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Effects of Mean Free Path and Neutron Lifetime on N.C. State's

Ultra-Cold Neutron Source

The purpose of N.C. State's Ultra-cold Neutron Source is to create ultra-cold neutrons from N.C. State's PULSTAR reactor. The source takes in thermal neutrons from the PULSTAR reactor, and reduces their energy to ultra-cold levels. These ultra-cold neutrons (ucn) can then be transported and stored for a wide variety of neutron-based experiments. For the purpose of the experiments, it is important to harness as many ultra-cold neutrons from the source as possible, providing a high enough ucn flux to the various experimental setups to get accurate results. In order to maximize the amount of ultra-cold neutrons that can be created from the source, it is important to understand how certain experimental parameters affect the amount of ucns that make it out of the source, and which of those parameters researchers can effectively control. Two of these parameters include the ucn's mean free path and the effective neutron lifetime as they travel through the deuterium source. These two parameters greatly affect the number of ultra-cold neutrons that make it out of the ultra-cold neutron source, and can be controlled to some degree by the researchers responsible for constructing the source. Therefore, by exploring the effects these two parameters have on the ultra-cold neutron source, researchers can gain a better understanding of the ultra-cold neutron source itself, as well as maximize the number of ultra-cold neutrons they can produce.

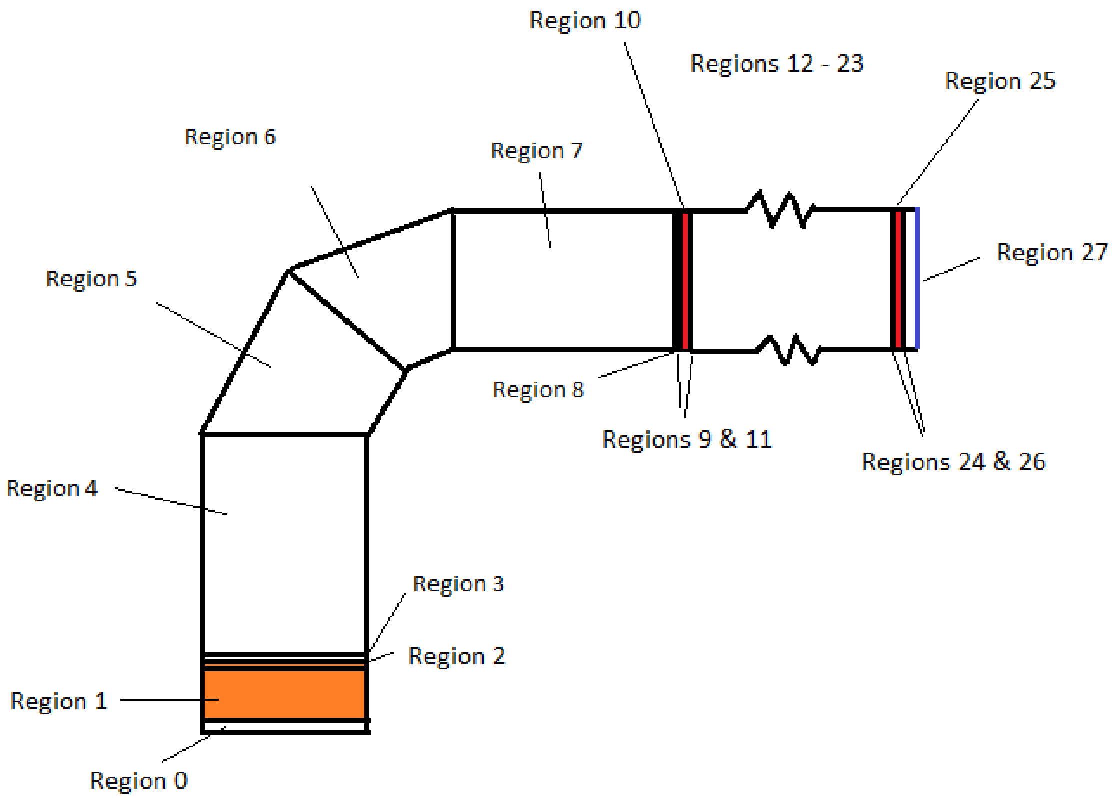
The mean free path of a neutron can be defined as the average distance the neutron travels before it experiences an interaction, such as elastic scattering. The parameter is statistical in nature, and can be affected by properties such as the neutron's speed and the makeup of the medium it is travelling in. The effective neutron lifetime represents the average time the neutron is present in the bulk source medium before being 'lost.' This parameter takes into account any neutron loss, be it absorption, up-scattering, or simple neutron decay, which together give an idea of how long the neutrons last in the medium on average before being 'lost.' In order to maximize the amount of ucns that make it out of the source, it is important to understand how these two parameters will likely affect ucn flux from the source. Conceptually, when ultra-cold neutrons are 'born' inside the deuterium source, researchers want them to be able to make it out of the source as soon as possible. The longer they remain present in the source, scattering and interacting with the source materials, the greater the chance they will be lost before making it out and into the guide tubes. The question then becomes, what changes should be made in order to allow ultra-cold neutrons to easily leave the deuterium source?

