Pseudomagnetism

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Phenomena occurring when polarized particles (neutrons, electrons, γ-ray quanta, and optical frequency photons) pass through polarized targets are examined. The change in the state of polarization of the particles, passing through the target is described phenomenologically in terms of their motion in a pseudomagnetic field. The method of computation is illustrated in detail on the example of a beam of slow monoenergetic neutrons passing through a polarized nuclear target. Results of experiments with neutrons, electrons, and γ-ray quanta are presented.

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INTRODUCTION

Progress in the development of techniques for dynamic polarization of nuclei (DPN) and for optical orientation of atoms has opened up new possibilities for obtaining a high (~100%) degree of polarization of protons in solid targets, of nuclei and electrons, of atomic vapors and of molecules of a substance. On the other hand, methods have been developed for creating, forming, and detecting beams of polarized monoenergetic particles with spin: neutrons, protons, electrons, gamma quanta, and photons in the optical frequency range. As a result, there now exists the possibility of performing a series of new experiments on the passage of particles with spin through polarized targets, which, not so long ago, could not even be considered.

Targets with oriented nuclei, for example, protons, are used in nuclear physics for studying the dependence of the energy of nuclear interactions on the orientation of the spins of the interacting particles, and in cryogenic technology, for obtaining and measuring superlow temperatures. By adiabatic demagnetization of such a target with a sufficiently low initial temperature, it is possible to strongly cool the nuclear spin system to extremely low temperatures, unattainable by other methods. This opens up the possibility of experimentally creating conditions, under which long range order arises in a nuclear system due to the magnetic interaction of nuclear spins, so that it is possible for a state of nuclear antiferromagnetism or ferromagnetism to form.[1,2,29]

Experiments to study polarization of neutrons, passing through polarized nuclear targets under such conditions, allow a direct determination of the appearance of a nuclear ferromagnetic or antiferromagnetic state and other possible magnetic structures. The study of such states is especially interesting, since in this case the law governing the interaction between the spin magnetic moments is well-known.

Such experiments are also important because the same information can be extracted from single scattering of a particle with spin by a polarized target, as from observation of double scattering on an unpolarized target. When a beam of polarized particles passes through a polarized target, phenomena occur that are related to correlated changes in the orientations of the scattering particles. These phenomena are completely analogous with the phenomena of the rotation of the plane of polarization and birefringence well-known in

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the optics of anisotropic media.

Methods for describing such phenomena in a simple and instructive way can be demonstrated for the interesting and practically important example of the passage of a beam of slow neutrons through a polarized nuclear target.

In moving through a substance, neutrons experience not only magnetic dipole-dipole interactions with the nuclei and electrons of the target, but also purely nuclear interactions, caused by the action of nuclear forces. The energy of nuclear interaction, as is well-known, depends strongly on the mutual orientation of the spins of the scattering nuclei and the neutron. It causes a stronger scattering of neutrons than the weaker nuclear magnetic dipole-dipole interaction. In some cases, its cross section turns out to be comparable with the cross section for scattering by the electrons in the target. This purely nuclear interaction between nuclei and neutrons can always be represented as some effective magnetic interaction, and, in this way, the neutron can be viewed as being located in some pseudomagnetic field, created by the nuclei in the target.[3] The magnitude and orientation of this field are determined by the vector sum of the polarizations of the nuclei. As has been demonstrated in Refs. 3, 4, the existence of a pseudomagnetic nuclear field inside a polarized target must lead to precession of the neutron spin, to a shift in the paramagnetic resonance frequency, and to the appearance of a new type of resonance, a pseudomagnetic resonance, in which a magnetic resonance for the neutrons is excited by the variable pseudomagnetic field. The first experimental work, supporting the existence of the first and third effects, has already appeared.[5-7]

Inasmuch as the scattering of neutrons by nuclei depends on the orientation of the nuclear system as a whole, there appears a new possibility for studying experimentally with the help of the scattered neutron beam effects related to the orientation of the nuclei, in particular, nuclear magnetic resonance, nuclear magnetic ordering, and so on.

The concept of a pseudofield can be used, under appropriate conditions, to describe the passage through matter of other particles with spin, for example, electrons, γ-quanta, photons of arbitrary, but in particular of optical, frequencies, interacting with polarized targets.

It is important to note that this concept is not new. It has a long history. A pseudomagnetic field was first introduced by Weiss in 1907 in order to describe the ferromagnetic state (the Weiss molecular field). As it became clear much later, this field owes its existence to the Coulomb exchange interaction between electrons and strongly depends on the mutual orientation of their spins, i.e., just as for the case examined above, it is of a nonmagnetic nature.

In recent times, the pseudofield method has found application in solid state theory for describing a wide range of different phenomena. With its help it is possible to describe phenomena of interest from many points of view and to make quantitative estimates of the expected effects. One should not be prejudiced against this method because of its pragmatic nature, if for no other reason than that it is always possible to recall many cases when one must have more faith than rigor.

If the first experimental work[5] was devoted mainly to the determination of scattering lengths, of nuclear pseudomagnetic fields, to the demonstration of the existence of spin precession of neutrons around the direction of the nuclear polarization, then the latest work[6-9,45] points clearly to the great possibilities of the pseudomagnetic method in studying various problems in the physics of solids. Thus, for example, the study of the precession of neutron spins in cobalt crystals led to information concerning the magnitude of the internal field created by electrons and neighboring ions at the nuclei. Prior to this, similar information was obtained only from nuclear magnetic resonance (NMR) experiments and from measurements of the specific heat.

If the pseudomagnetic field is known, then from pseudomagnetic measurements it is possible to obtain such important characteristics of the system as the absolute value of the nuclear polarization, the nuclear spin-lattice relaxation time, and so on. At the same time, in contrast to NMR, which is the usual method for measuring nuclear polarization and relaxation, pseudomagnetic precession has two advantages: it offers the possibility of measuring the absolute value of the nuclear polarization and can be used in those cases, when the NMR signal is not observable (broadened line, NMR in metals, and so on). The experiments carried out[9] have not only verified what has been said above, but they have allowed the authors of this work to obtain completely new information concerning relaxation processes in holmium ethylsulfate and to identify new relaxation mechanisms.

The concept of the pseudomagnetic field is illustrated below, using as examples beams of slow monoenergetic neutrons, electrons, γ-rays, and optical-frequency photons passing through targets with polarized particles. The simple phenomenological theory presented below allows not only qualitative, but also quantitative description of various aspects of the phenomena that arise. In all cases, where it was possible, the results of completed experiments are presented.

1. PASSAGE OF NEUTRONS THROUGH A POLARIZED CRYSTAL

a) Scattering of slow neutrons by nuclei with spin. The pseudopotential

The interaction energy for a neutron interacting with electrons and nuclei in a paramagnetic crystal is made up of the nuclear and magnetic interaction energies. In diamagnetic crystals, the short-range nuclear interaction gives the main contribution to the scattering amplitude of slow neutrons.

The scattering, arising from the interaction of dipole magnetic moments of the neutrons and nuclei, is always significantly less than the nuclear scattering. The scattering by the nonuniform magnetic fields of the electron shells in the atoms is small due to the smallness of the magnetic moment of the neutron.

In weakly magnetic substances, the magnetic fields of the electron shells in atoms average out and scattering by electrons is not observed. It can become noticeable, if the electrons are polarized. However even in this case it constitutes not more than a tenth of the nuclear scattering. The magnetic dipole interaction in paramagnetic and ferromagnetic crystals has been studied in detail in Ref. 11 and will not be examined here. Below, we will only study nuclear scattering and its dependence on the orientation of spins.

The total effective cross section σ_t for scattering of sufficiently slow neutrons by the nuclei of atoms or molecules is determined by a single complex parameter, the forward scattering amplitude $f(0)$ or the scattering length $a = -f(0)$[10]:

$$\sigma_t = \frac{4\pi}{k}\,\mathrm{Im}\, f(0), \tag{1}$$

where $k = 2\pi/\lambda = 1/\lambda\!\!\!^{-}$. The imaginary part β of the scattering length $a = \alpha + i\beta$ is negative, and furthermore, $|\beta| \ll \alpha$. For most nuclei $\alpha > 0$.

The wavelengths $\lambda\!\!\!^{-}$ of slow neutrons ($E_n < 0.025$ eV, $\lambda > 0.3\cdot 10^{-8}$ cm) are of the order of or greater than the average interatomic distance, while $|a| \approx \alpha$ is of the order of the effective range of nuclear forces ($\alpha \sim 5\cdot 10^{-3}$ cm). In the center of mass system of the neutron and the scattering nucleus, the scattering is isotropic and does not depend on the energy of the neutron.

The energy of interaction between the spin particles depends significantly on the mutual orientation of the spins. A neutron with spin S forms together with a nucleus I, by which it is scattered, a quantum system characterized by the quantum numbers F and m_F, where $\mathbf{F} = \mathbf{I} + \mathbf{S}$ is the total angular momentum vector for the system, while m_F is the magnetic quantum number, corresponding to integral projections onto a specified direction. Therefore,

$$F(F+1) = I(I+1) + S(S+1) + 2(\mathbf{IS}). \tag{2}$$

The scattering length a for a nuclear particle with spin S scattered by a nucleus with spin I is uniquely determined by the expression

$$a = A + B(\mathbf{IS}),$$

which follows simply from the general properties of the angular momentum operator.[10] Here, A and B are constants.

It is easy to see that, having found IS from (2), the scattering length a_+ corresponding to $F = I + S$ equals $a_+ = A + BIS$. For $F = I - S$, it equals $a_- = A - B(I+1)S$. Eliminating A and B, we obtain

$$a = \frac{(I+1)a_+ + Ia_-}{2I+1} + \frac{2(\mathbf{IS})}{2I+1}(a_+ - a_-). \tag{3}$$

The first term on the right side of (3) does not depend on the orientation of the spins of the neutron and the nucleus, and describes the coherent scattering length (a_{coh}), while the second term describes the incoherent scattering length. Incoherent scattering depends on the spin state of the particles and is accompanied by a reorientation of the neutron spin. This type of scattering is detected by its large contribution to the effective scattering cross section or, as will be shown below, by the change in the orientation of the polarization vector of the spins in the polarized neutron beam.

