# Time Reversal Symmetry Experiment: emiT

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The emiT experiment searches for time reversal invariance in the decay of ultracold, polarized neutrons. Time reversal implies CP violation, under the assumption of the theorem of CPT invariance. CP violation in previously unknown sectors of physics may provide an explanation for why matter is dom- inant over antimatter in the visible universe. emiT is a “null experiment”; the aim is to search for T violation different from zero.

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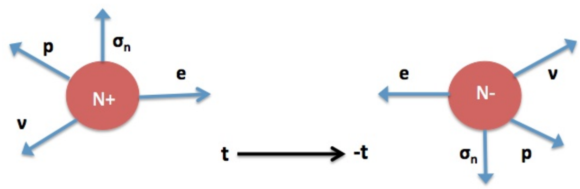
emiT’s primary competitors come from other experiments searching for neutron beta decay as well as EDM experiments. EDM experiments are similar insofar as they are triple correlation experiments. They are, however, T-odd / P-odd (as opposed to T-odd / P-even) and therefore are not directly comparable to neutron beta decay experiments. Neutron beta decay experiments are also more cost effective and simpler ways to search for CP violation, as opposed to their higher energy counterparts such as Belle and Babar.




A general beta decay amplitude allowing the violation of parity, time-reversal and charge conjugation was published by Jackson. The probability of decay of polarized neutrons can be written according to the following:

$$dW \propto \big(1 + a\frac{p_e \cdot p_\nu}{E_e E_\nu} + A\frac{\sigma_n \cdot p_\nu}{E_e} + B\frac{\sigma_n \cdot p_\nu}{E_\nu} + D\frac{\sigma_n \cdot p_e \times p_\nu}{E_e E_\nu}\big) dE_e d\Omega_e d\Omega_\nu \tag{1}$$

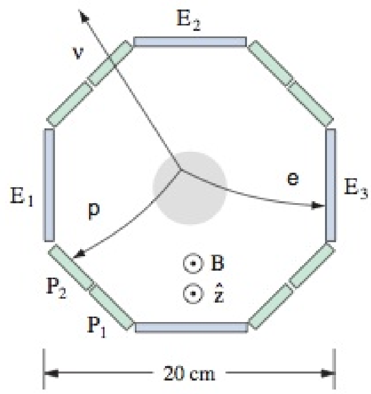
The triple correlation in D is what determines T violation. D is sensitive to the phase between axial and vector currents.

$$D \approx 2\frac{|\lambda| sin\phi}{3|\lambda|^2 + 1}$$

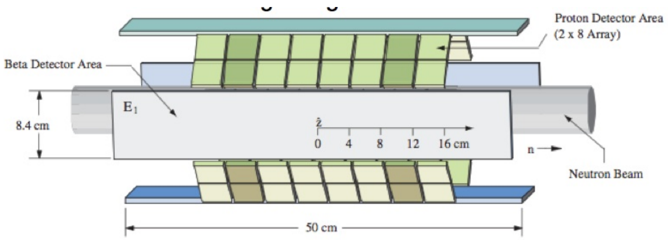
Once $\tilde{D}$ is measured and averaged, it is then possible to calculate $D$.

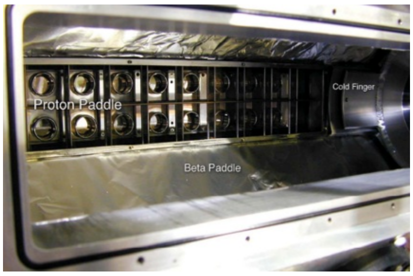
The experiment took place at the NIST (National Institute for Science and Technology) Center for Neutron Research (NCNR). The data consisted of $4.7 \times 10^8$ raw events which was honed down to 512 coicidence events by the end of the analysis.

The emiT detector is designed so as to have octagonal symmetry of the detector optimizes electron/proton coincidence rates and reduces systematic effects.

