Spin rotation and birefringence effect for a particle in a high energy storage ring and measurement of the real part of the coherent elastic zero-angle scattering amplitude, electric and magnetic polarizabilities

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20th June 2012

Abstract

In the present paper the equations for the spin evolution of a particle in a storage ring are analyzed considering contributions from the tensor electric and magnetic polarizabilities of the particle. Study of spin rotation and birefringence effect for a particle in a high energy storage ring provides for measurement as the real part of the coherent elastic zero-angle scattering amplitude as well as tensor electric and magnetic polarizabilities.

We proposed the method for measurement the real part of the elastic coherent zero-angle scattering amplitude of particles and nuclei in a storage ring by the paramagnetic resonance in the periodical in time nuclear pseudoelectric and pseudomagnetic fields.

1 INTRODUCTION

Investigation of spin-dependent interactions of elementary particles at high energies is a very important part of program of scientific research has been preparing for carry out at storage rings (RHIC, CERN, COSY, GSI). It is well known in experimental particle physics how to measure a total spin-dependent cross-section of proton-proton (pp) and proton-deuteron (pd) or proton-nucleus (pN) and deuteron-nucleus (dN) interactions.

Through analicity we can get dispersion relations between the real and imaginary parts of the forward scattering amplitude. These relations are very valuable for analyzing interactions, especially if we know both real and imaginary parts of the forward scattering amplitude in a broad energy range through independent experimental measurements.

There are several experimental possibilities for the indirect measurement of the real part of the forward scattering amplitude [1].

Since no scattering experiment is possible in the forward direction, the determination of the real part of the forward amplitudes has always consisted in the measurement of well chosen elastic scattering observables at small angles and then in the extrapolation of these observables towards zero angle [1]. All of these methods, however, contain discrete ambiguities in the reconstruction of the forward scattering matrix, which can be removed only by new independent measurements. Consequently,what is needed is a direct reconstruction of the real part of the forward scattering matrix such we have in the case of the imaginary part through the measurement of a total cross section.

It has been shown in [2]-[8] that there is an unambiguous method which makes the direct measurement of the real part of the spin-dependent forward scattering amplitude in the high energy range possible. This technique is based on the effect proton (deuteron, antiproton) beam spin rotation in a polarized nuclear target and on the phenomenon of deuteron spin rotation and oscillation in a nonpolarized target. This technique uses the measurement of angle of spin rotation of high energy proton (deuteron, antiproton) in conditions of transmission experiment - the so-called spin rotation experiment.

The analogous phenomenon for thermal neutrons was theoretically predicted in [12] and experimentally observed in [9]-[11] (the phenomena of nuclear precession of neutron spin in a nuclear pseudomagnetic field of a target).

Spin rotation and oscillation experiments as well as investigation of spin dichroism (i.e. investigation of dependence of beam absorption on spin orientation) also allow to carry out new experiments to study P- and T-odd interactions [13]. Deuteron spin rotation and oscillation experiments allow to measure the tensor electric polarizability and, as it is shown below, the tensor magnetic polarizability, too. Change of spin state of a particle at passing deep into target can influence the experiments, studying nonelastic processes at collisions of polarized nucleons and nuclei. This impels to investigate possible influence of spin rotation on the cross-section of such processes.

Observation of particle spin rotation and birefringence effect with a storage ring requires to cancel influence of $(g-2)$ precession (g is the gyromagnetic ratio). This precession appears due to interaction of the particle magnetic moment with an external electromagnetic field. The requirement for $(g-2)$ precession influence cancellation also arises when searching for a deuteron electric dipole moment (EDM) by the deuteron spin precession in an electric field in a storage ring [14, 15].

In the present paper it is shown that the influence of particle spin precession in a magnetic field on the process of measurement of spin rotation of a particle passed through a polarized target can be eliminated with the aid of making the vector (tensor) polarization of the target rotating (oscillating) with the frequency coinciding with the frequency of particle spin rotation due to the particle magnetic moment interacting with a magnetic field i.e. providing for the paramagnetic resonance under the action of periodic in time pseudomagnetic (pseudoelectric) field of the target.

