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A SEARCH FOR QUARKS PRODUCED IN HEAVY-ION INTERACTIONS

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We propose to search for fractional charges produced in the exciting new environment of ultra-relativistic heavy-ion collisions. This proposal is a continuation of work done by members of this collaboration at other accelerators. We use a novel technique to search for fractionally charged particles produced in particle interactions. Our method is based on testing macroscopic samples of matter (mercury) for non-integral net charge, with a technique similar to that used by Millikan on oil drops. The SFSU automated Millikan apparatus has been running well for six years and null results for fractional charge searches have been published. To enhance the sensitivity of this experiment we enrich the sample of mercury (by a factor $\sim 10^5$). This involves distilling the mercury which has been exposed to the accelerator beam, and depends on arguments that quarked atoms or molecules will remain in the distillate. This experiment, conservatively, will be sensitive to one quark produced per 10^8 beam particles.

I. Theoretical Background and Other Quark Searches

There is an enormously impressive body of experimental and theoretical literature supporting the doctrine of quark confinement. We accept the widely held belief based on many theoretical investigations that unbroken non-Abelian gauge theories confine the charges of the local-symmetry group. However, it is not possible to determine definitively from present theoretical and experimental results whether the exact local symmetry in nature is $SU(3)^{color} x U(1)^{em}$, in which case particles with color are confined. Models have been presented in which $SU(3)^{color}$ is spontaneously broken[1,2] and color is not an exact local gauge symmetry. Here free quarks (or perhaps diquarks[2]) could be produced in certain experiments and yet not violate present experimental constraints. In fact, it was suggested[3] that the production of free fractional charge might be greatly enhanced in relativistic heavy-ion collisions as compared to elementary-particle collisions. That is, where it is difficult to separate a particle with fractional charge from the remaining colored fragment in the vacuum, the separation process may be greatly enhanced in the environment of a quark-gluon sea created in a heavy-ion collision.

From our theoretical considerations,[3] we believe that the presently designed CERN 225 GeV/A ion beam presents a tremendously important, completely new environment for free fractional charge production that is not at all in conflict with the accurate bounds set in much higher energy elementary particle collisions.[4] In the glow model,[2] $SO(3)^g$, of broken QCD, five of the eight gluons acquire a mass m for which free, low-mass, fractionally charged, glow singlet, color $\underline{6}$ diquarks Q can be produced. As a result of the composite structure of the diquark, m is not so constrained by experiment[4] as in other models[1], and might be as large[3] as 75-100 MeV with a corresponding Q mass as small as a few GeV. In order for the (non-equilibrium) quark-gluon sea created in the heavy-ion collision to enhance greatly the separation of fractional charge, we need the range 1/m of the $\underline{5}^g$ gluons to be less than the size of the sea. Thus the size of a sea 1/m ~2-3 fm could readily be created with the CERN oxygen beam hitting a heavy target. Further, there should be enough energy in this non-equilibrium sea to create and free these light fractional charges.

Note that the more than 10^{13} oxygen (and sulphur) ions incident per cm^2 in this experiment is more than the number of heavy primary cosmic rays of energy >200 GeV/A incident per cm^2 on the moon over its lifetime. Furthermore, the techniques of this experiment allow for concentrations of $\sim 10^5$ for the material analyzed.

II. The Experimental Apparatus

This experiment requires a small cylinder containing mercury to be used in the exposure at CERN, distillation equipment to be used at Lawrence Berkeley Lab, and the automated Millikan apparatus of San Francisco State University. We will discuss these three parts of the experiment in turn. We stress that since the cylinder will simply replace a segment of the NA38 beam stop, no new resources or funds are required from CERN.

