New Possibilities for Investigation of TRI Violation with the use of Aligned Nuclei

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Abstract

The methods of investigation of Time Reversal Invariance (TRI) violation using polarized neutron beam and polarized or aligned nuclear target are briefly considered. The new method of dynamic nuclear alignment (DNA) of quadrupolar nuclei is proposed. An implementation of this method can significantly increase the number of aligned nuclei accessible for TRI violation experiments and for the other physical investigations.

1 Introduction

Polarized neutron beams are the excellent tool for investigation of fundamental symmetries violation, namely, parity (P) violation and time reversal invariance (TRI) violation. At the moment a great body of data is obtained on P violation in the interaction of polarized neutrons with unpolarized nuclei. On the other hand, a number of possible tests of TRI violation in similar experiments with polarized and aligned targets are discussed.

The method to search for P- and T-odd nuclear interaction by investigation of three-fold correlation ($n_s[n_k \times n_I]$) in transmission of polarized neutrons through polarized target was proposed in [1, 2]. Here $n_s$, $n_I$ and $n_k$ are unit vectors along neutron and nuclear polarization axes and neutron momentum, respectively. The possibility to search for P-even T-odd nuclear interaction by studying of five-fold correlation ($n_s[n_k \times n_I](n_k n_I)$) was first considered in [3]-[5]. This method needs an aligned target (note, that here $n_I$ is a unit vector along an alignment axis).

A difficulty of nuclear alignment presents a major obstacle for five-fold correlation experiment. Up to now the number of nuclei which were aligned is very limited. We propose the new method of dynamic nuclear alignment (DNA) which can be used to increase significantly the number of nuclei accessible for appropriate physical experiments.

2 TRI tests

Both three- and five-fold correlation experiments are unique null tests of TRI. The usually used methods as comparison of the cross sections of direct and inverse reactions or of the polarization and analyzing power in scattering experiments (see, e.g., [3]) are based on measurements of two values, which should coincide if TRI holds. Clearly, a measurement of a single value, which is nonzero only if TRI breaks, is much more reliable. Three- and five-fold correlations arise in the forward scattering amplitude $f_0$.

Thus, they appear in the total cross section, which is linear on $f_0$ as a result of the optical theorem

$$\sigma_{tot} = \frac{4\pi}{k} \text{Im} \text{Sp}(\rho f(0)). \tag{1}$$

Here $k$ is the relative wave vector of colliding particles, and $\rho$ is their spin density matrix.

Generally, the forward scattering amplitude may be represented in terms of S-matrix elements. Let us consider an elastic scattering of two particles with spins $s$ and $I$. The sum of the channel spin $F$ ($F = s + I$) and the relative orbital momentum $l$ in an entrance channel gives the total angular momentum $J$ ($J = F + l$). In an exit channel the channel spin $F'$ and the relative orbital momentum $l'$
can differ from $F$ and $l$, respectively, provided the rules of angular momenta summation $J = F' + l'$ and $F' = s + I$ are satisfied. Thus, such transition is described by the S-matrix element $S_{j}(lF \rightarrow l'F')$. If TRI holds, the S-matrix should be symmetric: $S_{j}(lF \rightarrow l'F') = S_{j}(l'F' \rightarrow lF)$. It can be shown that the terms in the total cross section related with the correlations $(n_{s}(n_{k} \times n_{l}))$ and $(n_{s}(n_{k} \times n_{l})(n_{k}n_{l})$ are proportional to differences

$$S_{j}(lF \rightarrow l'F') - S_{j}(l'F' \rightarrow lF).$$

Clearly, such terms are nonzero only if TRI breaks. When a light particle is scattered by a heavy particle, in particular, in neutron-nucleus interaction, it is more convenient to use the total angular momentum of the light particle $j$ ($j = s + l, J = j + 1$) instead of the channel spin $F$.

