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Tests of Time Reversal Invariance via Transmission Experiments

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TESTS OF TIME REVERSAL INVARIANCE VIA TRANSMISSION EXPERIMENTS

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ABSTRACT

The existing formalism used to describe spin observables in neutron transmission experiments is found to be inadequate. A suitable formalism is developed, through which time-reversal violating (and parity non-conserving) forward scattering amplitudes are identified, along with their corresponding spin observables. It is noted that new and more precise tests of T-symmetry are provided in transmission experiments and that such investigations are applicable more generally in nuclear and particle physics.

INTRODUCTION

Recent transmission experiments with slow neutrons have shown remarkable enhancements in two parity non-conserving (PNC) observables, the neutron spin rotation[1] and the neutron longitudinal analyzing power, A_z[2]. In the latter case, a value of A_z close to 10% has been measured in the transmission of neutrons through ^{139}La at the 0.734–eV resonance, and this nuclear enhancement of 10^5 to 10^6 is explained in terms of parity-mixed levels of ^{140}La and p-wave barrier hindrance of the parity conserving transition.

The suggestion that nuclear effects could also provide enhancements in time-reversal violating (TRV) neutron transmission observables, which become accessible with polarized targets[3], has generated considerable interest and acitivity in the investigation of that possibility[4]. Stodolsky and Kabir have developed a formalism to describe the spin aspects of neutron transmission, and they have suggested TRV observables to be measured.[3,4] I have found some difficulties with their treatment, which I discuss in this paper. I then consider, again, the prospect for measureable TRV observables in transmission experiments.

DEVELOPMENT

Stodolsky and Kabir use the plane-wave neutron coherent amplitude in the target material,

$$M = e^{i(n-1)kd}\,,\ \text{with}\ n-1 = \frac{2\pi}{k^2}\,\rho f(o),$$
$$f(o) = f_0 + f_x\,\hat{\sigma}\cdot\hat{s} + f_y\,\hat{\sigma}\cdot(\hat{k}\times\hat{s}) + f_z\,\hat{\sigma}\cdot\hat{k}\,, \qquad \text{(1a)}$$

where $n, k, d, \rho, f(o)$ are, respectively, the index of refraction, neutron wave number, distance of transmission in the target, density of target nuclei, and the neutron-nucleus forward elastic scattering matrix. It should be emphasized that only coherent non-spin-flip amplitudes contribute to the index of refraction, since scattering in which the target state is changed is incoherent.[5] In (1a) $\hat{\sigma}$ is the neutron spin operator and $\hat{s}$ the target polarization, so f_z is a PNC term and f_y is both PNC and TRV[3]. With the coordinate system chosen (Fig. 1), the neutron direction $\hat{k}$ and target polarization $\hat{s}$ along the z and x axes, respectively, the forward scattering matrix becomes

$$f(o) = f_o + f_x \sigma_x + f_y \sigma_y + f_z \sigma_z \; . \tag{1b}$$

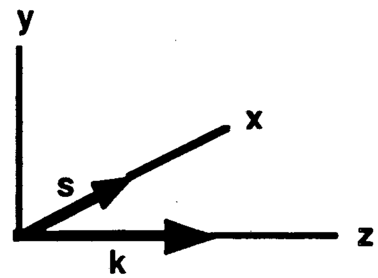

Fig. 1. Coordinate system defined by the neutron direction k and the target spin direction s. This choice of the quantization axis (z) defines the projectile helicity frame.

Then, taking

$$C_j = \frac{4\pi}{k} f_j \rho d \; , \; j = o, x, y, z$$

$$M = \exp\left[\frac{i}{2} \sum_j C_j \sigma_j\right] . \tag{2}$$

Since M is a two by two matrix in the neutron spin space, Stodolsky and Kabir take its most general form,

$$M = \sum_j B_j \sigma_j \quad , \quad j = o, x, y, z \; , \; \sigma_o = 1 \, , \tag{3}$$

and use (3) in the calculation of spin observables. For example, an analyzing-power component

$$A_j = \frac{Tr\, M\, \sigma_j M^{\dagger}}{Tr\, M\, M^{\dagger}} \quad . \tag{4}$$

The transformation from the C_j of (2) to the B_j of (3) is not simple, and one loses the direct association and interpretation of the spin observables with the spin-dependent terms of the scattering matrix.

