

Measurement of the electric dipole moment of the electron with a quantum interferometer

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(Submitted 21 September 1977)

Zh. Eksp. Teor. Fiz. 74, 466-471 (February 1978)

A superconducting quantum interferometer with a sensitivity of $\sim 10^{-11}$ G has been used to determine an upper limit of the value of the electric dipole moment of the electron $d_e = (8.1 \pm 11.6) \times 10^{-23}$ e-cm by measurement of the change in magnetic induction arising in a ferrite on application to it of an electric field.

PACS numbers: 13.10.+q, 14.60.Cd

Conservation of spatial parity (P) and time parity (T), which were previously considered universal laws of nature, forbid the existence of electric dipole moments in elementary particles. Actually, since a particle has only one distinguished direction—the direction of its spin, its electric dipole moment can be oriented only along the spin, either parallel or antiparallel to it. The spatial reflection operator acts differently on the collinear vectors of the spin \mathbf{s} and the electric dipole moment

$$\mathbf{d} = \int \mathbf{r} \rho(\mathbf{r}) dV \quad (1)$$

(\mathbf{r} is the distance to the center of mass of the particle and $\rho(\mathbf{r})$ is the volume charge density). Since the first is an axial vector and the second—polar, the vectors \mathbf{s} and \mathbf{d} change their relative orientation (Fig. 1a) and the inverted particle obtained as the result of spatial reflection turns out to be not identical to the original particle. Time reversal also leads to a change in the relative orientation of the vectors \mathbf{s} and \mathbf{d} (Fig. 1b). Therefore observation in elementary particles of electric dipole moments would unambiguously indicate violation of space and time parity.

The violation of space parity observed in weak interactions and the violation of T -invariance observed in decays of K^0 mesons not only indicate the possibility of existence of electric dipole moments in elementary particles, but also permit its magnitude to be estimated from dimensional considerations.

It is evident that the electric dipole moment of an elementary particle must be proportional to the coupling constant of the interaction responsible for existence of the electric dipole moment. Using the elementary charge e and the Compton wavelength of the particle to provide the correct dimensionality ($[d] = [q][L]$), we obtain for the electric dipole moment, in particular,

$$d_e \approx eG(\hbar/m_e c)^{-1}, \quad (2)$$

where e is the charge of the electron, m_e is the mass of the electron, and G is the constant of the interaction taking part in formation of the electric dipole moment.

Since P -invariance is violated in weak interactions described by the constant $G_w = 10^{-5}(\hbar/mc)^2 \text{ cm}^2$ (m is the nucleon mass), we can expect that this interaction will take part in formation of an electric dipole moment. Setting $G = G_w$, we obtain for the electron electric dipole moment

$$d_e \approx 10^{-22} \text{ e} \cdot \text{cm}.$$

However, the probability of violation of T -invariance in decay of K^0 mesons, which is a manifestation of the weak interaction, amounts to about 10^{-3} . Therefore it is natural to expect in the electron an electric dipole moment of the order

$$d_e \approx 10^{-25} \text{ e} \cdot \text{cm}.$$

More rigorous calculations in terms of various models of violation of T -invariance lead to estimates for the electron electric dipole moment lying in the same range of values: $10^{-23} - 10^{-25} \text{ e} \cdot \text{cm}$.^[1]

Repeated attempts have been made to observe the electric dipole moment of the electron, and all previously described experiments can be classified in two groups: In one group the electric dipole moment of the electron itself is determined, and in the other the electric dipole moment of the electron is calculated from the experimentally determined electric dipole moment of an atom. Experiments of the first type include:

1. Experiments on scattering of electrons by ^{12}C .^[2] The rise in the scattering cross section at the scattering angle $\theta \rightarrow \pi$ due to presence of an electric dipole moment in the electron leads to an estimate $d_e < 2 \times 10^{-16} \text{ e} \cdot \text{cm}$.