2 Interactions contributing to the spin motion of a particle in a storage ring

Considering evolution of the spin of a particle in a storage ring one should take into account several interactions:

1. interactions of the magnetic and electric dipole moments with an electromagnetic field;
2. interaction of the particle with the electric field due to the tensor electric polarizability;
3. interaction of the particle with the magnetic field due to the tensor magnetic polarizability;
4. interaction of the particle with the pseudoelectric and pseudomagnetic nuclear fields of matter.

The equation for the particle spin wavefunction considering all these interactions is as follows:

$$i\hbar\frac{\partial\Psi(t)}{\partial t} = \left(\hat{H}_0 + \hat{V}_{EDM} + \hat{V}_{\vec{E}} + \hat{V}_{\vec{B}} + \hat{V}_E^{nucl} + \hat{V}_B^{nucl}\right)\Psi(t) \qquad (1)$$

where $\Psi(t)$ is the particle spin wavefunction,

$\hat{H}_0$ is the Hamiltonian describing the spin behavior caused by interaction of the magnetic moment with the electromagnetic field (equation (1) with the only $\hat{H}_0$ summand converts to the Bargman-Myshel-Telegdy equation),

$\hat{V}_{EDM}$ describes interaction of the particle EDM with the electric field,

$$\hat{V}_{EDM} \quad = \quad -d\left(\vec{\beta}\times\vec{B}+\vec{E}\right)\vec{S}, \qquad (2)$$

$\hat{V}_{\vec{E}}$ describes interaction of the particle with the electric field due to the tensor electric polarizability:

$$\hat{V}_{\vec{E}} = -\frac{1}{2}\hat{\alpha}_{ik}(E_{eff})_i(E_{eff})_k, \qquad (3)$$

where $\hat{\alpha}_{ik}$ is the electric polarizability tensor of the particle , $\vec{E}_{eff} = (\vec{E} + \vec{\beta} \times \vec{B})$ is the effective electric field; the expression (3) can be rewritten as follows:

$$\hat{V}_{\vec{E}} = \alpha_S E_{eff}^2 - \alpha_T E_{eff}^2 \left(\vec{S}\vec{n}_E\right)^2, \ \vec{n}_E = \frac{\vec{E} + \vec{\beta} \times \vec{B}}{|\vec{E} + \vec{\beta} \times \vec{B}|} \tag{4}$$

where α_S is the scalar electric polarizability and α_T is the tensor electric polarizability of the particle.

A particle with the spin $S \geq 1$ also has the magnetic polarizability which is described by the magnetic polarizability tensor $\hat{\beta}_{ik}$ and interaction of the particle with the magnetic field due to the tensor magnetic polarizability is as follows:

$$\hat{V}_{\vec{B}} = -\frac{1}{2}\hat{\beta}_{ik}(B_{eff})_i(B_{eff})_k, \tag{5}$$

where $(B_{eff})_i$ are the components of the effective magnetic field $\vec{B}_{eff} = (\vec{B} - \vec{\beta} \times \vec{E})$; $\hat{V}_{\vec{B}}$ (5) could be expressed as:

$$\hat{V}_{\vec{B}} = \beta_S B_{eff}^2 - \beta_T B_{eff}^2 \left(\vec{S}\vec{n}_B\right)^2, \ \vec{n}_B = \frac{\vec{B} - \vec{\beta} \times \vec{E}}{|\vec{B} - \vec{\beta} \times \vec{E}|}. \tag{6}$$

where β_S is the scalar magnetic polarizability and β_T is the tensor magnetic polarizability of the particle.

$\hat{V}_B^{nucl}$ describes the effective potential energy of particle magnetic moment interaction the pseudo-magnetic field of the target [2]-[6],[17].

$\hat{V}_E^{nucl}$ describes the effective potential energy of particle electric moment interaction the pseudo-electric field of the target [2]-[6],[17].

It should be emphasized that $\hat{V}_B^{nucl}$ and $\hat{V}_E^{nucl}$ include contributions from strong interactions as well as those caused by weak interaction violating P (space) and T (time) invariance.

3 The equations describing the spin evolution of a particle in a storage ring

Let us consider particles moving in a storage ring with low pressure of residual gas (10^{-10} Torr) and without targets inside the storage ring. In this case we can omit the effects caused by the interactions $\hat{V}_B^{nucl}$ and $\hat{V}_E^{nucl}$.

