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PROPOSED EXPERIMENT TO MEASURE THE NEUTRON SPIN-ELECTRON ANGULAR CORRELATION IN POLARIZED NEUTRON BETA DECAY WITH ULTRA-COLD NEUTRONS

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PROPOSED EXPERIMENT TO MEASURE THE NEUTRON SPIN – ELECTRON ANGULAR CORRELATION IN POLARIZED NEUTRON BETA DECAY WITH ULTRA-COLD NEUTRONS

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1 Introduction

The Standard Model, which describes the structure of the strong, electromagnetic, and weak forces, has been very successful in describing a wide range of experimental data. Within the standard model the electroweak interaction is given by the Weinberg-Salam-Glashow (W-S-G) model which specifies a purely left-handed (V-A) interaction. This left-handed structure reproduces the observed state in nature, but the Standard Model does not provide any underlying reason for this structure. It is assumed that Standard Model is only part of a larger model. Various extensions of the model, such as Grand Unified field Theories (GUTs), SUperSYmmetric (SUSY) theories, and String Theories, attempt to unify the weak nuclear, electromagnetic, and strong nuclear forces in a single, comprehensive theory. These theories predict that a range of new phenomena beyond the Standard Model should exist, including proton decay, non zero neutrino masses and mixing, right-handed currents, and new particles. In the past two decades, much effort has been expended in searching for new physics beyond the Standard Model. One area in which the Standard Model can be probed is neutron beta decay. In particular, measurements of angular correlations in neutron beta decay can place constraints on the existence of right-handed currents, the presence of scalar and tensor terms in the weak interaction, and for evidence of Time Reversal Violation, which is expected from the observed violation of CP invariance in kaon decay.

A measurement of **A**, the correlation between the neutron spin and the direction of emission of the electron in neutron decay, can be combined with the neutron lifetime to determine the fundamental vector and axial vector weak coupling constants G_A and G_V. The value of G_V determined from neutron beta decay can also be compared with the value determined from measurements of superallowed $0^+ \rightarrow 0^+$ *nuclear* beta decay and from the value determined by requiring that the Cabibbo-Kobayashi-Maskawi (CKM) matrix (which describes the mixing between quarks) be unitary. This provides a sensitive means to search for Physics beyond the Standard Model.

In recent years four measurements of **A** have been carried out using cold neutron beams at reactors. These measurements quoted combined statistical and systematic uncertainty of about 1% in the determination of **A**. The three measurements preceding the most recent Perkeo II are in reasonable agreement with each other, but disagree with both the $0^+ \rightarrow 0^+$ beta decay and CKM unitarity.[1-7] Perkeo II[8] is in disagreement with the average of the previous three. The discrepancy between the various neutron measurements is likely due to the existence of systematic problems. In order to understand the origin of the discrepancies, it is obviously essential to carry out new measurements with very different systematic effects than those in the reactor experiments. It is also equally important to improve the accuracy of these experiments in order to search for new physics with increased sensitivity. The goal of our experimental program is to address these issues with a measurement of the A correlation with substantially improved accuracy.

A measurement of the A correlation using Ultra-Cold Neutrons (UCN) provides significant advantages over reactor beam experiments. As UCN can be transported through bent guide tubes, it is possible to place the experiment at a position distant (of order 10 m) from any neutron beam. In addition, at a Short-Pulse Spallation Source (SPSS), one can suppress backgrounds significantly by using timing information so that data are excluded during the period just after the proton pulse strikes the spallation target. It is also possible to 100% polarize UCN by passage through a magnetic field gradient with a maximum field of about 5 Tesla. Depolarization effects are calculated to be very small ($< 3 \times 10^{-4}$), thus a UCN source with essentially 100% polarization can be constructed. The main disadvantage of UCN is that rates obtainable are much lower than can be obtained in experiments using cold neutron beams.

2 UCN Measurement of A

The essential features of the experiment are shown in Figure 1. The UCN are stored (or rather flow through) a long, diffuse, windowless bottle. A longitudinal magnet field serves to maintain the neutron spin and to guide the beta decay electrons out to the beta spectrometers located at the ends of the bottle. Magnet field expansion is used to reduce electron backscatter. The transverse location of the decaying neutron is determined using a thin wire chamber located in front of the plastic scintillator used to measure the electron energy.

