DEVELOPMENT OF NEUTRON DETECTORS FOR KEY ASTROPHYSICAL NUCLEAR REATIONS

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Outline

- Motivation and thermal neutron scattering
- Monte Carlo benchmark setup
- Results
- Conclusions and outlook

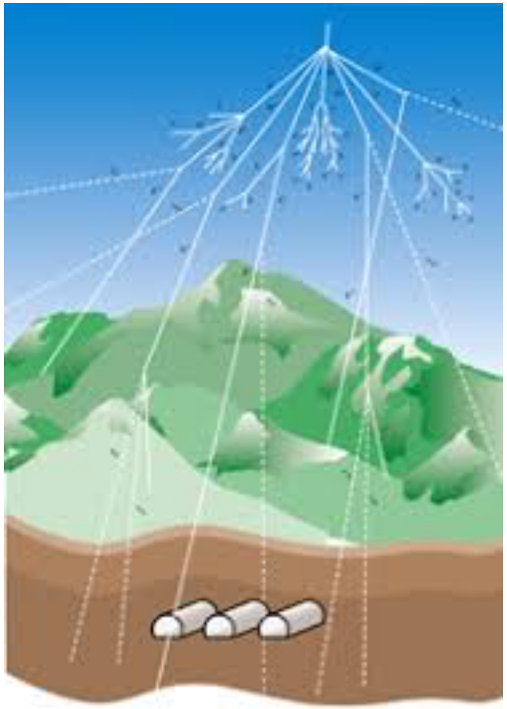
Motivation

In the energy region of interest of nuclear astrophysics, the cross section is strongly suppressed by the Coulomb barrier.

Extremely low counting rates

Most of the reactions in this range can not be measured on the surface of earth because of the cosmic ray induced background.

Experiment underground
↓↓ 10^4 for γ ↓↓ 10^3 for neutrons



For these low background conditions other sources become important, even dominant over the signal from the nuclear reaction.

Intrinsic background on the detectors/**Beam induced** background from **contaminants**

Motivation

Specifically for **reactions involving neutrons** in the **exit reaction channel**:

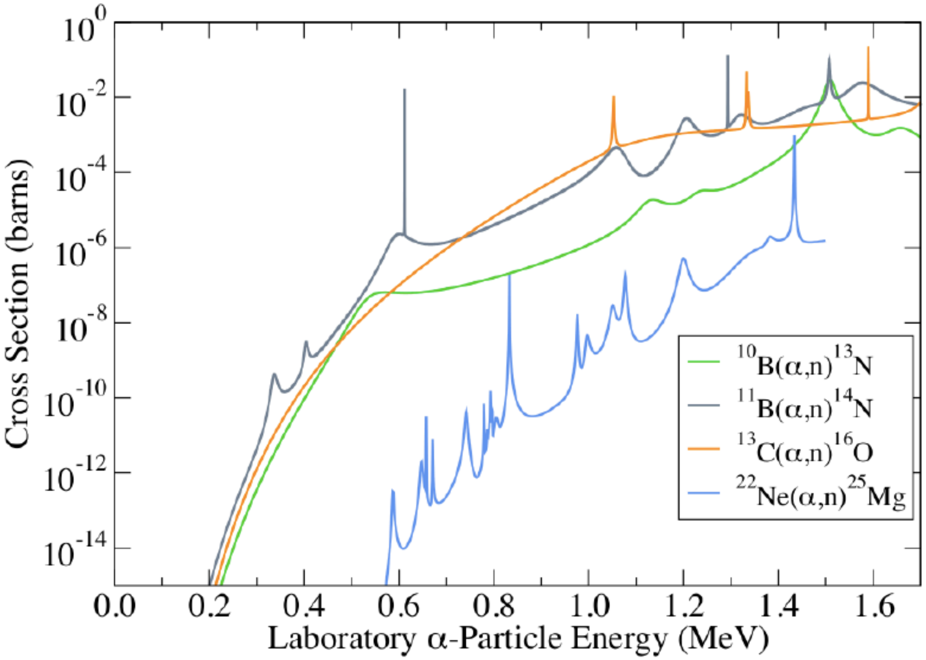
The key to suppress the remaining neutron background components could be **neutron energy discrimination**.

