Evidence for the Existence of Fractional Charge on Matter*

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(Received 8 April 1977)

Accepted without review at the request of Walter E. Meyerhof under policy announced 26 April 1976

We present results of a superconducting magnetic levitation experiment which provide evidence for the existence of fractional charge on matter. Three niobium balls heat-treated on a tungsten substrate were found to have residual charges of $(+0.337\pm0.009)e$, $(-0.001\pm0.025)e$, and $(-0.331\pm0.070)e$. All five niobium balls heat-treated on a niobium substrate had residual charges near zero.

Several unsuccessful searches for fractional charges on stable matter have been reported in the literature.[1-6] Garris and Ziock[7] reported possible fractional charges on iron balls. Identification was made uncertain because of background dipole forces. We report here evidence for the existence of residual charges q_r close to $+\frac{1}{3}e$ and $-\frac{1}{3}e$ on two superconducting niobium spheres heat-treated on a tungsten substrate and levitated by a magnetic field. The experiment is a continuation of the prior work of Hebard and Fairbank.[8-10]

The present apparatus consists of a suspended niobium ball of mass $\sim 9\times10^{-5}$ g which oscillates vertically at a frequency of ~ 0.8 Hz in a magnetic field. The ball is levitated between two horizontal capacitor plates 15 cm in diameter and separated by approximately 1 cm. The position of the ball is sensed by a superconducting pickup coil coupled to a superconducting-interference-device magnetometer. The charge on the ball can be changed at will with movable $\beta+$ or $\beta-$ emitters. A loading mechanism allows a ball to be inserted into or removed from the low-temperature region for measurement. The plates can be accurately moved with respect to the ball while maintaining a fixed separation.

A 2000-V peak-to-peak square wave is applied to the plates in phase quadrature with respect to the oscillations of the ball. Every 50 cycles the phase of the square wave is reversed. The difference between the time rate of change of the envelope of the ball's oscillation before and after reversal is independent of the damping and proportional to the charge.[11] Calibration of the difference in units of the electron charge is established by changing the charge on the ball by 1 electron charge.

Figure 1 shows a typical distribution of the measured charge plotted against frequency of occurrence. The smallest separation between the centroids of the peaks represents 1 electron charge. The centroids of the peaks can be described by an equation of the form $q_m + ne$, where q_m is the measured residual charge, n is an integer, and e is the electron charge. q_m is the sum of the residual charge q_r and additional terms from electric or magnetic dipole forces. The crucial problem in identifying fractional charges is to account for these additional terms.

First consider electric dipole effects by decomposing the electric field in the vertical z direction acting on the ball into two parts $E=E_A+E_F$, where E_A is the alternating applied field and E_F is a smaller fixed field. Dipole layers on the plates due to local contact-potential differ-

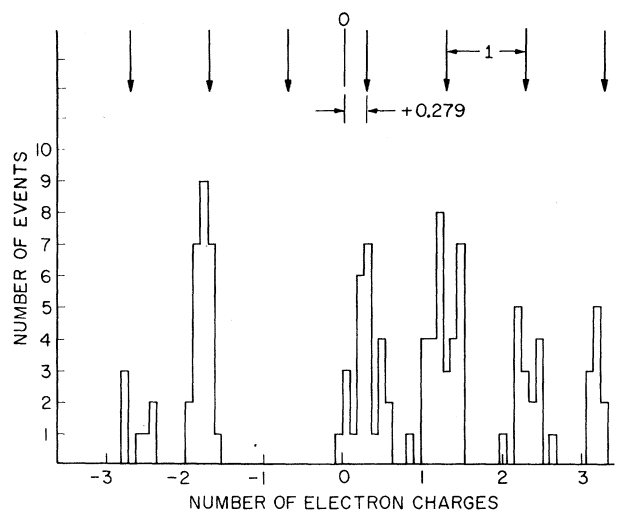

FIG. 1. Composite data of ball 6 taken at two positions ($z=0.0$ cm and $z=0.1$ cm) using copper-surfaced plates illustrate the separation of charge states. The offset represents an apparent nonzero residual charge. These data were collected in approximately 4 h and are only a small fraction of all the data taken.

ences create the constant nonuniform field E_F. Dipole layers on the ball create a permanent electric dipole on the ball, the z component of which, P_z, remains constant since trapped magnetic flux determines the ball's orientation. The z component of the total alternating force in cgs units on the sphere, excluding terms smaller than $0.02eE_A$, is

$$F_A = q_r E_A - P_z\,\partial E_A/\partial z - R^3 E_A\,\partial E_F/\partial z. \quad (1)$$

The last two terms, like the charge force $q_r E_A$, are odd in E_A and are the only dipole forces of appreciable size which can mimic a charge.

