Search for Fractional Charges

D. Liebowitz, M. Binder, and K. O. H. Ziock
Department of Physics, University of Virginia, Charlottesville, Virginia 22901
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The results of a search for fractional charges on 24 steel spheres with a total mass of 720 μg are reported. No fractional charges, spurious or otherwise, greater than $0.15e$ were found.

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Among the many techniques employed to search for fractionally charged particles, magnetic levitation of a macroscopic object in an electric field allows one to sample the greatest number of atoms in a single measurement. Both the dynamic magnetic levitation[1,2] and the diamagnetic levitation of superconductors[3] allow one to sample approximately 5×10^{17} atoms in one measurement. A thorough review of the field is presented in a paper by Marinelli and Morpurgo.[2]

The dynamic magnetic levitation method,[4] used in our experiment, works, briefly, as follows (see Fig. 1). The position of a small steel ball of 0.2 mm diam, located underneath an electromagnet, is sensed by a photocell onto which its shadow is projected. The photocell, through an amplifier, drives the magnet coil in such a way that a lowering of the ball raises the magnet current and vice versa. In this way the ball is stably suspended between two capacitor plates. The capacitor plates create an electric field $\vec{E}$ that

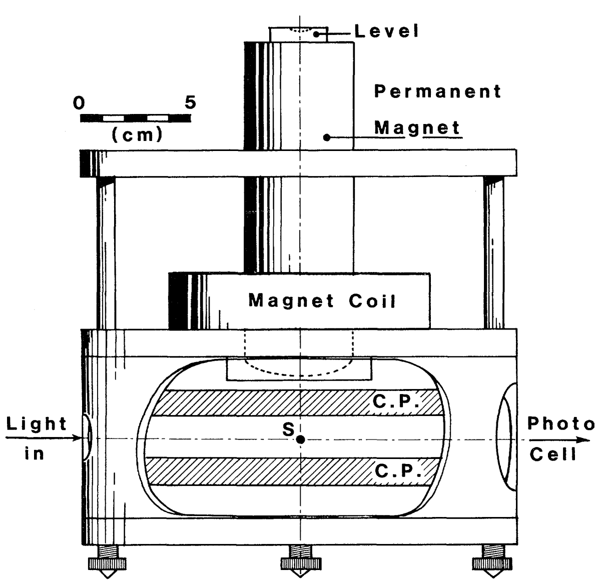

FIG. 1. Schematic of the apparatus. C.P., capacitor plates; S, suspended steel ball.

causes the force

$$\vec{F} = q\vec{E}$$

that we measure in order to determine the charge q on the ball. The electric field (3000 V/cm) alternates with a frequency $\nu = 2$ Hz. If the ball carries a charge there will be an alternating force on the ball that is compensated by the magnetic suspension. This results in the presence of a 2-Hz component in the magnet current which is detected by a lock-in amplifier.

The spurious effects that beset all levitation methods have been discussed in the literature.[1-3] The most intractable among them are due to the patch effect. The patch effect has its origin in the fact that metal surfaces are not truly equipotential surfaces because the work function may vary from place to place by as much as 50–100 mV. When such local variations in the work function (patches) occur on the plates that produce the electric field, they will interact with the induced dipole moment on the test body. This interaction can be distinguished from the effect due to true charges, $\vec{F} = q\times\vec{E}$, only through elaborate procedures.[3]

The patch-dipole interaction can be reduced by increasing the plate-to-plate distance and it can be held constant by minimizing the exposure of the plates to environmental influences.

A patch effect on the test bodies can be shown to cause a much smaller first-order effect (due to interaction with the inhomogeneity of the applied field). However, as both the Morpurgo group[2] and we have found, the presence of patches on the test bodies will lead to their rotation when the electric field is reversed. This rotation changes the orientation of the test bodies in the magnetic field and this in turn can cause forces that cannot easily be distinguished from the true $\vec{F} = q\vec{E}$ effect.[2]

An obvious way to eliminate such spurious forces seems to be to rotate the balls rapidly. Such a rotation should stabilize the axis of the test bodies as well as average the radial component of any spurious force. However, both the Morpurgo group[2] and we have found that spinning the test bodies did not eliminate the spurious residual charges that we observed.

Buckingham and Herring[5] have shown why spinning the balls does not eliminate the spurious effects. Under the influence of a torque due to the applied electric field the balls will no longer tilt but will precess and the net effect will remain the same. Marinelli and Morpurgo[2] therefore carefully measured each individual ball under a variety of field conditions and were able to separate the induced pseudocharges and subtract them.

