Constraints on a
Parity-Conserving/Time-Reversal-Non-Conserving
Interaction∗

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Abstract

Time-Reversal-Invariance non-conservation has for the first
time been unequivocally demonstrated in a direct measurement
at CPLEAR. One then can ask the question: What about tests
of time-reversal-invariance in systems other than the kaon sys-
tem? Tests of time-reversal-invariance can be distinguished as
belonging to two classes: the first one deals with parity vi-
olating (P-odd)/time-reversal-invariance-odd (T-odd) interac-
tions, while the second one deals with P-even/T-odd interac-
tions (assuming CPT conservation this implies C-conjugation
non-conservation). Limits on a P-odd/T-odd interaction fol-
low from measurements of the electric dipole moment of the
neutron (with a present upper limit of $8 \times 10^{-26}$ e.cm [95%
C.L.]). It provides a limit on a P-odd/T-odd pion-nucleon cou-
pling constant which is less than $10^{-4}$ times the weak interac-
tion strength. Experimental limits on a P-even/T-odd interac-
tion are much less stringent. Following the standard approach
of describing the nucleon-nucleon interaction in terms of me-
son exchanges, it can be shown that only charged rho-meson
exchange and $A_1$-meson exchange can lead to a P-even/T-odd
interaction. The better constraints stem from measurements of
the electric dipole moment of the neutron and from measure-
ments of charge-symmetry breaking in neutron-proton elastic
scattering. The latter experiments were executed at TRIUMF
(497 and 347 MeV) and at IUCF (183 MeV). Weak decay ex-
periments may provide limits which will possibly be comparable.

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All other experiments, like gamma decay experiments, detailed balance experiments, polarization - analyzing power difference determinations, and five-fold correlation experiments with polarized incident nucleons and aligned nuclear targets, have been shown to be at least an order of magnitude less sensitive. The question then emerges: is there room for further experimentation?

1. Introduction

Time-Reversal-Invariance non-conservation has for the first time been unequivocally demonstrated in a direct measurement at CPLEAR.[1] The experiment measured directly the difference in the transition probabilities $P(\overline{K}^0 \rightarrow K^0)$ and $P(K^0 \rightarrow \overline{K}^0)$. A non-zero value of this difference gives model independent evidence of time-reversal-invariance non-conservation. The deduction does not depend on the validity of the $\Delta S = \Delta Q$ rule. The result obtained for $A_T$ with

$$A_T = \frac{R(\overline{K}^0 \rightarrow K^0) - R(K^0 \rightarrow \overline{K}^0)}{R(\overline{K}^0 \rightarrow K^0) + R(K^0 \rightarrow \overline{K}^0)}$$

is in good agreement with the measure of CP violation in neutral kaon decay. Starting with CPT conservation and the well established non-conservation of CP in kaon decays, time-reversal-invariance should also be broken. The CPLEAR measurement is the first direct confirmation of that. The question that one then can ask is: what about time-reversal-invariance non-conservation in systems other than the kaon system?

Tests of time-reversal-invariance can be distinguished as belonging to two classes: the first one deals with time-reversal-invariance-odd (T-odd)/parity violating (P-odd) interactions, while the second one deals with T-odd/P-even interactions (assuming CPT invariance this implies C-conjugation non-conservation). However, it should be noted that constraints on these two classes of interactions are not independent since the effects due to T-odd/P-odd interactions may also be produced by T-odd/P-even interactions in conjunction with Standard Model parity violating radiative corrections. The latter can occur at the $10^{-7}$ level and consequently this presents a limit on the constraint of T-odd/P-even interactions, which can be derived from experiments. Limits on a T-odd/P-odd interaction follow from measurements of the electric dipole moment of the neutron (which currently stands at $< 6 \times 10^{-26}$ e.cm [95% C.L.]). It provides a limit on a T-odd/P-odd pion-nucleon coupling constant which is less than $10^{-4}$ times the weak interaction
measurements of the electric dipole moment of the neutron and from measurements of charge symmetry breaking in neutron-proton elastic scattering. All other experiments, like gamma decay experiments [4], detailed balance experiments [5], polarization - analyzing power difference measurements, and five-fold correlation experiments with polarized incident nucleons and aligned nuclear targets, have been shown to be at least an order of magnitude less sensitive. Haxton, Hoering, and Musolf [2] have deduced constraints on a T-odd/P-even interaction from nucleon, nuclear, and atomic electric dipole moments with the better constraint coming from the electric dipole moment of the neutron. In terms of a ratio to the strong rho-meson nucleon coupling constant, they deduced for the T-odd / P-even rho-meson nucleon coupling:

