Experimental study of time-reversal invariance in neutron–nucleus interactions

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Experimental approaches for the test of time-reversal invariance in neutron–nucleus interactions are reviewed. Possible transmission experiments with polarized neutron beams and polarized or aligned targets are discussed, as well as neutron-capture experiments with unpolarized resonance neutrons. Development of the conceptual methods of study which are in progress as well as the recent progress in efficient neutron polarizers and analyzers, polarized nuclear targets, and high-count-rate detectors are reviewed. Preliminary results of the experiments which have been performed are discussed. © *1996 American Institute of Physics.* [S1063-7796(96)00206-9]

1. INTRODUCTION

The reversal of time, $t \rightarrow t' = -t$, does not impose any conservation law and does not introduce any quantum number, in contrast to the case of space inversion. The corresponding *anti-unitary* operator **T** transforms the S matrix of a nuclear reaction into the S matrix of the reversed process: $\mathbf{TST}^{-1} = S^{-1}$. Combining this with the unitarity condition for the S matrix, $S^{-1} = S^{\dagger}$, we obtain specific relations for the relative phases of the S-matrix elements, which lead, e.g., to the detailed balance of reaction cross sections through a compound nucleus and to the equality of the polarization and the analyzing power in the direct and reversed reactions. Time-reversal invariance (TRI) can also be tested by measuring T-odd correlation terms which appear in angular distributions of γ rays and linear-polarization distributions in nuclear β decay after subtracting the contribution of final-state interactions.

TRI is known to be a broken symmetry from the experimental proof of the CPT theorem and from the violation of CP symmetry on the scale of 10^{-3} of the weak amplitude found by Cronin *et al.*[1] in the decay of neutral kaons. The CPT symmetry, which is the symmetry under the combined transformation of charge conjugation (C), space inversion (P), and time reversal (T), was tested experimentally in the $K^0 - \bar{K}^0$ system, and it was found that the strength of the CPT-violating interaction is limited at the level of 10^{-1} of that of the CP-violating interaction.[2] Furthermore, the CPT theorem is founded on the solid ground of field theory, using general principles of causality and locality. Therefore, CP violation can be equivalent to the breaking of TRI. Many theoretical approaches have been discussed to identify the origin of CP violation, and many experiments have also been carried out to search for CP violation and T violation in other processes. Early reviews of these topics were given by Henley[3] and Blin-Stoyle,[4] and recent reviews, were given, for example, by Wolfenstein,[5] Boehm,[6] Gudkov,[7] and Bunakov.[8]

Detailed-balance experiments found no difference between the S-matrix elements of the direct and reversed reactions at the level of 2×10^{-3} (Ref. 9). The set of measurements of the polarization and analyzing power put an upper limit of 10^{-2} on their relative difference, as reviewed by Conzett.[10] Electromagnetic tests of TRI in nuclei have not revealed the presence of any relevant correlation terms in nuclear γ transitions at the level of 3×10^{-3}, as reviewed by Rikovska.[11] The D term, $D\vec{s} \cdot \vec{k}_e \times \vec{k}_\nu$, which is the correlation between the spin of the neutron or parent nucleus, $\vec{s}$, and the momenta of the emitted electron and antineutrino, was sought in the β decay of the neutron and ^{19}Ne and was shown to be smaller than $(1-2) \times 10^{-3}$. Corresponding references can be found in the papers of Erozolimskiĭ *et al.*[12] and of Calaprice and co-workers.[13] The most precise TRI tests are thought to be in the fields of neutron and atomic physics, by searches for a T-violating permanent electric dipole moment of the neutron, $d_e(n)$,[14,15] and of neutral atoms, d_e(Xe), d_e(Hg), as reviewed by Sandars.[16] The upper limit has reached the level $d_e(n) < 2 \times 10^{-25}$ $e \cdot$cm.

The magnitude of the T-violating effect in neutron-induced nuclear reactions is commonly expressed as the value λ which is the relative strength of the P-violating and T-violating part to the P-violating part in the effective nucleon–nucleon interaction in the case of P-violating and T-violating effects. The value α, which is the ratio of the P-conserving and T-violating matrix element to the P-conserving and T-conserving matrix element, is used in the case of P-conserving and T-violating effects. Present experimental upper limits put the upper limits for both λ and α at the level of $(1-3) \times 10^{-3}$; see Ref. 19 and Refs. 17 and 18, respectively. The discovery of the enhanced P-violating effects in neutron p-wave resonances (see the reviews by Alfimenkov[20] and Bowman *et al.*,[21] and references therein) and the subsequent prediction of the enhanced sensitivity to T violation in the p-wave resonances (see the review by Bunakov[8] and references therein) stimulated new interest in searches for possible T violation. It is expected that the sensitivity of polarized-neutron–polarized-target experiments involving p-wave resonances can exceed the sensitivity of the $d_e(n)$ measurements by at least a factor of 10.

The origin of CP violation still remains unknown; even the standard electroweak and QCD theories give no definite explanation. Upper limits on the T-violating effect can be used to select theoretical models according to the prediction of the strength of the T-violating effect. Millistrong models, introduced soon after the discovery of CP violation,[22] are nearly ruled out by most of the studied phenomena. Many milliweak models based on the T-violating interaction, whose strength is of the order of $10^{-3}G_F$, where G_F is the Fermi constant of the universal weak interaction, are ruled out by the above-mentioned $d_e(n)$ limit, though some of them still survive as a result of additional specific inhibiting factors. A superweak interaction, whose strength is 10^{-9} times that of the standard weak interaction and which has strangeness change $\Delta S=2$, was suggested by Wolfenstein.[23] If only this superweak model survives, no effect should be seen in any weak reactions other than those involving K^0 mesons. However, the history of science knows many discoveries of unexpected phenomena, and most experimentalists tend to treat TRI as an assumed symmetry and test it as precisely as possible. In this review, we concentrate on the searches for TRI breaking in neutron scattering and reactions. The topic was reviewed by Masaike,[24] but only briefly.

2. THEORETICAL PREDICTIONS FOR T-VIOLATING EFFECTS

2.1. General approaches to estimate T-violating effects

The magnitude of T-violating effects in a compound nucleus can be estimated from the values of the effective meson-exchange coupling constants analogous to the case of parity violation discussed by Adelberger and Haxton.[25] The T-violating effect in meson-exchange coupling constants should be calculated according to each theoretical model. An estimate of the T-violating meson-exchange coupling constants $\bar{g}^I_{MNN}$ was given in Ref. 19 for the mediating mesons M $(M=\pi, \rho, \omega)$ and isospin I. Here $\bar{g}^I_{MNN}$ corresponds to the magnitude of the matrix element $\langle MN|H|N\rangle$. The upper limit imposed by phenomenological analysis of the experimental result for the neutron electric dipole moment (EDM) is

$$\bar{g}^I_{MNN}\simeq 10^{-11} \tag{1}$$

for the P- and T-violating interactions. This should be compared with the P-violating and T-conserving quantity $g^0_{\rho NN}$ (h^0_ρ in the notation of Ref. 25), which has the value

$$g^0_{\rho NN}=(2-3)\times 10^{-6}. \tag{2}$$

The constants $\bar{g}^I_{MNN}$ must be interpreted in terms of the values of the T-violating matrix elements in compound nuclei to estimate the magnitude of T-violating observables.

One method is to relate the two-body nucleon–nucleon Hamiltonian to the single-particle potential and to obtain the ratio w/v from the ratio $\lambda=g_{PT}/g_P$, where w and v are the P-violating and T-violating matrix elements in compound nuclei, and g_{PT} and g_P are the corresponding meson-exchange coupling constants.[7,19,26,27] In this method, the symmetry-breaking matrix elements for single-particle and compound states are assumed to be connected by the $\sqrt{N}$ factor, where $N\approx 10^5$ is the typical number of quasiparticle components in the wave function of a compound state.

Another method is to apply random-matrix theory to the compound state to calculate the variance of the distribution of the matrix elements $(H')_{\mu\mu'}$ with a Hamiltonian of the form

$$H=H_0+iH'=h+u+i\alpha V, \tag{3}$$

where H' is the T-violating part of the Hamiltonian, and H_0 is the T-conserving one and is the sum of the single-particle term u and the residual-interaction term V.[17] The quantities V and u are assumed to have the same magnitude, and thus α can be regarded as the relative strength of the effective T-violating residual nucleon–nucleon interactions. The spreading width associated with H',

$$\Gamma'\equiv 2\pi\frac{\langle|(H')_{\mu\mu'}|^2\rangle}{D}, \tag{4}$$

is commonly used, as shown in Ref. 17. Here the angular brackets denote the variance, and D is the average spacing of levels of the given spin and parity. The resulting expression

$$\Gamma'\simeq 2\times 10^{-5}\pi\cdot\alpha^2(\mathrm{eV}) \tag{5}$$

can be used to deduce the unknown strength of the T-violating interaction when the T-violating spreading width is obtained experimentally. Detailed-balance experiments put a bound of $\alpha\leqslant 10^{-3}$ on the P-conserving and T-violating interactions.

2.2. Strength of the P- and T-violating interaction

Stodolsky[28] and Kabir[29] introduced a P-and T-violating term in the neutron elastic forward scattering amplitude f describing transmission of a polarized-beam through a polarized target. The amplitude is given in the form[30]

$$f=A'+B'\vec{\sigma}\cdot\hat{I}+C'\vec{\sigma}\cdot\hat{k}+D'\vec{\sigma}\cdot(\hat{k}\times\hat{I}), \tag{6}$$

where $\vec{\sigma}$ and $\hat{k}$ are unit vectors parallel to the neutron spin and the momentum, and $\hat{I}$ is the unit vector parallel to the target-nucleus spin. The A' and B' terms represent strong interactions (spin-independent and spin-dependent), C' represents the (P-violating) weak interaction, and D' represents the P- and T-violating part. Neutron transmission and capture experiments with incident neutrons polarized longitudinally revealed enormously enhanced P-violating effects.[20,31] The spin–spin strong-interaction term $B'\vec{\sigma}\cdot\hat{I}$ was studied in the epithermal region long before the discovery of P violation in neutron p-wave resonances, as reviewed by Alfimenkov, Pikelner, and Sharapov.[32] The last term $D'\vec{\sigma}\cdot(\hat{k}\times\hat{I})$ is the quantity to be measured in searching for T violation, to be discussed in detail in Sec. 3.

