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Reconstructing a Dilution Refrigerator for use in Low Energy Nuclear Experiments

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The Gerasimov-Drell-Hearn (GDH) sum rule states that the difference between the parallel and antiparallel cross sections of a circularly polarized photon hitting a longitudinally polarized target is proportional to the square of the anomalous magnetic moment of the target. We plan to use the GDH sum rule to study the nuclear structure of the deuteron. To do that, we put our target material into a Frozen Spin setup, made possible by a dilution refrigerator originally constructed at CERN in the 1970s. However, when a leak was discovered in a critical part of the dilution unit, we had to remove it. This talk will discuss the reconstruction of this dilution unit, what still needs to be done, and how the experiment will be run.

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1. Physics Motivations

The Gerasimov-Drell-Hearn(GDH) Integrand is a sum rule used to relate the cross sections of a target with its anomalous magnetic moment. At the time of its formulation, it was more of a novelty than anything useful. But, as accelerator facilities advanced, it became possible to test this rule experimentally. It started with the GDH value of the proton, which was found to be in agreement with the theoretical value given by the GDH. However, when researchers at the Laser Electron Gamma Source (LEGS) attempted to use it on the neutron, they found a 10 percent difference between the experimental value and the value predicted by the GDH. The method used to measure the GDH value of the neutron was indirect, since a free neutron is unstable, and therefore unfit to be used as a target. Instead, they used a deuteron target and used the experimental data from that to derive a pseudo-experimental value for the GDH integrand of the neutron. The way they did that was use the ratios of certain reaction channels to determine what the neutron value would be. For example:

$$\frac{p(\gamma,\pi^+)}{d(\gamma,\pi^+)} \rightarrow \frac{n(\gamma,\pi^-)}{d(\gamma,\pi^-)} \tag{1}$$

They could find the ratio of how often a proton would emit a π^+ over how often a deuteron does it, and use it to infer how often a neutron would emit a π^- given the rate at which a deuteron does it. However, due to that discrepancy, they had a lot to think about. Given that the GDH is derived from well-established theories and principles, there should not be anything wrong with it unless there is something wrong with its origins. However, that is extremely unlikely, so they decided to look in another direction.

$$\int_{\nu_{Th}}^{\infty} \frac{\sigma_P - \sigma_A}{\nu} d\nu = \frac{4S\pi^2\alpha\kappa^2}{m^2} \tag{2}$$

Here, we have the GDH integrand written out with $\sigma_P(\sigma_A)$ being the cross section of the target with polarization parallel (anti-parallel) to the polarization of the beam, ν being the energy of the photons in the beam, S is the spin of the target, α is the fine structure constant, κ is the anomalous magnetic moment, and m is the mass of the target particle. In order to understand the discrepancy, they expanded out the integrand into three parts:

$$\int_{\nu_{Th}}^{\nu_\pi} \frac{\sigma_P - \sigma_A}{\nu} d\nu + \int_{\nu_\pi}^{\nu_{max}} \frac{\sigma_P - \sigma_A}{\nu} d\nu + \int_{\nu_{max}}^{\infty} \frac{\sigma_P - \sigma_A}{\nu} d\nu \tag{3}$$

For the deuteron, ν_{Th} is the threshold energy for the first inelastic channel, which in this case is the photodisintegration of the deuteron, ν_π corresponds to the photon energy where pion emission starts to happen, and ν_{max} is the maximum energy available to researchers. The second term was explored in detail by them, so if the GDH is unlikely to be flawed, and the second term in the equation was the subject of interest for the experiment at LEGS, that just leaves the first and third terms. For our upcoming experiment, we plan on focusing on the first term. The reason for this is because the third term is a high energy term, and any channels in this region will have their contributions reduced by the $\frac{1}{\nu}$ factor in the integral, and therefore not be enough to explain that discrepancy. Therefore, the most likely explanation lies in the first term, where there might be some inelastic channel between photodisintegration and pion threshold.