\[
|g_\rho| < 0.53 \times 10^{-3} \times \left| \frac{f_\pi^{DDH}}{f_\pi^{ meas}} \right|.
\]

Here one should note that the ratio of the theoretical to the measured value of \(f_\pi\) may be as large as 15! [6]

In the Standard Model a T-odd/P-even nucleon-nucleon interaction can hardly be accommodated. It requires C-conjugation non-conservation, which cannot be introduced at the first generation quark level. It can neither be introduced into the gluon self-interaction. Consequently one needs to consider C-conjugation non-conservation between quarks of different generations and/or between interacting fields. [7]

2. Nucleon-Nucleon Interaction

The nucleon-nucleon scattering matrix, assuming conservation of angular momentum, parity, time-reversal-invariance, and isospin, consists of five complex amplitudes, \(a, b, c, d,\) and \(e\), which are functions of centre-of-mass energy \(E\) and scattering angle \(\theta\). If isospin is broken (which leads to charge symmetry breaking in the neutron-proton system), the neutron-proton scattering matrix contains a sixth complex amplitude, \(f\). If in addition one no longer assumes time-reversal-invariance, the neutron-proton scattering matrix has two additional amplitudes, \(g\) and \(h\); the second one of these, \(h\), is simultaneously time-reversal-invariance violating and charge symmetry breaking. [8]

\[
M = \frac{1}{2} [(a + b) + (a - b)(\vec{\sigma}_1 \cdot \hat{n})(\vec{\sigma}_2 \cdot \hat{n}) + (c + d)(\vec{\sigma}_1 \cdot \hat{m})(\vec{\sigma}_2 \cdot \hat{m}) + (c - d)(\vec{\sigma}_1 \cdot \hat{l})(\vec{\sigma}_2 \cdot \hat{l}) + e((\vec{\sigma}_1 \cdot \hat{n}) + (\vec{\sigma}_2 \cdot \hat{n}))]
\]
\begin{align*}
+ f((\vec{\sigma}_1 \cdot \hat{n}) - (\vec{\sigma}_2 \cdot \hat{n})) & + g((\vec{\sigma}_1 \cdot \hat{l})(\vec{\sigma}_2 \cdot \hat{m}) + (\vec{\sigma}_1 \cdot \hat{m})(\vec{\sigma}_2 \cdot \hat{l})) \\
+ h((\vec{\sigma}_1 \cdot \hat{l})(\vec{\sigma}_2 \cdot \hat{m}) - (\vec{\sigma}_1 \cdot \hat{m})(\vec{\sigma}_2 \cdot \hat{l})),
\end{align*}

