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## Search for T violation in neutron decay: the emiT experiment

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**Summary.** — We describe an experiment to search for the P-even and T-odd correlation of the form  $D \langle \vec{J} \cdot \frac{\vec{p}_e}{E_e} \times \frac{\vec{p}_\nu}{E_\nu} \rangle$  in neutron beta decay. Our result,  $D = (-0.96 \pm 1.89 \text{ (stat)} \pm 1.01 \text{ (sys)}) \times 10^{-4}$  improves previous limits and now represents the most sensitive measurement of  $D$  in nuclear beta decays. According to the Standard Model  $D$  should be much smaller, so this search is a probe for potential new physics.

PACS 24.80.+y – Nuclear tests of fundamental interactions and symmetries.  
PACS 11.30.Er – Charge conjugation, parity, time reversal, and other discrete symmetries.  
PACS 12.15.Ji – Applications of electroweak models to specific processes.  
PACS 13.30.Ce – Leptonic, semileptonic, and radiative decays.

The study of the discrete symmetries C, P, and T has played an illuminating role in the history of physics. Assuming local Lorentz invariance leads to CPT as a good symmetry and, in that context, T and CP violation are equivalent. CP violation has been observed in many different experiments with K and B mesons. All evidence for CP and T violation observed so far in the laboratory can be reproduced by a single number (the phase in the CKM matrix), except for a 3.2-sigma deviation observed recently as an

asymmetry in the production of pairs of like-sign muons from D0 [1]. However, it is well known that, in order to explain the matter-antimatter unbalance in the universe, one needs additional sources of CP violation [2]. One possibility is that the lepton mixing matrix will provide this, but it is also possible that additional sources of CP violation exist in the hadronic sector which have not been detected yet. Here we describe a search for T violation in the decay of neutrons.

For nuclear beta decay, where the momentum transfer is negligible compared to the W masses, the most-general Hamiltonian that is only restricted to be Lorentz invariant and ignores possible pseudo-scalar contributions that are very small in the nucleus is [3]

$$(1) \quad H_{\text{int}} = \sum_{i=V,A,S,T} (\bar{\psi}_f O_i \psi_i) (C_i \bar{\psi}_\nu O_i \psi_e + C'_i \bar{\psi}_\nu \gamma_5 O_i \psi_e),$$

where the left side represents the hadronic current and the right side the leptonic part. The operators  $O_i$  are

$$O_V = \gamma_\mu, \quad O_A = \gamma_\mu \gamma_5, \quad O_S = 1, \quad O_T = \sigma_{\mu\nu}.$$

In the Standard Model the only currents that are non-zero are  $V$  and  $A$ , and the primed couplings are identical to the unprimed ones —reflecting the apparent absence of right-handed charged weak currents. The decay probability depends on the correlations between the momenta of the electron,  $\vec{p}_e$ , and neutrino,  $\vec{p}_\nu$ , and the average neutron angular momentum  $\langle \vec{J} \rangle$  [3]

$$(2) \quad d\Gamma \propto \left[ 1 + b \frac{m_e}{E_e} + a \frac{\vec{p}_e}{E_e} \cdot \frac{\vec{p}_\nu}{E_\nu} + \frac{\langle \vec{J} \rangle}{J} \cdot \left( A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e}{E_e} \times \frac{\vec{p}_\nu}{E_\nu} \right) \right].$$

Here the coefficients  $a$ ,  $b$ ,  $A$ ,  $B$ ,  $D$  depend on different combinations of the  $C_i$  couplings of eq. (1).

The triple correlation,  $\langle \vec{J} \rangle \cdot \frac{\vec{p}_e}{E_e} \times \frac{\vec{p}_\nu}{E_\nu}$ , is even under parity (P), but odd under time-reversal (T). A measurement of  $D$  is thus sensitive to T-odd/P-even interactions in semileptonic decays. The effects of the CKM matrix phase for the  $D$  coefficient turn out to be much smaller than the sensitivity of any presently-conceivable experiment. In addition there is a contribution to  $D$  that is not due to time-reversal symmetry breaking, but originates from the fact that this experiment is not exactly looking at an asymmetry with respect to the exchange of initial and final states. The latter are called “final-state interactions” and yield a contribution  $D_{f.s.} = 1.1 \times 10^{-5}$  [4-6]. This calculation depends on the assumption of the Conservation of the Vector Current, which has been tested to better than 10%. Thus, finding evidence for  $D > 10^{-6}$  beyond the expected final-state interactions contribution in neutron beta decay would provide evidence of new physics.