There are some clear difficulties with this procedure. By explicitly displaying the forward scattering matrix

$$f(o) = \begin{matrix} + \\ - \end{matrix} \begin{pmatrix} f_o + f_z & f_x - i f_y \\ f_x + i f_y & f_o - f_z \end{pmatrix} \tag{5}$$

it is seen that the TRV amplitude f_y appears in the off-diagonal neutron spin-flip terms. Since helicity is conserved in forward scattering, there must be a corresponding target-nucleus spin-flip. This, however, cannot contribute to the coherent neutron amplitude. Thus, in this treatment, a TRV observable is not available in coherent forward scattering.

The requirement of helicity conservation at $\theta = 0°$ is even more restrictive when the forward scattering matrix is taken to be (1b). The equivalent condition is that $f(o)$ be invariant with respect to rotation about the z-axis, so

$$f(o) = f_o + f_z \sigma_z \tag{6}$$

is the most general form. In this treatment, then, a TRV observable is excluded by conservation of angular momentum (z-component), whether the scattering is either coherent or incoherent.

Since (6) includes the PNC term f_z, it is of interest to calculate the PNC neutron *coherent* transmission observables in terms of C_o and C_z (thus f_o and f_z) of eq. (2). Expressing the complex amplitude

$$C_j = \alpha_j + i\beta_j \quad , \qquad j = o, z \ , \tag{7}$$

since σ_o and σ_z commute, (2) can be written as

$$M = R_o D_o R_z D_z \tag{8}$$

with

$$R_j = \exp\left[\frac{i}{2}\alpha_j \sigma_j\right] \ , \ D_j = \exp\left[-\frac{1}{2}\beta_j \sigma_j\right], \tag{9}$$

so R_j (D_j) is a rotation (attenuation) matrix.

With $\sigma_j = \sigma_j^{\dagger}$,

$$R_j^{\dagger} = R_j^{-1} \ , \ D_j^{\dagger} = D_j \ . \tag{10}$$

Also,

$$R_j = \cos\frac{\alpha_j}{2} + i\sin\frac{\alpha_j}{2}\sigma_j \, , \ D_j = \cosh\frac{\beta_j}{2} - \sinh\frac{\beta_j}{2}\sigma_j \ . \tag{11}$$

Defining the transmission factor, through a target distance d,

$$\frac{I(d)}{I(o)} \equiv T(d) = \frac{1}{2} Tr M M^{\dagger} \ , \tag{12a}$$

the analyzing power A_z and the polarization transfer (rotation) coefficient K_x^y are given by

$$\begin{aligned} T A_z &= \frac{1}{2} Tr M \sigma_z M^{\dagger} \\ T K_x^y &= \frac{1}{2} Tr M \sigma_x M^{\dagger} \sigma_y \ . \end{aligned} \tag{12b}$$

Using (8) – (12),

$$
\begin{aligned}
T &= e^{-\beta_0} \cosh \beta_z \underset{C_z \ll 1}{\Rightarrow} e^{-\beta_0} \\
A_z &= -\tanh \beta_z \Rightarrow -\beta_z \\
K_x^y = -K_y^x &= \frac{-\sin \alpha_z}{\cosh \beta_z} \Rightarrow R_z(-\alpha_z).
\end{aligned} \tag{13}
$$

Thus, one sees the known PNC differential attenuation of positive and negative helicity neutrons, i.e., A_z, due to β_z, the imaginary part of the amplitude C_z, and the PNC neutron transverse spin rotation around the direction of propagation, due to α_z, the real part of C_z. Since β_z is large ($A_z \simeq 0.1$) at the 0.734–eV neutron—^{139}La resonance, it would be most interesting to determine α_z there via a measurement of the transverse spin rotation coefficient K_x^y, assuming, of course, that the forward scattering is coherent at this energy (at 1–eV $\lambda \simeq 3 \times 10^4$ fm).

