Final Scientific/Technical Report

Award Number: DE-FG02-08ER41557

Project Title: Neutrons and Fundamental Symmetries

Recipient: University of Kentucky Research Foundation

Principal Investigator: Bradley Plaster

Executive Summary

The research supported by this project addressed fundamental open physics questions via experiments with subatomic particles. In particular, neutrons constitute an especially ideal “laboratory” for fundamental physics tests, as their sensitivities to the four known forces of nature permit a broad range of tests of the so-called “Standard Model”, our current best physics model for the interactions of subatomic particles. Although the Standard Model has been a triumphant success for physics, it does not provide satisfactory answers to some of the most fundamental open questions in physics, such as: are there additional forces of nature beyond the gravitational, electromagnetic, weak nuclear, and strong nuclear forces?, or why does our universe consist of more matter than anti-matter?

Although the neutrons bound within atomic nuclei (such as iron, aluminum, etc.) are stable, neutrons liberated from the nuclei of atoms undergo radioactive decay, with a lifetime of approximately fifteen minutes. Under the Standard Model, the decay of the neutron proceeds via the weak nuclear force, and theoretical predictions for how the decay proceeds can then be compared with experimental measurements. An inconsistency between the Standard Model prediction and experimental results would provide evidence for an additional force mediating the decay of the neutron. This proposal supported experimental work on measurements of the decay of the neutron to be carried out at the Los Alamos National Laboratory in New Mexico. The results from this experimental work have provided important input to an assessment of the limits of the Standard Model’s validity.

Finally, under the Standard Model, for every subatomic particle comprising “ordinary” matter, there is a corresponding “anti-particle” comprising “anti-matter”. For example, the anti-particle of the electron is the positron, the basis of Positron Emission Tomography (PET) scans in medicine. Despite the known existence of these anti-particles, it is not understood how the universe evolved from its beginning at the Big Bang with presumably equal numbers of particles and anti-particles to its present ordinary-matter-dominated state, consisting of significantly more particles than anti-particles. Experiments searching for a so-called “electric dipole moment” of the neutron, resulting from a tiny separation of positive and negative electric charge within the electrically-neutral neutron, are poised to address this question. In particular, the interactions responsible for the existence of such an electric dipole moment are closely related to the physics processes necessary for the generation of more matter than anti-matter during the early evolution of the universe. Thus, the discovery of a non-zero neutron electric dipole moment would provide key insight into the question of why we live in a matter-dominated universe. This proposal supported work towards the development of a new experiment to search for a neutron electric dipole moment at the Spallation Neutron Source at the Oak Ridge National Laboratory in Tennessee. The experiment requires precise knowledge of the magnetic field within the experimental apparatus. One of the primary novel and original results from this project included the development of a new technique which permits a determination of the magnetic field within the apparatus solely from non-invasive measurements of magnetic fields in regions located external to the measurement volume located in the internal region of the apparatus.

This project also contributed significantly to the training of the next generation of scientists, of considerable value to the public. Young scientists, ranging from undergraduate students to graduate students to post-doctoral researchers, made significant contributions to the work carried out under this project.

Comparison of Actual Accomplishments with the Goals and Objectives of the Project

The overarching original goals and objectives of this project were to:

(1) Carry out and publish the results from a precision measurement of parity violation in the decay of the neutron using the ultracold neutron source in operation at Los Alamos National Laboratory. As this work is collaborative across many institutions, the specific work included in the original proposal was to contribute to the data analysis and publication of the results.

(2) Contribute to the research and development of a new experimental search for a non-zero electric dipole moment of the neutron to be ultimately staged at the Spallation Neutron Source at Oak Ridge National Laboratory. Again, as this work is collaborative across many institutions, the specific work included in the original proposal was to contribute to the development of the requisite magnetic fields for the experiment.

The actual accomplishments of this project met (and, in some cases, exceeded) all of the above goals and objectives. Specifically:

- In support of (1), a comprehensive journal publication providing a detailed exposition of (1) was published. This is listed as Publication #10 in the section detailing the products from this project. In addition, Publications #3 and #7, #15, and #16 in the section detailing the products from this project also followed from this work. These five publications reported the primary physics results. In addition, numerous other publications reporting technical advances were also published. The experimental work here resulted in the achievement of the originally-proposed physics goals.
- In support of (2), Publications #1, #2, #4, #6, #9, #11, #12, and #13 reported the results of technical work on research and development. It is especially noteworthy here that a new concept, not originally included at the time of the original proposal (as the concept was, indeed, developed as a result of work undertaken during the project), resulted in Publications #1, #2, #6, and #6. That is, the accomplishments on (2) were significantly beyond those originally proposed.

