Designing a Uniform Magnetic to Help Detect the Electric Dipole Moment of a Neutron

Christopher Ian Delcher

July 13, 2022

1 Introduction

The breaking of time symmetry in particle systems is essential in uncovering the secrets of the early universe. Evidence of breaking time (T) invariance may help explain the abundance of matter over antimatter, or the Baryonic Asymmetry, of the Universe. If the T symmetry was truly invariant, theoretically, there should exist equal amounts of both types of matter (as Andrei Sakharov realized), contrary to what modern measurements are telling us. Physicists are searching for more evidence of T violations that could lead to an explanation to the aforementioned phenomena [1].

A promising piece of evidence, if can be proven with the development of an extremely uniform magnetic field, would be the electric dipole moment of a neutron (nEDM).The dipole moment results from a subtle separation of the quarks in a neutron, similar to the way a molecule is polarized with partial positive and negative charges. Evidence of a non-zero nEDM violates both Parity and Time symmetries [1]. The separation of these quarks behaves differently in a mirror-reflected world, or Parity symmetry, as well as in one where time is reversed. As my teammate Stephanie Betancourt denotes, this is evident in the equation $d_n = \vec{d} \cdot \vec{\sigma} = q\vec{r} \cdot \vec{r} \times m\frac{d\vec{r}}{dt}$. Parity symmetry is violated when $P : \vec{r} \to -\vec{r}$, so d_n is also reversed. Time invariance is violated because $T : t \to -t$, so d_n, the observable EDM range of frequency, becomes reversed as well. $\vec{d}$ is the EDM vector that is not measured. $\vec{\sigma}$ represents the spin or angular momentum of the neutron. In $q\vec{r}$ q is the charge of quarks and $\vec{r}$ presents the level of separation in respect to the center. Lastly, $m\frac{d\vec{r}}{dt} = P$ where P is momentum. These inconsistencies make the nEDM a potential piece of insight to the antimatter-matter imbalance in the universe.

Because the nEDM would be magnitudes of times smaller than the tiny neutron itself, a uniform magnetic field is imperative to highlight any possible resulting disturbances in the field. Even an extremely minuscule difference of 1 fT in a less uniform field can imitate the signal for a non zero nEDM [1]. Therefore, the design of these types of magnetic fields is one of the most important aspects in the search for an electric dipole moment in a neutron. However, this type of testing would be severely limited with the electromagnet currently designed [3]. Our project seeks to improve upon this electromagnet and test the magnetic fields associated with our designs so that they can be effective in future nEDM detection experiments.

2 Procedure

Our research is composed of two main parts. The first is to develop a design through computer-aided design (CAD) to improve upon a faulty design of the electromagnetic coils. The second part is testing, mapping, and comparing the strengths of the magnetic fields of multiple coils.

2.1 CAD Implementations

The electromagnet has an sturdy, aluminum skeleton, which a resin-printed ”skin” will envelop. The current model, which uses only grooves to hold the wire in place, does not do its job ably [3]. This results in a much less uniform magnetic field compared to when the wires are tightly secured in a confined space. A coil clip design has been provided to us, and it is our goal to implement this design with the preferred blueprint of the magnet that will be used in the nEDM experiments [3]. We will use either Fusion 360 or Inventor Pro to produce testable prints for the aluminum skeleton.

2.2 Testing and Mapping the Magnetic Field

In a nutshell, to detect a nEDM of 10^-23 cm we would need a magnet with a level of uniformity of

$$\frac{\Delta B}{|B|} = \frac{10^-7}{cm}$$

where B is the magnitude of the magnetic field [2] This will be taken into account in our testing and mapping. To mimic the geometry of the double cos theta coil that will be used for measuring the nEDM, we will wind copper wire around non-conducting skeletons of various sizes. Each point at which the coil sharply curves upwards or downwards along the cylinder will be mapped as a coordinate point using trigonometry (the “circle” of the cylinder acting as a unit circle). Since all designs will be cylindrical, the points can be mapped in respect to the center of the cross-section at the very bottom of the shape (x = 0, y = 0, z = 0). Given a previously developed program in MATLAB, we can then input these points as arguments in a function to find the strength of the B field at a given point on the cos theta coil. The coils should be wound along the equipotential lines of the magnetic field to produce the expected B field in the equation, which can be calculated with a magnetic scalar potential equation [2]. The theoretical values are to be compared with the experimental value measured using a magnetometer. By constantly testing and comparing, we can determine an optimal structure for the winding of the coils around the final magnet.

3 CAD Components for Electromagnets

A critical element of the process in building and testing electromagnets to assist in detecting the nEDM is knowing how to use CAD software. Popular applications include Autodesk Fusion 360 or Autodesk Inventor Pro. 3D resin design are printed using the former. Regardless of the fact that resin designs are being printed to fit the exact dimensions of the aluminum skeleton provided, the basic functions of the designs can be applied to any shape or type of electromagnet and wire.

For the aluminum cylinder, these designs include eight ”skins” that fit the curvature of the skeleton. On these skins, dugouts will be engraved onto the surface where the clips for the wire will lie. The clips consist of a rectangular base that has a curvature on which the wire will lie (also known as the ”trench”) as well as two lips that curve atop the wire to keep it in place. This design is shown below:

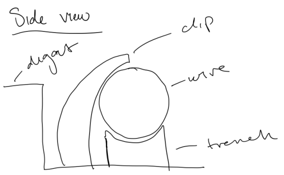

Figure 1: Clip Design

The dimensions of the clips will vary based on the gauge of the wire. Dimensions for 20 Gauge and 24 Gauge wire were calculated to be 0.34 mm and 0.55 mm in diameter, respectively. The designs for the trench should account for the size of the wire and should be adjusted to have large curvature than the cross section of the wire given its diameter. This is simply to allow for it to rest comfortably on the trench. On the contrary, the two clips (only one is shown above) should be at distance that is *less* than the length of the diameter. This is so that the wire is securely held in place. If the distance was the same or greater than the wire’s diameter, it would not be as stable while being held. Given this, the base of each clip must be thin enough to offer enough flexibility to have the clip move from its fixed position to allow the wire to enter. These dimensions are still in the process of being measured.

