In the meantime, we hope that the precision of (a) polarization and asymmetry measurements, (b) deep inelastic ν_μ and $\bar{\nu}_\mu$ scattering experiments which probe the high-y region, and (c) experiments with polarized muon beams will be pushed as far as possible.

(vi) The imposition of manifest left-right symmetry (after appropriate enlargement of the gauge group) renders natural a model recently proposed for muon-number nonconservation.[16] This feature will be discussed elsewhere.

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Electric Neutrality of Matter

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With the use of a new feedback levitation electrometer (with an increase in sensitivity by 10^3 in comparison to our previous graphite experiments) iron objects of mass $\sim 2\times10^{-4}$ g have been explored for fractionally charged quarks and/or a possible electron-proton charge difference. Upper limits found were $N(\text{quarks})/N(\text{nucleons}) < 3\times10^{-21}$ and $(Q_p - |Q_e|)/Q_p < 10^{-21}$. The present "sensitivity" is $\sim 10^7$ times that of the original Millikan experiment.

A grain of matter (initially charged as always happens in practice) is ionized, adding or removing an appropriate number of electrons; will the (residual) charge of the grain become *exactly* zero? In this Letter we present results from the second stage of an experiment[1] aimed at answering the above question. Clearly, an affirmative answer implies that (a) the charges of electron and proton are exactly equal and opposite (if the neutron has zero charge); (b) the grain of matter does not contain any stable particle with fractional charge (e.g., an isolated stable quark with charge $\frac{1}{3}e$ or $\frac{2}{3}e$). Vice versa, any deviation from zero of the residual charge implies that the assumptions (a) and/or (b) are not fulfilled.

The interest in the experiment increases in proportion to our ability to measure heavier and heavier grains. In the first stage of this experiment,[2] we established the neutrality (to a precision of $\frac{1}{20}e$) of grains of graphite having a mass $\sim 2\times 10^{-7}$ g—this is already 2×10^{4} times larger than the typical mass of the original Millikan droplets. This high "sensitivity" is due to a basic difference between our method and that of Millikan: Whereas he used the same electric force both to suspend the droplets and to measure their charge, we use magnetic levitation to suspend our objects and measure the charge by an electric field.

In the first set of experiments, we suspended graphite because its comparatively high diamagnetism at room temperature allows an easy static magnetic levitation. Recently we started a new set of experiments, based on the same principle, to improve further the sensitivity and, at the same time, to explore a larger variety of substances. The latter requirement implied changing the type of levitation: We decided to switch from the diamagnetic levitation to the more elaborate—but more flexible—feedback levitation of a ferromagnet.[3] At present we are exploring small cylinders of iron. We summarize our results so far as follows: Measurements on three iron cylinders (each having a mass $\sim 2\times 10^{-4}$ g) show neutrality for all the three to a precision of $\frac{1}{10}e$. This implies (a) absence of fractionally charged quarks inside the samples of iron explored so that

$$R = N(\text{quarks})/N(\text{nucleons}) < 3\times 10^{-21}; \tag{1}$$

(b) equality of the electron and proton charge[4]:

$$f = (Q_p - |Q_e|)/Q_p < 10^{-21}, \tag{2}$$

with the qualifications carefully described in Ref. 3.

Note that our present sensitivity is 500 times larger than that obtained in the graphite experiment; below we illustrate how this increase has been achieved and what is the presumed ultimate sensitivity of the method; a schematic diagram of the setup is presented in Fig. 1.

We shall assume in the following discussion some familiarity both with the idea of the method and with possible spurious charge effects (those dangerous effects that may also simulate a residual charge even if it is, in fact, zero). The experiment consists of measuring the oscillation amplitude of the object when an oscillating electric field is applied to it. On reducing the charge

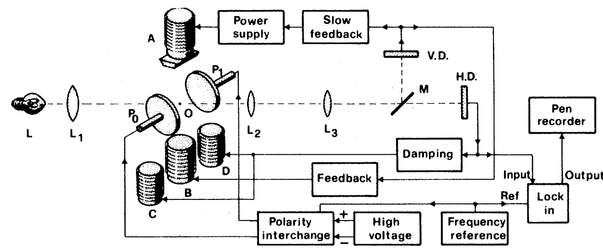

FIG. 1. A schematic view of the apparatus. L is the lamp, L_1, L_2, and L_3 are lenses, M is a half-transparent mirror, H.D. and V.D. are the horizontal and vertical photodiode systems, O is the levitating object, A is the main coil, B is the feedback coil; C and D, damping and auxiliary coils; P_0 and P_1, electric plates. The boxes showing the electronics are self-explanatory. We have not shown the vacuum-tight box containing the plates, the ultraviolet lamp, the TV transfer system, and several other minor details. The figure is not drawn to scale. The distance between the lower part of A and the upper part of B is 15 cm.

of the object by successive ionizations, the oscillation amplitude decreases by "steps"; if the object becomes neutral (and no spurious charge effects are present), the amplitude reduces to zero. The first stage of the ionization (to reduce the charge from, say, 10^5—as is often the case—to a few units) is performed quickly. It is only when the object is left with a few charges that the "step" is measured by expelling (possibly) one electron at a time and recording the successive values of the oscillation amplitude. The object is levitated in a vacuum chamber; and the frequency of the oscillating electric field is selected to be the same as the mechanical resonance frequency of the object in the magnetic valley (of the order of 1 Hz) so that the oscillation amplitude is amplified.