A. Apparatus to be used at CERN

The apparatus to be used at CERN is shown in Fig. 1. The beam is incident on a stainless steel cylinder 20 cm long and 5 cm in diameter and containing ~3 kg of mercury placed in the front part of the NA38 beam stop. Since this cylinder simply replaces one segment of the NA38's W beam stop, this experiment requires no new resources or funds. No monitoring is required (outside of the total number of beam particles incident on the NA38 target). All types of beam particles and at all energies incident on out cylinder will simply add to possible quark production with, of course, the highest A ions being of most interest. The cylinder will remain in the NA38 beam stop until the end of the second heavy-ion run in 1987.

The dimensions of the cylinder are taken to be compatable with the space provided by NA38. Although the volume of mercury is smaller than we would have proposed, we believe that a substantial fraction of all free fractional charge produced (in front of the tank and) in it might also be stopped there. This is especially true if, as expected, the quark interaction (with hadrons) is larger than that of ordinary colorless hadrons due to its extended color field.

B. The distillation apparatus

The 3 kilograms of mercury exposed to the CERN heavy-ion beam will be reduced afterwards by distillation to a hundred milligrams or so of material (the amount needed to fill the dropper of the SFSU Millikan apparatus). Then about one milligram of this residue will be measured in the Millikan apparatus. We have distilled mercury from our 1985 Fermilab experiment. Distillation by at least four orders of magnitude results in a liquid which can still be measured in the Millikan apparatus, and the residual radioactivity after exposure to about 10^{15} 800-GeV protons at Fermilab[5] indicates that induced radioactivity will not be a problem in the CERN exposure.

For the distillation scheme to be effective, we need to assume that any fractionally charged particles deposited in the mercury will remain in the residue. This property of quarked atoms or molecules was first suggested by George Zweig for concentration in sea water due to evaporation.[6] When the mercury is distilled, quarks will be retained in the residue by the image charge force. Comparing the image charge energy of a particle, with a charge of 1/3 of an electron, 5 angstroms from the mercury surface,

$$\text{P.E.} = q^2/d = .16 \text{ eV} \ ,$$

to the thermal energy per degree of freedom at 100 degrees Celsius,

$$\text{K.E.} = kT/2 = .02 \text{ eV} \ ,$$

it appears that the image-charge binding energy is more than sufficient to retain the quarks.

The mercury still has been built at SFSU, according to a design based on commercial stills used by Quicksilver Products of San Francisco. The still consists of a glass vessel about 2 liters in volume surrounded by a heating mantle. The mercury itself is grounded. A condensing column liquefies the mercury vapor. A vacuum pump (vented into an appropriate filter) maintains a steady pressure during distillation.

The distillation will take place at Lawrence Berkeley Laboratory, where the still is set up. Mercury from the Fermilab experiment is currently being distilled there. Factors larger than 10^4 are now readily achieved. Essentially all the radioactivity in the original target mercury (outside of radioactive Hg^{203}) remains in the small drop left after distillation.

C. The SFSU Millikan Apparatus

This measuring apparatus is a modification of the Millikan oil-drop experiment in which small drops are introduced one at a time into a measuring chamber by a piezoelectric drop ejector. The drop's drift velocity in a switched electric field is measured by timing the passage of an image of the illuminated drop over a series of slits (Fig. 2). The measurement is controlled and data are collected by an on-line computer. By switching the field polarity in mid-measurement, the mass and charge of each drop is determined. The measurement is highly redundant, allowing reliable rejection of badly measured drops. Drops which change charge during the measurement are identified and rejected.

Drops can be measured at a rate of one per second, and twenty micrograms of mercury can be measured in an hour of good running. The charge on an 8-micron-diameter mercury drop is measured to an accuracy of about 3.8% of $\underline{e}$ as shown in Fig. 3. To keep the charge on the drops near zero, a bias wire is inserted into the mercury in the dropper. The potential of this wire (a few volts) is adjusted by the computer. Drops with charge between ±25e are accepted. Rejection of charges outside this range accounts for most of the roughly 20% rejection rate of single measurements.

