Neutron Capture lifetime studies in Geant4

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Motivation

- Is it possible to measure the neutron capture time in the DEAP3600 detector ?

Overview

- Simulation in Geant4

- Simulation in an infinite sphere volume:
    - Primary and secondaries neutrons in Geant4
    - Simulation in 40 LAr
    - Simulation in LAr with isotopic composition
    - Short neutron capture times in cross section resonances

- Simulation in a finite sphere volume:
    - DEAP3600’s detector size and LAr working parameters
    - Neutron capture times for different neutron energies
    - Mean time vs neutron energy

- Comparison of mean lifetimes

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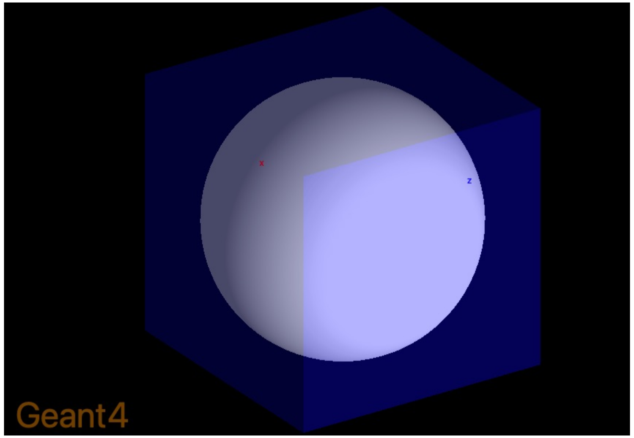
Simulation in Geant4

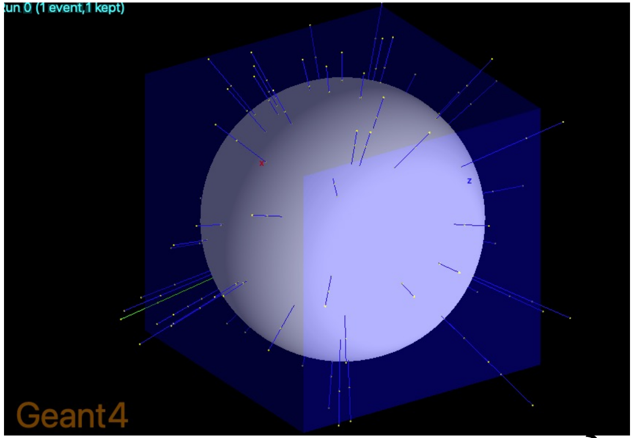
- Shot monoenergetic neutrons from the center of a LAr sphere volume

- Selected only neutrons captured (nCapture process) inside the LAr sphere volume

- Discarded neutrons exiting and reentering the sphere

- Physics list : neutronHP





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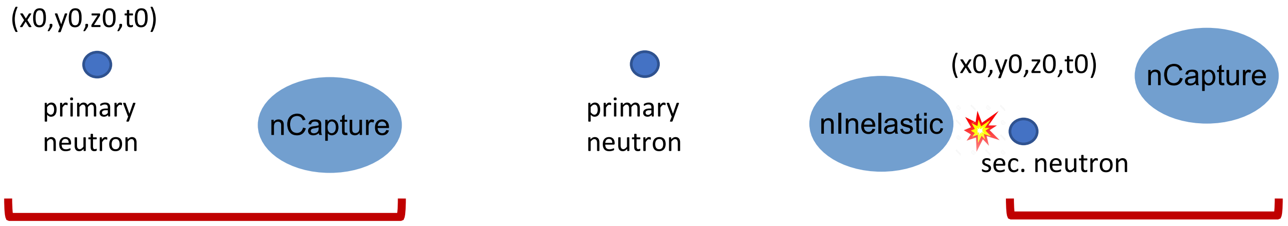
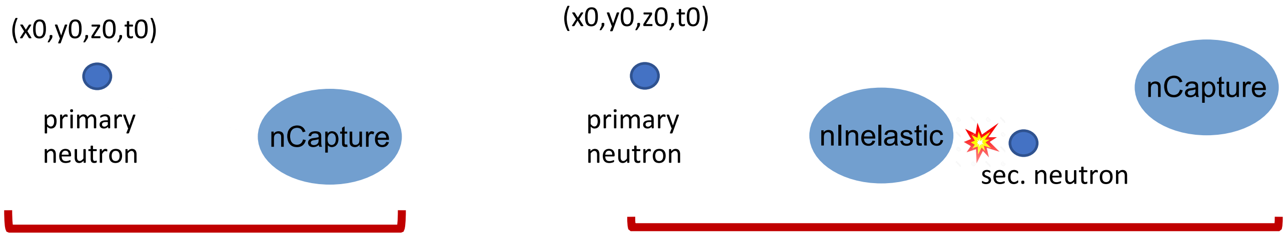
Primary and secondary neutron captures in Geant4

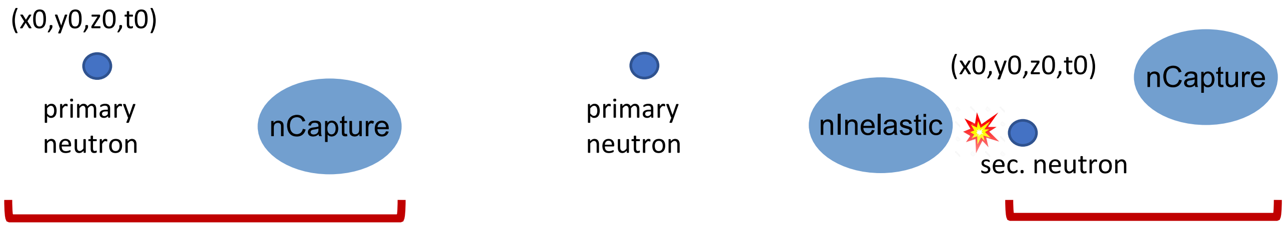
- Primary neutrons (parent ID=0) can be captured or killed by inelastic interactions
- Most of the times a primary neutron killed by an inelastic interaction will produce a secondary neutron (parent ID!=0)
- The secondary neutron has a capture time and trajectory measured from the inelastic interaction point where it was created



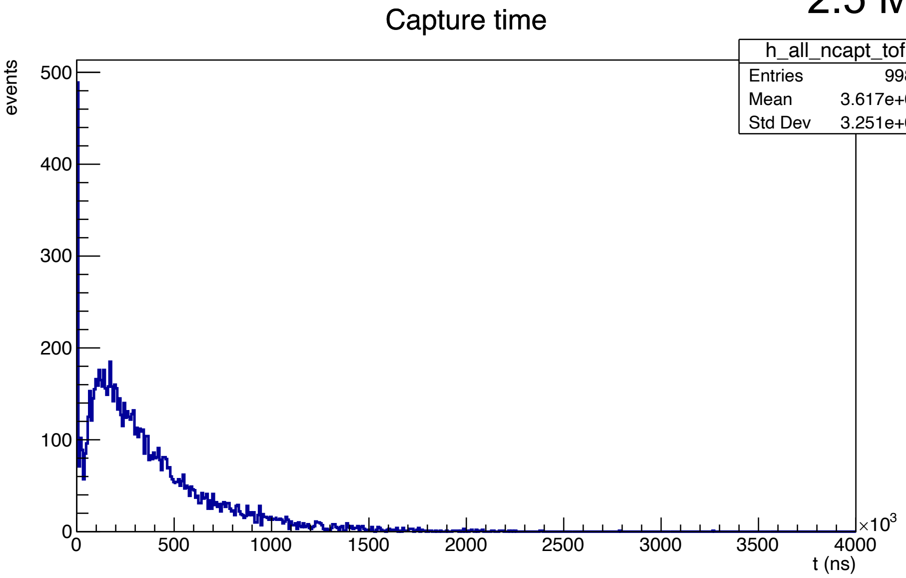
- The secondary neutron created in an inelastic interaction (n,n), is actually the primary neutron with different parentID
- A correction must be done to calculate the correct capture time and trajectory of primary neutrons

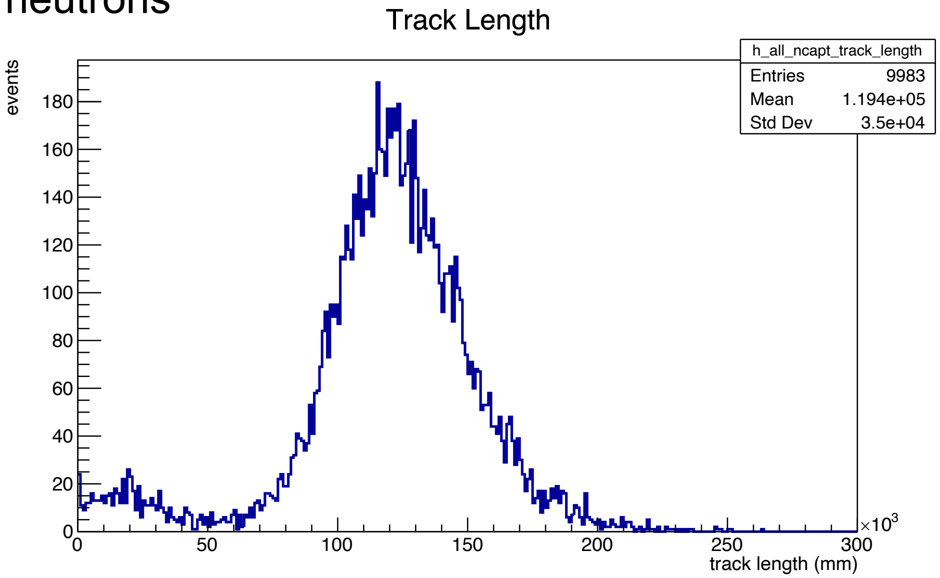


Considering only neutron captures (wrong)

