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QUARKS WITH UNIT CHARGE: A SEARCH FOR ANOMALOUS HYDROGEN

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QUARKS WITH UNIT CHARGE: A SEARCH FOR ANOMALOUS HYDROGEN

by

Richard A. Muller, Luis W. Alvarez
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ABSTRACT

We have searched for quarks of charge Z = +1, and other anomalous hydrogen, by using the 88-inch cyclotron at Berkeley as a high-energy mass spectrometer, with natural hydrogen and deuterium as the source of ions. We observed no quarks, and place limits on their ratio to protons on the earth that vary from $q/p < 2 \times 10^{-19}$ for high masses (3 to 8.2 amu) to 10^{-13} for the lowest masses (< 1/3 amu).

QUARKS WITH UNIT CHARGE: A SEARCH FOR ANOMALOUS HYDROGEN

Quarks, the components of the nucleon proposed by Gell-Mann and Zweig (1), have been the subject of extensive searches by both elementary-particle and cosmic-ray physicists (2). In most of these experiments the quark's fractional charge (1/3 or 2/3 that of the proton) was the distinctive signature that would have indicated their presence. But fractional charge is not required by all quark models; in particular, theories proposed by Lee (3) and by Han and Nambu (4) have quarks of integral charge. These theories were more complex, however, in that they required more than the three quarks of Gell-Mann and Zweig; the Han-Nambu theory, for example, had nine. When the classical quark theory was improved by the addition of the new quantum number "color", the number of fractionally-charged quarks had to be increased from three to nine (5). The integrally-charged quarks of Han and Nambu, on the other hand, accepted color in a very natural way and did not require an increase in number (6). It seems reasonable to speculate that the quark searches failed because they assumed the wrong signature; perhaps quarks have integral charge.

Experimental limits on the existence of quarks with integral charge are not nearly as good as the limits for quarks with fractional charge. Experiments at accelerators would have observed $Z = 1$ quarks only if they were produced with a cross-section at least 10^{-3} of that for $p\bar{p}$ and if their mass were no more than 4 GeV/c^2 (7,8). If quarks are stable against

decay, as they are in several versions of the theories, then a search in terrestrial material is potentially more sensitive than a search at accelerators since the natural production of quarks had literally aeons of time to take place. Quarks with Z = +1 would be equivalent chemically to a new isotope of hydrogen, and would be found on the earth mixed with that element. With this in mind, we decided to search in terrestrial hydrogen for Z = +1 quarks using the same technique that was used in the discovery of stable (and natural) ^{3}He by Alvarez and Cornog (9), i.e. to use a cyclotron as a high-energy mass spectrometer. After we began this work, we found that Zeldovich, Okun and Pikelner (7,10) had shown that if such particles existed they would be found in natural hydrogen not only from cosmic ray production, but also as remnants of the Big Bang, in much the same way that protons and the cosmic microwave radiation are thought to be remnants. The ratio q/p of quarks to protons predicted by Zeldovich et al. depends somewhat on the assumed values for the quark mass and cross-sections, but is of the order of $q/p = 10^{-10}$ to 10^{-12}. They also calculated that q/p from cosmic ray production is $\simeq 10^{-17}$.

The most sensitive search prior to ours was by Alvager and Naumann (11), who introduced deuterium into a mass separator and scanned in Z/m to look for new isotopes of hydrogen. Ions with Z > 1 were eliminated by sending the accelerated beam through a nickel foil which stopped molecules and particles of high Z. Unfortunately this technique works only for high values of mass where background from scattered beams

is low; for quark masses $m_q > 6$ amu (5.6 GeV/c^2), they were able to set the limit $q/p < 3 \times 10^{-18}$. For the low mass region, the best limit was obtained by Kukavadze, Memelova, and Suvorov (12), who used a mass spectrometer to find $q/p < 10^{-8}$ for $m_q > 2$ amu. Thus previous experiments do not rule out Z = +1 quarks with mass $m_q < 6$ amu at the levels predicted by Zeldovich and Okun.

We used the 88-inch sector-focused cyclotron at the Lawrence Berkeley Laboratory for our search. Both hydrogen and deuterium gasses were introduced as sample materials into the filament ion source. Only those ions with the appropriate value of Z/m, given by the cyclotron resonance equation, were accelerated. In their original discovery of stable ^{3}He, Alvarez and Cornog scanned in Z/m by varying the cyclotron's magnetic field; in our search we kept the magnetic field constant and scanned in frequency.

