SEARCH FOR TIME-REVERSAL NON-INVARIANCE IN NEUTRON BETA DECAY

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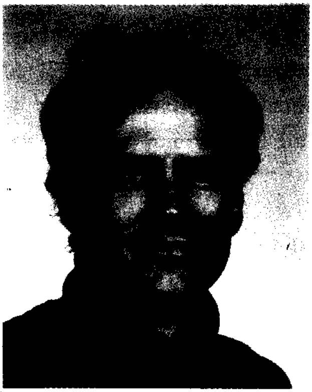

ABSTRACT

Since the discovery of CP-violation in 1964, its origin has remained a puzzle. Tests of the related time-reversal symmetry (T) have been pursued in the hope they will yield a solution. Measurement of the triple-correlation $(D\sigma_n \cdot p_p \times p_e)$ among the neutron spin, and the electron and proton momenta in neutron beta decay is a sensitive test of T-invariance in the weak interaction. The T-conserving electromagnetic final state contributions (FSC) to D are particularly small, two orders of magnitude below the present limits. The observation of D above the FSC would require physics beyond the Standard Model. We discuss previous measurements of D and progress in the development of a new experiment that should have an order of magnitude greater sensitivity.

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1. Introduction

In the thirty years since the discovery of CP-violation in the (weak) decay of the neutral kaon[1)] enormous experimental effort has been expended in attempting to elucidate the nature of this violation. In addition to direct searches for CP-violation in other systems, very precise tests have been made of the related time-reversal symmetry (T). It is expected on very general theoretical grounds that the combined symmetry CPT, simultaneous inversion under charge conjugation, parity, and time-reversal, is absolutely conserved. If this is the case, then CP-violation must be accompanied by T-violation. However, no other system has been shown to display either CP or T-violation. As a result, our understanding of CP-violation remains limited.

Standard electroweak theory accommodates the CP-violation observed in kaon decay by the inclusion of a complex phase in the Cabbibo-Kobayashi-Maskawa (CKM) quark mixing matrix[2)]. However, it offers no explanation for the magnitude of this phase which produces only tiny effects in most other systems. It is generally agreed that, despite its successes, the standard model (SM) does not represent the end-point of particle theory. In most extensions to the SM, additional CP/T-violating phases arise naturally with the inclusion of new particles and interactions. As such it would be surprising if further manifestations of CP/T-violation did not exist.

Standard model CP/T-violating effects arise in nuclear beta decay only at higher order, making them too small to be observed. However, several extensions to the SM do make tree-level contributions to T-violating angular correlations in beta decay. Among these are left-right symmetric models, models with leptoquark exchange, and models in which there are "exotic" quarks and leptons that mix with the usual ones[3)]. The effects of extensions of the SM on beta decay are considered in detail by P. Herczeg and others elsewhere in this volume.

The T-Violating Triple Correlation

Shortly after the discovery of parity violation, it was suggested that angular correlations in beta decay could be used to search for T-violation[4)]. From the general beta decay interaction Hamiltonian

$$\mathcal{H}_\beta = \sum_{i=\{S,V,A,T\}} (\bar{\psi}_p O_i \psi_n)\, \bar{\psi}_e O_i (C_i + C'_i \gamma_5)\, \psi_{\bar{\nu}_e} + \text{H.c.} \tag{1}$$

where $O_i = \{1, \gamma^\mu, \gamma^\mu\gamma_5, \sigma^{\lambda\mu}/\sqrt{2}\}$, one can derive the probability distribution function for neutron beta decay

$$w \sim G(E_e)\left[1 + a\frac{p_e \cdot p_\nu}{E_e E_\nu} + b\frac{m}{E_e} + \sigma_n \cdot \left(A\frac{p_e}{E_e} + B\frac{p_\nu}{E_\nu} + D\frac{p_e \times p_\nu}{E_e E_\nu}\right)\right] \tag{2}$$

in terms of the neutron polarization vector, σ_n, and the momenta of the outgoing electron (p_e) and neutrino (p_ν). The function $G(E_e)$ contains phase-space factors and the Fermi function. The coefficients *a, b, A, B* and *D* depend on the coupling constants C_i and the Fermi and Gamow-Teller nuclear matrix elements.