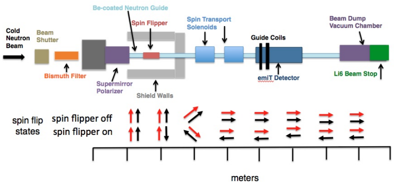



The neutrons are cooled so as to spend more time in the sensitive part of the detector. A 20 MW research reactor provides nominally unpolarized neutrons. The neutrons are moderated to thermal energies using the coolant, D2O. The neutrons are cooled by scattering them into liquid hydrogen, cooling them to about 40K. Neutrons move down a guide 68 m long coated with Ni-58. They exit through a thin Mg window and travels through 79 cm of air. Downstream of this aperture is the remote controlled beam shutter. The neutron beam passes through 1 m long air gap before entering a 15 cm thick cryogenically cooled beam filter made of bismuth. The filter attenuates fast neutrons and gamma rays which might otherwise contribute to the background. Cooling the filter elements to liquid nitrogen temperatures increases the probability of neutron transmission and reduces the probabilities of losses due to phonon scattering. Neutrons exit and pass through a polarizer and travel 1 m to the spin flipper through a Be-coated glass neutron guide tube. In the spin flipper, the beam passes through two parallel sheets of 0.5 mm Formvar-coated Alumnium wire. The main vacuum chamber begins just after the spin flipper with another 1 m long Be-coated glass neutron guide tube. A beam collimator section follows. High purity lead removes gamma rays. The setup is terminated by a glass beam stop and fluence monitoring chamber.




The neutron polarizer is a supermirror bender (PSM). The magnetic field for the current sheet upstream is parallel to the PSM field. The current in the sheet downstream can be set either parallel or antiparallel to the upstream sheet. The neutron spin is either aligned or anti-aligned with the magnetic field.




The magnetic field is 560$\mu$T. This is so the average transverse component of the neutron polarization varies less than $2\times10^{-3}$. The spin-flipper state is reversed every 10 s. The spin-flipper state is either off, in which case the spins are both parallel to the z-axis (magnetic field axis) or on, in which case the spins are antiparallel to the z axis.

The detector is made from a single piece of alumnium. The proton detector cells are made of a grounded box with the top and upper half covered with grounded wire mesh. Once inside the box, the protons were accelerated and focused onto a surface barrier detector or SBD. The electon detector cells were made of plastic scintillator connected to photomultiplier tubes. The proton segments alternate with the electron segments to form an octagonal geometry. This enables the proton and the electron to be tagged effectively.

In order to isolate spin-dependent terms, the following variable is defined, which is efficiency independent:

$$w^{p_ie_j} = \frac{N_+^{p_ie_j} - N_-^{p_ie_j}}{N_+^{p_ie_j} + N_-^{p_ie_j}}$$

This can also be written so that we can see the dependence on the triple correlation coefficient:

$$w^{p_ie_j} \approx \frac{A\left\langle \beta_e \mathbf{P}\cdot\hat{\mathbf{p_e}}\right\rangle + B\left\langle \mathbf{P}\cdot\hat{\mathbf{p_\nu}}\right\rangle + D\left\langle \beta_e(\frac{p_p}{p_\nu})\mathbf{P}\cdot(\hat{\mathbf{p_p}}\times\hat{\mathbf{p_e}})\right\rangle}{\langle 1\rangle + a\left\langle \beta_e\hat{\mathbf{p_e}}\cdot\hat{\mathbf{p_\nu}}\right\rangle}$$

For longitudinal polarization we can simplify this term to the following:

$$w^{p_ie_j} \approx P\kappa^{p_ie_j}\Big(D\left\langle \beta_e(\frac{p_p}{p_\nu})\hat{z}\cdot(\hat{p_p}\times\hat{p_e})\right\rangle + A\left\langle \beta_e cos\theta_e\right\rangle + B\left\langle cos\theta_\nu\right\rangle\Big)$$

where

$$k^{p_ie_j} = \frac{1}{\langle 1\rangle + a\left\langle \beta_e\hat{p_e}\cdot\hat{p_\nu}\right\rangle}$$

In order to simplify things, we define a constant to characterize the sensitivity to the triple correlation as follows:

$$K_D^{p_ie_j} \approx k^{p_ie_j}\left\langle \beta_e\left(\frac{p_p}{p_\nu}\right)\hat{z}\cdot(\hat{p_p}\times\hat{p_e})\right\rangle$$

