Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

LA-UR--83-3250

DE84 003781

TITLE: TIME REVERSAL INVARIANCE IN POLARIZED NEUTRON BETA DECAY

AUTHOR(S): T. J. Bowles, P-3
J. D. Moses, P-3
J. Sunier, P-3
R. E. Brown, P-3
P. Lisowski, P-3
W. Mampe, ILL, Grenoble, France
P. Liaud, U. of Chambery, Chambery, France

SUBMITTED TO: Conference on Reactor-Based Fundamental Physics, Grenoble
France--invited talk.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution or to allow others to do so for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Time Reversal Invariance in Polarized Neutron Beta Decay

T. J. Bowles, J. D. Moses, J. Sunier, R. E. Brown, P. Lisowski
Los Alamos National Laboratory
Los Alamos, New Mexico 87545 USA

W. Mampe
Institut Laue-Langevin, Grenoble, France

P. Liaud
University of Chambéry, Chambéry, France

Resume - La mesure de la triple correlation de la décroissance beta du neutron polarisé permet de tester la violation du reversement du temps. Nous présentons une expérience qui peut permettre d'étude les limites courantes de cette correlation.

Abstract - Measurements of the triple correlation $\vec{\sigma}_n(\vec{P}_e \times \vec{P}_\nu)$ in polarized neutron beta decay provide a test of time reversal violation. An experiment that will substantially improve the current limits on this correlation is discussed.

CP was believed to be a fundamental symmetry of nature until 1964 when this symmetry was observed to be broken in the decay of the neutral Kaon system. Subsequent measurements of this system have shown that CP violation is equivalent to T (time) reversal violation /1/, as expected from the CPT theorem. The origin of this observed T violation has not been determined, although several explanations have been suggested /1-5/, eg. weak interactions between three or more quark doublets, superweak $\Delta S=2$ force, Higgs mechanism, and V + A admixtures to the V - A theory. These theories are able to account for the observed T violation in the neutral Kaon system and also make predictions for T violating processes in other systems. Searches for T violation in other systems, eg. electric dipole moment of the neutron, transverse polarization of leptons in beta decay, detailed balance in nuclear reactions, have all yielded null results thus far /1/. While the limits from these experiments serve to constrain the theoretical models, more sensitive experiments are required to choose among the various models.

Polarized neutron beta decay provides a means to sensitively search for a component in the weak interaction that is odd under time reversal. The decay probability per unit time for polarized neutrons is given by

$$W(E, \vec{P}_e, \vec{P}_\nu) = F(E) \left[1 + a \frac{\vec{P}_e \cdot \vec{P}_\nu}{E_e E_\nu} + A \frac{\vec{\sigma}_n \cdot \vec{P}_e}{E_e} + B \frac{\vec{\sigma}_n \cdot \vec{P}_\nu}{E_\nu} + D \frac{\vec{\sigma}_n \cdot (\vec{P}_\nu \times \vec{P}_e)}{E_e E_\nu} \right],$$

where $F(E)$ is a function of the electron energy, P_e and P_ν (E_e and E_ν) are the electron and antineutrino momenta (energy) respectively, σ_n is the neutron spin, and a , A , B , and D are the coefficients of the electron-antineutrino, neutron spin-electron, neutron spin-antineutrino, and triple correlations, respectively. We note that we have neglected recoil order terms (eg. weak magnetism) in the above expression. The triple correlation term is the one we are particularly interested in since it is odd under time reversal. We note that by conservation of energy and momentum, we can rewrite this correlation in terms of observables of the electron and proton:

$$\vec{\sigma}_n \cdot \frac{(\vec{P}_e \times \vec{P}_\nu)}{E_e E_\nu} = - \vec{\sigma}_n \cdot \frac{(\vec{P}_e \times \vec{P}_p)}{E_e (\Delta - E_e - E_p - m_e c^2)},$$

where $\vec{p}_p$ (E_p) is the recoil proton momentum (energy), Δ is the mass difference between the neutron and proton, and m_e is the electron mass.

