Parity violation in nuclear interactions

Yu. G. Abov and P. A. Krupchitskiĭ

Institute of Theoretical and Experimental Physics, Moscow
Usp. Fiz. Nauk **118**, 141–173 (January 1976)

The current status of the problem of parity violation in the nuclear interactions is reviewed. Special attention is given to the experimental studies in which parity violation was first detected in nuclear electromagnetic transitions. The methodological achievements that made it possible to detect this phenomenon are described. A compendium of a large number of experiments is given. In concluding, the experimental results are compared with theoretical predictions, and directions are indicated in which further research is desirable.

PACS numbers: 21.10.Hw, 23.20.–g

CONTENTS

1. INTRODUCTION

The search for a parity nonconserving nucleon-nucleon interaction began soon after the discovery of parity violation in β decay. In 1958 Feynman and Gell-Mann[1] advanced the hypothesis that the weak interaction is universal. According to this hypothesis the weak interaction between any two fermions is characterized by the same interaction constant G, which is equal (in units in which $\hbar = c = 1$) to $10^{-5}/m^2$, where m is the nucleon mass. And even though we still cannot regard this hypothesis as established, almost everything that we know about the weak interactions can be interpreted in terms of the universal four-fermion weak-interaction theory. In any case, at present we cannot give preference to any other theories. The universal weak interaction hypothesis envisions a parity nonconserving weak interaction between the nuclear particles—protons and neutrons. A weak interaction between nucleons can only appear against the "background" of the strong interactions, and this makes it very difficult to investigate it experimentally.

Wilkinson was the first to discuss the types of experiments in which a parity nonconserving internucleon potential might be detected.[2] These experiments can be divided into two groups. The first group consists of experiments in which one looks for violations of absolute selection rules. These are mainly experiments in which one looks for forbidden α decays of the type $I^{\pi} \to 0^{\pi'}$, where $\pi' = (-1)^{I+1}\pi$ (I is the spin of the nucleus and π and π' are the parities of the states before and after decay, respectively). The $2^- \to 0^+$ transition in the α decay of ^{16}O to ^{12}C has been investigated with great care. In these experiments the expected effect is proportional to F^2, where F is the dimensionless parameter characterizing the relative strength of the weak nucleon interaction and is of the order of 10^{-7}–10^{-6}.

The second group of experiments consists of those in which states of the nuclear system with opposite parities should interfere. In such experiments one looks for circular polarization of the γ rays emitted by unpolarized nuclei, or, in the case of polarized nuclei, for asymmetry in the emission of the γ rays (in the directions parallel and antiparallel to the nuclear polarization). In this case the effect is proportional to F, i.e., it is many orders of magnitude greater than in the experiments of the first group.

Several theoretical review articles in which various theories of the P-odd interaction of nucleons are discussed in considerable detail have been published in recent years.[3–6] However, no review articles devoted to the experimental situation have been published since 1968.[7] The time has come to fill this gap.

We begin our review by estimating the magnitude of the expected P-odd effect on the basis of the state of the theory obtaining before 1964, i.e., before the P-odd nuclear interaction was discovered; next, we examine the experimental studies in which the P-odd nuclear interaction was detected; and finally, we compare the experimental results with the current theory of the weak interaction of nucleons, and this enables us to point out a certain program for further experimental research.

2. THEORETICAL ESTIMATES OF THE EXPECTED P-ODD EFFECTS AND POSSIBLE EXPERIMENTS

A. The weak nucleon-nucleon interaction Hamiltonian

According to the Cabibbo model[8] the weak nucleon-nucleon interaction Hamiltonian (interaction-energy density) can be written in the form

$$\mathscr{H}_W = -\frac{G}{2\sqrt{2}}(\cos^2\theta\{J_\lambda, J_\lambda^*\}_+ + \sin^2\theta\{S_\lambda, S_\lambda^*\}_+), \qquad (2.1)$$

in which J_λ is the strangeness-conserving ($\Delta S=0$) hadron current, S_λ is the strangeness-changing ($\Delta S=\pm 1$) hadron current, $J_\lambda^* \equiv J_1^+, J_2^+, J_3^+, -J_4^+$, and $S_\lambda^* \equiv S_1^+, S_2^+, S_3^+, -S_4^+$, where the cross denotes the Hermitian conjugate. The currents J_λ and S_λ contain polar- and axial-vector parts which, according to the ideas of $SU(3)$ symmetry, belong to octets of polar- and axial-vector currents, respectively.[5,6,9] The relative magnitudes of the strangeness-conserving and -changing interactions is determined by the Cabibbo angle $\theta \approx 0.24$.

A specific form for the weak nucleon-nucleon interaction potential can be obtained from Eq. (2.1) by adopting some specific mechanism for the interaction.[5,6] The relative magnitude of the weak nucleon-nucleon interaction is characterized by the dimensionless parameter F, which is defined as the amplitude for mixing of states of opposite parity and can be estimated by equating it to the ratio of the weak and strong nucleon-nucleon interaction potentials. I. S. Shapiro[10,11] obtained the following estimate for F under the assumption that the average distance between nucleons in nuclei is of the order of $1/\mu$, where μ is the pion mass:

$$F = \sqrt{\frac{\operatorname{Sp}\mathscr{H}_W^2}{\operatorname{Sp}\mathscr{H}^2}} \approx G\mu^2 = 10^{-5}\left(\frac{\mu}{m}\right)^2 \approx 3\cdot 10^{-7}; \qquad (2.2)$$

here the symbol Sp indicates that the trace (spur) of the matrix is to be taken, and $\mathscr{H}_W$ and $\mathscr{H}$ are the Hamiltonians for the weak and strong nucleon-nucleon interactions, respectively. Blin-Stoyle[9] made a similar estimate.

In the first calculations of P-odd nuclear effects[12,13] the part of Hamiltonian (2.1) containing $\sin^2\theta$ was neglected and the simplest diagrams, corresponding to direct contact[13] and two-pion exchange[12] interactions were used. More detailed calculations—in particular, allowance for the repulsive core of the nucleon—did not improve the agreement between theory and experiment, but to the contrary, revealed discrepancies that still await explanation.[5,6] We shall return to this problem later.

B. Mechanisms for the enhancement of P-odd effects in electromagnetic nuclear transitions

Since the weak nucleon-nucleon interaction is small compared with the strong interaction, we are justified in treating it as a perturbation on a system of strong-interacting particles. Then the complete interaction Hamiltonian can be written as the sum

$$\mathscr{H} = \mathscr{H}_0 + V,$$

where $\mathscr{H}_0$ is the main (scalar) part of the Hamiltonian, while V is the pseudoscalar part, the so called parity-violating potential; i.e., V is the part of the interaction that mixes states of opposite parity. The eigenstates of $\mathscr{H}$ are given in the first approximation of perturbation theory[14] by the formula

$$\Psi_i = \psi_i + \sum_{j\neq i}\frac{\langle j\,|\,V\,|\,i\rangle}{E_j - E_i}\psi_j. \qquad (2.3)$$

Here ψ_i and ψ_j are eigenfunctions of $\mathscr{H}_0$ and have opposite parities, E_i and E_j are the energies of the corresponding unperturbed states, and the sum is taken over all states whose parity is opposite to that of ψ_i.

Formula (2.3) is valid provided

$$\langle j\,|\,V\,|\,i\rangle \ll |\,E_j - E_i\,|,$$

and this condition is very well satisfied in the present case.

It is convenient to write the wave function Ψ_i of the nuclear system in the form

$$\Psi_i = \psi_i^+ + F\psi_i^-. \qquad (2.4)$$

The functions ψ_i^+ and ψ_i^- are called the regular and irregular parts of the wave function, respectively. Formulas (2.3) and (2.4) serve to define the amplitude F for mixing of the regular and irregular parts of the wave function; Eq. (2.2) may be taken as an estimate of its magnitude.

For the sake of convenience later on, we shall treat here the simplest case of the nuclear transition $\Psi_i \to \Psi_f$ $\to \Psi_f$.[9] In accordance with Eq. (2.4) the functions Ψ_i and Ψ_f are of the form

$$\Psi_i = \psi_i^+ + F\psi_i^-,$$
$$\Psi_f = \psi_f^+ + F\psi_f^-.$$

For simplicity we take the mixing amplitude F to be the same for the initial and final states.

In the first approximation, the matrix element for the regular transition (taken as an ML transition for definiteness) is given by

$$\langle\Psi_f\,|\,ML\,|\,\Psi_i\rangle \approx \langle\psi_f^+\,|\,ML\,|\,\psi_i^+\rangle$$

and that for the irregular $\widetilde{EL}$ (we mark the irregular transition with a tilde) may be written in the form

$$\langle\Psi_f\,|\,\widetilde{EL}\,|\,\Psi_i\rangle \approx F\,[\langle\psi_f^-\,|\,\widetilde{EL}\,|\,\psi_i^+\rangle + \langle\psi_f^+\,|\,\widetilde{EL}\,|\,\psi_i^-\rangle].$$

Interference between the regular ML and irregular $\widetilde{EL}$ nuclear transitions results in the circular polarization of γ rays emitted by unpolarized nuclei or in the asymmetric emission with respect to the polarization direction of the γ rays emitted by a nuclear system having vector polarization. The interference term will be proportional to F:

$$\frac{\langle\Psi_f\,|\,\widetilde{EL}\,|\,\Psi_i\rangle}{\langle\Psi_f\,|\,ML\,|\,\Psi_i\rangle} \approx F\,\frac{\langle\psi_f^-\,|\,\widetilde{EL}\,|\,\psi_i^+\rangle + \langle\psi_f^+\,|\,\widetilde{EL}\,|\,\psi_i^-\rangle}{\langle\psi_f^+\,|\,ML\,|\,\psi_i^+\rangle} = FR. \qquad (2.5)$$

The factor R depends on the structure of the specific nucleus, but not on the form of the weak nucleon-nucleon interaction. Situations are possible in which

$R>1$, i.e., in which the P-odd effect is enhanced. In particular, if the regular transition is of ML type and the irregular one of $\widetilde{EL}$ type, as in the example discussed here, then, since the matrix element for the electric transition is proportional to kr (k is the wave number and r the nuclear radius), and that for the magnetic transition is proportional to $(v/c)kr$ (v is the velocity of the nucleons in the nucleus and c the velocity of light), we shall have $R\approx |EL|/|ML|\approx c/v\approx 10$.

Shapiro[10] has used the term "kinematic enhancement" for enhancement due to a mechanism of this type. Wilkinson[15] was the first to attempt to make experimental use of this enhancement mechanism.

Another enhancement mechanism becomes operative when the regular transition, whose matrix element occurs in the denominator in (2.5), is inhibited while the irregular transition is either not hindered at all or is inhibited to a lesser extent. Such cases are most frequently encountered among the deformed nuclei, where transitions may be forbidden by the additional quantum numbers. Some such cases have been considered by Michel,[13] and Wahlborn[16] has calculated the resulting enhancement R for a number of specific cases. Enhancement of this type is called "structural enhancement."[10]

Finally, the so called "dynamic enhancement" mechanism[10] may be encountered at high nuclear excitation energies because of the high level density. Energy levels having the same spin but opposite parities may lie close together. Then the mixing amplitude for such states may prove to be anomalously large because of the smallness of the energy denominator in one of the terms of the sum in Eq. (2.3).

Blin-Stoyle[12] and Shapiro[10,11] have shown that in the capture of neutrons by nuclei with mass numbers $A\approx 100$ the enhancement factor R may be as large as 10^2 as a result of the high level density. Of course more than one enhancement mechanism, e.g., kinematic and dynamic enhancement, may operate simultaneously; in that case R may reach values of 10^3 and larger.

C. Angular distribution of γ rays from polarized nuclei

The general theory of the angular distribution of γ radiation may be found in the well known review article by Biedenharn and Rose,[17] in monographs by Rose[18] and Ferguson,[19] or in the collection edited by Siegbahn.[20] Below we present the formulas that we shall need to interpret the experiments on P-odd effects in nuclei; these formulas were derived from the general theory of angular correlation by Blin-Stoyle.[9,12,21]

We shall be primarily interested in the angular distribution of radiation recorded by detectors that are insensitive to polarization. In this case, as Blin-Stoyle and Grace showed,[21] the angular distribution of the γ rays can be expressed in the form

$$W(\theta)=\sum_{\nu}\Omega_\nu B_\nu U_\nu F_\nu A_\nu P_\nu(\cos\theta). \qquad (2.6)$$

The coefficients Ω_ν in this formula were introduced to allow for the effect of the finite size of the source and detector,[12] and θ is the angle between the nuclear polarization and γ-ray emission directions. The orientation parameters B_ν are defined by the formula

$$B_\nu=\sum_M \sqrt{2\nu+1}\,C(I\nu I;\ M0)\,p(M), \qquad (2.7)$$

in which the C are Clebsch-Gordan coefficients and $p(M)$ is the probability for the population of a state with magnetic quantum number M. Equation (2.7) reduces to the following formulas for the cases $\nu=0$ and $\nu=1$:

$$B_0(I)=1,\quad B_1(I)=\frac{\sqrt{3}\sum_M Mp(M)}{\sqrt{I(I+1)}}.$$

As is easily seen, $B_1(I)$ is proportional to the nuclear polarization $P_{\text{nuc}}=\sum Mp(M)/I$. The coefficients U_ν take account of the change in the orientation of the nucleus due to transitions preceding the one under consideration. If there are no such transitions, i.e., if B_ν and F_ν refer to the same nuclear state, we have $U_\nu=1$. The F_ν are the F coefficients defined by the formula

$$F_\nu(LL'I'I)=(-1)^{I'+3I-1}\sqrt{(2I+1)(2L+1)(2L'+1)}\times C(LL'\nu;\ I-1)\,W(LL'II;\ \nu I'), \qquad (2.8)$$

in which the $W(LL'II;\nu I')$ are Racah coefficients. These F coefficients have been tabulated by Biedenharn and Rose.[17] In Eq. (2.8), L and L' are the multipole orders of the regular and irregular transitions, and I and I' are the spins of the emitted photon and the final nuclear state. Lobov[16,22] showed that there is a very simple analytic formula for $F_1(LLI'I)$, i.e., for the case in which $L=L'$:

$$F_1(LLI'I)=\frac{\sqrt{3}}{2}[L(L+1)+I(I+1)-I'(I'+1)][L(L+1)]^{-1}[I(I+1)]^{-1/2}. \qquad (2.9)$$

For the cases we shall be concerned with, the A_ν for odd ν (the P-odd terms) can be expressed in the form

$$A_\nu=\frac{2\varepsilon}{1+\delta^2}[F_\nu(LLI'I)+\delta F_\nu(LL'I'I)], \qquad (2.10)$$

in which ε is the ratio of the matrix elements for the irregular and regular transitions:

$$\varepsilon=\frac{\langle I'|\widetilde{L\pi'}|I\rangle}{\langle I'|L\pi|I\rangle}=RF, \qquad (2.11)$$

and δ is the mixing ratio for the γ transition under discussion:

$$\delta=\frac{\langle I'|L+1|I\rangle}{\langle I'|L|I\rangle}. \qquad (2.12)$$

The A_ν for even ν (parity-conserving terms) are given by

$$A_\nu=\frac{1}{1+\delta^2}[F_\nu(LLI'I)+\delta^2F_\nu(L'L'I'I)+2\delta F_\nu(LL'I'I)]; \qquad (2.13)$$

and the $P_\nu(\cos\theta)$ in Eq. (2.6) are Legendre polynomials.