A neutron is scattered by a nucleus (proton) when, having penetrated deeply inside the atom, it enters the range of nuclear forces, where the energy of interaction $U(\mathbf{r})$ between the neutron and the nucleus becomes different from zero. Since, in this case, the uncertainty in the position of the neutron is $\lambda\!\!\!^{-} \gg |a|$, the interaction with the nucleus has a point-like character and arises only in a direct head-on collision ($l = 0$, s-wave scattering). For this reason, it may be assumed that the dependence of the energy $U(\mathbf{r} - \mathbf{r}_j)$ of the nuclear interaction of the neutron with the j-th nucleus of the target on the mutual orientation of their spins has the form

$$U(\mathbf{r} - \mathbf{r}_j) = 2\pi \frac{\hbar^2}{m} a_j \delta(\mathbf{r} - \mathbf{r}_j), \tag{4}$$

where m is the mass of the neutron. This choice for the expression for U automatically leads to a constant scattering length and isotropic scattering. Indeed, in the Born approximation we have[10]

$$a_j = \frac{m}{2\pi\hbar^2} \int U(\mathbf{r} - \mathbf{r}_j)\, d\mathbf{r}. \tag{5}$$

It is easy to see that (4) turns (5) into an identity. The expression (4), correctly describing the interaction of a slow neutron ($k\alpha \ll 1$) with a nucleus, is called the Fermi pseudopotential.[12,13]

As a beam of neutrons (or photons) passes through a medium (crystal), all nuclei (atoms) falling within its range simultaneously take part in the scattering process. For this reason, the pseudopotential (4) is written in the form

$$U(\mathbf{r}) = 2\pi \frac{\hbar^2}{m} \sum_{j=1}^{N_0} a_j \delta(\mathbf{r} - \mathbf{r}_j). \tag{6}$$

The average energy $\bar{U}$ of a neutron in a uniform medium does not depend on its position and equals

$$\bar{U} = \frac{1}{V} \int U(\mathbf{r})\, d\mathbf{r} = 2\pi \frac{\hbar^2}{m} Na, \tag{7}$$

where $N = N_0/V$ is the number of scattering nuclei per unit volume and a is the scattering length for scattering by a free atom.

Although the exact form of the dependence of nuclear forces on the distance between particles remains unknown, their dependence on the mutual orientation of spins is known exactly. This, however, is sufficient for solving a wide range of problems related to the interaction of spins. These include the computation of the scattering cross sections and their dependence on the orientation of spins, the absorption of a beam of nuclear particles as they pass through a substance, and effects related to the change in the polarization of the beam.

The application of pseudopotentials of this type can describe in an attractive way the interaction between complicated physical systems that are very different in their nature. It can be used for describing the interaction of particles with spin with spatially distributed systems, not only of atomic nuclei but also of molecules of atoms and electrons.

It can be shown that a system of δ-function potential wells, approximating the nuclear interaction of a slow neutron with the nuclei in a target, is equivalent to a square well potential if their density is sufficiently high. The potential energy of such a system in comparison with the distance between the potential wells changes very smoothly from place to place.[13,14]

Recently, the pseudopotential method has found numerous applications in different areas of solid state theory.[15]

b) Index of refraction

The intensity of a beam of polarized particles passing through a weakly scattering medium gradually decreases in proportion to the distance traversed through the medium, and the degree and nature of its polarization changes. All processes, which cause a neutron to leave the beam, can be viewed as absorption. The intensity of the beam decreases because the particles which make up the beam experience various types of elastic and inelastic collisions and on scattering leave the beam. The polarization of the beam changes as a result of the dependence of the scattering amplitude on the mutual orientation of the particle spins in the beam and in the target.

In order to describe the phenomena that occur when slow neutrons pass through a nonmagnetic crystal, it is convenient to use the average Fermi pseudopotential. In this case, the passage of the beam of particles through the substance can be described in an elegant way as the propagation of a plane wave in a homogeneous anisotropic medium, characterized by certain indices of refraction. The physical method described below is called the dielectric formalism.[16]

It is possible to speak of refractive indices for a medium to the extent to which it is possible to describe the propagation of neutrons in the medium with the help of a plane wave. For this, it is first necessary that scattering to the sides be negligibly small. For this reason, in spite of the widespread view, the idea of an index of refraction is not limited by the neutron wavelength and the number of scattering centers per unit volume, i.e., by the requirement that the average distance between the particles of the medium $N^{-1/3}$ be less than λ.

The Schrödinger equation for a neutron moving along the z axis in the field of nuclear forces with an average pseudopotential $\overline{U}$, has the form

$$\frac{d^2}{dz^2}|\psi\rangle+\frac{2m}{\hbar^2}(E_n-\overline{U})|\psi\rangle=0. \tag{8}$$

The solution of this equation, inasmuch as $\overline{U}$ does not depend on coordinates, has the character of a plane wave $|\psi\rangle=\exp(iKz)$ and corresponds to a neutron current $j_n=\hbar K/m$, $\langle\psi|\psi\rangle=1$ (the probability density is the same over the entire space). From (8) we easily find the dispersion equation

$$K^2=k^2\left(1-\frac{\overline{U}}{E_n}\right), \tag{9}$$

where $k^2=2mE_n/\hbar^2$ is the wave number of the free neutron. In a manner similar to what is done in optics, it is possible to determine the index of refraction n[13,17] as follows:

$$n^2=1-\frac{\overline{U}}{E_n}, \tag{10}$$

or, using Equation (3), to express it in a more convenient form[3a]:

$$n^2=1-4\pi\frac{N}{k^2}\left[a_{\text{coh}}+2\frac{\langle \mathbf{I}\rangle\mathbf{S}}{2I+1}(a_+-a_-)\right], \tag{11}$$

where $a_{\text{coh}}=(2I+1)^{-1}[Ia_-+(I+1)a_+]$.

It follows from here that the index of refraction of a crystal n depends on the mutual orientation of the spins of neutrons S in the scattered beam and the spins I of the nuclei in the target. If the target is unpolarized, i.e., $\langle \mathbf{I}\rangle=0$, then the dependence of n on the polarization of the neutron beam disappears. It is important to note that Equation (11) describes the results of the scattering of a neutron by many nuclei, i.e., the collective interaction of the neutron with the nuclei in the target. A polarized nuclear target represents, relative to the incident beam of particles with spin, a birefringent or active medium. The nature of the anisotropy of such a medium is determined by nuclear forces, and as a result of their large magnitude, the index of refraction may turn out to be far from small.

c) Rotation of the direction of polarization of neutrons on passing through a polarized nuclear target

We will describe a polarized target with the help of the single vector $\mathbf{P}=\langle \mathbf{I}\rangle/I$, where $\langle \mathbf{I}\rangle$ is the average value of the spin vector. We shall place the origin of coordinates on the front boundary of the target, and the z axis along the direction of motion of the neutrons. We shall assume that the neutrons in the beam are independent. Under these conditions, the state of a neutron $|\psi\rangle$ with arbitrary polarization can be represented in terms of spinors for the two states with opposite polarization:

$$|\psi(z)\rangle=A_+(0)\,e^{ikn_+z}\begin{pmatrix}1\\0\end{pmatrix}+A_-(0)\,e^{ikn_-z}\begin{pmatrix}0\\1\end{pmatrix}, \tag{12}$$

where $\binom{1}{0}$ and $\binom{0}{1}$ denote the eigenfunctions of the Pauli operator σ_z, n_+ is the index of refraction of the nuclear target for neutrons polarized in a direction parallel to the direction of the polarization vector of the target (in our case along the direction of the $0z$ axis), while n_- is the index of refraction for neutrons with the opposite polarization. In accordance with (11) the corresponding indices of refraction are equal to

$$n_\pm=1-4\pi\frac{N}{k^2}\left[a_{\text{coh}}\pm\frac{\langle I\rangle}{2I+1}(a_+-a_-)\right], \tag{13}$$

or

$$n_\pm=n_{\text{coh}}\pm\frac{1}{2}\Delta n, \tag{14}$$

$$n_{\text{coh}}=1-2\pi\frac{N}{k^2}a_{\text{coh}}, \tag{15}$$

$$\Delta n=4\pi\frac{N}{k^2}P\frac{I}{I+1}(a_+-a_-). \tag{16}$$

Thus we have

$$|\psi(z)\rangle=e^{ikn_{\text{coh}}z}\left[A_+(0)\,e^{ik(\Delta n/2)z}\begin{pmatrix}1\\0\end{pmatrix}+A_-(0)\,e^{-ik(\Delta n/2)z}\begin{pmatrix}0\\1\end{pmatrix}\right]. \tag{17}$$

It follows from this expression that after the neutrons pass through a target of thickness l their polarization will be rotated by an angle

$\varphi = k\,\Delta n l.$

The neutron spins will make a complete revolution after passing through a layer of thickness l given by:

$$l = \frac{2\pi}{k\,\Delta n} = \frac{(2I+1)\,k}{2N\langle I\rangle(a_+ - a_-)}.$$

The angular velocity $\omega_0 = d\varphi/dt$ of the rotation of the spin of a neutron in the target, evidently, is determined by the relationship

$$\omega_0 = \frac{\hbar k}{m}\frac{d\varphi}{az} = 4\pi\frac{\hbar}{m}N\frac{\langle I\rangle}{2I+1}(a_+ - a_-), \tag{18}$$

first obtained by Baryshevskiĭ and Podgoretskiĭ in 1964.[3a]

The rotation frequency of the polarization vector of slow neutrons does not depend on their speed, since $a_+ - a_-$ does not depend on the neutron energy, and therefore is a characteristic constant for a given substance.

When the scattering lengths a_+ and a_- are equal, there is no rotation due to nuclear forces. Of course, it also does not occur in the case when $\langle I\rangle = 0$.

Let us now examine the influence of absorption on the propagation of a neutron wave in a polarized medium. For slow neutrons, the main contribution to absorption comes from scattering with an inversion of the spin and from nuclear absorption. The cross section for the first process for a wave polarized along the direction of polarization of the nuclei in the target equals zero. For a wave with opposite polarization, it turns out to be equal to

$$\sigma = 8\pi P\frac{I}{2I+1}(a_+ - a_-)^2. \tag{19}$$

The ratio of the wavelength λ to the path length l of neutrons without taking nuclear absorption into account equals

$$\frac{\lambda}{l} = 4\pi\frac{k}{(2I+1)^2}(a_+ - a_-)^2,$$

and decreases with a decrease in the wave vector k. Nuclear absorption changes this ratio insignificantly.

The change in the wave function with the depth of penetration into the target, taking absorption into account, is described by the expression

$$\psi(z)\rangle = A_+(0)\,e^{-\varkappa_+ z}e^{ikn_{1+}z}\begin{pmatrix}1\\0\end{pmatrix} + A_-(0)\,e^{-\varkappa_- z}e^{ikn_{1-}z}\begin{pmatrix}0\\1\end{pmatrix}, \tag{20}$$

where $\varkappa_+ = kn_{2+}$ and $\varkappa_- = kn_{2-}$ are coefficients of absorption. If the change in the projection of the polarization of neutrons along the $0x$ axis is observed, then the probabilities for polarization p_+ in the direction of the $0x$ axis and polarization p_- in the opposite direction, vary with z according to the law

$$p_\pm = \frac{1}{2}[|A_+(0)|^2 e^{-2\varkappa_+ z} + |A_-(0)|^2 e^{-2\varkappa_- z} \pm 2|A_+(0)|\,|A_-(0)|\,e^{i(\varkappa_+ + \varkappa_-)z}\cos(k\,\Delta nz + \delta)], \tag{21}$$

where δ is the difference in the initial phases of the states, corresponding to polarization along and opposite to the direction of the z axis. For this reason, if at $z = 0$ the neutrons are polarized along the $0x$ axis $[A_+(0) = A_-(0) = 2^{-1/2}]$, then with an increase in z we have

$$\frac{\langle\psi(z)\,|\,\psi(z)\rangle}{\langle\psi(0)\,|\,\psi(0)\rangle} = \frac{1}{2}(e^{-2kn_{2+}z} + e^{-2kn_{2-}z}),$$

and neutrons with opposite polarization appear in the beam. Depending on their penetration into the target, the polarization of the beam of neutrons varies periodically. The intensity of the transverse components of the polarization vector exhibits spatial beats. One of the components decays more rapidly than the other and, at some point, the beam is polarized in a direction parallel or antiparallel to the $0z$ axis. If a beam of neutrons, polarized only parallel or antiparallel to the $0z$ axis is incident on the target, then "beats" do not occur and only a damping of the beam is observed.