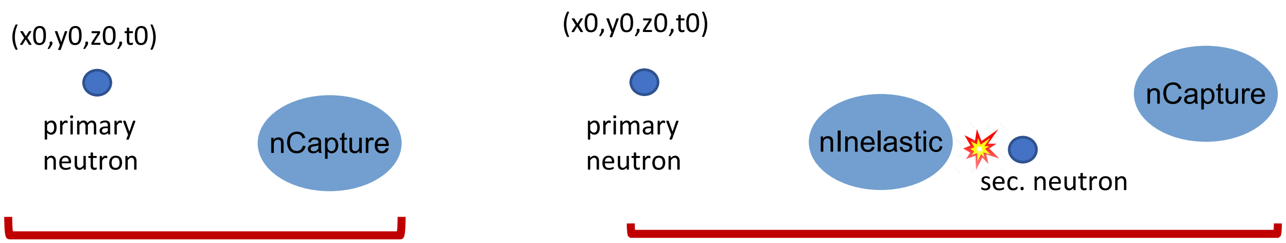


2.5 MeV neutrons

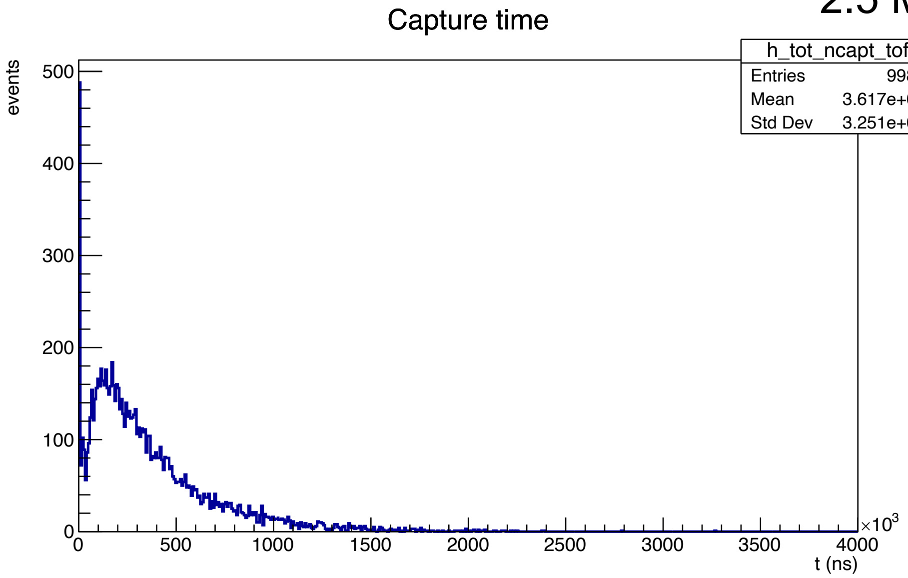


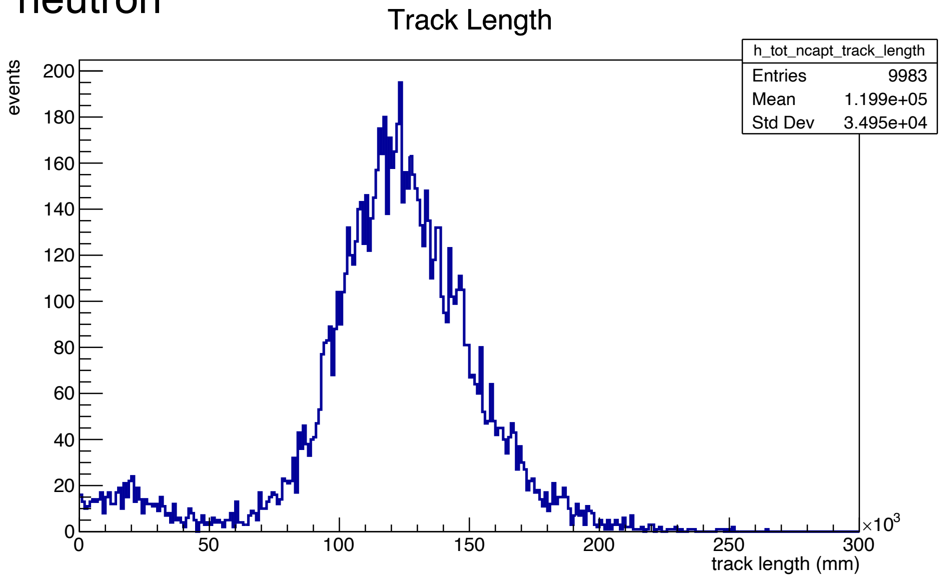


Correcting the neutron captures (correct)

