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*ELECTRIC DIPOLE MOMENTS OF ELEMENTARY PARTICLES**

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1. INTRODUCTION

THE question of whether elementary particles have constant electric dipole moments has become particularly significant in connection with the recent discovery of an observable violation of T-invariance (invariance to time reversal) in certain processes of neutral decay K-meson[1-3] †.

The constant electric dipole moment (EDM) of a particle is expressed in a well known form in terms of the charge distribution density:

$$\mathbf{d} = \int \mathbf{r}\rho(\mathbf{r})\, dV,$$

and is a polar vector in accordance with its transformation properties. The presence of an EDM leads to the appearance of an additional term $U = -\mathbf{d}\cdot\mathbf{E}$ in the particle interaction energy; this term depends on the mutual orientation of the EDM and on the electric field **E** acting on the particle. The elementary particles, atoms, or atomic nuclei have no other degrees of freedom characterizing the orientation in space, except those connected with the spin vector. The "orientation" of these particles reduces entirely to the orientation of the spin. In view of this, the effective EDM of the particle can be directed only along its spin‡. However, the spin is an axial vector and if the spin and the EDM are parallel in a given coordinate system, they become antiparallel as a result of space reflection (P) (Fig. 1). If invariance exists with respect to space reflection (≡ right-hand symmetry ≡ conservation of spatial parity), then both situations are equivalent and the average (observable) value of the EDM vanishes identically. A similar result is obtained also from the time-reversal operation (Fig. 2). If T-invariance exists, then the direct and time-reversed states are physically equivalent and again the mean value of the EDM vanishes.

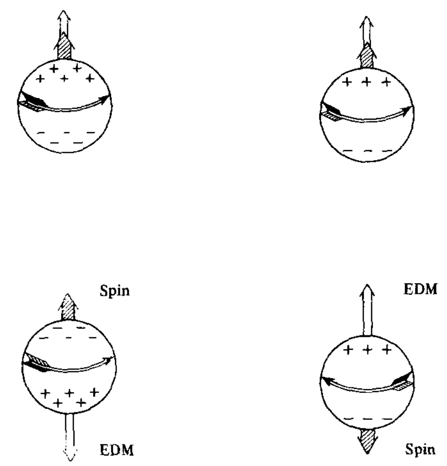

FIG. 1 FIG. 2

FIG. 1. Operation of spatial reflection (mirror reflection) as applied to spin and EDM.

FIG. 2. Operation of time reversal (reversal of the directions of all the velocities and replacement of the initial state by the final state) as applied to spin and to EDM.

Thus, as first noted by L. D. Landau[4], an EDM (directed along the spin) can exist only if both parity-conservation and T-invariance are violated. Observation of EDM in elementary particles will consequently be a direct proof that invariance with respect to time reversal is not a universal principle of nature.*

To this day, numerous attempts to find manifestations of T-noninvariance in processes other than K^0-meson decay have been unsuccessful, and the nature of this phenomenon remains puzzling.

A number of possibilities of theoretically describing the violation of T-invariance are discussed in the literature, and predictions have been made concerning the order of magnitude of the expected EDM of the particles[3,5]. Some estimates can be made on the basis of dimensionality considerations.

Since strong parity nonconservation is observed only in weak interactions, one might think that these interactions will participate in one manner or another in the formation of the EDM, which should thus be proportional to the weak-interaction constant $G = 10^{-5}\ (\hbar/mc)^2\ \text{cm}^2$ (m—nucleon mass). Using, to ensure correct dimensionality, the elementary electric charge e and the Compton wavelength of the nucleon, we obtain the following estimate for the EDM of the nucleon:

$$d \approx eG\left(\frac{\hbar}{mc}\right)^{-1} = e\cdot 10^{-5}\frac{\hbar}{mc} \approx 10^{-19}\ e\cdot\text{cm}.$$

*Paper delivered at the Seminar on CP-Violation (Moscow, 22–26 January, 1968).

†More accurately, violation of the conservation of combined (CP) parity was observed in K^0-meson decays. However, in view of the well known CPT theorem, the validity of which is so far not subject to any doubt, CP-parity nonconservation means that T-invariance is violated [3]. We shall henceforth make no distinction between CP- and T-invariance, and we shall use the latter term.

** The origin is assumed to be located at the mass center of the particle; furthermore, the EDM of an electrically neutral system ($\int\rho(\mathbf{r})dV = 0$) does not depend on the choice of the origin.

‡One speak classically of the rotation of a particle around the spin direction, leading to averaging of that component of the vector **d**, which is normal to the spin direction. The same follows from the uncertainty relation for the angular momentum and the angle, $\Delta L_z \Delta\varphi \geqslant \hbar/2$. At a specified momentum projection L_z we have $\Delta L_z = 0$, meaning that the angle φ and the projection of **d** on the plane normal to the z axis are completely undefined.

*Non-conservation of spatial parity (in weak interactions) is known to be a firmly established fact.

Since the K^0-meson decays are manifestations of weak interactions, and the violation of T-invariance in these decays is small ($\sim 10^{-3}$), one might think that the interaction responsible for the T-noninvariance is weaker than the usual weak interaction by the same factor 10^{-3}. Thus, it is more realistic to expect for the nucleon $d \sim 10^{-22}$ e-cm.

