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Measurement of the Neutrino-Spin Correlation Parameter B in Neutron Decay using Ultracold Neutrons

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We present a new approach to measuring the neutrino-spin correlation parameter B in neutron decay. The approach combines the technology of large-area ion-implanted silicon detectors being developed for the abBA experiment, with an ultracold neutron source to provide more precise neutron polarimetry. The technique detects both proton and electron from the neutron decay in coincidence. B is determined from an electron-energy-dependent measurement of the proton-spin asymmetry. This approach will provide a statistical precision of 1×10^{-4} . The systematic precision is still being evaluated, but is expected to be below 1×10^{-3} , and could approach 1×10^{-4} . A measurement of B with this precision would place constraints on supersymmetric extensions to the Standard Model.

Precision measurement of neutron decay parameters can provide accurate determination of important Standard Model parameters, and in some cases, tests for physics beyond the current Standard Model (SM). Under the assumption of time-reversal invariance, the neutron differential decay distribution can be described by [1]

$$dW \propto \frac{1}{\tau_n} F(E_e) \left[1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + B \frac{\vec{\sigma}_n \cdot \vec{p}_\nu}{E_\nu} + A \frac{\vec{\sigma}_n \cdot \vec{p}_e}{E_e} \right], \quad (1)$$

where \vec{p}_e and \vec{p}_ν are the outgoing electron and neutrino momenta, $\vec{\sigma}_n$ is the neutron spin, and E_ν is the neutrino energy. $F(E_e)$ is the familiar beta energy spectrum. The correlation coefficients A , B , a , and b (as well as the neutron lifetime τ_n) are experimentally accessible quantities. Much focus has been placed on the electron-spin correlation parameter A [2], which can be used in combination with τ_n to extract the quark mixing matrix V_{ud} . For the same reason, the neutrino-proton correlation a has also received recent attention. Less interest has been paid to the neutrino-spin correlation B , which gives the probability that the anti-neutrino from the neutron decay is emitted parallel to the initial neutron spin direction. There are two primary reasons responsible for this situation. First, B is less experimentally accessible than A , and second, it has been thought to be less sensitive to non-SM physics than other neutron decay parameters. Recent advances in both experiment and theory have obviated both of these limitations.

B has traditionally been thought to be quite insensitive to non-SM physics. Its sensitivity to g_A is several times less than A and a . Although it is sensitive to the presence right-handed gauge bosons from left-right symmetric models, the contribution is greatly suppressed [3, 4]

$$B \approx \left[1 - \left(\frac{M_L}{M_R} \right)^4 \right] B_{\text{SM}}. \quad (2)$$

However, it has recently been shown by Profumo, Ramsey-Musolf, and Tulin [5], that the sensitivity of B to certain super-symmetric extensions of the SM is more favorable. In this work, modifications to the SM value of B can be as large as 1×10^{-3} . The current experimental value of B is 0.9807 ± 0.0030 [6].

Although the antineutrino from neutron decay cannot be detected, the B parameter can be extracted from an electron-energy-dependent measurement of the proton-spin correlation, sometimes called C . For neutron decay events with low electron energy, the proton and antineutrino share most of the momentum. This implies that $C \rightarrow -B$ as $E_e \rightarrow 0$. Conversely, for high electron energy events, the proton and electron share most of the momentum, implying $C \rightarrow -A$ as $E_e \rightarrow E_{\text{max}}$.

The abBA experiment [7], being developed for the Fundamental Neutron Physics Beamline at the Spallation Neutron Source, plans to use large-area ion-implanted silicon detectors to allow detection of both electron and proton from neutron decay, allowing determination of the decay parameters a , b , B , and A . The goal precision is 1×10^{-4} (statistical) for each parameter. Unfortunately,

precision in the determination of B is limited to 1×10^{-3} by uncertainty in the neutron polarization, insufficient to test supersymmetry [15].

Fundamental neutron experiments using ultracold neutrons (UCNs) have different systematics from similar experiments using cold neutron beams. In particular, the neutron polarization is typically higher, $1 - P_n < 1 \times 10^{-2}$ versus $1 - P_n < 5 \times 10^{-2}$ for cold neutrons. This allows the uncertainty in the neutron polarization to, in principle, be substantially less in the UCN case. The UCNA experiment [8] to measure the A parameter, currently running at the Los Alamos Neutron Science Center (LANSCE) is the most relevant example of a UCN-based fundamental neutron experiment. This experiment uses a 1 T magnetic spectrometer with wire chamber electron detectors, coupled to the LANSCE UCN source. The UCNs are used to fill a bottle inside the spectrometer. Decay electrons pass through thin windows on the bottle and are guided to detectors at either end of the solenoidal magnetic field. The decay protons are not detected. The neutrons are polarized before entering the spectrometer by passage through a 7 T polarizing solenoid and the polarization direction is maintained by the magnetic field of the spectrometer. An adiabatic fast passage spin flipper allows the polarization of the neutrons to be established either parallel or antiparallel to the magnetic field direction. The asymmetry in electron count rates is used to determine A . The decay rate is currently 20–30 Hz and can be expected to improve as the UCN source and transport is further improved.