The San Francisco State University quark group has been searching for free fractionally charged particles (quarks) for the past 6 years. We have published results of three null searches, one in native mercury (180 micrograms),[7] one in water (50 micrograms),[8] and one in mercury exposed to a heavy ion beam at the Bevalac (500 micrograms)[9]. We are currently continuing our search in native mercury and have measured another 2 milligrams of material.[10] The Fermilab[5] Hg is now being analyzed.

III. Sensitivity of the Measurement

We define the sensivity of our experiment as the largest value of the ratio of beam interactions to quarks produced which can be rejected by a null experiment with 90% confidence. The sensitivity expected of either detection scheme is given by

$$S = \left(\begin{array}{c}\text{number of}\\ \text{beam}\\ \text{particles}\end{array}\right) \times \left(\begin{array}{c}\text{efficiency}\\ \text{for stopping}\\ \text{a quark}\end{array}\right) \times \left(\begin{array}{c}\text{efficiency}\\ \text{for observing}\\ \text{a stopped quark}\end{array}\right) \times (1/2.3)$$

Here the factor of 1/2.3 allows for the 90%-confidence-level rejection.

For mercury, the stopping efficiency has been modeled by Monte Carlo for another experiment by R. Slansky.[5] Based on reasonable extrapolations of those results, we estimate a stopping efficiency of ~.01 for the small cylinder of Hg that we will have in the NA38 beam stop. (In estimating the stopping, we assume that the hadronic interaction of free quarks is the same as for colorless hadrons. However, it is quite likely to be larger than that of ordinary hadrons due to their extended color field, and actually proportional to the quark mass. In this case, the actual sensitivity could be at least an order of magnitude greater than presented here.) While this is slightly dependent on the production mechanism, it should not decrease dramatically even for a wide variety of production mechanisms. The detection efficiency depends on the degree of distillation possible without concentrating too much dirt in the mercury to be able to run it in the drop ejector of the Millikan apparatus. We have tested distillation by a factor of 10^4 already. We see no obstacle to distilling by a factor of 3×10^4, down to a sample of 100 mg, about the smallest sample which can be conveniently handled. If 0.5 mg of this is measured in the Millikan apparatus, the observation efficiency becomes 0.005. Thus, for a 10^{13}-particle exposure,

$$S = (10^{13}) \times (.01) \times (.005) \times (1/2.3)$$

$$= 2 \times 10^8 \text{ beam interactions/quark.}$$

Similar apparatus to that described in this proposal has already been run at Fermilab in the high-intensity proton beam. The 800 GeV/c proton beam was pulsed every 60 seconds with a beam spill of 20 seconds. At the highest intensity run, 3×10^{11} protons/pulse, the maximum temperature of the mercury targets was 60°C. After an exposure of about 50×10^{13} protons, there was no radiation damage observed in the steel mercury containers. For this exposure, all targets were able to be shipped in four months.

We note that all the parts of this process have been tested.

V. Conclusion

We have described a method of detecting free quarks produced in relativistic oxygen/sulphur collisions with mercury. Quarks are collected and concentrated in mercury samples, using a distillation technique, and searched for using the proven SFSU automated Millikan apparatus. A sensitivity to better than one quark per $2x10^8$ beam interactions may be obtained. Our mercury tank forms part of the NA38 beam stop and thus requires no additional funds or resources from CERN. We believe that the CERN heavy-ion beam offers an exciting, completely new environment for producing quarks that is not at all in conflict with the accurate bounds set in higher energy elementary particle collisions.

