Neutron Electric Dipole Moment

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1 Introduction

Past prototypes of the Cosine Theta coil have exerted some groggy faults in its design. Gabija Ziemyte created a prototype that would eliminate the issues created by grooves. Her design encapsulates the copper wiring's diameter and allows for easy replacement if a wire faults. The goal of this project is to use computer aided design (CAD) to design a plastic "arch" like encasing that embodies Ziemyte's idea. We will then use the mapper robot to measure the magnetic fields and compare it against what we anticipated.

The observable universe is composed of mainly matter. In the early seconds after the Big Bang, equal portions of matter and antimatter were buzzing around an extremely hot and dense universe. Considering the laws of physics, matter and antimatter are created and destroyed together. This should have consequently left us with nothing but pure energy. A tiny portion of matter -or about one particle per billion to be exact- fought triumphantly over antimatter and is what composes the observable universe. Theoretically, the symmetry between matter and antimatter is known as CP. If nature treated matter and antimatter alike, then nature would be CP-symmetric, thus we, nor the observable Universe, would not exist. Since nature did not treat matter and antimatter alike, CP was violated.

2 CP Violation

CP violation, in particle physics, is the violation of the combined conservation laws associated with charge conjugation (C) and parity (P) by the weak force, which is responsible for reactions such as the radioactive decay of atomic nuclei. (C) is a mathematical operation that turns a particle into an antiparticle with reversed momentum but identical spin. (P) like a mirror, reverses the direction of the particle but preserves its spin. (C) and (P) symmetry was discovered in 1967 by Cronin and Fitch. In later years, Andrei Sakharov tried to make reason of why the visible universe appeared to be almost entirely matter even though equal quantities of matter and antimatter should have been produced in the Big Bang. He established that for asymmetry to occur, three necessary conditions, called the Sakharov conditions, must be met. Amongst the 3 conditions, Sakharov realized that CP violation was necessary to convert antimatter to matter without it converting back in equal amounts. Because of CP theorem, if there is a CP or (P) violation, then there is also a time reversal symmetry T violation. (P) violation occurs when the rate for a particle interaction is different for the mirror image of that interaction. Electromagnetic and strong nuclear forces have the same strength for left-handed and right-handed particles. So parity is a good symmetry for these interactions and is said to be conserved by them. Obtaining a non zero (nEDM) would in theory provide evidence of a (P) violation and time reversal invariance violation that leads to CP violation. So far, a non zero $nEDM$ has not been found. Its important to note that CP violation has been observed in the quark sector but, the measured amount is insufficient to explain the observed matter-antimatter asymmetry.

3 Neutron Electric Dipole Moment

The Neutron Electric Dipole Moment (nEDM) is a minuscule separation of electrically charged quarks within a neutron, that is used to measure the distribution of positive and negative charge. It behaves differently in a mirror reflected world (parity symmetry) than in one where time runs backwards, because $d_n = \vec{d} \cdot \vec{\sigma} = q\vec{r} \cdot \vec{r} \times m\frac{d\vec{r}}{dt}$. Parity is violated because when $P : \vec{r} \to -\vec{r}$, d_n is also reversed, and time reversal is violated because $T : t \to -t$ the same thing happens.d_n is the observable EDM range of frequency. $\vec{d}$ is the EDM vector that is not measured. $\vec{\sigma}$ Sigma pertains to the spin or angular momentum of a neutron. $q\vec{r}$ q is the charge of quarks and $\vec{r}$ is how much is being separated. $\cdot$ is the vector dot product, or in other words, length of vector a $\times$ length of vector b. $\vec{r}$ is how far off center you are. Lastly, $m\frac{d\vec{r}}{dt} = P$ where P is momentum or mass times velocity.

Neutrons have a hypersensitivity to magnetic fields. These magnetic fields must however be very uniform and precise in order for the neutron to engage in precession. Nuclear Magnetic Resonance (NMR) can measure that Electric Dipole Moment (EDM)—or the strength and orientation of that charge—. When the radio-frequency field is turned on for a short pulse, all of the neutron spins are tipped perpendicular to the field and begin precessing. The amount of precession is measured with He-3 atoms. Then the NMR sensors are able to detect the energy released as the protons realign with the magnetic field. It is important to note that when a neutron precesses, it does so at an angle. A medical application of NMR is Magnetic Resonance Imaging, or commonly known as (MRI).