The first five-fold correlation test of TRI was made in [8] in the interaction of 2 MeV polarized neutrons with aligned nuclei $^{165}$Ho. A bound of $10^{-3}$ on the ratio of T-odd forces to T-even ones in the effective nucleon-nucleon interaction was obtained. A similar test in the interaction of polarized protons with aligned deuterons is now under preparation at the cooler synchrotron COSY at Julich [9, 10].

Both three- and five-fold correlations were proposed to be studied in the interaction of resonance p-wave neutrons with heavy nuclei. Such tests of TRI have the advantage that the effects may be enhanced in a p-wave resonance by the factor of $10^{3}$ [11, 12]. The reason is the smallness of a resonance width and, hence, an increase of the time of T-odd forces action. Note, that the description of the effect for slow neutrons is quite simple because of only three partial waves participate in the scattering. Namely, $lj = s 1/2$, $p1/2$ and $p3/2$, where $l$ is a neutron orbital momentum, and $j$ is its total angular momentum. Thus all scattering effects for resonance neutrons are determined by nine S-matrix elements $S_{j}(lj \rightarrow l'j')$. Let us consider a total cross section of polarized neutron interaction with nuclei, which may be both polarized and aligned.

To describe nuclear orientation we choose an axis $z$ along the unit vector $n_{l}$. Let $m$ be a projection of the nuclear spin $I$ on the $z$ axis, and $n_{m}$ is a population of the $m$-substate ($\sum_{n} n_{m} = 1$). Thus, we define nuclear polarization and alignment as

$$p_{1}(I) = \frac{\langle m \rangle}{I}, \quad p_{2}(I) = \frac{3(m^{2}) - I(I + 1)}{I(2I - 1)},$$

where $\langle m \rangle = \sum m^{2}n_{m}$. In the case of pure alignment $n_{m} = n_{-m}$, thus $p_{1}(I) = 0$. Both parameters $p_{1}(I)$ and $p_{2}(I)$ equal unity when only the substate with the maximal projection $m = I$ is populated ($n_{m} = \delta_{mI}$). By the same way the neutron polarization is defined by $p_{1}(s) = \langle \sigma \rangle / s$, where $\sigma$ is a projection of the neutron spin $s = 1/2$ on the $z$ axis along the unit vector $n_{s}$.

The total cross section of the interaction of slow neutrons with nuclei is of the form

$$\sigma_{tot} = \sigma_{0} + a_{1}p_{1}(s)p_{1}(I)(n_{s}n_{l}) + a_{2}p_{1}(s)p_{1}(I)(3(n_{s}n_{k})(n_{s}n_{k}) - (n_{s}n_{l})) +$$

$$+ a_{3}p_{2}(I)(3(n_{s}n_{k})^{2} - 1) +$$

$$+ b_{1}p_{1}(s)(n_{s}n_{k}) + b_{2}p_{1}(I)(n_{s}n_{l}) + b_{3}p_{1}(s)p_{2}(I)(3(n_{s}n_{l})(n_{s}n_{l}) - (n_{s}n_{k})) +$$

$$+ c_{1}p_{1}(s)p_{1}(I)(n_{s}[n_{k} \times n_{l}]) + c_{2}p_{1}(s)p_{2}(I)(n_{s}[n_{k} \times n_{l}])((n_{k}n_{l})).$$

Here $\sigma_{0}$ is the total cross section for unoriented neutrons and nuclei. It can be presented in terms of S-matrix elements, as well as the quantities $a_{i}, b_{i}$ and $c_{i}$ (see [3, 4]). The terms related with $b_{i}$ are P-odd, while for T-odd terms we have

$$c_{1} = \frac{2\pi}{k^{2}} \sum_{j} C_{1}^{j}\text{Im} \left( S_{j}(0 \frac{1}{2} \rightarrow 1 j) - S_{j}(1 j \rightarrow 0 \frac{1}{2}) \right),$$

$$c_{2} = \frac{2\pi}{k^{2}} C_{2}^{j}\text{Im} \left( S_{j}(1 \frac{1}{2} \rightarrow 1 \frac{3}{2}) - S_{j}(1 \frac{3}{2} \rightarrow 1 \frac{1}{2}) \right),$$

