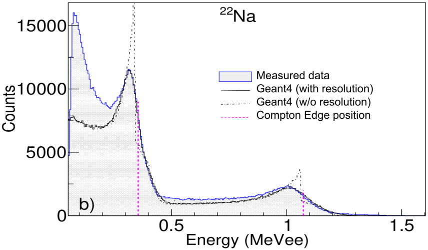


The Compton edge energy E_{CE}
is computed at a given gamma energy
by the following,

$$E_{CE} = E_{\gamma}(1 - \frac{1}{1 + \frac{2E_{\gamma}}{m_e c^2}})$$

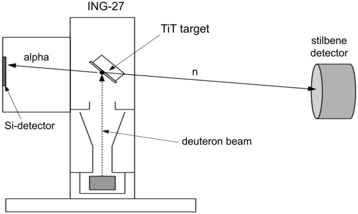
An example of Compton edge from stilbene scintillator using $^{22}\mathrm{Na}$



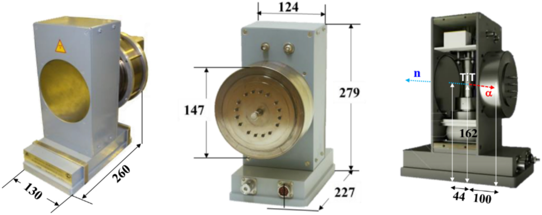


ING-27 DT neutron generator

The experimental schematic of DT-reaction

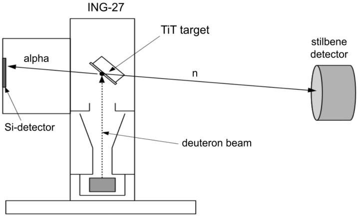


ING-27 dimensions (mm) in experiment

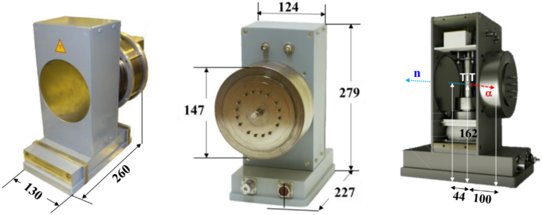


ING-27 DT neutron generator

The experimental schematic of DT-reaction

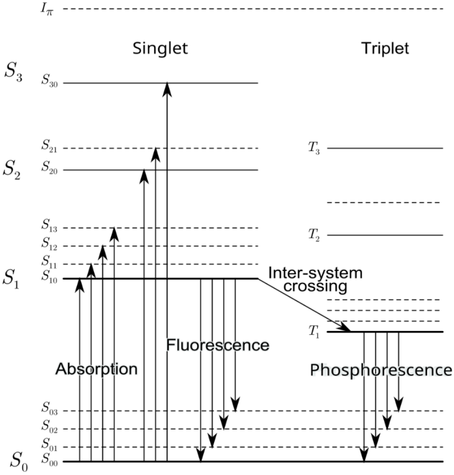


ING-27 dimensions (mm) in experiment



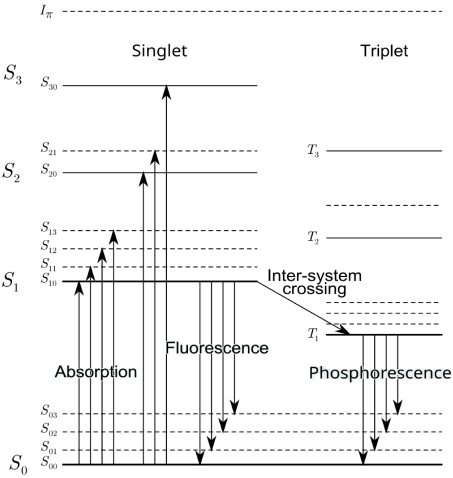
- a deuteron-beam @ 100 keV bombards a thin titanium-tritium TiT target by means of $d + t \rightarrow \alpha + n$ fusion reaction to produce 14-MeV neutrons,
- the neutron generator has an intensity up to 10^8 n/s in 4π,
- α-particles were registered by a 64-pixel (8×8 strip) DSSD @ 100 mm from the target,
- stilbene was placed at a distance of 15 cm for neutron detection.