4 Projected Procedure

During the first couple of weeks, I have read countless articles to help better understand the topic. I have learned about different programs such as Overleaf, Python Coding, and Matlab. I conducted an experiment with a group of peers that taught us how to take precise and accurate measurements by working with a pendulum. I studied the past research conducted by our fellow peers and looked at new avenues of approach. The current plan of action is as follows:

1. Using Autodesk Inventor app, Hena Kachroo and Christopher Delcher will design a model made of resin that will combine their new design along with Gabija Ziemyte's design. This design will be composed of 4 skins that will attach to a metal cylinder via pegs. The skins will have hollow indentations —referred to as grooves— that will enclose the cooper wiring and allow such to clip in. This design feature will evade the past flaw of the cooper wiring shifting out of place. 2. We will then use MATLAB along with a formula to predict the exact magnetic fields and annotate the collected data. 3. We will test the coil by using a power supply to run 2 amps of current through and measuring the field using the Physics Toolbox; Magnetometer feature. 4. We will then compare what we had predicted to the mapper robot's measurements from MATLAB.

The significance of this project heavily relies on the fact that neutrons can be manipulated through uniform magnetic fields. This magnet with precise field lines will be used in further research projects to try and obtain a non zero nEDM moment.

5 Mapping Magnetic Fields

How do you map a magnetic field? I remember in science class simply drawing out field lines. The professor explained that the closer the field lines are, the stronger the field is at that point and respectively, the farther out, the weaker it was. I started this project with the expectation that it would be very easy. I wanted to visualize magnetic field lines and found a video that showed that by using iron shavings and a magnet, we could actually see the magnetic field lines. However, we did not have access to this at the lab. Instead we opted to first learn how to take the measurements ourselves, and later, using MATLAB to do so for us.

I began by getting familiarized with the tools I'd be using such as:

1. Agilent power supply that allows you to turn the output on or off and toggle the amount of current.

2. A multi-meter to measure the resistance in Ohms of the cooper wires.

3. A magnetometer via Physics Toolbox phone application. I found the sensor on my phone by using a steel wire and moving it around until the fields were 0.

I then stripped the enamel coating off the Cosine Theta coil and connected it to the power supply. I turned the power supply on, placed my phone in the center of the magnet and toggled the current between 0 and 2. I observed as the relationship between the magnetic field vs time shifted respectively. After understanding how everything worked, I moved into the actual project with my partners Kachroo and Delcher.

Along with the help of Dr. Crawford, We established the different measurements we would be taking. We decided that X pertained to the left, right and center alignment. Y pertained to the displacement of measurement points. Z pertained to the low, mid, and high levels. During the first trial of data gathering, we were eyeballing the calculations and were not getting exact measurements. We had marked the points inside the Cosine Theta coil with a ruler. This wasn't effective because we couldn't pinpoint the exact positioning of the phone with relation to the marking and, it was hard to manipulate the wiring without moving it out of place. We also used different books for height. These were not equal in height and we realized that we were unable to displace 3 points of measurements of X at the low and high level. Furthermore, the data was all over the place. We were measuring the points, then giving a rounded number at each displacement. This data gathered in trial 1 was not used due to the variable inconsistencies.

The second time around I worked by myself. I decided to completely redesign the experiment set-up. I found a hollow casing cover belonging to a multi-meter that accommodated the Cosine Theta coil perfectly, whilst keeping it free from range of movement. I measured the Cosine Theta coil's diameter and determined the best places to get Z measurements (low, mid, and high level) were equally spaced out to 1 inch. I then found a 1/16" thin cardboard material and placed it in front of the Cosine Theta coil. Using a ruler, I measured 1/2 inch from the front of the coil and made a line where the phone aligned to collect Y points. I did this 7 more times ensuring the measurements were spaced out at exactly 1/2" from each other. I established that for X measurements, my phone would be placed to the far left and right corners and, for the center alignment, my phone would align with the origin of the magnet. I secured the components with tape to ensure there were no movement inconsistencies and proceeded to gather data. I found that even then, it wasn't precise or accurate. I was gathering the data points all at once and counting 2 seconds in between each point before I moved on to the next. The data was contaminated with the shifting factor each time we shifted from one point to the next. This is when I decided to use the magnetometer app's recording feature. The great thing about this feature is that it gathers the data for you and expedites it in an Excel spreadsheet. I got the idea to take one single measurement at a time and record the data.

Once I discovered this, I made a table on Excel that was divided into 3 sections: low level measurements, mid level measurements, and high level measurements. In each section I labeled the 6 columns x,y,z,Bx,By,Bz. X,Y, and Z all pertained to the measurement placing I established above, and the Bx, By, and Bz pertained to the data collected from the magnetometer app respectively. At each point, I placed my phone for 5 seconds and recorded the data. Since the data changes every millisecond, each column was averaged for a final number. Around this time, I also discovered that background noise existed in our measurements . In order to account for this, I shut down the power supply and measured the earths magnetic field at 3 displacement points in all 3 levels. I then averaged these totals and subtracted them in MATLAB. This is how I got the final measurements for the magnetic field.

