A new approach to measuring the neutron decay correlations with cold neutrons at LANSCE

W.S. Wilburn^a, J.D. Bowman^a, G.L. Greene^a, G.L. Jones^b,
J.S. Kapustinsky^a, and S.I. Penttilä^a

^a *Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

^b *National Institute of Standards and Technology, Gaithersburg, Maryland, 20899, USA*

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Abstract

Precision measurements of the neutron beta-decay correlations A , B , a , and b provide important tests of the standard model of electroweak interactions: a test of the unitarity of the first row of the CKM matrix, a search for new weak interactions, a test of the theory of nuclear beta decays, and a test of the conserved-vector-current hypothesis. We are designing an experiment at the LANSCE short-pulse spallation source to measure all four correlations to an order of magnitude better accuracy than the existing measurements. The accuracy of the previous measurements was limited by systematics. The design of the proposed experiment makes use of the pulsed nature of the LANSCE source to reduce systematic errors associated with the measurement of the neutron polarization as well as other systematic errors. In addition, we are developing silicon strip detectors for detecting both the proton and electron from the neutron decay.

1 Introduction

Precision measurements of the neutron beta-decay correlations A , B , a , and b provide important tests of the standard model of electroweak interactions: a test of the unitarity of the first row of the CKM matrix, a sensitive search for real scalar and/or tensor interactions, a test of the theory of $0^+ \rightarrow 0^-$ nuclear beta decays, and a test of the conserved-vector-current hypothesis. We are designing an experiment to measure all four correlations to an order of magnitude better accuracy than the existing measurements. The proposed experiment is well suited to a short-pulse neutron source such as LANSCE, which allows the neutron energy to be determined from the time-of-flight. The accuracy of the earlier measurements (see [1] for references) was limited by systematics. The design of the proposed experiment makes use of the pulsed

nature of the LANSCE source to reduce systematic errors associated with the measurement of the neutron polarization as well as other systematic errors. Sources of systematic error are briefly discussed and shown to be small compared to 10^{-3} . The flux at the LANSCE spallation source will allow a statistical sensitivity below 10^{-3} in a few weeks.

The decay rate for neutrons of polarization P_n as a function of electron energy E is given by [2]:

$$\frac{dW}{dE} = W_0 \left\{ 1 + P_n [\beta A \cos(\theta_{\sigma-e}) + B \cos(\theta_{\sigma-\nu})] + \beta a \cos(\theta_{\nu-e}) + b \frac{m}{E} \right\}. \quad (1)$$

The proposed apparatus is designed to measure simultaneously the coefficients A , B , a , b , and observe the weak magnetism term (an energy-dependent $\sim 2\%$ correction to A). The experimental study of spectra and angular correlations in neutron beta decay addresses a number of crucial issues in particle and nuclear physics:

- (i) The determination of the size of the electron-spin correlation A in polarized neutron β -decay can determine $\lambda = G_A/G_V$ with the assumption that scalar and tensor couplings vanish and that the vector (V) and axial-vector (A) couplings are real. From λ and the neutron lifetime $\tau = 1/(3G_A^2 + G_V^2)$, G_V^2 can be determined without uncertainty due to nuclear structure. The first element of the CKM matrix V_{ud} can then be determined as $V_{ud}G_\mu = G_V$. The unitarity of the first row of the CKM matrix can then be tested using the known values of the other, smaller first-row matrix elements. The unitarity of the CKM matrix tests the universality of weak couplings, and the existence of non-standard model sources of CP violation. We propose to determine the electron-spin correlation A to $\sigma A/A = 0.1\%$. The corresponding uncertainty in G_V^2 and V_{ud}^2 will be 0.04% . The neutron lifetime is known to 0.2% [?], and work is underway at NIST to improve this uncertainty by an order of magnitude [3]. Neutron decay is the best laboratory in which to test the unitarity of the CKM matrix. The precision of the unitarity tests are dominated by the uncertainty of the large diagonal elements of the matrix. It is unlikely that the weak decay rates needed to determine the other diagonal matrix elements, V_{cs}^2 and/or V_{tb}^2 , can be determined to 0.1% in the near future.
- (ii) Once λ is known from A , the consistency of the values of the neutrino-spin correlation B (proposed error of 0.01%) and the electron-neutrino correlation a (proposed error of 0.5%), and the Fierz term b (proposed error of 0.0004), provide further tests of the standard model. The Fierz term is zero in the standard model, while a and B are non-zero. The deviations of a and B from their standard-model values are quadratic in

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scalar and tensor couplings. Unlike a and B , the Fierz term, given by

$$b \propto \text{Re}(G_S G_V^* + 3G_A G_T^*), \quad (2)$$

results from an interference between the small S and T couplings and the large V and A couplings [1]. The coefficient b is therefore linear in scalar and tensor couplings.