Neutron-gamma discrimination



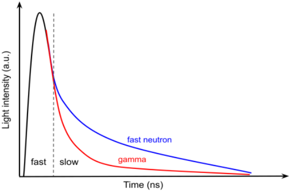
The scintillation process by means of π-electronic energy levels of an organic molecule.

Neutron-gamma discrimination



The scintillation process by means of π-electronic energy levels of an organic molecule.

Timing signals for gamma and neutron in the scintillator.



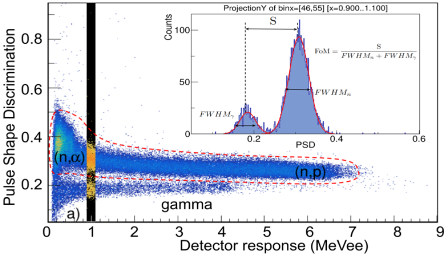
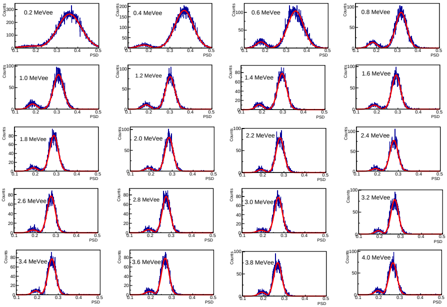


Illustration of neutron-gamma separation by Pulse Shape Analysis from the 14-MeV neutron generator.

Neutron-gamma discrimination (cont.)

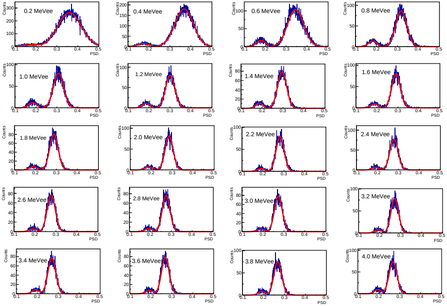
The neutron-gamma discrimination is projected

into different ranges from 0.2 to 4 MeVee

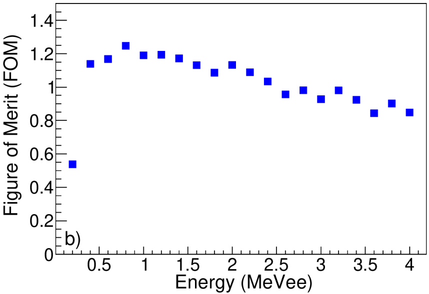


Neutron-gamma discrimination (cont.)

The neutron-gamma discrimination is projected into different ranges from 0.2 to 4 MeVee



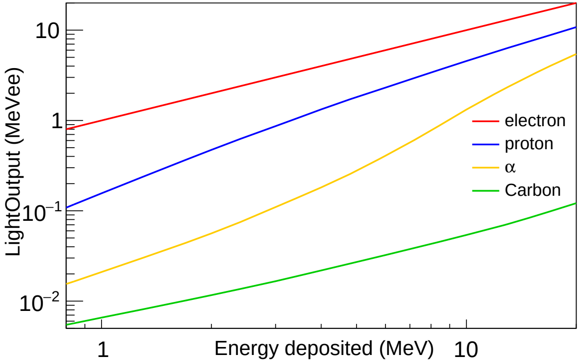
The FOM quantity as a function of stilbene response from 0.2-4.0 MeVee



→ Figure of Merit determine its neutron-gamma discrimination capacity,
→ Apparently, neutron and gamma are well separated @ above 0.3 MeVee, which is in accordance with the incident neutron energy around 1 MeV.

Light output response in organic scintillator

- The recoil α-particles become dominant with incoming neutron energy > 6 MeV, $^{12}\mathrm{C}(n,\alpha)^{9}\mathrm{Be}$, Q $=$ -5.702 MeV and $^{12}\mathrm{C}(n,n'\alpha)$, Q $=$ -7.275 MeV,



Scintillator light output (MeVee) as a function the recoil particle energy (MeV). Data adapted from [4].

