

**Growth of Interaction Between Antiprotons
(Negative Hyperons) and a Nuclear
Pseudomagnetic Field Under Deceleration in
Matter with Polarized Nuclei: The Possibility
to Study the Spin-Dependent Part of the
Forward Scattering Amplitude in the Range
of Low-Energies**

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Abstract

The influence of Coulomb interaction on the phenomenon of "optical" spin rotation of negatively charged particles (antiprotons, etc.) moving in matter with polarized nuclei is considered. It is shown that because the density of the antiproton (negative hyperon) wave function on the nucleus increases, the spin precession frequency grows as the particle decelerates. As a result, spin rotation of negatively charged particles becomes observable despite their rapid deceleration. This provides information about the spin-dependent part of the amplitude of coherent elastic zero-angle scattering in the range of low energies, where scattering experiments are practically impossible to perform.

Introduction

The advent of the Facility for Low-Energy Antiproton and Ion Research has spurred the rapid development of low-energy antiproton physics (FLAIR) [1,2].

The possibility to obtain polarized antiprotons by a spin-filtering method [3] opens up opportunities for investigation of a large number of spin-dependent fundamental processes arising when antiprotons pass through matter with polarized nuclei (protons, deuterons, ^3He , etc.) In particular, study of the phenomenon of particle "optical" spin rotation in a nuclear pseudomagnetic field of matter with polarized nuclei enables investigation of the spin-dependent part of the amplitude of scattering [4,5,6,7].

For low-energy neutrons, the phenomenon of "optical" spin rotation (the phenomenon of nuclear precession of the neutron spin in a nuclear pseudomagnetic field of a polarized target) was predicted in [8] and experimentally observed in [9,10]. This phenomenon is used for measuring the spin-dependent forward scattering amplitude of thermal neutrons [11,12,13,14,15,16].

In contrast to neutrons, a charged particle moving in matter undergoes Coulomb interaction with the atoms of matter, which causes multiple scattering and rapid deceleration of the charged particle due to ionization energy losses.

With decreasing particle energy, the influence of Coulomb interaction on particle scattering by the nucleus grows in significance. In particular, when the energy of a positively charged particle diminishes, the Coulomb repulsion suppresses nuclear interaction between the incident particle and the target nucleus

and hence, the phenomenon of spin rotation due to nuclear interaction. Conversely, a negatively charged particle (antiproton, hyperon) is attracted to the nucleus and, as a result, participates in nuclear interaction even at low energies. As a consequence of this, spin rotation of a negatively charged particle in polarized matter does not disappear at very low energies either.

The present paper considers the influence of Coulomb interaction on the phenomenon of "optical" spin rotation of negatively charged particles moving in matter with polarized nuclei. It is shown that because the density of the antiproton (negative hyperon) wave function on the nucleus increases, the spin precession frequency grows as the particle decelerates. As a result, spin rotation of negatively charged particles becomes observable despite their rapid deceleration. This provides information about the spin-dependent part of the scattering amplitude in the range of low energies, where scattering experiments are practically impossible to perform.

1 Forward Scattering Amplitude of Negatively Charged Particles

According to [4,5,6,8], the spin rotation frequency Ω_{nuc} of a nonrelativistic particle passing through a target with polarized nuclei can be expressed as

$$\Omega_{\text{nuc}} = \frac{\Delta \text{Re} U_{\text{eff}}}{\hbar} = \frac{2\pi\hbar}{m} N P_t \Delta \text{Re} f(0), \quad (1)$$

where $\Delta \text{Re} U_{\text{eff}}$ is the difference between the real parts of the effective potential energy of interaction between the particle and the polarized target for oppositely directed particle spins, m is the mass of the particle, N is the number of nuclei in 1 cm^3 , P_t is the degree of polarization of the target nuclei, $\Delta \text{Re} f(0)$

is the difference between the real parts of the amplitudes of coherent forward scattering for particles with oppositely directed spins.

The scattering amplitude $f(0)$ is related to the T-matrix as follows (see, e.g. [17,18]):

$$f(0) = -\frac{m}{2\pi\hbar^2} \langle \Phi_a | T | \Phi_a \rangle, \quad (2)$$

where $|\Phi_a\rangle$ is the wave function describing the initial state of the system "incident particle-atom (nucleus)". The wave function $|\Phi_a\rangle$ is the eigenfunction of the Hamiltonian $\hat{H}_0 = H_p(\vec{r}_p) + H_A(\vec{\xi}, \vec{r}_{\text{nuc}})$, i.e., $\hat{H}_0|\Phi_a\rangle = E_a|\Phi_a\rangle$; $H_p(\vec{r}_p)$ is the Hamiltonian of the particle incident onto the target; \vec{r}_p is the particle coordinate; $H_A(\vec{\xi}, \vec{r}_{\text{nuc}})$ is the atomic Hamiltonian; $\vec{\xi}$ is the set of coordinates of the atomic electron; \vec{r}_{nuc} is the set of coordinates describing the atomic nuclei.

