Violation of P parity in the reaction $^{113}Cd(n,\gamma)^{114}Cd$

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A generalization is made of the results of three experiments carried out at the Institute of Theoretical and Experimental Physics on the asymmetry of 9.0-MeV γ rays in the reaction $^{113}Cd(n,\gamma)^{114}Cd$ in a polarized beam of thermal neutrons. The weighted mean asymmetry without taking into account the background and the admixture of the 8.5-MeV transition is found to be $a=(-3.3\pm0.6)\times10^{-4}$. An estimate of the effect of the admixture gives a result $a=(-4.1\pm0.8)\times10^{-4}$. The results obtained are compared with the data of other published studies in which the same reaction was investigated.

1. INTRODUCTION

In 1964 we first reported[1] observation of a weak nucleon-nucleon interaction in the reaction $^{113}Cd(n, \gamma)^{114}Cd$ in a polarized beam of thermal neutrons. We investigated the asymmetry in emission of γ rays of the 9.0-MeV ground-state transition of ^{114}Cd with respect to the neutron polarization vector.

The angular distribution of γ rays emitted after capture of particles with spin 1/2 cannot contain harmonics of order higher than $2l$, i.e., in the case of capture of s neutrons it should be isotropic. However, in the case where spatial parity is not conserved in nuclear electromagnetic transitions the angular distribution of the γ rays emitted by the nuclei after capture of polarized neutrons has the form

$$W(\theta)=\text{const}(1+P_n a\cos\theta), \quad (1)$$

where P_n is the degree of polarization of the neutrons, a is the asymmetry coefficient desired, and θ is the angle between the direction of polarization of the neutron beam and the momentum of the γ ray. In this case the asymmetry coefficient is

$$a=2ARF. \quad (2)$$

The coefficient F in this expression is a dimensionless parameter characterizing the relative strength of the weak nucleon-nucleon interaction which does not conserve spatial parity. In order of magnitude $F \approx 10^{-6}-10^{-7}$ (ref. 2). The factor R does not depend on the weak interaction of the nucleons. If $R > 1$, this quantity is called the enhancement coefficient of the effect. The various enhancement mechanisms have been discussed by Shapiro.[3] He has shown, in particular, that for the cadmium nucleus being considered the factor R can reach a value of $\sim10^3$. Unfortunately, the enhancement coefficient cannot be calculated accurately for complex nuclei, and therefore the mixing amplitude can be evaluated from asymmetry measurements only in order of magnitude. Finally, the coefficient A in Eq. (2) is determined by the spins of the nuclear states and the multipolarity of the transition. A general expression for A is given by Lobov.[4]

In practice the asymmetry is measured for γ-ray emission in and opposite to the direction of polarization of the neutron beam. In this case Eq. (1) takes the form

$$N^{\pm}=\text{const}(1\pm aP_n\Omega), \quad (3)$$

where $N^{\pm}$ are the numbers of counts in the detector for γ-ray momenta parallel and antiparallel to the neutron spin; Ω is a geometrical factor taking into account the finite size of the detector and target. By calculating the difference or ratio of the counting rates N^+ and N^-, we can determine the value of the coefficient a. The asymmetry value obtained in experiments in a polarized neutron beam must be corrected for the instrumental asymmetry determined in an experiment in an unpolarized neutron beam. An experiment of this type was first carried out in 1959 by Adair and co-workers.[5]

2. DESCRIPTION OF THE ITEP EXPERIMENTS

In all three of the ITEP experiments[1,6,7] polarized neutron beams were obtained in the horizontal channel of the ITEP reactor by reflection from magnetized cobalt mirrors. The beam of polarized neutrons passed through a series of collimators and magnets and hit a cadmium target 0.4 mm thick. Gamma rays leaving the target were detected by two identical scintillation spectrometers with NaI(Tl) crystals 70 mm in diameter and 100 mm thick with a resolution of 11–12% for the ^{137}Cs line with E_γ = 660 keV. The entire apparatus was separated from the reactor room by a thick concrete wall. Neutrons scattered in the target were absorbed either by a layer of pressed lithium carbonate enriched in ^6Li or by a layer of pressed boron carbide. The photomultipliers and crystals were shielded from the magnetic fields by several shields of steel and Permalloy and were covered by a layer of lead at least 70 mm thick. All of the experiments recorded the same γ-ray energy interval corresponding to the 9.0-MeV transition and covering 8.5–9.5 MeV. In our first report[1] we erroneously gave a different energy interval. An energy calibration of the spectrometers was carried out every day on the basis of the peaks in the γ spectrum from the reactions $^{56}Fe(n, \gamma)^{57}Fe$ or $^{58}Ni(n, \gamma)^{59}Ni$, and in the last experiment also from the cadmium spectrum studied.

