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"Optical" spin rotation phenomenon and spin-filtering of antiproton (proton, deuteron) beams in a nuclear pseudomagnetic field of a polarized nuclear target: the possibility of measuring the real and imaginary spin-depended part of the coherent zero-angle scattering amplitude

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Despite long-lasting study and seeming simplicity, the investigation of two- and three-particle interactions is still a topical problem. Because these investigations are very important, the experiments with antiproton, proton and deuteron interactions are included in scientific programs of modern accelerators COSY, GSI and LHC. In studding of these interactions, polarization observables sensible to different mechanisms of interaction are of particular interest as well as the differential reaction cross-section. Modern storage rings with a long lifetime of a beam permit one to carry out qualitatively new experiments with polarized beams and targets. Particularly, in the spin-filtering experiments [1] of antiprotons (protons, deuterons), it is possible to measure a spin-dependent part of a forward scattering amplitude [1]-[3]. Moreover, it is possible to measure the real part of a coherent elastic amplitude of proton (antiproton, deuteron) scattering at zero angle when the plane formed by the target polarization vector and the beam momentum direction lies in the orbit pane of the beam and the angle between these two vectors differs from 0, π or $\pi/2$ [2]. Measurement of the spin-dependent part of a forward scattering amplitude is possible by measuring the lifetime of the unpolarized beam passing through a polarized internal target [2]. Direct measurement of the tensor part of the deuteron-proton interaction can be performed by measuring the lifetime of the unpolarized proton beam passing through a tensor polarized deuterium target [3]. The influence of high-frequency (g-2) spin precession in a ring is one of the problems that we encounter in spin rotation measurements in a storage ring. In this regard, attention should be drawn to the EDM experiments based on freezing the horizontal spin motion, i.e., forcing the particles' spin to always point along the direction of motion thus cancelling the (g-2) precession [1]. Applying this method and polarized targets,one can observe the "optical" spin rotation phenomenon in a nuclear pseudomagnetic field of a polarized nuclear target which is beneficial for the investigation of spin-depended interactions in the above experiments.

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1. "Optical" spin precession of relativistic particles in polarized targets

Let us remember the consideration of the effects of "optical" spin rotation arising when high-energy particles pass through matter with polarized nuclei [4]-[6]. To be more specific, we shall consider refraction of relativistic protons (antiprotons) in matter. To begin with, let us analyze scattering by a particular center. The asymptotic expression for a wave function describing scattering of relativistic particles in the field of a fixed scatterer far from it can be represented in the form [7]

$$\Psi = U_{E,\vec{k}} e^{ikz} + U'_{E'\vec{k}'} \frac{e^{ik'r}}{r}, \tag{1.1}$$

where $U_{E\vec{k}}$ is the bispinor amplitude of the incident plane wave; $U'_{E'\vec{k}'}$ is the bispinor describing the amplitude of the scattered wave; E and $\vec{k}(E',\vec{k}')$ are the energy and the wave vector of the incident (scattered) wave.

The bispinor amplitude is fully determined by specifying a two-component quantity — a three-dimensional spinor W, which is a non-relativistic wave function in the particle rest frame. For this reason, the scattering amplitude, i.e., the amplitude of a divergent spherical wave, in (1.1), similarly to the non-relativistic case, can be defined as a two-dimensional matrix of $\hat{f}$ by the relation $W' = \hat{f} W$, where W' is the spinor determining the bispinor $U'_{E'\vec{k}'}$. Thus determined scattering operator is quite similar to the operator scattering amplitude in the non-relativistic scattering theory allowing for spin.

As a result, deriving the expression for the index of refraction by analogy with a non-relativistic case (see [6], we obtain the following expressions for the wave function of a relativistic neutron (proton) in a medium

$$\Psi = \frac{1}{\sqrt{2E}} \begin{pmatrix} \sqrt{E+m} e^{ik\hat{n}z} & W \\ \sqrt{E-m}(\vec{\sigma}\vec{n}) e^{ik\hat{n}z} & W \end{pmatrix}, \tag{1.2}$$

where

$$\hat{n} = 1 + \frac{2\pi\rho}{k^2} \hat{f}(0) \tag{1.3}$$

is the operator refractive index, $\hat{f}(0)$ is the operator amplitude of coherent elastic zero-angle scattering by a polarized scatterer; $\vec{\sigma}$ is the vector made up of the Pauli matrices; $n = \vec{k}/\vec{k}$. Using $\vec{\sigma}$, $\vec{J}$, $\vec{n}$ ($\vec{J}$ is the nuclear spin operator), we may write the amplitude of coherent elastic forward scattering by a polarized nucleus in the general case of strong, electromagnetic, and PT violating weak interactions [4, 5].