6 MATLAB's Magnetic Field Calculator

MATLAB is a programming platform designed specifically for engineers and scientists to analyze and design systems and products that transform our world. MATLAB is considered to be one of the easier platforms to use containing one of the simplest coding languages. After gathering all the data, I placed them on a separate Excel spreadsheet called Data1.csv. I then prompted the program to read the data and assigned the data a variable $d = dlmread('Data1.csv')$. The next step was to multiply the first 3 columns by 25.4 to convert them from inches to millimeters $d(:, 1 : 3) = d(:, 1 : 3) * 25.4$. We then needed to subtract the background noise so we set the variable $bkg = [-11.51242285 - 18.08695719 - 39.96819748]$, and $x = d(:, 1); y = d(:, 2); z = d(:, 3)$. After establishing these variables, we moved on to subtracting it by inputting $bx = d(:, 4) - bkg(1); by = d(:, 5) - bkg(2); bz = d(:, 6) - bkg(3)$. We then created our first figure which contained my measured values $figure(1); quiver3(x, y, z, bx, by, bz)$. After this, we wanted to see what the calculated data points would look like compared to the measured ones. We ran a file created by Dr. Crawford for this specifically $c = dlmread('coil_point.csv')$. We then counted the amount of loops (or coils) in the magnet and totaled it to 15 and multiplied by 25.4 to convert from inches to millimeters for n=1:15 coiln=reshape(c(n,3:end),3,5)*25.4; end. We created a grid $grid = d(:, 1 : 3)'$ and a $bc = bfield(coil, grid) * -2.0001 * 1000$. We then established the new columns $bcx = bc(1, :)'; bcy = bc(2, :)'; bcz = bc(3, :)'$ and finally made our 3-D figure $figure(2); quiver3(x, y, z, bcx, bcy, bcz)$. These side by side figures let us see an almost identical magnetic field to what was calculated. There was one vector in the measured figure that was not in line with the field but, we can account that to many different factors such as a misreading the data or a wrong positioning of the measurement tools. MATLAB helped us see that we were correctly taking measurements.

7 3D Printing Prototypes

My partner Hena Kachroo was tasked with designing the skin for the Cosine Theta coil. As noted before, precise uniform lines are the main focus of this project. Due to the nature of the double Cosine Theta coil, and the importance of uniformity in the field, the wires must be coiled at specific equipotential lines. One slight shift in the wiring would completely throw off the magnetic field. An aluminum casing —referred to as the skeleton— will be the core of the magnetic field for this project. Using these dimensions, Gabija Ziemyte created the concept of detachable skins. She noted that adding clips in place could help mitigate the risk of shifting. Grasping this concept, the dimensions of the clips are currently being designed and tested individually to fit the wiring before adding them to the skins by Kachroo. She plans on making them big enough to keep the wire in place as it is wound around the skin.

However due to the shape of the skeleton, it was decided the best way to print the skins was in quarter sections. Since the curvature from the inside and outside of the skeleton differ, 8 skins will be printed. 4 to accommodate the inner layers and 4 to accommodate the outer layers. Additionally, adjustments have been made to better the fit of the skin onto the skeleton. For example, pegs on the skin have been made slightly smaller to better fit into the skeleton and will contain mechanisms which allow it to stay latched onto the inner portion of the skin. This will ensure the skin fits tightly onto the skeleton and prevent the uniformity of the field from being disrupted. The skin will also contain a lip to cover the bottom and top of the aluminum skeleton.

Lastly, Kachroo and Dr. Crawford settled on a design for the clips which included adding a trench where the wire would fit into. This trench will hopefully act like a groove and will be attached to a dig-out —which is a small box cut out of the resin skin—. The clip will then sit in this dig-out rather than being directly attached to the trench. This would allow for the clip to be flexible in hugging the wire and adjusting for it to be fit in.

8 References

Cartlidge, E. "Physicists place stringent limits on the neutron electric dipole moment". In: Physics World (2020).

Greene, Geoffrey L., and Geltenbort, Peter. The Neutron Enigma. United States: N. p., 2016. Web. doi:10.1038/scientificamerican0416-36.

Crawford CB, Straley JP. Improved prescription for winding an electromagnet. Rev Sci Instrum. 2021 Dec 1;92(12):124707. doi: 10.1063/5.0063057. PMID: 34972404.