Experiments with polarized neutrons and polarized nuclei

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Research into polarized neutrons and nuclei was one of the fields of physics which interested Fedor L'vovich Shapiro and in which he did fruitful work. He had the ideas for a whole range of experiments, many of which were subsequently realized and became significant steps in the development of neutron physics. In this review a description is given of some of the foundations and methods of the polarization of neutrons and nuclei which are linked with the name Shapiro. Descriptions are also given of several experiments in which he took part or which were linked to his field of interests; in particular, research into the spin dependence of neutron strength functions and measurements of magnetic moments of the compound states of rare-earth nuclei are described. Some definitions and relations describing the polarization and alignment of systems of microscopic particles are given. © *1995 American Institute of Physics.*

1. POLARIZATION AND ALIGNMENT OF SYSTEMS OF MICROPARTICLES

A system of microparticles with nonzero spin is said to be polarized if the angular distribution of the spins is not isotropic. For particles with spin I, there are $2I+1$ possible values of the m-projection of the spin onto a distinguished direction. These values lie between I and $-I$. The probabilities $W(m)$ of the projections, which are also called the occupancies of the levels, determine the spatial orientations of the spins. If the normalization $\Sigma_m W(m)=1$ is adopted, then $2I$ independent values of $W(m)$ are possible, on the basis of which one can construct a corresponding number of independent functions of them. The most widely used is a set of parameters f_i (Ref. 1) for which $f_i=0$ for isotropic spin distribution and $f_i=1$ for spin systems which are completely ordered in one direction.

In the majority of cases, one considers only the first parameters, which are called the polarization and alignment of the system:

$$f_1=\frac{\langle m\rangle}{I}, \tag{1}$$

$$f_2=\frac{3}{I(2I-1)}\left[\langle m^2\rangle-\frac{I(I+1)}{3}\right]. \tag{2}$$

In the case of nonvanishing polarization, there exists a direction along the chosen axis z in which the spins are predominantly directed. The alignment indicates only an axis along which the spins are predominantly directed. The concept of polarization is applicable for all particles with nonzero spin, but an alignment is applicable only for particles with $I\geqslant 1$.

In this review, we will basically consider the interaction of neutrons with nuclei, and therefore we will briefly consider the methods of polarizing neutrons and polarizing the nuclei that are the targets in such experiments.

Effective methods were first of all developed for polarization of thermal neutrons. These were based on magnetic scattering of neutrons by ferromagnetic substances. A detailed description of these methods is given, for example, in the monograph of Ref. 2, and here we note only that they are basically used for thermal neutron beams in stationary reactors. When the neutron energy is increased, the intensity and polarization of the beam fall rapidly, and when the energy is greater than a few electron volts these methods cannot be used.

The method of neutron transmission through a polarized nuclear target significantly extends the energy interval of polarized neutrons. We will study the basic elements of this method. It is convenient to represent the unpolarized neutron beam as two completely polarized beams with intensities $C_{\rm p}^0$ and $C_{\rm a}^0$ with oppositely directed polarization along a chosen axis, for which we take the direction of polarization of the nuclear target. Obviously, $C_{\rm p}^0=C_{\rm a}^0$. We denote by $\sigma_{\rm p}$ and $\sigma_{\rm a}$ the cross sections for interaction of the neutrons with the nuclei for parallel and antiparallel directions of the polarization of the neutrons and nuclei. If $\sigma_{\rm p}$ and $\sigma_{\rm a}$ are not equal, then after the neutron beam has been transmitted through such a polarized target, the numbers of neutrons are different, $C_{\rm p}\neq C_{\rm a}$, i.e., the beam has become polarized. We write the expression for the polarization of the nuclei in the form

$$f_N=(n_+-n_-)/(n_++n_-). \tag{3}$$

Here n_+ and n_- are the numbers of nuclei per square centimeter of the target with spin direction along or opposite to the chosen direction. This expression is only rigorous for $I=1/2$, but it allows us to trace the process in which we are interested clearly and leads to the correct final result for any I. The transmission of the neutron beams with $C_{\rm p}^0$ and $C_{\rm a}^0$ through the polarized target can be expressed in the form

$$T_{\rm p}=\frac{C_{\rm p}}{C_{\rm p}^0}=\exp[-(n_+\sigma_{\rm p}+n_-\sigma_{\rm a})]$$

$$T_{\rm a}=\frac{C_{\rm a}}{C_{\rm a}^0}=\exp[-(n_-\sigma_{\rm p}+n_+\sigma_{\rm a})]. \tag{4}$$