Example: ^{22}Ne(α,n)^{25}Mg reaction

Possible contaminants as ^{10}B and ^{11}B isotopes

Different Q-values:

Q(^{22}Ne(α,n)^{25}Mg)= **-0.478** (MeV)
Q(^{10}B(α,n)^{13}N)= **1.05** (MeV)
Q(^{11}B(α,n)^{14}N)= **0.157** (MeV)



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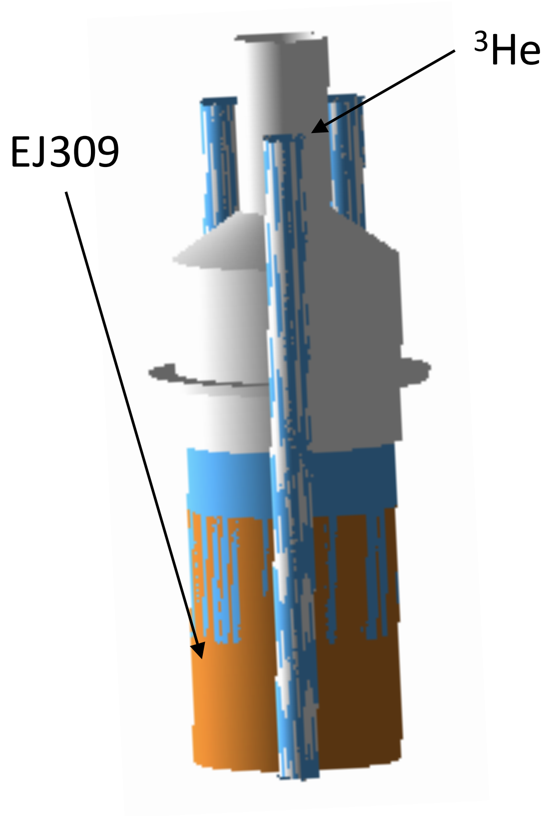

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Possible solution not using time-of-flight technique:

- Coincidence for ^{3}He +EJ309 detectors for ”high” energy neutrons

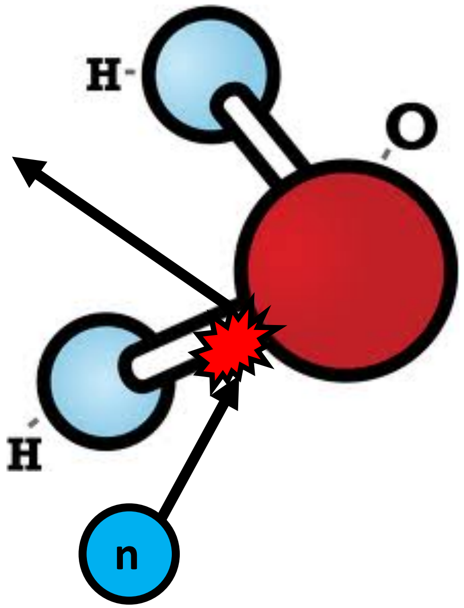
The neutron coincidences will depend on the moderation in the EJ309

⇓

Knowledge of the moderation for this particular material (Thermal scattering)

Thermal neutron scattering

It is considered **thermal scattering** when the **energy of a neutron** is **comparable** with the **thermal motion energy** of the atoms.



In the thermal scattering process**, the neutron can gain energy by inelastic collisions**.

