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Time reversal in polarized neutron decay: the emiT experiment

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Abstract

The standard electro-weak model predicts negligible violation of time-reversal invariance in light quark processes. We report on an experimental test of time-reversal invariance in the beta decay of polarized neutrons as a search for physics beyond the standard model. The emiT collaboration has measured the time-reversal-violating triple-correlation in neutron beta decay between the neutron spin, electron momentum, and neutrino momentum often referred to as the *D* coefficient. The first run of the experiment produced 14 million events which are currently being analyzed. However, a second run with improved detectors should provide greater statistical precision and reduced systematic uncertainties. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

CP violation, observed so far only in the neutral kaon system, can be explained in the standard model using a Kobayashi–Maskawa phase [1]. This phase is small, however, and its effects are highly suppressed in processes involving only the lighter quarks. The small standard-model values of time-reversal violating observables in beta decay provide an opportunity to search for interactions

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beyond the standard model. Left–right symmetric models, "exotic" fermions, and leptoquark models [2] can all lead to violations of time-reversal symmetry at potentially measurable levels.

Beta emitters, and neutrons in particular, are a natural laboratory for studying weak interaction symmetries. A general beta decay amplitude allowing the violation of parity, time-reversal, and charge conjugation was first published by Jackson et al. [3] in 1957. This decay amplitude, $\mathrm{d}\Gamma$, which forms a basis for angular correlation tests of the standard model, is given by

$$\mathrm{d}\Gamma \propto \left(1 + a\frac{\boldsymbol{p}_{\mathrm{e}}\cdot\boldsymbol{p}_{\nu}}{E_{\mathrm{e}}E_{\nu}} + A\frac{\boldsymbol{J}\cdot\boldsymbol{p}_{\mathrm{e}}}{E_{\mathrm{e}}} + B\frac{\boldsymbol{J}\cdot\boldsymbol{p}_{\nu}}{E_{\nu}} + D\frac{\boldsymbol{J}\cdot\boldsymbol{p}_{\mathrm{e}}\times\boldsymbol{p}_{\nu}}{E_{\mathrm{e}}E_{\nu}}\cdots\right). \qquad (1)$$

Here p_{e}, p_{ν}, E_{e}, and E_{ν} refer to the electron and neutrino momenta and energy. $\boldsymbol{J}$ is the spin of the parent nucleus and a is the electron–neutrino correlation. The neutrino asymmetry [4], B, and the beta asymmetry [5–7], A, have been used to set limits on right-handed weak currents [8]. This experiment measures the triple correlation D. A nonzero value for D implies a violation of time-reversal symmetry. Electromagnetic final state effects that can mimic time-reversal violation in neutron decay are estimated to be well below the sensitivity of this experiment [9].

Previous measurements limit D to $-0.0005(15)$ and 0.0001(6) for neutron and ^{19}Ne decay, respectively [10]. The first run of this experiment was expected to achieve five times greater sensitivity for the neutron triple-correlation. However, detector performance and other experimental problems limited the statistical precision to around the same sensitivity as the best previous results. These shortcomings are being addressed in a second run scheduled for 2000.

2. Experimental method

The emiT apparatus detected electrons and recoiling protons produced by neutrons decaying in flight. Long segments of scintillator and proton detectors surround a longitudinally polarized neutron beam. The neutrino direction is inferred from the electron and proton momenta using conservation of momentum.

The emiT detector consists of four 50 cm long electron detectors and four 30 cm long proton detectors arranged octagonally around the neutron beam as shown in Fig. 1. The octagonal geometry maximizes the experiment's sensitivity to D by placing the beta and proton detectors 135° apart. This angle balances the sine dependence of the cross product $\boldsymbol{J}\cdot\boldsymbol{p}_{\mathrm{e}}\times\boldsymbol{p}_{\nu}$ against decay kinematics which favor large angles between the proton and electron momenta [11].

