The Electric Dipole Moment of Elementary Particles.

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Summary. — The detection of electric dipole moments (EDM) of elementary particles is discussed and a new limit to the size of the electron EDM is presented ($\lesssim e \cdot 1.5 \cdot 10^{-15} \text{cm}$). This result is used in a discussion of recent observations of positronium annihilation.

1. Introduction.

It is still of considerable interest in the testing of time-reversal invariance and parity conservation to attempt to detect the electric dipole moment (EDM) of an elementary particle. The existence of an EDM implies non-invariance under time reversal and non-conservation of parity (1-5) and its absence under

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a severe test is a sensitive indication of invariance of the particle under space reflection or time reversal (*).

Smith, Purcell and Ramsey (1) in an atomic beam resonance experiment have set an upper limit to the electric dipole moment of the neutron. Their result is $D_n < 10^{-29}$ cm where $D_n$ multiplied by the electric charge gives the dipole moment. Since we know that parity is not conserved, we may regard this measurement as showing that $|F|^2 \cdot |G|^2 < 3 \cdot 10^{-13}$, where $G$ is the probability amplitude for parity mixing (which may be large), and $F$ is the relative amplitude non-invariant under time reversal (*).

Motivated by the desire to find some difference between the muon and the electron other than the rest mass, a search has been made for a muon electric dipole moment with the following result (5):

$$D_\mu \lesssim 10^{-15} \text{ cm}.$$  

A discussion (7) of the effects of a possible electron electric dipole moment in the spectroscopy of the hydrogen atom led to the results (this applies equally well to the proton):

$$D_e \lesssim 10^{-13} \text{ cm}.$$  

Recent reports (7) of the observation of effect proportional to $\sigma \cdot E$ in positronium have led us to a further examination of this question. We call attention in this note to three points:

i) Many proposed experiments designed to detect the electric dipole moment of charged particles are based on the incorrect notion that it is, in practice, possible to apply an electric field to such a particle without the consequent free acceleration implied by Newton's second law.

ii) There exist in the literature, data on the behaviour of free electrons which enable a more sensitive limit than (2) to be found for the electron EDM. This type of experiment may be improved by an additional order of magnitude.

iii) The limit thus set makes it extremely unlikely that intrinsic electric moments are responsible for the $\sigma \cdot E$ effect observed in positronium.


(*) Alternatively, $|E|^2 < 3 \cdot 10^{-13}$, where $E$ is that amplitude which introduces both parity and time-reversal mixing.


2. - Analysis of some incorrect experiments.

Many experiments have been performed or proposed for the measurement of the EDM of charged particles. These generally run into a difficulty which does not exist for neutral particles (1). The problem caused by the charge is simply that to measure an EDM one must apply an electric field at the particle in order to generate an interaction energy for the parameter being observed. A charged particle cannot exist unaccelerated in an electric field. However, charged particles in matter have time-averaged motions which are either rest or uniform (drift) velocity with respect to the applied electric field. Such arrangements have essentially no sensitivity to EDM. The essential reason is that all forces acting on the particle in matter are electrical. For example, the mobility of ions in liquids is well known to be of the order ~ some cm/s per kV/cm of applied field. Charged particles, e.g. ions in the liquid, move at constant velocity in zero average field since the electric drag exerted by the medium exactly equals the applied field. Thus, for example, proposals to observe a shift in the resonant frequency in nuclear magnetic resonance carried out in the presence of a strong electric field, i.e. observing the parameter $d$ in $(\mu \cdot H + d\sigma \cdot E)$, fail because the nucleus shifts to the new minimum in the total electric potential which it experiences. Quantum mechanical considerations do not alter the conclusion that the charged particle must be accelerated by the applied field in order to detect the EDM (*).

3. - EDM of the free electron.