2. Experiments of the $g-2$ type.^[3] A particle moves in a magnetic field \mathbf{H} along a circular trajectory in a plane perpendicular to \mathbf{H} . In the presence of an electric dipole moment the spin of the particle precesses around the direction of \mathbf{H} and around the direction of $\mathbf{E} = \mathbf{H} \times \mathbf{V}$, as the result of which a polarization component \mathbf{P}_H parallel to \mathbf{H} arises. Measurement of the amplitude of variation of \mathbf{P}_H gives for the electric dipole moment of

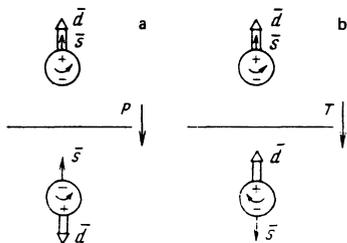


FIG. 1. Operation of spatial reflection (a) and time reversal (b).

the electron $d_e < 4 \times 10^{-16} e\text{-cm}$.

The experiments of the second group require further discussion. The question of the magnitude of the combined electric dipole moment of a system of charged particles whose electric dipole moment is different from zero has been discussed by Schiff.^[4] He showed that on the assumption of identical distributions of charges and electric dipole moments in a system the Hamiltonian of its interaction with a constant electric field in the nonrelativistic case does not contain terms of first order in the electric dipole moment, i.e., the electric dipole moment of such a system is equal to zero. However, in the transition to the nonrelativistic limit in the Dirac equation (fine structure constant $\alpha \rightarrow 0$) if terms of second order in α are retained, the Hamiltonian of the interaction has added to it a term linear in the electric dipole moment. Then, as has been shown,^[5-7] atoms having unpaired electrons acquire an effective electric dipole moment

$$d_a = R d_e, \quad (3)$$

where R is the enhancement coefficient of the electric dipole moment of the electron in the atom and d_e is the electric dipole moment of the electron.

The enhancement coefficient R is a superposition of the enhancement coefficients R_i of the electric dipole moments of the unpaired electrons of the atom. It has been shown by Ignatovich^[6] that R_i increases rapidly with increase of the charge number Z ($R_i \sim Z^4$) and takes on the large values for electrons with small orbital and principal quantum numbers. The combined enhancement coefficient of the electric dipole moment of the electron in atoms varies from element to element over a wide range and reaches values of ~ 130 for atoms of Cs.

The second type of experiment includes experiments with atomic beams. For example, if a beam of Cs atoms is passed through constant parallel electric and magnetic fields, the splitting of the energy levels which arises can be determined by the magnetic resonance method. Experimentally^[8] the electric dipole moment of the Cs atom was found to be $d_{Cs} < (0.8 \pm 1.8) \times 10^{-22} e\text{-cm}$. Hence, taking into account the enhancement coefficient of the electric dipole moment of the electron in the Cs atom the following estimate is obtained for the electric dipole moment of the electron $d_e < 3 \times 10^{-24} e\text{-cm}$. It is evident from the results presented that experiments of the second type are indirect but substantially more sensitive.

Shapiro^[9] has proposed an additional experiment for measurement of the electric dipole moment of an atom. The material under study, which contains atoms with unpaired electrons, is placed in a strong electric field. The electric dipole moments of the atoms of the sample, and with them their spins, are aligned along the direction of the applied field, as a result of which the magnetic flux in the sample changes by an amount

$$\Delta\Phi = 4\pi\kappa d_a S E' / \mu_a, \quad (4)$$

where d_a is the electric dipole moment of the atom of

the sample; E^* is the effective electric field strength acting on an atom of the sample; S is the cross-sectional area of the sample perpendicular to the direction of the external field; μ_a is the magnetic moment of the atom; κ is the magnetic susceptibility of the sample. The creation of superconducting quantum interferometers, which have a high sensitivity to change of the magnetic flux, provided a real possibility of searching for the electric dipole moment of the electron in an experiment of this type.

An important aspect in preparation of the experiment described was the choice of the sample, which must satisfy the following requirements: 1) high concentration of atoms having unpaired electrons, 2) largest possible enhancement coefficient of the electric dipole moment of the electron in the atom, 3) high magnetic susceptibility, 4) low electrical conductivity and high dielectric strength, and 5) absence of parasitic effects.

The experiment was carried out in a nickel-zinc ferrite, which has a relatively high electrical strength—up to 2kV/cm, extremely high resistivity at helium temperature, uncompensated magnetic moments of Fe^{+3} ions: $\mu_{\text{Fe}^{+3}} = 4\mu_B$,^[10] and in view of the cubic lattice (with an inversion center) has no linear magneto-electric effect,^[11] which can imitate the effect of an electric dipole moment. The magnetic permeability of this ferrite at helium temperature, unfortunately, is low, approximately 11.