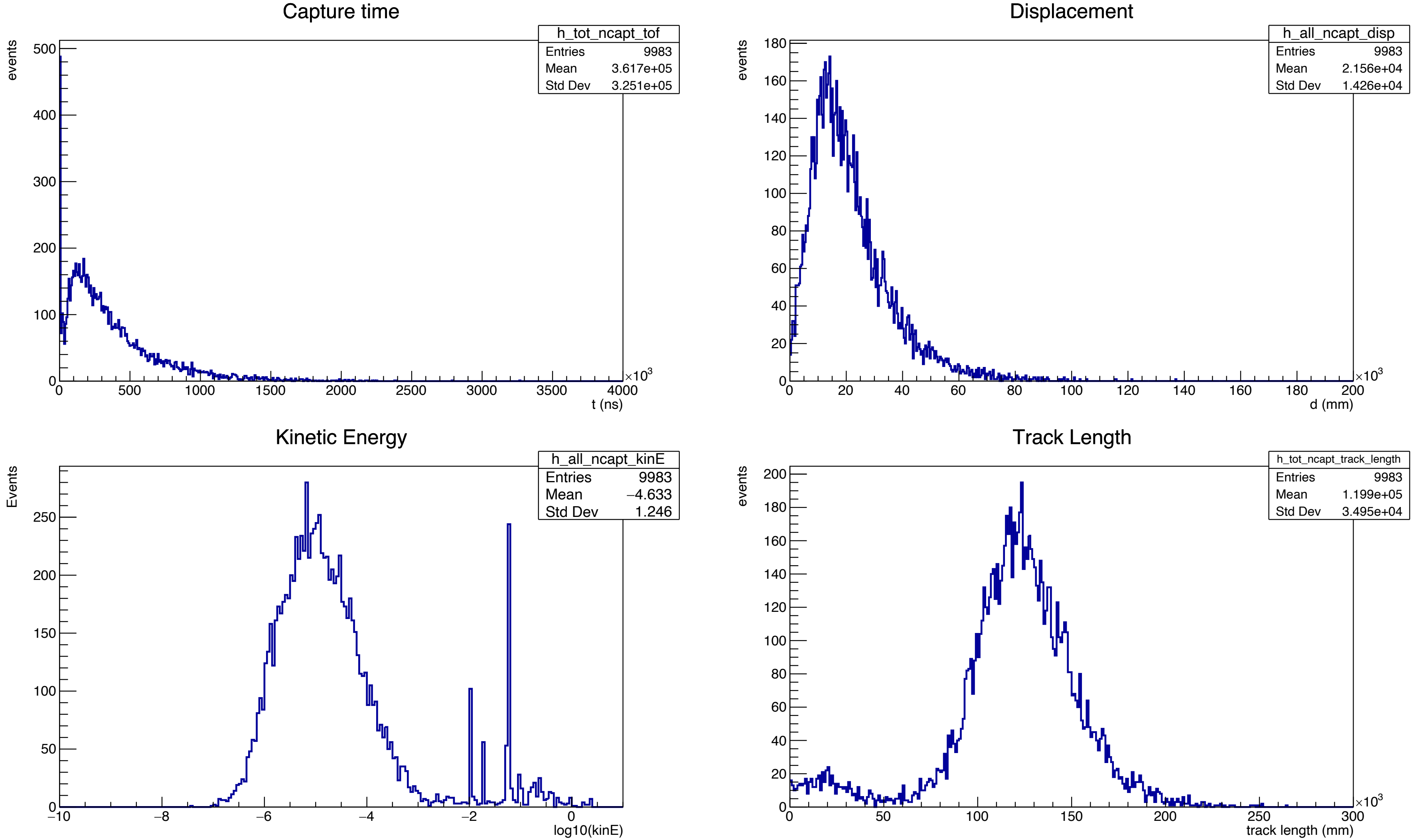


2.5 MeV neutron

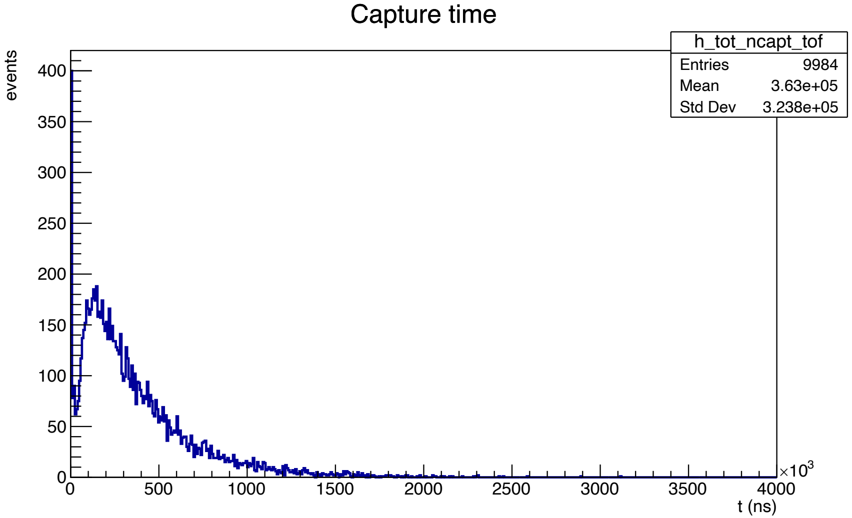


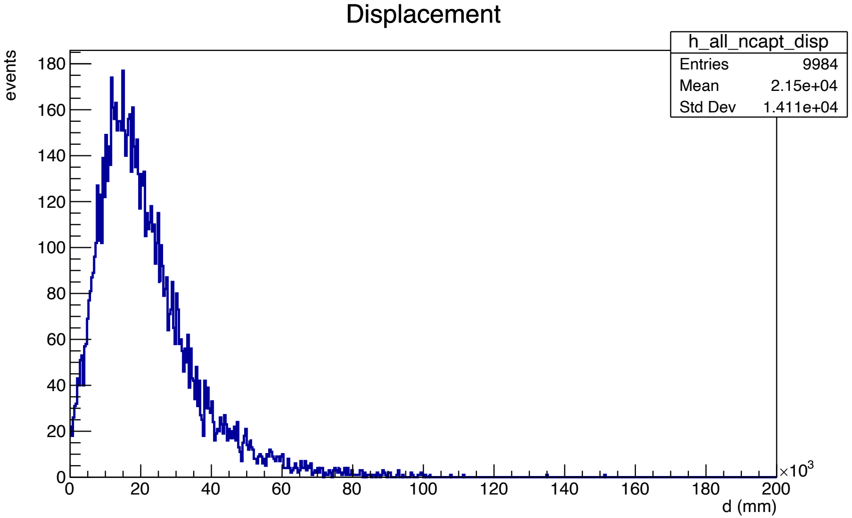


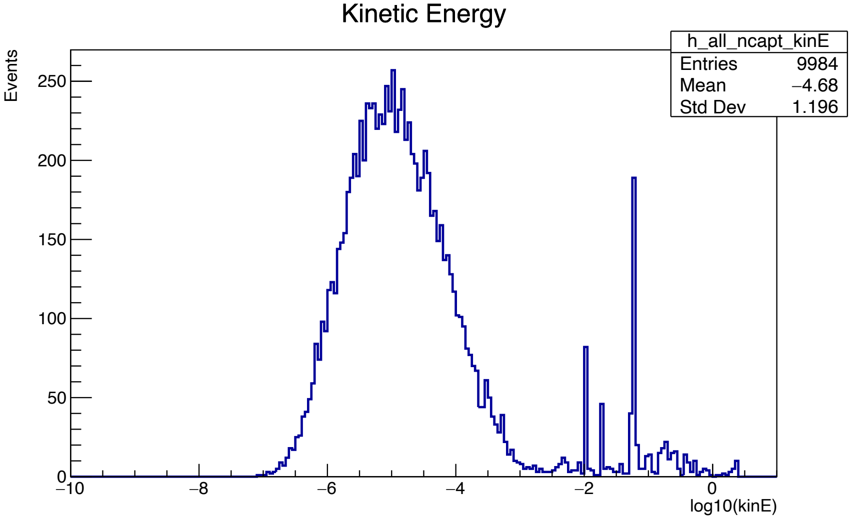
2.5 MeV neutron captures in 40 LAr

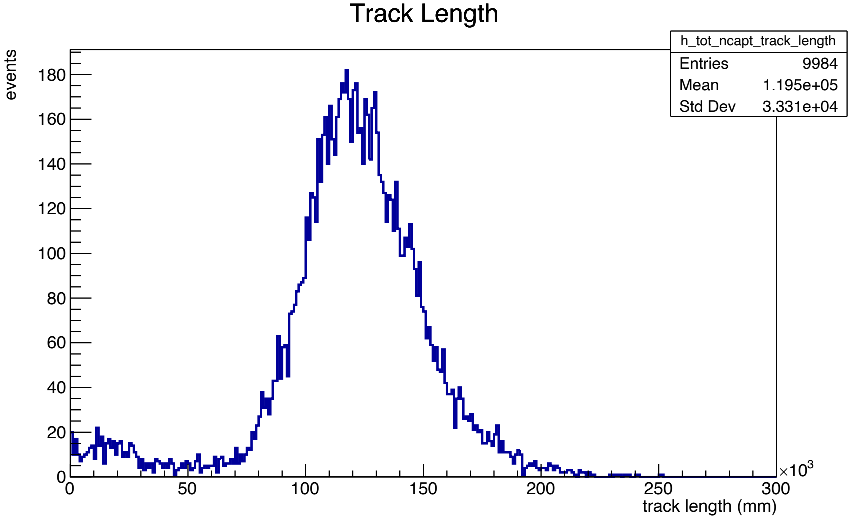


2.5 MeV neutron captures in LAr (Isotopic composition)

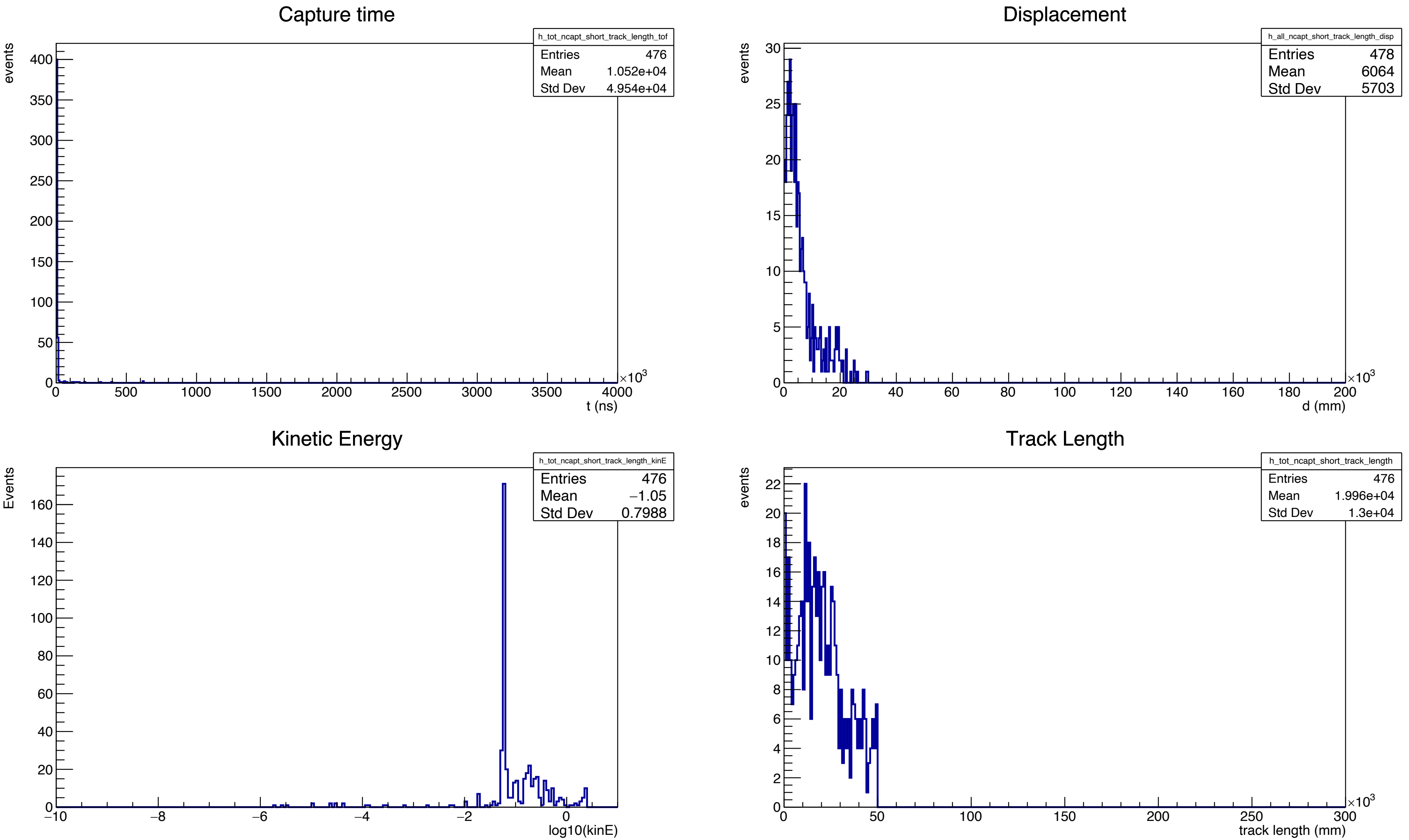








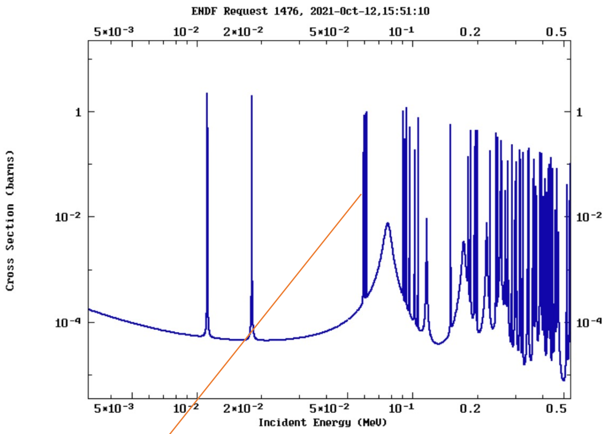
2.5 MeV neutron captures in LAr (Isotopic composition & trajectory < 50 m)



2.5 MeV neutron captures in LAr (Isotopic composition & trajectory < 50 m)

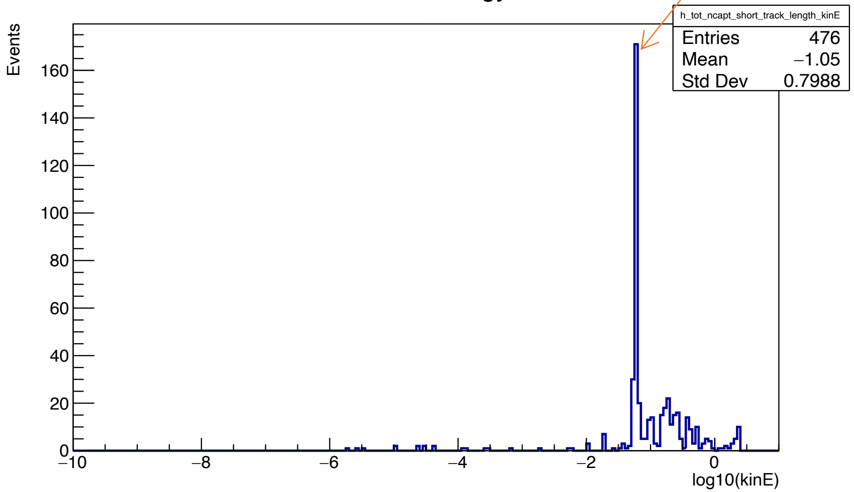
Neutron radiative capture cross section 40 LAr

Evaluated Nuclear Data File (ENDF)

