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SEARCHES FOR MONOPOLES AND QUARKS

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Within the last year, several sensitive searches for monopoles and quarks have been done. Recent experiments at the Tevatron and at the CERN $p\bar{p}$ collider have detected no evidence for free fractional charge. An experiment in a iron refinery, which searched for GUT monopoles trapped in iron ore with two SQUID detectors, found no monopole candidate. However, an experiment looking for monopoles in cosmic rays has measured an interesting event which could be interpreted as a monopole. Several detectors are being built to achieve significant improvements in sensitivity for detection of quarks and monopoles.

1. FREE QUARK PRODUCTION

Since the discovery of quantized electric charge by Millikan in 1909, no accelerator experiment has claimed detection of fractional charge(1,2). While there is one experimental group(3) which claims measurement of fractional charge in niobium, there are many other bulk matter(2,4) searches and cosmic ray experiments which only have measured integer charged particles.

After Gell-man and Zweig (5) proposed that quarks are the fundamental building blocks of hadrons, it was assumed that measurement of a fractionally charged quark would be necessary to prove their theory. However, with the development of Quantum Chromodynamics (QCD), theorists have postulated that color is an unbroken local gauge symmetry, so quarks are confined and consequently only integer charged particles can be found in nature. However, there is no proof of confinement in QCD. There exist several models(6,7) which postulate that color symmetry is broken and therefore, free fractionally charged particles could be found.

The signature of a quark produced at an accelerator is very different from that of a typical hadron. De Rujula et al. (6) 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 then 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 quark content(8).

a) FERMILAB FRACTIONAL CHARGE EXPERIMENT

As Fermilab recently entered a new fixed target energy regime with its 800 GeV/c Tevatron program, a LBL-Irvine-San Francisco State collaboration(9) undertook a quark search experiment using a method that had been used in a previous accelerator experiment(4) and that had also been used in several bulk matter searches(2).

In order to avoid problems that many quark search experiments have had, bulk matter was used to capture any produced quark. Since quarks are stable because of charge conservation, the analysis of the stopping material can be done later in a laboratory. A nuclear target, which maximizes the quark density that can be achieved, was used because in some models(7) free fractional charges are produced only when conditions similar to production of the quark-gluon plasma occur. In addition, the target material was designed to be examined because quarks can be detected even if they were absorbed shortly after production.

In the first run, four steel cylinders filled with mercury were centered in a primary proton beam line which ran at 800 GeV/c for an integrated intensity of 1.0 x 10^{15} protons on target. Each cylinder contained about 1.5 liters of mercury. In order to sample different depths of the hadronic shower, 10 cm of lead were interspersed between the mercury targets to slow any produced quarks. A sample of mercury was extracted from the last two tanks and processed in the San Francisco State Millikan apparatus which measures the residual charge of the drop.

The Millikan apparatus(4) consists of a electrically biased mercury dropper which produces small drops of mercury which fall between two electrically charged plates. The polarity of the electric field is switched two times while the drop falls between the plates. Using measurements of the position of the drop, the net charge can be inferred. Consistency checks which include charge changing during the measurement, drop radius and multiple drops are made for each measurement of charge.

Fig. 1 shows a fitted velocity curve that was measured from a typical drop. The velocity is fitted in the three different regions shown on that curve. The curve shows the difference between the fitted and the measured velocity. In the first region, the drop falls and reaches terminal velocity. The first arrow shows when the sign of the electric field is reversed. After a short time, the drop again reaches its terminal velocity. At the second arrow the field is once again reversed. After passing a few more slits, it reaches its terminal velocity. For this particular drop, the measured charge was 19e where e is the electric charge of an electron. The net charge resolution for the apparatus was measured to be about 0.03e.