Writing $n_++n_-=n$, and bearing Eq. (3) in mind, we readily obtain

$$T_{\rm p}=\exp\left[-n\left(\sigma_0+f_N\,\frac{\sigma_{\rm p}-\sigma_{\rm a}}{2}\right)\right],$$

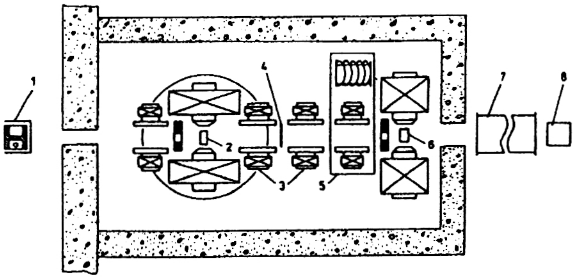

FIG. 1. Schematic arrangement of the facility POLYaNA: 1) IBR-30 booster; 2) polarized proton target; 3) magnets of guiding field; 4) current foil; 5) interchangeable magnets of guiding field; 6) polarized nuclear targets; 7) vacuum neutron guide; 8) neutron detector; 9) cryostat of additional sample.

$$T_a=\exp\left[-n\left(\sigma_0-f_N\,\frac{\sigma_p-\sigma_a}{2}\right)\right]. \tag{5}$$

Here $\sigma_0=(\sigma_p+\sigma_a)/2$ is the cross section for interaction of unpolarized neutrons with unpolarized nuclei. From this it is easy to go over to an expression for the polarization of neutrons which have passed through a polarized target. Bearing in mind that

$$f_n=(C_p-C_a)/(C_p+C_a), \tag{6}$$

we obtain

$$f_n=(T_p-T_a)/(T_p+T_a)=-\tanh\left(f_N n\,\frac{\sigma_p-\sigma_a}{2}\right). \tag{7}$$

Instead of $(\sigma_p-\sigma_a)/2$, a different expression is used more often:

$$\frac{\sigma_p-\sigma_a}{2}=\sigma_{pol}=\frac{I}{2I+1}\,(\sigma_+-\sigma_-). \tag{8}$$

Here σ_+ and σ_- are the cross sections for interaction of neutrons with nuclei through the channels with spins $J=I\pm1/2$.

It can be seen from these relations that a good neutron polarizer is a target with strongly differing σ_+ and σ_- and for which high polarization f_N can be achieved. In 1961, F. L. Shapiro suggested using a dynamically polarized proton target as such a target. A report of the creation of this target for research in the field of high-energy physics is given in Ref. 3. A very important advantage of the polarized proton target was the large polarization cross section $\sigma_{pol}=16.7$ b, which is practically constant in the range of neutron energies from a fraction of an electron volt to tens of kilo-electron-volts. Over the course of a few years, a polarized proton target was built and experiments with it began at Dubna in a beam of the IBR pulsed fast reactor. A detailed description of this neutron polarizer was given by Shapiro and his colleagues in Refs. 4–6. In the following years, the polarized proton target was perfected and is being used today at Dubna for research involving polarized neutrons and nuclei, as part of the POLYaNA[7] facility. Here we present only its basic parameters, and in Fig. 1 we show the arrangement of the facility.

A single crystal of lanthanum-magnesium nitrate $La_2Mg_3(NO_3)_{12}\cdot24H_2O$ is used as a target containing polarized protons. The hydrogen of the crystallization water is polarized by means of the "solid effect" method. For this, a single crystal with an area of 25 cm^2 and a thickness of 1.7 cm is placed in a cryostat at a temperature of approximately 1 K. The 2-T magnetic field of an electromagnet with uniformity and stability in time better than 10^{-4} and a 4-mm wavelength microwave generator ensure the necessary transitions between the levels in the spin system of the single crystal. A proton polarization of 0.60 was obtained. For the target thickness given above, which is optimal, the neutron polarization was approximately equal to the proton polarization, and in prolonged measurements lasting 10 days and more in succession was on average 0.55–0.60.

The polarized proton target was placed at a distance of 9 m from the neutron source—the core of the IBR-30 reactor. The total number of polarized neutrons in the beam that passed through the target was $3\cdot10^5E^{-0.9}$ neutrons$\cdot s^{-1}\cdot eV^{-1}$.

