Creating a Uniform Magnetic Field to Detect a Non-Zero Electric Dipole Moment Using CAD

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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

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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 trenches— 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 the grooves. 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.

5.1 Manual Calculation Procedures

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 wires 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.
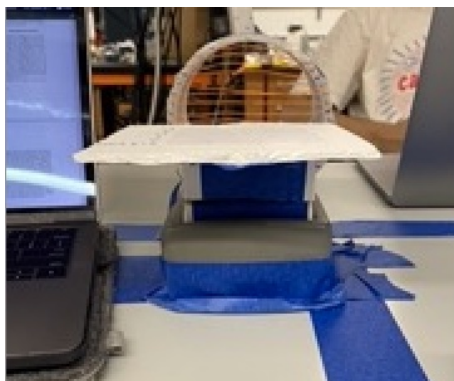

Figure 1: Experiment set-up.

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 were also erroneously estimating and rounding up the measurements given at each point by the magnetometer app. We used different books to manipulate the height (or level) of the measurements. 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 levels. Furthermore, the data was all over the place. This data gathered in trial 1 proved to be inconsistent and not reliable. Needless to say, it was not used due to the variability.

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.

In my second round of data collection, 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 each time we shifted from one point to the next After playing around with the app I found it had a recording feature. This feature allows you to gather and record the data in chunks and, expedites it in an Excel spreadsheet with columns denoting: time in seconds, bx, by, bz and total magnetic field measurements. This is where I got the idea to take one single measurement at a time and record the data for that precise point averaged for a 5 second lapse of time.
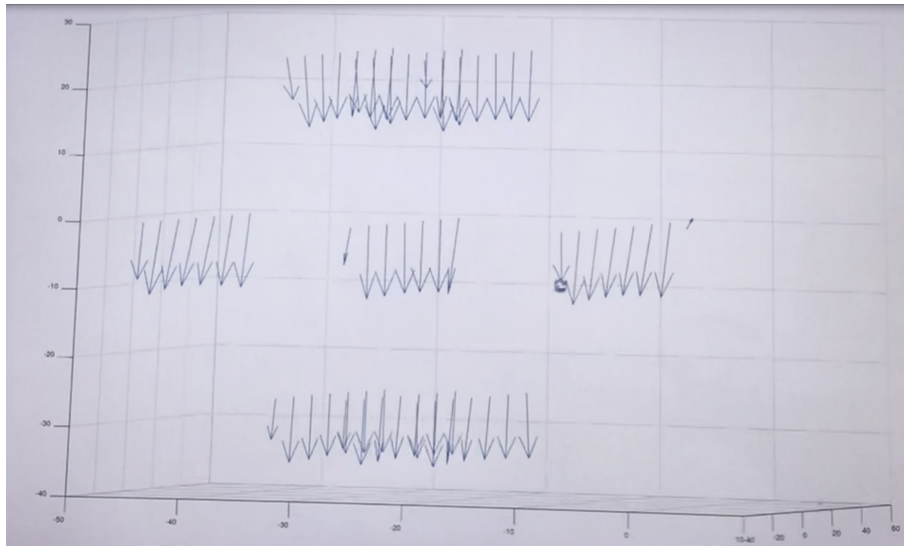

Figure 2: Measured Magnetic Field

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 displayed on figure 1 for the magnetic field.Building the magnetic field on MATLAB for these measurements was a challenge, however after learning how to better navigate MATLAB, I realized it was a very helpful tool.

5.2 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. Although MATLAB is considered to be one of the easier platforms to use containing one of the simplest coding languages, it was a challenge for me since I had never worked with it. 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 $figure(1); quiver3(x, y, z, bx, by, bz)$ pictured above.
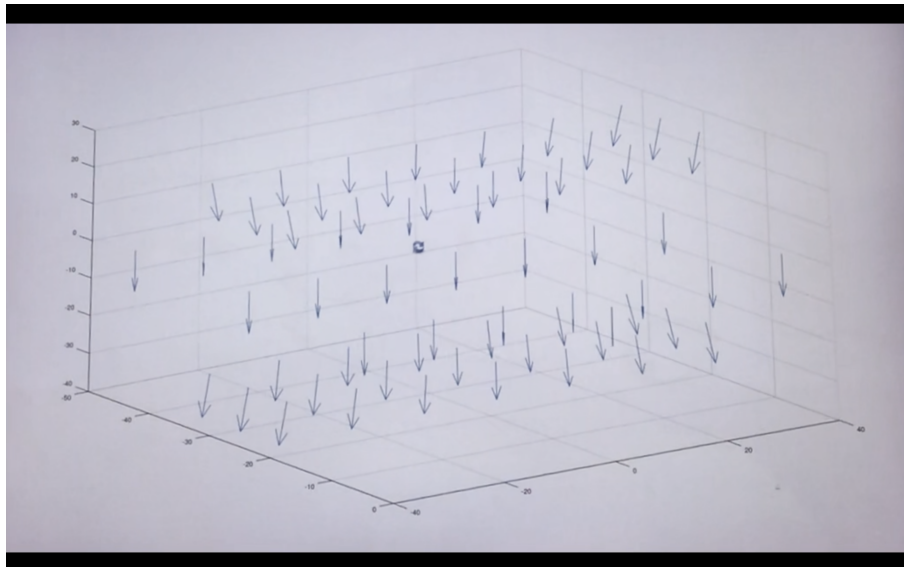