In the experiment an electric field E was applied to a pellet prepared of nickel-zinc ferrite (diameter 1 cm and thickness 1 mm) and placed between the plates of a parallel-plate capacitor. The end plates of the sample, after polishing, were covered with an In-Ga alloy to assure reliable contact with the capacitor plates. The change in magnetic induction arising was recorded by means of a superconducting quantum interferometer, the arrangement of which has been described previously.^[12]

A certain difficulty in the present experiment results from the transfer of magnetic flux from the sample to the interferometer probe. In operation with an ordinary two-coil single-contact probe of the Zimmerman type,^[13] which has a self-screening coefficient of $\sim 10^{-3}$, it is possible to use for this purpose a superconducting flux transformer. Use of such a transformer turns out to be desirable for samples of large volume. However, experiment shows that large samples are difficult to mount satisfactorily in such a way as to adequately avoid vibration. In our case the increase in volume of the sample also leads to a significant increase in the working voltage, which is inconvenient from the technical point of view, and in addition the primary coil of the transformer, which is wound on the sample, greatly distorts the electric field, reducing its effective value. For these reasons we avoided use of a superconducting flux transformer and used a single-coil probe in the experiment, similar to that described by Zimmerman *et al.*,^[13] the sensitivity of which to change in the external magnetic field is significantly higher than the sensitivity of the ordinary self-screening probe.

In order to increase as much as possible the coupling of the sample with the probe of the interferometer, the end of the probe was polished and pressed firmly against the grounded plate of the capacitor. The sample and the probe were placed together in an ampoule over which was applied a superconducting screen made of lead foil and having a bottle shape (Fig. 2). The attenuation of the external magnetic field for this screen was very high, amounting to about 10^8 . The ampoule was immersed in a helium bath and, after the end of the cooling process for the sample and ampoule, the measurements were carried out.

The electric dipole moment of the Fe^{+3} ion, according to the results of the present experiment, can be defined as

$$d_{\text{Fe}^{+3}} = \frac{\mu_{\text{Fe}^{+3}} \Delta\Phi}{E^* S 4\pi\kappa k} \quad (5)$$

Here $\mu_{\text{Fe}^{+3}} = 4\mu_B$ is the magnetic moment of the Fe^{+3} ion, $\Delta\Phi$ is the change in magnetic flux through the interferometer probe arising on application of an electric field to a sample of area S , and E^* is the strength of the effective electric field acting on the ion in a cubic crystal lattice; according to Kittel^[14]

$$E^* = E(2 + \epsilon)/3 \quad (6)$$

(E is the strength of the electric field applied to the sample). To determine the effective electric field strength E^* it was necessary in addition to measure the dielectric permittivity ϵ of the ferrite. Measurements showed that for the nickel-zinc ferrite at low temperatures and a frequency ~ 100 Hz the value is $\epsilon = 2.2 \pm 0.2$.

To determine the electric dipole moment from Eq. (5) it is necessary to know also the coefficient $4\pi\kappa k$ (k is the coefficient of coupling of the magnetic flux of the sample and the interferometer probe, which is determined by the experimental geometry). To measure the coefficient $4\pi\kappa k$ we used the following procedure. The interferometer probe was placed in calibrated Helmholtz coils which produced a uniform magnetic field with a strength

$$H = aI_1, \quad a = 0.90 \pm 0.05 \text{ Oe/A} \quad (7)$$

and the transfer coefficient k_1 of the external magnetic

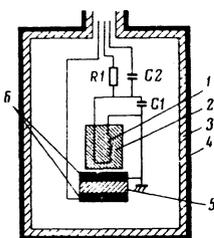


FIG. 2. Internal arrangement of the ampoule containing the superconducting quantum interferometer for measurement of the electric dipole moment of the electron: 1—modulation coil, oscillator circuit coil; 2—interferometer probe; 3—ampoule jacket; 4—superconducting shield; 5—ferrite; 6—capacitor plates.

field to the probe was measured:

$$k = \frac{\Phi_1}{S_p a I_1} \quad (8)$$

Here S_p is the opening area in the single-coil interferometer probe; I_1 is the current in the circuit of the Helmholtz coils which produced a change in flux in the probe by an amount Φ_1 .