Setting $\Omega_\nu=U_\nu=1$, it is convenient to write Eq. (2.6) in the form[9]

$$W(\theta)=\pi^2 \sum_{LL'\nu} B_\nu(I)\, F_\nu(LL'I'I)\, [\delta_{L+L'+\nu,\,\text{even}}\, (m_L^* m_{L'} + e_L^* e_{L'}) + \delta_{L+L'+\nu,\,\text{odd}}\, (m_L^* e_{L'} + e_L^* m_{L'})]\, P_\nu(\cos\theta), \tag{2.14}$$

where e_L and m_L are reduced matrix elements for electric and magnetic 2^L-pole transitions, and $\delta_{L+L'+\nu,\text{even}}$ and $\delta_{L+L'+\nu,\text{odd}}$ are Kronecker deltas. It is obvious from Eq. (2.14) that terms sensitive to parity violations, i.e., terms containing odd powers of $\cos\theta$ (odd value of the subscript) appear in the angular distribution of γ radiation from polarized nuclei in two cases: when $L+L'+\nu$ is even, and when $L+L'+\nu$ is odd. In the first case $L+L'$ must be odd. This corresponds to interference between electromagnetic transitions of different multipole orders but of the same kind, e.g., between $E1$ and $E2$ transitions. In the second case, when $L+L'$ must be even, we have interference between transitions of the same multipole order but of different kinds, e.g., between $M1$ and $E1$ transitions.

In experiments on the angular distribution of γ rays from polarized nuclei, the P-odd asymmetry is defined as follows:

$$a=\frac{W(0^\circ)-W(180^\circ)}{W(0^\circ)+W(180^\circ)}; \tag{2.15}$$

here $W(0^\circ)$ and $W(180^\circ)$ are the numbers of counts recorded with a polarization-insensitive detector when the polarization of the nuclei and the momentum of the γ rays are, respectively, parallel and antiparallel. Sometimes an asymmetry parameter a', twice as large as a, is used:

$$a' \equiv 2a=\frac{W(0^\circ)-W(180^\circ)}{\overline{W}}, \tag{2.16}$$

where

$$\overline{W}=\frac{W(0^\circ)+W(180^\circ)}{2}.$$

With the aid of Eq. (2.6) one can evaluate RF from the asymmetry a (or a') found experimentally.

The following means for obtaining a large value of $B_1(I)$ have been used in the experimental studies that have been made up to now with the aim of finding and investigating P-odd angular correlations: the method of $\beta-\gamma$ correlations, polarized slow neutron capture, the Mössbauer effect, and the polarization of nuclei at low temperatures.

Michel[13] called attention to the fact that the mixing of nuclear states with opposite parities could lead to longitudinal polarization of the internal conversion electrons, as though circularly polarized γ-ray photons had been internally converted. Although in this case the P-odd effect could be substantially enhanced, no experimental attempts to make use of this effect have yet been published. Neither have any experiments been undertaken to detect the rotation of the polarization plane of neutrons on traversing nonmagnetic material.[13] Positive results have been obtained in studies of the angular distribution of the γ rays from polarized nuclei, of the circular polarization of γ rays from unpolarized nuclei, and of the $^{16}O \to {}^{12}C+\alpha$ decay.

D. Capture of polarized thermal neutrons

In the capture of polarized s neutrons by nuclei the substate population factor $p(M)$ is given by[9]

$$p(M)=\frac{2}{2I+1}\sum_\mu p_n\left(\tfrac{1}{2}\right)\left|C\left(I_i\tfrac{1}{2}I;\ M-\mu\mu\right)\right|^2, \tag{2.17}$$

where I_i is the spin of the nucleus before capturing the neutron, I is the spin of the compound nucleus that emits the photon, and $p_n(m)$ is the probability that the z component of the neutron spin is m ($m=\pm 1/2$). Substituting this expression into Eq. (2.7) gives

$$B_0(I)=1,\quad B_1(I)=\frac{(3/4)+I(I+1)-I_i(I_i+1)}{[3I(I+1)]^{1/2}}\,P_n, \tag{2.18}$$

in which P_n is the polarization of the s-neutron beam:

$$P_n=\frac{p_n(1/2)-p_n(-1/2)}{p_n(1/2)+p_n(-1/2)}. \tag{2.19}$$

In the capture of s neutrons, $B_\nu(I)=0$ when $\nu>1$.

Now let us consider the particular case in which the regular transition is an $E(L+1)+ML$ mixture. Then the irregular transition may be of $\widetilde{EL}$ type (we neglect the possible $\widetilde{M}(L+1)$ admixture). Taking $B_\nu(I)=0$ for $\nu>1$ and $\Omega_\nu=U_\nu=B_0(I)=1$, we obtain the following expression for the asymmetry a

$$a=\frac{2B_1(I)}{1+\delta^2}\left[F_1(LLI'I)\frac{e_L}{m_L}+\delta^2 F_1(LL+1I'I)\frac{e_L}{e_{L+1}}\right]. \tag{2.20}$$

Here δ is the mixing ratio as defined by Eq. (2.12). If the regular transition is of pure ML type and the irregular one is an $\widetilde{EL}$ transition, then, setting $\delta=0$ and substituting $B_1(I)$ from (2.18) into Eq. (2.20), we obtain

$$a=2P_n\frac{(3/4)+I(I+1)-I_i(I_i+1)}{[3I(I+1)]^{1/2}}F_1(LLI'I)\frac{m_L e_L^*}{|m_L|^2+|e_L|^2} = 2P_n ARF, \tag{2.21}$$

where

$$2RF=2m_L e_L^*/(|m_L|^2+|e_L|^2)\approx 2e_L/m_L;$$

and

$$A=\frac{(3/4)+I(I+1)-I_i(I_i+1)}{[3I(I+1)]^{1/2}}F_1(LLI'I). \tag{2.22}$$

We assume that the reduced matrix elements in Eqs. (2.20)–(2.22) are real, i.e., that $m_L^*\approx m_L$ and $e_L^*\approx e_L$.

We recall that $F_1(LLI'I)$ is given by Eq. (2.9). If the γ transition $|IM\rangle \to |I'M-\mu\rangle$ is preceded by other transitions, A will contain a factor U to take into account the consequent change in the polarization of the nucleus. In the most favorable cases A is unity. In addition, the factor $\Omega=\overline{\cos\theta}$, which takes into account the finite size of the source and detector and the distance between them, must also be included. We shall discuss this later on.

E. $\beta-\gamma$ angular correlations

Parity violation in β decay results in the emission of longitudinally polarized electrons, and this, in turn, results in polarization of the daughter nucleus. The γ

rays emitted by the daughter nucleus should therefore be asymmetric, provided mixing of nuclear states of opposite parity takes place. Blin-Stoyle[9,12] and Krüger[23] considered the case of an allowed β decay and interference between transitions of the same multipole order: ML–EL interference. In this case the angular distribution of the γ rays is of the form

$$W(\theta) = \pi^2(|m_L|^2 + |e_L|^2)(1 + a\cos\theta), \tag{2.23}$$

where the asymmetry a is given by

$$a = \frac{2p}{E}\left[\left(\pm\lambda_{I_\beta I} + 2\delta_{I_\beta I}|y|\sqrt{\frac{I}{I+1}}\right)(1+y^2)^{-1}\right]F_1(LLI'I)\frac{m_L^* e_L}{|m_L|^2 + |e_L|^2}; \tag{2.24}$$

here p and E are the momentum and energy of the β particle, I_β is the spin of the β-active nucleus, I is the spin of the daughter nucleus,

$$\lambda_{I_\beta I} = \begin{cases} 1 & \text{for} \quad I_\beta = I - 1, \\ 1/(I+1) & \text{for} \quad I_\beta = I, \\ -I/(I+1) & \text{for} \quad I_\beta = I + 1 \end{cases}$$

(the upper (lower) sign before $\lambda_{I_\beta I}$ is for electron (positron) emission), $y = G_V\langle t_\pm\rangle / G_A\langle\sigma t_\pm\rangle$, and $\langle t_\pm\rangle$ and $\langle\sigma t_\pm\rangle$ are the matrix elements for the allowed β transition. The validity of the usual $V-A$ weak interaction theory is assumed.

F. Circular polarization of rays

When unpolarized nuclei emit γ rays, interference between electric and magnetic transitions of the same multipole order, which is possible because of parity violation, should result in the emission of circularly polarized radiation. In classical language this means that the oscillations of the electric and magnetic dipoles are 90° out of phase; as is well known from optics, such a phase shift leads to the emission of circularly polarized light.

The magnitude of the resulting circular polarization is given by the formula[9,13]

$$P_\gamma = \frac{2\sum\limits_L m_L^* e_L}{\sum\limits_L (|m_L|^2 + |e_L|^2)} = 2RF. \tag{2.25}$$

Formula (2.25) shows that in this case the P-odd effect is due only to the interference between transitions of the same multipole order. If the regular transition is an $E(L+1) + ML$ mixture and the circular polarization is due to interference between the regular ML transition and an irregular EL transition, the magnitude of the circular polarization will be given by

$$P_\gamma = \frac{2}{1+\delta^2}\frac{e_L}{m_L} = \frac{2}{1+\delta^2}RF, \tag{2.26}$$

in which $\delta = \langle E(L+1)\rangle / \langle ML\rangle$ is the mixing ratio. On comparing Eqs. (2.25) and (2.26) with Eqs. (2.6), (2.10), and (2.21) for the P-odd angular asymmetry, we note that the circular polarization P_γ due to parity nonconservation, unlike the asymmetry a due to the same cause, is independent of the spin factor A. We shall refer to this circumstance later in discussing the experimental results.

G. P-odd α decay

The search for α decay due to parity nonconservation falls among the experiments in which the expected P-odd effect should be proportional to F^2, since the magnitude of the effect will be entirely determined by the intensity of the irregular admixture. If parity is a good quantum number, α decay from a state of total spin I and parity $(-1)^{I+1}$ to a 0^+ state will be absolutely forbidden. It will be possible for such an α decay to occur at a rate proportional to F^2 provided the regular and irregular parts of the wave function mix with the mixing amplitude F.

From experiment one obtains the width Γ_α of the forbidden α decay. The ratio of the width of the parity-forbidden α decay to that of the allowed decay is taken as a measure of F^2. If we assume that the ratio of the width for γ-ray emission to that for α decay is about 10^{-6} for the case of normal α decay, we obtain the following estimate of the magnitude of the expected P-odd effect:

$$F^2 = \frac{\Gamma_{\alpha\ \mathrm{irreg}}}{\Gamma_{\alpha\ \mathrm{reg}}} = \frac{\Gamma_{\alpha\ \mathrm{irreg}}}{\Gamma_\gamma}\frac{\Gamma_\gamma}{\Gamma_{\alpha\,\mathrm{reg}}} \approx \frac{\Gamma_{\alpha\ \mathrm{irreg}}}{\Gamma_\gamma}\cdot 10^{-6}. \tag{2.27}$$

The α decay most thoroughly studied from this point of view is that of ^{16}O. We shall discuss this case in more detail later.

3. EXPERIMENTAL STUDY OF THE ASYMMETRY OF THE ANGULAR DISTRIBUTION OF γ RADIATION FROM POLARIZED NUCLEI

A. Choice of nuclei for study

Cadmium is a very favorable material to use in the search for P-odd angular correlations in (n, γ) reactions. It consists almost entirely of the single isotope ^{113}Cd, the spin and parity I^π of whose ground state are $1/2^+$. The thermal-neutron capture cross section is large and is due almost entirely to the resonance at 0.178 eV, which leads to the formation of ^{114}Cd in an excited state with $I^\pi = 1^+$. The part of the decay scheme for this level of interest to us is shown in Fig. 1. The transition from the 1^+ capture state (excitation energy 9.04 MeV) to the 0^+ ground state of ^{114}Cd is of pure $M1$ type. The level density in cadmium at excitation energies of ~9 MeV is fairly high, and one may expect there to be levels of the same spin and parity lying close together. As was noted above, this results in dynamic enhancement of the P-odd effect.[10] Moreover, the $1^+ - 0^+$ transition is of $M1$ type, so the irregular transition should be an $\widetilde{E1}$ transition, and $M1$–$\widetilde{E1}$ interference leads to kinematic enhancement. As a result, as estimates by Blin-Stoyle and Shapiro[12,10,11] show,

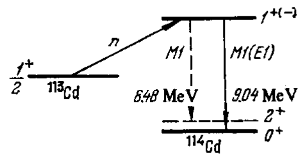

FIG. 1. Part of the decay scheme for the neutron-capture state of ^{114}Cd.

