Search for an electric dipole moment of the neutron

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A *CP*-breaking effect of an electric dipole moment of the neutron has been measured by a method of prolonged confinement of ultracold neutrons. The measured value, $d_n = -(1.4 \pm 0.6) \times 10^{-25}$ e·cm, is interpreted as a new upper limit: $|d_n| < 2.6 \times 10^{-25}$ e·cm at a 95% confidence level.

In this letter we report the results of new experiments in a search for an electric dipole moment of the neutron. The experiments were carried out with ultracold neutrons at the VVR-M reactor at the B. P. Konstantinov Leningrad Institute of Nuclear Physics.

Earlier experiments[1,2] had used a magnetic-resonance spectrometer of the so-called continuous-flow type with confinement of the ultracold neutrons for an average time on the order of 5 s. Two chambers were used to confine neutrons with oppositely directed electric fields (this is a differential method for measuring the electric dipole moment).

The results of those measurements yielded a value $d_n = -(2 \pm 1) \times 10^{-25}$ e·cm for the electric dipole moment of the neutron. This result was interpreted as a limitation on the magnitude of the dipole moment: $|d_n| < 4 \times 10^{-25}$ e·cm at a 95% confidence level.

It appeared to be difficult to achieve any further improvement in the sensitivity in the continuous-flow version of the spectrometer, so a modification was developed with prolonged confinement of ultracold neutrons in a closed chamber. In recent experiments by a group from the Laue-Langevin Institute (Grenoble), a confinement time on the order of 80 s was achieved in a storage version with a single chamber, and the result $d_n = (0.3 \pm 4.8) \times 10^{-25}$ e·cm was achieved.[3]

In the present experiments we have gone back to the differential method, using two neutron-confinement chambers with oppositely directed electric fields (Fig. 1)

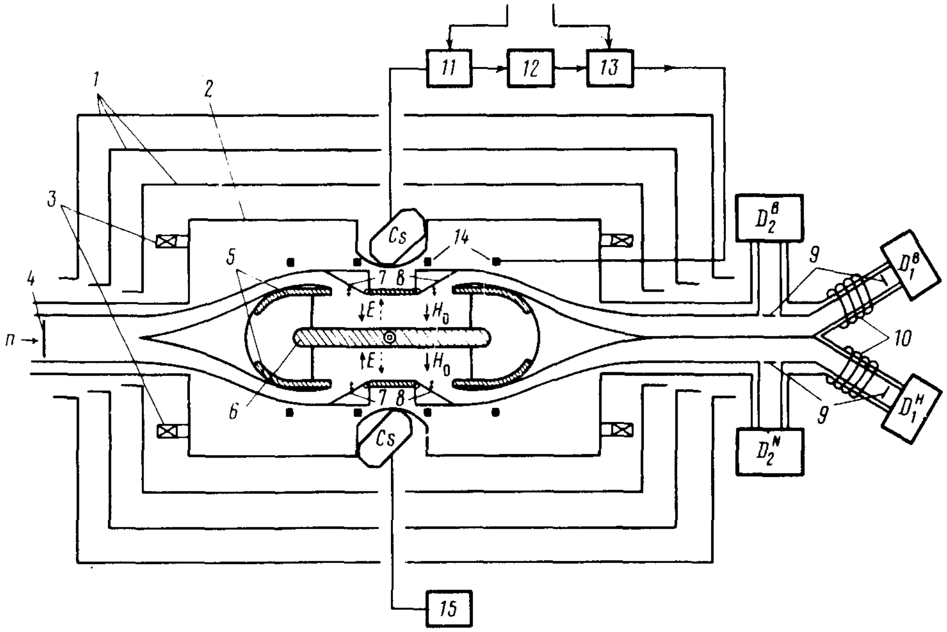

FIG. 1. The magnetic-resonance spectrometer for ultracold neutrons for measuring the electric dipole moment of the neutron. 1—Magnetic shields; 2—vacuum chambers; 3—Helmholtz coils for producing a static magnetic field H_0; 4—polarizer of the ultracold neutrons; 5—grounded electrodes; 6—high-voltage electrode; 7—entrance shutters; 8—exit shutters; 9—analyzers; 10—rf flipper; 11—computer-controlled Cs magnetometer; 12—frequency divider; 13—computer-controlled unit for producing the rf pulses; 14—coils for producing an oscillating field; 15—Cs magnetometer; *D*—ultracold-neutron detectors ("*U*" and "*L*" specify the upper and lower chambers; 1 and 2 specify opposite polarizations of the ultracold neutrons).