The measurements showed that the coefficient was $k_1 = 0.95 \pm 0.08$. We then placed the ferrite sample in the field of the coils in such a way that the geometry reproduced the geometry of the experiment on measurement of the electric dipole moment of the electron, and recorded the current I_2 in the Helmholtz coil circuit which produced the same change in magnetic flux Φ_1 in the probe. In this case

$$\Phi_1 = I_2 a (k_1 S_p + 4\pi\kappa k S), \quad (9)$$

from which

$$4\pi\kappa k = k_1 S_p (I_1 - I_2) / S I_2. \quad (10)$$

As the result of the calibration we obtained a coefficient value $4\pi\kappa k = 0.25 \pm 0.03$.

Presence in the interferometer and ferrite of $1/f$ noise does not permit measurements of the electric dipole moment to be made in a circuit with direct current. In the experiment described an electric field of 1 kV/cm was applied to the ferrite sample in the form of pulses of alternating polarity with a frequency of about ~ 30 Hz. The generator of these pulses served simultaneously as a standard for a digital synchronous detector,^[15] to the input of which was fed the output signal from the interferometer (Fig. 3). Counting circuits permitted the time constant of the synchronous detector to be increased to several hours.

The result of a statistical analysis of 40 measurement cycles whose combined time was 3.5 hours turned out to be

$$\Delta\Phi = (4.65 \pm 4.88) \cdot 10^{-6} \Phi_0,$$

which on conversion to the magnetic field recorded in the experiment gives about 3×10^{-11} Oe. Hence we have for the electric dipole moment of the Fe^{+3} ion

$$d_{\text{Fe}^{+3}} = (4.2 \pm 6.0) \cdot 10^{-23} e \cdot \text{cm}.$$

Taking into account an enhancement coefficient R

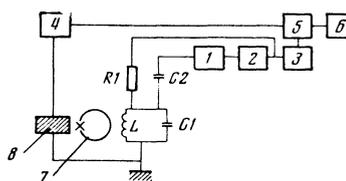


FIG. 3. Block diagram of apparatus for measurement of the electric dipole moment of the electron: 1—interferometer amplifier; 2—integrator; 3—amplifier; 4—rectangular pulse generator; 5—digital synchronous detector; 6—counting circuit; 7—interferometer probe; 8—sample.

=0.52 of the electric dipole moment of the electron in the Fe^{+3} ion,^[6] we obtain the following estimate of the electric dipole moment of the electron:

$$d_e = (8.1 \pm 11.6) \cdot 10^{-23} \text{ e} \cdot \text{cm}.$$

This result is significantly inferior in accuracy to the result of the beam experiment,^[8] but nevertheless in our opinion it presents definite interest, first of all as a result of the fact that the estimate was obtained by an independent means and secondly in that the conclusion of absence of an electric dipole moment of the electron at this level is made on the basis of absence of an electric dipole moment of the atom, which is measured with a higher accuracy.

The problem of further increasing the accuracy in measurement of the electric dipole moment of the electron in an experiment of the type described is not simple. The prospect of a substantial increase in accuracy as the result of an increase of sensitivity of the apparatus or as the result of increase of the measurement time appears unlikely, since the high field sensitivity achieved at the level 10^{-11}G is apparently limited simultaneously by several noise sources which have large time constants: 1) change in the helium level in the cryostat and the associated slow drift of the parameters of the apparatus; 2) increase of the level of interference in the daytime and penetration of pickup through the shields; 3) microvibrations of the probe in the field of the shields, and so forth.

The possibility of a significant increase in sensitivity as the result of choice of a different type of ferromagnetic material is not clear. In any case, our attempts to carry out experiments with the compounds EuO and EuS , which promised an improvement as the result both of a higher coefficient of enhancement of the electric dipole moment and as the result of a higher magnetic permeability at helium temperature, were not

crowned with success as the result of the high conductivity and low electrical strength of these compounds. About ten other ferrites and ferroelectrics showed at helium temperature a low permeability and either a low electrical strength or a high electrical conductivity.

The authors are sincerely grateful to F. L. Shapiro and V. K. Ignatovich, who proposed the idea and who stimulated setting up the present experiment, and also to V. M. Lachinov, A. V. Sermyagin, and A. Yu. Sukhanov for assistance in preparing the electronic apparatus.

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Translated by Clark S. Robinson