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Search for Free Quarks Produced by 14.5 GeV/A Heavy Ions

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ABSTRACT

An experiment was carried out to detect free quarks produced in collisions of 14.5 GeV/A oxygen nuclei with a heavy target at BNL. Secondaries from the collisions were stopped in liquid argon tanks, and charged atoms were collected electrostatically on gold coated electrodes. The gold coatings were dissolved in mercury, which was then tested for quarks in the SFSU automated Millikan apparatus. No evidence for free fractional charge was found. The resulting upper limit is less than 1.0×10^{-9} quarks produced per incident ^{16}O ion at 90% c.l.

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Since the proposals by Gell-Mann and by Zweig that fractionally charged quarks are basic subnuclear particles, a variety of experiments have failed to establish the existence of free fractionally charged particles. Searches of naturally occurring materials [1-7] have established limits on free quark abundance of less than one per 10^{21} nucleons. Production experiments at accelerators have also given negative results [8-11]. An experiment using 2.8 GeV/A ^{54}Fe ions at the Bevalac [9] yielded no evidence for fractional charge at a limit less than 1 quark produced per 2 x 10^{6} incident ions. We present here a measurement using the newly commissioned 14.5 GeV/A ^{16}O ion beam at Brookhaven National Laboratory. Arguments have been given [12] that relativistic heavy-ion collisions might be a much more favorable environment to produce free fractional charge than elementary particle interactions because the collision region could be much larger than 10^{-13} cm. Fractional charge could be in the form of 1/3e or 2/3e charged particles or even in the form of charge 4/3e diquarks. As this experiment is sensitive to any non-integrally charged particle, all types of strongly interacting fractional charge can be measured. Any produced unstable high mass state would decay to a stable fractionally charged state. Further, the detection efficiency is essentially independent of the quark mass once the quark is produced. In this paper we use the term quark to refer to any free fractionally charged particle.

This experiment (E801) used the BNL 14.5 GeV/A oxygen ion beam to search for free quarks produced in relativistic heavy-ion collisions. The experimental layout is shown in Fig. 1. In this paper we report on a search for quarks stopped in liquid argon. The tanks of mercury served both as a production target and as an absorber for quarks. In the future the mercury from these tanks will be tested for quarks. Each tank contained about 1.1

liters of mercury. The tank and steel container presented 1.6 inelastic collision lengths [13] to the beam. Four tanks of liquid argon were arranged in such a way as to stop secondaries from beam collisions, through strong and electromagnetic energy loss. The liquid-argon volume of each tank was 24 liters and each tank represented 0.64 interaction lengths to the ^{16}O beam. The stopping efficiency of the argon tanks was estimated by Monte Carlo calculations to range from 1% to 20% per produced quark, dependent on many aspects of the quark production and its hadronic collision cross sections.

Each tank contained two vertical collector wires placed 10 cm on either side of the beam. Each wire consisted of a 125-micron quartz fiber with a layer of about 200 angstroms of gold deposited on the quartz by sputtering. The wires were held at ± 7.5 kV with respect to the grounded tanks. This field resulted in a typical collecting time on the order of minutes for argon atoms with residual electron charge of one-third. In laboratory tests of a scaled down tank, we could see charged macroscopic particles drifting between the electrodes, while other visible neutral particles in the same liquid volume remained essentially stationary. Therefore we conclude that any type of mass motion of the liquid due to electroconvection [14] could safely be neglected. The collection of charged atoms or molecules in the argon tanks has an estimated efficiency of 80%, based on a calculation of the fraction of field lines terminating on wires rather than on the grounded container.

The apparatus was exposed to 7×10^{12} relativistic ^{16}O ions over a period of several days. The wires were held at high voltage until all of the argon evaporated. One week after the exposure, the gold layer was removed from the quartz fibers by rinsing them in small drops of mercury. The gold from the four tanks was transferred to a sample of 10 milligrams of mercury. We assume the transfer of quarks from the gold layers on the wires to the mercury drop to be complete, based on visual observation of the disappearance of the gold and on the transfer of the radioactive contamination on the wires (following the exposure) to the mercury.

The mercury sample with the dissolved gold was then tested for quarks using the San Francisco State automated Millikan experiment a few weeks later. This technique, which has been used in searches of naturally occurring mercury and water samples, has been fully described [6-9]. The measurement was carried out as follows: Small (8-micron-diameter) mercury drops were projected into an air-filled space between two electrodes. The terminal drift velocity through air was measured, with (a) no electric field, (b) an upwards electric field of about 25 kV/cm, (c) the same electric field downwards, and (d) the electric field upwards again. These four velocities determined the radius and charge of the drop, and gave a cross check on the size of the drop and a test for a change in the drop's charge during the measurement. The velocities were determined from a highly redundant set of timing measurements, with good rejection of drops whose characteristics change during the measurement.

