AN UPPER BOUND ON THE NUMBER OF QUARKS CONTAINED IN SOME SOLIDS

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Three series of experiments have been performed in search of fractionally charged rare particles, making use of an improved method. None of the experiments has revealed a statistically significant deviation of the charges from integers, corresponding to a quark concentration of less than 10^{-17} quarks per nucleon. Difficulties of the method are considered. Consequences of the results in relation to the structure of hadrons are discussed.

1. EXPERIMENTAL RESULTS

In this paper we list the results of an experiment with the purpose of detecting in solids the presence of rare fractionally charged stable particles. The method used in the experiment, as well as some preliminary data have been described in their essence in a previous paper[1].

In the first series of experiments[1] effects have been observed which could have been caused by fractional charges. As was indicated in[1], one of the causes which could imitate fractional electric charges might be the presence of a static dipole moment p of the particle which in a inhomogeneous electric field behaves like a charge $q_{\text{im}} = (p/E)(\partial E/\partial r)$. In a new series of measurements reported in the present paper, an improved installation has been used for the determination of the minimal (in absolute value) charge of the graphite particles. After the particle was introduced into the magnetic potential well in the manner described in[1], the capacitor was gradually moved in such a manner that its plates remained in the same plane. That part of the capacitor plates which was covered by a thin layer of graphite powder (thickness of approximately 100 μ) was at about 30–40 mm from the mobile particle. As a result of this the magnitude of $\partial E/\partial r$ near the particle was about two orders of magnitude smaller than in the first series of experiments[1].

After this change in the experimental method, no results beyond the limits ±0.1e were found in any series of experiments.

The results of the measurements of minimal absolute values of the graphite particles are listed in Table I. The right column contains the masses of the particles, the left column lists the results of measurements and the confidence limits at a 0.99 likelihood level. The electron charge has been set equal to unity. The first fifteen particles are ordinary graphite. The particles from No. 16 to No. 23 are from graphite which has been treated previously in the following manner: 1 gram of graphite powder (particle size 20–30 μ) was mixed with 10 cm³ of water. This quantity of water was the residue from the evaporation of at least 100 liters of water. Under continuous stirring the graphite water mixture was slowly evaporated. The additional dry residue was of the order of 0.5 g. In accord with the recommendations of[2], this should have led to an essential enrichment in quarks of the graphite powder.

The particles No. 24 to No. 36 consisted of a mixture of graphite with rock meteorite (approximate mass ratio 1 : 0.3). The meteorite substance was initially dissolved in a weak solution of fluorhydric acid to which the graphite powder was added. Then the mixture was dehydrated slowly(1).

It can be seen from the results listed in Table I that with the exception of a single case (particle No. 30 with q = −0.08e ± 0.052e) the minimal absolute value of the electric charge is statistically indistinguishable from zero. The total mass of graphite subjected to measurements in the present series of experiments was about 7×10^{-7} g. In the preceding experiments, involving measurements on a mass of 2.4×10^{7} g, six cases were observed which simulated fractional charges. It is extremely unlikely that this difference is accidental.

Thus one should draw the conclusion that in the conditions of the first series of measurements[1] one has really observed simulated fractional electric charges produced by static dipole moments in the particles in the presence of a significant gradient of the electric field. Taking into account the total mass of the particles on which measurements were performed, as well as the method of mixing, one can reach the conclusion that

Table I

Particle No.	$q(e=1)$	$m \times 10^{-9}$, г	Particle No.	$q(e=1)$	$m \times 10^{-9}$, г
1	0.000±0.003	8.9	19	−0,020±0.047	13,0
2	−0,002±0,01	10,2	20	+0,09 ±0,19	21,0
3	0.000±0,02	6.9	21	−0,07 ±0.17	26.0
4	+0.001±0.006	11,0	22	−0,05 ±0,08	37,0
5	+0,02 ±0.04	27.0	23	−0.04 ±0.27	27.0
6	+0,013±0,023	25,0	24	+0,02 ±0,07	18,0
7	+0.001±0.008	14.0	25	−0,04 ±0,13	23.0
8	+0.019±0.022	24.0	26	−0.07 ±0.12	27,0
9	−0,004±0,016	19.0	27	+0,08 ±0.15	34.0
10	0,000±0,002	5.6	28	−0,04 ±0.14	25.0
11	+0.004±0.005	9,6	29	−0,06 ±0.25	55,0
12	0,000±0,001	3,9	30	−0.08 ±0.052	19.0
13	0,000±0.004	9.5	31	−0.04 ±0.07	15.0
14	+0,001±0.002	4,6	32	−0,06 ±0,13	16,0
15	+0,001±0.002	4,5	33	+0,07 ±0.24	21.0
16	−0.044±0.09	13.0	34	−0,04 ±0,14	25.0
17	−0.004±0.29	32,0	35	−0,04 ±0.07	15.0
18	−0.030±0.056	14.0	36	+0.04 ±0,08	17.0

