Neutron kinematics update I

13/7/2023

Premise

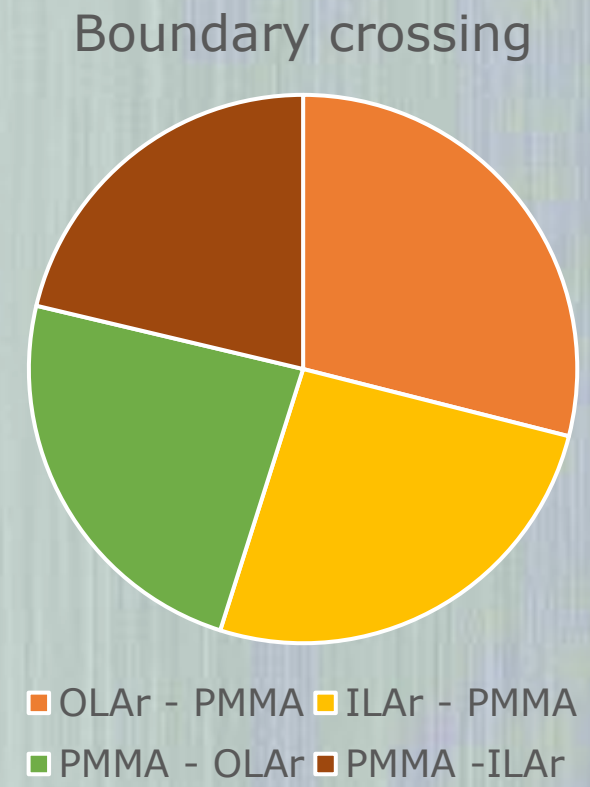
- A detailed, technical examination of the behavior of muon-induced neutrons in and near the shield
- This update focuses specifically on the behavior of neutrons at the shield boundaries (inside and outside)
- Information collected at the Geant4 “step level”, mostly at the end of the step
- Typically, these types of studies try to avoid neutron double counting, but we explicitly allow double counting as part of the study (to see how the neutrons “bounce around”)
- 10^6 muons, PMMA shield of 2m radius/height, MUSUN input, single re-entrance tube geometry

Terminology

- Boundary crossing – the movement of a particle from one volume to another
    - In our case, neutrons moving between the LAr and the shield
- Outside neutrons – neutrons within the LAr volume outside of the shield
- Inside neutrons – neutrons within the LAr volume inside of the shield
- Reflection – A neutron which originates and exits the shield from the same “side” (out-out or in-in)
- Transmission – A neutron which originates in one side of the shield and exits the other (out-in or in-out)

Statistics for LAr and PMMA boundary crossings

Parameter	Value	Notes
Number of unique neutrons	37002	Only neutrons which touch the shield
Total boundary crossings	113478	Max for 1 neutron: 18
LAr to PMMA boundary crossings	62286	
PMMA to LAr boundary crossings	51192	
# of neutrons captured in shield	11494	Could include neutrons originating in shield

