Letter of Intent

Test of Time Reversal Invariance Using Electron Scattering on Polarized Protons

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Abstract

We propose to test the time reversal invariance properties of the electromagnetic interaction, improving the precision of current measurements by a factor of 100 to 250, in 60 days of running. The measurement can be done using TJNAF's electron beam, a solid polarized

target capable of polarizing NH_3 material in the direction normal to the scattering plane and one of the medium or high resolution spectrometers in Hall A or C.

1. Motivation

Invariances of the laws of physics under discrete symmetry operations, such as space translations or space rotations, reflect fundamental properties of matter. For example, it is well known that the invariances just mentioned reflect the laws of linear and angular momentum conservation for isolated systems. It is also well known that not all physical processes are invariant under every symmetry operation: the weak interaction violates invariance under space reflection (parity, P) and the decay of the neutral K meson violates invariance under the combined charge conjugation (C) and parity operations CP.

However, it is not known for certain whether all the C, P and CP conserving interactions are also invariant under time reversal (T). T invariance is reflected in the law of conservation of energy for systems with conservative forces. A fundamental theorem of relativistic field theory states that all interactions must be invariant under the combined CPT operation [1], and therefore CP invariance implies T invariance, and correspondingly CP violation implies T violation, as in the K^0 decays. But there are no precision direct tests of T non-invariance in the CP conserving interactions, which would imply CPT violation. Also, P could be conserved while C and T are separately violated.

The strong interaction H_h has been shown to a high precision to be invariant under parity P_h, time reversal T_h and particle-anti particle conjugation C_h, where the subscript h denotes operations on hadronic systems. Similarly, the electromagnetic interaction H_γ is invariant under P_γ, T_γ and charge conjugation C_γ. An example of C_γ invariance is the high suppression of the decay $\pi^0 \to 3\gamma$ which has a $< 3 \times 10^{-8}$ branching ratio [2]. Both H_γ and H_h are invariant under $P_\gamma = P_h$ and under the combination $C_\gamma P_\gamma T_\gamma = C_h P_h T_h$. However, as pointed out in ref. [3], H_γ has not yet been shown to be invariant under particle-anti particle conjugation C_h, which for hadrons is not necessarily identical to charge conjugation

C_γ. It is assumed that H_γ is invariant under C_h, or $C_h = C_\gamma$, for both leptons and hadrons, but it has not been tested for hadrons in a model independent way to better than $\sim 10^{-4}$ [2,4]. Any violation of C_h by H_γ implies T_h non-invariance, by the CPT theorem and the observed P_h invariance of both H_h and H_γ.

The non-invariance of the electromagnetic interaction under T_h or C_h would manifest itself as a non-zero additional component K_μ of the hadronic part of the electromagnetic current [3]

$$e\mathcal{J}_\mu = e(j_\mu + J_\mu + K_\mu), \tag{1}$$

where j_μ is the leptonic current and J_μ is the normal hadronic current. $\mathcal{J}_\mu$ changes sign under $C_\gamma \mathcal{J}_\mu C_\gamma^{-1} = -\mathcal{J}_\mu$, but K_μ may not change sign under $C_h K_\mu C_h^{-1} = +K_\mu$. Then, by CPT, a non-zero K_μ implies that H_γ is not C_h and T_h invariant, since

$$\begin{aligned} T_\gamma \mathcal{J}_\mu T_\gamma^{-1} &= -\mathcal{J}_\mu \\ T_h J_\mu T_h^{-1} &= -J_\mu \\ T_h K_\mu T_h^{-1} &= K_\mu. \end{aligned} \tag{2}$$

A direct test of T_h violation in electromagnetic interactions would involve studying a process in which current signs in lepton-hadron scattering are reversed without resorting to charge conjugation. As suggested by several authors [3,5–7] polarized scattering in which either the initial state is polarized, or the polarization of the final state is observed, meet this condition. In what follows, we will concentrate on the first approach, since, unlike the second method, it does not require accounting for all contributions to the polarization from final states other than the chosen one.

It should also be pointed out that there are other processes that can be used to test T invariance of the various interactions, either directly or through C or P invariance, such as the limits on the dipole moments of the electron, neutron and other particles. Among the direct tests, the angular correlations in neutron, muon and other weak decays are notable.

These and other direct tests indicate that T invariance for the weak interaction is obeyed at the 1% to 0.1% level [2].