where $C_{1}^{j}$ and $C_{2}^{j}$ are numerical coefficients of the unit scale. The three-fold correlation arises from the asymmetry of scattering from $s 1/2$-wave to $p1/2$- and $p3/2$-waves and vice versa. It is P-odd as the transitions between $s$- and $p$-waves are parity violating. The five-fold correlation tests the equality of the transition rates from $p1/2$-wave to $p3/2$-one and vice versa, thus it is P-even. Clearly, both correlation should be studied in p-wave resonances to maximize p-wave contribution to the scattering. There exist
additional possibilities to test TRI using neutron spin rotation in transmission through polarized and aligned targets (see, e.g., [4, 13]).

Experimental setup for development of research technique for investigation of TRI violation by studying three-fold and five-fold correlations are being constructed now at neutron beam of pulsed reactor IBR-30 (JINR). The setup will include well known neutron polarizer [13], neutron analyzer (constructed in ITEP [15]), system fo precise control and adjustment of neutron spin and oriented nuclear targe. The description of setup will be publised elsewhere.

3 Dynamic nuclear alignment (DNA) method

Let us consider a nucleus with a spin $I \geq 1$ and quadrupolar moment $Q$ which is acted upon by an axial symmetric electric field gradient (EFG) directed along an axis $z$. An interaction of $Q$ with EFG results in a set of $(2I+1)/2$ sublevels (we assume for simplicity that $I$ takes half-integer values). Each of them is a degenerated doublet of substates with projections $\pm m$ of spin $I$ on the axis $z$. The energy splitting of sublevels is determined by a parameter which is proportional both to nuclear quadrupolar moment $Q$ and EFG value. In the case under consideration the energy differences between sublevels are equal to $a, 2a, 3a \ldots$ (from sublevel with $m = \pm 1/2$). One can observes the signals of nuclear quadrupolar resonance (NQR) at frequencies determined by the energy splitting. Their intensities depend on substate populations $n_m$ and define the value of nuclear alignment.

If the spins are in equilibrium at the temperature $T_0$, the distribution $n_m$ over substates is given by the Boltzman law. For the case of $I = 3/2$ the quadrupolar spectrum falls into two sublevels with $m = \pm 1/2$ and $\pm 3/2$ separated by the energy $a$. Then, $n_2/n_1 = \exp(-a/kT_0)$, and for $a/h \sim 100 \text{ MHz}$ (for a typical value of $a$ for heavy nuclei) and $T_0 = 0.5 \text{ K}$ the equilibrium value of an alignment is $p_2(I) = 4.9 \times 10^{-3}$.

To obtain a higher nuclear alignment the method of dynamic nuclear alignment (DNA) is proposed.

DNA method is similar to dynamic nuclear polarization (DNP) method. However, in the case of DNA there is no need in an external magnetic field. The idea is following. Ground states of paramagnetic ions with electron spin $S \geq 1$ are being split in an electric field of crystal in the same way as the states of quadrupolar nuclei. This splitting results from the interaction of quadrupolar (and higher order) moment of an electron shell of paramagnetic ion with EFG. The energy differences between sublevels $\Delta_0$ is a frequency of electron paramagnetic resonance - EPR in zero magnetic field may be of several orders of magnitude more than those for nuclear quadrupolar splitting, and $\Delta_0$ may be of order of tens GHz. Taking, for example, $S = 3/2$, $\Delta_0 = 50 \text{ GHz}$ and $T = 0.3 \text{ K}$, we obtain completely aligned electron spins $p_2(S) = 1$. One should emphasize that in this case there is no necessity in an external magnetic field, and the direction of quantization axis $z$ coincides with the main axis of the crystal electric field. The dynamic nuclear alignment method is based on the transmission of high alignment of electron spins of paramagnetic admixture to the nuclei of the basic crystal lattice.