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(1) The authors would like to use this occasion to express their gratitude to I. P. Vinogradov and T. M. Chubukova, which have made available the solution of meteoritic substance.

there are no quarks in the substances investigated, to an accuracy of 1 quark per 10^{17} nucleons. The negative result of our experiments agrees with the result of[3], referring to a total mass of 10^{-8} g of meter. Assuming that when the water was evaporated all the quarks remained in the liquid phase, one may reach an even higher limit for the initially present water, namely 1 quark per 10^{22} nucleons.

The method of statistical treatment of the measurement results was the same as in the first series of experiments[1]. The total number of photographs of particle displacements, used as a basis, for the results listed in the table, was approximately 50,000.

2. METHODOLOGICAL REMARKS

As remarked in Sec. 1, a comparison of the results of the present paper and[1] bears witness to the fact that individual graphite particles have an electric dipole moment of the order of 5×10^{-9} cgs esu for a mass of the order of 10^{-8} g. Such an additional moment correspond to a contact potential difference of 1—2 V between two parts of the surface of the dust particle, and should not be considered as unexpected or unnatural.

In an inhomogeneous electric field the dipole moment gives rise to a force which produces a displacement of the particle. In a strictly homogeneous electric field the dipole moment is subject to a torque which rotates the particle (as long as p and E are not parallel). It is curious that under the conditions of the experiment there is a possibility that there is a mechanism due to which the rotation of the particle leads to its displacement in a manner linear in E. This mechanism is related to the anisotropy of the magnetic properties of graphite. For single crystal graphite the anisotropy is considerable ($\chi = 4 \times 10^{-6}$ along the axis, and $\chi = 22 \times 10^{-6}$ along the two other axes). We do not know the anisotropy of the particles we have utilized.

In the presence of anisotropy at equilibrium and in the absence of the field E the particle aligns itself in such a manner that the axis of minimal χ is parallel to the magnetic field H. After the particle is rotated by the electric field E the principal axes of the tensor χ do not coincide with the direction of the magnetic field. A mixed term $\chi_{12}H_xH_y$ appears in the expression of the magnetic energy. Near the symmetry plane $H_x = a + bx^2$, $H_y = cx$ and consequently in the expression of the energy there appears a term which is linear in x, giving rise to a force along x, i.e. parallel to E, proportional to the rotation angle φ and to the difference $\Delta\chi = \chi_{\max} - \chi_{\min}$.

If the anisotropy of χ is not too small ($\Delta\chi/\chi > r/d$, where r is the particle size, d the pole gap) this anisotropy is responsible for the restoring torque which impedes the rotation.

Here $\varphi \sim |p \times E/H^2\Delta\chi|$ and $\Delta\chi$ cancels in the force expression. For the expected value of $|p|$ this effect is wholly capable of simulating a fractional charge of the order of e/3. It is possible that this effect explains the presence of a "fractional charge" in particle No. 30 ($q = -0.08e \pm 0.05e$).

As the size of the particles increases, one should expect perturbing effects even in a homogeneous electric field and in the absence of an electric dipole moment. These effects are due to induced dipole moments and electrostatic image forces in the condenser plates. These effects are proportional to E^2. They decrease if the particle is placed exactly in the symmetry plane of the condenser, but only up to a certain value of E, when even an exactly centered equilibrium position becomes unstable.

