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EXPERIMENTAL SEARCHES FOR FRACTIONALLY CHARGED QUARKS IN MATTER

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THE hypothesis of Gell-Mann[1] and Zweig[2], that there may exist particles with fractional charges $-e/3$ and $+2e/3$ (and $+e/3$ and $-2e/3$ for the corresponding antiparticles), and that hadrons can be constructed from them, at once led to attempts at its experimental verification. Searches for quarks, made with proton accelerators, and also searches for quarks in cosmic rays, have so far given negative results. (A detailed analysis of the situation is given in the article by E. L. Feĭnberg.[3])

There have been three recent experiments on the search for quarks in matter: in air, water, and iron meteorites,[4] and also in graphite.[5,6] The work described in [4], for all of the materials studied, made use of the remarkable property of quarks, that atoms and molecules to which they have attached themselves can never become electrically neutral. The substances studied were passed in gaseous form through a strong electric field, so as to separate out fractionally charged atoms or molecules. In most of the experiments the atoms collected by the electric field were then concentrated on a small platinum wire, which was at a positive potential and retained negatively charged particles. It was assumed that by this method one could separate out atoms or molecules to which quarks with charge $-e/3$ had attached themselves. A quark with charge $+2e/3$ would have an ionization potential of 6.04 eV, and in most cases would be evaporated, mainly in association with an electron or a negative ion. Therefore such quarks should also get onto the platinum wire. A strongly heated negatively charged filament was placed so as to guarantee that quarkic atoms that were evaporated in the much less probable form of positively charged ions would be collected, reevaporated, and returned to the small platinum wire. This wire was then placed in an apparatus which would sublimate the negative ions, accelerate them through a potential difference of 15 kV, and direct them onto the first diode of an electron multiplier; the pulses from the multiplier were registered as a function of the time. In some experiments a 100-inch mass spectrometer was used for the purpose of identifying masses.

Nothing definite can be said about the chemical properties of quarkic atoms, but it can be assumed that noble gases, for example argon, which have acquired a quark with charge $-e/3$ will retain their chemical properties. The only difference from ordinary argon would be an increase of the solubility in water and an increase of the adsorbability by surfaces. In the experiments with atmospheric air a large quantity of air (10^{10}–10^{11} liters in 24 hours) was sent through an electric filter consisting of aluminum tubes of diameter 0.6 cm, the electric field intensity being not less than 350 V/cm (potential 20,000 volts). Any charges separated out were stripped out at room temperature and at temperature 200°C of the aluminum tubes, the separated matter being washed out with an inert gas flowing through the electric field. In order to allow for the possibility that quarkic atoms adhere to atmospheric dust, a quantity of the dust taken from the filters of the laboratory building was examined in the following way: the dust was heated to 400°C and was washed with an inert gas, and then the substance with the inert gas passed through the electric field and all of the charged particles were collected. If the charges adsorbed in small concentration by the surface of the platinum wire are driven off by heating the wire, their intensity should decrease exponentially owing to the decrease of the surface concentration. The functioning of the system for detecting the charges depends on the sign of the accelerating field. If the sign is changed, the evaporation should go on without change, since (this is the basic idea of the experiment) all known substances which form negative ions evaporate essentially only in the form of neutral atoms, so that the surface concentration decreases exponentially, independent of the sign of the field. When the accelerating field is turned on again we should get the intensity of negative ions which corresponds to this exponentially decreased concentration. Substances which form positive ions, for example cesium, behave differently under analogous conditions. When the accelerating field changes sign the concentration on the wire no longer falls, since the substance must evaporate mainly in the form of positive ions, and they cannot get away because of the field. The effect when the field is again reversed is that the counting rate in the detecting system begins from the same level as it had reached at the time it was blocked. Since negatively charged molecules which have combined with quarks cannot become neutral, they must evaporate like cesium. In some of the experiments with air and with dust precisely this sort of effect was observed for the negative ions; but this behavior was observed in only a small number of runs and the reproducibility was poor, this being ascribed by the authors of [4] to uncontrollable meteorological factors. Sea water was studied in great detail. Twenty liters of water were evaporated and the vapor was sent through the electric field, Fields $\geqslant 10^3$ V/cm were used. The salt left behind was heated to 400°C and washed with argon. The charges so separated were collected on a filament, as in the case of the air and the dust. Also in the case of water a strange behavior of the rate of evaporation of negative ions was observed, which can be ascribed to the presence of quarks. It was not, however, possible to identify the mass of the structures responsible for this behavior; the authors state that this would have required a very great amount of time and effort. There were also studies of iron meteorites, but no similar effect is reported for them. Some experiments like those of Millikan were made, with polyethylene spheres 5 μ diameter, which fell through a region in which the atoms collected from air and sea water were retained by an electric field; the hope was that quarkic atoms might accidentally adhere to spheres. The charges of about 1000 spheres were measured, but no case of a fractional charge was observed. Since very little is known about the evaporation of negative ions, the effect found in the experiments may quite as well be due to some unknown negatively charged ions. A table can be used to summarize the results.