- (iii) G_V^2 has been determined from the decay rates of $0^+ \rightarrow 0^-$ nuclear beta decays. The comparison of the results from neutron decay and nuclear beta decay will test the nuclear theory needed to make Coulomb and other corrections in nuclei.
- (iv) Weak magnetism produces a small additional energy dependence in A ; this correction is predicted by the CVC hypothesis. Measurement of the energy dependence of A with the proposed accuracy will test CVC to 5%.

2 Experiment

The proposed experiment, illustrated in figure 1, consists of the LANSCE pulsed cold neutron source, an optically polarized ^3He neutron spin filter, RF spin flipper, and a spectrometer for the decay particles. Neutrons are produced by the spallation process from 800 MeV protons incident on a tungsten target. The neutrons, which are produced in pulses at a rate of 20 Hz, are then moderated by liquid hydrogen. Cold neutrons are transported to the apparatus by a neutron guide and then polarized by transmission through polarized ^3He . An RF spin flipper can be turned on to reverse the neutron polarization for alternate beam pulses. The spectrometer consists of a magnetic field, approximately 1 T in the central region, decreasing to 0.25 T at the detectors, an electric field for accelerating the protons, and two silicon strip detector assemblies. This design improves upon previous measurements in three major areas:

- (i) The energy of the neutron is measured by time-of-flight.
- (ii) The detector solid angles are defined by a magnetic field.
- (iii) The neutron polarization is produced by transmission through polarized ^3He .
- (iv) Silicon strip detectors are used to detect both the electron and proton from neutron decay. The silicon detectors allow precise determination of the electron energy.
- (v) The fiducial decay volume is defined by the position information from the segmented silicon detectors.
- (vi) Backgrounds are greatly reduced by requiring coincidence between the electron and proton.

The advantages of these techniques are discussed in detail in the following sections.

Fig. 1. The conceptual design for the apparatus showing the most important elements (not to scale). The spectrometer is shown both from the side (left) and from the end (right).

2.1 Magnetic Field

One difficulty in obtaining absolute values for the neutron decay correlation coefficients arises from the angular dependence of the observed decay rate. For example, in the case of A , it appears that both the angle $\theta_{\sigma-e}$ and the angular acceptance of the detector must be known very precisely. In fact, the use of a magnetic field to guide the decay particles to the detector, first used for neutron decay measurements in the PERKEO experiments [4,5], greatly reduces this problem. Because the charged particles are constrained to spiral around the magnetic field lines, particles emitted in the angular range $0 < \theta_{\sigma-e} < \pi$ are directed to one detector, while those emitted in the range $\pi < \theta_{\sigma-e} < 2\pi$ are directed to the opposite detector. Because the same magnetic field determines the neutron spin direction, there is no possibility of misalignment.

It is still necessary to define the fiducial decay volume. In the past, this has been done with apertures. That solution, however, contributes both end effects and background. In our case, we define the fiducial volume with the silicon detectors. Since the magnetic field projects specific volume elements within the neutron beam onto specific areas of the segmented detectors, it is possible to define the decay volume by selecting events from only the central elements of the detectors. This technique avoids the use of apertures and the associated problems.

2.2 Neutron Polarizer

The combination of a short-pulse neutron source, where the neutron energy is correlated to the arrival time, and a polarized ^3He neutron spin filter, where there is an exact relationship between the neutron polarization and transmission, provides a powerful tool for determining the neutron polarization absolutely.

The use of polarized ^3He gas targets as neutron polarizers makes possible a new technique for an absolute neutron beam polarization measurement. For monochromatic neutrons, there is a simple relation between the neutron polarization P_n produced by transmission through a polarized ^3He target and the relative transmission of neutrons through polarized (T_n) and unpolarized (T_n^0) ^3He :

$$P_n = \sqrt{1 - \left(\frac{T_n^0}{T_n}\right)^2}. \quad (3)$$

For a transmission neutron polarizer based on polarized ^3He , where the target has negligible multiple scattering and the neutron cross section is dominated by absorption rather than scattering, this equation holds to a high degree of accuracy under realistic beam conditions. Since this relation requires only relative neutron transmission measurements, it represents a new and reliable way to measure and monitor on-line the absolute polarization of a neutron beam [6]. This method has been proven to an absolute accuracy of 0.2%, which was limited by statistics. There are no obstacles to measuring the neutron polarization by this technique to an accuracy of $< 0.1\%$ [7].

