Further Evidence for Fractional Charge of $\frac{1}{3}e$ on Matter

George S. LaRue, William M. Fairbank, and James Douglas Phillips
Physics Department, Stanford University, Stanford, California 94305
(Received 29 September 1978)

We report further evidence for fractional charge of $\sim\frac{1}{3}e$ on niobium spheres. With a modified apparatus in which we can determine all of the background dipole forces we have measured fractional charges of $(0.304\pm0.040)e$ and $(0.345\pm0.035)e$.

In a previous publication, we presented results of a superconducting magnetic levitation experiment which provided evidence for the existence of fractional charge on matter.[1,2] We report here further evidence of fractional charge with an improved apparatus. We have observed two more fractional charges of $(0.345\pm0.035)e$ and $(0.304\pm0.040)e$. A new technique allows us to measure directly the horizontal dipole on the balls. Together with the technique used in the earlier measurements to determine the vertical dipole forces this allows us to show that neither horizontal nor vertical dipole forces could have caused the fractional charges observed in our latest measurements. Calculations indicate that no other electric or magnetic force could have mimicked the fractional charge.

Low-temperature techniques have allowed us to suspend a superconducting niobium ball of $\sim 9\times10^{-5}$ g in a magnetic field between two horizontal capacitor plates. By measuring the response of the ball to an alternating electric field $\vec{E}_A$ applied to the capacitor plates, the force applied to the ball can be measured. The alternating force on the ball in the vertical z direction is

$$F_A=(q_r+ne)E_A-R^3E_A\,\partial E_F/\partial z-\vec{P}\cdot\nabla E_A+F_M+F_Q, \quad (1)$$

where n is the integer charge number, R is the radius of the ball, E_A is the z component of $\vec{E}_A$, $\vec{P}$ is the permanent dipole on the ball, F_M is the magnetic force, and F_Q is the quadrupole force. E_F is the z component of the fixed electric field arising from dipole layers on the plates due to local contact-potential differences.

We have developed a technique which can measure F_A to within $0.01eE_A$.[1] In order to determine if the fractional charges we have observed are not spurious we need to accurately determine all of the background forces. The previous paper showed how the vertical dipole force, $-R^3E_A\partial E_F/\partial z-P_z\,\partial E_A/\partial z$, could be taken into account. We also showed that the magnetic force could not account for the fractional charges observed of $\pm\frac{1}{3}e$. From the known and assumed parameters of the experiment our calculations indicated that the horizontal dipole forces $F_{\mathrm{HD}}=-P_x\,\partial E_A/\partial x-P_y\,\partial E_A/\partial y$ and the quadrupole forces were less than $0.02eE_A$. The magnetic and horizontal dipole forces depend on the magnitude of the horizontal dipole which previously could only be estimated from the measured value of P_z.[3]

We have now developed a techninique to measure directly all three components of the permanent dipole. In order to measure $\vec{P}$, we move a grounded copper sphere with radius 0.25 cm between the plates to positions along the x or y axes ~1 cm from the niobium ball. When E_A is applied symmetrically with respect to ground an alternating dipole is induced on the sphere which creates a large known alternating gradient $\sim10^{-1}$ esu cm^{-3} at the position of the niobium ball and in the direction between the copper sphere and the ball. When the niobium ball is diagonally above the copper sphere, a z component in the gradient is also present. Measurement of the change in F_A when the copper sphere is moved from outside the plates to each of several different positions between the plates enables each component of $\vec{P}$ to be determined. The changes observed in F_A are $\leq 1eE_A$. The values of $|\vec{P}|$ obtained with this technique are $\leq10^{-7}$ esu cm.

As a check on our calculations of ∇E_A from the sphere we determined ΔF_{Batt} (Ref. 1) when the ball was diagonally above the sphere and compared it with ΔF_{Batt} when the sphere was removed. This gave $\partial E_A/\partial z\sim10^{-1}$ esu cm^{-1} in agreement with our calculations.

The measurements of $\vec{P}$ together with an estimate of the maximum horizontal gradients in E_A allow us to calculate the contribution of F_{HD} to F_A. Optically flat and parallel quartz plates were installed for the latest measurements. With $|\vec{P}|=10^{-7}$ esu cm and the maximum gradients that can be produced by the aparallelism of the plates, $F_{\mathrm{HD}}<6\times10^{-4}eE_A$. Applying asymmetrical voltages to the plates with respect to ground pro-

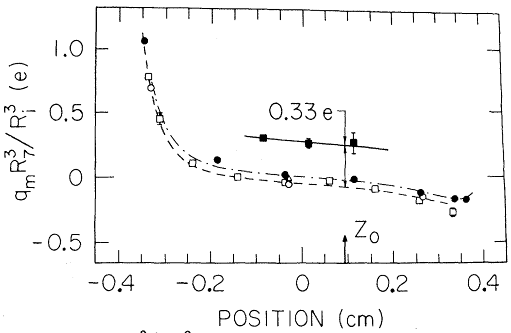

FIG. 1. $q_m R_7{}^3/R_i{}^3$ vs position for the first cooldown. R_i is the radius of ball number i. ($R_7{}^3/R_6{}^3 = 0.957$.) Data are for ball 6, levitation 1 (open triangle), levitation 2 (solid squares, solid line), levitation 5 (open squares, dashed line), and levitation 4 (open circles, dashed line); and for ball 7 (solid circles, dot-dashed line). Only the error bars larger than the size of the points are indicated.