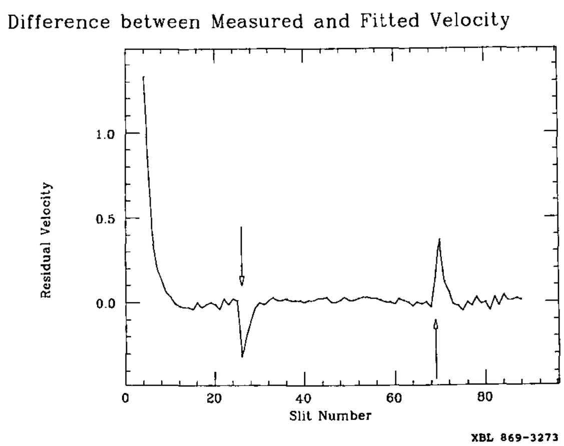

Fig. 1: The measured velocity minus the fitted velocity is shown for a typical drop. The arrows indicate the location of the drop when the field was reversed. The fitted velocity was fitted independently in each of the three regions.

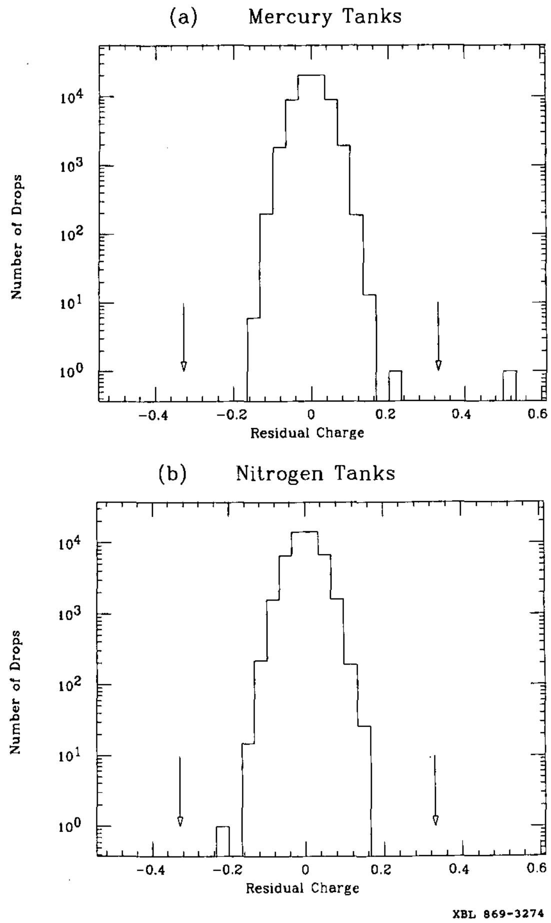

Fig. 2: This figure shows a histogram of residual charge for drops which passed all acceptance tests. The two arrows show the expected position for residual charge for any drop which contains a net fractional charge. a) Data from the distilled mercury samples. b) Data from the liquid nitrogen run.

This apparatus has processed samples whose mass was of the order of milligrams. In order to increase the amount of mercury that can be processed, a distillation apparatus is necessary. Since a quarked mercury atom is attracted to its neighbors by its image charge(8), these atoms do not evaporate when the mercury is heated. When the mercury is gently heated, the residue should contain the quarked atoms. The mercury in the third tank was distilled by a factor of 6,000 while the mercury in the fourth tank was distilled by a factor of 391,000. The reason for the large difference in the distillation factor between the two tanks was due to much larger contamination in the mercury used to fill the third tank.

From the mercury tested for the first run, a total of 230 micrograms of Hg from the third tank and 47 micrograms of Hg from the fourth tank passed all tests. These tests included checks for charge-changing, multiple drops, and good chi-squared for fits to the velocity. The residual charge of all drops is shown in Fig. 2a. The measured electric charge for these events is consistent with all drops having integer residual charge. The event with a net charge of 0.48 can probably attributed to a charge-change during the first reversal of the electric field and a complementary charge-change during the second reversal. From this data, an upper limit at 90% confidence level for quark production can be set at 2×10^{-10} quarks per interacting proton for the third tank and 2×10^{-11} for the fourth tank.