The detailed thermal cross sections and scattering matrices depends on several physical variables:

- Atomic binding energy.
- Molecular binding energy.
- Lattice structure of the material

Thermal neutron scattering

The thermal neutron scattering cross section is usually divided:

- Inelastic: Important for all materials $S(\alpha,\beta)$
- Incoherent elastic (σ_b^{inc}): Important for hydrogenous solids (Polyethylene)
- Coherent elastic (σ_b^{coh}): Important for crystalline solids (Graphite/UO_2)

$$\frac{d^2\sigma}{d\Omega dE'}(E\to E',\Omega\to\Omega')=\frac{\sigma_b}{4\pi kT}\sqrt{\frac{E'}{E}}\,e^{-\frac{\beta}{2}}S(\alpha,\beta)$$

Momentum transferred:

$$\alpha=\frac{E'+E-2\sqrt{E'E}cos\theta}{AkT}$$

Energy transferred:

$$\beta=\frac{E'-E}{kT}$$

Bound scattering cross section:

$$\sigma_b=\sigma_b^{inc}+\sigma_b^{coh}$$

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$$\frac{d^2\sigma}{d\Omega dE'}(E \rightarrow E', \Omega \rightarrow \Omega') = \frac{\sigma_b}{4\pi kT}\sqrt{\frac{E'}{E}}\, e^{-\frac{\beta}{2}} S(\alpha,\beta)$$

Momentum transferred:

$$\alpha = \frac{E' + E - 2\sqrt{E'E}\cos\theta}{AkT}$$

Energy transferred:

$$\beta = \frac{E' - E}{kT}$$

Bound scattering cross section:

$$\sigma_b = \sigma_b^{inc} + \sigma_b^{coh}$$

Only calculated and implemented for a few elements in the libraries:

- **H in WATER** (TS_H_of_Water)
- **H in POLYETHILENE** (TS_H_of_Polyethylene)
- C in Graphite
- ….

Monte-Carlo benchmark setup

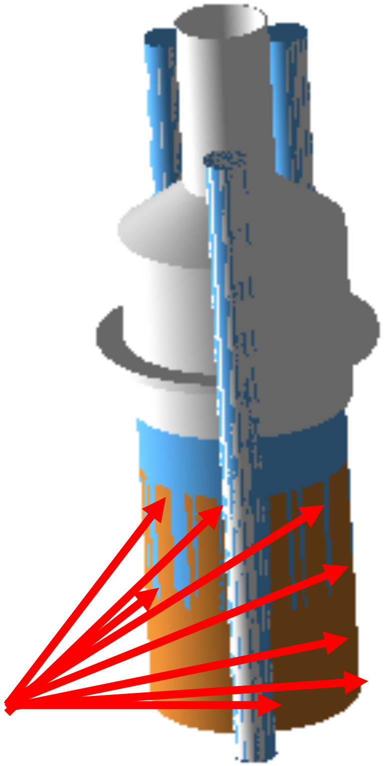
- Version of GEANT4: 10.4

- Three different cases were tested in EJ309:
  - H.
  - TS_H_of_Water.
  - TS_H_of_Polyethylene.

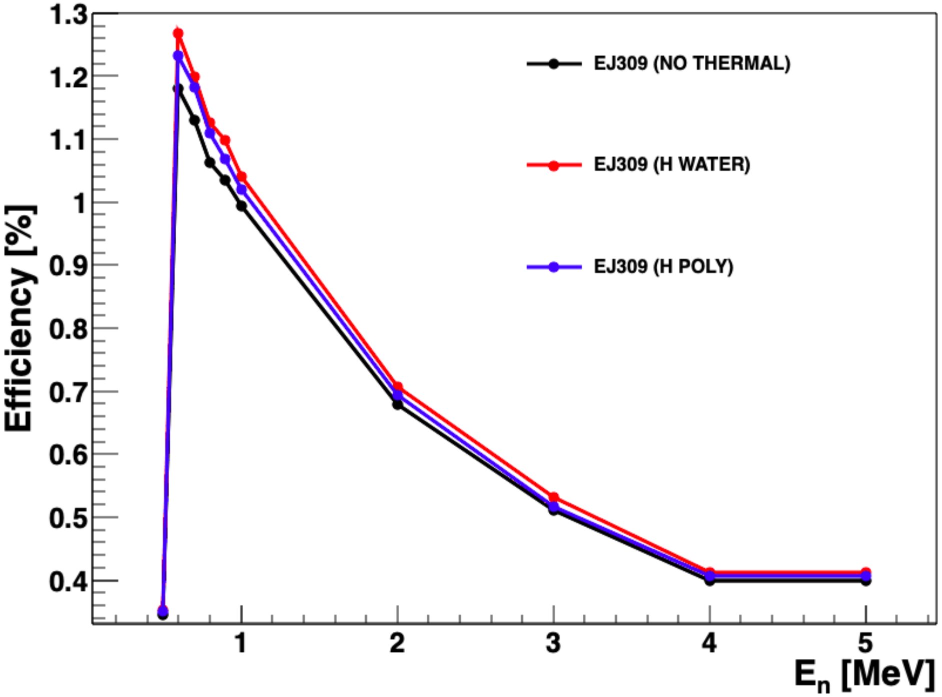
- 10 different energies were tested:
  0.5, 0.6, 0.7, 0.8, 0.9. 1, 2, 3, 4, 5.

