Parity violation in nuclear fission

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Experimental and theoretical work on parity violation in nuclear fission is reviewed.

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CONTENTS

1. INTRODUCTION

Recent experiments at the Institute of Theoretical and Experimental Physics, Moscow, have revealed an unusual parity-violation effect in nuclear interactions. In the fission of such nuclei as ^{233}U, ^{235}U, and ^{239}Pu by polarized thermal neutrons, the light fragments, and, correspondingly, the heavy fragments are emitted in an asymmetric fashion with respect to the polarization direction of the neutron beam. In the fission of ^{233}U and ^{235}U, for example, the light fragment is emitted preferentially along the spin direction of the neutron captured by the nucleus, while the preferred direction in the fission of ^{239}Pu is opposite to the spin.

The fact itself that the momentum of the particle is correlated with the nuclear spin is a trivial consequence of parity violation in the nuclear interaction. Such a correlation has been observed previously in γ emission.

The unusual aspect of this effect in fission is that it is not the momentum of one definite particle which is correlated with the nuclear spin but essentially a flow of nuclear matter which is formed into some "particle" or other only after the rupture of a "neck" connecting the two fragments.

The purposes of this review are to acquaint the reader with the results of the first experiments and to make a first attempt to interpret these results.

The review will begin with a brief account of the basic theoretical positions which stimulated the search for P-odd effects in nuclear interactions. There will also be a brief description of the experiments which led to the discovery of parity violation in electromagnetic transitions of nuclei. These questions are covered in more detail elsewhere in reviews[1-4] and in a monograph.[5]

Sections 3 and 4 describe the experiments on P-odd effects in fission. These experiments were carried out by four different groups of investigators, using different methods. The results are summarized and described in Section 5. Section 6 describes the only reported attempt at the time of this writing to interpret theoretically the experimentally observed asymmetry in fission. In the final chapter we will give a far from complete list of some possible experiments—apparently the most informative at this stage—which might cast some light on the mechanism for this phenomenon.

2. *P*-ODD FORCES IN NUCLEI

a) Soon after parity violation in weak interactions was established, Feynman and Gell-Mann[6] advanced the hypothesis of the universal nature of the weak interaction. According to their concept of the interaction of charged currents, one of the diagonal terms in the Hamiltonian reproduces the weak interaction between nucleons. In the unified theories for the weak and electromagnetic interactions,[7] in contrast with the model of Feynman and Gell-Mann, the weak interaction between nucleons may also be affected by neutral points, whose existence has been demonstrated experimentally, at least in lepton–hadron interactions.

The existence of a weak interaction between nucleons means that there should be a parity-violating weak nucleon–nucleon potential in a nucleus, with a relative magnitude which we can estimate roughly as

$$F \approx \frac{G}{\hbar c \bar{r}^2} \approx 10^{-7}, \tag{1}$$

where G is the universal weak-interaction constant, and $\bar{r}$ is the average distance between the nucleons in the nucleus.

Since F is small, the only consequence of the existence of a weak nucleon–nucleon potential which could be tested experimentally would seem to be a mixing of nuclear states with opposite parities.

In first-order perturbation theory, the nuclear wave function can be written as

$$\Psi_i = \psi_i + \sum_{j \neq i} \frac{\langle j | V_{\mathrm{PV}} | i \rangle}{E_j - E_i} \psi_j, \tag{2}$$

where ψ_i and ψ_j are the eigenfunctions of the unper-

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turbed Hamiltonian, which are of opposite parity, and V_{PV} is the parity-violating weak nucleon-nucleon potential.

Assuming that the level closest in energy dominates the sum, we can rewrite (2) as

$$\Psi_i = \psi_i + \alpha\psi_j, \tag{3}$$

$$\alpha = \frac{\langle j|V_{PV}|i\rangle}{E_j - E_i}. \tag{4}$$

For the nuclear ground states, α is probably approximately equal to F, but for highly excited states α may be much larger, because of the decrease in the energy denominator in (4).

This circumstance was first pointed out by Haas *et al.*,[8] who studied the P-odd asymmetry in γ emission,

$$W(\theta) = \text{const}\cdot(1 + a\sigma\mathbf{p}) = \text{const}\cdot(1 + a\cos\theta), \tag{5}$$

in the radiative capture of polarized slow neutrons by cadmium, indium, and silver nuclei. This asymmetry should result from an interference between the regular and mixed transitions from the capture state to a lower-lying state. Because of the high density of compound-nucleus levels, the admixture of states of opposite parity, α, would be expected to become much larger than F.

