TITLE: ANGULAR CORRELATIONS IN NEUTRON BETA DECAY

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MASTER
ANGULAR CORRELATIONS IN NEUTRON BETA DECAY

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The search for new physics and the state-of-the-art technology in experiments at the forefront of the search were foremost among the things which motivated Walter Mampe as a physicist. He was a person of many remarkable qualities, both as a person and as a scientist. He was also my friend and will be sorely missed. Thus, I dedicate this paper to the memory of Walter Mampe, as he had a deep interest in the physics described here and participated with us in the development of a new generation experiment searching for time reversal violation in polarized neutron beta decay.

1. INTRODUCTION

Our current understanding of the physical world is embedded in the Standard Model, which describes the structure of the strong, electromagnetic, and weak forces as:

\[ SU(3)_C \otimes SU(2)_L \otimes U(1)_{EM}. \]

The Weinberg-Salam-Glashow (W-S-G) model of the electroweak interactions is contained within this and provides us with a pure left-handed (V-A) interaction. While this of course reproduces the observed state in nature, the Standard Model does not provide any underlying reason for this structure, it is not able to predict the observed mass spectrum of quarks and leptons, it does not reduce the number of coupling constants of the interactions, nor does it include gravity. While the Standard Model is in spectacular agreement with all experimental data, it is assumed that it is only part of a larger model. It is this belief that has motivated the formulation of Grand Unified field Theories (GUTs), SUperSYmmetric (SUSY) theories, and String Theories. All of these theories attempt to unify the weak nuclear, electromagnetic, and strong nuclear forces in a single, comprehensive theory. They generally 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 both 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 search for 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.

In order to search for new physics beyond the Standard Model, one can either measure known quantities with ever increasing accuracy and precision and hope to find a difference between the Standard Model predictions and the measurements. Or one can
look for new effects which are not included in the Standard Model, but are predicted by the Grand Unified field Theories. Angular correlation measurements in neutron beta decay provides a means to do both. By accurately and precisely measuring the coefficients of the allowed angular correlations (electron-neutrino, spin-electron, and spin-neutrino) one can search for the presence of right-handed currents and scalar and tensor terms in the weak interaction. By searching for a non-zero time-reversal-violating correlation coefficient, one can test for the existence of Time Reversal Violation. Thus, the need for experiments with ever increasing accuracy and precision in neutron beta decay is clear.

2. THEORETICAL DESCRIPTION OF POLARIZED BETA DECAY

One can write the Hamiltonian which provides the most complete description of neutron beta decay as 1):

$$H_{\text{int}} = \Sigma_i \left( \begin{array}{c} p \Gamma_i n \end{array} \right) \left[ e \left( C_i \Gamma_i + C_i' G_i \gamma_5 \right) \bar{\nu} \right] + \text{h.c.}$$

where $p$, $n$, $e$, $\bar{\nu}$ are the spinor wave functions of the proton, neutron, electron, and antineutrino, respectively, h.c. is the Hermitean conjugate, and

$$\Gamma_i = 1, \gamma_{\mu}, \sigma_{\mu_{\nu}}/\sqrt{2}, i\gamma_{5}\gamma_{\mu}\gamma_{5}$$

expressed in terms of the usual Pauli matrices. Under the most general assumptions that allow possible time reversal violation and both right- and left-handed currents, there are 19 real free parameters. If one places the condition of time reversal invariance on the Hamiltonian, then there are still 10 arbitrary constants. The matrix element $M_\beta$ for neutron beta decay can then be written using this Hamiltonian in a current-current formulation as 2):

$$M_\beta = (2\pi)^4 \left( G_\beta / \sqrt{2} \right) j_\mu^1 j_\mu^n$$

where $G_\beta$ is the Fermi coupling constant, and

$$j_\mu^1 = -i \left\langle u_e \left| \gamma_{\mu} \left(1 + \gamma_5\right) \right| u_{\bar{\nu}} \right\rangle$$

where $u_e$ and $u_{\bar{\nu}}$ are the electron and spinor wavefunctions, and

$$j_\mu^n = j_\mu^V + j_\mu^A$$

where

$$j_\mu^V = i \left\langle u_p \left| g_5 \gamma_{\mu} - (g_M - g_V) \sigma_{\mu \nu} q_\nu / 2m_n - i g_S q_\mu / 2m_n \right| u_n \right\rangle$$

and

$$j_\mu^A = i \left\langle u_p \left| g_A \gamma_{\mu} - g_\Pi \sigma_{\mu \nu} \gamma_5 q_\nu / 2m_n - i g_P \gamma_5 q_\mu / 2m_n \right| u_n \right\rangle$$
and the form factors describe the vector \( (g_V) \), axial vector \( (g_A) \), induced pseudotensor \( (g_M - g_V) \), induced tensor \( (g_T) \), induced scalar \( (g_S) \), and induced pseudoscalar \( (g_P) \) interactions.

The differential probability that a polarized neutron will decay with the emission of an electron and an antineutrino in specified directions is given by 2):

\[
d^3W(p_e, p_\nu | \sigma) = dW(p_e) d\Omega_e d\Omega_\nu \left[ 1 + a p_e \cdot p_\nu / E_e E_\nu \\
+ \sigma \cdot (A p_e / E_e + B p_\nu / E_\nu + D p_e \times p_\nu / E_e E_\nu) \right]
\]

The coefficients correspond to the electron-neutrino \( (a) \), neutron spin-electron \( (A) \), neutron spin-antineutrino \( (B) \), and time reversal violating \( (D) \) correlations, respectively.