The lowest estimate of the EDM of the nucleon is obtained from the Wolfenstein hypothesis (see[3]), according to which violation of T-invariance is due to a special superweak interaction which causes an admixture of approximately 10^{-3} of the K_1^0 state in the K_2^0 state. The energy H′ of this interaction should amount then to approximately one-thousandth of the mass difference of the K_1^0 and K_2^0 mesons, i.e., $H' \sim 10^{-8}$ eV. Within the framework of perturbation theory we have

$$d \sim \frac{H'}{E_1 - E_0} e \frac{\hbar}{mc} \sim \frac{H'}{mc^2} e \frac{\hbar}{mc} \sim 10^{-31} \; e \cdot \mathrm{cm}.$$

Here E_1 is the energy of the excited state of the nucleon, which is mixed with the ground state (E_0) as a result of the P- and T-odd superweak interaction H′ [$(E_1 - E_2) \sim mc^2$]. To preserve the dimensionality, we use again the charge e and the length $\hbar/mc$. For an electron, certain models predict $d \sim 10^{-3}$–10^{-25} e-cm.[5]

It is clear from the foregoing that establishment of sufficiently low experimental estimates of the values of the EDM of elementary particles, and all the more the measurement of EDM, would be very important for a clarification of the very confused situation with CP- and T-invariance violation, and particularly, for a rejection of a number of conceivable mechanisms of this violation. Experiments with this purpose in mind are carried out in a number of laboratories, and significant results are already being received. In this paper we present a review of methods of measuring EDM and of the results obtained with their aid.

2. METHODS OF MEASURING EDM

As already noted, the EDM of elementary particles, atoms, and nuclei is assumed to be parallel to the spin. In view of this, the additional electromagnetic interaction caused by the presence of the EDM can be represented in the form

$$U = -\mathbf{d}\mathbf{E} = -\frac{d}{I}\mathbf{I}\mathbf{E}, \tag{1}$$

where d—EDM of the particle, I—its spin, and **I**—spin operator. This interaction leads to the following effects, which are used for estimating the value of EDM;

A. Shift of atomic levels.

B. Scattering in a Coulomb field, electromagnetic reactions.

C. Spin precession in an external electric field.

A. Level Shift

As shown by Salpeter[6] and Sternheimer[7], the presence of EDM in particles making up the atomic system leads to corrections to the distances between the levels, proportional to d^2. In view of this, comparison of the observed distances between the levels and those calculated theoretically does not lead to sensitive estimates of EDM. Thus, from the hyperfine splitting of the levels of positronium we get for the EDM of the positron[6]

$$d_{e^+} < 8 \cdot 10^{-13} \; e \cdot \mathrm{cm}.$$

From the level shift $2P_{1/2}$—$2S_{1/2}$ of the hydrogen atom (Lamb shift) we get for the EDM of the proton[7]

$$d_p < 10^{-13} \; e \cdot \mathrm{cm}.$$

B. Scattering, Reactions

1. Neutrino. Bernstein, Feinberg, and Ruderman estimated the largest possible value of the magnetic dipole moment (EDM) of the neutrino from experimental data on the upper limits of the effective cross section of electromagnetic processes in which the neutrino takes part[8]. The results of this investigation can also be applied to the EDM of the neutrino. In fact, the existing data on the neutrino mass (electronic neutrino: $m_{\nu_e} < 250$ eV[9], muonic neutrino: $m_{\nu_\mu} < 1000$ eV[10]), have enabled the authors of[8] to assume in all cases that the neutrino is relativistic. On the other hand, for a relativistic particle, the energies of interaction of equal EDM and MDM with the electromagnetic field are close to each other, meaning that the cross sections of the processes produced by these interactions are also close.*

The best estimate follows from astrophysical data indicating that the reaction of the production of neutrino-antineutrino pairs by photons ($\gamma \to \nu + \bar{\nu}$) does not make a large contribution to the rate of cooling of the stars. Hence $d_\nu < 4 \times 10^{-21}$ cm for both electronic and muonic neutrinos. Estimates of d_ν from certain other effects are listed in Table II below.

2) Neutron. The interaction (1) between the EDM of the neutron and the intra-atomic Coulomb field causes an additional scattering, the amplitude of which in the Born approximation is equal to

$$ib'' = id \frac{2Zem(1-F)}{\hbar^2 q}(\mathbf{pe}), \tag{2}$$

where Ze—charge of nucleus, m—mass of neutron, $\mathbf{q} = \mathbf{k} - \mathbf{k}_0$—difference between the wave vectors of the neutron after scattering (**k**) and before scattering ($\mathbf{k}_0$), $\mathbf{e} = \mathbf{q}/q$—unit vector of scattering, $F = F(q)$—form factor of electron shell of the atom (the same that determines the elastic scattering of the x-rays by the atom, $0 \le F \le 1$), and **p**—unit vector of neutron polarization. The characteristic features of the amplitude (2) are that the amplitude is imaginary and maximal in magnitude

*This can be readily verified by changing over to a coordinate system connected with the particle. In this system the field (**E**, **H**) is transformed into a field (**E′**, **H′**) such that the longitudinal components (along the particle velocity **v**) remain the same, while the transverse components increase by a factor $\gamma = [1 - (v^2/c^2)]^{-1/2}$:

$$\mathbf{E}'_\perp = \gamma\left(\mathbf{E}_\perp + \frac{1}{c}[\mathbf{H}\times\mathbf{v}]\right), \quad \mathbf{H}'_\perp = \gamma\left(\mathbf{H}_\perp - \frac{1}{c}[\mathbf{E}\times\mathbf{v}]\right).$$

When $\gamma \gg 1$, the longitudinal components can be neglected, while the transverse components $\mathbf{E}'_\perp$ and $\mathbf{H}'_\perp$ are in this case practically perpendicular to each other and are equal in absolute magnitude. Consequently, the interaction energies $-\boldsymbol{\mu}\cdot\mathbf{H}'$ and $-\mathbf{d}\cdot\mathbf{E}'$ are equal if $|\mu| = |d|$ and $\boldsymbol{\mu} \perp \mathbf{d}$. The corresponding cross sections, averaged over the particle spin direction in the proper coordinate system of the particle, will also be equal.

