Search for parity-violation effects in the total neutron cross section of uranium-233 nuclei

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The weak polarization which a beam of thermal neutrons acquires as a result of parity violation in the total neutron cross section has been measured. The parity violation stems from the dependence of the cross section on the helicity of the incident neutrons in an interaction with uranium-233 nuclei. The asymmetry found in the total cross section by this procedure, $(-0.9 \pm 1.1) \times 10^{-7}$, does not support the theoretical predictions of this quantity. A way to interpret the experimental data in terms of known resonances is pointed out.

Measurements of the *P*-odd asymmetry of the expansion of the fission fragments of uranium-233 at various energies of polarized neutrons have revealed that the asymmetry changes sign near a neutron resonance at[1] 0.17 eV. In accordance with the study by Bunakov and Gudkov,[2] the resonance at 0.17 eV has been identified as a *p*-wave resonance, and the magnitude of the weak nucleon-nucleus matrix element has been estimated. An estimate of the *P*-odd asymmetry in the total cross section for the neutron-nucleus interaction on the basis of these results and the equations of the two-level approximation[2,3] for thermal-energy neutrons has yielded an asymmetry of about 5×10^{-5}.

An experimental test of this estimate has shown[4,5] that the asymmetry is less than 1.4×10^{-6}.

Sushkov and Flambaum[6] have carried out a more accurate analysis of the *P*-even and *P*-odd asymmetries which arise in the interaction of neutrons with uranium-233 nuclei. For thermal neutrons they predicted an asymmetry of about 5×10^{-7} in the total cross section. Sushkov and Flambaum explained the results of Refs. 1, 4, and 5 in terms of the existence of a very weak *p* resonance in the neutron cross section at a neutron energy of 0.2–0.4 eV, with a width on the order of 10^{-11} eV. The resonance at 0.17 eV was interpreted as a weak *s*-wave resonance. A similar interpretation was offered by Rzhevskiĭ.[7]

A subsequent search[8–11] for a *P*-odd asymmetry in the total cross section near the resonance at 0.17 eV for uranium-233 has yielded only an upper limit on this asymmetry: $\mathscr{P} = (\sigma^+ - \sigma^-)/(\sigma^+ + \sigma^-) = (3.0 \pm 2.6) \times 10^{-6}$ for the neutron energy interval 0.12–0.23 eV (Ref. 10).

The *P*-odd asymmetry was measured in the total neutron cross section for uranium-233 in the thermal neutron region by determining the weak polarization of neutrons produced as a result of the parity-violating neutron-optical dichroism of the target. A wide-aperture polarimeter was used in the measurements.[12]

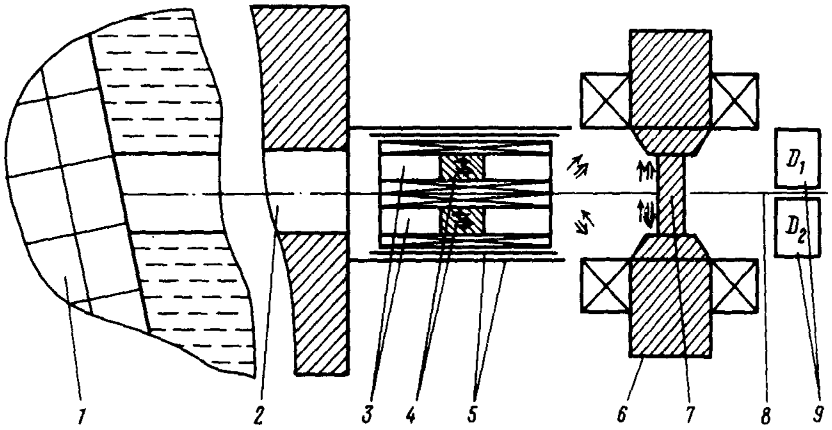

FIG. 1. Layout of the apparatus used for measuring the neutron polarization which arises from the P-odd dichroism of the test sample. 1—Reactor core; 2—horizontal experiment channel; 3—solenoids; 4—test samples; 5—magnetic shields; 6—analyzer magnet; 7—analyzer, and iron plate; 8—cadmium barrier; 9—neutron detectors. The thin arrows show the direction of the magnetic field, and the double arrows the direction of the neutron spins.