Special attention was given to avoiding the pileup of γ-ray pulses, which could result in appearance of pulses from lower-energy γ rays in the energy interval studied and, consequently, in the distortion of the effect being investigated. Aluminum absorbers 85 mm thick were used in front of the detectors in order to reduce the soft γ-ray counting rate. In addition, in order to reduce the pileup of pulses it was necessary in the second and third experiments to reduce the neutron beam intensity to 10^7 sec^{-1} by means of diaphragms. For the same reason the electrical pulse from the photomultiplier was shaped to a length of 0.25 μsec.

The electronic equipment was substantially different in all of the experiments, both in the arrangement of the block diagram and in the nature of the individual elements. The main difficulty in experiments of this type is in avoiding the instrumental asymmetry arising as the result of unstable operation of the electronics or as the result of instability in the neutron beam intensity. Different means were employed for this purpose in the three experiments.

In the first experiment we made a rapid comparison of the effects in polarized and unpolarized neutron beams. For this purpose we placed in the neutron beam path a rotating depolarizer in the form of circle in which two opposite quadrants were covered with an iron foil and the two others were left open. Twenty times per second the neutron beam was covered by a foil and thus completely depolarized. Differential discriminators were used to separate the required energy region from the pulse-height spectrum. The separated pulses were then sent by means of an electronic switch alternately to scaling circuits corresponding to the two states of the neutron beam. To avoid instrumental asymmetry, every twenty minutes the direction of the neutron spin relative to the direction of the constant magnetic field in the target region was reversed.

In the second and third experiments we made a rapid comparison of the effects for opposite directions of the neutron spins. For this purpose a special device [8] was used to change the direction of polarization of the neutron beam ten times per second with a constant magnetic field direction in the target region. As in the first experiment, the energy range required was separated and then the pulses were sent by an electronic switch to scaling circuits corresponding to the two directions of polarization of the neutron beam. Measurements in polarized and depolarized beams were alternated every twenty minutes. The experiment in the depolarized beam permitted determination of the instrumental asymmetry. By combining the results obtained in the polarized and depolarized neutron beams, we obtained the desired asymmetry value.

In the first two experiments we determined the asymmetry from the ratio of the numbers of counts obtained in the two channels with different beam polarization states. The ratios were obtained in such a way that the effect of inequality in the time intervals corresponding to two consecutive beam polarization states was avoided. In the third experiment the asymmetry was calculated as the relative difference in the counting rates for the two directions of neutron beam polarization and the measurement time intervals were identical within an accuracy assuring a negligible instrumental asymmetry.

In addition to the three experiments we carried out a large number of control experiments. Among these was an experiment in polarized neutrons with detection of ^{114}Cd γ rays in another energy interval where there should be no effect as a result of the fact that this interval received contributions from many transitions and we would not expect that the asymmetry of all the transitions would have the same sign. In the first experiment this interval was 4.1–5.5 MeV, and in the second experiment 6.8–7.8 MeV, and both control experiments were carried out in the time intervals between the main experiments. In the third experiment the control experiment in the γ-ray energy interval 6.3–8.5 MeV proceeded in parallel with the main experiments. Control experiments were also made with nuclei in which P-odd effects should not exist: these were experiments with targets of samarium, titanium, lead, and graphite. The experiments with titanium and lead check that the apparatus is insensitive to circular polarization of γ rays, since the circular polarization of the selected γ rays is equal to the circular polarization of ^{114}Cd γ rays with $E_\gamma = 9.0$ MeV.

The experiment with graphite checks that the apparatus is insensitive to the effects of neutron scattering in the target. The asymmetry of the apparatus was also measured without a target.

