Cylindrical Apertures to Measure Neutron Lifetime

Tyler J. Mason
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1 Introduction

The decay lifetime of an isolated Neutron, τ_n, has been studied extensively in the past, however both scrutinized results do not agree on the precise value. The 2 main studies took place at the Institute Laue-Langevin using the "Bottle" method, and at the National Institute of Standards and Technology Center for Neutron Research using the "Beam" method. The "Bottle" method uses ultracold neutrons confined in a bottle and counts the remaining neutrons to record decay, and the "Beam" method passes neutrons through a magnetic field and counting the fraction of decay products per neutron passing through. These studies were both verified, but their results are significantly different. The studies report a difference of 8.7±2.0 seconds, a value far outside of the bounds of uncertainty of both experiments. The puzzling thing about this difference is that in studies targeting other particles, the "Beam" and "Bottle' methods produce agreeing results. There are a few possible explanations that are very exciting, such as some interaction of the weak force interfering, or some "exotic" process unknown to us occurring in the experiments. However, on a much duller note, this difference, while unlikely, could be the result of error. To eliminate this possibility, the experiment needs to be repeated with more accurate apparatuses to rule out any significant chance that this observed difference is the result of error.

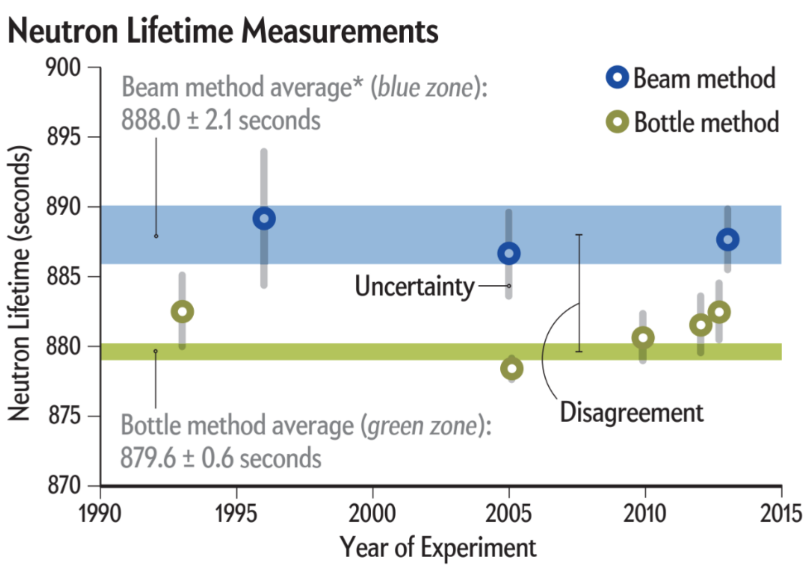

Figure 1: [1] *Diagram showing the disagreement of the 2 experiments over time, demonstrating the need for more accurate experimental methods*

2 Problem and Objectives

As sees above in figure 1, the beam method is naturally more susceptible to error with the nature of how the experiment is conducted, and to move forward in determining the precise lifetime of the neutron we need to find better experimental methods for the beam method. A contributor to the experimental error of the beam method is the detectors located outside of the beam trap. The

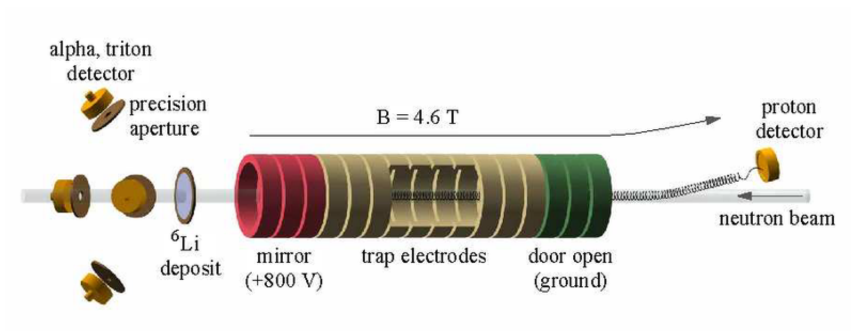

Figure 2: [2] *Schematic showing the detectors and apertures positioned with the proton trap*

width of the neutron beam results in a variation of the origin when considering the solid angle of incident particles to the apertures, therefore particles leaving the trap to be detected all have a differing solid angle to the detectors. This leads to an inaccurate measurement of total neutron flux, and therefore a less accurate experimental result. My mentor, Dr. Christopher Crawford, believes that it is possible to design apertures that create a uniform solid angle for all particles leaving the system, by limiting the solid angle of certain paths using caustics. Therefore my goal is to design precise azimuthally-symmetric apertures for the proposed BL3 experiment to reduce experimental error. Under the guidance of Dr. Crawford, I will work to develop a set of apertures that provides uniform solid angle, and therefore uniform acceptance for every detector, across the width of the neutron beam. My objectives to accomplish this are developing a repeatable coded process for accurately deriving solid angle of a parametric surface, creating an optimization problem with this process, and then producing CAD models using the best results from the optimization problem.