We now look at certain methods of nuclear-target polarization that are used in neutron research. The definition of the polarization (1) shows that its absolute magnitude will be maximal in the case of complete occupation of one of the levels $m=I$ or $m=-I$. Such occupation is destroyed by the atomic thermal motion, which makes a low temperature and as much splitting of the levels as possible necessary, i.e., a high magnetic field is applied. This method of polarization, which is the simplest in principle and is applicable to all nuclei with nonzero magnetic moment, is called the brute-force method. Unfortunately, this seemingly simple method only permits a high polarization when very high magnetic fields and extremely low temperatures are used. This of course makes it far from simple. The parameter which determines the nuclear polarization is $\chi=\mu_0H/kT$, and the amount of polarization is given by the well-known Brillouin function:

$$f_N=\frac{2I+1}{2I}\coth\left(\frac{2I+1}{2I}\,\chi\right)-\frac{1}{2I}\coth\left(\frac{1}{2I}\,\chi\right). \tag{9}$$

If the parameter is small, this expression can be written in the form

$$f_N=\frac{I+1}{3I}\,\chi. \tag{10}$$

To illustrate this method, we present the following example: Nuclei with $I=3/2$, magnetic moment of one nuclear magneton, and a target temperature of 30 mK in a magnetic field of 5 T have the polarization $f_N=3.4\%$.

A significantly greater polarization under less stringent experimental conditions can be achieved for the nuclei of transition elements, such as rare-earth elements, actinides, and nuclei of the iron group. These elements, because of the uncompensated electrons in their inner shells, have large magnetic fields of the nuclei, reaching tens and even hundreds of teslas. Orienting the atomic shells is relatively simple, because the magnetic moments of the electrons exceed the magnetic moments of the nuclei by approximately three orders of magnitude. In a number of cases, ferromagnetic ordering of the atoms takes place at sufficiently low temperatures. In these cases, large external fields are often needed to achieve a high orientation of the shells because of the magnetic rigidity of the samples. An example of such polarization of a target can be found in the experimental data on the polarization of holmium in the form of metallic foil.[8] The hyperfine magnetic field at the nuclei is about 730 T, and the magnetic moment of the nucleus is 4 nuclear magnetons. At a temperature of 30 mK, the parameter is $\chi=36$, which gives, in accordance with Eq. (9), practically 100% polarization. However, even with an external field of 1.5 T, the polarization was 60%. A similar picture was obtained for other rare-earth elements; the results also revealed a dependence of the polarization on the mutual orientation of the direction of rolling of the metallic foil and on the direction of the magnetic field.

In a number of cases, the ordering of the atoms in the target on cooling brings about an antiferromagnetic state. In this case, alignment is achieved but not polarization. This situation can be corrected if one uses not pure metals but instead chemical compounds of them that are ferromagnetic at low temperatures. Such samples were $PrAl_2$ and $TmFe_2$ (Ref. 8), and fissioning nuclei in the compounds US and $NpAl_2$ (Refs. 9 and 10).

Another method for achieving large targets with high polarization is the method of dynamic polarization already mentioned above. This method was used for the design of an effective neutron polarizer. A detailed description of this method can be found, for example, in the review by Abragam and Goldman.[11] Meanwhile, many different uses have been found in neutron research for polarized proton targets, which have already been created at a number of scientific centers: Los Alamos (USA),[12] KEK (Japan),[13] and the Kurchatov Institute of Atomic Energy (Moscow).[14] These are being used for neutron polarization. For the creation of the investigated polarized targets, this method was practically not used, this being due, to a large degree, to the complexity of the method. An exception is the polarized deuterium target created at Dubna by Shapiro's group[15] for investigation of the spin dependence of (n,d) scattering.

It has been reported recently that work is being done in Japan on a lanthanum target polarized by the dynamic method and intended for investigation of time-reversal invariance.[16]

