LBL-29336

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Presented at the Quark Matter 90 Conference,
Menton, France, May 7–11, 1990, and
to be published in the Proceedings

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July 1990

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Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

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This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098

SEARCH FOR FREE QUARKS PRODUCED IN ULTRA-RELATIVISTIC COLLISIONS AT BNL AND CERN

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A high intensity experiment was performed to search for free quarks at BNL and CERN using ultra-relativisitic beams. The experiment was designed to trap quarks in a Hg target or liquid Ar tank. No free quark candidate was found. Limits from 10^{-7} to 10^{-10} quarks per incident ion are reported.

1. INTRODUCTION

With the development of QCD, the concept of quark confinement or the statement the color is an exact symmetry of nature explains the non-observation of fractional charge or "free quarks". The fact that there is impressive evidence against the existence of free quarks supports that statement.[1]

Moreover, with the new ultra-relativistic machines at CERN and BNL, new experimental conditions can be reached. In particular, the conditions created in the hot dense region of ultra-relativistic collisions could liberate free quarks. Ultra-relativistic collisions can produce a large hot region is space which probes QCD over large distances, while elementary particle collisions probe QCD over point-like regions of space.

Theoretically, it is widely believed that unbroken non-Abelian gauge theories confine the charges of the local symmetry group. However, it is not possible to determine definitely from present theoretical and experimental results if the exact local symmetry in nature is $SU(3)_{color} \times U(1)_{em}$. If this theory is exact, color is confined and consequently, no free quarks can be produced. Models have been produced in which $SU(3)_{color}$ is spontaneously broken and color is not an exact local gauge symmetry. Free quarks could be produced in certain experiments and yet not violate the present experimental constraints. In fact, it was suggested that the production of free fractional charge might be greatly enhanced in relativistic heavy-ion collisions as compared to elementary particle collisions.[2,3] The environment of a quark-gluon sea created in the heavy-ion collision would enhance the separation of a particle with fractional charge from the remaining colored fragment by maximizing the quark density that can be achieved.

hadron. De Rujula *et al.* argued that after a quark is produced it would capture nucleons as it passes through a detector. Since a bare quark could have a net color charge, its interaction with matter could be significantly stronger than a typical hadron. Therefore, its signature could be a particle with varying electric charge to mass ratio. Such characteristics are very difficult to detect with conventional detectors, so many previous accelerator or cosmic ray experiments would have missed such a signature. In addition, refined material, which has been used in many bulk matter experiments, might have been depleted of its original quark content during its production process.[4]

The San Francisco State University (SFSU) automated Millikan drop apparatus provides a well-established method for testing bulk Hg for free quarks. It has been successfully used in high sensitivity searches[5,6] for quarks produced at accelerators and for quarks trapped inside bulk matter. Previous work on ultra-relativistic collisions has already been published.[7] We present here the complete results of experiment NA39 at CERN and experiment E801 at BNL which searched for free quarks produced in ultra-relativistic collisions.

The SFSU apparatus can detect free quarks with charge of |4/3|e in addition to |1/3|e or |2/3|e where e is the charge of an electron. In fact, any fractionally charged particle can be measured, as long as its residual charge is outside the resolution for measuring integral charge. Thus, exotic objects such as hadronic color singlets and lepto-quarks can be detected. However, as we have assumed in our Monte Carlo calculations that quarks stop via the strong interaction, the quoted limits must be modified for exotic processes which have much weaker quark-nucleon couplings.

In this paper, we define free quarks as any strongly interacting fractionally charged particle. Charges are measured in the unit of "e".

2. EXPERIMENTAL DESIGN AT CERN

A stainless steel container was placed downstream from the NA38 target in the middle of the NA38 beam stop. This cylindrical container was filled with 2.4 kg of Hg. The Hg target was designed to stop and capture quarks produced in interactions with the liquid target. In addition, the Hg could also capture quarks produced upstream in the NA38 target. Any produced quark should slow down via nuclear collisions and electromagnetic energy loss. Once a quark stops, it should then be captured by a Hg nucleus. This Hg was later analyzed for trapped quarks. The Hg was left in the beam stop for proton, O and S beam exposures.