In estimating the matrix element $\langle j|V_{PV}|i\rangle$, Haas *et al.* made an error and having failed to detect an asymmetry within $\sim 10^{-3}$ concluded that $F \leqslant 10^{-8}$.

A more accurate estimate of the admixture enhancement for the compound nucleus $^{114}\mathrm{Cd}^*$ was carried out by Blin-Stoyle[9] and Shapiro,[10] according to which the experimental results of Ref. 8 means only that $F \leqslant 10^{-6}$.

b) In 1964, Abov *et al.*,[11] improved the experimental accuracy and observed an asymmetry which they were seeking in the γ emission in the reaction $^{113}\mathrm{Cd}(\vec{n},\gamma_0)^{114}\mathrm{Cd}$. The asymmetry coefficient turned out to be $a = (-3.7 \pm 0.9)\times 10^{-4}$, which agrees in order of magnitude with some rough theoretical estimates.

Two years later, Lobashov *et al.*,[12] discovered another P-odd effect: the circular polarization of γ quanta emitted by polarized nuclei in transitions between low-lying levels. The enhancement mechanism in this case is different from that in γ emission by highly excited nuclei. In the terminology of Ref. 10, these mechanisms are "structural" in nature, i.e., result from structural features of the initial and final states, as a result of which the regular transition is suppressed, while the admixed transition is not.

Effects resulting from structural enhancement have recently been discovered for many nuclei, while the asymmetry in the γ emission by $^{114}\mathrm{Cd}$ nuclei is probably the sole manifestation of the dynamic[1] enhancement mechanism. Furthermore, attempts by other groups to repeat this experiment have been unsuccessful.[4] Only in 1972 did Alberi and Wilson[13] confirm the existence of a P-odd effect in the reaction $^{113}\mathrm{Cd}(n,\gamma)^{114}\mathrm{Cd}$, detecting a circular polarization of the γ quanta accompanying the capture of unpolarized neutrons. Shortly thereafter, another group,[14] at the Institute of Theoretical and Experimental Physics, Moscow, observed an asymmetry in the reaction $^{117}\mathrm{Sn}(\vec{n},\gamma_0)$. The asymmetry coefficient here turned out to be $(8.9 \pm 1.5)\times 10^{-4}$.

It thus became clear that the highly excited compound-nucleus levels do in fact have an admixture of states of the opposite parity. It is accordingly worthwhile to look for evidence of this admixture also in other processes which accompany the capture of thermal nucleons by nuclei. Lobov and the present author[15] have suggested studying the P-odd asymmetry in the (n, α) reaction; unfortunately, the cross section for this reaction for heavy and intermediate nuclei is extremely small, while in the case of light nuclei ($^6\mathrm{Li}$, $^{10}\mathrm{B}$), we could hardly expect a substantial enhancement by the dynamic mechanism.

c) Another process which accompanies the capture of thermal neutrons by heavy nuclei is fission. If the nucleus does not "forget", as is usually assumed, the compound-nucleus stage in the course of the fission, the enhancement mechanisms responsible for the relatively large effects which have been observed experimentally in reactions on radiative neutron capture could in principle also "operate" in the fission channel. The level density of fissile compound nuclei is roughly an order of magnitude higher than for the compound nuclei $^{114}\mathrm{Cd}$ and $^{118}\mathrm{Sn}$, so that, if the effects during the γ decay of these nuclei are in fact due to a dynamic enhancement mechanism, then we can expect a significant admixture of states of the opposite parity in fissile compound nuclei also.

How might this admixture be seen in fission?

Conservation of the total angular momentum and conservation of parity in fission require that

$$J_C = J_L + J_H + L = F + L,$$

$$\pi_C = (-)^L\,\pi_L\pi_H \text{ — (all } L \text{ are of the same parity)}, \tag{6}$$

where $J_c^{\pi_c}$, $J_L^{\pi_L}$, and $J_H^{\pi_H}$ are the spins and parities of the compound nucleus, the light fragment, and the heavy fragment, respectively; and L is the orbital angular momentum of the two fragments.