The Hamiltonian H describing the particle-nucleus interaction can be written as:

$$H = H_0 + V_{\text{Coul}}(\vec{r}_p, \vec{\xi}, \vec{r}_{\text{nuc}}) + V_{\text{nuc}}(\vec{r}_p, \vec{r}_{\text{nuc}}), \quad (3)$$

where V_{Coul} is the energy of Coulomb interaction between the particle and the atom, V_{nuc} is the energy of nuclear interaction between the particle and the atomic nucleus.

According to the quantum theory of reactions [17,18], the matrix element of the operator T that describes the system transition from the initial state $|\Phi_a\rangle$ into the final state $|\Phi_b\rangle$ in this case of two interactions has the form:

$$T_{ba} = \langle \Phi_b | V_{\text{Coul}} + V_{\text{nuc}} | \Psi_a^+ \rangle, \quad (4)$$

where the wave function Ψ_a^+ satisfies the Schrödinger equation with the Hamiltonian of Eq. (3). At large distances from the scatterer, the wave function Ψ_a^+ has the asymptotics of the diverging spherical wave [17,18].

The Schrödinger equation for the wave function Ψ_a^+ can be written in the integral form:

$$\Psi_a^+ = \Phi_a + (E_a - H_0 + i\varepsilon)^{-1}(V_{\text{Coul}} + V_{\text{nuc}})\Psi_a^+. \quad (5)$$

Let us introduce (see e.g. [17,18,19]) the wave functions $\varphi_a^{(\pm)}$ describing the interaction between particles and atoms via Coulomb interaction alone: ($V_{\text{nuc}} = 0$):

$$\varphi_a^{(\pm)} = \Phi_a + (E_a - H_0 \pm i\varepsilon)^{-1}V_{\text{Coul}}\varphi_a^{(\pm)}, \quad (6)$$

where the wave function $\varphi_a^{(-)}$ at large distances has the asymptotics of a converging spherical wave [17,18,19].

Using Eq. (6), Eq. (5) for Ψ_a^+ can be written in the form:

$$\Psi_a^+ = \varphi_a^+ + (E_a - H_p - H_A - V_{\text{Coul}} + i\varepsilon)^{-1}V_{\text{nuc}}\Psi_a^+. \quad (7)$$

According to Eq. (7), the wave function Ψ_a^+ can be represented as a sum of two waves: wave φ_a^+ , defining scattering due to the Coulomb interaction alone, and the wave that appears as a result of scattering of wave φ_a^+ by the nuclear potential V_{nuc} (the second term).

It eventually follows from Eqs. (4), (7) that the matrix element T_{ba} is representable as a sum of two terms [18]:

$$T_{ba} = T_{ba}^{\text{Coul}} + T_{ba}^{\text{nuc Coul}} = \langle \Phi_b | V_{\text{Coul}} | \varphi_a^+ \rangle + \langle \varphi_b^{(-)} | V_{\text{nuc}} | \Psi_a^{(+)} \rangle. \quad (8)$$

The first term T_{ba}^{Coul} describes the contribution to the T-matrix that comes from the Coulomb scattering alone. The second term describes the contribution to the T-matrix that comes from nuclear scattering and takes account of the distortion of waves incident onto the nucleus, which is caused by the Coulomb interaction.

Equation (8) can also be presented in the form:

$$T_{ba} = T_{ba}^{\text{Coul}} + T_{ba}^{\text{nuc Coul}} = \langle \Phi_b | T_{\text{Coul}} | \Phi_a \rangle + \langle \varphi_b^{(-)} | T_{\text{nuc}} | \varphi_a^{(+)} \rangle, \quad (9)$$

where the operator

$$T_{\text{Coul}} = V_{\text{Coul}} + V_{\text{Coul}}(E_a - H_0 + i\varepsilon)^{-1}T_{\text{Coul}} \quad (10)$$

and the operator

$$\begin{aligned} T_{\text{nuc}} &= V_{\text{nuc}} + V_{\text{nuc}}(E_a - H_0 - V_{\text{Coul}} + i\varepsilon)^{-1}T_{\text{nuc}} \\ &= V_{\text{nuc}} + V_{\text{nuc}}(E_a - H_0 - V_{\text{Coul}} - V_{\text{nuc}} + i\varepsilon)^{-1}V_{\text{nuc}}. \end{aligned} \quad (11)$$

Let us give a more detailed consideration of matrix element $\langle \varphi_b^{(-)} | T_{\text{nuc}} | \varphi_a^{(+)} \rangle$. Because nuclear forces are short-range, for this matrix element the radius of the domain of integration is of the order of the nuclear radius (of the order of the radius of action of nuclear forces in the case of the proton). The Coulomb interaction V_{Coul} in this domain is noticeably smaller than the energy of nuclear interaction V_{nuc} . We can therefore neglect the Coulomb energy in the first approximation in the denominator of Eq. (11), as compared to V_{nuc} .

