Experiments with oriented nuclei and polarized neutrons

V. P. Alfimenkov, L. B. Pikel'ner, and É. I. Sharapov

Joint Institute for Nuclear Research, Dubna
Fiz. Elem. Chastits At. Yadra 11, 411–453 (March–April 1980)

Some possible experiments with oriented nuclei and polarized neutrons and methods of polarization of neutrons and nuclei are considered. Experiments reviewed include the investigation of the spin dependence of the neutron cross sections for fissile and nonfissile nuclei, the measurement of the magnetic moments of neutron resonances, and the study of radiative capture of polarized neutrons.

PACS numbers: 24.70. + s, 25.85.Ec, 25.40.Lw

INTRODUCTION

In experiments in nuclear physics, oriented nuclei and polarized neutrons are used to obtain information about features of the interaction and properties of neutrons and nuclei associated with the spin. In some cases, such information can also be obtained from investigations with ordinary neutrons and nuclei, though frequently these investigations do not ensure the necessary accuracy or give results only under unusual circumstances. However, many of the results obtained in experiments with polarized neutrons and oriented nuclei cannot be obtained by other methods at all.

A system of microscopic particles is said to be oriented if the spatial distribution of the orientations of the spins of the particles of the system is not isotropic. In accordance with quantum mechanics, the projection I_z of the spin I onto a given z axis can take $2I+1$ discrete values from $-I$ to I. If the conditions are characterized by axial symmetry, the distribution of the orientations of the spins with respect to this axis is obviously completely characterized by the $2I+1$ values of the probabilities $W(I_z)$ of observing all possible projections I_z. Since the energy level of a particle in a magnetic field is split into individual sublevels associated with different spin projections, the probabilities of realization of these sublevels are frequently called the relative populations of the corresponding sublevels. By virtue of the normalization $\sum_{-I}^{I} W(I_z)=1$, only $2I$ of the probabilities $W(I_z)$ are independent. This means that for the complete description of the distribution of the orientations of the spins of the system in the considered case it is sufficient to specify $2I$ values $W(I_z)$ or $2I$ independent parameters constructed by means of them. The parameters most widely used in experiments are the orientations f_i (Ref. 1), which are defined to be zero for an isotropic distribution and equal to unity for a system completely ordered in a given direction. The first two orientation parameters, which are the ones most frequently used, are defined by the expressions

$$\left.\begin{array}{l} f_1=\langle I_z\rangle/I; \\ f_2=[3/I\,(2I-1)]\,[\langle I_z^2\rangle-I\,(I+1)/3]. \end{array}\right\} \qquad (1)$$

Here, as usual, the angular brackets denote the expectation values. The parameters f_1 and f_2 are called, respectively, the polarization and alignment of the system of spins. The polarization characterizes the predominant orientation of the spins of the system in one of the directions of the z axis, while the alignment characterizes the orientation of the spins along the axis, irrespective of the direction on it. The polarization f_1 is used very frequently, since, on the one hand, it completely characterizes the spin orientation state of systems of particles with spin 1/2 and, on the other hand, it is sufficient for the description of a number of the simplest processes that take place in systems of particles with spin greater than 1/2. Sometimes, it is also necessary to use the orientation parameter f_3. This parameter, which has not received a special name, is defined by

$$f_3=[5/I\,(I-1)\,(2I-1)]\,[\langle I_z^3\rangle-(3I\,(I+1)-1)\,\langle I_z\rangle/5]. \qquad (2)$$

In the general case, a system of spins is said to be polarized if at least one of the parameters f_k with odd k is nonzero. If all f_k with odd k are zero but $f_k \neq 0$ for some even k, the system is said to be aligned.

If an investigated interaction of neutrons with nuclei depends on the relative orientation of the spins of the neutrons and the nuclei, the experimental results depend in general on the polarization of the beam and the orientation parameters of the target. This means that information about the spin dependence of the interaction can be obtained from experiments with polarized neutrons and oriented nuclei. Such experiments also make it possible to investigate spin-related properties of the compound nuclei produced by the capture of neutrons by the target nuclei. This last possibility is due to the circumstance that the system of compound nuclei produced by the capture of polarized neutrons by oriented nuclei is oriented in a definite manner.

In experiments using neutrons, one is dealing with two interacting systems of microscopic particles: the neutron beam (spin of the particles $s=1/2$) and the nuclear target (nuclei with arbitrary spin I). The neutron beams of the majority of sources and ordinary nuclear targets are usually not oriented. Special methods are used to polarize neutron beams and orient nuclei in targets.

Although investigations with polarized neutrons and oriented nuclei have now been made for more than a quarter of a century, it cannot be said that the accumulated experimental material is rich. This is due to the great technical difficulties encountered in obtaining polarized neutrons and oriented nuclei. It is necessary to use superlow temperatures and very high magnetic fields and various subtle methods. In recent years, the situation has somewhat improved. A number of major

 0090-4759/80/020154-18$02.80

physical and technical advances, such as the development of the method of polarization of slow neutrons by passing them through a polarized proton target, the development of cryostats with a solution of ^{3}He in ^{4}He at temperatures $T \approx 10^{-2}$ °K, and of superconducting magnets producing fields $H \approx 10^5$ Oe, offer hope of a significant intensification in the near future of investigations with polarized neutrons and oriented nuclei.

A number of reviews, for example, Refs. 2 and 3, have been devoted to methods of obtaining polarized neutrons and oriented nuclei and investigations made by means of them. However, the most recent of these reviews are already a decade old, and much new material has been accumulated in the meanwhile. This has prompted us to writing the present review. In it, we consider some possibilities of investigations with beams of polarized neutrons and oriented nuclear targets and the methods of obtaining such beams and targets, and we also consider some of the latest experiments made with polarized neutrons and oriented nuclei. The review in no way pretends to a complete survey of the problem but reflects rather the interests of its authors.

1. SOME POSSIBILITIES OF INVESTIGATIONS WITH POLARIZED NEUTRONS AND ORIENTED NUCLEI

The majority of investigations with polarized neutrons and oriented nuclei are made for s neutrons, i.e., for neutrons of sufficiently low energies when the orbital angular momentum of the neutrons in the interaction process is zero. We shall therefore restrict ourselves in practice to considering just this case.

We begin by considering the spin dependence of the total interaction cross sections of neutrons with nuclei. When s neutrons interact with a nucleus with spin $I \neq 0$, there are two possible values of the channel spin, $J = 1 \pm 1/2$, to which the interaction cross sections $\sigma_\pm$ correspond. The total cross section observed for polarized neutrons and oriented nuclei is obtained by averaging the cross sections $\sigma_\pm$ with weights equal to the probabilities $W_\pm$ of the realization of the corresponding states:

$$\sigma = W_+\sigma_+ + W_-\sigma_-. \tag{3}$$

The probabilities $W_\pm$ can be expressed as follows in terms of the probabilities $W(m)$ and $W(m_s)$ of the projections m and m_s of the spins of the nucleus and the neutron:

$$W_\pm = \sum_{m,\, m_s} W(m)\, W(m_s)\, (I, 1/2, m, m_s \mid I \pm 1/2, m + m_s)^2. \tag{4}$$

Here, $(I, 1/2, m, m_s | I \pm 1/2, m + m_s)$ are the coefficients of vector addition. Simple calculations give for W_+ and W_- the expressions

$$\left.\begin{array}{l} W_+ = (2I+1)^{-1}[I(1+f_nf_1)+1]; \\ W_- = I(2I+1)^{-1}(1-f_nf_1). \end{array}\right\} \tag{5}$$

If either of the polarizations f_n or f_1 (of the neutrons and the nuclei) is zero, these probabilities are equal to the well-known g factors for spin-disordered beam and target. Thus, polarization effects are manifested in the total cross sections for the interaction of s neutrons with nuclei only if both polarizations are simultaneously nonzero. Using the expressions (5) for the total cross section, we readily obtain

$$\sigma = (2I+1)^{-1}[I(1+f_nf_1)+1]\sigma_+ + I(2I+1)^{-1}(1-f_nf_1)\sigma_-. \tag{6}$$

In practice, it is more customary to use for this cross section the different and more compact expression

$$\sigma = \sigma_0 + f_nf_1\sigma_{\rm pol}. \tag{7}$$

It is obtained from the expression (6) by separating the cross section in the absence of polarization,

$$\sigma_0 = (I+1)(2I+1)^{-1}\sigma_+ + I(2I+1)^{-1}\sigma_-, \tag{8}$$

and introducing the so-called polarization cross section

$$\sigma_{\rm pol} = I(2I+1)^{-1}(\sigma_+ - \sigma_-). \tag{9}$$

The polarization cross section characterizes the spin dependence of the interaction between the s neutrons and the nuclei. For known I and σ_0, it enables one to determine σ_+ and σ_-, i.e., to describe completely the spin dependence of the interaction.

In the total cross section for the interaction of neutrons with medium and heavy nuclei it is customary to distinguish two components: the cross section of potential scattering $\sigma_{\rm pot}$ and the cross section σ_a for the formation of a compound nucleus. The resonances observed in the neutron cross sections are associated with excited states of compound nuclei which have definite quantum numbers. One such quantum number is the spin J, which for s neutrons can take the two values $J = I \pm 1/2$. Determination of the spins of neutron resonances is one of the problems of neutron spectroscopy. In experiments with polarized neutrons and nuclei, the solution of this problem reduces simply to determining the sign of $\sigma_{\rm pol}$ at resonances. Indeed, since the contribution from the potential cross section can be ignored at the resonance, and only one of the cross sections σ_+ or σ_- is nonzero, it follows from (9) that $\sigma_{\rm pol} > 0$ for $J = I + 1/2$ and $\sigma_{\rm pol} < 0$ for $J = I - 1/2$. In the region of the so-called averaged cross sections, when the resonances are not resolved, the mean value $\langle\sigma_a\rangle$ and $\sigma_{\rm pot}$ are comparable in magnitude. Here, if additional information is not available, one cannot separate the contributions to $\sigma_{\rm pol}$ made by these two processes.

What has been said above is also valid for the various partial cross sections for the interaction of s neutrons with nuclei. For processes that proceed only through a compound nucleus, such as the (n, γ) or (n, f) processes, the situation is actually simpler, since here there is no need to separate from the polarization cross section the contribution due to the potential scattering.

