Parity violation in nuclear reactions with polarized neutrons

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A review is given of the general properties of reactions with polarized tagged neutrons in which spatial parity is not conserved. Descriptions are given of the methods of investigation and experimental facilities. Results for many nuclei are reviewed and compared with theoretical predictions. © *1994 American Institute of Physics.*

1. INTRODUCTION

Violation of spatial parity in nuclear reactions was discovered in 1964 in the radiative capture of polarized neutrons.[1] Since then, polarized neutrons have been widely used to investigate parity violation.

In this review, we identify the general features typical of reactions with polarized neutrons. These general features are as follows:

1. Asymmetry of the emission of secondary reaction products relative to the direction of the spins of the polarized neutrons.

2. Mechanisms of dynamical and kinematic enhancement of the weak nucleon–nucleon interaction, which lead to a significant enhancement of the bare weak interaction.

3. A mechanism of mixing of states of opposite parity in the compound-nucleus stage.

We shall consider systematically methods of investigating parity violation in reactions with polarized neutrons such as measurement of the anisotropy of γ radiation in distinguished γ transitions, the γ radiation in the integrated spectrum of γ rays, and the anisotropy of proton emission. We shall consider neutron-optical effects—the rotation of the neutron spins, the asymmetry of transmission of polarized thermal and resonance neutrons, and P-even effects in p resonances. A fuller exposition of parity-violation effects in neutron p resonances appeared in the review of Ref. 2, and of P-even effects in p resonances in the review of Ref. 3.

In this review we shall consider some aspects of the theory of the weak interaction that are needed to interpret the investigated phenomena. A more detailed exposition of these questions can be found in the monograph of Ref. 4. At the end of the review we shall list the results of measurements on individual nuclei and compare them with each other and with theoretical predictions.

We shall not consider parity-violation effects in fission, the description of which requires an independent review.

2. SOME ASPECTS OF THE THEORY

To calculate parity-violation effects in nuclei, it is convenient to use, as a first approximation, a parity-violating effective single-particle potential. It can be regarded as the average potential through which a single nucleon outside the core of the nucleus is affected by the remaining nucleons. Such a single-particle potential of the weak interaction of a nucleon in the nucleus can be written in the form[5]

$$V_{\rm PV} \simeq G\mathbf{sp}\rho/2m, \tag{1}$$

where G is the universal constant of the weak interaction (Fermi constant), $\mathbf{s}$, $\mathbf{p}$, and m are the spin, momentum, and mass of the nucleon, and ρ is the density of nucleons in the nucleus (we use a system of units in which $\hbar=c=1$).

To estimate the amplitude of the mixing of states with opposite sign of the parity in the single-particle approximation, we divide $V_{\rm PV}$ by the characteristic energy $w\simeq p^2/2m$ of a nucleon in the nucleus. Then, bearing in mind that in the nucleus $p\simeq m_\pi$, $\rho\simeq m_\pi^3$ (m_π is the mass of the π meson), we obtain an estimate of the relative strength of the weak interaction of the nucleons in the form of the dimensionless parameter

$$F\simeq V_{\rm PV}/\omega\cong Gm_\pi^2=(10^{-5}/m^2)m_\pi^2\simeq 3\cdot 10^{-7}. \tag{2}$$

It is possible to estimate w as the mean energy separation ΔE between the single-particle states. Thus, $F\cong V_{\rm PV}/\Delta E$.

Since the parameter F is very small, in the first experimental investigations of the weak nucleon–nucleon interaction it was necessary to choose experimental conditions under which the initial value of F was increased by means of some enhancement mechanism.

The main enhancement mechanism in experiments with polarized neutrons is the dynamical enhancement due to a high density of energy levels in a compound nucleus.[6] There is a mixing of states of the nuclear system with parities of opposite signs but with the same angular momenta. Considering the weak nucleon–nucleon interaction as a perturbation in a system of strongly interacting particles, we find the mixing coefficient

$$\alpha=M/D, \tag{3}$$

where $M=\langle j|H_w|i\rangle$ is the matrix element of the Hamiltonian H_w that mixes the states i and j of the compound nucleus with opposite parities (it is usually called the matrix element of the weak interaction), and D is the mean separation between the levels of the compound nucleus. The matrix element M is related to the single-particle potential $V_{\rm PV}$ and the number N of states of the compound nucleus in an interval ΔE:

$$M=\frac{V_{\rm PV}}{\sqrt{N}}=\frac{F\Delta E}{\sqrt{\Delta E/D}}. \tag{4}$$

Therefore, the mixing coefficient is

$$\alpha=F\sqrt{\Delta E/D}. \tag{5}$$

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The quantity $R_{\rm dyn} = \sqrt{\Delta E/D}$ has become known as the dynamical enhancement factor.

The second, kinematic, enhancement mechanism arises as a result of interference of either the entrance or exit channels of the reaction of neutron capture with formation of a compound nucleus. The value of the kinematic enhancement factor is determined by the expression $R_{\rm kin} = \sqrt{\Gamma_{L'}/\Gamma_L}$, where $\Gamma_{L'}$ is the width of the entrance (or exit) reaction channel with parity violation, Γ_L is the width of the regular entrance (or exit) reaction channel without parity violation, and L and L' are the orbital angular momenta of the incoming and outgoing particle. The total enhancement factor is $R=R_{\rm dyn}R_{\rm kin}$.

The angular correlations of the secondary products of reactions involving polarized neutrons contain three main terms:

$$w(\mathbf{s},\mathbf{p},\mathbf{p}_n)=1+a\mathbf{s}\mathbf{p}+a_t\mathbf{s}\mathbf{p}_n+a_{lr}\mathbf{s}(\mathbf{p}_n\times\mathbf{p}), \tag{6}$$

where $\mathbf{s}$ is the neutron spin, $\mathbf{p}$ is the momentum of the emitted particle, and $\mathbf{p}_n$ is the momentum of the incident neutron (unit vectors). The second and third terms contain the pseudoscalar quantities $\mathbf{sp}$ and $\mathbf{sp}_n$, the existence of which is a sign of parity violation.

The correlation $\mathbf{sp}$ is manifested in the P-odd asymmetry of the emission of the secondary reaction products:

$$w(\theta)\sim 1+P_n a \cos\theta, \tag{7}$$

where a is the coefficient of the P-odd asymmetry, θ is the angle between the direction of the neutron spin $\mathbf{s}$ and the momentum $\mathbf{p}$ of the emitted particle, and P_n is the degree of polarization of the neutrons. The coefficient a is proportional to the mixing coefficient α. To make this correlation as large as possible, one chooses a geometry of the experiment in which the spin $\mathbf{s}$ is parallel or antiparallel to the momentum $\mathbf{p}$ (θ=0 or 180°).

The correlation $\mathbf{sp}_n$ is manifested in neutron-optical phenomena, in which parity violation arises as the result of the combined effect of a large number of nuclei in matter, and it has therefore been called coherent parity violation. In the case of longitudinally polarized neutrons there is a difference $\sigma_{\rm t}^+-\sigma_{\rm t}^-$ of the cross sections for neutrons having positive or negative helicity $\mathbf{sp}_n$. The ratio

$$a_t=\frac{\sigma_{\rm t}^+-\sigma_{\rm t}^-}{\sigma_{\rm t}^++\sigma_{\rm t}^-} \tag{8}$$

is called the coefficient of asymmetry of the total cross sections $\sigma_{\rm t}$ for the interaction of neutrons with helicities of opposite signs. In the case of transversely polarized neutrons, there is a rotation of the neutron spin $\mathbf{s}$ around the direction of its momentum $\mathbf{p}_n$ in matter.

The correlation $\mathbf{s}(\mathbf{p}_n\times\mathbf{p})$ is responsible for the left–right asymmetry of the emission of secondary particles after the capture of polarized neutrons. This is a P-even correlation. It is due to interference of the s and p waves in the reaction amplitudes. The mixing of states of the compound nucleus with parities of opposite signs does not occur as a result of the weak interaction but as a result of overlap of the s- and p-wave neutron resonances.[7] When neutrons are captured from s- and p-wave states, compound-nucleus states having parities of opposite sign are formed. The P-even left–right asymmetry has the form

$$w(\theta)\sim 1+P_n a_{lr}\sin\theta, \tag{9}$$

where a_{lr} is the coefficient of left–right asymmetry, and θ is the angle between the direction of the neutron spin $\mathbf{s}$ and the momentum $\mathbf{p}$ of the emitted particle. To make this correlation as large as possible, one chooses a geometry of the experiment in which all three vectors $\mathbf{s}$, $\mathbf{p}_n$, and $\mathbf{p}$ are mutually orthogonal (θ=90° or 270°).

The term $\mathbf{s}(\mathbf{p}_n\times\mathbf{p})$ is P-even and T-noninvariant. However, its detection in the studied reactions does not signify violation of time-reversal invariance in these reactions. The fact is that the coefficient $a_{\rm lr}$ contains the factor $\sin(\delta_s-\delta_p)$, where δ_s and δ_p are the phase shifts of neutron capture by the nucleus in the s and p states, respectively. This factor also changes sign under time reversal,[8] so that the correlation (9) is T-invariant as a whole.

3. METHODS OF INVESTIGATING PARITY VIOLATION BY MEANS OF NEUTRONS

3.1. Anisotropy of γ rays emitted by nuclei after capture of polarized neutrons

3.1.1. Fundamentals of the method

When nuclei capture polarized neutrons and emit γ rays, two mechanisms of enhancement of the P-odd effects are important: the dynamical and the kinematic one. Since most experiments are performed with nuclei of intermediate mass numbers, we make estimates for them.

For nuclei with $A\cong 100$ and excitation energies $E\cong 10$ MeV, the mean separation between the single-particle states is $\Delta E\cong 1$ MeV, while the mean distance between the levels of the compound nucleus is $D\simeq 10$–100 eV. Therefore the dynamical enhancement factor $R_{\rm dyn} = \sqrt{\Delta E/D}$ can reach 100.

To estimate the kinematic enhancement factor, we recall that in the case of (n,γ) reactions on polarized neutrons there is interference of the exit channels for the same entrance channel, namely, interference of the regular ML and irregular $\widetilde{EL}$ nuclear electromagnetic transitions.

If the compound nucleus is polarized, which is the case if polarized neutrons are captured by a nucleus, there is an asymmetry of the emission of the γ ray with respect to the direction of the polarization vector. In this case, the interference term is proportional to $R_{\rm kin} = \sqrt{\Gamma(EL)/\Gamma(ML)} = |EL|/|ML|$, where $|EL|$ and $|ML|$ are the matrix elements of the corresponding transitions. In accordance with single-particle estimates, $|EL|\sim kr$, where k is the wave number, r is the radius of the nucleus, and $|ML|\sim (v/c)kr$, where v is the velocity of nucleons in the nucleus. Therefore, in the given case $R_{\rm kin}\cong c/v\cong 10$. Thus, for some nuclei it can be expected that the total enhancement factor will reach $R=R_{\rm dyn}R_{\rm kin}\cong 10^3$.

The general formula for the angular distribution of the γ rays must take into account all possible forms of correlation of four vectors: the neutron spin $\mathbf{s}$, the neutron momentum $\mathbf{p}_n$, the momentum $\mathbf{p}_\gamma$ of the γ ray, and the helicity λ of the γ ray. In general form these correlations were considered by

Sushkov and Flambaum.[9] We write down from the expression for the cross section of the (n,γ) reaction, which takes into account 17 terms, only those correlations that are actually measured in experiments (the helicity $\boldsymbol{\lambda}$ of the γ ray was not measured in the experimental studies):

$$\sigma=\sigma_0+a(\mathbf{s}\mathbf{p}_\gamma)+a_{fb}(\mathbf{p}_n\mathbf{p}_\gamma)+a_{lr}\mathbf{s}(\mathbf{p}_n\times\mathbf{p}_\gamma). \tag{10}$$

This expression reflects both P-odd (the term with the coefficient a) and P-even angular correlations (the terms with a_{fb} and a_{lr}). The term with a_{fb} characterizes the forward–backward asymmetry, and the term with a_{lr} characterizes the left–right asymmetry. The remark concerning T-noninvariance made at the end of Sec. 2 applies fully to the last term.

We consider first the pure case of P-odd correlation. The angular distribution in this case is determined by the term $a(\mathbf{s}\mathbf{p}_\gamma)$. The geometry of the experiment must ensure that the vectors $\mathbf{s}$ and $\mathbf{p}_\gamma$ are parallel.

The coefficient a of the P-odd asymmetry is determined experimentally as follows:.

$$a=\frac{N^+-N^-}{P_n(N^++N^-)}, \tag{11}$$

where $N^{\pm}$ are the counts of the γ-ray detectors placed along and opposite to the direction of polarization of the neutron beam, respectively.