2. THE NUCLEAR PSEUDOMAGNETIC FIELD

a) Definition of the field

A neutron, moving through a polarized nuclear target, feels an average (effective) nuclear field, which depends on the polarization of the nuclei. Its energy is given by

$$U = 2\pi\frac{\hbar^2}{m}N\left[a_{\text{coh}} + \frac{2\langle \mathbf{I}\rangle\mathbf{S}}{2I+1}(a_+ - a_-)\right]. \tag{22}$$

Since the total energy of the neutrons moving in a polarized target can be taken as constant, a change in their orientation is accompanied by a change both in their potential and kinetic energies. For this reason, the momentum of a neutron in the target depends on the orientation of its spin.

For the case examined above, the potential energy of a neutron in the target has the value

$$\overline{U}_\pm = 2\pi\frac{\hbar^2}{m}Na_{\text{coh}} \pm 2\pi\frac{\hbar^2}{m}N\frac{\langle I\rangle}{2I+1}(a_+ - a_-). \tag{23}$$

The change in the energy of a neutron ΔU when its spin is inverted equals

$$\Delta U = 4\pi\frac{\hbar^2}{m}NP\frac{I}{2I+1}(a_+ - a_-). \tag{24}$$

It is easy to see, comparing this last expression with the formula obtained above for the angular velocity of the rotation of a neutron spin in the target (18), that $\Delta U = \hbar\omega_0$.

This leads to the idea of viewing the quantum neutron-medium system as a two-level system, for which the energy separating the two levels is given and is determined by Eq. (24). The precession frequency in this case can be formally viewed as the transition frequency between these two levels. The energy levels $\overline{U}_\pm$ arise as a result of all the nuclei in the polarized target acting on the neutron. For this reason, when the neutron spin is inverted the energy is transmitted to the entire crystal or is removed from it. Of course, there is no radiation emitted in this case. The kinetic energy of the neutron increases (or decreases) by an amount equal to the decrease (or increase) in the potential energy.

The action of the average nuclear field on the neutrons in the beam leads to phenomena, completely analogous to magnetic rotation of the plane of polarization and birefringence, well-known in ultrahigh frequency technol-

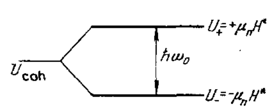

FIG. 1. The energy levels of a neutron in the pseudomagnetic field of a nuclear target.

-ogy, physical optics, and in the theory of magnetic resonance. Its effect on the neutrons can be identified with the effect of some "molecular magnetic" or simply "pseudomagnetic" field, which can be defined in such a way that it gives a correct quantitative description of the same phenomena. This can be done most simply by defining the magnitude of the intensity vector $\mathbf{H}^*$ of this field by the obvious expression:

$$H^* = \frac{\hbar}{2\mu_n}\omega_0 = \frac{\omega_0}{\gamma_n}, \qquad (25)$$

where μ_n is the magnetic moment of the neutron, γ_n is the gyromagnetic ratio of the neutron,[1)] while ω_0 is the precession frequency of the neutron spins, defined by Eq. (18).

This can be done in a more systematic manner, starting with Eq. (7) for the energy of interaction between the neutron and the nuclei of the target, depending on the spins, part of which, in accordance with (3), can be written for this purpose in the form

$$U_s(\mathbf{r}) = 4\pi\frac{\hbar^2}{m}\frac{a_+ - a_-}{2I+1}\mathbf{S}\sum_{j=1}^{N_0}\mathbf{I}_j\delta(\mathbf{r}-\mathbf{r}_j). \qquad (26)$$

Assuming that the pseudomagnetic field acts on the magnetic moment of the neutron $\mu_n = \gamma_n\hbar\mathbf{S}$, i.e., assuming that $U(\mathbf{r}) = -[\mu_n\mathbf{H}^*(\mathbf{r})]$, and using (26), we find that

$$\mathbf{H}^*(\mathbf{r}) = -4\pi\frac{\hbar}{m\gamma_n}\frac{a_+ - a_-}{2I+1}\sum_{j=1}^{N_0}\mathbf{I}_j\delta(\mathbf{r}-\mathbf{r}_j).$$

It is convenient to express this last expression in the form of a sum, of the spatially averaged and independent of the coordinates intensity vector of the homogeneous pseudomagnetic field and the spatially inhomogeneous part of the field $\mathbf{h}^*$ which depends only on the coordinates, the average value of which equals zero:

$$\mathbf{H}^* = -4\pi\frac{\hbar}{m\gamma_n}\mathbf{P}\frac{I}{2I+1}(a_+ - a_-) + \mathbf{h}^*(\mathbf{r}), \qquad (27)$$

where $\mathbf{P} = \langle\mathbf{I}\rangle/I$ is the polarization vector of the nuclei in the target. The field $\mathbf{h}$ is "seen" by the neutrons moving in the crystal as being periodic in time. Its magnitude fluctuates with frequency $2\pi v/d$, where v is the speed of a neutron, while $d \sim N^{-1/3}$. This frequency, even for slow neutrons, is always significantly greater than the instantaneous value of the Larmor precession frequency of a neutron in the local magnetic field in the crystal.[5] For this reason, it has almost no effect on the scattering of neutrons and it may be neglected. Thus, we obtain

$$\mathbf{H}^* = 4\pi\mu^* N\mathbf{P}, \qquad (28)$$

where

$$\mu^* = -\frac{\hbar}{m\mu_n}\frac{I}{2I+1}(a_+ - a_-), \qquad (29)$$

is a convenient auxiliary constant, having the dimensions of a magnetic moment and depending only on the nuclear characteristics of the target. Formally, it can be viewed as a pseudomagnetic moment, associated with a single nucleus in the target. This terminology was introduced by Abragam and is used in the foreign literature. The numerical value of μ^* can in some cases significantly exceed not only the magnetic moment of a nucleus, but also that of an electron. The pseudomagnetic moment, however, cannot be viewed as a source for the pseudomagnetic field and does not have ponderomotive effects on other particles. Equation (28) allows the introduction of the idea of pseudomagnetization of a medium $\mathbf{M}^*$, which can be defined as

$$\mathbf{H}^* = 4\pi\mathbf{M}^*. \qquad (30)$$

The intensity of the pseudomagnetic field and the quantity μ^* corresponding to it can be evaluated, if the difference in the scattering lengths $a_+ - a_-$ is known. Thus, for a hydrogen target $a_+ - a_- = 5.8\times10^{-12}$ cm and $\omega_0 = 2.3\times10^8$ sec^{-1}, which gives for H^* the value 1.3×10^4 Oe, exceeding the real magnetization created by the magnetic moments of the polarized protons in the target by about two orders of magnitude. The pseudomagnetic moment of the proton turns out to be especially large, $\mu_p^* = 5.4\mu_B = 3600\mu_p (\mu_B = 658\mu_p)$. This field can be made especially large in lanthanum-magnesium nitrate (LMN),[2)] in which the hydrogen nuclei in the hydrated water can be polarized with a polarization coefficient P, close to unity.[18] In this case it equals 25×10^3 Oe.

The concept of a nuclear pseudomagnetic field was first introduced in Ref. 3a. It allows for describing the behavior of neutrons in a crystal using language familiar in the theory of magnetism and having a well-established terminology. In describing the motion of neutrons in a crystal, the action of a nuclear field on the neutron spins can be completely replaced by the action of a pseudomagnetic field on neutron magnetic moments. This gives the possibility of using purely magnetic methods for finding the neutron transitions between two states, in particular, the methods of magnetic resonance. In Refs. 3, 4 it was shown that the existence of a pseudomagnetic nuclear field in a polarized target must lead to the precession of the neutron spin, to a shift in the paramagnetic resonance frequency, and to the appearance of a new type of resonance, in which the spin of a neutron is inverted under the action of the rotating pseudomagnetic field. We have already convinced ourselves of the existence of the first effect. The second effect is obvious from the theory presented below, while the third effect will be examined somewhat later.

The energy of the neutron magnetic moment in a magnetic field H_0 equals $-(\mu_n\mathbf{H}_0) = -\gamma_n\hbar(\mathbf{S}\mathbf{H}_0)$. For this reason, if the target is located in an external magnetic field, the expression for the energy (26) according to (27) takes the form

$$\overline{U} = U_0 - \mu_n(\mathbf{H}^* + \mathbf{H}_0), \qquad U_0 = 2\pi\frac{\hbar^2}{m}Na_{\text{coh}}. \qquad (31)$$

The magnetic field shifts the precession frequency of the neutron spins and changes the difference between the energy sublevels and, with $\mathbf{H}^* + \mathbf{H}_0 = 0$, can even make it equal to zero, i.e., it can compensate the splitting, caused by the nuclear pseudomagnetic field.

[1)] $\gamma_n = -2\pi\cdot2.917\cdot10^3$ Hz/Oe $= 18.33\times10^3$ rad/Oe-sec.

[2)] Lanthanum-magnesium dinitrate $La_2Mg_3(NO_3)_{12}\cdot2H_2O$ in which 1% of the lanthanum is replaced by neodymium (donor of unpaired electrons) has all the conditions required for effective dynamic polarization of nuclei.

It is important to note that in contrast with a true magnetic field a pseudomagnetic field cannot change the trajectory of a moving electrically charged particle. The situation here is completely analogous to the theory of ferromagnetism. The Weiss pseudomagnetic field, as was first demonstrated in the experiments by Dorfman[19] and later verified many times,[20] also does not have any ponderomotive effects on moving electrical charges.

The pseudomagnetic field, originating from exchange interactions as well as of nuclear origin, acts not on the electrical charges and not even on the magnetic moments of particles, but directly on their spin moments. This, at first glance, is an unusual force of interaction between particles related not to the familiar dependence of nuclear forces on spatial coordinates, but to their angular dependence on the mutual orientation of spins. The pseudomagnetic field acts on a neutron moving in a target only through a torque, which can only change the orientation of the neutron spin.