The beta detectors are 6.4 mm thick plastic scintillator paddles attached to light guides at both ends. The scintillators are thick enough to stop betas with the endpoint energy of 782 keV. The light guides pass out of the vacuum chamber and attach to phototubes (PMTs). The PMTs were shielded from the axial holding field by μ-metal and

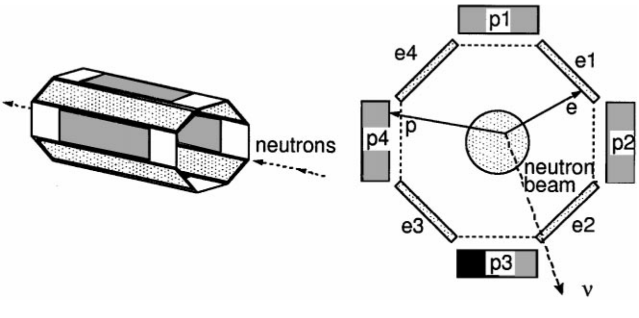

Fig. 1. The emiT detector geometry showing proton detector array p1–p4 and electron scintillators e1–e4.

a pair of concentric solenoids of differing diameter. The dipole moments of the solenoids were equal and opposite to reduce their effect on the magnetic field in the detector region. Incomplete cancellation of the inner solenoid fields was used to cancel the holding field at the PMT positions. The scintillators were wrapped in a 17 μm thick Al foil and a grounded 13 μm thick aluminized mylar sheet to reduce their sensitivity to light and to electrons created by field emission in the high-voltage electrodes.

The protons drifted in a field free region 20 cm across before being focused by a 30–36 kV potential into PIN diode detectors.[4] With a maximum recoil energy of 750 eV, most of the protons arrived between 0.5 and 2 μs after the betas. The electric fields were shaped by focusing tubes into sixteen thin dead layer PIN diodes arranged in two rows. A fully working detector array would have nearly complete coverage over a 30 cm × 7.6 cm area, however, not all PIN positions were filled during the run. Detector and preamp cooling under vacuum was accomplished with a copper ladder that ran the length of each proton detector array, which was in turn cooled by chilled liquid or liquid nitrogen.

The detectors and preamps were floated at high voltage, and their signals came out to VME boards in a rack also maintained at high voltage. Timing pulses and digitized signal amplitudes for the protons were generated in specially designed VME boards and sent to low-voltage electronics via optical fiber links. Proton energy, proton and beta arrival time difference, beta energy for each PMT, and relative timing between PMTs for a given scintillator were stored for each event. The measured proton energy, related to the accellerating voltage, was recorded to help distinguish proton events from noise. The drift time between beta and proton detection also helped discriminate against noise. The relative timing between the two ends of the beta detectors was intended to allow position sensitivity along each beta detector, but was not necessary for our analysis.

This experiment was performed at the National Institute of Standards and Technology's Cold Neutron Research Facility in Gaithersburg, MD, USA. Neutrons were produced by a 20 MW research reactor and moderated in heavy water and in liquid hydrogen at 20 K. Neutron guides coated with ^{58}Ni transport the cold neutrons 68 m to the NG6 end station with a neutron capture flux at the shutter of $1.4 \times 10^9\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. A cooled Bi filter removed reactor gammas and fast neutrons. The neutrons were then polarized in a bender supermirror polarizer [12] providing a polarization of 96%. The polarizer was followed by a current sheet spin flipper which reversed the neutron spin every 2 or 5 s. The polarized neutrons followed Be coated guide tubes through a series of collimators and scrapers providing a 5 cm diameter beam at the beginning of the detector region. The neutron capture flux at the detector was measured to be $1 \times 10^8\ \mathrm{s}^{-1}$ after the final collimator. The 0.55 mT (5.5 G) magnetic holding field in the detector region is aligned along the beam line to within 3 mrad. Beyond the detector, the beam travels 3 m before being stopped in a ^{6}Li-glass beam dump.

3. The first run

The first experimental run lasted for five six-week cycles in 1997. From this run around 14 million neutron decay coincidences were gleaned from over one billion raw events using timing and energy cuts. An additional 0.7 million neutron decay coincidences were recorded during a systematic check with the beam purposefully misaligned and the magnetic field transverse to the beam. The neutron coincidence rate reached a peak of 7 Hz, which is over a factor of 3 below the expected value. However, real event rates were limited throughout the run by excessive energy loss in the PINs and the associated dead time, noise, and electronic failures due to high-voltage emission and sparks.

