Test of Time Reversal Invariance in Polarized Proton-Deuteron Scattering

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Abstract

A novel test of time-reversal invariance in proton-deuteron scattering is planned as an internal target transmission experiment at the cooler synchrotron COSY. The P-even, T-odd observable is the polarization correlation $A_{y,xz}$ of the total cross section measured using a polarized internal proton beam (polarization $p_y$) and an internal polarized deuterium target (tensor polarization $p_{xz}$). Measuring this observable is a true null test of time reversal invariance and therefore allows to reach a high accuracy. Sufficient luminosity can be obtained using a window-less storage cell placed on the axis of the proton beam. Tensor polarized atoms are produced in an atomic beam source based on Stern-Gerlach separation in permanent sextupole magnets and adiabatic high frequency transitions. The total cross section correlation is measured by monitoring the beam transmission in the COSY storage ring mode of operation. The proton beam momentum will be in the range 2-3 GeV/c. This momentum is ideally suited to test possible short range contributions, i.e. natural parity charged $\rho$-type and unnatural parity $a_1$-type meson exchange contributions. The feasibility of the experiment, systematic errors and the expected accuracy are discussed.

1 Introduction

The CPT-theorem connects the symmetry operation of time reversal T with the particle-antiparticle and space inversion CP. The existence of CP-violation is well established through neutral kaon decays. Assuming CPT-conservation CP-violation implies also T-violation. In nuclear reactions detailed balance, polarization-analyzing power (P-A) tests and charge symmetry breaking (CSB) tests in neutron-proton scattering have been performed yielding upper limits for T-odd interactions. However because of the requirement to compare a reaction observable to an observable in the inverse reaction the experimental accuracy is limited to a level of $10^{-2} - 10^{-3}$. The accuracy can be increased by several orders of magnitude if a null test is performed, i.e. a single observable is measured which must be zero by time reversal invariance (TRI). As shown by Conzett the correlation $A_{y,xz}$ of the spin 1/2 polarization $p_y$ and the spin 1 tensor polarization $p_{xz}$ in the proton-deuteron total cross section is such an observable. The aim of the present experiment is to measure this spin-dependent total cross section with an accuracy of $10^{-6}$.

In discussing tests of time reversal invariance (TRI) one distinguishes parity violating (P-odd) from parity conserving (P-even) time reversal noninvariant (T-odd) interactions. The most precise constraints
on P-odd/T-odd interactions come from upper limits of the electric dipole moment of the neutron and the atoms ¹²⁹Xe and ¹⁹⁹Hg providing a limit on a P-odd/T-odd pion-nucleon coupling constant which is less than $10^{-4}$ times the weak interaction strength. Constraints on P-odd/T-odd and P-even/T-odd interactions are not independent since weak corrections to P-even/T-odd interactions can generate P-odd/T-odd observables. Therefore the electric dipole measurements provide also upper limits on the P-even/T-odd coupling strengths. In a recent analysis a limit on the P-even/T-odd $\rho NN$ coupling strength, $g_{\rho NN}^T/g_{\rho NN} \leq 1 \cdot 10^{-3}$, was deduced [4].

Direct experimental limits on P-even/T-odd interactions are much less stringent. Detailed balance tests of the reactions $^{24}\text{Mg}(\alpha,p)^{27}\text{Al}$ and its inverse [5] yield an accuracy of $\Delta = 5.1 \cdot 10^{-3}$ (80% CL) and $\alpha_T \leq 2 \cdot 10^{-3}$ [6] where $\alpha_T$ is the ratio of T-odd to T-even nuclear matrix elements. A recent P-even/T-odd TRI test of the forward scattering amplitude using polarized neutrons and nuclear spin aligned Holmium yielded $\alpha_T \leq 7 \cdot 10^{-4}$ [7] corresponding to a bound of the P-even/T-odd $\rho NN$ coupling constant $g_{\rho NN}^T/g_{\rho NN} \leq 6 \cdot 10^{-2}$. Simonius [8] analyzed charge symmetry breaking (CSB) tests in neutron-proton scattering and deduced $g_{\rho NN}^T/g_{\rho NN} \leq 6.7 \cdot 10^{-3}$.

2 Effective T-odd NN Interactions

In order to analyze TRI tests at low and intermediate energies effective meson exchange potentials may be used [9]. For P-odd/T-odd interactions the longest range potential may be parametrized as a $\pi$-exchange potential,

$$V_\pi^{PT} = \phi^{PT}_\pi \frac{g_{\pi NN}^2}{2m_p(q^2 + m_\pi^2)} (\vec{\sigma}_1 - \vec{\sigma}_2) \cdot \vec{q} \left(\vec{r}_1 \times \vec{r}_2\right)$$

with $\vec{q} = (\vec{p}_f - \vec{p}_i)$ and $\phi^{PT}_\pi$ the P-odd/T-odd coupling strength.