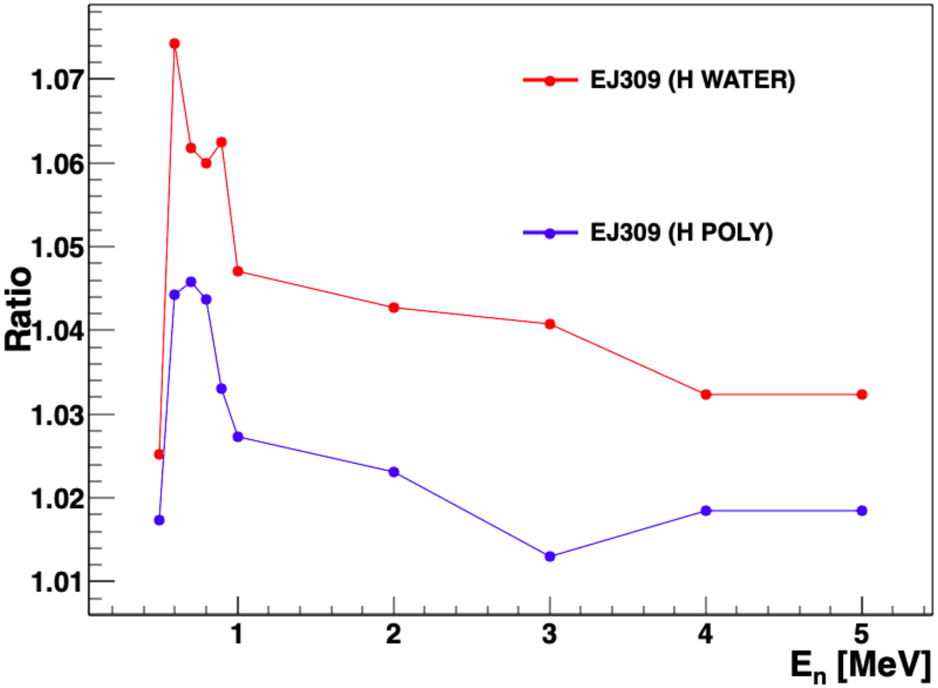
- Source at 30 cm from the detector’s surface.

- Observables:
  - Coincidence ^{3}He-EJ309 efficiency.
  - Time coincidence distribution.
  - Outcoming angular distribution of moderated thermal neutrons.