3. EXPERIMENTAL DESIGN AT BNL

Two types of quark absorbers were used for the BNL experiment. As shown in Fig. 1, two cylinders full of Hg were placed in beam line followed by four liquid Ar tanks. Following the liquid Ar tanks were two more tanks of Hg. The liquid Hg tanks stopped quarks in the same manner as the one used for the CERN experiment. The tanks were cylindrical with a radius of 6.35 cm and a length of 9.9 cm. An air gap of 3 cm was left in the Hg tank to allow for expansion of the Hg.

The liquid Ar tanks were designed to stop quarks in the same manner. However, once a quark stopped it would be attracted to one of two oppositely charged wires which were immersed in the

The liquid Ar tanks were designed to stop quarks in the same manner. However, once a quark stopped it would be attracted to one of two oppositely charged wires which were immersed in the liquid. As the quark can never be neutralized with integer charges, it would always have a net charge and be attracted to one of the wires. After the quark reaches the wire, it will be trapped on the surface of the wire through its image charge.

4. PREPARATION OF HG SAMPLES

As the SFSU Millikan apparatus can only measure material whose mass is of order milligrams, it is necessary to concentrate any quarks in the original volume of mercury to a much smaller volume. A distillation apparatus was used to concentrate the Hg that was in the Hg tanks. The most significant argument for quarks remaining in the residue when Hg is heated is that a "quarked" atom is attracted to its neighboring atoms through its image charge.[4] The quarked atom cannot be neutralized by other integrally charged atoms. The attraction of the image charge holds the quarked atom within the sample of Hg when the sample is gently heated during the process of distillation, as long as the kinetic energy of the atoms are less the binding energy of the image charge. For the CERN beam exposure there was 2.42 kg of Hg in the target. This amount was distilled to 10 mg. Hg from the first BNL Hg tank was distilled from its original mass of 12.45 kg to 32 mg. The distillation process increased the sensitivity of our measurement by 2.4×10^5 for CERN and 3.9×10^6 for BNL.

The BNL liquid Ar tanks were only analyzed for the O beam run. Each of the wires was passed through a small bead of Hg enclosed in a glass tube. The wire was carefully checked to make sure all of the gold was dissolved. The beads from all of the wires in the four tanks were combined to form a new sample with at mass of 10 mg.

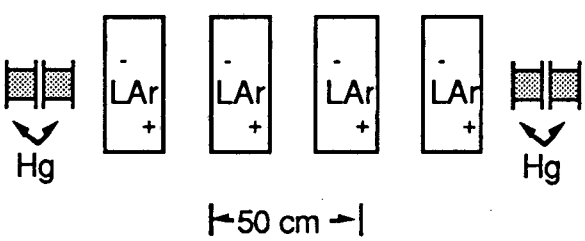

Fig. 1. Top view of the experimental apparatus for the O and Si exposures. The boxes show the active area of the liquid Ar (LAr) tanks. The "+" and the "-" symbols indicate the position of the gold-coated electrodes in the tank. The beam comes from the left.

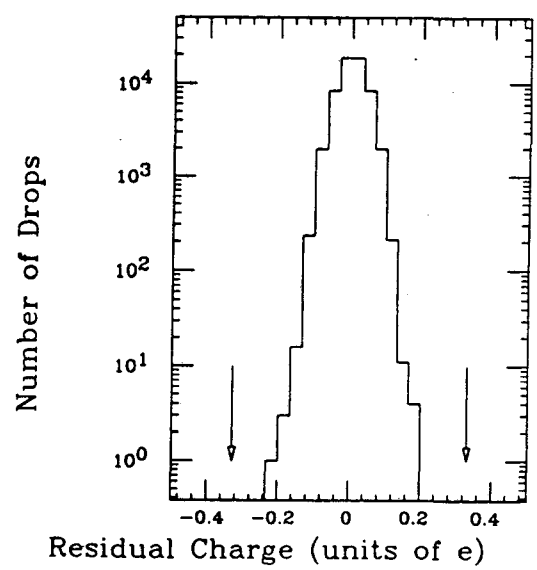

Fig. 2. A histogram of the measured residual charge for drops which passed all acceptance tests for the distilled mercury. The two arrows show the expected position for residual charge for any drop which contains a charged 1/3 or 2/3 quark.