and with common static magnetic and rf fields. This approach has made it possible to cancel the fluctuations in the magnetic field and to monitor possible systematic errors. The chamber is designed in such a way that the high-voltage electrode which separates the chambers is between two grounded electrodes (caps), which in a sense form a grounded screen around the high-voltage electrode. The average electric field is $\pm (12 - 15)$ kV/cm at leakage currents below 30 nA. The chamber walls are quartz rings on which films of BeO and Be_3N_2 have been deposited. A system of shutters in the entrance and exit neutron ducts can be opened and closed in a time ~ 0.3 s. As in the earlier measurements,[1,2] we use a system for simultaneously detecting ultracold neutrons polarized in opposite directions.

Since the three-layer shield of the Permalloy type used by us does not ensure the stability of the magnetic field which would be required for a confinement time of 50–100 s, the position of the resonance is stabilized by means of self-generating cesium quantum magnetometers, positioned above and below the neutron confinement chamber. Since the ratio of the resonant frequency of the cesium magnetometers to the frequency of the neutron resonance is 119.9—approximately 120—we developed a stabilization system in which the frequency of one magnetometer or the average frequency of two magnetometers is divided by 120. The signal is sent from the divider to an rf coil wound around the neutron confinement chamber.[4] This system makes it possible to maintain resonance conditions with a stability corresponding to a magnetic-field stability better than 2×10^{12} T over 5–10 min. The effective stabilization factor in the single-channel version is ~ 7, and that in the two-channel version is ~ 15.

A further suppression of the fluctuations in the resonance conditions is achieved by virtue of the differential measurement method, so that the difference between the mean square scatter and the statistical scatter is no more than 5–10%.

In the early measurements, the source of ultracold neutrons was a liquid-hydrogen converter in a beryllium reflector.[5] In the bulk of the measurements we used a new, universal source of cold and ultracold neutrons.[6]

The three- or fourfold increase in the intensity of the ultracold neutrons from the new source, combined with the confinement system of the spectrometer which was developed, with an ultracold-neutron confinement time ~ 50 s, made it possible to achieve a maximum sensitivity $\sim (2.5\text{–}2.7) \times 10^{-25}$ e·cm per day in the measurement of the electric dipole moment.

The measurement cycle includes filling the chamber with ultracold neutrons (30 s), confinement (50–55 s), and the discharge and counting of the ultracold neutrons (30 s). Radio-frequency signals 1.2 s long are applied at the beginning and end of the confinement time. The polarity of the electric field is switched in a 40-s interval between measurement cycles. Otherwise, the measurement conditions are similar to those in Ref. 1.

For each detector we calculate the magnitude of the electric dipole moment, $d^{\mu,L}_{1,2}$. The "U" and "L" and the 1 and 2 match the notation used in Fig. 1.

The results of the measurements for the four detectors are used to form the following combinations, by analogy with Ref. 1:

$$d_n = \frac{1}{4} \left[(d_1^U + d_2^U) + (d_1^L + d_2^L) \right]$$

$$R = \frac{1}{4} \left[(d_1^U + d_2^U) - (d_1^L + d_2^L) \right]$$

$$P = \frac{1}{4} \left[(d_1^U - d_2^U) - (d_1^L - d_2^L) \right]$$

$$C = \frac{1}{4} \left[(d_1^U - d_2^U) + (d_1^L - d_2^L) \right]$$

The quantity d_n determines the effect which is being sought: the electric dipole moment of the neutron. The quantity R determines the synchronous displacement of the neutron resonance in the two chambers; P serves as a measure of the effect of the switching of the high voltage on the counting systems; and C is a measure of how well these systematic and random factors are canceled out.

Table I summarizes the results of the various measurements of the electric dipole moment, including the results of Refs. 1 and 2 with a continuous-flow system. We see that the results found on the electric dipole moment by the continuous-flow method and those found by the confinement method agree well. In some series of measurements, the value of R is extremely large, but the accuracy with which the synchronous effects for the two chambers have been canceled—estimated from an analysis of individual measurements with a large value of R—yields a factor ~ 0.05. In other words, the possible contribution is, on the average, smaller than 0.3×10^{-25} e·cm.

According to our estimates, other possible systematic effects are inconsequential. For example, the contribution of the effect of a deviation of the electric and magnetic fields from a parallel alignment and the effect of leakage currents $\langle$at $1 < 30$ nA$)$ do not exceed 10^{-26} e·cm.