Early in the run we discovered that the energy loss in the PIN diodes was larger than expected. The problem was unexpected since PIN diodes had

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[4] Hamamatsu Corp. part S3204-06. See Hamamatsu Technical Data publication No. S-505-02. Certain trade names and company products are mentioned or identified in an illustration in order to adequately specify the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

performed as predicted in the prototype run. Acceptance testing of a small sample of the PIN diodes two years before the run gave no indication of problems. However, during the run we were forced to raise the potential accelerating the protons into the PIN diodes to 36 kV, beyond the apparatus design parameters. The resulting high-voltage emission led to higher background rates and dead time. The higher voltage increased the frequency of sparks which occasionally damaged proton detector preamps and electronics. Even with the raised voltage, the signals from some PINs were pushed well into the noise by the unexpected proton energy loss. These PINs were either turned off, or their discriminator thresholds were raised high enough to cut out many real events. There were even some runs taken with entire proton detector arrays turned off. A soft discriminator threshold compounded the problem of dead time. Details of detector and electronics performance are beyond the scope of this paper but are described elsewhere [13,14].

The differences in efficiencies of individual PINs and loss of whole proton detector arrays reduced the symmetry of the detector. This reduced symmetry increases our sensitivity to two particular systematic effects that are related to the correlations a, A and B shown in Eq. (1). The first effect comes about due to the anisotropy of the decay from a, A, and B, combined with detector nonuniformities. For example, a single PIN detector (left side of p3 in Fig. 1) makes slightly different angles with the two beta detectors (e4 and e1) opposite to it. This should be balanced by a neighboring PIN on the same detector array (right side of p3) at the same axial position. If one of these PINs is not functioning, the symmetry of the detector is broken. Broken symmetry along the beamline can also cause a systematic error. For our analysis, we use only working pairs of detectors that recover the necessary symmetry. Individual detector efficiencies are taken into account using the sum of detector counts over both neutron polarization states [13,14].

The second systematic effect can be caused by a slight misalignment of the magnetic field. There is a large preference for ejecting an electron in the direction opposite the neutron spin which can couple to a beam displacement to induce a false asymmetry. This effect is quite efficiently cancelled by a ratio involving all four proton detectors. However, it is not as efficiently cancelled with our reduced symmetry.

One possible analysis technique involves using pairs of PINs to determine a value of D for each proton detector array on a run-by-run basis. As mentioned above, this can be done using pairs in a way that has reduced sensitivity to the nonuniform detector efficiency. These pair D values can be combined to get a total D value for each detector array. The values from all four detector arrays may now have the symmetry required to reduce the effect of a transverse polarization. Several other analysis ideas are also being considered, but each results in reduced sensitivity to the detector symmetry at the expense of larger statistical uncertainty.

Data from the first run is currently being analyzed. Most systematic errors cancel to first order, so that two problems are necessary to produce a false asymmetry. The lack of proton detector symmetry provides one such problem making the first run more susceptible to systematic errors. However, preliminary analysis looks promising for a statistically limited result with an uncertainty comparable to the uncertainty in the world average for the neutron D coefficient.

4. Plans for the second run

In a second run planned for 2000, we will replace the PIN diodes with surface barrier detectors (SBD) or passivated implanted planar silicon (PIPS) detectors. PIPS detectors have a thinner silicon dead layer than PINs. For protons in this energy range, the gold used for contacts on the SBDs has a lower energy loss than silicon for a given dead layer thickness [15]. Toward the end of the first run, we replaced two PINs with SBDs. The SBDs demonstrated considerably less energy loss in the front layer than the PINs. In addition to the new proton detectors, fiber optic cables will carry signals directly from the preamps at high voltage to VME electronics run at low voltage. The new fibers will reduce the amount of electronics at high voltage, minimize the sensitivity of the electronics to sparks, and reduce electronic noise by isolating individual proton detectors. Improved shaper/discriminator boards will further reduce electronic noise and have an improved discrimination circuit. The overall data acquisition readout scheme has been redesigned to decrease the dead time. The high-voltage sparking and emission are being tested off line using a window to identify problem surfaces. Other improvements include a new cooling manifold for the proton detector and re-designed preamps which consume less power and are easier to cool.

5. Conclusions

The lack of detector symmetry on the first run requires a creative approach to analysis. However, these new ideas are expected to lead to a robust result with a statistical error comparable to that of the current world average. A second run is being planned with strategies to overcome the problems experienced in the first run. With these improvements in place we intend to push the statistical error down to 3×10^{-4}.

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