The measurement reported here is based on a sample of 55,200 mercury drops. The measurement of each drop is subjected to a number of automatic online tests. Drops too highly charged to be measured reliably are rejected; they constitute between 10 and 50 percent of the drops, depending on the quality of the drop-ejector tip being used. In addition, drops that show a change of charge during the measurement are rejected. About one percent of the drops are rejected for this reason. This rejection rate is higher than that observed with mercury that does not have radioactive contamination. Drops that survive these automatic cuts are subjected to a close scrutiny, during which they may be rejected on the basis of abnormal drop radius, goodness of fit to the timing data, and other criteria. To assure that this procedure is not biased against quarks, artificial fractionally charged test events are generated at random and added to the data sample.

The data included only one drop which passed the automatic cuts and offline tests and which had a substantial fractional charge. This drop was subsequently identified as a test event. Previously [7], we have used this technique to demonstrate the efficiency of the Millikan analysis to be 90%.

In Fig. 2, we show the distribution of residual charge (the non-integral part of the calculated charge) for the 29,971 drops that passed all tests. All of the measurements except one lie in a Gaussian distribution of width 0.05e, representing integrally charged drops. The remaining measurement (crosshatched) is the test event. There are no background events near residual charge $|1/3|e$ and $|2/3|e$. Thus, there is no evidence for free fractional charge in this sample.

The sensitivity of this measurement depends on the efficiency of stopping quarks in the collector tanks, of attracting the fractionally charged atoms they form to the wires, and of transferring them to the mercury sample. The production process and stopping efficiency have been calculated by Monte Carlo. For purposes of setting a bound on quark production, the stopping efficiency of 5% per produced quark for the four argon tanks was used. This value corresponds to the following model: a quark is produced isotropically with a mean transverse momentum of 2 GeV/c in a frame defined by a rapidity equal to 1.2 of the incoming ^{16}O rapidity. For electromagnetic part of the stopping, the charge is taken to be 1/3e. For the hadronic part, the quark, with mass 2 GeV/c^2, slows down by nuclear collisions where the quark nucleon inelastic cross section is 20 mb and the quark inclusive cross section is similar to a typical leading particle distribution. As these parameters were varied over a reasonable range, the stopping efficiency for the four tanks changed from 1% to 20% per produced quark, where the lower values correspond to using a quark-nucleon inelastic cross section of 5 mb.

The overall efficiency for detecting a quark in this experiment is estimated to be 0.04%. This estimate is derived from the stopping efficiency of 5%, the drifting collection efficiency of 80%, the transfer efficiency of 100%, the Millikan apparatus efficiency of 90%, and the total fraction of the mercury sample that was measured which is 1.1%. Combined with the integrated beam flux of 6×10^{12} beam particles, this sets a limit of less than 1.0×10^{-9} fractionally charged particles per incident ^{16}O ion at 90% confidence level.

Work is in progress at BNL on producing a silicon beam, which is expected to be available in the near future. We will search for quark production using this beam. We would like to thank Dana Beavis and the BNL operating staff for help in carrying out this experiment. We also thank Alan Hahn for helpful discussions.

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Figure Captions

Figure 1 Top view of the experimental apparatus for the ^{16}O exposure. The boxes show the active area of the liquid argon (LAr) tanks. The "+" and "-" symbols indicate the position of the gold-coated electrodes in the tanks.

Figure 2 Histogram of the residual (non-integral) charge for all mercury drops which passed the final cuts. The arrows point to where a charged $|1/3|e$ or $|2/3|e$ drop would lie. The crosshatched region represents a test event as described in the text. There are no background events near the two arrows.