According to (1.2), the spinor W' defining the spin state of a particle in the rest frame after passing the path length z in the target has the form

$$W' = e^{ik\hat{n}z} W. \tag{1.4}$$

Note that (see [4]-[6]), $\hat{n}$ can be written as

$$\hat{n} = n_0 + \frac{2\pi\rho}{k^2} (\vec{\sigma}\vec{g}), \tag{1.5}$$

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where n_0 is the $\vec{\sigma}$-independent part of n,

$$n_0 = 1 + \frac{2\pi\rho}{k^2}(A + A_3\vec{n}\vec{n}_1 + B_4\vec{n}\langle\vec{J}\rangle + \ldots). \tag{1.6}$$

$$\vec{g} = A_1\langle\vec{J}\rangle + A_2\vec{n}(\vec{n}\langle\vec{J}\rangle) + B\vec{n} + B_1[\langle\vec{J}\rangle\vec{n}] + \ldots, \tag{1.7}$$

where $\langle\vec{J}\rangle = Sp\,\hat{\rho}_J\vec{J}$, $\hat{\rho}_J$ is the spin density matrix of the target. Assume that $\langle\vec{J}\rangle = J\vec{p}$, where $\vec{p}$ is the target polarization vector, $\vec{n}_1$ has the components $n_i = \langle Q_{ik}\rangle n_k$, $\langle Q_{ik}\rangle$ is the quadrupolarization tensor of the target. Let the target thicknesses be such that the spin-dependent contributions to the wave-function phase are small, i.e., inequalities $k\mathtt{Re}gz \ll 1$ and $k\mathtt{Im}gz \ll 1$ (see (1.7)) are fulfilled. In this case we have

$$W' = e^{ik\hat{n}z}W \simeq e^{ikn_0z}(1 + i\frac{2\pi\rho}{k}(\vec{\sigma}\vec{g})z)W \tag{1.8}$$

From (1.8) follows the expression for the number of particles N transmitted through the target in the same direction as the direction of the momentum of the particles N_0 incident on the target without being scattered.

$$N = N_0 e^{-\rho\sigma z}[1 - \frac{4\pi\rho}{k}\vec{P}_0\mathtt{Im}\vec{g}z], \tag{1.9}$$

where σ is the spin-independent part of the total scattering cross-section determined by the imaginary part of n_0 in (1.6)

$$\sigma = \frac{4\pi}{k}\mathtt{Im}(A + A_3\vec{n}\vec{n}_1 + \ldots), \tag{1.10}$$

$\vec{P}_0$ is the particle polarization vector before entering the target, $\vec{g}$ is defined by (1.7). According to (1.9), the number of particles N transmitted through the target depends on the orientation of $\vec{P}_0$: $N_{\uparrow\uparrow} \neq N_{\downarrow\uparrow}$, where $N_{\uparrow\uparrow}$ describes N for $\vec{P}_0 \uparrow\uparrow \mathtt{Im}\vec{g}$, $N_{\downarrow\uparrow}$ denotes N for $\vec{P}_0 \downarrow\uparrow \mathtt{Im}\vec{g}$. So, spin dichroism occurs because the absorption coefficient of incident particles in the target depends on the orientation of their spin. Using (1.8) for the spinor wave function W', one can obtain the following expression for the polarization vector $\vec{P}$ of the particles transmitted through a polarized target:

$$\vec{P} = \frac{\langle W'|\vec{\sigma}|W\rangle}{\langle W'|W\rangle} = \vec{P}_0 + \frac{4\pi\rho z}{k}\mathtt{Im}((\vec{P}_0\vec{g})\vec{P}_0 - \vec{g})z + \frac{4\pi\rho z}{k}[\vec{P}_0 \times \mathtt{Re}\vec{g}]. \tag{1.11}$$

In view of (1.11), the polarization vector of high-energy particles undergoes rotation about the direction of $\mathtt{Re}\vec{g}$. In a similar manner as in the case of low energies, the contributions associated with strong and P-, T-odd weak interactions can be distinguished by measuring the magnitudes of N and $\vec{P}$ for different orientations of the polarization vector $\vec{P}_0$ of the particles incident on the target.

2. Proton (Antiproton) Spin Rotation in a Thick Polarized Target

With the increase in the target thickness, the influence of the spin-dependent part of particle absorption in matter is enhanced. In order to obtain equations describing the evolution of intensity and polarization of a beam in the target, we shall split vector $\vec{g}$ into real and imaginary parts:

$$\vec{g} = \vec{g}_1 + i\vec{g}_2, \tag{2.1}$$

where $\vec{g}_1 = \mathtt{Re}\vec{g}$; $\vec{g}_2 = \mathtt{Im}\vec{g}$.