Let us consider a particle with $S = 1$ (for example, deuteron) moving in a storage ring. According to the above analysis spin behavior of such a particle can not be described by the Bargman-Myshel-Telegdy equation. The equations for particle spin motion including contribution from the tensor electric polarizability were obtained in [17, 16]. Considering that deuteron possesses also the tensor magnetic polarizability and adding the terms caused by it to the equations obtained in [17, 16] finally we get:

$$\begin{cases} \frac{d\vec{P}}{dt} = \frac{e}{mc}\left[\vec{P} \times \left\{\left(a + \frac{1}{\gamma}\right)\vec{B} - a\frac{\gamma}{\gamma+1}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(\frac{g}{2} - \frac{\gamma}{\gamma+1}\right)\vec{\beta} \times \vec{E}\right\}\right] + \\ +\frac{d}{\hbar}\left[\vec{P} \times \left(\vec{E} + \vec{\beta} \times \vec{B}\right)\right] - \frac{2}{3}\frac{\alpha_T E_{eff}^2}{\hbar}[\vec{n}_E \times \vec{n}'_E] - \frac{2}{3}\frac{\beta_T B_{eff}^2}{\hbar}[\vec{n}_B \times \vec{n}'_B], \\ \\ \frac{dP_{ik}}{dt} = -\left(\varepsilon_{jkr}P_{ij}\Omega_r + \varepsilon_{jir}P_{kj}\Omega_r\right) - \\ -\frac{3}{2}\frac{\alpha_T E_{eff}^2}{\hbar}\left([\vec{n}_E \times \vec{P}]_i n_{E,k} + n_{E,i}[\vec{n}_E \times \vec{P}]_k\right) - \\ -\frac{3}{2}\frac{\beta_T B_{eff}^2}{\hbar}\left([\vec{n}_B \times \vec{P}]_i n_{B,k} + n_{B,i}[\vec{n}_B \times \vec{P}]_k\right), \end{cases} \tag{7}$$

where m is the mass of the particle, e is its charge, $\vec{P}$ is the spin polarization vector, $P_{xx}+P_{yy}+P_{zz} = 0$, γ is the Lorentz-factor, $\vec{\beta} = \vec{v}/c$, $\vec{v}$ is the particle velocity, $a = (g-2)/2$, g is the gyromagnetic ratio,

$\vec{E}$ and $\vec{B}$ are the electric and magnetic fields in the point of particle location, $\vec{E}_{eff} = (\vec{E} + \vec{\beta} \times \vec{B})$, $\vec{B}_{eff} = (\vec{B} - \vec{\beta} \times \vec{E})$, $\vec{n} = \vec{k}/k$, $\vec{n}_E = \frac{\vec{E}+\vec{\beta}\times\vec{B}}{|\vec{E}+\vec{\beta}\times\vec{B}|}$, $\vec{n}_B = \frac{\vec{B}-\vec{\beta}\times\vec{E}}{|\vec{B}-\vec{\beta}\times\vec{E}|}$, $n'_i = P_{ik}n_k$, $n'_{E,i} = P_{ik}n_{E,k}$, $n'_{Bi} = P_{il}n_{Bl} = P_{i3}$, $\Omega_r(d)$ are the components of the vector $\vec{\Omega}(d)$ ($r = 1, 2, 3$ correspond to x, y, z, respectively).

$$\vec{\Omega}(d) = \frac{e}{mc}\left\{\left(a + \frac{1}{\gamma}\right)\vec{B} - a\frac{\gamma}{\gamma+1}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(\frac{g}{2} - \frac{\gamma}{\gamma+1}\right)\vec{\beta}\times\vec{E}\right\} + \\ + \frac{d}{\hbar}\left(\vec{E} + \vec{\beta}\times\vec{B}\right). \quad (8)$$