If π_c is undetermined, then both even and odd values of L are evidently allowed. The interference of the amplitudes of transitions with even and odd values of L from the capture state to a definite final state $(J_L^{\pi_L}, J_H^{\pi_H}, F, L)$ leads to a P-odd angular correlation between the momentum of the light fragment (or, correspondingly, the heavy fragment) and the spin of the fissile nucleus:

$$W(\theta) = \text{const}\cdot(1 + a_f\sigma\mathbf{p}_L) = \text{const}\cdot(1 + a_f\cos\theta). \tag{7}$$

In general, both the modulus and the sign of the asymmetry coefficient a_f depend on the quantum numbers of the final state. Various estimates put the number of possible final states in fission between 10^7 and 10^{10}. Therefore, it would seem that if we did not single out a definite final state (and this is essentially impossible to do), but instead measured the angular distribution

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[1] Adopting the terminology of Ref. 10, we refer as "dynamic enhancement" to that enhancement which is due to the decrease in the denominator in Eq. (4) with increasing excitation energy of the nucleus.

of all light fragments in the fission of polarized nuclei, we would be carrying out a statistical averaging of the asymmetry coefficients, and the resultant asymmetry would turn out to be indistinguishable from zero.[2)]

Actually, these arguments may be incorrect, because of the peculiarities which distinguish fission from particle-emission processes. We know that in the fission of several heavy nuclei there is a preferential formation of fragments of unequal mass if the nuclear excition energy exceeds the pertinent barriers by only a small amount. The most natural explanation for this fact is that the formation of the fragments is probably preceded by nuclear states with an asymmetric deformation. If the weak interaction mixes such states of opposite parity, then the asymmetry in the emission of the fragments will be independent of the final state. As early as 1961, Vladimirskiĭ and Andreev[16] ascribed an asymmetric deformation of this type to the ground state of a fissile nucleus; they suggested a possible barrier enhancement and also suggested a study of the asymmetry of the emission of the light fragment (or the heavy one) in the spontaneous fission of polarized nuclei.

According to the present concepts, an asymmetric deformation occurs in the late stage of the process—after the saddle point has been crossed. If this is in fact the case, then there will of course be no enhancement associated with the dependence of the barrier on the parity of the state.

An interference of states of opposite parity, characterized by an asymmetric deformation, can lead to a nonzero asymmetry in the emission of light fragments if the number of interfering states is not too large.

We know that the fission process goes through a small number of intermediate states—open or nearly open fission "channels"—characterized by certain values of the quantum number K, the projection of the nuclear spin onto the deformation axis. A fission process with only a few channels is indicated, in particular, by an analysis of the angular distribution of the fragments in the fission of aligned nuclei. Just what role fission channels may play in the mechanism for the formation of the P-odd asymmetry in the emission of fragments, however, remains unclear.

d) In 1976, these considerations motivated an experimental search for P-odd asymmetry in the emission of fragments in the fission of ^{235}U nuclei by polarized thermal neutrons in the Institute of Theoretical and Experimental Physics, Moscow.

From the methodological standpoint, this experiment was less complicated than, for example, a study of the asymmetry in the (n,γ), reaction. Because of the particular nature of fission, it is possible to measure both the asymmetry in the emission of the "particle" (the light fragment) and the asymmetry for the "recoil nucleus" (the heavy fragment) in a single experiment. By virtue of the two-particle kinematics, the asymmetry coefficients for the light and heavy fragments should be equal in modulus, within the measurement error, but opposite in sign. This is an important test of the reliability of the experimental results. Furthermore, experiments of this type are almost completely free of background problems and "line" overlap. Together, these favorable factors indicate that there is at least some hope that it will be possible to measure asymmetry in fission, even if its level turns out to be much lower than expected.

3. EXPERIMENTAL DISCOVERY AND STUDY OF ASYMMETRY IN THE EMISSION OF FISSION FRAGMENTS

a) Figure 1 shows the experimental arrangement used for the study of the fission fragment asymmetry in the Institute of Theoretical and Experimental Physics, Moscow.[17] A beam of polarized thermal neutrons was produced by reflection from a magnetized cobalt mirror and had a horizontal dimension of 10 mm and a vertical dimension of 100 mm. The neutron spins were oriented horizontally, normal to the "plane" of the beam. The target was an aluminum foil 0.15 mm thick and 30 mm in diameter, covered with a thin film (100 μg/cm^2) of the oxide of uranium-235. The target was arranged along the median "plane" of the beam. A silicon surface-barrier detector outside the beam detected fragments leaving the target along the polarization direction of the neutron beam. An electronic system selected pulses corresponding to groups of light and heavy fragments and directed them to various counters. Then the polarization direction of the neutron beam was adiabatically reversed, and the detector detected fragments leaving the target in the direction opposite to the polarization direction. The asymmetry coefficient for the light (heavy) fragments was found as the relative difference between the count rates for light (heavy) fragments in the two opposite orientations of the neutron spin.