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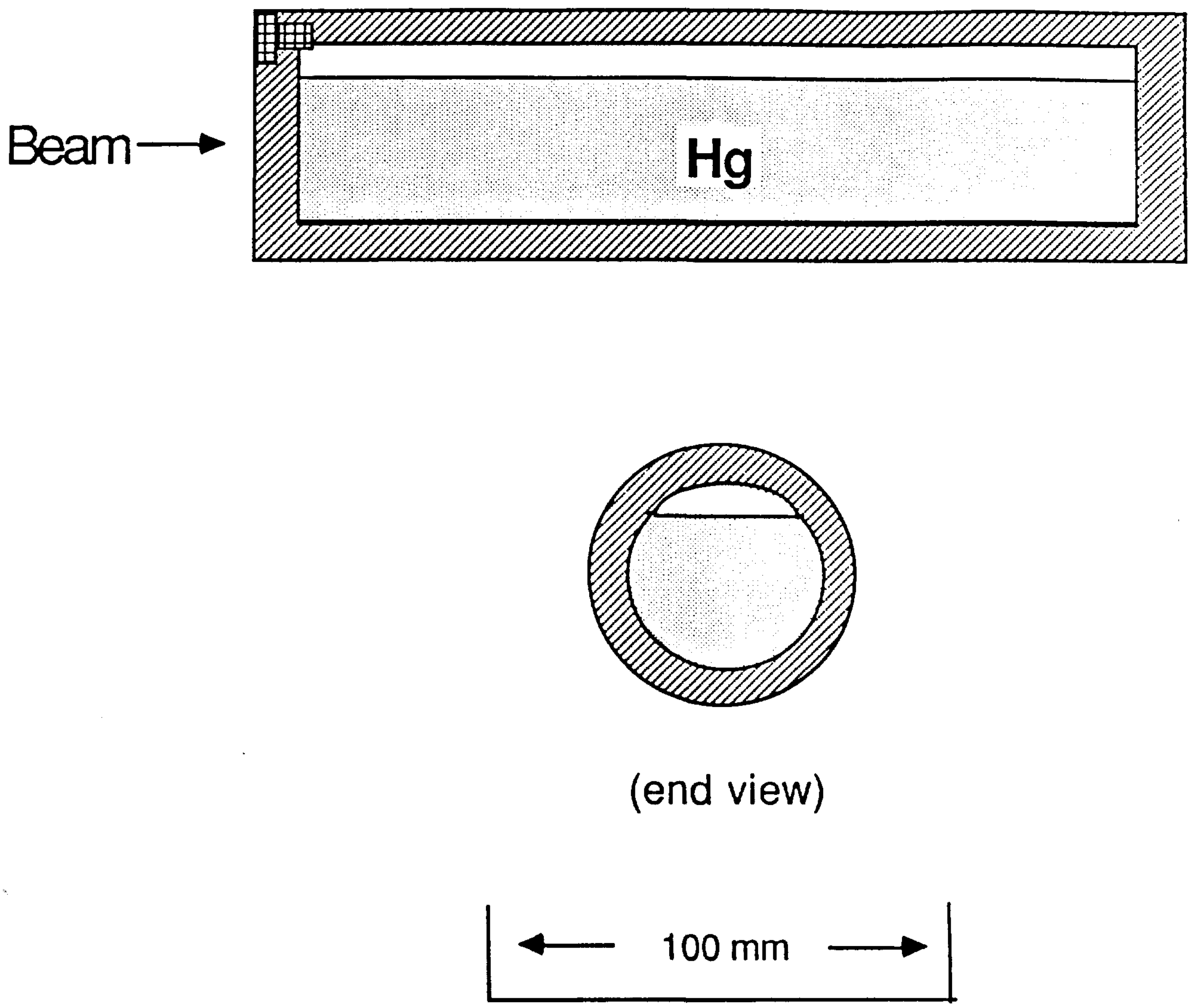

Figure 1-1: Schematic for mercury target. The cylinder is made from stainless steel.