We now consider the spin ordering of the ensemble of compound nuclei resulting from the capture of polarized s neutrons by oriented nuclei. The angular distributions of the decay products of the ensemble of compound nuclei are, for example, related to this ordering. In the simplest case, when only one of the possible spin states is formed during the capture process, the orientational ordering of the spins of the system of compound nuclei can be described by corresponding orientation parameters F_i. These parameters depend on the neutron polarization, the spin and orientation parameters of the original system of nuclei, and the spin J of the realized state of the compound nucleus. Using the notation introduced above, we can write the expression for the polarization F_1 in the form

$$F_1 = \langle J_z \rangle / J = \frac{1}{J} \frac{\sum_{m, m_s} W(m) W(m_s) (I, 1/2, m, m_s | J, m+m_s)^2 (m+m_s)}{\sum_{m, m_s} W(m) W(m_s) (I, 1/2, m, m_s | J, m+m_s)^2} \tag{10}$$

which, after some calculations, gives the result

$$\left.\begin{aligned} F_1 &= \left\{ \frac{I(2I+3)}{(I+1)(2I+1)} f_1 + \frac{f_n}{3} \left[\frac{2I+3}{2I+1} + \frac{2I(2I-1)}{(I+1)(2I+1)} f_2 \right] \right\} \\ &\times \left(1 + \frac{I}{I+1} f_1 f_n\right)^{-1}, \quad J = I + 1/2; \\ F_1 &= [f_1 - (f_n/3)(1+2f_2)](1 - f_1 f_n)^{-1}, J = I - 1/2. \end{aligned}\right\} \tag{11}$$

For the alignment F_2, similar calculations lead to

$$\left.\begin{aligned} F_2 &= \left\{ \frac{(I+2)(2I-1)}{(I+1)(2I+1)} f_2 + \frac{f_n}{5} \left[\frac{3(2I-1)(I-1)}{(2I+1)(I+1)} f_3 \right.\right. \\ &\left.\left. + \frac{(2I+3)(2I+4)}{(2I+1)(I+1)} f_1 \right] \right\} \left(1 + \frac{I}{I+1} f_1 f_n\right)^{-1}, \quad J = I + 1/2; \\ F_2 &= \left[f_2 - \frac{f_n}{5}(3f_3 + f_1) \right] (1 - f_1 f_n)^{-1}; \ J = I - 1/2. \end{aligned}\right\} \tag{12}$$

In the expressions for F_1 and F_2 when $J = I - 1/2$ and $f_n = f_1 = 1$ the apparent divergence is in fact an indeterminate form, since when $f_1 = 1$ all the remaining orientation parameters of the target nuclei are also necessarily equal to unity. This indeterminate form is due to the fact that under such conditions the state with $J = I - 1/2$ simply is not realized. It follows from the obtained expressions that when polarized neutrons are captured by unoriented nuclei (all $f_i = 0$) the ensemble of compound nuclei is polarized but does not have an alignment.

In the more general case when two possible values of the final spin result from the capture of s neutrons by nuclei, the compound nuclei are produced in a spin-mixed state. Here, to describe the orientational state of the spins of the compound nuclei the orientation parameters introduced above are insufficient, and it is customary to use directly the density matrix of the spin states.[4]

We now consider the method proposed by F. L. Shapiro for determining the magnetic moments of neutron resonances. He proposed[5] that for this purpose one should use the energy shift of neutron resonances in experiments with polarized neutrons or polarized nuclei due to the hyperfine interaction of the magnetic moment of the nucleus with the intra-atomic magnetic field in certain atoms. Suppose that target nuclei with spin I and magnetic moment μ_0 are placed in a magnetic field with intensity H. This splits the ground state of the nucleus into $2I+1$ equidistant magnetic sublevels. The magnetic energy of these sublevels is given by the expression

$$E_m^I = -\mu_0 H m / I, \tag{13}$$

where m is the projection of the spin of the nucleus onto the direction of the magnetic field. If a nucleus in such a magnetic sublevel goes over after capture of a neutron with spin projection m_s into a compound nucleus with spin J and magnetic moment μ, the magnetic energy of the corresponding sublevel of the compound nucleus will have the value

$$E_{m+m_s}^J = -\mu H (m+m_s) / J. \tag{14}$$

The difference between the magnetic energies in the final and the initial state is compensated by the kinetic energy of the captured neutron. This means that for nuclei in a magnetic field the neutron resonance is split into several subresonances, which correspond to the possible transitions between different magnetic sublevels of the original nucleus and the compound nucleus. Because of the small values of the nuclear magnetic moments, the magnetic splitting of nuclear levels is very small compared with the width of the nuclear levels even in the maximal (intra-atomic) fields $H \approx 10^7$ Oe. This strong overlapping of the individual subresonances has the consequence that the observed total resonance is hardly broadened but is under certain conditions shifted in energy by an amount up to $\langle \Delta E \rangle = H(\mu - \mu_0)$. The amount of this shift can be obtained by simple averaging of the shifts of individual subresonances with weights equal to the probabilities of their realization:

$$\langle \Delta E \rangle = \frac{\sum_{m, m_s} W(m) W(m_s) (I, 1/2, m, m_s | J, m+m_s)^2 (E_{m+m_s}^J - E_m^I)}{\sum_{m, m_s} W(m) W(m_s) (I, 1/2, m, m_s | J, m+m_s)^2}. \tag{15}$$

Calculations of the shift in the general case lead to rather cumbersome expressions. However, the experiments are performed in practice under conditions when only one of the spin systems (the beam or the target) is orientationally ordered. In these cases, the expressions for the shifts simplify strongly and take the form

$$\left.\begin{aligned} &\langle \Delta E \rangle = f_1 H \{\mu_0 - [1 - 1/(2I+1)(I+1)] \mu\}, \\ &J = I + 1/2; \\ &\langle \Delta E \rangle = f_1 H (\mu_0 - \mu), \quad J = I - 1/2, \end{aligned}\right\} \tag{16}$$

for unpolarized neutrons and

$$\left.\begin{aligned} &\langle \Delta E \rangle = (1/3) f_n H \{\mu_0 - [1 + 2/(2I+1)] \mu\}, \\ &J = I + 1/2; \\ &\langle \Delta E \rangle = (1/3) f_n H [\mu - (1 + 1/I) \mu_0], \\ &J = I - 1/2, \end{aligned}\right\} \tag{17}$$

for unoriented nuclei. These expressions make it possible to determine from the measured shifts the magnetic moments of the compound nuclei in the states corresponding to the neutron resonances. Of course, all the other quantities in the expressions for the shifts must be known.

Finally, we consider the phenomenon known as nuclear precession of neutrons, which was predicted and analyzed in detail in Ref. 6. To consider this phenomenon, it is necessary to use the concept of the direction of polarization of a system of spins. We define the direction of polarization as the direction in space for which the first orientation parameter f_1 (the polarization) defined above takes its maximal value. The phenomenon of nuclear precession of neutrons is as follows: When a beam of polarized slow neutrons passes through a polarized nuclear target, the direction of polarization of the beam is rotated around the direction of the polarization in the nuclear target. This process is due to a purely nuclear interaction, though it can be described formally by the introduction of a fictitious magnetic field associated with the nuclear polarization. This last circumstance is the basis of a different name of the phenomenon—nuclear pseudomagnetism. This was the name given to it in the later study of Ref. 7 (after the experimental discovery of the phenomenon). Let us consider the physical essence of nuclear precession of neutrons and obtain an expression for the angle through which the direction of polarization of the beam is turned. This can be most readily done in the language of neutron optics. We introduce a polar coordinate system with z axis in the direction of polarization of the target and regard z as the quantization axis. We consider the passage through the target of neutrons with spin projections $m_s = \pm 1/2$ onto the quantization axis, the neutrons being described by the spin neutron wave functions $X_\pm$. Let b_J be the amplitudes for scattering of neutrons by bound nuclei of the target in states with total spin $J = I \pm 1/2$. Then the effective scattering amplitudes $\langle b \rangle_{1/2}$ for the waves $X_\pm$ are obtained by appropriate averaging of the amplitudes b_J:

$$\langle b \rangle_{\pm 1/2} = \sum_{m,\, J} W(m)\, (I,\ 1/2,\ m,\ \pm 1/2 \,|\, J,\ m \pm 1/2)^2\, b_J. \quad (18)$$

For polarization f_1 of the target nuclei, the calculations give the result

$$\left.\begin{aligned} \langle b \rangle_{+1/2} &= \frac{I+1}{2I+1}\left(1+\frac{I}{I+1} f_1\right) b_+ + \frac{I}{2I+1}(1-f_1)\, b_-; \\ \langle b \rangle_{-1/2} &= \frac{I+1}{2I+1}\left(1-\frac{I}{I+1} f_1\right) b_+ + \frac{I}{2I+1}(1+f_1)\, b_-, \end{aligned}\right\} \quad (19)$$

where we have used the notation $b_\pm = b_{I \pm 1/2}$. With the effective scattering amplitude of the neutron wave there is associated the refractive index of the wave in matter[8]:

$$n^2 = 1 + 4\pi N \langle b \rangle / k^2, \quad (20)$$

where k is the wave number of the neutrons and N is the number of neuclei per unit volume of the target. Since the nuclear amplitudes are comparatively small, the refractive index of neutron waves in real substances differs only slightly from unity even for thermal neutrons. If the nuclear polarization is nonzero and there is a spin dependence of the scattering, i.e., $b_+ \neq b_-$, the effective scattering amplitudes for the waves X_+ and X_- are different. This leads to a difference between the refractive indices of the polarized nuclear target for the two waves. Bearing in mind that these refractive indices are near unity, we can write the expression for their difference in the form

$$\Delta n = n_{+1/2} - n_{-1/2} = (4\pi N f_1 / k^2)\, I\, (2I+1)^{-1} (b_+ - b_-). \quad (21)$$

The difference between the refractive indices, which is equivalent to a difference between the phase velocities of the corresponding waves, leads to a phase difference between these waves which arises as they penetrate the material of the target:

$$\Delta\varphi = k\, \Delta n\, Z = (4\pi N f_1 Z / k)\, I\, (2I+1)^{-1} (b_+ - b_-), \quad (22)$$

where Z is the path traversed by the waves in the target. By analogy with the rotation of the plane of polarization of light in birefringent materials, it is to be expected that in our case too there will be a rotation of the direction of polarization of the neutron beam. We shall show that this is indeed the case and that the rotation is through an angle $\Delta\varphi$ about the direction of polarization of the nuclear target.

We consider a completely polarized beam of neutrons with direction of polarization having the angles θ and φ in the chosen coordinate system. The spin wave function of the beam[9] in this case can be written in the form

$$X = \cos(\theta/2) \exp(i\varphi)\, X_+ - \sin(\theta/2)\, X_-. \quad (23)$$

The angle φ occurs in this wave function as a phase shift between the waves X_+ and X_-. It was shown above that it is precisely the difference between the refractive indices of the material of the polarized target for these waves that leads to the appearance of such a shift. Thus, when spin-dependent scattering is decisive in the interaction of neutrons with the target nuclei, the result of the passage of a completely polarized beam of neutrons through a polarized nuclear target will be a rotation of the direction of polarization of the beam around the direction of polarization of the target through the angle $\Delta\varphi$ given by the expression (22). In the case of practical interest when the beam is not completely polarized, the description of the neutron beam by a single wave function is not valid. Such a beam is described by an incoherent mixture of waves determined by the relation (23). However, since the treatment given above is valid for any of the waves of this mixture, a similar rotation of the direction of the polarization will be observed for a partly polarized neutron beam. By means of analyzers of the polarization of the neutron beam the rotation of the direction of polarization can be measured. This makes it possible to determine $b_+ - b_-$ experimentally and, using data on the scattering cross section from experiments in the absence of polarization, to obtain the values of the amplitudes b_+ and b_-.

2. ORIENTATION OF NUCLEI AND POLARIZATION OF NEUTRONS

To orient a spin system, it is necessary in some manner to make the populations of the magnetic sublevels different. The methods employed differ strongly for the orientation of nuclei in targets and the polarization of neutrons in a beam. We shall therefore consider these methods separately.

Methods of orientation of nuceli. The methods currently used to orient nuclei can be divided into two groups—static and dynamic.

In the static methods, one uses the interaction of the magnetic moment of the nucleus with a magnetic field or the interaction of the electric quadrupole moment of the nucleus with an inhomogeneous electric field to achieve an energy splitting of the magnetic sublevels, and deep cooling of the material of the target. If an interaction energy E_m with the field corresponds to the sublevels with spin projection $I_z = m$, the populations of these sublevels in thermal equilibrium are proportional to the well-known Boltzmann factors

$$W(m) \sim \exp(-E_m / kT), \quad (24)$$

where k is Boltzmann's constant and T is the absolute temperature of the material of the target. At a sufficiently low temperature of the target, when kT is approximately equal to or less than the energy difference between the magnetic sublevels, the system of nuclear spins is to a considerable degree oriented under conditions of thermal equilibrium.

