Magnetic Shielding for Sterile Neutrino Research

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Abstract

Neutrinos are known to be one of the strangest particles under the Standard Model, leading to many unsolved questions about the nature of our universe. One of the more common questions in the realm of particle physics is whether or not sterile neutrinos exist. These sterile neutrinos would not interact with other particles via the weak force which is why they are called "sterile". Sterile neutrinos would lie outside of what we know under the Standard Model of Particle Physics and could explain why the mass of ordinary neutrinos is so small. A project called HUNTER (Heavy Unseen Neutrinos from Total Energy-momentum Reconstruction), has been developed to use electron capture decay in Cesium-131 to search for heavy sterile neutrinos through mass reconstruction. HUNTER uses a combination of laser cooling techniques as well magnetically shielded solenoids and detectors to calculate the kinematics of electron capture decay in a controlled setting. A team at Princeton has specifically been tasked to design the magnetically shielded solenoids to control the motion of electrons in the apparatus.

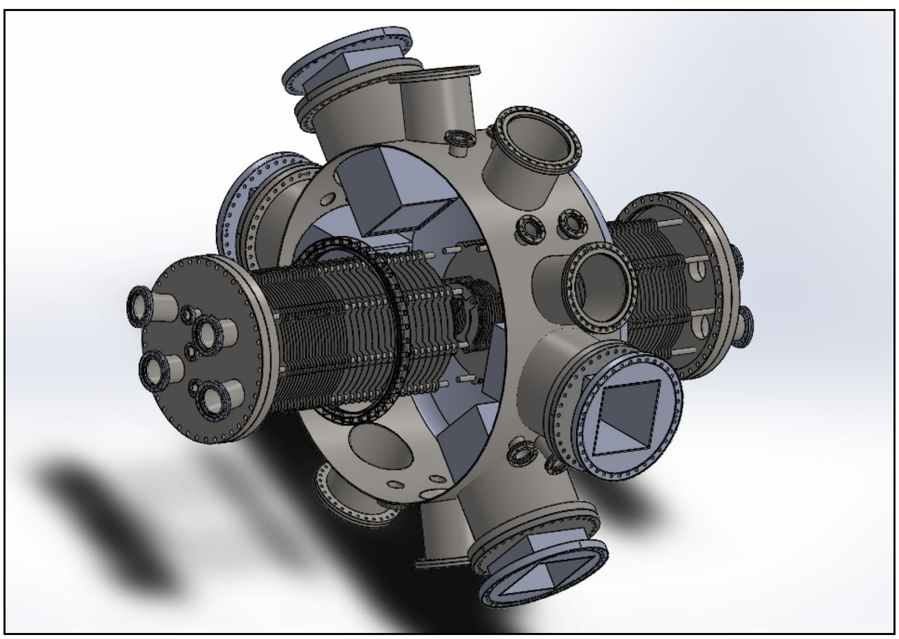

FIG. 1. External view of HUNTER apparatus.

Introduction

Neutrinos are particles with very small mass compared to other particles with mass. There are three types or “flavors” of neutrinos: electron, muon, and tau neutrinos, each described by the particle involved in the type of decay the neutrinos come from. Further research shows that there might exist a fourth flavor called a sterile neutrino. A project called HUNTER (Heavy Unseen Neutrinos from Total Energy-momentum Reconstruction), has been developed to use electron capture decay in Cesium-131 to search for heavy sterile neutrinos. The hypothesis for HUNTER is that if the sterile neutrino exists then it would be heavier than the ordinary flavors. Many other projects have tried to detect sterile neutrinos through other methods, but no other project has used the method of mass-reconstruction through decay kinematics at the level of detail that HUNTER has proposed.

Electron capture decay involves the absorption of an electron from the innermost shell (K-shell) of a Cesium-131 atom by its nucleus. This occasionally happens when a Cesium-131 atom has less neutrons than protons. One of the protons in the nucleus combines with the captured electron to form a neutron and an electron neutrino. This changes the Cesium atom to excited Xenon-131 and is excited because of the missing electron in the K-shell as well as the extra electron in the outermost shell (P-shell) which ground state Xenon-131 does not have. Typically, one of the electrons from one of the middle shells would fall into the place where there is a missing electron in the K-shell. The specific situation that will be recorded is a K-capture followed by an electron falling from a sublevel of the N-shell to the K-shell. An electron falling from the N-shell to the K-shell will produce an x-ray that must be detected. An electron from a sublevel of the O-shell will then fall into the N-shell and produce an electromagnetic wave that is powerful enough to be absorbed by an electron in another sublevel of the O-shell which ejects the electron out of the Xenon-131 atom. This lone electron (Auger electron) must be detected. Finally, the electron from the P-shell falls to take the spot of the electron in the sublevel of the O-shell that fell into the N-shell which produces a negligible amount of radiation. The final product is a Xenon-131 ion which must be detected. The momentum of all the particles that were detected can be used to reconstruct the mass of the neutrino. If the hypothesis that sterile neutrinos are much heavier than ordinary neutrinos is correct then the reconstructed mass should agree with the hypothesis.