The increase in sensitivity[5] stated above is due to two circumstances: (a) The (horizontal) movement of the object is measured now through the signal produced by its shadow on a differential photodiode system[6] (H.D. in Fig. 1), whereas in the graphite experiment we used a microscope and visual detection on a television screen (we have kept this, but for qualitative purposes only); (b) the signal from the horizontal photodiode is sent to a lockin amplifier locked to the oscillating electric field. By exploiting the stability of the whole system, the lockin amplifier improves, in the usual way, the signal-to-noise ratio. An additional improvement is obtained by decreasing the damping of the oscillation of the object. The control of damping is now performed electronically, whereas in Ref. 2 it was due to the residual air pressure.

The stability of the whole system is remarkable. Since part of the noise is due to the traffic outside, we usually prepare an object so as to have it ready in the evening with one or two electron charges left. We follow this practice especially for "heavy" objects. The 10^{-4}-g mass range was reached only recently; for a long period we used spheres with mass of 3×10^{-5} g. During the night, a few spontaneous changes of charge take place (two on the average); the next morning we find a recording consisting of flat "plateaus," each lasting several hours, with steps due to the changes in charge. Note that by "flat" we do not mean that the noise is irrelevant (often it is still large), but that no long-term drifts are present. This raises a particularly important point: At some stage we found a frequent presence of long-term drifts that could not be attributed to drifts in the feedback.[6] For example, in measurements on the steel spheres we found situations like those of the Fig. 2(a)—this appears to be a perfect example of neutrality to a precision $\frac{1}{40}e$; and almost certainly it is so. However, when the recording was continued overnight (not shown in the figure), a slow drift took place so that the next morning the sphere—which, in this case, had not changed charge—showed an apparent spurious charge of about $\frac{1}{4}e$.

Although the story is too long to be given here, we realized that in order to eliminate these drifts we had either to keep the orientation of the object strictly fixed[7] (small torques can arise under the action of the oscillating electric field) or, preferably, to let our objects spin at a reasonably high frequency (30–40 rotations per second) about a vertical axis. This is what we did (using cylinders); the data of Eqs. (1) and (2) refer to them. The present spinning procedure is far from satisfactory because it often introduces noise. We shall try to improve it, but two points should be stressed: (1) spinning has eliminated all the slow drifts previously present; (2) also it has eliminated any periodic variation of the shadow of the object on the horizontal photodiodes produced by torques due to the oscillating electric field; such variations produce signals simulating a residual charge. A recording of a spinning cylinder is presented in Fig. 2(b).

In addition to the above effects due to torques, we have to consider the spurious charge effects, due to forces, discussed in detail in Ref. 2. An increase in sensitivity such as that obtained here would have been pointless without eliminating, at the same time, these effects, some of which are proportional to the volume of the object.

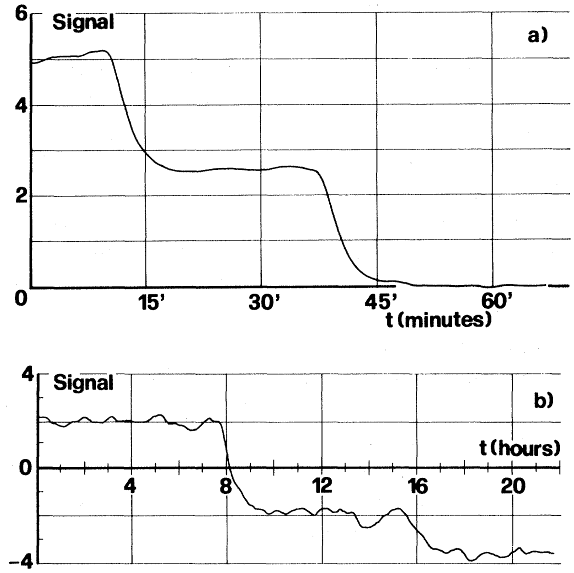

FIG. 2. (a) The changes in charge of a steel sphere having a mass of 3.3×10^{-5} g. The plot shows the sequence of changes in charge $2\rightarrow 1\rightarrow 0$; this sequence took a little more than one hour (the residual charge is zero to $\frac{1}{40}e$, but compare the text for discussion of a subsequent slow drift). (b) A rotating cylinder of mass $\sim 2.5\times 10^{-4}$ g changing its charge from $+1$ to -1 and next to -2; the whole measurement took 22 h. Clearly the residual charge is zero to $\frac{1}{10}e$. There are no drifts. This and the other measurements on spinning cylinders were done at 4-cm relative distance between the plates. [Both in (a) and (b) the signal is the output of the lock-in amplifier expressed in conventional units.]