As shown by Simonius [9] P-even/T-odd nucleon-nucleon interaction can only occur for $J\neq 0$ single meson exchange. Thus, there is no long-range pion exchange possible. For natural parity $\pi = (-1)^J$ exchanges ($J^P=1^-, 2^+, ...$) the meson must be charged (e.g. $\rho^\pm$ exchange) and can only contribute to the np interaction in singlet-triplet transitions $^1P_1 \leftrightarrow ^3P_2$, $^1D_2 \leftrightarrow ^3D_2$, etc. T-violation is due to the isospin operator $|\vec{r}_1 \times \vec{r}_2|_3 = i(\vec{r}_1 \times \vec{r}_2)$. For unnatural parity $\pi = (-1)^{J-1}$ exchanges ($J^P=1^+, 2^-, ...$) like the $a_1(J^P=1^+)$ exchange there is no charge restriction. They may contribute to the np as well as the nn and pp interaction. T-violation must be in the spin-space operator. For nn and pp the lowest partial wave transition is $^3P_2 \leftrightarrow ^3F_2$. The P-even/T-odd potentials may be written

$$V_\rho^T = i\phi^T_\rho \frac{g_{\rho NN}^2}{8m^2_p(q^2 + m_\rho^2)} (\vec{\sigma}_1 - \vec{\sigma}_2) \cdot \vec{q} \times \vec{p} \left(\vec{r}_1 \times \vec{r}_2\right)_3$$

$$V_{a_1}^T = i\phi^T_{a_1} \frac{g_{\rho NN}^2}{8m^2_p(q^2 + m_{a_1}^2)} (\vec{\sigma}_1 \cdot \vec{p}) \vec{\sigma}_2 \cdot \vec{q} + \vec{\sigma}_2 \cdot \vec{p} \vec{\sigma}_1 \cdot \vec{q} - \vec{\sigma}_1 \cdot \vec{\sigma}_2 \vec{q} \cdot \vec{p}).$$

with $\vec{p} = (\vec{p}_f + \vec{p}_i)/2$ and $\phi^T_\rho$ and $\phi^T_{a_1}$ the P-even/T-odd coupling strengths.

The proton-deuteron system was analyzed by Beyer [8] in terms of effective P-even/T-odd nucleon-nucleon interactions. He showed that measuring $\sigma_{tot}$ with an experimental accuracy of $1 \cdot 10^{-6}$ yields tight bounds on the P-even/T-odd $\rho NN$ and $a_1 NN$ coupling constants, $\phi^T_\rho = g_{\rho NN}^T/g_{\rho NN} \leq 1 \cdot 10^{-4}$ and $\phi^T_{a_1} = g_{a_1 NN}^T/g_{a_1 NN} \leq 2 \cdot 10^{-3}$.
Figure 1: Pictorial demonstration of T-odd polarization correlation in pd forward scattering. System b is time-reversed to a. For a direct comparison system b is rotated through 180° about the x- and y-axis yielding system c and d, respectively. The arrows denote cm momenta of the incoming particles p and d. The symbols $\bigcirc$ and $\bigotimes$ denote positive and negative spin polarization $p_y$ of the proton, the symbol $\leftrightarrow$ tensor polarization $p_{xz}$ of the deuteron.

3 P-even/T-odd Observable

The total cross section $\sigma_{tot}$ involving polarized particles is described by the generalized optical theorem\cite{10}

$$\sigma_{tot} = \frac{4\pi}{k} \text{Im} \frac{\text{Tr} F(0) \text{Tr} \rho}{\text{Tr} \rho}.$$  \hspace{1cm} (4)

Here, $\rho$ is the polarization density matrix of the initial state, $k$ the cm-wave number and $F(0)$ the matrix of the spin-dependent forward scattering amplitudes.

For a P-even/T-odd experiment one may then choose polarized protons (polarization $p_y$) and tensor polarized deuterons (tensor polarization $p_{xz}$) (see fig.1), and the total cross section has a P-even/T-odd term

$$\sigma_{tot} = \sigma_{tot}^0 (1 + A_{y,xz} p_y p_{xz}).$$  \hspace{1cm} (5)

Here, $\sigma_{tot}^0$ is the total cross section for unpolarized beam and unpolarized target and $A_{y,xz}$ is the P-even/T-odd polarization correlation. The number $N$ of stored beam particles decreases exponentially with time $t$,

$$N(t) = N_0 \exp\left[-\left(\sigma_{tot} + \sigma_{loss}\right) f t\right] = N_0 \exp\left[-\lambda t\right].$$  \hspace{1cm} (6)