A similar interaction mechanism is well-known in the theory of optical orientation of atoms. A circularly polarized photon, absorbed by an atom, transmits to the atom an angular momentum $\hbar$, thereby orienting the atom in a definite way in space. The magnitude of the spin angular momentum of a circularly polarized photon, surprisingly, does not depend on its frequency and equals $\hbar$, for optical photons as well as radio frequency or industrial frequency photons. For this reason the effects related to the transfer of the spin angular momentum of a photon are proportional to the number of photons absorbed.

b) Equation of motion

We have seen that the passage of a beam of slow neutrons through a polarized target can be viewed as the propagation of a plane wave in a medium, the complex index of refraction of which depends on the mutual orientation of the spins of the neutrons in the beam and the nuclei in the target. On the other hand, the behavior of neutrons in a nuclear target can be described as the precession of their magnetic moments in some pseudomagnetic field. In those cases, in which both of these methods are used for describing one and the same phenomenon, both methods are completely equivalent. The second method, however, is preferable, since it gives the possibility of writing down an equation of motion describing the temporal evolution of the polarization vector of the neutron beam and revealing some important properties of the behavior of neutrons in a nuclear target, which escape the first method.

It is convenient for what follows to equate the energy levels of a neutron in the target $\overline{U}_{\pm}$ to

$$\overline{U}_{\pm}=\pm\mu_n|\mathbf{H}^*+\mathbf{H}_0|, \tag{32}$$

and to assume that their splitting is caused by constant pseudomagnetic H^* and magnetic H_0 fields. For this, in accordance with (23) and (31) it is enough to shift the reference level of the energy by U_0. This does not change the magnitude of their splitting:

$$\overline{U}_{+}-\overline{U}_{-}=\hbar\omega_0=2\mu_n|\mathbf{H}^*+\mathbf{H}_0|, \tag{33}$$

which we will consider as given.

The energy operator $\mathscr{H}_0$, the eigenvalues of which are determined by (32), is well-known:

$$\hat{\mathscr{H}}_0=-\hbar\gamma_n(\mathbf{S},\ \mathbf{H}^*+\mathbf{H}_0). \tag{34}$$

If, in addition to a constant field, a time-varying field $\mathbf{H}_1$ acts on the neutron, then we have

$$\hat{\mathscr{H}}=\hat{\mathscr{H}}_0-\hbar\gamma_n(\mathbf{S},\ \mathbf{H}_1). \tag{35}$$

The equation describing the change in time of the neutron spin operator $\mathbf{S}=\boldsymbol{\sigma}/2$ or the Pauli operator $\boldsymbol{\sigma}$

$$-i\hbar\frac{d\boldsymbol{\sigma}}{dt}=\{\hat{\mathscr{H}},\ \boldsymbol{\sigma}\},$$

where $\{\ldots\}$ are quantum Poisson (commutator) brackets for the two-level system described by the Hamiltonian (35), after simple transformations takes the form[44]

$$\frac{d\boldsymbol{\sigma}}{dt}=\gamma_n[\boldsymbol{\sigma},\ \mathbf{H}_0+\mathbf{H}_1]. \tag{36}$$

In order to avoid misunderstandings, we note that the brackets [,] on the right side of (36) denote the vector product of the quantities separated by the comma.

Let us introduce the vector $\vec{\mathscr{P}}$, describing the orientation and the degree of polarization of the neutron spins in the beam:

$$\vec{\mathscr{P}}=\langle\boldsymbol{\sigma}\rangle=\langle\psi\,|\,\boldsymbol{\sigma}\,|\,\psi\rangle.$$

Then, according to (36) we have

$$\frac{d\vec{\mathscr{P}}}{dt}=\gamma_n[\vec{\mathscr{P}},\ \mathbf{H}], \tag{37}$$

where $\mathbf{H}=\mathbf{H}_0+\mathbf{H}_1$. The vector $\vec{\mathscr{P}}$ is related in a simple way to the average spin vector $\langle\mathbf{S}\rangle=\vec{\mathscr{P}}/2$ and the average magnetic moment of the neutron $\langle\mu_n\rangle=\hbar\gamma_n\langle\mathbf{S}\rangle$.

Equation (37) allows the use of classical language to describe in a unified manner the motion of the neutron spin in a pseudomagnetic field H^* as well as in external magnetic fields, with the interaction of the neutrons with the nuclear force field, described by means of the pseudomagnetic field, being determined by the mutual orientation of their spin angular momenta. The external magnetic field acts directly on the magnetic moments of the neutrons.

Equation (37) is valid for a field that is constant, as well as for one that varies arbitrarily with time.

The interaction of neutrons with unpaired electrons and nuclear magnetic moments, the electron angular momenta of various impurities, and so on leads to a disorientation of the neutron spins. Together with the usual processes related to the precession of the polarization vector of the beam, there occurs a dissipation of its energy and degree of polarization. It can be taken into account by adding to Eq. (37) relaxation terms, completely analogous to the manner in which this is done in the theory of magnetic resonance.[21] It is well-known that taking relaxation into account leads in this case to an equation of the Bloch type. Here, we will not examine the dissipation processes for the polarization of neutrons, caused by the reasons cited above. In the situations considered, they do not have a significant effect on the experimental results.

We can consider the pseudomagnetic field of the target as being homogeneous. It acts in an identical manner on each neutron of a monoenergetic beam. For this reason, if the initial coherent state, in which the polarized neutrons in the beam are incident on the target, is the same, the new state, in which they exit from the target, will also be the same. Its polarization will change due to the action of the pseudomagnetic field in proportion to the distance that the neutrons traverse in the target $z=\hbar kt/m$. This change can be described with the help of Eq. (37) as if it occurs in time. Both of these methods, of course, are equivalent.

By describing the precessional motion of neutrons with the help of Eq. (37), we neglect not only the relaxation processes, leading to a change in the length of the polarization vector $\vec{\mathcal{P}}$, but also effects related to the coherent structure of the beam, which leave the length of the vector $\vec{\mathcal{P}}$ unchanged. A stationary flux of polarized neutrons, incident on the pseudomagnetic field of the target, is a non-equilibrium state, which is well-known in the theory of two-level systems. Such states arise every time that an ensemble of polarized particles with spin can be viewed as a single quantum mechanical system.[14]

It can be shown that taking the coherent structure of the neutron beam into account leads to the necessity of supplementing Eq. (37) with a relaxation term. As a result, it takes on the form

$$\frac{d}{dt}\vec{\mathcal{P}}=\gamma_n[\vec{\mathcal{P}},\mathbf{H}]-\alpha\frac{\gamma_n}{\mathcal{P}}[\vec{\mathcal{P}},[\vec{\mathcal{P}},\mathbf{H}]],\qquad(38)$$

known as the Landau-Lifshitz equation.[33] A relaxation term of this type does not change the length of the polarization vector $\vec{\mathcal{P}}$; it can only change the vector's orientation. The tip of the polarization vector always moves on the surface of a sphere of radius $\mathcal{P}$, the magnitude of which, under the stated assumptions, does not change. It is convenient to normalize the length of the vector $\vec{\mathcal{P}}$ in such a way that it is equal to unity.

Let us examine the case, when $\mathbf{H}=\mathbf{H}^*$ does not depend on time. Forming a scalar product of (38) with $\mu_n\mathbf{H}^*$, we find

$$-\frac{d}{dt}(\mu_n\vec{\mathcal{P}}\mathbf{H}^*)=-\frac{\alpha}{\hbar\mathcal{P}}[\mu_n\vec{\mathcal{P}},\mathbf{H}^*]^2.$$

The left side of this last expression determines the change of the average energy of a neutron $-\mu_n(\vec{\mathcal{P}}\mathbf{H}^*)$ as it moves in the field $\mathbf{H}^*$.

Assuming that $\mathcal{P}_z=\mathcal{P}\cos\theta$, we find an equation, determining the change in the angle θ, formed by the vector $\vec{\mathcal{P}}$ and the direction of the field $H=H_z$:

$$\frac{d\theta}{dt}=-\alpha\omega_0\sin\theta,\qquad(39)$$

where $\omega_0=\gamma_n H^*$. If at the instant $t=0,\theta=\theta_0$, its solution

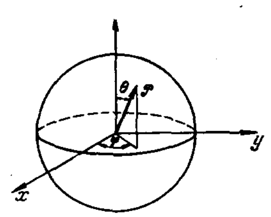

FIG. 2. The system of coordinates for describing the evolution of the polarization vector $\vec{\mathcal{P}}$ of a neutron beam.

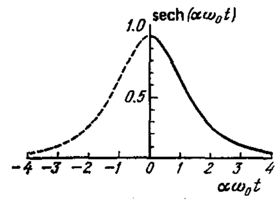

FIG. 3. A graph of the hyperbolic secant solution as a function of time.

has the form

$$\mathrm{tg}\frac{\theta}{2}=\mathrm{tg}\frac{\theta_0}{2}e^{-\alpha\omega_0 t}.\qquad(40)$$

From here, if $\theta_0=\pi/2$, then we have

$$\sin\frac{\theta}{2}=\frac{\exp(\alpha\omega_0 t/2)}{\sqrt{2\,\mathrm{ch}(\alpha\omega_0 t)}},\quad\cos\frac{\theta}{2}=\frac{\exp(-\alpha\omega_0 t/2)}{\sqrt{2\,\mathrm{ch}(\alpha\omega_0 t)}}\qquad(41)$$

and

$$\sin\theta=\mathrm{sech}(\alpha\omega_0 t).\qquad(42)$$

These solutions of Eq. (38) are well-known in quantum optics. They are used for describing the phenomena of superradiation, the optical echo, and induced transparency. Completely identical phenomena can, in principle, occur also with the passage of sufficiently short neutron pulses through a nuclear target.

In this way, the polarization vector $\vec{\mathcal{P}}$, rotating around the direction of the homogeneous field $\mathbf{H}^*$ with an angular velocity ω_0 and describing a spiral curve on the surface of a sphere of radius $\mathcal{P}$, relaxes, inclining away from the initial direction $\theta=\theta_0$ in accordance with (40). The graph of the function $\theta(t)$ is illustrated in Fig. 3.

It is convenient to examine the motion of the vector $\vec{\mathcal{P}}$ in a system of coordinates rotating around the direction of the field $\mathbf{H}^*$ with frequency $\omega_0=\gamma_n H^*$. Larmor's theorem is valid for the pseudomagnetic field, just as for the normal magnetic field as well as for their sum $\mathbf{H}_0+\mathbf{H}^*=\mathbf{H}$.