Before discussing experimental issues, we should properly recognize the smallness of the T-violating term. Bunakov and Gudkov,[33] Herczeg,[19] and Gudkov[7] estimated the quantity λ, as summarized in Table I. The estimation depends slightly on the authors, and we give Herczeg's results for λ and $\bar{g}_{MNN}$ in the table.

TABLE I. Theoretical estimation of the strength of the P- and T-violating interaction.

λ	$\bar{g}^{T}_{MNN}$	Model
4×10^{-3}	10^{-11}	Upper limit of $d_e(n)$, simplest π-loop mechanism
2×10^{-4}	7×10^{-12}	Upper limit of $d_e(n)$, θ term in QCD Lagrangian
$\leq10^{-4}$	3×10^{-12}	Standard model with Weinberg's Higgs extension
7×10^{-5}	-	Horizontal interactions
7×10^{-10}	-	Horizontal interactions
$\leq10^{-11}$	10^{-16}	Standard model with Kobayashi–Maskawa mixing phase

The upper limit deduced from the measurement of $d_e(n)$ is fairly small in either model. Neutron-transmission experiments should be sensitive to λ at the level of better than 10^{-3} to set a new limit. In other words, the magnitude of the T-violating asymmetry related to the $D'\vec{\sigma}\cdot(\hat{k}\times\hat{I})$ term is expected to be less than 10^{-3} of the P-violating longitudinal asymmetry in transmission, which has typical values of 10^{-2} for low-energy neutron resonances. This provides criteria for planning a neutron-transmission experiment; namely, it should be capable of measuring the asymmetry in transmission through a polarized target around the p-wave resonance with an accuracy better than 10^{-5}. Thus, the experimental apparatus must be designed very carefully to achieve such accuracy.

2.3 Strength of the *P*-conserving and *T*-violating interaction

P-conserving and T-violating interactions, which are often referred to as pure T violation, have been considered by many authors. Simonius[34] discussed the general form of P-even and T-odd meson-exchange potentials and came to the conclusion that there is no scalar pion-range interaction as long as the participating vector mesons are charged. As a result, the magnitudes of the corresponding coupling constants $\bar{g}^{T}_{MNN}$, e.g., $\bar{g}^{T}_{\rho NN}$, are expected to be essentially less than in the case of P-odd and T-odd interactions. Haxton and Horing[18,35] analyzed the experimental limits on the magnitude of P-conserving and T-violating matrix elements and reviewed the theoretical work as well. We summarize the results obtained by Herczeg[19] in Table II, giving representative values of $\bar{g}^{T}_{MNN}$ for several models without specifying the corresponding mass and isospin structure.

Evidently, the magnitudes of $\bar{g}^{T}_{MNN}$ are less than 10^{-5} of those of $\bar{g}_{MNN}$. This leaves little hope for the observation of pure T violation. Nevertheless, any precise experiment would be of interest to set an upper limit. Neutron transmission and neutron capture offer possibilities of studying P-conserving and T-violating effects with an enhanced sensitivity due to nuclear effects. The corresponding observables are the fivefold correlation term in the transmission of polarized neutrons through a spin-aligned nuclear target and the energy shift in the forward–backward asymmetry term in the capture cross section. These experiments were carried out recently and will be reviewed in subsequent sections.

TABLE II. Theoretical estimation of the strength of the P-conserving and T-violating interaction.

$\bar{g}^{T}_{MNN}$	Model
10^{-16}	θ term in QCD Lagrangian
4×10^{-18}	Standard model with Weinberg's Higgs extension
10^{-18}	Horizontal interactions
10^{-23}	Horizontal interactions
10^{-16}	θ term in QCD Lagrangian

2.4. Compound-nucleus enhancement of *T* violation

P- and T-violating effects can be enhanced in spin observables in compound nuclei by a factor of $\sim10^{-6}$ in comparison with those in the nucleon–nucleon interaction.[33] Theoretical aspects of this phenomenon were discussed by many authors, and the results obtained as well as the historical background were reviewed recently by Bunakov[8] and by Flambaum and Gribakin.[36] The sources of the enhancement are the same as for the enhanced P-violating effects in compound nuclei. There are several possible mechanisms contributing to T violation in neutron–nucleus scattering. Theorists agree that the internal-mixing mechanism, which is also referred to as resonance–resonance mixing, dominates the weak interaction of nucleons in the compound nucleus.

In such a case, T violation leads to the appearance in the T matrix ($S=1-T$) of an amplitude T^{PT} whose imaginary part is expressed within first-order perturbation theory[33] as

$$\mathrm{Im}\, T^{PT}(E)=\frac{1}{2k}\sum_{\nu}\times\frac{g_{\mu n}g_{\nu n}v^{T}_{\mu\nu}[(E-E_\nu)\Gamma_\mu+(E-E_\mu)\Gamma_\nu]/2}{[(E-E_\mu)^2+\Gamma^2_\mu/4)][(E-E_\nu)^2+\Gamma^2_\nu/4)]},\tag{7}$$

where E_ν are the resonance energies of admixed levels, and $g_{\nu n}$ and Γ_ν are the partial-width amplitude for channel n and the total width of the resonance at energy E_ν, respectively. Considering the case of nonoverlapping levels, $D\gg\Gamma$ ($\Gamma=\Gamma_\mu=\Gamma_\nu$), and approximating $(E-E_\nu)$ by $(E_\mu-E_\nu)$, one has, in the vicinity of the μ resonance at which the measurement is performed,

$$\mathrm{Im}\, T^{PT}(E)=\frac{1}{2k}\sum_{\nu}\frac{g_{\mu n}g_{\nu n}\Gamma_\mu/2}{(E-E_\mu)^2+\Gamma^2_\mu/4}\frac{v^{PT}_{\mu\nu}}{(E_\mu-E_\nu)}.\tag{8}$$

The mixing coefficient $v^{PT}_{\mu\nu}/(E_\mu-E_\nu)\simeq v^{PT}_{\mu\nu}/D$ in this expression is commonly known as the *dynamical* enhancement factor. Its value is, as mentioned above, $\sim\sqrt{N}\simeq5\times10^2$. Symmetry-violation effects measured in experiments are expressed in terms of the asymmetry coefficients P_μ, defined as the relative difference of the σ^+ and σ^- cross sections for the considered μ resonance due to the reversal of the beam polarization. With the use of the optical theorem, the absolute difference $\Delta\sigma$ can be expressed in terms of Im $T^{PT}(E)$, whereas the resonance cross section is

$$\sigma(E)=\frac{\pi}{k^2}\frac{g_{\mu n}^2\Gamma}{(E-E_\mu)^2+\Gamma_\mu^2/4}. \tag{9}$$

This leads to an expression for the asymmetry P_μ,

$$P_\mu=2\sum_\nu \frac{v_{\nu\mu}^T}{(E_\mu-E_\nu)}\frac{g_{\nu n}}{g_{\mu n}}, \tag{10}$$

which contains, according to Flambaum,[36] the *kinematic* enhancement factor $g_{\nu n}/g_{\mu n}$. This factor for low-energy neutrons has the value $g_{\nu n}/g_{\mu n}=(kR)^{-1}\simeq 10^3$. The dynamical enhancement factor is present in the asymmetry P_μ as well.

The enhancement factors of symmetry-violating effects probing P- and T-violating interactions enter simultaneously into the D' and C' terms of the neutron elastic scattering amplitude f. There could also be an enhancement of purely T-violating (P-conserving) effects in cross sections of nuclear reactions for different regimes, as discussed by Moldauer.[37] Detailed estimates for an isolated-resonance regime[38] gave an enhancement factor $\simeq 10^3$ as applied to the fraction of the T-violating term α in the nuclear Hamiltonian of medium-heavy nuclei. The enhancement has the same origin as in the case of the P- and T-violating interaction. An argument for a lower value of α was given by Gudkov.[39] Moreover, for reliable extraction of the symmetry-violating matrix elements there exists a minimum number of resonances with measurable effects, as analyzed by Davis.[40] The unknown spectroscopic information on resonance parameters (on the decay amplitudes $g_{\mu n}$ especially) should be studied as well.[41,42]

3. TRI TESTS IN NEUTRON SCATTERING AND REACTIONS

3.1. Triple correlation in neutron transmission

It is customary to use the amplitude f given in Eq. (6) to calculate the symmetry-violation effects, including the neutron spin rotation due to the weak interaction,[43] and the neutron transmission through a polarized target. The 2×2 matrix $\mathscr{S}$ defined below connects the initial neutron spin state ψ_i and the final state ψ_f:[30]

$$\psi_f=\mathscr{S}\psi_i=e^{i\delta}\psi_i, \tag{11}$$

where the phase δ is related to the nuclear property of the target material through the index of refraction n as

$$\delta=(n-1)kz=2\pi k^{-1}\rho z f\equiv\zeta f, \tag{12}$$

for transmission through the thickness z and the number density of nuclei ρ.

The matrix $\mathscr{S}$ has the form

$$\mathscr{S}=A+B\vec{\sigma}\cdot\hat{I}+C\vec{\sigma}\cdot\hat{k}+D\vec{\sigma}\cdot(\hat{k}\times\hat{I}), \tag{13}$$

where the coefficients A,B,C,D can be shown[30] to be related to the coefficients A',B',C',D' in the amplitude f by the expressions

$$A=e^{i\zeta A'}\cos b,$$
$$B=B'e^{i\zeta A'}(\sin b/b)i\zeta,$$
$$C=C'e^{i\zeta A'}(\sin b/b)i\zeta,$$
$$D=D'e^{i\zeta A'}(\sin b/b)i\zeta, \tag{14}$$

in which b is given by

$$b=\zeta\sqrt{B'^2+C'^2+D'^2}. \tag{15}$$

The primed coefficients are functions of the neutron energy and depend on the neutron resonance parameters.[28] The total cross section, the analyzing power, the produced polarization, and the spin correlation coefficient along any direction **n** can be obtained by a standard density-matrix calculation.[44] The spin density-matrix technique for the neutron spin transport was developed by Lamoreaux and Golub[45] for detailed calculations in the realistic geometry of an experiment. Here, however, we restrict ourselves to physical arguments given by Stodolsky[30] and Kabir[46] and to qualitative results obtained by them. Applications of K-matrix theory,[47] of the R-matrix formalism for nuclear reactions,[48,49] and of the latter in conjunction with the statistical-tensor technique[50,51] to the problem of symmetry violation are beyond the scope of our review.

