«ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА»
1996, ТОМ 27, ВЫП.6

УДК 539.172.4

# EXPERIMENTAL STUDY OF TIME-REVERSAL INVARIANCE IN NEUTRON-NUCLEUS INTERACTIONS

*E.I.Sharapov*

Joint Institute for Nuclear Research, 141980, Dubna, Russia

*H.M.Shimizu**

National Laboratory for High Energy Physics, 1-1, Oho, Tsukuba 305, Japan

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 analysers, polarized nuclear targets and high count rate detectors are reviewed. Preliminary results of the experiments which have been performed are discussed.

Обзорная статья посвящена экспериментальным подходам, проверяющим инвариантность к обращению времени во взаимодействиях нейтронов с ядрами. Обсуждаются возможные эксперименты по пропусканию поляризованных нейтронов через поляризованные или выстроенные мишени, а также эксперименты по захвату неполяризованных резонансных нейтронов. Сделан обзор предложенных методов исследования и современных достижений в создании эффективных поляризаторов и анализаторов, поляризованных мишеней и нейтронных детекторов. Обсуждаются предварительные результаты некоторых экспериментов, выполненных к настоящему времени.

## 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 an $S$-matrix of a nuclear reaction into the S-matrix of the reversed process: $\mathbf{T}S\mathbf{T}^{-1} = S^{-1}$. Combining with the unitarity condition of the $S$-matrix: $S^{-1} = S^{\dagger}$, one obtains

*Present address: Institute of Physical and Chemical Research (RIKEN), 2–1, Hirosawa, Wako, Saitama 351-01, Japan specific relations in the relative phases of the S-matrix elements, which lead to provable consequencies, e.g., to the detailed balance of reaction cross sections through compound nucleus and to the equality of the polarization and the analyzing power in a direct and reversed reactions. The time-reversal invariance (TRI) can be tested also by measuring $T$-odd correlation terms which appear in angular distribution of $\gamma$-rays and linear polarization distribution in nuclear $\beta$-decay after subtracting the contribution of final state interactions.

TRI is known to be a broken symmetry from the experimental proof of 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 $K^0 - \overline{K}^0$ system, and it was found that the strength of CPT-violating interaction, if exists, is limited by the level of $10^{-1}$ of that of 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 $T$-breaking. Many theoretical approaches have been discussed to identify the origin of CP-violation and many experiments have been also carried out to search for CP-violation and $T$-violation in other processes. The early reviews of these topics were given by Henley [3] and by Blin-Stoyle [4], and recent reviews, for example, by Wolfenstein [5], Boehm [6], Gudkov [7] and Bunakov [8].

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

The magnitude of $T$-violating effect in neutron induced nuclear reactions is commonly expressed as the value $\lambda$ which is the relative strength of $P$-violating

$T$-violating part to $P$-violating part in the effective nucleon-nucleon interaction in the case of $P$-violating $T$-violating effects. The value $\alpha$, which is the ratio of $P$-conserving $T$-violating matrix element to $P$-conserving $T$-conserving matrix element, is used in the case of $P$-conserving $T$-violating effects. Present experimental upper limits put the upper limits for both $\lambda$ and $\alpha$ at the level of $(1-3)\cdot 10^{-3}$; see Ref.[19] and Refs.[17,18], respectively. The discovery of the enhanced $P$-violating effects in neutron p-wave resonances (see reviews by Alfimenkov [20], by 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 the new interest to the searches for possible $T$-violation. It is expected that the sensitivity of polarized neutron-polarized target experiments in $p$-wave resonances can exceed the sensitivity of the $d_e(n)$ measurements by a factor of 10 at least.

The origin of CP-violation still remains unknown; even the standard electroweak and QCD theories give no definite explanation. Upper limit 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 of which the strength is at 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 due to the additional specific inhibiting factors. The superweak interaction, whose strength is $10^{-9}$ times that of the standard weak interaction and with strangeness change $\Delta S = 2$, was suggested by Wolfenstein [23]. If only this superweak model survives, no effect should be seen in any other weak reactions than those involving $K^0$ mesons. However, history of science knows many discoveries of unexpected phenomena and most of experimentalists tend to treat TRI as an assumed symmetry and test it as precisely as possible. In this review, we concentrate to the searches for TRI breaking in neutron scattering and reactions. The topic was reviewed by Masaike [24], but 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 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 a particular theoretical model. An estimation of the $T$-violating meson-exchange coupling constants $\bar{g}^{I}_{MNN}$ was given in Ref.[19] for mediating mesons $M(M = \pi, \rho, \omega)$ and isospin $I$ $(I = 0,1,2)$. $\bar{g}^{I}_{MNN}$ corresponds to the magnitude of the matrix element $\langle MN \mid H \mid N \rangle$. The upper limit imposed by phenomenological analysis of experimental result of neutron electric dipole moment (EDM) measurement is

$$\bar{g}^{I}_{MNN} \simeq 10^{-11}, \qquad (1)$$

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

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

The constants $\bar{g}^{I}_{MNN}$ must be propagated to the value of $T$-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 obtain the ratio $w/v$ from the ratio $\lambda = g_{PT}/g_{P}$, where $w$ and $v$ are $P$-violating $T$-violating matrix elements in compound nuclei, and $g_{PT}$ and $g_{P}$ are corresponding meson-exchange coupling constants [7,19, 26,27]. In this method, 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 quasi-particle 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 the Hamiltonian of the form

$$H = H_0 + iH' = h + u + i\alpha V, \qquad (3)$$

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

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

is commonly used as introduced 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

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

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

**2.2. Strength of *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 polarized beam through polarized target. The amplitude is given in the form [30]

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

where $\boldsymbol{\sigma}$ and $\hat{\mathbf{k}}$ are unit vectors parallel to the neutron spin and the momentum, $\hat{\mathbf{I}}$ is the unit vector parallel to target nucleus spin. $A'$ and $B'$ terms represent strong interactions (spin independent and spin dependent), $C'$ represents $P$-violating) weak interaction; and $D'$, 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 $B'\boldsymbol{\sigma}\cdot\hat{\mathbf{I}}$ was studied in 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 $D'\boldsymbol{\sigma}\cdot(\mathbf{k}\times\hat{\mathbf{I}})$ is the quantity to be measured in searching for $T$-violation, to be discussed in detail in section 3.

Before discussing experimental issues, we should properly recognize the smallness of the $T$-violating term. Bunakov and Gudkov [33], Herczeg [19], Gudkov [7] estimated the quantity $\lambda$ as summarized in Table 1. The estimation depends slightly on authors, and we refer Herzeg's results for $\lambda$ and $\bar{g}_{MNN}$ in the table.

The upper limit deduced from the measurement of $d_e(n)$ is fairly small in either model. Neutron transmission experiments should be sensitive to $\lambda$ 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 $D'\boldsymbol{\sigma}\cdot(\hat{\mathbf{k}}\times\hat{\mathbf{I}})$-term is expected to be less than $10^{-3}$ of the $P$-violating longitudinal asymmetry in transmission which has typical value of $10^{-2}$ for low energy neutron resonances. This provides criteria for planning the neutron transmission experiment; namely, it should be capable of measuring asymmetry in transmission through the 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.

**Table 1. Theoretical estimation of the strength of *P*- and *T*-violating interaction**

| $\lambda$ | $\bar{g}^{I}_{MNN}$ | Model |
|---|---|---|
| $4 \cdot 10^{-3}$ | $10^{-11}$ | Upper limit of $d_e(n)$, simplest $\pi$-loop mechanism |
| $2 \cdot 10^{-4}$ | $7 \cdot 10^{-12}$ | Upper limit of $d_e(n)$, $\theta$-term in QCD Lagrangian |
| $\le 10^{-4}$ | $3 \cdot 10^{-12}$ | Standard model with Weinberg's Higgs extension |
| $7 \cdot 10^{-5}$ | — | Horizontal interactions |
| $7 \cdot 10^{-10}$ | — | Horizontal interactions |
| $\le 10^{-11}$ | $10^{-16}$ | Standard model with Kobayashi–Maskawa mixing phase |

**2.3. Strength of *P*-Conserving *T*-Violating Interaction**. *P*-conserving *T*-violating interactions, which is often referred to as pure *T*-violation, are considered by many authors. Simonius [34] discussed the general form of *P*-even *T*-odd meson-exchange potentials and came to the conclusion that there is no scalar pion-range interaction while the participating vector mesons should be charged. As a result, the size of the corresponding coupling constants $\bar{g}^{T}_{MNN}$, e.g. $\bar{g}^{T}_{\rho NN}$, is expected to be essentially less than in the case of *P*-odd *T*-odd interactions. Haxton and Horing [18,35] analyzed the experimental limits on magnitude of *P*-conserving *T*-violating matrix elements and reviewed the theoretical works as well. We summarize the results obtained by Herzeg [19] in Table 2 giving representative values of $\bar{g}^{T}_{MNN}$ for several models without specifying the corresponding mass and isospin structure.