For the 88-inch cyclotron to be "in tune", i.e. for it to accelerate particles into our detectors, several criteria must be met. The magnetic field profile (i.e. the field as a function of radius) must be appropriate to compensate the relativistic increase in mass as the particle is accelerated, and the voltages applied to the electrostatic deflector and Dee must be at the correct values to assure efficient beam extraction. In order to eliminate the need to change the magnetic-field profile during a scan, we operated the cyclotron in the third-harmonic mode, where the particle revolution frequency is 1/3 of the oscillator frequency and the maximum

particle velocity is only 0.1 c. During scans we changed the deflector and Dee voltages in proportion to the change in frequency. The ultimate proof that we were in tune in our scans came from the observation of expected beams; for example, when we set the cyclotron to accelerate Z/m = 1/2 (D^+) and scanned to Z/m = 1/3, we found that DH^+ molecular ions were being efficiently accelerated and extracted.

The emerging beam from the cyclotron was focused onto two silicon detectors: a thin one (20-60 μ) to measure the ionization rate dE/dx, followed by a thick one (1 mm) to measure the total energy. By requiring a coincident signal between the two detectors, and that the signals in them correspond to a single Z = 1 particle with the correct energy, we were able to discriminate against heavier particles, molecules, and background radiation from the cyclotron. Except when the cyclotron was tuned near the resonant frequency for known species (integral values of Z and m) the number of background counts was essentially zero; during one run we operated for over an hour with no background counts. The rapid fall-off of the tails of the cyclotron resonance allowed us to search quite close to values of Z/m for which known particles exist. Figure 1 shows the beam current vs. frequency for a $^2H^+$ beam. By the time we had moved off a main peak by about 1%, the rate of particles emerging from the cyclotron was reduced to less than one per minute.

The advantage of the cyclotron over an ordinary mass spectrometer came not from its high resolution (see Fig. 1)

or from its beam current (10-50 μA), but from the high energy of the emerging beam: several MeV per nucleon. This high energy allowed us to send the beam into the particle-identification detectors, and to get useful information on a particle-by-particle basis. The cyclotron has, of course, one additional advantage. Had we discovered quarks in natural material, we would have had a high energy beam of them; and study of their properties would have been straight-forward.

For quark masses above 2 amu, we used deuterium gas in the cyclotron ion source. The deuterium had been separated from water at the Savannah River Heavy Water Plant, using the GS process followed by vacuum distillation and electrolysis (13). The efficiency for each of these concentration processes increases as the mass of the isotope increases; thus for masses just above 2 amu quarks would have been concentrated by <u>at least</u> a factor of 6600, the ratio of ^{1}H to ^{2}H in river water. For masses >> 2 amu we know that the concentration of quarks could not have been increased by more than a factor of 5 x 6600 = 33 x 10^{3}, since 20% of the original deuterium in the water was recovered, and obviously no more than 100% of the original quarks could have been recovered. Leventhal and Libby (14) have shown that for electrolytic separation, this transistion to maximum concentrations takes place below mass 3 amu. Thus by searching in deuterium, the sensitivity is 6600 times greater than a search in hydrogen for quark masses near 2 amu, and 33,000 times as sensitive for quark masses above 3 amu. In a typical run a 13 μA deuterium beam was observed as we tuned through the $^{2}H^{+}$ frequency, corresponding to 8 x 10^{13}

ions/sec. The deuterium beam was measured with a Faraday cup, preceded by collimators which simulated the acceptance geometry of the silicon detectors. Our typical dwell time for a particular value of Z/m as we manually scanned in frequency was 2 seconds, during which time we would have recorded as significant the observation of even a single particle with the proper signature in the dE/dx and total E detectors; no quarks were observed. Thus the ratio of quarks to deuterons was less than 6×10^{-15}. The ratio of quarks to ^1H is then less than 10^{-18} near mass 2, and less than 2×10^{-19} for masses ≥ 3 amu.

For quark masses in the range 1-2 amu we used ordinary hydrogen in the source rather than deuterium; our sensitivity was corresponding 6600 times poorer. We repeated the scan in the mass range 1.5-2 amu using deuterium, with the thought that it would give us some additional sensitivity in the range just below 2 amu. We saw no quark events in this scan. It is difficult to estimate the sensitivity of this scan without studying the detailed physical chemistry of the isotope separation process; thus we claim no limit obtained from this scan. For the mass range 0 to 1, we looked for quark-hydrogen molecules Hq, assuming that they would have chemistry similar to H_2. The mass range was covered in two runs; for quark masses 1/3 to 1 amu, the H_2^+ current we obtained was 1.7 μA, and for the mass range 0 to 1/3 amu, the H_2^+ current was 0.16 μA. The corresponding sensitivities are in the range $q/H = 10^{-14}$ to 10^{-13}.