If the interaction $\mathcal{H}_\beta$ is time-reversal invariant, then D will be zero, up to final-state electromagnetic effects. This can be understood by considering the D–term under the transformation $t \rightarrow -t$. The triple product changes sign

$$D\sigma_n \cdot p_e \times p_\nu \rightarrow D(-\sigma_n) \cdot (-p_e) \times (-p_\nu) = -D\sigma_n \cdot p_e \times p_\nu \tag{3}$$

whereas the other terms in Eq. (2) do not. More precisely, T-invariance requires the C_i to be relatively real. In the allowed approximation, we have

$$D = \frac{2\Im(C_S C_T^* + C'_S C'_T{}^* + C_V C_A^* + C'_V C'_A{}^*)}{(|C_S|^2 + |C'_S|^2 + |C_V|^2 + |C'_V|^2) + 3(|C_A|^2 + |C'_A|^2 + |C_T|^2 + |C'_T|^2)}. \tag{4}$$

The vector (V) and axial-vector (A) interactions are known to dominate the scalar (S) and tensor (T) interactions so D is primarily a measure of the phase between C_A and C_V.

Observation of a non-zero D does not automatically imply T-violation. Interference between the weak and final-state electromagnetic interactions contributes to D even if all of the interactions involved are T-conserving. Fortuitously, first-order Coulomb scattering makes no contribution to D in the absence of non-V, A couplings[5)]. The leading contribution comes at nuclear recoil order, depending on the weak magnetism term in the vector current. This contribution has been calculated[6)] to be 2×10^{-5} for the case of neutron decay, about two orders of magnitude below the present limits on D.

2. Measurements of *D*

There have been several measurements of D in neutron decay. The most recent and sensitive of these were carried out at the Institute Laue-Langevin (ILL) in Grenoble[7)] and the Kurchotov Atomic Energy Institute (IAE) in Moscow[8)]. The results are shown in Table 1. The correlation has also been measured in ^{19}Ne decay using atomic beams and, more recently, storage cells. The latest ^{19}Ne result, from the Princeton group,[9)] provides the best limit to date on D of $(0.4\pm0.8)\times10^{-3}$.

The IAE and ILL neutron decay experiments shared many features. Neutrons produced by high-flux research reactors were polarized by reflection from magnetized channels. The neutrons then passed through a "spin flipper" with which their polarization could be reversed by nonadiabatic passage through a region of rapidly changing

Table 1: Important parameters of experiments measuring the D coefficient in neutron decay.

Experiment	Capture Flux ($cm^{-2}s^{-1}$)	Neutron Polarization	Coincidence Rate (s^{-1})	Signal/ Background	D
IAE	3.6×10^7	66%	0.8	2/1	$(2.2 \pm 3.0) \times 10^{-3}$
ILL	2×10^9	70%	1.5	4/1	$(-1.1 \pm 1.7) \times 10^{-3}$
emiT, proposed at NIST CNRF	4.4×10^7	95%	18	10/1	$\pm 3 \times 10^{-4}$

magnetic field. Finally, the beam, polarized either parallel or anti-parallel to its direction, passed through an array of detectors.

The neutron momentum can be neglected and the triple-correlation term rewritten using momentum conservation as

$$D\sigma_n \cdot \frac{p_p \times p_e}{E_e E_\nu} \tag{5}$$

where p_p is the recoil proton's momentum. In both experiments, electron and proton counters were arranged around the beam so coincidences counted in them would result from decays in which the three vectors in Eq. (5) were, on average, mutually orthogonal. A sketch of the ILL detector is shown in Fig. 1. The value of D was determined by comparing numbers of coincidences where the average triple-product was positive to the number for which it was negative.