2. Experimental Technique

We propose to carry out a direct test of T invariance in the electromagnetic interactions of hadrons by measuring the inclusive asymmetry in the scattering of electrons on polarized protons in the region of the nucleon resonances. Any individual final state or all the final states combined can be considered, as long as they are not identical to the initial state. For the latter case, which corresponds to elastic scattering, the asymmetry is zero by current conservation and hermiticity, in the single photon exchange approximation. Therefore, we also plan a simultaneous measurement of the elastic asymmetry, to quantify the contributions to the asymmetry of deviations from single photon exchange.

T non-invariance would manifest itself in the presence of non-zero structure functions proportional to the correlation [3]

$$\mathbf{S_{in}} \cdot \mathbf{k} \times \mathbf{k}' \tag{3}$$

where $\mathbf{S_{in}}$ is the polarization of the nucleus, and $\mathbf{k}, \mathbf{k}'$ are the initial and scattered electron three-momenta in the laboratory. Thus, for this test, the nucleus has to be polarized in a direction normal to the electron scattering plane, usually horizontal in the lab.

Writing the correlation in the approximation $m_e/E \ll 1$, where m_e is the electron mass, $\mathbf{S_{in}} \cdot \mathbf{k} \times \mathbf{k}'$ reduces to $P_t E E' \cos\phi \sin\theta$, where P_t is the magnitude of the target polarization and the angle ϕ is defined in fig. 1. The cross section for this type of scattering can then be written as

$$\frac{d^2\sigma}{dE'd\Omega} = \sigma_{Mott} \frac{E'}{E} \Big(2W_1 \tan^2(\theta/2) + W_2 + \frac{E^2 - E'^2}{M^2}\ P_t W_3 \cos\phi \tan(\theta/2) \Big), \tag{4}$$

where E, E' are the beam and scattered electron energies in the lab system, θ is the scattering angle, M is the nucleon mass and the Mott cross section is $\sigma_{Mott} = (\alpha \cos(\theta/2)/E \sin^2(\theta/2))^2$. $W_1(Q^2, \nu)$ and $W_2(Q^2, \nu)$ are the usual inelastic structure functions of the four-momentum transfer squared Q^2 and the electron energy loss $\nu = E - E'$, and $W_3(Q^2, \nu)$ is non-zero only if the electromagnetic interaction is not invariant under T. If W_3 is not zero, the T transformation introduces an up-down asymmetry, because both the time-reversed momenta and the spin change sign.

The counts asymmetry

$$\varepsilon = \frac{U - D}{U + D}, \tag{5}$$

where U, D are numbers of events for the nuclear spin $\mathbf{S_{in}}$ parallel or anti parallel to the $\mathbf{k} \times \mathbf{k}'$ vector, can be written in terms of the counting rates for each orientation. For an ammonia (NH_3) target[1], including the polarization of hydrogen and nitrogen, one has

$$\begin{aligned} U(D) = & \quad \Phi(N_N \sigma_{eN}^{U(D)} + N_H \sigma_{eH}^{U(D)} + \sum N_A \sigma_{eA}) \\ & = \Phi(N_N \sigma_{eN}(1 \pm P_N A_N) + N_H \sigma_{eH}(1 \pm P_H A_H) + \sum N_A \sigma_{eA}) \end{aligned} \tag{6}$$

where the flux factor Φ includes the beam current and detector acceptance; the $N_{X=N,H,A}$ represent the numbers of nitrogen, hydrogen and other unpolarized nuclei in the target; $\sigma_{eX}(Q^2, \nu)$ is the inelastic inclusive unpolarized electron-nucleus cross section for each case; $A_{X=N,H}$ are the corresponding asymmetries ($+(-)$ sign corresponds to $U(D)$) and $P_{X=N,H}$ are the polarizations. Since the scattering is in the region of the nucleon resonances, only incoherent $e - nucleon$ processes are involved. The numerator of ε is

$$U - D = 2\Phi N_H \sigma_{eH} P_H A_H (1 + C_N) \tag{7}$$

where $C_N = 1/3(P_N/P_H)\beta$ is the contribution of the unpaired polarized proton in ^{15}N, with β being the effective proton polarization in polarized nitrogen, approximately 1/3. C_N is on the order of 0.02± 0.002, although the accuracy of this figure can be improved by a factor of 5 or more. The denominator is

$$U + D = 2\Phi(N_N \sigma_{eN} + N_H \sigma_{eH} + \sum N_A \sigma_{eA}). \tag{8}$$

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[1]Ammonia $^{15}NH_3$ is the best target material for polarized protons, for its high polarization, radiation resistance and fraction of polarizable nucleons

The resulting counts asymmetry is

$$\varepsilon = \quad f P_H A_H (1 + C_N)$$
$$f(Q^2, \nu) = \frac{N_H \sigma_{eH}}{N_N \sigma_{eN} + N_H \sigma_{eH} + \sum N_A \sigma_{eA}}, \tag{9}$$

$f(Q^2, \nu)$ is the dilution factor.