It is possible to write the correlation coefficients in terms of the ratio of the axial vector \( (g_A) \) and vector \( (g_V) \) coupling constants as 2):

\[
a = \left( 1 - |\lambda|^2 \right) / \left( 1 + 3 |\lambda|^2 \right)
\]

\[
A = -2 \left( |\lambda|^2 + |\lambda| \cos \phi \right) / \left( 1 + 3 |\lambda|^2 \right)
\]

\[
B = -2 \left( |\lambda|^2 - |\lambda| \cos \phi \right) / \left( 1 + 3 |\lambda|^2 \right)
\]

\[
D = 2 \left| \lambda \right| \sin \phi / \left( 1 + 3 |\lambda|^2 \right)
\]

where \( \lambda = g_A / g_V = |\lambda| \exp (i\phi) \).

In the above definitions of the correlation coefficients, we have not included the possibility of scalar and tensor terms or of right-handed currents. These can easily be included in a rather more complicated definition 3). For the sake of simplicity, the more complicated expressions are not given here.

3. MEASUREMENTS OF ANGULAR CORRELATIONS

3.1. Measurements of the electron-neutrino angular correlation

A measurement of the a coefficient can be made by measuring the proton recoil energy spectrum. The most accurate measurement made to date is that of Stratowa et al 4) at the ASTRA reactor in Vienna. In that measurement, the source consisted of neutrons decaying in an evacuated tangential through-tube near the core of the reactor. One end of the beam tube led to a 90° spherical condenser electrostatic spectrometer, while the other end of the tube housed a proton source for calibration. After analysis in the spectrometer, the protons (maximum recoil energy 751 eV) were accelerated by a potential of 20-35 kV and struck a thin (30 μg/cm²) aluminum foil. The secondary electrons ejected from both sides of the foil were accelerated to ground potential and measured in scintillation detectors. A total of 35 runs were made. A typical spectrum
The value for \( a \) was measured to be:

\[ a = -0.1017 \pm 0.0051, \]

resulting in a determination of \( \lambda \) of:

\[ |\lambda| = 1.259 \pm 0.017. \]

The precision of the measurement was predominately limited by systematic uncertainties in the absolute proton energy and possible effects which might distort the recoil proton energy spectrum. Great care had to be exercised to reduce the effect of stray electric and magnetic fields, as well as to ensure an accurate calibration of the system with a special proton gun.

Figure 1. Recoil proton energy spectrum from the measurement of Stratowa et al.

3.2. Measurements of the spin-electron angular correlation

A measurement of the A coefficient can be made by simply measuring the forward-backward asymmetry of the beta with respect to the direction of the neutron polarization. A precise measurement \(^5\) was made at ILL using the PERKEO spectrometer, which is shown in figures 2 and 3. In this experiment, a beam of cold neutrons are polarized by a supermirror polarizer, strongly collimated to restrict the beam divergence, and then pass through the bore of a 2-m-long superconducting magnet. A small fraction (about \(10^{-6}\)) of the neutrons decay within the solenoid. The betas spiral along the field lines and are deflected out of the beam at the ends of the solenoid by a set of transverse field coils. The betas are then detected in plastic scintillators at the two ends of the solenoid. One advantage to this scheme is that any betas which backscatter from the scintillators either are reflected back into the scintillator by the magnetic mirror effect, or are detected a few tens of ns later in the scintillator at the other end. Timing information allows one to determine which scintillator was hit first, thus largely eliminating effects due to backscattering.
The PERKEO experiment determined the value of $A$ to be $^{5)}\quad A_0 = -0.1146 \pm 0.0019$.

resulting in a determination of $\lambda$ of $\quad \lambda = -1.262 \pm 0.005$

The subscript 0 on $A_0$ indicates that the measured asymmetry $A$ has been modified to incorporate radiative corrections that must be applied in order to derive the correct value of $\lambda$.

The experiment limited predominantly by systematic effects associated with the transverse magnetic fields at the ends of the solenoid and the determination of the absolute neutron polarization. The magnetic field effects were due to uncertainties in the correction necessary due to magnetic mirror effects.

The measurement with the highest claimed precision was carried at the Institute for Atomic Energy (IAE) at the Kurchatov reactor. $^{6)}$

The IAE experiment determined the value of $A$ to be:

$A_0 = -0.1131 \pm 0.0014$, 
resulting in a determination of $\lambda$ of

$$\lambda = -1.2544 \pm 0.0036$$

As we will see further in section 5, it is important to note that the values of $\lambda$ determined by the ILL and IAE measurements disagree at about the 1.2 $\sigma$ level.