The apparatus used to detect the particles consists of a Magneto Optical Trap (MOT), spectrometers, and magnetically shielded solenoids. The MOT is designed to trap the gas of Cesium-131 atoms and cool them down to only a few millikelvin. The mechanism used to cool the atoms uses a technique called laser cooling which involves the use of lasers to counteract the momentum of the atoms which effectively reduces the speed of the atoms and therefore cools them down. The spectrometers are designed to measure where the detected particles landed on the detector as well as the time of flight. Given the constant distances across the apparatus, this information can be used to accurately calculate the momentum of each particle. Magnetically shielded solenoids are used to steer the Auger electrons into the detector and they must produce a uniform 8 gauss field along the axis of apparatus where the electrons are detected. This is not very straightforward as there must be gaps between the solenoids to allow room for other pieces of the apparatus. Magnetic shielding must be placed to prohibit external magnetic fields from disturbing the field inside the apparatus. This magnetic shielding must also be set up so that the magnetic field inside the apparatus does not saturate the magnetic shielding. A team at Princeton

University has been tasked to design the magnetic shielded solenoids and make sure the design is effective. This paper will go in depth about the processes used to design and test the most effective setups for the magnetically shielded solenoids.

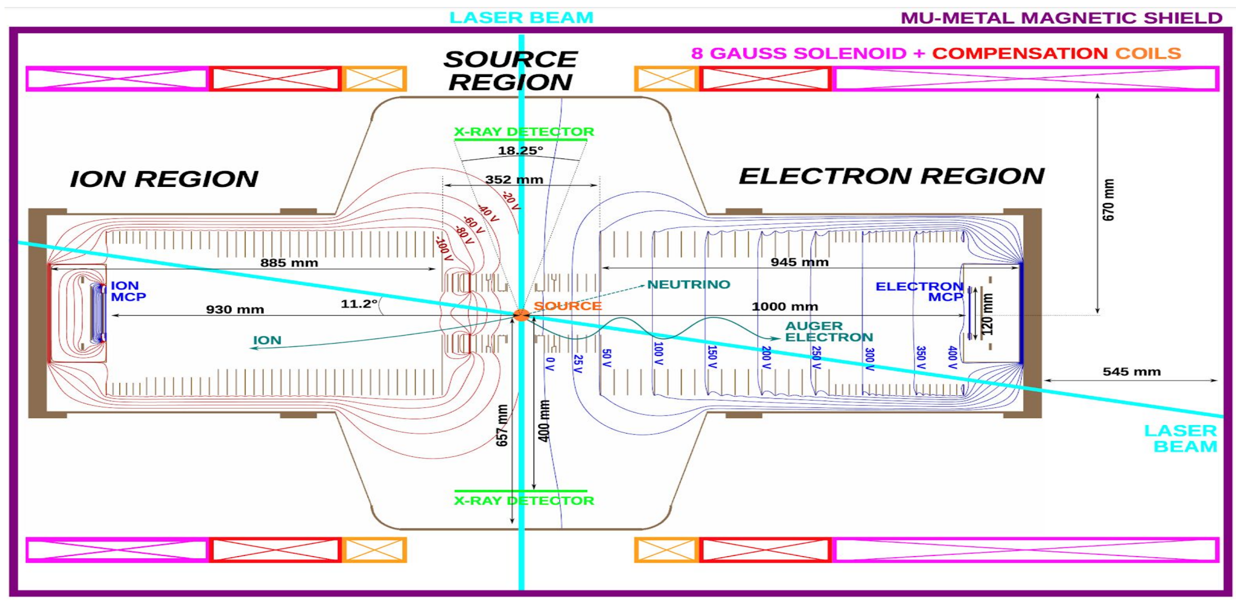

FIG. 2. Cutaway plan-view of HUNTER apparatus.