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

**Table 2. Theoretical estimation of the strength of *P*-conserving *T*-violating interaction**

| $\bar{g}^T_{MNN}$ | Model |
|---|---|
| $10^{-16}$ | θ-term in QCD lagrangian |
| $4{\cdot}10^{-18}$ | 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 $\sim 10^6$ compared with those in nucleon-nucleon interaction [33]. Theoretical aspects of this phenomena were discussed by many authors and the results obtained as well as historical background were reviewed recently by Bunakov [8] and by Flambaum and Gribakin [36]. The sources of the enhancement are the same as for enhanced *P*-violating effects in compound nuclei. There are several possible mechanisms contributing to *T*-violation in neutron-nucleus scattering. Theorists agree that internal mixing mechanism, which is also referred to as resonance-resonance mixing, dominates the weak interaction of nucleons in compound nucleus.

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

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

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

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

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 size is, as mentioned above, $\sim\sqrt{N} \simeq 5\cdot10^2$. Symmetry violation effects to be measured in experiments are expressed in terms of asymmetry coefficients $P_\mu$ defined as relative difference of $\sigma^+$ and $\sigma^-$ cross section for the considered $\mu$-resonance due to the reverse of the beam polarization. With the use of the optical theorem, the absolute difference $\Delta\sigma$ can be expressed through the $\mathrm{Im}T^{PT}(E)$, whereas the resonance cross section is

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

This leads to the expression for the asymmetry $P_\mu$

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

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

The enhancement factors of symmetry-violating effects probing *P*- and *T*-violating interactions enter simultaneously into $D'$ and $C'$ terms of the neutron elastic scattering amplitude *f*. There also could be 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 the value of an enhancement factor $\simeq 10^3$ as applied to the fraction of *T*-violating term $\alpha$ in the nuclear Hamiltonian of the medium-heavy nuclei. The enhancement is of the same origin as in the case of *P*- and *T*-violating interaction. An argument for a lower value of $\alpha$ 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 polarized target. The $2 \times 2$ matrix $\mathcal{S}$ defined below connects the initial neutron spin state $\psi_i$, and the final state $\psi_f$ [30].

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

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

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

upon transmission through the thickness $z$ and number density of nuclei $\rho$.

The $\mathcal{S}$ has the form of

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

where the coefficients $A$, $B$, $C$ and $D$ are shown [30] to be connected with coefficients $A'$, $B'$, $C'$, $D'$, in the amplitude $f$ by expressions

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

where $b$ is given as

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

The primed coefficients are functions of neutron energy and depend on 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 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 by physical arguments given by Stodolsky [30] and Kabir [46] and by qualitative results obtained by them. The applications of the $K$-matrix theory [47], of the $R$-matrix formalism of nuclear

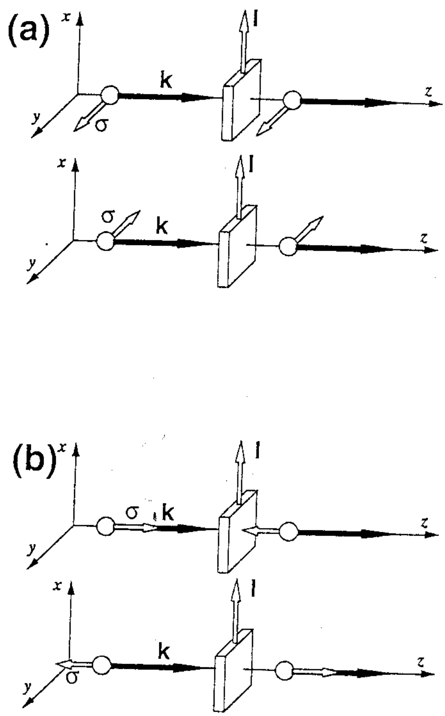


Fig.1. Geometry of experiments to search for triple correlation term in neutron total cross section: (a) transverse polarization of the beam, (b) longitudinal polarization of the beam

reactions [48,49] and of the latter in conjunction with the statistical tensors technique [50,51] to the problem of symmetry violation are beyond our review.

Stodolsky suggested searching for the *P*- and *T*-violating term $D\boldsymbol{\sigma} \cdot (\hat{\mathbf{k}} \times \hat{\mathbf{I}})$ by performing the polarization analysis of the initially polarized neutron beam before and after transmission through a polarized target. Such experiment would have the geometry shown in Fig.1a,b and would use the polarizer and analyzer simultaneously. Perfect alignment of the spins as well as a perfect homogeneity of the medium are assumed. For the geometry of Fig.1a (**n** along the $\hat{y}$-axis), only the $\boldsymbol{\sigma}_y$ 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:

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

where + or – means the direction of the beam polarization with respect to $\hat{y}$-axis and $N_y$ is experimental normalization constant. For Fig.1b geometry (**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 helicity-minus beam producing helicity-plus neutrons. The resulting difference in the count rate is

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

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 experimental apparatus are completely time-reversed states for the case of elastic scattering whose reversed reaction is identical to itself. The experimental effects are represented 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 two particle reaction can be found which is required to vanish if TRI symmetry is conserved,* and thus 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 rôle of false effects related to neutron spin precession in the target about the direction of **I** due to magnetic and pseudomagnetic fields which arise from the spin-dependent strong interaction $\boldsymbol{\sigma} \cdot \hat{\mathbf{I}}$ term [55,56]) followed by an absorptive weak $\boldsymbol{\sigma} \cdot \hat{\mathbf{k}}$ interaction. They suggested several experimental schemes aimed to reduce the spin precession and the contribution of the strong $\boldsymbol{\sigma} \cdot \hat{\mathbf{I}}$ 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 pseudo-magnetic fields is beneficial for the 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 on the distance $z$. The factor $\sin b/b$ is close to unity for a small $b$ and goes as $1/b$ for $b$ large, thus suppresses the contribution of the corresponding term.

Kabir [46] analyzed TRI tests in term of classic polarization-asymmetry relations and showed that the 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 effect from false effects. For $\mathbf{n} = \hat{z}$ direction and any $T$-invariant effects masking $T$-violation, the asymmetry $A_z$ must be the same in sign as the corresponding polarization $P_z$ ($P_z = A_z$ holds), while for the true $T$-noninvariant effects $P_z = -A_z$. For $\mathbf{n} = \hat{y}$ 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 $D$-term in the neutron cross section of $^{139}$La around the $P$-violating resonance at the 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-Gudkov [54], Bowman [60] and Masuda [57]. The detailed calculations by matrix technique were performed by Lamoreaux and Golub [45]. It was shown that to guarantee the result $\lambda < 10^{-4}$, the absolute direction of spin and field must be determined with the accuracy better than $10^{-4}$ rad. Skoy [61] performed calculations by the same technique for modelling experiment with alternate measurements of polarization and the analyzing power with a single polarizer/analyzer device rotated in turn by 180 degree around the $\hat{\mathbf{k}} \times \hat{\mathbf{I}}$ axis going through the centre of the target. In such a scheme, control of the rotation at the level of $\simeq 10^{-5}$ rad is necessary to obtain $\lambda \leq 10^{-4}$.

**3.2. Five-Fold Correlation in Neutron Transmission.** The $E$-term, $E\sigma \cdot (\hat{\mathbf{k}} \times \hat{\mathbf{I}})(\hat{\mathbf{k}} \cdot \hat{\mathbf{I}})$, in the neutron-nucleus forward scattering amplitude $f$ was considered first by Baryshevsky [62] and by Kabir [63]. It is $P$-even and $T$-odd, therefore the search for this term constitutes the test of a pure $T$-violation without $P$-violation. In contrast to the case of triple correlation, one needs an aligned (not polarized) target to study this five-fold correlation (FC) term because it is quadratic with respect to the target spin **I**. Only a few align targets are available and the best of them is holmium single crystal. Gould, Haase and others [64] suggested experiment for polarized beams of fast neutrons with energies 2 — 10 MeV. Dynamical and resonance enhancement factors are absent for such neutrons due to the beam energy broad spread ~100 keV. At the same time, the effects of neutron spin rotation in the polarized target are negligibly small since external magnetic field is absent in the experiment and only a small pseudomagnetic field can be presented. As a result, the 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 addition of possibility to rotate the target around the $\hat{y}$-axis by the angle $\theta$ between **k** and the target alignment axis which lays in the plane $(\hat{x}, \hat{z})$. The FC term has an angular dependence varying as sin $2\theta$ which helps to isolate the possible $T$-violating effect from systematical errors. The difference between cross sections for neutrons polarized parallel/antiparallel (+/−) to the direction $\hat{\mathbf{k}} \times \hat{\mathbf{I}}$ is connected with the corresponding amplitudes $f$ by the optical theorem as

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

which allows one to express this quantity in terms of the constant $A_{FC} \equiv E$ called the $FC$-correlation coefficient

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

Measuring the transmission asymmetry $\varepsilon = (N^{+} - N^{-})/(N^{+} + N^{-})$ as a function of angle $\theta$, one obtains the 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 a framework of a definite model, this limit leads to a bound on the strength $\alpha$ of $P$-conserving $T$-violating neutron-nucleus forces. Experiments were carried out and their results are reviewed in section 5.3.