We give theoretical expressions for the asymmetry coefficient that will be needed for comparison of the experimental results with the theoretical predictions. They are obtained on the basis of the Blin–Stoyle general theory of angular correlations.[10]

We consider at once the case in which the regular transition is a pure ML transition, and the irregular transition is an $\widetilde{EL}$ transition:

$$a=2A\alpha=2ARF=2A\,\frac{M}{D}, \tag{12}$$

where

$$A=\frac{3/4+J_c(J_c+1)-J_i(J_i+1)}{[3J_c(J_c+1)]^{1/2}}\,F_1(LLJ_fJ_c) \tag{13}$$

is the spin factor; RF is the ratio of the matrix elements; J_{i}, J_{c}, and J_{f} are the spins of the initial, compound, and final nuclei; and the coefficients $F_1(LLJ_fJ_c)$, which have the simple analytic form[11]

$$F_1(LLJ_fJ_c)=\frac{\sqrt{3}}{2}\,\frac{L(L+1)+J_c(J_c+1)-J_f(J_f+1)}{L(L+1)[J_c(J_c+1)]^{1/2}}, \tag{14}$$

are tabulated in Ref. 12.

In the expression for the asymmetry coefficient a, we have separated the factor A, which depends only on the characteristics of the nucleus (the spins J_{i}, J_{c}, and J_{f}) and the γ transition (multipolarity L), and the factor RF, which determines the relative contribution of the potential F of the weak nucleon–nucleon interaction multiplied by the enhancement factor R.

In recent investigations of parity violation in p resonances, much attention has been devoted to P-even angular correlations in (n,γ) reactions. A review of this subject has been published in this journal.[3] Several theoretical studies have been carried out by Barabanov.[13] The P-even angular correlations make it possible to establish the quantum numbers of the resonances and to compare P-odd effects in the thermal and resonance regions of neutron energies.

Neutron capture in a p resonance can occur in two possible ways. The neutron orbital angular momentum $l=1$ can be added to the neutron spin $s=1/2$, giving total angular momentum $j=l+s=3/2$, or the neutron spin can be subtracted, giving $j=l-s=1/2$. The widths of these channels are different, $\Gamma_{p1/2}$ and $\Gamma_{p3/2}$, and the total width is $\Gamma_p=\Gamma_{p1/2}+\Gamma_{p3/2}$. The channel-mixing parameters, denoted by x and y, are

$$x=(\Gamma_{p1/2}/\Gamma_p)^{1/2},\quad y=(\Gamma_{p3/2}/\Gamma_p)^{1/2};\quad x^2+y^2=1. \tag{15}$$

They can be determined in experiments to measure the P-even left–right asymmetry for transversely polarized neutrons, in which all three vectors $\mathbf{s}$, $\mathbf{p}_n$, and $\mathbf{p}_\gamma$ are mutually orthogonal [the term with a_{lr} in Eq. (10)], and the forward–backward asymmetry in an unpolarized beam, in which $\mathbf{p}_n$ and $\mathbf{p}_\gamma$ are parallel [the term with a_{fb} in Eq. (10)].

The left–right asymmetry is determined in a beam of transversely polarized neutrons as follows:

$$\varepsilon_{\text{lr}}(E)=\frac{N^+(E)-N^-(E)}{P_n[N^+(E)+N^-(E)]}, \tag{16}$$

where $N^{\pm}(E)$ are the counts of the γ-ray detectors corresponding to the two directions of polarization of the beam, and E is the neutron energy.

The forward–backward asymmetry is measured in an unpolarized neutron beam and is determined by the expression

$$\varepsilon_{\text{fb}}(\theta,E)=\frac{N(\theta,E)-N(180^\circ-\theta,E)}{N(\theta,E)+N(180^\circ-\theta,E)}, \tag{17}$$

where $N(\theta,E)$ and $N(180^\circ-\theta,E)$ are the counts of the γ-ray detectors placed at angles θ and $180^\circ-\theta$ to the direction of the neutron momentum.

Finally, there is one more even correlation. This is the angular anisotropy of the p-wave part $\varepsilon_p(\theta,E)$ of the cross section; it is defined as the ratio of the area of the p resonance for a detector placed at angle 90° to the beam, $N_p(90^\circ,E)$, to the half-sum of the areas of the same resonance for detectors at the angles θ and $180^\circ-\theta$:

$$\varepsilon_p(\theta,E)=\frac{2N_p(90^\circ,E)}{N_p(\theta,E)+N_p(180^\circ-\theta,E)}. \tag{18}$$

3.1.2. Measurements of P-odd effects in $(\vec{n},\gamma)$ reactions in distinguished γ transitions

The history of the discovery and investigation of the P-odd effect in $(\vec{n},\gamma)$ reactions is full of drama. The first attempt was made in Ref. 14. However, the intensity of the beam of polarized neutrons was small for a statistically reliable detection of the effect. The flux on a target of natural cadmium was $2\cdot10^4$ neutron/s.

The first reliable result was obtained by experiments at the Institute of Theoretical and Experimental Physics (ITEP, Moscow), which used a much more intense beam of thermal polarized neutrons, with flux $(3-4)\cdot 10^7$ neutron/s.

Even more intense beams of cold polarized neutrons with flux $3\cdot 10^8-10^9$ neutron/s were used at the Laue–Langevin Institute (ILL, Grenoble). A feature of these beams was that they emerged from a liquid-deuterium source of cold neutrons in a reactor and were transported by means of long (80 m) neutron guide tubes to the experimental facilities. Such beams were purified of the background of γ rays and fast neutrons.[4] The neutron polarization in all cases reached 90%.

We consider the details of the measurements of the P-odd effects in the $(\vec{n},\gamma)$ reaction for the example of the facilities at ITEP and at ILL.

At ITEP, the asymmetry of γ-ray emission along and in the opposite direction to the polarization of the neutron beam was measured. With allowance for the finite sizes of the detector and target, the expression (7) takes the form

$$N^{\pm}=\text{const}(1\pm P_n a\Omega), \tag{19}$$

where $N^{\pm}$ are the numbers of counts of the γ-ray detectors for the cases in which the momentum of the γ ray and the spin of the neutron are parallel (+) and antiparallel (−), and $\Omega=\overline{\cos\theta}$ is the geometrical factor that takes into account the finite sizes of the detectors and target. To reduce the influence of the instrumental asymmetry, the drift of the electronics, and drift of the neutron flux, it is necessary to have two detecting channels that operate simultaneously, are as identical as possible, and are situated on opposite sides of the target and detect the counts $N^{\pm}$. Such symmetrization of the facility is needed in experiments in which a very small asymmetry is measured. Symmetrization appeared already in the first attempt to detect P-odd asymmetry in the (n,γ) reaction,[14] and since then it has always been used in such measurements.

An important device, first used at ITEP, in the struggle to overcome the instability of the neutron flux and the instability of the operation of the electronics, was rapid comparison of the effects, either in polarized and depolarized neutron beams or in beams having opposite directions of the neutron polarization. The spins were flipped by means of a Dabbs nonadiabatic wire spin flipper, which flipped the neutron spins 10 times per second (see Ref. 4). This device in conjunction with the use of two symmetrized γ-ray detection channels made it possible to separate the required effect reliably.

The ITEP experiments studied P-odd effects in the isotopes ^{113}Cd and ^{117}Sn. The scheme of production and decay of the ^{113}Cd nucleus is shown in Fig. 1. For the ^{117}Sn nucleus, the scheme is nearly the same as that for ^{113}Cd.

The natural mixture of cadmium isotopes is very convenient in the search for P-odd asymmetry. Practically the single isotope ^{113}Cd with spin and parity $J_1^{\pi}=1/2^+$ contributes to the (n,γ) reaction. Thermal neutrons are captured with cross section $\sigma=2520\cdot 10^{-24}$ cm^2 as a result of the s resonance with $I^{\pi}=1^+$ at energy $E_s=0.178$ eV. It leads to the formation of an excited compound state of ^{114}Cd with

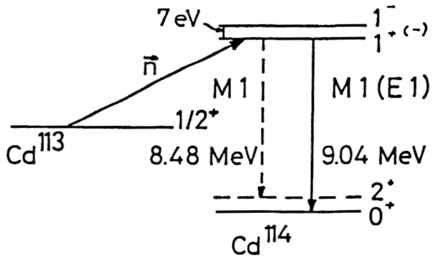

FIG. 1. Part of the scheme of production and decay of the ^{113}Cd nucleus.

$I_c^{\pi}=1^+$. The transition from the compound state with $I_c^{\pi}=1^+$ to the ground state with quantum numbers $J_f^{\pi}=0^+$ is an M1 transition with energy 9.04 MeV. The level density in ^{114}Cd at excitation energy around 9 MeV is fairly high. Indeed, in 1987 at the Frank Laboratory of Neutron Physics at the Joint Institute for Nuclear Research (LNP, JINR, Dubna) a weak p-wave resonance with $E_p=7.0$ eV with width $g\Gamma_p^n=(31\pm3)\cdot 10^{-8}$ eV (Ref. 15) was found. Here, $g=(2I_c+1)/2(I_c+1)$ is a statistical factor. Subsequent measurements of P-even angular correlations near this resonance established its spin and parity: $I^{\pi}=1^-$ (Ref. 16). This p resonance, mixed with the s-wave resonance of ^{113}Cd at $E_s=0.178$ eV, ensures the condition for the existence of a P-odd effect in the thermal region of energies.

Because of the proximity of resonances with opposite parity, there is a dynamical enhancement of the P-odd effect. Since the γ transition $1^+\rightarrow 0^+$ is an M1 transition, the $\widetilde{E1}$ transition must be irregular. The M1−$\widetilde{E1}$ interference (interference in the exit channels of the reaction) leads to kinematic enhancement of the effect.

The spin factor A determined by the expression (13) for the considered transition is +1, i.e., it has the maximum possible value. The closest (in energy) γ transition from the 1^+ state to the lowest excited 2^+ state has energy 8.48 MeV. It is also an M1 transition. However, the spin factor A in this case has the opposite sign, $A=-0.5$, as a result of which the asymmetry coefficient a has the opposite sign to a for the main transition $1^+\rightarrow 0^+$. The decrease in the absolute value of the spin factor A is compensated by the higher intensity of the $1^+\rightarrow 2^+$ transition, so that if the facility does not have sufficient energy resolution to resolve these two transitions with nearly equal energies, there may be a subtraction of effects of opposite signs.

The cadmium experiments at ITEP were repeated three times on modified facilities.[1,17,18] In all three experiments, the beams of polarized thermal neutrons were obtained in the horizontal channel of a heavy-water reactor by reflection from magnetized cobalt mirrors. The methods for creating polarized neutron beams are described in the monographs of Refs. 4 and 19.

A transversely polarized neutron beam, passing through various collimators and magnetic guide tubes, was incident on the target (Fig. 2). The γ rays emitted by the target were detected by two channels—scintillation spectrometers with NaI(Tl) crystals of diameter 70 and thickness 100 mm. The entire detection part of the facility was separated from the reactor hall by a thick concrete shield. The neutrons scattered

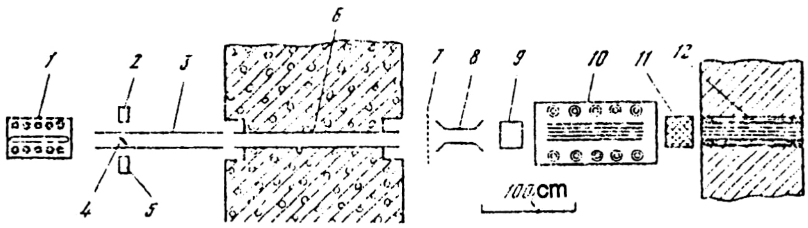

FIG. 2. Schematic diagram of the neutron tract in the ITEP experiment: *1)* mirror analyzer in magnet; *2)* detector of the first channel; *3)* magnetic guide tube; *4)* target; *5)* detector of the second channel; *6)* magnetic guide tube in shielding wall; *7)* wire spin flipper; *8)* magnet for rotating the spins; *9)* magnet with vertical field; *10)* stack of cobalt mirrors in the magnet; *11)* target shutter; *12)* collimator in shield of reactor.

by the target were absorbed by a $^6Li_2CO_3$ layout. The photomultipliers together with the NaI(Tl) crystals were shielded from the influence of magnetic fields by several screens of steel and permalloy and were covered from the background by a layer of lead. In all three experiments the same energy interval 8.5–9.5 MeV of the γ rays was separated. A detailed description of the struggle to overcome instabilities and of control experiments was given in Ref. 4.

The weighted mean value of the asymmetry coefficient a from the three experiments, with corrections for γ rays with energy 8.48 MeV entering the measured interval of energies—this effect reduces the asymmetry—and for the background from superposition of γ-ray pulses of lower energies, is $a=-(4.1\pm0.8)\cdot10^{-4}$.