A diamond-coated UCN guide tube will transport UCN from the rotor source to the A correlation spectrometer. The UCN will be 100% polarized by passage through a 5 T superconducting solenoid. The UCN will then pass through an Adiabatic Fast Passage (AFP) resonator that will allow rapid spin flipping of the UCN. In our geometry, the adiabatic condition for spin flipping should be well satisfied and under less favorable conditions, experiments at SLAC achieved AFP spin-flip efficiencies of > 99.9%. The UCN will then be fed to the center of the A correlation spectrometer, as shown in Fig. 1.

The spectrometer consists of a 6-m long, 10 cm diameter UCN open-ended bottle that defines a decay volume for the UCN. A suitable wall material is diamond film, made from deuterated precursors, deposited onto the inner surface of a quartz tube. Such a surface has a rather high effective potential (with a cutoff velocity of 7.6 m/s) and a loss rate corresponding to a lifetime of about 50 seconds at room temperature. Furthermore, the depolarization time for such a surface would be extremely long. Data from the ILL Electric Dipole Moment (EDM) experiment already provide a lower limit of 1000 s for the spin relaxation time.

A highly-uniform ($< 10^{-3}$ variation) strong (0.5 T) magnetic field is generated along the axis of the UCN trap by a conventional solenoid. At the ends of the bottle, the magnetic field is expanded in the region before the detector. The strong magnetic field in the solenoid is used to determine the neutron spin direction and is used to guide the betas from neutron decay in the bottle to the detectors, as shown in Fig. 2. The betas are detected in a Multi-Wire Proportional Chamber (MWPC) - scintillator system at the ends of the spectrometer in the expanded field region. This detector system allows both position information from the multi-wire proportional counters (MWPC), total energy information (from the scintillator), and some information on the pitch angle of the electron (from the dE/dx measurement in the MWPC). The pitch angle of the betas decreases as the beta moves from the high field to the low field region, which reduces the backscattering amplitude of electrons from the MWPC windows and the scintillator, thus substantially reducing one of the largest systematic effects in measuring the A correlation. This geometry strongly suppresses backscattering effects by mirroring the backscattered betas back into the detector. The spectrometer is shielded against both neutron and gamma backgrounds

Full calibration of the energy resolution function of the spectrometer is of paramount importance for an **A** correlation experiment. In the previous reactor experiments, this has been done using thin film conversion line sources such as ^{109}Cd and ^{207}Bi. While we will certainly calibrate the spectrometer using this type of source introduced at the center of the spectrometer, it would be advantageous to have a source which filled the spectrometer active volume in the same manner as the UCN. At least one such a source does exist - several isotopes of Xe decay by internal conversion or by beta decay with energies up to a few hundred keV. In addition to filling the UCN bottle region fully, such a source is massless and thus does not have the scattering tails typical of conversion line sources deposited on thin films. The Xe isotopes can be easily produced in mCi quantities in one day of irradiation in a thermal reactor. The lifetimes of the isotopes are relatively short (a few days to a few weeks), but enough of the Xe isotopes can be produced in a single irradiation to provide a useful source for 1 - 2 months.

There are two features of the **A** experiment as designed that are central to achieving a high signal-to-background ratio (of order 100/1 with a threshold of 100 keV or lower): the use of a strong magnetic guide field that allows 4π collection efficiency of the betas in a relatively small detector, and the use of a coincidence requirement between the proportional counter and scintillator in the spectrometer.

The UCN exiting the decay tube are monitored in an array of UCN detectors, are transported down a diamond-coated UCN guide to a ^{3}He detector, or are captured on ^{6}LiH surfaces in the region between the decay tube and the detectors. Thus, the UCN are effectively pumped away at the ends of the decay tube, thereby strongly reducing the number of neutron decays in the field expansion region. This arrangement also provides the means to monitor both the total number of UCN exiting the bottle as well as the number of UCN in the field expansion region.