Stodolsky suggested searching for the P- and T-violating term $D\vec{\sigma}\cdot(\hat{k}\times\hat{I})$ by performing a polarization analysis of an initially polarized neutron beam before and after transmission through a polarized target. Such an experiment would have the geometry shown in Figs. 1a and 1b, and would use a polarizer and analyzer simultaneously. Perfect alignment of the spins as well as perfect homogeneity of the medium are assumed. For the geometry of Fig. 1a (**n** along the $\hat{y}$ axis), only the σ_y component of the Pauli matrix is taken into account, and the D term is extracted after taking the count-rate (CR) difference for the process and its reversed process:

$$\mathrm{CR}(+\to+)-\mathrm{CR}(-\to-)=N_y\,\mathrm{Re}\,AD^*, \tag{16}$$

where the plus and minus signs indicate the direction of the beam polarization with respect to the $\hat{y}$ axis, and N_y is an experimental normalization constant. For the geometry of Fig. 1b (**n** along the $\hat{z}$ axis), three different Pauli matrices are involved, and one must compare a helicity-plus beam producing helicity-minus transmitted neutrons with a helicity-minus beam producing helicity-plus neutrons. The resulting difference in the count rate is

$$\mathrm{CR}(+\to-)-\mathrm{CR}(-\to+)=N_z\,\mathrm{Im}\,BD^*. \tag{17}$$

In both cases the dependence of the transmission on the neutron spin is measured by simultaneously reversing the states of the polarizer and the analyzer. These two states of the experimental apparatus are completely time-reversed states in the case of elastic scattering, whose reversed reaction is identical to itself. The experimental effects are represented

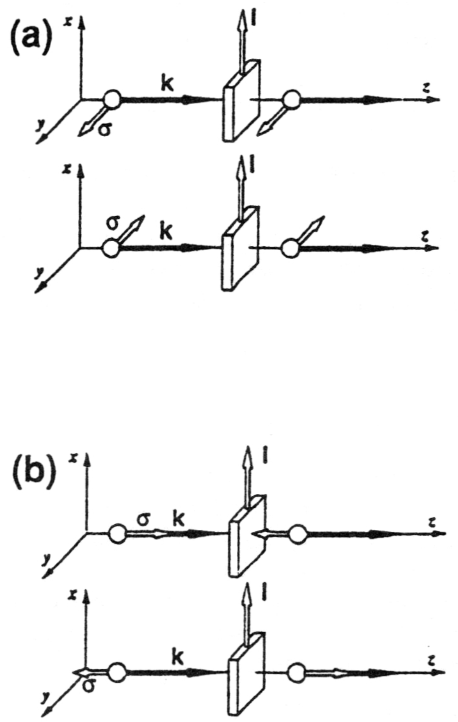

FIG. 1. Geometry of experiments to search for the triple-correlation term in the neutron total cross section: (a) transverse polarization of the beam; (b) longitudinal polarization of the beam.

by a term proportional to the amplitude D, and any false effect does not appear in the ideal geometry if $D=0$. This conclusion was supported by Conzett's[52] study of the symmetry properties of M amplitudes of nuclear reactions with different spin structure. It was shown that certain polarization observables in the neutron transmission experiments are excluded from the "no null-test of TRI" theorem,[53] which states that *no single observable in a two-particle reaction can be found which is required to vanish if TRI symmetry is conserved*, and thus a T-symmetry test is possible.

The situation was more troublesome for earlier suggested tests of TRI with only one polarizer to study the D term.[28,29,33] Generally speaking, changing the state of the polarizer does not correspond to time-reversal of the process. In particular, Bunakov and Gudkov[54] emphasized the role of false effects related to neutron spin precession in the target about the direction of $\vec{I}$ due to magnetic and pseudomagnetic fields which arise from the spin-dependent strong-interaction $\vec{\sigma}\cdot\hat{I}$ term,[55,56] followed by an absorptive weak $\vec{\sigma}\cdot\hat{k}$ interaction. They suggested several experimental schemes aimed at reducing the spin precession and the contribution of the strong $\vec{\sigma}\cdot\hat{I}$ effect. Japanese projects[57,58] discussed in Sec. 5.1 started from these suggestions and refined a method to suppress the spin precession. Compensation of the magnetic and pseudomagnetic fields is beneficial for Stodolsky's polarizer and analyzer scheme as well. Though false effects cannot be produced by a pseudomagnetic field there, the real T-violating effects will be suppressed in size. The parameter $b\simeq\zeta B'$ in the expressions for the coefficients B,C,D has the meaning of the number of rotations of the neutron spin at the distance z. The factor $\sin b/b$ is close to unity for small b and behaves as $1/b$ for large b, thus suppressing the contribution of the corresponding term.

Kabir[46] analyzed TRI tests in terms of classic polarization-asymmetry relations and showed that a measurement with a single analyzer/polarizer of the polarization P_n for an unpolarized beam and of the asymmetry A_n (the analyzing power of the reaction) for a polarized beam can distinguish T-violating effects from false effects. For the $\mathbf{n}=\hat{z}$ direction and any T-invariant effects masking T violation, the asymmetry A_z must have the same sign as the corresponding polarization P_z ($P_z=A_z$ holds), while for the true T-noninvariant effects $P_z=-A_z$. For the $\mathbf{n}=\hat{y}$ direction the signs are just opposite. Serebrov[59] used this idea and the experimental geometry of Fig. 1b (recommended by Stodolsky as the optimal one) for his polarization/asymmetry project to search for the D term in the neutron cross section of ^{139}La around the P-violating resonance at an incident-neutron energy of 0.734 eV. He suggested the analysis of the data in terms of the ratio $X=A_z/P_z$, which can be directly measured with the use of various combinations of states of the two spin-flippers placed behind the polarizer and in face of the analyzer. The quantity X was shown to be less sensitive to false effects.

In real experimental setups, polarizers and analyzers are not identical, and there always exist neutron-spin polarizer/analyzer direction misalignments which can produce false asymmetries. Their influence was discussed by Bunakov and Gudkov,[54] Bowman,[60] and Masuda.[57] Detailed calculations by matrix techniques were performed by Lamoreaux and Golub.[45] It was shown that to guarantee the result $\lambda<10^{-4}$, the absolute directions of the spin and field must be determined with accuracy better than 10^{-4} rad. Skoy[61] performed calculations by the same technique for modeling an experiment with alternate measurements of the polarization and the analyzing power, using a single polarizer/analyzer device rotated in turn by 180° around the $\hat{k}\times\hat{I}$ axis going through the center of the target. In such a scheme, control of the rotation at the level of $\simeq10^{-5}$ rad is necessary to obtain $\lambda\leqslant10^{-4}$.

3.2. Fivefold correlation in neutron transmission

The E term, $E\vec{\sigma}\cdot(\hat{k}\times\hat{I})(\hat{k}\cdot\hat{I})$, in the neutron–nucleus forward scattering amplitude f was first considered by Baryshevsky[62] and by Kabir.[63] It is P-even and T-odd, and therefore the search for this term constitutes a test of pure T violation without P violation. In contrast to the case of the triple correlation, one needs an aligned (not polarized) target to study this fivefold correlation (FC) term because it is quadratic in the target spin $\vec{I}$. Only a few aligned targets are available, and the best of them is a holmium single crystal.

Gould, Haase, and others[64] suggested an experiment for polarized beams of fast neutrons with energies 2–10 MeV. Dynamical and resonance enhancement factors are absent for such neutrons, owing to the broad beam-energy spread ~100 keV. At the same time, the effects of neutron spin rotation in the polarized target are negligibly small, since there is no external magnetic field in the experiment and only a small pseudomagnetic field can be present. As a result, a meaningful FC experiment can be performed without analyzing the polarization of the beam transmitted through the target. The geometry of the experiment is similar to that of Fig. 1a, with the additional possibility of rotating the target around the $\hat{y}$ axis by an angle θ between $\vec{k}$ and the target alignment axis which lies in the $(\hat{x},\hat{z})$ plane. The FC term has an angular dependence varying as $\sin 2\theta$, which helps to isolate the possible T-violating effect from the systematical errors. The difference between the cross sections for neutrons polarized parallel/antiparallel $(+/-)$ to the direction $\hat{k}\times\hat{I}$ is related to the corresponding amplitudes f by the optical theorem as

$$\sigma^+ - \sigma^- = \frac{4\pi}{k}\,\mathrm{Im}(f^+ - f^-), \tag{18}$$

which makes it possible to express this quantity in terms of the constant $A_{FC}\equiv E$, called the FC correlation coefficient:

$$\sigma^+ - \sigma^- = 2\sigma_0\sqrt{\frac{15}{8}}\,P_n \hat{t}_{20} A_{FC}\sin 2\theta. \tag{19}$$

Measuring the transmission asymmetry $\varepsilon=(N^+ - N^-)/(N^+ + N^-)$ as a function of the angle θ, one obtains an experimental limit on the FC coefficient A_{FC} after taking into account the beam polarization P_n and the alignment parameter $\hat{t}_{20}$. In the framework of a definite model, this limit leads to a bound on the strength α of the P-conserving and T-violating neutron–nucleus forces. Experiments were carried out, and their results are reviewed in Sec. 5.3.