3.3. Measurements of the spin-neutrino angular correlation

There have only been two measurements of $B$ made with a precision of a few per cent. Both measurements are more than 20 years old and no further improvements in precision have been made in the interim. The measurement of Christensen et al. \(^7\) was made at the CP-5 reactor at Argonne National Laboratory. The betas were detected in a plastic scintillator and the recoil protons were accelerated by 10 kV to the cathode of an open photomultiplier assembly where they were detected. The measurement of Erozolimskii et al. \(^8\) was carried out at the IRT-M reactor at the Kurchatov Atomic Energy Institute. Although the detector geometry was different that of the Argonne detector, the principle was the same. The betas were detected in a plastic scintillator and the recoil protons were accelerated to 2.5 kV, focused by a set of spherical grids, and then accelerated by 30 kV onto a thin scintillator on the front face of a photomultiplier tube. The two experiments resulted in measurements of $B$ and the derived value of $\lambda$ of:

$$B = 1.01 \pm 0.05 \quad \text{Christensen et al.}$$

$$\lambda = 1.26 \pm 0.02$$

and

$$B = 0.995 \pm 0.034 \quad \text{Erozolimskii et al.}$$

Both of these measurements are in agreement with the Standard Model prediction that $B \equiv 1.0$, consistent with a pure V-A theory.

3.4. Measurements of the time-reversal-violating triple correlation

A measurement of the $D$ coefficient involves measuring the triple correlation between the spin of the neutron ($\sigma_n$), the momentum of the beta ($p_e$), and the momentum of the neutrino ($p_\nu$). By conservation of energy and momentum, one can write the correlation as:

$$\sigma_n \cdot p_e \times p_\nu / (E_e E_\nu) = -\sigma_n \cdot p_e \times p_p / [E_e (\Delta - E_e - E_p - m_e c^2)]$$

where $\Delta = m_p - m_n$, and $p_p$ is the momentum of the recoil proton. Thus, in order to determine the value of $D$, one must detect both the beta and the recoil proton, as well as determine the angle between them and the neutron spin.
The theoretical motivation to search for a non zero value of D is driven by the desire to understand the origin of CP violation. To date, CP (charge conjugation-parity) violation has been observed only in the case of kaon decay 9) at about the $10^{-3}$ level. According to the CPT theorem, CP violation also requires T (time reversal) violation. Numerous searches have been carried out to search for CP or T violating effects 10), but none have observed any evidence. In the case of polarized neutron beta decay, a non zero D would arise from a T-odd, P-even interaction. Such an interaction can occur due to new physics involving right-handed currents, leptoquarks, or exotic fermions. By contrast, models involving the Higgs mechanism, supersymmetric theories, or superweak theories all predict D to be zero. The standard KM (Kobayashi-Maskawa) theory predicts $D \leq 10^{-10}$. Thus, observation of a non zero value of D in the $10^{-5}$ to $10^{-3}$ experimentally accessible range would strongly restrict which models can correctly account for the origin of CP violation. 11)

However, one needs to realize that observation of a non zero value of D does not necessarily mean that T is violated. Final state interactions can also produce a finite value of D. In the case of the neutron, the contribution to a non zero D by such effects is calculated to be at the $2 \times 10^{-5}$ level 12). This is much lower than, for example, in the case of $^{19}$Ne decay, where final state effects are at the few $\times 10^{-4}$ level. Thus, neutron beta decay provides a clean test for a value of D larger than a few $\times 10^{-5}$.

The two most sensitive measurements of D have been carried out at the Institute Laue-Langevin 13) and one at the Kurchatov Institute of Atomic Energy 14). Both of these employed longitudinally polarized neutron beams passing through a detector array. In both experiments, the detector consisted of a pair of opposing plastic scintillators to detect the betas and orthogonal to them, a pair of opposing thin scintillators made of NaI or CsI deposited on the front of a photomultiplier. The geometry of the ILL measurement is shown in figure 4. In these geometries, the recoil protons (which have a maximum kinetic energy of 751 eV) are accelerated to 30 keV in order to be detected.

Pertinent information for the two experiments, as well as the final results achieved, are given in Table 1.

Table 1. Summary of previous triple correlation experiment parameters and results.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Neutron Capt. Flux</th>
<th>Neutron Polar.</th>
<th>Beam Size</th>
<th>Coincidence Rate</th>
<th>Signal to Noise</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILL 10^{-3}</td>
<td>$2 \times 10^9$</td>
<td>70</td>
<td>$4 \times 8$ cm$^2$</td>
<td>1.5</td>
<td>4</td>
<td>(-1.1 ± 1.7) x</td>
</tr>
<tr>
<td>Kurchatov 10^{-3}</td>
<td>$3.5 \times 10^7$</td>
<td>66</td>
<td>$14 \times 2$ cm$^2$</td>
<td>0.8</td>
<td>1.0</td>
<td>(+2.2 ± 3.0) x</td>
</tr>
</tbody>
</table>
The signature for a non zero $D$ in these experiments is a left-right asymmetry in the number of protons relative to a given beta detector. The symmetry of the detectors helps to reduce possible systematic problems. The dominant systematic uncertainties arise due to couplings between the allowed angular correlations in neutron beta decay and asymmetries in the efficiencies of the different detector segments.

Figure 4. Cross-sectional view of the ILL D-coefficient experiment.

4. THEORETICAL IMPLICATIONS

Prior to 1990, essentially all of the measurements of angular correlations in neutron beta decay agreed well with each other and arrived at a common value of $\lambda$, as shown in figure 5. A combined analysis of the data (together with measurements of the neutron half-life and $0^+ \rightarrow 0^+$ nuclear beta decay) yielded:

$$\lambda = -1.261 \pm 0.004 \quad \text{(from correlation measurements)}$$

while

$$\lambda = -1.267 \pm 0.007 \quad \text{(from neutron lifetime measurements)}$$

indicating good agreement between the different techniques of determining $\lambda$. An analysis for the possible presence of scalar, tensor, or right-handed components of the weak interactions indicated that the data were consistent with a pure $V - A$ interaction and set limits on the possible contributions of either pure scalar or pure tensor at about the 10-15% level, and a limit on possible $V + A$ contributions at about the 10% level.
Possible combinations of scalar plus tensor contributions could not be ruled out at less than about the 40% from neutron beta decay measurements alone.