**3.3. Forward-Backward Asymmetry in Capture Reactions.** Barabanov [65] noted that a limit on the strength of $P$-conserving $T$-violating interaction may 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 unpolarized neutron capture reaction measured around a $p$-wave resonance. In the simple case of a spin $I = 1/2$ nuclei (considered here for simplicity of presentation) the differential cross section for the capture of $p$-wave and $s$-wave neutrons with subsequent emission of the $E1$- and M1- gamma rays is represented by the expression

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

where $\mathbf{n}_\gamma$ and $\mathbf{n}_k$ are unit vectors in the direction of the photon and neutron momenta, $A_0(E)$ is the total resonance cross section, $P_2(\mathbf{n}_\gamma \cdot \mathbf{n}_k)$ 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 latters 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 an experiment is subject to «no null-test theorem» and nonvanishing contributions are provided even by the first-order terms of strong interaction.

The effect arises from the difference $\delta S_J$ between $S$-matrix elements $S_L(lj, l'j')$ for a process and its inverse

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

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 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 can get

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

where $E_p$ and $\Gamma_p$ are the energy and the total width of $p$-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 non-zero imaginary part signals $T$-violation. A $P$-conserving $T$-violating interaction $H^T$ gives phases $\delta_n(lj)$ to these amplitudes and mixes the amplitudes of the neighbouring $p$-resonances so that

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

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

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

where $\alpha$ is the relative strength of $P$-conserving $T$-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])

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

$$\times \left[\frac{E - E_{p1} - \Delta E_{p1}}{E - E_s}\right], \tag{25}$$

where

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

With $\Delta E_{p1} = 0$, the forward-backward asymmetry has the standard expression (as obtained, e.g., in Ref.[68,51]) with zero crossing at the resonance energy $E_{p1}$. There are two terms in the shift $\Delta E_{p1}$. The first term represents contribution of the nearest $s$-wave resonance for $T$-conserving case. Though $\Gamma_s/2(E_{p1} - E_s) \sim 5\cdot 10^{-3}$ is a small quantity, it disturbs 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 a reliable upper limit on $T$-violation.

## 4. EXPERIMENTAL DEVELOPMENTS

**4.1. Polarized Neutron Filter.** The polarized neutron spin filter has an advantage of being able to polarize and analyze 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 energy dependence of the symmetry breaking observables. Both the neutron spin polarizer and analyzer work due to 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 cross section description for simplicity. Transmittance of neutrons with polarization of $P_{n0}$ through a polarized target with polarization of $P_I$ can be written as

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

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

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

We define the figure of merit in the polarizer application as

$$(FOM)_p = (P_n|_{P_{n0}=0})^2 T(P_{n0}=0) =$$

$$= \tanh n\Delta\sigma P_I t \sinh n\Delta\sigma P_0 t\, e^{-n\bar{\sigma} t}. \qquad (29)$$

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

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

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 as

$$(FOM)_a = \varepsilon^2 \left( T_+ \left( \frac{\partial\varepsilon}{\partial T_+} \right)^2 + T_- \left( \frac{\partial\varepsilon}{\partial T_-} \right)^2 \right)^{-1} =$$

$$= 2P^2 e^{-n\bar{\sigma} t} \frac{\sinh^2 n\Delta\sigma P_I t \cosh^2 n\Delta\sigma P_I t}{\cosh^2 n\Delta\sigma P_I t - P^2 \sinh^2 n\Delta\sigma P_I t}. \qquad (31)$$

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

Polarized $^3$He system has been desired since it does not require strong magnetic field which may disturb a precise control of neutron spin, in contrast to the polarized proton system which requires a complicated cryogenic apparatus due to the necessity of low temperature and strong magnetic field. Polarized $^3$He gas cell has been studied and improved by the group at TRIUMF as a polarized nuclear target. The 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 ion is controlled by adjusting the temperature of the cell. Nuclear polarization of $^3$He is built up according to the hyperfine interaction between $^3$He and rubidium ion which is polarized by a circularly polarized laser irradiation. 90% nuclear polarization of $^3$He was obtained with the pressure of 9 atm in a 8 cm thick cell under the magnetic field of 3 mT [72]. The first use of the polarized $^3$He-filter at a neutron beam as a polarizer of the epithermal neutrons is described in Ref.[73]. 20% nuclear polarization of $^3$He is normally in operation at KEK with the pressure of 3 atm. in a 8 cm thick cell under the magnetic field of 3 mT [74,75,76]. The figure of merit of the polarized $^3$He gas cells is 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 section 5.1. Further improvement in figure of merit is desired for the final set-up of *T*-violation experiment.

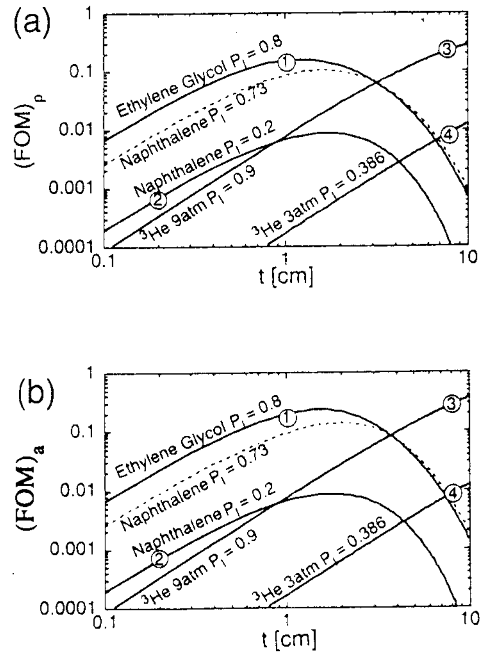


Fig.2. Figure of merit for 1 eV neutron is shown as a function of thickness in (a) polarizer application (b) analyzer application, for the cases of commonly used (1) ethylene glycol, (2) naphthalene, (3) TRIUMF $^3$He gas cell and (4) KEK $^3$He gas cell. $P$ = 70% is assumed in the figure of merit in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

Recently, another device has become available. A proton polarization of 17% has been achieved in naphthalene single crystal doped with pentacene molecules at liquid nitrogen temperature with laser irradiation and the external magnetic field of 0.3 T [77,78,79]. Pentacene molecules in the naphthalene crystal are excited by the laser irradiation and paramagnetism appears in a quasi-stable triplet state through the intersystem crossing, which has the lifetime of about 20μsec. The electrons in the triplet state are spin-polarized with the polarization of 73% according to the selection rule on the intersystem crossing. The electron polarization is transferred to proton polarization by a microwave irradiation. The spin transfer efficiency was remarkably improved by modulating 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, finally a large proton polarization is built up. The proton spin relaxation time was 1000 min. which is remarkably long compared with 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 a potential to be improved up 73% the intrinsic electron polarization in the triple state.

**4.2. Polarized Nuclear Target.** A nuclear polarized target is necessary in the search for the *P*-odd *T*-odd term $D\boldsymbol{\sigma} \cdot (\hat{\mathbf{k}} \times \hat{\mathbf{I}})$. 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 non-zero 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 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, nuclear polarization should be kept under a thermal inequilibrium 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 *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 of $D\boldsymbol{\sigma} \cdot (\hat{\mathbf{k}} \times \hat{\mathbf{I}})$ and experimental sensitivity is maximized when the neutron spin is precisely directed parallel to $\hat{\mathbf{k}} \times \hat{\mathbf{I}}$ on transmission through the target. However, the real parts of 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 $\mathcal{S}$ 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 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 $\mathrm{Re}\, B'\boldsymbol{\sigma} \cdot \hat{\mathbf{I}}$ can be described as the contribution of the pseudomagnetic field which is defined as

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

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

Dynamic nuclear polarization (DNP) method is a common and well-established method to obtain large nuclear polarization of proton, deuteron, etc., in bulk materials under a thermal inequilibrium condition. The DNP is the method to transfer electron spin polarization to nuclear polarization through double spin-flip processes enhanced by a 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 taking into account the $^{139}La$ dominance and the availability of large size of single crystals of the order of cubic centimeters. Lanthanum trifluoride, lanthanum aluminate, lanthanum gallate were proposed as the candidate materials for the dynamically polarized lanthanum target [82,83,84]. According to the additional condition of the possibility to keep the nuclear polarization at lower field, the lanthanum trifluoride was rejected, since the net nuclear polarization of $^{139}La$ is lost under a low external magnetic field due to the quadrupole coupling between 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.