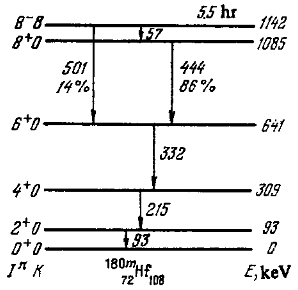

FIG. 2. Part of the decay scheme for the isomeric state of ^{180m}Hf.

in this case one can expect the P-odd correlations to be substantially enhanced: $R \approx 10^3$.

There should be even greater enhancement in ^{180m}Hf. Part of the decay scheme of the isomeric level of this nuclide is shown in Fig. 2. The transitions from the $I^\pi K = 8^-8$ metastable state to levels of the $K = 0$ band should be strongly inhibited by the K selection rule. If the regular and irregular transitions are equally inhibited, then, as was noted above, the P-odd correlations may be substantially enhanced. Lawson and Segel[24] and Vogel (see the review article by Gari[5]) pointed out the possibility of a large enhancement in this case.

The light nuclei are of special interest since for them the P-odd effect can be calculated more or less correctly. Study of some of them might, in principle, disclose the isotopic structure of the weak interactions; we shall discuss this in more detail later.

B. A specific feature of the ^{113}Cd(n,γ) ^{114}Cd reaction

The angular distribution of γ rays emitted following capture of spin-$\frac{1}{2}$ particles cannot contain harmonics of order higher than $2l$ (l is the orbital quantum number), so the γ rays emitted following s-neutron capture should be isotropically distributed.[25] For the case of parity violation in nuclear electromagnetic transitions, however, the angular distribution of the γ rays emitted by nuclei following capture of polarized neutrons is given by Eq. (2.6) which can be written in the form

$$W(\theta) = \text{const}\cdot(1 + P_n a \cos\theta); \qquad (3.1)$$

here θ is the angle between the neutron-beam polarization direction and the momentum of the γ ray, P_n is the polarization of the neutron beam, and a is the asymmetry coefficient to be determined, which, in accordance with Eq. (2.21), we shall express as the following product:

$$a = 2ARF. \qquad (3.2)$$

The coefficient A is given by Eq. (2.22), and for the 9.04 MeV $1^+ \to 0^+$ transition in ^{114}Cd, we have $A = +1$. Since $R \approx 10^3$ and $F \approx 10^{-7}$, we may expect to find $a \approx 10^{-4}$. In addition to the transition from the 1^+ capture state to the 0^+ ground state, there is also a transition in ^{114}Cd from the same 1^+ state to the first excited 2^+ state at 0.56 MeV. This 8.48 MeV $1^+ \to 2^+$ transition is also of the type $M1$. If the initial 1^+ state contains a P-odd admixture, the γ rays from the $1^+ \to 2^+$ transition will also be asymmetrically distributed. Unfortunately, in this case the spin factor A, and hence also the effect itself, has the opposite sign: $A = -0.5$. Any advantage arising from the fact that the negative value of A is smaller in magnitude than the positive value may be nullified by the fact that the $1^+ \to 2^+$ transition is twice as strong as the $1^+ \to 0^+$ one. Hence if these two transitions, which are close in energy, are not separated well enough, perhaps because of poor energy resolution of the apparatus, the two effects of opposite signs may cancel each other.[1)] We note, however, that no such cancelling takes place in measurements of the circular polarization of the γ rays since in this case both transitions give effects of the same sign. In fact, the spin factor A does not occur in Eq. (2.25) for the circular polarization, and the effect should have the same sign for both of the two transitions under consideration. In practice one measures the asymmetry of the emission of the γ rays in directions parallel and antiparallel, respectively, to the neutron-beam polarization. In this case Eq. (3.1) takes the form

$$N^\pm = \text{const}\cdot(1 \pm aP_n\Omega), \qquad (3.3)$$

in which $N^\pm$ represents the numbers of counts for the cases in which the γ-ray momentum and the neutron spin are, respectively parallel and antiparallel, and $\Omega = \overline{\cos\theta}$ is the geometric factor to take account of the finite sizes of the detector and target.

The asymmetry a can be calculated from either the ratio of or the difference between the numbers N^+ and N^- of counts. To reduce the effect of instrumental asymmetry it is desirable to have two identical channels working simultaneously, one to record the γ rays emitted in the direction of the beam polarization and the other to record the γ rays emitted in the opposite direction.

The asymmetry obtained in an experiment with a polarized neutron beam should be corrected for the instrumental asymmetry as determined in an experiment with a depolarized neutron beam. The beam polarization direction should also be periodically reversed.

C. The first attempt to detect the P-odd effect in (n,γ) reactions

Haas, Leipuner, and Adair[26] were the first to use a polarized slow neutron beam in a search for the P-odd asymmetry in γ-ray emission. They examined the angular distributions of the γ rays emitted following neutron capture by cadmium, indium, and silver nuclei. The polarized neutron beam (polarization ~ 80%, neutron energy 0.09 eV) was obtained reflection from the (111) planes of a magnetized cobalt-iron alloy single crystal. The beam intensity at the target was 2×10^4 neutrons/sec on the entire specimen surface (~ 6.5 cm^2). Two identical scintillation counters employing NaI(Tl) crystals were used to record the γ rays emitted parallel

1)If the $1^+ \to 2^+$ transition is an $M1 + E2$ mixture, the P-odd asymmetry in this case will be given by Eq. (2.20). In this case, too, it will be necessary carefully to separate the $1^+ \to 0^+$ and $1^+ \to 2^+$ transitions.

and antiparallel to the neutron beam polarization direction. The pulses from the photomultipliers were amplified and analyzed with single-channel differential analyzers. The neutron beam polarization was reversed periodically, but the reversing period was rather long since, with the apparatus employed, reversing the polarization required making and breaking a circuit carrying a current of 400 A.

No asymmetry was detected for the 9.04-MeV $1^+ - 0^+$ transition in ^{114}Cd, the result being

$$a = (1.2 \pm 7.8) \cdot 10^{-4}.$$

The measurements with silver and indium targets were even less precise. Unfortunately the authors considerably overestimated the enhancement factor R for the ^{113}Cd(n, γ) ^{114}Cd reaction, and drew far-reaching conclusions concerning the smallness of the parameter F from their result. Attention was called to this error by Blin-Stoyle[12] and I. S. Shapiro (see[27]). Using the correct value of R, one can conclude from the result of Haas *et al.*[26] that $F \leqslant 10^{-6}$.

D. Experimental observation of the effect

A much more intense beam of polarized neutrons was available at the Institute of Theoretical and Experimental Physics (ITÉF) at Moscow, and this made it possible to improve the accuracy of the measurements over that achieved by Haas *et al.*[26] by an order of magnitude. According to the estimates by Blin-Stoyle and I. S. Shapiro mentioned above, this gave grounds for hope that the P-odd effect in the ^{113}Cd(n, γ) ^{114}Cd reaction could be detected. It was decided in 1961 at the initiative of I. S. Shapiro to perform the experiment at ITÉF. The experiment was performed three times with different apparatus.[27,18,29] In all three ITÉF experiments the polarized neutron beam was taken at the horizontal channel of the heavy-water reactor at the Institute by reflection from magnetized cobalt mirrors.[30] The experimental setup is shown schematically in Fig. 3.

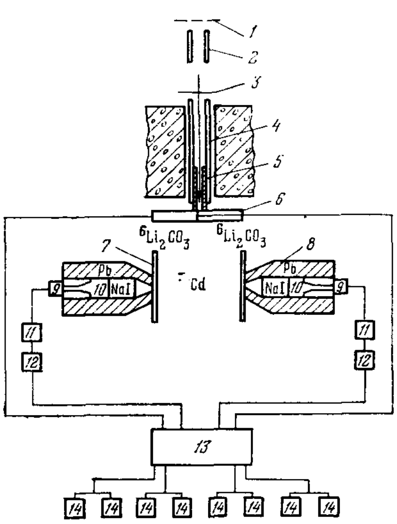

FIG. 3. Experimental setup for measuring the angular asymmetry of the γ radiation from polarized ^{114}Cd nuclei. 1—iron-foil depolarizer, 2—bending magnet, 3—current-carrying foil, 4—magnetic circuit, 5—collimator, 6—rotating iron-foil depolarizer, 7—first spectrometer, 8—second spectrometer, 9—cathode followers, 10—photomultipliers, 11—amplifiers, 12—analyzers, 13—electronic switch, 14—scaling circuit.

In the second and third experiments,[28,29] the polarizer was a pile of thin mirrors reminiscent of the Soller collimator,[31] which focused the beam onto the target. The polarized neutron beam, after passing through a series of collimators and magnetic ducts, struck a metallic cadmium target 0.4 mm thick.

The γ rays from the target were recorded with two identical scintillation counters using NaI(Tl) crystals 70 mm in diameter and 100 mm thick giving a resolution of 11–12% at the 660 keV ^{137}Cs line. The entire detecting part of the apparatus was separated from the reactor room by a thick concrete wall. The neutrons scattered from the target were absorbed in a layer of pressed boron carbide or ^{6}Li-enriched lithium carbonate. The photomultipliers and their crystals were shielded from magnetic fields by several steel and permalloy screens and were enclosed in lead walls at least 70 mm thick.

In all the experiments pulses from γ rays in the same energy range[2)] (8.5–9.5 MeV) corresponding to the 9.04 MeV transition in ^{114}Cd were singled out. The spectrometers were calibrated daily in energy against known peaks in the γ-ray spectra from the ^{56}Fe(n, γ) ^{57}Fe and ^{58}Ni(n, γ) ^{59}Ni reactions and in the investigated cadmium spectrum.

Great care was taken to avoid γ-pulse pileup, which might lead to the appearance in the investigated energy range of pulses from lower-energy γ rays and thus dilute the effect. Aluminum screens 85 mm thick were placed in front of the detectors to reduce the counting rate from soft γ rays. Moreover, in the second and third experiments it was necessary to stop the beam down to reduce its intensity (10^7 neutrons/sec) in order further to reduce the effect of pulse pileup. The photomultiplier pulses were also shaped to a length of 0.25 μsec for the same purpose.

In each of the three experiments the electronic equipment differed substantially from that used in the other two, both in the design of the separate units, and in their interconnections (block diagram). The main difficulty in such experiments is to eliminate the instrumental asymmetry resulting from drift of the electronics or of the neutron flux.

Various measures were taken to avoid effects of drift. In the first experiment[27] the effects obtained with the polarized and depolarized neutron beams were compared rapidly. For this purpose a rotating depolarizing disk with two opposite quadrants covered with iron foil and the other two left open was placed in the path of the neutrons. The foil came into the path of the neutron beam and thus fully depolarized it[32] 20 times each second.

Differential discriminators were used to separate the

[2)]A different energy interval was erroneously given in[27].

pulses corresponding to the desired γ-ray energy range. The pulses were then successively directed by an electronic switch to the counting circuits corresponding to the two states of the neutron beam. The direction of the neutron spins relative to the direction of the magnetic field near the target was reversed every 20 min to eliminate instrumental asymmetry. In the second and third experiments, the effects obtained with oppositely directed neutron spins were compared rapidly. For this purpose a special device was used to reverse the polarization of the neutron beam 10 times per second while leaving the direction of the magnetic field near the target unchanged. The pulses corresponding to the desired energy range were separated as in the first experiment and were then directed by the electronic switch to scaling circuits corresponding to the two neutron beam polarization directions.

Measurements with polarized and depolarized beams were alternated every 20 minutes. The instrumental asymmetry could be determined from the measurements with the depolarized beam, and the desired asymmetry could then be obtained from the results of the measurements made with the polarized beams.

Many control experiments were run in connection with each of the three main experiments.[34] For example, measurements were made of the angular asymmetry of the γ rays from ^{114}Cd in a different energy range where the effect should be substantially smaller since γ rays from many transitions fall in this interval and one can hardly expect them all to contribute asymmetry of the same sign. This control interval was taken as 4.1–5.5 MeV in the first experiment and 6.8–7.8 MeV in the second one; in both cases the control experiments were performed in time intervals between the main experiments. In the third experiment the control was run concomitantly with the main experiment and covered the energy range 6.3–8.5 MeV.

Control experiments were also performed with other nuclei which should not give observable P-odd effects. These were experiments with samarium, titanium, and lead targets in which strong $E1$ transitions were examined. The experiments with titanium and lead proved that the apparatus was insensitive to circular polarization of γ rays since the circular polarization of the γ rays selected for control was equal to that of the 9.04-MeV γ rays from ^{114}Cd.

A control experiment was performed with a graphite target to check the sensitivity of the apparatus to neutrons scattered from the target. The asymmetry was also measured with no target in the beam (the "background asymmetry"). In the first and third experiments, control experiments were run with the neutron beam polarized vertically (it was polarized horizontally in the main experiments); In this case we have $\cos\theta = 0$ and there should be no P-odd correlations. However, if there is an admixture of p neutrons, then, as I. S. Shapiro pointed out, interference between s and p levels might give rise to correlations of the form $\mathbf{P}\cdot[\mathbf{p}_n\times\mathbf{p}_\gamma]$, where $\mathbf{P}_n$ is the neutron beam polarization vector, and $\mathbf{p}_n$ and $\mathbf{p}_\gamma$ are the momenta of the neutron and the photon. Despite the fact that the geometry of the experiment was such that there could be no correlations of this type since $\mathbf{P}_n\cdot[\mathbf{p}_n\times\mathbf{p}_\gamma]=0$, the actual geometry might differ enough from the ideal to permit them to appear. The control experiment was made with a different geometry, chosen so that such correlations could manifest themselves strongly. The operation of the electronic switches and scaling circuits was checked daily.