^{3}He-EJ309 coincidence efficiency



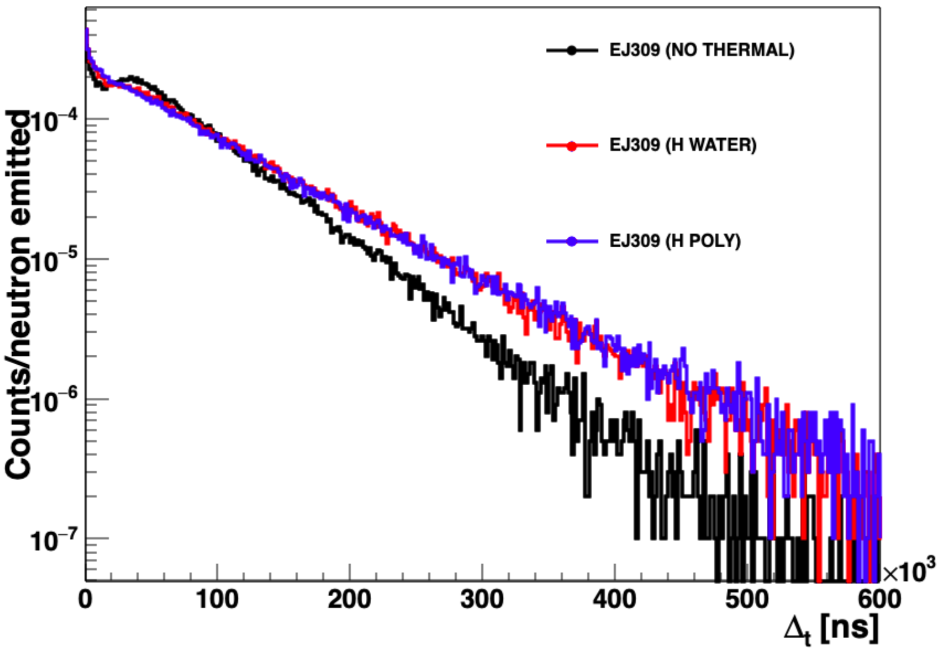


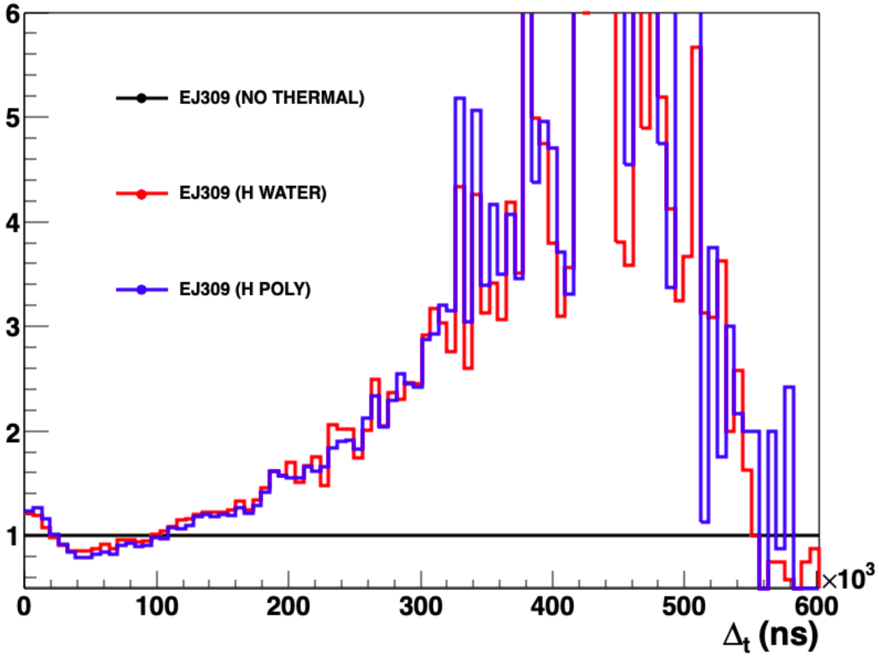
Adding the thermal libraries to the simulation the ^{3}He-EJ309 **coincidence efficiency** increases:

- **WATER: ~ 7% (Low neutron energies) ~ 4% (High neutron energies)**
- **POLYETHILENE: ~ 4.5% (Low neutron energies) ~ 2% (High neutron energies)**

^{3}He-EJ309 time-coincidence distr.