Several steps were taken to reduce systematic effects. The neutron polarization was periodically reversed to cancel asymmetries in the detectors. The effects of the large parity-violating but T-conserving $\sigma_n \cdot p_\nu$ and $\sigma_n \cdot p_e$ correlations were minimized by placing the detectors in a plane whose normal was parallel to σ_n.

3. The emiT Experiment

A new measurement of D has been undertaken by the emiT Collaboration†. Advancements in detector and neutron polarization technology since the previous experiments were performed will help us improve on the already impressive sensitivity of the previous experiments. In addition, we will exploit an octagonal detector geometry that has improved sensitivity while retaining the symmetry crucial for limiting the size of systematic effects. The experiment will be run at the Cold Neutron Research Facility (CNRF) of the National Institute of Standards and Technology

† The emiT Collaboration is made up of participants from U.C. Berkeley/Lawrence Berkeley Laboratory; NIST in Gaithersburg, MD; U. of Washington; U. of Notre Dame; and Los Alamos National Laboratory.

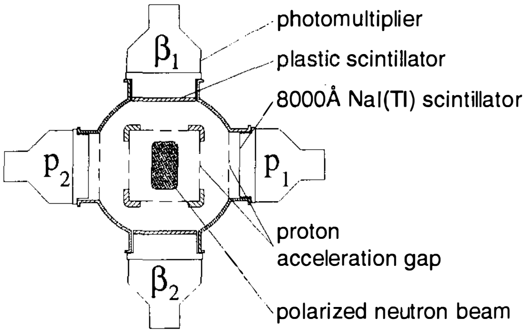

Fig. 1: The detector of the ILL experiment. The neutron polarization is into the page.

(NIST) in Gaithersburg, Maryland where we expect to reach a sensitivity to D of 3×10^{-4}.

Polarizer

The statistical sensitivity to D is proportional to the neutron polarization. The most recent experiments achieved a neutron polarization of about 70%. The development of supermirror neutron polarizers[10] has improved the situation to the extent that polarizations of 95% or greater are now routinely achieved. We will use this established technology in the initial phase of the experiment. The Michigan and NIST members of our collaboration are also developing a novel spin filter that exploits the strong spin dependence of the ^{3}He neutron capture cross section to polarize a transmitted neutron beam. The initial test of this method, using spin-exchange from optically pumped Rb to polarize the ^{3}He, was promising[11]. We plan to switch to the ^{3}He spin filter in subsequent runs since it promises to produce much less background and a more uniform spatial distribution of the neutron polarization.

Detector

The design and much of the fabrication of the detector system has been completed. A schematic diagram is shown in Fig. 2. As in previous experiments, it consists of an array of alternating electron and proton detectors. There are several important differences. The average angle between the two types of detectors is 135°. Although the triple-product ($\sigma_n \cdot p_p \times p_e$) is maximum when the three vectors are mutually orthogonal, this configuration does not maximize the sensitivity to D. The limited phase space in the decay strongly anticorrelates the electron and proton momenta so there are many more decays in which the electron and proton are separated by an obtuse angle. This skews the sensitivity toward large angles. This is indicated in Fig. 3 which shows the figure-of-merit, $M \propto 1/\sigma_D^2$, where σ_D is the uncertainty in D, as a function of the separation angle, $\Delta\theta$, between small detectors.

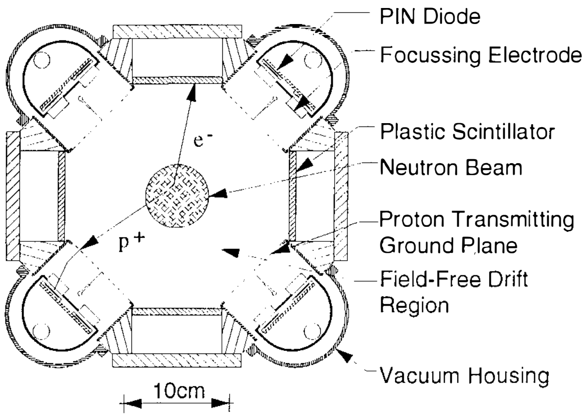

Fig. 2: The octagonal emiT detector array.