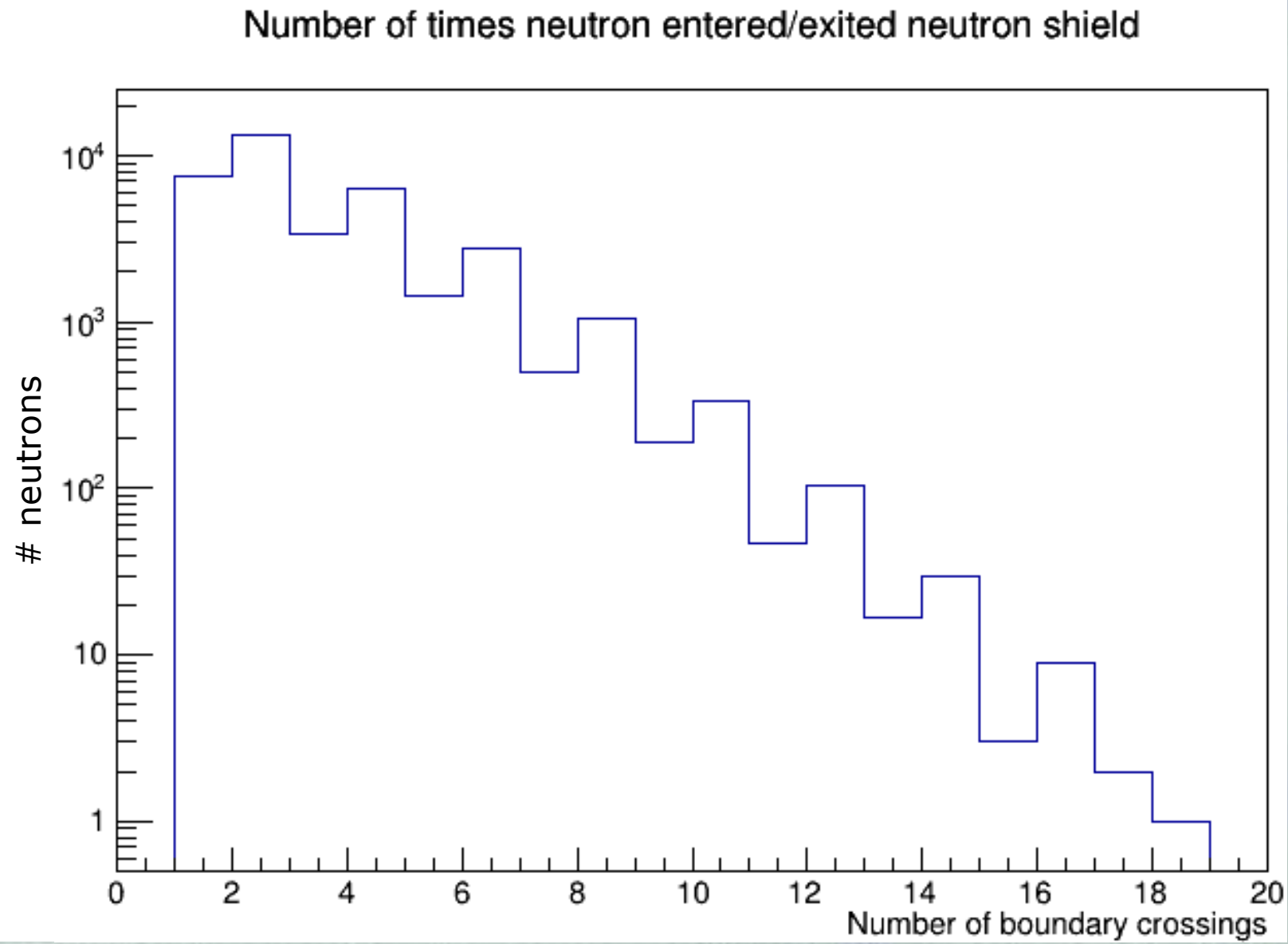


Statistics for shield transmissions and reflections

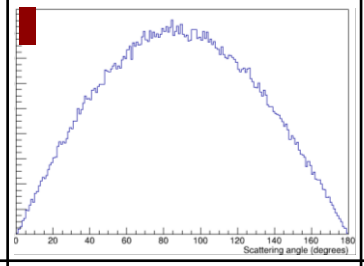
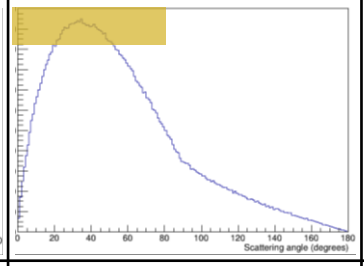
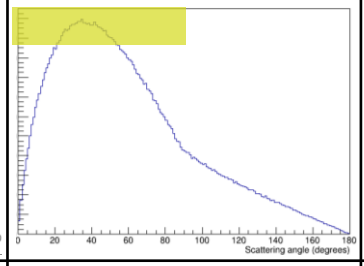
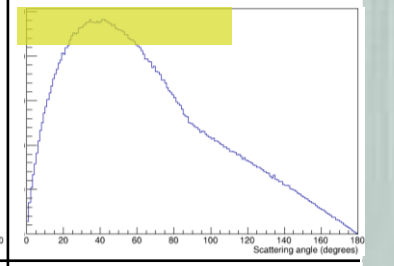
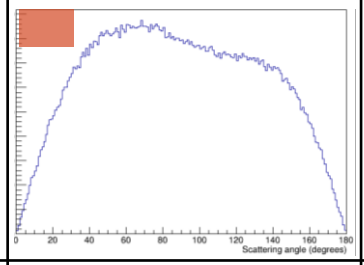
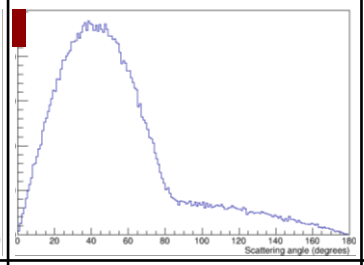
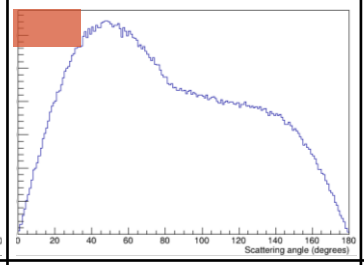
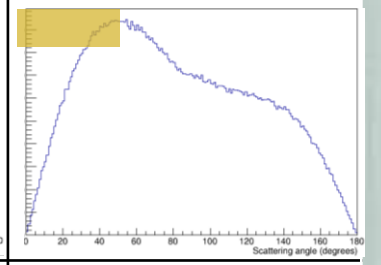
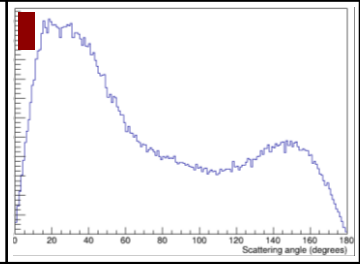
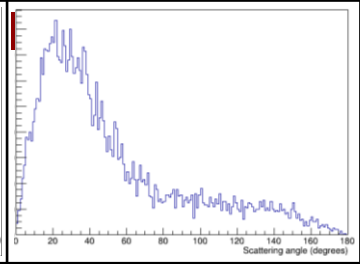
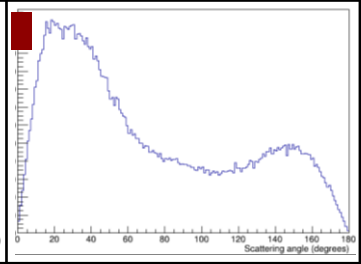
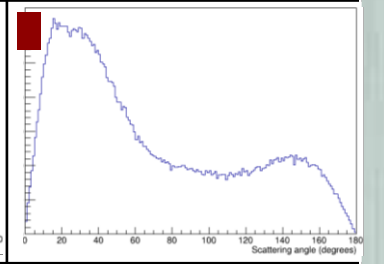
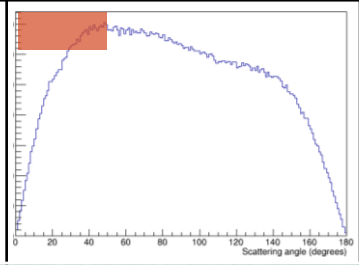
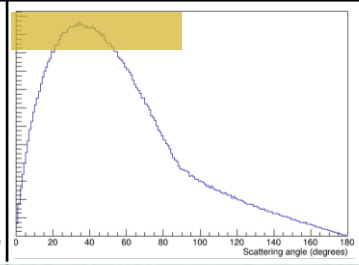
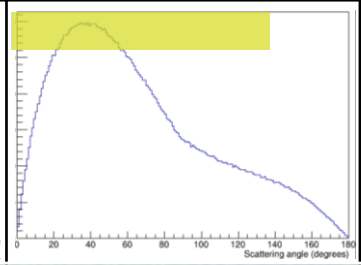