3.3. Forward–backward asymmetry in capture reactions

Barabanov[65] noted that a limit on the strength of the P-conserving and T-violating interaction can be obtained from a quite different kind of experiment, namely, from the measurement of the forward–backward asymmetry in the yield of gamma rays from individual transitions in an unpolarized-neutron capture reaction measured around a p-wave resonance. In the simple case of nuclei with spin $I=1/2$ (considered here for simplicity of presentation) the differential cross section for the capture of p-wave and s-wave neutrons with subsequent emission of E1 and M1 gamma rays is represented by the expression

$$d\sigma(\vec{n}_\gamma,E)/d\Omega = A_0(E) + A_1(E)(\vec{n}_\gamma\cdot\vec{n}_k) + A_2(E) \times P_2(\vec{n}_\gamma\cdot\vec{n}_k), \tag{20}$$

where $\vec{n}_\gamma$ and $\vec{n}_k$ are unit vectors in the directions of the photon and neutron momenta, $A_0(E)$ is the total resonance cross section, and $P_2(\vec{n}_\gamma\cdot\vec{n}_k)$ is the second-order Legendre polynomial. The T-violating effect introduces a small energy shift in the interference term $A_1(E)$ between the s-wave amplitude and the two p-wave resonance amplitudes, the latter being mixed by T violation and by the interference of E1 and M1 gamma transitions. If the energy shift is observed, however, the effect would not be an unambiguous test of TRI because this kind of experiment is subject to the "no null-test theorem" and nonvanishing contributions are provided even by the first-order terms of the strong interaction.

The effect arises from the difference δS_J between the S-matrix elements $S_J(l_j, l' j')$ for a process and its inverse:

$$\delta S_J \equiv S_J\left(1\frac{1}{2}\to 1\frac{3}{2}\right) - S_J\left(1\frac{3}{2}\to 1\frac{1}{2}\right). \tag{21}$$

The arrows correspond to the transition of p-wave neutrons $(l=l'=1)$ in a resonance with spin J from a channel with neutron total angular momentum $j=1/2$ to a channel with $j'=3/2$ and vice versa. Using the explicit forms for the scattering matrix elements of Ref. 66, one obtains

$$\delta S_J = \frac{2\,\mathrm{Im}\left(g_n\left(1\frac{1}{2}\right)g_n^*\left(1\frac{3}{2}\right)\right)}{E-E_{p1}+i\Gamma_{p1}/2}, \tag{22}$$

where E_p and Γ_p are the energy and the total width of the p-wave resonance, and $g_n(lj)$ is the neutron partial-width amplitude $[\Gamma n(lj)=|g_n(lj)|^2]$. If TRI holds, the amplitude $g_n(lj)$ is real, and a nonzero imaginary part signals T violation. A P-conserving and T-violating interaction H^T gives phases $\delta_n(lj)$ to these amplitudes and mixes the amplitudes of neighboring p resonances, so that

$$g_n(1j) = g_n^{(1)}\exp i\delta_n^{(1)}(1j) - i\frac{v^T}{E-E_{p2}+i\Gamma_{p2}/2}\,g_n^{(2)}\exp i\delta_n^{(2)}(lj), \tag{23}$$

where $g_n^{(1,2)}\equiv g_n(1j)^{(1,2)}$, in which the superscripts 1 and 2 correspond to the considered p-wave resonance (labeled 1) and the neighboring p-wave resonance (labeled 2). Here v^T is the matrix element of the P-conserving and T-violating interaction between two p-wave resonances. The enhancement factor of Bunakov[38] gives the estimate

$$v^T/D_p \sim 10^3\cdot\alpha, \tag{24}$$

where α is the relative strength of the P-conserving and T-violating nuclear interaction. Neglecting the small phases $\delta(lj)$ and the T-violating effect between s-wave levels, one obtains in the first order in v^T near the resonance 1 (for detailed derivations, see Ref. 67)

$$A_1(E) = -(g_J/2k^2) \times\left[\frac{g_n^s\left(0\frac{1}{2}\right)\left[\left(g_n^{p1}\left(1\frac{1}{2}\right) - g_n^{p1}\left(1\frac{3}{2}\right)/\sqrt{2}\right]g_\gamma^s g_\gamma^{p1}}{(E-E_{p1})^2+(\Gamma_{p1}/2)^2}\right] \times\left[\frac{E-E_{p1}-\Delta E_{p1}}{E-E_s}\right], \tag{25}$$

where

$$\Delta E_{p1} = -\frac{\Gamma_{p1}}{2}\left[\frac{\Gamma_s/2}{E_{p1}-E_s} + \frac{v^T}{D_p}\left[\frac{g_\gamma^{p2}}{g_\gamma^{p1}} - \frac{g_n^{p2}\left(1\frac{1}{2}\right) - g_n^{p2}\left(1\frac{3}{2}\right)/\sqrt{2}}{g_n^{p1}\left(1\frac{1}{2}\right) - g_n^{p1}\left(1\frac{3}{2}\right)/\sqrt{2}}\right]\right]. \tag{26}$$

With $\Delta E_{p1}=0$, the forward–backward asymmetry is given by the standard expression (as obtained, e.g., in Refs. 51 and 68) with zero crossing at the resonance energy E_{p1}. There are two terms in the shift ΔE_{p1}. The first term represents the contribution of the nearest s-wave resonance for the T-conserving case. Though $\Gamma_s/2(E_{p1}-E_s)\sim 5\cdot 10^{-3}$ is a small quantity, it makes it hard to obtain a good upper limit on the factor v^T/D_p, which is related to the second term. Spectroscopic parameters such as the neutron and gamma decay-width amplitudes must be determined to interpret an experimental result to give a reliable upper limit on the T violation.

4. EXPERIMENTAL DEVELOPMENTS

4.1. Polarized-neutron filter

The polarized-neutron spin filter has the advantage of being able to polarize and analyze the neutron spin for a wide range of neutron energy, which is suitable for identifying a symmetry breaking enhanced in a p-wave resonance by taking the energy dependence of the symmetry-breaking observables. The neutron-spin polarizer and analyzer both work because of the same principle. Neutrons are spin-selectively transmitted through a polarized material according to a spin-dependent cross section. We discuss spin filters for both spin-polarizer and analyzer applications, using a cross-section description for simplicity. The transmittance of neutrons with polarization P_{n0} through a polarized target with polarization P_I can be written

$$T=e^{-n\bar{\sigma}t}(\cosh n\Delta\sigma P_I t-P_{n0}\sinh n\Delta\sigma P_I t), \qquad (27)$$

where n and t are the number density and thickness of the target, and $\bar{\sigma}=(\sigma_+ +\sigma_-)/2$, $\Delta\sigma=(\sigma_+ -\sigma_-)/2$; $\sigma_\pm$ are the total cross sections for neutrons polarized parallel and antiparallel to the target nuclear polarization. The neutron polarization after transmission is given by

$$P_n=\frac{-\sinh n\Delta\sigma P_I t+P_{n0}\cosh n\Delta\sigma P_I t}{\cosh n\Delta\sigma P_I t-P_{n0}\sinh n\Delta\sigma P_I t}. \qquad (28)$$

We define the figure of merit in the polarizer application as

$$(\mathrm{FOM})_p=(P_n|_{P_{n0}=0})^2 T(P_{n0}=0)$$
$$=\tanh n\Delta\sigma P_I t\,\sinh n\Delta\sigma P_I t e^{-n\bar{\sigma}t}. \qquad (29)$$

In the analyzer application, a neutron is incident on the filter after its spin is flipped with a spin-flipper, and the neutron polarization is measured as a transmission asymmetry, which is given by

$$\epsilon=\frac{T_+-T_-}{T_++T_-}=-P\tanh n\Delta\sigma P_I t \qquad (30)$$

for incident-neutron polarization P, where $T_\pm=T(P_{n0}=\pm P)$. Thus, the figure of merit in the analyzer application can be written

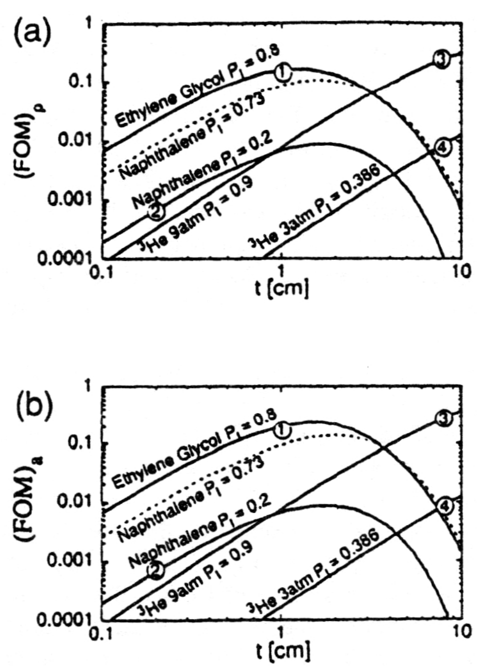

FIG. 2. Figure of merit for 1-eV neutrons as a function of thickness in (a) polarizer application and (b) analyzer application, for the cases of commonly used (1) ethylene glycol, (2) naphthalene, (3) TRIUMF ^{3}He gas cell, and (4) KEK ^{3}He gas cell. The value $P=70\%$ is assumed in the figure of merit in the analyzer application.

$$(\mathrm{FOM})_a=\epsilon^2\left(T_+\left(\frac{\partial\epsilon}{\partial T_+}\right)^2+T_-\left(\frac{\partial\epsilon}{\partial T_-}\right)^2\right)^{-1}$$
$$=2P^2e^{-n\bar{\sigma}t}\frac{\sinh^2 n\Delta\sigma P_I t\cosh^2 n\Delta\sigma P_I t}{\cosh^2 n\Delta\sigma P_I t-P^2\sinh^2 n\Delta\sigma P_I t}. \qquad (31)$$

A polarized-proton filter making use of the strong spin dependence of the (n,p) total cross section[69] is commonly employed as a spin-polarizer, since the method of dynamic nuclear polarization (DNP) was established to obtain a stable large proton polarization.[70] The most effective cryogenic spin filter of this type[71] is in operation at the Los Alamos Neutron Scattering Center. The neutron beam after the filter has diameter 80 mm, and the polarization of the resonance neutrons is about 85%.

