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ON LIMITS DETERMINING THE POSSIBILITY OF DETECTING RARE FRACTIONAL CHARGES

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Abstract

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PHYSICS

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ON LIMITS DETERMINING THE POSSIBILITY OF DETECTING RARE FRACTIONAL CHARGES

(Presented by Academician Ya. B. Zel' dovich on 21 II 1967)

The method now being developed for searching in solids for rare stable quarks possessing a fractional charge (relative to the electron) makes it possible to detect a single quark in a particle containing $10^{16} \div 10^{17}$ nucleons ([1-3]). In these experiments a modification of Millikan' s method is used, in which a diamagnetic particle suspended by means of a nonuniform magnetic field has discrete positions of equilibrium in an electric field for different excess charges of the particle. The mass of the particles is several orders of magnitude greater than the masses of drops in Millikan' s experiments. It is clear that the upper limit of the mass of a particle in which a single quark can still be detected follows from the condition

$$\frac{e}{3}E \gg \sqrt{4\varkappa T H \Delta f}, \tag{1}$$

where E is the electric-field strength; e is the electron charge; $\varkappa$ is Boltzmann' s constant; H is the coefficient of friction coupling the particle to the laboratory; T is the absolute temperature and Δf is the frequency band. Since the magnitude E can be determined from frequency and phase, $\Delta f = 2/\tau$ ([4]), where τ is the time for extracting the signal corresponding to the force $\frac{e}{3}E$ from Brownian fluctuations. It follows from relation (1) that it is desirable in experiments to have H as small as possible and τ as large as possible. In the experiments already carried out ([2,3]) the value of H is relatively large; as will be seen below, the mass of the particles is considerably smaller than possible, and one can detect a single quark corresponding to a significantly larger number of nucleons.

Let us suppose that it is possible to set up an experiment under conditions of weightlessness and that the test particle is subjected to the fluctuational action of molecules of a highly rarefied gas; then condition (1) will have the form

$$\frac{e}{3}E \gg A\sqrt{\frac{64}{3\sqrt{2}}\pi^{1/2}a^2\mu^{1/2}(\varkappa T)^{3/2}n\tau^{-1}}, \tag{2}$$

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Fig. 1

Figure 1: Fig. 1

where a is the radius of the particle (if its form is assumed to be approximately spherical); μ is the mass of gas molecules; n is their concentration; A is a dimensionless multiplier, of the order of several units and dependent on the chosen level of detection reliability (for the magnitude A, see in more detail ([5]). Taking $\tau = 10^2$ sec, $\mu = 3{\cdot}10^{-24}$ g, $T = 100°$K, $n = 10^9$ cm^{-3}, $E = 60$ kV/cm, we obtain $a \simeq 3.5 \cdot 10^4$ cm. In other words, for substances with density of the order of 3 g/cm^3 it is, in principle, possible to detect a single quark corresponding to $3 \cdot 10^{33}$ nucleons (mass $m = 5 \cdot 10^{-14}$ g). However, the displacement of such a "particle" caused by the force $\frac{e}{3}E$ is too small:

$$\Delta x = \frac{e}{3} E \tau^2 (2m)^{-1} \simeq 3 \cdot 10^{-19} \text{ cm},$$

which is substantially smaller than the macroscopic displacements resolvable by optical and radio-engineering methods ($\sim 10^{-12}$ cm ([6,7])). If m is determined on the basis of the attained level of the technique for measuring small displacements, then for a particle in weightlessness one could detect a single quark corresponding to $10^{30} \div 10^{32}$ nucleons, which is 15–14 orders of magnitude greater than the resolving power achieved.

Let us note two circumstances important for the further discussion. It is known that under terrestrial laboratory conditions a body can be suspended in vacuum by means of an electromagnet controlled by a tracking system. For the torsional motion of the body the friction (and, consequently, the fluctuating forces) does not exceed the friction of the residual gas down to a vacuum $p \sim 10^{-8}$ mm Hg [8]. This means that, if it were possible under terrestrial conditions to measure not the force $\frac{e}{3}E$, but its moment applied to a body suspended in this way, then for a massive body one could satisfy condition (2) (at present, masses $m \sim 25$ kg "hang" in displacement suspensions).

Fig. 1

The second important circumstance is the following: the distribution function of the charge on a well-conducting body is determined only by the shape of the body' s surface and by the relative position of the electrodes near the body; moreover, this rule is preserved also in the case where the charge of the body is equal to one electron, or to one quark, or to a smaller quantity, regardless of the part of the body in which this charge is placed. It is clear that this statement is valid to within fluctuations of surface charges, whose role will be estimated below in a concrete example.