where $\hat{l}$, $\hat{m}$, and $\hat{n}$ are unit vectors given as $\hat{l} = (\vec{k}_i + \vec{k}_f)/|\vec{k}_i + \vec{k}_f|$; $\hat{m} = (\vec{k}_f - \vec{k}_i)/|\vec{k}_f - \vec{k}_i|$; $\hat{n} = (\vec{k}_i \times \vec{k}_f)/|\vec{k}_i \times \vec{k}_f|$ and $\vec{k}_i$ and $\vec{k}_f$ are the initial and final state centre-of-mass nucleon momenta. $\vec{\sigma}_1$ and $\vec{\sigma}_2$ are Pauli spin matrices for the two nucleons. The proton-proton system may only contain one additional, sixth time-reversal-invariance non-conserving amplitude, $g$. In a partial wave decomposition the four lowest, parity conserving, transition amplitudes in which time-reversal-invariance violation may occur are $^3S_1 \leftrightarrow ^3D_1$, $^1P_1 \leftrightarrow ^3P_1$, $^1D_2 \leftrightarrow ^3D_2$, $^3P_2 \leftrightarrow ^3F_2$. Of these only the latter one is allowed for identical nucleons because of the Pauli exclusion principle. Thus time-reversal-invariance violating effects, if these exist, are strongly suppressed in the proton-proton and neutron-neutron systems. As shown by Arash, Moravcsik, and Goldstein [9] null tests of time-reversal-invariance do not exist in a two-particle in and two-particle out reaction. Observables are bilinear product combinations of scattering amplitudes. Tests of time-reversal-invariance can be accomplished only through a comparison of two distinct observables. As prime example, polarization - analyzing power difference determinations, $P - A = -2 \times Im(c^*h + d^*g)/\sigma_0$, are based on two independent measurements with their own systematic errors in polarimeter analyzing power and beam polarization calibrations. The best calibration standards to date carry uncertainties of a few parts in $10^3$. Writing the polarization - analyzing power difference as $\epsilon(1 - D)/2$, with $\epsilon$ the normalized spin-flip differential cross sections difference and with $D$ the depolarization parameter, one can show that most such difference determinations for the neutron-proton system were made in an angular region where $D$ is close to one [10], causing a measure of insensitivity to time-reversal-invariance non-conservation. Similarly, time-reversal-invariance tests performed in the proton-proton system are rather inconclusive. [8] As noted by Conzett [11] transmission experiments are not included in the nonexistence proof of Arash, Moravcsik, and Goldstein. Indeed, since the total cross section can be expressed in terms of the imaginary part of the forward scattering amplitude, null tests of time-reversal-invariance can be devised for transmission experiments (a selected spin-dependent total cross section linearly dependent on the time-reversal-non-invariant amplitude). Transmission experiments that test a $T$-odd / $P$-even interaction require spin 1/2 particles incident on target particles with spin $J \geq 1$ or vice versa.

Charge symmetry breaking (CSB) in neutron-proton elastic scattering manifests itself as a non-zero difference of the neutron ($A_n$) and proton ($A_p$) analyzing powers, $\Delta A = A_n - A_p = 2 \times [Re(b^*f) + Im(c^*h)]/\sigma_0$. The three precision experiments performed (at TRIUMF at 477 MeV
and at 369 MeV [13], and at IUCF at 183 MeV [14]) have unquestionably shown that charge symmetry is broken and that the results for ∆A at the zero-crossing angle of the average analyzing power, are very well reproduced by meson exchange model calculations (see Fig.1). As shown above a T-odd / P-even interaction corresponds to a term in the scattering amplitude which is simultaneously charge symmetry breaking. Thus, Simonius [15] deduced an upper limit on a T-odd / P-even CSB interaction from a comparison of the experimental results with the theoretical predictions for the above mentioned three CSB experiments. The upper limit so derived is |\overline{g}_ρ| < 6.7 \times 10^{-3} [95\% C.L.]. This is therefore comparable to the upper limit deduced from the electric dipole moment of the neutron, taking the present experimental limit of \( f_π \), and is considerably lower than the limits inferred from direct tests of a T-odd / P-even interaction. For instance the detailed balance experiments give a limit on \(|\overline{g}_ρ| < 2.5 \times 10^{-1}. [16] \) As remarked above, it is inconceivable in the Standard Model to account for a T-odd / P-even interaction. Nevertheless, there is a need to clarify the experimental constraint on a T-odd / P-even interaction by providing a BETTER experimental limit.