Incident neutron energy: 0.5 MeV



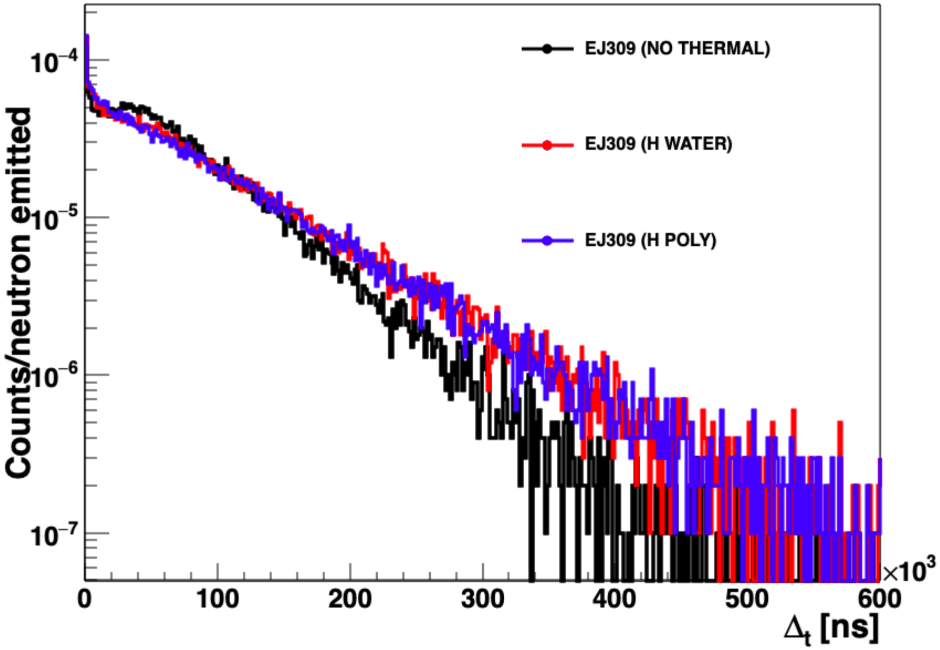


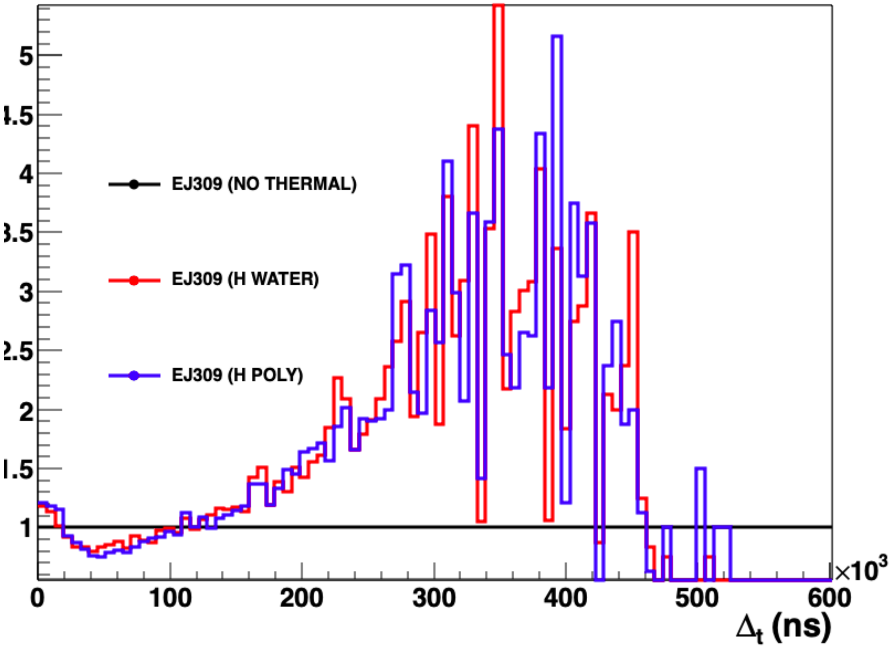
Time distribution for "low" energy neutrons:

- **Increase of 20%** probability for **fast coincidences**
- **Reduction of 30%** probability for coincidences in the period Δt<100 μs
- **Increase of factor 2-6** for coincidences in the period Δt>200 μs

^{3}He-EJ309 time-coincidence distr.