The polarized ^{3}He system has been desirable, since it does not require a strong magnetic field, which may disturb the precise control of the neutron spin, in contrast to the polarized proton system, which requires a complicated cryogenic apparatus because of the need for a low temperature and a strong magnetic field. A polarized ^{3}He gas cell has been studied and improved by the group at TRIUMF as a polarized nuclear target. A mixture of ^{3}He gas and nitrogen gas is contained in a warmed quartz cell with a small amount of rubidium vapor. The concentration of rubidium ions is controlled by adjusting the temperature of the cell. Nuclear polarization of ^{3}He is built up according to the hyperfine interaction between the ^{3}He and rubidium ions, polarized by circularly polarized laser irradiation. A 90% nuclear polarization of ^{3}He was obtained with a pressure of 9 atm in an 8-cm thick cell in a magnetic field of 3 mT.[72] The first use of a polarized ^{3}He filter in a neutron beam as a polarizer of epithermal neutrons is described in Ref. 73. A 20% nuclear polarization of ^{3}He is normally in operation at KEK with a pressure of 3 atm in an 8-cm thick cell in a magnetic field of 3 mT.[74–76] The figures of merit of the polarized ^{3}He gas cells are shown in Fig. 2, in comparison with the polarized-proton filter. The polarized ^{3}He was used in the measurement of P-violating neutron spin rotation in an unpolarized lanthanum target, as discussed in Sec. 5.1. Further improvement in the figure of merit is desired for the final setup of a T-violation experiment.

Recently, another device has become available. A proton polarization of 17% has been achieved in a naphthalene single crystal doped with pentacene molecules at liquid-nitrogen temperature with laser irradiation and an external magnetic field of 0.3 T.[77–79] Pentacene molecules in the naphthalene crystal are excited by the laser irradiation, and paramagnetism appears in a quasistable triplet state through the intersystem crossing, which has a lifetime of about 20 μsec. The electrons in the triplet state are spin-polarized with a polarization of 73% according to the selection rule for the intersystem crossing. The electron polarization is transferred to proton polarization by microwave irradiation. The spin transfer efficiency was improved remarkably by modulating the external magnetic field so that the condition of the integrated solid effect is satisfied. Proton polarization does not have any channel to relax through the inverse process, since the paramagnetism disappears after the decay of the triple state. Repeating the cycle of proton-spin pump-up, a large proton polarization is finally built up. The proton-spin relaxation time was 1000 min, which is remarkably long compared with that of conventional proton filters. The figure of merit of the polarized naphthalene is shown in Fig. 2. One can see that this device is already at the level of real application. The proton polarization has the potential to be improved up to 73% of the intrinsic electron polarization in the triple state.

4.2. Polarized nuclear target

A polarized nuclear target is necessary in the search for the P-odd and T-odd term $D\vec{\sigma}\cdot(\hat{k}\times\hat{I})$. Among the possible nuclear targets for the triple correlation term, polarized ^{139}La is the most important device, since ^{139}La shows the largest P-violating effect among nonzero-spin nuclei in the well resolved p-wave resonance at $E_n=0.734$ eV.

There are several requirements for the polarized lanthanum target. First, the nuclear polarization should be at the level of tens of percent and preferably as large as 100%, so that the spin-dependent parts can be unambiguously extracted from the total interaction with neutrons. Second, the contribution of ^{139}La should dominate in the spin-dependent interactions with neutrons, and preferably also in the total interaction. Third, the nuclear polarization should be kept under a thermal nonequilibrium condition, so that the neutron spin precession can be controlled by applying an appropriate external magnetic field in order to maximize the experimental sensitivity to the P-odd and T-odd term D. Fourth, the target material should be dense and thick enough to obtain a sufficient sensitivity to the p-wave resonance in a transmission experiment.

The third requirement arises from the fact that the relevant triple correlation has the form $D\vec{\sigma}\cdot(\hat{k}\times\hat{I})$, and the experimental sensitivity is maximized when the neutron spin is precisely directed parallel to $\hat{k}\times\hat{I}$ on transmission through the target. However, the real parts of the spin-dependent terms in Eq. (13) cause neutron spin rotation around the related axes, and the net experimental sensitivity to the T-violating effect should be considered in $\mathscr{S}$, in which the coherent effect of the spin rotations is taken into account. Those spin-rotation effects are expressed as the factor $\sin b/b$ in Eq. (14), which always suppresses the net experimental sensitivity unless $b=0$. As discussed later, the value of b in Eq. (15) in most cases is dominated by the real part of B', which is referred to as pseudomagnetism, since the interaction $\mathrm{Re}B'\vec{\sigma}\cdot\hat{I}$ can be described as the contribution of the pseudomagnetic field, defined as

$$H^*=4\pi n\mu^*P, \tag{32}$$

where n is the nuclear number density, P is the nuclear polarization, and μ^* is the pseudomagnetic moment.[56,80,81] Thus, the experimental sensitivity can be improved by adjusting the external magnetic field to minimize the magnitude of b, which implies that the nuclear polarization must be achieved under a thermal nonequilibrium condition. The "brute force" method, in which the nuclei are polarized in thermal equilibrium, is not an appropriate method in this respect.

Dynamic nuclear polarization (DNP) is a common and well-established method for obtaining large nuclear polarizations of the proton, deuteron, etc., in bulk materials under a thermal nonequilibrium condition. DNP is a method of transferring electron spin polarization to nuclear polarization through double spin-flip processes enhanced by microwave irradiation. The transferred polarization is accumulated if the material is refrigerated at a sufficiently low temperature at which the spin relaxation processes are considerably suppressed.

Target material must be chosen with allowance for the ^{139}La dominance and the availability of large-size single crystals of the order of cubic centimeters. Lanthanum trifluoride, lanthanum aluminate, and lanthanum gallate have been proposed as candidate materials for a dynamically polarized lanthanum target.[82–84] According to the additional condition of the possibility of keeping the nuclear polarization at a lower field, lanthanum trifluoride was rejected, since the net nuclear polarization of ^{139}La is lost in a low external magnetic field, owing to the quadrupole coupling between the nuclear quadrupole moment of ^{139}La and the local electric-field gradient, which is diagonalized in a different direction from that of the crystal axis.[83,84] Lanthanum aluminate doped with neodymium ions Nd^{3+}:$LaAlO_3$ was found to have a narrow electron-spin-resonance width and to be an appropriate material for DNP. The quadrupole interaction is diagonalized in the crystal-axis frame, which does not cause any decrease of the net nuclear polarization according to the quadrupole interaction.

TABLE III. Values of A', B' and C' for $LaAlO_3$ at E_n=0.734 eV. The p-wave resonance state is assumed to have spin $J=4$.

	A' [fm]	B' [fm]	C' [fm]
La	$-8.3+0.019i$	$-2.7+0.0050i$	$0.0000004+0.00033i$
Al	$-3.5+0.0022i$	$-0.22+0.000069i$	0
O	$-5.8+0.0056i$	0	0
$LaAlO_3$	$-29+0.038i$	$-2.9+0.0050i$	$0.0000004+0.00033i$

A DNP polarized lanthanum target has been developed by the Kyoto–KEK group. The most recent result shows that 20% ^{139}La polarization has been achieved at 1.5 K and with a 2.3-T magnetic field in a 15 mm×15 mm×15 mm single crystal of Nd^{3+}:$LaAlO_3$ with 0.03 mol % neodymium ion concentration.[85] The relaxation time was 83 min. The DNP experiment was also carried out with a lower magnetic field of 0.8 T, and 4.2% ^{139}La polarization was obtained. The low-field polarized target makes it feasible to carry out a layered-target application, which is discussed later in Sec. 5.1. These values are expected to be improved by lowering the temperature, using pumped ^3He or a dilution cryostat.

Numerical values of the forward scattering amplitude of $LaAlO_3$ are listed in Table III. One can see that $LaAlO_3$ is suitable for the triple correlation experiment, since the spin-dependent terms are dominated by ^{139}La. In addition, single crystals of $LaAlO_3$ can be grown large enough for a neutron transmission experiment.

Values of A, B, and C can be calculated using the values in Table III and Eq. (13). The case of transmission through a 1-cm thick 100% polarized $LaAlO_3$ target is shown in Fig. 3, with no external magnetic field and with a magnetic field which cancels the real part of B' perfectly.

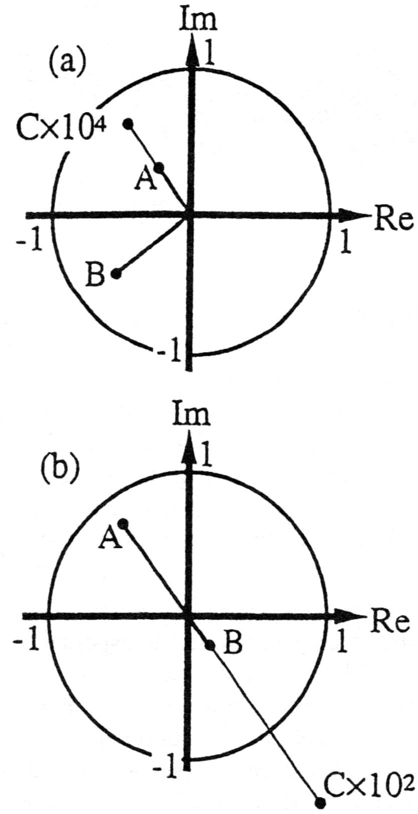

FIG. 3. Values of A, B and C for 1-cm thick $LaAlO_3$ with all nuclei 100% polarized: (a) with no external magnetic field; (b) with compensating magnetic field which completely cancels the real part of B'. The value of C is magnified.

4.3. High-count-rate detectors

A good timing characteristic is preferred in neutron transmission measurements using a spallation neutron source in a wide neutron energy band, since the neutron energy is determined by the neutron time of flight. A ^6Li glass detector was commonly used to detect neutrons in a wide neutron energy band, but the pulse width is rather long, which adversely affects the experimental possibility of carrying out a measurement at higher energy. A ^{10}B-loaded liquid scintillator has become more commonly used in epithermal neutron transmission experiments.

Neutrons are identified by detecting scintillation light generated by the neutron-capture reaction

$$n+{}^{10}B\rightarrow{}^{7}Li^{*}+{}^{4}He+2.310\ \text{MeV}\rightarrow{}^{7}Li+\gamma(0.482\ \text{MeV}) \quad (33)$$

with photomultipliers. A ^{10}B-loaded liquid scintillator is more sensitive to low-energy neutrons, since the reaction cross section obeys the $1/v$ law. Higher-energy neutrons are detected after being moderated mainly by hydrogen contained in the organic liquid. The mean free path of a neutron in the liquid is approximately 1 cm, almost independently of the incident-neutron energy. Thus, the liquid scintillator should be a few centimeters in size.