4 Deuteron birefringence effect in electromagnetic field

When omitting contribution from interaction of the particle EDM with the electric field $\hat{V}_{EDM}$ we can rewrite the equations for particle spin motion (7) as follows:

$$\frac{d\vec{P}}{dt} = [\vec{P}\times\vec{\Omega}] + \Omega_T[\vec{n}_E \times \vec{n}'_E] + \Omega_T^{\mu}[\vec{n}_B \times \vec{n}'_B],$$

$$\frac{dP_{ik}}{dt} = -(\epsilon_{jkr}P_{ij}\Omega_r + \epsilon_{jir}P_{kj}\Omega_r) + \Omega'_T([\vec{n}_E \times \vec{P}]_i n_{Ek} + n_{Ei}[\vec{n}_E \times \vec{P}]_k) + \\ + \Omega_T'^{\mu}([\vec{n}_B \times \vec{P}]_i n_{Bk} + n_{Bi}[\vec{n}_B \times \vec{P}]_k) \quad (9)$$

where

$$\vec{\Omega} = \frac{e}{mc}\left[\left(a + \frac{1}{\gamma}\right)\vec{B} - a\frac{\gamma}{\gamma+1}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(\frac{g}{2} - \frac{\gamma}{\gamma+1}\right)\vec{\beta}\times\vec{E}\right],$$

$$\Omega_T = -\frac{2}{3}\frac{\alpha_T E_{eff}^2}{\hbar}, \quad \Omega'_T = -\frac{3}{2}\frac{\alpha_T E_{eff}^2}{\hbar}, \quad \Omega'_T = -\frac{2}{3}\Omega_T,$$

$$\Omega_T^{\mu} = -\frac{2}{3}\frac{\beta_T B_{eff}^2}{\hbar}, \quad \Omega_T'^{\mu} = -\frac{3}{2}\frac{\beta_T B_{eff}^2}{\hbar}, \quad \Omega_T'^{\mu} = -\frac{2}{3}\Omega_T^{\mu}.$$

Thus presence of the electric and magnetic tensor polarizabilities makes impossible to describe the spin evolution of a particle in a by the Bargman-Myshel-Telegdy equation

$$\frac{d\vec{P}}{dt} = [\vec{P}\times\vec{\Omega}] \quad (10)$$

but requires considering of the system (9).

Let us consider the coordinate system and vectors $\vec{v}, \vec{E}, \vec{B}$ as shown in figure and denote the axes by x, y, z (or $1, 2, 3$, respectively).

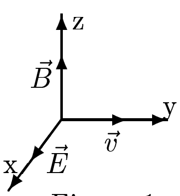

Figure 1:

Suppose that an electric field is absent and the particle initial polarization coincides with $\vec{v}$ direction, therefore, the components of the vectors are:

$$\begin{aligned}
&\vec{P} = (P_1, P_2, P_3)\,, \vec{P}_0 = (0, P, 0)\,,\\
&\vec{n}_E = (1,0,0)\,, n'_{Ei} = P_{il} n_{El} = P_{i1}\\
&[\vec{n}_E \times \vec{n}'_E]_1 = 0,\ [\vec{n}_E \times \vec{n}'_E]_2 = -P_{31},\ [\vec{n}_E \times \vec{n}'_E]_3 = P_2,\\
&[\vec{P} \times \vec{\Omega}]_1 = \Omega P_2,\ [\vec{P} \times \vec{\Omega}]_2 = -\Omega P_1,\ [\vec{P} \times \vec{\Omega}]_3 = P_2,\\
&[\vec{n}_E \times \vec{P}]_1 = 0,\ [\vec{n}_E \times \vec{P}]_2 = -P_3,\ [\vec{n}_E \times \vec{P}]_3 = P_2,
\end{aligned} \tag{11}$$

$$\begin{aligned}
&\vec{\Omega} = \tfrac{e}{mc}\left(a + \tfrac{1}{\gamma}\right)\vec{B} = (0,0,\Omega)\,,\\
&\vec{n}_B = (0,0,1)\,, n'_{Bi} = P_{il} n_{Bl} = P_{i3}\\
&[\vec{n}_B \times \vec{n}'_B]_1 = -P_{23},\ [\vec{n}_B \times \vec{n}'_B]_2 = -P_{13},\ [\vec{n}_B \times \vec{n}'_B]_3 = 0,\\
&[\vec{n}_B \times \vec{P}]_1 = -P_2,\ [\vec{n}_B \times \vec{P}]_2 = P_1,\ [\vec{n}_B \times \vec{P}]_3 = 0.
\end{aligned} \tag{12}$$