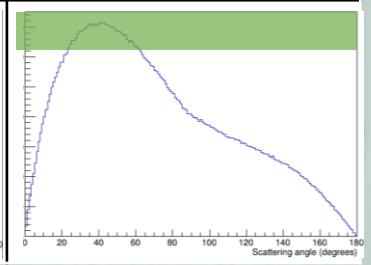
Parameter	Value	Notes
Total neutrons reflected	41626	Cannot include neutrons originating from the shield
Total neutrons transmitted	8467	

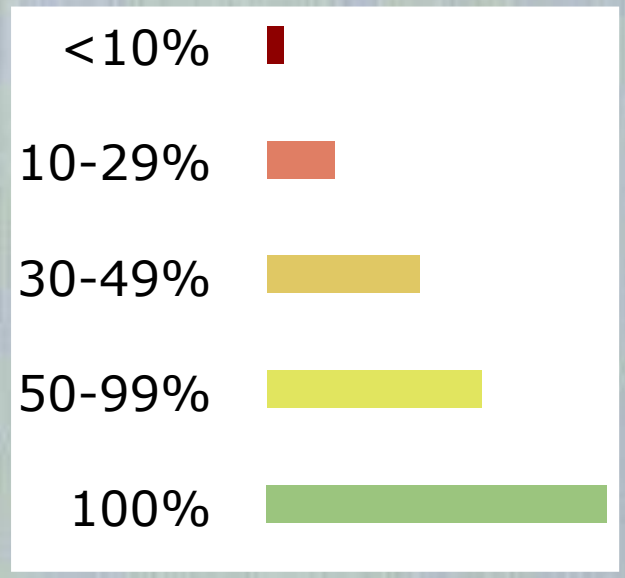
Neutrons seem 4-5X more likely to reflect off the shield than to transmit through

This is surprising, and will be investigated more closely


Number of times neutron entered/exited neutron shield
neutrons
10^4
10^3
10^2
10
1
0
2
4
6
8
10
12
14
16
18
20
Number of boundary crossings

Scattering angle of elastic scatters within the shield

	LAr scatters	Shield scatters	LAr+shield	All scatters
Low energy (<10 keV)				
10-1000 keV				
High energy (>1 MeV)				
All energies				