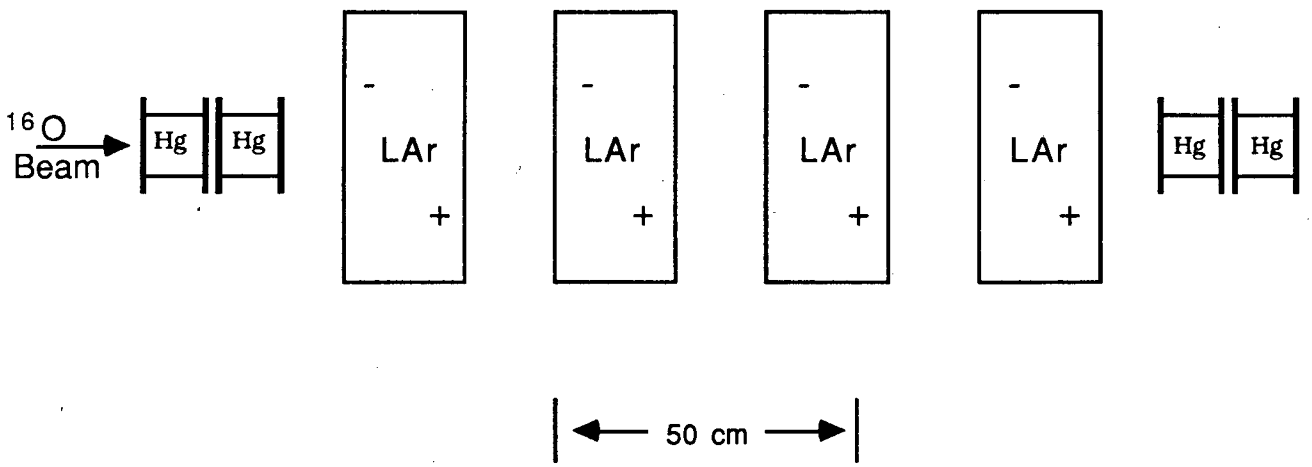

Fig. 1

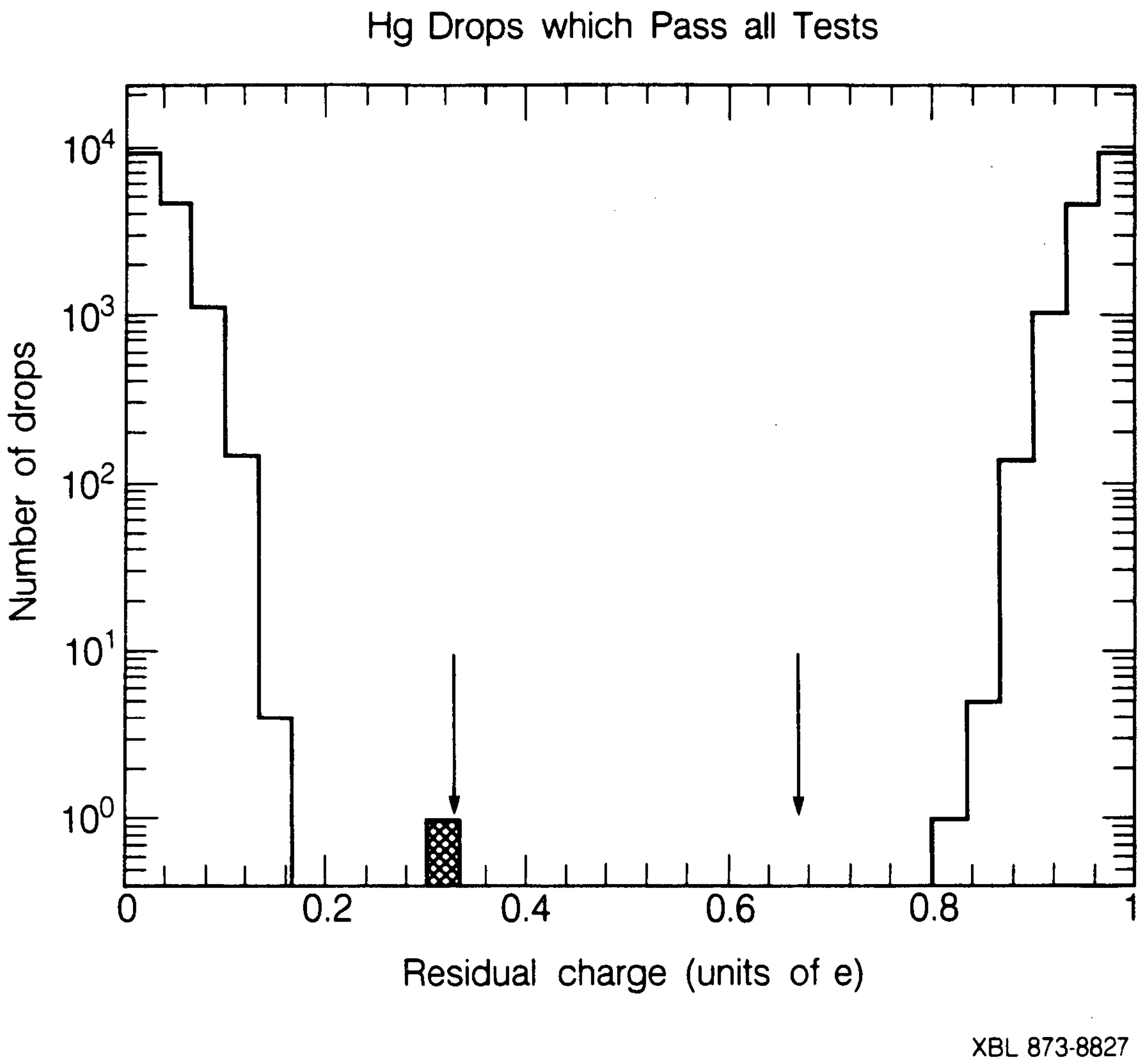
Hg Drops which Pass all Tests
10^4
10^3
10^2
10^1
10^0
Number of drops
0
0.2
0.4
0.6
0.8
1
Residual charge (units of e)
XBL 873-8827

Fig. 2

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