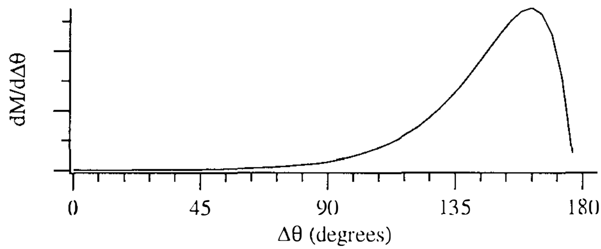

Fig. 3: Sensitivity versus angle between electron and proton detectors.

The difficult task of detecting the low energy (0–750 eV) recoil protons is accomplished by electrostatically focussing and accelerating them through about 35 keV onto PIN diode detectors. Each of the four $25\text{cm} \times 8\text{cm}$ proton detector panels is made up of 12 focussing cells. Each cell contains one PIN diode. A schematic of one of the focussing cells is shown in Fig. 4. The resulting segmentation of the proton detection is useful for controlling systematic effects due to variations in detection efficiency. The PIN diodes are variants of the 18 mm × 18 mm × 500μm Hamamatsu model S3204-06 that have been made with a thinner insensitive surface layer. Our tests with proton beams indicate the dead layer is 20 μg silicon equivalent, about half that of the standard S3204-06 detector.

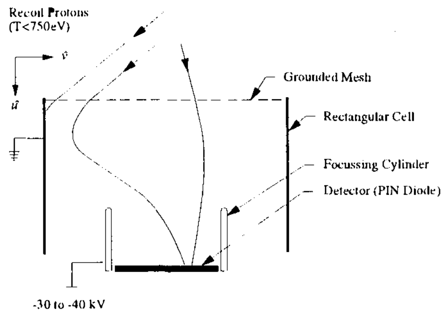

Fig. 4: A single proton focussing cell shown in cross section. Sample proton trajectories are shown.

The beta is detected in one of four slabs of plastic scintillator 50 cm × 8.4 cm × 6.4 mm. Each end of the scintillator is optically coupled to an acrylic light guide that pipes the light through the vacuum vessel to a photomultiplier tube (PMT). The signals from the PMT's are combined to give the beta's energy and, from relative timing, the position along the length of the scintillator of its impact.

Prototype Test

A prototype consisting of one electron and one proton detector panel was used in a test run at NIST with an unpolarized beam. The test demonstrated the viability of proton detection scheme and allowed us to study backgrounds with a neutron beam. Since the highest energy recoil protons take a minimum of 0.23 μs to drift to a detector, a delayed-coincidence is used to reject background. A spectrum of time delays from this run is shown in Fig. 5. The spectrum shows a small peak of prompt coincidences caused by backgrounds. The larger broad peak comes from neutron decay. The flat background is from uncorrelated coincidences due primarily to beam-associated (n,γ) reactions. The signal to background ratio was 3. This can easily be improved to 10 by the addition of shielding and by improving the beam transport.

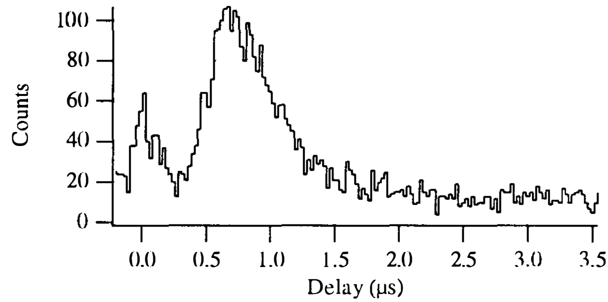

Fig. 5: Spectrum of time delays between the electron and proton detector. The spectrum represents one hour of data taking.

4. Conclusions

The parameters of the emiT experiment are summarized in Table 1. We expect to achieve a sensitivity to D at NIST of $\pm 3\times 10^{-4}$ with eight weeks of running plus time for studies of systematic effects. This could be improved with a higher intensity neutron source. For example, with the higher flux of the ILL, we might be able to improve this by as much as an order of magnitude.

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