Such a better experimental constraint may be provided by an improved upper limit on the electric dipole moment of the neutron. In fact a new measurement with a sensitivity of \( 4 \times 10^{-28} \) e.cm has been proposed at the Los Alamos Neutron Science Center.[17] But performing an improved n-p elastic scattering CSB experiment appears to be a very attractive alternative. One can calculate with a great deal of confidence the contributions to CSB due to one-photon exchange (the neutron magnetic moment interacting with the current of the proton) and due to the n-p mass difference affecting charged one-pion and rho-meson exchange. Furthermore, one can select an energy where the \( ρ^0 - ω \) meson mixing contribution changes sign at the same angle where the average of the analyzing powers \( \overline{A}_n \) and \( \overline{A}_p \) changes sign and therefore does not contribute. This occurs at an incident neutron energy of 320 MeV and is caused by the particular interplay of the n-p phase shifts and the form of the spin/isospin operator for the \( ρ^0 - ω \) mixing term. But also the contribution due to one-photon exchange changes sign at about the same angle at 320 MeV. The contribution due to two-pion exchange with an intermediate \( Δ \) is expected to be no more than one tenth of the overall CSB effect, essentially presenting an upper limit on the theoretical uncertainty (see Fig. 2).[18] It has been shown that simultaneous \( γ - π \) exchanges can only contribute through second order processes and can therefore be neglected.[19] Also the effects of inelasticity are negligibly small at 320 MeV. It appears therefore well within reach to reduce the theoretical uncertainty in the comparison between experiment and theory. Subtracting the calculated difference in the neutron and proton analyzing powers from the measured difference in
these permits establishing an upper limit on a P-even / T-odd / CSB interaction.

The second TRIUMF experiment measuring CSB in n-p elastic scattering at 347 MeV obtained the result \( \Delta A = A_n - A_p = (59 \pm 7 \text{(stat)} \pm 7 \text{(syst)} \pm 2 \text{(syst)}) \times 10^{-4} \) at the zero-crossing angle of the average of \( A_n \) and \( A_p \). In the experiment polarized neutrons were scattered from unpolarized protons and vice versa. The polarized (or unpolarized) neutron beam was obtained using the \((p,n)\) reaction with a 369 MeV polarized (or unpolarized) proton beam incident on a 0.20 m long LD\(_2\) target. At the TRIUMF energies one makes use of the large sideways-to-sideways polarization transfer coefficient \( r_t \) at 9 degrees in the lab. The only difference in obtaining the unpolarized and polarized neutron beams was the turning off of the pumping laser light in the optically pumped polarized ion source (OPPIS). The polarized proton target was of the frozen spin type with butanol beads as target material. The same target after depolarization was used as the unpolarized proton target. Great care was taken that the two interleaved phases of the experiment were performed with identical beam and target parameters except for the polarization states. Scattered neutrons and recoiling protons were detected in coincidence in the c.m. angular range 53.4 to 86.9 degrees in two left-right symmetric detector systems. Rather than measuring \( A_n \) and \( A_p \) directly (which would be troubled by not having polarization calibration standards of the required precision), the zero-crossings of \( A_n \) and \( A_p \) were determined by fitting the partial angular distributions with polynomials, deduced from n-p phase shift analyses. The difference \( A_n - A_p \) followed by multiplying the difference in the zero-crossing angles by the average slope of the analyzing powers (the experiment measured the slope of \( A_p \) at the zero-crossing angle, which is a very good approximation for the average slope at the zero-crossing angle and introduces a negligible error). The principle of the measurement is shown schematically in Fig. 3. The execution of the experiment depended on a great deal of simultaneous monitoring and control measurements (see Fig. 4 for a schematic view of the experiment).