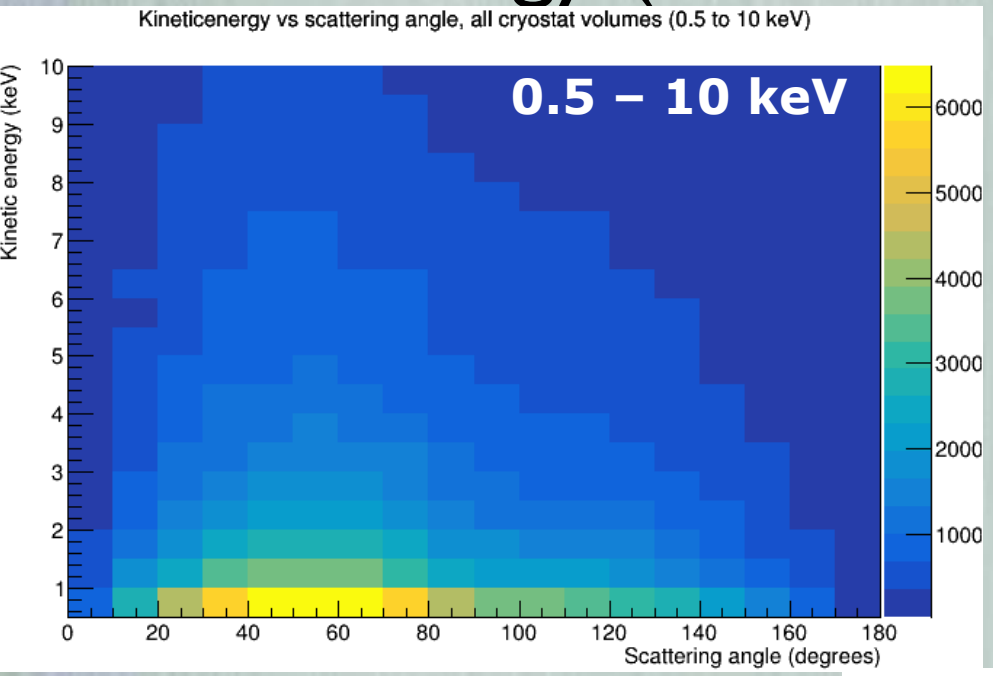
Total scatters in cryostat 3.58 x 10^6

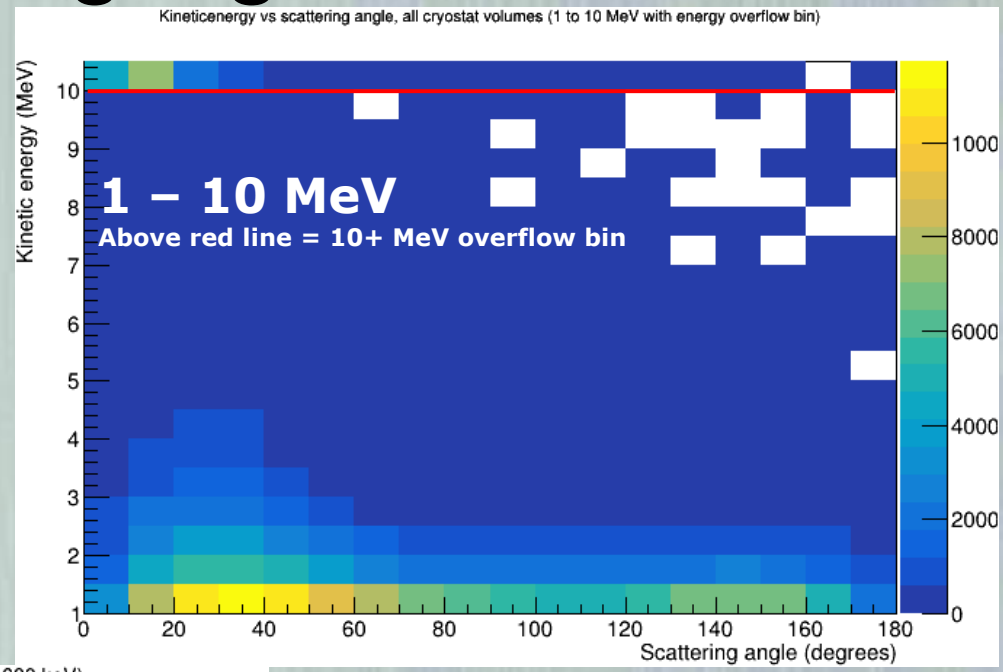
Energies recorded post-scatter