As a result, the operator T_{nuc} is reduced to the operator describing a purely nuclear interaction between the incident particle and the nucleus. The effect of Coulomb forces on nuclear interaction is described by wave functions $\varphi_{ba}^{(\pm)}$

differing from plane waves due to the influence of Coulomb forces on the incident particle motion in the area occupied by the nucleus (distorted-wave approximation [18]).

In the range of antiproton energies of hundreds of kiloelectronvolts and less, the de Broglie wavelength for antiprotons scattered by the proton is larger than the radius of action of nuclear forces (larger than the nuclear radius in the case of antiproton scattering by the deuteron, ^3He , etc.). Therefore, in Eq. (9) for T_{ba}^{nuc} , one can remove the wave functions $\varphi_{a(b)}^{\pm}$ outside the sign of integration over the coordinate of the antiproton center of mass, \vec{R}_p , at the location point of the nuclear center of mass, \vec{R}_{nuc} . As a result, one may write the following relationship:

$$T_{ba}^{\text{nuc Coul}} = g_{ba} T_{ba}^{\text{nuc}} = \langle \varphi_b^{(-)}(\vec{R}_p = \vec{R}_{\text{nuc}}) | \varphi_a^{(+)}(\vec{R}_p = \vec{R}_{\text{nuc}}) \rangle T_{ba}^{\text{nuc}}, \quad (12)$$

where T_{ba}^{nuc} is the matrix element describing a purely nuclear interaction (in the absence of Coulomb interaction) between the incident particle and the nucleus. The factor $g_{ba} = \langle \varphi_b^{(-)}(\vec{R}_p = \vec{R}_{\text{nuc}}) | \varphi_a^{(+)}(\vec{R}_p = \vec{R}_{\text{nuc}}) \rangle$ appearing in Eq. (12) defines the probability to find the antiproton (the negative hyperon, e.g. Ω^- , Σ^-) at the point of nucleus location.

From Eqs. (3), (12) follows the below expression for the amplitude of coherent elastic zero-angle scattering:

$$f(0) = -\frac{m}{2\pi\hbar^2} g_{aa} T_{aa}^{\text{nuc}} = g_{aa} f_{\text{nuc}}(0), \quad (13)$$

where $f_{\text{nuc}}(0)$ is the amplitude of particle scattering by the nucleus in the absence of Coulomb interaction, $g_{aa} = \langle \varphi_b^{(-)}(\vec{R}_p = \vec{R}_{\text{nuc}}) | \varphi_a^{(+)}(\vec{R}_p = \vec{R}_{\text{nuc}}) \rangle$ is the probability to find the particle incident onto the nucleus at the point of

nucleus location.

Thus, the Coulomb interaction leads to the change in the value of the amplitude of nuclear forward scattering. Let us estimate the magnitude of this change.

According to [19], when a particle moves in the Coulomb field, the probability g_{aa} can be written in the form:

- for the case of repulsion, i.e., scattering of similarly charged particles (e.g. scattering of protons, deuterons by the nucleus)

$$g_{aa}^{\text{rep}} = \frac{2\pi}{\kappa(e^{\frac{2\pi}{\kappa}} - 1)}, \quad \kappa = \frac{v}{Z\alpha c}, \quad (14)$$

where v is the particle velocity, Z is the charge of the nucleus, α is the fine structure constant, c is the speed of light;

- for the case of attraction (e.g. scattering of antiprotons, Ω^- , Σ^- by the nucleus)

$$g_{aa}^{\text{att}} = \frac{2\pi}{\kappa(1 - e^{-\frac{2\pi}{\kappa}})}, \quad (15)$$

With decreasing particle energy (velocity), κ diminishes, and for such values of κ when $\frac{2\pi}{\kappa} \geq 1$, one can write

$$g_{aa}^{\text{rep}} = \frac{2\pi\alpha Zc}{v} e^{-\frac{2\pi\alpha Zc}{v}}, \quad (16)$$

$$g_{aa}^{\text{att}} = \frac{2\pi\alpha Zc}{v}. \quad (17)$$

According to Eq. (16), with decreasing particle (proton, deuteron) energy, the amplitude $f(0)$ diminishes rapidly because of repulsion. For negatively charged particles (antiprotons, Ω^- , Σ^- -hyperons, and so on), the amplitude

of coherent elastic zero-angle scattering grows with decreasing particle energy (velocity).