when the neutron is polarized along the scattering vector, and reverses sign when the polarization of the neutron is reversed. The neutron scattering intensity is proportional to the square of the modulus of the summary amplitude of the scattering and to the effective volume V of the sample, i.e.,

$$J \sim [b^2 + (b' + b'')^2] V,$$

where b + ib′ is the amplitude of nucleon scattering. When the polarization of the neutron is reversed, the relative change of J amounts to (when $b'' \ll b'$)

$$\frac{\Delta J}{J} = \frac{4b'b''}{b^2 + b'^2}. \qquad (3)$$

The measurement time necessary to obtain a given statistical accuracy in b″ is proportional (in the absence of background) to

$$t \sim \frac{J}{(\Delta J)^2} \sim \frac{1}{b''^2} \frac{b^2 + b'^2}{b'^2 V}. \qquad (4)$$

It is clear therefore that the conditions for observing the EDM of the neutron will be the best if the real part of the scattering amplitude vanishes. If the sample volume is fixed, b = 0, and there is no background, then the value of b′ is immaterial from the statistical point of view. Actually, however, the effective volume of the sample increases with decreasing b′, since the depth of penetration of the neutrons is, roughly speaking, inversely proportional to the total interaction cross section, which in turn, according to the optical theorem, is proportional to b′. Taking this into account, small values of b′ become more convenient. A decrease of b′ (to a value $b' = |b|$ if $b \neq 0$) is also important because it contributes to a reduction of the role of the systematic errors by leading to an increase of $\Delta J/J$.

In a recently published paper[11], Shull and Nathans attempted to observe the amplitude (2) in experiments on the diffraction of neutrons by single-crystal CdS. They used in the experiment reflection from the (004) planes, the reflection density being dependent on the difference of the amplitudes of the coherent scattering of the cadmium and of the sulphur:

$$J \sim |a_{Cd} - a_S|^2.$$

For thermal neutrons $a_{Cd} = 3.8 + i1.2$ F and $a_S = 3.1$ F. Thus, the real parts of the coherent amplitudes of Cd and S are practically cancelled out, and the imaginary part of the resultant amplitude is close to its real part. This explains the choice of CdS as the working medium.

In the experiment of[11], much attention was paid to the exclusion of systematic errors, one of the sources of which can be the so-called Schwinger scattering, i.e., scattering caused by the energy $(1/c)\mu \cdot \mathbf{E} \times \mathbf{v}$ of interaction of the magnetic moment of the moving neutron with the Coulomb field of the atomic nucleus[12]. The amplitude of this scattering is also pure imaginary and depends on the neutron polarization, but it equals zero if the polarization is exactly parallel to the scattering vector.

By recording 400 million neutrons in three months, the authors obtained the following result for the EDM of the neutron:

$$d_n = (2.4 \pm 3.9) \cdot 10^{-22}\ e \cdot \mathrm{cm}.$$

3. Electron. The cross section of elastic (Mott) scattering of electrons by nuclei decreases rapidly with increasing scattering angle θ, and tends to zero as $\theta \to \pi$. To the contrary, the scattering cross-section component connected with the anomalous MDM of the electron and with possible EDM increases as $\theta \to \pi$. Although this increases the sensitivity to the presence of EDM, the experiments did not lead to significant estimates. Thus, from the scattering of electrons by C^{12} through 180°, at a momentum transfer 1 F^{-1}, they obtained $d_e < 2 \times 10^{-16}$ e-cm[13]. In principle, experiments with large momentum transfer are of interest because they can yield information on the form factor of the electron EDM; however, this requires that the accuracy be increased by many orders of magnitude compared with that presently obtained, which is hardly possible at present.

C. Spin Precession

1. Experiments of the g − 2 type. To estimate the EDM of the electron and muon, modifications of the method used to measure the anomalous magnetic moment were used, i.e., the deviations of the g-factor from the Dirac value g = 2 were measured.* In the experiments, the particles move in a magnetic field **H** along a circular orbit. The spin, which is initially directed along the particle velocity, then precesses around the direction of **H**, remaining at all time in the plane of the orbit if the EDM of the particle is equal to zero. On the other hand, in the presence of EDM, the spin precesses also around the electric field $\mathbf{E}' = (\gamma/c)\mathbf{H} \times \mathbf{v}$, which acts on the particle in its own coordinate system (Fig. 3). The resultant precession axis is inclined to the plane of the orbit, so that a polarization component parallel to **H** is produced:

$$P_H \cong P_0 \frac{\omega_d}{\omega} \sin \omega t, \qquad (5)$$

where P_0—initial polarization, $\omega = \omega_L - \omega_c$—frequency of rotation of the spin relative to the velocity, $\omega_c = eH/mc$—cyclotron frequency (as $v \to 0$). $\omega_L = 2\mu H/\hbar = g\omega_c/2$—Larmor frequency,

$$\omega_d = \frac{2dH}{\hbar} \frac{v}{c}$$

—precession frequency due to the EDM, and t—time.

The determination of the EDM thus reduces to a measurement of the amplitude of the change of the polarization in the direction of the magnetic field. We have thus obtained estimates of the EDM for the electron ([14], $d_{e^-} < 4 \times 10^{-16}$ e-cm) and for the μ^+ meson ([15], $d_{\mu^+} = (0.6 \pm 1.1) \times 10^{-17}$ e-cm). The low accuracy is due to two main factors. First, the "gratuitous" effective field E′ cannot be eliminated without changing the remaining experimental conditions. Second, the time of action of this field is small, $\tau = \pi/\omega = \pi(\omega_L - \omega_c)$.