Figure 5. Results for the neutron decay correlation coefficients.

However, with the new IAE result for the value of A, the situation has changed. A recent analysis of the results shows that if one uses the IAE result rather than the ILL result for the value of the neutron spin-electron correlation coefficient, one finds disagreement with the Standard Model. If one formulates the weak interactions in a left-right symmetric model, the presence of right-handed currents corresponds to the existence of a right-handed gauge boson $W_R$ in addition to the conventional left-handed gauge boson $W_L$. $W_L$ and $W_R$ are combinations of two mass eigenstates $W_1$ and $W_2$ with masses $m_1$ and $m_2$. Thus,

$$W_L = \cos \zeta \ W_1 + \sin \zeta \ W_2$$

$$W_R = -\sin \zeta \ W_1 + \cos \zeta \ W_2$$

where $\zeta$ is a mixing angle. One can then express the correlation coefficients in terms of $W_L$ and $W_R$ (or equally well in terms of $W_1$ and $W_2$) and plot the allowed regions in terms of the ratio of masses squared $\delta = (m_1^2 / m_2^2)$ and the mixing angle $\zeta$.

The allowed regions using values of the spin-electron correlation $A$ coefficient which either exclude the recent IAE measurement or use the value from the recent IAE measurement are shown in figure 6. One clearly sees that the conclusion one draws depends entirely on which measurement of $A$ is used. Supporting evidence for
disagreement with the Standard Model comes from the most recent measurement of the spin-electron correlation in $^{19}$Ne [16]. However, one also finds that the analysis of measurements in muon decay in terms of right-handed currents disagrees with the new IAE and $^{19}$Ne results. [16] While it is possible to derive models which would predict right-handed contributions in the semileptonic sector but not in the purely leptonic sector, it is perhaps more plausible that one or more of the measurements is in error.

\[ \left( \frac{M_1}{M_2} \right)^2 \]

\[ \chi^2 = 0 \]

Figure 6. Allowed regions (inside the solid lines) at the 90% CL in the ($\delta, \zeta$) region if one uses a) the spin-electron correlation $A$ coefficient data and the $f$$f$ value ratio $R_N$ in neutron decay, with the exclusion of the recent IAE measurement of $A$, and b) the most recent IAE data for the value of the spin-electron correlation $A$ coefficient and the $f$$f$ value ratio $R_N$ in neutron decay.

Thus, it is absolutely clear that new measurements with higher accuracy and precision are required to sort out the origin of this discrepancy. It is also absolutely clear that it is necessary to continue to push the sensitivity of neutron decay measurements ever further in order to search for (and conclusively demonstrate the existence of, if found) possible new physics beyond the Standard Model.

5. FUTURE POSSIBILITIES

Obviously, it is important to continue to improve the accuracy and precision of angular correlation measurements in neutron beta decay. Such improvements will further our
understanding of the structure of the weak interactions, as well as providing an opportunity to search for new physics beyond the Standard Model.

A number of advances in the technology of sources, polarizers, and detectors have been made in the last several years. In addition, more intense neutron sources are in the planning stages. I will discuss these advances as they apply in the case of possible improved measurements of each of the angular correlations.

5.1. Measurements of the electron-neutrino angular correlation.

There are three possible approaches which have been raised to improve the measurements of $\alpha$. In the first method, the pioneering work by Byrne et al. 17) demonstrated the possibility of trapping decay protons from neutron beta decay in an electromagnetic trap. In that experiment, a well collimated, small-diameter beam of neutrons passed through the bore of a superconducting magnet that had a set of trapping electrodes inside the magnet. By biasing the electrodes above the maximum recoil energy of the protons (0.751 keV), the recoil protons from any neutrons decaying between the electrodes are trapped in the decay volume. The trapped protons could be released by applying a 1-2 kV pulse to one of the electrodes. They were then accelerated to an energy of 30 keV and counted in a surface barrier detector. By knowing the volume of the decay region, the neutron beam density, and the proton detection efficiency, they were able to determine the neutron lifetime. The primary advantage of this technique was that the protons could be trapped for long periods without appreciable losses (tens of milliseconds) and the protons in the trap could be emptied and counted in a period of microseconds, resulting in a large suppression of backgrounds.

A second generation experiment using this idea is now underway at NIST by Greene et al. 18) In this experiment, the trapping electrodes are replaced by a series of cylindrical electrodes, as shown in figure 7. This makes it possible to use a larger diameter beam,
with the resultant improvement in statistics, as well as to vary the length of the trap by varying the potentials applied to the ring electrodes. This allows one to accurately determine the length of the trap by differential measurements. Again, the primary goal is a precise measurement of the neutron lifetime.

Figure 8. The upper plot shows the proton trapping rate in the Penning trap, normalized to the maximum rate, versus confinement voltage. The lower plot illustrates the sensitivity of the count rate to small changes in $\lambda$ (±0.02). Again, the changes are normalized to the maximum count rate.