In fact, there is an even better way of measuring *in situ* the neutron polarization in neutron β -decay which also makes use of the properties of ^3He . Because the correlation parameter B is independent of neutron energy, any change in the measured asymmetry ε as a function of neutron time-of-flight is due to the energy dependence of P_n

$$\varepsilon(t) = P_n(t)B = B \tanh(-t/\tau) \approx B(1 - e^{-2t/\tau}), \quad (4)$$

where τ depends upon the properties (thickness, polarization) of the ^3He polarizer. Therefore, B can be extracted from the asymptotic behavior of ε as $t \rightarrow \infty$, while τ can be independently determined from the time dependence of ε . Once τ is known, P_n is then determined for all t . Note that for the determination of P_n , it is only necessary that B is constant, not that B is known. In addition, since B is large ($B \sim 0.9$), the statistical accuracy of

the measurement of P_n is not a limitation in the determination of the other coefficients.

There are two very different methods of spin reversal available in this design. First, the polarization of the ^3He can be reversed, with a period of a few hours. This does not affect the neutron polarization methods mentioned above, so P_n can be equally well known for both states. Second, an RF spin flipper can be turned on for alternate beam pulses, providing a rapid (20 Hz) spin reversal. Although any neutron depolarization induced by the RF spin flipper is not detected by the polarization measurement, this effect can be made arbitrarily small by the design of the flipper. In addition, the reversal efficiency of the spin flipper can be measured. The availability of two, very different, spin reversal techniques is important for diagnosing systematic effects.

2.3 Silicon Detectors

Silicon strip detectors are required which can detect both 30 keV protons and up to 750 keV electrons with unit efficiency, energy response independent of position, good energy resolution, good timing resolution, and position information. We are presently working toward the demonstration of the detector technology. All of these criteria have been met individually with silicon detectors. Achieving them all simultaneously in the LANSCE environment, however, requires development. Once the detector performance has been demonstrated, the path to a series of measurements in neutron β -decay is clear.

The detector requirements which result from having to detect in coincidence both the decay protons and electrons are rather stringent. For detecting the low-energy protons, a detector with a very thin inactive layer and low noise is needed. Conversely, detection of the electrons requires a fairly thick detector so that all of the electron energy is deposited. In addition, since we intend to measure the shape of the electron spectrum, good energy resolution is needed. The need for coincidence information requires that the detector have good timing resolution for both particles. Timing resolution is particularly important in the case of the electrons, since one must be able to distinguish electrons that backscatter from one detector, pass through the magnetic field pinch and strike the second detector. A final requirement is segmentation of the detectors to define the decay volume and provide background information.

These requirements led to our choice of silicon strip detectors for this experiment. Silicon strip detectors have essentially unity efficiency and good (few keV) energy resolution. They are available with very thin inactive layers (equivalent to a loss of 4 keV for 30 keV protons and a few eV for 50 keV electrons [8]), and can be segmented with no inactive areas between the seg-

ments. The difficulties, however, include reducing the noise to a sufficiently low level, making a single detector thick enough to stop the electrons (≈ 2 mm), and achieving the necessary timing resolution (a few ns). We plan to design, construct, and test a small-scale version of the final detector, with associated electronics. The demonstration detector will meet all of the critical requirements of the final version, including inactive layer thickness, noise level, energy resolution, timing resolution, and efficiency.

3 Summary

Precision measurements of the neutron beta-decay correlations A , B , a , and b provide important tests of the standard model of electroweak interactions: a test of the unitarity of the first row of the CKM matrix, a search for new weak interactions, a test of the theory of nuclear beta decays, and a test of the conserved-vector-current hypothesis. We are designing an experiment to measure at LANSCE all four correlations to an order of magnitude better accuracy than the existing measurements. The accuracy of the earlier measurements was limited by systematics. The design of the proposed experiment makes use of the pulsed nature of the LANSCE source to reduce systematic errors associated with the measurement of the neutron polarization as well as other systematic errors. In addition, we are developing silicon strip detectors for detecting both the proton and electron from the neutron decay.

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