We will be able to measure the depolarization of the UCN *in situ* by using the 5 T superconducting solenoid as both a polarizer and an analyzer. This is done by polarizing the UCN when filling the UCN bottle, closing off the bottle for some time, then emptying the bottle first through the 5 T solenoid (now acting as an analyzer) and finally counting any wrong spin state neutrons left in the UCN bottle. By also installing UCN valves at the inlet of the polarizer and between the polarizer and the AFP unit, one can also search for depolarization effects due to multiple passes of the UCN through the AFP and polarizer.

We have carried out Monte Carlo calculations of the holding time integrated UCN density of UCN in the spectrometer, resulting in a bottle lifetime of about 5 seconds. Our count rate estimates are based on measurements made with the rotor source, and on expected improvements in the facility and the rotor. We typically detected 650 UCN/s at the end of a 3-m long, 8 cm diameter guide. The maximum rate that we expect to achieve in the experiment is a total decay rate in the bottle of 33.4 Hz. In order to achieve a given statistical accuracy σ_A, we expect that $\sigma_A = 2.7 / \sqrt{N}$. After correcting for live time, detection efficiency, fiducial volume cut, and timing cut efficiency we estimate a counting rate after all cuts of 6-18 Hz. We expect to acquire statistical data for 100-300 days, during which time we will observe 1.6×10^8 decays. Thus, we can achieve a statistical accuracy of $\sigma_A / A = 1.9 \times 10^{-3}$ ($\sigma_A = 2.1 \times 10^{-4}$). We note the important fact that the signal to background will be 68/1.

A central issue in accurately determining the beta-asymmetry is the systematic uncertainties in the measurement. As noted above, UCN offer significant reductions in the major systematic effects in a measurement of the **A** correlation. The systematic uncertainties can be broadly divided into three categories: those concerning knowledge of the A) neutron spin-dependent effects, B) electron collection, and C) detector-related effects.

The have estimated the systematic uncertainty introduced by various factors, and the results are summarized in Table 1. The total systematic uncertainty is determined by adding the individual systematic uncertainties in quadrature. We expect that the total systematic uncertainty will be $\sigma_A / A \leq 6.4 \times 10^{-4}$. Just as important, the total correction due to systematic effects ($\Delta A/A$) is less than 1.6×10^{-3}

3 Summary

We have presented the essential elements of our plans to carry out an **A** correlation measurement using the UCN source we have constructed at the Manuel Lujan Neutron Scattering Center (MLNSC). Our goal is an initial measurement with an accuracy of about 0.2% of **A** (which has a value of about -0.114). The count rate expected in the experiment will allow a determination at this statistical accuracy level in a running time of about four months. It is important to note that the systematic effects in an experiment with UCN will be very different than those in the reactor experiments. Our estimates indicate that the total systematic uncertainty will be at the $\leq 6.4 \times 10^{-4}$ level. With such accuracy, one could address the issues of the discrepancy between the $0^+ \rightarrow 0^+$ decays and the unitarity of the CKM matrix. With possible increases in the UCN source intensity and a better understanding of systematic effects, we ultimately expect to be able to improve the accuracy beyond that of existing experiments by an order of magnitude or better. This would provide unprecedented sensitivity in the search for new Physics Beyond the Standard Model.

5 References

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Table 1

Systematic Effect	$\Delta A/A$	σ_A/A
Polarization (including neutron spin flipping)	$\leq 1 \times 10^{-3}$	$\leq 1 \times 10^{-4}$
Depolarization	$< 1 \times 10^{-3}$	$< 1 \times 10^{-4}$
Spatial variations in UCN density	1×10^{-4}	1×10^{-4}
Temporal variations in UCN density	4×10^{-5}	4×10^{-5}
Neutron spin alignment	1×10^{-4}	1×10^{-4}
Neutron spin transport	1×10^{-4}	1×10^{-4}
Subtotal UCN Systematic Effects	**1.4×10^{-3}**	**2.3×10^{-4}**
Backscattered betas	5×10^{-4}	$\leq 1 \times 10^{-4}$
Scattered betas - residual gas contribution	$< 1 \times 10^{-5}$	$< 1 \times 10^{-5}$
Scattered betas - wall contribution	$< 3 \times 10^{-6}$	$< 3 \times 10^{-6}$
Field nonuniformities	2×10^{-4}	7×10^{-5}
Magnetic mirror effect	$< 5 \times 10^{-5}$	$< 5 \times 10^{-5}$
Fiducial volume definition	$< 7 \times 10^{-5}$	$< 7 \times 10^{-5}$
Subtotal Electron Collection	**5.5×10^{-4}**	**1.5×10^{-4}**
Detector inefficiencies	$< 2 \times 10^{-5}$	$< 2 \times 10^{-5}$
Detector resolution function	3×10^{-4}	3×10^{-4}
Detector nonlinearity	5×10^{-4}	5×10^{-4}
Detector backgrounds - room	$\leq 2 \times 10^{-5}$	$\leq 2 \times 10^{-5}$
Detector backgrounds - beam associated	$< 1 \times 10^{-4}$	$< 1 \times 10^{-5}$
Detector backgrounds - UCN related	$< 1 \times 10^{-4}$	$< 1 \times 10^{-5}$
Subtotal Detector Effects	**6.0×10^{-4}**	**5.8×10^{-4}**
TOTAL	**1.6×10^{-3}**	**6.4×10^{-4}**