Figure 3: Calculated Magnetic Field

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 $figure(2); quiver3(x, y, z, bcx, bcy, bcz)$ pictured bellow. These figures placed side by side let us see an almost identical measured magnetic field to what was calculated on MATLAB. 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 of the data or wrong positioning of the measurement tools. MATLAB helped us see that we were very close in taking measurements. Comparable to Figure 1, Figure 2 has pretty similar displacement vectors.

6 Computer Aided Design prototype

Kachroo and Delcher were 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.
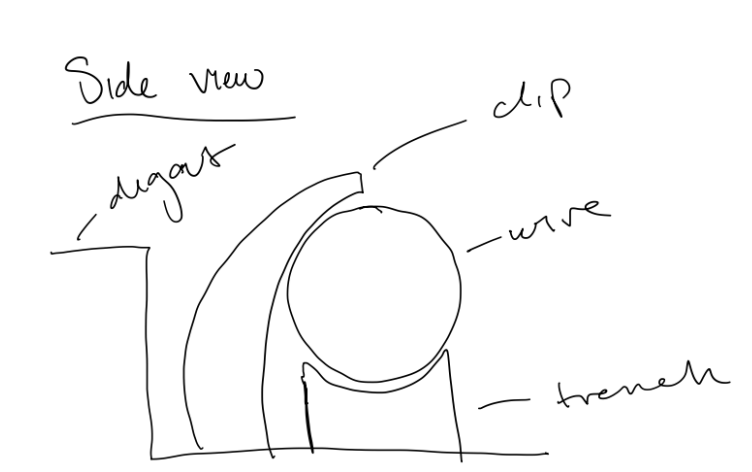

Figure 4: Clip Trench-like Design.

Using the dimensions of the skeleton, Gabija Ziemyte created the concept of detachable skins. She noted that adding clips in place could help mitigate

the risk of shifting. Ziememyte's prototype however, exerted incorrigible issues. Grasping these concepts, the dimensions of the clips were redesigned. In lieu of the past model, grooves were replaced by a trench-like design that corrected the issue with the shifting wires. This trench has a dig-out —which is a small box cut out of the resin skin— where the wire sits comfortably. Above the trench is a hemicirlce that is divided by an opening at the top. This design, although better, still had some issues of itself during testing. If the cut out at the top of the hemicircle is not big enough, the wires get bent and create multiple rogue dipoles that affect the magnetic field. This issue proved to be an easy fix when we discovered that applying pressure to the top of the clip versus the side seemed to correct that problem.
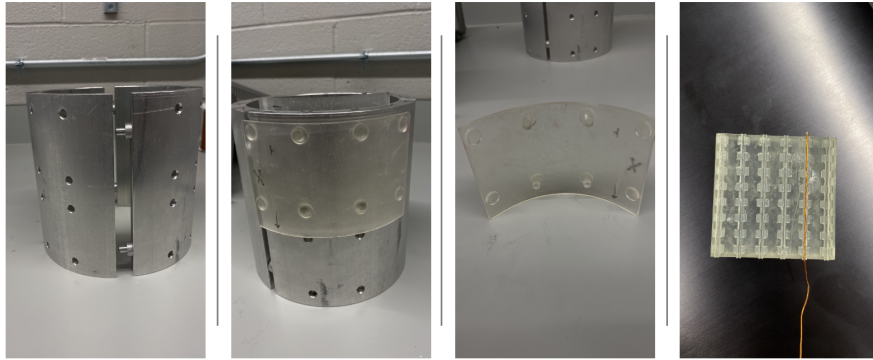

Figure 5: From left to right: The Skeleton, The clip attached to skeleton, The pegs on clips, The clip design.

It was initially decided the best way to print the skins was in octuple sections. This was due to the curvature of the skeleton. Naturally, the curvature from the inside and outside of the skeleton differ. As a result, it had been planned that 12 skins would be printed. 4 to accommodate the inner layers and 8 to accommodate the outer layers. Later, it was theorized that the amount of clips could create slight shifts and disruptions of the wiring, so it was decided that 1/4 sections were a better fit. We noted that in certain prints, the slips would misalign by millimeters. To correct this, the top and bottom clips were submerged together and the aligning of the clips approved our theory.