It is possible to increase τ by bringing the Larmor and cyclotron frequencies closer together with the aid of an external electric field **E** directed radially in the

*The g-factor is defined by the relation $\mu = ge\hbar S/2mc$, where μ, m, and S are respectively the magnetic moment, mass, and spin of the particle.

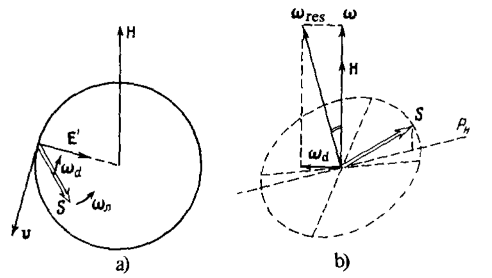

FIG. 3. a) Charged particle moves with cyclotron velocity ω_c on a circular trajectory in a plane normal to H. The spin S precesses around H with Larmor frequency ω_L and around $E' \sim H \times v$ with frequency ω_d. b) The vector E' is stationary in the coordinate system rotating with cyclotron frequency ω_c. The paper precesses with angular velocity ω_{res}, which is the resultant; $\omega_d \| E'$ and $\omega = (\omega_L - \omega_c) \| H$. When $\omega_d \neq 0$, a polarization component P_H appears and varies periodically with a frequency $\omega_{res} \approx \omega$.

plane of the particle orbit; in this case[16]

$$\omega = \frac{1}{2}\omega_H \left\{ (g-2) \pm \frac{cE}{vH}\left[\frac{g}{\gamma^2} - (g-2)\right]\right\}, \quad (6)$$

where the ± sign corresponds to two directions of **E** relative to the radius of the orbit. For the electron and positron $(g-2) \sim 10^{-3}$, so that for particles with not too high an energy it is possible, in principle, to increase τ to a value on the order of the lifetime of the particles in storage rings, making it possible to increase the accuracy with which EDM is measured by many orders of magnitude. This may be an interesting method for positrons; for electrons the method of atomic beams (see below) is apparently a cheaper solution.

2. Resonance experiments. These experiments are based on the well known Rabi method, in which the beam of particles is subjected to the action of a constant magnetic field H_0 and an alternating field $H_1 \ll H_0$ perpendicular to it, with frequency ω. As $\omega \to \omega_0$, where $\hbar\omega_0$ is the distance between the Zeeman-splitting components, a resonant change in the spin orientation takes place, accompanied by a sharp variation of the intensity of the registered particle beam (Fig. 4). The width of the resonance curve in the ideal case is determined by the time that the particle stays in the field H_0, namely $\Gamma = \pi/\tau$.

To determine the EDM, an electric field **E** is superimposed on the magnetic field; it must be parallel or antiparallel to the field H_0. The resonant frequency is

$$\omega_0 = \frac{1}{\hbar I}(\mu H \pm dE),$$

where I—particle spin; when the electric field is reversed, the frequency changes by an amount

$$\Delta\omega_0 = \frac{2dE}{\hbar I}. \quad (7)$$

The frequency ω or the field H_0 is set to correspond to the steepest slope of the resonance curve $J(\omega)$. In this case, when the electric field is reversed, the beam intensity is changed by an amount

$$\frac{\Delta J}{J} = \frac{1}{J}\frac{dJ}{d\omega}\Delta\omega_0 \approx \frac{\Delta\omega_0 \tau}{\pi} \quad (8)$$

(Since $dJ/d\omega \sim J/\Gamma$). Thus, the relative change of the beam intensity equals approximately the EDM precession angle in the applied electric field. It is quite small.

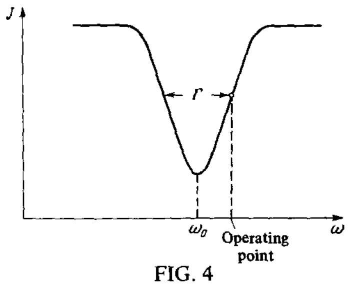

FIG. 4

Thus, at E = 120 kV/cm, I = 1/2, $\tau = 8 \times 10^{-3}$ sec, and $d = 10^{-22}$ e-cm we have $\Delta J/J \sim 10^{-4}$.

These conditions characterize a recent measurement of the EDM of a neutron, performed at Oak Ridge and described in detail in[17,18]. The result of the experiment is an upper limit for the neutron EDM, namely $d_n < 3 \times 10^{-22}$ e-cm.

Experiments of this type were performed also with atomic beams in searches for the EDM of the electron. They will be considered in the next section.

3. ATOMIC ELECTRIC DIPOLE MOMENT

The question of the EDM of atoms was considered by Schiff[19], who showed that in the nonrelativistic limit the existence of an EDM in an electron or nucleus does not lead to the existence of an EDM in the atom*. The gist of this theorem is clear from the following classical reasoning.

When a homogeneous electric field acts on an atom, the charges in the atom are displaced in such a way as to restore the equilibrium, i.e., to cause the resultant force acting on the nucleus or on the electron to remain equal to zero (at any rate, when averaged over the time). Since only the electric forces are significant in the nonrelativistic approximation, the resultant electric field intensity applied to the nucleus or to the electron is equal to zero. Consequently, the interaction $U = -\mathbf{d}\cdot\mathbf{E}$ vanishes, meaning the vanishing of the effective EDM of the atom.