The ratio of the difference to the sum of the cross sections for the two opposite spin orientations for unit target polarization $P_t = 1$ is

$$A_H = \frac{W_3 (E^2 - E'^2) \cos\phi \tan(\theta/2)}{M^2 (2W_1 \tan^2(\theta/2) + W_2)}. \tag{10}$$

Any non-zero ε is therefore an indication of a departure from T_h invariance of H_γ, except for interference effects. One effect comes from interference between single photon exchange and multi-photon processes, which are suppressed by at least a factor α. This effect is proportional to the lepton charge, so it can be calculated as well as tested and corrected for by $e^+ - polarized\ nucleon$ scattering. More details on this effect are given in a later section.

Another effect could be due to the interference between γ and Z exchanges, which could mimic T_h violation through the parity violating electroweak interaction. This effect would be present only if polarized lepton beams were used, and it may be minimized by taking equal amounts of data with positive and negative target polarization.

3. Existing Results

Only two measurements of the asymmetry A_H have been done to date [8,9], over thirty years ago. The slightly more precise results of SLAC experiment 029 [9] found no T violating asymmetry to a ∼2% precision, for four-momentum values ranging from $Q^2 = 0.4$ GeV^2 to 1 GeV^2, in the invariant mass W regions of the $\Delta(1232)$, $N^*(1512)$ and $N^*(1688)$ resonances (data in the range 1100 MeV$\leq W \leq$ 2600 MeV were measured). This kinematic region was chosen because the data available at the time seemed to indicate that the longitudinal photon absorption cross section σ_L was significant. An interference between the transverse cross section $\sigma_T = 4\pi^2 \alpha W_1/K$ and $\sigma_L = 4\pi^2\alpha((Q^2 + \nu^2)W_2/Q^2 - W_1)/K$ is equivalent to a non-zero $\sigma_{LT} = 4\pi^2\alpha\, \nu W_3/(K\sqrt{Q}^2)$. Here, $K = (W^2 - M^2)/(2M)$ is the real photon energy needed to produce the final state mass W. Both electron and positron beams gave similar null result. These results have been interpreted in detail in ref. [10].

The asymmetry for elastic scattering was also measured at SLAC in the same experiment [11]. No significant effects were observed at a similar 1 to 2% level.

SLAC E029 used a butanol target with an average polarization of 0.2 and a dilution factor $0.06 \leq f \leq 0.11$. The 20 GeV spectrometer in SLAC ESA with a 0.14 msr solid angle was used to detect the scattered electrons. Obviously, in the intervening time there has been substantial progress in polarized target, detector and accelerator technologies, that make it worthwhile to revisit this question. In what follows, we outline a proposed measurement that could improve the precision of the existing results by a factor of 100 to 250.

A recent measurement of the vector analyzing power in transversely polarized elastic $e-p$ scattering [12] indicates that the asymmetry due to multiphoton exchanges at $Q^2 = 0.1$ GeV^2 (200 MeV beam at 146° scattering angle) is -15.4 $\pm$ 5.4 ppm. The momentum transfer and energy dependence of this asymmetry are unknown. Taking into account the m_e/E supression of transverse beam polarization effects relative to longitudinal polarization (m_e is the electron mass, E the beam energy,) the observed effect would correspond to a sizable 0.6% asymmetry with longitudinally polarized beams. Confirming this result would be an interesting measurement in itself.

4. Proposed Measurement

We propose to study T violation in inclusive inelastic scattering of electrons on polarized protons using an ammonia ($^{15}NH_3$) solid polarized target, a 20 to 150 nA electron beam, and an electron spectrometer.

The kinematic region of interest is the region of the nucleon resonances at several values of Q^2. The presence of a significant σ_L component at some momentum transfer is a favorable indication, but is not necessarily a requirement, since the interference term may be larger than the σ_L component as, for instance, in the case of the neutron charge form factor. Elastic scattering data will be collected simultaneously, to control the multi-photon exchange contributions.