Let us now suppose that, with the aid of an electromagnet and a tracking system, a torsion pendulum made of a well-conducting material is suspended in vacuum so that one of its arms is near the plane of symmetry of a plane electric capacitor

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(see Fig. 1). The test body, in which the presence of a quark is assumed, is placed inside the conductor (a "Faraday cage"). The magnitude of the charge falling on the arm kd of the pendulum is not difficult to estimate from the capacitance of this arm with respect to the plates of the capacitor,

$$C_{kd} \simeq L \left(\ln \frac{a}{b}\right)^{-1}$$

(see the notation in the figure). For $L = 1$ cm, $a = 1$ cm, $b = 1 \cdot 10^{-3}$ cm, $C_{kd} \simeq 1$ cm, i.e., of the same order as the self-capacitance of the "Faraday cage" if its radius is $R \sim 1$ cm. If there is a unit quark in the test body, while the pendulum as a whole is electrically neutral to within one electron, then a force

$$F \simeq \alpha \frac{e}{3} E,$$

will act on the arm kd, where α is a constant factor of order $0.3 \div 0.2$ (a parameter of the setup), depending only on the ratio of the capacitance C_{kd} to the rest of the pendulum. It is important that in a preliminary calculation there is no need to know the value of α, since the system registering small oscillations of the pendulum can be calibrated by measuring the force that swings the pendulum when its charge is changed by one electron (analogously to how the particle mass was determined in experiment [2]).

Taking into account the estimates given above, it is clear that under such conditions one can reliably detect a force

$$\alpha \frac{e}{3} E,$$

assuming the total mass of the pendulum to be of order $1 \div 10$ g, if one proceeds from the fluctuation limitations (relations of type (2)) and from the limitations imposed by the minimum registered displacements. As an example, we note that in gravitational experiments on a torsion pendulum with an ordinary tungsten suspension and mass $m = 50$ g, it is possible to distinguish a variable force

$$F = 1.2 \cdot 10^{-7} \text{ dyn}$$

(if $\alpha = 0.3$; $E = 2 \cdot 10^2$ CGSE, then

$$\alpha \frac{e}{3} E = 1 \cdot 10^{-8} \text{ dyn}.$$

It is not difficult to show that the magnitude of the fluctuations of the charge on the beam of the pendu-

the quantity $\sqrt{\Delta q^2}$ for the values given above will be relatively small:

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$$\sqrt{\overline{\Delta q^2}} \simeq L \left(\ln \frac{a}{b} \right)^{-1} \sqrt{4\varkappa T \rho b^{-2} \tau^{-1}}, \qquad (3)$$

where T is the temperature of the pendulum; ρ is the resistivity of the material from which the pendulum is made; τ is the time required to extract the fully determined signal from the noise. Relation (3) is valid for sufficiently low modulation frequencies of the field voltage E, for which the condition

$$L^{-2} \left(\ln \frac{a}{b} \right) \omega_{\text{mod}}^{-1} \gg \rho L b^{-2}.$$

is satisfied. If one sets $\rho = 5 \cdot 10^{-6}\ \Omega \cdot \text{cm}$ (the resistivity of tungsten), $\tau = 10^3$ sec, $T = 300^\circ$ K, $L = 5$ cm, $a = 1$ cm, $b = 1 \cdot 10^{-3}$ cm, then $\sqrt{\overline{\Delta q^2}} \simeq 2 \cdot 10^{-12}$ CGSE, which is substantially smaller than $e/3 = 1.6 \cdot 10^{-10}$ CGSE.

Let us briefly consider parasitic effects which could imitate a quark in the realization of the experiment under discussion. The largest parasitic effect that could cause imitation of a fractional charge in the experimental arrangement under consideration may be caused, just as in experiment ([2]), by the presence of a static electric dipole moment of arm kd, having a component in the direction of the axis. Such a dipole moment may be caused by a contact potential difference if the torsion pendulum is made of different metals. But even when the torsion pendulum is made of a homogeneous (impurity-free) metal, its different parts, because of possible differences in surface treatment, will have different potentials (the so-called e.m.f. of cold working), whose difference may reach units of millivolts. A dipole moment of arm kd, interacting with the nonuniform electric field of the capacitor, imitates the presence of a fractional charge in such a torsion pendulum. For the most unfavorable case, when half of the arm kd has a potential U relative to the other, one can obtain the following majorizing estimate for the imitating charge q_{im}:

$$q_{\text{im}} = \frac{1}{E} \int\limits_L P_x \frac{\partial E}{\partial x}\, dy \simeq \frac{2}{\pi} \frac{\Delta a}{a} U b \ln \left(\frac{L}{a} \right), \qquad (4)$$

where P_x is the x-component of the linear density of the dipole moment along the arm kd. Taking in (4) $U = 3 \cdot 10^{-2}$ V, $\Delta a = 5 \cdot 10^{-4}$ cm, $L = 5$ cm, $a = 1$ cm, $b = 1 \cdot 10^{-3}$ cm, we obtain $q_{\text{im}} = 2 \cdot 10^{-11}$ CGSE. Thus expression (4) makes it possible to estimate the requirements on the accuracy of manufacture and centering of the torsion pendulum relative to the plane of symmetry of the electric capacitor. It can be shown that other possible effects imitating fractional charges in such an experiment are weaker than that considered above.

Summarizing the considerations given above, one may conclude that the achieved resolving power of 10^{-17} quarks per nucleon in experiments ([1–3]) is not a limit, and that, with present-day experimental technique, a resolving

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power of order $10^{-24} \div 10^{-25}$ quarks per nucleon is apparently attainable in Millikan-type experiments. Apparently, in order to obtain still greater resolving power, it is also expedient to combine experiments of this kind with methods for enriching matter with quarks, similarly to how this was done in the experiments ([9]).

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