Observation of Fractional Charge of (1/3)e on Matter

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Measurements on niobium spheres which show unambiguously the existence of fractional charges of $\frac{1}{3}e$ are reported. Charge changes of $\frac{1}{3}e$ on particular spheres when they contact other surfaces are continually observed. Of 21 new measurements, four charges of $+\frac{1}{3}e$, four of $-\frac{1}{3}e$, and thirteen of zero are found. Extensive measurements and critical analyses have assured us that the background forces are either negligible or have been measured and taken fully into account.

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In previous publications[1-4] we have presented results of a superconducting magnetic levitation experiment giving evidence for the existence of fractional charge. Since then we have continued to modify and improve the experiment and we report here 21 new measurements. These and earlier measurements are shown in Fig. 1. The data fall into three groups which have weighted averages of $(-0.343\pm0.011)e$ [5], $(+0.001\pm0.003)e$ [25], and $(+0.328\pm0.007)e$ [9] where the number of measurements is given in brackets.[5]

We can measure the force on the ball to within $0.01eE_A$ in several hours. By taking the background forces fully into account the residual charge can be determined to within the errors shown in Fig. 1. We are forced to conclude that fractional charges with magnitude $\frac{1}{3}e$ must exist.

Out of 26 repeat measurements, we have observed 11 residual-charge changes, in every case of $\pm\frac{1}{3}e$. These changes occurred only between levitations, when a ball contacted other surfaces. All 13 measurements of ball 6 have been consistent with $0e$ or $\pm\frac{1}{3}e$ with nine changes of $\frac{1}{3}e$. All eight measurements of ball 10 have been consistent with 0.

The apparatus is kept at 4.2 K and consists of a superconducting niobium ball (mass $\leq 9\times10^{-5}$ g) suspended magnetically between two horizontal capacitor plates. The ball's position is sensed by a SQUID (superconducting quantum interference device) magnetometer and its charge can be changed at will with movable β^+ and β^- emitters. The plates can be accurately moved with respect to the ball while a fixed separation is maintained between them.

By measuring the response of the ball to an alternating electric field $\vec{E}_A$ between the capacitor plates, the force applied to the ball can be measured. The alternating force on the ball in the vertical z direction is given by

$$F_A=(q_r+ne)E_A+\vec{P}_A\cdot\nabla E_F+\vec{P}_F\cdot\nabla E_A+F_M+F_Q, \tag{1}$$

where q_r is the residual charge, n is the integer charge number, E_A and E_F are the z components of $\vec{E}_A$ and $\vec{E}_F$ ($\vec{E}_F$ is the fixed electric field arising from contact potential variations on the plates), and $\vec{P}_F$ and $\vec{P}_A$ are the permanent and induced electric dipole moments on the ball. F_Q is the force due to an electric quadrupole and F_M is the force due to the tilting of the magnetic moment by the torque $\vec{P}_F\times\vec{E}_A$.[6]

The measured residual force $F_A{}^r$ is defined as the value of F_A for $n=0$ in (1). To correctly determine the residual charge from the residual force, we need to accurately determine all of the background forces.

We have shown before[1-4] and confirmed by various measurements, including measurements of $\vec{P}_F$ and $\partial E_A/\partial z$, that with one exception all background forces are negligible at the position z_0 where $\partial E_A/\partial z=0$. The exception is the force due to a fixed electric field gradient $\partial E_F/\partial z$ acting on the ball's induced alternating electric dipole moment $\vec{P}_A$. At positions different from z_0 a small force arises from P_z, the vertical component of $\vec{P}_F$, times the alternating field gradient $\partial E_A/\partial z$. The residual alternating force is

$$F_A{}^r(z)=q_rE_A+R^3E_A\partial E_F(z)/\partial z+P_z\,\partial E_A(z)/\partial z, \tag{2}$$

where we have put $R^3\vec{E}_A$ for $\vec{P}_A$, for a sphere of radius R. $\partial E_A(z)/\partial z$ is measured experimentally[1,2] by adding a constant voltage to E_A.

To determine $\partial E_F/\partial z$ as a function of z we measure, for every levitation, $F_A{}^r(z)$ for various val-