We consider the case of orientation of nuclear spins in a magnetic field. The energy is

$$E_m = -\mu_0 H m/I, \tag{25}$$

and the polarization is given by the well-known Brillouin function[1)]

$$f_1 = B_I(\varkappa) = \frac{2I+1}{2I}\,\mathrm{cth}\left(\frac{2I+1}{2I}\varkappa\right) - \frac{1}{2I}\,\mathrm{cth}\left(\frac{1}{2I}\varkappa\right), \tag{26}$$

and the alignment is given by the expression

$$f_2 = (2I-1)^{-1}\left[2(I+1) - 3f_1\,\mathrm{cth}\,\varkappa/2I\right], \tag{27}$$

where $\varkappa = \mu_0 H/kT$. The method of orienting nuclei by deep cooling of the target in a strong external magnetic field, which is sometimes called the "brute-force" method, is obviously the most universal method of orienting nuclei. Let us consider the present-day possibilities of this method. Suppose a target with hypothetical nuclei having unit spin and magnetic moment equal to the nuclear magneton is in a field of 10^5 Oe, effectively the maximal at present attainable, at temperature 10^{-2} °K. In this case, the equilibrium polarization is about 0.25, i.e., rather far from the maximal possible. It should also be noted that the time of establishment of thermal equilibrium in a system of nuclear spins, which is usually called the time of nuclear spin relaxation, is unacceptably long in such fields at such temperatures in diamagnetic nonmetallic targets. These considerations show that the "force" needed in this method is by no means a "brute force." Therefore, the method of orientating nuclei in an external magnetic field has not been widely used. It is much more effective to use the intra-atomic magnetic fields produced at the nuclei of magnetic atoms by the uncompensated electrons of their atomic shells for nuclear orientation. Such fields, which are usually called hyperfine fields, are present at the nuclei of atoms of transition elements (atoms of the iron group, atoms of the rare-earth elements, and the actinides). These magnetic fields reach values 10^5–10^7 Oe and in many cases make it possible to obtain a fairly high nuclear polarization. The uncompensated electrons in the atom lead to the existence in the atomic shells of magnetic moments of the order of the Bohr magneton. Since the atomic magnetic moments appreciably exceed the nuclear moments, it is much easier to orient the atomic shells by an external magnetic field than the nuclei. Thus, at a temperature of order 10^{-2} °K, a field $\approx 10^3$ Oe is sufficient for the virtually complete orientation of the shells. However, in a number of cases a serious difficulty arises in the orientation of the shells of magnetic atoms through the spontaneous ordering of the atomic magnetic moments observed in substances with a high concentration of magnetic atoms. In the case of ferromagnetic ordering, to ensure a sufficiently high orientation of the shells it is necessary to achieve magnetic saturation of the sample, which frequently requires high magnetic fields because of the high magnetic rigidity of the samples. But if there is antiferromagnetic ordering in the material, only alignment of the nuclei can be achieved. Spontaneous ordering can be avoided by lowering the concentration of the magnetic atoms, i.e., by diluting the material of the target with nonmagnetic "ballast" atoms. However, in many cases the presence in the target of a large number of ballast nuclei significantly reduces the quality of the oriented target. In crystalline substances with a complex structure, the electric fields of the atoms surrounding the magnetic atoms have a strong influence. This influence leads to an anisotropy of the magnetic moments of transition elements and to an anisotropy of the hyperfine magnetic fields associated with these moments. In the cases when the anisotropy is unacceptably large, it is necessary to use single crystals as targets, which greatly complicates the preparation of the targets. However, despite these difficulties, the majority of the polarized nuclear targets used in experiments have been produced by means of the hyperfine magnetic fields.

In dynamical methods of orienting nuclei, the equilibrium orientational state of the spins of the system is disturbed by means of spin orientation transitions excited by rf fields. The advantage of these methods is that they make it possible to obtain a fairly high nuclear orientation without cooling of the material of the target to superlow temperatures. This last circumstance is very important if one is using oriented targets under conditions when the heat release in the target is appreciable. Unfortunately, the possibilities of the dynamical methods of orienting nuclei are rather limited. These methods can be used only for nuclei and working substances of the targets that satisfy a number of very specific requirements. Of the dynamically oriented targets, only polarized proton targets[10] have been widely used in practice. We shall consider these targets in more detail, since they are the targets used to polarize slow neutrons.

Dynamical polarization of protons is achieved by the so-called solid effect. In this method, the nuclei of diamagnetic atoms are polarized in a diamagnetic substance containing a small number ($\approx 1\%$) of magnetic impurity atoms with effective spin $S = 1/2$ of the shell. The interactions between the magnetic moments of the protons and the magnetic moments of the shells of the magnetic atoms split the ESR transition in the external magnetic field into three transitions: an allowed transition corresponding to reorientation of only the spins of the shells of the magnetic atoms, and two forbidden transitions, corresponding to simultaneous reorientation of the spins of the shells and the spins of the protons. If the proton relaxation time in the working material of the target appreciably exceeds the electron relaxation time, saturation by an rf field of one of the forbidden transitions leads to a "pumping" of the polarization of the atomic shells of the impurity magnetic atoms to the system of proton spins. If a fairly high polarization of the atomic shells of the magnetic atoms has been achieved by application of an external magnetic field and cooling of such a target, exposure of the target to an rf field with the necessary frequency and intensity leads to a high proton polarization. Historically, the first polarized proton target obtained by this method with a fairly high polarization was a target in which the working material was a single crystal of

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1) *Translator's Note.* The Russian notation for the trigonometric, inverse trigonometric, hyperbolic trigonometric functions, etc., is retained here and throughout the article in the displayed equations.

double lanthanum-magnesium nitrate, $La_2Mg_3(NO_3)_{12} \times 24H_2O$, abbreviated LMN. Later, there were developed polarized proton targets with other working materials giving better target parameters than LMN. For work with slow neutrons, only LMN targets have been used. This is due to the fact that in this case the parameters of LMN targets are perfectly adequate, and the technology of their preparation is much simpler than that of targets with other working materials. In LMN, protons of crystallization water are polarized, and the magnetic impurity is provided by Nd atoms, which replace the La atoms. In practice, the polarization of the protons in LMN is achieved as follows. An LMN single crystal with 0.5-1% impurity Nd is placed in a homogeneous magnetic field of strength $\approx 2\times 10^4$ Oe and cooled to ≈ 1 °K, which leads to virtually complete polarization of the shells of the Nd atoms. Exposure of such an LMN single crystal to rf radiation at the resonance frequency of one of the forbidden transitions, which corresponds to a wavelength $\lambda \approx 4$ mm, makes it possible to obtain a proton polarization $f_1 = 0.6-0.7$. The intensity of the rf radiation needed to achieve a high polarization depends on the size of the target. For targets measuring ~10 cm³, the power is of order 0.1 W.

Methods of polarizing neutrons. Neutrons with energies below hundreds of kilo-electron-volts are obtained by moderating fission neutrons from reactors or neutrons from nuclear reactions in accelerators. The beams of neutrons from moderators are unpolarized and, since there are at present no methods capable of reorienting the spins of the neutrons in the necessary manner, the only possibility of polarizing the neutron beam is to extract from it neutrons with the necessary orientation of the spin. Since both spin projections of the neutrons onto a given axis are equally probable in an unpolarized beam, an ideal polarizer makes it possible to obtain a completely polarized beam with an intensity equal to half the intensity of the original unpolarized beam. Real polarizers are very far from ideal.

In practice, to polarize slow neutrons one exploits the spin dependence of their interaction with matter.

Historically, the first and hitherto most widely used polarizers have exploited the spin dependence of magnetic scattering of neutrons by the atomic shells of magnetic atoms.[2] In these polarizers, one uses ferromagnetics magnetized to saturation and one of the following three methods: filtration of a beam through a ferromagnet, total "internal" reflection from a ferromagnet, or diffraction by a ferromagnetic crystal. The first method does not ensure a sufficiently high polarization of the beam without an unacceptable loss of its intensity, and is therefore not widely used. The two last methods are widely used. They make it possible to obtain neutron beams with very high polarization $f_n \gtrsim 0.9$ and a loss of intensity by an order of magnitude or somewhat more. It should, however, be noted that these methods require a very good angular collimation of the beams. In a number of cases, the resulting loss of luminosity is a serious shortcoming. This shortcoming is overcome in the method with magnetic mirrors by using polarizing neutron tubes,[11] and proposals have been made[12] for using systems of magnetic mirrors that focus the neutrons. There is an important difference between the method with magnetic mirrors and the diffraction method: The former gives polarized neutron beams with only an upper limit on the energy, while the latter gives monochromatic beams. A recent development is the hybrid method,[13] in which an artificial "crystal" with interplanar separations ≈ 100 Å is constructed by means of thin magnetic mirrors separated by thin nonmagnetic layers. Diffraction by such a "crystal" makes it possible to obtain beams of polarized neutrons with a much higher intensity, though not so monochromatic. In some cases, the use of such a polarizer can significantly improve the experimental conditions. There is a very serious shortcoming inherent in all polarizers based on the use of magnetic scattering—because of the rapid weakening of magnetic scattering with increasing neutron energy, the use of these polarizers is restricted to comparatively low energies. Thus, the best diffraction polarizer from this point of view does not permit an increase of the neutron energy above 10 eV. Since polarizers with magnetic scattering have been considered in detail in the monograph of Ref. 2, we shall restrict ourselves to the above comments on these polarizers.

We now consider the method of polarizing neutrons based on exploiting the spin dependence of the interaction of slow neutrons with nuclei. An unpolarized beam can be assumed to consist of two beams of the half-intensity that are completely polarized parallel to and antiparallel to any chosen direction in space. If the interaction of the neutrons with the target nuclei depends on the spin, then in accordance with the expression (7) the mean cross sections for interaction with nuclei of a polarized target for neutrons polarized parallel or antiparallel to the direction of the polarization in the target will differ. This means that when an unpolarized beam is filtered through a polarized target, the beam will be relatively enriched by neutrons with the direction of polarization for which the interaction cross section is smaller, i.e., the beam will become polarized in that direction. Let us consider this question quantitatively. We restrict the treatment to *s* neutrons, for which the cross section of the interaction with nuclei of a polarized target is given by the expression (7). When considering filtration of a beam through a polarized nuclear target, we shall, as before, assume that the beam consists of two components with intensities J_+ and J_- that are completely polarized parallel and antiparallel to the direction of polarization in the nuclear target, respectively. The intensities of these components are related to the total intensity J of the beam and its polarization f_n by the obvious relations

$$J = J_+ + J_-; \quad f_n = (J_+ - J_-)/J. \tag{28}$$

If the spins of the neutrons do not change their orientation during the passage of the beam through the polarized target, which is true for the targets used in practice, each of the components is attenuated independently. The cross sections that determine the attenuation of the parallel and antiparallel components are given by the expression (7) with $f_n = \pm 1$, respectively. Using these cross sections and the relations (28) for the intensity and the polarization of the initially unpolarized beam filtered through the polarized target, we readily obtain the expressions

$$\left.\begin{array}{l} J=J_0 \exp(-n\sigma_0)\,\mathrm{ch}(f_1 n\sigma_{pol}); \\ f_n=\mathrm{th}(f_1 n\sigma_{pol}), \end{array}\right\} \quad (29)$$

where J_0 is the intensity of the original beam, and n is the thickness of the target measured in the number of nuclei per square centimeter. For neutrons of sufficiently high energies ($E \gtrsim 1$ eV), when a nucleus of the target can be regarded as free for its interaction with a neutron, the cross sections σ_{pol} and σ_0 are determined by (8) and (9), where $\sigma_\pm$ are to be understood as the cross sections for free nuclei in the corresponding spin channels. For neutrons of lower energies, if scattering makes an important contribution to their interaction with the target nuclei, the cross sections σ_{pol} and σ_0 depend in a complicated manner on the structure and dynamics of the material of the target, and also on the polarization of the nuclei and the energy of the neutrons. In this case, it is virtually impossible to calculate σ_{pol} and σ_0, and they must be determined experimentally. The expressions (29) were derived under the assumption that the target contains only polarized nuclei. If the target contains other, unpolarized, nuclei, the expression for f_n remains valid, but the expression for J must be corrected in the usual manner for the attenuation of the beam by the unpolarized nuclei.