The DNP polarized lanthanum target has been developed by Kyoto-KEK group. The newest result shows that 20% $^{139}La$ polarization has been achieved at 1.5 K and with 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 introduces a feasibility to carry out a layered target

**Table 3. Values of $A'$, $B'$ and $C'$ of $LaAlO_3$ at $E_n = 0.734$ eV. The $p$-wave resonance state is assumed to have the spin of $J = 4$**

| | $A'$ [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 |

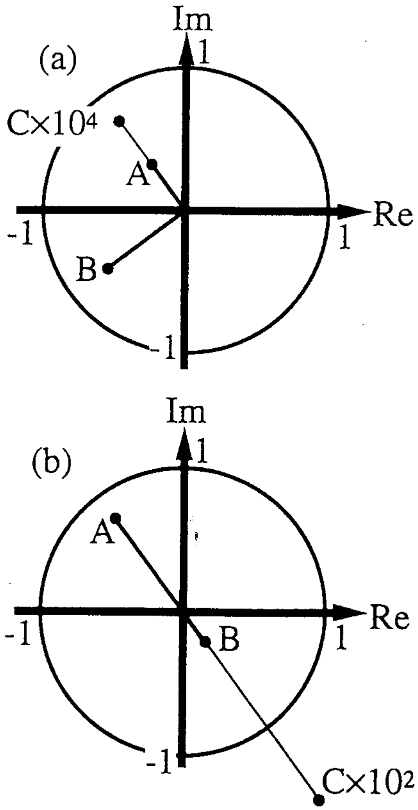


Fig.3. Values of $A$, $B$ and $C$ for 1 cm thick $LaAlO_3$ where all nuclei are 100% polarized (a) with no external magnetic field, (b) with cancellation magnetic field which completely cancels real part of $B'$. The value of $C$ is magnified

application which is discussed later in section 5.1. These values are expected to be improved by lowering temperature using pumped $^3He$ or dilution cryostat.

Numerical values of the forward scattering amplitude of $LaAlO_3$ are listed in Table 3. One can see that $LaAlO_3$ is suitable for the triple correlation experiment since 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 3 using Eq.13. The case of transmission through 1cm thick 100% polarized $LaAlO_3$ target is shown in Fig.3 with no external magnetic field and with the magnetic field which cancels real part of $B'$ perfectly.

**4.3. High Count Rate Detectors.** A good timing characteristics is preferred in neutron transmission measurements using spallation neutron source in a wide neutron energy band since neutron energy is determined by neutron time of flight. $^6Li$ 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 to carry out a measurement at higher energy. $^{10}B$ loaded liquid scintillator has become more commonly used in epithermal neutron transmission experiment.

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

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

with photomultipliers. $^{10}$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 neutron in the liquid is approximately 1 cm almost independent of 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 TRIPLE collaboration [86]. The detector is segmented to 55 honeycomb-shaped optically independent cells which are filled with liquid scintillator with $^{10}$B. The area of 40 cm in diameter is covered by the detector. Each cell is viewed by photomultipliers which are designed to have a quick recovery after an intense irradiation induced by 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 500 MHz instantaneous maximum count rate and enables neutron transmission measurements up to 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 to polarized lanthanum target and the polarization of transmitted neutrons is measured by a spin analyzer as schematically shown in Fig.4. Neutrons from the spallation neutron source are polarized by a polarized proton filter: (1) in the figure. The neutron polarization is transported adiabatically by solenoid magnets (2) and is flipped by reversing the polarity of the solenoid magnets. At the entrance of the target station, neutron polarization is directed to $x$-axis by the dipole magnet (3). Polarized target station is magnetically shielded by a surrounding superconductor (4). Target nuclear polarization is frozen under a

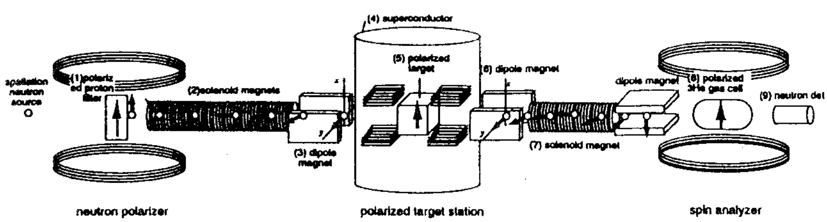


Fig.4. Schematic view of triple correlation measurement planned at KEK

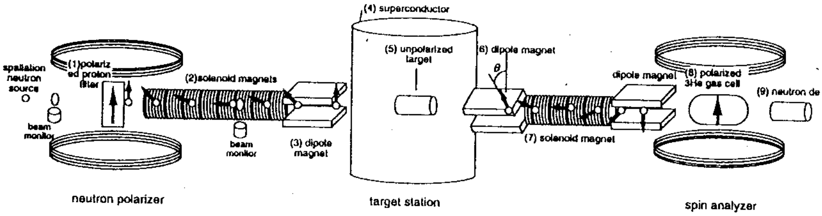


Fig.5. Experimental apparatus of the measurement of *P*-violating spin rotation at KEK

thermal inequilibrium 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 $D\sigma \cdot (\hat{\mathbf{k}} \times \hat{\mathbf{I}})$. The component of the polarization of transmitted neutrons is held by the dipole magnet (6) and transported to a polarized $^3$He gas cell (8) by the solenoid magnet (7).

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

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 neutron spin analyzer [87]. The experimental apparatus is shown in Fig.5. Polarized neutrons were incident to the target station with 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 $\theta$ in Fig.5. The result shows the neutron polarization direction can be determined with the accuracy of about 1°. *P*-violating spin rotation was measured in epithermal region using this system. The result is shown in Fig.7 and *P*-violating weak matrix element of $xW = 1.0 \pm 0.4$ meV was obtained consistently with the *P*-violating cross section asymmetry. The apparatus is applicable to *T*-violation measurement shown in Fig.4 by replacing the unpolarized target with 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

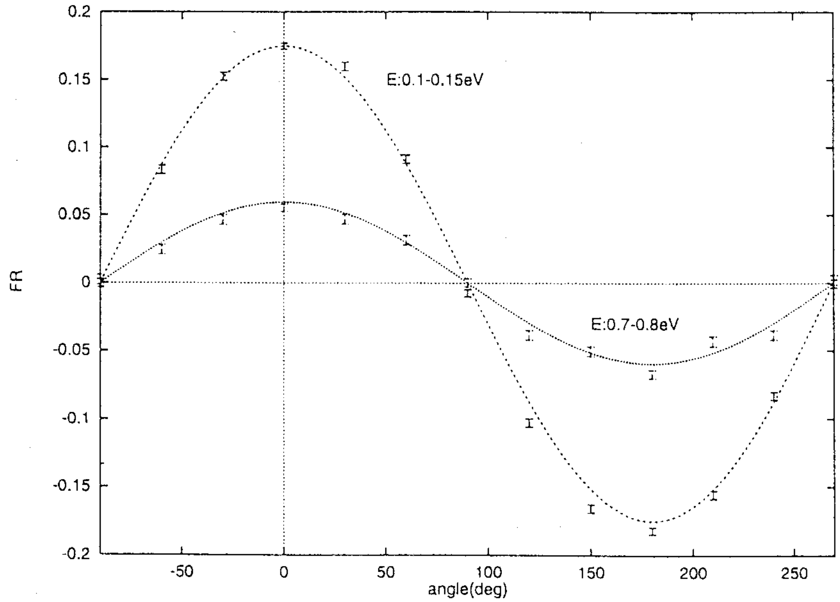


Fig.6. Measured neutron polarization as a function of the rotation angle θ of the dipole magnet place downstream of the target station

dominated by the term $A$ as shown in Fig.3. The magnitude of the quantity $|D/A|$ can be estimated by $T$-odd cross section asymmetry defined by $A_T = (\sigma^{+T} - \sigma^{-T})/(\sigma^{+T} + \sigma^{-T})$, where $\sigma^{\pm T}$ are the resonance cross section for incident neutrons polarized transversely parallel and antiparallel to $\hat{\mathbf{k}} \times \hat{\mathbf{I}}$. $A_T$ is related to $P$-violating cross section asymmetry $A_L$ as $A_T = \langle\lambda\rangle\kappa A_L$, where $\kappa$ is a function of the channel-spin mixing ratio and its explicit expression can be found in Ref.[7] (see also Ref.[50]). $\langle\lambda\rangle$ is related to $\lambda$ through the relation $\langle\lambda\rangle = \lambda(1 + 2\xi)$, where $\xi$ represents the nuclear effect which can be theoretically calculated and its size is of the order of 1 [7]. Thus $\langle\lambda\rangle\kappa \simeq 0.1\lambda$ assuming $x = 1$ and $J = 4$ for the $p$-wave resonance of $^{139}$La at $E_n = 0.734$ eV, where $x = g_n\left(1\frac{1}{2}\right)/\sqrt{g_n\left(1\frac{1}{2}\right)^2 + g_n\left(1\frac{3}{2}\right)^2}$. Therefore, experimental sensitivity must reach the level of $10^{-5}$ to exceed the existing upper limit $\lambda \simeq 4 \times 10^{-3}$ derived from the measurement of $d_e(n)$ based on the one-π-loop mechanism as discussed in section 2. It should be noted that κ strongly depends on the value of $x$, and $x = 1$ does not give the maximum sensitivity to $T$-violating effect. The