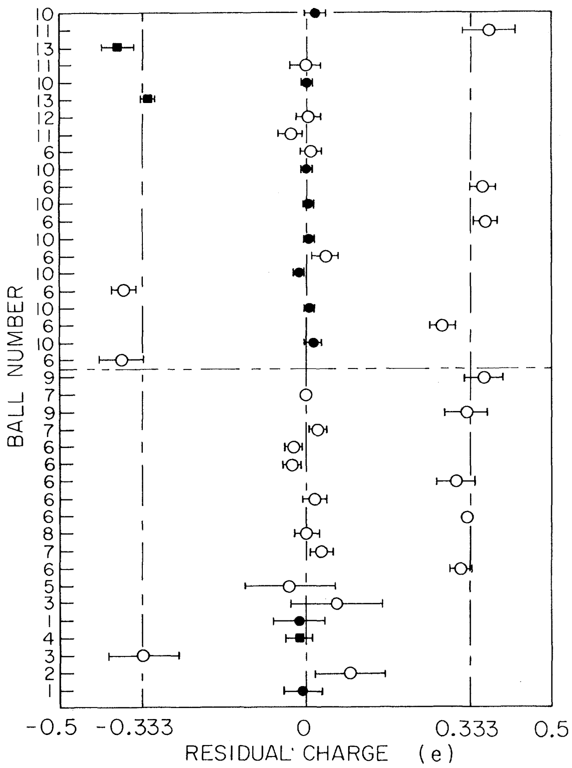

FIG. 1. Residual charges in chronological order from bottom to top. New measurements appear above the line. Symbols: $R = 140$ (open circles), 116 (solid squares), and 98 μm (solid circles). The error for point 2 of ball 6 is smaller than the point. Point 3 for ball 7 was assumed to be zero and is not counted.

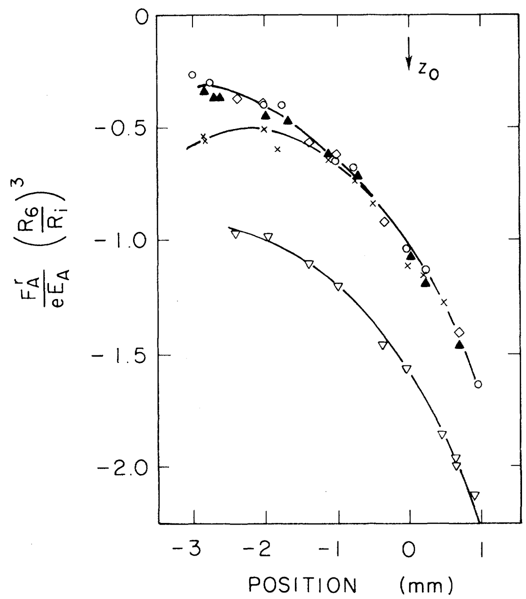

FIG. 2. $(F_A{}^r/eE_A)(R_6/R_i)^3$ vs position for the five balls in set 1 of cooldown 2. R_i = radius of ball i. Symbols: ball 10 (circles); ball 6 (crosses); ball 11 (solid triangles); ball 12 (diamonds); ball 13 (open triangles). The departure of the crosses from the upper curve is due to $P_z \sim 5\times10^{-8}$ esu cm on ball 6. The effect of P_z is zero at z_0 where $\partial E_A/\partial z = 0$. $\frac{1}{3}e$ for ball 13 corresponds to 0.58 on the vertical axis.

ues of z. For a given ball or for balls of identical radius, differences in $F_A{}^r/E_A$ at z_0 are differences in q_r since in (2) the last term vanishes and the second term is the same. Only charge differences, not actual values for the charge on each ball, can be determined without further information. This can be obtained by measuring balls of different radii.

This comparison of the measured residual force for different balls is valid only as long as $\partial E_F/\partial z$ remains constant. Changes in $\partial E_F/\partial z$ do occur occasionally, and are evident from changes in the form of $F_A{}^r(z)$ which cannot be attributed to the constant or the dipole term in (2). Almost all such changes have occurred between levitations. Whenever a change occurs the data must be broken up into sets, each with constant $\partial E_F/\partial z$. For such a set, (2) is fitted to the data. Parameters corresponding to q_r and the vertical dipole P_z are then determined for every levitation in the set. The same function representing $\partial E_F/\partial z$ must fit the entire set.

The 21 measurements reported here were made during two consecutive cooldowns. In the first

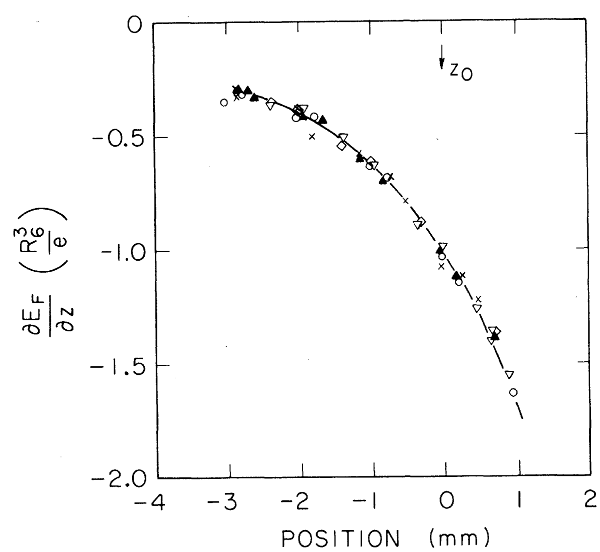

FIG. 3. $\partial E_F/\partial z$ for set 1 of cooldown 2. The data show that $\partial E_F/\partial z$ remained constant. Symbols are as in Fig. 2. One unit is 1.0e for ball 6.