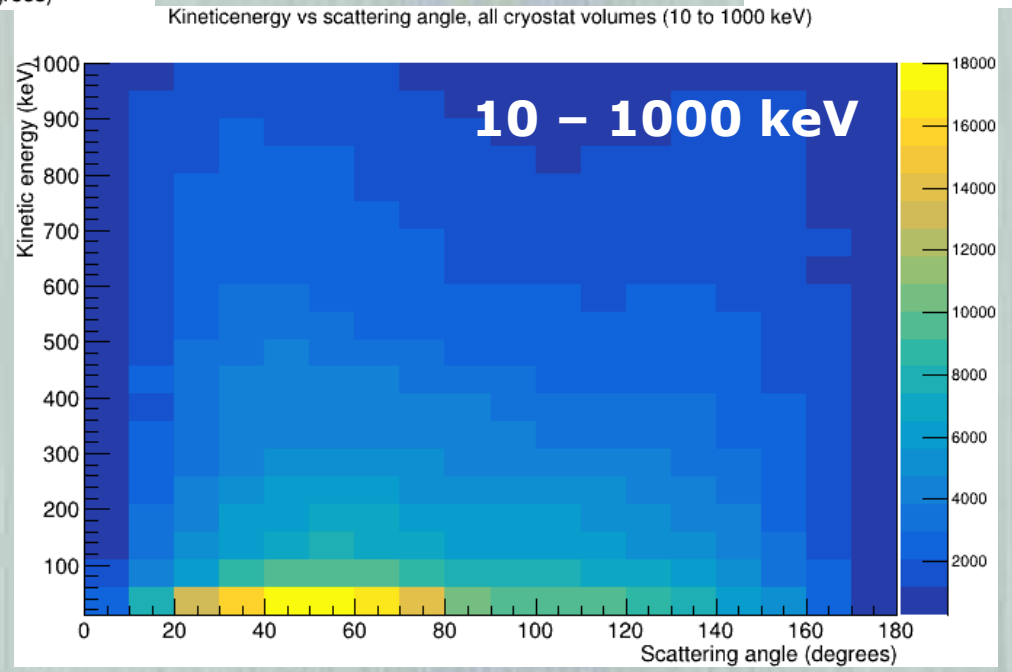
A scattering angle of 0 = no change in direction

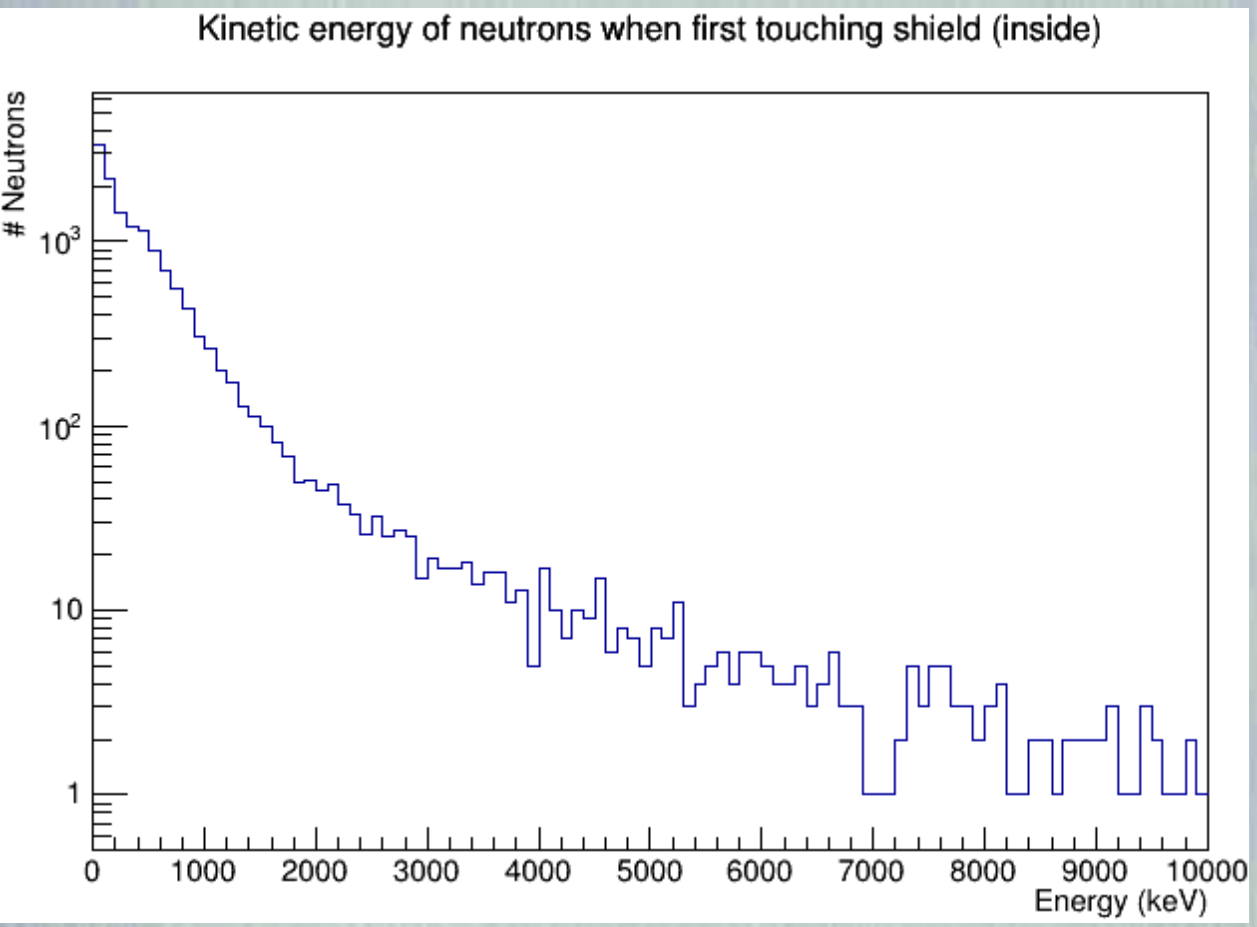
A scattering angle of 180 = reversed direction