The transverse component of the vector $\vec{\mathcal{P}}$ can be easily found directly from Eq. (38). In the rotating coordinate system we have

$$\frac{d\mathcal{P}_x}{dt}=-\frac{\alpha\omega_0}{\mathcal{P}}\mathcal{P}_z\mathcal{P}_x,\quad\frac{d\mathcal{P}_y}{dt}=-\frac{\alpha\omega_0}{\mathcal{P}}\mathcal{P}_z\mathcal{P}_y,\qquad(43)$$

and in addition,

$$\frac{d\mathcal{P}_z}{dt}=\frac{\alpha\omega_0}{\mathcal{P}}(\mathcal{P}^2-\mathcal{P}_z^2);\qquad(44)$$

from here, transforming to a laboratory system of coordinates, we find

$$\mathcal{P}_x=\mathcal{P}\frac{\cos\omega_0 t}{\mathrm{ch}(\alpha\omega_0 t)},\quad\mathcal{P}_y=\mathcal{P}\frac{\sin\omega_0 t}{\mathrm{ch}(\alpha\omega_0 t)},\qquad(45)$$

while

$$\mathcal{P}_z=\mathcal{P}\,\mathrm{th}(\alpha\omega_0 t).\qquad(46)$$

Equations (45)–(46) can be obtained directly from geometrical considerations, noting that

$$\mathcal{P}_x=\mathcal{P}\sin\theta\cos\omega_0 t,\quad\mathcal{P}_y=\mathcal{P}\sin\theta\sin\omega_0 t,\quad\mathcal{P}_z=\mathcal{P}\cos\theta,$$

and using (42).[7]

Assuming that $2\theta=\varphi$, and differentiating (39) with respect to time, we find

$$\ddot{\varphi} = \alpha^2\omega_0^2 \sin\varphi.$$

This equation describes the motion of an inverted physical pendulum, which makes a complete revolution with a change in the angle θ from 0 to π. If at $t+0$, $\theta=\pi/2(\varphi=\pi)$, then with $t\to\infty$ $\theta\to\pi(\varphi\to 2\pi)$. The total energy of the pendulum, as follows from (39), is constant:

$$\frac{\dot{\varphi}^2}{2} + \alpha^2\omega_0^2\cos\varphi = \alpha^2\omega_0^2.$$

The relaxation term in (38), in accordance with (45), causes the neutron spin precession signal to depend on time, $\exp(i\omega_0 t)/\mathrm{ch}(\alpha\omega_0 t)$ (for $t>0$), which determines the shape of the absorption line. Its width is $\sim\alpha\omega_0$.

c) Pseudomagnetic resonance

It is well-known that in order to observe magnetic resonance a system of paramagnetic particles, located in a sufficiently strong constant magnetic field H_0, is subjected to the action of a weak oscillatory field, the frequency of which ω is close to the Larmor spin precession frequency $\omega_0=\gamma H_0$. As ω approaches ω_0, energy is absorbed from the oscillatory field, which is accompanied by an inversion of the particle spins.

This type of experiment can be performed with a beam of neutrons, passing through a polarized nuclear target, located in an oscillatory magnetic field at the resonant frequency. If such an experiment were successful, then it would not only verify the spin dependence of nuclear forces, but it would be a direct proof of the reality of the pseudomagnetic field and a direct method for measuring the magnitude of this field. Such a direct experiment has not yet performed. There are serious difficulties in performing such an experiment.

In order to determine the precession frequency of the neutrons in the pseudomagnetic field H^*, it is easiest to use the molecular beam method.[22] A sufficiently intense beam of neutrons can be obtained from a reactor. Having passed through a polarizer, the neutrons acquire a polarization exceeding 0.99. Subsequently, they pass through a target, the nuclei of which are polarized by the method of dynamic polarization. In the early experiments a lanthanum-magnesium nitrate crystal was used as such a target. The target was placed in the constant field H_0 of a magnet. The coil surrounding it created, perpendicular to $\mathbf{H}_0$, a radio frequency field $2H_1\cos\omega t$, which was equivalent to a field rotating around $\mathbf{H}_0$ with an amplitude H_1.

Having passed through the target and the analyzer, the neutrons enter a counter. If the analyzer is connected in such a way that only neutrons with polarization opposite to the initial polarization pass through it, then the counting rate will be negligibly small, if the radio frequency (RF) field does not change their orientation. A change can occur if the frequency of the RF field ω equals the resonant frequency. The fraction of neutrons with inverted spins will be significant only under the condition that the flight time of the neutrons through the target l/v is sufficiently great so that the angle through which the neutron spin rotates $\varphi=\gamma_n H_1 t$ equals π. If it is assumed that $l=0.4$ cm, $v=4\cdot10^5$ cm/sec, as was the case in the experiments,[5] then $2H_1\sim 100$ Oe.

The preparation of polarized targets using the method of dynamic polarization of nuclei is performed at a temperature ~1 °K and lower. Under these conditions it is technically difficult to apply a radio frequency field with an amplitude significantly greater than 1 Oe. The magnitude of the required field can be decreased by increasing, for example, the thickness of the sample by an order of magnitude and decreasing the speed of the neutrons. However, practical realization of these conditions is extremely difficult.

Fortunately, in the situation under consideration there is the interesting possibility of "amplifying" the radio frequency field by a method similar to the well-known method in the theory of nuclear ferromagnetic resonance.[25] The concept is simple and demonstrates persuasively the physical reality of the pseudomagnetic nuclear field. The essence of this method consists of the following. Let the direction of the constant magnetic field $\mathbf{H}_0$, in which the polarized target is located, form an angle θ with the direction of the nuclear polarization (Fig. 4). In this case the proton spins in the target, i.e., the polarization vector $\vec{\mathscr{P}}$, and therefore, the pseudomagnetic field $\mathbf{H}^*$ as well, will begin to precess about the direction of the external magnetic field with a frequency $\omega_p=\gamma_p H_0$, where γ_p is the gyromagnetic ratio of the proton. At the same time, there arises, in the plane perpendicular to the direction of $\mathbf{H}_0$, an oscillatory pseudomagnetic field H_1^*, the magnitude of which is determined by the relationship

$$H_1^* = H^*\sin\theta, \tag{46'}$$

while the rotational frequency is determined by the precession frequency of the protons ω_p in the field H_0. Naturally, when the frequencies ω_p and ω_n coincide, the field H_1^* will induce transitions of neutrons between states with different polarization, which can be detected experimentally by the method described above. This method can be appropriately called the pseudomagnetic resonance method. In order to create the conditions required for its appearance, it is necessary that the angle formed by the direction of the pseudomagnetic field or the nuclear polarization vector of the target and the acting magnetic field be different from zero. This can be done with the help of the rotating RF magnetic field, the frequency of which ω is close to the precession frequency of the magnetic moments of the protons in the target in the constant field H_0.

It is convenient to study the phenomena in a system, rotating about the direction $0z$ with frequency ω, close

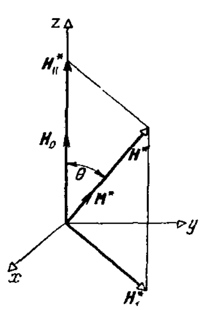

FIG. 4. The effective field in a rotating coordinate system.

to ω_p. The RF field is constant in this system, while the constant field is decreased by $-\omega/\gamma_p$. The protons in the target are located in the effective field

$$\mathbf{H}_{\text{eff}} = \left(H_0 - \frac{\omega}{\gamma_p}\right)\mathbf{k} + H_1\mathbf{i},$$

where $\mathbf{k}$ and $\mathbf{i}$ are the unit vectors for the z and x coordinate axes. As the steady state is attained, their magnetization aligns itself with the direction of this field. It forms an angle θ with the $0z$ axis given by

$$\operatorname{tg}\theta = \frac{H_1}{(\omega/\gamma_p) - H_0} = \frac{\gamma_p H_1}{\omega - \omega_p}. \tag{47}$$

If the detuning frequency $\Delta = \omega - \omega_p$ is not large, a stationary state is attained quite rapidly.

In the laboratory system of coordinates the effective field $\mathbf{H}_{\text{eff}}$, the pseudomagnetic field $\mathbf{H}^*$, and the proton magnetization precess about the direction $0z$. If the detuning frequency Δ is several times greater than $\gamma_p H_1$, which is always attainable, then we have $\operatorname{tg}\theta \approx \theta$. The component of the pseudomagnetic field H_1^* in this case equals

$$H_1^* \approx \frac{\gamma_p H^*}{\omega - \omega_p} H_1 = \eta H_1, \tag{48}$$

where the quantity $\eta = \gamma_p H^*/\Delta$, which, in analogy to the accepted practice in the theory of nuclear magnetic resonance in ferromagnets, can be called the amplification factor of the radio frequency field H_1 applied to the target. Let us estimate the magnitude of the field H_1^* for lanthanum magnesium nitrate. For $\Delta/\gamma_p = 100$ Oe and $P = 0.5$, we find $H_1^* = 125 H_1$. With $H_1 \approx 1$ Oe, the field H_1^* is great enough to have the time to invert the spins of the neutrons, passing through the target.

There is nothing to stop us from choosing the frequency of the field ω equal to the precession frequency of a neutron located in a field $H_0 + H^*$ acting on it, i.e., to take

$$\gamma_p H_0 + \Delta = \gamma_n (H^* + H_0).$$

This allows an estimate to be made of the intensity of the constant magnetic field H_0,

$$H_0 = \frac{H^* - (\Delta/\gamma_n)}{(\gamma_p/\gamma_n) - 1} \approx \frac{H^*}{(\gamma_p/\gamma_n) - 1}, \tag{49}$$

necessary for observing the pseudomagnetic resonance and for measuring the intensity of the pseudomagnetic field H^*. Inasmuch as $\gamma_p/\gamma_n \approx 3/2$, we obtain $H_0 = -(2/5)H^* = -10^{+4}P$. Thus, in order to induce neutron transitions it is necessary to have a negative proton polarization, which can be obtained with the help of the solid-effect.[18,21]

d) Expected results. Experimental observations of pseudomagnetic resonance[5]

For the purpose of observing paramagnetic resonance, a small quantity of a paramagnetic impurity (from 10^{-3} to 10^{-5}) is introduced into the sample that must be polarized. The sample is placed into a strong constant magnetic field H_c and subjected to an ultrahigh frequency field, the frequency of which is somewhat larger or smaller (depending on the sign of the required nuclear polarization) than the Larmor frequency $\omega_s = \gamma_s H_c^{\square}$ of the electrons in the paramagnetic impurities. The higher the frequency of the ultrahigh frequency field, the higher is the limiting DPN. For this reason, the field H_c, for which a large polarization appears, cannot be imposed at the same time as the field determined by Eq. (49).

As a result of this the experiment is carried out in two stages. First, the protons are polarized in a strong magnetic field H_c, where they acquire a negative polarization P. Then, this field is decreased to the magnitude H_0', somewhat less than $(2/5)H^*$, and a radio frequency field of frequency $\omega = \gamma_p H_0' + \Delta$, where $|\Delta| \ll \gamma_p H_0'$ is applied. In the presence of a radio frequency field the nuclear polarization decreases with some time constant τ (depending on Δ and H_1) and passes through the resonant value

$$P_{\text{res}} = -\frac{5}{2\varkappa} H_0' = -10^{-4} H_0' \qquad (H^* = \varkappa P). \tag{50}$$

When $\omega \approx \omega_p$, conditions arise for the resonant inversion of the neutron spins. After some time, the nuclear polarization disappears. At any stage in the magnetization decay process the polarization of the protons in the target can be measured with the help of the usual techniques of nuclear magnetic resonance. It can be controlled, and after calibration, it can be measured, while observing the changes in the intensity of the neutron beam passing through the target and the analyzer.