A large-acceptance ^{10}B liquid scintillator has been developed at LAMPF by the TRIPLE collaboration.[86] The detector is segmented to 55 honeycomb-shaped optically independent cells, which are filled with liquid scintillator with ^{10}B. An area 40 cm in diameter is covered by the detector. Each cell is viewed by photomultipliers, which are designed to have a quick recovery after the intense irradiation induced by the primary proton injection. Each light output is digitized independently, and 55 outputs are shaped and summed as an analog signal to reduce the number of readout electronics. Single photo-electron events are suppressed by filtering the output pulse with rise-time discrimination. Finally, the detector achieved a 500-MHz instantaneous maximum count rate and allowed neutron transmission measurements up to the keV region.

5. NEUTRON EXPERIMENTS, PERFORMED AND PLANNED

5.1. KEK approaches for triple correlation measurement

A triple correlation measurement is planned at KEK. Polarized neutrons are incident on a polarized lanthanum target, and the polarization of the transmitted neutrons is measured by a spin analyzer, as shown schematically in Fig. 4. Neutrons from a spallation neutron source are polarized by a polarized-proton filter [(1) in the figure]. The neutron polarization is transported adiabatically by solenoid magnets (2)

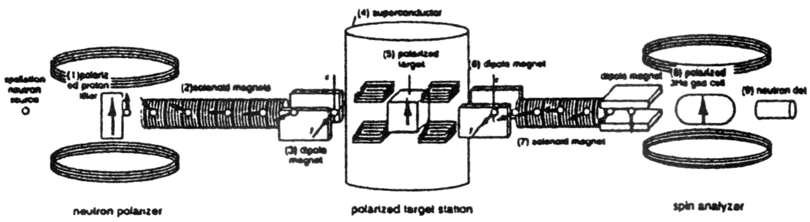

FIG. 4. Schematic view of the triple-correlation measurement planned at KEK.

and is flipped by reversing the polarity of the solenoid magnets. At the entrance of the target station, the neutron polarization is directed to the x axis by a dipole magnet (3). The polarized target station is magnetically shielded by a surrounding superconductor (4). The target nuclear polarization is frozen under a thermal nonequilibrium condition at a dilution temperature, so that the magnetic field inside the magnetic shield is adjusted to maximize the experimental sensitivity to the triple correlation term $D\vec{\sigma}\cdot(\hat{k}\times\hat{I})$. The component of the polarization of the transmitted neutrons is held by a dipole magnet (6) and transported to a polarized ^{3}He gas cell (8) by a solenoid magnet (7).

Necessary devices are a neutron-spin polarizer, a polarized lanthanum target, and a neutron-spin analyzer. A spin analyzer has already been in operation for many years and stably supplies 70% polarized neutrons in the epithermal region. A polarized lanthanum target has been developed at the level of application, as discussed in Sec. 4.3. A neutron-spin analyzer has also been developed, as discussed in Sec. 4.2. A polarized-proton filter at liquid-nitrogen temperature has also been developed, which can be an alternative choice of spin filter.

The neutron spin-control technique is being improved in the measurement of P-violating spin rotation, which requires polarized incident neutrons, spin control at the unpolarized target station, and a neutron spin analyzer.[87] The experimental apparatus is shown in Fig. 5. Polarized neutrons were incident on the target station, with the neutron spin controlled by adiabatic spin transportation. The target station is magnetically shielded by a superconductor box. The component of transmitted neutron polarization parallel to the field of the dipole magnet (6) is held and analyzed by the polarized ^{3}He. Figure 6 shows the measured neutron polarization with an empty target as a function of the dipole rotation angle θ in Fig. 5. The result shows that the neutron polarization direction can be determined with accuracy of about 1°. The P-violating spin rotation was measured in the epithermal region using this system. The result is shown in Fig. 7, and a P-violating weak matrix element $xW=1.0\pm0.4$ meV was obtained, in agreement with the P-violating cross-section asymmetry. The apparatus is applicable to the T-violation measurement shown in Fig. 4 if the unpolarized target is replaced by a polarized target.

The quantity to be measured is the interference term between A and D. Thus, the measurement of the relevant T-violating quantity is the search for a quantity whose magnitude is of the order of $|D/A|$, since the total interaction is dominated by the term A, as shown in Fig. 3. The magnitude of the quantity $|D/A|$ can be estimated by the T-odd cross-section asymmetry, defined by $A_T=(\sigma^{+T}-\sigma^{-T})/(\sigma^{+T}+\sigma^{-T})$, where $\sigma^{\pm T}$ are the resonance cross sections for incident neutrons polarized transversely parallel and antiparallel to $\hat{k}\times\hat{I}$. The quantity A_T is related to the P-violating cross-section asymmetry A_L as $A_T=\langle\lambda\rangle\kappa A_L$, where κ is a function of the channel-spin mixing ratio, and an explicit expression for it can be found in Ref. 7 (see also Ref. 50). The quantity $\langle\lambda\rangle$ is related to λ through the relation $\langle\lambda\rangle=\lambda/(1+2\xi)$, where ξ represents the nuclear effect, which can be calculated theoretically and is of the order of 1.[7] Thus, $\langle\lambda\rangle\kappa\simeq0.1\lambda$, assuming $x=1$ and $J=4$ for the p-wave resonance of ^{139}La at $E_n=0.734$ eV, where $x=g_n(1\ 1/2)/\sqrt{g_n(1\ 1/2)^2+g_n(1\ 3/2))^2}$. Therefore, the experimental sensitivity must reach the level of 10^{-5} to exceed the existing upper limit $\lambda\simeq4\times10^{-3}$ derived from the measurement of $d_e(n)$ based on the one-π-loop mechanism, as discussed in Sec. 2. It should be noted that κ depends strongly on the value of x, and $x=1$ does not give the maximum sensitivity to the T-violating effect. Preliminary values of κ and x for the lanthanum p-wave resonance are reported in Refs. 88 and 89, respectively. The value of x for specific resonances should be determined precisely to discuss the quantitative relation between the observables and the strength of the T-violating interaction in the pion–nucleon effective interaction.

In order to achieve excellent experimental accuracy, possible methods of reducing the systematic errors which arise from various misalignments and uncertainties in the experimental apparatus have been intensively studied. The most serious false effect arises from the misidentification of the

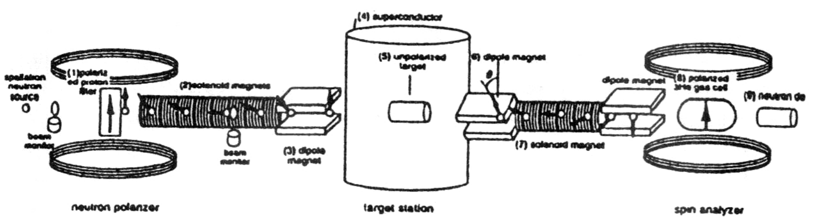

FIG. 5. Experimental apparatus for the measurement of P-violating spin rotation at KEK.

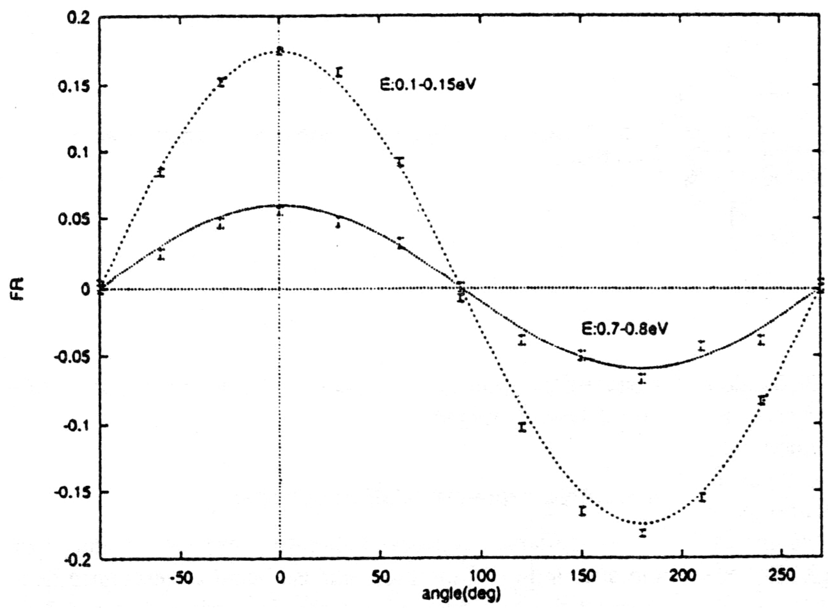

FIG. 6. Measured neutron polarization as a function of the rotation angle θ of the dipole magnet placed downstream from the target station.

spin effect due to magnetic and pseudomagnetic interactions. This requires perfect alignment of the neutron spin, neutron momentum, and target polarization. A method of canceling possible misalignment was proposed in Ref. 57. It introduces double cancellation of false effects. Part of the false effect is canceled during half-rotation, and further cancellation is achieved by taking the difference between configurations in rotations for the positive and negative directions. Finally, the systematic error can be reduced one order lower than the upper limit of the neutron EDM measurement in the sensitivity to λ.

Another scheme to use a stack of layered polarized lanthanum targets is discussed in Ref. 90. The neutron spin rotates a half-turn in the target material and another half-turn in the spacing between target materials in the plane perpendicular to $\hat{k}\times\hat{I}$. In this configuration, the neutron picks up only the positive or negative sign of $\vec{\sigma}\cdot(\hat{k}\times\hat{I})$ and is free from the suppression factor $\sin b/b$. The advantage of this method is that DNP can be applied continuously without the spin freezing technique.