The dependence of J and f_n in (29) on the thickness of the target is such that there exists an optimal thickness of the target polarizer. Indeed, since J decreases with increasing thickness, tending asymptotically to zero, and f_n increases, tending asymptotically to unity, it is not advantageous to achieve a very high polarization of the beam because of the considerable loss of intensity and, accordingly, accuracy of the results obtained with the beam. If the effects investigated with the beam are linear in the polarization of the beam, and if the background is ignored, the thickness of the target will be optimal when a maximum of Jf^2 is ensured. This optimal thickness depends on the cross sections σ_{pol} and σ_0 and on the nuclear polarization. As can be seen from the expressions for J and f_n, the quality of the target polarizer increases with increasing σ_{pol} and decreasing σ_0. Since σ_{pol} cannot be greater than σ_0, the ideal target polarizer corresponds to $\sigma_{pol}=\sigma_0$, $f_1=1$, and $n\to\infty$ in the expressions (29).

The first attempt to use a polarized nuclear target for polarizing neutrons was made on a target with polarized ^{149}Sm nuclei.[14] Because of the low nuclear polarization, this attempt was not very successful. But in principle the ^{149}Sm nuclei have, for neutrons of energy up to ≈ 1 eV, a good relation between σ_{pol} and σ_0 ($\sigma_{pol_2} \approx 0.8\sigma_0$), and for a sufficiently high polarization a target with ^{149}Sm nuclei can be a good neutron polarizer. Because the range of neutron energies in which a polarizer with a polarized Sm target works can be successfully covered by simpler polarizers using magnetic scattering of neutrons, the Sm polarized target was forgotten. Only recently has interest in this target been reawakened[15] in connection with the possibility of using it in beams with large angular divergence.

Polarized nuclear target polarizers of neutrons acquired wide practical importance only after the development of satisfactory polarized proton targets and the use at the Laboratory of Neutron Physics at the JINR, Dubna, of such a target as a neutron polarizer.[16] A great advantage of the polarized proton target is the fact that it enables one to polarize neutrons in a wide range of energies, since a favorable relationship between σ_{pol} and σ_0 for protons holds for neutrons with energies from the very lowest to $\approx 10^5$ eV. The use of a polarized proton target as a neutron polarizer made it possible to advance into the region of energies of the previously inaccessible but interesting region of resonance neutrons. Detailed information on the properties of the neutron polarizer produced on the basis of a polarization proton target with LMN working material is given in Ref. 17.

Let us now consider the practical possibilities of a neutron polarizer with an LMN polarized proton target. Suppose the target has a polarization $f_1=0.6-0.7$. The optical thickness of such a target for neutrons with energy $E \gtrsim 1$ eV is approximately 1.7 cm. This target ensures a polarization of a beam of resonance neutrons close to the proton polarization with an attenuation by about 5 times of the beam intensity. For low-energy neutrons ($E \leqslant 0.1$ eV), the optimal thickness of the target is reduced to ≈ 0.5 cm. At the same time, the quality of the target polarizer increases somewhat (the polarization of the beam increases by $\approx 10\%$, and the loss of its intensity is reduced by $\approx 20\%$). The beam intensities given above refer only to the LMN single crystal itself. However, constructional elements of the target are also present in the beam, and these attenuate it further by 1.5–2 times. The working area of an LMN target polarizer can be raised comparatively easily to ~10 cm^2. A further increase in the area entails difficulties, which relate both to the preparation of large LMN single crystals and to the need to ensure a high and very homogeneous magnetic field for the operation of the target.

3. INVESTIGATIONS WITH RESONANCE NEUTRONS

Interaction of polarized neutrons with polarized nuclei. The question of the existence of a spin dependence of the cross section for the interaction of neutrons with nuclei arose many years ago. Feshbach[18] proposed that this dependence should be described by the introduction into the optical potential of a spin–spin term of the form $-V_{SS}f(r)[\mathbf{I}\sigma/I]$, where $\mathbf{I}$ and σ are the spins of the nucleus and the neutron and $f(r)$ is a form factor of the same form as in the real part of this optical potential. The strength V_{SS} of this term must be found from experimental data.

Attempts at the experimental detection of a spin dependence of the neutron cross section were undertaken in two directions. One of them involved the passage of fast polarized neutrons through a polarized target. Such studies were made for a long period of time by the groups of Fisher in the United States[19,20] and Kobayashi in Tokyo.[21,22] Polarized neutrons with several energies from 0.3 to 8 MeV were obtained in reactions with a Van de Graaff accelerator and a cyclotron. Holmium and cobalt, polarized at low temperatures in a hyperfine magnetic field, were used as targets.

The conclusion drawn in Refs. 19 and 20 was that there is no spin–spin effect in holmium, this yielding the upper limit $|V_{SS}|<300$ keV. In cobalt, a spin–spin effect was observed, but its magnitude and energy variation were not reproduced by optical-model calculations, in connection with which the authors of Ref. 20 suggested that cobalt exhibits an influence of intermediate structure. In a later work, Heeringa and Postma[23] confirmed these results.

The second direction involved measurements of the parameters of neutron resonances, including determination of the spins, on the basis of which the values of the neutron strength function $(S_0)_J=(\bar{\Gamma}_n^0/D)_J$ for s neutrons were calculated separately for resonances with spins $J=I+1/2$ and $J=I-1/2$. Here, $\bar{\Gamma}_n^0$ is the mean reduced neutron width and D is the mean distance between the levels. The strength function determines the averaged cross section of the interaction that proceeds through a compound state. Approximately, this connection can be expressed in the form

$$\sigma_a=2\pi^2\lambda^2E^{1/2}S_0. \quad (30)$$

The first investigations of the interaction of polarized resonance neutrons with polarized nuclei[24-26] were made by means of magnetic scattering for polarization of the neutrons. The results of these experiments are primarily of methodological interest. The values of the constants of the hyperfine interaction for a number of rare-earth elements were obtained and the method of polarization of nuclei was improved. With regard to the determination of the spins of the neutron resonances, the results were not too significant: For each investigated nucleus, between three and five spins were identified, which is clearly inadequate for establishing any spin dependences of the interaction between neutrons and nuclei. Moreover, at that time similar or even more detailed data on the spins of resonances had already been obtained from measurement of the total and partial neutron cross sections or the spectra of γ rays produced by resonance capture of neutrons.[27,28,29]

Significantly better possibilities for investigations with polarized neutrons and nuclei were opened up by the development of the method of polarizing neutrons by passing them through a polarized proton target. The first experiments made with a polarized ^{165}Ho target made it possible to obtain the spins of 23 resonances.[30] However, even this number of resonances with known spin is also inadequate to obtain reliable information about the spin dependence of the strength function. This is due to the fact that the accuracy of S_0 obtained by averaging over a small number of resonances is low because of the strong fluctuation of the distances between the levels and, especially, of the neutron widths, which are distributed in accordance with a χ^2 distribution with one degree of freedom. The relative error of the strength function calculated over an energy interval containing N resonances is approximately

$$\Delta S_0/S_0=(2/N)^{1/2}. \quad (31)$$

It is readily seen that to detect a 10% difference between the strength functions of two spin states $(J=I\pm1/2)$ of one nucleus it is necessary to identity the spins of approximately one thousand resonances. At the present time, the luminosity and resolution of neutron spectrometers does not permit one to obtain such data by any of the known methods.

This difficulty can be overcome by measuring the transmission of polarized neutrons through a polarized nuclear target in the region of the averaged cross section, where the resonances are not resolved. In this case, one obtains information over an interval in which the number of resonances is sufficiently large to reduce the error associated with the fluctuations. In the case of averaging over an energy interval $\Delta E\gg D$, the averaged cross sections in the channels $J=I\pm1/2$ can be represented in the form

$$\left.\begin{aligned}\langle\sigma_+\rangle&=2\pi^2\lambda^2S_0^+\sqrt{E}+4\pi a_+^2; \quad (31)\\ \langle\sigma_-\rangle&=2\pi^2\lambda^2S_0^-\sqrt{E}+4\pi a_-^2, \quad (32)\end{aligned}\right\}$$

whence

$$\langle\sigma_{\rm pol}\rangle=I(2I+1)^{-1}[2\pi^2\lambda^2\sqrt{E}(S_0^+-S_0^-)+4\pi(a_+^2-a_-^2)]. \quad (33)$$

Here, $S_0^{\pm}$ and $a_{\pm}$ are the strength functions and amplitudes of potential scattering for the corresponding spin channels. The polarization cross section can be obtained from the so-called transmission effect ε, which is determined by the expression

$$\varepsilon=(T_p-T_a)/(T_p+T_a), \quad (34)$$

where T_p and T_a are the transmissions of neutrons through the target for parallel and antiparallel directions of the polarizations of the neutrons and the nuclei. It is easy to show that

$$\varepsilon=-f_n\,{\rm th}\,(nf_1\sigma_{\rm pol}). \quad (35)$$

Here, n is the thickness of the target (the number of nuclei per cm^2). When $nf_1\sigma_{\rm pol}\ll1$, the relation (35) simplifies to

$$\varepsilon=-nf_nf_1\sigma_{\rm pol}, \quad (36)$$

and then we arrive at the following expression for the transmission effect in the region of averaging over many s resonances:

$$\langle\varepsilon\rangle=-nf_nf_1I(2I+1)^{-1}[2\pi^2\lambda^2\sqrt{E}(S_0^+-S_0^-)+4\pi(a_+^2-a_-^2)]. \quad (37)$$

These relations show that by measuring the transmission effect one can obtain the difference between the cross sections for two spin states, and, using any additional information about the difference $(a_+^2-a_-^2)$, obtain from (37) the value of $S_0^+-S_0^-$.

In recent years, experiments have been made at the Laboratory of Neutron Physics at Dubna on the transmission of polarized neutrons through polarized nuclear targets in the region $E_n\leq100$ keV (Refs. 31–34).

The measurements were made by the time-of-flight method on neutrons from the pulsed IBR-30 reactor in the booster regime with the electron accelerator LUÉ-40. The scheme of the experiment is shown in Fig. 1. The neutron beam was polarized to $f_n\approx0.5$ by being passed through a polarized proton target (LMN crystal) with an area of about 30 cm^2 (Ref. 35). The direction of polarization of the neutrons could be changed by rotating the polarized proton target together with the cryostat and magnet through 180°. This reversal required

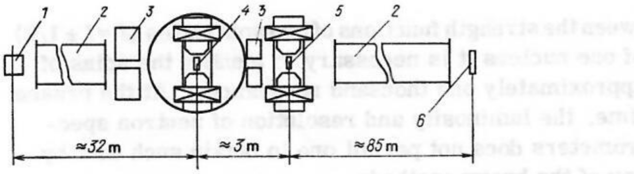

FIG. 1. Arrangement of experiment: 1) reactor, 2) neutron tubes, 3) collimator, 4) polarized proton target, 5) polarized nuclear target, 6) neutron detector.

about 10 sec.