Spin dependence of the neutron cross sections of nuclei

The probability of production of compound-nucleus states as a result of neutron capture has a resonance character, and the states themselves are characterized by a definite spin. For s-wave resonances, which are predominant in the range of energies up to tens of kilo-electron-volts, the spins of the compound states are equal to $I+1/2$ or $I-1/2$. The question of the spin dependence of the properties of neutron resonances and, in particular, the spin dependence of the neutron strength functions and of the cross sections averaged over many resonances arose many years ago. The strength function S_0 is one of the main parameters of the theory that describes the interaction of neutrons with nuclei, and it determines the cross section, averaged over resonances, for the production of compound states:

$$\sigma_c=2\pi^2\lambda\!\!\!^{-2}E^{1/2}S_0. \tag{11}$$

This is precisely why the question of the spin dependence of the neutron strength function attracted the attention of not only theoreticians but also experimentalists. Feshbach[17] suggested that such a dependence should be described by introducing into the optical potential a spin–spin term; however, the value of the term had to be determined experimentally. The neutron strength function for s-wave neutrons is $S_0=\overline{\Gamma}_n^0/D$, where $\overline{\Gamma}_n^0$ is the average value of the reduced neutron widths $\Gamma_n^0=\Gamma_n E^{-1/2}$, and D is the mean separation between levels. The reduced neutron widths of the resonances have a large spread, which can be described by a χ^2 distribution with one degree of freedom, the Porter–Thomas distribution. There are also large fluctuations in the level spacings. All this leads to the conclusion that the error in S_0 associated with these distributions is large and that in the case of averaging over a large number of levels N (several tens or more) it takes the approximate form

$$\Delta S_0/S_0=(2/N)^{1/2}. \tag{12}$$

This shows that in order to compare the strength functions of two spin states with a 10% degree of accuracy it is necessary to identify the spins of approximately 1000 resonances. This is a practically insoluble experimental task. The direct method to determine the spin of a resonance is to measure the transmission effect ε of polarized neutrons transmitted through a polarized nuclear target. The calculation, similar to the one above in the derivation of (7), is easy and gives

$$\varepsilon=\frac{T_p-T_a}{T_p+T_a}=-f_n\tanh(f_N n\sigma_{pol}). \tag{13}$$

The transmission effect is obtained experimentally by measuring the time-of-flight spectra for neutrons with polarization parallel and antiparallel with the nuclear polarization. The transmission of neutrons through the sample is $T=N/N_0$, where N and N_0 are the detector counts when the sample is in the beam and outside it. It is here assumed that the background is subtracted. To measure the usually small transmission effects, the N_p and N_a spectra are accumulated with frequent alternation of the neutron polarization direction by means of a flipper. Then the intensities N_{p0} and N_{a0} are equal, and consequently

$$\varepsilon=(N_p-N_a)/(N_p+N_a). \tag{14}$$

For neutron resonances with pure spin states $J=I+1/2$ and $J=I-1/2$, the polarization cross sections have opposite signs, and therefore the sign of ε already indicates the spin value of the given nucleus. The first experiments to measure the transmission effects in resonances were completed in a stationary reactor with neutron polarization by the method of reflection from a magnetized mirror.[18,19] With this, it was possible to determine the spins of 3–5 resonances. Indirect methods of spin determination turned out to be considerably more effective. They were based on the structure of gamma transitions accompanying neutron capture, which is sensitive to the spin of the initial state. In one of these methods,[20,21] the correlation between the spin of the level and the multiplicity of the emitted γ rays was used. By this method, it

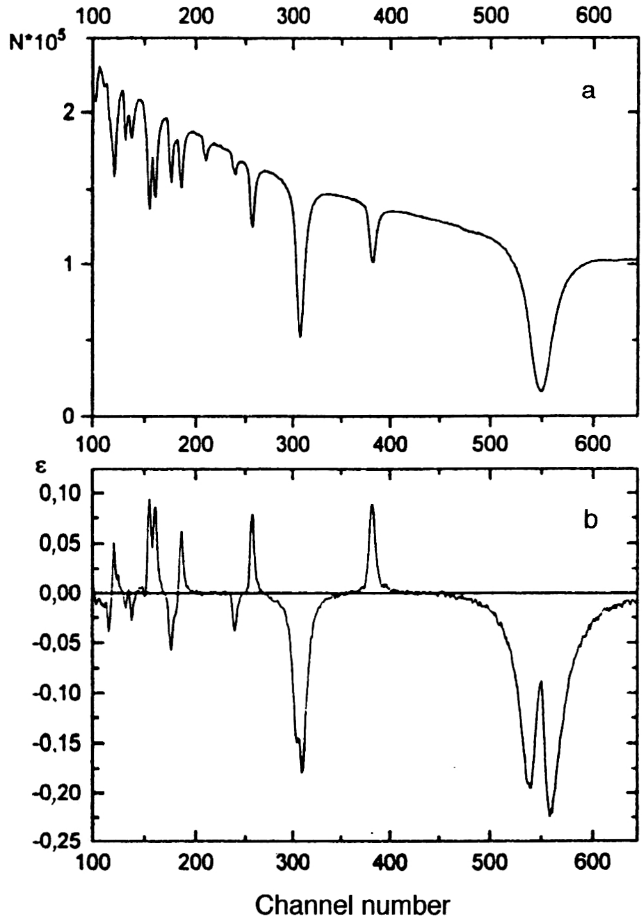

FIG. 2. Part of the time-of-flight spectrum in the case of the transmission of polarized neutrons through a polarized ^{165}Ho target (at the top) and the transmission effect ε (below).