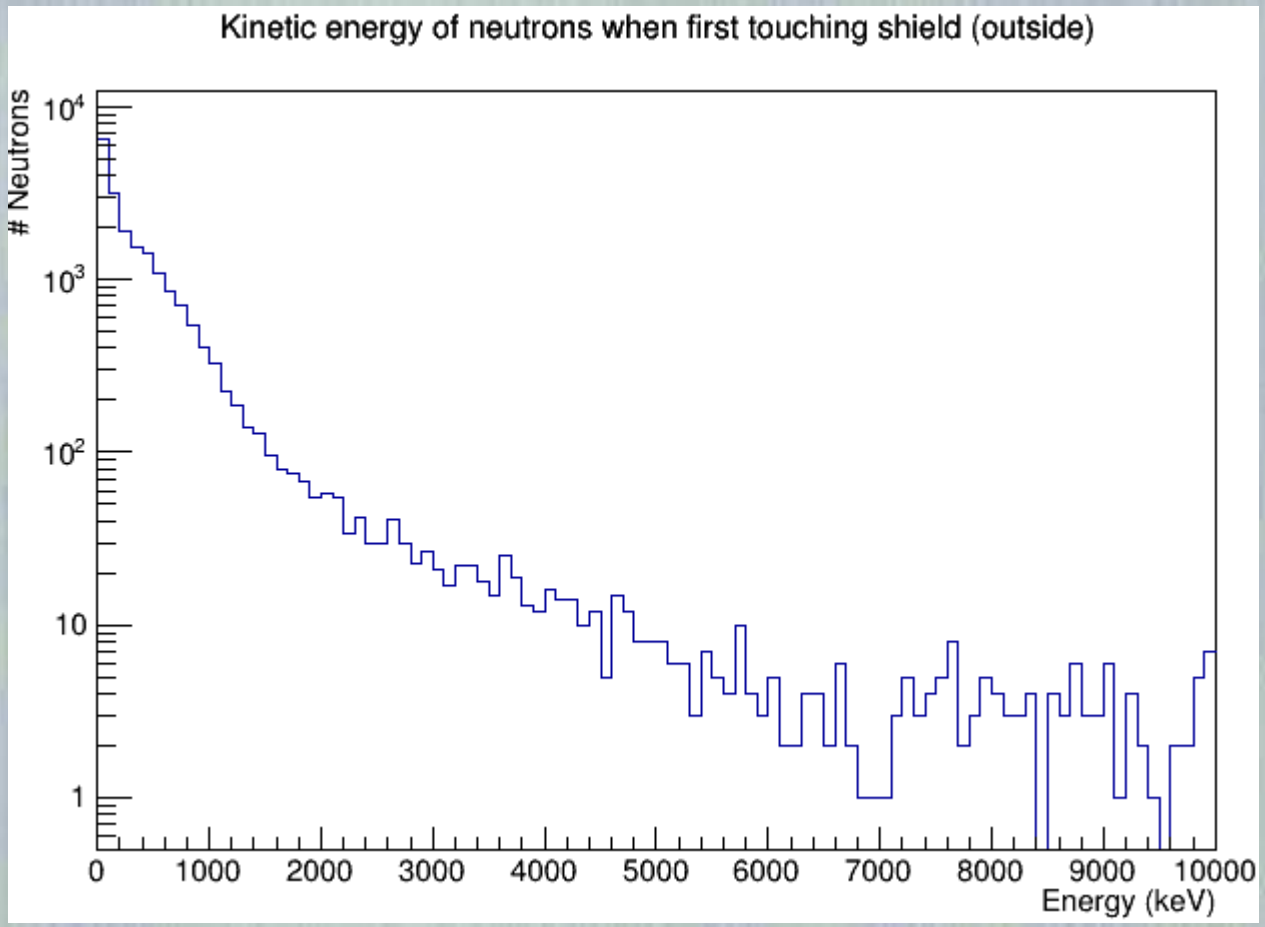
Kinetic energy (after scatter) vs scattering angle