Liquid nitrogen tanks were used to stop any produced quarks in the second run of this experiment. In this run, the 800 GeV/c proton beam struck a 10 cm thick lead target. A quark, produced in the interaction, could stop in one of the four tanks. Once it stopped, then it would be attracted to one of two electrically charged gold plated glass fibers which were in each tank. After the exposure, the gold was carefully dissolved in a small bead of mercury. As the radioactivity of the bead was sufficiently higher than the surrounding material, the ability to attract charged particles was demonstrated. Folding in the field configuration, the efficiency of this process to capture charged particles can be estimated to be about 50%.

One half of the beads of mercury, which was taken from all the charged wires, was dissolved in triple distilled mercury to make a sample of 7.0 mg. So far, approximately, 213 micrograms of material have been processed. The charge on all the 46,310 measured drops, histogramed in Fig. 2b, is consistent with all drops containing only integer charges. Using the flux for 4.1×10^{13} protons and the assumed stopping efficiency in the first two liquid nitrogen tanks of 0.02, the upper limit for quark production is 1.0×10^{-10} quarks per proton interaction at the 90% confidence level.

b) QUARK SEARCH AT THE CERN SPS COLLIDER

A collaboration from Oxford-Rutherford-Imperial has exposed 200 iron balls to collisions at the CERN $p\bar{p}$ collider(10). The iron balls were placed inside the beam pipe of the collider so that the balls would be the first material that any free quark would strike. If quarks interact very strongly, they could be trapped by the iron balls. From a Monte Carlo calculation, they calculated that with an integrated luminosity of 650 nb^{-1} about 200 jets would have struck each ball. After the exposure, the balls were carefully transported back to England where the net electric charge was measured in a room temperature magnetic levitation system. A total of 60 balls have already been measured. The offset charge for the measured sample was found to be 0.1e. When that offset was included, the residual fractional charge on all balls was found to be consistent with zero using the measured charge resolution of 0.02e.

c) FUTURE QUARK DETECTORS

The problem with bulk matter detectors is that only small quantities of matter have been measured with existing detectors. In fact, in seven recent bulk matter papers a total of only 12 mg of matter has been processed. In order to process much larger samples, new techniques are necessary.

A SLAC collaboration(11) is working a detector to measure the net charge of a sample with a rotor electrometer. The basis of this detector is that when a object with charge Q is placed inside a metal box, it produces a voltage (V) which can be related to capacitance of the box (C) by the formula $V=Q/(2C\sqrt{2})$. By measuring the voltage difference between that box and a grounded box, noise effects can be reduced. They have made a detector which keeps the sample fixed and then rotates a series of pads by the sample. Using a lock-in amplifier they can average their measurements to increase their detector's accuracy. So far they have been able to achieve a charge resolution of 0.31e.

In principle, this device should be able to achieve charge resolution of 0.05e which is sufficient to observe the charge of free quarks. Their collaboration is working on reducing the noise in the amplifier and identifying the source of some low frequency signals which are increasing their charge resolution.

Another detector(12) is being developed a LLNL which uses a different method to measure charge. In this apparatus, drops of oil fall in a vacuum between two charged plates which are 5.0 meters in length. The position of each drop, which is proportional to its net charge, is measured after the deflection. The authors estimate that they will be able to measure up to 50 grams/day with a background of 1 event in a measurement of 10^{23} nucleons.

With the new construction of high energy heavy-ion accelerators, new experiments will be be done to look for free quarks produced from creation of the quark-gluon plasma. Experiments will be run at both CERN(13) and at the BNL AGS(14) within the next year.

2. PRODUCTION OF MONOPOLES

In classic paper, Dirac(15) showed that if one monopole existed in our universe, then charge must be quantized. He found that the relationship between electric charge (E) and magnetic charge (G) can be expressed by the relationship $EG=n(\hbar c/2)$ where n is an integer. Using this expression, one can let n=1 and define g as the smallest magnetic charge. If one free quark with charge 1/3 exists, then $g=(3/2)(\hbar c/e)$; if only integer charges exist, $g=(1/2)(\hbar c/e)$. Therefore, a measurement of the spectrum of magnetic charges of monopoles could show whether quarks are confined.