2. The Dilution Refrigerator

In order to run this experiment, we need to achieve the best polarization possible. For our experimental setup, we will use a dilution refrigerator, microwave system, and a superconducting magnet. Data will be collected with the aid of 88 liquid scintillators held in a frame called the Blowfish. The dilution refrigerator stays with us at UVA where we do practice runs, or "cooldowns" with it. The cooldowns have three main purposes; it allows us to practice for the experiment, we can check on how it is functioning to see if anything needs to be fixed, and as a way to fine tune the $\frac{^3He}{^4He}$ mixture we plan to use for the experiment. A cooldown starts when liquid helium is introduced into the fridge. The liquid helium begins to cool the fridge from room temperature as it circulates through the system. As the temperature lowers, the liquid helium starts through the evaporator. The evaporator is a simple tub that is sealed and pumped on by our pump stack. The pumps suck out the more energetic helium atoms in the bath, and cool the bath below helium's boiling point, to about 1K. The 1K bath cools the insides of the fridge even more and prepare it for the next step in the dilution process. Once the fridge is cold enough, ^{3}He is introduced into the system and circulated. The gaseous ^{3}He is directed by pumps into a heat exchanger where it is cooled by liquid ^{4}He and eventually condenses into liquid. The heat exchanger then enters the 1K bath where it is cooled even further, then enters the still. The still contains a bath of ^{3}He/^{4}He mixture, and cools the incoming ^{3}He down to about 750 mK. It then exits the still and enters the final heat exchanger. The incoming ^{3}He is cooled by the outgoing ^{3}He/^{4}He mixture and enters the target chamber. Here, the fresh ^{3}He sits atop a mostly ^{4}He solution, similar to oil and water. The ^{3}He atoms in the less dense pure phase eventually break through the boundary and enter into the ^{4}He mixture, losing energy in the process. This endothermic phase boundary crossing provides the main cooling power in a dilution refrigerator, and can reach temperatures as low as 25 mK. As more and more ^{3}He atoms enter the ^{4}He phase, the mixture begins to crawl along the surface of the fridge, back to the still. The outgoing mixture is guided by special channels to follow along the heat exchanger, and flows through the sintered copper on the outside of the heat exchanger. The sintered copper help maximize the heat transfer between the two phases. When the mixture returns to the still, it is eventually pumped out and begins the process again. As the dilution refrigerator is running, the target is polarized using the superconducting magnet, and is bombarded with microwaves. The microwaves are at a specific frequency that allows electrons polarized by the magnet to "transfer" their polarization to the nucleon targets through a process known as Dynamic Nuclear Polarization (DNP). Once we reach a sufficient polarization, we turn off the microwaves and the magnet, and place the target into the beam for measurements to begin.

3. History, Modifications, and Current Status

Our fridge was first used at CERN for pion experiments, then sent to the Helmholtz-Zentrum Geesthacht facility in Germany at the end of its initial run. While in Germany, it was planned to be used for neutron experiments. However, in order to prevent any interference with the measurements, it was modified into a supercooled ^{4}He refrigerator. It was eventually sent to us at UVA and we changed it back into a dilution refrigerator. We ran cooldowns with it until November 2017, when we discovered a leak in the still. The only way forward was to remove the entire dilution unit, and rebuild it from scratch. They were first drawn up in SolidWorks, and the individual parts were fabricated by our machine shop. Since everything had to be leak tight, it was extremely important to leak check the assembly every time they were welded together. These leak checks dictated not only the schedule for assembly, but also how the assembly was designed. The assembly had to be leak checked as we went, so that we could spot any problems as we went. We began fabricating parts in 2019, and continued fabricating and welding until we had an incident in June 2021. The welding was flawed, so we had to almost start again from scratch. After some discussion, we came up with some design changes that will make it easier to assemble and prevent any future mishaps:

- Reduce Pumpout OD
- Add feedthrough
- Move still face weld prep
- Add bevelled inlet for ^{3}He line

Going down the list, the pumpout diameter on the old design was a problem for welders because of the close proximity of the welds for the pumpout and the central tube. The central tube had to remain at the same OD due to the final heat exchanger and precautions regarding the beam that will be used in the experiment. However, the cooling power of the fridge is also dependent on the cross-sectional area of the pumpout. So, with this dilemma, we came up with a creative solution: Change the shape of the pumpout's cross section in a way that maintains the cross-sectional area, while allowing for more room for the welders to do their job. The new cross section was shaped like a bean, with the concave side closer to the central tube. However, due to the unusual shape, the pumpout had to be fabricated into halves and welded together. The new pumpout was also given another new design feature: "fangs" on the underside. Since liquid helium has a tendency to creep up walls, the fangs were a deterrent for that phenomenon. They had a long, triangular cross-section with a U-shaped path along the underside. The fangs also helped during assembly, since they were designed to hit the upstream face of the still so that the pumpout would be flush with the Vacuum Layer Can for welding. The other larger bean-shaped cross-section present in Figure 1 is the feedthrough. In the