Table 1. Systematic effects and uncertainties. $\Delta A/A$ is the size of the systematic effect relative to A (which has a value of -0.114) and σ_A/A is the size of the systematic uncertainty relative to A.

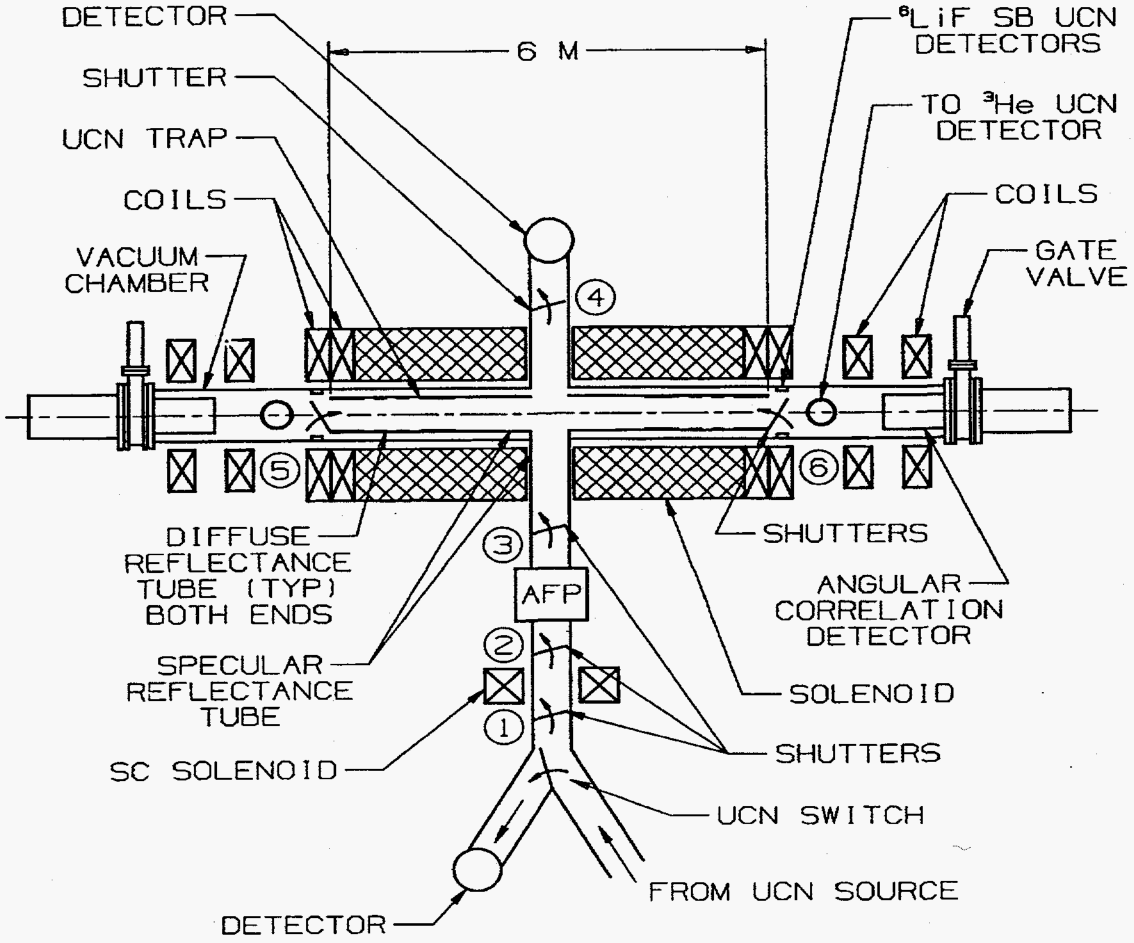

Figure 1: Layout of the **A** experiment. UCN enter from the guide tube at the bottom of the picture and pass through the polarizer and spin flipper before entering the