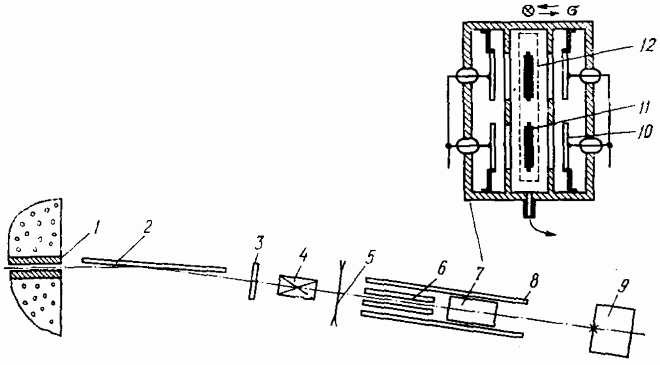

FIG. 1. Experimental arrangement. 1) Neutron collimator in the horizontal reactor channel; 2) magnetized cobalt mirror; 3) iron plate to depolarize the beam; 4) electromagnet to reverse the polarization direction of the neutron beam; 5) current-carrying foil for "joining" the magnetic fields; 6) collimator of the polarized-neutron beam 7) fission chamber; 8) poles of the "spin-guiding magnetic circuit"; 9) device for monitoring the intensity of the neutron beam; 10) silicon surface-barrier detectors for the fragments; 11) target of the fissile material; 12) neutron-beam profile.

[2)] A random fluctuation could lead to a resultant asymmetry a of order N where a_f is the asymmetry for a transition to a definite final state, and N is the number of final states.

In the actual experiment, measures were taken to avoid any instrumental asymmetry; the primary danger was that the fragment count rates for the two opposite opposite polarization directions of the beam were not measured simultaneously.[3] For this purpose, a symmetric apparatus was devised. It had two independent target–detector systems, arranged in a symmetric manner with respect to the neutron beam. The polarization direction was reversed quite frequently, and stochastically, to avoid an asymmetry due to a slow drift of the intensity of the neutron beam or of the characteristics of the electronic equipment. The electronic systems used in detecting the fragments were also switched in a stochastic fashion from cycle to cycle. Measurements with a polarized beam (the degree of polarization of the neutron beam $P_n = 0.84$) were alternated with measurements with a depolarized beam ($P_n = 0.08$).

Round-the-clock measurements over a period of 4 months revealed the following asymmetry coefficient for the emission of light fragments in the fission of ^{236}U:

$$a\,(^{236}\mathrm{U}) = (1.37 \pm 0.35)\cdot 10^{-4}.$$

The asymmetry is arbitrarily assigned a positive sign; it means that the light fragments are emitted preferentially along the direction of the neutron spin.

b) In a second experiment, the same group[18] studied the asymmetry in the fission of ^{239}Pu. The arrangement of the detectors with respect to the target was altered so that a simultaneous study could be made of both the P-odd correlation σp and the P-even correlation $\sigma[\mathbf{p}_n \mathbf{p}]$ ($\mathbf{p}_n$ is the momentum of the neutron), which was possible in principle in the interference of the s and p waves in neutron capture. The latter correlation, if it is large, can, under certain conditions, simulate the asymmetry observed in the experiment just described. As a control, the asymmetry in the fission of ^{235}U was first measured in this new arrangement. The result turned out to be $a(^{236}\mathrm{U}) = (2.5 \pm 1.0)\,10^{-4}$; the contribution of the P-even correlation $\sigma[\mathbf{p}_n \mathbf{p}]$ to the value found in the first experiment for the asymmetry was less than 4%. Measurements with a plutonium hydroxide target yielded

$$a\,(^{240}\mathrm{Pu}) = (-4.8 \pm 0.8)\cdot 10^{-4}.$$

c) In a third study by the same group,[19] the asymmetry in the fission of ^{233}U was examined. Two series of measurements were carried out: one to determine the effect of the P-even correlation (the statistical error was poorer here) and another to measure the P-odd asymmetry in a geometric arrangement analogous to that used in Ref. 17. In this second series of experiments, the asymmetry for the groups of light and heavy fragments was measured separately for the "soft" and "hard" parts of the fragment energy distributions. Figure 2 shows the intervals in these distributions singled out by the differential discriminators. The experimental results are listed in Table I. There is a slight difference between the asymmetry coefficients for the inner parts of the pulse-height distribution (II, III) and the outer parts (I, IV), and this difference can be attributed to a partial overlap of the corresponding peaks. The agreement, within the experimental errors, of the asymmetry coefficients for the "soft" and "hard" parts of the heavy-fragment distribution (I and II) is evidence that no significant monotonic dependence of the asymmetry coefficient on the mass of the heavy fragment is observed.