For some time this result was under suspicion because no asymmetry was found in analogous experiments of other institutes. The reason for this was that these other experiments allowed a large admixture of the γ transition with energy 8.48 MeV, which has an asymmetry of opposite sign. Later, a different group at ITEP confirmed the result of the first three experiments.[20] The results of all measurements of the coefficients of asymmetry of the γ radiation in the $(\vec{n},\gamma)$ reaction are given in Table I.

The value of the asymmetry coefficient obtained at ITEP agrees well with the results of measurements of the circular polarization of γ rays in the same ^{113}Cd$(n,\gamma)^{114}$Cd reaction made using an unpolarized beam of neutrons by a group at Harvard University in the United States.[21] The fact is that the expression for the degree of circular polarization P_γ of the γ rays that arise from the capture of unpolarized neutrons as a consequence of nonconservation of the parity P (for a pure γ transition), $P_\gamma=2RF$, differs from the expression for the asymmetry coefficient (12) only in the absence of the spin factor A (Ref. 22). Therefore, the sign of the circular polarization of the γ radiation of the ^{114}Cd nucleus is the same for the transitions with energies 9.04 and 8.48 MeV. The measured value $P_\gamma=-(6.0\pm1.5)\cdot10^{-4}$ agrees with the value of the asymmetry coefficient a obtained at ITEP within the accuracy of the experiments.

In another facility at ITEP, the asymmetry of γ radiation in the ^{117}Sn$(\vec{n},\gamma)^{118}$Sn reaction was measured.[20] The target was made of metallic tin enriched with the isotope ^{117}Sn to 90%. The same principles of measurement as in the cadmium experiment were used. However, the number of spectrometers with NaI(Tl) crystals was increased to four. They were placed on both sides of the target and made angles 22.5° and

TABLE I. Values of the coefficients of the P-odd asymmetry a of γ rays emitted by nuclei after capture of polarized neutrons.

Reaction	Energy of γ transition, MeV	Quantum numbers of regular transition	a, 10^{-6}	Source
^{1}H$(\vec{n},\gamma)^2$H	2.23	$0^+\xrightarrow{M1}1^+$	-0.015 ± 0.048	ILL (Ref. 25)
^{2}H$(\vec{n},\gamma)^3$H	6.24	$3/2^+,1/2^+\xrightarrow{M1}1/2^+$	$(4.2\pm3.9)(1\pm0.15)$	ILL (Ref. 27)
	8.58	$2^-\xrightarrow{M1+E2}2^+$	157 ± 53	ILL (Ref. 28)
^{35}Cl$(\vec{n},\gamma)^{36}$Cl	integrated spectrum		-27.8 ± 4.9	SPINP (Ref. 33)
	integrated spectrum		-21.2 ± 1.7	ILL (Ref. 28)
^{57}Fe$(\vec{n},\gamma)^{58}$Fe	integrated spectrum		4.04 ± 0.83	SPINP (Ref. 34)
^{79,81}Br$(\vec{n},\gamma)^{80,82}$Br	integrated spectrum		-19.5 ± 1.6	SPINP (Ref. 33)
^{113}Cd$(\vec{n},\gamma)^{114}$Cd	9.04	$1^+\xrightarrow{M1}0^+$	410 ± 80	ITEP (Refs. 1, 17, 18, and 22)
			-500 ± 120	ITEP (Ref. 20)
	integrated spectrum		-1.64 ± 0.36	SPINP (Ref. 34)
^{117}Sn$(\vec{n},\gamma)^{118}$Sn	9.31	$1^+\xrightarrow{M1}0^+$	810 ± 130	ITEP (Ref. 20)
			440 ± 60	ILL (Ref. 29)
			970 ± 130	SPINP (Ref. 30)
	integrated spectrum		2.4 ± 1.6	SPINP (Ref. 33)
^{139}La$(\vec{n},\gamma)^{140}$La	integrated spectrum		-17.8 ± 2.2	SPINP (Ref. 33)
^{207}Pb$(\vec{n},\gamma)^{208}$Pb	7.37	$1^-\xrightarrow{E1}0^+$	-8.9 ± 5.1	ITEP (Ref. 35)

157.5° with each other. The pulses from the detectors were shaped, discriminated with respect to the energy, and detected by two groups of conversion circuits (depending on the direction of polarization of the neutrons). The polarization vector was flipped every second stochastically. After each exposure, the electronic detection circles were also switched stochastically. Measurements in the polarized beam alternated with measurements in the depolarized beam every 16 min.

The value of the asymmetry coefficient a with all corrections was found to be $a = (8.1 \pm 1.3) \cdot 10^{-4}$.

In all experiments of this type, it was necessary to perform a large number of control experiments, which were used to show that the measured asymmetry coefficients did indeed reflect the required physical phenomenon. For this a study was made of the asymmetry of the angular distribution of γ rays emitted by targets in different (from the investigated range) energy ranges, where the effect should be strongly suppressed. Experiments were performed with other nuclei for which P-odd effects should not be observed at the investigated level of accuracy. In neither the first nor the second case was there any kinematic enhancement.

Control experiments were performed to test the influence of the P-even left–right asymmetry, i.e., the term $a_{lr}\mathbf{s}\cdot(\mathbf{p}_n \times \mathbf{p}_\gamma)$ in Eq. (10). For this, the neutron spins were flipped from the horizontal plane into the vertical direction, so that all three vectors $\mathbf{s}$, $\mathbf{p}_n$, and $\mathbf{p}_\gamma$ were mutually orthogonal (see Sec. 2). In the main experiments, the spin vector $\mathbf{s}$ and the momentum $\mathbf{p}_\gamma$ of the γ rays were parallel (or antiparallel). Therefore in an ideal case such a correlation should not be present. However, the difference between the actual geometry of the experiment and the ideal one could affect the results. The control experiment proved the absence of such left–right asymmetry in the region of energies of thermal neutrons at the level of the accuracy of the experiment.

Several studies to measure the P-odd asymmetry in $(\mathbf{n},\gamma)$ reactions were made at the Laue–Langevin Institute in different years, beginning in 1977. The effects on light nuclei—protons and deuterons—and also on the ^{35}Cl and ^{117}Sn nuclei were studied. The neutron polarizers were either Permendur magnetized mirrors or magnetized Mezei supermirrors (see Ref. 4). The neutron spins were flipped either by spin flippers of axial geometry[23] or by a Dabbs current foil spin flipper (see Ref. 4); these flipped the neutron spins once per second.

The facility is shown in Fig. 3.[24] In the experiments with hydrogen, the target used was liquid parahydrogen (to prevent depolarization of the neutrons when scattered by orthohydrogen), which was placed in a cryostat of volume 23 l. Half of all the incident neutrons were captured in such a target. The produced γ rays had energy 2.23 MeV. The γ-ray detectors were two liquid scintillation detectors of volume 0.5 m^3, each of which was scanned by four photomultipliers. The technique of integrated information readout was used. The current from the photomultipliers was integrated during 0.17 s, converted to a digital code, and stored on magnetic tape.

Wilson's paper[25] gives a detailed description of the struggle to overcome systematic errors that was needed in

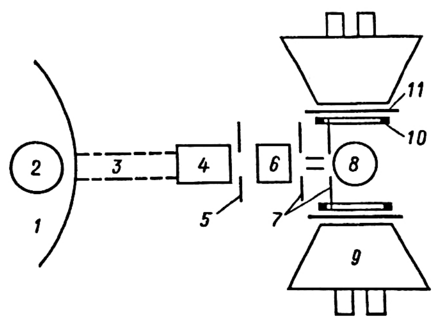

FIG. 3. Arrangement of the ILL experiments for investigation of the asymmetry of γ rays in radiative capture of polarized neutrons by protons: *1)* reactor; *2)* liquid-deuterium moderator; *3)* neutron guide tube; *4)* polarizer; *5)* lead shield; *6)* spin flipper; *7)* collimators; *8)* parahydrogen target; *9)* liquid scintillator; *10)* coil producing a constant field; *11)* soft iron.

order to achieve an accuracy $\cong 10^{-8}$ in the asymmetry coefficient as required by the theoretical predictions. The procedure included the use of two identical detectors placed along and in the opposite direction to the neutron spins, the use of a second spin flipper with flipping frequency once in 27 s, and an attempt to counter induction from the current switching in the spin flipper. A control experiment was made in which the source of the γ radiation was ^{60}Co.

The result of the first experiment in 1977, $a = (6 \pm 21) \cdot 10^{-8}$ (Ref. 24), had an error greatly exceeding the theoretical prediction[26] of the effect: $a_{\text{theor}} \cong 5 \cdot 10^{-8}$. In the second experiment, described by Wilson,[25] the error was reduced by several times but was still large: $a = -(1.5 \pm 4.8) \cdot 10^{-8}$.

The P-odd asymmetry in the $\vec{n} + {}^2\text{H} \to {}^3\text{H} + \gamma$ reaction was measured in Ref. 27. The experiment was performed in the same beam of cold polarized neutrons. The target was a cell containing heavy water D_2O (D/H$\cong$99.95%), measuring $8 \times 7 \times 6.5$ cm^3 at room temperature. The detectors of the γ rays with energy 6.24 MeV were NaI(Tl) crystals of diameter 23 cm and thickness 12 cm. They were mounted in an antimagnetic screen and were kept at a constant temperature 20 $\pm$0.2 °C. A difficulty of such an experiment was the fact that the cross section of the $nd \to t\gamma$ reaction (0.6 mb at thermal energy of the neutrons) is 500 times smaller than the cross section for the $np \to d\gamma$ reaction. At the same time, this gave hope of enhancement of the P-odd effect in this reaction. A complicated successive flipping of the spins from 32 positions during 27 s, aimed at reducing the fluctuations of the electronics, was used. The detectors were calibrated using the γ line from the $np \to d\gamma$ reaction. Corrections were made for depolarization of the neutrons on scattering by the D_2O (scattering cross section$\simeq$21 b), for the mean $\cos\theta$, and for the superposition of pulses. Control experiments were performed in other energy ranges of the γ rays, the asymmetry from a ^{117}Sn foil instead of heavy water was measured, and so was the asymmetry from ^{60}Co and some other sources. The result was represented by the authors in the form

$$a = (4.2 \pm 3.9)(1 \pm 0.15) \cdot 10^{-6},$$

where a scale factor is enclosed in the brackets. The result at

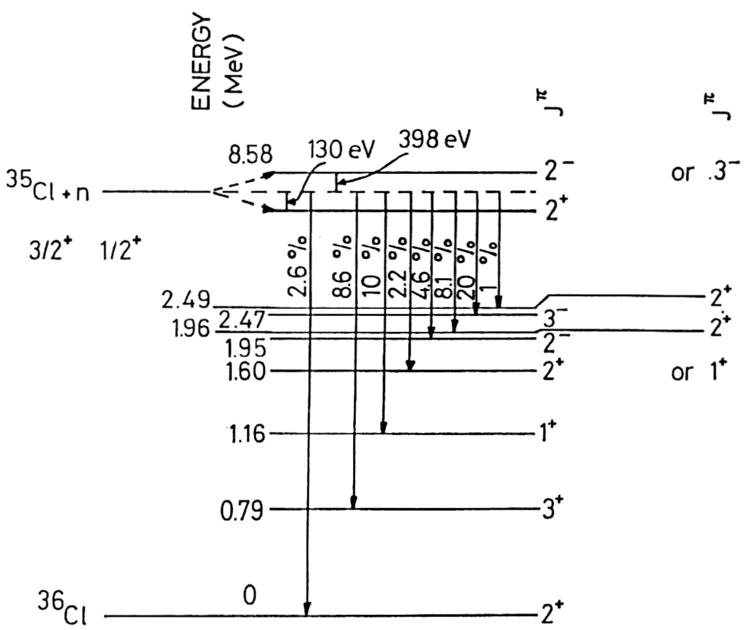

FIG. 4. Part of the scheme of production and decay of the ^{36}Cl nucleus.

one standard deviation was greater than the value predicted either by Cabibbo's model or by the gauge theory of weak interactions, which give

$$a_{\text{theor}} \simeq (0.5-1)\cdot 10^{-6} \text{ (Refs. 25 and 26).}$$

The asymmetry in the ^{35}Cl($\mathbf{n},\gamma$)^{36}Cl reaction was measured in a similar beam at ILL.[28] The target was NaCl salt measuring $1\times2\times3$ cm^3. The decay scheme of the ^{36}Cl nucleus is shown in Fig. 4. The energy of the main γ transition is 8.58 MeV. Two NaI(Tl) crystals with diameter and thickness 12 cm, placed on both sides of the target, were used for detection of the transition.

In this nucleus, as in ^{113}Cd, one can say which levels of the compound nucleus are mixed by the weak interaction and what is the spacing D between them. The mixed levels are 2^- (p resonance at energy $E_p=398$ eV) and 2^+ (s resonance at energy $E_s=-130$ eV). Therefore, $\mathscr{D}=528$ eV.

Control experiments were performed with a depolarized neutron beam, with reduced neutron flux, and with a ^{60}Co source. The measured asymmetry coefficient was $a=(1.57\pm0.53)\cdot10^{-4}$.