As shown in Ref. 2, the (force) spurious charge effects decrease (a) if the distance between the plates that carry the electric field is increased; and (b) if the gradient of the electric field is decreased. To satisfy both these requirements it is necessary to have a wide geometry. The decision to switch from the diamagnetic to the feedback levitation was taken having in mind that such technique could in principle allow a wide geometry. As a matter of fact, it was not trivial to achieve good levitation having the object at a distance of 7.5 cm from each coil as it is now; this was finally done using two separate coils (A and B in Fig. 1) to avoid an undesirable induction effect that was present if the main coil and the feedback coil were on the same core. We now levitate the object at the center of a cylindrical vacuum-tight brass box with a diameter of 15 cm; the two plates have a diameter of 11 cm and can be moved up to a relative distance of 4 cm. Note that the feedback system was, in a sense, complicated by our initial use of spheres of diameter $\frac{2}{10}$ mm. We may still use spheres in the future, but for cylinders the same value of $\vec{H}\cdot(\partial\vec{H}/\partial z)$ produces a magnetic force considerably higher (probably now it would be possible to increase to 20 cm the diameter of the box with a corresponding increase in that of the plates).

The gradient of the applied electric field is orders of magnitude lower than that in the graphite experiment, even with the plates at 4 cm. In the nomenclature of Ref. 2, this makes the first term of the Volta spurious force negligible; the dipole force is, in any case, averaged out by spinning (another reason for spinning); the "unbalance" force is small in spite of the fact that now the square-wave electric field is governed by reed relays having opening times of a few milliseconds (the "unbalance" is controlled as in Ref. 2). The only remaining spurious force is the second term $[\propto \vec{E}_a\cdot(\partial\vec{E}_V/\partial x)]$ of the Volta force. Under the assumption that on the plates there are a few patches, each of a size of a few millimeters, this effect should remain below the level of $\frac{1}{20}e$ at a distance between the plates of 4 cm even for the biggest objects examined so far. We add that the plates are pure graphite in order to prevent the formation of oxide layers.

We end with two comments: (1) We feel that the ultimate sensitivity of the method has not yet been reached. The experiment was planned for spheres with mass of 3×10^{-5} g, but the sensitivity in the range $(2-3)\times10^{-4}$ g is reasonably good. A decrease by a factor 3 or 4 in the noise or (less likely) a corresponding increase of the electric field (the present peak-to-peak value is usually 3 kV/cm) would lead us in the milligram range. (2) To obtain the present stability in charge, we had to filter away (by Kodak filters) all the frequencies higher than orange in the light on the object. Without this precaution, the chrome steel spheres, when illuminated in vacuum, expelled electrons at a rate of about seven electrons per minute even when the hardest part of the spectrum had been filtered by means of window glass.[8]

We thank deeply Mr. E. Bozzo, G. Franzone, and O. Rosati for invaluable technical assistance.

Note added.—After submission of this manuscript, measurements with two additional spinning cylinders have confirmed the above results to better than $\frac{1}{10}e$. These five cylinders are all that we have measured at this time.

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[3]As explained in the first footnote of our paper in Ref. 2, this type of levitation was used in connection with the *e-p* charge difference by R. Stover, T. Moran, and J. Trischka, Phys. Rev. 164, 1599 (1967).

[4]A list of experiments on the *e-p* charge difference performed in different ways is given in Ref. 3. At present, our experiment improves by a factor of 2 on the best value listed there.

[5]For a mass of 10^{-4} g, a peak-to-peak electric field of 3 kV/cm and a value of 40 for $N_{1/2}$ [$N_{1/2}$ characterizes the damping (Ref. 2)], the oscillation excursion for one electron charge is, approximately, half a micron. This corresponds to a signal (peak to peak) from the horizontal photodiode of the order 30 mV.

[6]This and other details (at an intermediate stage in the construction) are contained in a report by G. Gallinaro, M. Marinelli and G. Morpurgo, Istituto Nazionale di Fisica Nucleare Report No. INFN AE76/1 (unpublished). A complete paper is in preparation. A paper by one of us (M. Marinelli) will give details on the feedback system.

[7]As it was the case in the graphite experiment (Ref. 2).

[8]At the moment we do not know whether this is typical of the steel chrome spheres or it is so also for the iron cylinders; having recognized for the spheres the need of the filters, we have kept them in the subsequent measurements. Anyway, this technique is appropriate for studying some aspects of the photoelectric effect. Indeed, it seems more convenient than that considered by A. Ashkin and J. Dziedic [Phys. Rev. Lett. 36, 267 (1976)].