Additional 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 and angled to better fit into the skeleton. They will contain mechanisms that 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. During testing it was found that the angled pegs ensured a strong grip. The skin will also contain a lip to cover the bottom and top of the aluminum skeleton. This "lip" will also contain the equipotential lines needed. During the last staged of testing, we found that the lip was off-centered by 1

millimeter from the top and the bottom. That was corrected easily through the preforms application.

The 3D printing process has been a lengthy one. We have printed and tested many models. Like the Goldie Locks analogy, some were too small, too big and the final one was just right. We finally came up with a design that combined all the concepts together and passed testing.

7   Saddle Coil Wiring

As part of a sub project, I was tasked with rewiring a cylindrical electromagnet in the saddle coil format. This coil system is optimal when the space available is limited and of cylindrical symmetry. Cylindrical saddle-shaped systems are often used to generate magnetic fields that are perpendicular to the symmetry axis of probes with cylindrical symmetry. Saddle-shaped wiring is often used in high resolution NMR and NMR imaging technologies.
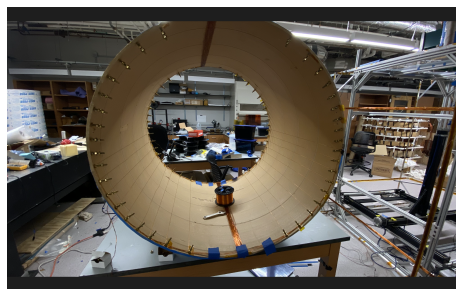

Figure 6: Cylindrical Saddle Coiling

When I first began winding this coil, I did a couple of trial runs with yarn. Using the cooper wiring was more complex and brought its own set of woes. My first actual "run" was wired without using washers in between every set of wires. Consequently, the force acted upon the wires while adjusting the nuts caused one of the wires to fault and break. I spent some time trying to realize why the magnetic field was not picking up correctly. I finally traced it to the broken wire, and rewound the entire coil. This time around, I thought about using washers in between each set of wires. Using these washers helped me locate the wires with more ease and keep track of the direction i was supposed to be moving in. I could also better manipulate the nuts so that the wires were unaffected by the constant adjustment. After about two days of working on this task, I finally picked up a hefty signal. This is when I realized I was moving in the right direction. I quickly noted that the polarity had to be switched around a couple of times due to the components of the saddle coil. Since it is wound in partial hemispheres, the wires must follow the same direction in order to keep the current flow appropriate. Interestingly enough, the polarity was fixed and we had the correct readings for the magnetic field. I spent some time moving the

magnetometer app around and looking at the correlation between the readings and the magnet.

7.1 Using a Robot Mapper to Map The Saddle Coil's Field

Physicist encounter many tools on an every day basis. One of these tools I had the inclination to use was a robotic mapper. This mapper is surrounded by a Helmholtz Coil —which is used to cancel the Earths magnetic field. In the center, there is a long rod with a device attached at the top. This device takes the measurements whilst the rod simply moves in the up or down Z-axis direction in increments of 1 centimeter. The rod is attached to a rectangular motor that moves left, right, up and down in 1 centimeter increments for the X-axis and Y-axis as pictured below. In order to use this mapper, a simple text file must be created where the values of x, y, and z are separated by spaces. This list of commands is then what dictates the mappers movements. Unfortunately due to unforeseen circumstances, I was not able to run the program.

Figure 7: Robot Mapper Diagram

8 Next Steps : 3D Printing

To reiterate, building a uniform precise magnetic field is essential in the discovery of a Non-zero electric dipole moment. For the 3D printing aspect of this project, we are left with several adjustments to be made. The clips on the final design print break easily and are difficult to wire; the design should be altered in some way. Additional clips can be added to surround the trench and stabilize the structure. Completion of the design for the skins that will line the inner walls of the skeleton to include aligning the clips based on the equipotential lines. Adjustments of the skin curvature based on the skeletons dimensions will also need to be done. Finally, wind the coil and map the magnetic field using the robotic mapper.

9 Next Steps: Saddle Coil

For the next steps in the saddle coil, it is important to run multiple test. Using the file I wrote, the magnetic robot mapper can be used to determine the magnetic field. Following that, we must determine if that magnetic field will work with the future projects the coil will be used in. Further adjustments may possibly have to be made to the design and placement of probes. Finally, the coil is also surrounded by some form of Mu Metal. At the testing stage, we need to ensure it does not disrupt the intended field.

10 Acknowledgements

11 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.

Hanssum, H. "The Magnetic Field of Saddle-Shaped Coils. I. Symmetry of the Magnetic Field around the Coil Centre." Journal of Physics D: Applied Physics, vol. 17, no. 1, 1984, pp. 1–18., https://doi.org/10.1088/0022-3727/17/1/006.

Bouquerel, Elian. "CP Violation." ESSNUSB, 12 Apr. 2018,
https://essnusb.eu/glossary/cp-violation/.
Sather, Eric. The Mystery of the Matter Asymmetry - SLAC.
https://www.slac.stanford.edu/pubs/beamline/26/1/26-1-sather.pdf.