Results of a Search for Fractional Charges on Mercury Drops

Christopher L. Hodges
Physics Department, University of California, Riverside, California 92521, and Physics and Astronomy Department, San Francisco State University, San Francisco, California 94132

and

Peter Abrams, Andrew R. Baden, Roger W. Bland, David C. Joyce, Jeffrey P. Royer, Frederick Wm. Walters, Edward G. Wilson, Patricia G. Y. Wong, and Karl C. Young
Physics and Astronomy Department, San Francisco State University, San Francisco, California 94132
(Received 9 September 1981)

Results are presented from a search for fractional charges on mercury drops. About 100 000 drops have been measured, comprising 60 μg of refined mercury and 115 μg of native mercury. No fractionally charged drops were observed in this sample.

PACS numbers: 14.80.Dq

In 1977 third-integral charges were observed by LaRue, Fairbank, and Hebard[1] on superconducting niobium spheres levitated in a magnetic field. Succeeding work by LaRue, Fairbank, and Phillips[2] continues to support this result. Other levitometer experiments[3-5] using steel samples at room temperature do not observe fractional charges, nor do experiments[6] using less direct, but possibly more sensitive, enrichment techniques.

The measurements reported here were made on small mercury drops, with a modification of the Millikan oil-drop technique in which the charge of many small drops is measured directly as they fall one by one through a measuring chamber. A diagram of the experimental apparatus is shown in Fig. 1. A piezoelectric drop ejector[7] produces single drops of mercury on demand. The drops are uniform in size to ±1% or less, and drops ranging from 3.5 to 6.5 μm in diameter have been used in this experiment. The falling drop is illuminated by an argon laser, and its image is formed on a plane of 92 horizontal slits. As the drop's image passes over the slits, pulses of light are detected by three photomultiplier tubes. The first and third tubes monitor pairs of guard slits, at the beginning and end of the slit pattern. The guard slits are used to reject certain types of bad data, as for instance when two drops pass through the chamber at nearly the same time. The second tube monitors the remaining 88 slits. Measuring the time between pulses from adjacent slits permits calculating the drop's velocity. The large number of slits gives a high degree of redundancy to the measurement, which helps in identifying measurement errors. The signals from the three tubes are sent to an electronic controller, and are also sampled by an on-line computer.

As the drop's image passes over the third slit, 10 000 V is applied across the plates. After the drop has passed 39 slits, at velocity v_1, the voltage is reversed. The drop crosses the next 35 slits at velocity v_2, and the voltage is reversed once again. The drop crosses the remaining slits at velocity v_4. It is easy to show, with use of Stokes's law and the assumption that the drop is spherical, that its radius a and charge q are given by

$$a^2=[9\eta(v_1+v_2)]/(4\rho g), \quad q=3\pi\eta a(v_1-v_2)/E.$$

(The time for a drop to reach terminal velocity when the field is switched is negligible in this experiment.) The calculation of a and q is performed for each drop by an on-line computer. Extensive checks are carried out, both by the computer and by hardware peak counters, to reject drops which cannot be measured reliably. The rejects are mostly drops too highly charged to be measured well, which may reverse their direction when the field is switched. Such rejects account for about 30% of all drops.

Drops whose charge changes during the measurement are a potentially troublesome source of

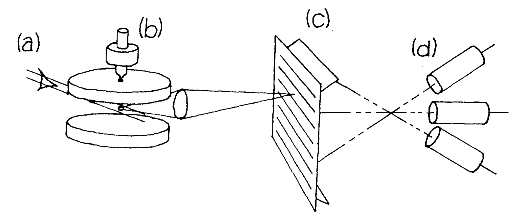

FIG. 1. Diagram of the experimental layout, showing (a) laser beam, (b) piezoelectric drop ejector, (c) slit array, and (d) photomultiplier tubes.

error in this experiment. These drops are identified by comparing v_4 with v_3, the velocity as determined from the first 10 slits after the voltage is turned on. The charge change dq is given by

$$dq = 3\pi\eta a(v_4 - v_3)/E .$$

dq is calculated for each drop, permitting us to reject drops with dq not consistent with zero. Under good running conditions we detect about one charge change per 1000 drops.