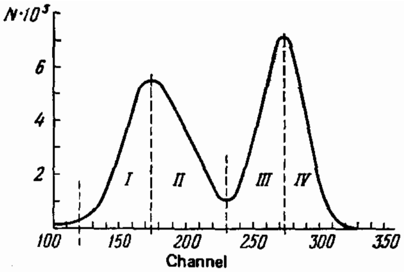

FIG. 2. Pulse-height spectrum of the fission fragments of ^{234}U. The dashed lines separate the intervals selected by the differential discriminators.

The average weighted value of the asymmetry coefficient for ^{234}U turned out to be

$$a\,(^{234}\mathrm{U}) = (2.8 \pm 0.3)\cdot 10^{-4}.$$

The possible effect of a P-even correlation on the measured asymmetry again turned out to be negligibly small in the case of ^{233}U.

d) A more detailed study of the dependence of the asymmetry coefficient on the fragment mass in the fission of ^{233}U was carried out by Petrov *et al*[20]. Their experimental procedure was quite different from that of Ref. 19. The light and heavy fragments, leaving the thin target in opposite directions along the alignment axis of the neutron spins, were detected by two detectors, I and II, which were connected in a coincidence circuit. An Élektronika-100 computer operating online with the experiment calculated the quantity $V_{\mathrm{I}}/(V_{\mathrm{I}} + V_{\mathrm{II}})$ for each fission event; here $V_{\mathrm{I,I}}$ is the height of the pulse from the corresponding detector, which is proportional to the kinetic energy of the fragment reaching the detector. This ratio is a measure of the mass of the fragment detected by detector II.

Figure 3 shows the asymmetry coefficients as a function of the fragment mass. The solid curve is the in-

Table I. Asymmetry coefficients for various intervals in the energy distribution of ^{234}U fission fragments

Beam polarization	Asymmetry $a_j \cdot 10^4$			
	Heavy fragments		Light fragments	
	I	II	III	IV
0.84	−2.07±0.31	−1.85±0.34	1.94±0.32	2.39±0.30
0.08	−0.14±0.35	−0.78±0.31	−0.16±0.35	0.06±0.32

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[3] The requirement that there be no instrumental asymmetry in this experiment is less stringent than in other, similar experiments, since the asymmetry coefficient is determined as the average value of the asymmetry coefficients for light and heavy fragments, and the instrumental asymmetry, which is not related to the individual properties of the groups of light and heavy fragments, is eliminated by the averaging. Nevertheless, it would be desirable to keep this instrumental asymmetry at a level much lower than the asymmetry to be measured.

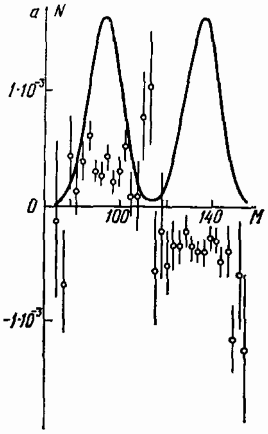

FIG. 3. Dependence of the asymmetry coefficient on the fragment mass in the fission of ^{234}U.

strumental mass spectrum of the fragments. Petrov *et al.* point out that the asymmetry is independent of the fragment mass in the first approximation. The integral asymmetry for the group of light fragments turns out to be

$$a\,(^{234}\mathrm{U}) = (4.8 \pm 0.4)\cdot10^{-4}.$$

e) Lobashov *et al.*[21] measured the asymmetry in the emission of light fragments in the fission of ^{235}U by polarized thermal neutrons by an integral method, which had been developed earlier at the Leningrad Institute of Nuclear Physics to measure the circular polarization of the γ quanta emitted by unpolarized nuclei.[12]