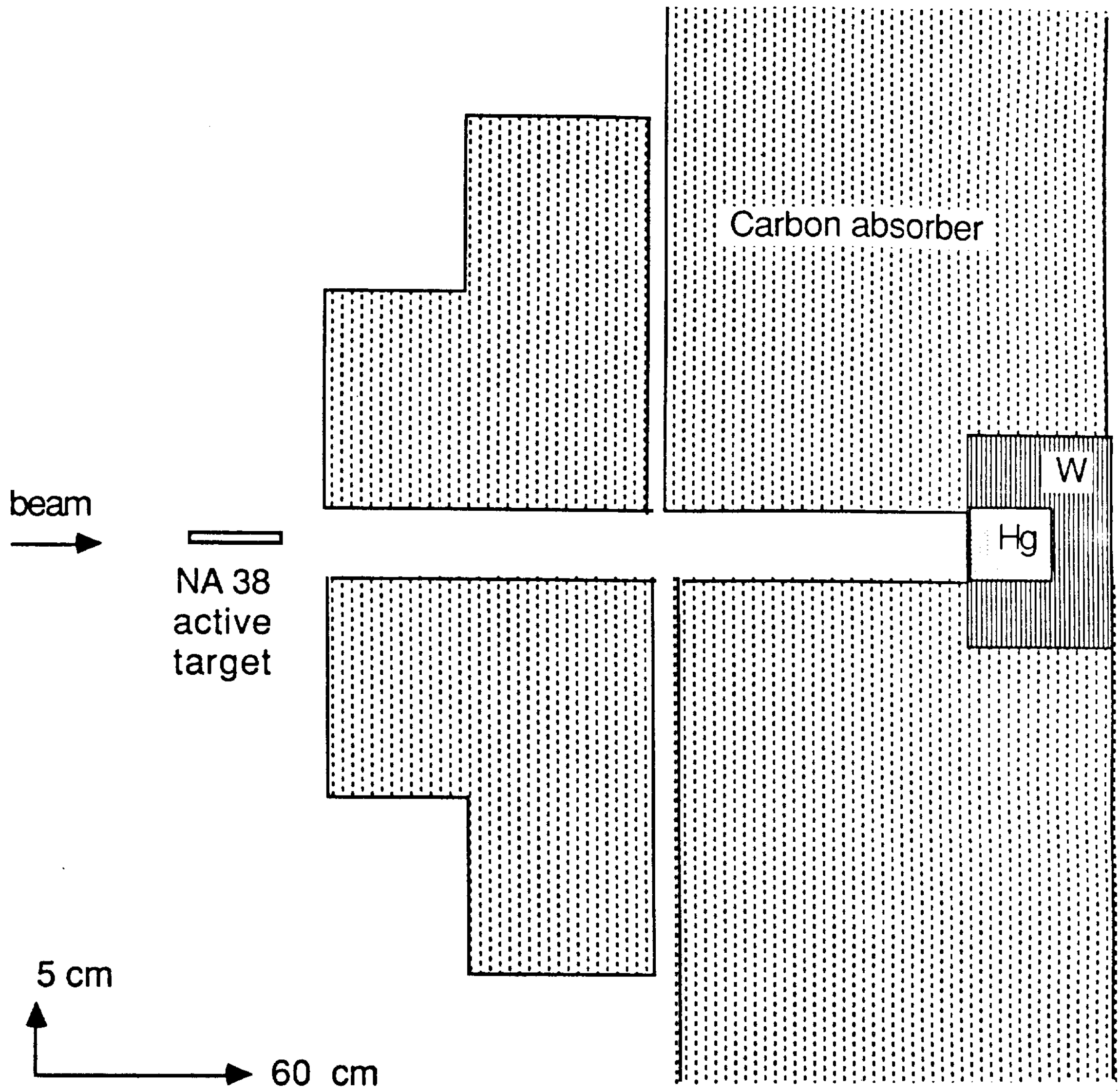

Figure 1-2: Proposed position for the mercury target in the NA38 target region.