In terms of the scalar (S), vector (V), axial vector (A), and tensor (T) coupling constants of the weak interaction, the coefficient D is given by

$$D = \frac{2 \operatorname{Im} (ST^* - VA^*)}{|V|^2 + |S|^2 + 3|T|^2 + 3|A|^2} .$$

Since any tensor component of the weak interactions is known to be small /6/, the dominant contribution is from the VA^* component. Thus, contributions to D from the scalar Higgs sector will be very small. However, as pointed out recently /7/, the possibility exists that in the left-right symmetric models of $SU(2)_L \times SU(2)_R \times U(1)$ there can be sizeable contributions to D due to T violation. Specifically, D is given by

$$D = -(g_R/g_L) \cos \zeta (\cos \theta_R / \cos \theta_L) \sin (\alpha + \omega) ,$$

where g_R (g_L) is the coupling constant for the right (left)-handed components of the weak interaction, ζ is the mixing angle between the left- and right-handed fields, θ_R (θ_L) is the mixing angle for the right (left)-handed coupling between quarks, and α and ω are CP violating phases. It is pointed out in Ref. 7 that it is necessary to introduce the phases α and ω (which are in addition to the usual Kobayashi-Maskawa CP-violating phase) in order to fully describe CP violation in the quark model. Data on semileptonic weak interactions do not rule out $|\sin \alpha|$ of the order of 1. Thus, we expect /7/ $|D| \lesssim 10^{-3}-10^{-4}$, this bound being set by experimental limits on the electric dipole moment of the neutron and measurements of the CP-violating parameters in neutral kaon decay of $|\eta_+ - \eta_{00}|$.

Before going on to discuss experimental approaches to measuring D, we must first be sure that a nonzero value of D indicates the existence of T violation. It is well known that final state electromagnetic interactions can produce a nonzero value of D that is not T-violating. However, these final state contributions can be accurately calculated and it has been shown /3/ that the dominant contribution to D arises from weak magnetism and produces a value of $D = 2 \times 10^{-5}$. Thus, an observed value of D larger than this would indicate that the weak interaction is not invariant under T reversal.

Several experiments to measure D have been carried out during the last 25 years. Most recently, experiments have been carried out at the Institute Laue-Langevin /9/ and at the Kurchatov Institute of Atomic Energy /10/ which set limits on D in polarized neutron beta decay and at Princeton University /11/ in the beta decay of polarized ^{19}Ne . We note here only that the present limit on D in ^{19}Ne is $(-0.5 \pm 1.0) \times 10^{-3}$ and that the contribution to D from weak magnetism is 1.6×10^{-4} .

Since the ILL and Kurchatov experiments are similar in design, we will discuss here only the ILL experiment. A 100-m-long guide tube transports neutrons from the liquid deuterium moderator in the core of the ILL reactor to an experimental area. The guide tube has a radius of curvature of 2700 m which serves to strongly attenuate fast neutrons and gammas from the reactor core while transporting cold neutrons with high efficiency. At the end of the guide tube the beam passes through a polarizer that produces high transverse polarization of the beam. The beam is then rotated 90° to form a longitudinally polarized beam. The longitudinal polarization is maintained over the length of the detector by a longitudinal magnetic field of a few gauss. The neutron beam then passes into an equipotential region at positive high voltage by grids that form the decay region. Betas from neutrons decaying in this region are detected in plastic scintillators above and below the beam. Recoil protons are accelerated to 20 KeV from the gridded region into detectors consisting of thin layers of NaI deposited onto photomultiplier tubes. The neutron beam then exits the detector and is stopped in a ^6LiF beam stop. Timing single channel analyzers were used to set windows on the beta and proton

energy signals and to form a time-of-flight spectrum for the protons. In order to minimize systematic effects, the detector was made as symmetric as possible with two beta and two proton detectors. With a beta detected in the upper counter, one then looks for a left-right asymmetry in the number of counts in the two proton detectors and similarly for betas detected in the lower counter. Data was collected with the neutron polarization both parallel and antiparallel to the beam direction. The data was then analyzed in terms of ratios of events in different detectors. This provides cancellation of most detector asymmetries. The pertinent parameters for the ILL and Kurchatov experiments are listed in Table I. The final results for the ILL and Kurchatov experiments are $D = (-1.1 \pm 1.7) \times 10^{-3}$ and $D = (+2.2 \pm 3.0) \times 10^{-3}$ respectively.

Table I. Experimental parameters in measurements of triple correlation in polarized neutron beta decay.