An opportunity to measure B with a precision of better than 1×10^{-3} , and perhaps approaching 1×10^{-4} (statistics and systematics) exists by combining appropriate techniques from the abBA and UCNA experiments. Previous experiments to determine B are described in [9, 10]. Instrumenting the UCNA spectrometer with the large-area silicon detectors designed for abBA and providing a modest electrostatic acceleration for the protons will allow coincident detection of decay electrons and protons. This will provide the electron-energy-dependent measurement of the C required to extract B . Extending the neutron polarimetry techniques of the UCNA experiment to better precision will reduce the limiting systematic effect, possibly below the expected statistical limit of 1×10^{-4} , assuming a decay rate of 40 Hz. A further modification required to the UCNA apparatus is that the UCN bottle must be windowless to allow the decay protons to exit. Since neutrons can also leak through these openings, the count rate will be reduced compared to the case of windows. Improvements in the UCN source performance are expected to more than compensate for this loss.

Systematic effects for the abBA experiment have been extensively studied [11]. Extrapolation to the UCN spectrometer geometry provides a guide to which effects will be of greatest concern. One effect that is of great concern for a measurement of A , electrons backscattering from the detector faces, is much less of a concern for

B . This is because while A requires accurate knowledge of the electron's initial direction, a determination of B only requires knowledge of the electron's energy. As long as electron energy that is shared between detectors in cases of backscattering can be accurately summed, the determination of B is unaffected. Systematic effects such as proton backscattering, are expected to be similar to the abBA estimates, and will not contribute significantly. Possibly the largest systematic will be proton scattering from residual gas in the spectrometer vacuum. This process can reverse the proton direction, resulting in a misidentification of its initial direction, and therefore a multiplicative correction to C . This effect was estimated in an approximate calculation to be small for abBA, however two differences make the effect larger for the UCN measurement. First, because the UCNA spectrometer has a warm bore instead of the cryogenic bore for abBA, the residual gas pressure is substantially higher. Second, because the bottled UCNs are less dense than neutrons in a cold beam, a larger decay volume is required, necessitating a longer path for protons to travel before acceleration. This effect will have to be studied in more detail to establish a safe residual gas pressure. In addition, other systematics may become significant as a precision of 1×10^{-4} is approached that have not yet been addressed.

The experimental concept is shown in figure 1. UCNs produced by the LANSCE source pass through a polarizing magnet and spin flipper and then enter the spectrometer magnet. The polarizer produces a neutron polarization $P_n \geq 0.991$. The spin flipper can reverse the polarization direction of the neutrons with an efficiency $\epsilon \geq 0.997$, allowing cancellation of systematic effects related to differing detector efficiencies. UCNs are partially confined by the windowless bottle, which reflects neutrons that strike the walls with a loss probability of 1×10^{-6} per bounce. Electrons and protons from neutrons that decay within the bottle are confined to spiral around the magnetic field lines of the 1 T spectrometer field. The charged particles are guided adiabatically to a silicon detector at either end of the spectrometer, preserving the initial direction with respect to the neutron spin direction. The endpoint energy of the protons is ~ 800 eV, undetectably low. Upon exiting the bottle, the protons are accelerated by the 30 keV electric potential, a detectable energy for the silicon detectors. The decay events are detected as a coincidence between a (fast) electron and the later arrival of a (slow) proton. As the protons are essentially mono-energetic due to the acceleration potential, they are easily identifiable. UCNs that decay after exiting the bottle do not generate coincidence events, since the protons are not accelerated.

The silicon detectors [12], designed for the abBA experiment, are produced from single wafers of single-crystal silicon 1 mm thick. The detectors are ion-implanted to form diode structures and produced through standard photo-lithography techniques. Charge particles en-