To start, it can be reasoned that by increasing the effective neutron lifetime, more ucns should be allowed to leave the source medium. Having an increased lifetime allows the neutrons more time to 'find their way out' before an interaction would occur that allows them to be lost. It can also be reasoned that increasing the mean free path will allow more ucns to exit the medium. By having an increased spacing between interactions, the neutrons will be able to travel longer in a certain direction before being deflected through elastic scattering, allowing them a more straightforward path towards exiting the source medium.

Experimentally, these parameters can be monitored and controlled in a number of ways, and their values depend heavily on the structure of the ucn source. The mean free path, for example, depends on the atomic structure of the deuterium source itself, which is put together as a solid crystal of almost pure deuterium. Ensuring that this crystal is grown as ideally as possible allows the spacing between atoms to become as distant and uniform as possible. The more uniform the crystal, the more clear a path an ultra-cold neutron has to escape. As for the effective neutron lifetime, it is largely affected by the purity of the deuterium crystal in regards to the presence of hydrogen. Hydrogen has a much higher absorption cross section for neutrons than deuterium (about 40 times greater); the more hydrogen present, the more likely neutrons are to be absorbed, and the shorter the effective neutron lifetime within the source.

For the Ultra-Cold Neutron Source being developed at N.C. State, it is estimated that the achievable effective neutron lifetime will be somewhere between 25 and 75 milliseconds. 75 milliseconds is ideal, but likely the achievable value will be closer to around 50. As for the mean free path parameter, the value should range between 1 and 6 cm, with the longest value being ideal. Therefore, in testing the effects of the two parameters, these range values will be used.

To test these parameters, a Monte-Carlo ultra-cold neutron modeling code developed by Adam Holley, UCNTransport, Version 29.9, was used. The basic source geometry which was used in the code can be summarized in the following diagram:



The red regions denote foils, the orange regions deuterium source regions, and the blue region the end detector. The actual geometry is much more precise, and covers all of 3-D space; this diagram merely serves to give the reader an idea about what the important regions are, and where they are relative to other regions. Regions 12-23 consist of connecting guides that bend in different 3-D directions, eventually ending in a straight section that contains regions 24-27.

The following tables display the results from the UCNTransport code, simultaneously varying the mean free path and lifetime parameters within the expected ranges of State's ucn source. The mean free path is broken up in increments of ½ centimeters, and the absorption time in increments of 10 milliseconds. Important variables related to the code are also listed.