Substituting (11,12) to the system (7) we obtain:

$$\begin{aligned}
&\tfrac{dP_1}{dt} = \Omega P_2 - \Omega_T^{\mu} P_{23},\\
&\tfrac{dP_2}{dt} = -\Omega P_1 + (\Omega_T^{\mu} - \Omega_T) P_{13},\\
&\tfrac{dP_3}{dt} = \Omega_T P_{12}
\end{aligned} \tag{13}$$

$$\begin{aligned}
&\tfrac{dP_{11}}{dt} = 2\Omega_3 P_{12},\\
&\tfrac{dP_{22}}{dt} = -2\Omega_3 P_{12},\\
&\tfrac{dP_{33}}{dt} = 0,
\end{aligned} \tag{14}$$

$$\begin{aligned}
&\tfrac{dP_{12}}{dt} = -\Omega\,(P_{11} - P_{22}) - \Omega'_T P_3,\\
&\tfrac{dP_{13}}{dt} = \Omega P_{23} + \Omega'_T P_2 - \Omega_T'^{\mu} P_2,\\
&\tfrac{dP_{23}}{dt} = -\Omega P_{13} + \Omega_T'^{\mu} P_1
\end{aligned} \tag{15}$$

remembering that $P_{11} + P_{22} + P_{33} = 0$ and $P_{ik} = P_{ki}$, then getting $P_{33} = const$ from the last equation in (14)we can conclude that $P_{11} + P_{22} = const$

4.1 Contribution from the tensor electric polarizability to deuteron spin oscillation

From the system (14) it follows

$$\frac{d(P_{11}-P_{22})}{dt} = 4\Omega P_{12},$$
$$\frac{d^2P_{12}}{dt^2} = -\Omega\frac{d(P_{11}-P_{22})}{dt} - \Omega'_T\frac{dP_3}{dt} = -(4\Omega^2 + \Omega_T\Omega'_T)P_{12}. \tag{16}$$

Thus we have the equation

$$\frac{d^2P_{12}}{dt^2} + \omega_{12}^2 P_{12} = 0 \tag{17}$$

where $\omega_{12} = \sqrt{4\Omega^2 + \Omega_T\Omega'_T} \approx 2\Omega$, because $\Omega_T\Omega'_T \ll \Omega^2$.

The solution for this equation can be found in the form:

$$P_{12} = c_1\cos\omega_{12}t + c_2\sin\omega_{12}t \tag{18}$$

Let us find coefficients c_1 and c_2: when $t = 0$ the equation (18) gives $c_1 = P_{12}(0)$. The coefficient c_2 can be found from

$$\frac{d(P_{12})}{dt}(t \to 0) = \omega_{12}c_2, \tag{19}$$

therefore

$$c_2 = \frac{1}{\omega_{12}}\frac{d(P_{12})}{dt}(t \to 0), \tag{20}$$

From the equation (15)

$$\frac{dP_{12}}{dt}(t \to 0) = -\Omega\left(P_{11}(t \to 0) - P_{22}(t \to 0)\right), \tag{21}$$

that

$$c_2 = -\frac{P_{11} - P_{22}}{2}, \tag{22}$$

and

$$P_{12} = P_{12}(0)\cos\omega_{12}t - \frac{P_{11} - P_{22}}{2}\sin\omega_{12}t \tag{23}$$

As a result we can write the following equation for the vertical component of the spin P_3:

$$\frac{dP_3}{dt} = \Omega_T P_{12}(t) = \Omega_T[P_{12}(0)\cos 2\Omega t - \frac{P_{11}(0) - P_{22}(0)}{2}\sin 2\Omega t] \tag{24}$$

As it can be seen the vertical component of the spin oscillates with the frequency 2Ω.

But it should be mentioned that according to the equations (7) interaction of the EDM with an electric field causes oscillations of the vertical component of the spin with the frequency Ω. According to the idea [18] these oscillations can be eliminated if the deuteron velocity is modulated with the frequency Ω:

$$v = v_0 + \delta v\sin(\Omega t + \varphi) \tag{25}$$

As a result E_{eff} depends on $\vec{\beta} = \vec{v}/c$ it also appears modulated:

$$E_{eff} = E^0_{eff} + \delta E_{eff}\sin(\Omega t + \varphi) \tag{26}$$

here φ is a phase. Therefore,

$$\frac{dP_3}{dt} = \Omega_T P_{12} - dE_{eff}P_2 \tag{27}$$

as P_2 also oscillate with Ω frequency, then in the product $E_{eff}P_2$ there non-oscillating terms and P_3 linearly grows with time.