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 amplitudes alone, as in (13), 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 consider in detail, as a prototype, the simplest case with spin-$\frac{1}{2}$ projectile and target. There the 4x4 scattering matrix, including the same factor as in (2),

$$
F(o) = \frac{4\pi}{k} \rho d\, f(o) \quad , \tag{14}
$$

can be constructed as the direct product of the 2x2 projectile and target spin matrices:

$$
\begin{aligned}
&F = F_1 \otimes F_2 \quad , \quad \text{with} \\
&F_n = \sum_j C_{nj}\, \sigma_{nj} \quad , \quad n = 1, 2
\end{aligned} \tag{15}
$$

and $n = 1$ (2) labeling the projectile (target) matrix.

Then, a typical term in F is $C_{1x}\ C_{2y}\, \sigma_{1x} \otimes \sigma_{2y}$, which I will abbreviate to $C_{xy}\, \sigma_x\, \sigma_y$, so that the ordering of the subscripts provides the $n = 1{,}2$ labeling. Recall from Fig. 1 that unit vectors along the coordinate axes are chosen to be

$$
\hat{z} = \hat{k}\ ,\ \hat{x} = \hat{\sigma}_2\ ,\ \hat{y} = \hat{z} \times \hat{x}\ . \tag{16}
$$

Then, with $\sigma_{1x} \equiv \hat{\sigma}_1 \cdot \hat{x}$, etc., we have the following transformations under the P, T symmetry operations:

$$
\begin{array}{c|ccc}
 & \sigma_x & \sigma_y & \sigma_z \\
\hline
P & \sigma_x & -\sigma_y & -\sigma_z \\
T & \sigma_x & -\sigma_y & \sigma_z
\end{array} \tag{17}
$$

The 16 F-matrix amplitudes,

$$C_{oo}, C_{ox}, \underline{C_{oy}}, \underline{C_{oz}}, C_{xo}, C_{xx}, \underline{C_{xy}}, \underline{C_{xz}}, \underline{C_{yo}}, \underline{C_{yx}}, C_{yy}, C_{yz}, \underline{C_{zo}}, \underline{C_{zx}}, C_{zy}, C_{zz}, \tag{18}$$

can then be classified according to their P and/or T symmetry. For example, the underlined in (18) are PNC amplitudes.

A particulary useful and more visual realization of these symmetries is obtained from the F-matrix itself,

$$F = \begin{array}{c|cccc|} T & ++ & +- & -+ & -- \\ \hline ++ & F_{11} & F_{12} & F_{13} & F_{14} \\ +- & F_{21} & F_{22} & F_{23} & F_{24} \\ \hline -+ & F_{31} & F_{32} & F_{33} & F_{34} \\ -- & F_{41} & F_{42} & F_{43} & F_{44} \end{array} \quad P \quad , \tag{19}$$

with the columns (rows) designated by the initial (final) helicities. Then, the amplitudes above the horizontal P-symmetry line are equal to the amplitudes below in inverse order,

$$(F_{11} \text{ to } F_{24}) = \pm (F_{44} \text{ to } F_{31}) \ , \tag{20}$$

and, for elastic scattering, the amplitudes are similarly related across the diagonal T-symmetry line. Finally, imposing the condition of $\theta = 0°$ helicity conservation, $F(o)$ becomes

$$F(o) = \begin{pmatrix} F_{11} & 0 & 0 & 0 \\ 0 & F_{22} & F_{23} & 0 \\ 0 & F_{32} & F_{33} & 0 \\ 0 & 0 & 0 & F_{44} \end{pmatrix} , \tag{21}$$

so that R_z-invariance alone reduces the number of amplitudes from 16 to 6. P-symmetry requires that

$$F_{11} = F_{44} \ , \ F_{22} = F_{33}, \ \ F_{23} = F_{32} \tag{22}$$

and the latter condition is required also by T-symmetry. Thus

$$F_{23} \neq F_{32} \tag{23}$$

is both PNC and TRV.