These results for the amplitude $f(0)$ generalize a similar, well-known relationship for taking account of the Coulomb interaction effect on the cross section of inelastic processes, σ_r , [19].

So in the range of low energies, the amplitude of coherent elastic forward scattering of the antiproton (negative hyperon) by the nucleus can be presented in the form:

$$f(0) = \frac{2\pi\alpha Zc}{v} f_{\text{nuc}} = \frac{2\pi\alpha Zc}{v} \text{Re} f_{\text{nuc}} + \frac{i}{2} \frac{\alpha Z}{\lambda_c} \sigma_{\text{tot}}, \quad (18)$$

where $\lambda_c = \frac{\hbar}{mc}$, σ_{tot} is the total cross section of nuclear interaction between the particle and the scatterer. In deriving Eq. (18), the optical theorem $\text{Im} f(0) = \frac{\hbar}{4\pi} \sigma_{\text{tot}}$ was applied, where k is the wave number of the incident particle.

2 Effective Potential Energy of Negatively Charged Particles in Matter

Using the amplitude $f(0)$, one can write the expression for the refractive index \hat{n} of a spin particle in matter with polarized nuclei, as well as the expression for the effective potential energy \hat{U}_{eff} of interaction between this particle and matter [4,6]:

$$\hat{n}^2 = 1 + \frac{4\pi N}{k^2} \hat{f}(0) \quad \text{and} \quad \hat{U}_{\text{eff}} = -\frac{2\pi\hbar^2}{m} N \hat{f}(0), \quad (19)$$

where in the case considered here, $\hat{f}(0) = \frac{2\pi\alpha Zc}{v} \hat{f}_{\text{nuc}}(0)$ is the amplitude of coherent elastic zero-angle scattering being the operator in the particle spin space.

The amplitude $\hat{f}(0)$ depends on the vector polarization \vec{P}_t of the target nuclei and can be presented in the form:

$$\hat{f}(0) = A_0 + A_1(\hat{S} \vec{P}_t) + A_2(\hat{S} \vec{e})(\vec{e} \vec{P}_t), \quad (20)$$

where A_0 is the scattering amplitude independent of the incident particle spin, \hat{S} is the particle spin operator, \vec{e} is the unit vector in the direction of the particle momentum. If the spin of the target nuclei $I \geq 1$, then the addition depending on the target tensor polarization also appears [4,6].

Correspondingly, the effective potential energy \hat{U}_{eff} of particle interaction with polarized matter looks like

$$\hat{U}_{\text{eff}} = -\frac{2\pi\hbar^2}{m} N (A_0 + A_1(\hat{S} \vec{P}_t) + A_2(\hat{S} \vec{e})(\vec{e} \vec{P}_t)). \quad (21)$$

Expression (21) can be written as

$$\hat{U}_{\text{eff}} = U_{\text{eff}} + \hat{V}_{\text{eff}}(\vec{P}_t), \quad (22)$$

where

$$U_{\text{eff}} = -\frac{2\pi\hbar^2}{m} N A_0, \quad (23)$$

$$\hat{V}_{\text{eff}}(\vec{P}_t) = -\vec{\mu} \vec{G} = -\frac{\mu}{S} (\hat{S} \vec{G}), \quad (24)$$

where μ is the particle magnetic moment,

$$\vec{G} = \frac{2\pi\hbar^2 S}{m\mu} N(A_1 \vec{P}_t + A_2 \vec{e}(\vec{e} \vec{P}_t)), \quad (25)$$

Recall now that the energy of interaction between the magnetic moment μ and a magnetic field \vec{B} is as follows:

$$V_{\text{mag}} = -(\vec{\mu} \vec{B}) = -\frac{\mu}{S}(\hat{S} \vec{B}). \quad (26)$$

Expressions (24) and (25) are identical. Therefore, \vec{G} can be interpreted as the effective pseudomagnetic field acting on the spin of the particle moving in matter with polarized nuclei and appears due to nuclear interaction between the incident particles and the scatterers. Similarly to particle spin precession in an external magnetic field, particle spin precesses in field \vec{G} . This phenomenon was called the nuclear precession of the particle spin, first described for slow neutrons in [8] and then observed in [9,10].