The limits on the concentration, which are in sharp contradiction with the estimates made on the basis of the hot model of the universe, [7,8] were obtained by starting from the number of observed particles which were not identified with impurities of known mass. The estimates so obtained must not be regarded with too much confidence, as the authors of the paper also state, since the efficiency with which quarks are extracted as the result of the operations described is entirely unknown. If the extraction is not complete, the concentration of quarks is actually larger than shown in the table. On the other hand, the evaporated particles charged by the field could have had integer charges, and in this case the concentration of quarks is smaller than indicated; in particular, it is possible

Substance	Number of molecules	Limit on number of fractionally charged particles	Concentration per nucleon
Meteorites	10^{19}	10^4	10^{-17}
Air at 200°	$3 \cdot 10^{33}$	10^5	10^{-30}
Air at 25°	$3 \cdot 10^{33}$	10^2	10^{-33}
Dust at 200°	10^{32} (number of molecules in air in the volume from which the dust was taken)	10^6	$3 \cdot 10^{-27}$
Sea water at 200°C	$7 \cdot 10^{26}$	$5 \cdot 10^4$	$3 \cdot 10^{-24}$

that quarks do not exist at all. Thus strictly speaking the concentration shown in the table is neither an upper nor a lower limit, and gives only the order of magnitude of the sensitivity of the experiment.

The electric charges of grains of graphite, which is diamagnetic, were measured in [5]. The method used was that proposed for this purpose in [9,10]. A grain of graphite of size 10—25 μ and with mass $(0.3-2.0) \times 10^{-8}$ g was held in an oscillator-type potential well produced by an inhomogeneous magnetic field $\sim 14-18$ kOe. The grain was between the plates of a condenser, so that the equilibrium position recorded on a photographic film depends linearly on the charge of the grain, for a given electric field; the values of the field were 0.9 kV/cm and 1.5 kV/cm for two different series of measurements, and the sign of the field was frequently reversed. The electric charge of the grain was changed by means of x-radiation. In this way a method was developed and tested in [5] which works well for measuring small values of electric charges and is suitable for the search for quarks. Out of 26 selected grains (7 in the first series and 19 in the second series with somewhat improved experimental conditions) 6 gave distributions of the equilibrium positions of the grains which could be caused by their having fractional charges with the following values: $-0.25e \pm 0.207e$; $+0.334e \pm 0.339e$; $+0.260e \pm 0.09e$; $+0.375e \pm 0.185e$; $-0.296e \pm 0.244e$; $+0.385e \pm 0.182e$.

The values given are ratios of the minimum deflections x_m of the grain to the "value for the electron" x_e, i.e., to the deflection corresponding to one electron. The limits of error correspond to a so-called "confidence interval," i.e., they are about 2.7 times the root-mean-square error. Only the statistical error of the numerator x_m is taken into account, however.

As the authors of [5] state, possible influences of various disturbing factors, and particularly of the interaction of the electric dipole moment of the grain with the not completely uniform field of the condenser, can give deflections corresponding to fractional charges. For the reasons that have been noted one cannot give a statistical estimate of the significance of the concentration of the results around the values $+e/3$ and $-e/3$. The authors do not feel it possible to draw a definite conclusion about the existence or absence of quarks, and confine themselves to an estimate that the concentration of quarks in the graphite sample examined is less than 10^{-16} per nucleon.

Another paper [6] presents preliminary results on the development of the methods for a similar experiment and on measurements of the electric charges of grains of graphite. The charges of five graphite particles of mass $\sim 2 \times 10^{-9}$ g, containing about 10^{16} nucleons, were measured in an electric field ~ 1000 V/cm, and for none of them was there observed a deflection from the equilibrium position which could be caused by the presence of a fractional charge or by other causes.

Since graphite is probably not the best substance in which quarks could occur, it is proposed in further work to make experiments with specimens enriched in quarks, in particular from sea water.

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