Both the statistical and systematic errors obtained in the experiment can be considerably improved upon. With the OPPIS developments that have taken place in the intervening years and with the addition of a biased Na-ionizer cell, it will be possible to obtain up to 50 \( \mu \)A of beam with a polarization of 80% incident on the neutron production LD\(_2\) target (a factor of 50 increase in neutron beam intensity over the previous CSB experiment).\(^{[20]}\) A 342 MeV proton beam incident on a 0.20 m long LD\(_2\) target would present a heat load of 500 W. LH\(_2\) targets allowing such heat loads have been developed for electron scattering experiments. However, reducing the LD\(_2\) target thickness to 0.05 m would give a better defined neutron energy spectrum reducing the uncertainty in the difference in apparent energies of the \( A_n \) and \( A_p \) measurements. Correcting for the apparent energy difference contributes significantly
to the systematic error budget. The median of the intensity distribution of the proton beam incident on the LD$_2$ target will again be kept fixed to within 0.05 mm at two places through feedback loops to two sets of steering magnets placed upstream in the beam line. This freezes position and direction of the proton beam at the LD$_2$ target, necessary to meet the secondary neutron beam energy and direction stability requirement. The polarized proton target should again be of the frozen spin type; choosing a target material with improved ratio of free protons to bound protons and a lower magnetic holding field ($<0.2$ T) would greatly improve on the systematic error by reducing the uncertainty in the background subtraction. It appears entirely feasible to reduce the statistical and systematic errors by a factor three to four. Such an experiment would constitute a measurement of CSB in n-p elastic scattering of unprecedented precision, of great value on its own, and would be simultaneously provide the best upper limit on a T-odd/P-even interaction.

3. Null Tests

As remarked above true null tests of time-reversal-invariance do not exist for spin 1/2 particles scattered from spin 1/2 particles. However, null tests exist as transmission measurements for spin 1/2 particles interacting with aligned nuclear targets.[11] In such tests one measures the total cross section asymmetry $A_{y,xz}$ of vector polarized spin 1/2 particles interacting with an aligned nuclear target (for instance a tensor polarized spin 1 deuteron target). Huffman et al [16] have extracted the five-fold correlation parameter $A_{y,xz}$ by observing polarized neutron transmission through nuclear spin-aligned $^{165}$Ho. This resulted in an upper limit for $|\bar{g}_p|$ of $5.9 \times 10^{-2}$ even though the measured value of $A_{y,xz}$ was $(8.6 \pm 7.7) \times 10^{-6}$. It is to be noted that only the valence proton in $^{165}$Ho contributes to $A_{y,xz}$.

Storage rings provide a completely different environment, with the advantages outweighing the disadvantages possibly, for high precision tests of fundamental symmetries (like testing time-reversal-invariance in the GeV range), as discussed for instance by S.E. Vigdor.[21] At COSY a proton-deuteron transmission experiment has been proposed to measure the T-odd/P-even observable $A_{y,xz}$ using a polarized internal proton beam (polarization $P_y$) and an internal polarized deuterium target $P_{xz}$. Tensor polarized deuterium atoms are produced in an atomic beam source based on Stern-Gerlach separation in permanent sextupole magnets and adiabatic high frequency transitions. Adequate luminosities can be obtained using a window-less storage cell placed on the axis of the proton beam [22]. The polarized proton beam is obtained from an atomic crossed beam polarized ion source. For this test of a T-odd / P-even interaction the COSY ring will serve as accelerator, forward spectrometer, and detector.[23] Figure 5 presents a schematic view of
the COSY facility with the EDDA internal target and detector system for this T-odd/P-even test. Crucial to the experiment is a current monitor which can register with the required precision the decrease in circulating beam intensity with time as function of the circulating proton beam spin state. Also of great importance is the precise alignment of the proton beam vector and deuteron beam tensor polarizations in order to suppress unwanted spin correlation coefficients, which could produce a false result. An accuracy of $10^{-6}$ in $A_{\mu,xx}$ has been planned for the experiment, which would give a predicted sensitivity to $|g_\rho|$ of $10^{-3}$ and to $|g_A|$ of $2 \times 10^{-3}$ for center of mass momenta in the range 200 to 400 MeV/c. The predicted sensitivity is decreasing for higher momenta. There is a further measure of uncertainty due to the relatively large inelasticity (pion production) in the momentum range 2-3 GeV/c, for which the COSY experiment is planned.[24] The dilution effect of Coulomb multiple scattering decreases significantly with increasing proton beam energy. It will be a tour-de-force for the experiment to reach a sensitivity comparable to the present n-p CSB experiments.