If magnetic forces play a role besides the electric ones, then application of an external electric magnetic field leaves their sum equal to zero. The electric forces separately may no longer vanish, i.e., the atom can have a finite effective EDM. In atoms with large Z the magnetic forces or, more accurately speaking, the relativistic effects, become more significant in the motion of the electrons, and one can expect the EDM of the atom, due to the EDM of the unpaired electrons, to increase with increasing Z.

Sandars[21], using the Hartree-Fock wave functions and the Dirac equation for the description of the perturbation of the wave function of the valence electron, due to the presence of the EDM of the electron, perform numerical calculations of the effective EDM of the alkali-element atoms. He not only confirmed the increase of d_{eff} with increasing Z, but also observed the

*It is assumed in [19] that there are no P- and CP-violating interactions between the component parts of the atoms, with the exception of those due to the EDM of the electrons and of the nucleus (see in this connection [20]).

Table I

Element	Z	d_{eff}/d_e without allowance for screening of the EDM by the internal-shell atomic electrons	d_{eff}/d_e with allowance for screening
Li	3	$4.5\cdot10^{-3}$	$4.3\cdot10^{-3}$
Na	11	$3.3\cdot10^{-1}$	$3.18\cdot10^{-1}$
K	19	2.65	2.42
Rb	37	27.5	24
Cs	55	133	119
Fr	87	1150	—

existence of a considerable enhancement of the EDM of heavy atoms compared with the EDM of the free electron (Table I).

Similar calculations were made by V. Ignatovich in Dubna. The results obtained by him confirm the presence of the enhancement. In essence, this effect signifies that at large values of Z the disturbance of the electron motion by the external field is such that the tremendous electric and magnetic forces acting on the electron in the region close to the nucleus reverse direction, so that the change of each of them in absolute magnitude is large compared with the external force. An effect of atomic enhancement of a different nature has been known for a long time, namely the so-called anti-screening of the nuclear quadrupole moment, observed by Sternheimer[22].

The EDM of the atom, due to the presence of the EDM of the nucleus, will be smaller by many orders of magnitude than the EDM of the nucleus, since the large mass of the nucleus makes the relativistic effects negligible. As shown by Schiff[19], the principal role is played by the force acting on the nuclear magnetic moment as a result of the gradient of the magnetic field produced at the location of the nucleus when the electron shell is deformed by the external electric field. A value $d_{eff}/d_{nuc} = -1.5 \times 10^{-7}$ was obtained for helium-three.

Another effect considered in[19] is connected with the fact that the spatial distribution of the EDM density in the nucleus is determined by the state of one or two unpaired external nucleons, and therefore differs greatly from the spatial distribution of the charge density. If the nucleus is an inhomogeneous electric field, then it is located in such a way that the field intensity averaged over the electric-charge distribution vanishes. The field intensity averaged over the distribution of the nuclear EDM is in this case different from zero. This leads to the occurrence of an effective EDM of the order of

$$\frac{d_{eff}}{d_{nuc}} \sim \frac{R_0^2}{a_0^2} \sim 10^{-8},$$

where R_0^2—difference between the mean square radii of the EDM and electric-charge distributions in the nucleus ($R_0^2 = \langle r^2\rangle_{EDM} - \langle r^2\rangle_{el.ch}$), and a_0—atomic unit of length.*

Sandars[23] noted that in polar molecules the inhomogeneity of the electric field in the region of the nucleus is so large that, for example in the FlF molecule, the energy of interaction of the EDM of the thallium nucleus corresponds to an effective field of 20 kV/cm acting on the EDM of this nucleus. According to Sandars, who measured with a molecular beam of TlF the NMR frequency shift of the thallium isotopes ($_{81}Tl^{203}$ and $_{81}Tl^{205}$) upon reversal of the orientation of the TlF molecule axis relative to the external magnetic field, it is possible to attain an accuracy on the order of 10^{-22} e-cm in the measurement of the nuclear EDM.

In this connection, it is worthwhile to analyze the question of how the EDM of the nucleus is connected with the proper EDM of the unpaired nucleon, and what contribution can be made to the EDM of the nucleus by the P- and CP-violating internucleon interactions.

*There is no effect linear in the nuclear dimension if the centers of gravity of the distribution of the EDM and of the electric charge coincide. If they do not coincide, then the linear term should be P- and T-even and would not appear in experiments on the measurement of the EDM.

Experiments With Atomic Beams

Recently several experiments were performed aimed at measuring the EDM of the Cs atom. They were based on a modification of the resonance method proposed by Ramsey (separated radio-frequency fields; see, for example,[24]).

The spin of the Cs^{133} nucleus is I = 7/2, the spin of the electron shell is J = 1/2, and the total spin assumes values F = 3 or 4. In the experiments they investigated the dependence of the frequency (in fact, of the intensity, see above) of the transition between the Zeeman components (F, m_F):(4, −4) and (4, −3), on the magnitude of the applied electric field.* The electric field produces in this transition a small quadratic Stark effect, i.e., a frequency shift proportional to E^2, from which it is necessary to separate the linear effect due to the proposed EDM. Such a separation can be attained, for example, by measuring the frequency shift when the electric field is reversed, since the quadratic effect does not depend on the sign of **E**.

If the electric and magnetic fields are not strictly parallel, then an effect linear in **E** is produced as a result of the additional magnetic field $\mathbf{H}' = (1/c)\mathbf{v} \times \mathbf{E}$ acting in the coordinate system that moves at the velocity **v** of the atom. In fact, neglecting terms of order v^2/c^2, the total magnetic field equals, with sufficient accuracy,

$$|\mathbf{H}+\mathbf{H}'| = H \pm \frac{v}{c} E \sin\vartheta, \tag{9}$$

where ϑ is the angle between H and the projection of **E** on the plane normal to the plane containing **H** and **v**. This effect (the v/c effect) imitates the sought influence of the EDM. In the first experiment, Sandars and Lipworth[25] observed a linear effect exceeding the limits of errors, corresponding to an angle on the order of 0.5° between E and H. In this connection, further efforts were aimed at eliminating the interfering v/c effect.