We have carried out an experiment using the direct beam from the core of the IR8 reactor at the Kurchatov Institute of Atomic Energy in Moscow. The flux density of thermal neutrons at the edge of the biological shielding of the reactor was 3×10^9 $\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$. The experimental layout is shown in Fig. 1. Two identical test samples (Fig. 1) are placed in identical solenoids, one of which produces a field which is directed along the momentum of the neutron, while the field of the other solenoid is directed opposite the neutron momentum. In the gap between the solenoids and an analyzer, the neutron spins are adiabatically flipped from a longitudinal polarization to a transverse polarization, so that the beams from the two solenoids pass through the polarimeter with the opposite polarizations, $P = \mathscr{P} l$. The neutron beams are then detected by two separate detectors (l is the thickness of the samples, expressed in units of the neutron mean free path).

To eliminate fluctuations in the reactor power, we used an integral-compensation measurement method. The difference current from the two detectors was proportional to twice the P-odd effect at each detector: $2P_n P_A$, where P_A is the analyzing power of the polarimeter. The fluctuations in the reactor power in it were suppressed to the level of the statistical fluctuations of the neutron fluxes.

As the neutron detectors we used a set of standard SNM-17 counters, with a detection efficiency of about 90%. Samples of a mixture of the lower and higher oxides of uranium-233, each with a mass of 20 g, were packed in hermetically sealed containers with a cross sectional area of 35×45 mm^2. The thickness of each sample was measured and found to be 1.83 neutron mean free paths. As the polarimeter we used saturation-magnetization iron. The analyzing power P_A, measured by a single-pass method, was[12] 0.36 ± 0.02.

The voltage caused by the difference current from the detectors across a load resistance, averaged over 1 s, was measured with a highly stable V7-18 voltmeter on line with an E-60 computer and stored as the quantity U_i^+. The fields of the solenoids were then reversed, and we measured the corresponding voltage U_i^-. We found the average polarization of the neutron beam over the total measurement time, P_n, from

$$P_n = \frac{\overset{N}{\Sigma} (U_i^+ - U_i^-)}{4P_A NU}, \tag{1}$$

where N is the total number of measurements, and U is the voltage caused by the current of one of the detectors. In order to eliminate (in the linear approximation) the error caused by a possible zero drift,[13] we reversed the fields of the solenoids (or, equivalently, we reversed the neutron spins) in the pattern $+ - - +$, $- + + -$, $- + + -$, $+ - - +$, etc. To eliminate the effect of possible stray electrical pickup, we mechanically switched the solenoid fields (or, equivalently, we reversed the magnetic fields at the targets) over the course of a day.[5]

To calibrate and test the sensitivity of the apparatus as a whole, we measured the weak polarization of a neutron beam as it emerged from a KBr target with a thickness of either 1.74 or 0.083 of a neutron mean free path (Table I). The instrumental asymmetry was measured with the help of a neutron beam blocked by a thick (1-mm) cadmium plate, i.e., for neutrons with an energy above 0.5 eV for which the analyzing power of saturated iron is essentially zero.

TABLE I. Results of measurements of the weak polarization acquired by a neutron beam as a result of a weak interaction of neutrons with ^{233}U nuclei and KBr, along with the corresponding asymmetry of the total neutron cross section. The instrumental zero was measured with neutrons with an energy above 0.5 eV.