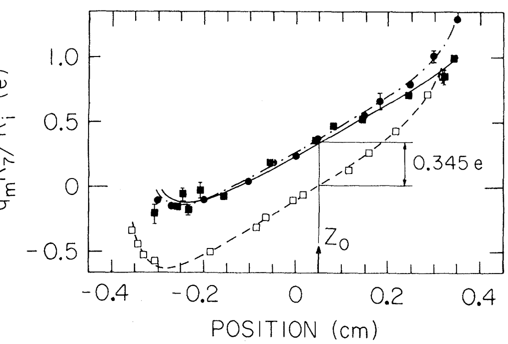

FIG. 2. $q_m R_7{}^3/R_i{}^3$ vs position for the second cooldown. ($R_7{}^3/R_9{}^3 = 0.985$.) Data are for ball 9, levitation 1 (solid squares, solid line); for ball 7 (open squares, dashed line); and for ball 9, levitation 2 (solid circles, dot-dashed line). Only the error bars larger than the size of the points are indicated.

duced no measurable change in F_A, indicating that grounded metal objects outside the plates do not contribute measurably to F_A. Calculations of the alternating gradients from the dielectric plate spacers and high-voltage contacts give $\Delta E_A < 10^{-3}$ esu cm^{-3}. This coupled with the measured value of $\vec{P}$ indicate that $F_{HD} < 0.02eE_A$. Such a gradient is sufficient to explain the asymmetry in ΔE_{Batt} in Figs. 1 and 2.

F_M arises from an interaction of $\vec{P}$ with E_A producing a torque which tends to reorient the magnetic moment due to the trapped magnetic flux. The maximum value of $F_M < 0.01eE_A$ with $|\vec{P}| = 10^{-7}$ esu cm^{-3}.

Within 0.25 cm of the center of the plates the force from either a quadrupole moment or an induced horizontal dipole is less than $0.01eE_A$. Magnetic fields due to the currents which charge up the plates, the changing penetration depth of the superconducting balls in an electric field, etc., contribute $\ll 0.001eE_A$.

For all balls whose horizontal dipole was measured Eq. (1) reduces to

$$F_A = (q_r + ne)E_A - P_z \frac{\partial E_A}{\partial z} - R^3 E_A \frac{\partial E_F}{\partial z} \qquad (2)$$

after eliminating all terms that contribute less than $0.01eE_A$.

As described in Ref. 1, we measure F_A for several values of n and determine F_A for $n=0$. We define $q_m \equiv F_A/E_A(n=0)$. We measure q_m for each ball as a function of position between the plates. We also measure $\partial E_A/\partial z$ at each position by measuring the change in F_A when a fixed electric field E_{Batt} is applied between the plates to induce an additional fixed dipole moment $R^3 E_{Batt}$ to P_z. There is one position z_0 of the ball where $\partial E_A/\partial z$ is measured to be zero. At z_0,

$$q_m = q_r - R^3[\partial E_F/\partial z]_{z_0}.$$

If two balls have identical radii a difference in q_m at z_0 equals the difference in q_r. Such a comparison is valid only if $\partial E_F/\partial z$ remains constant throughout the experiment. This constancy is determined by repeated measurements as a function of position.

Figure 1 shows the results of the first cooldown with the new apparatus. Ball 6 with $R = 0.0140$ cm, which previously had $q_r = +\frac{1}{3}e$,[1,2] was levitated and measured four times with an electric discharge occurring between levitations. The discharges were caused by the following sequential process: (1) field emission of electrons from the ball when E_A was increased above ~13 esu cm^{-2}, (2) amplitude buildup due to increased charge on the ball, and (3) assumed discharge when the ball came near a plate causing the ball to heat up and drop. The residual charge changed by $+\frac{1}{3}e$ between levitations 1 and 2 and then by $-\frac{1}{3}e$ between levitations 2 and 3. No change in the residual charge occurred between levitations 3 and 4. To compare and calibrate the position dependence of q_m we also measured ball 7 (with $R = 0.0138$ cm) which previously had been measured to have $q_r = 0$.[1] Assuming that q_r for ball 7 was still 0, we determined that q_r for ball 6 was 0 on levitations 1, 3, and 4 and $+\frac{1}{3}e$ on levitation

2. The exact values are listed later in this paper. We viewed the ball under a microscope, visually inspected the plates, and observed no damage from the discharges.