Figure 1: New Still Design

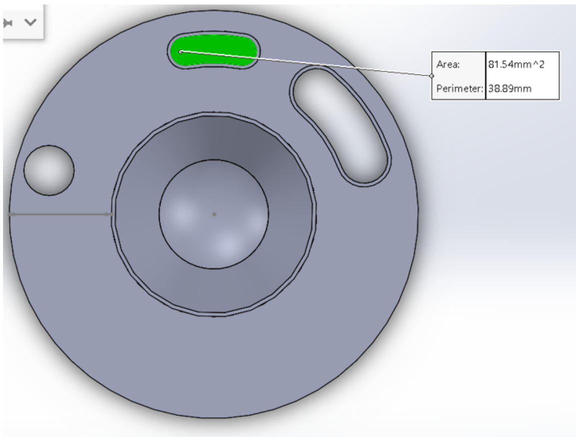
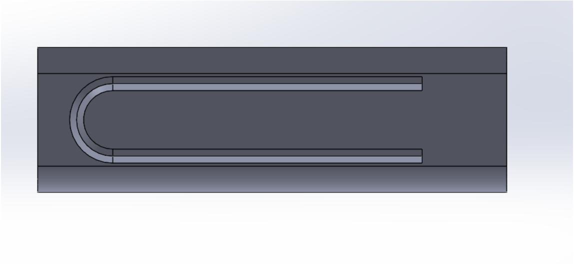


Figure 2: Underside of the pumpout



old design, we planned to just have the wires for the necessary electronics enter the still through the pumpout, in an effort to have less flanges, and therefore have a lower chance of having a leak. However, it was brought to our attention that because it was impossible to have the wires fed through after the welding was finished, therefore exposing the wires to high temperatures. We consulted Chris Keith at Jefferson Lab and he was able to provide us with a simple instruction manual on how to make our own feedthrough. The body is made from Torlon 4203, and is attached to the flange using DP190 epoxy. The body is machined, and conductive material is fed through holes in the body to maintain the electrical connections on both sides. The manual uses resistor leads, but we substituted them for pairs of terminal pins and pin receptacles due to difficulty in maintaining the connections. The wires were soldered into one of the two, and then both ends were connected into the body of the feedthrough. The feedthrough was then filled with the epoxy in order to seal it, sitting overnight as the epoxy hardened. The feedthrough was then added to the dilution unit and held in place with epoxy. The third adjustment was moving the weld prep on the downstream face of the still. In the old design, the weld between the face and the waveguide tube was done on the outside, which was right next to the shelf for the indium seal. When the weld was attempted, the shelf was accidentally hit, making it unable to seal properly. The fix was simple, by moving the

Figure 3: The feedthrough (dark yellow) being attached to dilution unit

weld prep to the other side we could avoid making the same mistake twice. The other change we made was adding a bevelled inlet for the ^{3}He line. Like the wires for the electronics, this change was made to make it possible to add the line after the welding was completed. This change would allow us to feed the line through by feeling for the hole since we would not be able to have eyes on it.

4. Getting the unit ready

With the changes to the design done, we were able to finish welding the redesigned unit in January of 2022. After that, we began to add the electrical connections and the ^{3}He line. We got the line into the unit and tested it with a cooldown in February. We were able to show that the unit was circulating liquid helium, meaning that the unit was a good fit and that the line was good. We then focused on setting up the electrical connections; installing the feedthrough, mapping the connections, and attaching the components. Once that was done, we began leak checking the final heat exchanger from the old unit. We made some flanges and attached them to our leak checker and waved helium around it. We found some blockages in a few areas and were able to remove them with a soldering iron. We then leak checked each segment of that line, and reassembled it.

References

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