It is well-known that the cross section for scattering of neutrons by protons is minimum when their spins are parallel. From this it follows that the intensity J_p of the beam passing through the target with polarization parallel to the polarization of the target is greater than the intensity J_a of the beam with opposite polarization. The decrease in J_p or the increase in J_a to their common value allows the decay of the nuclear polarization with time to be monitored.

Let us assume that the neutron beam has negative polarization ~100%. The nuclei also have negative polarization. Then, the experiment can be set up as illustrated in Fig. 5. The neutrons, having passed through the target, are incident on the analyzer, a FeCo crystal, which passes negatively polarized neutrons into the counter C and deflects into the other control counter C' some fraction f of the neutrons, which have positive polarization. As soon as the transient process, in which the field approaches a magnitude somewhat less than $2/5H^*$, begins, the radio frequency field is switched on

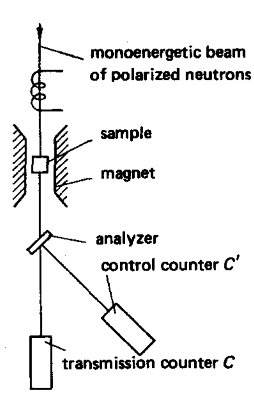

FIG. 5. Diagram of the experimental arrangement.[5b]

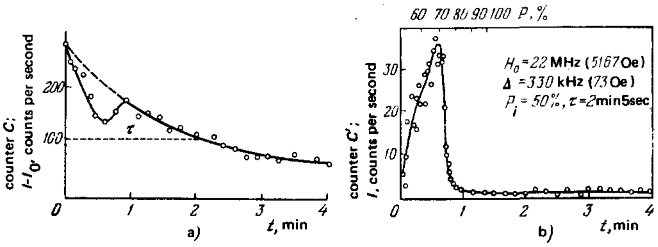

FIG. 6. a) The appearance of the pseudomagnetic resonance signal on the graph of the counts detected by the counter C^{5b}; b) the pseudomagnetic resonance signal on the graph of the counts detected by counter C'^{5b}.

with frequency $\omega = \gamma_p H_0' + \Delta$, and the counting rates $N(t)$ and $N'(t)$ of the counters C and C' become functions of time. The nuclear polarization P decreases with the time constant τ from some initial value P_i to the resonance value P_{res} and then to zero. The counting rate N' of the counter C' remains negligibly small until the value P_{res} is attained. At this instant, it increases to some maximum value and then drops to zero. This increase arises from the influence of resonance transitions, induced by the oscillatory field and accompanying the inversion of the neutron spins. In this way, the counting rate $N(t)$ decreases with a time constant τ from its value $J(0)$ to J_0 and exhibits a bump when $P = P_{res}$. Conversely, with a change in the counting rate $N'(t)$ at the instant of the neutron resonance, a dip must appear.

The results of experiments carried out at Saclay at the suggestion and under the guidance of A. Abragam,[5] completely agree with the theoretical predictions presented above.[3,4]

In these experiments, a lanthanum magnesium nitrate crystal was used as a polarized target. A diagram of the experiment is presented in Fig. 5. Figure 6 shows the experimental graphs of the counting rates $N(t)$ and $N'(t)$ for given values of the parameters Δ, H_0', P_i. The dip (Fig. 6a) and the peak (Fig. 6b) are clearly visible for the corresponding quantities as a function of decay time for the nuclear magnetization. The experiments do not leave any doubt as to the reality of the concept of the pseudomagnetic field, allowing an adequate, convenient, and correct description of the phenomenon of pseudomagnetic resonance. The control experiment with positive nuclear polarization P_i, as expected, did not exhibit resonance behavior in the decay curves of nuclear magnetization.

e) Experiments on detecting precession of neutron spin

For most nuclei the attainable degree of polarization and the magnitudes of the pseudofield intensities corresponding to them are many times smaller than for protons. In order to measure such fields, the French group at Saclay[9] used Ramsey's method.[22] In this method, sensitive to small changes in a strong constant field, it is not the Larmor frequency that is measured, but rather the precession angle φ of the neutron polarization vector $\vec{\mathscr{P}}$ is measured as a function of the nuclear polarization of the target. A diagram of the apparatus used is shown in Fig. 7.

A monoenergetic neutron beam from a reactor, pass-

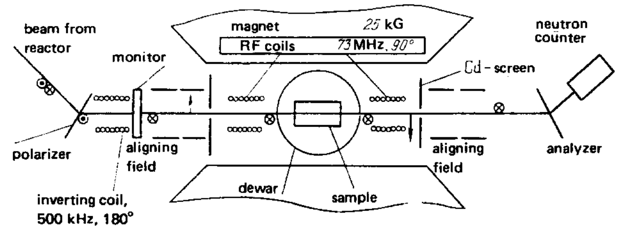

FIG. 7. Diagram of the experiment in Ref. 6.

es through a polarizer and enters the space between the poles of a magnet producing a constant homogeneous magnetic field $H_0 = 25$ kOe. In this field, directed perpendicular to the direction of motion of the neutrons in the beam, there are placed two coils fed from the same generator and in which a radio frequency field is produced at the resonant frequency $\omega = \gamma_n H_0$ and directed along the beam. The amplitude H_1 of the RF field component in the first coil, rotating in the direction of the precession of the neutron spins in the field H_0, is chosen in such a way that after it passes, the neutron spins, having been rotated by $\pi/2$, would be oriented perpendicular to H_0. After leaving the coil, and situated only in the field H_0, the neutron spins, precessing about its direction with a frequency $\gamma_n H_0$, after a time L/v reach the second coil (L is the distance between the coils).

Thus, during the time of flight through the space between the coils by the time the beam enters into the active zone of the second coil the direction of the neutron spins, i.e., the vector polarization $\vec{\mathscr{P}}$ of the neutron beam, will rotate by an angle $\varphi = \gamma_n H_0 L/v$. Since the RF field in the second coil is produced by the same generator as in the first coil, if the field H_0 is homogeneous enough and the frequency of the RF field is exactly equal to the resonant frequency, the corresponding rotating component of the field in the second coil likewise rotates by an angle $\varphi_{RF} = \varphi$. In this case, it is as if the second coil picks up the neutrons without a loss in phase at the point where they left the first coil. After the second coil has been traversed the vector polarization $\vec{\mathscr{P}}$ of the neutrons rotates again by an angle $\pi/2$ and becomes antiparallel to the initial direction, independently of the speed of the neutrons and of the distance L between the coils.

A target with polarized nuclei and having a thickness d is placed in the space between the coils. The pseudomagnetic field H^* existing in this space contributes an additional phase shift to the phase of the polarization of the beam of precessing neutrons, rotating the polarization vector by an angle $\Delta\varphi = \gamma_n H^* d/v$. If an additional phase shift φ_0 is added in some way to the polarization of the beam, then the RF field will affect only that component of the polarization that is perpendicular to H_1. For this reason, the component of the polarization along the direction of the field H_0, which is measured by the analyzer after the neutrons pass through the field of the second coil, will be decreased to $\mathscr{P}_\perp = \mathscr{P}\cos(\varphi_0 - \Delta\varphi)$.

Thus by measuring the component of the neutron polarization vector $\mathscr{P}_\perp$ for different values of φ_0, it is possible to calculate the phase shift $\Delta\varphi$, the intensity of the pseudomagnetic field H^* or, the more convenient

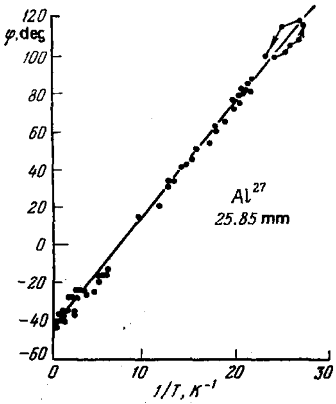

FIG. 8. The phase shift φ as a function of the reciprocal temperature for Al^{27}.[6]

nuclear constant for the substance μ^*, independent of the concentration N of nuclear spins in the target and the degree of its polarization P, according to the formula

$$\Delta\varphi = 4\pi\gamma_n N \frac{d}{v} \mu^* P. \tag{51}$$

If the target is polarized in a magnetic field by cooling in a refrigerator, it is possible to use without great error the high temperature expansion of the Brillouin function,[20] according to which

$$P = \frac{I+1}{3} \gamma_N \frac{\hbar H_0}{kT},$$

where γ_N is the gyromagnetic ratio for the nuclei in the target. Then we have

$$\Delta\varphi = 4\pi \frac{\hbar\gamma_n}{k} d \frac{H_0}{v} N \frac{I+1}{3} \gamma_N \frac{\mu^*}{T}. \tag{52}$$

The description of the cooling system, the control and measurement of the radio frequency signals, the technique for counting the neutrons and the method used for determining the angle can be found in Ref. 6.

The characteristic dependence of $\Delta\varphi$ on $1/T$, obtained for Al^{27}, is shown in Fig. 8. In Ref. 6 the magnitudes of μ^* and $a_+ - d$ were measured with this method for a series of nuclei shown in Table I. The same method was used in Ref. 8 to measure systematically the pseudomagnetic moments of the nuclei. The results are shown in Table I. The details concerning these measurements can be found in Refs. 26, 27. The work by Forte,[7] cited above, is conceptually similar to this work.

We will present some results illustrating the possibility of performing experiments on the behavior of spins in a pseudomagnetic field with the aim of studying the physical processes, in particular, relaxation processes, occurring in nuclear systems. According to (51), by measuring the precession angle of the spins $\Delta\varphi$ with a known value of μ^*, it is possible to determine the absolute value of the degree of polarization of the nuclei in the target. The change in P with time is determined by the longitudinal relaxation time. By studying the dependence of the precession angle of the spins on the magnitude of the nuclear polarization, it is possible to measure not only the intensity of the pseudomagnetic field H^* or the pseudomagnetic moment μ^*, but also the spin-lattice relaxation time. The nuclear polarization in a holmium (Ho^{165}) ethylsulfate monocrystal was studied, the value of $\mu^* = (0.74 \pm 0.08)\mu_B$ was measured, and the spin-lattice relaxation time was found for Ho^{165} and H^1 nuclei, and their temperature dependence was also studied in Ref. 9.

The method of pseudomagnetic precession has definite advantages in comparison with the usual, well-known NMR methods for measuring nuclear polarization and relaxation. This method allows, as already noted, the absolute value of the nuclear polarization to be measured directly. It can be used under experimental conditions in which the NMR signal is difficult to observe. Thus, it can be successfully used for observing NMR in massive metallic samples, when the line is broadened due to electron magnetism. Without dwelling on the many interesting results in Ref. 9, falling outside the scope of the present review, we note only that the method of pseudomagnetic resonance can also be used successfully for observing the usual electron or nuclear resonance in crystals.