The on-line computer accumulates histograms of a, q, and dq in its memory. It also identifies charge changes and quark candidates (q not consistent with an integral value), and prints out detailed information for these drops. Data is accumulated in runs of about 4000 drops, with a data summary printed at the end of each run. In addition to rejecting badly measured single drops, entire runs are rejected if they fail to pass any one of a number of preset criteria. The principal criteria are (a) that there be no more than four charge changes per thousand events, and (b) that the measuring error for q be less than $0.045e$. About one-third of the runs are so rejected.

Part of the charge distribution for one good run is shown in Fig. 2. The regularly spaced peaks correspond to integrally charged drops, and the peaks are narrow enough to permit clear identification of drops with $q = (n \pm \frac{1}{3})e$, where n is an integer.

To summarize the data better, the peaks are superimposed so that their centers line up and are combined. This gives the distribution of residual charge, q_r; this is the nonintegral part of the charge q. The residual-charge distribution is shown in Fig. 3 for all good events from good runs over the period January 8 to June 12, 1981. Figure 3(a) shows results from 60 μg of reagent-grade refined mercury, and Figs. 3(b) and 3(c) show results from 115 μg of native mercury from the Socrates mine.[8] Four-bin-wide regions centered on $q_r = \pm\frac{1}{3}e$ are indicated on the graphs. These bands correspond to about $\pm 1.9\sigma$, where σ is the standard deviation of the integral-charge peak, and they include none of our measurements. We conclude that we have detected no third-integral charges in this sample.

Figure 3(c) shows data from runs with all charge changes rejected. During earlier runs, shown in Figs. 3(a) and 3(b), charge changes were rejected only if the calculated residual charge lay in the band $0.25e < q_r < 0.75e$. We think that the nonstatistical tail of the integral peak seen in Figs. 3(a) and 3(b) is due to charge changes which were not rejected from the data sample. This tail is much reduced in Fig. 3(c), permitting a more sensitive test for quarks with nonintegral charges other than $\pm\frac{1}{3}e$. We note in particular that there are only six measurements in the $q_r > \frac{1}{6}e$ tail, and one measurement in the $q_r < \frac{5}{6}e$ tail. This lets us set an upper limit on the rate of occurrence of $\pm\frac{1}{6}e$ residual charges. Using Poisson statistics with the numbers just given,

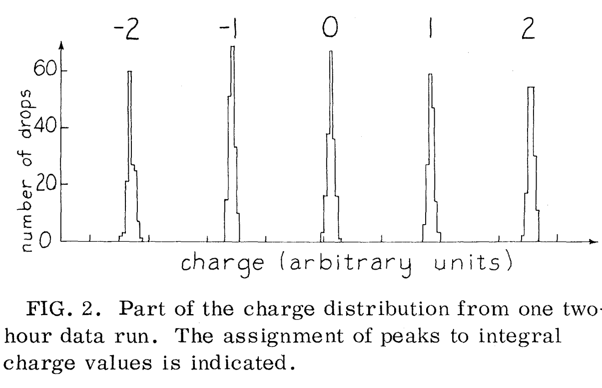

FIG. 2. Part of the charge distribution from one two-hour data run. The assignment of peaks to integral charge values is indicated.

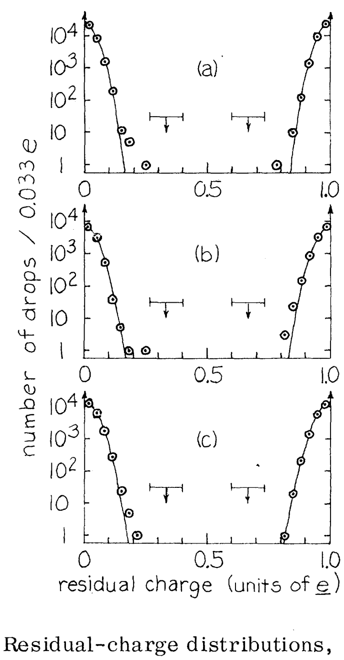

FIG. 3. Residual-charge distributions, for (a) 60 μg of laboratory mercury, (b) 30 μg of native mercury from earlier runs, and (c) 85 μg of native mercury from later runs of this experiment. The curves are Gaussian distributions with standard deviations of $0.035e$, $0.038e$, and $0.040e$, for (a), (b), and (c), respectively.

and doubling to account for the other half of the error distribution, we conclude, with 95% confidence, that the average number of sixth-integral charges in a sample like that of Fig. 3(c) is less than 24, for $q_r = \frac{1}{6}e$, and less than ten, for $q_r = \frac{5}{6}e$.