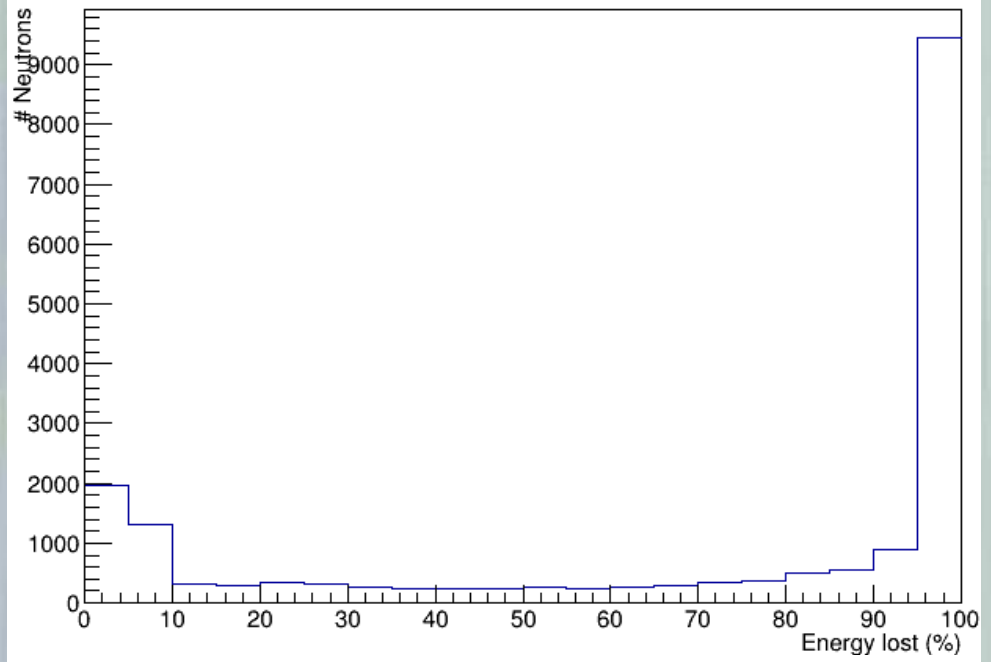



Kinetic energy of neutrons when first touching shield (inside)
Neutrons
10^3
10^2
10
1
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Energy (keV)


Kinetic energy of neutrons when first touching shield (outside)
Neutrons
10^4
10^3
10^2
10
1
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Energy (keV)