Table II

K	L^P
2	1^+
3	1^-, 3^-
4	1^+, 2^+
5	$(1^-)^2$, 2^-, $(3^-)^2$, 4^-, 5^-
6	0^+, 1^+, $(2^+)^2$, 3^+, $(4^+)^2$, 6^+

In individual measurements with higher values of the field strength E, quadratic effects have been observed: the displacement of the particle to the same side of the equilibrium position (at E = 0) for different signs of E. This effect was larger than what was to be expected from image forces. At the same time the quadratic effect was insignificant in the series of measurements with E = 5 cgs esu/300 V for d = 2 mm. It had no effect on the results, since the coordinate differences of the particles were measured for opposite signs of E, and the terms proportional to E^2 cancelled.

Thus the remarks made above are significant mainly for future improvements of the method.

3. GENERAL CHARACTERISTICS OF THE QUARK PROBLEM

The hypothesis that there are particles of fractional charge (quarks) has resulted from attempts to classify the strongly interacting particles (hadrons = baryons and mesons). It is important to stress the fact that such indirect arguments in favor of quarks have increased in force in the past two years, and the "demand for quarks" has not diminished. High energy scattering experiments and the electromagnetic properties of hadrons were successfully described by quark models. A detailed discussion of the work in this direction goes beyond the framework of the present paper, and we limit ourselves to references to the review articles[4,5]. They stress, in particular, that the quark hypothesis predicts a series of specific facts which do not follow from the theory of SU_3, or SU_6 symmetry, etc, and there is reasonable agreement between these predictions and experiment. The principal difficulty of a realistic naive (to use Gell-Mann's term) quark hypothesis is the fact that there is no dynamical principle explaining why the three quarks are bound most tightly in the state A0 which is completely antisymmetric with respect to permutations of each two quarks (A) with orbital angular momentum L = 0. Forces which depend only on the mutual distance would obviously yield a symmetric ground state S0, which is in complete disagreement with the existence of the octet and decuplet.

One could attribute to pair "exchange" forces a repulsive character in symmetric states and an attractive character in antisymmetric states. Then only the A-states would be bound, but the ground state would be a three-particle state with $L = 1^+$[6,7]. For the harmonic oscillator potential the three-particle problem can be solved completely[8], and the sequence of A-levels listed in Table II is obtained.

It can be seen from Table II that only for K = 6 there appears a level 0^+, which is degenerate with seven other states. The parameter K is related to the energy: $E = (K + 3)\hbar\omega$. The level A0 is situated so high, that it is hard to imagine that a modification of the shape of the potential or perturbations would lower it below all other levels. It seems that three-particle forces are required for a realistic model. If one assumes that such forces are responsible for an equilibrium configuration of three quarks aligned in a straight line, the Regge trajectory of the excited states of the baryons is a rotational spectrum of such a linear triatomic molecule. The dependence of the mass on angular momentum indicates a strong centrifugal elongation of the "molecule" at large angular momenta.

One should admit, however, that adding on assumptions (three-particle forces, linearity of the configuration, or in other models a structure of the type 4q, $\bar{q}$[9]) not only make the model unesthetic, but also forces one to renounce the predictions of the simplest model mentioned above, which were counted on the credit side of the quark model.

On the whole, in addition to successes, the difficulties of quark models have become apparent.

However the principal difficulty is the negative result of searches for quarks both in[10,11] and in the present work.

We recall that present-day cosmological theory predicts a cosmic abundance of quarks of the order of 10^{-10}—10^{-12} per nucleon[12]. Over the past two years since the calculations described in[2] were performed, the theory of the "hot Universe" has been confirmed. It was noted that in cooling down the numbers of quarks and antiquarks must remain approximately equal. If the stable species of quarks is positively charged (+2/3e) then the stable species of antiquarks is negative (−2/3e). In the contrary situation the stable particles are q, $-\frac{1}{3}$e and q, $+\frac{1}{3}$e. In both cases negative particles of fractional charge are among the stable particles, which according to[2] should attach themselves to heavy nuclei, a fact which increases the likelihood of survival of quarks in the course of stellar evolution.

Searches for fractional charges in different substances will be continued. The results obtained so far have essentially a methodical significance. Nevertheless, in addition to the question: "do quarks exsit?" it becomes important to raise another question: "is there a theory that unites the virtues of the quark hypothesis and forbids the real existence of free quarks?".

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