In the first and third experiments we carried out a control experiment with a vertical direction of the neutron spins, in contrast to the main experiments in which the neutron spins were directed horizontally. This experiment checks the absence of asymmetry due to the existence in the γ-ray angular distribution of correlations of the type

$$\sigma[\mathbf{p}_n\mathbf{p}_\gamma], \tag{4}$$

where σ is the neutron polarization vector, and $\mathbf{p}_n$ and $\mathbf{p}_\gamma$ are the neutron and γ-ray momenta. Such a correlation can arise if there is an appreciable admixture of p neutrons in the beam. Although this term in our case is zero for an ideal geometry, the departure of the real geometry from ideal can lead to its appearance. The control experiment was carried out in such a geometry that the term defined by Eq. (4) was maximal.

A daily check was made of the correct operation of the switches and scaling circuits. For this purpose a signal from one of the channels was fed to the inputs of both switches and it was required that the scaling circuit readings corresponding to the same spin direction be the same within an accuracy of 10^{-5}. In the first two experiments, no asymmetry was observed in the control experiments within the experimental accuracy. In our last experiment the accuracy of the control experiments was substantially increased. The weighted mean asymmetry value obtained on averaging the results of all the control experiments turned out to be different from zero: $a_{\text{instr}} = (-0.5 \pm 0.2) \times 10^{-4}$. Averaging of the results of the control experiments, which were carried out at different times and under different conditions, gives only an estimate of the possible value of the instrumental asymmetry.

The results of all the control experiments permit us to state that the asymmetry effect observed in the main experiments is due to the angular asymmetry of 9.0-MeV ^{114}Cd γ rays emitted after capture of polarized neutrons.

3. EXPERIMENTAL RESULTS AND THEIR COMPARISON

In the first ITEP experiment we obtained [1] the result:

$$a=(-3.7\pm0.9)\cdot10^{-4}. \tag{5}$$

In this result we have taken into account the instrumental asymmetry, since the results in the depolarized beam are included in it. In the second ITEP experiment [6] the asymmetry in the polarized beam turned out to be

$$a_{\text{pol}}=(-3.5\pm0.8)\cdot10^{-4}$$

and in the depolarized beam it was

$$a_{\text{depol}}=(+0.7\pm0.8)\cdot10^{-4}.$$

Since the instrumental asymmetry was measured with the same accuracy as the effect, and the signs of the asymmetry turned out to be different, we took into account in the final result only the error in measurement of the instrumental asymmetry, representing it in the form

$$a=(-3.5\pm1.2)\cdot10^{-4}. \tag{6}$$

For comparison of the results of the three experiments we must subtract the instrumental asymmetry from the effect in the polarized beam. As a result we obtain

$$a=(-4.2\pm1.2)\cdot10^{-4}. \tag{7}$$

Finally, in the third ITEP experiment[7] we obtained:

$$a=(-2.5\pm0.9)\cdot10^{-4}. \tag{8}$$

The weighted mean asymmetry in all three ITEP experiments, which are in good agreement with each other, is found to be

$$a=(-3.3\pm0.6)\cdot10^{-4}. \tag{9}$$

Thus, the ITEP results on the γ-ray asymmetry in the reaction $^{113}Cd(n, \gamma)^{114}Cd$ undoubtedly indicate nonconservation of spatial parity in the electromagnetic transition $1^+ \to 0^+$ with energy 9.0 MeV in ^{114}Cd.

However, the effect has not been observed in several similar experiments of other groups of investigators. A summary of all published results is given in the table in chronological order. In the work of Eichler and Heine[9] the effect turned out to be close to zero. They made an asymmetry measurement in the γ-ray energy interval beginning at 8.1 MeV, and the γ-ray detector was a NaI(Tl) crystal. This is evidently the reason for the absence of the effect in their work. The point is that in this expanded energy interval there are γ rays with energy 8.5 MeV corresponding to the transition from the upper 1^+ level to the first excited 2^+ state. This transition also is an M1 transition (an E2 admixture is possible). Consequently, the E1 transition is also an irregular transition, as in the case of the ground-state transition with energy 9.0 MeV.

However, the spin coefficient for the transition with E = 8.5 MeV is A = −0.5 (for a pure M1 transition), i.e., opposite in sign to the spin coefficient of the transition with E = 9.0 MeV, which is A = +1. The intensity of the softer transition is higher by a factor of two. These two transitions give asymmetries of opposite signs. If measures are not taken to provide good energy separation of the two transitions, the measured asymmetry will naturally be reduced.