As in the case of DNP it may be realized by saturating irradiation of a target by microwaves on a frequency $\Delta_0 + \delta$ near the resonance frequency of paramagnetic ions. The decreasing of spin temperature due to the shift $\delta$ from the precise resonance frequency (which corresponds to the center of EPR line in zero magnetic field) leads to the decreasing of spin temperature $T_d$ of the electron dipole-dipole subsystem

$$
\frac{T_0}{T_d} \approx \frac{\Delta_0}{2\omega_L}. \tag{7}
$$

Here $\omega_L$ is a parameter of electron spin-spin interaction which is of order of EPR linewidth at zero magnetic field (typical values of $\omega_L$ are 100-300 MHz). As a consequence of electron-nucleus dipole interaction this temperature is transmitted to the spin subsystem of quadrupole nuclei. Thus, an enhancement of nuclear alignment $p_2(I)$ arises by a factor of $T_0/T_d \sim 10^2 - 10^3$ both in the cases of low energy ($\delta < 0$) and high energy ($\delta > 0$) sublevels. The change of sign in $\delta$ can lead to change sign in $p_2$. The values 0.4-0.8 for nuclear alignment parameter $p_2(I)$ can be obtained. Besides, a further nuclear alignment can be provided by "solid effect" which can be used when EPR linewidth of paramagnetic admixture is less than NQR linewidth. In this case it is possible to obtain a full transmission of electron alignment to nuclei.

Theory of dynamic cooling and solid-effect is described in [16, 17]. The decreasing of spin temperature at zero magnetic field by the factor of $10^2$ was observed in [18] with the use of Cr$^{3+}$ ions in rutile crystal (TiO$_2$) at 1.7 K and microwave frequency $\Delta_0 = 43 \text{ GHz}$. The method of dynamic cooling was realized. This work did not involve nuclear alignment. However, according our estimation an alignment
of quadrupolar nuclei included in a crystal at 0.3 K would be 0.5. The value of nuclear alignment can be further increased by lowering of the temperature and increasing of the pumping frequency.

A requirement on precise crystal orientation relative to the fixed direction in the case of DNA is less strict than in the case of DNP. Some misalignment would result in the lowering of an alignment. However, it would not influence EPR linewidth which is constant in the absence of magnetic field. So a misalignment of the order of 20° is acceptable. This allows to produce a sample with a large volume using a set of small crystals.

The main problem in realization of DNA method is a choosing of the appropriate sample which has to fulfill the following criteria:

1) high content of nuclei of interest,
2) high quadrupolar energy splitting of nuclear sublevels (NQR frequency should be more than 30 MHz),
3) high energy splitting of sublevel of paramagnetic admixture (EPR frequency at zero magnetic field should be more than 30 GHz),
4) the absence of the disoriented and nonequivalent sites of quadrupole nuclei and paramagnetic ions in crystal.

The last requirement is significant for achievement of an acceptable degree of orientation along a separated axis.

4 Summary

From above consideration it is clear that any nuclei with spin \( I \geq 1 \) having low lying p-wave resonances are good candidates for TRI tests with aligned nuclei. Note, that about two tens nuclei with low energy p-wave resonances were involved in P violation experiments. However, only eight of them have quadrupolar moment. From our point of view the more appropriate nuclei among them are \(^{35}\)Cl, \(^{81}\)Br and \(^{139}\)La.

It should be pointed out that aligned target is of interest not only for TRI violation experiment. An alignment of deformed nuclei allows to study the deformation effects in nuclear reactions. Up to now, such effects were investigated only in the cross section of the elastic scattering of neutrons by the aligned nuclei \(^{59}\)Co [19] and \(^{165}\)Ho [20]. Angular correlations of secondary radiation provide also the worth information on spin dependent reaction amplitudes. For example, the energy and spin dependence of fission amplitudes was recently obtained in the measurements of fission fragment angular distributions in the fission of aligned nuclei \(^{235}\)U by resonance neutrons [21].

In conclusion we shall exemplify some materials containing quadrupolar nuclei and doped with paramagnetic admixtures which have large splitting of levels in EFG of crystal (the NQR frequencies for this materials were not measured): \(^{45}\)Sc, \(^{71}\)Ga, \(^{177}\)Hf. This list is preliminary and can be significantly extended.

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