5.2. PNPI triple-correlation project

The Gatchina PNPI project is designed for performance at the steady-state research reactor of the St. Petersburg Nuclear Physics Institute. As was stated in Sec. 3.1, the Gatchina approach is to measure the ratio of the asymmetry to the polarization. The experimental layout proposed in Ref. 59 is shown in Fig. 8. It consists of a polarizer P, an analyzer A, a polarized nuclear target T, two spin-flippers F_1 and F_2, and a detector D. The neutron beam is polarized, and the polarization is analyzed by two identical single crystals made

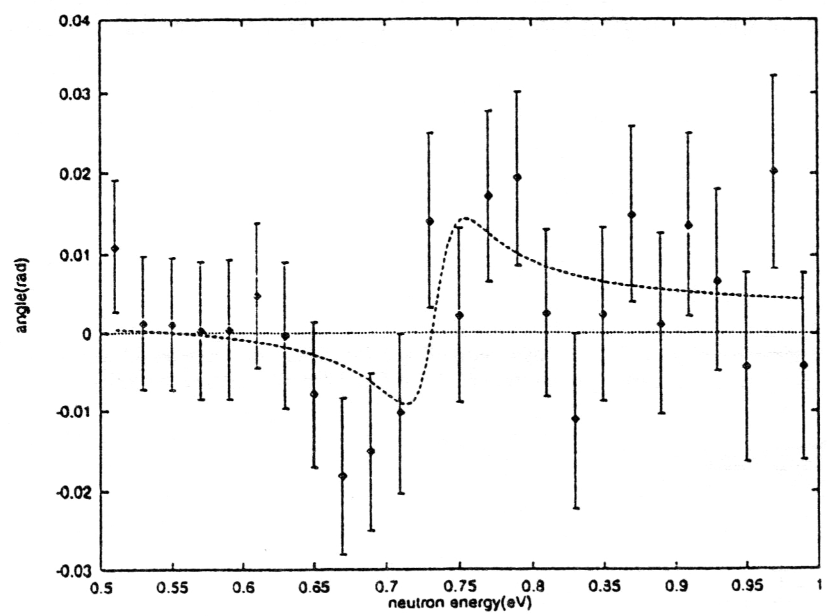

FIG. 7. P-violating spin rotation around the p-wave resonance of ^{139}La at 0.734 eV measured at KEK.[87]

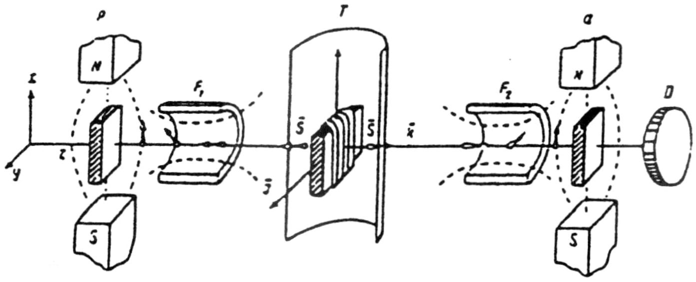

FIG. 8. Experimental layout of the asymmetry/polarization measurement at PNPI.

from Heusler alloys Cu_2MnAl. Single-crystal diffraction polarizer/analyzers of this type were already used successfully in Ref. 91 for a study of parity violation in fission with neutrons of energy up to about 1 eV. The magnetically saturated Cu_2MnAl crystal forms a monochromatic beam of neutrons, polarized initially in the vertical direction. The energy of the beam is changed by changing the Bragg angle. Reflection from the diffraction planes with $2d_{111}=6.869$ Å is used. The reflection coefficient of the crystals was about 2%, and the polarization of the beam of first-order reflected neutrons was 95%; however, there was a strong background of the second-order reflected neutrons with polarization 30%.

In the absence of the polarized target, test measurements were made of the parity-violating effect in a lanthanum target near the 0.75-eV p-wave resonance.[92] The asymmetry of the total cross section and the weak spin rotation were measured. The results are shown in Fig. 9. The upper part shows the asymmetry, and the lower part shows the spin precession angle. The calculations for ideal resolution are given by dotted curves. The full curves correspond to calculations when the instrumental resolution function was taken into account. The resolution poorer than in time-of-flight experiments presents no problem and is overcompensated by the gain in intensity. In fact, the PV asymmetry of the cross section was measured with a statistical accuracy of 2% during 20 min only with the use of one single crystal. The spin precession measurements with two single crystals took 16 hours per energy point to achieve the accuracy shown in Fig. 9.

This setup will be used for systematic study of the spurious effects which can appear in the search for the triple correlation coefficient D.

5.3. LANL triple-correlation scheme

Los Alamos National Laboratory has the advantage of the availability of the most intense beam of resonance neutrons at the Los Alamos Neutron Scattering Center, LANSCE. LANSCE uses the 800-MeV proton beam from the Los Alamos Meson Physics Facility linac. The proton beam is injected into and accumulated by a storage ring that compresses the pulse width from 650 μsec to 125 nsec. The pulses are extracted from the ring with 20-Hz repetition frequency and transported to a tungsten target, where they produce spallation neutrons. The average yield of the fast neutrons is about 10^{16} s^{-1}. The polarized-neutron beam intensity and details of the beam geometry can be found in Ref. 31 and in references therein.

The scheme of the experimental apparatus for the test of time-reversal invariance at LANSCE was discussed in Ref. 93. It is a standard one and includes, as can be seen from Fig. 10, a polarizer and an analyzer, two spin rotators, and a polarized target, besides the detector described in Sec. 4.3. It is assumed that the target is polarized perpendicular to the reaction plane. The polarizer and analyzer have the same polarization directions, which are perpendicular to both the neutron momentum and the target polarization. The time-reversal condition can be accomplished by simultaneously flipping the spin directions of the polarizer and analyzer.

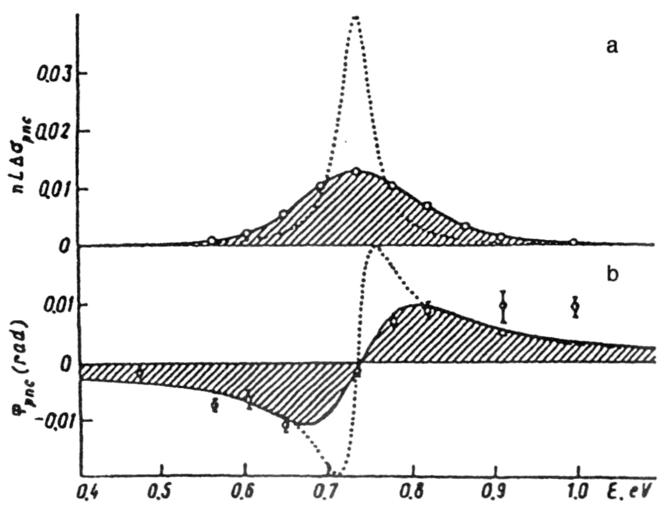

FIG. 9. P asymmetry (a) and P-violating spin rotation (b) around the p-wave resonance of ^{139}La at $E_p=0.734$ eV measured at PNPI.[92]

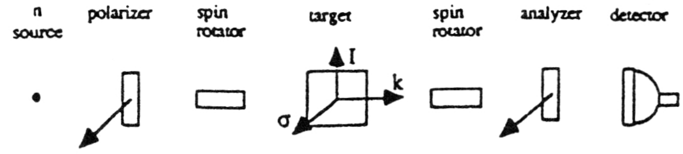

FIG. 10. Schematic view of the triple-correlation measurement proposed at LANL.

Two polarized ^{3}He systems will be built for the polarizer and analyzer. They are essentially the same as those developed recently at TRIUMF, in Canada,[72] where target cells of 17-mm outer diameter and 80-mm length filled at 9 atm were used to produce a ^{3}He polarization of 65%.

A ^{3}He polarization of 70% has been achieved recently at Los Alamos by optical pumping with high-power diode laser arrays.[94] The TRI asymmetry of the total cross section near the 0.75-eV p-wave resonance in lanthanum will be measured at the existing flight path with the existing boron-10 detector. The polarized lanthanum targets for the experiment were developed at Kyoto University and KEK, and are described in Sec. 4.2. The lanthanum polarization of 20% achieved by the DNP technique is still far from the optimum. A higher value of the polarization (about 60%) may be obtained by using a dilution refrigerator for cooling and by using a better single-crystal growing technique. On the basis of the sensitivity of the existing apparatus for parity-violation measurements, it is estimated that in 2×10^6 s a statistical sensitivity of about 10^{-3} in the λ value can be achieved.

5.4. TUNL parity-even test of TRI with MeV neutrons

The first search for the FC term $\vec{\sigma}\cdot(\hat{k}\times\hat{I})(\hat{k}\cdot\hat{I})$ was carried out at Triangle University Nuclear Laboratory, using 2-MeV polarized neutrons and an aligned holmium target.[95] The polarized neutrons were produced in the $t(\vec{p},\vec{n})$ reaction, using tritiated titanium foil and a 1-μA beam of 3.2-MeV polarized protons. The sample was a single crystal of 99.8% pure holmium, 2.29 cm in diameter and 2.8 cm long, with the c axis in the radial direction. The sample was cooled to a temperature of 29 mK by a dilution refrigerator,[96] so that the nuclear spin was aligned along the c axis. The sample was rotated during the measurements by a computer-controlled stepping motor system. The angle was varied from $-135°$ to $+135°$ in steps of 45°. The transmission of neutrons through this sample was measured by a 12.7 cm×12.7 cm×5 cm BC-501 organic liquid scintillator, with the use of pulse-shape discrimination and a threshold of 1 MeV, which ensured that only neutrons from the $t(p,n)$ reaction were detected. The measured transmission asymmetry was related to the T-odd analyzing power in Eq. (19), with the result $A_{FC}=(1\pm5)\cdot10^{-4}$.

A second, improved search[97] was performed with a more intense beam, better temperature conditions of the target, and an advanced detector system. The polarization-transfer reaction $d(\vec{d},\vec{n})$ was used to produced polarized neutrons with energies above 5.9 MeV with a beam current of 2.0 μA in a liquid-nitrogen cooled deuterium gas cell. To handle a high counting rate up to 4×10^6 s^{-1}, the neutrons were detected with a segmented array of plastic scintillators. The deformation-effect cross section and its energy dependence were measured[98] to confirm the alignment of the target, and to choose an optimal energy where the deformation-effect cross section is close to zero. Fitting of the angular dependence with a function of the form $a+d\cdot\sin2\theta$ gave the value $d=(1.1\pm1.0)\times10^{-6}$ and the corresponding value of the FC coefficient $A_{FC}=(0.98\pm0.88)\times10^{-5}$, which is consistent with time-reversal invariance.