The nuclear targets were polarized by cooling to the superlow temperatures 0.03–0.04 °K in a cryostat with a solution of ^3He in ^4He (Ref. 36) placed in the field of an electromagnet.

The samples used in the investigations were metallic terbium, holmium, and erbium, and also the intermetallic compounds $TmFe_2$ and $PrAl_2$, which are ferromagnetic at these temperatures. The rare-earth atoms are characterized by the presence of large internal magnetic fields of order 10^6-10^7 Oe. The nuclei within the domains are almost completely polarized, and the external field, which was 15 kOe in the experiment, ensured spatial ordering of the domains. The polarization f_1 of the targets averaged over the domains was 0.4-0.6. The thicknesses of the targets were $\sim(1-1.5)\times10^{22}$ nuclei/cm^2.

The neutrons that passed through the targets were detected by a scintillation detector at a distance of 116 m from the reactor. The spectra were accumulated and the polarization of the neutrons reversed by means of

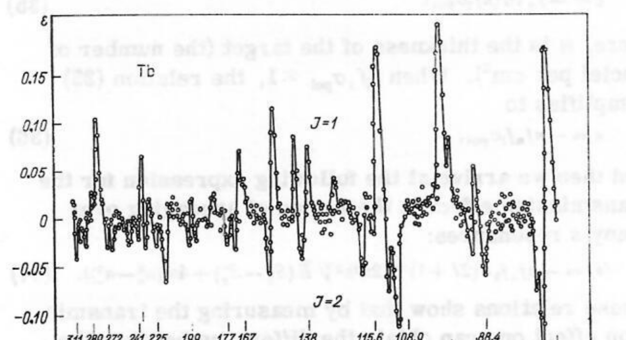

FIG. 2. Region of resolved resonances. At the bottom, one of the ^{159}Tb spectrograms obtained during 20 h of measurements; at the top, the transmission effect ε. The numbers between the curves are the energies of the resonances in electron volts, and t is the number of the channel of the time-delay analyzer (channel width 1 μsec).

an automated system based on a TPA minicomputer.

Sections of the spectrum obtained in one of the series of measurements with Tb are shown in Fig. 2 (in the region of the resolved resonances) and in Fig. 3 (averaged region). In the latter, the structure is due to constructional materials (copper and aluminum) in the beam.

The evaluation of the low-energy sections of the spectra with allowed resonances had the aim of determining the spins of the resonances. In this region, the sign of ε directly gives the value of the spin, as can be seen in Fig. 2. Altogether, the spins of approximately 250 levels were determined, some of them for the first time, for the five investigated nuclei.

As we have noted above, the region of unresolved resonances, which in the present experiments covered the energy interval from several keV to 100 keV, carries much more information about the spin dependence of the average neutron cross section than the region of resolved resonances. The high statistical accuracy of the measured spectra, and also the special measures taken to eliminate systematic errors in the experiment, made it possible to obtain the transmission effect with an accuracy better than 0.1% for each of the sections of the spectrum into which the range $E_n \leq 100$ keV was divided. The polarization cross sections obtained from these experimental data by means of the relation (36) are given for all the investigated nuclei in Fig. 4. It can be seen that σ_{pol} changes appreciably with the energy, and that the energy dependence is very different for different nuclei. It is difficult to attribute such behavior to potential scattering, for which the interval 100 keV is insufficient for appreciable structure to be manifested. More probable is the assumption that we here observe a spin-dependent intermediate structure of the type of doorway states, the structure being associated with the production of a compound nucleus. In this case, one can estimate from (37) the difference $S_0^+ - S_0^-$ of the strength functions by setting $a_+ = a_-$. These differences are shown in Fig. 5. The error includes the indeterminacy associated with the Porter–Thomas fluctuations of the neutron widths. In the majority of cases, this indeterminacy is predominant in the estimate of

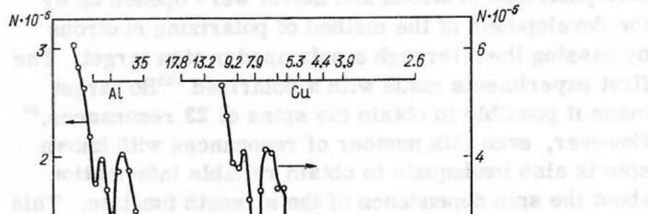

FIG. 3. ^{159}Tb spectrogram in the averaged region obtained during 30 h of measurements: 1) channel number of the analyzer (channel width 2.5 μsec). The numbers at the top give the energy in kilo-electron-volts.

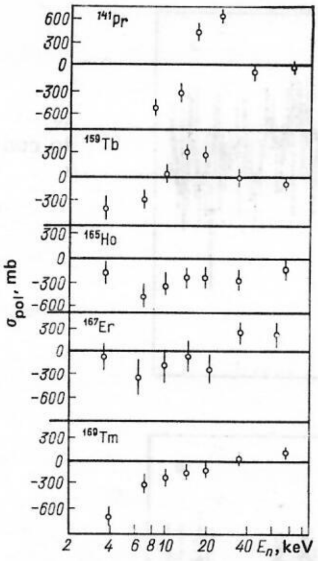

FIG. 4. Energy dependence of the polarization cross section σ_{pol}.

the error.

The differences $\langle S_0^+ - S_0^- \rangle$, averaged with allowance for the statistical weights over the complete investigated energy interval, are given in Table I. For all the nuclei except holmium, the difference between the strength functions for two spin states does not exceed the errors of the measurement. At the present time, these data are the most accurate estimate of the spin effect in the strength functions of nuclei.

It should be noted that the experiments described above are characterized by a high sensitivity to the manifestation of intermediate structure. Indeed, the measurements were made on a given nucleus under completely identical conditions except for the relative orientation of the directions of polarization of the neutrons and the nuclei, which makes it possible to observe an effect of spin dependence in the cross section that is many times smaller than the value of the cross section itself. In connection with the indications of intermediate structure, it appears interesting to investigate the same nuclei but through a different reaction channel, for example, to study the spectrum of γ rays pro-

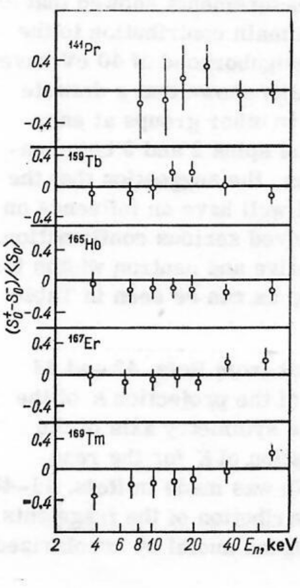

FIG. 5. Energy dependence of the relative difference between the strength functions $(S_0^+ - S_0^-)/\langle S_0 \rangle$ for two spin states.

TABLE I. Averaged values $\langle S_0^+ - S_0^- \rangle$.

Target nucleus	S_0, 10^{-4}	Averaging interval, keV	$\langle S_0^+ - S_0^- \rangle$, 10^{-4}
^{141}Pr	1.9	6.6–110	0.02±0.17
^{159}Tb	1.6	2.1–100	0.03±0.07
^{165}Ho	1.8	2.1–100	−0.20±0.07
^{167}Er	2.0	2.1–90	0.01±0.08
^{169}Tm	1.3	2.1–125	−0.04±0.07

duced by the capture of neutrons in different energy intervals.

Investigation of fissile nuclei. Interest in the spin dependence of the fission cross section of nuclei by resonance neutrons is due, in the first place, to the concept of fission channels developed by Bohr[38] and Hill and Wheeler.[37,39] According to the channel theory of fission, a nucleus, having passed through the saddle point, "cools," the excitation energy is expended largely on deformation, and the remaining energy can be distributed only between a small number of states (fission channels) with definite values of the spin J, the parity π, and the spin projections K onto the symmetry axis of the nucleus. In this connection, a spin identification of the resonances of fissile nuclei together with the determination of other resonance parameters is very important for testing the theory.

Another important feature of fission in which the manifestation of a spin dependence is possible is associated with the intermediate structure in below-barrier fission, which was discovered in the investigation of the fission of ^{237}Np (Ref. 40) and was later discovered in other nuclei. According to the model of a two-hump fission barrier, such a structure can be associated with the levels in the second well, and one then expects an enhancement of the probability of fission at resonances with the same spin as the level with the corresponding energy in the second well. Attempts to determine the spins of the resonances of fissile nuclei have frequently been made, but reliable and fairly detailed data have been obtained only as a result of experiments with polarized neutrons and nuclei in the United States.[41-43] These experiments were made at Oak Ridge using a neutron beam from the pulsed electron linear accelerator ORELA. The neutrons were polarized by means of the method of transmission through a polarized proton target developed at Dubna. The investigated nuclei ^{235}U and ^{237}Np, which occur in the ferromagnetic compounds US and $NpAl_2$, were polarized in a hyperfine field with cooling of the samples in a refrigerator with a solution of ^{3}He in ^{4}He. Measurements were made of the transmission of the neutrons and the number of fissions in the sample (from the yield of fission neutrons).

The first measurements[41] with ^{235}U had the aim of identifying the spins of the resonances in order to find the spin dependences of the mean widths $\langle \Gamma_n^0 \rangle$ and $\langle \Gamma_f \rangle$ and establish the connection between the quantum number K and the spin. Investigations with ^{235}U were continued,[43] and these not only extended the energy region in which the spins of resonances were determined but also investigated the region of unresolved resonances up to 25 keV.

Table II gives some of the characteristics obtained

TABLE II. Mean parameters of ^{235}U resonances (Ref. 43).

J^{π}	D, eV	S_0, 10^{-4}	$\langle \Gamma_f \rangle$, eV
3⁻	0.953±0.082	0.945±0.098	0.180±0.018
4⁻	0.809±0.070	1.043±0.089	0.091±0.011

in Ref. 43 from the parameters of the resonances in the region $E_n < 100$ eV. It should be noted that measurements by the polarization method made it possible to detect doublets with different spins where previously only one resonance had been assumed, and also to detect weak levels. This led to a significant reduction of the mean distance D between the levels compared with the value calculated on the basis of the resonance parameters given in Ref. 44. In addition, a correction for the omitted levels has been introduced in the data of Table II. The relationship between the D_J values for two spin states agrees with the value expected on the basis of the statistical model of the nucleus.

The values of the s-wave strength functions for levels with spins 3 and 4 differ by 10%, which does not exceed the limit of the statistical uncertainty associated with the Porter–Thomas distribution. The averaged data for the region 0–25 keV reveal a somewhat greater difference: $(S_0)_3 = 0.84 \times 10^{-4}$ and $(S_0)_4 = 1.04 \times 10^{-4}$. However, the authors themselves do not draw attention to these values, since they were obtained as a result of nonunique evaluation of the experimental data. The mean fission widths $\langle \Gamma_f \rangle$ differ most strongly for the two spin states, which indicates a higher fission barrier for the state 4^-. This fact is not in doubt; with regard to the values of $\langle \Gamma_f \rangle$ and their errors, the situation is more complicated. The emission of levels with small neutron and large fission widths is very probable, and this may significantly change $\langle \Gamma_f \rangle$. It is not fortuitous that different authors, using different methods of evaluation, in particular many-level analysis, find mean values of $\langle \Gamma_f \rangle$ without separation according to the spins in the range 50–175 eV (as was shown in Ref. 45).