Finally, the same ^{117}Sn($\mathbf{n},\gamma$)^{118}Sn reaction as at ITEP was studied at ILL.[29] The detectors were two NaI(Tl) crystals of diameter and thickness 7.6 cm, placed on both sides of the target.

Control experiments were performed in a range of γ-ray energies different from the investigated one, with the neutron polarization vector turned through 90°, with a depolarized neutron beam, and with a ^{60}Co source.

The measured asymmetry coefficient $a=(4.4\pm0.6)\cdot10^{-4}$ differed by more than the experimental errors from the value measured at ITEP.[20]

At the Konstantinov Institute of Nuclear Physics at St. Petersburg a facility has recently been created for measuring the P-odd asymmetry in the ($\mathbf{n},\gamma$) reaction; in it the γ-ray detectors are Ge(Li) crystals and not the traditional NaI(Tl). This makes it possible to improve the energy resolution and to measure effects not just at one main transition, having the greatest energy, but at several resolved γ transitions having lower energy. In particular, for the asymmetry coefficient in the ^{117}Sn($\mathbf{n},\gamma$)^{118}Sn reaction for γ rays with energy $E_\gamma=9.31$ MeV the value $a=(9.7\pm1.3)\cdot10^{-4}$, confirming the ITEP data, was obtained.[30]

3.1.3. Measurements of P-odd effects in the (n, γ) reaction in the integrated spectrum of the γ rays

The integrated method of detecting large particle fluxes is used when the counting method does not ensure the necessary counting rates on account of inadequate time resolution of the pulses. The integrated method was first proposed by Lobashev[31] and was used at the St. Petersburg Institute of Nuclear Physics (SPINP) to measure the circular polarization of γ rays emitted by unpolarized nuclei.[32]

Already in the ILL experiment to measure the asymmetry of the γ radiation in the (n,γ) reaction on the proton the technique of integrated information readout was used.[24] However, since the energies of the γ rays in the reaction on the proton are monochromatic, integrated information readout did not represent anything new in that case and was needed merely because it was impossible to resolve the large number of γ rays by the counter method.

In contrast, in the SPINP studies the integrated information readout was a new approach to the investigation of P-odd effects on neutrons. Investigations of P-odd effects in distinguished lines in (n,γ) reactions on complex nuclei encountered serious difficulties associated with the need to separate photopeaks from a very complicated γ spectrum. Therefore, only the individual cases of P-odd effects in distinguished lines listed in Sec. 3.1.2 were observed. The time of accumulation of the statistics in these cases was several months. It seemed hardly realistic to expect appreciable effects for the majority of nuclei, since in the high-energy region of the spectrum in (n,γ) reactions regular E1 transitions, for which there is no kinematic enhancement, are dominant.

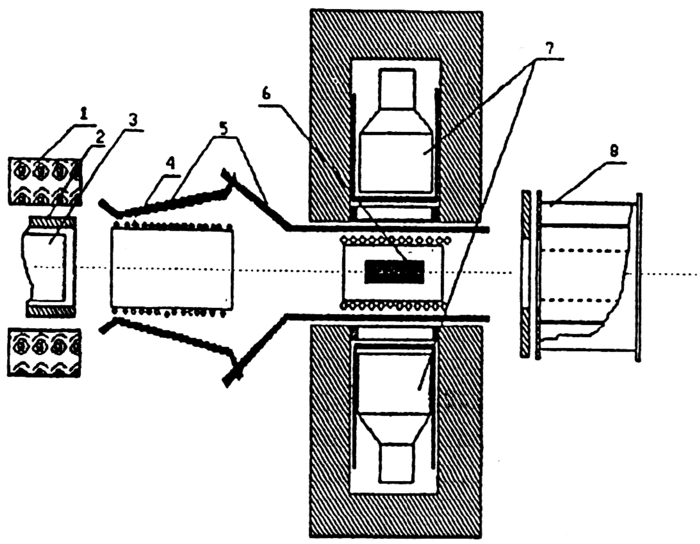

FIG. 5. Schematic diagram of the experimental facility at SPINP for simultaneous measurement of asymmetry effects in the integrated γ-ray spectrum and in the total and radiative cross sections: *1)* shielding blocks; *2)* magnets of neutron guide tube; *3)* neutron guide tube; *4)*, *5)* guiding magnets and rf fields; *6)* target; *7)* detectors of γ rays; *8)* neutron detector.

It appeared that averaging over many γ transitions must strongly reduce the effect.

This point of view was successfully refuted in the SPINP experiments using thermal polarized neutrons.[33] The SPINP facility, which was placed in the horizontal channel of the VVR-M reactor, is shown in Fig. 5. With this facility, P-odd effects were measured simultaneously in the total and radiative cross sections for neutron interaction on nuclei, as will be discussed below in Sec. 3.3.3.

For the investigation of the P-odd asymmetry in the integrated spectrum of γ rays, targets of ^{35}Cl, Br, ^{117}Sn, and ^{139}La in ^{6}LiF containers were placed between Helmholtz rings, whose planes were perpendicular to the γ-ray pulse (they are not shown in Fig. 5). Thermal polarized neutrons that had passed through an adiabatic high-frequency spin flipper (see Ref. 4) were incident on the targets. The polarization was flipped once in 2 s. The degree of beam polarization was $P_n=95\%$. The γ-ray detectors were NaI(Tl) crystals of diameter 150 mm and thickness 100 mm, placed on both sides of the targets. Thus, a configuration was realized in which the neutron spins **s** were parallel to the momenta $\mathbf{p}_\gamma$ of the γ rays as needed for observation of the pseudoscalar quantity $\mathbf{sp}_\gamma$.

The output signals of the photomultipliers were fed to the input of a differential amplifier, integrated during the time of an individual measurement (2 s), converted to digital code, and stored for subsequent analysis. Since the P-odd effects in the detectors had opposite signs, the difference effect contained twice the value of the effect, and all fluctuations of the neutron flux were annihilated. In a different version of the experiment, the signal of a monitor of the neutron beam from the facility placed in a more intense neutron flux of the same reactor was fed to a second input of the differential amplifier. In this way the power fluctuations of the reactor were compensated.

Measurements of the P-odd asymmetries in the integrated spectrum of Fe and Cd nuclei (natural mixtures of the isotopes) were made in a beam of polarized neutrons in a vertical channel of the reactor.[34] The flux of polarized neutrons with degree of polarization $P_n=80\%$ reached 10^9 neutron/s. The Fe and Cd targets were placed in ^{6}LiF containers. The spin flipper and electronic apparatus were similar to those used in the horizontal channel of the reactor.

In the ILL study of Ref. 28, measurements were made not only of the P-odd effect in the main transition in the $^{35}\mathrm{Cl}(\mathbf{n},\gamma)^{136}\mathrm{Cl}$ reaction, but also of the P-odd effect in the integrated spectrum of this reaction. The beam in this case was much more intense, and it was therefore impossible to separate the γ line of the main transition. Liquid-scintillation γ-ray detectors were used. A control experiment with a depolarized beam was performed.

The results of measurements of the P-odd effects in the integrated spectrum of γ rays are given in Table I with the identification "integrated spectrum."

Parity violation in the $^{207}\mathrm{Pb}(\mathbf{n},\gamma)^{208}\mathrm{Pb}$ reaction was investigated at ITEP.[35] Interest in this reaction arose because the result of the investigation could be decisive for the choice between the compound-nucleus and valence mechanisms of mixing of states with opposite signs of the parity. The theoretical aspect of this problem will be discussed below in Sec. 4. Here we merely mention that since in the spectrum of the (n,γ) reaction on the ^{207}Pb nucleus there is one dominant γ line (the main transition, whose intensity is at least three orders of magnitude above the intensities of the remaining γ lines), it was possible to use the integrated method of γ-ray detection.

The study was made in a beam of thermal polarized neutrons from the ITEP reactor in the same geometry as in the series of cadmium studies. A lead target of cross section 1.5×9 cm^2 and thickness 2.5 cm was enriched with the isotope ^{207}Pb to 87.3%. Since the scattering cross section is 92% of the total cross section for interaction of thermal neutrons with the ^{207}Pb nucleus, to reduce the background from the scattered neutrons lithium ($^{6}\mathrm{Li}_2\mathrm{CO}_3$) screens were placed in front of the NaI(Tl) crystals; they absorbed 99% of the scattered neutrons. The background was formed by γ rays of the direct beam, γ rays scattered by the target, and γ rays from (n,γ) reactions in the detectors and construction materials. The total background was $\simeq10\%$ of the total load on the detectors. A control experiment measured the P-odd asymmetry of γ-ray emission in the integrated spectrum of the $^{35}\mathrm{Cl}(\mathbf{n},\gamma)^{36}\mathrm{Cl}$ reaction.

The measured asymmetry coefficient was $a=-(0.89\pm0.53)\cdot10^{-5}$, which gave an upper limit on the P-odd asymmetry: $a\leqslant1.7\cdot10^{-5}$ at the 90% confidence level.

3.2. Anisotropy of protons in the (n,*p*) reaction

3.2.1. Fundamentals of the method

In Ref. 36 a new method was proposed for investigation of the violation of spatial parity in nuclear interactions, namely, investigation of the anisotropy of α particles and other light nuclei emitted from nuclei after capture of polarized neutrons. A series of studies on this subject, made at SPINP and ITEP[37–40] did not give positive results. However, appreciable P-even effects of left–right asymmetry were found.[37,38]

A P-odd effect in a reaction with proton emission was first found in the $^{35}Cl(\mathbf{n},p)^{35}S$ reaction in a study of SPINP and the Laboratory of Neutron Physics.[41] The same study found P-even effects of left–right asymmetry in the previous reaction and in the $^{14}N(\mathbf{n},p)^{14}C$ reaction. Thus, these reactions exhibit a P-odd correlation $\mathbf{sp}_p$ and a P-even left–right asymmetry $\mathbf{s}(\mathbf{p}_n \times \mathbf{p}_p)$, where $\mathbf{s}$ and $\mathbf{p}_n$ are the spin and momentum of the incident neutron, and $\mathbf{p}_p$ is the momentum of the emitted proton [see Sec. 2, Eq. (6)].

The general expression for the coefficient of the P-odd asymmetry is

$$a = \frac{M}{E_p}\left(\frac{\Gamma_p^p}{\Gamma_s^p}\right)^{1/2}(x^p - y^p)\cos\Delta\varphi_{sp}, \tag{20}$$

and for the coefficient of the P-even left–right asymmetry it is

$$a_{\mathrm{lr}} = \frac{E_s}{E_p}\left(\frac{\Gamma_p^p\Gamma_p^n}{\Gamma_s^p\Gamma_s^n}\right)^{1/2}(x^p - y^p)\left(x^n + \frac{y^n}{2}\right)\sin\Delta\varphi_{sp}, \tag{21}$$

where M is the matrix element of the weak interaction; Γ_s^p and Γ_p^p are the proton widths of the s and p resonances; Γ_s^n and Γ_p^n are the neutron widths of the s and p resonances; $\Delta\varphi_{sp}$ is the phase difference of the Coulomb interaction in the s and p states; x^p, x^n, y^p, and y^n are the parameters of the mixing of the channels with total angular momentum $j=l-s=1/2$ and $j=l+s=3/2$:

$$x^{p(n)} = (\Gamma_{p1/2}^{p(n)}/\Gamma_p^{p(n)})^{1/2}; \quad y^{p(n)} = (\Gamma_{p3/2}^{p(n)}/\Gamma_p^{p(n)})^{1/2};$$

$$(x^{p(n)})^2 + (y^{p(n)})^2 = 1;$$

$$\Delta\varphi_{sp} = \varphi_p - \varphi_s = \arctan(Ze^2/\hbar v_p). \tag{22}$$

3.2.2. Measurements

The measurements were made in a horizontal beam of polarized thermal neutrons of the VVR-M reactor of SPINP. At the target, the flux of neutrons with polarization $P_n = 96\%$ was $6\cdot 10^7$ neutron/s. By means of an adiabatic spin flipper (see Ref. 4), the direction of the spin was reversed every 2.8 s. Protons with energy $E_p = 0.6$ MeV from the $^{35}Cl(\mathbf{n},p)^{35}S$ reaction were detected by a double proportional chamber with a grid that made it possible to create an insensitive gas gap for collimation of the protons. Targets measuring 110×7 cm^2 were deposited $BaCl_2$ or AlN salts of thickness 2 mg/cm^2. The counter method was used to detect the proton pulses. The correlation coefficients were found to be

$$a = -(1.51\pm 0.34)\cdot 10^{-4},$$

$$a_{\mathrm{lr}} = -(2.40\pm 0.43)\cdot 10^{-4}$$

for the $^{35}Cl(\mathbf{n},p)^{35}S$ reaction and

$$a_{\mathrm{lr}} = (0.66\pm 0.18)\cdot 10^{-4}$$

for the $^{14}N(\mathbf{n},p)^{14}C$ reaction.