The pseudomagnetic resonance method was recently applied to strongly magnetic substances.[8] Using cobalt, which has a body centered and hexagonal lattice, as an example, it was shown that measurement of the precession angle can give precise information concerning the internal magnetic field created by bound (d or f) and free electrons, which "see" the nuclei, as well as concerning fields of dipole origin, created by neighboring ions, and so on.[34b]

TABLE I.

isotope	spin	μ^*/μ_B	$(a_+ - a_-)\cdot 10^{-12}$, cm	isotope	spin	μ^*/μ_B	$(a_+ - a_-)\cdot 10^{-12}$, cm
H^1	1/2	5.4	5.8	Co^{59}	7/2	−1.88	−1.16
Li^7	3/2	−0.62	−0.45	Cu^{63}	3/2	1.97	0.045
Al^{27}	5/2	0.077	0.52	Cu^{65}	3/2	0.51	0.37
Sc^{45}	7/2	1.95	1.2	Pt^{195}	1/2	−0.21	−0.23
Zr^{91}	5/2	0.7	0.58	Au^{197}	3/2	−0.49	−0.36
Nb^{93}	9/2	−0.046	−0.028	Te^{125}	1/2	0.03	—
La^{139}	7/2	1.2	0.75	Ag^{109}	1/2	−0.16	—
Ta^{181}	7/2	−0.1	−0.06	Pb^{207}	1/2	0.02	0.02
Na^{23}	3/2	0.99	0.71				

f) The pseudomagnetic moment

The part of the neutron scattering amplitude a_n that depends on the mutual orientation of spins, according to (3), is equal to $(a_+ - a_-)/(I+\frac{1}{2})$. This quantity is an important nuclear constant for the target substance and for a given concentration of nuclei N and polarization P of the target, it determines, according to (28), the intensity of the pseudomagnetic field $\mathbf{H}^*$. Here, we had the opportunity to demonstrate the naturalness and convenience of introducing this concept, its informal nature and we were also able to present proof of its reality.

The concept of the pseudomagnetic moment μ^* defined by means of (29) differs from a_n only by the constant factor $\hbar/m\gamma_n$, which contains, in addition to the ratio of universal constants $\hbar$ and m, the g-factor for the neutron g_n, equal to −1.19. The nuclear pseudomagnetic moment is likewise a nuclear constant. Its magnitude does not depend on N and P and enters clearly into the definition of the pseudomagnetization of the target M^*.

It can be viewed quantitatively as the pseudomagnetic moment per scattering nucleus. The information contained in the scattering amplitude a_n and in the concept of the pseudomagnetic moment μ^* is identical. However, the use of the quantity μ^* in some cases can be more convenient, since it allows for comparison with the true magnetic moments of electrons or nuclei and for interpretation of neutron scattering experiments with the help of concepts distinguished by the simplicity and clarity of the theory of magnetism. The pseudomagnetic moment can be expressed in terms of the electron Bohr magneton as follows:

$$\frac{\mu^*}{\mu_B} = -\frac{1}{g_n}\frac{a_+ - a_-}{r_0\left(I+\frac{1}{2}\right)}, \tag{53}$$

where $r_0 = e^2/m_e c^2$ is the classical electron radius. Substituting numerical values for g_n and r_0, we find that

$$\frac{\mu^*}{\mu_B} = 1{,}85\,\frac{a_+ - a_-}{I+(1/2)}\cdot 10^{12}. \tag{54}$$

The measured values for the difference $a_+ - a_-$ were presented above in Table I. The value of $a_+ - a_-$ is largest for protons.

The use of the pseudomagnetic moment concept cannot serve as a basis for excluding the physical concept of the pseudomagnetic field H^*. Its value has been repeatedly noted above.

The fact that the true magnetic moment and the pseudomagnetic moment do not have anything in common is easily traced also from a comparison of the two mathematically equivalent expressions (55), the first of which is used for introducing the pseudomagnetic field H^* and the second is used for the pseudomagnetic moment:

$$U = -(\mu_n \mathbf{H}^*) \text{ и } U = -(\mu^* \mathbf{A}_n). \tag{55}$$

Here, $\mathbf{A}_n$ denotes the quantity $4\pi N \mu_n \mathbf{P}$, which cannot be viewed as the intensity of a magnetic field created by the magnetic moments of the neutrons in the beam, since $\mathbf{P}$ is the polarization vector of the target and not of the neutrons.

The pseudomagnetic fields, acting on neutron spins in a target with polarized nuclei, have some interesting properties. The normal component of the pseudoinduction at the surface of the target is always continuous, while the magnetic induction, if the applied field is perpendicular to it at the surface, is discontinuous. The polarized nuclear target can play the same role as a magnetic crystal or a magnetic mirror. The gradient of pseudomagnetization in this case can be made much greater than in the case of ordinary magnetization. It is possible that apparatus capable of focusing neutrons strongly will be created on this basis.[3,5b]

g) Scattering of neutrons by nuclei in a magnetically ordered state

Recently, as a result of significant progress in the theory and techniques of nuclear magnetism, there has been a tendency toward a deeper study of nuclear spin systems in an ordered magnetic state (ferro- or antiferromagnetic).[2]

The basic difficulty arising in the study of ordered nuclear spin structures consists of the exceptionally low temperatures for the magnetic transition ($T \sim 10^{-6}$ °K). This is caused by the smallness of the magnetic moments of nuclei ($\sim 10^{-3}\mu_B$, where μ_B is the electron Bohr magneton), and therefore, of spin-spin interactions. For this reason, the present high degree of interest of crystalline He^3, the spin-spin interactions of which are of an exchange character and have a transition temperature of the order of a few thousandths of a degree, is understandable. For all other nuclear spins, the interactions are of a purely magnetic character. These can be direct magnetic dipole-dipole interactions, as well as indirect interactions, occurring via the atomic electrons. The transition temperature for such states turns out to be of the order of $10^{-6}-10^{-7}$ °K. In order to obtain magnetically ordered spin states, it is sufficient to cool not the entire crystal but only the system of nuclear spins.[2] This is accomplished by adiabatic demagnetization of nuclei preliminarily polarized by the method of dynamic polarization of nuclei. Recent experiments have verified the existence of such structures. They were detected by the method of nuclear magnetic (ferro-magnetic) resonance. These indirect methods, as applied to the problem being examined, were based on introducing the concept of spin temperature (the temperature of the dipole-dipole reservior[1,2]) in a rotating coordinate system.

The scattering of neutrons by such ordered nuclear structures enables one to hope to detect their existence directly and to observe their appearance and decay. The methods of magnetic neutron diffraction analysis have long since found widespread use and are used successfully for studying magnetic properties of crystals with electron, ferro- and antiferromagnetism[11] and, for the present, are the only direct methods for determining the magnetic structure of a system. However, their use in studying nuclear ordering until recently was not justified. The basis for this is the small magnitude of nuclear magnetic moments in comparison with electron moments. The contribution of nuclear magnetic scattering of neutrons in this case is masked by the stronger scattering by the electrons[28]. A different situation exists in the case when the scattering of neutrons by nuclei in crystals arises not from weak magnetic, but from strong nuclear interaction, which, as we have seen, depends on the orientation of the spins of the nuclei and the neutrons, and can significantly exceed magnetic scattering in magnitude. In this case, it can be formally viewed as scattering by pseudomagnetic moments μ^*, which in some cases exceed the magnitude of the electron moment. However, the real objects of study are only those systems, in which not only the value of μ^* is large, but for which it is possible to lower the temperature of the nuclear spins to the required value using available methods. For example, at the present time it is not yet possible to observe the ordering of fluorine nuclei in CaF_2, for which the spin temperature can be lowered to the record low value of 10^{-7} °K: the magnetic moment is too small ($\mu^* \approx 0.01\mu_B$). The most promising in this respect is the compound LiH: $\mu^*(Li^7) = -0.6\mu_B$, $\mu^*(H^1) = 5.4\mu_B$. It is in this par-

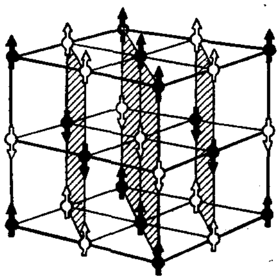

FIG. 9. Magnetic sublattices of nuclei in LiH.

ticular system that the first successful experiments of Abragam and his co-workers at Saclay were carried out.[40]

With a decrease in temperature the nuclear spins in LiH form an antiferromagnetic structure with two magnetic sublattices, as illustrated in Fig. 9. Neutrons incident on the crystal are scattered differently depending on the two opposite orientations of the nuclear spins. The LiH crystal and the neutron counter were situated in such a way that it would be possible to observe scattering of neutrons from the (110) plane. Scattering from this plane (in Fig. 9 these planes are shaded) was not detected until the expected transition temperature was attained in the demagnetization process. The results of the experiment are presented in Fig. 10. The ordinate axis shows the reading of the neutron counter, while the abscissa axis shows the cooling time, for cooling by the method of adiabatic demagnetization. The marker on the time axis shows the instant the nuclear system of the crystal makes a transition into the antiferromagnetic state and the termination of the cooling process. The right side of the curve characterizes the decay of the signal with a damping constant comparable with the spin-lattice relaxation time for the nuclear system.

The results of this experiment are very interesting and have far reaching consequences. The direct observation of nuclear ordering in LiH verifies the real meaning of the concepts of a dipole-dipole reservior and of a dipole temperature, which up to now have been viewed cautiously as a hypothesis. The success of this experiment testifies in favor of the problems raised in this review.

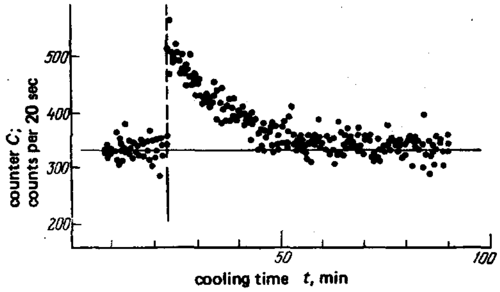

FIG. 10. Scattering of neutrons by nuclear spins in the case of adiabatic demagnetization. The marker shows the instant when the nuclei make a transition from the paramagnetic into the antiferromagnetic state.

3. EXAMPLES OF PSEUDOFIELDS OF A DIFFERENT KIND

The problem of scattering of neutrons by polarized proton targets examined in detail above with the help of a pseudomagnetic field, as we have already remarked, is by no means the only example of this type of problem. A number of other phenomena (some verified by experiment), which can be successfully explained with the help of the pseudofield concept, can be cited. Let us examine some examples, which are of definite interest.

Passage of electrons and atoms through a magnetized medium. Assume that an electron beam penetrates into a layer of substance, containing polarized atomic electrons. Such a medium can be made of, for example, a film magnetized to saturation or a flask filled with vapors of optically polarized atoms. The presence of macroscopic magnetization of the sample will lead, as we already know, to precession of the spin of the incident electrons around the direction of the field, associated with this magnetization. However, in contrast with neutrons, for electrons, in addition to the direct process of elastic coherent scattering, there exists an additional process depending on the spin state of the colliding particles, exchange scattering. In this case, the contribution of exchange scattering occurs as a result of two processes, related to the Coulomb exchange and magnetic exchange scattering, respectively. The existence of an interaction dependent on the spin state indicates that in the polarized target the particle beam is affected by some effective field, causing the precession of their spins with a frequency[31]

$$\omega = kv\,(n_{\uparrow\uparrow} - n_{\downarrow\uparrow}), \tag{56}$$

where k is the wave vector of the particles in the beam, v is their velocity, while $n_{\uparrow\uparrow}$ and $n_{\downarrow\uparrow}$ are the indices of refraction of the target medium for particles with spin parallel and antiparallel to the polarization vector of the target.