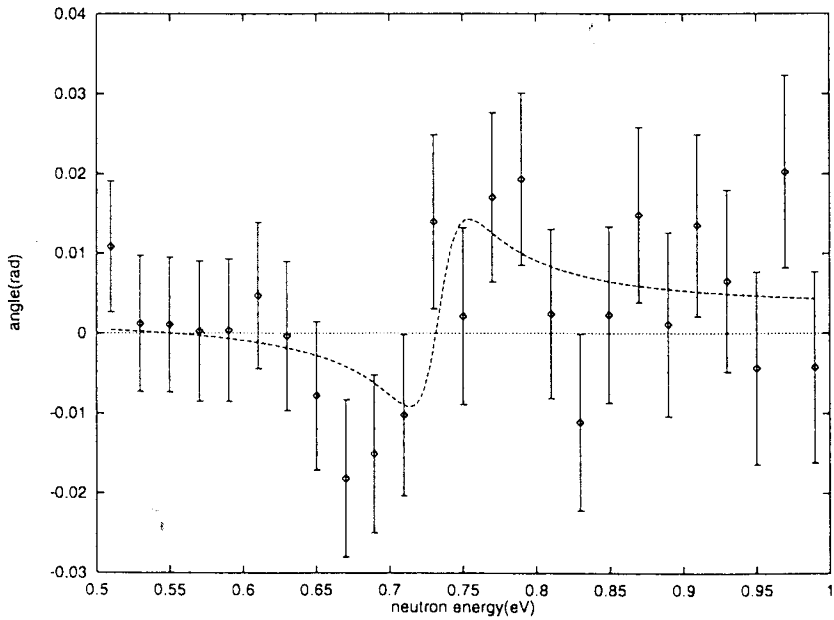


Fig.7. *P*-violating spin rotation around the *p*-wave resonance of $^{139}$La at 0.734 eV measured at KEK [87]

preliminary values of κ and *x* for the lanthanum *p*-wave resonance are reported in Ref.[88] and Ref.[89], correspondingly. The value of *x* in the specific resonances should be determined precisely to discuss the quantitative relation between observables and the strength of *T*-violating interaction in pion-nucleon effective interaction.

In order to achieve the excellent experimental accuracy, possible methods to reduce the systematic errors which arise from various misalignment and uncertainty in experimental apparatus have been intensively studied. The most serious false effect arises from the misidentification of spin effect due to magnetic and pseudomagnetic interactions. This requires a perfect alignment of neutron spin, neutron momentum and target polarization. A method to cancel possible misalignment is proposed in Ref.[57]. It introduces double cancellation of false effects. A part of false effects is cancelled during the half rotation and further cancellation is made by taking the difference between configuration in rotations for positive and negative directions. Finally, systematic error can be reduced one order lower than the upper limit of neutron EDM measurement in the sensitivity to λ.

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

**5.2. PNPI Triple Correlation Project.** The Gatchina PNPI project is designed for performance at the steady state research reactor of S.-Petersburg Nuclear Physics Institute. As stated in Sec.3.1, the Gatchina approach is to measure the ratio of the asymmetry to the polarization. The proposed in Ref.[59] experimental layout is shown in Fig.8. It consists of a polarizer $P$, an analyzer $A$, the polarized nuclear target $T$, two spin-flippers $F_1$ and $F_2$ and a detector $D$. Neutron beam is polarized and the polarization is analyzed by two identical single crystals made from Heusler alloys $Cu_2MnAl$. The single crystal diffraction polarizer/analyzers of this type were already used successfully in Ref.[91] for parity violation study in fission with neutrons up to about 1 eV energy. The magnetically saturated $Cu_2MnAl$ crystal formates a monochromatic beam of neutrons polarized initially in the vertical direction. The energy of the beam is changed by changing the Bragg angle. The reflection from the diffraction planes with $2d_{111} = 6.869$ Å is used. The reflection coefficient of the crystals was about 2%, polarization of the beam of first order reflected neutrons was 95%, however, there was strong background of the second-order reflected neutrons with polarization of 30%.

In the absence of the polarized target, the test measurements were made of the parity violating effect in a lanthanum target near the 0.75 eV $p$-wave resonance [92]. Asymmetry of the total cross section as well as the weak spin rotation were measured. The results are shown in Fig.9. The upper part presents

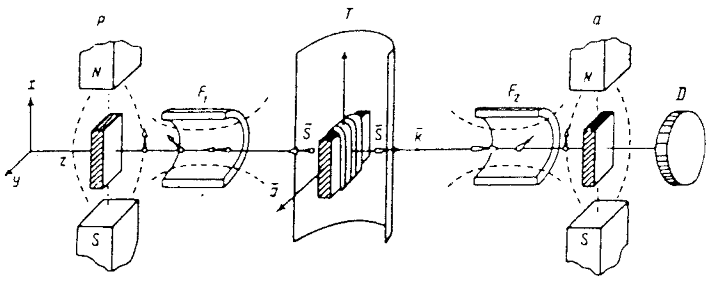


Fig.8. Experimental layout of asymmetry/polarization measurement at PNPI

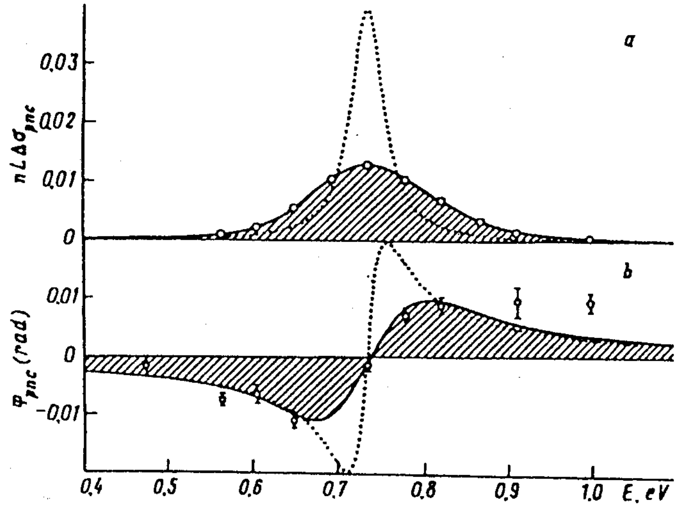


Fig.9. *P*-asymmetry (a) and *P*-violating spin rotation (b) around the *p*-wave resonance of $^{139}La$ $E_p = 0.734$ eV measured at PNPI [92]

the asymmetry and the down part presents the spin precession angle. The calculations for an ideal resolution are given by dotted curves. Full curves correspond to calculations when the instrumental resolution function was taken into account. The worser than in time-of-flight experiments resolution presents no problem and is overcompensated by the gain in the intensity. In fact, the *PV*-asymmetry of the cross section was measured with the 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 one energy point to achieve accuracy shown in Fig.9.

This set up 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 Centre, 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 [31] and in references therein.

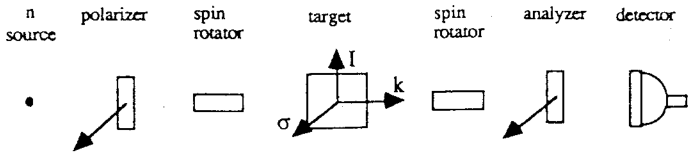


Fig.10. Schematic view of triple correlation measurement proposed at LANL

The scheme of the experimental apparatus for the time-reversal invariance test at LANSCE was discussed in Ref.[93]. It is a standard one and includes, as seen from Fig.10, a polarizer and an analyzer, two spin rotators and a polarized target besides the detector which was described in the 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. Two polarized $^3$He systems will be built for the polarizer and analyzer. They are essentially the same as those developed recently at TRIUMF, Canada [72], where the target cells of 17 mm outer diameter and 80 mm length filled at 9 atm were used to produce the $^3$He polarization of 65%.