3.3. Parity-violation effects in neutron-optical phenomena

3.3.1. Fundamentals of the method

Coherent effects due to the P-odd weak interaction of neutrons with the matter of targets arise because the refractive indices in matter of neutron waves having different spin states are not the same. The expression for the refractive index n contains the coherent scattering length $b_N = -f(0)$ for neutron scattering by bound nuclei:[42]

$$n = 1 - (\lambda^2 N/2\pi) b_N = 1 + (2\pi/p^2) N f(0). \tag{23}$$

In (23) we have set $\hbar = c = 1$; N is the number of scattering nuclei in 1 cm^3; p is the neutron momentum; $f(0)$ is the coherent amplitude for forward neutron scattering. As is well known,[42] for slow neutrons the scattering is isotropic, and the coherent scattering amplitude f of the neutrons does not depend on the angle: $f(0) = f$.

With allowance for the weak interaction the coherent scattering amplitude should be represented as consisting of two parts:

$$f = f_{PC} + f_{PNC} \tag{24}$$

where f_{PC} is the parity-conserving part of the amplitude, and

$$f_{PNC} = G^1 \mathbf{sp} \tag{25}$$

is a small parity-nonconserving correction to the amplitude, whose sign depends on the neutron helicity. By definition, the neutron helicity is positive if $\mathbf{sp} > 0$ and negative if $\mathbf{sp} < 0$. In Eq. (25), G^1 is a complex constant that in absolute magnitude is of the order of the weak interaction constant G.

As it traverses a distance l in the target, a neutron wave acquires a phase $\Delta = \mathrm{Re}(pnl)$. States with opposite signs of the helicity acquire the phase difference

$$\Delta_+ - \Delta_- = \mathrm{Re}[p(n_+ - n_-)l] = (2\pi/p) l N\ \mathrm{Re}(f_+ - f_-), \tag{26}$$

where the plus and minus signs correspond to the two neutron helicities.

For transversely polarized neutrons, the polarization vector is rotated around the momentum through the angle

$$\varphi_{PNC} = -(\Delta_+ - \Delta_-) = -4\pi l N\ \mathrm{Re}\, G^1. \tag{27}$$

The angle of spin rotation per unit length of the target will be denoted by

$$\Delta\varphi = \varphi_{PNC}/l.$$

At the same time, the imaginary part of the amplitude f_{PNC} is related by the optical theorem $\sigma_t = (4\pi/p)\mathrm{Im} f(0)$ to the difference $\Delta\sigma_t$ of the total cross sections for the two states of the neutrons with helicities of opposite signs:

$$\Delta\sigma_t = \sigma_t^+ - \sigma_t^- = (4\pi/p)\mathrm{Im}(f_+ - f_-) = 8\pi\ \mathrm{Im}\, G'. \tag{28}$$

In the experiments with longitudinally polarized neutrons measurements were made of three physical quantities that must be related to each other and also to the angle of rotation of the spins of the transversely polarized neutrons.

First, there is the coefficient of asymmetry of the transmission:

$$\varepsilon=(N^+-N^-)/P_n(N^++N^-), \quad (29)$$

where $N^{\pm}$ are the counting rates (or values of the beam intensities) of the neutrons of opposite helicities that have passed through the target. Second, there is the coefficient of asymmetry of the total cross sections for interaction of neutrons of opposite helicities:

$$a_t=(\sigma_t^+-\sigma_t^-)/(\sigma_t^++\sigma_t^-)\cong\Delta\sigma_t/2\sigma_t. \quad (30)$$

Since usually $n\Delta\sigma_t\ll 1$, where n is the thickness of the target (nucleus/cm^2), we have

$$\varepsilon=-\text{th}(n\Delta\sigma_t/2)=-n\sigma_t a_t=-a_t l/\lambda, \quad (31)$$

where l is the length of the target; $\lambda=1/n\sigma_t$ is the mean free path of neutrons in the target. Third, there is the coefficient of asymmetry of the cross sections σ_γ for radiative capture of neutrons of opposite helicities:

$$a_\gamma=(\sigma_\gamma^+-\sigma_\gamma^-)/(\sigma_\gamma^++\sigma_\gamma^-). \quad (32)$$

The first such investigations were proposed by Michel in 1964.[43] He showed that in the case of transmission of transversely polarized neutron beams it is possible to detect a rotation of the neutron spins around the direction of their momentum in matter. However, the effects in pure form are very small, and therefore a mechanism was needed to enhance them. Forte noted that the effects must be enhanced near a single-particle p-wave resonance[44] and proposed an experiment to measure the rotation angle of neutron spins in a ^{124}Sn target, whose nuclei have a p-wave resonance at energy 62 eV.

The first experiment to observe rotation of the polarization vector was performed at ILL in 1980.[45] Its results were unexpected. For the ^{124}Sn nucleus, no spin rotation was found, but in a control experiment with a target of the natural mixture of the ten isotopes a comparatively large rotation of the spins was found. The investigators replaced the ^{124}Sn target by a ^{117}Sn target, for whose nuclei a large P-odd transmission asymmetry of γ rays had previously been detected.[20,29] The spin rotation was found to be large. For the same nucleus the transmission asymmetry of longitudinally polarized neutrons of opposite helicities predicted by Forte was found.

The large effects for ^{117}Sn stimulated Stodolsky to seek to explain them by completely new weak forces.[46] However, elucidation of the role of resonance effects in coherent parity violation made it possible to obtain a correct understanding of the influence of the enhancement factors and to explain the large magnitude of the observed effects. The possibility of kinematic enhancement of the effects of parity violation near a p-wave resonance was first pointed out by Karmanov and Lobov.[47] Forte reexamined this question in Ref. 48. A kinematic enhancement factor of the type $(\Gamma_s^n/\Gamma_p^n)^{1/2}$ arose when allowance was made for the interference of the entrance s and p channels for the same exit channel (see Sec. 2). Here, Γ_s^n and Γ_p^n are the neutron widths of the s and p resonances. At low energies, $(\Gamma_s^n/\Gamma_p^n)^{1/2}\cong 1/pr$, where r is the radius of the nucleus, so that for nuclei with $A\cong 100$ and neutron energies of order 1–10 eV this enhancement factor reaches 10–10^3. The kinematic enhancement in this case reflects the difference between the penetrabilities of s and p waves for neutrons incident on a nucleus.

Sushkov and Flambaum[5] pointed out that in Ref. 48 the effects of coherent parity violation were explained by the interaction of neutrons with a P-odd potential of the nucleus, i.e., the nucleus was treated as a particle without internal degrees of freedom. The virtual excitation of a compound nucleus must lead to a dynamical enhancement factor $(\Delta E/D)^{1/2}$, where $\Delta E\simeq 1$ MeV is the mean separation between the single-particle states, and $D\simeq 1-10$ eV is the mean separation between the levels of the compound nucleus. This factor has a value of order 10^2–10^3.

This approach to the role of resonance effects became known as the model of mixed composite states (see the review of Ref. 49). According to this model, the difference between the total cross sections for interaction of neutrons of opposite helicities near p-wave resonances can be conveniently represented in the form

$$\Delta\sigma_t=2P(E)\sigma_t(E), \quad (33)$$

where

$$P(E)=2\alpha\sqrt{\Gamma_s^n(E)/\Gamma_p^n(E)}\,. \quad (34)$$

In this expression it is assumed that $\Gamma_p^n=\Gamma_{p1/2}^n$, i.e., that $\Gamma_{p3/2}^n=0$ and $x=1$, $y=0$ (see Sec. 3.1.1).

A more complete expression contains

$$\sqrt{\frac{\Gamma_s^n}{\Gamma_p^n}\,\frac{\Gamma_{p1/2}^n}{\Gamma_p^n}} \text{ (Ref. 5).}$$

In Eq. (34), α is the coefficient of level mixing with respect to the parity (see Sec. 2), and $\sigma_t(E)$ is the Breit–Wigner cross section near the p resonance. Near it, the value of $P(E)$ is practically constant and equal to $P(E_p)$ at the p-resonance energy E_p. It is readily seen that $P(E_p)$ plays the role of an asymmetry coefficient $a_t(E_p)$ at the resonance.

We give an expression that is used to compare the transmission asymmetry coefficients for the same nucleus but at thermal, E_{th}, and resonance, E_p, energies:

$$a_t(E_{\text{th}})/P(E_p)=[\sigma_t(E_p)/\sigma_t(E_{\text{th}})](\Gamma_p/2E_p)^2. \quad (35)$$

For comparison of the results on spin rotation and the asymmetry of the total cross sections, we give the relation between the rotation angle $\Delta\varphi$ and $\Delta\sigma_t$:

$$\Delta\varphi=N\Delta\sigma_t(E-E_p)/\Gamma_p. \quad (36)$$

In Eqs. (35) and (36), Γ_p is the total width of the p resonance.

Stodolsky[50] analyzed the contribution of the elastic and inelastic channels of neutron interaction with nuclei to the rotation angle $\Delta\varphi$ of the polarization vector and to the difference $\Delta\sigma_t$ of the total cross sections and investigated the dependence of this contribution on the neutron energy. He found that: 1) the rotation angle $\Delta\varphi$ in a significant energy range is independent of the energy; 2) the difference of the total cross sections consists of two terms, $\Delta\sigma_t=\Delta\sigma_s+\Delta\sigma_{\text{exo}}$, where σ_s is the cross section of coherent elastic scattering, and σ_{exo} is the cross section of the exothermic reactions, the largest of which is the cross section σ_γ for radiative capture;

TABLE II. Results of measurements of the neutron spin rotation $\Delta\varphi$ at ILL.

Target nucleus	$\Delta\varphi$, 10^{-6} rad/cm	Source
$Sn_{(nat.)}$	-3.19 ± 0.40	Ref. 54
^{117}Sn	-37.0 ± 2.5	Ref. 45
^{124}Sn	-0.48 ± 1.49	Ref. 45
^{139}La	-219 ± 29	Ref. 55
$Pb_{(nat.)}$	$+2.24\pm 0.33$	Ref. 54

at the same time, $\Delta\sigma_s$ is proportional to the neutron momentum p, while $\Delta\sigma_{exo}$ does not depend on the momentum. Therefore, at thermal energies of the neutrons the main contribution to $\Delta\sigma_t$ must be made by the process of radiative capture of neutrons, i.e., $\Delta\sigma_t\cong\Delta\sigma_\gamma$, and this was confirmed by the SPINP experiments.[51,52]

A somewhat different approach to the role of resonance effects in coherent parity violation was developed by Zavetskiĭ and Sirotkin.[53] This approach will be discussed below in Sec. 4.

3.2.2. Measurements of spin rotation of transversely polarized neutrons

Experiments to measure the spin rotation of neutrons were performed using a beam of cold transversely polarized neutrons at ILL. A description of the facilities and their operation can be found in the original papers[45,54,55] and in the monograph of Ref. 4. The results are given in Table II.

3.3.3. Measurements of the asymmetry of the total cross sections and the cross sections for capture of thermal longitudinally polarized neutrons

The first measurement of the transmission asymmetry of longitudinally polarized neutrons was performed at ILL with a ^{177}Sn target in the same study[45] in which a spin rotation of transversely polarized neutrons was found. The facility was modified in such a way that longitudinally polarized neutrons were incident on the target (see Ref. 4). The asymmetry coefficient $\varepsilon=-(9.78\pm4.01)\cdot10^{-6}$ was obtained.

A more accurate value for the asymmetry coefficient of the total cross section for interaction of neutrons of opposite helicities, a_t, was obtained in studies at SPINP,[51,52] in which the asymmetry coefficient a_γ in the cross section of radiative capture was simultaneously measured. The measurements were made on the ^{117}Sn and ^{139}La nuclei and the natural mixture of isotopes $^{79,81}Br$. The arrangement of the facility is shown in Fig. 5, and it is described in the papers of Refs. 51 and 52 and in the monograph of Ref. 4. It can be verified that the relation $\Delta\sigma_t\cong\Delta\sigma_\gamma$ does indeed hold.

In a study at ITEP,[56] the asymmetry of the total cross sections for interaction of longitudinally polarized neutrons was also investigated for a number of targets.

In a study at the "Kurchatov Institute Research Center" in Moscow[57] the polarization of a neutron beam after it had passed through a KBr target was measured. The polarization analyzer was iron magnetized to saturation. This method gives results similar to those obtained by measuring the asymmetry of the total cross section for interaction of neutrons of opposite helicities. In a further IAE study,[58] the same method was used to measure the asymmetry of the total cross section for the interaction of thermal longitudinally polarized neutrons with the ^{239}Pu nucleus.

All the experimental results are given in Table III.