Angel, Sandars, and Tinker[26] constructed an instrument in which the atomic beam of cesium could pass through the region of magnetic and electric fields in opposite directions. When the atomic beam was reversed, the EDM effect did not change, whereas the v/c effect reversed sign.

*In the calculation of $\Delta\omega_0$ for atoms it is necessary to take into account the Lande factor in (7). In a weak magnetic field we have $\Delta\omega_0 = d_{Cs}E/2\hbar$ for the transition in question.

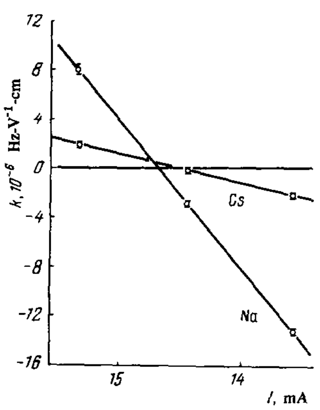

FIG. 5

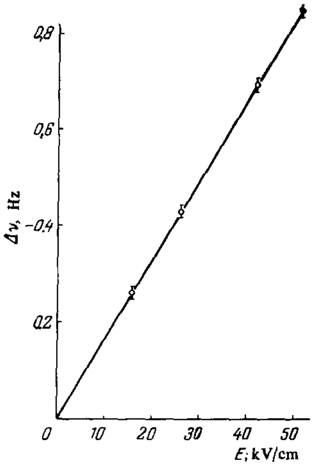

FIG. 6

FIG. 5. Dependence of the shift of the resonance frequency on the angle between **E** and **H**. The ordinates represent the change in the frequency $\Delta\nu/E$ of the Zeeman transition upon superposition of an electric field, referred to its intensity. Abscissas—current in coil, causing rotation of H (1 mA corresponds to a change of the angle between **E** and **H** by 0.08°).

FIG. 6. Resonance shift $\Delta\nu$ for the Cs atom as a function of the intensity of the electric field at a fixed angle between **E** and **H**.

With the beam moving from east to west, the observed effect corresponds to $d' = (57 \pm 20) \times 10^{-21}$ e-cm, and for motion from west to east $d'' = (-39 \pm 8) \times 10^{-21}$ e-cm. The mean value $d_{Cs} = (8 \pm 10) \times 10^{-21}$ e-cm should no longer contain the contribution of the v/c effect.

The instrument of Stein et al.[27] made it possible to perform, under identical conditions, measurements with atomic beams of cesium and sodium alternately. To increase the measurement accuracy, a longer field region was used (large τ in formula (8)). With the aid of the additional Helmholtz coils, a field $\mathbf{H}_1$ normal to **H** and **v** was produced, and variation of this field could regulate the angle ϑ between the electric and magnetic fields. In experiments with Na, the value of $\mathbf{H}_1$ was chosen such that the linear effect in E vanished (Fig. 5). Inasmuch as the EDM of sodium should be very small compared with the EDM of cesium, one could assume that the v/c effect was eliminated at this value of $\mathbf{H}_1$. Measurements with cesium gave at the same value of $\mathbf{H}_1$ a nonzero linear effect (Fig. 6) amounting to $d_{Cs} = (2 \pm 0.6) \times 10^{-21}$ e-cm. This result should not be taken literally, since there is no assurance that the v/c effect has been completely eliminated together with other systematic errors. It is more correct to assume that an upper bound $d_{Cs} < 3 \times 10^{-21}$ e-cm was obtained for EDM of the cesium atom. Taking into account the Sandars enhancement factor, this leads to an upper bound $d_{e^-} < 3 \times 10^{-23}$ e-cm for the electron EDM.

4. PROSPECTS

In Table II are gathered the latest experimental data on the upper bounds of the EDM of elementary particles. The best estimates were obtained for the electron ($d_e < 3 \times 10^{-23}$ e-cm) and the neutron ($d_n < 3 \times 10^{-22}$ e-cm).

The last result already gives experimental grounds for casting doubts on some of the theoretical models

Table II. Electric dipole moments of particles (latest experimental estimates).

Particle	d or $\|d\|$, e·cm	Literature	Method
Muon (μ^+)	$(0.6\pm1.1)\cdot10^{-17}$	15	Spin procession in g-2 experiment
	$(-7\pm13)\cdot10^{-17}$	35	Spin procession in g-2 experiment
Positron	$<8\cdot10^{-13}$	6	Positronium levels
Rb Atom	$1\cdot10^{-18}$	32	Optical pumping
Cs Atom	$(9\pm10)\cdot10^{-21}$	26	Atomic bean
Cs-Na Atoms	$(2\pm0.6)\cdot10^{-21}$	27	Atomin beams; d_{Cs}-d_{Na} was measured
Electron	$<4\cdot10^{-16}$	14	Spin procession in g-2 experiment
	$<2\cdot10^{-16}$	13	Back scattering of electrons by C^{12} (momentum transfer 1 F^{-1})
	$(7.5\pm8)\cdot10^{-23}$	26	Recalculated from d_{Cs} and $d_{Cs\text{-}Na}$ on the basis of the calculations of [21]
	$(1.7\pm0.5)\cdot10^{-23}$	27	
Proton	$<1.3\cdot10^{-13}$	7	
Na^{23} Nucleus	$<1\cdot10^{-14}$	36	From the Lamb shift
Neutron	$(2.4\pm3.9)\cdot10^{-22}$	11	Relaxation of nuclear spin in gas mixtures
	$(-2\pm3)\cdot10^{-22}$	18	Neutron diffraction in Cds
	$<3\cdot10^{-22}$	17	Nuclear magnetic resonance on neutron beam
Neutrino ν_e	$<5\cdot10^{-20}$	8	Ditto
	$<4\cdot10^{-21}$	»	From the upper limit of the ν-e scattering cross section, which follows from the experiments of Cohen and Reines on the inverse process
Neutrino ν_μ	$<4\cdot10^{-21}$	»	From astrophysical data and the absence of a noticeable contribution of photoproduction of neutrinos ($\gamma\to\nu+\bar{\nu}$) to the rate of cooling of stars
			The same (assuming $m_{\nu\mu}<1$ keV)
	$<4\cdot10^{-19}$	»	From the absence of generation of pions in experiments with high-energy neutrinos