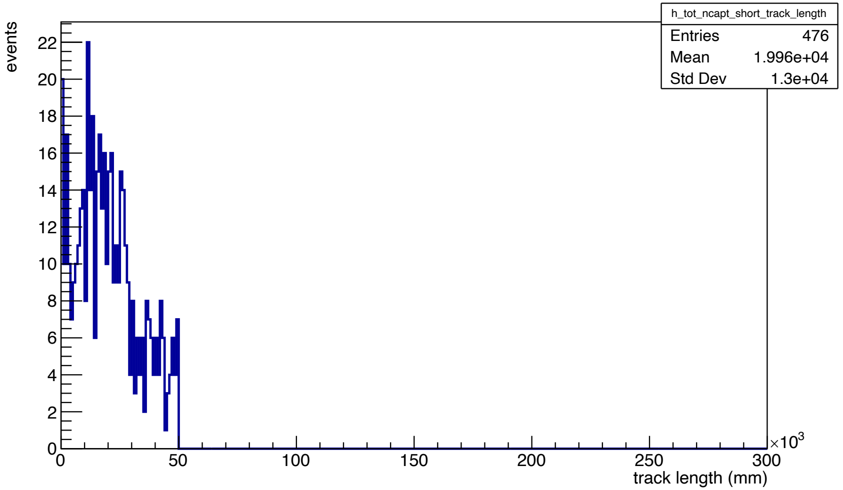


- Short capture times correspond to the resonance peaks of the cross section

Kinetic Energy

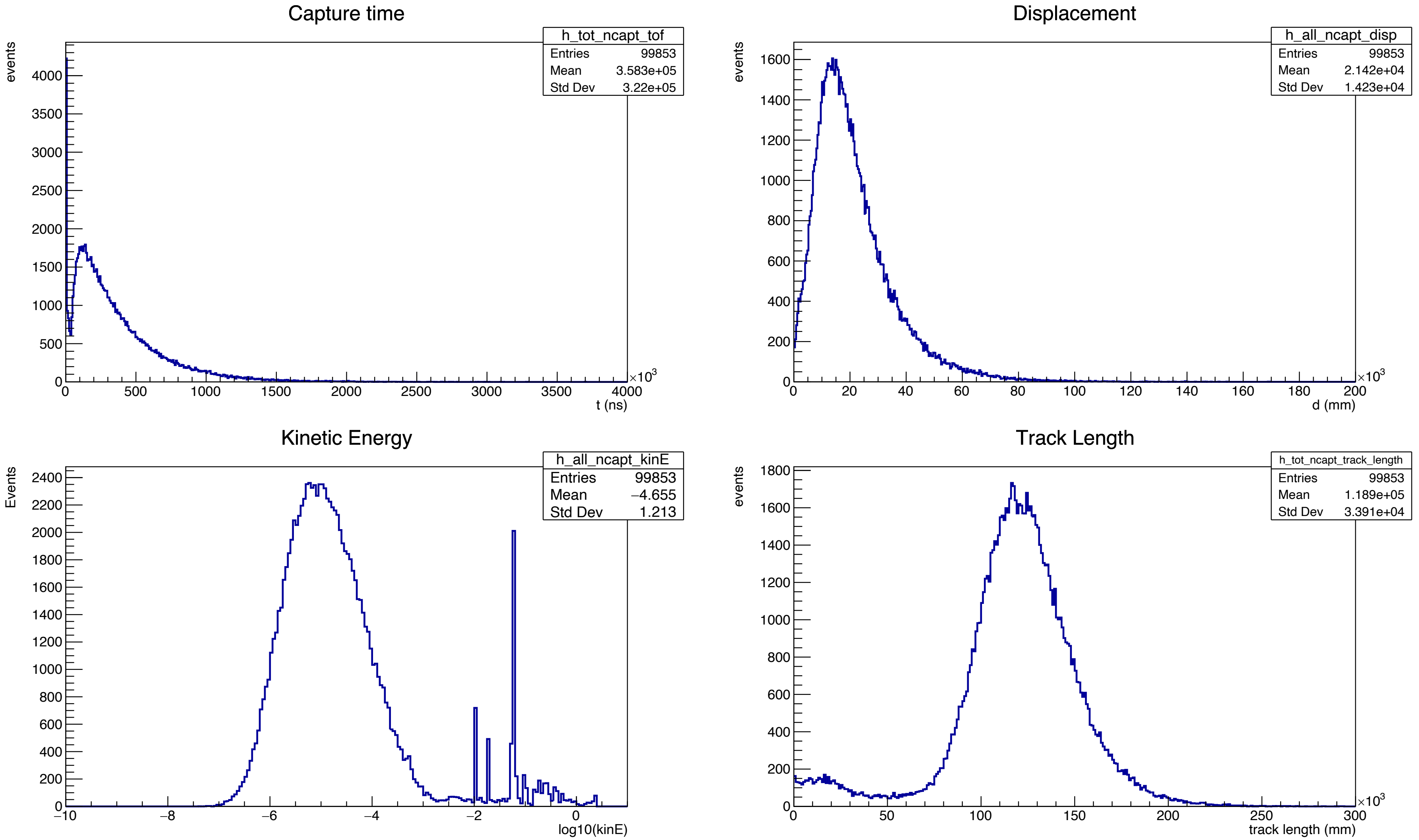


Track Length



2.5 MeV neutron captures in LAr (Isotopic composition)

100K neutrons stats.



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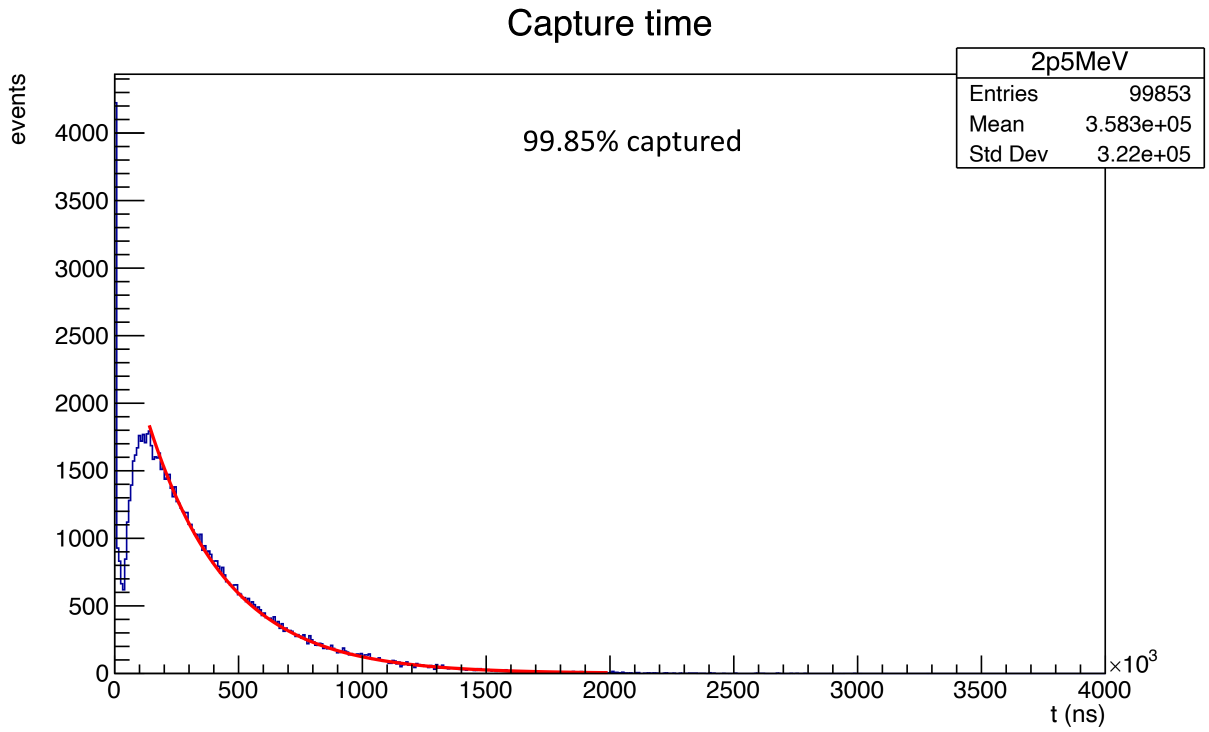

Analytical calculations shows the neutron capture time distribution should be exponential:

$$N(t) \sim e^{(-\lambda t)}$$

Mean lifetime

$$\tau = 1/\lambda = 318548 \ \pm 0.36\% \, ns$$

- 100K neutrons simulated and none escaped the LAr volume
- A few primary neutrons were killed in inelastic scatterings and didn't produce secondary neutrons

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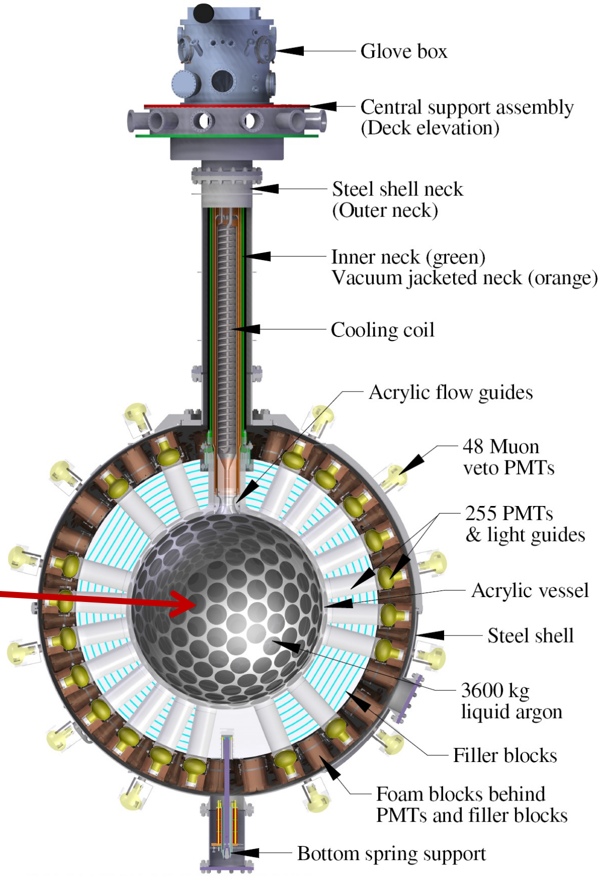
DEAP3600 parameters for the simulation

- The acrylic vessel is an 86 cm radius sphere

- Cryogenic system operation :
  - 84 – 87 K
  - 13 - 15 psia (0.884 – 1.02 atm)

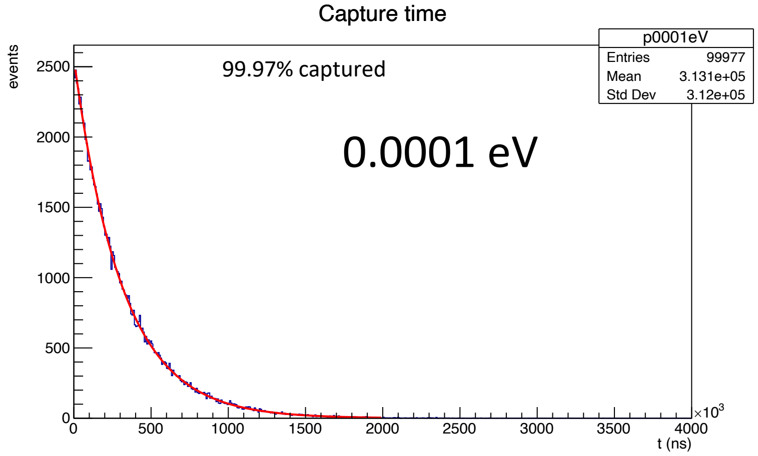
Parameter values for the simulation:

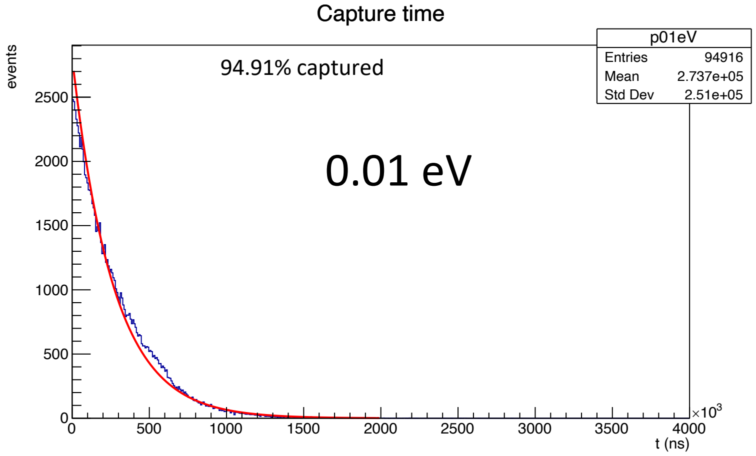
- **86 cm radius sphere filled with LAr**
- **LAr:**
  - **Isotopic composition**
  - **Temperature = 85.5 K**
  - **Pressure = 14 psia (0.952 atm)**
  - **Density = 1.406 g/cm3**

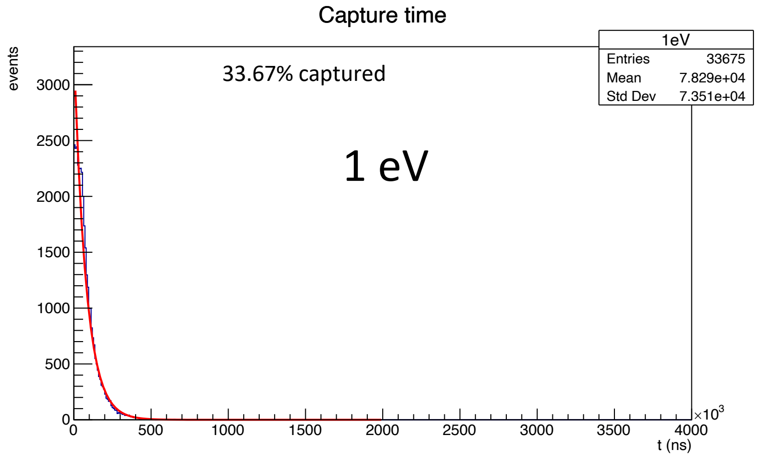


Capture time with DEAP3600 parameters

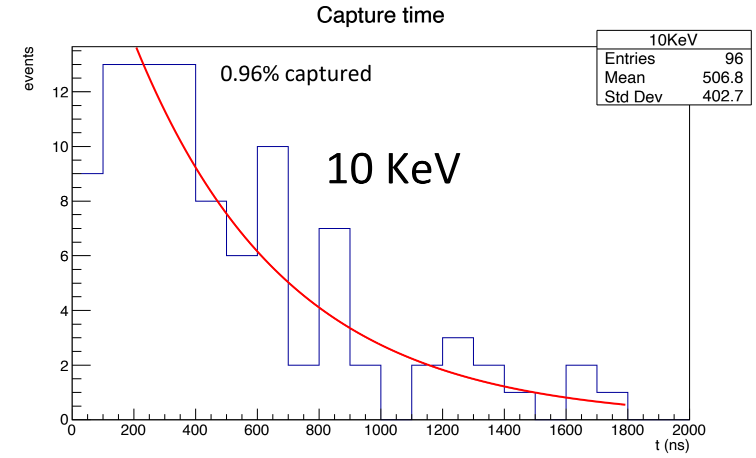
100K neutrons stats.







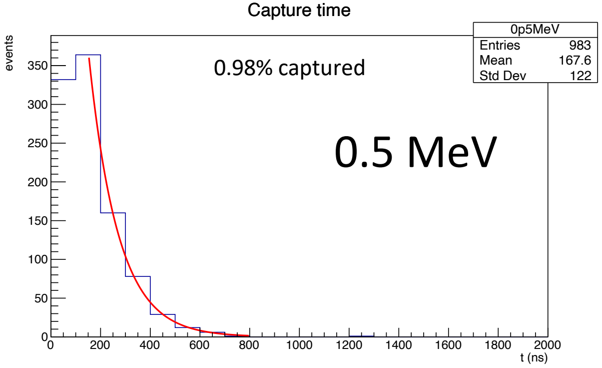
statistics x 5

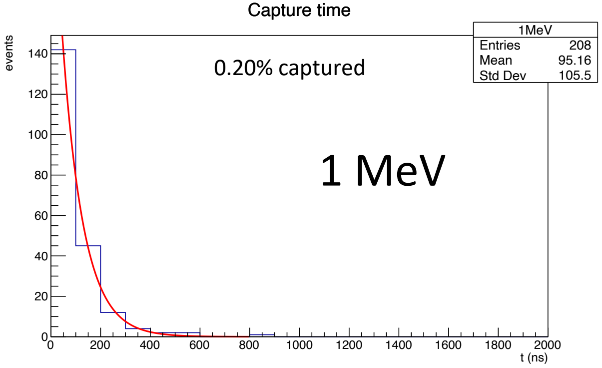


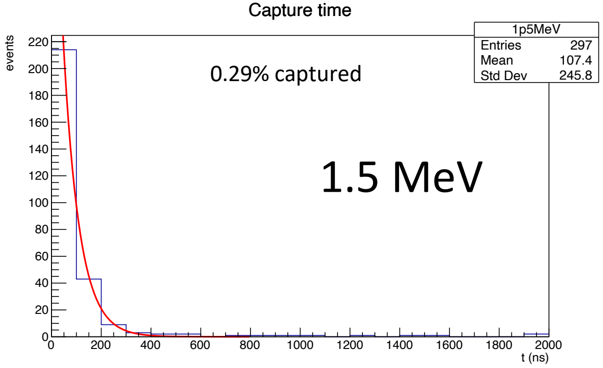
Capture time with DEAP3600 parameters

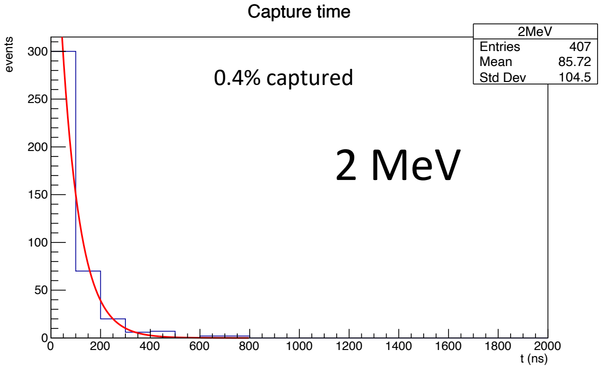
100K neutrons stats.

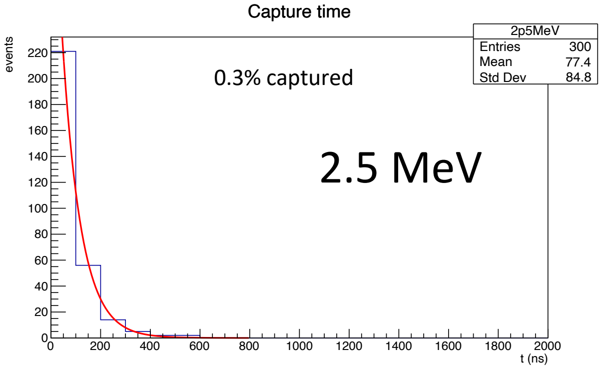
statistics x 5

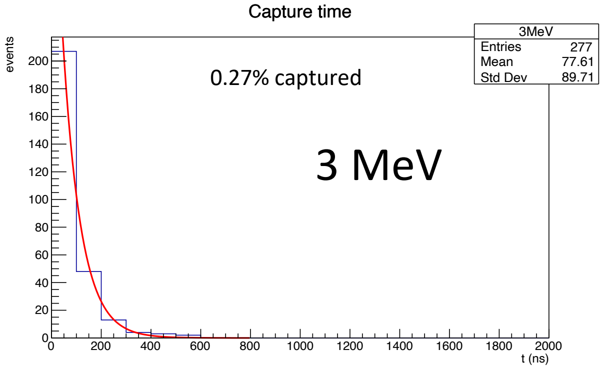




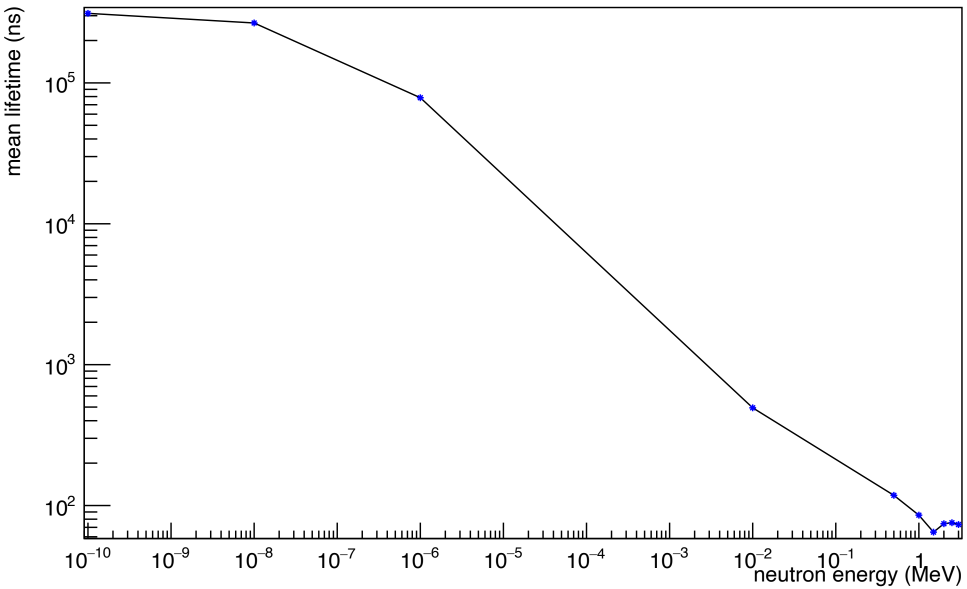








Mean lifetime and neutron energy with DEAP3600 parameters



Energy (MeV)	Mean time (ns)	Mean time error (ns)
1.00E-10	311730	1010.95
1.00E-08	266320	745.004
1.00E-06	78488.4	388.865
0.01	493.92	109.425
0.5	118.158	4.63815
1	85.4363	6.84525
1.5	64.7572	4.83844
2	74.2713	4.67904
2.5	75.4865	5.2277
3	73.3043	5.49377

- As we decrease the energy of neutrons, fewer escape the 86 cm radius sphere of LAr
- The mean lifetime of 1e-10 MeV (1e-4 eV) neutrons in this small volume approaches the mean lifetime of 2.5 MeV neutrons in an infinite volume, as expected.