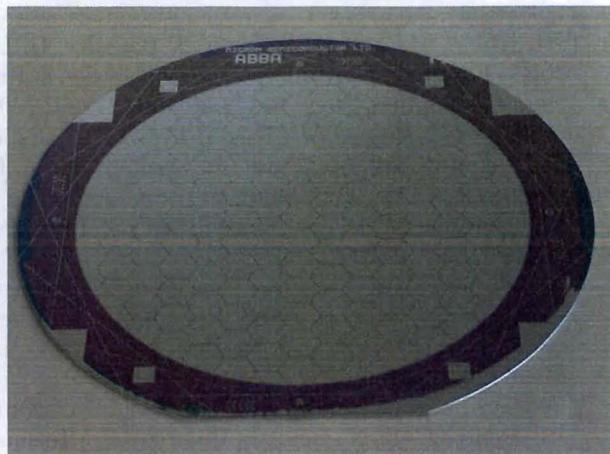
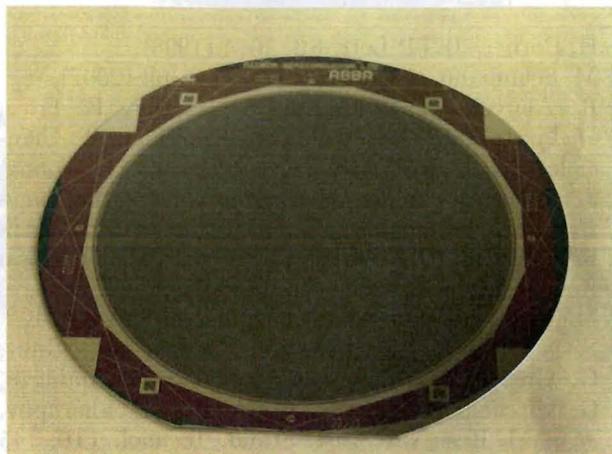


FIG. 2: A prototype abBA detector, showing the front (left) and back(right) sides.

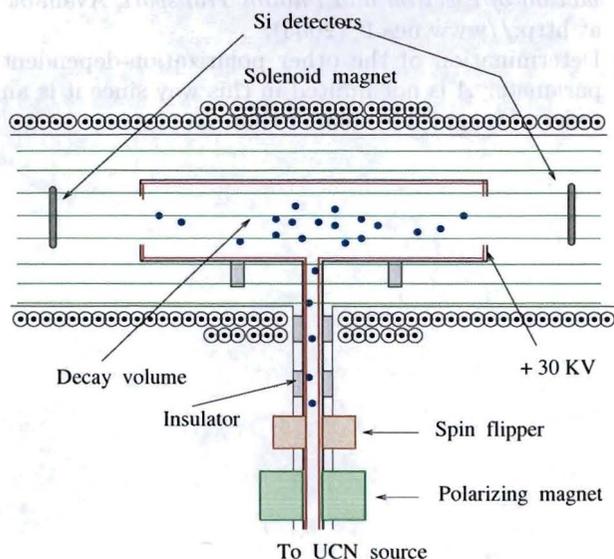


FIG. 1: Schematic design of the UCNB experimental concept.

ter through the front (*p*-implant) side, that consists of a shallow implant layer with a very fine (0.4% of active area) aluminum grid to provide electrical conductivity. The detector has an entrance window of < 100 nm equivalent of silicon [13]. Signals are collected from the back (ohmic) side of the detector, which is segmented into 127 hexagonal pixels, with area 70 mm^2 each. Figure 2 shows both sides of a prototype detector. Custom low-noise preamplifiers read out the detector signals for digitization in ADCs.

At 1 mm thick, the detectors are not sufficient to stop the highest energy electrons, which have an endpoint energy of ~ 800 keV, requiring 1.7 mm of silicon to fully stop. However, since the determination of B relies upon events with low electron energy, it is possible to use thinner detectors if the higher energy electrons don't contaminate

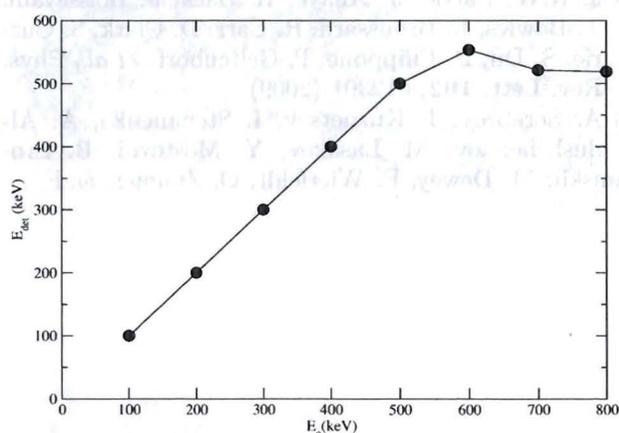


FIG. 3: Detected energy versus initial energy for electrons normally incident on a 1 mm silicon detector.

inate the desired region of the electron spectrum. We have conducted simulations using the PENELOPE computer code [14] to show that the energy spectrum is to greater than 400 keV, sufficient for this experiment (see figure 3).

In summary, we propose a measurement of the the antineutrino-spin correlation parameter B in neutron decay. The experiment concept uses ultracold neutrons, an electromagnetic spectrometer, and large-area ion-implanted silicon detectors to measure the proton asymmetry C as a function of electron energy. A precision approaching 1×10^{-4} is possible, providing useful information to constrain supersymmetric extensions to the Standard Model.

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