The $^3$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 achieved by the DNP technique lanthanum polarization of 20% is far from the optimum yet. The higher value of polarization (about 60%) may be obtained by using a dilution refrigerator for cooling and by using a better single crystal growing technique. Based on the sensitivity of the existing apparatus for parity violation measurements, it is estimated that in $2 \times 10^6$ 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 $\boldsymbol{\sigma} \cdot (\hat{\mathbf{k}} \times \hat{\mathbf{I}})(\hat{\mathbf{k}} \cdot \hat{\mathbf{I}})$ 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 $t(\mathbf{p}, \mathbf{n})$ reaction using tritiated titanium foil and a 1 μ*A* beam of 3.2 MeV polarized protons. The sample was a single crystal of 99.8% pure holmium of 2.29 cm in diameter and 2.8 cm long with the *c*-axis in the radial direction. The sample was cooled to temperature of 29 mK by a dilution refrigerator [96] so that the nuclear spin was aligned along

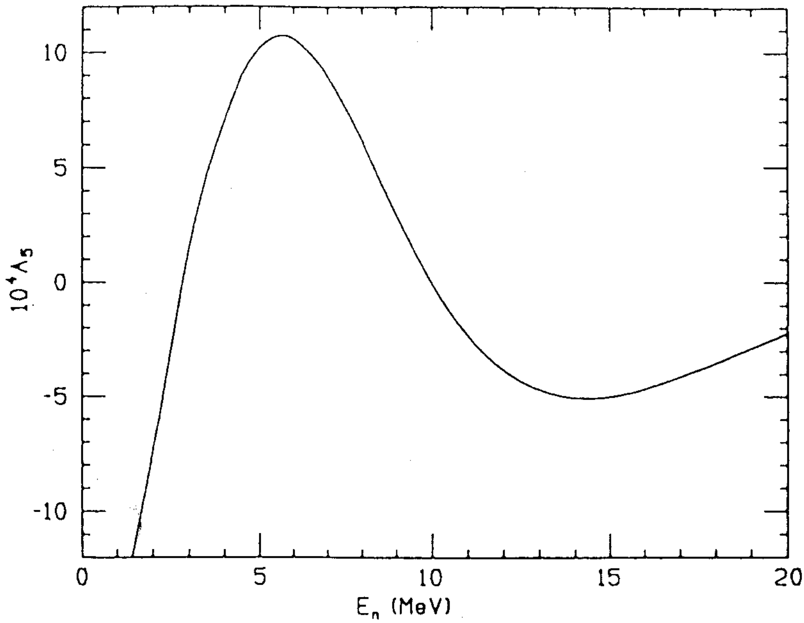


Fig.11. FC correlation coefficient for $\bar{g}_{\rho NN} = 1$ as a function of neutron energy using Refs.[99,100]

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 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 a $T$-odd analizing power in Eq.19, with the result $A_{FC} = (1 \pm 5) \cdot 10^{-4}$.

The second, improved search [97], was performed with more intense beam, better temperature conditions of the target and an advanced detector system. The polarization transfer reaction $d(\mathbf{d}, \mathbf{n})$ was used to produce polarized neutrons with energies above 5.9 MeV under the beam current of 2.0 μ$kA$ in a liquid nitrogen cooled deuterium gas cell. To handle a high counting rate up to $4 \times 10^6$ 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 alignment of the target, and to choose an optimal energy where the deformation effect cross section is close to zero. Fitting the angular dependence with the function of the form $a + d \cdot \sin 2\theta$ gave the value $d = (1.1 \pm 1.0) \times 10^{-6}$ and the corresponding value of the $FC$ coefficient $A_{FC} = (0.86 \pm 0.77) \times 10^{-5}$ which is consistent with time reversal invariance.

Theoretical calculations of the microscopic $T$-violating optical potential were performed [99] starting from ρ-meson-nucleon coupling constant $\bar{g}_{\rho NN}$ and the corresponding ρ-exchange potential of Refs.[34,18]. The FC coefficient $A_{FC}$ was calculated for different values of $\bar{g}_{\rho NN}$ as a function of neutron energy using optical potential of Ref.[100] as shown in Fig.11. According to these calculations, the above experimental value of $A_{FC}$ implies a bound on the ratio of $T$-violating to $T$-conserving nuclear matrix elements $\alpha = (2.8 \pm 2.5) \times 10^{-4}$. 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.** The 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 $10^4/E^{0.9}$ $\mathrm{sm}^{-2}\,\mathrm{eV}^{-1}\,\mathrm{sec}^{-1}$. 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 first excited state (8.48 MeV). The pulse height spectra were collected in 16 time gates. The gate widths were small compared to the value of the total width $\Gamma_p = 0.16$ eV of $p$-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 with arbitrary units. The error bars represent the statistical uncertainty associated with each data point. The solid line is the result of the analysis. The difference in cross sections $[\sigma(53°) - \sigma(127°)]/2$, is shown in bottom part of Fig.13 in the same units. Data were fitted to Eq.25 using the CERN least squares minimization program MINUIT and subprograms used to take into account the

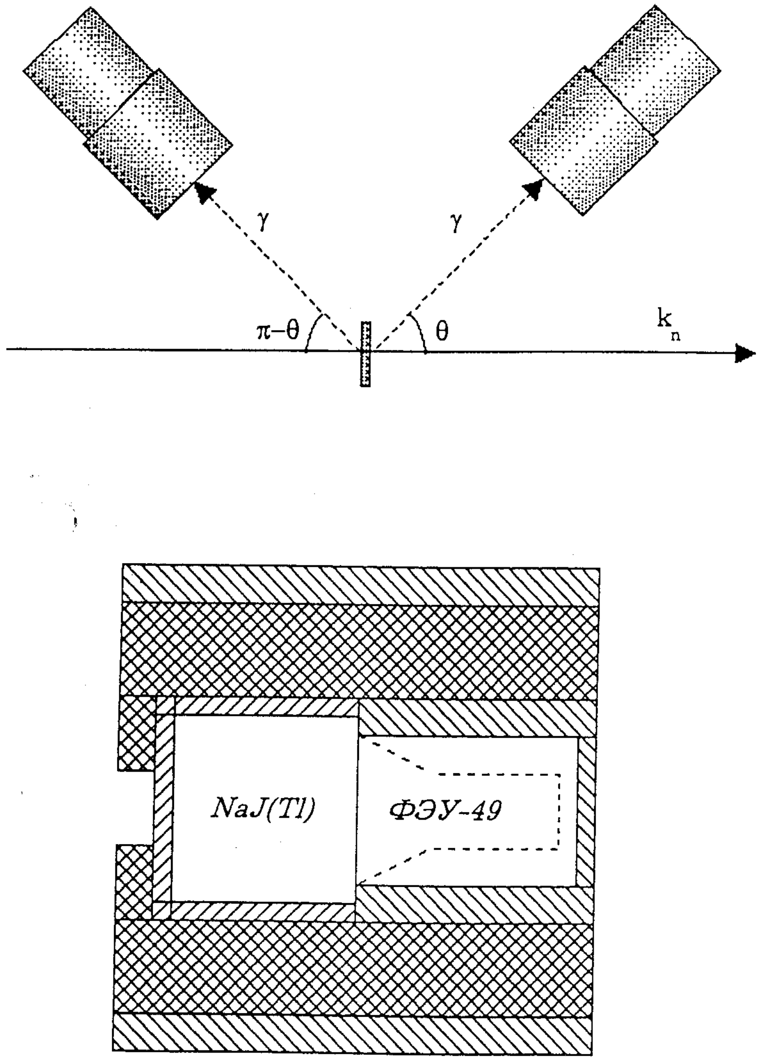


Fig.12. Schematic view of forward-backward asymmetry measurement carried out at JINR

Doppler broadening of the resonance and the TOF-spectrometer resolution function. The free parameters in the fit were the energy shift $\Delta E_p$ and the mixing ratio of the $g_n\left(1\frac{1}{2}\right)$ and $g_n\left(1\frac{3}{2}\right)$ amplitudes.