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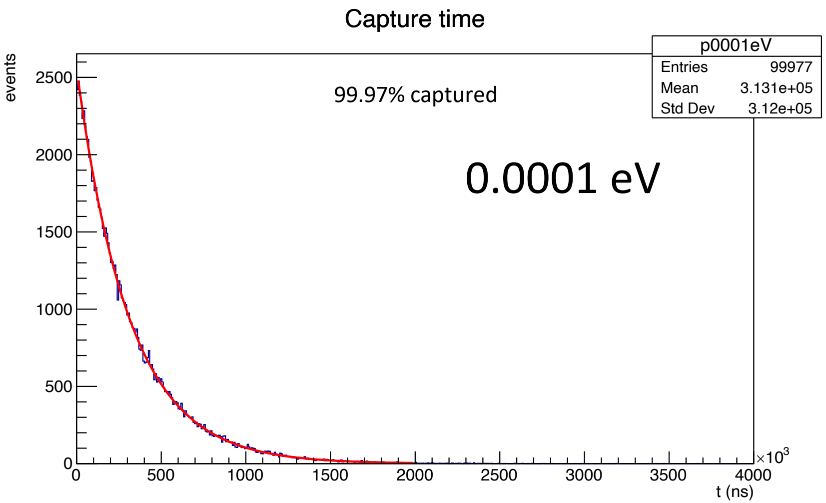
Mean lifetimes in LAr

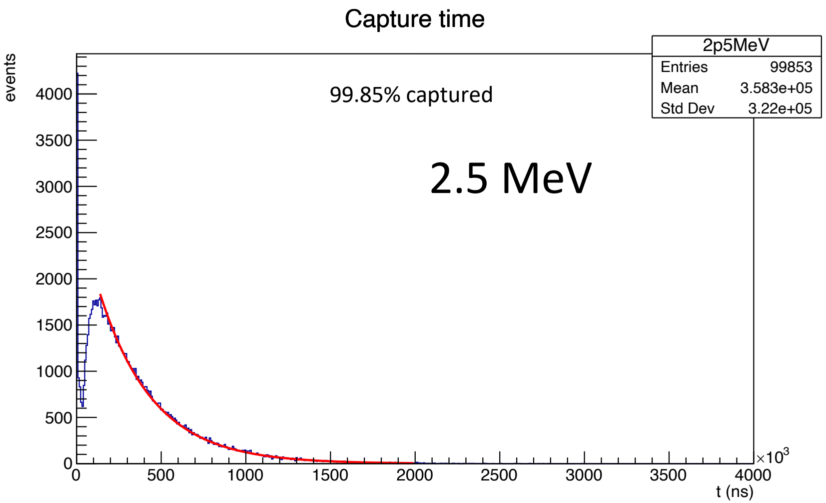
100K neutrons stats.

86 cm radius sphere (DEAP3600 size)



$$\tau = 311730 \pm 0.32\%\, ns$$

500 m radius sphere (infinite size)

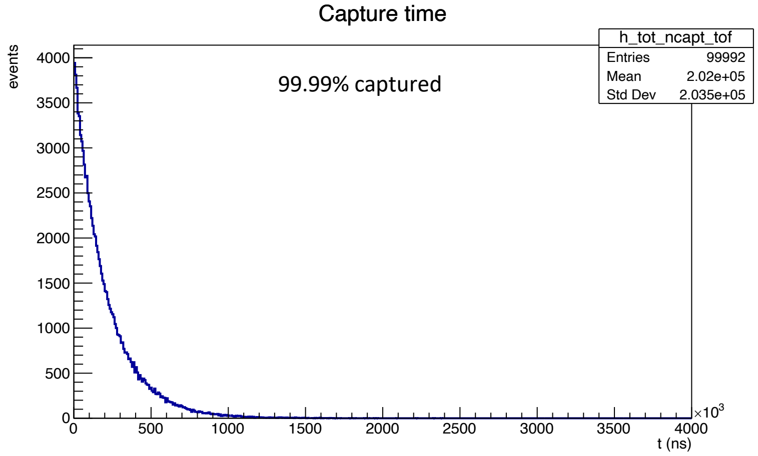


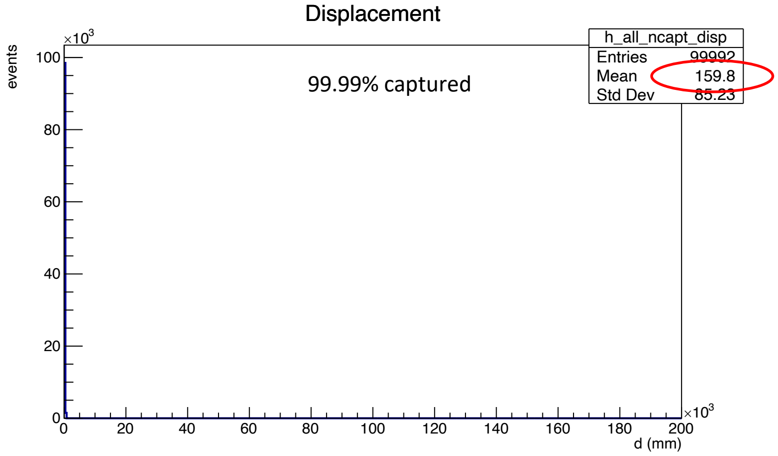
$$\tau = 318548 \pm 0.36\%\, ns$$

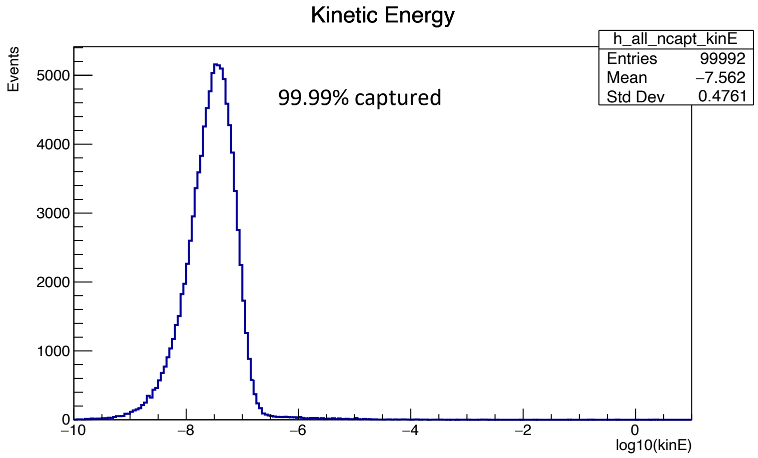
- 100K neutrons simulated and none escaped the LAr volume
- The neutrons that were not captured are primary neutrons killed in inelastic scatterings without producing secondary neutrons
- 2.5 MeV neutron capture time distribution show short capture times that correspond to the resonance peaks of the cross section (slide 13)

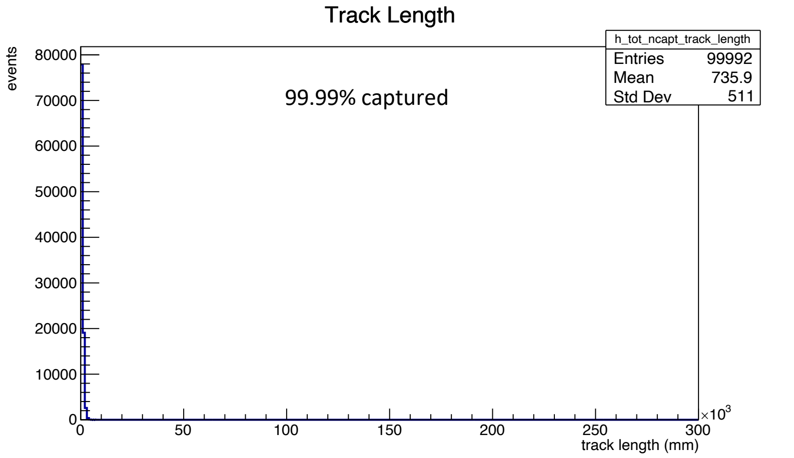
2.5 MeV neutron captures in H_2O (86 cm radius sphere)

100K neutrons stats.







