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ON NULL TESTS OF TIME-REVERSAL INVARIANCE

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ON NULL TESTS OF TIME-REVERSAL INVARIANCE

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It has been proved[1] that there exists no null test of time-reversal invariance (TRI) in nuclear and particle physics in any reaction with two particles in and two particles out. That is, there is no single experimental observable that is required to be zero by TRI. This follows from the fact that TRI equates a reaction observable to an observable in the inverse reaction, so the difference (or sum) of the two is zero. Even in elastic scattering, which is its own inverse reaction, two different observables are related by TRI; e.g., polarization and analyzing power, so that $A_y - P_y = 0$. Because of this requirement to compare two experimental observables, one of which is often difficult to measure with precision (say 1%), it is easy to understand why such tests of T-symmetry have rarely attained the 1% level of experimental accuracy. In strong contrast, since null tests of parity conservation are available, e.g. $A_z = 0$ from P-symmetry, the weak-interaction parity non-conserving contribution to A_z in pp scattering has been determined to the truly remarkable accuracy of 2.2×10^{-8} (ref. 2). Thus, it is clear that a comparable **null test** of T-symmetry would permit an improvement in experimental precision of several **orders of magnitude**.

Recent transmission experiments with slow neutrons have shown remarkable enhancements in two parity non-conserving (PNC) observables, the neutron spin rotation[3] and the neutron longitudinal analyzing power, A_z (ref. 4); and Stodolsky and Kabir have suggested that nuclear effects could also provide enhancements in time-reversal violating (TRV) neutron transmission observables which become accessible with polarized targets[5]. They have developed a formalism to describe the spin aspects of neutron transmission and have suggested some TRV observables to be measured. However, these again involve

two observables and can be viewed as transmission analogues of A - P, even though they are really spin-correlation transmission experiments, which involve both projectile and target polarizations. Also, their treatment assumes neutron *coherent* forward scattering, and it describes the forward-scattering matrix simply in the 2 X 2 neutron spin-space. I have found that this is not an adequate treatment, and, in fact, their TRV amplitude must vanish in order that the requirement of helicity conservation in forward scattering be maintained[6].

Since target polarization is required in order to provide a TRV term in the forward scattering matrix, it is necessary for that matrix to encompass **both** the projectile and target spin-matrices. That is, an observable that involves only the projectile (target) polarization can be expressed in terms of the projectile(target) spin-matrix ampitudes alone, but the combined spin-space amplitudes are required for an observable that involves both projectile and target polarizations.

To investigate, then, the possibility of finding a TRV observable in transmission experiments, I have considered in detail, as prototypes, the cases with spin-1/2 projectile and spin-1/2 or spin-1 targets[6]. Choosing the projectile helicity frame, unit vectors along the coordinate axes are taken to be

$$\boldsymbol{z} = \boldsymbol{k}, \quad \boldsymbol{y} = \boldsymbol{s}, \quad \boldsymbol{x} = \boldsymbol{y} \times \boldsymbol{z}, \tag{1}$$

where **k** and **s** are the neutron momentum and the target polarization. These unit vectors then have the same behavior under P and T transformations as do the corresponding ones in non-forward scattering with **y** taken as normal to the scattering plane. Then imposing R_z symmetry, i. e. invariance under rotation around the z-axis, which corresponds to helicity conservation, the complete R_z-invariant PNC and TRV forward-scattering matrix for a spin-1/2 target is

$$\begin{aligned} F(o) = {} & C_{oo} + C_{oz}\sigma_o\sigma_z + C_{zo}\sigma_z\sigma_o + C_{xx}(\sigma_x\sigma_x + \sigma_y\sigma_y) \\ & + C_{zz}\sigma_z\sigma_z + C_{xy}(\sigma_x\sigma_y - \sigma_y\sigma_x) \ . \end{aligned} \tag{2}$$

Here the σ_j, with $j = o, x, y, z$, $\sigma_o = 1$, are the 2 X 2 Pauli spin-matrices, and in each term the first (second) σ_j is the projectile (target) spin operator. The C_{oz} and C_{zo} terms are PNC and the C_{xy} term is both PNC and TRV. However, the C_{xy} term is a double spin-flip amplitude which changes the target spin-state and, thus, cannot contribute to the *coherent* scattering. In this instance, then, coherent forward scattering does not provide a TRV observable.

However, and more importantly, the term C_{xy} in the forward scattering matrix suggests that a corresponding PNC, TRV observable is available in the more ordinary and widespread possibilities for *incoherent* transmission experiments in nuclear and particle physics at all energies. The appropriate treatment then features transmitted *intensities* rather than amplitudes; and the spin-dependent observables, the total cross-sections, are then related to the forward-scattering amplitudes by the (spin dependent) optical theorem[7],

$$\sigma_{xy} = (4\pi/k) Im[\rho_{xy} F(0)] \ , \tag{3}$$

where ρ_{xy} is the density matrix representing the beam and target polarizations p_x and p_y, and σ_{xy} is the corresponding total cross-section. Also,

$$\sigma_{xy} = \sigma(1 + p_x p_y A_{xy}), \tag{4}$$

where σ is the (unpolarized) total cross-section and A_{xy} is the spin-correlation coefficient. From (2)-(4),

$$A_{xy} = ImC_{xy} / ImC_{oo} \ , \tag{5}$$

which vanishes for $C_{xy} = 0$, and thus is the observable that constitutes a ***null test*** of (both) TRI and PC.

Target spin > 1/2 is required in order to have a uniquely TRV (parity conserving) forward amplitude, because tensor polarization (alignment) is the necessary additional condition. With a spin-1 target , eq. (2) becomes

$$F(0) = C_{oo} + C_{oz}\sigma_o P_z + C_{zo}\sigma_z P_o + C_{zz}\sigma_z P_z + C_{o,zz}\sigma_o P_{zz} + C_{z,zz}\sigma_z P_{zz}$$
$$+ C_{xx}(\sigma_x P_x + \sigma_y P_y) + C_{xy}(\sigma_x P_y - \sigma_y P_x) + C_{x,yz}(\sigma_x P_{yz} - \sigma_y P_{xz}) , \qquad (6)$$

where the $P_j(P_{kl})$ are the vector, rank 1 (tensor, rank-2) components of the spin-1 matrix operator. The result corresponding to eq. (5) is then

$$A_{x,yz} = ImC_{x,yz} / ImC_{oo} . \qquad (7)$$

As the notation indicates, this corresponds to the beam polarization p_x in combination with the target tensor polarization P_{yz}, i.e. alignment along y = z. These, then, are true ***null tests*** of T-symmetry, and their exploitation throughout nuclear and particle physics can provide the indicated several orders of magnitude improvement in the level to which T-symmetry has been tested.

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