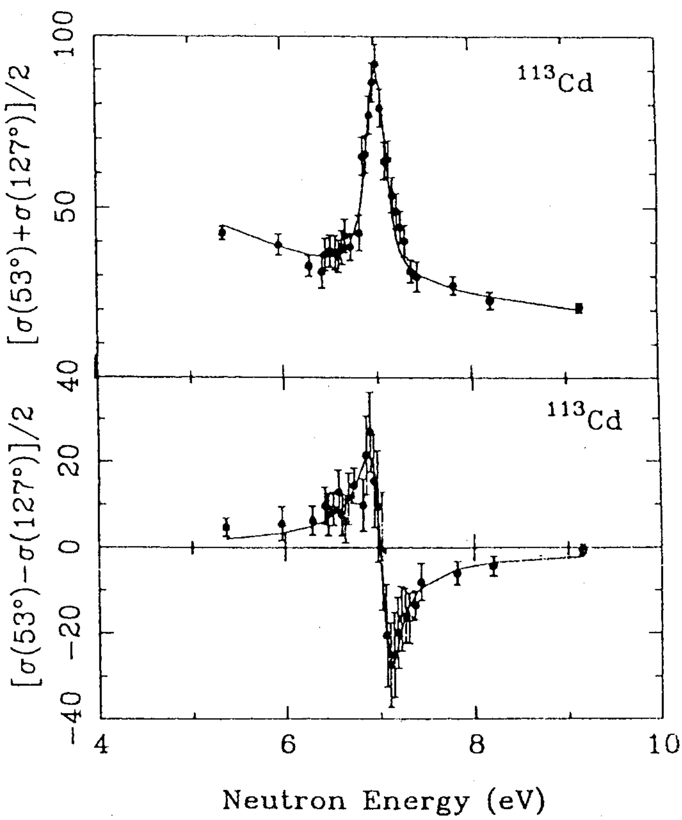


Fig.13. Experimental results for ($\sigma(53°) + \sigma(127°))/2$ (upper part) and ($\sigma(53°) - \sigma(127°))/2$ (down part) in JINR capture experiment. The error bars represent the statistical uncertainty. The solid lines are the results of the analysis

The weighted value of the energy shift from the measurements is $\Delta E_p =$ $= -\ 0.0016 \pm 0.0062$ eV, 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 $\Delta E_p$ 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 bound was obtained as $v^T/D \simeq 0.08$. The use of the dynamical enhancement factor in the relation $v^T/D$ ' $10^3 \cdot \alpha$ sets an upper bound of $\sim 10^{-4}$ on $\alpha$.

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 the candidates for a future studies. The second experiment of this type was performed by the same technique for the *p*-wave resonance 1.35 eV in $^{117}$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 are reviewed. The pure *T*-violation test using spin-aligned target and polarized beam of MeV neutrons has been carried out and the result put the most precise upper limit on the strength of *T*-violating interaction relative to *T*-conserving interaction. The «on resonance» neutron capture measurements with *p*-wave neutrons demonstrated feasibility of the forward-backward asymmetry method as well as the urgent need for the spectroscopic experiments related to the open problem of the spin-channel mixing in neutron amplitudes.

In the search for *P*- and *T*-violating effect in neutron-nucleus interaction, there has been substantial progress in techniques of necessary devices. All necessary devices already exist although some of them must still be developed. Bearing in mind that several resonances are needed for obtaining statistically useful constraint on the strength of *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 neutron spin direction in a polarized target is one of the most crucial requirement to exceed the upper limit set by the measurement of 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 effect the experimental accuracy of the order of $10^{-5}$. An intense beams can also be used to determine nuclear spectroscopic factors which are necessary to extract *T*-violation in a *p*-wave resonances.

REFERENCES

1. **Christenson J.H., Cronin J.W., Fitch V.L., Turlay R.** — Phys. Rev. Let., 1964, vol.13, p.138.
2. **Hayakawa M., Sanda A.I.** — Phys. Rev., 1993, vol.D48, p.1150.
3. **Henley E.M.** — Ann. Rev. Nucl. Sci., 1969, vol.19, p.367.

4. **Blin-Stoyle R.J.** — Fundamental Interactions and the Nucleus, North-Holland, Amsterdam, 1973.
5. **Wolfenstein L.** — Ann. Rev. Nucl. Part. Sci., 1986, vol.36, p.137.
6. **Boehm F.** — Hyperfine Interactions, 1988, vol.43, p.95.
7. **Gudkov V.P.** — Phys. Rep., 1992, vol.212, p.77.
8. **Bunakov V.E.** — Fiz. Elem. Chastits At. Yadra, 1995, vol.26, p.285.
9. **Blanke E., Driller H., Glocke W., Gens H., Richter A., Schreider G.** — Phys. Rev. Lett., 1983, vol.51, p.355.
10. **Conzett H.E.** — In: Polarization Phenomena in Nuclear Physics, A.I.P. Conf. Proc. No.69, 1981, p.1422.
11. **Rikovska J.** — In: Tests of Time-Reversal Invariance in Neutron Physics, ed. N.R. Roberson, C.R. Gould, J.D. Bowman, Word Scientific, Singapore, 1987, p.152.
12. **Erozolimskii B.G., Mostovoi Yu.A., Fedunin V.P. et al.** — Sov. J. Nucl. Phys., 1978, vol.28, p.48.
13. **Hallin A.L., Calaprice F.P., MacArthur D.W., Piilinen L.E., Schneider M.B., Schreiber D.F.** — Phys. Rev. Let., 1984, vol.52, p.337.
14. **Smith K.F. et al.** — Phys. Lett., 1990, vol.B234, p.191.
15. **Altarev I.S. et al.** — Phys. Lett., 1992, vol.B276, p.242.
16. **Sandars P.G.H.** — Physica Scripta, 1993, vol.T46, p.16.
17. **French J.B., Kota V.K.B., Pandey A., Tomsovic S.** — Ann. Phys., 1988, vol.181, p.235;
**French J.B. et al.** — In: Tests of *T*-Reversal Invariance in Neutron Physics, ed.N.Roberson, C.Gould, J.D.Bowman, World Scientific, Singapore, 1987, p.80.
18. **Haxton W.C., Horing A., Musolf M.J.** — Phys. Rev., 1994, vol.D49, p.3422.
19. **Herczeg P.** — Hyperfine Interactions, 1988, vol.43, p.77; In: Tests of Time-Reversal Invariance in Neutron Physics, ed. N.R. Roberson, C.R. Gould, J.D. Bowman, Word Scientific, Singapore, 1987, p.24.
20. **Alfimenkov V.P.** — Usp. Fiz. Nauk, 1984, vol.144, p.361.
21. **Bowman J.D., Garvey G.T., Johnson M.B., Mitchell G.E.** — Ann. Rev. Nucl. Part. Sci., 1993, vol.43, p.829.
22. **Okun L.** — Yad. Fiz., 1965, vol.1, p.938.
23. **Wolfenstein L.** — Phys. Rev. Lett., 1964, vol.13, p.180.
24. **Masaike A.** — JSPS-INS Spring School at Shimoda, 1993, Kyoto University Report KUNS-1253. In: The First Internatinal Symposium on Symmetries in Subatomic Physics, Taipei, 1993, and Kyoto University Report KUNS-1310.
25. **Adelberger E.G., Haxton W.C.** — Ann. Rev. Nucl. Part. Sci., 1985, vol.35, p.501.
26. **Lobov G.A.** — Time-Reversal Invariance and Parity Violation in Neutron Reactions, ed. C.Gould, J.D.Bowman, Yu.P.Popov, World Scientific, Singapore, 1994, p.118.
27. **Flambaum V.V.** — Phys. Rev., 1992, vol.C45, p.437.
28. **Stodolsky L.** — Nucl. Phys., 1982, vol.B197, p.213.
29. **Kabir P.K.** — Phys. Rev., 1982, vol.D25, p.2013.
30. **Stodolsky L.** — Phys. Lett., 1986, vol.B172, p.5.
31. **Frankle C.M., Seestrom S.J., Popov Yu.P. et al.** — Fiz. Elem. Chastits At. Yadra, 1993, vol.24, p.939 [Phys. Part. Nucl., 1993 , vol.24, p.401].
32. **Alfimenkov V.P., Pikelner L.B., Sharapov E.I.** — Fiz. Elem. Chastits At. Yadra, 1980, vol.26, p.285.