In this experiment we made use of the fact, pointed out by Buckingham and Herring,[5] that the precession effects can be eliminated by aligning the direction of the electric field with that of the magnetic field and spinning the balls around a vertical axis. Such a vertical geometry requires that considerable attention be paid to the reduction of noise: The force due to the presence of a $\frac{1}{3}e$ net charge on a ball is only about 5×10^{-8} of its weight, which in turn is only 30 μg.

Fortunately the use of horizontal capacitor plates greatly reduces the distance between the suspension magnet and the suspended ball. This makes it possible to generate the levitating field with a permanent magnet as shown in Fig. 1. It is, of course, not possible to suspend an object stably in the field of a permanent magnet but in our new apparatus we are able to adjust the magnet position in such a way that the average current through the magnet coil providing the dynamic equilibrium is zero.

With this new apparatus we have measured a total of 24 balls; most of them twice, once at rest and once spinning around a vertical axis. The balls were spun up by the application of a rotating 2-MHz magnetic field. As a result of the near perfect surface of these steel balls it is not possible to ascertain in each case whether or with what angular velocity a ball is rotating. We have, therefore, scratched the surface of one steel ball and measured its angular acceleration under the influence of the rf field. We found this acceleration to be 30 rev/sec^2. During the course of the experiment we accelerated each ball for 6 minutes, leading to a rate of rotation of ~600 000 rpm.

A simple calculation, confirmed by a measurement, showed that at our operating pressure of approximately 10^{-3} μm, air friction reduces the angular velocity of the balls by no more than 25% during the course of a measurement (1–3 h).

In Fig. 2 we show the result of a typical run. The electrostatic force acting on the ball is plotted as a function of time. The force is given directly in units of the force on a single electron in our standard electric field of 3000 V/cm. The steps at points a and b are due to charge changes by a single electron that we induced by exposing the apparatus to uv light.

Our calibration rests on the observation that, except for small day-to-day variations at the few percent level, we never observed charge changes that were not an integer multiple of the steps shown at points a and b. Indeed, by reducing the uv intensity and using only short exposures we could make sure that charge changes, when they

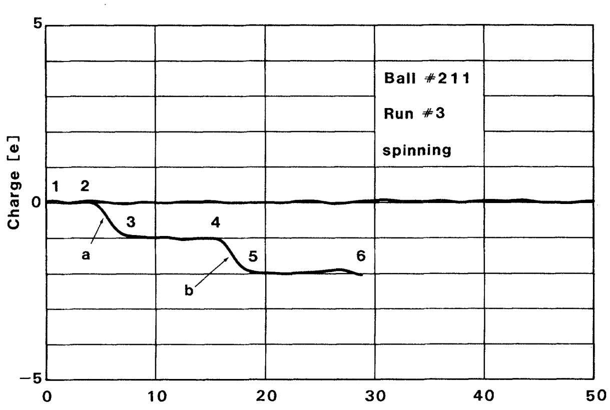

FIG. 2. The charge on a spinning ball as a function of time. The ball starts out neutral at point 1, remains neutral for 50 min. After another 5 min a charge change is induced (point 2); another charge change is induced at point 4.

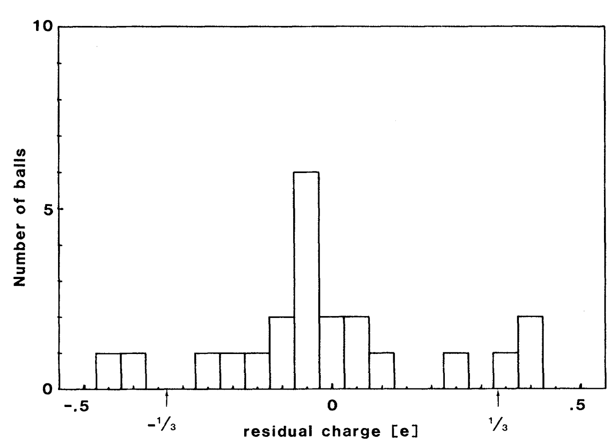

FIG. 3. Frequency distribution of the residual charges on 22 balls (not spinning).

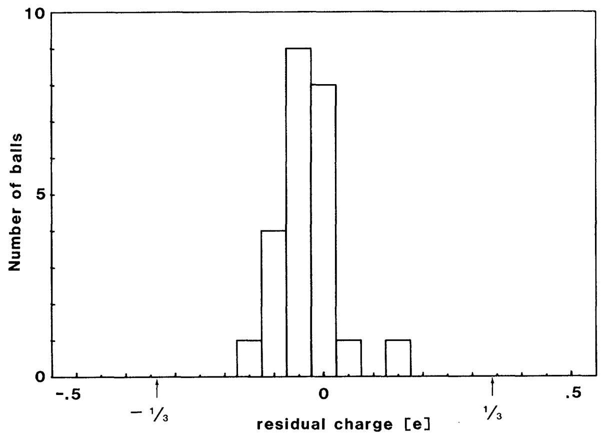

FIG. 4. Frequency distribution of the residual charges on 24 balls (spinning).