It is important that modulation of the velocity $v = v_0 + \delta v \sin(\Omega t + \varphi)$ results in oscillation of E^2_{eff} also oscillates with time and appears proportional to $\sin^2(\Omega_T + \varphi)$. As a result

$$\frac{dP_3}{dt} \sim \Delta\Omega_T \sin^2(\Omega_T t + \varphi)[P_{12}(0)\cos 2\Omega t - \frac{P_{11}(0) - P_{22}(0)}{2}\sin 2\Omega t] \tag{28}$$

i.e.

$$\frac{dP_3}{dt} \sim -\frac{1}{2}\Delta\Omega_T \cos(2\Omega t + 2\varphi)[P_{12}(0)\cos 2\Omega t - \frac{P_{11}(0) - P_{22}(0)}{2}\sin 2\Omega t] \tag{29}$$

According to (29) if the phase $\varphi = 0$ then the contribution to the linear growth of P_3 is provided by the term $P_{12}(0)$. If $\varphi = \pi/4$ then linear growth is due to the second term proportional to $(P_{11}(0) - P_{22}(0))$.

Measurement of these contribution provides to measure the tensor electric polarizability.

According to the evaluations [19] $\alpha_T \sim 10^{-40}$ cm^3 for the field $E_{eff} = B \sim 10^4$ gauss, therefore the frequency $\Omega_T \sim 10^{-5}$ sec^{-1}. When considering modulation we should estimate $\Delta\Omega_T \sim \Omega_T(\frac{\delta}{v_0})^2$, then suppose $(\frac{\delta}{v_0})^2 \sim 10^{-2} - 10^{-3}$ we obtain $\Delta\Omega_T \sim 10^{-7} - 10^{-8}$ sec^{-1}.

4.2 Contribution from the tensor magnetic polarizability to deuteron spin oscillation

Let us consider now contributions caused by the tensor magnetic polarizability β_T. Let we omit the terms proportional to the tensor electric polarizability in the system (14):

$$\begin{aligned}
\frac{dP_1}{dt} &= \Omega P_2 - \Omega^{\mu}_T P_{23},\\
\frac{dP_2}{dt} &= -\Omega P_1 + \Omega^{\mu}_T P_{13},\\
\frac{dP_{13}}{dt} &= \Omega P_{23} - \Omega'^{\mu}_T P_2,\\
\frac{dP_{23}}{dt} &= -\Omega P_{13} + \Omega'^{\mu}_T P_1
\end{aligned} \tag{30}$$

Introducing new variables $P_+ = P_1 + iP_2$ and $G_+ = P_{13} + iP_{23}$ and recomposing equations (30) to determine P_+ and G_+ we obtain:

$$\begin{aligned}
\frac{dP_+}{dt} &= -i\Omega P_+ + i\Omega^{\mu}_T G_+,\\
\frac{dG_+}{dt} &= -i\Omega G_+ + i\Omega'^{\mu}_T P_+,
\end{aligned}$$

or

$$\begin{aligned}
i\frac{dP_+}{dt} &= \Omega P_+ - \Omega^{\mu}_T G_+,\\
i\frac{dG_+}{dt} &= \Omega G_+ - \Omega'^{\mu}_T P_+,
\end{aligned}$$

Let us search $P_+, G_+ \sim e^{i\omega t}$ then (31) transforms as follows:

$$\begin{aligned}
\omega\tilde{P}_+ &= \Omega\tilde{P}_+ - \Omega^{\mu}_T\tilde{G}_+,\\
\omega\tilde{G}_+ &= \Omega\tilde{G}_+ - \Omega'^{\mu}_T\tilde{P}_+.
\end{aligned}$$

The solution of this system can be easily find:

$$(\omega - \Omega)^2 - \Omega^{\mu}_T\Omega'^{\mu}_T = 0 \tag{31}$$

that finally gives

$$\omega_{1,2} = \Omega \pm \sqrt{\Omega_T^{\mu} \Omega_T^{\prime\mu}} \tag{32}$$