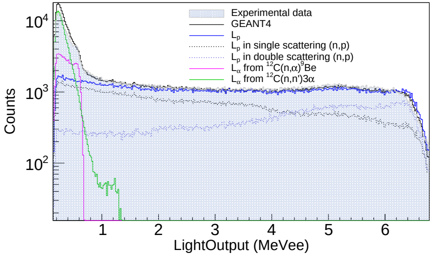
- Due to the quenching effect, the light output cannot be considered linear with regard to energy deposit in organic scintillators for heavy ions,
- The heavier the particle, the less the light it produces at a given energy.

[4] V. Verbinski et al., Nucl. Instrum. Methods 65 (1), 8–25 (1968).

Light output response in organic scintillator (cont.)

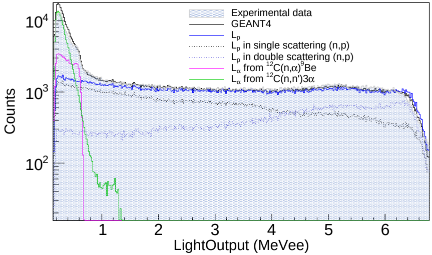
The neutron interaction with stilbene scintillator

leads to a large number of different processes

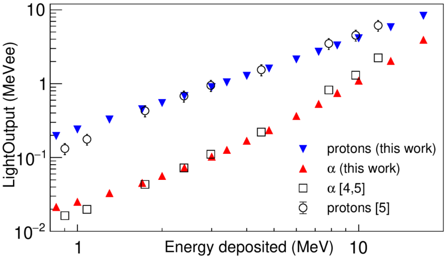


Light output response in organic scintillator (cont.)

The neutron interaction with stilbene scintillator leads to a large number of different processes



Light output response of stilbene organic scintillator to protons and alpha particles

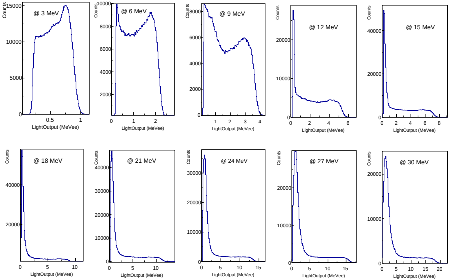


→ Chiefly, protons and α-particles produce the main light in the stilbene detector,
→ The response of proton + α-particles was simulated and reconstructed with measured data, and compared with other works.
→ Knowing the proton response is the key to determine the energy and TOF of incoming neutrons.

[4] V. Verbinski et al., Nucl. Instrum. Methods 65 (1), 8–25 (1968).
[5] R.L. Craun and D.L. Smith, Nucl. Instrum. Methods 80, 239–244 (1970).

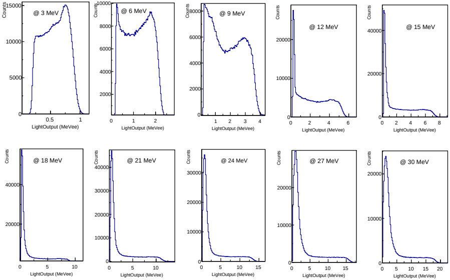
Neutron registration efficiency

The calculated response in the stilbene detector
to various incident neutron energies

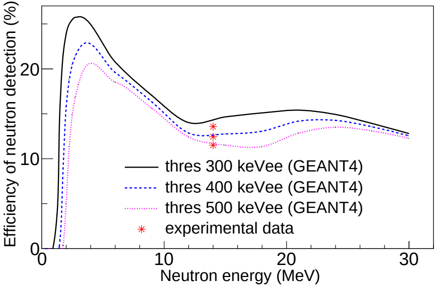


Neutron registration efficiency

The calculated response in the stilbene detector to various incident neutron energies



The measured and calculated neutron efficiency in the energy range of 3-30 MeV



→ Measured data at 14 MeV was compared with GEANT4,
thus neutron registration can be estimated in other energy ranges from 3-30 MeV.

Conclusions

- The performance of stilbene based modular neutron spectrometer (MONES) @ ACCULINNA-2 was characterized in this work,
- The 1st derivative of measured response combined with Geant4 simulations were to calibrate the stilbene detector,
- The neutron-gamma separation ability was examined by the use of Pulse Shape Analysis,
- The light output response functions of stilbene scintillator to charged particles (protons and α-particles) was reconstructed and compared with other studies,
- The neutron registration efficiency were determined by means of 14-MeV neutron generator and compared with simulated data.

Much appreciated for your attention.!