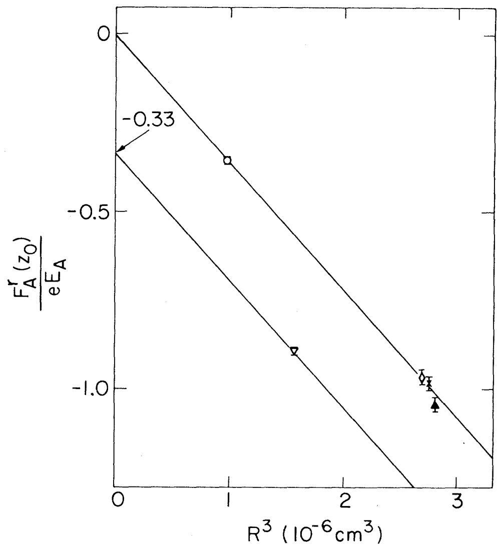

FIG. 4. R^3 dependence of $F_A{}^r/E_A$ at z_0 for set 1 of cooldown 2. The slope of the lines is $\partial E_F/\partial z$ at z_0. Intercepts of lines through these points with this slope are the residual charges. Ball 13 has a residual charge $(-0.324 \pm 0.014)e$.

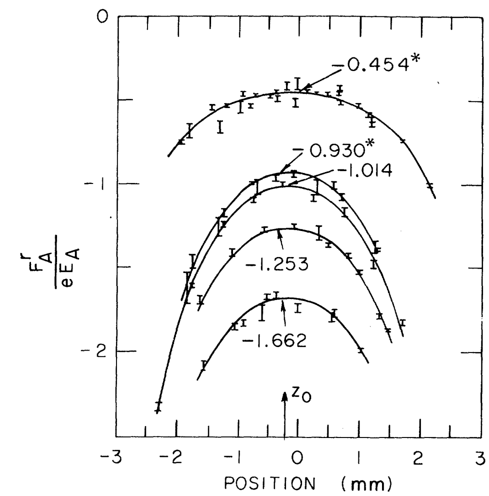

FIG. 5. $F_A{}^r/eE_A$ vs position for set 2 of cooldown 1. The labels for the best fit curves are values of $F_A{}^r/eE_A$ at z_0. The four levitations of ball 10 with $F_A{}^r/eE_A|_{z_0}$ of -0.448, -0.451, -0.469, and -0.448 are represented by one curve labeled with the average -0.454*. The levitations of ball 6 with $F_A{}^r/eE_A|_{z_0}$ of -0.927 and -0.934 are represented by one curve labeled -0.930*. The other three curves represent single levitations of ball 6.

cooldown, 11 measurements were made alternately on balls 6 and 10. $\partial E_F/\partial z$ changed after the first two measurements but remained constant for the remaining nine. In the second cooldown, ten measurements were made on five balls. $\partial E_F/\partial z$ changed after the fifth and seventh measurements, thus giving three sets. These 21 measurements represent all of the balls measured during this period.

Figure 2 shows the measured values of $(F_A{}^r/eE_A)(R_6/R_i)^3$ for the five balls in set 1 of cooldown 2. R_i indicates the radius of ball number i. If every ball had $q_r = 0$ then the values plotted in Fig. 2 at z_0 would all be the same. Clearly the results for ball 13 differ from those of the other balls at z_0, indicating that all of the balls cannot have $q_r = 0$. Figure 3 shows how well the data presented in Fig. 2 fit the same function $\partial E_F/\partial z$. The data represent the measured values of $(F_A{}^r - q_r E_A - P_z\, \partial E_A/\partial z)R_6{}^3/R_i{}^3 eE_A$. From (2) this expression equals $(\partial E_F/\partial z)R_6{}^3/e$.

Figure 4 illustrates $F_A{}^r(z_0)/E_A$, obtained from Fig. 2 for each ball, plotted against R^3. For all balls in the same set with the same value of residual charge q_r, the measured values of $F_A{}^r(z_0)/E_A$ should fall on a straight line with slope $\partial E_F/\partial z$ at z_0 and intercept q_r when plotted against R^3. It is apparent that no straight line through zero can fit all of the data in Fig. 4 so that at least one of the residual charges is not zero, as already seen from Fig. 2. However, the data fit well by assigning a residual charge near zero for balls 6, 10, 11, and 12. This gives a residual charge for ball 13 near $-\frac{1}{3}e$. The error in determining $R^3 \partial E_F/\partial z$ at z_0 has been added in quadrature to the error in $F_A{}^r(z_0)/E_A$ to obtain the errors in Fig. 1.