decay volume. The circled numbers 1-6 indicate UCN shutters that may be opened and closed to make *in situ* measurements of the UCN depolarization. The beta detectors at the left and right end of the decay volume are shown in more detail in Figure 2.

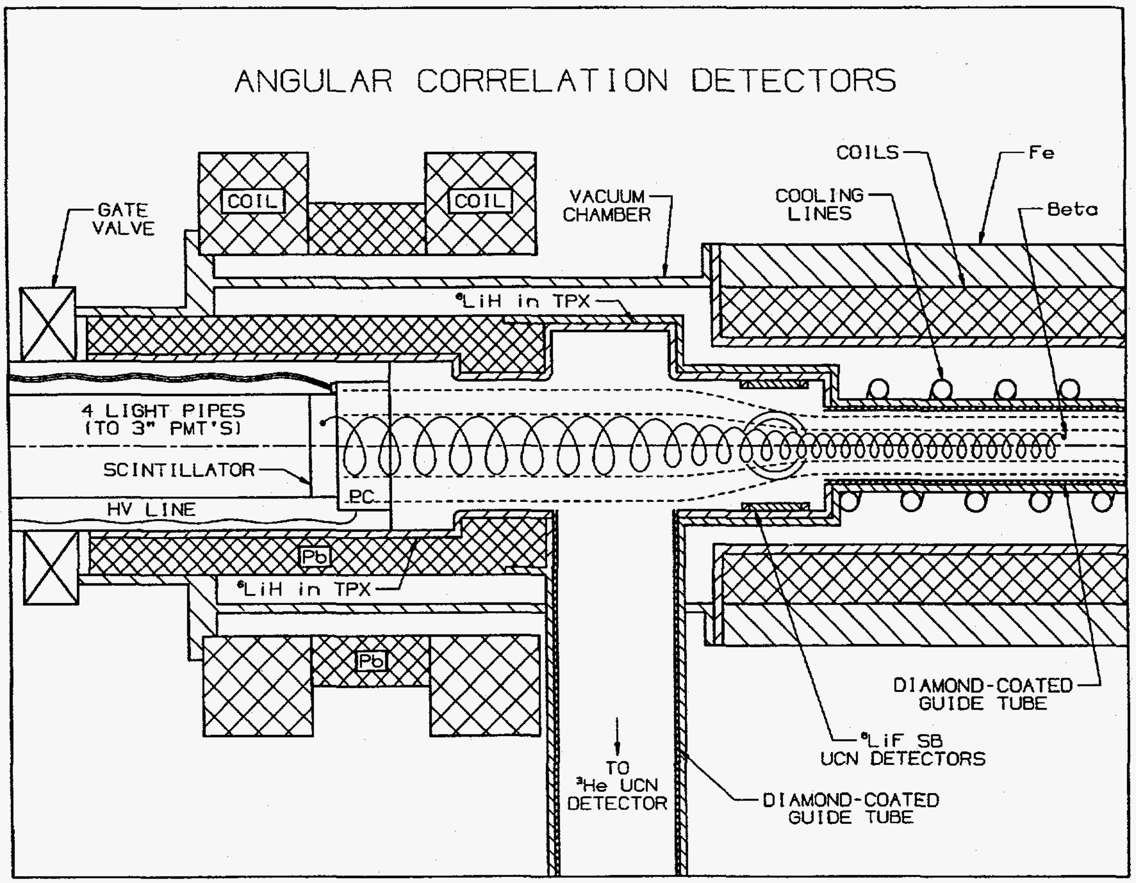

Figure 2: Detail showing the end of the UCN bottle and the beta detectors.

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