The corresponding requirements of R_z, P, and T-symmetries yield, from (15) and (17), the $F(o)$-matrix

$$F(o) = C_{oo} + C_{xx}(\hat{\sigma}_1 \cdot \hat{\sigma}_2) + C'_{zz}\,\sigma_z\,\sigma_z \quad ,$$

so (24)

$$F(o) = C_{oo} + C_{xx}(\sigma_x\,\sigma_x + \sigma_y\,\sigma_y) + C_{zz}\,\sigma_z\,\sigma_z \quad ,$$

This agrees with (22) in that only 3 independent amplitudes survive, and, specifically,

$$F(o) = \begin{pmatrix} (C_{oo} + C_{zz}) & 0 & 0 & 0 \\ 0 & (C_{oo} - C_{zz}) & 2C_{xx} & 0 \\ 0 & 2C_{xx} & (C_{oo} - C_{zz}) & 0 \\ 0 & 0 & 0 & (C_{oo} + C_{zz}) \end{pmatrix} , \tag{25}$$

in agreement with (21) and (22). Note, immediately that the C_{xx} term conserves helicity via a double spin-flip process, so it cannot contribute to the coherent neutron amplitude.

Now add the PNC terms from (18) that are R_z-invariant. These are

$$C_{oz}\,\sigma_o\sigma_z + C_{zo}\,\sigma_z\,\sigma_o \ , \tag{26}$$

so

$$F(o) = C_{oo} + C_{oz}\sigma_o\,\sigma_z + C_{zo}\sigma_z\,\sigma_o + C_{zz}\sigma_z\,\sigma_z \tag{27}$$

is the PNC coherent forward scattering matrix. Then proceeding analogously to (7) – (12), the result is

$$A_{zo} = -\tanh\beta_{zo} \xrightarrow{C_{zo}<<1} -\beta_{zo} \ , \tag{28a}$$

Thus, the statement immediately following (12), regarding the analyzing power, remains true with the simple substitutions A_{zo}, β_{zo}, C_{zo} for A_z, β_z, C_z. Clearly, the target PNC analyzing power, i.e., using a polarized target and an unpolarized neutron beam, is given by

$$A_{oz} = -\tanh\beta_{oz} \xrightarrow{C_{oz}<<1} -\beta_{oz} \ , \tag{28b}$$

and this could be a very useful PNC observable in situations where a polarized target is more readily available than is a polarized beam.

Finally, the sixth R_z-invariant term to be considered is

$$C_{xy}\,(\hat{\sigma}_1 \times \hat{\sigma}_2)_z = C_{xy}\,(\sigma_x\,\sigma_y - \sigma_y\,\sigma_x\,) \ , \tag{29}$$

which, from (17), is seen to be both PNC and TRV. Thus, from (24), (26), and (29),

$$F(o) = C_{oo} + C_{oz}\,\sigma_o\,\sigma_z + C_{zo}\sigma_z\,\sigma_o + C_{xx}\,(\sigma_x\,\sigma_x + \sigma_y\,\sigma_y) + C_{zz}\sigma_z\,\sigma_z + C_{xy}\,(\sigma_x\,\sigma_y - \sigma_y\,\sigma_x) \tag{30}$$

is the complete R_z-invariant PNC and TRV forward-scattering matrix. Again, the C_{xy} term is a double spin-flip amplitude, so I conclude that in the $\frac{1}{2}+\frac{1}{2}\rightarrow\frac{1}{2}+\frac{1}{2}$ system, coherent forward scattering does not provide a TRV observable.

However, and perhaps 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. There one uses a treatment that features transmitted *intensities* rather than amplitudes; and the spin-dependent observables, i.e. the total cross-sections, are then related to the spin-dependent forward scattering amplitudes by the optical theorem.

The transmission factor (12a) is now

$$T(d) = \exp[-\sigma_T \rho d] \equiv \exp[-\sigma] \ , \tag{31}$$

where σ_T is the unpolarized total cross-section, and thus σ is a dimensionless "total cross-section" which includes the areal density factor ρd. The corresponding spin-dependent cross sections are

$$\sigma_{jk} = \sigma(1 + p_j\, p_k\, A_{jk})\ ; j, k = x, y, z \ , \tag{32}$$

where $p_j(p_k)$ is the projectile (target) polarization along the $j(k)$ direction, and A_{jk} is the corresponding (total cross-section) spin-correlation coefficient, which is essentially defined by this equation. Then, with $\sigma_{jk}(++)$ ($\sigma_{jk}(+-)$) defined as the cross section for the pure spin states $p_j = p_k = 1$ ($p_j = -p_k = 1$), we have

$$\begin{aligned} \sigma_{jk}(++) &= \sigma_{jk}(--) = \sigma(1 + A_{jk}) \,, \\ \sigma_{jk}(+-) &= \sigma_{jk}(-+) = \sigma(1 - A_{jk}) \ . \end{aligned} \tag{33}$$