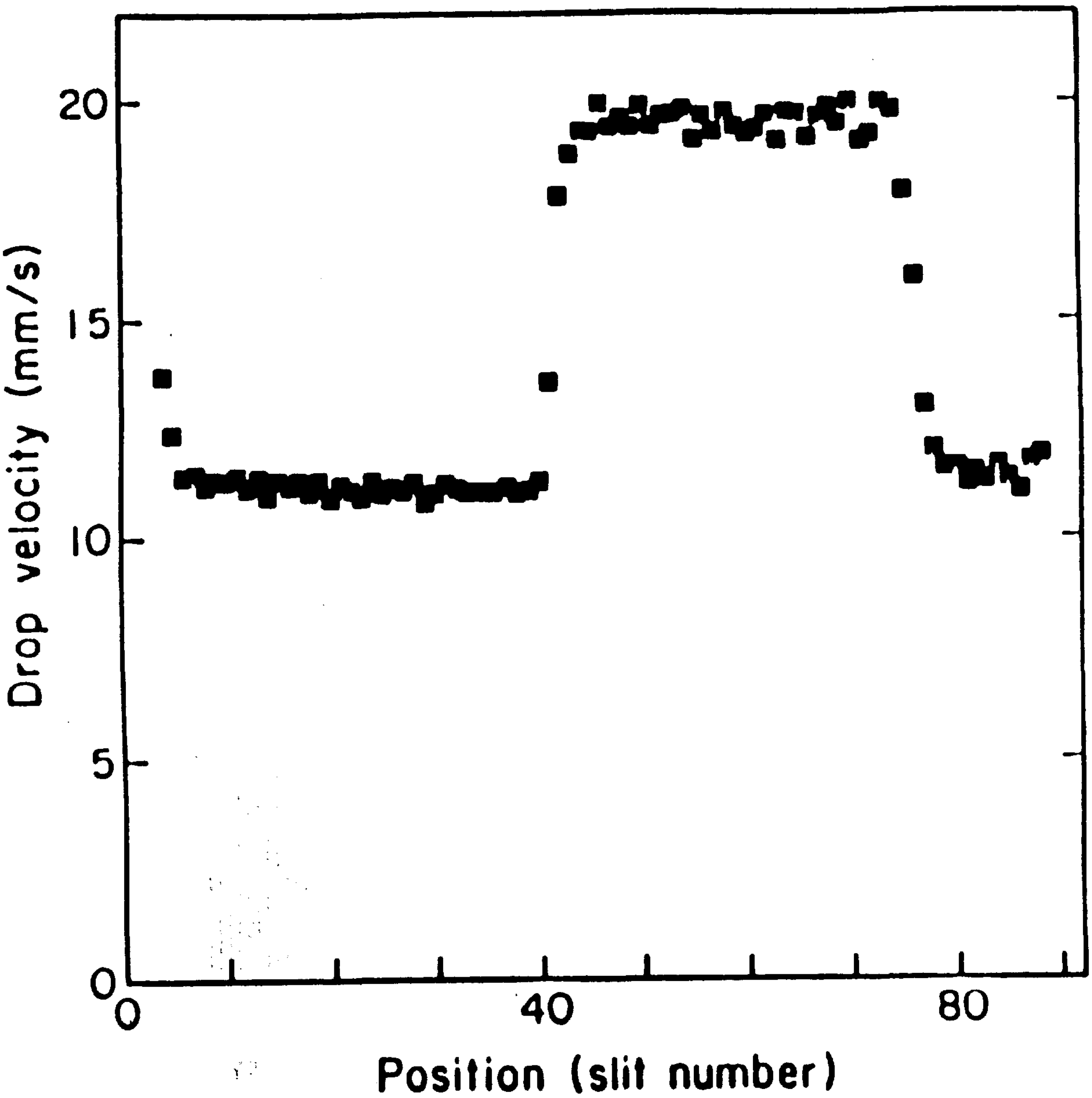

Figure 2: Drift velocity as a function of position for a typical mercury drop. Reversals of the electric field occur at slits 39 and 74.