It is worth noting that the amplitudes A_1 and A_2 determining the effective field \vec{G} depend on the energy, the orientation of vectors \vec{e} and \vec{P}_t and are complex values. As a result, unlike the magnetic field \vec{B} , the effective pseudomagnetic field \vec{G} depends on the particle energy and the orientation of vectors \vec{e} and \vec{P}_t . The field \vec{G} is a complex value. The spin precession frequency in this field is determined by $\text{Re}\vec{G}$.

From Eq. (18) follows that in the range of low energies, \hat{U}_{eff} can be presented in the form:

$$\hat{U}_{\text{eff}} = \frac{2\pi\alpha Zc}{v} \hat{U}_{\text{eff}}^{\text{nuc}}, \quad (27)$$

where $\hat{U}_{\text{eff}}^{\text{nuc}}$ coincides in form with that in Eq. (21) with the amplitudes A_0 , A_1 , and A_2 replaced by A_0^{nuc} , A_1^{nuc} , and A_2^{nuc} calculated ignoring the Coulomb interaction.

According to Eq. (27), with decreasing particle velocity, \hat{U}_{eff} grows, as well as the field \vec{G} , and particle spin precession in this field:

$$\Omega_{\text{pr}} \sim \text{Re } G \sim \frac{1}{v}. \quad (28)$$

Let us take a somewhat different view of this issue.

In view of Eqs. (21), (24), and (27), U_{eff} depends on the orientation of vectors \vec{e} and \vec{P}_t .

According to Eq. (21), two simpler cases can be distinguished:

Let $\vec{e} \perp \vec{P}_t$, then

$$\hat{U}_{\text{eff}}^{\perp} = -\frac{2\pi\hbar^2}{m} N(A_0 + A_1(\hat{S}\vec{P}_t)), \quad (29)$$

If the target polarization vector \vec{P}_t is directed along vector \vec{e} , then

$$\hat{U}_{\text{eff}}^{\parallel} = -\frac{2\pi\hbar^2}{m} N(A_0 + (A_1 + A_2)(\hat{S}\vec{P}_t)), \quad (30)$$

Direct the quantization axis parallel to the polarization vector \vec{P}_t . Hence for particle states with magnetic quantum number M_s , one can write the below expression for $U_{\text{eff}}^{\perp}(M_s)$, which follows from Eq. (29):

$$U_{\text{eff}}^{\perp}(M_s) = -\frac{2\pi\hbar^2}{m} N(A_0 + A_1 M_s P_t). \quad (31)$$

$U_{\text{eff}}^{\parallel}$ is obtained by replacing A_1 with $A_1 + A_2$.

In the case of antiprotons ($M_s = \pm \frac{1}{2}$), from Eq. (22) one can obtain two values of the effective potential energy, depending on the antiproton spin orientation:

$$U_{\text{eff}}^{\perp} = -\frac{2\pi\hbar^2}{m}N(A_0 \pm \frac{1}{2}A_1P_t), \quad (32)$$

$$U_{\text{eff}}^{\parallel} = -\frac{2\pi\hbar^2}{m}N(A_0 \pm \frac{1}{2}(A_1 + A_2)P_t), \quad (33)$$

The difference of the real parts of these energies defines the spin precession frequency of the antiproton in matter with polarized nuclei:

$$\begin{aligned} \Omega_{\text{pr}}^{\perp} &= \frac{\text{Re}(U_{\text{eff}}^{\perp}(+\frac{1}{2}) - U_{\text{eff}}^{\perp}(-\frac{1}{2}))}{\hbar} \\ &= -\frac{2\pi\hbar}{m}NP_t\text{Re}A_1 = -\frac{2\pi\hbar}{m} \cdot \frac{2\pi\alpha Zc}{v}NP_t\text{Re}A_{1\text{nuc}}, \end{aligned} \quad (34)$$

$$\Omega_{\text{pr}}^{\parallel} = -\frac{2\pi\hbar}{m} \cdot \frac{2\pi\alpha Zc}{v}NP_t\text{Re}(A_{1\text{nuc}} + A_{2\text{nuc}}) \quad (35)$$

Thus, the spin precession frequency of a negatively charged particle grows with decreasing energy (velocity):

$$\Omega_{\text{pr}} \sim \frac{1}{v}.$$

3 Spin Rotation Angle of Low-Energy Antiprotons in Polarized Matter

Let us estimate the magnitude of the effect. Because in the range of low energies the de Broglie wavelength of a particle is much larger than the nuclear radius, in making estimations we shall concentrate on S -scattering (one should bear in mind, though, that the analysis of the antiproton–proton interaction in protonium has shown that at low energies, P -waves also contribute to antiproton–proton interaction [1]). In S -wave scattering, the amplitude A_2^{nuc}

equals zero.