Using (1.4), (1.5), one may obtain the following system of equations defining the relation between the number of particles $N(z)$ transmitted through the target and their polarization $\vec{P}(z)$ [6]:

$$\frac{d\vec{P}(z)}{dz} = \frac{4\pi\rho}{k}[\vec{g}_1 \times \vec{P}(z)] - \frac{4\pi\rho}{k}\left\{\vec{g}_2 - \vec{P}(z)[\vec{g}_2\vec{P}(z)]\right\}. \tag{2.2}$$

$$\frac{dN(z)}{dz} = -2\mathtt{Im}(n_0)kN(z) - \frac{4\pi\rho}{k}[\vec{g}_2\vec{P}(z)]N(z). \tag{2.3}$$

Equation (2.2) and (2.3) should be solved together under the initial conditions $\vec{P}(0) = \vec{P}_0$, $N(0) = N_0$. According to (2.2), the polarization of the incident particles passing through the polarized nuclear target undergoes rotation through the angle

$$\theta = \frac{4\pi\rho}{k}g_1 z. \tag{2.4}$$

Assume that the target polarization $\vec{P}_t = \frac{\langle\vec{J}\rangle}{J}$ is parallel (this is the case of longitudinal polarization) or orthogonal (transversal polarization) to the momentum $\vec{k}$ of the incident particle. Then $\vec{g}_1 \parallel \vec{g}_2 \parallel \vec{P}_t$, and (2.2), (2.3) are reduced to a simple form. Consider two specific cases for which the initial polarization of the incident beam is (a) $\vec{P}_0 \parallel \vec{P}_t$ or (b) $\vec{P}_0 \perp \vec{P}_t$.

Case (a) is a standard transmission experiment wherein we observe the process of absorption in the polarized target without a change in the direction of the initial beam polarization. The absorption is different for particles polarized parallel and antiparallel to the target polarization. The number of particles N changes according to

$$N(z) = N_0 \exp(-\sigma_\pm \rho z), \tag{2.5}$$

where

$$\sigma_\pm = \frac{4\pi}{k}\left[\mathtt{Im}(A + A_3\vec{n}\vec{n}_1) \pm \mathtt{Im}A_1JP_t \pm \mathtt{Im}A_2JP_t\right]. \tag{2.6}$$

In case (b), the coherent scattering by the polarized nuclei results in spin rotation of the incident particles about the target polarization $\vec{P}_t$. According to (2.4), the spin rotation angle

$$\vartheta = \frac{4\pi\rho z}{k}\mathtt{Re}g = \frac{4\pi\rho z}{k}\left[\mathtt{Re}A_1JP_t + \mathtt{Re}A_2J(\vec{n}\vec{P}_t)\right] \tag{2.7}$$

is directly connected with the real part of the forward scattering amplitudes.

The values of $\mathtt{Re}A_1$ and $\mathtt{Re}A_2$ can be determined separately by measuring spin rotation angles for two cases when the target spin is parallel and antiparallel to the beam direction $\vec{n}$. This means that by measuring the final intensity and polarization of the beam in cases (a) and (b) we can directly reconstruct the spin-dependent forward scattering amplitude.

Case (c): let us assume now that the target polarization is directed at some angle (which does not equal $\pi/2$) with respect to the incident particle momentum and that the incident beam polarization is perpendicular to the plane formed by the vectors $\vec{P}_t$ and $\vec{n}$ (see figure 1). In this case, the effect of proton (antiproton)spin rotation about the vector $\vec{g}_1$ combined with absorption dichroism, determined by the vector $\vec{g}_2$, will cause the dependence of the total number of particles transmitted through the target on $\mathtt{Re}A_1$ and $\mathtt{Re}A_2$ [6]:

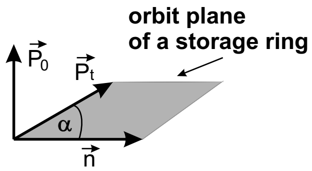

Figure 1: Directions of the vectors for the case (c).

$$N(z) \sim (\mathrm{Re}A_1 \cdot \mathrm{Im}A_2 - \mathrm{Re}A_2 \cdot \mathrm{Im}A_1)\left[\vec{P}_t \times \vec{n}(\vec{n}\vec{P}_t)\right]\vec{P}_0 \tag{2.8}$$

Such behavior of $N(z)$ enables measuring spin-dependent contributions to the amplitude $f(0)$ in the transmission experiment without measuring the polarization of the beam transmitted through the target [6]. This implies that if a vertically polarized beam rotates in the storage ring (the beam's spin is orthogonal to the orbit plane), then the decrease in the beam intensity (the beam lifetime in the storage ring) in the case when vectors $\vec{P}_t$ and $\vec{n}$ lie in the horizontal plane (in the orbit plane) enables determining $\mathrm{Re}A_1$ and $\mathrm{Re}A_2$.