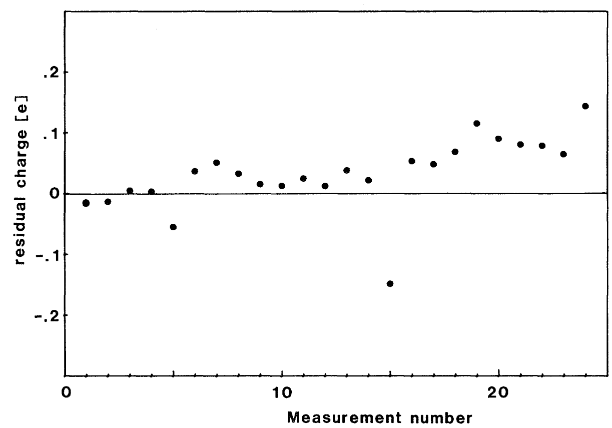

FIG. 5. Residual charges measured on 24 spinning balls displayed in the order in which they were measured.

occurred, were always of the same step size.

The only analysis that we performed on our data was to average the "charge" over the straight sections of a trace; here between points 1 and 2, 3 and 4, and 5 and 6, respectively. The difference of the averages over two consecutive sections always gave the value of the unit charge, or a multiple thereof. The deviation of the actual charges from integer values gave us the "residual charge," an indication of either fractional charges or pseudocharges. For the run represented in Fig. 2, the residual charge was $(0.013 \pm 0.001)e$.

Figure 3 gives a summary of our data for balls that were not spinning. As can be seen there is a substantial peak at $Q=0$. This gives us hope that more careful handling of the balls might eventually suffice to eliminate pseudocharges altogether.

Figure 4 shows the distribution of residual charges for a total of 24 balls, measured while spinning. This includes some balls that were not measured at rest. This distribution is narrower and the largest pseudocharge is now less than $0.15e$. We believe that the larger values of Q are due to a patch effect on the plates, caused by a deterioration of the plate surfaces with time. This is borne out by Fig. 5 which shows the residual charges on the 24 spinning balls in the order in which they were measured. There seems to be a systematic upward trend which is also reflected in the correlation coefficient $C=0.58$.

The deterioration of the plates could have the following cause: Occasionally a ball will drop out of suspension during a measurement. Upon touching the bottom plate, it will become very highly charged and fly to the top plate; there its charge will be reversed and it will shoot to the bottom plate, etc. To make things worse, after such an accident we have to let the vacuum chamber up to atmospheric pressure to retrieve the ball. (During the normal course of events a ball is dropped onto a special holder after a measurement and removed without touching either plate.)

It might be argued that some of our results were due to the presence of fractional charges that were driven off by the slight heating that inevitably accompanies the application of the rf field. We do not believe this to be the case: Figure 6 shows the distribution of the differences

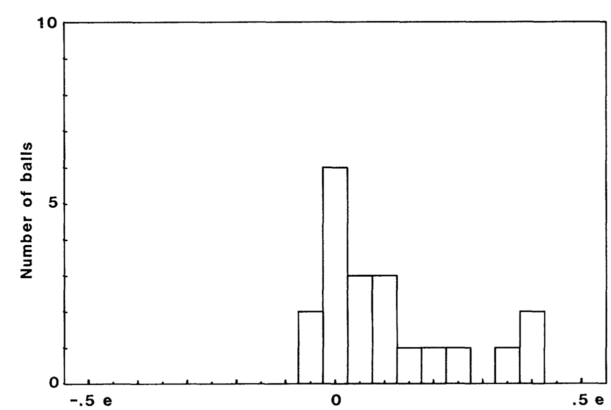

FIG. 6. Frequency distribution of the differences in the absolute values of the residual charge, not spinning and spinning, (20 balls total).

between the absolute values of the residual charge measured before and after the balls were spun up. There is clearly no peak near $Q = \frac{1}{3}e$ to indicate such an effect.

We have measured a total of 24 steel balls, representing a total mass of 720 μg, and have found no evidence for the presence of fractional charges on them. This confirms our contention that the fractional charges that we found in an earlier measurement[1] were indeed spurious. Our new result agrees with that of Marinelli and Morpurgo,[2] who used steel balls of the same size from the same manufacturer. Our results do not contradict those of the Fairbank group[3] who used balls made of a different material.

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