proved possible to determine the spins of several tens of resonances for one nucleus. Another method used the correlation of the spin of the compound state with the occupation of the low-lying levels[22] and created approximately the same possibility for spin determination.

The method of the transmission of polarized neutrons through a polarized nuclear target became considerably more informative after a polarized proton target began to be used at Dubna as a neutron polarizer.[6] Shapiro's group determined the spins of 18 resonances of ^{165}Ho (Ref. 23). Figure 2 shows a part of the time-of-flight spectrum and the transmission effect obtained in measurements with ^{165}Ho in the region of resolved resonances. Later on, a method of measuring the spin dependence of averaged cross sections was developed at Dubna.[24] This made it possible to advance into the region of higher neutron energies and to determine more accurately the spin dependence of the neutron strength function for a number of rare-earth nuclei.[8]

The averaged cross section (11) for the production of compound states as a result of neutron capture can be written for the two spin states in the form

$$\langle \sigma_c^+ \rangle = 2\pi^2 \lambda\!\!\!^{-2} S_0^+ \sqrt{E}, \quad J = I + 1/2,$$

$$\langle \sigma_c^- \rangle = 2\pi^2 \lambda\!\!\!^{-2} S_0^- \sqrt{E}, \quad J = I - 1/2, \tag{15}$$

on the basis of which the averaged polarization cross section will have the form

$$\langle \sigma_{\rm pol} \rangle = \frac{I}{2I+1} 2\pi^2 \lambda\!\!\!^{-2} \sqrt{E} (S_0^+ - S_0^-). \tag{16}$$

Thus, by measuring the transmission effect (14) in the region of high energies, where the resonances are no longer resolved, one can determine $\langle \sigma_{\rm pol} \rangle$ on the basis of (13), and, consequently, the difference of the strength functions $(S_0^+ - S_0^-)$.

The transmission of polarized neutrons through polarized nuclear targets was measured by the time-of-flight method with the pulsed booster of the IBR-30 reactor. The polarized proton target ensured a polarization of the neutrons $f_n \cong 0.50$ in the range of energies up to 50 keV. A significant advantage of the facility was the possibility of changing the sign of the neutron polarization by a rotation through 180° of the polarized proton target together with the magnet and cryostat. This ensured 100% efficiency of the spin reversal at all neutron energies.

Rare-earth elements were used for the targets, for which a polarization of 0.4–0.6 was easy to achieve on cooling to 0.03 K in a magnetic field of 1.5 T. Terbium, holmium, and erbium were used in the form of single-element metallic plates, while thulium and praseodymium were used in the form of intermetallic compounds. All these were ferromagnetic at the given temperature.

The high statistical accuracy of the measurement of the transmission effect and the measures taken to eliminate systematic errors allowed the value of ε to be obtained with an accuracy better than 10^{-3} for every one of several sections of the spectrum over which averaging was performed. All the listed nuclei, with the exception of the magic praseodymium, have a characteristically high level density; for them, D is 5–8 eV. Thus, approximately 10^4 resonances lie in the complete averaging interval 1–70 keV, and this practically eliminates the uncertainty associated with the fluctuations mentioned above.

As a result of the experiments, it was found that the difference between the strength functions for the two spin states is $(S_0^+ - S_0^- / \bar{S}_0) \leqslant 0.1$ for all the listed nuclei. Thus, it was shown for the first time to that degree of accuracy that in the region of rare-earth nuclei the spin dependence of the strength function, if it exists at all, is fairly weak.