Experiment	Flux (n/s)	Polarization	Beam Size	Length of Decay Region	Coincident Decay Rate	Signal to Noise	Number of Events
ILL	1×10^9	70%	4 x 8 cm	40 cm	1.5 cts/s	4	5.9×10^6
Kurchatov	1×10^9	70%	4 x 8 cm	12 cm	0.8 cts/s	2	2.5×10^6
Proposed	2×10^9	95%	4 cm	100 cm	100 cts/s	>10	10^9

In designing an experiment to substantially improved on the above results, we realized three things would be essential: 1) much higher event rates with better signal to noise, 2) the detector geometry must be as symmetrical as possible, and 3) it must be possible to study systematic effects on line. In order to achieve these goals, we have designed a system in which 1) the use of supermirror polarizers increases both the polarized flux and the polarization, 2) the decay region is made as long as practical (100 cm); 3) the neutron beam is circular in cross-section and is relatively small (4 cm diam), 4) the detector is extremely symmetrical so that betas and protons can both be detected at all azimuthal angles, 5) noise is reduced by multiple coincidence requirements for betas and anticoincidence requirements for protons, and 6) every decay can be kinematically reconstructed. The real key to this experiment is the ability to kinematically reconstruct each event. This allows us to bin the neutron beam to look for systematic effects as a function of radius and position along the beam. It also allows us to study the correlation as a function of beta and recoil proton energy and to place computer cuts during analysis on energy spectra and angles between the neutron spin and the electron and proton momenta. The experimental parameters are listed in Table I. The detector is shown in Fig. 1. A decay region at positive high voltage (35KV) is defined by grids. The betas from neutrons decaying in this region pass through two X and two Y proportional drift chambers and are stopped in plastic scintillator which is viewed by photomultiplier tubes at both ends. The recoil protons are accelerated to 35 KeV into multistep avalanche counters [11] where they are stopped. These counters have very thin ($40 \mu\text{g}/\text{cm}^2$) windows and operate at pressures of 5-10 Torr of isobutane. These counters provide two dimensional readout of the proton position, energy, and timing which allows determination of the proton time-of-flight. From these measured quantities and conservation of energy and momentum, we can determine the momenta and energies of the electron, proton, and neutrino as well as the location of the decay vertex. However, the equation giving the decay vertex is quadratic, so that the solution is two-valued. For our particular detector design, we can resolve this ambiguity 30% of the time due to the boundary condition that the decay occurs within the neutron beam.

Possible sources of spurious asymmetries have been discussed in detail in the literature [9,10]. We have written an extensive Monte Carlo program to study the detector response that allows us to determine our sensitivity to these sources of asymmetries. The experiment will be run and data analyzed in much the same way as

Fig. 1 - Cross sectional view of detector.

described for the previous ILL experiment. For decays in which only one decay vertex is allowed, we will fit the data using a least squares fit. For decays in which two decay vertices are allowed, we will average these decays and fit them using an average geometrical factor, exactly as was done in the previous ILL experiment. While this somewhat reduces our overall sensitivity, our Monte Carlo calculations indicate this does not introduce a false asymmetry. The result of our analytic and Monte Carlo calculations indicates that we should be able to keep all systematic effects well below our statistical accuracy of $1-2 \times 10^{-4}$ for D.

In summary, we have shown that use of new detector and beam polarizing technologies will allow us to carry out an experiment which will test for time reversal violation in polarized neutron beta decay with an order of magnitude higher sensitivity than previous experiments. This will provide much stronger constraints than now exist on theories attempting to explain CP violation by $V + A$ admixtures into the standard $V - A$ theory.

References

- [1] Fitch (V. L.) and Cronin (J. W.), Rev. Mod. Phys. (1981), 53, 270
- [2] Kobayashi (M.) and Maskawa (T.), Prog. Theor. Phys. (1973) 49, 652
- [3] Wolfenstein (L.), Phys. Rev. Lett. (1964) 13, 569
- [4] Weinberg (S.), Phys. Rev. Lett. (1976) 37, 657
- [5] Mohapatra (R. N.) and Pati (J. C.), Phys. Rev. (1975) D11, 566
- [6] Paul (H.), Nucl. Phys. (1970) A154, 160
- [7] Herczeg (P.), Phys. Rev. (1983) D28, 200
- [8] Callan (C. G.) and Treiman (S. B.), Phys. Rev. (1967) D162, 1494
- [9] Steinberg (R. I.), Liaud (P.), Vignon (B.), and Hughes (V. W.), Phys. Rev. (1976) D13, 2469
- [10] B. Erozinakii (B. G.), Mostovoi (Yu. A.), Fedunin (V. P.), Frank (A. I.), and Khakhan (O. V.), Sov. J. Nucl. Phys. (1978) 28, 48
- [11] Brekin (A.), Charnak (G.), Majewski (S.), Melchart (G.), Petersen (G.), and Sauli (F.), Nucl. Instr. and Meth. (1979) 161, 19