Let us review the idea underlying this method: Instead of counting the particles, measurements are made of the average current which arises in the detector. The temporal characteristics of the detector thus place no limitation on the particle flux arriving at the detector. In their experiments on fission [they also studied the (n, α) reaction in the case of ^{6}Li and ^{10}B nuclei], Lobashov *et al.*, made use of the circumstance that the range of light fragments in a medium is slightly greater than that of the heavy fragments. By thus choosing the appropriate gas pressure in the special fission chamber they were able to achieve that only the light fragments reached the sensitive volume of a counter held at a certain distance from the target. These measurements, carried out in the polarized-neutron beam of the VVR-M reactor of the Leningrad Institute of Nuclear Physics, yielded

$$a\,(^{236}\mathrm{U}) = (0.84 \pm 0.06)\cdot10^{-4}.$$

4. STUDY OF THE ASYMMETRY IN THE EMISSION OF FISSION NEUTRONS

Fission nuetrons are known to be emitted preferentially along the momentum direction of light fragments.[22] Andreev *et al.*[23-25] made use of this circumstance to develop a different, independent method for studying the asymmetry in the emission of light fragments in the fission of ^{239}Pu, ^{235}Pu, and ^{233}Pu. This method has an advantage over direct detection of the fragments in that it permits the use of rather thick targets, so that all the incident neutrons are absorbed; the necessary statistics can thus be acquired in a shorter time. On the other hand, since the method is direct, its sensitivity to the asymmetry of the fragments is of course less than unity, so that the requirements on the stability of the apparatus and the absence of any instrumental asymmetry are much more stringent.

In these experiments, a target of a fissile material which absorbs nearly all the incident neutrons was placed in a beam of polarized thermal neutrons. Fission neutrons were detected by two plastic scintillators; one detected neutrons emitted along the polarization direction of the neutron beam, while the other detected the neutrons emitted in the opposite direction. Lead filters were used to suppress the γ background from the target. The polarization direction of the neutron beam was reversed at a frequency of 8 Hz. Measurements in a polarized beam were alternated with measurements in a depolarized beam. Several control experiments which were carried out showed that the spatial shift of the beam upon the polarization reversal, the oscillation of the beam intensity, and the instrumental instabilities were all within limits such that an asymmetry of less than 10^{-5} could be measured.

Calibration experiments were carried out for a quantitative comparison of the neutron asymmetry with the fragment asymmetry.[18,19] A thick target was replaced by a thin one (0.1 mg/cm^2), and the fission fragments were detected with semiconductor detectors. The coincidences of pulses from the scintillators with pulses from light and heavy fragments were counted for various angles between the fragment emission axis and the direction to the neutron detector. The results were used along with the known asymmetry for the fission neutrons. The results turned out to be $(-4.1\pm0.7)\times10^{-5}$ for ^{240}Pu, $(0.7\pm0.4)\times10^{-5}$ for ^{236}U, and $(4.0\pm0.6)\times10^{-5}$ for ^{234}U. The measurements yielded the following results:

$$a_n\,(^{240}\mathrm{Pu}) = (-6.7 \pm 0.7)\cdot10^{-5},$$
$$a_n\,(^{236}\mathrm{U}) = (0.7 \pm 0.4)\cdot10^{-5},$$
$$a_n\,(^{234}\mathrm{U}) = (4.0 \pm 0.6)\cdot10^{-5}.$$

5. SUMMARY OF RESULTS

Table II lists the results of all the experiments which have been carried out on these three nuclei. The sec-

Table II. Asymmetry coefficients in the fission of ^{234}U, ^{236}U, and ^{240}Pu

Target nucleus	J_i^π	$a\cdot10^4$	Reference
^{233}U	$\frac{5}{2}^+$	2.8±0.3 4.8±0.4 3.7±0.6 *)	19 20 25
^{235}U	$\frac{7}{2}^-$	1.37±0.35 2.5±1.0 **) 0.5±0.3 *) 0.84±0,06	17 18 24 21
^{239}Pu	$\frac{1}{2}^+$	−4.8±0.8 −7.8±0.8 *)	18 23

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*The result of a recalculation of the asymmetry coefficient for the emission of fission neutrons.

**Obtained in a control experiment with low statistics.

ond column gives the spin of the target nucleus. The third gives the experimental asymmetry coefficient, in units of 10^{-4}, corrected for the finite fragment-detection angle and referred to a 100% polarization of the neutron beam. Interestingly, the results obtained by the different groups differ by a factor of 1.5–2 in some cases. Although we cannot rule out a physical reason for these discrepancies (the energy resolution of the apparatus, the solid angle, the neutron spectra, etc.), it is most likely that they are due to some systematic effects which have not been taken into account—different effects for the different installations. At this stage of the research, a discrepancy like this is not of fundamental importance, since the data in this table are not yet good enough to extract a value for the degree of parity violation in fission. The compound states of the fissile nuclei ^{234}U, ^{236}U, and ^{240}U are coherent mixtures of two competing spin states, $J_i \pm 1/2$, for which both the degree of polarization of the nuclei and its relative sign are different. For this reason, the experimental results are not referred to 100% polarization of the nuclei, and the signs of the coefficients of the asymmetry are determined arbitrarily—with respect to the orientation of the neutron spins. Actually, these corrections are not small. If we assume, for example, that the 3^- and 4^- states in ^{236}U do not interfere, the corrected value of the asymmetry coefficient would be about 4×10^{-4}.