The sample searched in this experiment is the third largest sample of material (0.175 mg) to be subjected to a direct quark search, after those of Morpurgo *et al.* (3.7 mg) and Fairbank *et al.* (1.2 mg). Ours is the largest sample of mercury, or of any element higher in the periodic table than niobium ($Z=41$). The object of these searches is, however, not normal atoms of mercury, niobium, or any known element. Quarks may manifest themselves as atoms with negative quarks closely bound to their nuclei, atoms with positive quarks as nuclei, or perhaps more complicated arrangements of quarks and atoms. Zweig[9] and Lackner and Zweig[10] have discussed some of these possibilities. It seems clear that, in any sample tested for quarks, the interesting part of the sample is not known elements or compounds, but traces of materials with unknown chemical properties. For this reason, native mercury seems more likely to bear quarks than refined (triply distilled) mercury. Our samples have been analyzed semiquantitatively by two different methods.[11,12] The mercury from the Socrates mine showed a percent or so of iron and a trace of copper, and another sample of native mercury (not used for the data of this paper) showed substantial amounts of Pb and Bi, and traces of Re, Ir, Pt, Cu, Ag, and Au. This variety of trace impurities suggests that the native mercury may be a reasonable carrier for negative quarks bound to the nuclei of atoms, which in a liquid metal should behave much like normal atoms. The properties of atoms formed with positive quarks as nuclei are harder to predict, and we can draw no conclusions about the advantages of native mercury for detecting these atoms.

In conclusion, we have measured 175 μg of mercury, more than half of it unrefined native mercury, without finding any third-integral charges. We have also set upper limits for nonintegral charges of $+\frac{1}{6}e$ and $-\frac{1}{6}e$, of thirty events and eight events, respectively, in a 85-μg sample of native mercury.

We would like to thank Professor Gerald Fisher for his generous support of this project, Robert Johnson for technical assistance, Dan Werthimer for assistance and helpful discussions, and Kimberly Coburn, Victoria Lindsay, and Betty Young for participation in later stages of this work. This work was supported in part by a grant from the Research Corporation, and in part by the U. S. Department of Energy under Contract No. DE-AC03-81ER40009.

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

[2]G. S. LaRue, W. M. Fairbank, and J. D. Phillips, Phys. Rev. Lett. 42, 142, 1019(E) (1979); G. S. LaRue, J. D. Phillips, and W. M. Fairbank, in *High Energy Physics—1980,* edited by L. Durand and L. G. Pondrom, AIP Conference Proceedings No. 68 (American Institute of Physics, New York, 1981), and Phys. Rev. Lett. 46, 967 (1981).

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

[4]G. Gallinaro, M. Marinelli, and G. Morpurgo, Phys. Rev. Lett. 38, 1255 (1977); this paper contains references to the work with the graphite levitometer by the same group.

[5]M. Marinelli and G. Morpurgo, Phys. Lett. 94B, 433 (1980), and in *High Energy Physics—1980,* edited by L. Durand and L. G. Pondrom, AIP Conference Proceedings No. 68 (American Institute of Physics, New York, 1981), Part 1, and invited paper presented at the Lisbon Conference of the European Physical Society, July 1981 (to be published).

[6]C. M. Stevens, J. P. Shiffer, and W. Chupka, Phys. Rev. D 14, 716 (1976); W. A. Chupka, J. P. Schiffer, and C. M. Stevens, Phys. Rev. Lett. 17, 60 (1966).

[7]Described by David Joyce, San Francisco State University Quark Search Group Internal Report No. QS-1, 1980 (unpublished).

[8]Native mercury from the Socrates mercury mine near Calistoga, California (now closed), was kindly supplied to us by Dennis Sorg, U. S. Geological Survey, Menlo Park, Cal. 95025.

[9]George Zweig, Science 201, 973 (1978).

[10]K. C. Lackner and G. Zweig, in Proceedings of the Twentieth International Conference on High Energy Physics, Madison, Wisconsin, July 1980 (unpublished), California Institute of Technology Report No. CALT-68-781.

[11]A qualitative analysis of mercury samples by optical spectroscopy was kindly performed for us by William Young.

[12]A qualitative analysis of mercury samples by x-ray fluorescence was kindly carried out for us by Clair Alvarez, of Spectra Diagnostics Laboratory, San Jose, Cal. 95150.