3.3.4. Measurements of the asymmetry of the total cross sections and of the cross sections for capture of resonance longitudinally polarized neutrons

Studies to measure the asymmetry of the total cross sections and the asymmetry of the cross sections for capture of resonance longitudinally polarized neutrons have been made in several centers. The first investigations were studies of the Laboratory of Neutron Physics of JINR at Dubna. They were then continued at Kurchatov Institute in Moscow, at the National Laboratory for High Energy Physics KEK (Japan), and, finally, at the Los Alamos National Laboratory (LANL, USA). The complete set of studies on this subject is well reflected in the recently republished review of Ref. 2. Therefore, omitting the details of the experimental technique, we shall merely dwell on some of the main aspects.

The P-odd effects at neutron resonances were studied in two ways. One of them is transmission of longitudinally polarized neutrons through a thick target with studied nuclei for which $n\sigma_t\cong2$. This makes it possible to measure the asymmetry $P(E)=\Delta\sigma_t/2\sigma_t$ of the total cross sections. The second method is to measure the asymmetry of the cross sections for radiative capture of longitudinally polarized neutrons by a thin target, for which $n\sigma_t\ll1$. The ratio $P_\gamma(E)=\Delta\sigma_\gamma/2\sigma_\gamma$ is measured. Since in the region of p-wave resonances the total resonance width Γ_p is practically equal to the radiative width Γ_γ, the two methods give the same results.

The LNP experiments made use of the IBR-30 pulsed

TABLE III. Results of measurements of the asymmetry coefficient a_t of the total interaction cross sections and the asymmetry coefficient a_γ of the cross sections of capture for thermal neutrons of opposite helicities.

Target nucleus	σ_t (E_{th}), 10^{-24} cm^2	σ_γ (E_{th}), 10^{-24} cm^2	a_t, 10^{-6}	a_γ, 10^{-6}	Source
$^{79,81}Bz$	15.5	9.8	9.8 ± 1.0	15.5 ± 1.5	SPINP (Ref. 52)
	12.8		9.5 ± 1.7		ITEP (Ref. 56)
			15.3 ± 1.5		IAE (Ref. 57)
^{117}Sn	3.7	1.2	6.2 ± 0.7	22.6 ± 1.9	SPINP (Ref. 51)
	4		11.2 ± 2.6		ITEP (Ref. 56)
^{139}La	19	9.4	9.0 ± 1.4	16.1 ± 2.0	SPINP (Ref. 51)
^{239}Pu			0.67 ± 0.16		IAE (Ref. 58)

reactor.[59,60] The resonance neutrons were polarized by transmission through a polarized proton target. This method is described in the review of Ref. 2 and in the monograph of Ref. 4. An advantage of using a polarized proton target is the possibility of obtaining polarized neutrons in a wide range of energies—from thermal energies to 10^5 eV. By virtue of the use of the neutron time-of-flight method with the pulsed reactor, this made it possible to study in a comparatively simple manner the spin states of individual resonances in the neutron cross sections.

The main parameters of the LNP facility were as follows. The protons were polarized by the dynamical method (solid effect) in a single crystal of double lanthanum–magnesium nitrate with a 0.5–1% admixture of ^{142}Nd nuclei at temperature 1–1.5 K in a magnetic field of strength 8 kA/cm. The longitudinal polarization of the neutrons and flipping of the polarization vector were achieved by appropriate configurations of a guiding magnetic field. The polarization vector was flipped every 40 s. Every two days, the direction of polarization of the proton target was changed in order to change the sign of the investigated effect without changing the instrumental and geometrical conditions of the experiment. The neutron detector was a segmented liquid scintillator that used a neutron–gamma converter made of europium oxide, terbium oxide, and water. Its efficiency varied from 40 to 30% for neutron energies from 1 to 500 eV.

Studies[61–64] at the LNP measured the transmission of longitudinally polarized neutrons of opposite helicities directly at p resonances for the nuclei ^{81}Br, ^{111}Cd, ^{113}Cd, ^{117}Sn, ^{139}La, and ^{232}Th. The coefficients of asymmetry of the total cross sections were found to be of order 10^{-2}–10^{-3}, while for ^{139}La they even reached 10%.

In the IAE facility[65] a measurement was made of the small polarization of a neutron beam resulting from the transmission of unpolarized neutrons through thick investigated targets as a result of the P-odd dependence of the capture cross section on the neutron helicity. The analyzer of the produced polarization was a polarized proton target. A time-of-flight spectrometer for polarized resonance neutrons was developed on the basis of the electron linear accelerator Fakel. Measurements were made of P-odd effects in the neighborhood of p resonances of ^{117}Sn and ^{139}La.

The experiment at the KEK facility[66–69] used neutrons produced by the action of protons of the booster synchrotron in depleted uranium. The neutrons moderated in a block of solid methane were polarized by passing through a polarized proton target and were then incident on the investigated targets. The polarization of the protons was produced by the dynamical method and reached 80%. The neutron energy was measured by the time-of-flight method. The neutron helicity was varied adiabatically by a spin flipper.

Measurements were made of both the asymmetry of the capture cross sections and the asymmetry of the total cross sections. In the first case, either counters of a scintillating plastic or BaF_2 crystals surrounding the investigated targets were used. The asymmetry of the total cross sections was measured simultaneously by means of a liquid-scintillator counter with ^{10}B added, this being placed at the end of the time-of-flight base.

The Los Alamos National Laboratory (LANL) has the most intense beam of resonance polarized neutrons. Because of this, the maximum energy of the investigated neutron resonances at the LANL facility is much greater than at the LNP, KEK, and IAE facilities. As a result, it proved possible at LANL to measure the effects of parity violation on one nucleus at several energies of resonance neutrons. This could not be done at the other facilities. The facility and the measurements with it are described in detail in the review of Ref. 2. We shall only mention the main points. The neutron beam was produced by irradiating a tungsten target with protons of energy 800 MeV from a linear accelerator. The neutrons were moderated and encountered a polarized proton target. The neutron spins were flipped by a spin flipper of a special construction, which is described in detail in Ref. 2. The neutrons were detected by scintillating glass with ^{6}Li. Analysis of the transmission data at several resonances required a multiparameter program with allowance for the Doppler broadening of the resonance line, the dependence of the neutron flux on the energy, the Breit–Wigner shape of the resonance, and the energy efficiency of the neutron detector.[2]

The results of all measurements of the asymmetry of the total cross sections and the asymmetry of the cross sections for capture of resonance longitudinally polarized neutrons are given in Table IV.

The absolute values of the matrix elements $|M|$ of the weak interaction given in Table IV are, in many cases, lower bounds for M, since they were calculated under the assumption that the capture of neutrons in a p resonance takes place completely in the channel with total angular momentum $j=1/2$, i.e., under the assumption that $\Gamma_p^n=\Gamma_{p1/2}^n$ $(x=1, y=0)$ (see Sec. 3.1.1). An attempt to avoid this condition was made in the LNP studies[16,76] for ^{113}Cd and ^{117}Sn, in which measurements were made of the P-even angular correlations of γ rays at p resonances of the studied nuclei (see Sec. 3.4).

3.4. Investigations of *P*-even effects at *p* resonances

The P-even correlations at p-wave resonances have been studied only at the LNP, on ^{113}Cd and ^{117}Sn targets. The theory of P-even angular correlations is given in the review of Ref. 3. We have already given the necessary expressions (see Sec. 3.1.1).

In what follows, we shall consider the geometry of the experiments and the corresponding facilities. All the experiments were performed by the time-of-flight method in beams from the LNP reactors IBR-30 and IBR-2. The geometry of the experiment for measurement of the left–right asymmetry is shown in Fig. 6a. In this case, transversely polarized beams with mutually orthogonal directions of all three vectors $\mathbf{s}$, $\mathbf{p}_n$, and $\mathbf{p}_\gamma$ were used. An unpolarized beam in the geometry shown in Fig. 6b was used to measure the forward–backward asymmetry.

The γ-ray detectors were NaI(Tl) crystals of diameter and thickness 200 mm, shielded by lead, paraffin with boron, and cassettes with $^6Li_2CO_3$. A slab of paraffin with boron of thickness 10 cm was placed at the detector entrance to eliminate direct detection of fast neutrons.

The study of Ref. 75 led to the first observation of left–right asymmetry ε_{lr} of the emission of γ rays of the main

TABLE IV. Results of measurements of P-odd effects for resonance neutrons.

Target nucleus	Measurement	E_p, eV	Γ_p, meV	$g\Gamma_p^n$, 10^{-8} eV	$P(E_p)$, 10^{-3}	$\lvert M \rvert$, meV	Source
^{81}Br	a_t	0.88 (1)	190(20)	5.8 (3)	24 ± 4	3.0 ± 0.5	LNP (Refs. 49 and 62)
	a_t				17.7 ± 3.3		LANL (Ref. 74)
	a_γ				21 ± 1	2.6 ± 0.1	KEK (Ref. 69)
^{111}Cd	a_t	4.53 (3)	163(10)	107(5)	-8.6 ± 1.2	2.6 ± 0.4	LNP (Refs. 16, 49, and 62)
	a_γ				13^{+7}_{-4}	$1.6^{+0.8}_{-0.5}$	KEK (Ref. 69)
^{113}Cd	a_t	7.0	160(20)	31(3)	-9.8 ± 3.0	0.31 ± 0.10	LNP (Refs. 15, 16, and 64)
^{117}Sn	a_t	1.33 (1)	180(18)	16.6(2.0)	4.5 ± 1.3	0.38 ± 0.10	LNP (Refs. 16, 49, and 62)
	a_t				7.7 ± 1.3	0.7 ± 0.1	IAE (Ref. 65)
	a_γ				11 ± 2		LANL (Ref. 73)
^{139}La	a_t	0.75 (1)	45 (5)	3.6 (3)	73 ± 5	1.28 ± 0.12	LNP (Refs. 49 and 62)
	a_t				76 ± 6	1.3 ± 0.1	IAE (Ref. 65)
	a_t				97 ± 5		KEK (Ref. 68)
	a_t				92 ± 17		LANL (Ref. 70)
	a_t				95.5 ± 3.5		LANL (Ref. 71)
	a_t				101.5 ± 4.5		LANL (Ref. 71)
	a_t				95 ± 5		LNP (Ref. 64)
	a_γ				98 ± 3	1.7 ± 0.1	KEK (Ref. 69)
^{232}Th	a_t	8.33(3)*	32 (3)	26.8(1.5)	17.9 ± 9.2	0.62 ± 0.31	LNP (Ref. 63)
	a_t				14.8 ± 2.5		LANL (Refs. 72 and 74)

*The results of measurements at other ^{232}Th resonances and at ^{238}U resonances are given in the review of Ref. 2.

transition with energy $E_\gamma = 9.32$ MeV at the neutron p resonance of ^{117}Sn with energy $E_p = 1.33$ eV after radiative capture of polarized neutrons. The relative partial neutron width in the channel with total angular momentum $j = 1/2$ of the neutron was found to be $x^2 = \Gamma_{p1/2}/\Gamma_p = 0.27 \pm 0.33$ (this is the channel-mixing parameter of Sec. 3.1.2).

However, in the subsequent study of Ref. 76, in which measurements were made of the left–right asymmetry, the forward–backward asymmetry ε_{fb}, and the angular anisotropy ε_p of the p-wave part of the cross section in the region of the same ^{117}Sn resonance, it was found that the results could not be reconciled with the results of the measurements of the left–right asymmetry ε_{lr}. This dramatic situation is described in detail in the review of Ref. 3. This discrepancy still persists.

In the study of Ref. 16, measurements were made of the γ-ray yields of the main transitions near p-wave neutron resonances of ^{111}Cd, ^{113}Cd, and ^{117}Sn at angles 45°, 90°, and 135°. This made it possible to calculate the angular anisotropy ε_p. These data were used to determine the spins J of the p resonances, the total widths Γ_p of the p resonances, the partial widths $\Gamma_p^{\gamma_0}$ of the main γ transitions, and the contributions to the neutron widths of states with definite spin of the channel, $\mathbf{s} = \mathbf{J}_i + \mathbf{s}_n$, where J_i is the spin of the target nucleus. We note that these results determined for the first time that the spin and parity of the p resonance of ^{113}Cd at the energy $E_p = 7.0$ eV are $J^\pi = 1^-$. This gave the correct interpretation of the nature of the P-odd asymmetry of γ rays from ^{113}Cd in the thermal range of energies (see Sec. 3.1.2).

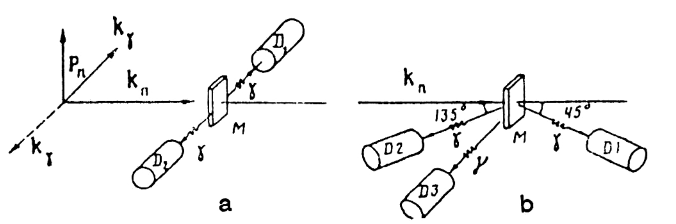

FIG. 6. Geometry of the LNP experiments to measure the left–right asymmetry (a) and forward–backward asymmetry (b). The target is M, and D_1, D_2, and D_3 are γ-ray detectors.