In the current popular Grand Unified Theories (GUT), GUT monopoles are produced when the symmetry U(1) breaks spontaneously(16). The masses are in the range 10^{16} to 10^{17} GeV or even up to 10^{19}. Becauses of their large masses, GUT monopoles can only be produced in the Big Bang and not in any forseeable accelerator. Experimenters have looked for these monopoles in cosmic rays and materials. For perspective, a 10^{17} GeV monopole has a mass of 0.18 micrograms.

A goal for cosmic ray detectors is to have a sensitivity which is greater than the Parker bound(17). The Parker bound (f) which is deduced from the measured magnetic field of the Universe can be expressed for a monopole with mass M and velocity $(10^{-3})c$ by the expression:

$$f < \begin{cases} 10^{-15}\ cm^{-2}sr^{-1}s^{-1} & M<10^{17}\ GeV \\ \frac{10^{17}}{M}\, 10^{-15}\ cm^{-2}sr^{-1}s^{-1} & M>10^{17}\ GeV \end{cases}$$

Currently upper limits from experiments are at a level of about a few times 10^{-12}. A monopole with mass of 10^{19} GeV at the Parker limit would just escape detection.

a) MONOPOLE SEARCH IN IRON ORE

A magnetic monopole, incident upon the earth, would fall toward the earth's center due to its gravational attraction. A likely place for a GUT monopole to be trapped would be in magnetic material such as iron ore. This ore would be a trap for monopoles as long as its temperature was below the Curie point (590°C).

A group from Kobe University(18) made a search for such monopoles in old iron ore. In order to examine a large amount of material, they placed two 20 cm diameter SQUID detectors underneath a conveyor belt of an industrial sintering furnace. The ore on the conveyor was heated to a maximum temperature of 1500°C which is sufficient to release any monopole. The freed monopole should fall toward the center of the earth and through their detector.

They ran their detector for about 1200 hours. During that time the furnace processed 140,000 tons of ore. They estimated that their detector was sensitive for 6600 tons of material. No monopole candidate was found, so an upper limit of 4.5 x 10^{-9} monopoles/gram at 95% confidence limit can be found. Since their detector was also sensitive to cosmic ray monopoles, they also set a limit on monopole cosmic ray flux which is 1.4 x 10^{-10} $cm^{-2}sr^{-1}s^{-1}$ at 90% confidence limit.

b) MONOPOLE CANDIDATE

Recently, an experiment(19) looking for GUT monopoles in cosmic rays, reported on a candidate monopole event. Their detector consisted of two parallel horizontal SQUID loops (T and B) with a third vertical rectangular loop (WF) which has one of its sides going through the center of the two horizontal loops. In a total of 8,242 hours of operation, 170 possible monopole events were observed. All but one of these events can be explained by causes such as low helium level in the cryostat or mechanical shock to the apparatus.

The interesting event showed a signal (0.83 +/- 0.04) Φ_0 in the WF loop, but no significant signal in detectors T and B. A standard Dirac magnetic monopole should generate a flux of $2\Phi_0$ in the T and B detectors, while the signal generated by a standard monopole in the WF detector should vary between 0 and Φ_0. The authors have estimated that 70% of the monopoles which would produce a signal between 0.78 and 0.88 Φ_0 in the WF detector should induce an undetectable signal in the other loops. In their paper, they ruled out known causes of such a signal such as "unauthorized" interference, electronics problems, mechanical shock, motion of the trapped flux. However, they noted that it is possible for the event to be produced from some other unknown process.

If the event is caused by a cosmic ray

monopole, then one would expect the three other large monopole detectors, which have collectively set a limit at 2×10^{-12} $cm^{-2}sr^{-1}s^{-1}$, to have seen about 2 events. Thus, this event is not statistically ruled out by the other experiments. However, if this event is real, then the monopole cosmic ray flux would be orders of magnitude greater than the Parker limit for a standard GUT monopole of 10^{16} GeV but could be consistent with a monopole with mass 10^{19} GeV.