Rewriting the solution

$$P_+(t) = c_1 e^{-i\omega_1 t} + c_2 e^{-i\omega_2 t} = |c_1| e^{-i(\omega_1 t + \delta_1)} + |c_2| e^{-i(\omega_2 t + \delta_2)} \tag{33}$$

Therefore,

$$P_1(t) = |c_1| \cos(\omega_1 t + \delta_1) + |c_2| \cos(\omega_2 t + \delta_2) \tag{34}$$

This means that spin rotates with two frequencies ω_1 and ω_2 instead of Ω and, therefore, experiences beating with the frequency $\Delta\omega = \omega_1 - \omega_2 = 2\sqrt{\Omega_T^{\mu} \Omega_T^{\prime\mu}} = \frac{\beta_T B_{eff}^2}{\hbar}$.

According to the evaluation [19] the tensor magnetic polarizability $\beta_T \sim 2 \cdot 10^{-40}$, therefore for the beating frequency $\Delta\omega \sim 10^{-5}$ in the field $B \sim 10^4$ gauss.

Measurement of the frequency of this beating makes possible to measure the tensor magnetic polarizability of the deuteron (nuclei).

Thus, due to the presence of tensor magnetic polarizability the the horizontal component of spin rotates around $\vec{B}$ with two frequencies $\omega_1,\ \omega_2$ instead of expected rotation with the frequency Ω. The resulting motion of the spin is beating: $P_1(t) \sim \cos \Omega t \sin \Delta\omega t$.

This is the reason for the component P_3 caused by the EDM to experience the similar beating. Therefore, particle velocity modulation with the frequency Ω ($v = v_0 + \delta v \sin(\Omega t + \varphi)$) provides for eliminating oscillation with Ω frequency, but oscillations with the frequency $\Delta\omega$ rest.

5 Spin rotation of proton (deuteron, antiproton) in a storage ring with a polarized target and paramagnetic resonance in the nuclear pseudoelectric and pseudomagnetic fields

Another class of experiments deals with the use of polarized targets. Preparing such experiment one should remember that density of polarized gas target is lower than nonpolarized that and for example for COSY density of polarized target is $j = 10^{14} cm^{-2}$.

In 1964 it was shown [12] that while slow neutrons are propagating through the target with polarized nuclei a new effect of nucleon spin precession occurred. It is stipulated by the fact that in a polarized target the neutrons are characterized by two refraction indices ($N_{\uparrow\uparrow}$ for neutrons with the spin parallel to the target polarization vector and $N_{\uparrow\downarrow}$ for neutrons with the opposite spin orientation , $N_{\uparrow\uparrow} \neq N_{\uparrow\downarrow}$). According to the [2], in the target with polarized nuclei there is a nuclear pseudomagnetic field and the interaction of an incident neutron with this field results in neutron spin rotation. The results obtained in [12], initiated experiments which proved the existence of this effect [9]-[11].

The effective potential energy of a particle in the pseudomagnetic nuclear field $\vec{G}$ of matter can be written as:

$$\hat{V}_B^{nucl} = -\vec{\mu}\vec{G}, \tag{35}$$

where $\vec{\mu}$ is the magnetic moment of the particle and $\vec{G}$ can be expressed as [2]-[6]

$$\vec{G} = \vec{G}_s + \vec{G}_w,$$

$$\vec{G}_s = \frac{2\pi\hbar^2}{\mu m} \rho [A_1 \langle \vec{J} \rangle + A_2 \vec{n} (\vec{n} \langle \vec{J} \rangle) + ...], \tag{36}$$

$$\vec{G}_w = \frac{2\pi\hbar^2}{\mu m} \rho [b\vec{n} + b_1 [\langle \vec{J} \rangle \times \vec{n}] + b_2 \vec{n}_1 + b_3 \vec{n} (\vec{n}\vec{n}_1) + b_5 [\vec{n} \times \vec{n}_1] + ...]$$

where $\vec{n} = \vec{v}/v$, $\vec{J}$ is the spin of nuclei of matter, $\langle\vec{J}\rangle = \mathrm{Sp}\rho_{nucl}\vec{J}$ is the average value of nuclear spin, $\vec{n}_1$ has the components $n_{1j} = \langle Q_{ij}\rangle n_j$, where $\langle Q_{ij}\rangle = \mathrm{Sp}\rho_{nucl}Q_{ij}$ is the polarization tensor

$$Q_{ij} = \frac{1}{2J(2J-1)}\left\{J_iJ_j + J_jJ_i - \frac{2}{3}J(J+1)\delta_{ij}\right\}, \tag{37}$$