In Ref. 43, Moore *et al.* analyzed the averaged cross section of ^{235}U fission up to 25 keV, separating the contribution from each of the spin states. They concluded that there is an intermediate structure in the cross section of fission through the $J=4$ channel; for spin $J=3$, a structure is also manifested, but it is established at a lower confidence level and may be due statistical fluctuations. The energy dependence of $\langle \Gamma_f \rangle_J$ is shown in Fig. 6. Note the similar nature of the fluctuations for $\langle \Gamma_f \rangle_3$ and $\langle \Gamma_f \rangle_4$. As one of the main arguments in favor of reality of the structure for spin 4, Moore *et al.*[43] adduce the impossibility of matching the calculated fission cross section in many energy intervals with the values of $(S_0)_4$ and $\langle \Gamma_f \rangle_4$ obtained over an interval of 100 eV (with respect to allowed resonances). However, it is easy to see that the value $\langle \Gamma_f \rangle_4 = 0.091$ eV cannot serve as a good reference point, since it clearly does not correspond to the mean value over the interval 25 keV, but lies appreciably lower. At the same time, the value $\langle \Gamma_f \rangle_3 = 0.180$ eV found from the resonances for $J=3$ agrees well with the mean value over the complete in-

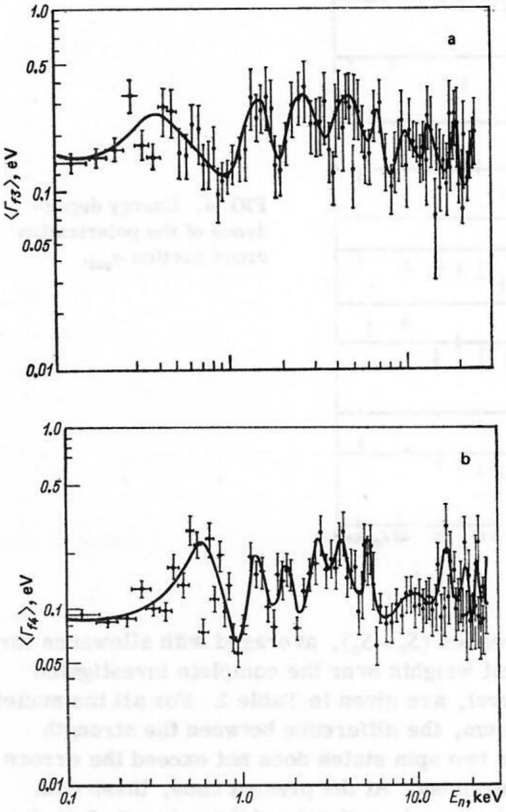

FIG. 6. Averaged values of ^{235}U fission widths for states with spin $J=3$ (a) and $J=4$ (b) (Ref. 43).

terval. One must therefore wonder whether the difference in the estimate of the reliability of the structure for $J=3$ and 4 is not a consequence of the reference points for the calculations.

The same group (Keyworth *et al.*[42]) investigated the interaction of polarized neutrons with polarized neptunium nuclei. The main attention was devoted to determining the spins of the individual resonances in the region of satisfactory resolution of the time-of-flight spectrometer (below 100 eV), and in the energy range 100–1000 eV the spins of the groups of levels forming the gross structure in the fission cross sections were determined (Fig. 7). The measurements showed that all the resonances that make the main contribution to the fission cross section in the neighborhood of 40 eV have the same spin $J=3$. It was also shown that a definite spin could also be attributed to other groups at energies 120 eV, 190 eV, etc., the spins 2 and 3 being encountered equally often. Thus, the suggestion that the levels in the second potential well have an influence on the nature of the fission received serious confirmation. The values of the mean radiative and neutron widths for two spin states are the same, as can be seen in Table III.

One further important result from Refs. 42 and 43 relates to the determination of the projection K of the angular momentum J onto the symmetry axis of the nucleus. A detailed investigation of K for the resonances of ^{233}U, ^{235}U, and ^{237}Np was made in Refs. 46–48 by measuring the angular distribution of the fragments produced by the fission of aligned nuclei by unpolarized

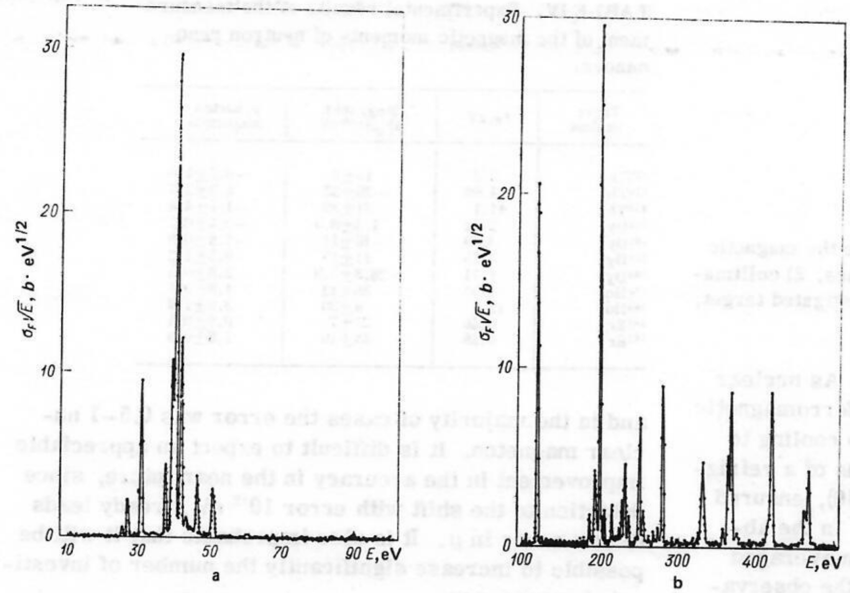

FIG. 7. Fission cross section of ^{237}Np for $E_n < 100$ eV (a) and $100 \leq E_n \leq 500$ eV (b).

neutrons. However, an unambiguous interpretation of the results is possible if the spins of the resonances are known. A combined analysis of the data enabled the authors of Refs. 42 and 43 to draw some conclusions. For the ^{235}U and ^{237}Np resonances, the effective value of K is not an integer, i.e., there is a mixture of states with different K. For ^{235}U, states with $K=1$ and 2 contribute to the resonances with spin $J=4$; for resonances with spin 3, a mixture of states with $K=0$, 1, and 2 is probable. Neptunium fissions predominantly through the channels $(J,K)=(3, 2)$ and $(2, 2)$. The channels (3, 3) and (2, 1) make a smaller contribution.

Magnetic moments of compound states of rare-earth nuclei. There exists a number of methods for determining the magnetic moments of excited states of nuclei, the methods based on the Mössbauer effect and perturbation of angular correlations being the ones most widely used. A limitation of the first method arises from the impossibility of observing the Mössbauer effect at excitations higher than 100 keV, and only the range $10^{-6}-10^{-10}$ sec is accessible for the lifetime of the excited state. The method of perturbed angular correlations is more universal, but it too does not permit one yet to advance into the region of lifetimes shorter than 10^{-12} sec.

However, the compound states produced by the capture of resonance neutrons have a lifetime of about 10^{-15} sec, and their magnetic moments were not amenable to measurement for a long time. The magnetic moments of the compound states can now be determined by measuring the shifts of the resonances that arise in a polarization experiment, although the problem is very complicated because the effect is small. To estimate its magnitude, we use the expression (16) for the shifts of the resonances. Taking $f_1=1$, $H=10^7$ Oe, and the difference $\mu-\mu_0$ of the order of one nuclear magneton, we obtain a level shift $\approx 3\times 10^{-5}$ eV. It should be borne in mind that the inherent width of the level is about 0.1 eV.

TABLE III. Mean parameters of ^{237}Np resonances (Ref. 42).

J^π	$\langle \Gamma_\gamma \rangle$, MeV	$\langle \Gamma_n^0 \rangle$, MeV
2^+	51.7±3.2	0.019±0.007
3^+	52.3±1.7	0.018±0.006

Despite the obvious difficulties, experiments were made at Dubna to determine the magnetic moments of the neutron resonances of a number of levels of the rare-earth nuclei Tb, Dy, Ho, and Er (Refs. 49–51).

From the two possible variants of the experiment, the method of passing unpolarized neutrons through a polarized nuclear target was chosen.[2)]

To determine the magnetic moment of the compound state of the nucleus, it is necessary to measure the energy shift of the resonance for a polarized target from the unpolarized position. The measurements were made using the pulsed IBR-30 reactor by the time-of-flight method. The arrangement of the experiment is shown in Fig. 8. The choice of nuclei suitable for measuring the magnetic moments was greatly limited by the requirement of large internal magnetic fields $H \gtrsim 2\times 10^6$ Oe. This is important both on account of the direct dependence of ΔE on H as well as in connection with the value of the polarization f_1, which also depends on H. A second requirement is that the investigated nuclei should have low-energy resonances. In the time-of-flight method, the energy and time shifts are related by

$$\Delta t \sim \Delta E\, E_0^{-3/2}. \quad (38)$$

It can be seen that with increasing energy E_0 of the resonance the time shift measured in the experiment decreases rapidly, so that the accuracy of the determination of the magnetic moment deteriorates.

The nuclei of the rare-earth elements Tb, Dy, Ho,

2) The other variant (using polarized neutrons) was realized for Er at Brookhaven,[52] but it is complicated by side effects and requires development.

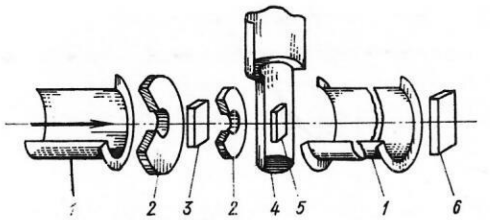

FIG. 8. Arrangement of experiment to measure the magnetic moments of neutron resonances: 1) neutron tubes, 2) collimators, 3) reference targets, 4) cryostat, 5) investigated target, 6) neutron detector.

and Er satisfy the two requirements best. As nuclear targets, foils of these metals, which are ferromagnetic at helium temperatures, were used. Deep cooling to 0.03–0.04 °K, which was achieved by means of a refrigerator with a solution of ^{3}He in ^{4}He (Ref. 36), ensured a polarization $f_1 \geqslant 0.9$ within the domains. In the absence of an external field, the polarization averaged over the target is zero, which simplifies the observation of the shift of the resonance. To destroy the polarization, the temperature in the targets was raised to 0.5–1.5 °K.

The beam of neutrons from the IBR passed through the polarized sample 5 and was measured by the detector 6 (see Fig. 8). The time spectrum was accumulated in the memory of the analyzing system, which was based on a TPA-1001 minicomputer.

The alternation of measurements with a polarized and unpolarized target (approximately every 10 h) could not be frequent, since the change in the temperature in the refrigerator required about an hour. Two such spectra formed a pair for simultaneous evaluation. For each of the investigated nuclei, about 30–40 pairs were accumulated. To monitor the time scale of the analyzer, Te, Sb, or Ir targets were placed in the beam. Figure 9 shows one of the spectra obtained during 6 h of measurements with Dy. Each pair of spectra was evaluated independently of the others. The time shift of each resonance of the polarized target with respect to the unpolarized target was determined by the method of least squares with allowance for the reference resonances of Te, Sb, and Ir.