The alternating field gradient $\partial E_A/\partial z$ can be measured experimentally by applying a bias voltage from a battery to create a fixed electric field $E_{\rm Batt}$ between the plates. This adds a fixed dipole moment $R^3 E_{\rm Batt}$ to P_z and a fixed field gradient $\partial E_{\rm Batt}/\partial z$ to $\partial E_F/\partial z$. When the field $E_{\rm Batt}$ is reversed, the change in force

$$\Delta F_{\rm Batt} = F_A(E_{\rm Batt}) - F_A(-E_{\rm Batt}) = -4R^3 E_{\rm Batt}\,\partial E_A/\partial z \quad (2)$$

is a direct measure of $\partial E_A/\partial z$. An experimentally determined curve of $\Delta F_{\rm Batt}/E_A$ vs z is shown in Fig. 2 for runs C and D. The effect of the unknown dipole P_z in (1) will be proportional to $\partial E_A/\partial z$ and can vary from ball to ball. There is one position z_0 of the ball determined from measurements of $\Delta F_{\rm Batt}$ where $\partial E_A/\partial z$ is zero.

In Table I, we report data on eight different niobium balls in chronological order. To improve the Q of oscillations, five balls were heat-treated at 1850°C on a niobium substrate ($Q \gtrsim 8000$) and three on a tungsten substrate ($Q \gtrsim 1000$). The estimated maximum departure of the balls from perfect sphericity is about 1% of the radius. Capacitor plates were made of titanium sputtered onto Pyrex (runs A and B) and with an additional copper layer in runs C and D. The use of copper was suggested by the results of Lockhart, Witteborn, and Fairbank.[12,13] They found a low-temperature transition to a state in which the gradients in the electric field due to patch effects on the surface of a copper tube were completely absent. We have also found no evidence for patch-effect fields from the copper plates. Since this greatly simplifies the analysis of the data, we will present first the data from runs C and D.

In Fig. 3 the measured residual charge $q_m = F_A/E_A$ is plotted as a function of the ball position between the plates. The arrow at $z = z_0$ indicates where q_m is unaffected by any permanent electric dipole on the ball. Since the radii of the balls are nearly the same, the effect of the last term in (1) will be the same for each ball. Therefore, the difference in q_m for two balls at $z = z_0$ will be equal to the difference in q_r. Such a comparison is valid only if $\partial E_F/\partial z$ from the plates remains constant throughout the experiment. Ball 6 was measured in both runs to confirm this constancy.

If $\partial E_F/\partial z = 0$, the experimental dependence of $\partial E_A/\partial z$ can be used to perform a least-squares fit to $q_m(z)$ by adjusting q_r and P^* for each ball. The optimum values of $q_m(z = z_0)$ and of P_z are given by q_m^* and P_z^* listed in Table I. If $\partial E_F/\partial z = 0$, $q_m^* = q_r$. The best-fit curves are drawn

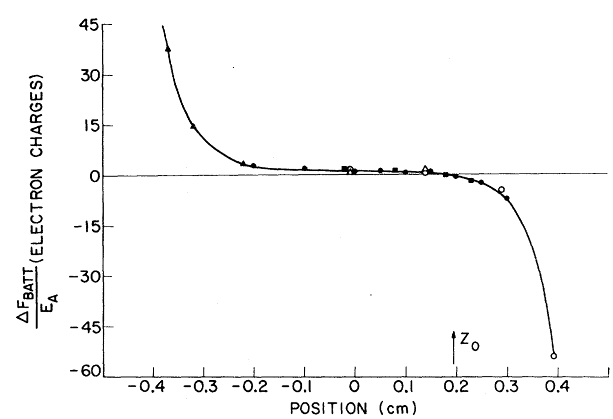

FIG. 2. Experimental determination of $\Delta F_{\rm Batt}/E_A$ for runs C and D where $E_{\rm Batt} = 325$ V/cm. The positions and symbols correspond to those in Fig. 3. The solid line agrees with theory (Ref. 11).

TABLE I. Tabulated values for eight different balls. The characters in the code correspond, respectively, to ball (1–8), run (A–D), niobium (N) or tungsten (W) heat-treating substrate, and titanium (T) or copper (C) plate surface. P^* is in units of 10^{-9} esu cm.

