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CONCERNING TESTS OF TIME-REVERSAL INVARIANCE VIA THE POLARIZATION-ANALYZING POWER EQUALITY

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ABSTRACT

Previous tests of time-reversal invariance via comparisons of polarizations and analyzing powers in nuclear scattering have been examined. It is found that all of these comparisons fail as adequate tests of time-reversal invariance either because of a lack of experimental precision or the lack of sensitivity to any time-reversal symmetry violation.

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I. *Introduction*

Among the various tests of time-reversal invariance (TRI), the polarization-analyzing power theorem[1] has the virtue that it follows directly from TRI. The theorem states that the spin-polarization (P) of a final-state particle in a (binary) nuclear reaction is equal to the analyzing power (A) for that polarized particle incident in the inverse reaction.

Recently experimental differences have been reported [2] between P and A in the two-nucleon transfer reactions

$$^{7}\mathrm{Li}(^{3}\mathrm{He},\vec{p})^{9}\mathrm{Be},\ \ P(\theta)\ ;\ \ ^{9}\mathrm{Be}(\vec{p},{}^{3}\mathrm{He})^{7}\mathrm{Li},\ A(\theta) \qquad \text{and}$$

$$^{9}\mathrm{Be}(^{3}\mathrm{He},\vec{p})^{11}\mathrm{Be},\ P(\theta)\ ;\ \ ^{11}\mathrm{B}(\vec{p},{}^{3}\mathrm{He})^{9}\mathrm{Be}\ ,\ A(\theta).$$

If these P-A differences are confirmed independently, the clear implication is that time-reversal invariance (TRI) is broken in some component of the nuclear interaction.

In view of these results, it is important to examine the question of why no significant deviations from P=A have been seen in the previous comparisons. Since elastic scattering is its own inverse process, it has been used in essentially all of the tests of TRI that use the polarization-analyzing power equality. I want to show here that *all of* these *previous* P-A comparisons fail as adequate tests of TRI either because of a lack of sensitivity to T-symmetry violation or a lack of experimental precision.

II. Previous P-A Comparisons

The majority of P-A comparisons have been made in pp elastic scattering, the older ones at energies between 142 and 635 MeV before the advent of accelerated polarized beams.[3] More recently, a comparison was made at 6 GeV/c from data acquired in measurements of pp scattering in polarized initial and final spin states.[4] Two more accurate comparisons have been made in p-nucleus elastic scattering, p-^{3}He (ref. 5) and p-^{13}C (ref. 6). The previous P-A comparisons in nuclear reactions were incidental to the main purpose of the experiments. For example, Hardekopf et al.[7] compared their A(θ) results in $^{3}H(\vec{p},d)^{2}H$ with the P(θ) results of others in $^{2}H(d,\vec{p})^{3}H$. The apparently significant P-A differences at E_d=2 and 3 MeV were attributed, presumably, to experimental errors in the more difficult P(θ) measurements.

III. Discussion of P-A Comparisons

The most accurate of these P-A comparisons have been made in p-^{3}He and p-^{13}C scattering; it is necessary to scatter from a nonzero spin nucleus, otherwise parity conservation alone ensures that P=A. I have found that neither of these comparisons was accurate enough to provide a significant test of TRI, because the equality between P and A depends on the equality of the two possible spin-flip probabilities. And, it is now known from measurements of the depolarization in p-nucleus elastic scattering that the spin-flip probabilities are very small, leading to P-A≃0 even if the probabilities are not equal as required by TRI.

Specifically, in terms of the spin-dependent cross sections,

$$P = (\sigma^{++} + \sigma^{-+} - \sigma^{+-} - \sigma^{--})/2\sigma \text{ and}$$

$$A = (\sigma^{++} + \sigma^{+} - \sigma^{-+} - \sigma^{--})/2\sigma \ ,$$

where σ^{-+} is the cross section for the scattering of a proton from an initial negative spin-state to a final positive spin-state, and

$$\sigma = (\sigma^{++} + \sigma^{+-} + \sigma^{-+} + \sigma^{--})/2.$$

The positive (+) direction is along $\vec{k}_i \times \vec{k}_f$. Thus

$$P - A = (\sigma^{-+} - \sigma^{+-})/\sigma. \qquad (1)$$

Since here the time reversed process of $\sigma^{-+}(\theta)$ is $\sigma^{+-}(\theta)$, TRI then insures that $\sigma^{-+} = \sigma^{+-}$, for which the equality $P=A$ is established.