The polarized target needs to have a vertically oriented magnetic field, but otherwise it can be identical to the existing solid polarized target used in JLab's Hall C: dynamic nuclear polarization (DNP) in a 5 T field at 1 K, using a He evaporation refrigerator. Target cells of the same right horizontal cylinder type and capacity as those used in past spin structure experiments [13–15] are also suitable for the present experiment. This choice simplifies some of the design requirements, especially of the auxiliary beam raster system needed to distribute the beam dose uniformly over the target cell face. A chicane system is needed to correct for the horizontal deflection of the beam introduced by the target field.

As mentioned earlier, ammonia is the material of choice because of its favorable characteristics. Although the initial polarization of the material decays during data taking due to radiation damage, ammonia can be restored repeatedly to near original conditions by annealing at $\sim$ 100 K. The average time between anneals depends on the beam current, and ranges from about 5 hours to longer than 12 hours. The overhead due to the anneals can be kept to a minimum by optimizing the beam current for the best counting rate.

An electron spectrometer with a solid angle of about 5 msr and a momentum bite of $\sim$ 10% or more is needed. The associated detector package must have the electron detection and particle identification capabilities commonly used in single arm $e - nucleus$ scattering. The Hall C HMS and Hall A HRS meet these requirements. A dedicated device specifically assembled for this measurement is another possibility. The transverse target field precludes the use of the Hall B CLAS.

With existing polarized target luminosities of 10^{35} cm^{-2} Hz, and detector solid angles of several msr, the precision of the proposed measurement is determined by the counting rate that can be accepted by the detector system and the length of the data taking run. The average $P_t = 0.85$ and the dilution factor $f \sim 0.19$ for ammonia are a factor of $\sim$ 8 better than in E029. This factor would need to be combined with an additional factor of 12 to 15 to attain the proposed improvement of 100 or better. Such factor would require about 150 times more events detected than in the SLAC experiment. E029 had statistics of 4 million events/60 MeV-wide bin, implying that 600 million would be needed in our case. These can be accumulated in a 60 days run at 100% efficiency, if the rate per bin is about 120 Hz in the region of the $\Delta(1232)$, or ~ 1.2 kHz for the invariant mass region from the elastic peak to ~ 2000 MeV. This rate can easily be achieved at JLab at the Q^2 of interest.

Significant improvements in optimizing the kinematics settings and the beam current are possible, which would result in a shortening of the run time, or improved statistics, if a high rate data acquisition system were available. The option of replacing the current wire chambers with hodoscopes to increase the rate capabilities of the packages and reduce the event record size is very attractive, given the moderate W resolution needed (~ 60 MeV). Thus, an overall improvement of a factor of at least 100 and possibly 250 or higher in the statistical uncertainty is achievable in a reasonably long run. It should be mentioned that independent of the detector rate limitations, high energy beams are preferred in order to have the highest scattering rates possible.

The systematic uncertainties must be kept at the same or lower level as the statistical error. The important systematic errors are those that would introduce false asymmetries (add extra up or down counts). Since the beam is unpolarized, there is no concern over a beam charge asymmetry. More important are rate effects, since the detector, electronics and computer dead time are sensitive to the slightly different counting rates for up versus down counts. These effects need to be monitored carefully for appropriate correction. The errors in the normalization factors P_t and f do not introduce false asymmetries but, of course, must be kept as small as possible.

Numerous reversals of the target polarization will average out much of the fluctuations in detector and current monitor efficiencies. The polarization can be inverted by changing the frequency of the microwaves that induce the DNP. The time needed to invert the polarization under microwave pumping is less than 25 minutes, and can be reduced further. A target system with two cells, one of which is in the beam, can speed the time needed for polarization reversals. Also, half of the reversals can be synchronized with the anneals, further reducing overhead. A reversal every 4 hours is one option, which would represent a total of 360 reversals for the run.

An alternative configuration would be to have two cells in the beam path each with opposite polarization orientations. This configuration requires the microwave cavities of the target cells to be isolated from each other so that they can be independently pumped at their corresponding frequencies. Vertex reconstruction resolution capable of identifying events as originating in either cell is also needed for this option.