Using the relationship, familiar to us, between the indices of refraction and the elastic coherent forward scattering amplitude, we find that the contribution of exchange processes to the index of refraction for electrons with spin, oriented parallel to the electron polarization vector, is equal to

$$\delta n_{\uparrow\uparrow} = -2\pi \frac{N}{k^2} (f'_{\uparrow\uparrow} + f''_{\uparrow\uparrow}), \tag{57}$$

where $f'_{\uparrow\uparrow}$ and $f''_{\uparrow\uparrow}$ are the amplitudes of elastic coherent forward scattering due to Coulomb exchange and magnetic exchange interactions, respectively. The minus sign is related to the fact that in the triplet state the exchange amplitude is subtracted from the amplitude of the direct process. In order to simplify the calculation we assume that the electrons in the medium are completely polarized.

The contribution of exchange to the real part of the index of refraction for electrons with spin, antiparallel to the polarization vector of the scatterers $\delta n_{\downarrow\uparrow}$, is zero. This is related to the circumstance that, as a result of exchange, the spins of the incident electrons as well as those of the electrons belonging to the medium, change direction. Such a process is incoherent and leads only to absorption. Therefore, the contribution to the difference $n_{\uparrow\uparrow} - n_{\downarrow\uparrow}$, additional compared to the difference in the indices of refraction $n^{(0)}_{\uparrow\uparrow} - n^{(0)}_{\downarrow\uparrow}$ for electrons in the magnetic field of the target, can be written in the following form:

$$\delta n_{\uparrow\uparrow} - \delta n_{\downarrow\uparrow} = \frac{N}{k^2}(f'_{\uparrow\uparrow} + f''_{\uparrow\uparrow}). \tag{58}$$

Taking into account (56) and (58) we find that the change in the precession frequency of an electron spin, caused by exchange scattering, equals

$$\Delta\omega = -2\pi \frac{\hbar N}{m_e}(f'_{\uparrow\uparrow} + f''_{\uparrow\uparrow}), \tag{59}$$

where m_e is the electron mass. Thus, the precession frequency of the spin of electrons in the beam in the polarized target are determined by the relationship $\omega = \omega_L + \Delta\omega$, where ω_L is the Larmor frequency of an electron spin in the magnetic field of the polarized target.

For sufficiently fast electrons ($E \sim 1$ keV) with $kb \gg 1$ (b is the size of an atom) f' and f'' practically coincide with the amplitudes of elastic forward exchange scattering by a free electron initially at rest. As a result, for f' and f'' it is possible to write the following expressions:

$$f'_{\uparrow\uparrow} = -\frac{2e^2}{m_e v^2}, \quad f''_{\uparrow\uparrow} = \frac{4m_e}{\hbar^2}\mu^2\cos^2\theta, \tag{60}$$

where $\mu \approx \mu_B$ is the magnetic moment of the electron, θ is the angle between the momentum of the incident electron and the polarization vector of the electrons in the substance. From here it follows that

$$\omega = \omega_L + 4\pi \frac{\hbar}{m_e} N \left(\frac{e^2}{m_e v^2} - \frac{2m_e}{\hbar^2}\mu^2\cos^2\theta\right). \tag{61}$$

The presence of exchange leads to the dependence of the precession frequency on the velocity of the electrons and their direction of propagation relative to the direction of the target polarization. In this case the velocity dependence is related to the Coulomb exchange scattering, while the dependence on the angle θ is related to the magnetic exchange scattering.

For electrons of energy $E \sim 10$ keV, the contribution to ω originating from the Coulomb exchange scattering ($N \sim 10^{22}$ cm^{-3}) equals $\Delta\omega' \sim 10^{12}$ sec^{-1}, which corresponds to a pseudomagnetic field $H_1^* = \hbar\Delta\omega'/2\mu \approx 10^5$ Oe and increases with decreasing beam energy. The contribution to the frequency ω due to the magnetic exchange interactions is equal, as can be easily estimated, to $\Delta\omega'' = 4\pi, N\mu^2/\hbar \approx 10^{10}$ sec^{-1}. The corresponding effective field is $H_2^* \approx 10^3$ Oe, i. e., is of the same order of magnitude as the macroscopic field created by the polarized electrons.

Thus, due to exchange scattering, the spins of the electrons in a beam in a polarized target are affected not by the magnetic field $H_0 = 4\pi M_e$, where M_e is the magnetization of the electrons in the target, but by an effective magnetic field

$$\mathbf{H} = \mathbf{H}_0 + \mathbf{H}_1^* + \mathbf{H}_2^*. \tag{62}$$

For electrons of energy $E \sim 10$ keV and lower we have $H_1^* \gg H_0, H_2$. In this case, the precession frequency of the electron spins is determined not by the field H_0 but by the pseudomagnetic field H_1^*. The distance l, over which the spins undergo a complete revolution, is determined by the expression $2\pi\theta/\omega$. For electrons with $E \approx 10$ keV, we have $l \approx 10^{-2}$ cm, and this increases with increasing energy.

This phenomenon has not yet been studied experimentally. However, it is clear that in order to observe the precession of spins in the pseudomagnetic field the experimental arrangement discussed in detail earlier for neutrons is applicable.

Fields, analogous to H_1^* and H_2^*, act not only on free electrons, but also on electrons which are constituent parts of atoms forming a beam passing through a medium with polarized electrons. These fields lead to a shift of the ground and excited states of atoms moving, for example, in a polarized paramagnetic gas. In such a case inasmuch as the kinetic energy of electrons in an excited state of an atom is not large, the determining role in line splitting will be played by the field, caused by the Coulomb exchange interaction. The polarized atomic target or beam can be prepared by the method of optical orientation. At the present time such experiments can be performed.

It should not be overlooked that the field H^*, arising from the exchange Coulomb scattering is, by its nature, related to the effective field, acting on conduction electrons in the $s-d$ exchange model of ferromagnetism.[20,32] The difference lies only in the fact that in the case under consideration it is possible, by changing the energy of the electron beam, to change also the magnitude of the field. In ferromagnetic substances, the effective field arises from the exchange interaction of electrons in the medium, and for this reason, its parameters, at constant temperature, are known beforehand. In addition, the wave functions of electrons in the beam and electrons in the medium overlap much more strongly than the wave functions of electrons in the medium. For this reason, at speeds comparable to the speed of s electrons, i. e., with $v \sim 10^5$ cm/sec, the field H^* turns out to be greater in magnitude than the field "created by" the d-electrons. Undoubtedly, fields similar to H^* exist not only in ferromagnetic substances, but under certain conditions can also be produced in paramagnetic substances in an arbitrary aggregate state.

CONCLUSION

The rotation of the plane of polarization of neutrons and electrons, examined in this work, is characteristic not only of this type of particles. A similar phenomenon is observed for photons as well.

The magnitude of the intrinsic rotation of the plane of polarization of electromagnetic waves at optical frequencies is determined by the electron structure of atoms and molecules in the medium through which the radiation propagates. If one goes outside the optical range of the spectrum when the energy of short wavelength quanta becomes much greater than the average energy of electrons in the atoms and molecules, the interaction of the radiation with matter reduces to the interaction of photons with free electrons. In this case, the structure of atoms and molecules becomes insignificant and, therefore, the usual rotation of the plane of polarization, caused by the oscillations of the electron density in atoms, must disappear. But, it is precisely in this region, i. e., with quanta having large energies, that a different, unexpected, usually neglected, mechanism for the rotation of the plane of polarization of radiation, completely analogous to the nuclear precession of the neutron spin examined above, occurs in a polarized electronic target. This mechanism appears during the passage of γ-quanta through a polarized target. The state of the photon with left- and right-handed circular polarization in the target is determined by indices of refraction n_- and n_+, and as we have seen,

$$n_- - n_+ = \Delta n = 2\pi \frac{c^2}{\omega^2} N (f_- - f_+),$$

where f_- and f_+ are the amplitudes for elastic forward scattering of photons with left- and right-handed circular polarization by polarized electrons, N is the number of electrons per unit volume, and ω is the frequency of the photon.[35,36a,b]

No less interesting phenomena must arise in the case of passage of light at optical or radio frequencies through a naturally or artificially polarized anisotropic medium. Different indices of refraction, which can always be described in the pseudofield language, correspond to different polarizations of light. This is equivalent to the existence of an energy difference between two states of polarization for the same wavelength.[4a,36] But then, under the action of a high frequency electromagnetic wave with a resonant, in relation to the separation between these levels, frequency, the polarization of the light passing through an anisotropic medium can experience a change, accompanied by a change in frequency at a fixed wavelength. In such a case absorption or emission of photons of corresponding energy must occur.

The rotation of the plane of polarization of light by a spin-polarized system of atoms was predicted by Kastler[38] and was observed experimentally by Gozzini.[39] The angle of rotation of the plane of polarization of light of frequency ω, close to the resonant frequency, in an ensemble of optically oriented atoms of rarified alkali metal vapors turns out to be quite significant. It is proportional to the difference of the populations of the sublevels between which the optical transition occurs, and to the characteristic factor $\delta/(1+\delta^2)$, where $\delta = (\omega - \omega_0)/\Delta\omega$ is the detuning, while $\Delta\omega$ is the width of the line. Such a characteristic analog of the Faraday effect can by used to detect magnetic resonance without destroying the atomic polarization.

It is important to note that the phenomena discussed above involving a change in the state of polarization of particles (neutrons, electrons, photons) in a polarized medium, examined above, are greatly changed if the particles are incident on a crystal under conditions for which diffraction can occur.[41] It turns out that in this case the particle spins precess in the crystal with several frequencies, depending on the angle of incidence of the beam and on the orientation of the surface of the crystal relative to the crystallographic planes. The appearance of such anomalies is due to the fact that in a periodic lattice the energy spectrum of particles has a band structure of crystalline solids, which in the final analysis are responsible for effects noted above.

Phenomena, completely analogous to those examined here, must occur when any kind of particles with spin pass through polarized targets[34a]. The pseudomagnetic field, and in particular, the effective exchange field, affects the orientations of the spins of μ^+ mesons or positrons (muonium, positronium).[42]

The examples presented above provide ample testimony to the existence of a wide variety of qualitatively new and interesting phenomena that are, as we have seen, by no means always weak and difficult to observe, arising when particles with spin, pass through a polarized (anisotropic) medium. It can be hoped that their study will stimulate new experiments[30] and the appearance of new ideas in different areas of physics, which will, undoubtedly, find a variety of applications.[43]

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