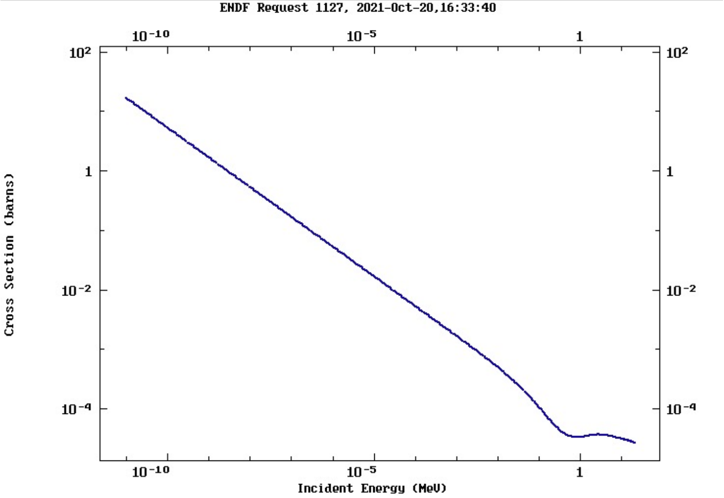


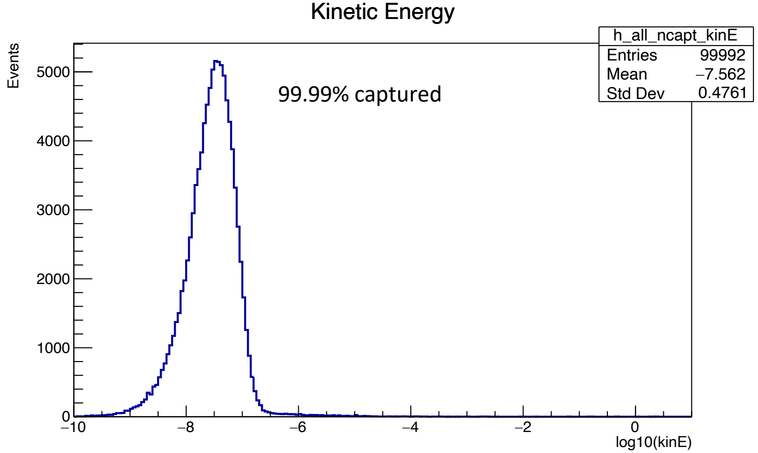
2.5 MeV neutron captures in H2O (86 cm radius sphere)

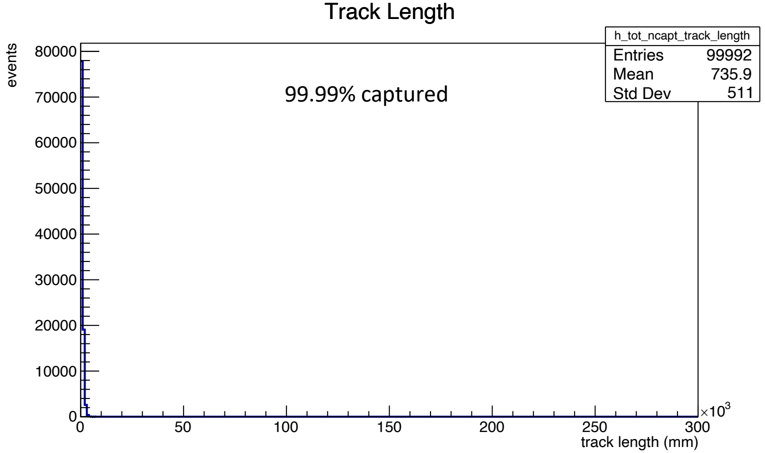
100K neutrons stats.

Neutron radiative capture cross section in 1H

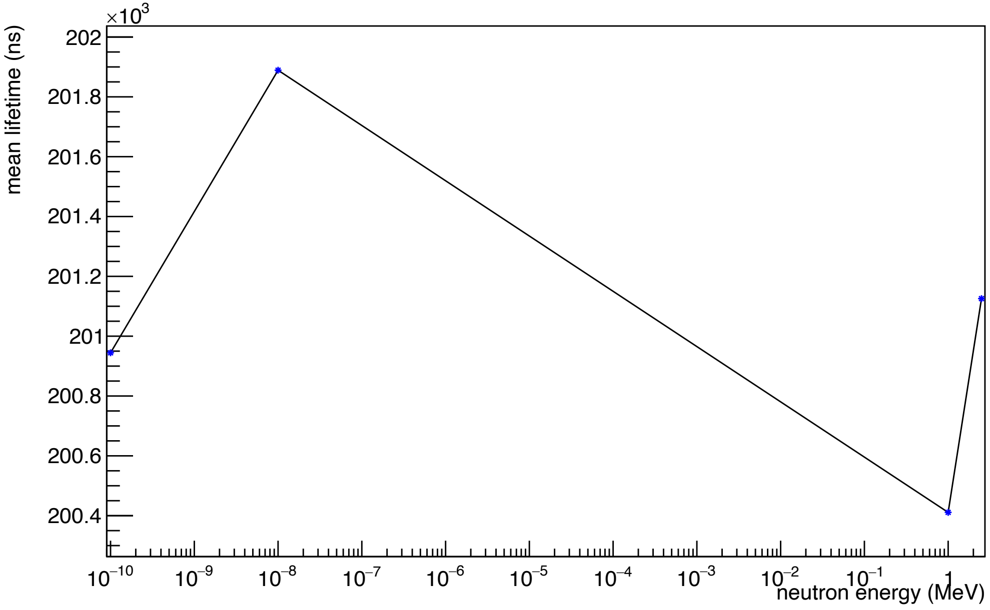
Evaluated Nuclear Data File (ENDF)







Mean lifetime and neutron energy with DEAP3600 parameters in H_2O (86 cm radius sphere)



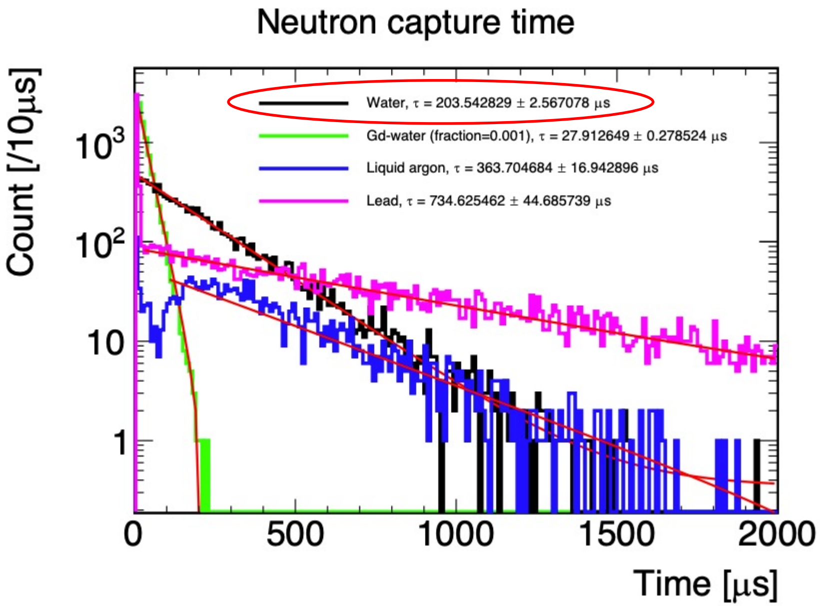
Energy (MeV)	Mean lifetime (ns)	Mean lifetime error (ns)
1.00E-10	200944	638.219
1.00E-08	201889	634.682
1	200411	633.078
2.5	201126	647.385

- The mean lifetime as a function of neutron energy remains the same in the 1e-10 eV - 2.5 MeV energy range

2.5 MeV neutron captures in H2O

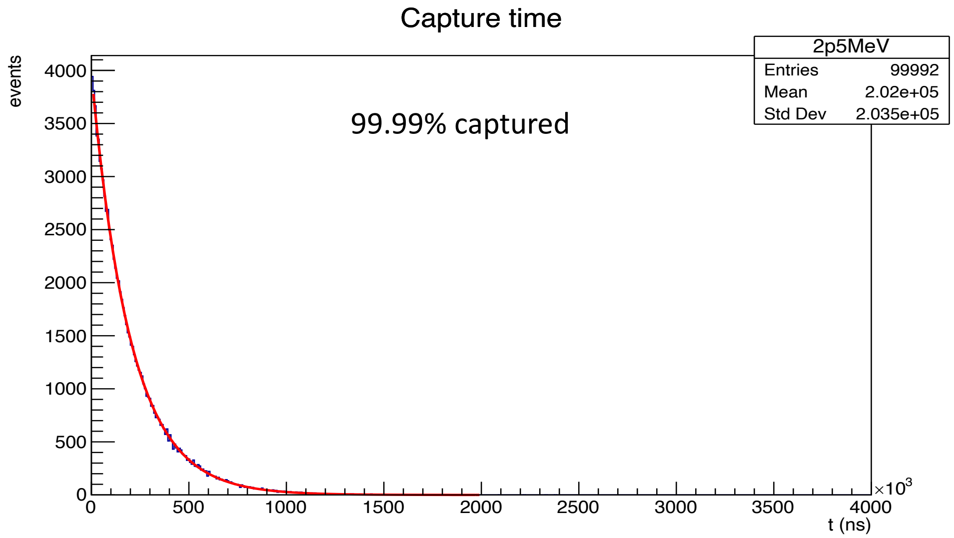
Jingbo's calculation

Infinite radius sphere



$$\tau = 203542 \pm 1.2\%\, ns$$

86 cm radius sphere



$$\tau = 201126 \pm 0.32\%\, ns$$

- Mean lifetime for 2.5 MeV neutrons in the 86 cm radius sphere of water is consistent with Jingbo's calculations for an infinite volume

Comments and Next steps

- Very low energy neutrons ~ 1e-10 MeV (1e-4 eV) in the DEAP size LAr sphere (86 cm radius) have the mean lifetime of 2.5 MeV neutrons in an infinite LAr sphere (slide 20)

- Neutron mean lifetime in H2O remains constant as the neutron energy changes, as it is expected (slide 25)

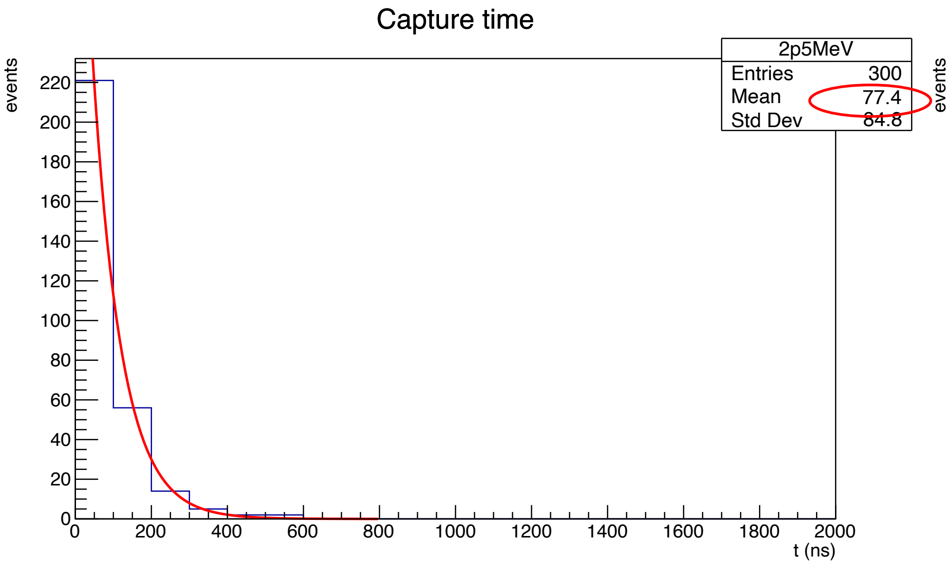
Next steps:

- Change the fitting range in the calculation of the mean lifetimes to check if it approaches to the results in an infinite sphere

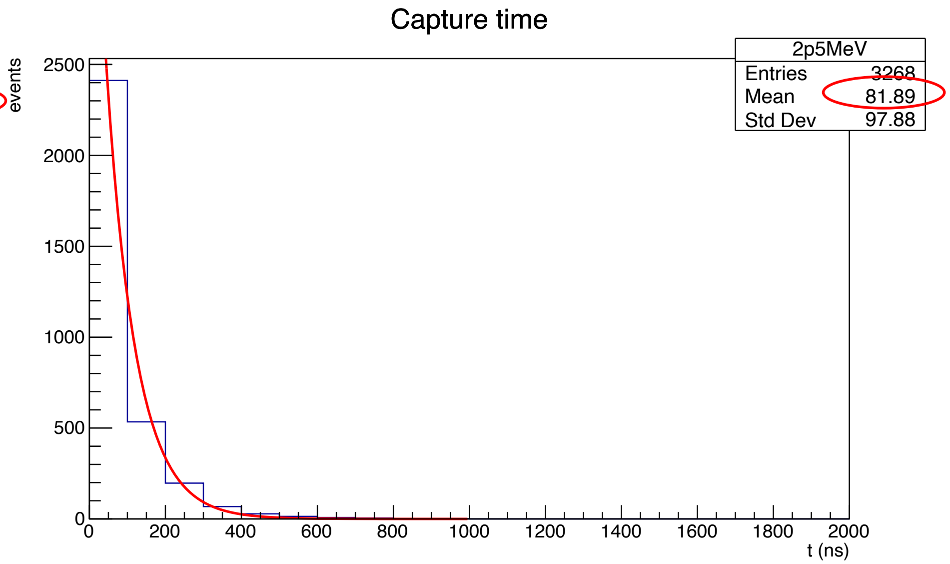
Progress on the next steps

2.5 MeV neutron capture time with DEAP3600 parameters

100K neutrons



1 million neutrons

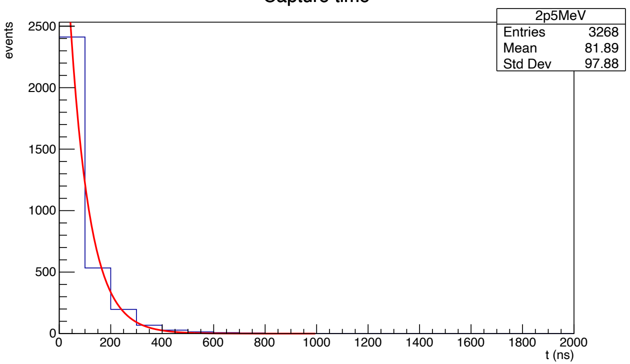


- Increasing the statistics to 1 million of neutrons (~4 hrs simulation) also increases the mean of the distribution

2.5 MeV neutron capture time with DEAP3600 parameters

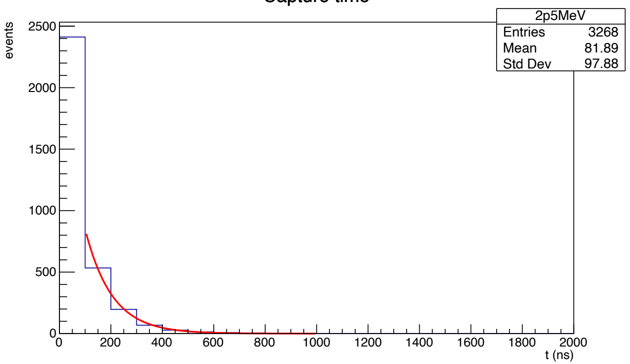
1 million neutrons stats.

$fitting\ from\ 0\ ns\ to\ 1000ns$



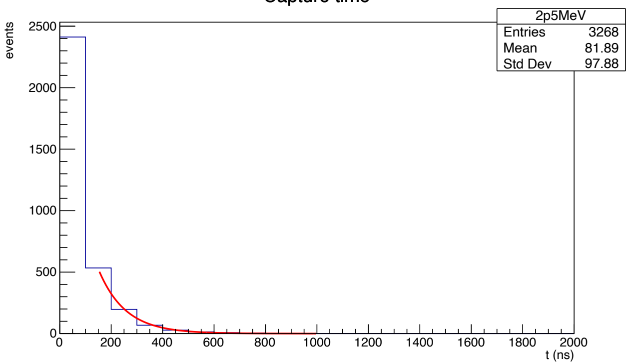
$$\tau = 77.6 \pm 2.3\%\ ns$$

$fitting\ from\ 100\ ns\ to\ 1000ns$



$$\tau = 104.2 \pm 4.0\%\ ns$$

$fitting\ from\ 150\ ns\ to\ 1000ns$



$$\tau = 104.2\ \pm 4.1\%\ ns$$

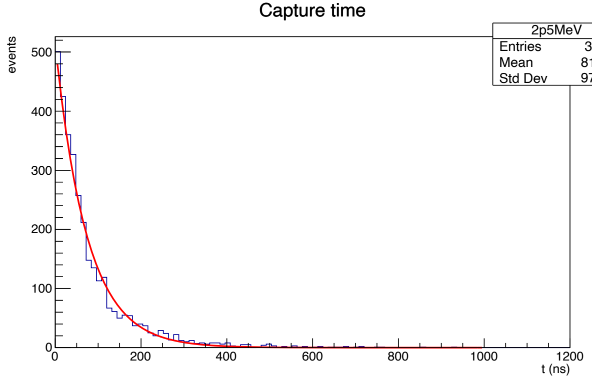
- Changing the fitting range in the calculation of the mean lifetime slightly increases the neutron capture lifetime

2.5 MeV neutron capture time with DEAP3600 parameters

(Finer binning)

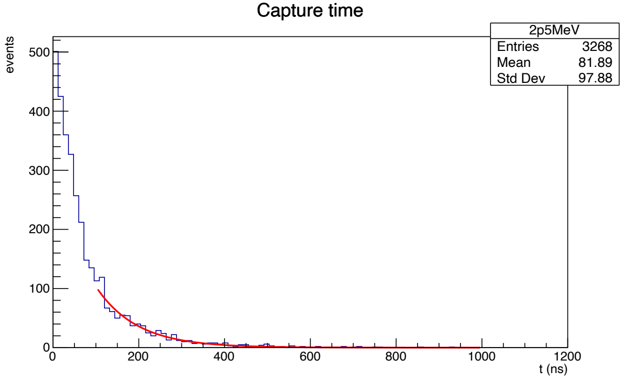
1 million neutrons stats.

$fitting\ from\ 0\ ns\ to\ 1000ns$



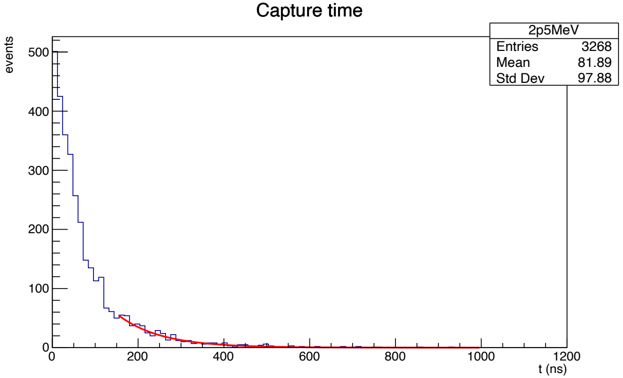
$$\tau = 73.9 \pm 2.2\%\ ns$$

$fitting\ from\ 100\ ns\ to\ 1000ns$



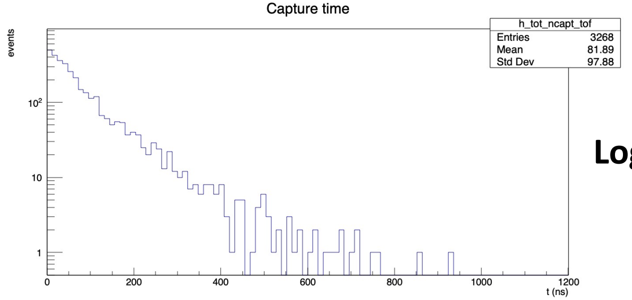
$$\tau = 95.0 \pm 4.0\%\ ns$$

$fitting\ from\ 150\ ns\ to\ 1000ns$



$$\tau = 100.1\ \pm 5.4\%\ ns$$

- Changing the fitting range in the calculation of the mean lifetime slightly increases the neutron capture lifetime
- There's a small change in the results for a different binning
- The fitting until 1000 ns is justified by looking at the logarithmic scale of the distribution



Log scale

Some comments on the last progress

- The increment (x10 stats.) of the number of the 2.5 MeV neutrons simulated (~4hrs) slightly increased the mean of the distribution.

- For the capture lifetime of 2.5 MeV neutrons in a DEAP3600 size LAr sphere approach the capture lifetime in an infinite sphere, neutrons with larger capture times are needed. Is it possible to achieve this by increasing the neutron statistics?

  What is the probability of a 2.5 MeV neutron bounce inside an 86 cm LAr sphere and finally be captured in it ?

Backup

LAr

```
//
// Sphere with LAr
// Isotopic composition
G4Isotope* I36Ar = new G4Isotope("Ar36", 18., 36, 35.967*g/mole);
G4Isotope* I38Ar = new G4Isotope("Ar38", 18., 38, 37.962*g/mole);
G4Isotope* I40Ar = new G4Isotope("Ar40", 18., 40, 39.962*g/mole);


G4Element* Ar_isotopes = new G4Element("Ar_isotopes","Ar",3/*number of isot*/);
Ar_isotopes->AddIsotope(I36Ar, 0.337*perCent);
Ar_isotopes->AddIsotope(I38Ar, 0.063 *perCent);
Ar_isotopes->AddIsotope(I40Ar, 99.6*perCent);


G4double density = 1.406*g/cm3;
G4double temperature = 85.5 * kelvin;
G4double pressure = 0.952 * atmosphere;
G4int ncomponents;
G4Material* sphere_mat = new G4Material("Ar_isotopes_mat", density, ncomponents=1,
kStateLiquid, temperature, pressure);
sphere_mat->AddElement(Ar_isotopes, 1);
```

40 LAr

```
//
// Sphere with LAr
//
G4double density = 1.390*g/cm3;
G4double a = 39.95*g/mole;
G4Material* sphere_mat = new G4Material("liquidArgon",18.,a,density);
```