A variation in this technique offers the possibility of measuring $a$. In the lifetime measurement, the trap is emptied quickly, so that protons of all energies are accelerated and detected in a short period. However, if one instead slowly reduces the trap voltage, one can energy analyze the protons. In this case, as the trap voltage is slowly lowered, all protons with kinetic energies above the trap voltage will be extracted, accelerated, and detected. As the trap voltage continues to be lowered, lower energy protons will be extracted and detected. Thus, by measuring the count rate versus trap voltage, one can determine the energy spectrum of the trapped protons. In the same manner as used by Stratowa et al, one can then determine $a$ from the energy spectrum of the trapped protons. Figure 8 shows the effect on the spectrum as a function of the value of $a$. It is clear this experiment is quite difficult, as it requires a measurement of the shape of the proton energy spectrum with an accuracy of $10^{-4}$ in order to substantially improve the determination of $a$ and $\lambda$ over that already obtained. It is expected that the present
effort to measure the neutron lifetime to an accuracy of 1 s will provide the information necessary to evaluate the possibility of handling the statistical and systematic uncertainties in a measurement of a to the required level. As the neutron lifetime experiment is scheduled to be completed during 1994, it may be possible to envision an improved measurement of a starting in 1995.

The second method of improving the measurement of a would involve a setup similar to that used by Stratowa et al, but would rely on much higher beam intensities in order to accumulate the required statistical accuracy as well as to carefully study possible systematic effects. In order to do this, the next generation of reactor will be required in which a through port exists to allow one to extract the recoil protons. Such a facility is included in the plans for the PIK reactor in St. Petersburg and for the Advanced Neutron Source (ANS) reactor at Oak Ridge. Extracted proton fluxes are anticipated to be three to four orders of magnitude higher at these facilities than in the measurement of Stratowa et al. However, as funding for these two facilities is uncertain at present, it is not clear when such an improved measurement might be possible.

The third method would involve a direct measurement of the angular correlation by measuring both the momenta of both the recoil proton and the beta. Such a measurement of could be envisioned with an unpolarized neutron beam with a detector similar to that being developed by the EMIT collaboration for studies of time-reversal violation. In this case, one averages over the energy spectrum of the proton in determining the angular correlation. By an appropriate choice of kinematic constraints, one can unambiguously reconstruct the neutrino momenta by conservation of energy and momentum. It would likely be necessary to incorporate tracking of the betas using a TPC in front of the scintillators to provide enough information to reconstruct the decays. Knowing the electron and neutrino momenta, one can then directly determine the value of a. A variety of possible systematic effects can be studied by varying cuts on the electron and proton momenta. This could be done both by software, as well as by hardware (for example, by installing a cylindrical trapping grid around the neutron beam so that only protons with transverse energies above the trap voltage would be accelerated and detected). While detailed calculations of the sensitivity of such a setup have not been carried out, it appears possible to reach a precision five to ten times better than in the previous measurement of a. Experience with the EMIT detector during the next two years should allow one to better assess the feasibility of this method.

5.2. Measurements of the spin-electron angular correlation.

An improved version of the PERKEO spectrometer, called PERKEO II, is under construction. The primary difference is that instead of a superconducting solenoid, the experiment will use a completely transverse magnetic field produced by a set of superconducting coils. This should effectively reduce the systematic uncertainty due to magnetic mirror effects. The remaining dominant limitation to the precision of a new measurement with PERKEO II will be due to the precision with which the absolute value of the polarization can be measured. It may be possible to improve this, resulting
in a measurement perhaps 2-3 times more precise than in the previous PERKEO measurements.

As the dominant limitation of the measurements of A are largely limited by the precision with which the absolute polarization can be measured, it would be a great advantage to carry out the measurement in which the polarization can be made effectively unity. Such a scheme has been proposed by Greene 18) in which the ultra cold neutrons (UCN) would be trapped in a linear hexapole with reflecting surfaces at the ends. Previous work by Paul et al. 19) showed it is possible to trap UCN in a toroidal hexapole. This arrangement was used to measure the neutron lifetime and it was demonstrated that losses of neutrons within the trap are quite small. As the hexapole field configuration can trap only one spin state, the polarization of the trapped UCN is 100%. Windows of thin films of materials such as BeO could be placed at the ends of the linear hexapole. The UCN would be reflected from such a film without any loss in polarization, while the betas from the decays of UCN in the hexapole trap could pass through the foil, and be detected in a scintillation counter. It is likely that the dominant systematic uncertainty in such an experiment would come from scattering effects of the betas in the windows. As the backscattering from the foils will be of order 10%, great attention must be paid to such effects to reach the desired precision of a fraction of a per cent for A. One of the technical problems to be resolved would be the means of filling the hexapole trap with UCN. However, it seems plausible that such a measurement could improve substantially on the present precision and accuracy to which A is known.

Another possible scheme using UCN have been proposed. 20) In this scheme, the UCN are held in a trap in a superconducting solenoid-polarizer attached to a correlation spectrometer. The spectrometer consists of a Si(Li) detector for the betas and an accelerating grid with microchannel plate detectors for the protons. Thus, one is able to study the correlations between the betas and recoil protons, thus making possible measurements not only of A, but also of a and B.