Theoretical calculations of the microscopic T-violating optical potential were performed[99] starting from the ρ-meson–nucleon coupling constant $\bar{g}_{\rho NN}$ and the corresponding ρ-exchange potential of Refs. 18 and 34. The FC coefficient A_{FC} was calculated for different values of $\bar{g}_{\rho NN}$ as a function of the neutron energy, using the optical potential of Ref. 100, as shown in Fig. 11. According to these calculations, the experimental value of A_{FC} implies a bound on the ratio of the T-violating to the T-conserving nuclear matrix elements, $\alpha=(3.2\pm2.9)\times10^{-4}$. This result is the most precise direct test of parity-even time-reversal invariance in neutron–nucleus interactions.

5.5. JINR forward–backward capture experiments

A capture experiment[67] has been performed at the Joint Institute for Nuclear Research, using neutrons from the Dubna IBR-30 pulsed reactor. The reactor was operated in the booster mode as a multiplier of neutrons from the target of an electron accelerator. The duration of the electron pulse was 4.5 μs, with pulses occurring at a 100-Hz repetition rate. The neutron flux on the flight path of 52 m was equal to $10^4/E^{0.9}$ cm^{-2} eV^{-1} sec^{-1}. Two identical NaI(Tl) crystals, 200 mm in diameter and 200 mm thick, were used as gamma-ray detectors. They were placed at 53 and 127 degrees with respect to the beam direction at a distance of 40 cm from the ^{113}Cd sample, as shown in the upper part of Fig. 12. The detectors were shielded by Li-6 layers, lead, and borated paraffin, as shown in Fig. 12. The sample was in the form of a 116-g, 70-mm diameter cadmium disk 95% enriched in ^{113}Cd. The angular positions were chosen because the second Legendre polynomial, Eq. (20), vanishes totally at these angles. The energy resolution of the crystals permitted separation of the transitions to the ground state (9.04 MeV) and the first excited state (8.48 MeV). The pulse-height spectra were collected in 16 time gates. The gate widths were small compared with the total width $\Gamma_p=0.16$ eV of the p-wave resonance at $E_p=7.0$ eV.

After background subtraction, the number of counts in each detector (8.8-MeV threshold) was converted to a differential cross section for each neutron energy window. The resulting sum $[\sigma(53°)+\sigma(127°)]/2$ is plotted in the upper part of Fig. 13 in arbitrary units. The error bars represent the statistical uncertainty associated with each data point. The

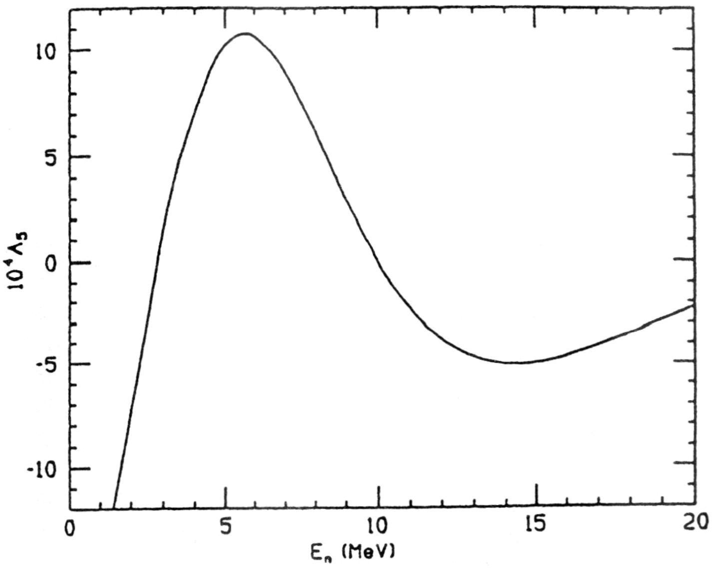

FIG. 11. FC correlation coefficient for $\bar{g}_{pNN}=1$ as a function of the neutron energy, using the optical potential of Ref. 100.

solid line is the result of the analysis. The difference in cross sections, $[\sigma(53°)-\sigma(127°)]/2$, is shown in the lower part of Fig. 13 in the same units. The data were fitted to Eq. (25), using the CERN least-squares minimization program MINUIT and subprograms used to take into account the Doppler broadening of the resonance and the TOF-spectrometer resolution function. The free parameters in the fit were the energy shift ΔE_p and the mixing ratio of the $g_n(1\ 1/2)$ and $g_n(1\ 3/2)$ amplitudes.

The weighted value of the energy shift from the measurements is $\Delta E_p=-0.0016\pm0.0062$ eV, which is consistent with time-reversal invariance. The contribution $\Gamma_p\Gamma_s/(4(E_p-E_s))=0.00066$ eV of the nearest s-wave resonance ($E_s=0.178$ eV, $\Gamma_s=0.113$ eV) to ΔE_p was omitted as too small. With the optimal choice for the neutron partial-width amplitudes, Eq. (26) was reduced to the approximate relation $\Delta E_p\approx(\Gamma_p/2)v^T/D$. Then the experimental upper

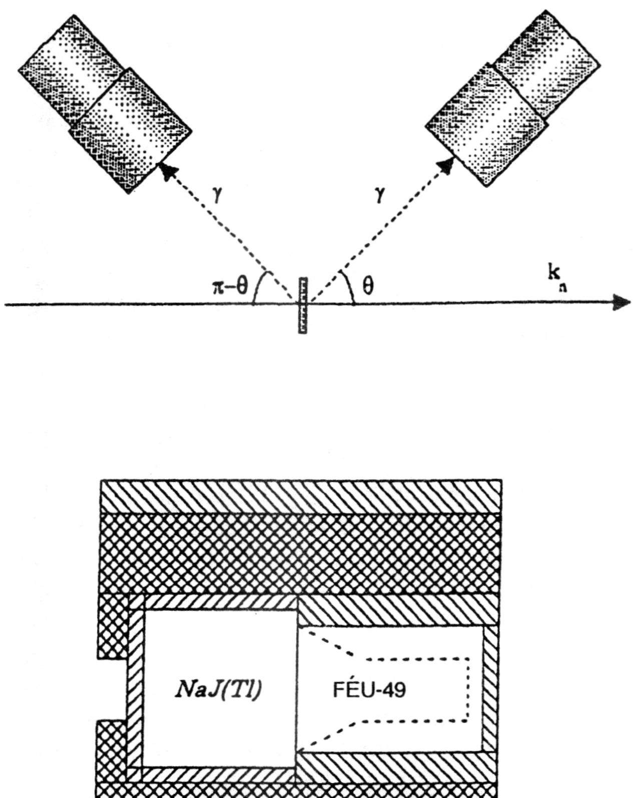

FIG. 12. Schematic view of the forward–backward asymmetry measurement carried out at JINR.

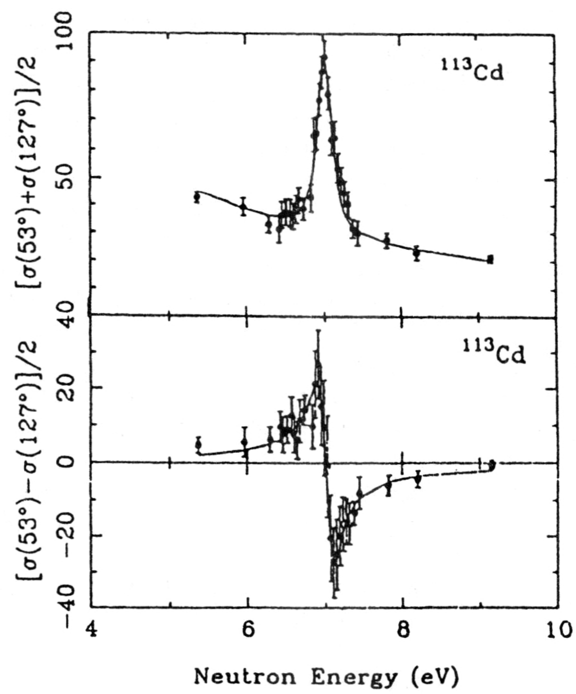

FIG. 13. Experimental results for $[\sigma(53°)+\sigma(127°)]/2$ (upper part) and $[\sigma(53°)-\sigma(127°)]/2$ (lower part) in the JINR capture experiment. The error bars represent the statistical uncertainty. The solid lines are the results of the analysis.

bound was obtained as $v^T/D \simeq 0.08$. The use of the dynamical enhancement factor in the relation $v^T/D \simeq 10^3 \cdot \alpha$ sets an upper bound of $\sim 10^{-4}$ on α.

These measurements proved the new technique for testing time-reversal invariance. They are the first "on-resonance" measurements of TRI. In a recent study[101] of the p-wave resonances in ^{113}Cd several close-lying pairs of p-wave resonances were found. Pairs with small energy denominators should have large dynamical enhancements. They might be candidates for future studies. A second experiment of this type was performed by the same technique for the p-wave resonance at 1.35 eV in the $^{117}Sn(n,\gamma)^{118}Sn$ reaction.[102] No energy shift was found at the same level of the experimental accuracy.

6. CONCLUSION

The searches for T violation in neutron–nucleus interactions have been reviewed. A pure T-violation test using a spin-aligned target and a polarized beam of MeV neutrons has been carried out, and the result put the most precise upper limit on the strength of the T-violating interaction relative to the T-conserving interaction. The "on-resonance" neutron-capture measurements with p-wave neutrons demonstrated the feasibility of the forward–backward asymmetry method as well as the urgent need for spectroscopic experiments related to the open problem of the spin-channel mixing in neutron amplitudes.

In the search for P- and T-violating effects in the neutron–nucleus interaction, there has been substantial progress in the techniques of the necessary devices. All the necessary devices already exist, although some of them must still be developed. Bearing in mind that several resonances are needed for obtaining a statistically useful constraint on the strength of the T violation, the important problem for the future is the search for optimal p-wave resonances and the subsequent development of corresponding polarized targets.

The control of the neutron spin direction in a polarized target is one of the most crucial requirements to exceed the upper limit set by the measurement of the neutron electric dipole moment. Promising results are obtained for the lanthanum p-wave resonance in the study of neutron spin rotation due to the weak interaction.

An intense epithermal neutron beam is essential to achieve in the neutron search for P- and T-violating effects the experimental accuracy of order 10^{-5}. An intense beam can also be used to determine nuclear spectroscopic factors, which are necessary to extract the T violation for a p-wave resonance.

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