We have observed no quarks of Z = +1, nor other anomalous isotopes of hydrogen. The limits from our search and previous experimental results, are plotted in Figure 2. These limits correspond to one standard deviation, i.e. a confidence level of 67%. For 95% confidence levels, each limit must be adjusted upward by a factor of three, as is indicated on the plot. In addition, we have taken the calculations of Zeldovich, Okun, and Pikelner, and, after scaling them appropriately with energy, plotted the predicted quark-to-proton ratios. For several regions corresponding to integral values of Z and m, the intensity from known ions (such as $^{2}H_2^{+}$ and $^{14}N^{2+}$) was sufficiently high to require the removal of the silicon detectors from the beam. As a result there are regions, generally less than 1% wide in mass, in which we were unable to search for quarks. These regions are indicated in Fig. 2 by short vertical bars. The existence of these beams served the useful purpose of proving that the cyclotron was still in tune, and that if there were quarks at concentrations greater than the limits we have placed, they would have been observed.

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Footnotes and References

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Figure Captions

Fig. 1. Beam current as a function of frequency for D^+ ions, as measured by a Faraday cup. The smooth curve is a quide to the eye. The effective width of a "flattop" curve with the same area is 4 kHz (0.028%), as shown. For these measurements, we reduced the beam current to prevent heat damage to the cyclotron deflector electrodes. The fine structure at the top of the resonance curve reflects changes in the number of turns made by the beam in the cyclotron before extraction.

Fig. 2. Quark-to-proton ratio as a function of quark mass. Shown are the experimental limits, as well as predictions of the levels expected from cosmic-ray and Big Bang production if Z = +1 quarks exist. The predictions were scaled with mass to take into account changing cross-sections and cosmic-ray fluxes. The short vertical bars indicate the narrow regions (generally less than 1% wide) where we could not search because of the existence of beams of common ions with integral values of Z and m. The experimental limits plotted as solid lines are for 67% confidence level, corresponding to approximately one standard deviation. Each limit must be raised by a factor of 3 (as indicated with dashed lines) for a 95% confidence level.