5.3. Measurements of the spin-neutrino correlation.

Although the last measurement of B was carried out more than 20 years ago, there are at present no experiments planned which would provide a new measurement of B.

At least two detector systems are capable of measuring B, the system of Erozolimskii and the EMIT detector (see section V.4). Basically, it is necessary to track both the recoil proton and the beta with respect to the neutron spin in order to handle possible systematic problems. Presumably, it is the relative insensitivity of B to $\lambda$ that has not prompted people to pursue a new measurement of B. However, it has been noted independently by a number of people that by simultaneously measuring both A and B in the same apparatus, one can make a very precise determination of $\lambda$. This is due to the fact that one of the dominant systematic uncertainties in measuring $\lambda$ has been in the determination of the polarization in measurements of A. By measuring A and B simultaneously, one can form the ratio $\lambda = (A - B) / (A + B)$. To first order, the
polarization, as well as many geometrical and detector efficiency effects, cancel. It is possible that such a measurement may provide the most accurate single determination of $\lambda$. Plans to pursue such a measurement are underway at St. Petersburg by Serebrov et al. The possibility of such a measurement using the EMIT detector has also been raised, but would not occur until after the measurement searching for a finite $D$ is completed. While count rates are likely to be sufficient to provide the most precise measurement of $\lambda$ to date at both the St. Petersburg and ILL reactors, a careful determination of possible systematic effects has not yet been carried out.

5.4. Measurements of the time-reversal-violating triple correlation

Two new efforts are planned to search for a non zero value of $D$. The first involves an improved version of the earlier IAE experiment of Erozolimskii. In the new version, the detector can be rotated about the neutron beam axis in order to study possible systematic effects due to asymmetries in the beam. While it is possible to run this experiment at the IRT-M reactor, in order to obtain the necessary statistics to reach into the few $x 10^{-4}$ range, it will be necessary to use the beams from the new PIK reactor presently under construction. It is likely to be a few years before the PIK reactor is available for research, but in the meantime it is possible to study systematics with the present beam.

Figure 9. Geometry of the EMIT detector. The beam and neutron polarization are into the page. Electron detectors are designated by "e" and proton detectors by "p".

The second effort is that of the EMIT (TIME spelled backwards) collaboration. 21) This experiment will utilize a new geometry as well as arrays of PIN diodes to detect the protons in order to push down the few $x 10^{-4}$ range. The detector geometry is shown in Figure 9. An important feature to note is that the proton and beta detectors are not orthogonal as in the earlier experiments at ILL and IAE. The reason for this is that due
to the effect of the other angular correlations, the electron and proton are strongly peaked in opposite directions. Thus, while naively one would assume that the product $\sigma_n \cdot p_e \times p_p$ would be maximized by having the neutron spin, electron, and proton detectors all orthogonal to each other, this is not true. Taking into account the other angular correlations in polarized neutron beta decay, the maximal sensitivity to D comes when the beta and proton detectors are at about 150°, as shown in figure 10.

![Monte Carlo results for the contribution of the D-term as a function of beta-proton angle ($\theta_{e-p}$) for right-handed events. The solid curve is an empirical fit to the Monte Carlo data. The dashed curve shows the sine of $\theta_{e-p}$ which would be the contribution to the D-term if it had only the sine dependence of the cross product.](image)

A uniformly high efficiency, low background polarimeter is essential to this experiment, as well as for other experiments requiring polarized beams. Supermirror polarizers have been developed at the ILL which consist of multiple layers of cobalt and gadolinium. The layers are thin (typically a few Å) and numerous, thus forming an interference film for the neutrons. The layers are typically deposited on thin layers of glass, which are then slightly bent so that neutrons must scatter at least once in passing through the polarizer. The cobalt is magnetized in one direction by an external magnet. Neutrons of the correct spin state pass through with high efficiency, typically greater than 95% for cold neutrons (those neutrons with wavelengths centered around 6 Å). Neutrons of the wrong spin state are scattered isotropically and are mostly absorbed in the gadolinium layers of the supermirror. While the supermirrors are easy to operate, have fairly uniform high polarization over the entire polarizer aperture, have uniformly high polarization for cold neutrons, and have high transmission, they do have some disadvantages. Since neutrons with the wrong spin state are primarily captured in the gadolinium layers, there are typically 4 gammas produced for every neutron captured. This results in an intense gamma background from the supermirror. In addition, the supermirror increases the divergence of the beam, due to the scattering from the curved glass surfaces of the supermirror. In order to overcome these difficulties, efforts are
underway to produce a new polarizer based on polarized $^3$He. A $^3$He polarizer has the advantages that all of the wrong spin state neutrons are captured in the $^3$He(n,p)$^3$T reaction. The $^3$He(n,$\gamma$) branch is less than $2 \times 10^{-5}$, so that essentially all of the wrong spin state neutrons are captured without producing a gamma. In addition, the only increase in the beam divergence is due to a small amount of elastic scattering in the glass windows of the polarizer cell, and the increase in beam divergence is very small. The disadvantage is that a fairly complex system is required to produce polarized $^3$He. In order to produce polarized $^3$He, a small cell containing atomic cesium is optically pumped by an intense laser. $^3$He is then polarized by spin exchange with the Cs, and migrated through a connecting tube to fill the glass cell which acts as the neutron polarizer. In order for this scheme to work, cells with very long relaxation times must be built, and this is not so easily achieved. A joint effort between part of the EMIT collaboration and a research initiative funded for 5 years by NIST has been formed to develop usable $^3$He polarizers with beams of cross section up to 5 cm in diameter.