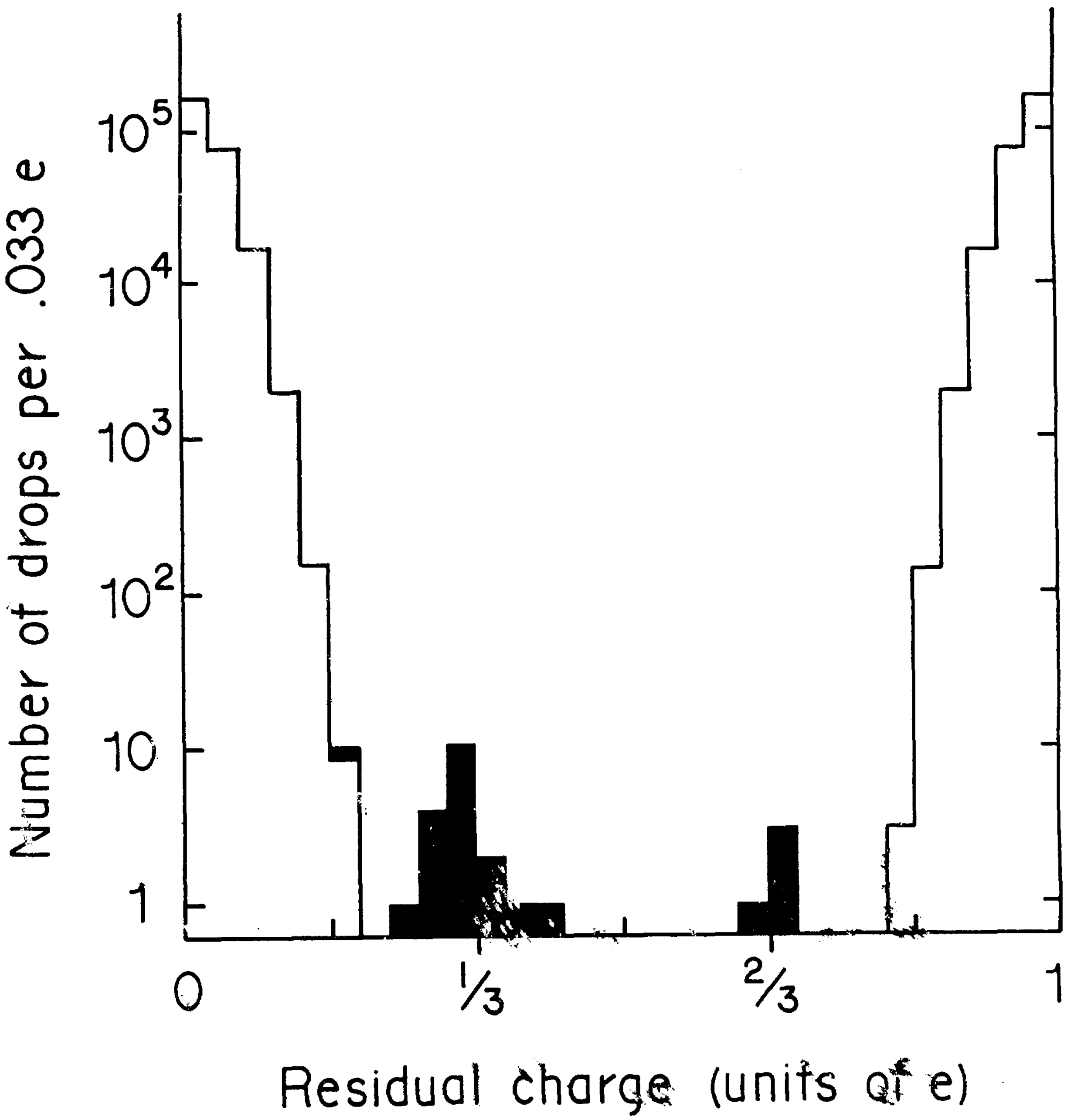

Figure 3: Distribution of the residual charge for an analyzed sample of mercury with computer simulated fractional charged events superimposed on that data. The computer generated events are shaded black. With the measured charge resolution (0.030e), the fractional charged drops are clearly discernible from integer charged drops.