For the next cooldown (Fig. 2) the plates were resputtered with copper and a new ball 9 was measured. This ball had been heat treated on a tungsten plate and had a radius $R = 0.0139$ cm. The standard zero ball 7 was measured after which ball 9 was remeasured. The weighted average of $q_m(z_0)$ for the two levitations of ball 9 differ by $(0.345 \pm 0.035)e$ from the q_m of ball 7.

For each cooldown it was found that all of the q_m data could be fitted by an equation

$$q_m = q_r - P_z\, \partial E_A/\partial z - R^3\, \partial E_F/\partial z\,.$$

The lines drawn in Figs. 1 and 2 are least-square fits of this equation to the data. The term $\partial E_A/\partial z$ was determined experimentally from ΔF_{Batt}. The term $\partial E_F/\partial z$ was found from the best fit to the data and was required to be the same for all measurements during one cooldown. For each levitation of each ball the data was fitted with a constant term corresponding to q_r and a vertical dipole term corresponding to P_z. Because all of the data for each run could be fitted well with the same plate term $\partial E_F/\partial z$, the data were considered to be valid.

For the data in the second cooldown shown in Fig. 2 we measured the three components of the permanent dipole of each ball during each levitation. In all three levitations each component of $\vec{\mathrm{P}}$ was less than 10^{-7} esu cm. From the best fit to the data, P_z of levitation 1 differed by $\sim 10^{-7}$ esu cm from P_z for levitations 2 and 3 causing the curves in Fig. 2 to be nonparallel. This agrees with the differences in the measured values of P_z using the copper-sphere technique.

The data in Fig. 2 represents the most definitive data we have obtained indicating fractional charge on matter. All three components of the permanent dipole were measured and found to be less than 10^{-7} esu cm. The complete position dependence of ball 9 was measured and found to be constant on two different levitations before and after a complete measurement on ball 7. The weighted average of the difference between q_r of ball 7 and 9 is $(0.345 \pm 0.035)e$. Table I lists our estimate of the maximum systematic errors from all the known background electromagnetic forces for the data in Fig. 2. These sum to $< 0.083e$.

We have required that the data satisfy the criterion that the plate function remain constant during the measurement of at least two balls in order for the data to be considered valid. If the plate functions change with time because of the presence of a foreign substance on one of the plates, the run is discontinued. The data presented here and in Ref. 1 comprise all of the data which meet the above criterion. The values of the residual charge obtained are shown in Fig. 3 and are listed as follows. Before each value is listed, in brackets, the ball number. Balls 1, 2, 4, 5, and 7 were heat treated on a Nb plate; balls 3, 6, 8, and 9 were heat treated on a tungsten plate. Results reported in Ref. 1 are [1] $(0.007 \pm 0.039)e$; [2] $(0.089 \pm 0.073)e$; [3] $(-0.331 \pm 0.070)e$; [4] $(0.016 \pm 0.030)e$; [1] $(-0.015 \pm 0.054)e$; [3] $(0.060 \pm 0.092)e$; [5] $(-0.034 \pm 0.093)e$; [6] $(0.313 \pm 0.091)e$; [7] $(0.303 \pm 0.023)e$; [8] $(-0.001 \pm 0.026)e$; [6] $(0.327 \pm 0.010)e$.[4] Results obtained since Ref. 1 are [6] $(0.016 \pm 0.024)e$; [6] $(0.304 \pm 0.040)e$; [6] $(-0.029 \pm 0.017)e$; [6] $(0.026 \pm 0.016)e$; [7] $(0.023 \pm 0.015)e$; [9] $(0.325 \pm 0.043)e$; [7] $0e$ assumed.

Initially six of the balls had q_r within experimental error of zero, one of the balls had q_r of $-\frac{1}{3}e$ and two had q_r of $+\frac{1}{3}e$. After handling and washing in acetone and alcohol, the ball with $q_r = -\frac{1}{3}e$ changed to zero. The first ball with $q_r = -\frac{1}{3}e$ remained $+\frac{1}{3}e$ for two different cooldowns, and after scrubbing with acetone, q_r became zero. Subsequently an electric discharge at low temperatures changed q_r of this ball to $+\frac{1}{3}e$ and another discharge changed it back to 0. The final ball with $q_r = \frac{1}{3}e$ has remained $+\frac{1}{3}e$ for two cooldowns of the ball and care was taken not to bring it into contact with any liquids between cooldowns. We conclude from these experiments on nine balls of total mass 7×10^{-4} g that we had fractional charge of $\pm\frac{1}{3}e$ on three balls. We further conclude that the fractional charges are near the surface since they can be removed by washing and can be

TABLE I. Systematic errors for the data shown in Fig. 2.