c) FUTURE MONOPOLE DETECTORS

In order to make a significant attempt to measure the cosmic monopole flux or confirm the previously mentioned event, it is necessary to construct much bigger detectors. The limitation to making SQUID detectors large arises from the fact that they must operate in a very small magnetic field. Shielding such large detectors is very difficult. A Chicago-Fermilab-Michigan group(20), one of several groups trying to significantly improve the technology of monopole detection, has been working on an induction detector that can operate in 1-10 mGauss fields. A prototype has already been built that has 1.1 m diameter loops and 1 cm separation. This is about 2.2 times greater solid angle than previous detectors. For 12 days of running they have set a limit for monopole flux of 7.1×10^{-11} $cm^{-2}sr^{-1}s^{-1}$ at 90% confidence level. In principle this detector can achieve a limit of about 10^{-13}. They are working on a design that can use an array of these detectors to measure at the Parker limit for a monopole with mass of 10^{16} GeV.

3. CONCLUSIONS

Experiments, using new techniques, have failed to find any evidence for free fractional charge at the Tevatron and the CERN $p\bar{p}$ collider. An experiment searching for monopoles trapped in the earth found no candidates. There is interesting evidence for a cosmic ray monopole. However, like Cabrera's candidate(21), it was only detected in a single loop. Significant advances are being made in constructing both quark and monopole detectors which have much greater sensitivities than previous experiments. Soon experiments will be run to search for monopoles and quarks in heavy-ion collisions.

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REFERENCES

1) M. Banner et al., Phys. Lett. 156B, 129 (1986).
2) G. Morpurgo, contributed paper 5088 to this conference; L. Lyons, Phys. Rept. 129, 225 (1985).
3) G. LaRue, J. D. Phillips and W. D. Fairbank, Phys. Rev. Lett. 46, 967 (1981).
4) M. L. Savage et al., Phys. Lett. 167B, 481 (1986).
5) M. Gell-man, Phys. Lett. 8, 214 (1964); G. Zweig, CERN Rep. TH-401 (1964); CERN Rep. TH-412 (1964).
6) A. De Rujula, R. C. Giles and R. L. Jaffe, Phys. Rev. D17, 285 (1978).
7) R. Slansky, T. Goldman and G. L. Shaw, Phys. Rev. Lett. 47, 887 (1981); G. L. Shaw and R. Slansky, Phys. Rev. Lett. 50, 1967 (1983).
8) G. Zweig, Science 201, 973 (1978).
9) H. Matis, R. W. Bland, D. Calloway, S. Dickson, A. A. Hahn, C. L. Hodges, M. A. Lingren, H. G. Pugh, M. L. Savage, G. L. Shaw, R. Slansky, A. B. Steiner, R. Tokarek, contribution 825 to this conference and LBL-21670.
10) L. Lyons, P. F. Smith, G. J. Homer, J. D. Lewin, H. W. Walford, W. G. Jones, contribution 5088 to this conference.
11) J. C. Price, W. Innes, S. Klein, M. Perl, SLAC-PUB-3938 (1986).
12) C. Hendricks, LLNL report to be published.
13) CERN proposal NA39, G. Shaw spokesman (1986); CERN proposal EMU02, B. Price spokesman.
14) AGS proposal 793, B. Price spokesman (1985); AGS proposal 801, R. Bland spokesman (1985); AGS proposal 804, G. Tarle and S. P. Ahlen co-spokesmen (1985).
15) P. A. M. Dirac, Proc. Roy. Soc. London A133, 60 (1931)
16) For instance see the following reviews: R. A. Carrigan, Jr. and W. P. Trower, FERMILAB-Pub-83/31 (1983); G. Giacomelli, IFUB 82-26, published in Racine Magnetic Monopole Workshop, 42 (1982).
17) M. S. Turner, E. N. Parker, T. J. Bogdan, Phys. Rev. D26, 1296 (1982).
18) T. Ebisu and T. Watanabe, contribution 620 to this conference.
19) A. D. Caplin et al., Nature 321, 402 (1986).
20) J. Incandela et al., EFI 85-75.
21) B. Cabrera, Phys. Rev. Lett. 48, 1378 (1982).

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