Once all of the clip components are measured, printed, and tested, they can be added onto the skins for the aluminum cylinder through Fusion (or another CAD Application). Once one complete skin included with the clips on the surface is fully designed, eight can be printed and cover the aluminum skeleton. At this point, the magnet will be prepared to be wound and tested in MATLAB.

4 B-Field Mapping Simulation Set Up

Before mapping the b-field vectors and strength using the completed magnet, it is best to be acquainted with the experiment process through running a simulation. For our simulation of the B-field vector mapping, we wound an already-printed resin cylinder with grooves along the sides in the form of a cos-theta coil. For measuring the strength of the field for the simulation, an application called Physics Toolbox Magnetometer was installed on my teammate's cellphone, which reads changes in the B-Field relative to the defined axes on the phone. The measurements are taken at every millisecond and are very precise for a mobile application. Since this a simulation of the final project, we accepted the experimental error that this measuring device brought.

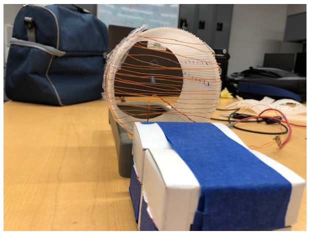

Figure 2: Cos-Theta Coil: Simulation Set Up

4.1 Measuring With Axes

Placed on its side with its circular plane facing towards us, the dimensions of the cylinder can be defined by the three axes x, y, and z. In respect to this configuration of the coil's circular face, the horizontal plane corresponds to the x axis, the vertical plane to the z axis, and the plane perpendicular to the circular face going into the cylinder is the y axis.

It is important to note that the z axis is divided into evenly spaced units of distance, d (they can arbitrarily defined and are only used for convention). The diameter of the cylinder is 0d; everything below the diameter is, counter intuitively, increments of positive d. Everything above the diameter is the negative d increments. The z axis is split up into designated points of low, medium, and high heights relative to the bottom of the cylinder. These conventions are given the values -1, 0, and 1, respectively, which are equally spaced out to an inch. The magnetometer is then aligned with the corresponding values by placing the cell phone on top of small boxes one inch in width as shown above (one box for -1, two boxes for 0, and three boxes for 1).

The y axis (plane going into the cylinder), is split into increments of 1/2 inch along the inner side of the cylinder. The cell phone's magnetometer can be carefully placed at these designated points using a crude measurement device as in Figure 3. The cell phone's built-in magnetometer reader would be y inches into the cylinder when the bottom of the phone is at the y mark on the device.

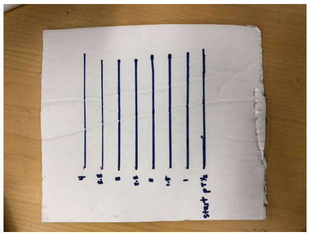

Figure 3: Incremental Measurements for Y Points

Finally, the x axis is separated into qualitative increments, with the magnetometer sensor either to the far left, far right, or exactly in the middle in respect to the center of the circular face. With these values defined at each of the axes, one can begin to plot points and gather data for B-Field strength calculations.

4.2 Gathering Data

Using the right hand rule, and given the orientation of the electromagnet as shown above, the B-field vector travels vertically, pointing downwards. Instead of measuring the B-field produced by each individual coil due to the inefficiency of measuring so many points, it made more sense to measure the B-field produced by all the coils at individual points within the cylinder. These points are determined using the axes discussed in the previous sub-section. The cell phone's magnetometer is placed into the magnet, perpendicular to the B-Field vector, at each of the defined points inside the coil. For example, the magnetometer would read all the y points along the inside of the coil at z = -1, and at the x point corresponding the far right. It would continue measuring each of the y points along the inside for each combination of x and z.

The Physics Toolbox Magnetometer application has a built-in function that records the data for the b-field strength at the axes of the phone for five seconds. The app then puts this data into a document that can be edited (Note: the phone's axes are *not* the same as the axes of the coil; we'll call these bx, by and bz). These values of bx, by, and bz collected for five seconds are the data for one point on the axes of the *cylinder*. Since the magnetometer detects in increments of 1 millisecond, the abundance of bx, by, bz data points in the five-second reading are each averaged. The process must be repeated for all y points along the inside of the cylinder at every combination of z and x points.

Given the average bx, by, and bz data for each point in the cylindrical coil, we can start to organize it into an Excel Spreadsheet. This data is categorized in the spreadsheet by z point first, then by x point, then finally by y point. The averaged bx, by, and bz data is included here. Once the data has been gathered, it can be entered as arguments into a script in MATLAB to get a more precise and theoretical calculation of the magnetic field in the cylindrical coil.

5 References

[1] Crawford, C. ”Robotic Mapping of Magnetic Fields in a Magnetically Shielded Environment”. In: KY NSF EPSCoR PROJECT DESCRIPTION.

[2] Hunter, B. Spencer, L. K. and Crawford, C. “Drilling a double cosine – theta coil”. In: University of Kentucky poster presentation.

[3] Ziemyte, G. ”Designing and Winding an Electromagnetic Coil”. In: REU Project Proposal