To avoid this uncertainty, it is necessary to measure the asymmetry coefficients for isolated neutron resonances. Even in this case, however, additional information on the effects of the various fission channels for the given resonance might be necessary for an unambiguous interpretation of the results. The channels with $K=0$ obviously cannot contribute to the measured asymmetry, so that fission through these channels is essentially a background and must be taken into account.

6. ATTEMPT AT A THEORETICAL INTERPRETATION

A theory for the observed phenomenon must answer two basic questions:

1) What is the mechanism for the formation of a P-odd correlation in fission which has the consequence that the asymmetry coefficients for all light fragments have the same sign?

2) What determines the level of the observed effects?

Flambaum and Sushkov[26] have attempted to answer both these questions. They begin with the assumption that the P-odd asymmetry, like P-even angular distributions, is formed at the stage of a "cold," highly deformed quasisteady state of the nucleus, which determines a fission channel with a fixed value of K (the projection of the total angular momentum J onto the nuclear deformation axis). Since the asymmetry in the fragment masses is apparently formed at the same stage, the nucleus is a pear-shaped top. For a fixed internal state $|a,K\rangle$, the rotational states of the system with $K \neq 0$ split into two levels of opposite parity and approximately equal energy, by analogy with Λ-doubling in molecules:

$$|a,K\rangle^{\eta}_{JM} = \sqrt{\frac{2J+1}{8\pi}}\{D^J_{MK}(\varphi,\theta,0)\,|a,K\rangle + \eta\,(-1)^{J+K} D^J_{M,-K}(\varphi,\theta,0)\,|a,-K\rangle\}, \tag{8}$$

where η is the parity of the state, and $D^J{}_{MK}$ is the rotation matrix. These states, however, are not mixed by the weak interaction, by virtue of the T-invariance of the weak-interaction Hamiltonian H_W. Mixing occurs with the state $|b,K\rangle^{\bar\eta}_{JM}(\bar\eta \equiv -\eta)$, which differs from $|a,K\rangle^{\eta}_{JM}$ by its internal state,

$$|\widetilde{a,K}\rangle^{\eta}_{JM} = |a,K\rangle^{\eta}_{JM} + \sum_b \frac{\langle b,K\,|H_W|\,a,K\rangle}{E_a - E_b}\,|b,K\rangle^{\bar\eta}_{JM}. \tag{9}$$

The states $|a,K\rangle^{\eta}_{JM}$ do not interfere, however, because of the orthogonality with respect to internal variables. For an interference to occur, the system has to be returned from the state $|b\rangle$ to the state $|a\rangle$. Such a transition could be caused by any interaction H_k which violates adiabaticity; that part of the operator H_k which changes the sign of K is important. In summary, the wave function of the state $|a\rangle$ is

$$\begin{gathered} |\widetilde{a,K}\rangle^{\eta}_{JM} = |a,K\rangle^{\eta}_{JM} + \frac{i\eta U_W}{E_\eta - E_{\bar\eta}}\,|a,K\rangle^{\bar\eta}_{JM}, \\ iU_W = -2A(J,K)\sum_b \frac{\langle a,-K\,|H_k|\,b,K\rangle\,\langle b,k\,|H_W|\,a,K\rangle}{E_a - E_b}. \end{gathered} \tag{10}$$

An energy splitting of the states $\bar\eta$ and η is caused by the interaction H_k,

$$E_\eta - E_{\bar\eta} = 2\eta A(J,K)\,\langle a,-K\,|H_k|\,a,K\rangle, \tag{11}$$

so that for a rough estimate of the mixing coefficient $\beta = i\eta U_W/(E_\eta - E_{\bar\eta})$ we can cancel the matrix elements H_k in the numerator and the denominator so that the enhancement will be determined by the difference $E_a - E_b$. If the states $|a\rangle$ and $|b\rangle$ are single-particle states, and $E_a - E_b \simeq 1$ MeV, there will be no important enhancement. Flambaum and Sushkov believe that, first, the distances between the levels in highly elongated nuclei are much smaller than in undeformed nuclei and, second, the states $|a\rangle$ are probably not single-particle states but collective states with $K=1$, by analogy with the low-lying branch of the octupole excitation in symmetrically deformed nuclei.