Methodology

Francesco Granato, a graduate student at Temple University, found that the uniform magnetic field can be produced by setting up solenoids with the necessary gaps between them and tweaking the currents in each solenoid so that a uniform 8 gauss field with uniformity to a few milli gauss is produced along the axis of the electron side of the apparatus. Once the solenoids are set to the right currents, the next step is to magnetically shield the apparatus, however, it will later be found that the solenoids will need to be retweaked to account for changes due to the magnetic shielding. To get a better understanding of magnetic shielding, a better understanding of magnetic materials must first be established. Materials containing iron work the best for shielding like mu metal and pure iron. The program used to simulate the effects of magnetic fields on the magnetic shielding is called FEMM (Finite Element Method Magnetics). This program is 2D and uses a cross section of modeled objects so that all objects must be axially symmetric. We tried different scenarios to get a better understanding of what the best design might be. In most scenarios, there are a few layers of shielding rather than one layer to avoid saturating the shielding material. We tried another program called Radia which links with Mathematica to make full 3D models allowing modelity of more realistic situations.

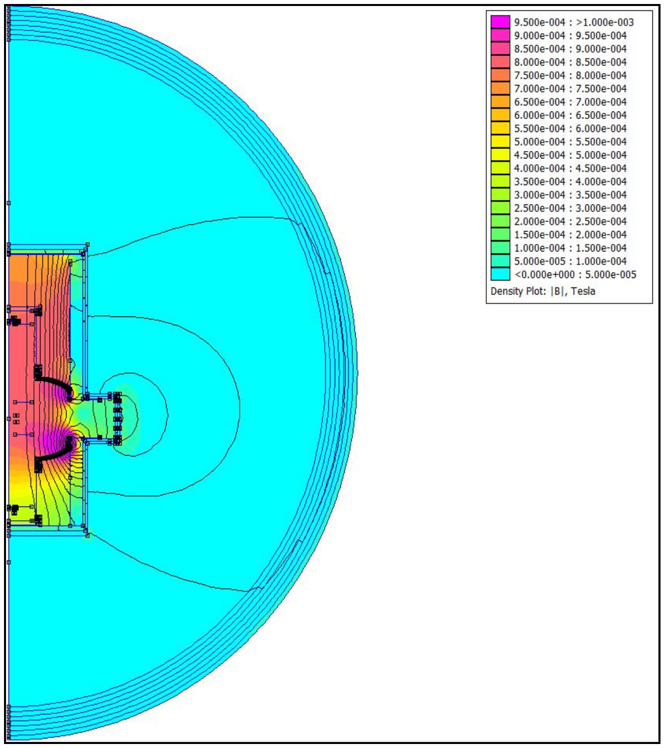

FIG. 3. FEMM Model of cross section of spectrometer with a “mesh” built over the gap.

Results

After experimenting with FEMM, it was discovered that the best setup to protect against external magnetic fields was to completely enclose the apparatus with magnetic shielding. FIG. 4 shows results from placing cylindrical magnetic shielding in a uniform magnetic field of 0.42 gauss and measuring along the axis of the shielding. “None” refers to no magnetic shielding, “Regular” refers to a can of magnetic shielding with a gap in the middle of the can, “Cylinder w/ Gap” refers to a can with no top or bottom with a gap in the middle, “Plates Only” refers to only the top and bottom circles , and “No Gap” refers to a full can with no missing shielding. The results show that “No Gap” reduces the field to near zero which shows that full shielding is the best setup. However, the solenoids inside the apparatus no longer produced a uniform magnetic field which only meant the solenoids needed to be retweaked. This is not difficult to do and is a simple solution to the problem at hand. Unfortunately the apparatus cannot be completely enclosed with shielding as there must be holes in the shielding to allow for wires to reach the apparatus as well as to see what is happening inside the apparatus during the experiment. Tests in FEMM show that any gaps of reasonable size in the shielding can drastically change the magnetic field inside the apparatus. A problem with making this conclusion is that since everything in FEMM is axially symmetric, even gaps in the shielding are built completely around the apparatus when what really needs to be simulated is holes in the shielding. This is when it was necessary to use Radia to get a better understanding, however understanding how the program functions is where there were difficulties. Applying materials to objects in Radia seem to differ a little from how FEMM works. We did comparisons between Radia and FEMM and did not get the same answers, which is an issue if the goal is to get a more accurate understanding of how magnetic fields affect magnetic shielding.