Here, $\rho$ is the arial density of the target, $\sigma_{loss}$ the loss cross-section taking beam losses outside the target into account, $f$ the revolution frequency of the circulating beam, $t$ the time and $\lambda$ is the corresponding decay rate of the beam. The decay rate depends on the signs of $p_y$ and $p_{xz}$. By measuring in a sequence
the decay rates $\lambda^{++}$, $\lambda^{+-}$ and $\lambda^{-+}$ (see fig. 2, the superscripts refer to the signs of $p_y$ and $p_{xz}$, respectively) and assuming $|p^+_y| = |p^-_y|$ and $|p^+_x| = |p^-_x|$ one finally obtains

$$A_{y,xz} = \frac{\sqrt{\lambda^{++} \lambda^{--}} - \sqrt{\lambda^{+-} \lambda^{-+}}}{\sqrt{\lambda^{++} \lambda^{--}} + \sqrt{\lambda^{+-} \lambda^{-+}}} \frac{1}{|p_y p_{xz}|} \left(1 + \frac{\sigma_{\text{loss}}}{\sigma_{\text{tot}}} \right).$$

(7)

4 Experiment

The experiment is planned to be performed as an internal target experiment in the cooler synchrotron COSY [11]. Thus, a pure but in contrast to solid targets low density polarized atomic beam target can be used. The low target density is compensated by the principle of recycling the beam with a frequency of about $1.5 \times 10^6$ s$^{-1}$. The experimental scheme is shown in fig. 3. Basically the experiment needs equipment that is already provided for the EDDA-experiment [12] at COSY, i.e. the measurement of $\vec{p}\vec{p}$ elastic scattering excitation functions. Tensor polarized deuterium atoms are produced in an atomic beam source based on Stern-Gerlach separation in permanent sextupole magnets and adiabatic Abragam-Winter RF-transitions. In order to increase the luminosity the tensor polarized deuterium atoms are stored in a windowless storage cell placed on the axis of the proton beam. The tensor polarization is monitored by a spin filter located in the beam dump of the polarized atomic beam target.

The quantization (3) axis of the polarized atomic beam source is an axis of cylindrical symmetry and the vector and tensor components are $p_3$ and $p_{33}$. For the measurements a pure $p_{33} = +1$ polarization state is prepared. For a holding field along the direction $x = \pm z$ the resulting tensor components are: $p_{xz} = \pm 3/4$, $p_{xx} = +1/4$, $p_{yy} = -1/2$ and $p_{zz} = +1/4$. Thus, while flipping $p_{xz}$ the components $p_{xx}$, $p_{yy}$ and $p_{zz}$ stay constant.
The statistical accuracy of the measurements depends on the luminosity. With a target areal density of about $5 \times 10^{13}$ cm$^{-2}$, $10^{11}$ polarized protons in the ring and a revolution frequency of $1.5 \times 10^6$ s$^{-1}$ the luminosity will be $7.5 \times 10^{30}$ cm$^{-2}$s$^{-1}$. Thus, a statistical accuracy of about $10^{-6}$ can be reached in a 10 day run.

The signs of the beam and target polarizations $p_y$ and $p_{xz}$ are chosen on a random basis. A standard sequence of the experiment will be: (i) The polarized proton beam is injected into the COSY ring and accelerated to the appropriate energy. (ii) The decay rate of the beam is measured in the storage mode of operation by counting the number of protons as a function of time. (iii) The tensor polarization of the target is flipped by an appropriate change of the holding field. (iv) The decay rate of the beam is now measured with a flipped tensor polarization. (v) The beam is decelerated and dumped. Step (iii) and (iv) may be repeated several times. The time period for a single decay rate measurement depends on the statistical accuracy. It will be in the order of 100 s. So, in a 10 day run about $10^4$ single measurements can be performed.

5 Systematic errors

Beam losses in the ring are harmless as long as they are smaller than the losses due to the target, i.e. $\sigma_{\text{loss}} \leq \sigma_{\text{tot}}^0$. They can be easily measured and corrected (see eq. 7). The holding field of the polarized deuterium target causes a small distortion of the closed orbit. Fortunately a correlation error can be
avoided since the transverse component of the holding field is not changed while flipping the tensor polarization. Correlations between the phase space distribution of the stored beam and the sign of the beam polarization are expected to be very small. They are cancelled by flipping the tensor polarization of the target.

The most severe source of systematic errors are competing polarization correlations. Fortunately many polarization correlations, especially $A_{y,xx}$, $A_{y,yy}$ and $A_{y,zz}$, vanish in forward scattering, since they are odd with respect to a rotation about the $z$-axis. In addition the invariant spin axis of the COSY ring is in the $y$-direction and the proton polarization vector $(0, p_y, 0)$ is an eigenvector of the ring. Therefore, effects due to the polarization components $p_x$ and $p_z$ are negligible. Several correlations like for instance $A_{y,x}$ violate parity conservation and are therefore expected to be negligible (order $10^{-7}$). The most dangerous polarization correlation is $A_{y,y}$ yielding a correlation between beam and target vector polarization. Therefore, a pure tensor polarized deuterium target with negligible vector polarization is prepared. In addition a precise alignment of the target holding field with respect to the $y$-axis is of great importance. Summarizing, it can be shown that all systematic errors can be kept below the $10^{-6}$ level.

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