It is clear, however, from Eq. (1) that another reason for $P-A\approx 0$ could be the very small values of the individual spin-flip terms, even if they were not equal as required by TRI. And, it is now known from measurements of the depolarization in elastic p-nucleus scattering that this is, indeed, the case.[8] Defining the spin-flip asymmetry as

$$\varepsilon_S \equiv (\sigma^{-+} - \sigma^{+-})/(\sigma^{-+} + \sigma^{+-}), \qquad (2)$$

its absolute limits are $-1\leq\varepsilon_S\leq 1$, but TRI requires that $\varepsilon_S = 0$. Since the depolarization parameter is given by

$$D = 1 - 2S \qquad (3)$$

with the (total) spin-flip probability

$$S = (\sigma^{+-} + \sigma^{-+})/2\sigma \;, \tag{4}$$

measurements of D provide determinations of S. It follows, then, from Eqs. (1)-(4) that

$$P - A = (1 - D)\varepsilon_S = 2S\varepsilon_S \tag{5}$$

Thus, even though ε_S, which is the real measure of time-reversal violation, may be significantly different from zero, a small value of the factor (1 -D) would make the P-A comparison quite insensitive to this violation. This is, in fact, just the case in these p-^{3}He and p-^{12}C experiments. A measurement of 1-D = 0.05±0.03 has been made[9] at an energy and angle very close to that of the p-^{3}He experiment,[5] and one can estimate 1-D at the energy (32.9 MeV) and angle (θ_L=60^o) of the p-^{13}C P-A comparison.[6] That is, from determinations of D(θ) in p-^{9}Be scattering at 25 MeV,[10] one finds from a linear interpolation, using the three D(θ) values between θ=60^o-100^o, that D=0.94±0.02 for the same qR as the p-^{13}C experiment. Here q is the momentum transfer and $R=r_oA^{1/3}$ is the nuclear radius. I take this to be the lower limit of D(32.9 MeV, θ_L=60^o) for p-^{13}C scattering since the quadrupole spin-flip mechanism[11] is not available here because of the spin-1/2 value of ^{13}C. Thus 1-D $\leq$ 0.06±0.02. Then, for example, with a value of the spin-flip asymmetry ε_S=1/3, which would constitute a clear and substantial violation of TRI, Eq. 5 yields $|P-A| \leq 0.017$ and 0.02 for p-^{3}He and p-^{13}C, respectively. These P-A values are essentially as small as the experimental errors in these P-A comparisons, so no tests of TRI were really made.

It is immediately obvious from this discussion that tests of TRI in elastic scattering, using the P-A equality, should be made through measurements where the spin-flip probability is expected or known to be large. Even better, more stringent and conclusive tests are provided by P-A comparisions in a reaction and its inverse, since the tesing of TRI is not then limited to the spin-flip cross sections. This can be seen by writing, now for a rection and its inverse, P and A in terms of the spin-dependent cross sections for spin-1/2 projectile and ejectile.

For the reaction $A(a,\vec{b})B$

$$P_{ab} = (\sigma_{ab}^{++} + \sigma_{ab}^{-+} - \sigma_{ab}^{+-} - \sigma_{ab}^{--})/2\sigma_{ab}, \qquad (6a.)$$

and for the inverse reaction $B(\vec{b},a)A$

$$A_{ba} = (\sigma_{ba}^{++} + \sigma_{ba}^{+-} - \sigma_{ba}^{-+} - \sigma_{ba}^{--})/2\sigma_{ba}, \qquad (6b.)$$

where

$$2\sigma_{ab} = \sigma_{ab}^{++} + \sigma_{ab}^{+-} + \sigma_{ab}^{-+} + \sigma_{ab}^{--} .$$

Without time-reversal symmetry

$$\sigma_{ab}^{ij} \neq \sigma_{ba}^{ji} \quad i,j = +,- \quad \text{and}$$

$$P_{ab} \neq A_{ba}$$

for inverse reactions. TRI imposes the conditions

$$\sigma_{ab}^{ij} = \sigma_{ba}^{ji} \quad i,j = +,- \qquad (7)$$

for which Eqs. (6) then give

$$P_{ab} = A_{ba}. \quad (8)$$

One sees that the conditions (7) provide for more exhaustive and conclusive tests of TRI in a reaction and its inverse than is afforded by the single $\sigma^{+-} = \sigma^{-+}$ condition of elastic scattering.