In addition, in work that was not originally proposed, a new concept for assessing the impact of precision measurements of neutron decay in terms of underlying physics was developed. This is listed as Publication #5.

Project Activities for the Entire Period of Funding

The accomplishments on the neutron electric dipole moment experiment (nEDM experiment) to be carried out at Oak Ridge National Laboratory included, over the course of the entire period of funding (i.e., from 2008-2015) included:

- The group developed a technique for constructing magnetic shields made of "Metglas", a commercially-available, amorphous, high-permeability magnetic alloy, which led to significantly reduced residual axial fields in the Earth's/background magnetic field environment. The motivation for these studies was that the innermost ferromagnetic shield in the nEDM experiment surrounding primary magnetic field coil will be constructed from Metglas. A former graduate student, S. Malkowski, a non-traditional student (i.e., she returned to school in later adulthood) who graduated with a M.S. degree, was the first author on a technical publication.
- The group led the development of the technical specifications for the nEDM experiment's original design for a multi-layer room-temperature magnetic shield. Doing so required a number of prototyping studies and finite-element-analysis calculations, which were carried out by the group and subsequently published. Again, this same student, S. Malkowski, was the first author on a technical publication, and wrote a M.S. thesis on this topic (and on the previous bullet point).
- The PI developed a GEANT4-based simulation of the experimental signal and backgrounds in the nEDM experiment (i.e., of the "detector response"). The development of such a simulation resulted from a recommendation by the review committee from the March 2010 DOE Annual Review of the nEDM experiment as a means for investigating the possibility of various systematic effects related to the extraction of the signal in the presence of (time-dependent) backgrounds. In particular, one potential time-dependent background results from neutron beta-decay, where the direction of the emitted electrons is correlated with the neutron spin (i.e., the neutron beta-asymmetry parameter), which oscillates at the neutron Larmor precession frequency. The collaboration conducted a "mock data challenge" in which simulated data sets with a "blind" input value for the neutron EDM were provided to independent analysis teams. The PI himself wrote nearly all of the GEANT4 code, and the PI's group, including his graduate student M. Brown, made major contributions to the analysis. Of order 1 billion events were generated (on the University of Tennessee Titan supercomputer) and subsequently analyzed. The end result was that Fourier analyses of the data revealed no biases to the extracted frequency from the neutron asymmetry term. Note that this exercise provided excellent early training in analysis methods for M. Brown, who then went on to full-time work on the UCNA experiment (described next).

On the neutron decay experiment at Los Alamos National Laboratory (UCNA experiment), the group's research accomplishments included the following over the entire period of funding (2008-2015):

- The PI was the first author on a detailed archival paper which provided a complete and detailed discussion of the experiment's methods and analysis procedures. Given past discrepancies in the results from different experiments, the collaboration felt it was important to publish all of the details, and the writing of this archival paper was deemed a high priority. This work can reasonably be viewed as a significant service to the neutron physics community. Further, although the PI himself performed the analysis which led to the first physics result from the UCNA experiment, the PI was less connected with the intimate analysis details from the next (and first-precision) result, as the PI was just starting his faculty position at that time. Thus, writing the archival paper re-connected the PI with the intimate details of the analysis, which has served the PI well in bringing his current graduate student, M. Brown, up to speed where this student is now at the point of leading the current analysis.

- One of the group's former graduate student S. Hasan lived on-site at LANL from the period of August 2011 - February 2013, and contributed significantly to the operation of the experiment. During this time period, S. Hasan also made contributions to the development of the high-voltage and silicon detector systems for the UCNB experiment. The PI has been collaborating with external collaborators in developing the physics case for additional neutron decay experiments using the UCNA spectrometer, including measurements of electron-proton coincidences using a modfied version of the UCNA apparatus. In particular, this work has investigated the sensitivity of carrying out simultaneous fits to the various electron-proton asymmetries and the electron spectrum as a probe of the Fierz interference terms, which are sensitive to non-standard physics.