A test run carried out at NIST was carried out by the EMIT collaboration in order to determine count rates, backgrounds, efficiency of the focusing of the recoil proton detectors, and whether or not a TPC in front of the scintillators was required to achieve a reasonable signal to background. The results indicated that the backgrounds were tractable, that the efficiency of focusing was at least 50%, count rates were about as expected, and that a TPC was not required. Data from one of the runs showing the time coincidence between betas and protons is shown in figure 11. Using this data, with estimates of the effect of improvements in background suppression, it is expected that a signal to background of about 10 can be realized. This will allow a statistical accuracy of $3 \times 10^{-4}$ to be reached in 2 months of running time at NIST. Systematic effects have been studied by Monte Carlo in detail and it is believed they can be held to the $10^{-4}$
level. Final design of the beamline and full scale detector is now underway and it is expected that running should begin in 1994. Assuming the experiment reaches the design sensitivity at NIST, it would be possible to move the experiment to the ILL to take advantage of the higher fluxes there. It should be possible to reach a sensitivity of about $10^{-4}$ at the ILL.

5.5. Measurements of weak magnetism.

The magnitude of weak magnetism is predicted by the Conserved Vector Current (CVC) theorem, which relates the weak magnetism form factor to the anomalous magnetic moments of the neutron and proton. Previous tests $^{22}$ of CVC in masses 8, 12, and 20 have resulted in accuracies of only about 10-15%, and concern about the precision in some of the measurements due to possible systematic effects has been raised. Thus, it is quite important to provide an accurate and precise test of CVC. In principle, the beta decay of the neutron offers an ideal place for such a test. The effect of weak magnetism is to produce an energy dependent term in the decay amplitude:

$$W(E, \theta) = (\text{allowed spectrum}) \times \{(1 + a_{\text{wm}}E) + \sigma_n \cdot p/E (A + a'_{\text{wm}}E)\} \, dE \, d\Omega$$

where $a_{\text{wm}}$ and $a'_{\text{wm}}$ are the amplitudes of the weak magnetism form factors, which are predicted by CVC to be:

$$a_{\text{wm}} = 3.4 \times 10^{-3}/\text{MeV} \quad \text{and} \quad a'_{\text{wm}} = 2.1 \times 10^{-3}/\text{MeV}.$$ 

Thus, the measurement of the weak magnetism form factor $a'_{\text{wm}}$ requires an accurate determination of the energy dependence of $A$. Earlier plans by the PERKEO collaboration to measure weak magnetism proved impossible due to an asymmetry in the energy dependence of the background in the two PERKEO detectors. The source of this background was the supermirror polarizer, which was located 3 m upstream from the detector. Because the detector closer to the polarizer could be better shielded from beam halo backgrounds, there was an energy dependent asymmetry in the background between the two detectors. Due to the small effects in the energy dependence which must be measured accurately to provide an interesting test of CVC, these backgrounds have presented an insurmountable obstacle in trying to measure weak magnetism. Although the scientific interest is quite high, at present, there are no plans to try to measure weak magnetism.

However, such a measurement may prove possible at future facilities. Strong efforts are underway to develop $^3$He polarizers for use in EMIT and other experiments. A usable $^3$He polarizer will substantially reduce the polarizer backgrounds which have prevented a measurement of weak magnetism. However, until such a polarizer exists, it is essentially impossible to accurately determine what background levels might be achieved and whether or not a measurement of weak magnetism might be possible.
5.6 Measurements at Spallation Neutron Sources

Two of the dominant systematic problems facing measurements of neutron beta decay are those due to beam associated backgrounds and detector end effects. It is possible to ameliorate both of these effects using pulsed neutron beams from spallation neutron sources. Of course, it is also possible to chop DC beams from reactors to provide pulsed beams. In fact, chopped reactor beams have been used in several experiments in neutron beta decay, including lifetime measurements 23) and a measurement of the A coefficient 24). However, chopping DC beams results in a tremendous loss of total intensity. With pulsed spallation neutron sources, the average beam flux may be lower than that available at reactors, but the peak intensity can be considerably higher (by more than an order of magnitude) than the average intensity at reactors. Future spallation neutron sources are under discussion with intensities higher than present sources by at least a factor of five.

The desired characteristics of a chopped or pulsed neutron beam is that the beam can be contained entirely within the detector during the period when decays are observed. Given detector lengths of typically 0.5 - 2 m, and cold neutron beams with typical velocities of about 1000 m/s, this implies beam pulses in the range of 0.1-1.0 ms in duration. Spallation sources typically have beam pulses with widths of order 0.1 - 10 μs. However, the pulse duration is determined primarily by the moderation time rather than the beam pulse width. Moderation times can be tuned by using different moderators and neutron poisoners (such as Cd), but they are typically in the 0.1-1.0 ms range. Thus, the pulse width from a spallation source is well suited to the requirements for neutron beta decay measurements. The second desired characteristic is that any scattering surfaces (such as collimators, supermirrors, beam stops, analyzers, etc.) be located sufficiently far away from the detector active volume that a timing cut during the period the neutrons are within the decay region of the detector can effectively suppress all prompt neutron induced gamma activities. Again, with beam pulses of typically 0.1-1.0 ms and typical velocities of 1000 m/s, this requires that all scattering surfaces be located a minimum of about 10-100 cm away to ensure that all of the beam has passed by the scattering surface by the time the beam enters the detector decay region. This is also a requirement which can be relatively easily met.