We now see that tests of TRI in the basic nucleon-nucleon interaction, via comparisons of P and A in p-p and/or n-p scattering, also should be made at energies and angles for which the quantity (1 - D) is maximized. Since spin-exchange forces are well-known components of the nucleon-nucleon interaction, spin-flip probabilities are generally substantial, so there should be little difficulty in satisfying this criterion. For example, in one report that includes both P-A comparisions and measurements of D in p-p scattering at 142 MeV,[3] values of (1 - D) range between 0.7 and 1.2. The (P-A) values are generally consistent with zero within the experimental errors of several percent, although differences of 0.04 to 0.08 are listed. Similar differences are seen in the p-p data at 213 MeV and at 635 MeV.[3]

Very recently, in response to a preliminary report of our results,[12] Bystricky et al.[13] have examined the status of TRI from these p-p experiments in a very novel, convincing, and quantitative analysis. Their p-p scattering matrix, usually written in terms of five invariant (including TRI) amplitudes a(θ), b(θ), c(θ), d(θ), and e(θ), is modified to include a T-violating amplitude m(θ):

$$M(\theta) \equiv M(\theta;a,b,c,d,e,m). \quad (9)$$

They then find

$$\sigma(P-A) = -2\text{Im}\, d^{*}m,$$

which depends linearly on the T-violating amplitude. Noting that Im $d^{*}m$ = $|d||m|\sin\phi_{md}$, where ϕ_{md} is the phase angle between m and d, they use the P-A data and σ and d from previous phase-shift analyses in a calculation of the angular dependence of $|m|\sin\phi_{md}$. This quantity showed non-zero values, beyond experimental error, in several regions of energy and angle. These authors pointed out, however, that the more difficult P(θ) measurements are subject to systematic errors that are not easily evaluated. Their interesting conclusion was that, contrary to prevailing opinion, TRI in nucleon-nucleon scattering was not well established.

Since then, Aprile et al.[14)] have used the M-matrix of Eq. (9) in an analysis of their set of sixteen polarization parameters measured at six angles in pp scattering at 579 MeV. This extensive set of data makes possible the direct experimental determination of the scattering matrix. They find an upper limit of about 1% on the T-violating fraction of the cross section, i.e.

$$|m|^2/(|a|^2+|b|^2+|c|^2+|d|^2+|e|^2+|m|^2).$$

This then corresponds to an upper limit of about 10% in the amplitude ratio $|m|/\sqrt{\sigma}$.

In spite of this very significant improvement in the determination of an upper limit for the T-violating amplitude m(θ) at 579 MeV, it is important to note that the pp system is less than ideal for use in searches for evidence of T-violation. It is somewhat ironic that, as Bryan et al.[15]

have noted, the identical-particle symmetry reduces the possibilities for T-symmetry violation, as compared with the np system. That is, T-asymmetry can show up only in the pp coupled states of $J^P = 2^-, 4^-$, etc. since only these states have off-diagonal terms in the S-matrix. Then in a model[15] where the nucleon-nucleon T-asymmetry is due to the exchange of the A_1 (1070 MeV) meson, the consequent short range of the interaction is such that the angular momentum barrier drastically inhibits the observable effects of T-violation in the pp system at the energies (up to about 635 MeV) that were investigated. For example, the same T-violating exchange in the np system, where the coupled 1^+ state is also available, produced a T-violating phase-shift parameter that was about a factor of ten larger.