The overall result of the measurements is therefore

$$d_n = -(1.4 \pm 0.6) \times 10^{-25} \text{ e} \cdot \text{cm}.$$

Although the value found for the electric dipole moment differs slightly from zero, we cannot draw the conclusion that the existence of a nonzero electric dipole moment, determined by the magnitude of this error, is a certainty, particularly in view of the fundamental importance of this phenomenon. Accordingly, the most natural interpretation of this result is that it gives us a new upper limit

$$|d_n| < 2.6 \times 10^{-25} \text{ e·cm (95\% confidence level).}$$

This result definitely contradicts the estimates of the electric dipole moment based on the Weinberg model, e.g., $d_n = -9 \times 10^{-25}$ e·cm (Ref. 7) or $d_n \sim 10^{-22}$ e·cm (Ref. 8). Limitations on the parameters which can be used can be extracted from several other models.

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Table I. Results of the measurements of the electric dipole moment (EDM) of the neutron (in units of 10^{-25} e·cm).

Measurement conditions	EDM	Effect of magnetic field	Effect of transients	Cancellation effect
	$d_n\left(\frac{\text{S.D.}}{\text{stat}}\right)$	R (S.D.)	P (S.D.)	C (S.D.)
Continuous-flow spectrometer	$2{,}1\left(\frac{2{,}4}{2{,}4}\right)$	16,6 (4,8)	5,3 (3,5)	4,8 (2,4)
	$-1{,}0\left(\frac{2{,}8}{2{,}7}\right)$	1,5 (5,8)	− 5,0 (4,1)	− 2,6 (2,7)
	$-3{,}4\left(\frac{1{,}3}{1{,}3}\right)$	1,1 (2,8)	0,4 (2,2)	− 3,6 (1,3)
Average	− 2,0 (1,0)	4,5 (2,2)	0,6 (1,7)	− 1,8 (1,0)
Storage spectrometer				
Source of ultracold neutrons in beryllium reflector; single-channel stabilization of the resonance	$0{,}97\left(\frac{2.60}{2.55}\right)$	− 3,7 (4,5)	1,3 (2,9)	0,8 (2,6)
Universal source of cold and ultracold neutrons				
$H_0\downarrow$; two-channel stabilization	$10{,}4\left(\frac{4{,}9}{4{,}2}\right)$	− 12,5 (8,2)	5,0 (5,7)	2,9 (4,8)
$H_0\downarrow$; two-channel stabilization	$-1{,}9\left(\frac{1{,}1}{1{,}1}\right)$	8,9 (1,7)	− 0,7 (1,6)	0,9 (1,1)
$H_0\downarrow$; single-channel stabilization	$-0.6\ \frac{2.3}{2.3}$	9,4 (4,4)	− 0,8 (3,1)	− 1,2 (2,1)
$H_0\uparrow$; single-channel stabilization	$-3{,}9\left(\frac{2{,}2}{2{,}1}\right)$	5,2 (4,4)	− 0,5 (2,5)	1,0 (2,1)
$H_0\uparrow$; two-channel stabilization	$-0{,}5\left(\frac{1{,}4}{1{,}3}\right)$	− 1,9 (2,3)	5,4 (1,7)	0,3 (1,3)
Average	− 1,1 (0,7)	4,0 (1,2)	1,7 (1,0)	0,4 (0,7)
Overall average	− 1,4 (0,6)	4,1 (1,0)	1,4 (0,9)	0,3 (0,6)

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[1] I. S. Altarev *et al.*, Phys. Lett. **102B**, 269 (1981).
[2] V. M. Lobashev and A. P. Serebrov, J. Phys. (Paris) **45**, 3-11, 1984.
[3] M. J. Pendlebury *et al.*, Phys. Lett. **136B**, 327 (1984).
[4] I. S. Altarev, Yu. V. Borisov, A. B. Brandin, S. N. Ivanov, V. M. Pobashev, A. P. Serebrov, and P. P. Tal'daev, Preprint LIYaF-1117, Leningrad Institute of Nuclear Physics, Leningrad, 1985.
[5] I. S. Altarev *et al.*, Phys. Lett. **80A**, 413 (1980).
[6] I. S. Altarev *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **44**, 269 (1986) [JETP Lett. **44**, 344 (1986)].
[7] A. R. Zhitnitskiĭ and I. B. Khriplovich, Yad. Fiz. **34**, 167 (1981) [Sov. J. Nucl. Phys. **34**, 95 (1981)].
[8] A. A. Anselm *et al.*, Phys. Lett. **152B**, 116 (1985).

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