Note that the contribution under study reverses sign when vector $\vec{P}_t$ rotates about $\vec{n}$ through π (or $\vec{P}_0$ changes direction: $\vec{P}_0 \to -\vec{P}_0$). Measuring the difference between the beam's damping times for these two orientations of $\vec{P}_0$ ($\vec{P}_t$), one can find the contribution of $\mathrm{Re}A_1$ and $\mathrm{Re}A_2$ to the real part of the amplitude $f(0)$. Unlike a spin rotation experiment, this transmission experiment does not allow us to determine $\mathrm{Re}A_1$ and $\mathrm{Re}A_2$ separately.

There is also an inverse process [1]: if a unpolarized beam of particles is incident on the target, then after passing through the target, the beam acquires polarization orthogonal to the plane formed by $\vec{P}_t$ and $\vec{n}$. This phenomenon is most interesting in the case of a storage ring. If $\vec{P}_t$ and $\vec{n}$ lie in the orbit plane of a circulating beam (i.e., the horizontal plane), then in the course of time, the beam acquires vertical polarization orthogonal to the orbit plane. By measuring the arising vertical polarization, it is also possible to determine the spin-dependent part of the coherent elastic zero-angle scattering amplitude. In particular, in spin-filtering experiments on obtaining polarized beams of antiprotons (protons), it is sufficient to perform the experiment under the conditions when the polarization vector $\vec{P}_t$ of a gas target is directed at a certain angle, which is not equal to 0, π or $\pi/2$, with respect to the particle momentum direction $\vec{n}$. If $\mathrm{Re}A_{1,2} \sim \mathrm{Im}A_{1,2}$, the degree of arising polarization is comparable to the anticipated degree of polarization of the anti(proton) beam arising in the PAX method and enables one to measure the contribution proportional to $\mathrm{Re}A_{1,2}$.

Worthy of mention is that in the case under consideration, the beam lifetime depends on the orientation of $\vec{P}_t$ in the $\vec{P}_t,\vec{n}$-plane. In this case the measurement of the beam lifetime also gives information about $\mathrm{Re}A_{1,2}$.

3. Measuring the imaginary part of the spin-dependent amplitude of zero-angle coherent elastic scattering of the deuteron in a transmission experiment

According to (1.9), (1.10) the deuteron spin dichroism arise when an unpolarized deuteron beam passes through an unpolarized target. There are several types of transmission experiments that can be carried out to perform deuteron spin dichroism measurements.

The first type is a transmission experiment of an extracted beam from an accelerator where the unpolarized deuterons pass through an unpolarized target. In such experiments, the deuteron spin dichroism brings about tensor polarization of the transmitted deuteron beam [2]. The experiments [8, 9] were carried out this way. The main advantage of this method is its technical simplicity, because only an unpolarized deuteron beam, an unpolarized solid target, and a polarimeter are required. Since the magnitude of the effect is proportional to the target thickness, with growing thickness the energy losses in the target increases. These losses limit the target thickness, especially at low beam energies, and are the reason why the measured spin-dependent amplitudes have to be averaged over the deuteron energy in the target.

Another method uses multiple transmissions of an unpolarized deuteron beam through an internal unpolarized gas target in a storage ring [10]. In this case, the effect is accumulated, and is limited only by the lifetime of the stored beam. However, birefringence effects in electric and magnetic fields of the storage ring are possible in this method [11].

The third method is a spin-filtering experiment. Since the total cross-sections σ_0 and $\sigma_{\pm 1}$ are invariant, it does not matter whether the deuteron is used as a target or as a beam probe. The method consist in making an unpolarized beam (for example of protons) pass, for a sufficiently long time in a storage ring through a tensor polarized target of deuterons in state $m = \pm 1$. After time t, the intensity $I_{\pm 1}(t)$ of the stored beam is measured; the initial intensity $I_{\pm 1}(0)$ of the beam is known as well. The measurement is repeated with new unpolarized beam and a tensor polarized target with deuterons in state $m = 0$, and the values of $I_0(0)$ and $I_0(t)$ are determined. For all measurements, the time of storing is the same. Because $\sigma_0 \neq \sigma_{\pm 1}$, the final beam intensity in this measurement should differ from the average beam intensity in the previous measurements (see figures 2 and 3). As a result, we obtain two independent ratios for the beam intensity,