It happens that an experiment has been performed for quite a different purpose which has considerable sensitivity to the electron EDM. This is the anomalous $g$-factor experiment of Pidd, Louisell and Crane (9). In this experiment electrons polarized normal to a uniform magnetic field are caused to execute a large number ($\sim 10^7$) of orbital revolutions in a magnetic field. The vertical plane precession induced by the supposed EDM builds up only for a single half-period of the anomalous moment precession before decreasing again, since thereafter the spin points in the opposite sense in the orbit plane. However, no significant reduction in polarization is observed thereby setting

(*) W. Paul however notes that a second order effect may be observed in a strong electric field gradient. In this case the resultant electric field is proportional to the EDM times the field gradient.

a limit on the electric dipole moment equal to that of the anomalous magnetic moment \((v/c \approx 1)\):

\[
D_e \lesssim \frac{\alpha}{2\pi} \left( \frac{\hbar}{mc} \right),
\]

\[
\therefore D_e \lesssim 3 \cdot 10^{-14} \text{ cm}.
\]

A quite different calculation can be made using the results of this experiment. An electric dipole moment of magnitude \(\varepsilon\) times the anomalous magnetic moment would change the anomalous precession period by a factor \(\approx 1 + \varepsilon^2/2\). This can be seen by treating the EDM precession in the electric field \((v/c) \times H_0\) as if a rotating magnetic field of magnitude \((\varepsilon v/2 \pi)(v/c) \times H_0\) were applied and \(\text{EDM} = 0\). In the CS rotating with the cyclotron frequency we observe two stationary orthogonal fields: \((\varepsilon v/2 \pi)(v/c) \times H_0\) and \(H_0 = (\omega/\gamma) = (\varepsilon/2 \pi) \times H_0\). Since this experiment agrees with measurements of the anomalous moment of the bound electron \((7)\) and with theory to within at least \(10^{-2}\) of the anomalous moment, we find immediately that

\[
(3) \quad D_e \lesssim 1.5 \cdot 10^{-15} \text{ cm}.
\]

A further increase in sensitivity can be obtained by a direct analysis by Mott scattering of the out-of-plane polarization for electrons which have been stored in the magnetic field for \(\frac{1}{4}\) and \(\frac{3}{4}\) periods of the anomalous precession. A measurement to \(1^\circ\) would yield a sensitivity \(D_e \approx 10^{-16} \text{ cm}\).

**4. \(\sigma \cdot E\) effect in positronium.**

In this experiment, an effect is observed when positronium is formed by polarized positrons in a 15 kV/cm electric field \((\ast)\). The effect (a change in the detected rate of 2-quantum annihilation) has the symmetry \(\sigma \cdot E\). We only comment here on the impossibility of this effect being due to intrinsic EDM of the elementary particles as limited by (3) (we invoke the CPT theorem here only to similarly restrict the EDM of the positron). The argument is independent of the details of the experiment and is made as follows. The maximum interaction energy produced by the electric field is, using (3)

\[
eD_e E \lesssim (5 \cdot 10^{-18})(10^{-15})(50) = 3 \cdot 10^{-23} \text{ erg}.
\]

The corresponding angular frequency of the free oscillations between eigenstates of the perturbed system is thus

\[
\omega \sim \frac{eD_e E}{\hbar} \lesssim 3 \cdot 10^4 \text{ s}^{-1}.
\]
Since this corresponds to a period considerably longer than the lifetime of triplet positronium ($\sim 10^{-7}$ s) the maximum amplitude of such a presumed intrinsic EDM effect is

$$\lesssim (10^{-7})(4 \cdot 10^4) = 4 \cdot 10^{-3}$$

which is far from the 5\% effect observed. This is certainly an absolute maximum, since detailed calculation of matrix elements, symmetry considerations, etc., can only reduce the effect. Thus, if the effect should turn out to actually have the symmetry $\sigma \cdot E$ (and not be a $p \cdot E$ effect masquerading as $\sigma \cdot E$ because of the $\sigma \cdot p$ correlation in weak interactions (\textsuperscript{8})) it would have to be attributed to the interactions involved in positronium formation and decay.

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RIASSUNTO (\textsuperscript{*})

Si discute la rivelazione dei momenti di dipolo elettrico (EDM) delle particelle elementari e si ottiene un nuovo limite della grandezza dell'EDM dell'elettrone ($\lesssim 1 \cdot 1.5 \cdot 10^{-18}$ cm). Si usa tale risultato nella discussione di recenti osservazioni dell'annichilamento del positonio.

\textsuperscript{*} Traduzione a cura della Redazione.