The results of all these control experiments allow us to assert that the asymmetry observed in the main experiments is due to angular asymmetry in the emission of the 9.04-MeV γ rays from ^{114}Cd following polarized thermal neutron capture.

The first ITÉF experiment, completed in 1964,[27] gave the result

$$a = -(3.7 \pm 0.9)\cdot 10^{-4}.$$

This result has already been corrected for the instrumental asymmetry as measured with a depolarized beam.

In the second ITÉF experiment[28] the asymmetry as measured with the polarized beam was

$$a_{\mathrm{pol}} = -(3.5 \pm 0.8)\cdot 10^{-4},$$

and with the depolarized beam,

$$a_{\mathrm{dep}} = +(0.7 \pm 0.8)\cdot 10^{-4}.$$

Since the instrumental asymmetry was measured with the same accuracy as the effect and the two asymmetries had opposite signs, only the error in measuring the instrumental asymmetry was taken into account in[28] and the final result was reported as

$$a = -(3.5 \pm 1.2)\cdot 10^{-4}.$$

In order to compare properly the results obtained from the three ITÉF experiments, however, one should subtract the instrumental asymmetry from the effect as measured with the polarized beam. Then the result of the second experiment will be

$$a = -(4.2 \pm 1.2)\cdot 10^{-4}.$$

Finally, the third experiment[29] yielded

$$a = -(2.5 \pm 0.9)\cdot 10^{-4}.$$

The weighted mean of the asymmetry from all three experiments is

$$a = -(3.3 \pm 0.6)\cdot 10^{-4}.$$

However, some of the γ rays from the 8.48-MeV transition fell within the 8.5–9.5 MeV energy window chosen for the ITÉF experiments, and this, as was mentioned above, reduces the asymmetry. In addition, there is a background due to pileup of pulses from lower-energy γ rays. The adopted[34] corrected weighted mean value of the asymmetry is

$$a = -(4.1 \pm 0.8)\cdot 10^{-4}.$$

Assuming that the observed asymmetry is due to a P-odd interaction and taking $R \approx 10^3$ for the enhancement factor, we find (see Eq. (3.2)) $|F| \approx 2\times 10^{-7}$; this result is in agreement with the estimates by Shapiro[10] and Blin-Stoyle,[12] and with the more recent estimate by McKellar.[35]

The value of the asymmetry in the angular distribution of γ rays from the $^{113}Cd(n,\gamma)^{114}Cd$ reaction obtained at the ITEF using a polarized neutron beam agrees well with the results of measurements of the circular polarization of the γ rays from the same reaction made by Prof. Wilson's group in 1972[36] with an unpolarized ne neutron beam; those measurements, which we shall discuss in more detail later, gave the following value for the circular polarization:

$$P_\gamma = -(6.0 \pm 1.5)\cdot 10^{-4}.$$

E. Other attempts to investigate the angular symmetry of the γ rays from the $^{113}Cd(n,\gamma)\ ^{114}Cd$ reaction

The angular distribution of the γ rays from the $^{113}Cd(n,\gamma)^{114}Cd$ reaction has been investigated with polarized neutron beams in several other laboratories. In Ispre (Italy)[37] and Karlsruhe (West Germany)[38] the $1^+\to 0^+$ and $1^+\to 2^+$ transitions were not separated, and as was pointed out above, this is unacceptable. It is not surprising that no asymmetry was found in these experiments. The results obtained by the group from Riso (Denmark) are not inconsistent with the ITÉF results. A substantial effect was reported in the first communication from this group[39]:

$$a = -(8.4 \pm 2.8)\cdot 10^{-4}.$$

The γ-ray spectrometers were scintillation counters using NaI(Tl) crystals. The γ rays from the $1^+\to 0^+$ transition were recorded over the energy range 8.2–9.9 MeV. With the energy window chosen in this way, γ rays from the 8.48 MeV $1^+\to 2^+$ transition were necessarily included in the measurements. The reported effect therefore seems much too large. Later the authors attributed this large effect to the fact that the instrumental asymmetry was measured with a depolarized neutron beam only after all the measurements with the polarized beam had been completed.

In repeating the experiment[40] the Danish group recorded γ rays in the energy range 8.8–9.5 MeV and obtained the following result:

$$a = -(2.5 \pm 2.2)\cdot 10^{-4}.$$

This result is in full agreement with the ITÉF results.

A third experiment[41] was performed using a germanium detector in a single-channel setup. The resulting asymmetry over the 8.0–9.2 MeV energy range was

$$a = -(0.6 \pm 1.8)\cdot 10^{-4}.$$

The results of experiments on the angular asymmetry and circular polarization of γ rays from the $^{113}Cd(n,\gamma)^{114}Cd$ reaction are listed in the accompanying table. The results reported in[37–39] are not included (for the reasons mentioned above). The last result of the Riso group[41] is not in sharp contradiction with the ITÉF results. The weighted average value of the asymmetry obtained at the ITÉF, the circular polarization obtained by Wilson's group,[36] and the last two results of the Danish group[40,41] are compatible, as is easily seen by applying the χ^2 test.

Thus, the presence of interference between nuclear states of opposite parity in the 9.04-MeV $1^+\to 0^+$ γ transition in the $^{113}Cd(n,\gamma)^{114}Cd$ reaction can be regarded as established.

F. Asymmetry in the γ decay of polarized ^{180}Hf nuclei

In measuring the L-shell conversion coefficients of the 57.5-keV $8^-\to 8^+$ transition in ^{180m}Hf, Scharff-Goldhaber and McKeown[42] found an anomaly, which they first attributed to the presence of a 10% irregular $\widetilde{M1}$ admixture in this $E1$ transition. In this case one would expect the P-odd circular polarization (or, in the case of polarized nuclei, angular asymmetry) of the γ rays due to $E1-\widetilde{M1}$ interference to be anomalously large. However, no such large effect was found[43–45], and the phenomenon itself found its natural explanation as an effect of nuclear penetration of the electron wave function.[42,46]

Krane *et al.*[47] investigated the angular asymmetry of the γ rays from another transition in ^{180m}Hf nuclei, which were polarized by Samoĭlov's method.[48] The transition from the metastable 8^- state to the 6^+ level is accompanied by emission of 501-keV γ rays. This transition is an $M2+E3$ mixture with $\delta = \langle E3\rangle/\langle M2\rangle = +5.5\pm 0.1$. A P-odd $\widetilde{E2}$ admixture could interfere both with the regular $M2$ transition and with the $E3$ one.

The experimentally determined quantity was the asymmetry a' (Eq. (2.16)), which in the present case (and neglecting terms with $\nu > 4$) can be expressed in the form

$$a' = \frac{W'(0^\circ) - W'(180^\circ)}{\overline{W}} = \frac{2\Omega_1 B_1 A_1 + 2\Omega_3 B_3 A_3}{1 + \Omega_2 B_2 A_2 + \Omega_4 B_4 A_4}. \qquad (3.4)$$

The specimens were disks of a ferromagnetic $(Hf_xZr_{1-x})Fe_2$ alloy 6 mm in diameter and 0.5 mm thick. The metastable ^{180m}Hf nuclei were obtained by irradiating the specimens in a reactor. A ^{3}He–^{4}He mixture was used to cool the irradiated specimens. The apparatus is depicted schematically in Fig. 4. To polarize the Hf nuclei, the cooled specimen was placed in the magnetic field produced by two pairs of superconducting Helmholtz coils. These coils were so mounted that the axes of the two pairs were mutually perpendicular (Fig. 4); hence the magnetic field, and therefore also the polarization direction, could be slowly rotated. The γ-ray detectors were Ge(Li) crystals mounted on opposite sides of the specimens on the axis of one of the Helmholtz-coil pairs. With this setup one can measure not only the $W(0^\circ)-W(180^\circ)$ asymmetry, but also the $W(0^\circ)-W(90^\circ)$ anisotropy, as is necessary for an experimental determination of the orientation parameters B_ν. To determine these parameters, the angular distribution of the γ rays from the 444-keV pure $E2$ transition was investigated. The angular asym-

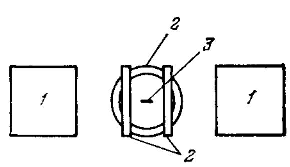

FIG. 4. Experimental setup for measuring the asymmetry of the γ radiation from polarized ^{180m}Hf nuclei. 1—detectors, 2—Helmholtz coils, 3—source.

metry $W(0°)-W(90°)$ of the 501-keV line was used for an independent determination of the mixing parameter δ.

The count rates recorded during the measurements were corrected for the half life of the metastable state of hafnium. The even coefficients A_ν were calculated with Eq. (2.13). The only unknown parameter occurring in Eq. (3.4) is the P-odd parameter $\varepsilon = RF$, which is defined by Eq. (2.11) and occurs in the coefficients A_ν and A_3. Thus, the authors used the measured asymmetry a' to evaluate ε.

The very large P-odd asymmetry $a' = -(16.6 \pm 1.8) \times 10^{-3}$ found in this experiment was record breaking. The following value of ε was obtained from this value of a':

$$|\varepsilon| = 0.038 \pm 0.004 \quad (\chi^2 = 0,7).$$

This result is in full accord with the results obtained in studies of the circular polarization of the same γ transition[49,50]; we shall discuss these experiments later. In accordance with the work of Lawson and Segel,[24] the result is consistent with the assumption that $F \approx 3 \times 10^{-7}$.

Thus, the results of studies of the P-odd correlations in cadmium and hafnium are consistent among themselves. Unfortunately, in neither case can we speak of more than a qualitative agreement with theory. These experiments convince us that interference between nuclear states with opposite parities does indeed take place, but for a quantitative test of the theory it will be necessary to investigate very simple nuclear systems.

G. Attempts to investigate light nuclei

A recent communication[51] reported a successful study of the P-odd asymmetry in the emission of γ rays from the 110 keV $1/2^- \to 1/2^+$ transition in ^{19}F. The ^{19}F nuclei were obtained in the excited and polarized state from the $^{22}\mathrm{Ne}(p,\alpha)^{19}\mathrm{F}$ reaction, using a polarized proton beam. Asymmetry in the emission of the radiation of the form $W(\theta) = \mathrm{const}(1 + Pka\cos\theta)$ was observed, where P is the polarization of the beam, k is the polarization transfer constant, a is the asymmetry under study, and θ is the angle between the polarization direction and the momentum. The $^{22}\mathrm{Ne}(p,n)^{22}\mathrm{Na}$ reaction, in which 74-keV γ rays are emitted isotropically, was used to investigate the instrumental asymmetry. It was found that $k = -(0.73 \pm 0.15)$. The following value was obtained for the asymmetry: $a = -(1.8 \pm 0.9) \times 10^{-4}$.

4. EXPERIMENTAL STUDY OF THE CIRCULAR POLARIZATION OF γ RADIATION FROM UNPOLARIZED NUCLEI

A. Choice of nuclei for study

Another physical phenomenon that indicates parity violation in nuclear electromagnetic processes is the circular polarization of γ radiation from unpolarized nuclei. To detect this effect one must select γ transitions with large enhancement factors R (see Eq. (2.25)), just as in investigating γ-ray angular distributions. In this connection it must be borne in mind that, because of the low efficiency of polarimeters (see below), even with enhancement factors $R \approx 10^2 - 10^3$, i.e., circular polarizations $P_\gamma \approx 10^{-4} - 10^{-5}$, the observed asymmetry proves to be two orders of magnitude lower. To detect such small effects one must not only have fairly high radiation intensities, but must also achieve a greater degree of freedom from systematic errors.

The greatest number of studies have been concerned with the circular polarization of the γ rays from the 482 keV $5/2^+ \to 7/2^+$ transition in ^{181}Ta. This nucleus is obtained from β decay of ^{181}Hf. Part of the decay scheme is shown in Fig. 5. The $M1$ regular transition is strongly forbidden by selection rules (inhibition factor 3×10^6). The physical reason for this inhibition is the fact that (according to the shell model) the $5/2^+ \to 7/2^+$ transition in ^{181}Ta involves a change in the orbital angular momentum of the nucleon by two units, as a result of which the emission of an $M1$ photon by one nucleon is forbidden. There is a large structural enhancement factor. The irregular $\widetilde{E1}$ transition is enhanced even more by the kinematic mechanism.

It must be borne in mind, however, that the investigated transition has a large, parity-allowed $E2$ admixture (97% in intensity), which provides a background against which the $\widetilde{E1}-M1$ interference appears. According to estimates, the over-all enhancement factor R lies between 10 and 100.

Another well investigated case is the 501-keV $8^- \to 6^+$ transition in ^{180}Hf. The level scheme for this nucleus is shown in Fig. 2. This transition is notable for the fact that for it, as in the case of the $^{113}\mathrm{Cd}(n,\gamma)^{114}\mathrm{Cd}$ reaction, both the circular polarization and the angular asymmetry of the γ rays have been investigated; moreover, the greatest effect of parity violation in the nuclear forces has been observed for this transition.

Unlike the angular asymmetry, which is sensitive to $E3-\widetilde{E2}$ interference as well as to $M2-\widetilde{E2}$ interference, the circular polarization is determined only by the interference between the $M2$ and $\widetilde{E2}$ transitions, the $E3$ transition merely providing background. Hence the circular polarization effect should be smaller than the asymmetry effect by a factor of $1 + \delta = 6.5$; this follows from a comparison of Eqs. (2.10) and (2.26).

Among the medium-mass nuclei, only the 1290-keV $7/2^- \to 3/2^+$ $M2$ transition in ^{41}K has been investigated. This nucleus is of interest because it is both spherical and fairly light, so that more accurate theoretical estimates of the effect can be made.