In Table IV, we give the obtained values of the magnetic moments of all the resonances, and in Fig. 10 the values of $g = \mu / J$. The accuracy in the measurement of the magnetic moments of the neutron resonances is low,

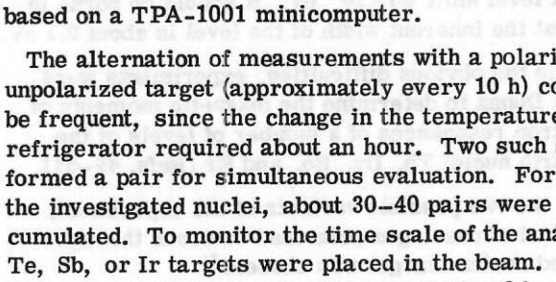

FIG. 9. Section of one of the experimental spectra obtained by measurement of the magnetic moments of disprosium resonances. Time of measurement 6 h; t is the channel number of the analyzer (channel width 2.5 μsec).

TABLE IV. Experimental results of the measurement of the magnetic moments of neutron resonances.

Target nucleus	E_0, eV	Energy shift, ΔE_0, 10^{-6} eV	μ, nuclear magnetons
^{159}Tb	3.35	19±9	−0.2±1.0
^{159}Tb	4.99	−20±33	4.3±3.7
^{159}Tb	11.1	31±39	−1.7±4.4
^{161}Dy	2.72	1,3±8,9	−0.4±0.7
^{161}Dy	3.69	−16±11	−1.8±0.9
^{161}Dy	4.35	11±15	0.5±1.2
^{163}Dy	1.71	−28,3±5,9	2.8±0.5
^{165}Ho	3.93	36±12	1.8±0.7
^{165}Ho	12.7	4±30	3.9±1.9
^{167}Er	0.46	27±7	0.9±0.4
^{167}Er	0.58	44±16	1.8±0.9

and in the majority of cases the error was 0.5–1 nuclear magneton. It is difficult to expect an appreciable improvement in the accuracy in the near future, since detection of the shift with error 10^{-5} eV already leads to this error in μ. It is also improbable that it will be possible to increase significantly the number of investigated resonances.

Nevertheless, the information obtained on the magnetic moments of the compound states makes it possible to draw some conclusion and make a comparison with theory.

The first theoretical estimates of the magnetic moments of the compound states of nuclei were obtained in Ref. 53 on the basis of a thermodynamic description for an excitation energy of the order of the neutron binding energy. The expression $\langle g \rangle \approx Z/A$ was obtained for the mean value of the g factor. For the rare-earth nuclei, the charge-to-mass ratio is equal to about 0.4. The value of the fluctuations around the mean value was found to be $\Delta g = \langle g \rangle [(A-Z)/Z]^{1/2}$, which is about 0.5.

A more rigorous treatment has been given by Bunatyan.[54] Using the method of thermal Green's functions, he obtained the values of the g factors for the compound states of deformed nuclei, and also the dependence of g on the excitation energy and the energy of pairing correlations. He showed that the limiting value $\langle g \rangle = Z/A$ is achieved only for excitation energy ~10 MeV, and that $\langle g \rangle \approx 0.27$ for rare-earth nuclei at an excitation of the order of the binding energy. With regard to the rms deviations from this value for different resonances and nuclei, the lower estimate is $\Delta g \approx 0.25$. It is, however, noted that this value may be greater because of

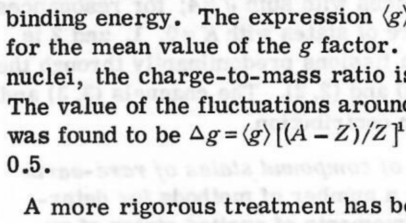

FIG. 10. g factors of the investigated resonances. At the top, the designations of the target nuclei and the energies of the resonances in electron volts.

the difference between the energies of the pairing correlations for different states and also when allowance is made for the individual properties of the nuclei.

As can be seen in Fig. 10, the differences in the g values appreciably exceed the experimental errors. This made it possible to separate the fluctuations associated with the measurement form the values of Δg due to the physical nature of the levels, and to obtain the experimental values $\langle g\rangle = 0.34 \pm 0.22$ and $\Delta g = 0.51 \pm 0.20$.

The mean value $\langle g\rangle$ and Δg agree with the theoretical estimates given above.

Thus, it can be concluded that the experimental data on the magnetic moments of the compound states are in satisfactory agreement with the theoretical estimates and confirm the applicability of the statistical model of the nucleus to the obtained accuracy.

4. SOME EXPERIMENTS WITH THERMAL NEUTRONS

Investigation of the Spin Dependence of the Scattering Lengths. Data on the spin dependence of the scattering lengths for neutrons on nuclei have great practical importance for many experiments with thermal neutrons. They are used, for example, in the study of the magnetic properties of matter and for determining the parameters of nuclear levels lying below the neutron binding energy. With regard to the theoretical analysis of the spin dependence of the scattering lengths, it is as yet intractable for complex nuclei. For nuclei with a comparatively small number of nucleons, in which a theoretical analysis can be made [^2H (Ref. 55), ^3He (Ref. 56), ^{13}C, ^{17}O, and ^{19}F (Ref. 57)], experimental determinations of the scattering lengths make it possible to test the correctness of the theories.

Information about the scattering lengths $b_\pm$ of neutrons on nuclei in states with total spin $J = I \pm 1/2$ can be obtained from measurements of the total and coherent scattering cross sections. In this case, the experiment gives two possible sets of scattering lengths. The resulting uncertainty is eliminated by means of additional information. In recent years, successful use for this purpose has been made of the resonance parameters of the investigated nuclei, and the scattering lengths for neutrons on ^3He (Ref. 58) and some other nuclei (Refs. 59–61) have been obtained.

Unambiguous information about $b_\pm$ is given by experiments that use polarized neutrons and nuclei. The direct method of determining $b_\pm$ from the polarization cross section in experiments in which polarized neutrons are passed through polarized nuclear targets is frequently complicated by the absence of data on the contribution of capture to the polarization cross section. This method is used to select the true set of scattering lengths of the neutron on the deuteron.[62] The scattering lengths $b_\pm$ of the nuclei of some magnetic atoms can be obtained from neutron diffraction experiments on deeply cooled antiferromagnets.[63] Here, information on the spin dependence of the scattering lengths is extracted from the variation of the intensity at the "antiferromagnetic reflection" when the sample is cooled to a temperature of the order of hundredths of a degree Kelvin. This change is due to the contribution from nuclear scattering, which arises because of the polarization of the nuclei of the magnetic atoms in the magnetic sublattices of the sample. The diffraction method is not widespread; as yet, it has been used to measure $b_\pm$ for some rare-earth nuclei.[64–66] A specific restriction of the method is the requirement of exact measurement of the temperature within the sample, which is needed to calculate the polarization of the nuclei.

The majority of the currently available data on $b_\pm$ were obtained using the method of nuclear precession of neutrons considered in Sec. 1. Since 1972, this method has been used to measure b_+ and b_- at Saclay.[67–70] The scheme of this experiment is shown in Fig. 11. The arrows, crosses, and points indicate the directions of the spins of the neutrons along their path through the apparatus. The neutron beam from the reactor is polarized and monochromated by the diffraction polarizer P. The beam then enters the gap of the electromagnet M through the polarization reversal system F and the region with the guiding field H, which ensures that the polarization of the beam is parallel to the field of the magnet when it enters the gap. In the magnet gap, on the path of the beam, there are two identical coils K_1 and K_2 with an rf field, each of which turns the polarization perpendicular to the direction of the field in the gap. On the path from the coil K_1 to the coil K_2 the polarization of the beam processes around the direction of the field of the magnet. The distance between the coils is such that in the absence of a sample the polarization makes an integral number of rotations and has the same direction on entering K_2 as on leaving K_1. After it has left K_2, the beam is polarized antiparallel to the field of the magnet. In the region of the guiding field H between the electromagnet and the diffraction analyzer A, the polarization is turned through a further 90° to the direction that coincidences with the direction of the polarization on the exit from the reversing device. The analyzer is oriented in space in such a way as to permit measurement of the polarization of the beam in precisely this direction. Behind the analyzer is the neutron detector D, which measures the beam intensity. The presence in the gap of the magnet (between the coils K_1 and K_2) of the polarized sample S leads to an additional precession of the beam polarization and, therefore, to a rotation through a certain angle $\Delta\varphi$ of the direction of the polarization at the entrance to the analyzer. This rotation results in a decrease in the beam polarization measured by the analyzer to the value $f_n \cos\Delta\varphi$, where f_n is the neutron polarization at the exit to the polarizer. The directly measured quantity is the polarization ratio

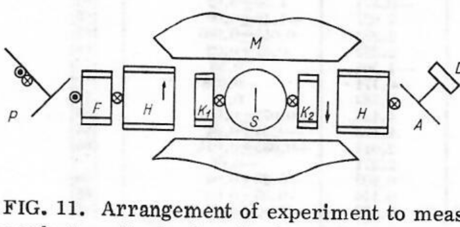

FIG. 11. Arrangement of experiment to measure the spin-dependent scattering lengths by nuclear precession of neutrons (explanations in the text).

R, i.e., the ratio of the counting rates of the detector with the beam polarization reversal system switched on and off. The quantity $f_n \cos\Delta\varphi$ can be related to R and the polarization efficiency P_a of the analyzer by (see (see, for example, Ref. 2)

$$f_n \cos\Delta\varphi = (R-1)/(R+1)\,P_a. \quad (39)$$

The relation (39) and the relation (22), which relates the angle through which the beam polarization direction is turned to the characteristics of the polarized sample, enable one to find the required difference $b_+ - b_-$ between the scattering lengths.

In Table V, we give the data currently available for the difference $b_+ - b_-$ (with reference to the source), and also the spins and magnetic moments of the nuclei. The overwhelming majority of the results have been obtained during the last five or six years. The extension and revision of the table of data on $b_\pm$ continues apace.

Gamma Emission Accompanying Radiative Capture. The use of polarized neutrons and oriented nuclei makes it possible to obtain definitely oriented systems of compound nuclei. The angular characteristics of the gamma emission of such systems are related to the characteristics of the gamma emission itself and the nuclear levels between which the corresponding transitions take place. Figure 12 shows the general scheme of the reaction of radiative capture of a neutron by a nucleus with mass number A and indicates the designations of the spins of the levels participating in the process used in the text below. The investigation of the gamma emission accompanying the radiative capture of polarized thermal neutrons by oriented nuclei makes it possible to obtain information on the properties of low-lying nuclear levels obtained after the emission of gamma rays by compound nuclei.

In the case of a unique value of the spin J of the compound nucleus, the system of spins of the compound nuclei has orientation parameters F_1 and F_2, which are determined by the expressions (11) and (12). For the angular distribution $W(\theta)$ of the probabilities of

TABLE V. Information on the spin dependence of scattering lengths.

Target nucleus	Spin I	μ_0, nuclear magnetons	$b_+ - b_-$, 10^{-12} cm	Reference
^{1}H	1/2	−1.913	2.900±0.008 *	[71]
^{2}H	1	0.857	0.570±0.005 *	[62, 72]
^{3}He	1/2	−2.128	(−0.4±0.1)+i·0.445 *	[58, 73]
^{6}Li	1	0.822	−0.38±0.05	[69]
^{14}N	1	0.404	0.37±0.07	[59]
^{19}Fe	1/2	2.629	−0.0135±0.0002	[74]
^{23}Na	3/2	2.217	0.71±0.03	[68]
^{27}Al	5/2	3.641	0.077	[70]
^{35}Cl	3/2	0.822	1.20±0.04	[60]
^{51}V	7/2	5.151	1.28	[67]
^{53}Cr	3/2	−0.474	1.39±0.02	[61]
^{59}Co	7/2	4.627	−1.16±0.06	[68]
^{63}Cu	3/2	2.223	0.045±0.005	[68]
^{65}Cu	3/2	2.382	0.37±0.02	[68]
^{91}Zr	5/2	−1.304	0.58	[70]
^{93}Nb	9/2	6.171	−0.028	[70]
^{139}La	7/2	2.783	0.75	[70]
^{141}Pr	5/2	4.136	−0.072±0.007	[66]
^{165}Ho	7/2	4.173	−0.34±0.04	[64]
^{159}Tb	3/2	2.014	−0.035±0.014	[65]
^{181}Ta	7/2	2.371	−0.06	[70]
^{195}Pt	1/2	0.609	−0.23±0.04	[68]
^{197}Au	3/2	0.146	−0.35±0.03	[68]
^{207}Pb	1/2	0.582	−0.02±0.04	[68]

*The values for free nuclei.