5. SFSU MILLIKAN APPARATUS

Once the Hg was concentrated, it was tested in a Millikan type apparatus which has been described in a previous publication.[6] This detector measures the residual charge of a Hg drop with at resolution of about 0.03e. Fig. 2 shows the charge distribution obtained with the BNL Hg target. A total of 58,132 drops which had a total mass of 142 μg was examined. There were no drops which had a significant residual fraction charge. Therefore, there is no evidence for fractional charge in this sample. Similarly, 118 μg of the CERN Hg sample and 110 μg of the BNL liquid Ar sample were measured without any evidence for quark production.

6. MONTE CARLO CALCULATION OF QUARK STOPPING

An estimate of the bound on the inclusive quark production rate requires a model for quark production, and a model for hadronic quark scattering. Ref. 6 provides a detailed discussion of the calculation which assumes that quarks are produced and interact similarly to protons.

It is necessary to define the center of mass for the quark-nucleus scattering, so we must assume a quark mass and again an effective target mass. Table 1 shows the probability for quark stopping for |1/3|e quarks with $\langle k_T^2 \rangle^{1/2}$, the transverse momentum of the produced quark, at 0.5 GeV/c for an interaction cross section of 20 mb for the first BNL Hg tank. The probability decreases approximately by a factor of 4 for an interaction cross section of 5 mb and slightly decreases for $\langle k_T^2 \rangle^{1/2}$ equal to 2 GeV/c.

Table 1. Probability that a quark produced in the first BNL Hg tank will stop in the tank.

Quark Mass	Effective Target Mass (GeV)			
(GeV)	0.5	1.0	2.0	8.0
0.5	0.220	0.208	0.226	0.360
1	0.228	0.279	0.330	0.424
2	0.296	0.310	0.338	0.366
5	0.240	0.256	0.286	0.388
10	0.206	0.238	0.240	0.254

This experiment is sensitive to lighter quark masses then the ones shown in the table and to heavier masses as long as there is enough energy in the center of mass frame. If the charge were higher than the assumed |1/3|e, then quarks would be slowed down faster and thus more quarks would be stopped. For the purposes of calculating an upper limit, we chose 0.2, an average value from Table 1 which is a very conservative estimate of the quark-nucleon interaction. The capture probability for the CERN Hg target was 0.03, while the value for the BNL liquid Ar data was 0.04.

7. CALCULATION OF UPPER LIMITS

Using the quark stopping calculation, efficiency of quark collection, measured beam flux, upper limits can be calculated. Table 2 shows the results. An efficiency of 80% was used for the distillation and an efficiency of 50% was used for the fraction of quarks collected by the liquid Ar tanks. The CERN Hg tank was exposed to beams of O and S. The limits for each ion are calculated separately. The CERN Hg tank also had an exposure to protons. Similarly, the BNL Hg tank had beam exposures of both O and Si. The BNL liquid Ar tanks were only measured for the O beam.

Table 2. Summary of beam conditions for each of the quark stopping materials. The limit is the 90% confidence value and is expressed in quarks per interacting ion.

Beam Momentum (Gev/c)	Stopping Material	Beam	Integrated Intensity	Limit (90% cl)
14.5	LAr	O	6×10^{12}	1.0×10^{-9}
14.5	Hg	O	6×10^{12}	5.1×10^{-10}
14.5	Hg	Si	4×10^{11}	8.1×10^{-9}
60	Hg	O	1×10^{12}	1.7×10^{-6}
200	Hg	O	3×10^{12}	3.5×10^{-7}
200	Hg	S	1.5×10^{12}	1.3×10^{-6}

8. CONCLUSIONS

In summary, no evidence for fractional charge has been found in searches performed at CERN and BNL. Limits have been set at about 10^{-10} quarks per ion interaction using 14.5 GeV/c O and Si beams and about 10^{-7} quarks per ion interaction for 200 GeV/C beams. It will become most interesting in the future when higher mass beams become available.

This research was supported in part by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Nuclear Physics Division of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098, U. S. Department of Energy Contract No. DE-AC03-81ER40009, and by the National Science Foundation.

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