5. Positron asymmetry

As indicated earlier, some processes other than single photon exchange can produce an up-down asymmetry that may interfere with the T violating process we want to study. The authors of ref. [10] have thoroughly studied the question and their result indicates that only processes of order α^3 are of concern. They have derived the formulas needed for calculating the size of this effect. In addition, the terms involved in the α^3 asymmetry are of opposite signs for positrons and electrons. Thus, this asymmetry cancels when A_H measured with a positron beam is combined with the corresponding electrons asymmetry.

Since the usable beam current is very small (< 150 nA), the performance required of a positron source is not excessive. With a 6 GeV 60 μA beam incident on a 1 X_0 thick production target, the average energy of a shower particle would be 3 GeV and the average shower multiplicity 2. A system capable of collecting one 3 GeV positron in ~ 1000 would generate a 60 nA beam. Detailed simulations and calculations are obviously needed to design an efficient system, that would have to meet specifications defined by the choice of kinematics of the experiment.

6. Polarized beam effects

When polarized beams are used there are four additional correlations [3] between the spins and momenta, that give rise to 3 more structure functions $W_{4,5,6}$.[2] Of these, only the correlation $\mathbf{S_N} \cdot (\mathbf{k} - \mathbf{k}') \times (-\mathbf{S_l}) \cdot \mathbf{k}$ involving W_6 would show a possible T violation. Here

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[2]There are actually ten general structure functions that can be formed, six W's and four G's, including the well known G_1 and G_2 spin structure functions [16]

$\mathbf{S}_l$ is the beam helicity. The existing literature gives little additional information on the significance of W_6 (or on the other W's and G's) and of the possible advantages of measuring its associated correlation over the one for unpolarized beam regarding, for example, multiple photon exchange effects. This approach will be investigated further by our collaboration, and additional input from theoreticians and members of the lepton scattering community is welcome.

7. Summary.

We believe that a major improvement in our knowledge of the invariant properties of the electromagnetic interactions of hadrons can be achieved thanks to the advances in beam, target and detector technologies. It is likely that a null result will be found. On the other hand, we should not forget that P and even CP turned out to be non-invariant when examined at the right level of precision. The more than two orders of magnitude improvement that we propose will test T in an entirely new regime.

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FIGURES

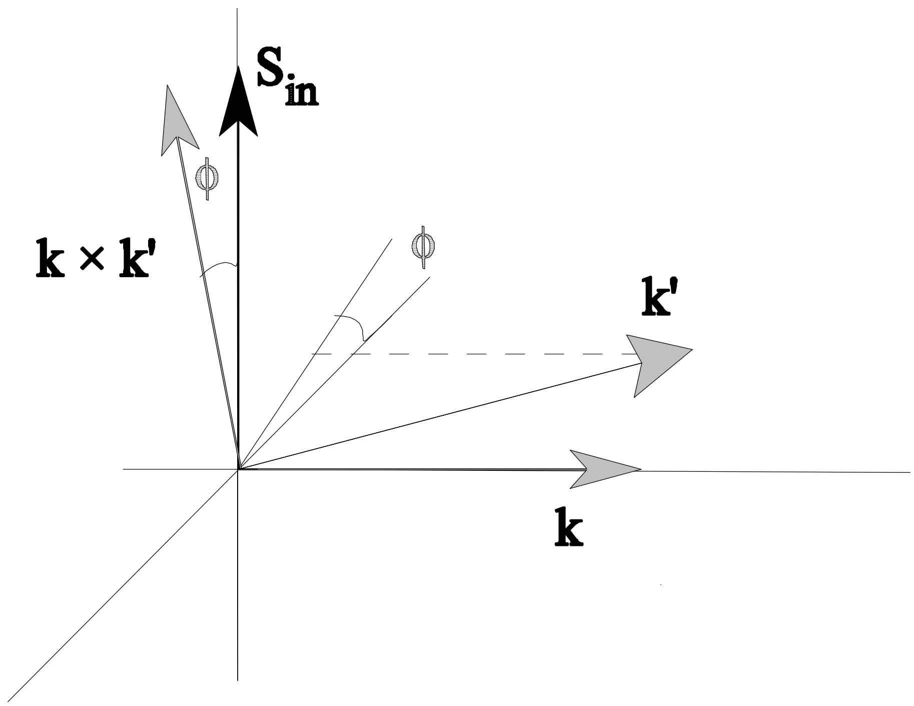

FIG. 1. Coordinate system. A large vertical acceptance of the spectrometer is favored, since $\cos\phi$ is within 1% of unity for $\phi \leq \pm 142$ mr.