Using these spin dependent cross-sections, the corresponding transmission factors (31) are defined as

$$T_{jk} = \frac{1}{2}\{\exp[-\sigma_{jk}(++)] + \exp[-\sigma_{jk}(+-)]\} \tag{34a}$$

and

$$\Delta T_{jk} = \frac{\exp[-\sigma_{jk}(++)] - \exp[-\sigma_{jk}(+-)]}{\exp[-\sigma_{jk}(++)] + \exp[-\sigma_{jk}(+-)]} \tag{34b}$$

Thus, T_{jk} is the transmission factor for a completely polarized beam transmitted through an unpolarized target (and vice versa), while ΔT_{jk} is the *transmission asymmetry* of the polarized beam for opposite states of the target polarization. Using (33),

$$T_{jk} = e^{-\sigma} \cosh \sigma A_{jk} \,, \tag{35a}$$

$$\Delta T_{jk} = -\tanh \sigma A_{jk} \,. \tag{35b}$$

We now use the spin-dependent form of the optical theorem[6] to express σA_{jk} in terms of the imaginary part of the corresponding forward scattering amplitude. That is

$$\sigma_T(\rho) = \frac{4\pi}{k} Im\ Tr\ [\rho\ f(o)], \tag{36}$$

where ρ_{jk} is the density matrix representing the inital polarizations and $\sigma_T(p_j, p_k)$ is the corresponding total cross-section. The normalization $Tr\rho = 1$ has been chosen. Then, in the established notation,

$$\rho_{jk} = \frac{1}{4}(\sigma_o + p_j\, \sigma_j) \otimes (\sigma_o + p_k \sigma_k) \tag{37}$$

so

$$\rho_{jk}\ (+\pm) = \frac{1}{4}(1 + \sigma_j\, \sigma_o \pm \sigma_o\, \sigma_k \pm\ \sigma_j\, \sigma_k)\ . \tag{38}$$

With (14), (36) becomes

$$\sigma_{jk} = Im\ Tr\ [\rho_{jk}\, F(o)]\ , \tag{39}$$

and with

$$\sigma A_{jk} = \frac{1}{2}[\sigma_{jk}(++) - \sigma_{jk}(+-)\ ]\ , \tag{40}$$

we have

$$\sigma A_{jk} = \frac{1}{4} Im\ Tr\ [\ (\sigma_o\, \sigma_k\ + \sigma_j\, \sigma_k)\, F(o)\ ]. \tag{41}$$

Then noting that

$$T_r\, (\sigma_j\, \sigma_k)\, (\sigma_{j'}\, \sigma_{k'})\ =\ 4\ \ \delta_{jj'}\, \delta_{kk'} \tag{42}$$

the only terms in $F(o)$, (30), that survive in (41) are the terms C_{ok} and C_{jk}, once the polarizations p_j, p_k have been selected. For our purpose here, to identify a TRV observable corresponding to the amplitude C_{xy}, the appropriate choice is $p_j = p_x, p_k = p_y$ (or vice versa), for which

$$\sigma A_{jk}\ = Im\ C_{xy} = \beta_{xy}\, . \tag{43}$$

Finally, then, the corresponding transmission asymmetry,

$$\Delta T_{xy} = -\tanh \beta_{xy} \overset{C_{xy}<<1}{\rightarrow} -\beta_{xy}\ \ , \tag{44}$$

is the observable to measure, with a vector (rank 1) polarized target, in the search for a combined PNC, TRV effect. This is also the simplest experimentally, for which high accuracy can be achieved.