Magnetic moments of compound states of nuclei

Measurements of the magnetic moments of the compound states of nuclei formed during neutron capture could not be achieved for a long time by the methods that existed at that time, including methods such as perturbed angular correlations or Mössbauer spectroscopy. This was due both to the high excitation energy (E_B=6–8 MeV) and to the short lifetime of the compound states ($\tau \cong 10^{-15}$ s). A bold idea for a new way to measure the magnetic moments of such states was proposed by Shapiro in 1966.[25] This was based on the measurement of the shifts of neutron resonances due to the effect of a magnetic field on the magnetic moment of the nucleus. A target nucleus with spin I, spin projection m, and magnetic moment μ_0 changes its energy by $\mu_0 Hm/I$ when a magnetic field H is applied. For a compound nucleus, there is an analogous shift, which depends on corresponding parameters μ_c, m', and J. The difference of these shifts can be written in the form

$$\Delta E_{mm'} = -H\left(\mu_c \frac{m'}{J} - \mu_0 \frac{m}{I}\right). \qquad (17)$$

For the transition to the observed shift of a neutron resonance, it is necessary to sum the expressions (17) over all the projections m when neutrons with spin projections $m_s = \pm 1/2$ are captured:

$$\Delta E_0 = \sum_{mm_s} W(m) W(m_s) (Ismm_s|JM)^2 \Delta E_{mm'}; \qquad (18)$$

here $(Ismm_s|JM)$ is the Clebsch–Gordan coefficient. The occupancy of the level of the target nucleus can be written in the form

$$W(m) = C \exp\left(\frac{\mu_0 H}{kT} \frac{m}{I}\right), \qquad (19)$$

while its relation to the polarization of the nuclei f_N is given by

$$\sum_m mW(m) = \langle m \rangle = f_N I. \qquad (20)$$

For polarized neutrons with polarization f_n,

$$W(\pm 1/2) = \tfrac{1}{2}(1 \pm f_n). \qquad (21)$$

Finally, the normalization condition is

$$\sum_{mm_s} W(m) W(m_s) (Ismm_s|JM)^2 = 1. \qquad (22)$$

Equations (18)–(22) allow the shift ΔE_0 for arbitrary f_N and f_n to be obtained; however, the experiment can actually be conducted if one of the polarizations is zero. In this case, the resonance shift for $f_n = 0$ takes the form

$$\Delta E_0 = -f_N H\left[\frac{(2I+3)I}{(2I+1)(I+1)} \mu_c - \mu_0\right], \quad J = I + 1/2,$$

$$\Delta E_0 = -f_N H(\mu_c - \mu_0), \quad J = I - 1/2. \qquad (23)$$

When the nuclear polarization is zero,

$$\Delta E_0 = -\frac{1}{3} f_n H\left(\frac{2I+3}{2I+1} \mu_c - \mu_0\right), \quad J = I + 1/2,$$

$$\Delta E_0 = -\frac{1}{3} f_n H\left(\frac{I+1}{I} \mu_0 - \mu_c\right), \quad J = I - 1/2. \qquad (24)$$

In both cases, the resonance shift is measured relative to the position for both polarizations equal to zero. The magnetic moment μ_c of the compound state can be determined if all the remaining quantities in (23) or (24) are known. A serious difficulty with this experiment is the small value of the shift. In fact, let us estimate the value of $\Delta E_0 = H(\mu_c - \mu_0)$ with $\mu_c - \mu_0$ equal to one nuclear magneton and a magnetic field of $H = 100$ T. Then $\Delta E_0 = 3 \cdot 10^{-6}$ eV, and this value is smaller by about four orders of magnitude than the intrinsic widths of the resonances of heavy nuclei, which are usually $(5–10) \cdot 10^{-2}$ eV. It can be seen from this that a shift can only be measured for very high magnetic fields at nuclei, which, as noted above, can be obtained in rare-earth ferromagnets. It was also a fortunate circumstance that the rare-earth nuclei have many low-energy resonances, for which the accuracy of measurement of the resonance position is greater.

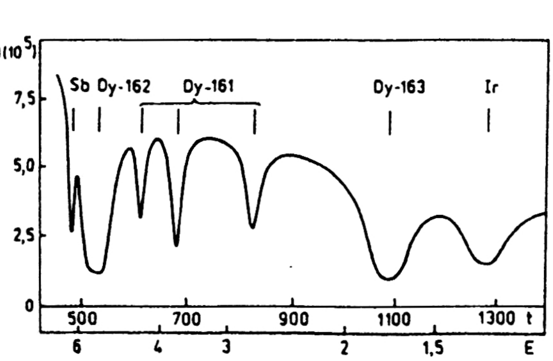

FIG. 3. Part of the experimental spectrum obtained from measurement of the magnetic moments of dysprosium resonances. The horizontal axes are the channel number (t) of the time-of-flight spectrum and the neutron energy E (eV). The isotopes to which the resonances belong are indicated above the curve.