Products Developed Under the Award

(a) Publications

1. “A prototype vector magnetic field monitoring system for a neutron electric dipole moment experiment”, N. Nouri, A. Biswas, M. A. Brown, R. Carr, B. Filippone, C. Osthelder, B. Plaster, S. Slutsky, and C. Swank, JINST **10**, P12003 (2015).

2. “Sensitivity requirements for accessing interior magnetic field vector components in neutron electric dipole moment experiments via exterior boundary-value measurements”, N. Nouri and B. Plaster, JINST **9**, P11009 (2014).

3. “Beta decay measurements with ultracold neutrons: A review of recent measurements and the research program at Los Alamos National Laboratory”, A. R. Young, S. Clayton, B.W. Filippone, P. Geltenbort, T. M. Ito, C.-Y. Liu, M. Makela, C. L. Morris, B. Plaster, A. Saunders, S. J. Seestrom, and R. B. Vogelaar, J. Phys. G: Nucl. Part. Phys. **41**, 114007 (2014).

4. “Systematic optimization of exterior measurement locations for the determination of interior magnetic field vector components in inaccessible regions”, N. Nouri and B. Plaster, Nucl. Instrum. Methods Phys. Res. A **767**, 92 (2014).

5. “Framework for maximum likelihood analysis of neutron β decay observables to resolve the limits of the V − A law”, S. Gardner and B. Plaster, Phys. Rev. C **87**, 065504 (2013).

6. “Comparison of magnetic field uniformities for discretized and finite-sized standard cos θ, solenoidal, and spherical coils”, N. Nouri and B. Plaster, Nucl. Instrum. Methods Phys. Res. A **723**, 30 (2013).

7. “Precision measurement of the neutron beta-decay asymmetry”, M. P. Mendenhall et al., Phys. Rev. C **87**, 032501(R) (2013).

8. “Performance of the Los Alamos National Laboratory spallation-neutron driven solid deuterium ultracold neutron source”, A. Saunders et al., Rev. Sci. Instrum. **84**, 013304 (2013).

9. “Overlap technique for end-cap seals on cylindrical magnetic shields”, S. Malkowski, R. Adhikari, J. Boissevain, C. Daurer, B. W. Filippone, B. Hona, B. Plaster, D. Woods, and H. Yan, IEEE Trans. Magnetics **49**, 651 (2013).

10. “Measurement of the neutron β-asymmetry parameter A_0 with ultracold neutrons”, B. Plaster et al., Phys. Rev. C **86**, 055501 (2012).

11. “High uniformity magnetic coil for search of neutron electric dipole moment”, A. Perez Galvan, B. Plaster, J. Boissevain, R. Carr, B. W. Filippone, M. P. Mendenhall, R.

Schmid, R. Alarcon, and S. Balascuta, Nucl. Instrum. Methods Phys. Res. A **660**, 147 (2011).

12. "Technique for high axial shielding factor performance of large-scale, thin, open-ended, cylindrical Metglas magnetic shields", S. Malkowski, R. Adhikari, B. Hona, C. Mattie, D. Woods, H. Yan, and B. Plaster, Rev. Sci. Instrum. **82**, 075104 (2011).

13. "Impact of motion along the field direction on geometric-phase-induced false electric dipole moment signals", H. Yan and B. Plaster, Nucl. Instrum. Methods Phys. Res. A **642**, 84 (2011).

14. "Sealed drift tube cosmic ray veto counters", R. Rios et al., Nucl. Instrum. Methods Phys. Res. A **637**, 105 (2011).

15. "Determination of the axial-vector weak coupling constant with ultracold neutrons", J. Liu et al., Phys. Rev. Lett. **105**, 181803 (2010).

16. "First measurement of the neutron β asymmetry with ultracold neutrons", R. W. Pattie, Jr. et al., Phys. Rev. Lett. **102**, 012301 (2009).

17. "Multi-wire proportional chamber for ultra-cold neutron detection", C. L. Morris et al., Nucl. Instrum. Methods Phys. Res. A **599**, 248 (2009).

18. "A solenoidal electron spectrometer for a precision measurement of the neutron β-asymmetry with ultracold neutrons", B. Plaster, R. Carr, B. W. Filippone, D. Harrison, J. Hsiao, T. M. Ito, J. Liu, J. W. Martin, B. Tipton, and J. Yuan, Nucl. Instrum. Methods Phys. Res. A **595**, 587 (2008).