Important Parameters:

- Starting # of UCN = 10,000
- Vcutoff = 8 m/s
- Random Seed = 3
- Incremental distance, 'scattfuzz' = 10^-5 m

Final # of UCN's that Escape the Source Cryostat

	Absorption time (1/s)					
Mean Free Path (cm)	**40**	**28.571**	**22.222**	**18.182**	**15.385**	**13.333**
1	426	578	686	807	904	989
1.5	604	753	939	1097	1227	1359
2	706	930	1134	1292	1437	1583
2.5	872	1021	1255	1422	1570	1719
3	874	1121	1333	1531	1729	1886
3.5	942	1194	1390	1609	1798	1919
4	996	1277	1483	1681	1882	2049
4.5	1035	1304	1554	1791	1972	2159
5	1059	1371	1650	1872	1977	2186
5.5	1096	1423	1643	1857	2017	2203
6	1108	1464	1752	1928	2054	2298

Fig 1

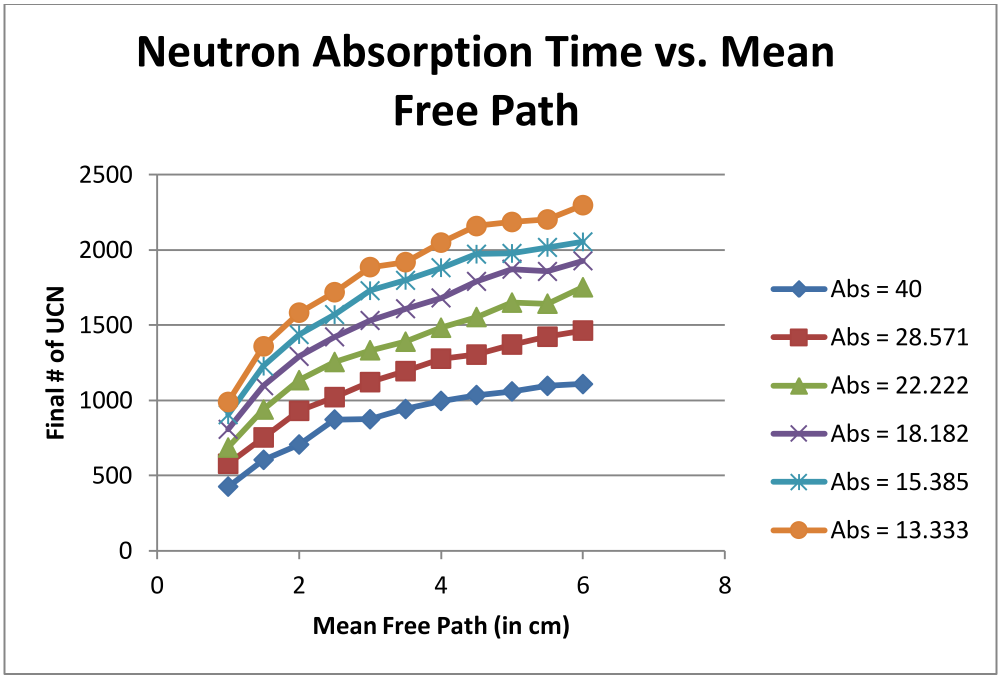


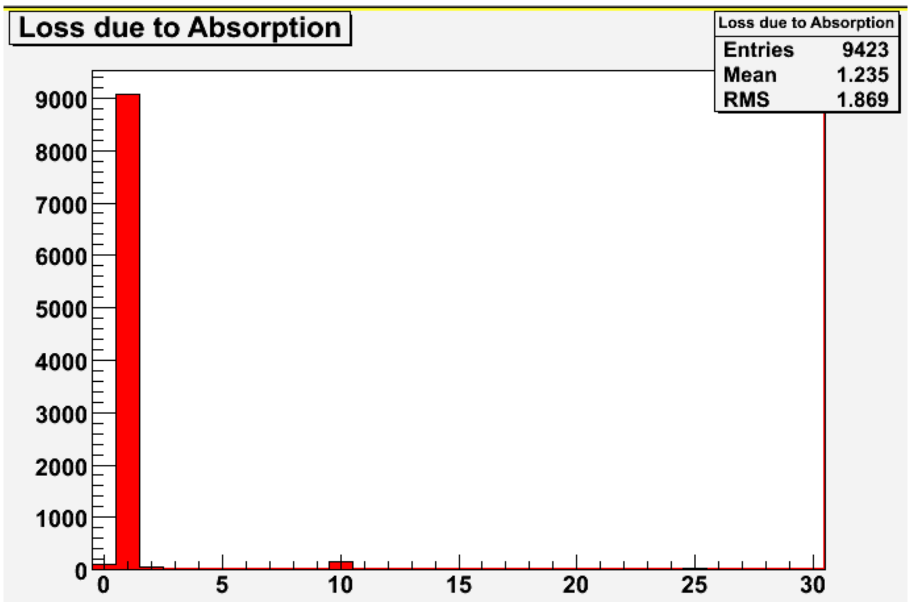
Fig 2

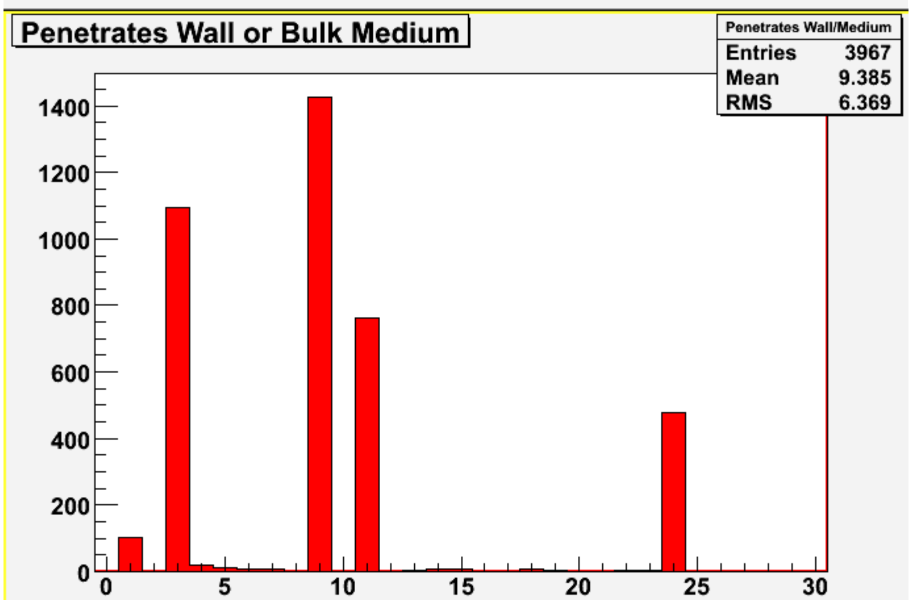
The results from Figs 1 and 2 show that by increasing both the ucn mean free path and the effective neutron lifetime, the final number of ucns that make it out of the source is increased. This matches the previously stated assumptions as to how the parameters would behave, and provides some estimates for the expected output of the ucn source if the two variables are known. For example, the reasonable values of mean free path = 4cm and effective lifetime = 45 ms leads to a surviving ucn fraction of 1483/10,000 ≈ 15%

It is interesting to note that for an individual effective neutron lifetime, the function of mean free path vs. number of surviving ucn is parabolic in nature, possibly leveling out as the mean free path increases past a certain point. The deuterium source itself is only about 4 cm long, so it would make sense that once the mean free path surpasses actual source geometry, further increases would have a negligible effect, and the final ucn count would approach a maximum value.

To gain a better picture of what is happening with the ultra-cold neutrons as they travel through the source cryostat, histograms were also made for certain runs to show where each ucn was lost. Four important points of interest were chosen to observe how ucns were lost, and in what region they were lost, in order to see if there is any noticeable effect on this by the mean free path and lifetime. The region in which each event occurred is on the x axis, and the number of neutrons lost in that region is displayed on the y axis.