Since it is clear from the foregoing development that there is no purely TRV forward amplitude in the $\frac{1}{2} + \frac{1}{2} \rightarrow \frac{1}{2} + \frac{1}{2}$ spin system, it is important to examine the suggestion[7] for an additional T-odd, P-even term [presumably in $f(o)$, (1a)] of the form $(\hat{\sigma} \cdot \hat{k} \times \hat{s})\ (\hat{k} \cdot \hat{s})$, with target spin $S \geq 1$ since S^2 represents an alignment. It is clear that this term would not contribute to f_z in (1b), so it is excluded by R_z-invariance. It can, however, be provided by a term in the F–matrix (15) for a system with the spin structure $\frac{1}{2} + 1 \rightarrow \frac{1}{2} + 1$. Since space limitations preclude a discussion here in the detail of that for the $\frac{1}{2} + \frac{1}{2} \rightarrow \frac{1}{2} + \frac{1}{2}$ system, I will simply indicate the result, and the details will be available elsewhere.[8] In (15), F_2 now becomes a 3x3 spin-1 matrix, with

$$F_2 = \sum_j C_j P_j + \sum_{kl} C_{kl}\ P_{kl}\ , j = o, x, y, z\ ; k, l = x, y, z \quad , \tag{45}$$

with the second sum limited to five independent terms. The P_j (P_{kl}), $j \neq 0$, are the vector, rank 1 (tensor, rank 2) components of the spin-1 matrix-operator.[9] Thus, the 9-term F_2 combined with the 4-term F_1 provides the required 36 terms of the F-matrix. The forward scattering matrix then is

$$F(o) = \begin{array}{c c} & \begin{array}{cccccc} \frac{3}{2} & \frac{1}{2} & -\frac{1}{2} & \frac{1}{2} & -\frac{1}{2} & -\frac{3}{2} \end{array} \\ \begin{array}{c} \frac{3}{2} \\ \frac{1}{2} \\ -\frac{1}{2} \\ \frac{1}{2} \\ -\frac{1}{2} \\ -\frac{3}{2} \end{array} & \begin{pmatrix} F_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & F_2 & 0 & F_3 & 0 & 0 \\ 0 & 0 & F_4 & 0 & F_5 & 0 \\ 0 & F_5 & 0 & F_4 & 0 & 0 \\ 0 & 0 & F_3 & 0 & F_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & F_1 \end{pmatrix} \end{array} \quad , \tag{46}$$

with the columns (rows) now labeled with the initial (final) channel helicities. P-symmetry has been invoked, so there remain only 5 independent amplitudes. From inspection, T-symmetry requires $F_3 = F_5$, so $F_3 \neq F_5$ will supply the TRV amplitude, and this condition is provided via the term

$$C_{y,zx}\,(\sigma_x P_{yz} - \sigma_y P_{zx}) \ , \tag{47}$$

in a straightforward extension of the previous notation. Thus, $C_{y,zx}$ is the TRV amplitude and the corresponding TRV observable is the transmission asymmetry

$$\Delta T_{y,zx} = \tanh \beta_{y,zx} \overset{C_{y,zx}<<1}{\rightarrow} \beta_{y,zx} \quad , \tag{48}$$

As the notation indicates, this corresponds to neutron polarization p_y in combination with the target tensor polarization p_{zx}, i.e. alignment along the direction z = x.

SUMMARY

It has been established that the complete spin-space matrix must be used in the description of TRV effects in transmission experiments, and it is seen that transmission observables can provide new and sensitive tests of T-symmetry. An especially important result is that the TRV/PNC observable is given directly by the imaginary part of the corresponding TRV/PNC forward scattering amplitude, in contrast to the situation that exists for the standard (non-forward) scattering experiment. There, T-symmetry tests can be accomplished only via comparison of two *separate* observables (e.g. $P_y = A_y$), and, as has been established,[10] no single null test is possible. Now, $\Delta T_{y,zx}$ (48) provides just such a null test of T-symmetry, and such an experiment is capable of attaining an unprecedented precision, comparable to that reached in *P*-symmetry tests, where, for example, A_z values of the order 10^{-7} have been measured.[11]

Finally, although the motivation for the development of this spin formalism for transmission experiments was derived from the exciting results achieved with slow neutrons, this development clearly has application at higher energies in nuclear and particle physics with respect to attaining considerably higher precision in tests of *T*-symmetry.

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