The amplitudes A_0^{nuc} and A_1^{nuc} can be expressed in terms of the amplitudes a^+ and a^- , where a^+ is the scattering amplitude in the state with total momentum $I + \frac{1}{2}$, and a^- is the same in the state with total momentum $I - \frac{1}{2}$ (I is the nuclear spin) [19]:

$$\begin{aligned} A_0^{\text{nuc}} &= \frac{I+1}{2I+1}a^+ + \frac{I}{2I+1}a^- \\ A_1^{\text{nuc}} &= \frac{2I}{2I+1}(a^+ - a^-). \end{aligned} \quad (36)$$

As a consequence, one can write the following expression for Ω_{pr} :

$$\Omega_{\text{pr}} = -\frac{2\pi\hbar}{m} \cdot \frac{2\pi\alpha Zc}{v} NP_t \frac{2I}{2I+1} \text{Re}(a^+ - a^-). \quad (37)$$

When antiprotons pass through a hydrogen target ($I = \frac{1}{2}$), we have:

$$\Omega_{\text{pr}} = \frac{\pi\hbar}{m} \cdot \frac{2\pi\alpha c}{v} NP_t \text{Re}(a^+ - a^-). \quad (38)$$

The factor $\frac{2\pi\alpha c}{v}$ makes Eq. (38) different from the equation for spin precession frequency of slow neutrons moving in a target with polarized protons.

Recall that in the range of low energies, the amplitudes a^+ and a^- are often expressed in terms of the scattering lengths b^+ and b^- [19]:

$$a^+ = -b^+ \quad \text{and} \quad a^- = -b^-.$$

When the neutron is scattered by the proton, $b^+ = 5.39 \cdot 10^{-13}$ cm, $b^- = -2.37 \cdot 10^{-12}$ cm [19]. As a result, in the case of $n - p$ scattering, for the amplitude A_0^{nuc} (see Eq. (36)) we have $A_0 \approx -1.9 \cdot 10^{-13}$ cm, while for the amplitude A_1^{nuc} , we have $A_1^{\text{nuc}} \approx 1.46 \cdot 10^{-12}$. As is seen, $A_1 \gg |A_0|$.

In the case of antiproton–proton interaction, the spin–independent part of the scattering length, "b", is $b \sim 10^{-13}$ cm [1], which is comparable with $|A_0^{\text{nuc}}|$ for the case of $n - p$ scattering. For antiproton scattering by the proton, the magnitude of A_1 is unknown in the considered range of low energies.

To estimate the magnitude of A_1 , let us assume that $\text{Re } A_1^{\text{nuc}}$ in the case of $\bar{p} - p$ scattering is comparable with $\text{Re } A_1^{\text{nuc}}$ in the case of $n - p$ scattering, i.e., $\text{Re } A_1^{\text{nuc}}$ is of the order of 10^{-12} .

We can finally obtain the following estimation for the antiproton spin precession frequency in matter with polarized protons:

$$\Omega_{\text{pr}} = \frac{2\pi\alpha c}{v} \cdot \frac{2\pi\hbar}{m} N P_t \text{Re } A_1 \simeq \frac{2\pi\alpha c}{v} 6 \cdot 10^7 \frac{N}{N_1} P_t, \quad (39)$$

where N_l is the number of atoms in 1 cm³ of liquid hydrogen, $N_l \simeq 4.25 \cdot 10^{22}$. It will be recalled that $\frac{2\pi\alpha c}{v} \gg 1$ for slow antiprotons with velocity $v < 10^9$ cm/s.

Let us estimate now the spin rotation angle of the antiproton. Eventually, the antiproton that moves in matter soon appears captured by the proton and forms a bound state, protonium. We shall therefore estimate the magnitude of the spin rotation angle during the characteristic time τ necessary for the antiproton to be captured into a bound state:

$$\tau \sim \frac{1}{N v \sigma_{\text{pr}}}$$

where σ_{pr} is the cross section of the protonium formation.

The antiproton spin rotation angle ϑ during this time can be estimated using

formula:

$$\vartheta \sim \Omega_{\text{pr}}\tau = \frac{2\pi\hbar}{m} \cdot \frac{2\pi\alpha c}{v^2} P_t \frac{\text{Re}A_1}{\sigma_{\text{pr}}} = \frac{2\pi^2\hbar}{E} \alpha c \frac{\text{Re}A_1}{\sigma_{\text{pr}}} P_t, \quad (40)$$

where $E = \frac{mv^2}{2}$ is the antiproton energy.