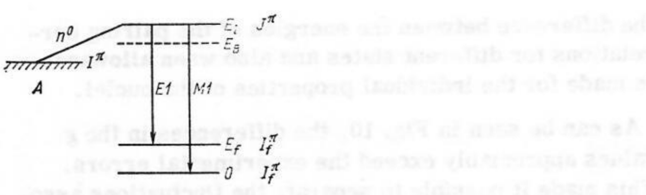

FIG. 12. Level scheme of nuclei studied by means of radiative capture of neutrons. The dashed line is the excitation energy corresponding to the neutron binding energy E_B in the product nucleus (E_B= 6–10 MeV).

emission of dipole gamma rays ($L=1$) and the values of their circular polarization $P_\gamma(\theta)$ we have in this case the expressions[1]

$$\left.\begin{aligned} W(\theta) &\sim 1 + F_2 A_2 P_2(\cos\theta); \\ P_\gamma(\theta) &\sim F_1 A_1 \cos\theta. \end{aligned}\right\} \quad (40)$$

Here, θ is the angle between the direction of emission of the gamma rays and the quantization axis, and the coefficients $A_1(J, I_f)$ and $A_2(J, I_f)$ are known functions of the spins:

$$A_1 = \begin{cases} -1/2, & I_f = 3/2, \quad I = 0; \\ 1, & I_f = 1/2, \quad I = 0; \end{cases}$$

$$A_2 = \begin{cases} 3J^2/2\,(J+1)\,(2J+3), & I_f = J+1; \\ 3J/2\,(J+1), & I_f = J; \\ 3J/2\,(2J-1), & I_f = J-1. \end{cases}$$

The experimental determination of the coefficients A_1 or A_2 leads in this case to a unique determination of the spins I_f of the final states.

However, when the compound nucleus is formed in a mixed-spin state, the picture is greatly complicated by the interference between transitions from the states $J = I + 1/2$ and $J = I - 1/2$. This problem is analyzed in Refs. 75–77, in accordance with which the expressions (40) must be replaced by

$$\left.\begin{aligned} W(\theta) &\sim \sum_{k_1 k_2 k} f_{k_1}(n)\, A_k^{k_1 k_2} f_{k_2}(I)\, P_k(\cos\theta); \\ P_\gamma(\theta) &\sim \sum_{k_1 k_2} f_{k_1}(n)\, A_1^{k_1 k_2} f_{k_2}(I) \cos\theta, \end{aligned}\right\} \quad (41)$$

where $f_{k_2}(I)$ are the orientation parameters of the target nucleus $[f_0(I) \equiv 1]$, $f_1(n)$ is the polarization of the neutrons $[f_0(n) \equiv 1]$, and the indices k, k_1, k_2 satisfy the conditions $0 \leqslant k_1 \leqslant 1$, $0 \leqslant k \leqslant 2$, $|k_1 - k| \leqslant k_2 \leqslant k_1 + k$, with $k_1 + k_2 + k$ an even number. As before, the coefficients $A_k^{k_1 k_2}$ in (41) depend on the spins I and I_f and they can be calculated as functions of the parameter α of the mixture of the spin states. The example of the frequently employed coefficient of circular polarization A_1^{10} is shown in Fig. 13. Interference effects are mani-

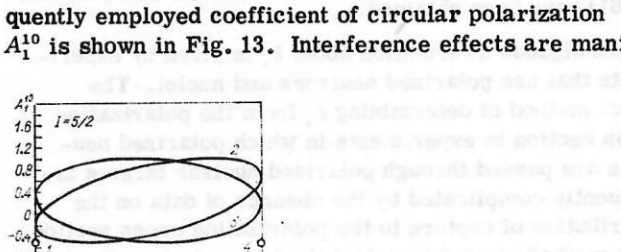

FIG. 13. Calculated values of the coefficient of circular polarization A_1^{10} as a function of the mixture parameter α of the spin channels for different values of the spins of the investigated levels.

fested for transitions to levels with spins $I_f = I \pm 1/2$ (in the given example, $I_f = 2, 3$) and are absent for $I_f = I \pm 3/2$ ($I_f = 1, 4$), when a transition is possible only for one of the spin states $J_\pm$ because of the dipole nature of the emission. Simultaneous determination of several coefficients $A_k^{k_1 k_2}$ makes it possible to find the values of the spin I_f.

In the majority of the experiments so far made, either aligned nuclear targets or polarized neutrons have been used. In the first case, the capture of unpolarized neutrons gives an aligned system of spins of the compound nuclei, whose gamma emission is anistropic. This anistropy has been investigated, for example, for some rare-earth nuclei,[78,79] for which a single-spin state is dominant in the thermal cross section of radiative capture. In the second case (polarized neutrons and unoriented nuclei), a polarized but not aligned system of compound nuclei arises; the angular distribution of its gamma emission is isotropic and it is the circular polarization that one studies. This method was used to obtain the spins of nuclear levels in Refs. 76, 80, and 81 for targets with $I=0$, in which there are no difficulties due to interference effects.

The first measurements of the angular distributions of gamma rays using both polarized neutrons and polarized nuclei were made at Prague[82] and Petten[83] with approximately the same arrangement of the experiment for a ^{59}Co target. The arrangement of the experiment at Petten is shown in Fig. 14, which is taken from Ref. 77. The thermal neutrons from the reactor 1 are monochromated and polarized on reflection from the magnetized $Co_{0.92}\ Fe_{0.08}$ single crystal 2. By means of the rf coil 4, the neutron spin can be rotated with nearly 100% efficiency. The neutrons then reach the target 7, which is placed in a cryostat with a solution of ^{3}He in ^{4}He, the cryostat also containing a superconducting magnet with two coils 6 (field up to 50 kOe). At the entrance and exit of the beam, outside the cryostat, there are massive iron rings 5, which act as magnetic screens to

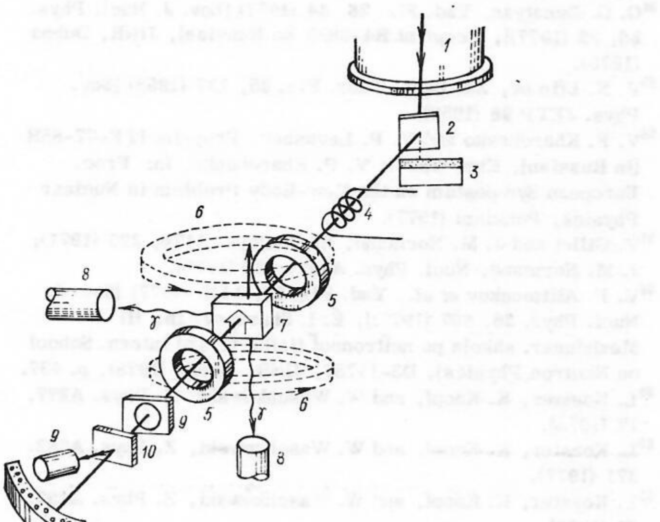

FIG. 14. Arrangement of experiment using polarized neutrons and oriented nuclei to investigate the gamma emission from radiative capture of thermal neutrons (explanations in the text).

eliminate depolarization of the neutrons by the external field of the coils. Outside the cryostat, at an angle to the field direction (the direction of polarization of the target) of $\theta = \pi$ and $\theta = \pi/2$ there are placed the Ge(Li) gamma detectors 8. There is also an analyzing crystal and neutron counters 9, which are used to measure the neutron and nuclear polarizations. The measurements are made simultaneously by two detectors.

The counts of the detectors can be written in accordance with the expression (41) in the form

$$N_{p,a}(\theta) = N_0(\theta)\,[1 \pm A_0^{11} f_1(n)\, f_1 + (A_2^{02} f_2 \pm A_2^{11} f_1(n)\, f_1 \pm A_2^{13} f_1(n)\, f_3)\, P_2(\cos\theta)], \quad (42)$$

where the symbols ± correspond to parallel (p) and antiparallel (a) orientations of the polarization of the neutron beam with respect to the magnetic field; $N_0(\theta)$ denotes the detector counts in the absence of a polarization of the neutrons and orientation of the target nuclei.

From this one can, for example, obtain the pair of coefficients A_0^{11} and A_2^{11}, which determine the spins I_f:

$$A_0^{11} = [\varepsilon(\pi) + 2\varepsilon(\pi/2)]/3 f_1(n)\, f_1;$$
$$A_2^{11} = 2\,[\varepsilon(\pi) - \varepsilon(\pi/2)]/3 f_1(n)\, f_1.$$

Here, ε is the relative difference between the counts of the detectors: $\varepsilon = (N_p - N_a)/(N_p + N_a)$.

In such experiments, one usually observes a large effect ($\varepsilon \approx 10\%$), though complications can arise through depolarization of the thermal neutrons. The corresponding corrections were studied in Refs. 84 and 85.

The main advantage of the quoted investigations consists of the development of a reliable and direct method of measuring the spins of nuclear levels. The method yields rich spectroscopic information.[86,87] Its further development is intimately related to progress in the polarization of nuclei by the "brute-force" method which is expected in connection with the development of a cryostat with nuclear demagnetization to a temperature ≈ 0.004° K (Ref. 88).

CONCLUSIONS

The review of investigations using polarized neutrons and oriented nuclei shows how many phenomena can be studied by this method. Interesting information has been obtained by measuring the spins of neutron resonances and the spin dependence of the total neutron cross sections, in fission, in the spectroscopy of low-lying nuclear levels, and in the investigation of scattering lengths, in particular, for few-nucleon systems.

However, despite this obvious wealth of possibilities of the method, the investigations develop relatively slowly. In the first place, this is due to the complexity of the experimental techniques and the difficulties in obtaining intense polarized neutron beams and producing oriented targets. Therefore, the further development of these investigations will to a large extent require an extension of the technical possibilities. Polarization of neutrons by passing them through a polarized proton target is the most universal in the considered energy range and will undoubtedly be used in the new powerful neutron sources that are being commissioned and developed. With regard to the development of the methods of polarization of nuclei, the main problem is still that of extending the class of polarized nuclei. In the near future, successes in the use of the "brute-force" method can be expected. However, the need to cool targets to superlow temperatures under conditions of intense neutron irradiation and poor heat transfer restricts the possibilities of this method. There is therefore need for the further development of dynamical methods of polarizing nuclei, which do not require super temperatures.

The combination of such improved facilities suitable for polarizing the majority of nuclei with high-resolution time-of-flight spectrometers will significantly enlarge the investigated region of neutron resonances and extend the investigation of the spin dependence to the partial neutron cross sections. It will also be possible to investigate low-lying states of nuclei, study problems of parity violation using resonance neutrons, and solve many other problems. Work in these directions is already being done in a number of laboratories in different countries.

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Translated by Julian B. Barbour