Figure 1 shows a sketch of the emiT apparatus. Scintillator paddles of approximately  $50 \times 8.4$  cm were used to detect betas and silicon surface barrier detectors biased to  $-28$  kV were used to detect protons. Details of the experimental setup can be found in ref. [7]. A picture of the insides of the emiT apparatus is shown in fig. 2.

The emiT experiments were performed using cold neutrons (velocities between 500 and 1000 m/s) from the research reactor at NIST, Gaithersburg, Maryland, USA. Two emiT runs have now been completed at NIST. The first run, in 1997, used PIN-diode proton detectors with the result [8]  $D = [-0.6 \pm 1.2(stat) \pm 0.5(sys)] \times 10^{-3}$ . The 1997 NIST run and study of systematic effects led to an upgrade of the apparatus, most

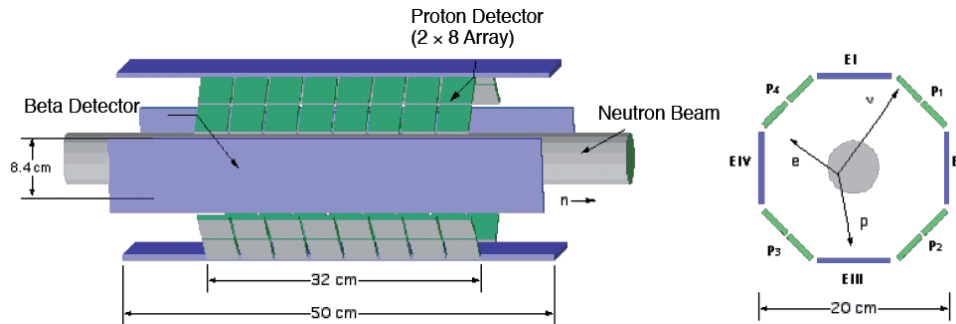


Fig. 1. – Sketch of the emit apparatus. Scintillating paddles were used as electron detectors and Si surface barrier detectors were used as proton detectors. The Si detectors were set at  $\sim -28$  kV so protons can be detected.

importantly improved electronics, proton-acceleration geometry and implementation of surface-barrier detectors for protons. The improved emit-II apparatus took data at NIST over 14 months in 2002-2003 collecting over 300 million proton-electron coincidence events.

A blind analysis and extensive study of systematic effects has recently been published [9]. Our result is  $D = (-0.96 \pm 1.89 (stat) \pm 1.01 (sys)) \times 10^{-4}$ . The Particle Data Group average of recent measurements from neutron decay is  $D = (-4 \pm 6) \times 10^{-4}$  [10, 11]. Previously the most sensitive measurement was in  $^{19}\text{Ne}$  with  $D(^{19}\text{Ne}) = (1 \pm 6) \times 10^{-4}$  [12]. Our result can be interpreted as an upper limit on the complex phase between the axial-vector and vector currents ( $g_A/g_V = |\lambda|e^{i\phi_{AV}}$ ) with  $\phi_{AV} = 180.013^\circ \pm 0.028^\circ$  (68% confidence level). This result represents the most sensitive measurement of  $D$  in nuclear beta decay.

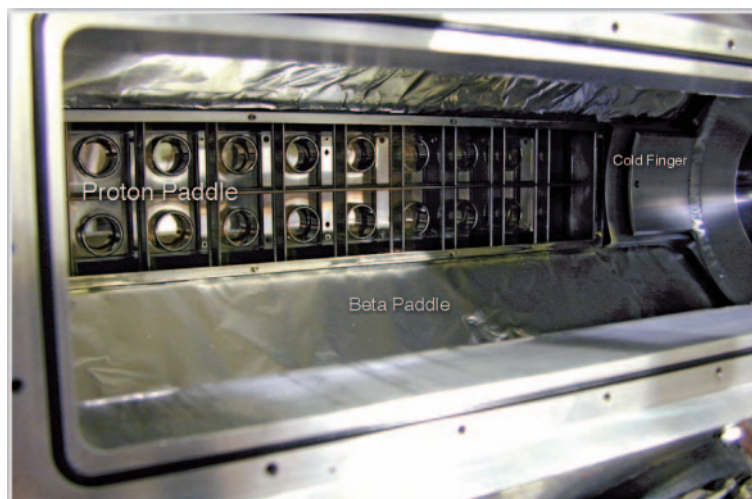


Fig. 2. – Picture showing the insides of the emit apparatus. The proton paddle contains two rows of 8 Si surface barrier detectors at  $\sim -28$  kV. The beta paddles are plastic scintillators wrapped with aluminum foil. The Cold finger was used to improve the vacuum in the chamber.

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