Antiproton beams with the energy of hundreds of electronvolts and smaller are presently available. According to [20], in the range of energies higher than 10 eV, the cross section of antiproton capture by hydrogen with the formation of protonium is $\sigma_{\text{pr}} \leq 10^{-18}$. As a result, the spin rotation angle for antiprotons with the energy of 10^2 eV can be estimated as $\vartheta \simeq 6 \cdot 10^{-2} P_t$. For antiproton energies of 20 eV, the same is $\vartheta \sim 3 \cdot 10^{-1} P_t$. When antiprotons are decelerated in a polarized gaseous target, the degree of proton polarization is close to unity. As a consequence, the rotation angle in such a target reaches quite appreciable values, $\vartheta \sim 10^{-1}$, giving hope for experimental observation of the effect. Thus, this effect will be applicable for $\text{Re} A_1$ measurement in the region where the scattering experiments are really difficult to realize. Note that for studying the polarization state, one can use a polarized target with nuclei having a large Z (in fact, a thin film, in which case nuclei in a static magnetic field can be polarized far more readily).

After the antiproton has been captured into a bound state by hydrogen, a new atom appears, called protonium. This atom is neutral and, moving in matter, undergoes interactions with a nuclear pseudomagnetic field of polarized matter in a similar way as a neutron. Such interaction leads to splitting and shifts of energy levels of excited and ground states of the protonium (and similar atoms, such as $\bar{p}d$, $\bar{p}^3\text{He}$), as well as to spin rotation and oscillations of the excited and ground states of these atoms.

In this regard, we would like to specially mention the system $\bar{p}^3\text{He}$ for having, like $\bar{p}^4\text{He}$, a considerably long lifetime ($\approx 10^{-6}$ s). The long lifetime of the system $\bar{p}\text{He}$ makes it possible to use presently available laser-microwave techniques [24,25,26] for studying the systems's values of splitting, shifts, and widths of energy levels caused by the nuclear pseudomagnetic field produced by the gas from polarized atoms in which the system $\bar{p}\text{He}$ moves (e.g. \bar{p} capture in a mixture of polarized H, D, ^3He gases or in polarized H, D, or ^3He mixed with ^4He). Because the nuclear pseudomagnetic field depends on the spin part of the scattering amplitude, by measuring the shift and width of the level one can obtain information about the amplitude of antiproton scattering by atomic nuclei of the gas in which the system $\bar{p}\text{He}$ ($\bar{p}^3\text{He}$, $\bar{p}^4\text{He}$) moves. In such experimental arrangement, the system $\bar{p}\text{He}$ acts as a probe. Analyzing how the shifts, splitting and widths of the energy levels depend on, e.g., the density of polarized gas, one can obtain the values of the shift (splitting) and width of the level that we are concerned with [6] and thus obtain information about the amplitude of \bar{p} scattering by the nuclei of neighboring atoms. Note here that in the considered experimental arrangement, the antiproton beam incident onto the target can be unpolarized.

It is worth noting in conclusion that, as we have shown in [21,22,23], in annihilation of positronium (the bound state of positronium e^+ and electron e^-), one can observe quantum time-oscillations of the counting rate of the annihilation products for ortho-positronium placed in a magnetic field. These quantum oscillations were experimentally observed and laid the basis for the methods of studying fundamental interactions and the properties of matter [6].

Similar phenomena of quantum oscillations of the counting rate of the anni-

hilation products, depending on the time passed from the moment when the particle entered the target, can also be observed for long-lived systems ($\bar{p}^3\text{He}$, $\bar{p}^4\text{He}$). It should be noted that quantum oscillations of the counting rate of the annihilation products occur at the frequencies determined by the difference of energies between the levels of the bound system. For this reason, use of the external magnetic field enables changing distances between the energy levels of the considered atoms and thus selecting optimal conditions for observation of the phenomenon of quantum oscillations.

The author is grateful to K. Fregat for valuable discussions.

References

- [1] E. Klempt, F. Bradamante, A. Martin, J.-M. Richard, Antinucleon-nucleon interaction at low energy: scattering and protonium *Phys. Rep.* **368**(2002) 119.
- [2] E. Widmann, FLAIR, A next-generation facility for low-energy antiprotons, in: *8th International Conference on Nuclear Physics at Storage Rings*, STORI11 October 9-14, 2011 Frascati (Rome) Italy, PoS(STORI11)035.
- [3] H. Ströher, P. Lenisa, F. Rathmann, The road towards polarized antiprotons, in: *8th International Conference on Nuclear Physics at Storage Rings*, STORI11 October 9-14, 2011 Frascati (Rome) Italy, PoS(STORI11)030.
- [4] V.G. Baryshevsky, Rotation of particle spin in a storage ring with a polarized beam and measurement of the particle EDM, tensor polarizability and elastic zero-angle scattering amplitude, *J. Phys.* **G35** (2008) 035102.