As a result of these studies, we can compare the P-even and P-odd effects in (n,γ) reactions for ^{113}Cd and ^{117}Sn at resonance and thermal energies of the neutrons in order to determine the matrix elements of the weak interaction. This is done in Sec. 4.

In Ref. 77, measurements were made of the forward–backward angular asymmetry ε_{fb} of γ-ray emission and the angular left–right asymmetry ε_{lr} for γ rays of the main transition with $E_\gamma = 9.04$ MeV in the $^{113}Cd(n,\gamma)^{114}Cd$ reaction in the region of the p resonance with $E_p = 7.0$ eV. These measurements yielded the values

$$x = (\Gamma_{p1/2}/\Gamma_p)^{1/2} \quad \text{and} \quad y = (\Gamma_{p3/2}/\Gamma_p)^{1/2}.$$

However, as in the case of ^{117}Sn, the solutions obtained in the experiments with ^{113}Cd were found to be incompatible. The problem of the interpretation of the P-even effects that arose after the study of Ref. 76 remains open.

4. COMPARISON OF THE RESULTS OF MEASUREMENTS AND COMPARISON OF THEM WITH THEORETICAL PREDICTIONS

In this section, we shall compare the experimental results for individual nuclei with one another and with theoretical predictions. The results of measurements of the asymmetry of the total cross sections and the cross sections for the capture of resonance longitudinally polarized neutrons are compared in the review of Ref. 2.

4.1. ^{1}H

Measurements were made of the P-odd asymmetry of the γ radiation on thermal polarized neutrons.[24,25] In the process $n+p\rightarrow d+\gamma$ there is no enhancement of the effect. The regular M1 transition is not suppressed, and therefore the effects that arise are very small, as the experiment showed (Table I).

A second important experiment performed for this reaction was the measurement of P_γ, the circular polarization of γ rays on unpolarized neutrons. It was performed at SPINP and gave, as in the measurement of the P-odd asymmetry of the γ radiation, only an upper limit: $P_\gamma \leqslant 5\cdot 10^{-7}$ (Ref. 78).

The importance of both experiments is difficult to overestimate; they make it possible to separate experimentally the contributions with different changes ΔT of the isotopic spin, and this should help to establish the form of the original Hamiltonian of the weak interaction of the nucleons. As Danilov showed,[79] the asymmetry in the emission of γ rays following capture of polarized neutrons by protons is sensitive to the isovector part ($\Delta T=1$) of the potential of the weak nucleon–nucleon interaction, whereas the circular polarization of the γ rays resulting from capture of unpolarized neutrons is sensitive to the isoscalar ($\Delta T=0$) or isotensor ($\Delta T=2$) parts. Thus, experiments to determine a and P_γ at a sufficient level of accuracy make it possible to establish the isotopic structure of the weak nucleon–nucleon interaction.

Measurement of the asymmetry a in the reaction $n+p\rightarrow d+\gamma$ is also a good test for the role of neutral currents in the np system because allowance for the neutral currents leads to an enhancement of the isovector part ($\Delta T=1$) in the potential of the weak nucleon–nucleon interaction.

The theoretical predictions[26,80] for the values of a fluctuate from $1.5\cdot 10^{-8}$ to $5\cdot 10^{-8}$.

4.2. ^{2}H

A measurement was made of the P-odd asymmetry of γ radiation on thermal polarized neutrons.[27] In the case of the reaction $n+{}^2\mathrm{H}\rightarrow {}^3\mathrm{H}+\gamma$, enhancement of the effect is possible, since the regular M1 transition is suppressed.[81] The accuracy of the value of a is not sufficient to speak of a discrepancy between the experiment and the theory, which predicts $a\cong 10^{-6}$ (Refs. 26 and 82).

The reaction $n+{}^2\mathrm{H}\rightarrow {}^3\mathrm{H}+\gamma$ must be investigated in three experiments: the beam and target are not polarized, when the circular polarization of the γ rays is measured; the neutron beam is polarized and the target is unpolarized; and, conversely, the beam is unpolarized and the target is polarized—in both of these cases, the asymmetry of the angular distribution of the γ rays is measured. The effects are due to both isoscalar and isovector P-odd interactions. These three experiments in conjunction with the two experiments with the reaction $n+p\rightarrow d+\gamma$ make it possible in principle to find five constants, which completely determine the isotopic structure of the weak nucleon–nucleon interaction.

4.3. ^{35}Cl

In the case of this nucleus, measurements were made of the P-odd angular correlations in the $(\mathbf{n},\gamma)$ reaction at a distinguished line with $E_\gamma=8.58$ MeV (Ref. 28) and in the integrated spectrum of the γ rays,[28,33] and also in the $(\mathbf{n},p)$ reaction.[41] The results are given in Table I. Since in the expression (12) the spin factor A for ^{35}Cl is calculated and the separation between the mixed levels is also known, $\mathscr{D}=528$ eV, it is possible from the measured asymmetry coefficient a to find the matrix element of the weak interaction that mixes the 2^- and 2^+ levels: $M=\langle 2^-|H_w|2^+\rangle=250\pm 80$ meV (with scale factor 3 due to the uncertainty in the values of the wave functions of both levels).

A more definite estimate of M was made in Ref. 41. Substituting the known values in the expression (20), we obtain $M=\langle 2^-|H_w|2^+\rangle=60\pm 20$ meV, which is not in contradiction with the previous estimate.

Measurements of the P-odd angular correlations in the integrated γ-ray spectrum[28,33] gave results that agreed within the errors (Table I).

A theoretical estimate of the P-odd effects in the integrated γ-ray spectrum is difficult, since all the effects are averaged with a certain detection efficiency over the complete spectrum of γ rays or over part of it.

Here there are two approaches to the averaging of the matrix elements for γ transitions between different states. The first approach assumes complete statistical independence of the matrix elements. Since the matrix elements for the majority of electromagnetic transitions are unknown, the calculation gives only a mean-square estimate of the magnitude of the effect, this being obtained by summing the squares of the partial effects.[83–85] The second approach presupposes the existence of a certain coherence of the P-odd effects in the nucleus, which may arise because of the valence mechanism in the radiative capture of neutrons.[53] We mention immediately that the experimental results confirm the statistical hypothesis and contradict the valence mechanism. Thus, to explain the already existing effects it is necessary in the valence mechanism to take the matrix element of the weak interaction to be $M_{\mathrm{val}}\cong 20$ eV in order to describe the experimental data satisfactorily, although from analysis of the P-odd effects and theoretical estimates made on the basis of nucleon–nucleon weak potentials that describe a large set of experiments the widely accepted value $M_{\mathrm{stat}}\cong 100$ meV follows,

The measured P-odd asymmetry in the integrated spectrum in the (n,γ) reaction with allowance for only the two s and p resonances closest to the thermal point can be expressed for the statistical model in the form

$$a^{\Sigma}=(2M/E_p)A_\gamma^{\Sigma}, \qquad (37)$$

where M is the matrix element of the weak interaction, E_p is the energy of the p resonance, and A_γ^{Σ} is an averaging factor for the calculation of which it is necessary to use the statistical approach. In the mechanism of compound mixing, the value averaged over the resonances is $\bar{M}=0$. Therefore one takes the statistical estimate obtained by calculating the mean-square deviation. In Ref. 84 an empirical expression is given for it:

TABLE V. Results of investigations of radiative transitions.

Target nucleus	E_{γ_0}, MeV	a, 10^{-4}	$\Gamma_p^{\gamma_0}$, meV	$\Gamma_s^{\gamma_0}$, meV	$I_{\gamma 0}$, 10^{-2}	$\|M\|$, meV	Source
^{113}Cd	9.04	−4.1 (8)	4.5(9)	113	0.275	0.4±0.1	Refs. 16, 22, and 89
^{117}Sn	9.32	8.1(1.3)	1.2 (3)	78	2.8	0.7±0.1	Refs. 16, 20, and 89

$$M_{\text{stat}}^{\text{theor}}=1.3\cdot 10^{-5}M_0\sqrt{AB_nD}, \tag{38}$$

where $M_0\cong 1$ eV is the single-particle matrix element of the weak interaction; A is the atomic number of the compound nucleus; B_n is the neutron binding energy (in mega-electron-volts); and D is the mean separation between the compound resonances (in electron volts).

All the results on the measurement of a^{Σ} make it possible to draw the following conclusions:

1. The magnitude of the effect is essentially determined by the proximity of the p resonance to the neutron thermal energy.

2. The observed effects, except for the effect on ^{117}Sn, are consistent with the calculations based on the statistical approach.

Specifically, for the ^{35}Cl($\mathbf{n},\gamma$)^{36}Cl reaction this approach gives $M_{\text{stat}}^{\text{theor}}\cong 25$ meV, whereas analysis of the experimental result in accordance with the expression (37) gave $M=(78^{+22}_{-15})$ meV, in agreement with the previous estimates.[84]

4.4. ^{57}Fe

For this nucleus, measurements have only been made of the P-odd angular correlation in the integrated γ-ray spectrum. The use of the expression (38) yielded $M_{\text{stat}}^{\text{theor}}=30$ meV, whereas analysis of the experimental result in accordance with (37) gave $M=(46^{+15}_{-12})$ meV.

4.5. ^{79,81}Br

Many interesting measurements have been made on this nucleus. Measurements were made of the P-odd asymmetry a^{Σ} in the integrated spectrum of the (n,γ) reaction[33] (Table I), of the asymmetry of the total cross sections a_t and of the capture cross sections a_γ on thermal polarized neutrons (Refs. 51, 52, 56, and 57; Table III), and of the asymmetry of the total cross sections and the capture cross sections $P(E_p)$ at the p resonance with energy $E_p=0.88$ eV (Refs. 49, 62, 69, and 74; Table IV). The values of a_t and $P(E_p)$ measured at different institutes agree within the experimental errors.

The difference between the values of a_t measured at SPINP[52] and at ITEP[56] and the value of a_t measured at IAE[57] can be explained by the harder neutron spectrum in the study of Ref. 57.

We now compare the P-odd effects on this nucleus at different energies (thermal energy E_{th} and the resonance energy E_p). For this we reduce the value of $P(E_p)$ to the thermal energy E_{th} in accordance with the expression (35). In the conversion we take into account the fact that in the thermal region of energies both isotopes ^{79}Br and ^{81}Br contribute, whereas in the resonance region only the ^{81}Br isotope does. The converted value $a_t^*(E_{\text{th}}) = (8.1 \pm 2.5)\cdot 10^{-6}$ agrees well with both the result $a_t=(9.8\pm 1.0)\cdot 10^{-6}$ of Ref. 52 and the result $a_t=(9.5\pm 1.7)\cdot 10^{-6}$ of Ref. 56.

The values of the matrix elements calculated from the results of measurement of the P-odd asymmetry in the integrated spectrum of the (n,γ) reaction, $M_{\text{stat}}^{\text{theor}}=3.2$ meV and $M=4.6\pm 0.4$ meV (Ref. 84), agree with the results of the measurements of the asymmetry of the total cross section at the p resonance: $M=3.0\pm 0.5$ meV (Refs. 49 and 61).

4.6. ^{111}Cd

For this nucleus, measurements were made of the asymmetry of the total cross sections and of the cross sections for radiative capture $P(E_p)$ at the p resonance with energy $E_p=4.53$ eV (Refs. 16, 49, 62, and 69; Table IV).

The results agree with each other.

4.7. ^{113}Cd

For this nucleus a large number of P-odd effects have been measured. We recall that this was the first nucleus on which parity violation in nuclear interactions was discovered by measurement of the P-odd asymmetry a of γ rays in the thermal integrated spectrum of polarized neutrons (Refs. 1, 17, 18, and 22; Table I). Measurements were made of the P-odd asymmetry in the spectrum of the (n,γ) reaction (Ref. 34; Table I), the asymmetry of the total cross sections $P(E_p)$ at the p resonance with energy $E_p=7.0$ eV (Refs. 15, 16, and 64; Table IV), and the P-even correlations.[16,77]

Using the results of measurements of the characteristics of the p resonance[15] and measurements of the characteristics of the radiative transition at the energy of the p resonance with $E_p=7.0$ eV (Ref. 16), and also of the asymmetry coefficient of the γ rays in the thermal spectrum,[22] we can find the absolute value $|M|$ of the matrix element that mixes the p resonance at $E_p=7.0$ eV with the s resonance at $E_s=0.178$ eV. We use the expression (12). The kinematic enhancement factor R_{kin} is determined by the ratio of the partial radiative widths of the main γ transitions at the p and s resonances: $R_{\text{kin}} = (\Gamma_p^{\gamma_0}/\Gamma_s^{\gamma_0})^{1/2}$. We can replace $\mathscr{D}$ by E_p under the conditions $E_n\ll|E_s|$ and $E_n\ll E_p$ that obtained.[86] The value of $\Gamma_p^{\gamma_0}$ was measured in Ref. 16. We can obtain $\Gamma_s^{\gamma_0}$ from the value of the total radiative width Γ_s^{γ} (Ref. 87) and the probability Γ_{γ_0} of a partial transition.[88] We obtain the value of the matrix element M in accordance with the expression

$$M=\frac{aE_p}{2A\sqrt{\Gamma_p^{\gamma 0}/\Gamma_s^{\gamma 0}}}. \tag{39}$$

In Table V we give the results for ^{113}Cd together with similar results for ^{117}Sn (Ref. 89).