3 Procedure

To begin, I will work back through the work done by Joshua Young on the 2D proof of concept apertures to bring myself up to speed on the project and try and spot any improvements or inefficiencies in the processes. Then I will derive a series of equations used to create an optimization problem who's solutions

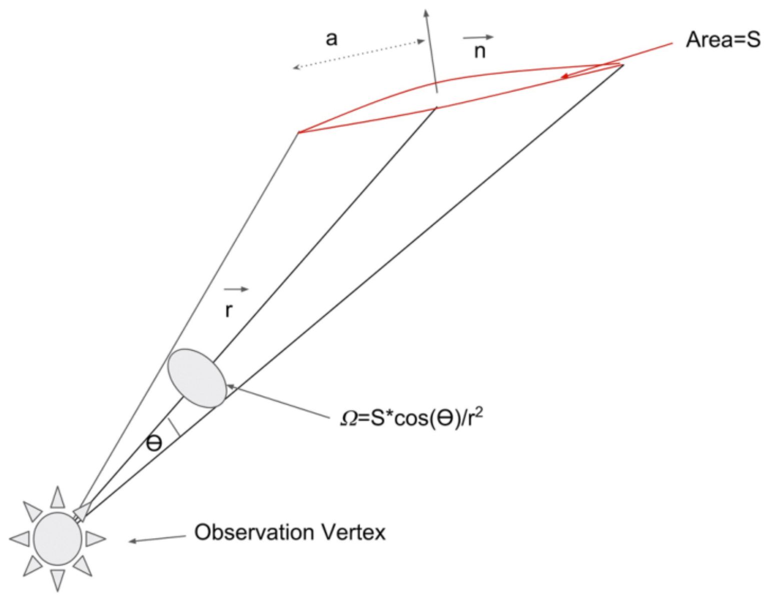

Figure 3: [3] *Graphic showing a similar process of calculating solid angle as proposed, for my work, the area of the surface will be defined as an unsolved integral, allowing for an optimization problem*

will be apertures for uniform or as close to uniform acceptance as possible. This will be done by taking advantage of the relationship between the differential solid angle and the differential equation that represents a cone created by the parameterized surface. With the best possible solutions, I plan on modeling them all with CAD and then 3D printing them, creating models to be used for physical testing of the design. With these models, I can begin to consider the best fit for the BL3 proposal, not just on their acceptance rate and uniformity, but on ease of construction, cost, and implementation into their model.

Starting work, I began exploring the capabilities of python and machine learning algorithms to try and optimize surfaces that give not only uniform but high acceptance. I came to realize that python has a shortcoming when working with mathematical functions. When creating defining a mathematical function in python you have to create it in the same way you would an algorithmic function, and it is stored as a unique data type. This makes adding, combining or modifying functions very difficult, and extremely difficult to implement for a learning algorithm.

Leaving python, I went on trying to establish a governing differential equation that represent equality amongst 2 detectors in the 3-Dimensional case. To simplify my starting point, I left the expressions that represent the aperture and the detector as variables, and wrote an equation that compares the solid angle from the center point to both detectors, an the solid angle from the left and right detector summed. This setup has its advantages, as I can represent the center point as one calculation doubled, as from the center point the 2 apertures are symmetrical. And when considering the solid angle from a non-center point, I can easily determine vectors from the point to the center of the detector and then normalize them, making unit vectors for the solid angle calculation. Then I went back and began to describe the detector in the equation. This proved to be the most challenging, as the most convenient way to describe the detector was with a Cartesian coordinate system, and the rest of my equation used a spherical system. This resulted in a very complex definition that will make modifying the equation to solve it very difficult. There is also the problem that in this equation I am solving for a surface, the aperture itself, and this process was foreign to me. I went about looking online for example problems or text on the subject but came up dry, and when speaking to Dr. Crawford about it, I came to realize that the solution to my equation would not be a well defined aperture, but a bound that would exist on all possible solutions. I do not believe that solving my equation would result in a usable solution, so I stored the idea for later. At this point in my work, I was admittedly lost, and needed to take