1. Lowest Mean Free Path (1cm) & Lowest Effective Lifetime (25 ms) – Figs 3 & 4





2. Highest Mean Free Path (6cm) & Lowest Effective Lifetime (25ms)

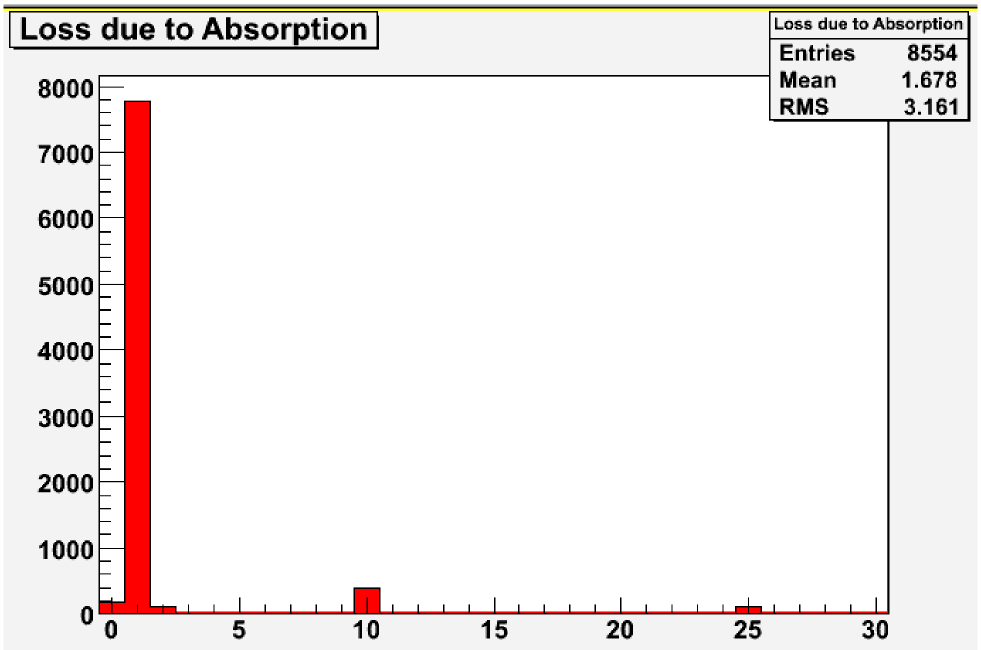


Fig 5

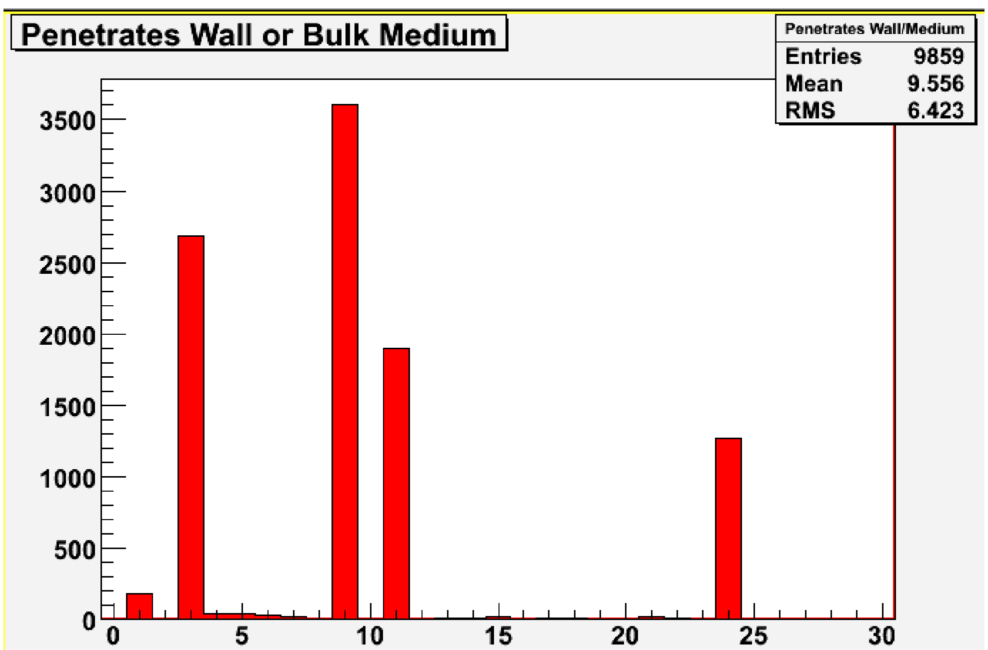


Fig 6

3. Lowest Mean Free Path (1cm) & Highest Effective Lifetime (75ms)

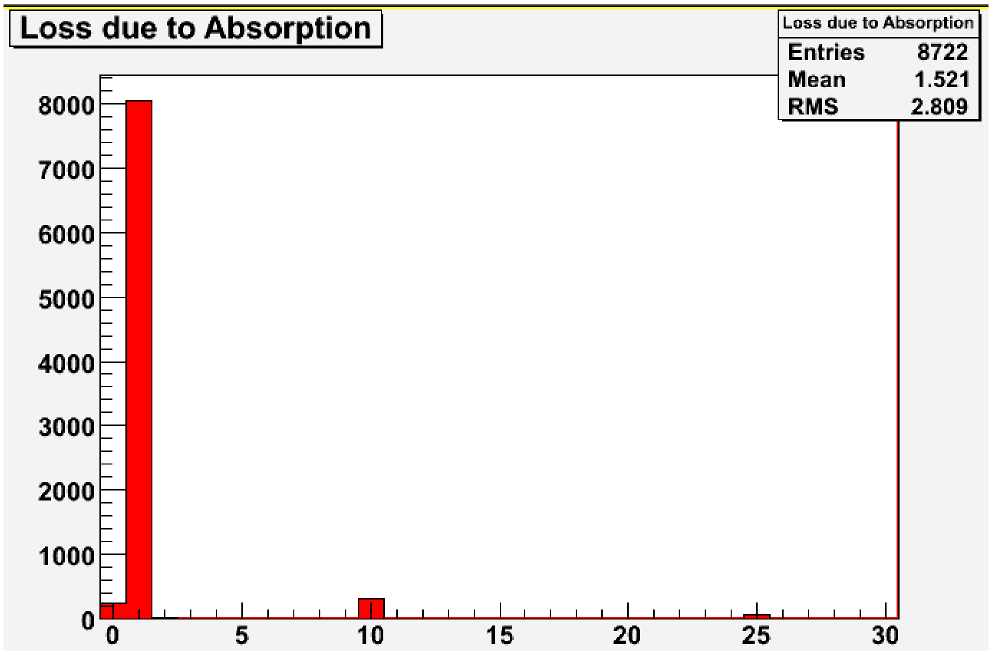


Fig 7

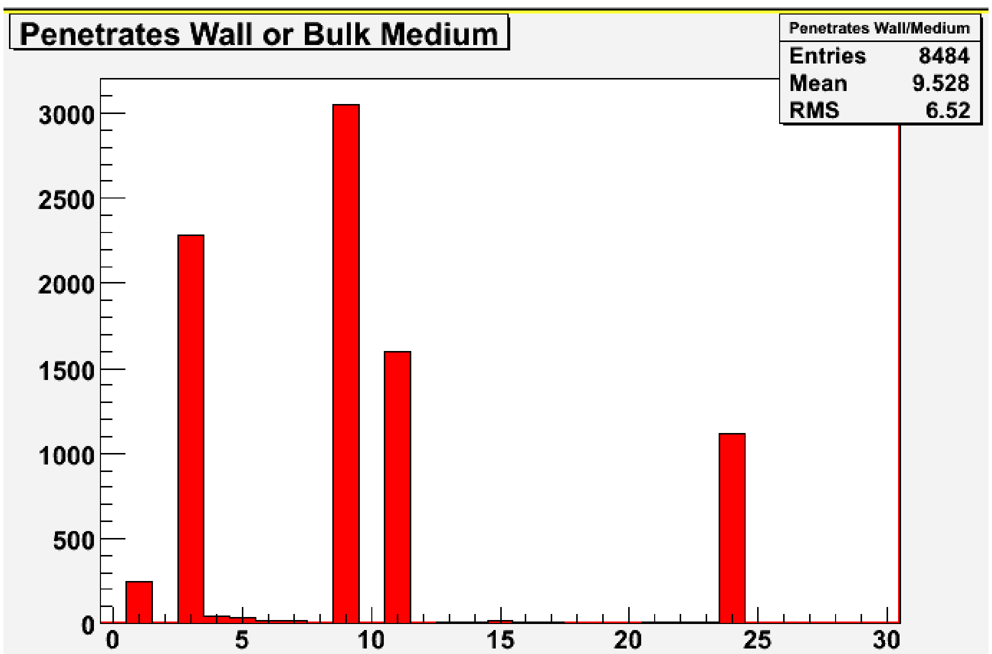


Fig 8

4. Highest Mean Free Path (1cm) & Highest Effective Lifetime (75ms)

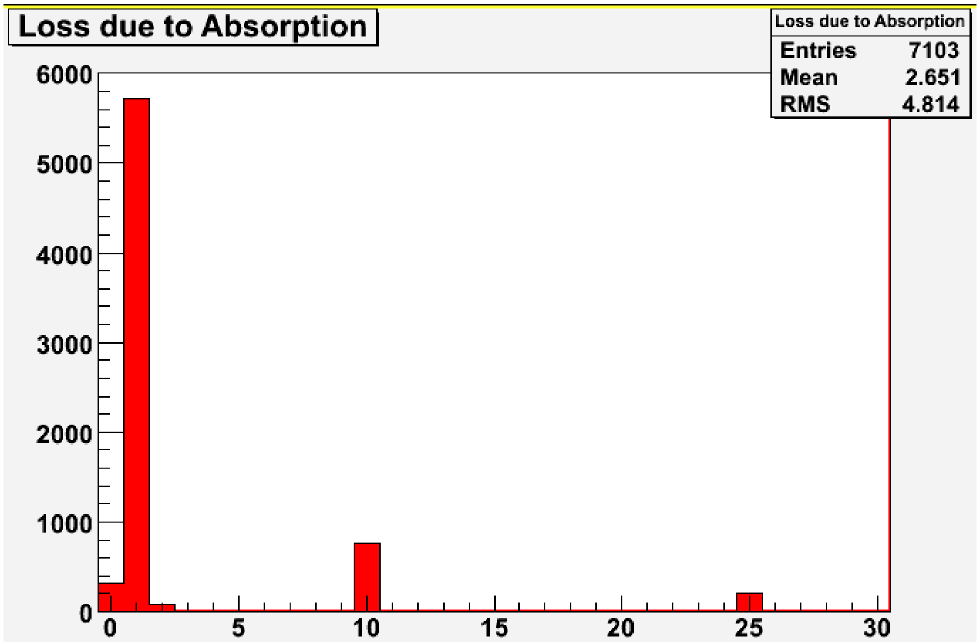


Fig 9

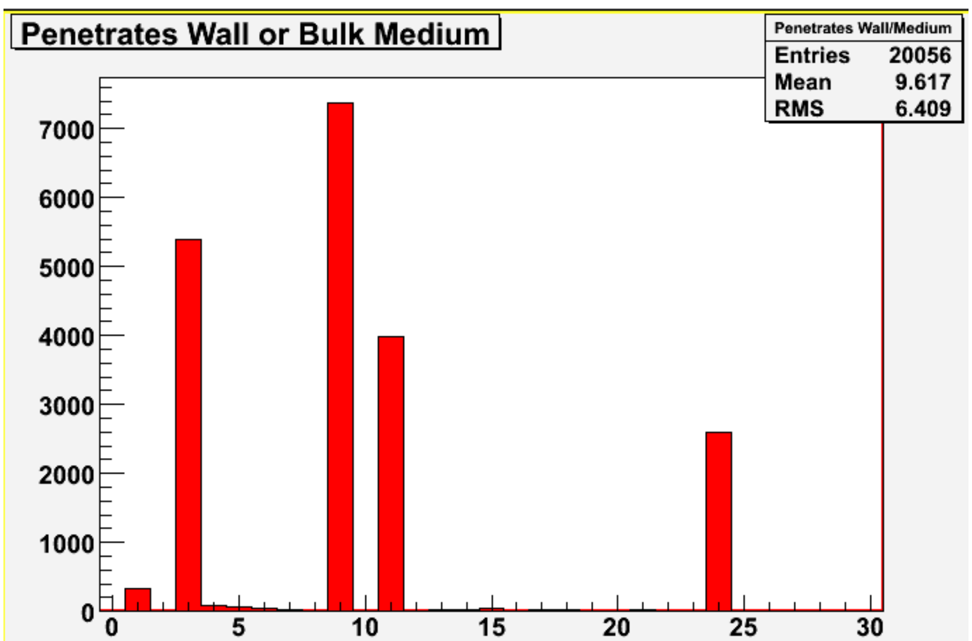


Fig 10

The ‘loss due to absorption’ graphs account for any neutron that is lost in any region due to absorption (other than in the detector region, 27). The ‘penetrates wall or bulk medium’ graphs are a little more complicated, as they account for both 1) the neutrons lost due to the penetration of a region, such as a particle exiting a wall, and 2) any time a particle penetrates a bulk medium. The important regions to take into account