It is very important to investigate the $n + p \to d + \gamma$ reaction, since in this simplest of reactions one can ob-

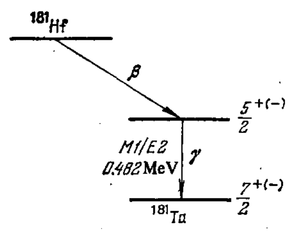

FIG. 5. Part of the decay scheme of ^{181}Hf.

Experimental results on the asymmetry a (or a') and circular polarization P_γ of γ radiation.

Nucleus	Transition energy, keV	Regular transition	Irregular transition	Result	References
^{2}H	2230	$0^+ \xrightarrow{M1} 1^+$	$\tilde{E}1$	$P_\gamma = -(1.30 \pm 0.45) \cdot 10^{-6}$	65
^{3}H	6250	$3/2^+, 1/2^+ \xrightarrow{M1} 1/2^+$	$\tilde{E}1$	$a = (0.28 \pm 1.55) \cdot 10^{-4}$	37
^{19}F	110	$1/2^- \xrightarrow{E1} 1/2^+$	$\tilde{M}1$	$a = -(1.8 \pm 0.9) \cdot 10^{-4}$	51
^{41}K	1290	$7/2^- \xrightarrow{M2} 3/2^+$	$\tilde{E}2$	$P_\gamma = (1.9 \pm 0.3) \cdot 10^{-5}$	57
^{75}As	401	$5/2^+ \xrightarrow{E1} 3/2^-$	$\tilde{M}1$	$P_\gamma = -(6.0 \pm 2.0) \cdot 10^{-5}$	60
				$= -(1.8 \pm 6.0) \cdot 10^{-5}$	64
^{114}Cd	9040	$1^+ \xrightarrow{M1} 0^+$	$\tilde{E}1$	$a = -(4.1 \pm 0.8) \cdot 10^{-4}$	27–29, 34
				$= -(2.5 \pm 2.2) \cdot 10^{-4}$	40
				$= -(0.6 \pm 1.8) \cdot 10^{-4}$	41
				$P_\gamma = -(6.0 \pm 1.5) \cdot 10^{-4}$	36
^{159}Tb	363	$5/2^- \xrightarrow{E1} 3/2^+$	$\tilde{M}1$	$a' = (4.5 \pm 3.0) \cdot 10^{-4}$	66
				$P_\gamma = -(1.0 \pm 5.0) \cdot 10^{-4}$	50, 62
^{175}Lu	396	$9/2^- \xrightarrow{E1 + M2} 7/2^+$	$\tilde{M}1$	$P_\gamma = (4.0 \pm 1.0) \cdot 10^{-5}$	55
				$= (6.3 \pm 1.0) \cdot 10^{-5}$	58, 59
				$= (4.5 \pm 1.0) \cdot 10^{-5}$	67
				$= (5.7 \pm 0.8) \cdot 10^{-5}$	64
^{180}Hf	57	$8^- \xrightarrow{E1} 8^+$	$\tilde{M}1$	$a' = -(19.4 \pm 9.2) \cdot 10^{-4}$	45
	501	$8^- \xrightarrow{M2 + E3} 6^+$	$\tilde{E}2$	$P_\gamma = -(2.8 \pm 0.45) \cdot 10^{-3}$	49
				$= -(2.3 \pm 0.6) \cdot 10^{-3}$	50, 62
				$= -(2.0 \pm 0.4) \cdot 10^{-3}$	63
				$a' = -(16.6 \pm 1.8) \cdot 10^{-3}$	47
^{181}Ta	482	$5/2^+ \xrightarrow{M1 + E2} 7/2^+$	$\tilde{E}1$	$P_\gamma = -(6.0 \pm 1.0) \cdot 10^{-6}$	56
				$= -(3.9 \pm 1.2) \cdot 10^{-6}$	58, 59
				$= -(6.1 \pm 0.7) \cdot 10^{-6}$	67
				$= -(4.1 \pm 1.3) \cdot 10^{-6}$	61
				$= -(3.1 \pm 2.5) \cdot 10^{-6}$	62
				$= (1.0 \pm 4.0) \cdot 10^{-6}$	63
				$= -(7.0 \pm 6.6) \cdot 10^{-6}$	68
^{203}Tl	279	$3/2^+ \xrightarrow{M1 + E2} 1/2^+$	$\tilde{E}1$	$P_\gamma = -(3.0 \pm 1.8) \cdot 10^{-5}$	69
				$= (0.2 \pm 0.5) \cdot 10^{-5}$	60
				$= -(0.4 \pm 1.0) \cdot 10^{-5}$	62
				$= (0.1 \pm 0.7) \cdot 10^{-5}$	63
				$a = -(27 \pm 7) \cdot 10^{-5}$	70

serve the P-odd effects in pure form free of the effects of enhancement mechanisms, which cannot yet be calculated accurately.

All the investigated nuclei and transitions in which P-odd effects have been observed are listed in the accompanying table.

B. Methods of measuring the circular polarization of γ rays

The degree of circular polarization is calculated with the formula $P_\gamma = (N_L - N_R)/(N_L + N_R)$, where N_L and N_R are the numbers of left- and right-hand circularly polarized photons, respectively.

Ferromagnetic materials are suitable for use as analyzers of the circular polarization of γ radiation. On magnetization, the electrons in the atoms of ferromagnets become partially polarized and scatter left- and right-hand circularly polarized photons differently. For low-energy photons ($E_\gamma < 0.65$ MeV) the scattering cross section is maximal when the photon momentum and the magnetization vector are antiparallel and is minimal in the opposite case. (We note that in ferromagnets the electron spins are directed opposite to the magnetization vector.) For higher-energy γ rays ($E_\gamma > 0.65$ MeV) the opposite situation obtains as regards the cross sections.

Thus, an analyzer for the circular polarization of γ radiation should consist of a magnet, called the polarimeter, whose magnetization must be periodically reversed, and a γ-ray detector mounted behind the polarimeter.

The γ-ray beam passes through the polarimeter and the detector records the change in the photon flux through the polarimeter when the magnetization is reversed. This way of measuring circular polarization is called the transmission method; it is used, as a rule, for high energy γ rays.

For lower energy γ rays it is more efficient to use a different method—the forward scattering method. In this method the γ-ray beam is scattered at the surface of the polarimeter, whose magnetization is again periodically reversed. In this case the detector records the scattered γ rays.

In both cases the effect measured by the polarimeter is defined as the change in the photon flux on reversing the polarimeter magnetization:

$$\delta = 2\frac{N_1 - N_2}{N_1 + N_2},$$

where N_1 is the number of photons recorded by the detector during a certain time interval with the polarimeter magnetization parallel to the photon momentum, and N_2 is the number of photons recorded during an equal time interval with the polarimeter magnetization antiparallel to the photon momentum.

To extract the degree of circular polarization P_γ from the measured effect δ one must divide δ by the polarimeter efficiency ε, which must be either calculated or measured in a separate experiment. The efficiency of the polarimeter is approximately equal to the fraction of the electrons in the polarimeter magnet that participate in the magnetization reversal. This fraction does not exceed 8% even for a saturated iron magnet. Finally, we have $P = \delta/\varepsilon$.

C. The first attempt to detect the P-odd effect

The first attempt to measure the circular polarization of γ radiation from unpolarized nuclei was made in 1964 by the American physicists Boehm and Kankeleit at the California Institute of Technology (CIT).[52] The 482 keV γ rays from ^{181}Te were selected for study. The γ-ray detector was a plastic scintillator, which, as is known, permits much higher γ-ray fluxes to be recorded than does an NaI crystal. It is necessary to record higher γ-ray fluxes in experiments such as these in order to accumulate adequate statistics. The result of the CIT experiment was $P_\gamma = -(2.0 \pm 0.4) \times 10^{-4}$. However, as was shown in one of the first papers by the group at the B. P. Konstantinov Leningrad Institute of Nuclear Physics (LIYaF),[53] in this case $P_\gamma < 2 \times 10^{-5}$. Subsequently, the authors of[52] discovered large systematic errors in their measurements and repudiated their result.

D. Experimental discovery of circular polarization of γ radiation from unpolarized nuclei

The LIYaF group was the first to succeed in observing circular polarization of γ radiation from unpolarized nuclei. By using a new technique for recording high γ-ray fluxes,[54] this group was able to reduce the experimental errors by more than an order of magnitude as compared with those of the CIT experiment. This new technique and the apparatus used in the LIYaF experiments deserve special discussion in a separate review. Here, therefore, we shall only present the results.

Experiments with two nuclei, ^{175}Lu and ^{181}Ta, were performed in the period 1965–1967. The results were $P_\gamma = (4\pm1)\times10^{-5}$ for the circular polarization of the 396 keV ^{175}Lu γ rays,[55] and $P_\gamma = -(6\pm1)\times10^{-6}$ for the 482 keV ^{181}Ta γ rays.[56] The LIYaF experiment on ^{41}K was completed in 1969; the result was $P_\gamma = (1.9\pm0.3)\times10^{-5}$ for the 1.29-MeV γ rays.[57]

From a comparison of the LIYaF results on the circular polarization of γ rays with theoretical calculations of the corresponding enhancement factors R we can derive only a very rough estimate of the ratio F of the parity violating weak-interaction nucleon-nucleon potential to the strong interaction nucleon-nucleon potential, namely, that F lies in the range 10^{-7}–10^{-6}. This agrees with the estimate derived from the ITÉF experiments. We shall return later to the comparison of these results with the theoretical estimates.

E. Other studies

The results of the LIYaF experiments were later confirmed in a number of laboratories abroad, but only those groups that used the integral method developed at the LIYaF for recording the γ radiation succeeded in achieving the same accuracy.

Thus, in 1969 Vanderleeden and Boehm (USA) confirmed the LIYaF results for ^{175}Lu and ^{181}Ta.[58,59] They also found an effect with ^{75}As.[60] The results of these experiments are included in the table. The ^{181}Ta effect was also confirmed by Bock and Jenschke,[61] and by Lipson *et al.*[62]

Jenschke and Bock,[49] Lipson *et al.*,[50] and also Kuphal,[63] using the integral γ-ray recording method, found a very large circular polarization effect ($\approx 2\times10^{-2}$) for ^{180m}Hf. The values obtained in these studies for $\varepsilon = \langle\widetilde{E2}\rangle/\langle M2\rangle = RF$ are in good agreement with the value derived from the work of Krane *et al.*,[45] who measured the asymmetry of the γ radiation from decay of the polarized state of that same nuclide ^{180m}Hf (see Sec 3e)). Thus, the interference between nuclear states of opposite parity in ^{180}Hf has been very reliably established.

The circular polarization effect for ^{175}Lu has been again confirmed in a recent study by Kuphal *et al.*[64] At the same time the authors of[64] believe that the ^{75}As effect (for the 401-keV transition) reported in[60] is actually masked by a large systematic error.

F. Investigation of the $n+p\to d+\gamma$ reaction

The measurement at the LIYaF of the circular polarization of the γ rays from the $n+p\to d+\gamma$ reaction[65] is one of the most interesting experiments on P-odd effects in the nuclear forces. This reaction is interesting because the reactants are the simplest of all nuclei—the neutron and the proton. There are no mechanisms for the enhancement of the P-odd effects in this reaction, so these effects can be observed in pure form. By the same token, the effects are small and therefore difficult to detect.

The result obtained for the circular polarization of the γ rays from the $n+p\to d+\gamma$ reaction was $P_\gamma = -(1.30\pm0.45)\times10^{-6}$. We note that the observed effect is three times its standard error.

G. Measurement of the circular polarization of the γ radiation from the ^{113}Cd(n,γ) ^{114}Cd reaction

We pointed out earlier (Sec. 2F) that Eqs. (2.25) or (2.26) for the circular polarization differ from Eq. (2.21) for the angular asymmetry only in the absence of the spin factor A (the difference as regards the factor P_n—the neutron polarization—is not significant). Hence the sign of the circular polarization due to parity violation is the same for all transitions from the same level of a definite nuclide. (Here we are of course assuming that the parity mixing takes place in the high-lying nuclear level from which the electromagnetic transition takes place.)

Consequently, the sign of the circular polarization[3)] of the γ radiation from ^{114}Cd is the same for both the 9.04- and 8.48-MeV transitions. The group of experimenters at Harvard University under the direction of Professor Wilson made use of this circumstance when in 1972 they measured the circular polarization of the γ rays with energies above 8 MeV emitted in the $n+{}^{113}\mathrm{Cd}\to{}^{114}\mathrm{Cd}+\gamma$ reaction with unpolarized neutrons.[36] This is the reaction in which the ITÉF experimenters found parity violation. The asymmetries and circular polarizations found in the two experiments should agree with one another both numerically and in sign.

In the Harvard experiment, performed at the reactor of the National Bureau of Standards (USA), a cadmium target was placed at the center of a channel passing close to the active region of the reactor, and the γ rays produced in the cadmium were brought out of the reactor through collimators and were analyzed for circular polarization with a transmission type polarimeter (we recall that the investigated γ rays had energies above 8 MeV). The polarimeter had an iron analyzing magnet 17.8 cm long and an efficiency ε of ~6% for $\approx$ 9-MeV γ rays. The polarimeter magnetization was switched once each second.

The γ-ray detector, which at the same time effected the energy selection of the γ rays, was a 10 cm diameter 12.5 cm thick NaI(Tl) crystal coupled to a photomultiplier. Special measures were taken to avoid pileup of the pulses coming in great numbers from the cadmium target.

The NaI(Tl) crystal and the photomultiplier had reliable magnetic protection against the alternating magnetic fields that arose when the polarimeter magnet was switched. The counting rate for γ rays with energies above 8.0 MeV reached 5000 pulses/sec.