A series of experiments was carried out in the Laboratory of Neutron Physics of the Joint Institute for Nuclear Research to measure the magnetic moments of the target nuclei ^{159}Tb, ^{161}Dy, ^{163}Dy, ^{165}Ho, and ^{167}Er (Refs. 26 and 27). The measurements were made by the time-of-flight method using the IBR-30 pulsed reactor. Metallic foils of the listed elements, which are ferromagnetic at sufficiently low temperatures, were used as targets. From the two possible forms of the experiment, the one with polarized nuclei, which is free from various side effects that complicate the interpretation of the results in the case of polarized neutrons, was chosen. The nuclei were polarized by cooling the samples to temperatures of around 0.03 K in a refrigerator with a solution of ^{3}He/^{4}He. The magnetic fields at the nuclei were $(3–7) \cdot 10^2$ T, and this made it possible to obtain a polarization of the nuclei within domains of more than 85% for

TABLE I. Results of measurements of the magnetic moments of resonances.

Compound nucleus	E_0, eV	J	μ_c nuclear magnetons	g
^{160}Tb	3.35	2	-0.2 ± 1.0	-0.1 ± 0.5
	4.99	1	4.3 ± 3.7	4.3 ± 3.7
	11.1	2	-1.7 ± 4.4	-0.8 ± 2.2
^{162}Dy	2.72	3	-0.4 ± 0.7	-0.13 ± 0.23
	3.69	2	-1.8 ± 0.9	-0.90 ± 0.45
	4.35	2	0.5 ± 1.2	0.25 ± 0.60
^{164}Dy	1.71	2	2.8 ± 0.5	1.40 ± 0.25
^{166}Ho	3.93	4	1.8 ± 0.7	0.45 ± 0.17
	12.7	4	3.9 ± 1.9	0.98 ± 0.47
^{168}Er	0.46	4	0.9 ± 0.4	0.22 ± 0.10
	0.58	3	1.8 ± 0.9	0.6 ± 0.3

all the listed nuclei. At the same time, an external magnetic field was not applied to the target, and the macroscopic polarization was equal to zero, which simplified the observation of the effect. To destroy the polarization, the temperature at the target was raised to 1–1.5 K, but a small residual polarization was taken into account in the analysis of the measurements. Alternation of the measurements with polarized and unpolarized targets could not be done frequently because of the length of time required to change the temperature. Nevertheless, 20–30 pairs of measurements with polarized and unpolarized targets were made for every nucleus. It took about 10 hours to measure each pair. To monitor the time scale of the spectrum, targets of nuclei whose resonances do not overlap with those being investigated and which were convenient for the precise determination of their position were kept constantly in the beam. Figure 3 shows one of the characteristic time-of-flight spectra of Dy.

By least-squares matching of the analyzed resonances, the shifts of the resonances in each pair of spectra were obtained, after which the magnetic moments μ_c were found. The final results are presented in Table I, where the values $g=\mu_c/J$ are given.

The experimental values obtained for the first time for the magnetic moments of highly excited states allowed a comparison to be made with predictions based on theoretical models. A statistical analysis of the experimental data was carried out for the complete set of results, since the theory does not distinguish between nuclei with nearly the same A and with similar nature of the deformation. Average values for the g factor were obtained:

$$\langle g\rangle=0.34\pm0.22,$$

and for its fluctuation around the average,

$$\Delta g=0.51\pm0.20.$$

These values agree with those predicted by the theory based on a statistical model of the nucleus.

The whole series of measurements of the magnetic moments of the neutron resonances of nuclei lasted about four years, from 1972 to 1975, and the first results were obtained not long before the death of Fedor L'vovich Shapiro. Later, complicated experiments to study the magnetic moments were repeated for dysprosium by a group of physicists at Los Alamos, whose results agreed with the Dubna results.[28]

We have considered several experimental investigations initiated by F. L. Shapiro and begun with his participation. After his death, many of the investigations continued, and new directions arose. One of the promising directions was the study of parity nonconservation in neutron resonances. The very large effects of parity violation first observed at Dubna were discovered in experiments with polarized neutrons. For this, one of Fedor L'vovich's great ideas was used—a neutron polarizer in the form of a polarized proton target.

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