Incident neutron energy: 5 MeV



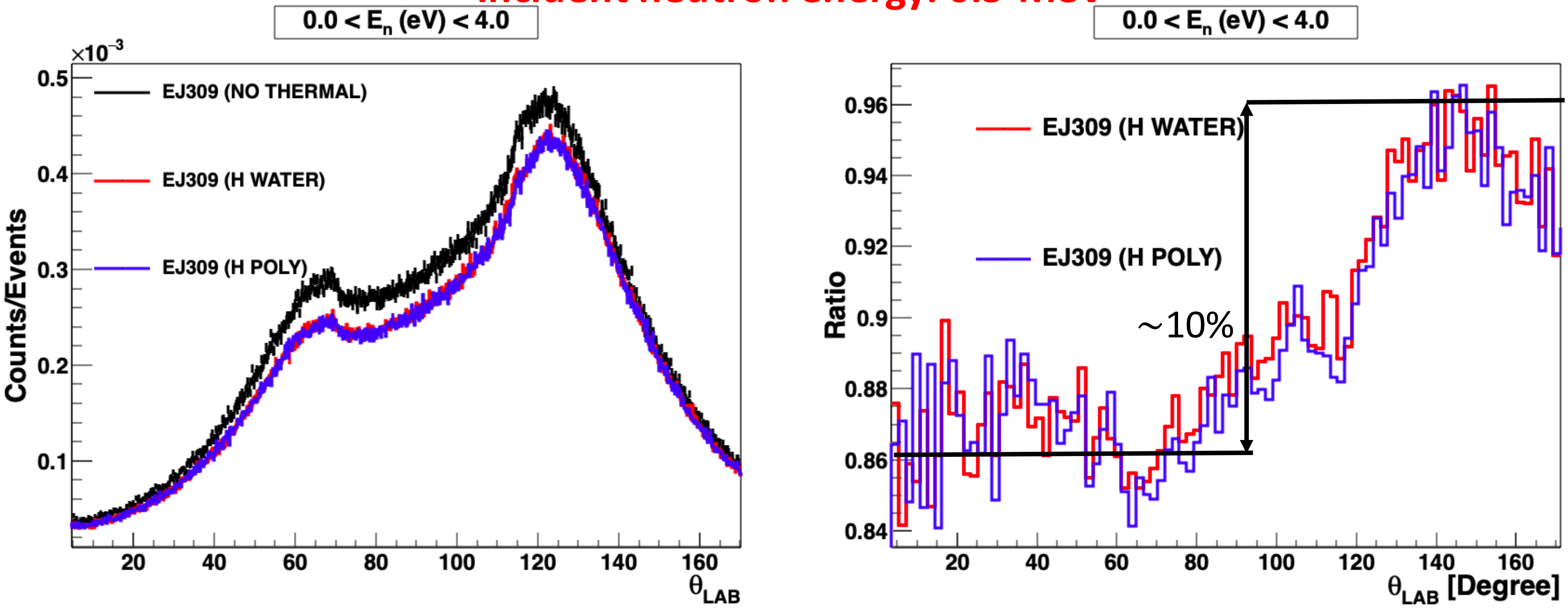


Time distribution for “high” energy neutrons:

- **Increase of 20%** probability for **fast coincidences**
- **Reduction of 30%** probability for coincidences in the period Δt**<100** μ**s**
- **Increase of factor 2-4** for coincidences in the period Δt**>200** μ**s**