The result obtained for the circular polarization of

---

3)The sign of the circular polarization was clarified as a result of correspondence between one of the present authors (Yu. A.) and Professor Wilson.

the 8.5- and 9.0-MeV γ rays was $P_\gamma = -(6.0 \pm 1.5) \times 10^{-4}$. Control experiments showed no circular polarization of the 6.3-MeV γ rays from the $^{48}Ti(n, \gamma)^{49}Ti$ reaction, in which no enhancement of the P-odd effect is expected.

Estimates indicated that the sources of systematic errors—internal bremsstrahlung from the active region of the reactor, magnetostriction, magnetic fringe fields, and others—could not significantly affect the result.

The circular polarization P_γ as measured in the Harvard study and the average angular asymmetry $a = -(4.1 \pm 0.8) \cdot 10^{-4}$ as measured for the 9.0-MeV ^{114}Cd γ rays at the ITÉF coincide within the accuracy of both experiments.[34]

Thus, the Harvard work provides independent experimental confirmation of the fact, established at the ITÉF, that parity is not conserved in the (n, γ) reaction on cadmium.

H. Compendium of experimental results on the angular asymmetry and circular polarization of γ radiation

The accompanying table is a compendium of experimental results on the angular asymmetry a and circular polarization P_γ of γ radiation. In view of the large number of papers on this topic, we decided to include only the most accurate results published up to 1975. In addition, we took into account the compatibility of the techniques employed with the problem attacked. For example, we decided to omit a number of papers on the circular polarization of γ radiation because the pulse counting method was used instead of the integral technique. We also omitted studies of the angular asymmetry of the cadmium γ radiation in which there were evident systematic errors.

5. EXPERIMENTAL STUDIES OF FORBIDDEN α DECAY

One of the important ways to seek P-odd effects in the nuclear interactions is to look for α decays that would be forbidden by selection rules if parity were conserved (Sec. 2G). The α decay most thoroughly and carefully investigated in this connection is that of the 8.87-MeV 2^- state of ^{16}O to the 0^+ ground state of ^{12}C.

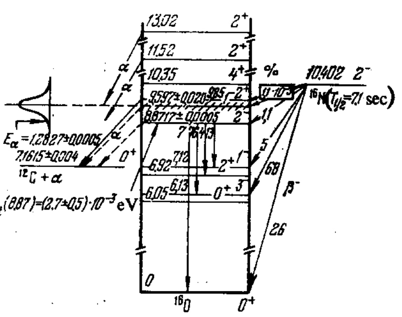

FIG. 6. Part of the level scheme for ^{16}O. The α-particle spectrum from decay of the 9.60 MeV level is shown to the left; the arrow marks the position of the α-particle group from decay of the 8.87 MeV level.

Part of the level scheme showing the production and decay of this 2^- level and nearby levels is presented in Fig. 6. All the states in this scheme have isospin $T = 0$. The emitted α particle has orbital angular momentum $l = 2$. Hence the parity of the final state consisting of the ^{12}C nucleus and the α particle is $P_C P_\alpha (-1)^l = (+1)(+1)(-1)^2 = +1$, while the parity of the initial ^{16}O state is -1. This α decay can therefore take place only with violation of parity conservation.

The 2^- level of ^{16}O is populated in the β decay of an excited state of ^{16}N with the relative probability $y(8.87) = 1.1\%$, while the only nearby ^{16}O state that can decay by an allowed α decay (the 9.60-MeV state) is populated with a very low probability: $y(9.60) \approx 10^{-3}\%$. The γ decay of the 8.87 MeV level, which competes with the α decay, is strongly inhibited; its radiative width is known: $\Gamma_\gamma = 2.7 \times 10^{-3}$ eV. Under these conditions it should be possible to observe the forbidden α decay of the 8.87 MeV state despite its very low intensity.

Experimenters have long sought this decay. By 1965 an upper bound of 6×10^{-9} eV had been set to the width Γ_α of this forbidden α decay by Segel *et al.*[71] and Wilkinson *et al.*,[72] and in 1968 Wilkinson *et al.*[73] reduced this bound to 1.1×10^{-9} eV.

In 1970 there appeared a preliminary communication concerning the work of Wäffler's group at the Max Planck Institute in Mainz (West Germany)[74] in which the decay under consideration was detected and its width determined as $\Gamma_\alpha = (1.8 \pm 0.8) \times 10^{-10}$ eV.

In 1974 the same group reported[76] the results of an experiment with better statistics. We shall discuss the methods used in this second experiment.

The ^{16}O excited state was obtained by β decay of ^{16}N (half life 7.1 sec), which in turn was obtained from the $^{15}N(d, p)^{16}N$ reaction by bombarding ^{15}N with 3 MeV deuterons. The deuteron bombarded gaseous nitrogen containing 96% ^{15}N flowed from the target container through fine capillaries into two small detector chambers. The α particles escaped from the detector chambers through small circular windows sealed with very thin collodion films and were registered with silicon surface-barrier detectors.

The detector pulses were amplified and brought to a multichannel pulse height analyzer, which accumulated pulses from α particles of specified energies in its several channels. The α-particle energies were determined within ± 5 keV. The purpose of the analyzer was to separate the 1282-keV α particles from the transition between the 2^- states of ^{16}O and 0^+ states of ^{12}C. The search for these α particles was greatly complicated by the presence of an enormous number of higher-energy α particles from the decay of the 9.60-MeV state. Moreover, a large number of β particles from ^{16}N decay produced a background in the lower-energy region.

Nevertheless the experimenters succeeded in distinguishing about 10^4 parity-forbidden α decays among the 2.5×10^8 recorded α particles. For this purpose the part of the pulse spectrum due to α particles of energy near 1282 keV was approximated by an exponential function, which was fitted to the experimental points by the least-squares method. Then in channels No. 30 to No. 34 there was observed a positive excess above the exponential, which could be fitted by a Gaussian function. The same spectrum was also approximated by the sum of a fifth degree polynomial and a Gaussian function, and by the sum of a Breit-Wigner function and a Gaussian function. All three approximations gave concordant results with reasonable χ^2 values.

The number of 1282-keV α particles can be found from the area under the Gaussian curve; the result was $N_\alpha(8.87) = 9538 \pm 1810$. Then from the total number of α particles emitted from the 9.60 MeV level, which was $N_\alpha(9.60) = 2.49\times10^8$, the ratio $y(9.60)/y(8.87)$, which was measured in a separate experiment and found to be $(9.98 \pm 0.70)\times10^{-4}$, and the total radiative width of the 8.87 MeV level, the authors calculated the width of the 8.87 MeV level for the forbidden α decay:

$$\Gamma_\alpha = \frac{N_\alpha(8.87)}{N_\alpha(9.60)}\,\frac{y(9.60)}{y(8.87)}\,\Gamma_\gamma = (1.03 \pm 0.28)\cdot 10^{-10}\ \text{eV}. \qquad (5.1)$$

This value agrees, within the experimental errors, with the result of the preliminary work.[74]

From formula (2.27) and the value (5.1) we obtain $F^2 = 3.8\times10^{-14}$ for the square of the parity-mixing amplitude. One can also evaluate F^2 from (5.1) and the typical width of an allowed $l=2$ α decay in this energy region, which has been estimated as $\Gamma_\alpha = 6.7$ keV.[72] Then

$$F^2 = \frac{\Gamma_{\alpha\,\text{irreg}}}{\Gamma_{\alpha\,\text{reg}}} = 1.5\cdot10^{-14}.$$

These values for F are in reasonable agreement with the values obtained in the ITÉF experiments on ^{114}Cd (Section 3D) the LIYaF experiments on ^{41}K, ^{176}Lu, and ^{181}Ta (Sec. 4D), and the experiments on ^{180}Hf (Sec. 3F).

A recent paper[76] casts doubt upon the conclusions reached in[75]. In this paper it is shown that there is a 0^+ level lying very close to, and indeed virtually merging with, the 2^- level at 8.87 MeV. The authors of[76] examined the scattering of α particles from ^{12}C with excitation of ^{16}O levels. The scattered α particles were recorded at three different angles with silicon detectors. The α-particle energy was varied in 0.5 keV steps. A resonance of width $\Gamma_\alpha = 100 \pm 20$ eV was observed at 2.305 MeV. This α-particle energy corresponds to a ^{16}O level at 8.87 MeV. However, the experimental width of this level is many orders of magnitude greater than the width of the 2^- level observed in[75]. The energy dependence of the α-particle scattering cross section near the resonance is such as to favor a 0^+ assignment for the level found in[76]. If this assignment is correct, the α decay found in[75] is not parity forbidden.

6. EXPERIMENTAL STUDY OF THE *pp* SCATTERING CROSS SECTION

A recent communication[77] reports an attempt to detect parity violation by determining the dependence of the scattering cross section on the helicity of the incident protons in the scattering of 15-MeV polarized protons from the protons in an unpolarized hydrogen target.

A pseudoscalar term $\boldsymbol{\sigma}\cdot\mathbf{p}$ ($\boldsymbol{\sigma}$ is the proton spin and $\mathbf{p}$ the proton momentum) appears as a result of interference between the parity-conserving and parity-nonconserving parts of the scattering amplitude, and this leads to a dependence of the total cross section on the polarization direction of the incident proton.

The counting rate for protons scattered from a gaseous hydrogen target at a pressure of 3 atm was taken as a measure of the total cross section. The scattered protons were detected in a 4π geometry with the aid of large liquid scintillators. The measured quantity was $F = (\sigma_R - \sigma_L)/(\sigma_R + \sigma_L)$, in which σ_R (σ_L) is the total cross section for protons having right-hand (left-hand) helicity.

The result, $F = (1 \pm 4)\times10^{-7}$, rules out any effects larger than those predicted by the Cabibbo theory.

7. COMPARISON OF THE EXPERIMENTAL RESULTS WITH CURRENT THEORY

A. General remarks

The theoretical description of the effects of parity violation in nuclear systems should be based, on the one hand, on some specific form for the parity-violating nucleon-nucleon potential, and on the other hand, on the use of parity mixed nuclear wave functions.

Within the framework of the Cabibbo model, which we spoke of in Sec. 2A, the most widely used internucleon potentials are those described by the Feynman diagrams shown in Fig. 7 (in the figure, G is the weak interaction constant, $G_{\pi NN}$ is the pseudoscalar pion-nucleon interaction constant, and f is the strong interaction constant). Diagram a) in Fig. 7 describes the two-nucleon contact interaction V_C, diagram b), the two-pion interaction $V_{2\pi}$, diagram c), the one-pion interaction V_π, and diagram d), the interaction $V_{\rho,\omega}$ mediated by the vector mesons ρ, ω, and others. Potentials of the type V_C and $V_{2\pi}$ have been used in earlier calculations by Blin-Stoyle[12] and Michel.[13]

Each of these potentials has its disadvantage. Thus, the contact potential V_C gives a negligibly small effect when the repulsive cores of the strong-interacting nu-

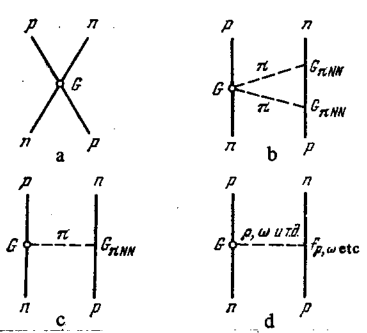

FIG. 7. Diagrams contributing to the weak nucleon-nucleon potential.

cleons are taken into account, and potential $V_{2\pi}$ takes no account of the rescattering of pions from pions and nucleons.

More recent calculations of the parity violating internucleon potentials are based on the one boson exchange potential (OBEP) proposed by Dashen *et al.*,[78] who also pointed out that the exchange of the lightest bosons, i.e., the pions, becomes the most important when allowance is made for the repulsive cores.

Dashen *et al.*[78] also called attention to the importance of investigating the isotopic structure of the weak nucleon-nucleon interaction. Allowing for the contributions from the potentials V_π and $V_{\rho,\omega}$ should make it possible to approach this problem.

Analysis of Eq. (2.1) for the weak nucleon-nucleon interaction potential shows that the hadron current J_λ is an isotopic vector. The product of two isovectors leads either to an isoscalar ($\Delta T=0$) or isotensor ($\Delta T=2$) interaction, but not to an isovector interaction ($\Delta T=1$). Formula (2.1) shows that the contribution from the $\Delta T=0$, 2 potentials is proportional to $\cos^2\theta$, where $\theta\approx 0.24$ is the Cabibbo angle, and that the contribution from the $\Delta T=1$ potential is proportional to $\sin^2\theta$. The ratio of the two contributions is proportional to $\cot^2\theta \approx 20$.

At the same time an analysis of the potentials V_π and $V_{\rho,\omega}$ from the point of view of *CP* invariance of the weak interactions made by Barton[79] shows that potentials with $\Delta T=0$, 2 ($\sim\cos^2\theta$) can result only from exchange of vector mesons (ρ, ω, and others) between free nucleons, while potentials with $\Delta T=1$ ($\sim\sin^2\theta$) permit any one-meson exchange, though pion exchange plays the dominant part.

Allowance for the binding of nucleons in nuclei,[80] as well as for neutral currents,[81] leads to the appearance of an isovector ($\Delta T=1$) part in the term of Hamiltonian (2.1) proportional to $\cos^2\theta$, i.e., to an increase in the importance of one-pion exchange.

In a recent study by Gari and Reid[82] an attempt was made to use the Weinberg-Salam[83] model of the weak interactions to describe the weak nucleon-nucleon potential. Neutral hadron currents were introduced, and these somewhat increase the isoscalar and isotensor parts of the potential (ρ and ω exchange) and lead to considerable enhancement (≈ 20) of the isovector part (pion exchange).

Thus, an experimental separation of the contributions involving different isospin changes ΔT would make it possible to determine the form of the weak nucleon-nucleon interaction Hamiltonian.