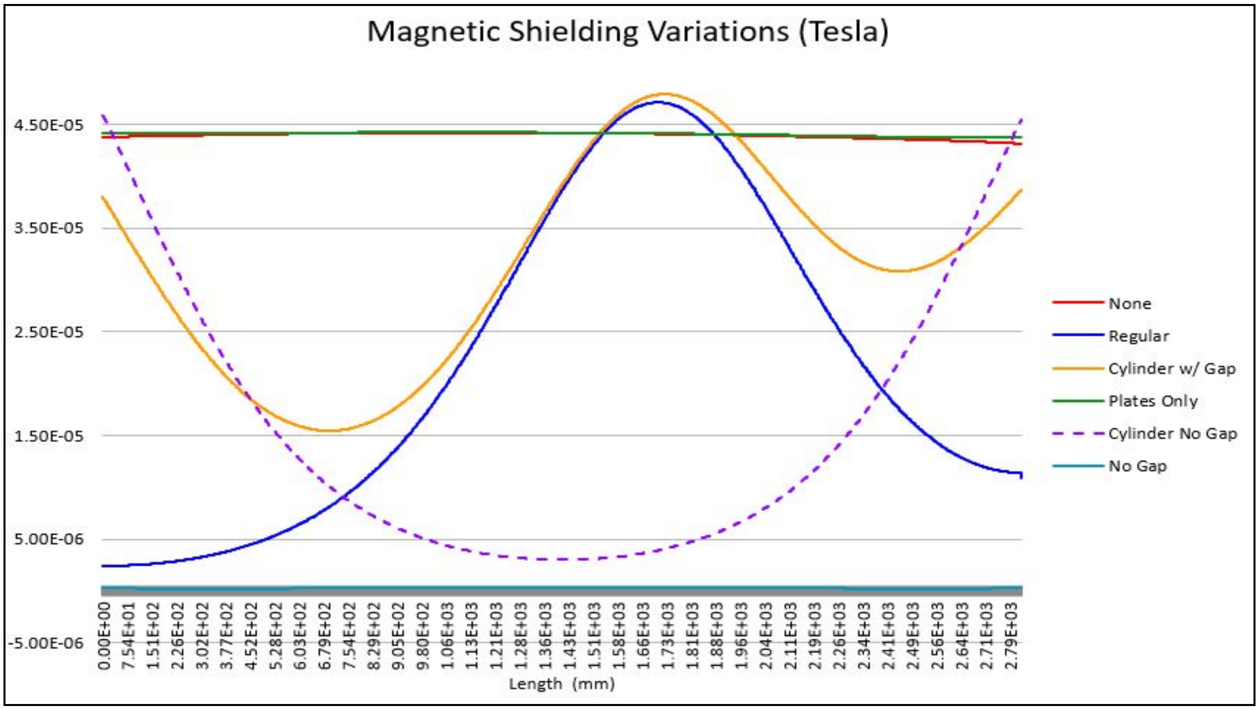

FIG. 4. Magnetic field strength along axis for different variations of shielding tested against a uniform field.

Conclusion

More research needs to be done to ensure that the best possible model is chosen. Current findings show that the variation in the internal magnetic fields due to gaps in the shielding is too large to be ignored. A better understanding of FEMM and Radia might lead to more consistent results, especially with Radia and its ability to model and calculate solutions in three dimensions. One idea that was proposed to help reduce effects from external fields was to put a mesh made of magnetic shielding material over the holes in the shielding and in this way the hole is not completely covered but is still shielded. Experiments in FEMM were done to test this with small gaps rather than small holes for the mesh and the results still showed that gaps of reasonable size had a significant effect on the internal magnetic field. However, since FEMM can only model gaps in the shielding and not holes, it is still possible that results may be different if there was a way to model holes in the shielding as well as with a complete mesh over the holes. This is where Radia can be useful as it is certainly possible to model this kind of design in Radia. If a better understanding of how Radia applies magnetic materials is developed, then one could simulate the true effects of holes in the magnetic shielding and how to reduce them.

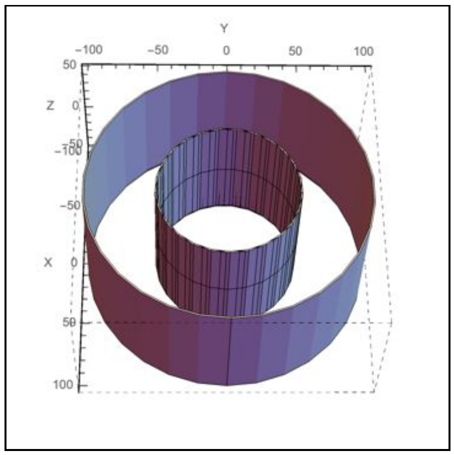

FIG. 5. Radia model of cylindrical iron shielding inside a short coil.

Acknowledgements

- Professor Peter D. Meyers
- Francesco Granato (Temple University Graduate Student)
- OURSIP
- HUNTER

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