Sample	$n\sigma$	$P \cdot 10^7$	$\mathcal{P} \cdot 10^7$
KBr	1,74	174 ± 7	100 ± 4
KBr	0.083	10,8 ± 1,2	130 ± 15
series 1			
^{233}U + "0"	1,83	4.99 ± 2,69	2,73 ± 1,47
"0"	1,83	8,67 ± 1,26	4,74 ± 0,69
^{233}U		−3,68 ± 2,96	− 2,01 ± 1,62
series 2			
^{233}U + "0"	1,83	1,06 ± 2,16	0,58 ± 1,18
"0"	1,83	0,89 ± 1,66	0,49 ± 0,97
^{233}U		0,16 ± 2,73	0,09 ± 1,49
average pure ^{233}U			− 0.9 ± 1,1

The results of the measurements and of a conversion of the polarization of the neutron beam into an asymmetry of the total cross section, $\mathscr{P} = (\sigma^+ - \sigma^-)/(\sigma^+ + \sigma^-)$, are shown in Table I. Two series of measurements were carried out for uranium-233. The instrumental asymmetry of the *P*-odd nature found in the first series turned out to be a consequence of an asymmetry of stray pickup, which depended on the sign of the currents in the solenoids; this instrumental asymmetry was eliminated in the subsequent measurements. The final result of the two series of measurements is

$$(^{233}\mathrm{U}) = (-0.9 \pm 1.1)\times 10^{-7} ,$$

which does not support the predictions of Sushkov and Flambaum.[6]

Using an estimate of the weak-interaction matrix element from Ref. 1, $\langle p|H_w|s\rangle = 3\times 10^{-4}$, along with our limitations on $\mathscr{P} \leqslant 2\times 10^{-7}$ and typical values of the parameters of the resonances from Ref. 14, we find $\Gamma^n_{p_{1/2}} \leqslant 3\times 10^{-13}$ eV from the expression[2,3,6] for $\mathscr{P}$. In (10) and (12) of Ref. 6 we should therefore ignore terms containing the amplitudes $V_{J-k}(1/2)$. The ternary correlation for the *p*-wave resonance with $J^\pi = 2^-$ then becomes

$$a^{rl} = \frac{\operatorname{Im}\left\{V^*_{2^-1}\left(\frac{3}{2}\right)[0.5V_{3^+1} - 0.625]\right\}}{|V_{2^+0}|^2 + |V_{2^+1}|^2 + |V_{3^+1}|^2} \tag{2}$$

and that for the 3^- resonance becomes

$$a^{rl} = \frac{\operatorname{Im}\left\{-0.9V^*_{3^-0}\left(\frac{3}{2}\right)V_{2^+0} - V^*_{3^-1}\left(\frac{3}{2}\right)(0.85V_{2^+1} + 0.38V_{3^+1})\right\}}{|V_{2^+0}|^2 + |V_{2^+1}|^2 + |V_{3^+1}|^2} . \tag{3}$$

Here $V_{J^-k}(3/2)$ is the amplitude for a fission event accompanied by the capture of *p*-wave neutrons with angular momentum $j = l + s = 3/2$, and V_{J^+k} are the amplitudes for fission accompanied by the capture of *s*-wave neutrons, summed over all resonances with the quantum numbers J^+k. From these expressions we find the magnitude of the ternary correlation, which agrees with the experimental value of 2×10^{-3} if the necessary cancellation occurs among the 2^+ 0, 2^+ 1, and 3^+ 1 amplitudes. For example, the resonance with an energy of 0.17 eV might be interpreted as a *p*-wave resonance with $2g\Gamma^n_{p^{3/2}} = 2\times 10^{-7}$ eV if the first neutron resonances[14] for ^{233}U have the following quantum numbers:

E_n (eV)	−2.81	0.17	1.55	1.79	2.29	3.66	4.76	5.89	6.42	6.82	9.26	9.28
J^+k	2^+ 0	2^-1	3^+ 1	2^+ 1	3^+ 1	3^+ 1	2^+ 1	3^+1	2^+ 1	2^+1	3^+ 1	2^+ 1 .

The value of a^{rl}, 1.7×10^{-3}, agrees well with experimental data. The validity of this interpretation of the 0.17-eV resonance requires further study.

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