In order to calculate the effects of parity violation in a specific nucleus one must know the structure of the nucleus, i.e., one must know the nuclear wave functions, the eigenstate spectrum of the Hamiltonian, etc. Perturbation theory could then be used to take account of the parity violating potentials, as was shown in Sec. 2B.

In this connection the most important requirements on the unperturbed wave functions for the system of strong interacting particles are the following:

1) The wave functions should give a "realistic" description of the bound states, i.e., they should yield level energies and transition probabilities in good agreement with the experimental values (at least in the several-MeV excitation energy region);

2) They should provide a good description of the relative motion of two particles within the nucleus at small distances ($<10^{-13}$ cm); this means that the wave functions should take into account the strong repulsive cores of the nucleons.

To fulfill the second requirement, the nucleon-nucleon potentials of Hamada and Johnston, Reid, and others (see[84]) have been invoked, and the short-range pairing correlations between the nucleons in the nucleus[85] have been taken into account.

The theory of finite Fermi systems[86] has been used to calculate certain effects.

The discrepancies that now exist between theory and experiment may be attributed to our insufficient understanding of nuclear structure, especially of the structure of complex nuclei. Making no pretensions of rigor or completeness in treating the problem, we shall compare certain experimental results (see the table) with the available calculations. We shall begin with few-nucleon systems, in which the isotopic structure of the weak nucleon-nucleon interaction can be investigated.

B. Few-nucleon systems

^{2}H. *The* 2.23-MeV $0^+ - 1^+$ $M1+\tilde{E}1$ *transition*. The following transitions take place in the radiative capture of thermal neutrons by protons, $n+p\to d+\gamma$: the regular $M1$ transition $^1S_0(T=1)\to{}^3S_1(T=0)$, and the irregular $\tilde{E}1$ transitions $^3S_1(T=0)\to{}^3P_1(T=1)$ and $^1S_0(T=1)\to{}^1P_1(T=0)$. The regular $M1$ transition is not inhibited, so the observable P-odd effects are very small.

As Danilov showed,[87] the circular polarization of the γ radiation from capture of unpolarized neutrons is sensitive only to the isoscalar part ($\Delta T=0$) of the potential, while the asymmetry in the emission γ rays from capture of polarized neutrons is sensitive only to the isovector part ($\Delta T=1$).

Only the first experiment has been performed[65]; the result was $P_\gamma=-(1.30\pm 0.45)\times 10^{-6}$. Cabibbo-model estimates by Danilov[87] gave $P_\gamma\approx 10^{-8}$.

In a more recent study[88] Danilov used the method of dispersion relations to calculate the same effects and obtained even lower values: $P_\gamma\approx 1.8\times 10^{-8}$ and $a\approx 4\times 10^{-9}$. Calculations using the potentials V_π and V_ρ[89] also gave a low value for P_γ.

A number of attempts have been made to reduce the existing gap between the experimental and theoretical values of P_γ. The deviation of the nucleons from the mass surface[80] and exchange effects in the nuclear forces[90] have been taken into account, and quark[91] and gauge[92] models of the parity violating potential have been considered. However, agreement with experiment was not obtained.

On the other hand, Danilov[93] showed that certain diagrams, which are usually neglected in calculating the strength of the weak interaction between nucleons and ρ mesons, are divergent, and that cutting off the quadratically divergent integral at $\Lambda = 10$ GeV brings the theoretical estimates into agreement with experiment.[4)]

^{3}H. *The* 6.25-MeV $3/2^+$, $1/2^+ \to 1/2^+$ $M1+\tilde{E}1$ *transition.* As Blin-Stoyle and Feshbach[94] pointed out, the effect may be enhanced in the $n+d \to {}^3\text{H}+\gamma$ reaction since the regular $M1$ transition is inhibited. Moskalev[95] estimated the effect, using the Cabibbo theory in the zero-range approximation for the nuclear forces, and found $P_\gamma \approx a \approx 10^{-6}$. Both the isoscalar and isovector parts of the weak nucleon-nucleon potential contribute to both a and P_γ.

The measurement of a is complicated by the unfavorable ratio of the deuteron cross sections for capture and and scattering of neutrons, as a result of which polarized neutrons are rapidly depolarized on entering the deuteron target (D_2O).

The only experiment with this nucleus[37] did not achieve the necessary accuracy, the result being $a = (0.28 \pm 1.55)\times 10^{-4}$.

^{10}B and ^{18}F. *The* 4.39-MeV $2^- \to 1^+$ $E1+\tilde{M}1$ *transition in* ^{10}B *and the* 1.08-MeV $0^- \to 2^+$ $E1+\tilde{M}1$ *transition in* ^{18}F. It has been suggested[78] that the effects of parity nonconservation in $E1$ or $M1$ transitions between isospin $T=0$ levels of light mirror nuclei could be used to investigate the isotopic structure of the weak nucleon-nucleon interaction. The matrix element for an $E1$ transition between $T=0$ states is inhibited by about two orders of magnitude while the matrix element for an $M1$ transition is inhibited by about one order of magnitude, and at the same time an irregular transition due to the admixture of a $T=1$ level to either the initial or the final state is correspondingly enhanced. These transitions are especially sensitive to the potential V_π.

Henley[96] made the corresponding calculations for the ^{10}B and ^{18}F transitions noted above and showed that in both cases the contribution to the circular polarization of the γ rays from V_π exceeds that from V_ρ by an order of magnitude. In both cases there is a $T=1$ level of opposite parity near the $T=0$ upper level, and as a result the $\tilde{M}1$ admixture is enhanced on account of the isovector ($\Delta T=1$) component. Cabibbo-model estimates for ^{18}F give $P_\gamma \approx 10^{-5}$, and when neutral currents are included, $P_\gamma \approx 2\cdot 10^{-4}$.

A new estimate[82] for ^{18}F based on the Weinberg-Salam model gives $P_\gamma \approx 5\times 10^{-3}$. This is a substantial effect. Hence an experiment with ^{18}F would seem to be of great importance, both as a test of the Weinberg-Salam model and to isolate the isovector part of the weak nucleon-nucleon potential.

^{19}F. *The* 110-keV $1/2^- \to 1/2^+$ $E1+\tilde{M}1$ *transition.* The large value of the observed angular asymmetry of the γ radiation from this transition (see the table) can be explained both in terms of the Cabibbo model[97] and in terms of the Weinberg-Salam model.[82] Unfortunately, in this case the effect is due to both the $\Delta T=0$ and $\Delta T=1$ parts of the potential.

^{16}O. *The* ^{16}O(2^-, 8.87 MeV) $\to$ ^{12}C(0^+) + α *decay.* Since isospin is conserved in α decay, a parity forbidden α decay is due entirely to the $\Delta T=0$ part of the potential, i.e., mainly to the potential V_ρ. The width Γ_α of the irregular α decay has been calculated using various isoscalar potentials for the weak nucleon interaction and various potentials for the strong interaction, depending on the radius of the hard repulsive core.[3,5,9]

The experimental result,[75] $\Gamma_\alpha = (1.03\pm 0.28)\times 10^{-10}$ eV, is in good agreement with the calculations for all the models, since the calculations are only weakly model dependent.

C. Many-nucleon systems

Although the division between few-nucleon and many-nucleon systems is arbitrary, we shall classify a nucleus as a many-nucleon system provided the contributions from definite isospin changes to the effects exhibited by that nucleus cannot be distinguished.

^{41}K. *The* 1290-keV $7/2^- \to 3/2^+$ $M2+\tilde{E}2$ *transition.* Vinh Mau[98] calculated the circular polarization of the γ rays from this transition on the basis of the Shell model using potentials V_π and V_ρ and allowing for short range pairing correlations. The value thus obtained for P_γ is an order of magnitude smaller than the experimental value (see the table).

A calculation by Gaponov and Fursov[86] based on the theory of finite Fermi systems is in better agreement with experiment.

^{114}Cd. *The* 9040-keV $1^+ \to 0^+$ $M1+\tilde{E}1$ *transition.* Only a rough order-of-magnitude estimate of the effect can be made in this case owing to the complexity and overlapping of the nuclear states. Such estimates have been made by Blin-Stoyle[12] and Shapiro,[10] using the single-particle oscillator model for the nucleus and the Cabibbo model for the weak interaction. McKellar[99] included the short-range correlations and used various weak-interaction models. All these calculations gave values of the asymmetry that lie in the range (2–10) $\times 10^{-4}$ and agree in order of magnitude with the measured asymmetry (see the table).

^{175}Lu. *The* 396-keV $9/2^- \to 7/2^+$ $E1+M2+\tilde{M}1$ *transition.* Early calculations of the effect in this transition using a single-particle parity-nonconserving potential and neglecting the potential V_π[13] led to values that agree with experiment (see the table).

A calculation in which the potentials V_π and V_ρ, the pairing correlations, and the short-range correlations were included[100] gave a value of P_γ that was smaller by an order of magnitude.

^{180}Hf. *The* 501-keV $8^- \to 6^+$ $M1+E3+\tilde{E}2$ *transition.* The theoretical interpretation of the effects in this transition is of great interest since the measured effects are unusually large (see the table). The reason for such large effects and their compatibility were discussed in Secs. 3A and 4E.

Vogel (see[5]) calculated P_γ with allowance for Coriolis mixing and obtained good agreement with the experimental value. However, no great importance need be attributed to this agreement because of the large number of ambiguities.

^{181}Ta. *The* 482-keV $5/2^+ - 7/2^+$ $M1+E2+\tilde{E}1$ *transition.* Many theoretical papers have been published on the value of P_γ. Most of the early estimates based on the Cabibbo model gave fairly good agreement with experiment.[16,101] More recent estimates, however, are considerably lower than the experimental values. Only the potentials V_π and V_ρ were taken into account in these calculations. Allowing for pairing correlations and the small repulsive cores of the nucleons, lead to values of P_γ in the vicinity of 0.2×10^{-6},[100] which is an order magnitude lower than the experimental values (see the table).

8. CONCLUSION

From all that was said above we can quite definitely conclude that nuclear states of opposite parity do indeed interfere as a result of a weak parity-nonconserving interaction between the nucleons. This conclusion is in accordance with the universal weak interaction hypothesis. In a number of cases, comparison of the experimental results with theoretical calculations reveals discrepancies that do not disappear, but rather get worse, when the correlations among the nucleons in the nuclei (pairing, the repulsive cores) are taken into account. These discrepancies emphasize the fact that our ideas concerning nuclear structure and the weak interactions between the nucleons are not entirely adequate.

At present the enhancement factor R for the P-odd effects in nuclei cannot be calculated accurately. When R is large, therefore, detailed information on the strength of the weak nucleon-nucleon interaction cannot be extracted from the experimental data. On the other hand, when R is small (i.e., in the case of light nuclei and low excitation energies) the observed effects are, as a rule, larger than the calculated values. The discrepancy is especially large in the case of the simplest process $n+p\to d+\gamma$, in which there is no structural enhancement at all. As was noted above, the circular polarization of the γ rays from this reaction is due to the isoscalar part of the weak nucleon-nucleon interaction. Up to now there is no direct experimental proof that the weak nucleon-nucleon interaction has an isovector part. Elucidation of the isotopic structure of the weak nucleon-nucleon interaction is now the principal problem facing investigators of the weak nuclear forces. In this connection it is of primary importance to repeat the measurement of the circular polarization of the γ rays from the $n+p\to d+\gamma$ reaction with an unpolarized neutron beam in order to confirm and improve the accuracy of the result already obtained. It is nevertheless important to investigate the asymmetry of the angular distribution of γ rays from this reaction with a polarized neutron beam. This would make it possible to evaluate the isovector part of the interaction. In addition, as was mentioned above, the isovector P-odd weak interaction should manifest itself in γ transitions between $T=0$ levels in light nuclei such as ^{10}B and ^{18}F, i.e., when the admixed P-odd state is a $T=1$ level.

The $n+d\to{}^3\text{H}+\gamma$ reaction should be examined in three different ways: The circular polarization of the γ rays should be measured with both the beam and the target unpolarized, and the angular asymmetry of the γ rays should be measured both with the neutron beam polarized and the target unpolarized, and with the beam unpolarized and the target polarized. The magnitude of the expected P-odd effects in this reaction lies in the range $10^{-7}-10^{-5}$. The effects are due to both the isoscalar and the isovector parts of the P-odd interaction. In principle, these three experiments together with the two experiments on the $n+p\to d+\gamma$ reaction would make it possible to evaluate five constants which would completely determine the isotopic structure of the weak nucleon-nucleon interaction. The search for parity-forbidden α decays of light nuclei is also of great interest in connection with the study of the isotopic properties of the weak interaction.

Of course the accumulation of data on P-odd effects in medium-mass and heavy nuclei will eventually shed some light on the part played by the weak interaction in complex many-nucleon systems.

Note added in proof: In a recent paper[102] Danilov has shown that there is another possible model for the weak NN_ρ vertex. In this model the vertex contains no quadratic divergence but is proportional to the square of a certain characteristic mass M. A value of 5–7 GeV for M is sufficient to account for the large experimental value of the circular polarization.