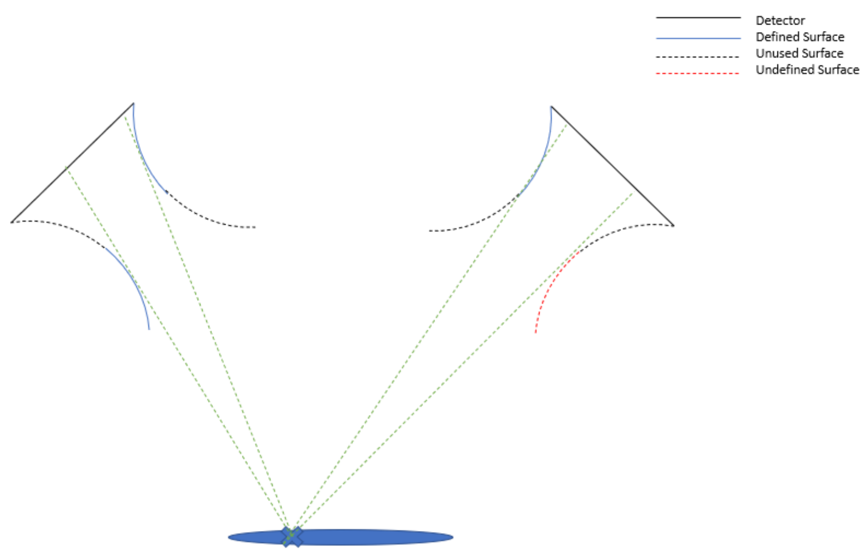

Figure 4: [1] *Diagram showing the "build up" process, assigning 3 of the surfaces to be constant, and using the 4th point of contact to build up a 4th surface that will provide uniformity. A good result will be a set of data points that can be interpolated into a defined function.*

the problem back down into its most basic roots. With the recommendation from Dr. Crawford, I am going back to a numerical approach using Matlab. I am writing a program that will numerically find the tangent to a curve from a differing starting location, starting in 2 dimensions and then moving into 3. This can be expanded to a program that can define tangent points of surfaces placed around the detectors, and therefore automate the process of evaluating the solid angle for a detector. Then using the same approach Joshua Young used to solve the 2 dimensional case, I will define 3 of the 4 surfaces that the particle could interact with, and using the Matlab program determine points on the 4th undefined surface that will provide uniform acceptance. Repeating this process for a lot of source points across the neutron beam, and then interpolating the results using Matlab splines will result in a final result.

Continuing forwards with this idea, I will be able to construct, multiple working 3D apertures, and moving forwards I want to continue with the simplest and most effective design, more specifically, the design that gives the most acceptance while remaining uniform, and is simple to construct and install. I will print models of the apertures using different methods, to visually test rigidity and any dimensional errors that come from printing, and make a spliced model that can easily be reprinted.

4 Significance of the Research

The value of this research is its contributions to the BL3 experiment, and working to close the gap between the determined neutron lifetimes. The precise lifetime of the neutron has large implications on nuclear physics as a whole, to include a better understanding of the weak force, possible implications to the big bang theory of creation with its effect on nucleosynthesis, and the potential of discovering new exotic nuclear processes currently unknown to us. The key to all of these discoveries may very well be the discrepancy in the 2 experiments, and narrowing in on whatever discovery the cause of this discrepancy is will have a profound impact on modern nuclear physics.

References

[1] Geoffrey L Greene and Peter Geltenbort. The neutron enigma, Apr 2016.

[2] David Bowman, Leah Broussard, S. Clayton, M. Dewey, N. Fomin, Kyle Grammer, G. Greene, P. Huffman, A. Holley, G.L Jones, C.-Y Liu, Mark Makela, M. Mendenhall, C. Morris, Jonathan Mulholland, K. Nollett, Pattie W., Seppo Penttila, M. Ramsey-Musolf, and Andrew Yue. Determination of the free neutron lifetime. 10 2014.

[3] Glenn Jocher, John Koblanski, Viacheslav Li, Sergey Negrashov, Ryan Dorrill, Kurtis Nishimura, Michinari Sakai, John Learned, and Saeeda Usman. mini-timecube as a neutron scatter camera. *AIP Advances*, 9:035301, 03 2019.