Cold neutron beams are presently available at spallation neutron sources such as the Los Alamos Neutron Scattering CEnter (LANSCE). The intensity of cold neutrons at LANSCE are typically a few times that available at the ILL, as shown in figure 12. The fluxes are for a beam power on target of about 50 kW. Plans for future spallation neutron sources call for beam power on target in the 1-5 MW range. Thus, fluxes of cold neutrons may be available in the future which have peak intensities which are perhaps two orders of magnitude higher than available at the ILL. At those intensities, the average flux of cold neutrons at such a spallation neutron source will even approach the average flux currently available at the ILL.

Rather than waiting for a new spallation source to be built, it has been proposed 25) that it may be possible to simply convert the LAMPF beam stop into an intense cold neutron
source. LAMPF can provide 800 kW of beam power (1 mA at 800 MeV) which could be directed onto a spallation neutron target. As the LAMPF beam width is typically 0.8 ms wide at 10\% duty factor, the neutron pulse width will be approximately 1 ms, which is reasonably well matched to the requirements of possible neutron beta decay measurements.

Future measurements of angular correlations may also be feasible using stored Ultra Cold Neutrons (UCN), as discussed earlier. Spallation neutron sources appear capable of currently producing densities of UCN which surpass that available at reactors. Thus, it may be possible to further push the sensitivity of the measurements using UCN at spallation sources.

UCN are produced at spallation sources by guiding neutrons from a cold (liquid hydrogen) moderator along a guide tube to a UCN converter. Various possible schemes for converters have been proposed. One relies on downscattering in liquid helium and is under development at KEK in Japan.\(^{26}\) Another scheme for a converter consists of a reflector (mica crystals or multi-layer mirrors) moving in the same direction as the neutron beam, but at half the velocity. The mirrors then Bragg scatter some fraction of the neutrons and Doppler shift them at the same time. Thus, it is possible to convert cold neutrons (with velocities in the 200-800 m/s range) into the UCN regime. Production of UCN at neutron spallation sources by this method has been demonstrated\(^{27}\) and it appears feasible to improve on these techniques. Estimates of UCN production at LANSCE using perfect mirrors indicates that densities (at the UCN converter) of a few hundred n/cm\(^3\) can be obtained.\(^{28}\) This is to be compared with the densities achieved using a turbine converter at the ILL of about 90 n/cm\(^3\).\(^{29}\) As the estimates at LANSCE are based on data from an existing moderator, they seem fairly reliable. It is possible to somewhat improve the densities achieved by optimization of the moderator for UCN production. At future spallation neutron sources, densities of perhaps up to 10\(^4\) n/cm\(^3\) seem feasible. However, one must keep in mind that these quoted densities are peak densities at the converter. As the UCN travel down a guide tube to an experimental apparatus, the packets of UCN will disperse due to the spread in velocities of the UCN. After traversing a very long guide tube, the UCN will reach an equilibrium density which is much less than that at the converter. Thus, whether or not one can take advantage of the high peak densities available at the converter will depend largely on the distance the UCN must be transported to the experimental apparatus. Nonetheless, it is likely that a number of experiments can take advantage of the peak densities available. And at future spallation neutron sources, the average UCN density will likely exceed that available at reactors. Thus, UCN production at spallation neutron sources offers a promising future to extend the sensitivity of angular correlation measurements.

6. SUMMARY

A number of very beautiful angular correlation measurements in neutron beta decay have been carried out during the past few decades. While the general agreement with
the Standard Model is good, recent measurements of the spin-electron angular
correlation indicate some possibility of new physics beyond the Standard Model. It is
essential to pursue further measurements with higher accuracies and precision. A
number of experiments under way or in the planning stages will certainly push our
sensitivity for physics beyond the Standard Model. Somewhat farther in the future are
prospects of intense new sources and new techniques which will dramatically improve
our ability to push these experiments to much higher levels of sensitivity. The next ten
years are bound to be exciting and offer the definite prospect of being able to find the
long-sought new physics beyond the Standard Model.

Walter Mampe was a man who contributed a great deal to our progress in the field of
fundamental physics measurements with neutrons. He was also a person who was
always looking to the future with excitement. It is a great loss to the field and a
tremendous personal loss to all of his friends and family that he will not be with us to
see this progress. His efforts to better understand Nature have formed much of the
basis with which we can continue to move forward. And we know in many ways he is
still with us and can see our excitement about the future.

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REFERENCES

1) Sakurai, J.J., Invariance Principles and Elementary Particles, Princeton University
5) Klemt E., Bopp P., Hornig L., Last J., Freedman S.J., Dubbers D. and Scharpf O.,
6) Erozolimskii, B.G., Kuznetsov, I.A., Stepanko, I.V., Kuida, I.A., Mostovoi, Yu. A.,
8) Erozolimsky, B.G., Bondarenko, L.N., Mostovoy, Yu.A., Obinyakov, B.A., Titov,


18) Greene, G., private communication


25) Michaudon, A., private communication


28) Gram, P., private communication

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