At higher energies the spin-dependent partial cross sections, measured in pp scattering at 6 GeV/c with polarized initial and final spin states, were used as tests of TRI at values of $P_\perp^2$ from 0.5 to 1.0 $(\mathrm{GeV/c})^2$ (ref.4). The experimental quantity

$$\varepsilon_T = [\sigma(++,0-)-\sigma(--,0+)]/\sigma \qquad (10)$$

was calculated, where the indices (ij,kl) denote the spin directions of the (beam, target; scattered, recoil) particles, and 0 indicates that the polarization of the scattered proton was not measured.

Now take

$$\begin{aligned} \sigma^{+-} &\equiv \sigma(0+,0-) \\ \sigma^{-+} &\equiv \sigma(0-,0+) \end{aligned} \qquad (11)$$

so that the target and recoil particle polarizations are designated. Since

$$\sigma(0+,0-)=\sigma(++,0-)+\sigma(-+,+-)+\sigma(-+,--) ,$$
$$\sigma(0-,0+)=\sigma(--,0+)+\sigma(+-,-+)+\sigma(+-,++) , \quad (12)$$

$\sigma(-+,--)=\sigma(+-,++) = 0$ from the parity conservation, and

$\sigma(-+,+-)=\sigma(+-,-+)$

from particle symmetry and rotational invariance,[4)] Eqs. (1) and (10)-(12) give

$$\varepsilon_T = (\sigma^{+-}-\sigma^{-+})/\sigma = A-P, \quad (13)$$

so that the concerns expressed in connection with Eq. (5) apply to this comparison as well. In fact, these data show values of 1-D = 0.15-0.24, so this comparison is less sensitive to T-violation than are P-A comparisons at lower pp energies where the quantity 1-D is considerably larger. From the data of Tables II and III (ref 4.) one can calculate the normalized T-violating quantity ε_S of Eq. (2). Values of ε_S and 1-D are listed in Table 1 where it is seen that the errors on ε_S vary between 30 to 100%.

Finally, a very recent P-A comparison in 800 MeV n-p scattering has been made by Bhatia et al.[16)] at $\theta_{cm} = 133^o$ where 1-D is estimated to be greater than unity. Their result at this angle is

$$P-A = 0.011\pm0.019$$

with an additional systematic uncertainty of ±0.02.. This is certainly the most sensitive test of TRI in the nucleon-nucleon system via the P-A theorem that has been made, and comparison of this datum with the model prediction of Bryan et al.[15)] establishes an upper limit on this T-violating observable which is an order of magnitude lower than the model prediction.

IV. Conclusions

An examination has been made of all of the tests of TRI via P-A comparisons which were made before our report of finding such differences in two (^{3}He,p) and (p,^{3}He) reactions.[2] It is seen that these comparisons were considerably less adequate tests of TRI than was believed, either because of lack of experimental precision or lack of sensitivity to T-violation. Essentially all of these comparisons were made in elastic p-p and p-nucleus scattering where it is now seen that the sensitivity to T-violation is directly proportional to the spin-flip probability $S(\theta)$. Consequently, kinematical regions in which $S(\theta)$ values are relatively large should be chosen for the P-A comparisons.

The most recent tests of TRI in p-p[14] and n-p[16] scattering have made substantial improvements in the determination of an upper limit for a T-violating amplitude and a T-violating observable, P-A, in those respective systems. The np result is noteworthy, both for its accuracy and for the fact that the np system is inherently more sensitive to T-violations than is the pp system.[15] This follows from the simple fact that all of the coupled J^P states are available to it, whereas the identical-particle symmetry forbids half of these states in the pp system.

Finally, it is seen that more sensitive and exhaustive tests of TRI are likely to be made in P-A comparisons that involve a nuclear reaction and its inverse. There, as shown in Eq. (7), the test is not confined to the TRI conditions imposed on the spin-flip cross sections alone, as is the case in elastic scattering. Additionally, large spin-flip probabilities are common to many reactions which are sutitable for these tests of TRI.

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Table 1. Values of 1-D and ε_S, defined in Eq. (2), in p-p scattering at 6 GeV/c. These are taken from the data listed in Tables II and III of reference 4.

$P_\perp^2 (GeV/c)^2$	0.5	0.6	0.8	1.0
1-D	0.14(10)	0.13(5)	0.20(6)	0.25(8)
ε_S	1.14(108)	0.08(39)	0.10(30)	0.44(35)

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