In order to completely isolate the triple correlation term, we must eliminate coefficients A and B. For that purpose we define another variable which is half the difference of two of the $w$ terms. The longitudinal component of the cross product has opposite polarization for $p_1e_3$ and $p_1e_2$

$$v^{p_1} = \frac{1}{2}(w^{p_1e_3} - w^{p_1e_2})$$

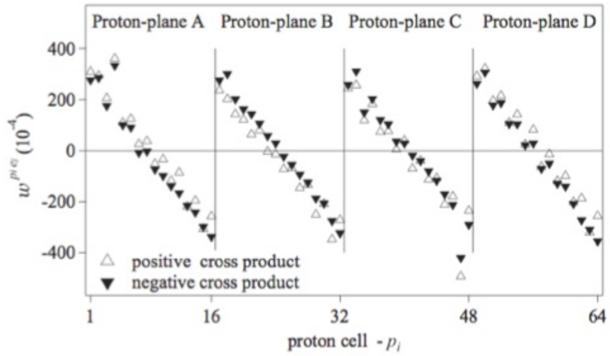
The longitudinal polarizations are

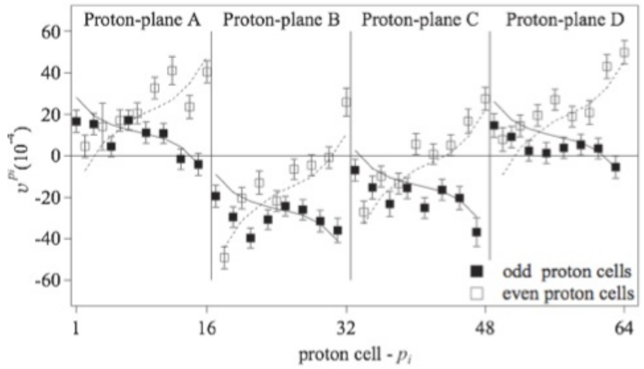
$$v^{p_1} \approx \tilde{K}_d PD + P\frac{A}{2}(k^{p_1e_3}\left\langle \beta_e cos\theta_e\right\rangle^{p_1e_3} - k^{p_1e_2}\left\langle \beta_e cos\theta_e\right\rangle^{p_ee_2}) + P\frac{B}{2}(k^{p_1e_3}\left\langle cos\theta_\nu\right\rangle^{p_1e_3} - k^{p_1e_2}\left\langle cos\theta_\nu\right\rangle^{p_1e_2})$$

Due to P-odd/T-odd correlations, these asymmetries depend strongly on the axial position of the proton cell hit for the event.

The following data are recorded during runs:
(1) Which detector segment
(2) Amplitude of the pulse
(3) Spin flipper state
(4) Proton time of flight

Events, however, are defined as the coincidence of a proton-detector signal and an electron-detector signal that met the following selection criteria:
(1) proton and electron energy
(2) proton time of flight
(3) monitor data



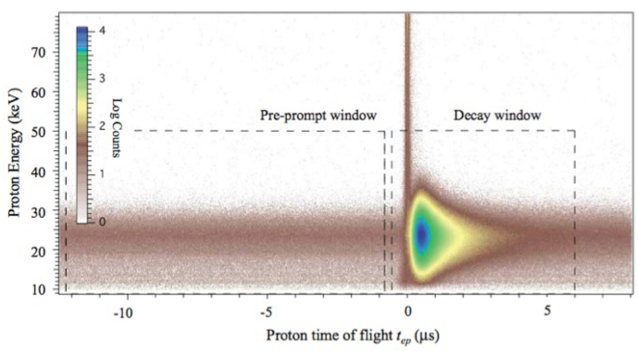




Measurements along the z axis are taken in eight separate locations along the detector (grouped in pairs). These positions are $z = \pm 2, \pm 6 \pm 10 \pm 14$. This serves as a cross-check and also maximizes the statistical power. For this reason, we define the following variable:

$$\tilde{D} = \frac{1}{\tilde{K}_D P} \sum_{|z^{p_i}|=const} v^{p_i}$$

Contribution to D can originate from T-violating interactions and from final state effects.