The angular distribution of the fragments in fission through the channel $|a,K\rangle$ from a state with an energy E, angular momentum J, angular-momentum projection M, and parity η is described by

$$\begin{gathered} w_{JM}(\theta) \sim |D^J_{MK}|^2(1+\gamma) + |D^J_{M,-K}|^2(1-\gamma), \\ \gamma = 2\eta\,\mathrm{Re}\,\frac{iU_W}{E - E_{\bar\eta} + i\Gamma/2}. \end{gathered} \tag{12}$$

When unpolarized nuclei undergo fission by capturing polarized neutrons, we have

$$\begin{gathered} w(\theta) \sim \sum_M |C^{JM}_{IM-\frac{1}{2},\,\frac{1}{2}\,\frac{1}{2}}|^2\, w_{JM}(\theta) \sim 1 + a\cos\theta, \\ a = \frac{\eta U_W \Gamma}{(E - E_{\bar\eta})^2 + \Gamma^2/4}\,\frac{K}{I+\frac{1}{2}}\,(-1)^{J-I-\frac{1}{2}}, \end{gathered} \tag{13}$$

where I is the spin of the target nucleus, and $C^{JM}_{IM-1/2,1/2\,1/2}$ are the Clebsch–Gordan coefficients.

If the fission involves several channels with different values of K, then we would have

$$\bar{a}=\sum_K \omega_K a_K, \tag{14}$$

where ω_K is the probability for fission through a channel with a given K. Unfortunately, because of the uncertainty mentioned above regarding the population of the spin states of the compound nuclei ^{234}U, ^{236}U, and ^{240}Pu, and in the absence of information on the fission channels, we cannot make an unambiguous comparison of the experimental asymmetry coefficient and the predictions of the model. Under certain assumptions which are consistent with the experimental data available, Eq. (13) does give a correct description of the sign correlation and the ratio of the magnitudes of the effects. With regard to absolute values, on the other hand, it is not clear what mechanism will give us the further enhancement, of the order of 10^2, which we need. It should also be noted that if the model in which the mixing of the compound-nucleus states is unimportant is correct, then the agreement of the magnitudes of the effects in (n,f) and (n,γ) reactions must be interpreted as a purely fortuitous result. On the other hand, if we assume that the enhancement mechanisms in these processes are the same and involve the proximity of the compound-nucleus levels, then the agreement of the magnitudes of the effects can be explained well.[27]

7. CONCLUSION

The discovery of the asymmetric emission of fission fragments is undoubtedly opening up new opportunities both for studying the parity-violating weak interaction between nucleons in a nucleus and for studying nuclear fission itself. This research has essentially already begun, and much more work will probably be required before we will be able to describe the observed effects quantitatively as well as qualitatively.

Here are some experiments the results of which, as it seems to us, would cast light on the mechanism for this phenomenon.

a) Study of the P-odd asymmetry in the fission of ^{233}U and ^{235}U by polarized resonance neutrons.

For these nuclei, experimental data are avilable on the anisotropy of the fragment emission for the various neutron resonances; these results have been obtained in measurements with aligned nuclei. In principle, therefore, it would be possible to analyze the contributions of the various fission channels to the asymmetry. Unfortunately, the low flux levels of resonance neutrons rule out measurements of the fission asymmetry over a neutron energy range broad enough for adequate statistics for a large number of resonances.

b) Study of the P-odd effects in the (n,γ) reaction involving fissile nuclei.

If the magnitudes of the effects here are the same as in the fission channel, this result will be a strong argument in favor of a common mechanism for the enhancement in (n,γ) and (n,f) reactions.

c) Study of the asymmetry in the spontaneous fission of polarized nuclei.

As mentioned above, information on the barrier enhancement factor can be obtained from experiments of this type. Analogous data can be found in the tunneling fission of certain nuclei induced by polarized thermal neutrons. In this case, in principle, we might also be seeing evidence of a mixing of states of opposite parity, corresponding to minima I and II of the nuclear deformation energy[28] in the model of a double-humped fission barrier. It would also be interesting to study the asymmetry in the fission of a nucleus from a metastable state (shape isomer).

We should mention again that barrier enhancement may not occur at all if the observed effects in fission are due to a mixture of states of a "cold" nucleus with a deformation corresponding to a second saddle point.

This list of very interesting and in principle feasible experiments on this question could be continued almost indefinitely, but even this short list would require a major experimental effort because of the serious methodological difficulties involved.

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