Warming[10] used a germanium detector and therefore even for the energy range chosen, as the author points out, the admixture of the 8.5-MeV transition amounted to only 5%. The result obtained is consistent with our data. The agreement will be more satisfactory if allowance is made for the effect of the background in Warming's work, which apparently was not completely done by the author.

In the energy interval 8.5—9.5 MeV chosen in the ITEP experiments, with a NaI(Tl) crystal resolution of the order of 12%, there is some contribution from the 8.5-MeV γ rays, which reduces the asymmetry. We estimate the contribution from this transition to be ~15%. In addition, the background due to pileup of pulses from γ rays with energies less than 8.5 MeV and the background of unrelated γ rays also reduce the asymmetry. The contribution of the two sources of background is estimated as ~5%.

TABLE I. Results of experiments on measurement of the asymmetry of 9.0-MeV γ rays in ^{114}Cd following capture of thermal polarized neutrons

Institute	Year	γ-ray energy interval, MeV	Asymmetry coefficient, $a \times 10^4$	Source
Brookhaven	1959	8.3—9.3	1.2±7.8	[5]
ITEP, Moscow	1964	8.5—9.5 *	−3.7±0.9	[1]
Risø, Denmark	1967	8.8—9.5	−2.5±2.2	[18]
ITEP, Moscow	1968	8.5—9.5	−3.5±1.2	[6]
Risø, Denmark	1969	8.0—9.2	−0.6±1.8	[10]
Karlsruhe	1969	8.1—9.5	1.2±1.2	[9]
ITEP, Moscow	1972	8.5—9.5	−2.5±0.9	[7]

*In our published article [1] the γ-ray energy interval is erroneously given as 8.1—9.4 MeV.

To a first approximation we can assume that 20% of the total intensity of the detected γ rays is background which does not contribute to the asymmetry. Then the corrected asymmetry value is found from the equation $a_{corr} = a/(1 - \alpha)$. Setting $\alpha = 0.2$, we obtain as the corrected average value of the asymmetry coefficients for the ITEP experiments

$$a_{corr}=(-4.1\pm0.8)^{-4}. \tag{10}$$

This value must be compared with the circular polarization of γ rays with energy greater than 8 MeV in the same reaction $^{113}Cd(n, \gamma)^{114}Cd$ in unpolarized neutrons, recently measured by Alberi et al.[11]

The circular polarization for unmixed transitions is determined by the equation

$$P_\gamma=2RF \tag{11}$$

and differs from the asymmetry coefficient defined by Eq. (2) in the absence of the factor A. As can be seen from this expression, the sign of the circular polarization does not depend on the spin factor A and is the same for the two transitions with E_γ = 8.5 MeV and E_γ = 9.0 MeV. Consequently, energy separation of these transitions in this case is not essential.

The circular polarization measured by Alberi et al.[11] turned out to be

$$P_\gamma=(-6\pm1.5)\cdot10^{-4} \tag{12}$$

and is in good agreement with Eq. (10). The sign of the value given in Eq. (12) was established subsequently.[12] It follows from what has been said that parity is not conserved in the 9.0-MeV γ transition in ^{114}Cd.

4. CONCLUSION

Using an enhancement coefficient of 10^3 for ^{114}Cd and the corrected average asymmetry coefficient from the ITEP experiments (10), we obtain an experimental estimate of the parameter $F \approx 2 \times 10^{-7}$. This result is in good agreement with the theoretical estimates.[2,13]

The existence of the weak nucleon-nucleon interaction which does not conserve parity and the estimate of the value of F are also confirmed by other experiments.

A large effect was observed[14] in an experiment on the γ-ray asymmetry from ^{180}Hf nuclei polarized by a low-temperature method. A large number of experiments on measurement of the circular polarization of γ radiation arising in decay of unpolarized nuclei, beginning with the experiments of Lobashov and co-workers[15], also show quite reliable effects (see the review by Henley[13]). Circular polarization of γ rays was recently found in the reaction $n + p \to d + \gamma$.[16] Finally, the appearance of a weak nucleon-nucleon interaction[17] has also been found in a class of experiments searching for violation of absolute selection rules in parity.

Thus, at the present time the existence of a weak nucleon-nucleon interaction predicted by the hypothesis of a universal weak interaction can be considered proven.

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179