$$D = D_{\not T} + D_{FSI}$$



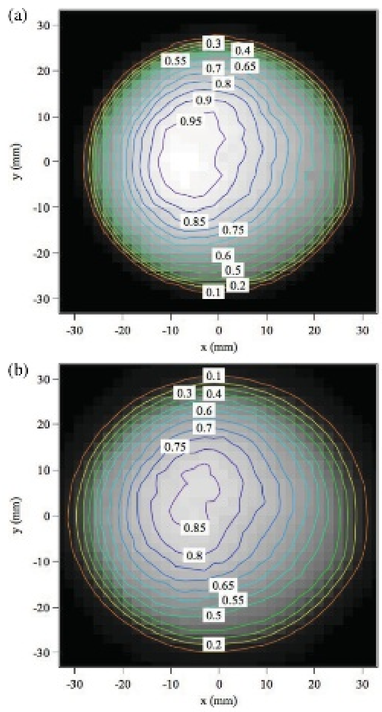

$$D_{FSI} \approx 1.1 \times 10^{-5} \frac{p_e}{p_e^{max}} + 0.3 \times 10^{-5} \frac{p_e^{max}}{p_e}$$

It just so happens that we can write the T violating term as follows:

This is how the D coefficient is dependent on the phase between the axial and vector currents, as this can be simplified to approximately the following:

$$D \approx 2 \frac{|\lambda| sin\phi}{3|\lambda|^2 + 1}$$

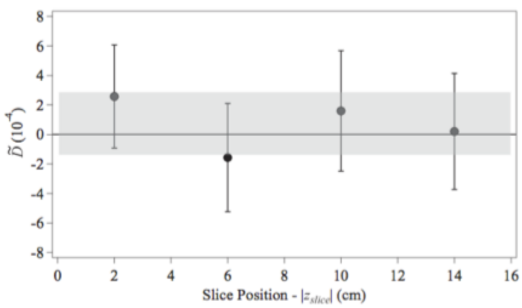
Many tests are run throughout the duration of the experiment to make sure that systematics are accounted for and reduced when possible. Most of the dominant effects are due to background and proton and electron backscattering. Monte Carlo simulations are run in order to try to understand the backscattering. Tests are run to check the beam and field uniformity. The beam uniformity is checked using dysprosium foil. The foil is activated by the beam neutrons and the laid on beta-sensitive film. Exposure is measured with an image reader. Additionally, any transverse polarization of the beam could lead to a false signal. Therefore, tests are run to accurately characterize the beam polarization.




The table lists systematic effects which were taken into consideration.

| |
|---|
| Background (additive and multiplicative) |
| Electron Backscattering |
| Proton Backscattering |
| Electron Threshold Nonuniformity |
| Proton Threshold Effect |
| Beam Expansion |
| Polarization Nonuniformity |
| ATP misalignment |
| ATP twist |
| Spin correlated flux |
| Spin correlated polarization |
| $K_D$ |

The final result consisted of the four measurements of $\tilde{D}$ along the z axis. The weighted average was $\tilde{D} = 0.72 \pm 1.89$ with $\chi^2 = 0.8$ for three degrees of freedom. The final result for $D$ was $D = [-0.94 \pm 1.89(stat) \pm 0.97(sys)] \times 10^{-4}$.




Though T violation has not been discovered, emiT-I measured D in neutron decay to be $(-6 \pm 13) \times 10^{-4}$ [5], which is comparable in sensitivity to the TRINE collaboration result of $(-2.8 \pm 7.1) \times 10^{-4}$ [6].

A measurement using $^{19}Ne$ gave a value of D of $(0.7 \pm 6) \times 10^{-4}$ [1] [3]. The most sensitive result so far was accomplished by emiT-II, as described above, with a final value of $D = -0.94 \pm 1.89(stat) \pm 0.97(sys) \times 10^{-4}$. [2] [4].

[1] FrankP. Calaprice. The use of atomic beam and optical methods in the study of fundamental symmetries. *Hyperfine Interactions*, 22(1-4):83–93, 1985.

[2] T. E. Chupp, R. L. Cooper, K. P. Coulter, S. J. Freedman, B. K. Fujikawa, A. Garcia, G. L. Jones, H. P. Mumm, J. S. Nico, A. K. Thompson, C. A. Trull, F. E. Wietfeldt, and J. F. Wilkerson. Search for a $t$-odd, $p$-even triple correlation in neutron decay. *Phys. Rev. C*, 86:035505, Sep 2012.

[3] A. L. Hallin, F. P. Calaprice, D. W. MacArthur, L. E. Piilonen, M. B. Schneider, and D. F. Schreiber. Test of time-reversal symmetry in the $\beta$ decay of $^{19}$Ne. *Phys. Rev. Lett.*, 52:337–340, Jan 1984.

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