4. K and B Decays

Other searches for a T-odd / P-even interaction are made in particle decays, e.g., in the decay $K^+ \rightarrow \mu^+\pi^0\nu_\mu$. A non-zero value of the muon polarization transverse to the decay plane would be an indication of time-reversal-invariance non-conservation. Several experiments have been performed using both neutral and charged kaons. There is a unique feature to the transverse muon polarization in that it does not have contributions from the Standard Model at tree level and that higher order effects are of order $10^{-6}$. With only one charged particle in the final state, a final state interaction, which can mimic a time-reversal-invariance breaking effect, is greatly reduced and is estimated to occur at the same level of $10^{-6}$. The more recent effort of measuring the time-reversal-invariance non-conserving transverse muon polarization is at KEK using a stopped $K^+$ beam. The experiment reports a result for $P_T = -0.0042 \pm 0.0049$ (stat) $\pm 0.0009$ (syst), based on the data taken in 1996 and 1997, which translates into a value of $\text{Im}\xi = -0.0013 \pm 0.0169$ (stat) $\pm 0.0009$ (syst).[25] The quantity $\xi$ is defined as the ratio of the two form factors, $f_+(q^2)$ and $f_-(q^2)$, in the $K_{\mu 3}$ decay matrix element: $\text{Im}\xi$ must be equal to zero for time-reversal-invariance to hold.[26] With the data already in hand and with the approved data taking time, it is anticipated to arrive at a statistical error of $\pm 0.0008$ in $\text{Im}\xi$. The best previous experimental limits were obtained with both neutral and charged kaons at the BNL-AGS.[27] A combination of both experimental results provided a limit on the imaginary part of the hadron form factors, $\text{Im}\xi = -0.01 \pm 0.019$. A new search for the time-reversal-invariance non-conserving transverse muon polarization with in-flight decays $K^+ \rightarrow \mu^+\pi^0\nu_\mu$ was proposed at the
BNL-AGS.[28] It was intended to obtain a sensitivity to the transverse muon polarization of ±0.00013, corresponding to a sensitivity to \( \text{Im}\xi \) of ±0.0007. The possibility of similar searches for the time-reversal-invariance non-conserving transverse \( \tau \) polarization in B semileptonic decays, \( B \rightarrow M\tau\nu_\tau \), has been discussed recently by Y. Kuno.[29] It is estimated that the polarization of the \( \tau \) leptons could reach as high as as 30\% in \( B^+ \rightarrow D^0\tau\nu \) decays. A non-zero value of the transverse muon polarization in \( K_{\mu 3} \) decay and of the \( \tau \) lepton in semi-leptonic B decays would constitute clear evidence for new physics.

5. Summary

In summary, searches for a T-odd / P-even interaction have so far resulted in only very modest limits on such an interaction. Most promising are the continuing efforts to measure the electric dipole moment of the neutron, to measure charge-symmetry breaking in neutron-proton elastic scattering at around 320 MeV, and to measure the five-fold correlation parameter \( A_{y,xz} \) in a proton-deuteron transmission experiment, as well as searches of transverse lepton polarizations in K and B decays.
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Figure 1: Experimental results of $\Delta A$ at the zero-crossing angle at incident neutron energies of 183, 347, and 477 MeV compared with theoretical predictions of Iqbal and Niskanen and Holzenkamp, Holinde, and Thomas. The inner error bars present the statistical uncertainties; the outer error bars have the systematic uncertainties included (added in quadrature). For further details see Ref. 13.
Figure 2: Angular distributions of the different contributions to $\Delta A$ at an incident neutron energy of 320 MeV (see Ref. 18). Note that the $\rho^0 - \omega$ mixing contribution passes through zero at the same angle as the average of $A_n$ and $A_p$. 
Figure 3: Principle of the TRIUMF neutron-proton elastic scattering CSB experiments.

\[ \Delta A = - \frac{dA}{d\theta} \Delta \theta \]
Figure 4: Schematic view of the TRIUMF CSB experiments.
Figure 5: Schematic view of the COSY facility.