In Ref. 64 a similar calculation was made on the basis of the value of the circular polarization $P_\gamma=-(6.0\pm 1.5)\cdot 10^{-4}$

of γ rays emitted following capture of unpolarized neutrons by ^{113}Cd (measured in Ref. 21). Allowance was made for the fact that contributions to this value come from γ rays with energies 9.04 and 8.48 MeV with corresponding intensities. The value obtained for the matrix element was $|M|=0.84 \pm 0.23$ meV.

As a result of the measurements of the asymmetry in the integrated spectrum of the (n,γ) reaction it was found that $M_{\rm stat}^{\rm theor}=1.3$ meV, $M=0.8$ meV (Ref. 84).

4.8. ^{117}Sn

All possible measurements of P-odd effects were made for this nucleus. Measurements were made of the asymmetry coefficients of γ rays following capture of thermal polarized neutrons,[20,29,30] and of the asymmetry effects in the integrated γ-ray spectrum (Ref. 33; Table I). The ITEP and SPINP values agree with each other but not with the value obtained at ILL.[29] The reason for the discrepancy has not been explained.

We recall that ^{117}Sn was the first nucleus for which at ILL a large spin-rotation effect was found (Ref. 45; Table II). Measurements were also made[51,56] of the asymmetry coefficients a_t of the total cross sections and the asymmetry coefficient of the capture cross sections for thermal neutrons (Ref. 51; Table III). The P-odd effects at the p resonance with $E_p=1.33$ eV were measured at three institutes (Refs. 16, 49, 62, 65, and 73; Table IV). It should be noted that the values of $P(E_p)$ measured at the LNP[16,49,62] and at LANL[73] disagree by more than the errors of the measurements.

The values of the matrix elements obtained from measurements of the asymmetry in the integrated γ-ray spectrum, $M_{\rm stat}^{\rm theor}=2$ meV and $M=3.7$ meV (Ref. 84), differ appreciably from the matrix elements obtained in measurements of the P-odd effects for resonance neutrons (Refs. 16, 49, 62, and 65).

We now compare the asymmetry coefficients of the total cross sections for thermal and resonance neutrons in the same way as was done for ^{79,81}Br. Using the expression (35) to convert the values $P(E_p)=(4.5\pm1.3)\cdot10^{-3}$ (Ref. 62), we obtain $a_t^*(E_{\rm th}) = (13.5 \pm 3.9)\cdot 10^{-6}$, in good agreement with the value $a_t=(11.2\pm2.6)\cdot10^{-6}$ (Ref. 56). It is possible to compare the results of measurements of the spin rotation $\Delta\varphi$ with a calculation based on data from measurement of the asymmetry of the total cross sections. For this, we use the expression (36). The converted value $\Delta\varphi^*=-(25\pm11)\cdot10^{-6}$ rad/cm (Refs. 16, 49, and 62) agrees with the value $\Delta\varphi=-(37.0\pm2.5)\cdot10^{-6}$ rad/cm (Ref. 45).

It can be seen that for the ^{117}Sn nucleus the greatest number of discrepant results are observed.

Table V gives the results of a calculation of the matrix element $|M|$ that mixes p and s resonances in the same way as was done for ^{113}Cd (Ref. 89).

4.9. ^{139}La

It is for this nucleus that the greatest number of measurements of P-odd effects have been made. This is not surprising, since it is for this nucleus that the maximum P-odd effect is observed in nuclear interactions. It was first obtained in a measurement of the asymmetry of the total cross sections for interaction of neutrons in the region of the p resonance with energy $E_p=0.75$ eV at the LNP (Refs. 49 and 62; Table IV). Subsequently, the effect was measured many times. The asymmetry of the radiative-capture cross sections was also measured.[69] It can be seen that, except for the first two, all the results, including the new LNP results,[64] agree with each other.

The neutron spin rotation angle $\Delta\varphi$ is also maximal for this nucleus (Table II).

The results of measurements of the asymmetry coefficients of the total cross sections for thermal and resonance neutron energies were compared in the same way as for ^{79,81}Br and ^{117}Sn in accordance with (35). The result of conversion to $a_t^*(E_{\rm th})$ of $P(E_p)$ (Refs. 49 and 62) gives $a_t^*(E_{\rm th}) = (9.3 \pm 2.9)\cdot 10^{-6}$, in good agreement with the result at the thermal energy, $a_t=(9.0\pm1.4)\cdot10^{-6}$ (Ref. 51). Measurements in the integrated spectrum of the (n,γ) reaction gave $M_{\rm stat}^{\rm theor}=4$ meV, whereas $M=0.96$ meV (Ref. 84). This experimental value is close to the value of the matrix element M obtained from the asymmetry of the total cross section for resonance neutrons: $|M|=(1.28\pm0.12)$ meV (Refs. 49 and 62).

4.10. ^{207}Pb

This nucleus is interesting in that the investigations on it may be decisive from the point of view of the choice between the compound-nucleus and the valence mechanism of the mixing of states with opposite parities. At the present time, there exist two theoretical approaches to the interpretation of the experimental results in parity-nonconservation effects.

In one of the approaches,[6,14,90] it is assumed that the mixing occurs during the compound-nucleus stage, during which the excitation energy is distributed over a large number of particles. In this case the magnitude of the parity-nonconservation effects is basically determined by the high level density of the compound nucleus. Essentially many-particle components of the wave function are mixed in the compound-nucleus state.

In the other approach,[53,91] the parity-nonconservation effects are due to mixing of the single-particle (valence) components of the wave function in the entrance channel. The main advantage of the valence model is its simplicity, which makes it possible in principle to carry out all the calculations to the end. Theoretical arguments against the valence model are advanced in Ref. 84; they were presented in Sec. 4.4. There is also a serious criticism in the review of Ref. 2.

Nevertheless, the situation can be clarified in experiments. One of the predictions of the valence model is that the valence mechanism must make the main contribution to the parity-nonconservation effects in light and magic nuclei and, in particular, in the ^{208}Pb nucleus.[92] Thus, the valence model explains the amount of spin rotation of thermal transversely polarized neutrons on a target of the natural mixture of lead isotopes (Ref. 54; see Table 2). It is assumed that the ^{207}Pb nuclei make the main contribution and that the P-odd spin rotation is due to interference of the p resonance of ^{207}Pb closest to the thermal point (the resonance with energy $E_p=3.07$ keV) with potential s scattering (resonance–potential mixing). On the basis of these data, the authors who proposed the valence mechanism predicted a large ($\simeq 5\cdot 10^{-5}$) P-odd asymmetry of γ-ray emission in the ^{207}Pb(**n**,γ)^{208}Pb reaction.[93] Subsequently, allowance was made for the fact that the main transition in ^{208}Pb* is an E1 transition, and therefore the kinematic factor $|M1|/|E1|$ reduces the asymmetry by an order of magnitude.[94] The observation of such a large effect would contradict the model of the compound-nucleus mechanism. Indeed, the lead isotopes have comparatively low level densities, and at low energies no weak resonances of them are known that could be p-wave resonances responsible for the parity-nonconservation effects.[49] Moreover, the lead isotopes also lack resonance s states suitable for mixing.

The experiment to measure the asymmetry coefficient of γ-ray emission in the ^{207}Pb(**n**,γ)^{208}Pb reaction at ITEP[35] did not achieve the necessary accuracy (see Table I). The upper limit on the asymmetry coefficient was found to be $a\leqslant 17\cdot 10^{-6}$ at the 90% confidence level.

It is very important to measure the spin rotation angle $\Delta\varphi$ of thermal transversely polarized neutrons on a lead target enriched with the isotope ^{207}Pb, and also to measure for the same target the P-odd asymmetry of γ-ray emission with better accuracy.

4.11. ^{232}Th

This nucleus is of great interest because investigations on it at LANL found a sign correlation of the parity-violation effects at different p resonances of this nucleus.[72,74]

This asymmetry effect of the total cross section $P(E_p)$ for the p resonance with lowest energy at $E_p=8.33$ eV was measured at the LNP[63] and later at LANL.[72,74] The results for this resonance are given in Table IV.

In the LANL experiments performed by the TRIPLE collaboration, measurements were made of the asymmetry of the total cross sections $P(E_p)$ at 23 p resonances in the range of energies from a few electron volts to 400 eV. At seven of these resonances the measured effect exceeded two standard deviations. The sign correlation of the effects is such that in all these cases the signs of the effects $P(E_p)$ are positive. The probability of random occurrence of seven positive signs in the distribution is 1.6%. This sign correlation of the effects stimulated a lively theoretical discussion. The results of the LANL measurements and their theoretical treatment are discussed in more detail in the review of Ref. 2, so that we shall not consider them here.

We merely note that despite the large number of theoretical studies that attempt to explain qualitatively the phenomenon of the sign correlation of the P-odd effects at p resonances, none of them describes the effect in ^{232}Th from the quantitative point of view.

We note that the LANL studies were the first to obtain a mean-square matrix element $M^2 = \overline{|\langle s|M|p\rangle|^2}$ averaged over many resonances of one nucleus.

In accordance with the compound-nucleus model of parity mixing, the matrix elements M of the individual p resonances are random Gaussian variables with mean value $\bar{M}=0$, and their spread is determined by M^2. The procedure for determining $\sqrt{M^2}$ from the set of individual $P_i(E_p)$ values is explained in Ref. 95, and is also described in the review of Ref. 22. For the 23 p resonances in ^{232}Th, the value $\sqrt{M^2} = (1.39^{0.55}_{-0.38})$ meV was obtained. It is noted that this value agrees with the estimate obtained using the formula for the mechanism of dynamical enhancement of the parity-violation effect. Using Eq. (4) in Sec. 2, we have

$$\sqrt{M^2}=\frac{V_{\rm PV}}{\sqrt{N}}=\frac{V_{\rm PV}}{\sqrt{\Delta E/D}},$$

and substituting $\Delta E=1$ MeV, $D=10$ eV, $N=\Delta E/D=10^5$, $V_{\rm PV}=F\Delta E=3\cdot 10^{-7}\cdot 1$ MeV$=0.3$ eV, we obtain $\sqrt{M^2}\cong 1$ meV.

4.12. ^{238}U

Measurements at the LNP of the asymmetry of the total cross sections at the three p resonance at energies $E_p=4.4$, 11.3, and 19.5 eV did not reveal nonvanishing effects.[49,62] At LANL, 16 p resonances in the range of energies from 6 eV to 300 eV were analyzed.[95,96] At four of these resonances, a P-odd asymmetry exceeding two standard deviations was found; two of these effects were positive and two were negative, i.e., there was no sign correlation. The results are given in Ref. 2. As in the analysis for ^{232}Th, the rms matrix element, obtained by averaging over 16 resonances, was obtained:

$$\sqrt{M^2}=(0.56^{+0.41}_{-0.20})\ \text{meV (Ref. 95).}$$

4.13. ^{239}Pu

This last nucleus, with the heaviest mass, was investigated only for asymmetry of the total cross section for the interaction of thermal neutrons of opposite helicities. An unsuccessful attempt was made at ITEP,[56] and the effect did not exceed the level of the errors: $a_t=(1.1\pm 1.2)\cdot 10^{-6}$. In a study,[58] the error was greatly reduced, and an effect was obtained (see Table III).

In this section, as in the complete review, we have given only the results and only the nuclei for which statistically significant effects were obtained or for which the measurements have fundamental importance. Many measurements with statistically insignificant results have been omitted.

CONCLUSIONS

Study of the violation of spatial parity in nuclear reactions with polarized neutrons confirms the general features that were described in the Introduction. The mechanism of the mixing of states with opposite parities during the compound-nucleus stage is the dominant mechanism. This is confirmed by the fact that although the values of the weak-interaction matrix elements M fluctuate for different nuclei, they are the same for the same nuclei but in different reactions. This is confirmed by the fact that the model of mixed compound states, on the basis of which the experimental results were compared, gives a fairly good description of the energy dependence of the effect if one bears in mind that the magnitudes of the effects in the resonance and thermal regions of energies differ by 3–4 orders of magnitude.

The investigation of parity violation in neutron optics opens up new possibilities for the study of the structure of a nucleus and its excited states. We recall that the existence of low-energy p resonances in a number of nuclei was established during the investigations of P-odd effects. It is to be expected that the accumulation of experimental data in this field of nuclear physics will make it possible to obtain new information about the structure of the weak nucleon–nucleon interaction.

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