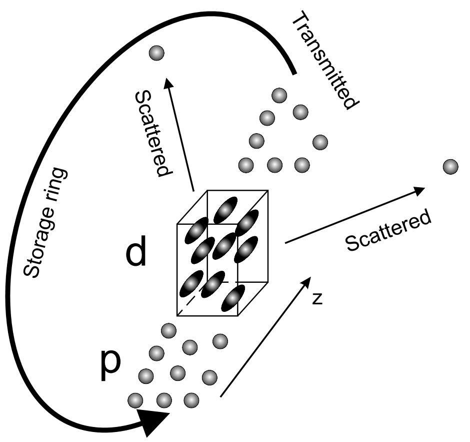

Figure 2: Transmission of an unpolarized proton beam in a storage ring through an internal tensor polarized target with deuterons in states $m = -1$ and $m = 1$.

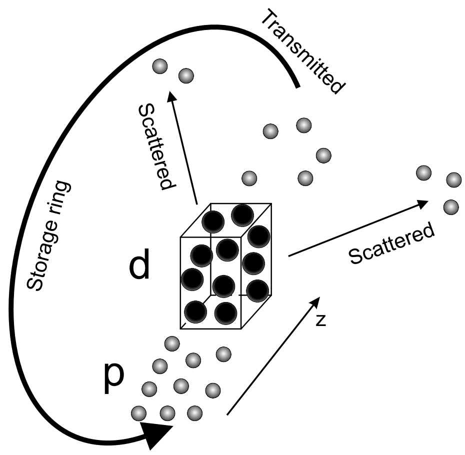

Figure 3: Transmission of an unpolarized proton beam in a storage ring through an internal tensor polarized target with deuterons in state $m = 0$.

$$\frac{I_{\pm 1}(t)}{I_{\pm 1}(0)} = e^{-\sigma_{\pm 1}\rho_{\pm 1} v t}, \quad \frac{I_0(t)}{I_0(0)} = e^{-\sigma_0 \rho_0 v t}, \tag{3.1}$$

where $\rho_{\pm 1}$ and ρ_0 are the density of the targets (number of scatterers per cm^3), and v is the revolution frequency. Let us now introduce new variables,

$$R_{\pm 1}(t) = \ln\left(\frac{I_{\pm 1}(t)}{I_{\pm 1}(0)}\right), \quad R_0(t) = \ln\left(\frac{I_0(t)}{I_0(0)}\right). \tag{3.2}$$

Then we can obtain the following relations,

$$\sigma_{\pm 1} - \sigma_0 = \frac{R_0(t)}{\rho_0 \nu t} - \frac{R_{\pm 1}(t)}{\rho_{\pm 1} \nu t}, \quad \Im d_1 = \frac{k}{2\pi}(\sigma_{\pm 1} - \sigma_0). \tag{3.3}$$

This shows that the spin-dependent part of the total cross-section can be determined by measuring the rate of the intensity decrease of an unpolarized proton beam in a storage ring while the beam passing through polarized. For the estimation of the storage time, in equation (3.1) we use the following parameters: $\rho \sim 10^{15}$ deuterons/cm^2, $\nu \sim$1.6 MHz, $\sigma_{\pm 1} - \sigma_0 \sim$4.3 mb [12], and $\sigma_{\pm 1} \sim$70 mb [12].

In order to obtain a 10% difference in the proton beam intensity due to the spin-dependent part of the total cross-section (see equation (3.1)), a storage time should be about 4 hours. During this time period, the beam intensity decreases by about a factor of four.

4. Conclusion

It was shown that in current spin-filtering experiments to produce polarized antiprotons (protons, deuterons), it is possible to measure a real part of the coherent elastic amplitude of proton (antiproton, deuteron) scattering at zero angle when the plane formed by the target polarization vector $\vec{P}_t$ and the beam momentum direction $\vec{n}$ lies in the orbit pane of the beam and the angle between $\vec{P}_t$ and $\vec{n}$ differs from 0, π, or $\pi/2$. Anticipated degree of polarization in this geometry can be compared to that of antiprotons (protons) (anticipated change in the beam lifetime with the change in the orientation of $\vec{P}_t$ in the ($\vec{P}_t, \vec{n}$) plane), which is observed with the spin-filtering method [13].

Several types of experiments for the investigation of deuteron spin dichroism (imaginary part of the spin dependent amplitude) were considered briefly. One of them is measurement of dichroism in a spin-filtering experiment by changing the tensor polarization of the deuterium target [2], [3]. According to our estimate, this type of experiment can be carried out at COSY and at GSI.

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