[1]R. P. Feynman and M. Gell-Mann, Phys. Rev. **109**, 193 (1958).
[2]D. H. Wilkinson, *ibid.*, p. 1603.
[3]E. M. Henley, Ann. Rev. Nucl. Sci. **19**, 367 (1969).
[4]E. Fishbach and D. Tadic, Phys. Rept. **C6**, 123 (1973).
[5]M. Gari, *ibid.*, p. 317.
[6]G. A. Lobov, Slaboe vzaimodeĭstvie i struktura yadra (konspekt lektsiĭ) (The Weak Interactions and Nuclear Structure (a Summary of Lectures)), MIFI, M., 1973; At. Energ. Rev. **12**, 505 (1974).
[7]W. D. Hamilton, Progr. Nucl. Phys. **10**, 3 (1963).
[8]N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963).
[9]R. J. Blin-Stoyle, Fundamental Interactions and the Nucleus, Amsterdam—New York, North-Holland—American Elsevier, 1973.
[10]I. S. Shapiro, Usp. Fiz. Nauk 95, 647 (1968) [Sov. Phys.-Usp. **11**, 582 (1969)].
[11]I. S. Shapiro, in: Materialy seminara po élektromagnitym vzaimodeĭstviyam v yadernykh reaktsiyakh (Materials from the Seminar on Electromagnetic Interactions in Nuclear Reactions). JINR Preprint 3-3442, Dubna, 1967, p. 76.
[12]R. J. Blin-Stoyle, Phys. Rev. **118**, 1605 (1960); 120, 181 (1961).
[13]F. C. Michel, *ibid.* **B133**, 329 (1964).
[14]L. D. Landau and E. M. Lifshitz, Kvantovaya Mekhanika (Quantum Mechanics), Fizmatgiz., M., 1963 [Pergamon, 1965].
[15]D. H. Wilkinson, Phys. Rev. **109**, 1610 (1958).

[16] S. Wahlborn, *ibid.* **B138**, 530 (1965).
[17] L. C. Biedenharn and M. E. Rose, Rev. Mod. Phys. **25**, 729 (1953).
[18] M. E. Rose, Multipole Fields, N. Y., J. Wiley and Sons, 1965.
[19] A. J. Ferguson, Angular Correlation Methods in Gamma-Ray Spectroscopy, North-Holland, Amsterdam and Wiley, N. Y., 1965 (Russ. Transl., Atomizdat, M., 1960).
[20] H. Frauenfelder and R. Steffen, in Alpha-, Beta-, and Gamma-Ray Spectroscopy (Kai Siegbahn, editor), North Holland, Amsterdam, 1965 (Russ. Transl., Atomizdat, M., 1969, Vol. 3, p. 124).
[21] R. J. Blin-Stoyle and M. A. Grace, Handb. Phys. **42**, 555 (1957).
[22] G. A. Lobov, Izv. Akad. Nauk SSSR Ser. Fiz. **32**, 886 (1968).
[23] L. Krüger, Zs. Phys. **157**, 369 (1959).
[24] R. D. Lawson and R. E. Segel, Phys. Rev. Lett. **16**, 1006 (1966).
[25] L. Wolfenstein, Phys. Rev. **75**, 1664 (1949).
[26] R. Haas, L. B. Leipuner, and R. K. Adair, *ibid.* **116**, 1221 (1959).
[27] Yu. G. Abov, P. A. Krupchitskiĭ, and Yu. A. Oratovskiĭ, Phys. Lett. **12**, 25 (1964); Yad. Fiz. **1**, 479 (1965) [Sov. J. Nucl. Phys. **1**, 341 (1965)].
[28] Yu. G. Abov, P. A. Krupchitskiĭ, M. I. Bulgakov, O. N. Ermakov, and I. L. Karpikhin, Phys. Lett. **B27**, 16 (1968); Yad. Fiz. **10**, 558 (1969) [Sov. J. Nucl. Phys. **10**, 320 (1970)].
[29] Yu. G. Abov, M. M. Danilov, O. N. Ermakov, I. L. Karpikhin, V. K. Rissukhin, and A. M. Skornyakov, Yad. Fiz. **16**, 1218 (1972) [Sov. J. Nucl. Phys. **16**, 670 (1973)].
[30] Yu. G. Abov, V. A. Beketov, A. D. Gul'ko, O. N. Ermakov, P. A. Krupchitskiĭ, Yu. V. Taran, and N. S. Shatlovskaya, Prib. Tekh. Eksp. No. 4, 51 (1960).
[31] Yu. G. Abov, M. I. Bulgakov, A. D. Gul'ko, O. N. Ermakov, P. A. Krupchitskiĭ, Yu. A. Oratovskiĭ, and S. S. Trostin, Prib. Tekh. Eksp. No. 4, 195 (1966).
[32] Yu. G. Abov, A. D. Gul'ko, and P. A. Krupchitskiĭ, Polyarizovannye medlennye neutrony (Polarized Slow Neutrons), Atomizdat, M., 1966.
[33] K. Abrahams, O. Steinsvoll, P. J. M. Bongaarts, and P. W. de Lange, Rev. Sci. Instr. **33**, 524 (1962).
[34] Yu. G. Abov, O. N. Ermakov, and P. A. Krupchitskiĭ, Zh. Eksp. Teor. Fiz. **65**, 1738 (1973) [Sov. Phys.-JETP **38**, 870 (1974)].
[35] B. H. J. McKellar, Phys. Rev. Lett. **20**, 1542 (1968); Phys. Rev. **178**, 2160 (1969).
[36] J. L. Alberi, R. Wilson, and J. G. Schröder, Phys. Rev. Lett. **29**, 518 (1972).
[37] M. Forte and O. Saavedra, Preprint EUR 3053e, Ispra, 1966.
[38] J. Eichler and P. Heine, Zs. Phys. **227**, 352 (1969).
[39] K. Abrahams, W. Ratynski, F. Stecher-Rasmussen, and E. Warming, in International Conference on Nuclear Structure, Antwerp, 1965, paper 42.
[40] E. Warming, F. Stecher-Rasmussen, W. Ratynski, and J. Kopecky, Phys. Lett **B25**, 200 (1967).
[41] E. Warming, *ibid.* **B29**, 564 (1969).
[42] G. Scharff-Goldhaber and M. McKeown, Phys. Rev. **158**, 1105 (1967).
[43] H. Paul, M. McKeown, and G. Scharff-Goldhaber, *ibid.*, p. 1112.
[44] P. Bock, B. Jenschke, and H. Schopper, Phys. Lett. **22**, 316 (1966).
[45] K. S. Krane, C. E. Olsen, and W. A. Steyert, Phys. Rev. **C5**, 1663 (1972).
[46] R. Hayer and E. Seltzer, Phys. Lett. **20**, 180 (1966).
[47] K. S. Krane, C. E. Olsen, J. R. Sites, and W. A. Steyert, Phys. Rev. **C4**, 1906 (1971).
[48] B. N. Samoĭlov, Zh. Eksp. Teor. Fiz. **38**, 359 (1960) [Sov. Phys.-JETP **11**, 261 (1960)].
[49] B. Jenschke and P. Bock, Phys. Lett. **B31**, 65 (1970).
[50] E. D. Lipson, F. Boehm, and J. C. Vanderleeden, *ibid.* **B35**, 307 (1971).
[51] E. G. Adelberger, H. E. Swanson, M. D. Cooper, J. W. Tape, and T. A. Trainor, Phys. Rev. Lett. **34**, 402 (1975).
[52] F. Boehm and E. Kankeleit, *ibid.* **14**, 312 (1965).
[53] V. M. Lobashev, V. A. Nazarenko, L. F. Saenko, and L. M. Smotritskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **3**, 76 (1966) [JETP Lett. **3**, 47 (1966)].
[54] V. M. Lobashev, Yad. Fiz. **2**, 957 (1965) [Sov. J. Nucl. Phys. **2**, 683 (1966)].
[55] V. M. Lobashev, V. A. Nazarenko, L. F. Saenko, L. M. Smotritskiĭ, and G. I. Kharkevich, Pis'ma Zh. Eksp. Teor. Phys. **3**, 268 (1966) [JETP Lett. **3**, 173 (1966)].
[56] V. M. Lobashev, V. A. Nazarenko, L. F. Saenko, L. M. Smotritskii, and G. I. Kharkevich, Pis'ma Zh. Eksp. Teor. Fiz. **5**, 73 (1967) [JETP Lett. **5**, 59 (1967)]; Phys. Lett. **B25**, 104 (1967).
[57] V. M. Lobashev, N. A. Lozovoy, V. A. Nazarenko, L. M. Smotritskii, and G. I. Kharkevich, *ibid.* **B30**, 39 (1969).
[58] J. C. Vanderleeden and F. Boehm, *ibid.*, p. 467.
[59] J. C. Vanderleeden and F. Boehm, Phys. Rev. **C2**, 748 (1970).
[60] J. C. Vanderleeden, F. Boehm, and E. Lipson, *ibid.* **C4**, 2218 (1971).
[61] P. Bock and B. Jenschke, Nucl. Phys. **A160**, 550 (1971).
[62] E. Lipson, F. Boehm, and J. C. Vanderleeden, Phys. Rev. **C5**, 932 (1972).
[63] E. Kuphal, Zs. Phys. **253**, 314 (1972).
[64] E. Kuphal, P. Dewes, and E. Kankeleit, Nucl. Phys. **A234**, 308 (1974).
[65] V. M. Lobashev, D. M. Kaminker, G. I. Kharkevich, V. A. Kniazkov, N. A. Lozovoy, V. A. Nazarenko, L. F. Sayenko, L. M. Smotritsky, and A. I. Egorov, *ibid.* **A197**, 241 (1972).
[66] W. Pratt, R. I. Schermer, J. R. Sites, and W. A. Steyert, Phys. Rev. **C2**, 1499 (1970).
[67] V. M. Lobashev, V. A. Nazarenko, L. F. Saenko, L. M. Smotritskiĭ, and V. A. Kharkevich, Yad. Fiz. **13**, 555 (1971) [Sov. J. Nucl. Phys. **13**, 313 (1971)].
[68] G. Schmidt and L. M. Simons, Zs. Phys. **269**, 421 (1974).
[69] P. De Saintignon and M. Chabre, Phys. Lett. **B33**, 463 (1970).
[70] F. Dydak, H. D. Polaschegg, P. Riehs, and P. Weinzierl, *ibid.* **B37**, 375 (1971).
[71] R. E. Segel, J. W. Olness, and E. L. Sprenkel, Phil. Mag. **6**, 163 (1961); Phys. Rev. **123**, 1382 (1961).
[72] D. E. Alburger, R. E. Pixley, D. H. Wilkinson, and P. F. Donovan, Phil. Mag. **6**, 171 (1961).
[73] D. P. Boyd, P. F. Donovan, B. Marsh, D. E. Alburger, D. H. Wilkinson, P. Assimakopoulos, and E. Beardsworth, Bull. Amer. Phys. Soc. **13**, 1424 (1968).
[74] H. Hättig, K. Hünchen, and H. Wäffler, Phys. Rev. Lett. **25**, 941 (1970).
[75] K. Neubeck, H. Schober, and H. Wäffler, Phys. Rev. **C10**, 320 (1974).
[76] A. E. Ignatochkin and F. E. Chukreev, Preprint IAE No. 2496, Moscow, 1975.
[77] J. M. Potter, J. D. Bowman, C. F. Hwang, J. L. McKibben, R. E. Mischke, D. E. Nagle, P. G. Debrunner, H. Frauenfelder, and L. B. Sorensen, Phys. Rev. Lett. **33**, 1307 (1974).
[78] R. Dashen, S. Frautschi, M. Gell-Mann, and Y. Hara, The Eightfold Way, N. Y., Benjamin, 1964.
[79] G. Barton, Nuovo Cimento **19**, 512 (1961).
[80] E. M. Henley, Phys. Rev. Lett. **27**, 542 (1971).
[81] R. J. Blim-Stoyle, and P. Herczeg, Nucl. Phys. **B5**, 291 (1968).
[82] M. Gari and H. Reid, Phys. Lett. **B53**, 237 (1974).
[83] S. Weinberg, Phys. Rev. Lett. **19**, 1264 (1967). A. Salam, in: Proc. of 8th Nobel Symposium, Stockholm, Almquist Vorlag AB, 1969, p. 367.
[84] R. V. Reid, Ann. Phys. (N. Y.—L.) **50**, 411 (1968).

[85]H. Kümmel, Nucl. Phys. **A176**, 205 (1971).
[86]Yu. V. Danilov and Yu. S. Fursov, Yad. Fiz. **9**, 963 (1969); **13**, 80 (1971) [Sov. J. Nucl. Phys. **9**, 564 (1969); **13**, 45 (1971)].
[87]G. S. Danilov, Phys. Lett. **18**, 40 (1965).
[88]G. S. Danilov, Yad. Fiz. **14**, 788 (1971) [Sov. J. Nucl. Phys. **14**, 443 (1972)].
[89]E. Hadjimichael and E. Fischbach, Phys. Rev. **D3**, 755 (1971).
[90]E. M. Henley, *ibid.* **C7**, 1344 (1973).
[91]H. J. Pirner and M. L. Rustgi, Nucl. Phys. **A239**, 427 (1975).
[92]A. Andrasi, J. Missimer, and D. Tadic, Phys. Rev. **D11**, 1331 (1975).
[93]G. S. Danilov, Yad. Fiz. **17**, 1052 (1973) [Sov. J. Nucl. Phys. **17**, 549 (1973)].
[94]R. J. Blin-Stoyle and H. Feshbach, Nucl. Phys. **27**, 395 (1961).
[95]A. N. Moskalev, Yad, Fiz. **7**, 554 (1968); **8**, 1156 (1968); **9**, 163 (1969) [Sov. J. Nucl. Phys. **7**, 344 (1968); **8**, 672 (1969); **9**, 99 (1969)].
[96]E. M. Henley, Phys. Lett. **B28**, 1 (1968).
[97]M. A. Box and B. H. J. McKellar, Phys. Rev. **C11**, 1859 (1975).
[98]N. Vinh Mau, in: Proc. of the Symposium on Nucleons and Weak Interactions, Zagreb, 1971, p. 99.
[99]B. H. J. McKellar, Phys. Rev. **178**, 2160 (1968).
[100]B. Desplanques and N. Vinh Mau, Phys. Lett. **B35**, 28 (1971).
[101]E. Maqueda and R. J. Blin-Stoyle, Nucl. Phys. **A91**, 460 (1968).
[102]G. S. Danilov, Yad. Fiz. **22**, 776 (1975) [Sov. J. Nucl. Phys. **22**, 401 (1976)].

Translated by E. Brunner