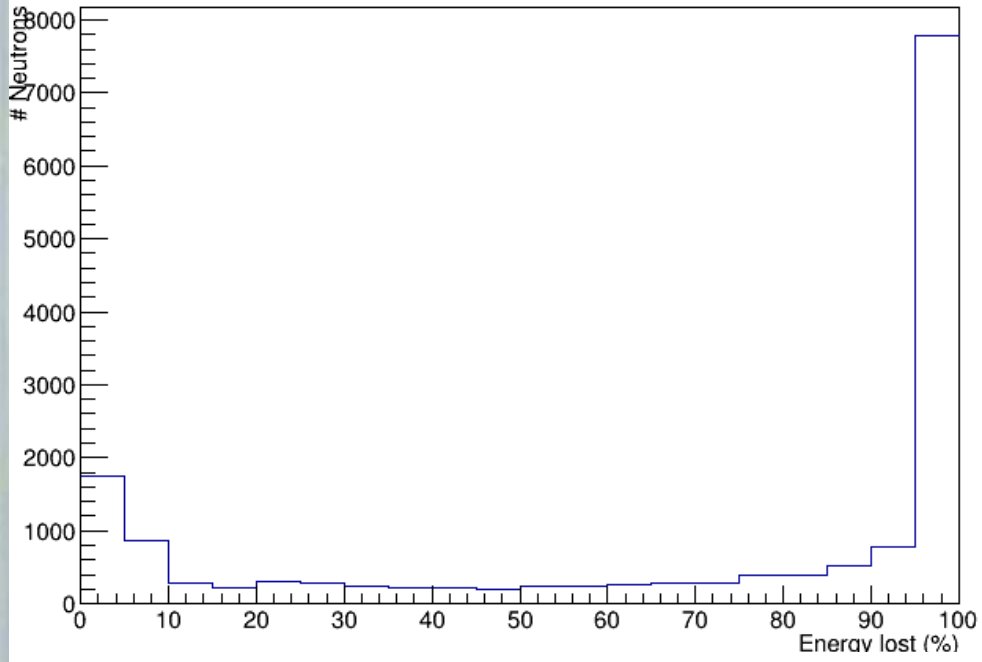
Fraction of energy lost in the shield

Outside neutrons, reflected



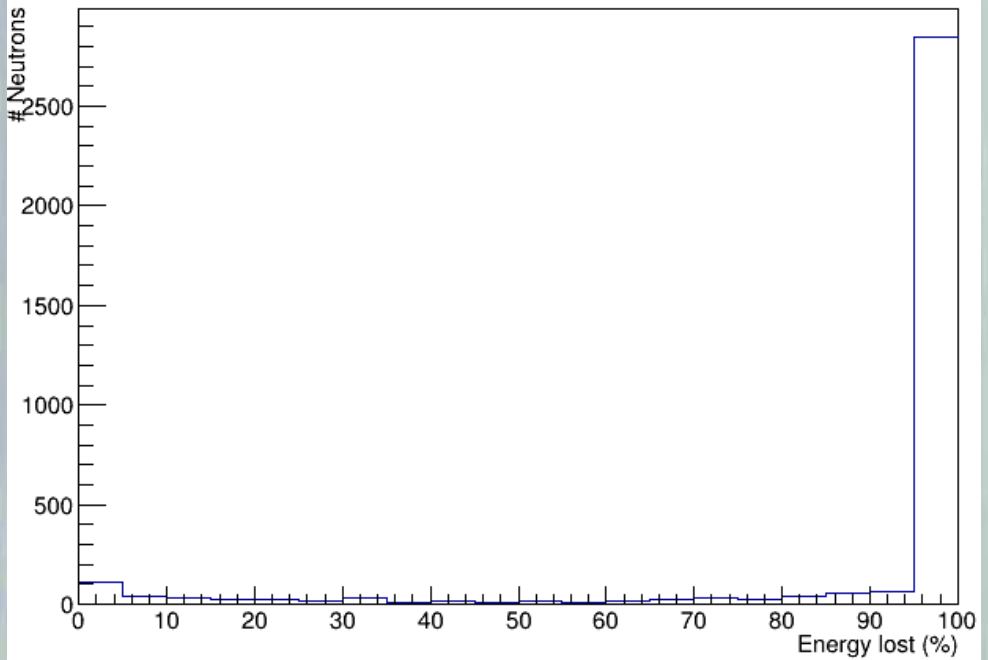
Fraction of energy lost in the shield

Inside neutrons, reflected



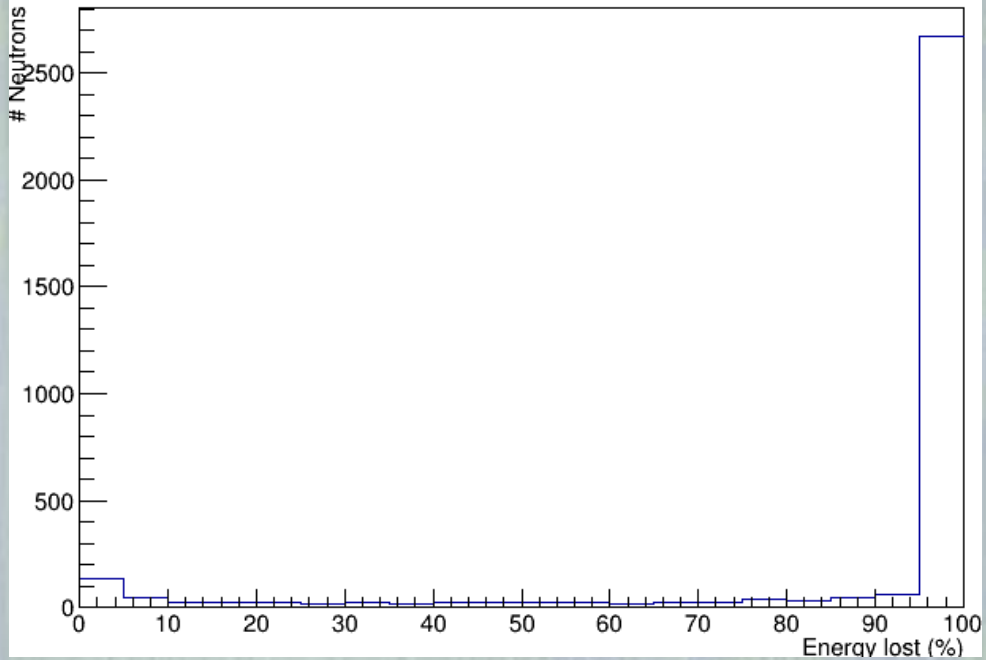
Fraction of energy lost in the shield

Outside neutrons, transmitted



Fraction of energy lost in the shield

Inside neutrons, transmitted



To do (non-exhaustive)

- Examine neutron capture in the shield more closely
- Check kinematics of muons which generate these neutrons
- Examine depth into PMMA that reflected neutrons reach
- DeltaE/E vs scattering angle plots
- DeltaE vs scattering angle 2D plots
- DeltaE per scatter plot
- DeltaE/DeltaX for the moderator