Out. neutron angular distribution

Incident neutron energy: 0.5 MeV

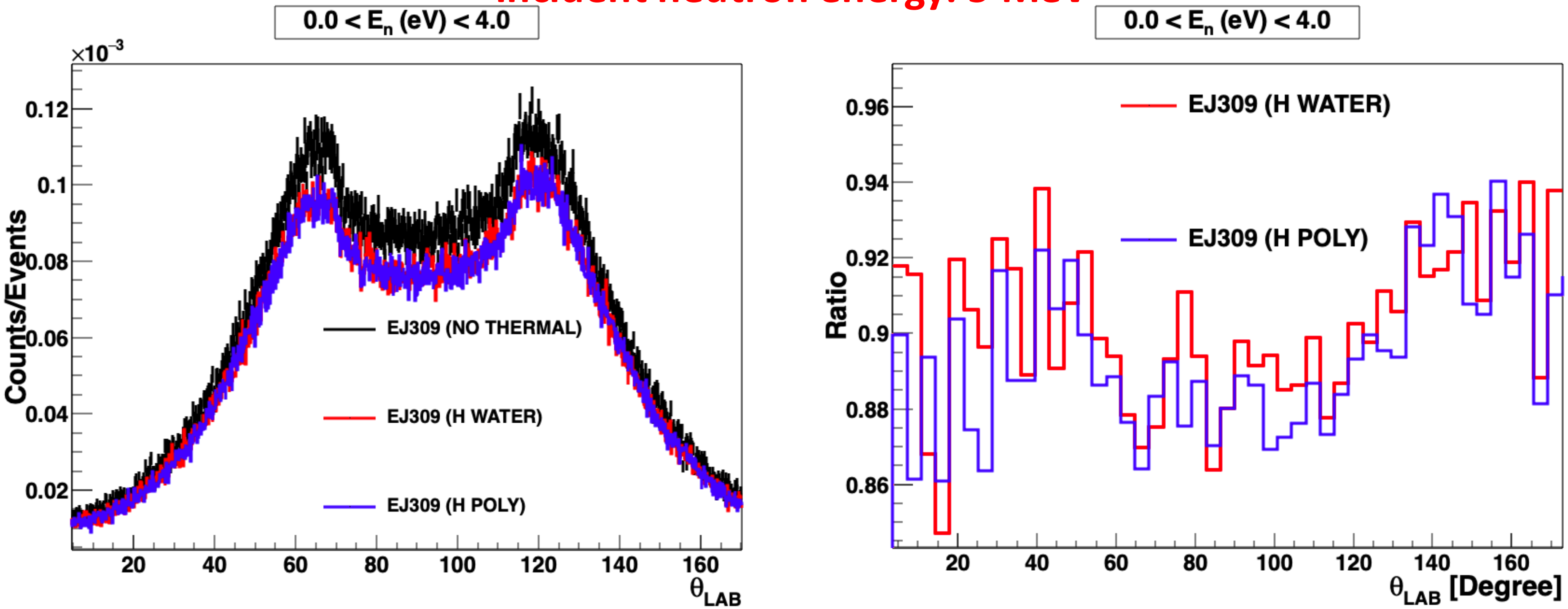


Angular distribution of outcoming moderated neutrons (E_n<4 eV) for “low” energy incident neutrons:

- Thermal libraries produce **differences between backwards and forward** that could be **up to 10%** for 0.5 MeV incident neutrons.

Out. neutron angular distribution

Incident neutron energy: 5 MeV



Angular distribution of outcoming moderated neutrons (E_n<4 eV) for "high" energy incident neutrons:

- Thermal libraries does not play a heavy role backward/forward asymmetry for high energy neutrons.

Conclusions

- We have tested the influence of the different thermal scattering cross-section implementation into our prototype detector setup:
  - The ^{3}**He-EJ309 coincidence efficiency** is increased $\sim$4-7% **depending on the thermal material/element cross-section** used.
  - **The fast time-coincidence** distribution is **increased by 20%**.
  - The time-coincidence distribution is reduced in the first 100 us by 30% and increased for Δt>200 us.
  - The **angular distribution** of the moderated neutrons for **low energy neutrons change** $\sim$ **10%** (maximum) between **backward and forward**.
  - For high energy neutrons the thermal libraries seems to be a scale factor in the outcoming moderated neutron flux.

The thermal libraries might play an important role for this kind of experimental setup!

Outlook

- To improve the Monte Carlo simulations of “low” energy neutrons require increase the knowledge and modeling of the interactions with the materials → Thermal neutron cross-sections.

- This require a huge effort from the community (measurements, calculations, libraries, validation…).

- Nevertheless, we think it is a worth effort. In particular for the liquid scintillators materials:

    - Improve Monte-Carlo simulation for low deposited energy events.
    - Improve description for new generation of non time-of-flight coincidence experimental setups.

- We will compare the simulations with experimental data acquired with the demonstrator.