Ball	R (cm)	q_m^* (e)	P^*	q_r (e)
1*ANT*	0.012	−0.094 ± 0.010	70	−0.007 ± 0.039
2*ANT*	0.014	−0.063 ± 0.030	1	+0.089 ± 0.073
3*AWT*	0.014	−0.476 ± 0.026	700	−0.331 ± 0.070
4*ANT*	0.011	−0.080 ± 0.011	0	−0.016 ± 0.030
1*BNT*	0.012	−0.167 ± 0.019	−200	−0.015 ± 0.054
3*BWT*	0.014	−0.195 ± 0.034	−300	+0.060 ± 0.092
5*BNT*	0.014	−0.289 ± 0.035	−200	−0.034 ± 0.093
6*CWC*	0.014	+0.313 ± 0.019	−200	+0.313 ± 0.019
7*CNC*	0.014	+0.030 ± 0.023	−20	+0.030 ± 0.023
8*DWC*	0.014	−0.001 ± 0.026	20	−0.001 ± 0.026
6*DWC*	0.014	+0.344 ± 0.010	−400	+0.344 ± 0.010

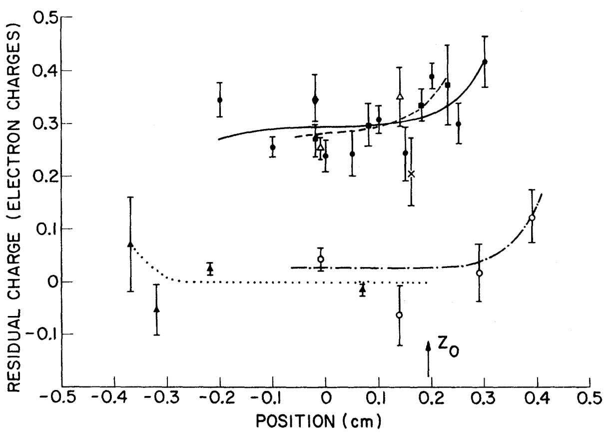

FIG. 3. The q_m-vs-z curves for each ball in runs C and D are least-squares fits by $q_m = q_m^* + P^* \partial E_A/\partial z$. Symbols are for ball 6$C$ (solid circles, solid line), with magnetic field reversed (open triangles), with $E_A = 1000$ V/cm (cross); for ball 6D (solid squares, dashed line), with $E_A = 1000$ V/cm (solid diamonds); for ball 7C (open circles, dot-dashed line); and for ball 8D (solid triangles, dotted line).

through the data in Fig. 3. The weighted average of the $q_r = q_m^*$ for ball 6 obtained in runs C and D is $(0.337 \pm 0.009)e$.

We have shown above that electric dipole forces cannot account for the nonzero q_r measured in runs C and D. In addition, calculations show that forces due to higher-order electric moments cannot have an appreciable effect on these measurements.[11] A nonzero q_r can also be mimicked by an alternating magnetic force which can arise from a change in orientation of the permanent magnetic moment of the ball due to the alternating electric field interacting with the permanent electric dipole $\vec{P}$. When ball 6 is levitated, a magnetic field of approximately 300 G penetrates the ball as determined from the magnetic field and magnetic field gradient required for levitation. Hysteresis of the magnetization curve indicates that the 300-G field is pinned. With the 300 G pinned in the ball, the maximum change in orientation due to the torque $\vec{P} \times \vec{E}_A$ is about 2×10^{-5} rad. If the magnetic force were to mimic a charge of $0.01e$, the magnetic support force would have to be at least $0.08R$ from the center of mass and the electric dipole moment would have to be its maximum reasonable value 7×10^{-7} esu cm, produced by a 1.5-V contact-potential difference across two hemispheres of the niobium ball. That this error in charge would in fact be smaller than $0.01e$ seems likely; the magnetization curve of ball 6 indicates that the penetration of magnetic field is symmetric since the magnetic field first enters the ball at a magnetic field near H_{c1} of pure niobium. The ball was rotated about an axis perpendicular to the magnetic field without flux penetration just below H_{c1}. Even if the unlikely assumption is made that all the 300 G is trapped at one edge of the ball, the maximum error in the measured charge is $\sim 0.1e$. These arguments seem to rule out the magnetic dipole force as an explanation for the residual charges observed.