developed for the violation of CP-invariance. In particular, the well known hypothesis of strong violation of CP in electromagnetic interaction[28] leads to essentially larger estimates for d_n[5,29].

There are real possibilities of appreciably increasing the accuracy of the measurement of the EDM of the neutron, of the electron, and also, on the basis of the Sandars proposal considered above, of nuclei.

In experiments on neutron scattering, we can advance further by choosing a crystal that ensures a more complete compensation of the real part of the coherent scattering amplitude at the lower value of the imaginary part than afforded by CdS. In this respect, the isotope W^{186} is of interest. The interference of the resonant and potential scattering amplitudes causes the thermal cross section for neutron scattering to be extremely small for this isotope[30]. The smallness of nuclear scattering favors observation of nuclear interactions of the neutron. In this connection, investigations of neutron diffraction by a single crystal made of tungsten enriched with W^{186} have been initiated at the Neutron Physics Laboratory in Dubna, for the purpose of measuring the neutron-electron scattering amplitude by a new method. Inasmuch as the thermal cross section for the capture of W^{186} is not very small (~ 35 b), this material can be suitable also for the measurement of the EDM of the neutron. It should be noted that with increasing sensitivity to the EDM of the neutron, the sensitivity to the Schwinger scattering also increases so that the difficulties connected with its separation still remain.

In resonance experiments, the increase of the sensitivity to the EDM is possible as a result of the increase of the time that the particle stays in the region of the action of the electric and magnetic fields. The obvious way is to lengthen the setup. Thus, Miller[17] indicates that with a setup 10 meters long, with a reactor producing a flux of 10^{15} neutron/cm^{2}sec (larger by two orders of magnitude than that used in the experiment[17,18]), it is possible to achieve a sensitivity to the neutron EDM on the order of 10^{-24}—10^{-25} e-cm.

Another possible way is to use the suggestion of Ya. B. Zel'dovich[31] of storing ultracold neutrons in a closed cavity (Fig. 7). The neutrons with velocity lower than the limiting value

$$v_{\text{lim}} = \frac{2\hbar}{m} \sqrt{\pi N b_{\text{coh}}}, \qquad (10)$$

experience total reflection from the surface of matter at all angles of incidence (m—neutron mass, N—number of nuclei per cm^3, b_{coh}—coherent scattering length). For Ni^{58}, $v_{\text{lim}} \sim 10$ m/sec. Since in a Maxwellian spectrum the flux of neutrons having all velocities lower than v_{lim} is proportional to v_{lim}^4, a change from a velocity 90 m/sec, such as used in[17], entails a decrease of the intensity by four orders of magnitude. However, it can be more than offset by the increased lifetime of the neutrons and by the possibility of gathering the ultracold neutrons from the more "luminous" area of the reactor. An important advantage of such a formulation of the experiment is also the appreciable suppression of the v/c effect.

A similar approach is applicable also to experiments with atoms; under such conditions, experiments were made aimed at measuring the EDM of Rb atoms[32]. The result of that investigation is not very accurate

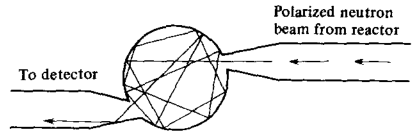

FIG. 7

($d_{\text{Rb}} < 1 \times 10^{-18}$ e-cm), but appreciable progress can be made here (see also the experiments aimed at observing the quadratic Stark effect with a hydrogen maser[33]).

In conclusion, let us consider the question of the possibility of searching for the EDM of atoms in macroscopic experiments.*

Let us consider a non-conducting ferromagnet magnetized to saturation with n atoms per unit volume. Since the atomic spins are fully oriented, the presence of the EDM leads to electric polarization of the medium, equal to P = nd, corresponding to an electric field intensity $E = 4\pi P/\epsilon$, where ϵ—dielectric constant of the medium. At $d = 10^{-21}$ e-cm, $n = 10^{22}$ cm^{-3}, and $\epsilon = 2$ we have $E \sim 10^{-5}$ V/cm, which apparently is measurable.

Another possible formulation of the experiment is to observe the change of the magnetic induction **B** when an electric field **E** is applied to the sample. The sample should in this case be magnetized in such a way that its magnetic permeability μ_1 be at a maximum. Application of an electric field changes the energy of the atomic spin by an amount $\mathbf{d} \cdot \mathbf{E}$. This is equivalent to changing the spin energy by applying an external magnetic field of magnitude $H_{\text{eff}} = dE/\mu$, where μ—magnetic moment of the atom. Such a change of H leads to a change in the magnetic induction by an amount $\Delta B = \mu_1 dE/\mu$. Assuming $\mu = 2\mu_B$ (μ_B—Bohr magneton), $\mu_1 = 10^2$, $d = 10^{-21}$ e-cm and E = 50 kV/cm, we obtain $\Delta B \sim 4 \times 10^{-7}$ G.