- [5] V.G. Baryshevsky, Optical” spin rotation phenomenon and spin filtering of antiproton (proton, deuteron) beams in a pseudomagnetic field of a polarized target: the possibility of measuring the real part of the coherent zero-angle scattering amplitude, LANL e-print arXiv:1101.3146v1 [hep-ph].
- [6] V.G. Baryshevsky, High-Energy Nuclear Optics of Polarized Particles, World Scientific Publishing, Singapore, 2012.
- [7] V.G. Baryshevsky, Growth of Interaction Between Antiprotons (Negative Hyperons) and Nuclei in Polarized Matter: The Possibility to Study the Spin-Dependent Part of the Forward Scattering Amplitude in the Range of Low-Energies. Lanl e-print arXiv:1202.3897v1 [nucl-th]
- [8] V. G. Baryshevskii and M. I. Podgoretskii, Nuclear precession of neutrons, *Zh. Eksp. Teor. Fiz.* **47** (1964) 1050 (*Sov. Phys. JETP* **20** (1965) 704).
- [9] A. Abragam, G.L. Bacchella, H. Glattli, P. Meriel, J. Piesvaux, M. Pino and P. Roubeau *C.R. Acad. Sci., (Paris)* **B274** (1972) 423.
- [10] M. Forte Neutron spin precession in polarized nuclear targets, *Nuovo Cimento* **A18** (1973) 726.
- [11] A. Abragam and M. Goldman Nuclear Magnetism: Order and Disorder, Oxford University Press, 1982.
- [12] H. Glattli and J. Coustham, Spin-dependent scattering and absorption of thermal neutrons on dynamically polarized nuclei, *J. Physiq.* **44** (1983) 957.
- [13] B. van den Brandt, H. Glattli, H.W. Griesshammer, P. Hautle, J. Kohlbrecher, J.A. Konter and O. Zimmer, The spin-dependent nd scattering length — a proposed high-accuracy measurement, *Nucl. Instrum. Methods* **A526** (2004) 91.
- [14] F.M. Piegsa, B. van den Brandt, P. Hautle and J.A. Konter, Neutron Spin Phase Imaging, *Nucl. Instrum. Methods* **A586** (2008) 15.

- [15] F. M. Piegsa, B. van den Brandt, H. Glattli, P. Hautle, J. Kohlbrecher, J.A. Konter, B.S. Schlimme and O. Zimmer, A Ramsey apparatus for the measurement of the incoherent neutron scattering length of the deuteron, *Nucl. Instrum. Methods* **A589** (2008) 318.
- [16] B. van den Brandt, H. Glattli, P. Hautle, J.A. Konter, F.M. Piegsa and O. Zimmer, The measurement of the incoherent neutron scattering length of the deuteron, *Nucl. Instrum. Methods* **A611** (2009) 231.
- [17] M. L. Goldberger and R. M. Watson, *Collision Theory*, Wiley, New York, 1984.
- [18] A. S. Davydov, *Quantum Mechanics*, Pergamon Press, Oxford, 1965.
- [19] L. D. Landau and E. M. Lifshitz, *Quantum Mechanics: Non-Relativistic Theory*, in: Landau, L. D. and Lifshitz, E. M., *Course of Theoretical Physics*, Vol. 3, 3rd edn., Pergamon Press, 1977.
- [20] J.S. Cohen, Formation of protonium in collisions of antiprotons with H and H^- , *Phys.Rev.* **A 36** (1987) 2024.
- [21] V. G. Baryshevsky, Positronium spin rotation and time oscillation of the normal to the three-photon positronium decay plane in magnetic field, *Phys. Stat. Sol.* **B124** (1984) 619.
- [22] V. G. Baryshevsky, O. N. Metelitsa and V. V. Tikhomirov, Oscillations of the positronium decay γ -quantum angular distribution in a magnetic field, *J. Phys.* **B22** (1989) 2835.
- [23] V. G. Baryshevsky, O. N. Metelitsa, V. V. Tikhomirov, S. K. Andrukhovich, A. V. Berestov, B. A. Martsinkevich and E. A. Rudak, Observation of time oscillation in 3γ -annihilation of positronium in a magnetic field *Phys. Lett.* **A136** (1989) 428.
- [24] E. Widmann, Precision physics with low-energy antiprotons - from antiproton decelerator to FLAIR *Acta Phys. Pol.* **B 41** (2010) 249.

- [25] T. Yamazaki, N. Morita, R. S. Hayano, *et al.*, Antiprotonic helium, *Phys. Rep.* **366** (2002) 183.
- [26] R.S. Hayano, M. Hori, D. Horváth, E. Widmann, Antiprotonic helium and CPT invariance, *Rep. Progr. Phys.* **70** (2007) 1995.