In runs A and B, when the plates had a titanium surface, the last term in (1) was significant. The values of q_m/R^3 for four balls in run A are presented in Fig. 4(a). At $z = z_0$, $q_m = q_r + R^3 \partial E_F/\partial z$. If $q_r = 0$ on every ball, then q_m/R^3 measured at z_0 is a constant and equal to $\partial E_F/\partial z$. Although this is approximately true for three balls, it is

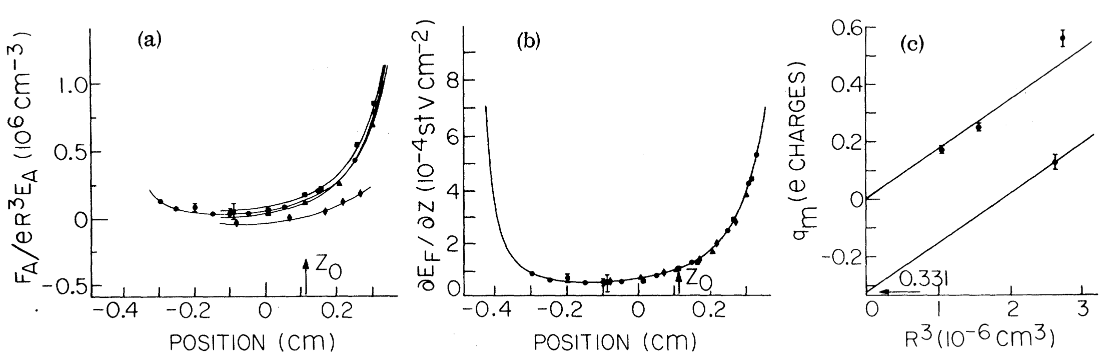

FIG. 4. (a) Position-dependent data for run A. Solid lines are best fits by (3). Ball 1 (solid circle), ball 2 (solid square), ball 3 (solid diamond), ball 4 (solid triangle). (b) Experimental determination of $\partial E_F^*/\partial z$ for run A. Symbols have the same meaning as defined in the caption of (a). (c) The R^3 dependence of q_m in run A at z_0. The upper three points are fitted by a straight line through zero having a slope equal to $\partial E_F/\partial z$. A line with the same slope drawn through the lower point indicates an offset of $-0.331e$.

not true for the other. We will show that $q_r \sim -\frac{1}{3}e$ for this ball.

It was found that all the q_m data could be fitted by an equation of the form of (1):

$$q_m = q_m^* + P^* \partial E_A/\partial_z + R^3 \partial E_F^*/\partial z, \qquad (3)$$

where $\partial E_F^*/\partial z = \partial E_F/\partial z - C$, $q_m^* = q_r + R^3 C$, and C is a constant. A function of z with two fitting parameters was found to describe $\partial E_F^*/\partial z$ well. These two parameters were required to remain the same for every ball in run A but each ball was allowed to have a different dipole parameter P^* and constant term q_m^*. Figure 4(b) illustrates how well the $\partial E_F^*/\partial z$ plate-gradient term fits the data for all four balls after subtracting out each ball's individual constant term q_m^* and dipole term P^*.

At z_0, $q_m = q_r + R^3 \partial E_F/\partial z$, and it is plotted for each ball against R^3 in Fig. 4(c). If every ball has $q_r = 0$, then the points should fall on a straight line through zero. This is obviously not the case. Under the assumption that there are no fractional charges less than $\sim 0.1e$, a least-squares-fitted line is drawn through zero which would make three of the balls have a q_r near zero. The slope of the line is $\partial E_F/\partial z$ at z_0. As shown in Fig. 4(c), the q_r on the other ball is then $(-0.331 \pm 0.070)e$. The best-fit parameters along with the calculated residual charges are given in Table I for these four balls.

The same titanium plates were cleaned and interchanged for run B. The analysis of the data is in every way similar to the analysis for run A. All of the data at z_0 could be fitted by a straight line through zero similar to the one in Fig. 4(c). The q_r of ball 3 which was $(-0.331 \pm 0.070)e$ in run A changed to $(0.060 \pm 0.092)e$ after handling, while q_r of ball 1 did not change.

In summary, we report evidence for fractional charges on matter close to $\pm \frac{1}{3}e$ apparently transferred to niobium from a tungsten substrate, which we cannot explain by magnetic or electric multipole forces. Additional data will be taken and included in a more complete article.

We are particularly indebted to B. Cabrera, H. A. Fairbank, J. N. Fields, R. P. Giffard, W. O. Hamilton, J. M. Lockhart, J. M. J. Madey, M. S. McAshan, B. J. Neuhauser, R. H. Roy, M. A. Taber, J. W. Wikswo, and P. W. Worden, Jr., who have provided valuable assistance during different stages of this project. We would like to thank the S.H.E. Corporation and M. B. Simmonds in particular for measuring the magnetization curves.

*Work presently supported in part by the National Science Foundation and originally supported in part by the U. S. Office of Naval Research.

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