33. **Bunakov V.E., Gudkov V.P.** — JETP Letters, 1982, vol.36, p.328; Z.Phys. A, 1982, vol.308, p.363.
34. **Simonius M.** — Phys. Lett., 1975, vol.B58, p.147.
35. **Haxton W.C., Horing A.** — Nucl. Phys., 1993, vol.A560, p.469.
36. **Flambaum V.V., Gribakin G.F.** — Progress in Particle and Nuclear Physics, 1995, vol.35, p.423.
37. **Moldauer P.** — Phys.Rev., 1968, vol.165, p.1136.
38. **Bunakov V.E.** — Phys. Rev. Lett., 1989, vol.60, p.2250. vol.42, p.1718.
39. **Gudkov V.P.** — Nucl. Phys., 1991, vol.A524, p.668.
40. **Davis E.D.** — Z. Phys., 1991, vol.A340, p.159.
41. **Bunakov V.E., Davis E.D., Weidenmüller** — Phys. Rev., 1990, vol.C42, p.1718.
42. **Bowman J.D., Lowie L.Y., Mitchell G.E., Sharapov E.I., Yi-Fen Yen** — Phys. Rev., 1996, vol.53, No.1.
43. **Michel F.C.** — Phys. Rev., 1964, vol.133B, p.329.
44. **Conzett H.E.** — Rep. Prog. Phys., 1994, vol.53C, p.285.
45. **Lamoreaux S.K., Golub R.** — Phys. Rev., 1994, vol.D50, p.5632.
46. **Kabir P.K.** — Phys. Rev., 1988, vol.D37, p.1856.
47. **Feshbach H., Hussein M.S., Kerman A.K.** — Z. Phys., 1995, vol.A351, p.133.
48. **Bunakov V.E., Gudkov V.P.** — Nucl. Phys., 1983, vol.A401, p.93.
49. **Barabanov A.L.** — Yad. Fiz., 1986, vol.44, p.1163.
50. **Gould C.R., Haase D.G., Roberson N.R. et al.** — International Journal of Modern Physics, 1990, vol.A5, p.2181.
51. **Vanhoy J.R., Bilpuch E.G., Shriner J.F.Jr., Mitchell G.E.** — Z. Phys., 1988, vol.A331, p.1; Z. Phys., 1989, vol.A333, p.229.
52. **Conzett H.E.** — Phys. Rev., 1995, vol.C52, p.1041.
53. **Arash F., Moravcsik M.J., Goldstein G.R.** — Phys. Rev. Lett., 1985, vol.54, p.2649.
54. **Bunakov V.E., Gudkov V.P.** — J. Phys. (Paris), 1984, vol.C45, Colloque C3, Suppl. No3, p.C3-77.
55. **Baryshevsky V.T., Podgoretsky M.I.** — JETP, 1964, vol.47, p.1050.
56. **Abragam A. et al.** — C. R. Acad. Sc. (Paris), 1966, vol.274, p.423.
57. **Masuda Y.** — Time-Reversal Invariance and Parity Violation in Neutron Reactions, ed. C.Gould, J.D.Bowman, Yu.P.Popov, World Scientific, Singapore, 1994, p.126.
58. **Masuda Y.** — KEK Preprint 93-185, 1994 Tsukuba.
59. **Serebrov A.P.** — Pis'ma Zh. Eksp. Theor. Fiz., 1993, vol.58, p.15.
60. **Bowman J.D.** — In: Tests of Time-Reversal Invariance in Neutron Physics, ed. N.R. Roberson, C.R. Gould, J.D. Bowman, Word Scientific, Singapore, 1987, p.121.
61. **Skoy V.R.** — Phys. Rev. D, 1996, vol.53, p.4070.
62. **Baryshevsky V.G.** — Sov. J. Nucl. Phys., 1983, vol.38, p.699.
63. **Kabir P.K.** — In: The Investigation of Fundamental Interactions with Cold Neutrons, ed. G.L.Greene, NBS Special Publication No.711, Washington DC, 1986, p.81.
64. **Gould C.R., Haase D.G., Soderstrum J.P., Seagondollar L.W.** — In: Tests of Time-Reversal Invariance in Neutron Physics, ed. N.R. Roberson, C.R. Gould, J.D. Bowman, Word Scientific, Singapore, 1987, p.130.
65. **Barabanov A.L.** — In: Weak and Electromagnetic Interactions in Nuclei, JINR Report No.E1,3,6, 15-92-241, Dubna, 1992, p.23.
66. **Lane A.M., Thomas R.G.** — Rev. Mod. Phys., 1958, vol.30, p.257.

67. **Barabanov A.L., Sharapov E.I., Skoy V.** — Rev. Lett., 1993, vol.70, p.1216.
68. **Flambaum V.V., Sushkov O.P.** — Nucl. Phys., 1985, vol.A435, p.352.
69. **Lushchikov V.I. et al.** — Sov. J. Nucl. Phys., 1970, vol.28, p.669.
70. **Masuda Y., Ishimoto S., Ishida M. et al.** — Nuclear Instruments and Methods in Physics Research, 1988, vol.A264, p.169.
71. **Delheij P.P.J., Bowman J.D., Frankle C.M. et al.** — Nuclear Instruments and Methods in Physics Research, 1995, vol.A356, p.120.
72. **Brash E.J., Delheij P.P.J. et al.** — Phys. Rev., 1995, vol.C52, p.807.
73. **Coulter K.P., McDonald A.B., Happer W. et al.** —Nuclear Instruments and Methods in Physics Research, 1988, vol.A270, p.90.
74. **Masuda Y., Asahi K., Kura J. et al.** — Hyperfine Interactions, 1992, vol.74, p.149.
75. **Sato H., Masuda Y., Sakai K. et al.** — KEK Preprint 92-125, 1992 Tsukuba.
76. **Sato H. et al.** — KENS REPORT-X, 1995, p.196.
77. **Daigo M. et al.** — AIP Conference Proceedings, 1994, No.343, p.567.
78. **Iinuma M. et al.** — Phys. Lett., 1955, vol.A208, p.251.
79. **Daigo M. et al.** — Proceedings of 6th Workshop on High Energy Spin Physics, Protvino, Russia, Sep.18-23, 1995 (in press).
80. **Abragam A. et al.** — J. de Phys. Lett., 1975, T.36, p.L-263.
81. **Glattli H. et al.** — Z. Phys., 1987, vol.A327, p.149.
82. **Mäsuda Y. et al.** — 18th INS Int. Symp. on Physics with High Intensity Hadron Accelerators, Tokyo, March 14–16, 1990.
83. **Takahashi Y., Shimizu H.M., Yabuzaki T.** — Nuclear Instruments and Methods in Physics Research, 1988, vol.A336, p.583.
84. **Shimizu H.M., Maekawa, Takahashi Y., Yabuzaki T.** — Time-Reversal Invariance and Parity Violation in Neutron Reactions, ed. C.Gould, J.D.Bowman, Yu.P.Popov, World Scientific, Singapore, 1994, p.135.
85. **Maekawa T. et al.** — Nucl. Instr. and Methods Phys. Res., 1995, vol.A366, p.115.
86. **Yen Y.-F. et al.** — Time-Reversal Invariance and Parity Violation in Neutron Reactions, ed. C.Gould, J.D.Bowman, Yu.P.Popov, World Scientific, Singapore, 1994, p.210.
87. **K.Sakai et al.** — AIP Conference Proceedings 1994, vol.338, p.290.
88. **Adachi T. et al.** — Nucl. Phys., 1994, vol.A577, p.433c.
89. **Alfimenkov V.P. et al.** — JINR Preprint E3-95-244, Dubna, 1995.
90. **Takahashi Y., Shimizu H.M., Maekawa T., Yabuzaki T.** — Phys. Lett., 1994, vol.B326, p.27.
91. **Petrov G.A., Valsky G.V., Petukhov A.K. et al.** — Nucl. Phys., 1989, vol.A502, p.297.
92. **Serebrov A.P., Petukhov A.K., Valskii G.V., Petrov G.A., Pleva Yu.S.** — Pis'ma Zh. Eksp. Theor. Fiz., 1995, vol.62, p.529.
93. **Yen Y.-F. et al.** — In: Proc. of the 8th Intern. Symp. on Polarization Phenomena in Nuclear Physics, Bloomington, USA, Sep.15–22, 1994.
94. **Cummings W.J. et al.** — In: Proc. of the 8th Intern. Symp. on Polarization Phenomena in Nuclear Physics, Bloomington, USA, Sep.15–22, 1994.
95. **Koster J.E. et al.** — Phys. Lett., 1991, vol.B267, p.23.
96. **Haase D.G., Gould C.R., Mitchell G.R., Roberson N.R.** — Hyperfine Interactions, 1988, vol.43, p.127.

97. **Gould C.R., Haase D.G., Keith C.D. et al.** — In: Intersections between Nuclear and Particle Physics, AIP Conference Proceedings, New York, 1995, vol.338, p.270; **Huffman P.R.** — Ph.D.Thesis. Duke University, 1995.
98. **Koster J.E., Gould C.R., Haase D.G., Roberson N.R.** — Phys. Rev., 1994, vol.C49, p.710.
99. **Engel J., Gould C.R., Hnizdo V.** — Phys. Rev. Lett., 1994, vol.73, p.3508.
100. **Hnizdo V., Gould C.R.** — Phys. Rev., 1994, vol.C49, p.R612.
101. **Frankle C.M., Sharapov E.I., Popov Yu.P. et al.** — Phys. Rev., 1994, vol.50C, p.2774.
102. **Sharapov E.I., Skoy V.R.** — Time-Reversal Invariance and Parity Violation in Neutron Reactions, ed. C.Gould, J.D.Bowman, Yu.P.Popov, World Scientific, Singapore, 1994, p.183.