Recently developed magnetometers, based on quantization of the magnetic flux, make it possible to register changes of the magnetic field amounting to 10^{-8}—10^{-9} G against a background of $B \sim 10^3$ G[34].

Besides the linear magnetoelectric effects considered above, there will exist quadratic effects connected, for example, with electrostriction and magnetostriction. They will lead to the occurrence of a signal at double the frequency compared with the frequency of variation of the electric field. A linear magnetoelectric effect not connected with EDM should not exist in ferromagnets, although it is not excluded that it can be caused by the presence of defects in the crystal.

An important problem is the enhancement of the electronic EDM by atoms (ions) responsible for ferromagnetism (Fe, Eu, U, etc.). The appropriate calculations are being performed in Dubna, and their results will make it possible to choose the optimal substance for the performance of these experiments.

[1] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Lett. 13, 138 (1964).
[2] D. Dorfan, et al., Phys. Rev. Lett. 19, 987 (1967); S. Bennett et al., Phys. Rev. Lett. 19, 993 (1967).

*This question was raised by V. Ignatovich.

[3] L. B. Okun', Usp. Fiz. Nauk 89, 603 (1966) [Sov. Phys.-Usp. 9, 574 (1967)].
[4] L. D. Landau, Zh. Eksp. Teor. Fiz. 32, 405 (1957) [Sov. Phys.-JETP 5, 336 (1957)].
[5] Papers by A. Filippov and B. A. Arbuzov at Seminar on CP Violation, Moscow, January 1968 (Yad. Fiz. 8, 197 (1968) and Usp. Fiz. Nauk 95, 460 (1968)) [Sov. J. Nuc. Phys. 8 and Sov. Phys.-Usp. 11, in press].
[6] E. E. Salpeter, Phys. Rev. 112, 1642 (1958).
[7] R. M. Sternheimer, Phys. Rev. 113, 828 (1959).
[8] J. Bernstein, G. Feinberg and M. Ruderman, Phys. Rev. 132, 1227 (1963).
[9] D. R. Hamilton, W. P. Alford and L. Gross, Phys. Rev. 92, 1521 (1953).
[10] S. S. Gershteĭn and Ya. B. Zel'dovich, ZhETF Pis. Red. 4, 174 (1966) [JETP Lett. 4, 120 (1966)].
[11] C. G. Shull and R. Nathans, Phys. Rev. Lett. 19, 384 (1967).
[12] J. Schwinger, Phys. Rev. 73, 407 (1948).
[13] E. E. Rand, Phys. Rev. B140, 1605 (1965).
[14] D. T. Wilkinson and H. R. Crane, Phys. Rev. 130, 852 (1963).
[15] G. Charpak, F. J. M. Farley, R. L. Garwin, T. Muller, J. C. Sens, and A. Zichichi, Nuovo Cimento 22, 1043 (1961).
[16] W. Bargmann, L. Michel, and V. L. Telegdi, Phys. Rev. Lett. 2, 435 (1959).
[17] P. D. Miller, Paper at Seminar on CP Violation, Moscow, January 1968, Usp. Fiz. Nauk 95, 470 (1968) [Sov. Phys.-Usp. 11, in press].
[18] P. D. Miller, W. B. Dress, J. Baird and N. Ramsay, Phys. Rev. Lett. 19, 381 (1967).
[19] L. I. Schiff, Phys. Rev. 132, 2194 (1963).
[20] M. Sachs and S. L. Schwebel, Ann. Phys. (N. Y.) 6, 244; 8, 475 (1959).
[21] P. G. H. Sandars, Phys. Lett. 14, 194 (1965); 22, 290 (1966).
[22] R. M. Sternheimer, Phys. Rev. 95, 736 (1954).
[23] P. G. H. Sandars, Phys. Rev. Lett. 19, 1396 (1967).
[24] N. F. Ramsay, in: "Experimental Nuclear Physics," E. Segre, ed., 1955.
[25] P. G. H. Sandars and E. Lipworth, Phys. Rev. Lett. 13, 718 (1964).
[26] J. R. P. Angel, P. G. H. Sandars and M. H. Tinker, Phys. Lett. A25, 160 (1967).
[27] T. S. Stein, J. P. Carrico, E. Lipworth and M. C. Weisskopf, Phys. Rev. Lett. 19, 741 (1967).
[28] J. Bernstein, G. Feinberg and T. D. Lee, Phys. Rev. B139, 1650 (1965).
[29] G. Feinberg, Phys. Rev. B140, 1402 (1965).
[30] Yu. A. Aleksandrov, JINR Preprint 3-3442, Dubna, 1967, p. 112.
[31] Ya. B. Zel'dovich, Zh. Eksp. Teor. Fiz. 36, 1952 (1959) [Sov. Phys.-JETP 9, 1389 (1959)].
[32] E. S. Ensberg, Phys. Rev. 153, 36 (1967).
[33] E. N. Fortson, D. Kleppner and N. F. Ramsay, Phys. Rev. Lett. 13, 22 (1964).
[34] R. L. Forgacs, and A. Warnick, Rev. Sci. Instr. 38, 214 (1967).
[35] D. Berley, G. Gidal, Phys. Rev. 118, 1086 (1960).
[36] A. T. Ramsay and L. W. Anderson, Nuovo Cimento 32, 1151 (1964).

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