Figure 5 shows the nine measurements made alternately on balls 6 and 10 during set 2 of cooldown 1. The measurements on ball 10 by themselves indicate that the residual charges as well as $\partial E_F/\partial z$ remained constant. $F_A{}^r(z_0)/E_A$ for the five levitations of ball 6 show without further analysis residual charges separated by $\frac{1}{3}e$. The data fit well to a common curve when plotted as in Fig. 3. Figure 6 is a plot of $F_A{}^r(z_0)$ vs R^3 from which the actual charges, not just the differences, have been obtained.

The charges on balls 6 and 11 changed between levitations. For these two cooldowns, the balls contacted their plastic holders and the capacitor plates between levitations but remained in the low-temperature environment.

We measure the residual force to ~0.01 eE_A. We have shown that all background forces are negligible or have been taken into account yielding the errors shown in Fig. 1. We are forced to

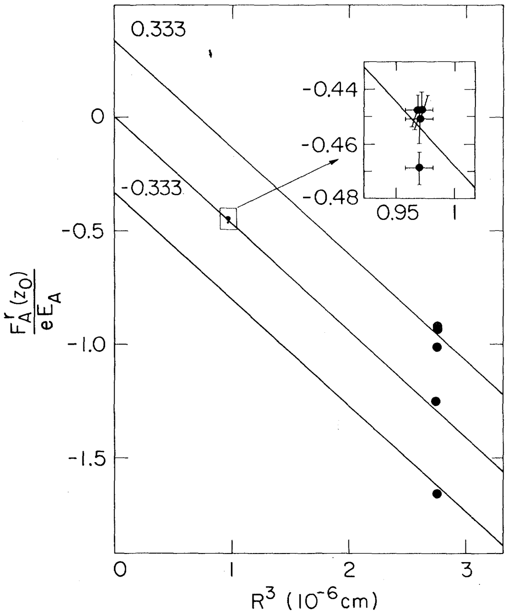

FIG. 6. $F_A{}^r/eE_A$ at z_0 vs R^3 for set 2 of cooldown 1. The statistical errors are the size of the points unless otherwise indicated.

conclude that residual charge of $\frac{1}{3}e$ exists on niobium spheres. We are continuing with the experiment and are preparing a detailed paper.

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[3]G. S. LaRue, W. M. Fairbank, and J. D. Phillips, Phys. Rev. Lett. 42, 142, 1019(E) (1979).

[4]G. S. LaRue, J. D. Phillips, and W. M. Fairbank, in Proceedings of the Twentieth International Conference on High Energy Physics, Madison, Wisconsin, July 1980 (to be published).

[5]The values of χ^2 per degree of freedom for the three groups are, respectively, 1.3, 0.9, and 1.2.

[6]M. Marinelli and G. Morpurgo, Phys. Lett. 94B, 427, 433 (1980), have reported a charge-mimicking effect which they attributed to a new magnetoelectric effect. M. Buckingham and C. Herring, Phys. Lett. 98B, 461 (1981), have shown that this can be accounted for by a tilting of the mean magnetic moment, even for a spinning ball. M. Marinelli and G. Morpurgo, to be published, agree. They report zero fractional charges on 3.7 mg of steel. In our experiment, because the electric and magnetic fields are parallel, this effect is $< 0.01\ e$ (see Refs. 1–4).

Search for Baryon-Exchange Production of Strange Exotic Mesons

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Results are presented of a search for strange, doubly charged, narrow [full width at half maximum ≤ 0.2 (GeV/c^2)^2] meson states produced in the baryon-exchange reaction $\pi^+ p \to \Lambda_f{}^0 S^{++}$ at 9.8 GeV/c. No evidence is found for such states. The 95%-confidence-level limit for the production cross section is < 20 nb for $M(S^{++}) \leq 2$ GeV/c^2. Limits on σB from a kinematic reconstruction of final states with $S^{++} \to K^+\pi^+$ are ≤ 10 nb for $M(K^+\pi^+) \leq 2.0$ GeV/c^2.

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Multiquark exotic mesons are expected in many models of hadrons[1] having quantum numbers in excess of the values available to simple $\bar{q}q$ systems. In contrast to these models, perturbative quantum-chromodynamic analysis based on single-gluon exchange, or multiple-gluon exchange in the limit of a large number of colors, suggests that exotic states do not occur.[2]

This paper reports on a search for exotic mesons produced in the baryon-exchange reaction

$$\pi^+ p \to \Lambda_f{}^0 S^{++}. \tag{1}$$

The simplest quark diagram of this reaction is given in Fig. 1. The interest in baryon-exchange reactions is primarily based on two component duality schemes which suggest that exotic states