Force	Maximum error	Comments
F_{HD}	$< 0.02eE_A$	$\lvert\vec{\mathrm{P}}\rvert \leq 10^{-7}$ esu cm
$P_z\,\partial E_A/\partial z$	$< 0.003e$	Measurement error in $\partial E_A/\partial z$
$R^3 E_A \partial E_F/\partial z$	$< 0.03e$	Position errors
Magnetic	$< 0.01e$	
Quadrupole	$< 0.01e$	For $\lvert z\rvert < 0.025$ cm
Other	$< 0.01e$	Induced horizontal, etc.

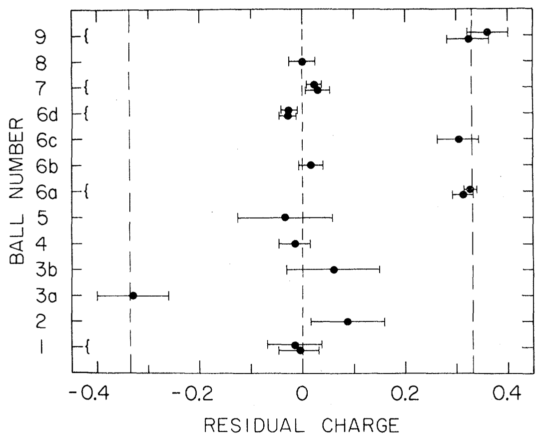

FIG. 3. The residual charge of the nine different balls is shown. Letters following the ball number indicate the chronological order of changes in the residual charge of that ball by approximately $\frac{1}{3}e$. Brackets denote q_r measurements which were nearly the same in different cooldowns of the same ball except for *6d* where they indicate different levitations with a discharge in between. Dashed lines are at $\frac{1}{3}e$ and $0e$. The errors are statistical and represent 1 standard deviation. The weighted average is $(0.001\pm0.007)e$ for the twelve 0's and $(0.325\pm0.008)e$ for the five $+\frac{1}{3}e$'s.

changed by $\frac{1}{3}e$ with an electric discharge.

The niobium balls were initially multicrystalline. After heat treating the balls at 1800° C for 17 h in a high vacuum, measurements using x rays and optical examination of balls cut in half showed that the balls are single crystal. The process of forming single crystals during heat treatment provides a mechanism in which the fractional charges could be trapped on crystal boundaries and carried to the surface as the crystal boundaries move.

These experiments present evidence for fractional charges for the following reasons: (1) We have developed a technique which will measure q_m to an accuracy of $0.01e$ and have demonstrated by measurement that no electromagnetic multipole force can account for the fractional charges observed. (2) All of the residual charges obtained have fallen within experimental error of either 0, $+\frac{1}{3}e$, or $-\frac{1}{3}e$. (3) We have modified the essential parts of the apparatus by inserting optically flat parallel plates, by using different plate surfaces, and by adding an additional support coil to change the magnetic field. All measurements under these different conditions have yielded results consistent with 0 and $\pm\frac{1}{3}e$.

Two room-temperature magnetic levitation experiments have reported finding no fractional charges on 2×10^{-4} g of iron[5] and 10^{-3} g of iron.[6] Garris and Ziock[7] reported the possible existence of fractional charges on twelve steel balls of total mass 4×10^{-4} g. These experiments and the experiment reported here in which we find four fractional charges on 7×10^{-4} g of niobium are not necessarily inconsistent. Together they show that either fractional charges are not uniformly distributed between iron, niobium, and steel, or that there are not very many fractional charges on 10^{-3} g of these materials. No other experiments have looked at the total charge on a larger amount of material. All other experiments that have claimed more sensitivity depend on enrichment procedures and detection methods that cannot guarantee detection.[8]

This work was supported by the National Science Foundation Grant No. PHY76-23559.

[1]G. S. LaRue, W. M. Fairbank, and A. F. Hebard, Phys. Rev. Lett. 38, 1011 (1977).

[2]G. S. LaRue, Ph.D. thesis, Stanford University, 1978 (unpublished).

[3]The values of P_z quoted in Ref. 1 are large by a factor of 2 as a result of an error in calculation.

[4]This was mistakenly reported to be 0.344 in Ref. 1.

[5]V. B. Braginsky, L. S. Kornienko, and S. S. Poloskov, Phys. Lett. 33B, 613 (1970).

[6]G. Gallinaro, M. Marinelli, and G. Morpurgo, Phys. Rev. Lett. 38, 1255 (1977).

[7]E. D. Garris and K. O. H. Ziock, Nucl. Instrum. Methods 117, 467 (1974).

[8]L. W. Jones, Rev. Mod. Phys. 40, 717 (1977).