when viewing these graphs are regions 1 and 2, source regions of deuterium, and 10 and 15, which contain foils. For the absorption graphs, neutrons are absorbed in regions 0, 1, 2, 10 and 15, with most of the absorption occurring in the larger deuterium source region, 1. For the penetration graphs, the regions beside the regions being entered, such as foils, have high counts since particles are leaving those regions by penetrating into another bulk medium.

Overall, it appears that the results are proportionally similar for each of the four situations. Of course, there are some subtle differences for each case. For example, when the mean free path is increased, it appears that absorption fraction in the foils increases, likely due to the higher number of ucn that manage to escape the deuterium regions. For the penetration graphs, the ratios of each peak appear to be similar; the overall height of each peak is simply increased due to the higher number of neutrons from the source regions. As for when the absorption time is increased, the number of neutrons absorbed in the source regions decrease while the number absorbed in the foils increase. This could be due to the fact that 1) neutrons become more likely to escape the deuterium source regions, and 2) the particles are given a longer time to bounce in between and through the foil regions, increasing the recorded counts. This also likely explains the increase in column height for the penetration graphs. Still, what was being looked for in these graphs was if any drastic changes in the ratios of peak numbers appeared between the different scenarios, and it looks like the two graphs indeed maintained their characteristic shapes for each scenario.

It is clear from the results of the UCNTransport experiments that the mean free path and effective lifetime parameters for ultra-cold neutrons greatly affect the number of ucns that are successfully gathered from the ucn source. The data trends indicate that by increasing both parameters, the number of ultra-cold neutrons that survive their trip through the source cryostat increases. Therefore, it is in the research group's best interests to effectively maximize both parameters when constructing the ucn source cryostat, in order to maximize the number of neutrons that make it to the various experiments waiting at the end. The results from these modeling experiments match the expected theoretical outcomes, and raise additional questions to explore in future research endeavors. One area to explore is whether or not the number of surviving neutrons for a certain effective lifetime approaches a maximum value as the mean free path increases. Another would be to create more precise histogram plots of where and how the ultra-cold neutrons are being lost, to gain more of an understanding of what is going on inside the system. Finally, the experiment can be repeated with a higher initial count of ultra-cold neutrons to increase accuracy, or instead be changed to measure the steady-state neutron density that could be maintained within the system.