It is easy to see that interaction (35) looks like the interaction of a magnetic moment with a magnetic field, thus the field $\vec{G}$ contributes to the change of the particle polarization similar a magnetic field does. It should be especially mentioned that $\hat{V}_B^{nucl}$ contains both the real part, which is responsible for spin rotation, and imaginary part, which contributes to spin dichroism (i.e. beam absorption dependence on spin orientation). The detailed analysis of the effects caused by the nuclear pseudoelectric field was done in [17].

Interaction with the field $\vec{G} = \vec{G}_s + \vec{G}_w$ contains two summands: the first $\vec{G}_s$ corresponds to the strong interaction, which is T,P-even, while the second $\vec{G}_w$ describes spin rotation by the weak interaction, which has both T,P-odd (the term containing the constant b_1) and T-odd, P-even (the term containing the constant b_5) terms.

If either vector or tensor polarization of a target rotates then the effects provided by $\vec{G}_s$, $\vec{G}_w$ periodically depend on time i.e. equation (1) converts to:

$$i\hbar\frac{\partial\Psi(t)}{\partial t} = \left(\hat{H}_0 + \hat{V}_{EDM} + \hat{V}_{\vec{E}} + \hat{V}_{\vec{B}} + \hat{V}_E^{nucl}(t) + \hat{V}_B^{nucl}(t)\right)\Psi(t). \tag{38}$$

This equation coincides with the well-known equation for the paramagnetic resonance. Really, if we have the strong field orthogonal to the weak one (in this case $\vec{B}\perp\vec{G}$) and $\vec{G}$ either rotates or oscillates with the frequency corresponding to the splitting, caused by the field $\vec{B}$, the resonance occurs. In our case this leads to the conversion of horizontal spin component to the vertical one with the frequency determined by the frequency of spin precession in the field $\vec{G}$. Thus we can measure all the constants containing in $\vec{G}_s$ and $\vec{G}_w$: constants A_i give the spin-dependent part of elastic coherent forward scattering amplitude of proton (deuteron, antiproton) that is important for the projects at GSI and COSY; amplitudes b_i provides to measure the constants of T-,P-odd interactions.

First of all we should pay attention to the effects caused by the T-odd nucleon-nucleon interaction of protons (antoprotons) and deuterons with polarized nuclei and, in particular, interaction described by $V_{P,T}\sim\vec{S}\,[\vec{p}_N\times\vec{n}]$, where $\vec{P}_N(t)$ is the polarization vector of target. The interaction $V_{P,T}$ leads to the spin rotation around the axis determined by the unit vector $\vec{n}_T$ parallel to the vector $\left[\vec{P}_N(t)\times\vec{n}\right]$. Spin dichroism also appears with respect to this vector $\vec{n}_T$ i.e. a proton (deuteron) beam with the spin parallel to $\vec{n}_T$ has the absorption cross-section different from the absorption cross-section for a proton (deuteron) beam with the opposite spin direction.

P-even T-odd spin rotation, oscillation and dichroism of deuterons (nuclei with $S\geq 1$) caused by the interaction either $V_T\sim(\vec{S}[\vec{P}_N(t)\times\vec{n}])(\vec{S}\vec{n})$ could be observed [17]; P-even T-odd spin rotation and dichroism for a proton, deuteron (nucleus with the spin $S\geq 1/2$) $V_T'\sim b_5[\vec{n}\times\vec{n}_1(t)]$ could be observed [20] in paramagnetic resonance conditions, too.

6 Conclusion

In the present paper the equations for the spin evolution of a particle in a storage ring are analyzed considering contributions from the tensor electric and magnetic polarizabilities of the particle. Study of spin rotation and birefringence effect for a particle in a high energy storage ring provides for measurement as the real part of the coherent elastic zero-angle scattering amplitude as well as tensor electric and magnetic polarizabilities.

We proposed the method for measurement the real part of the elastic coherent zero-angle scattering amplitude of particles and nuclei in a storage ring by the paramagnetic resonance in the periodical in time nuclear pseudoelectric and pseudomagnetic fields.

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