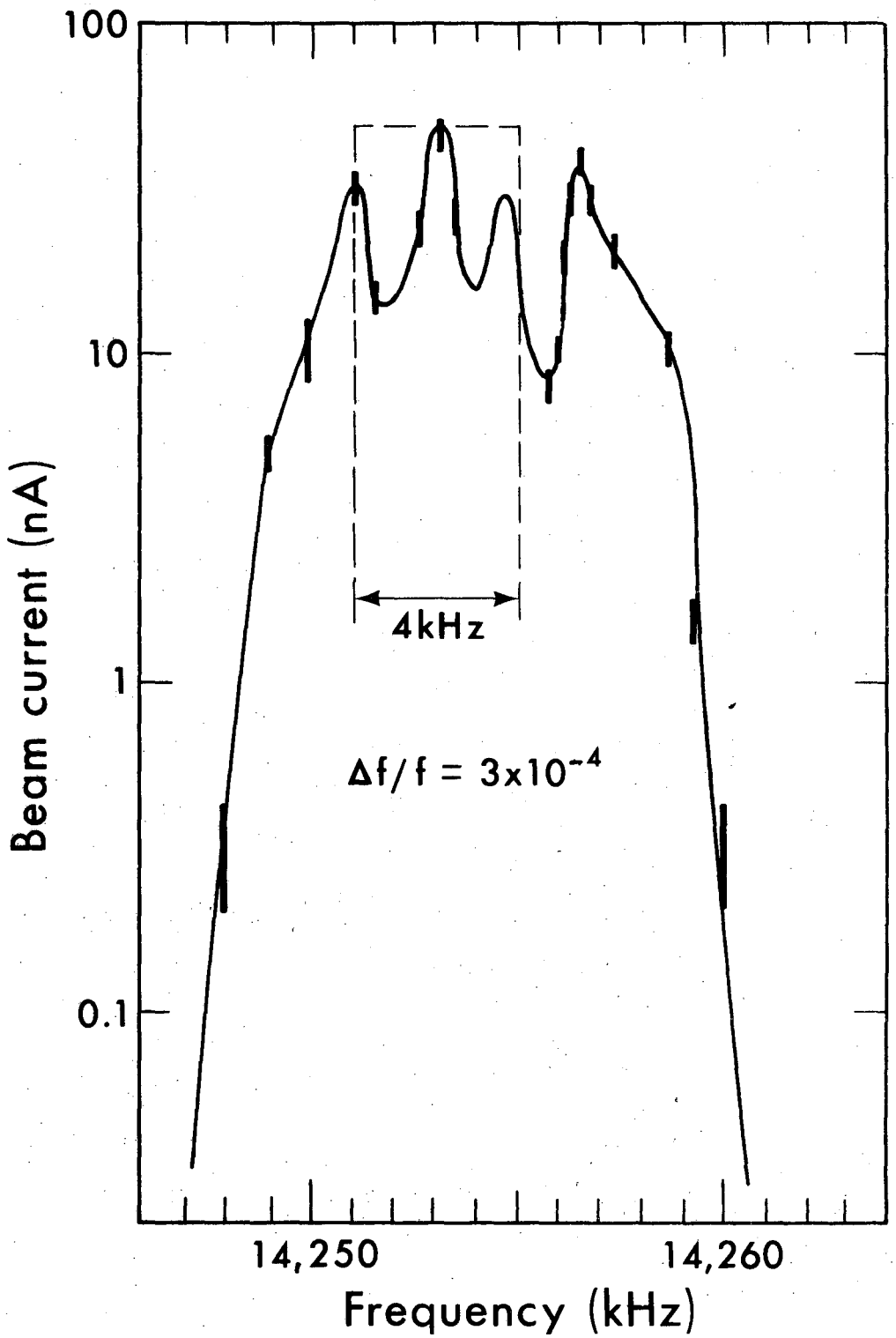

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Fig. 1

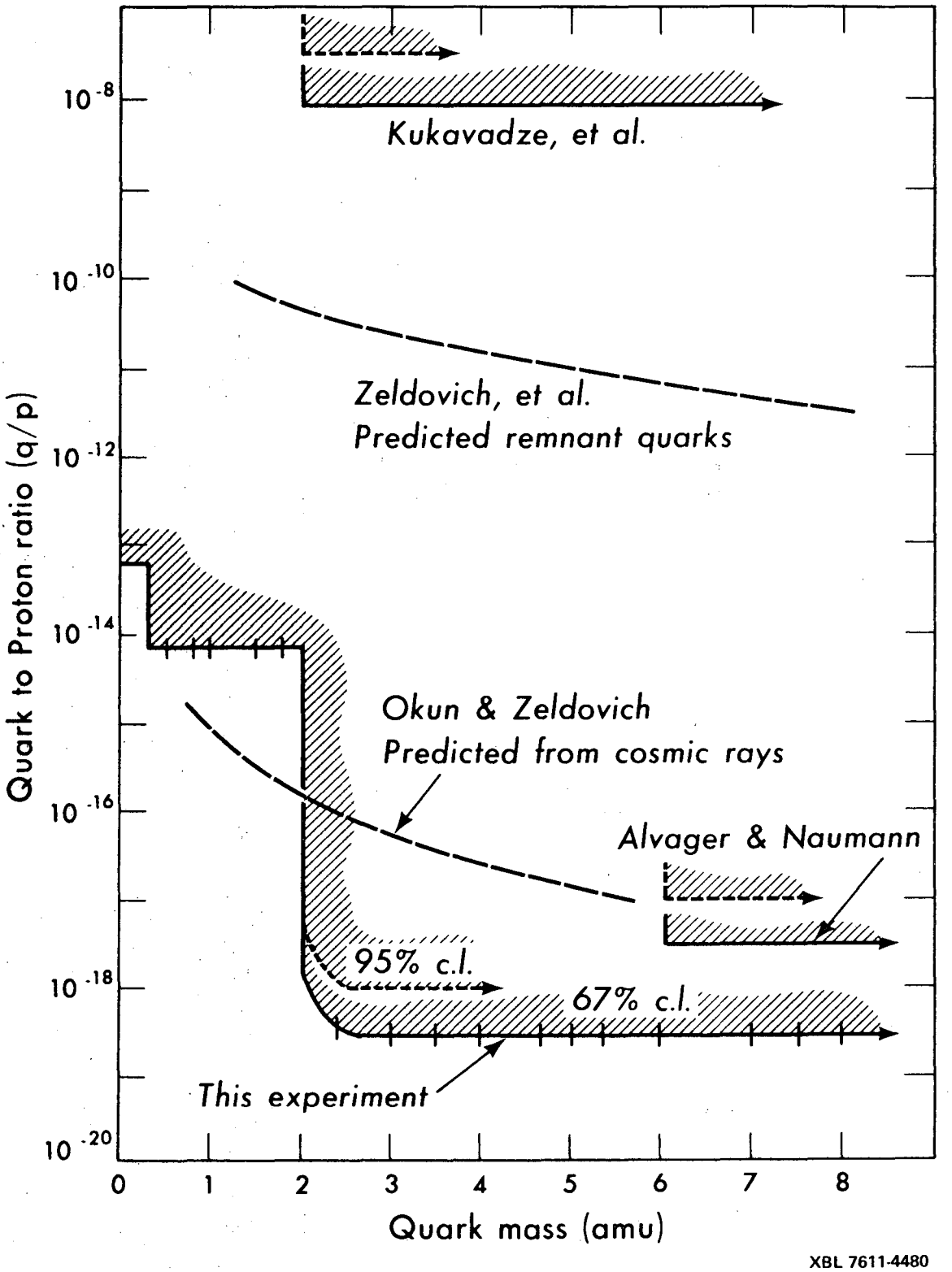
Kukavadze, et al.
Zeldovich, et al.
Predicted remnant quarks
Okun & Zeldovich
Predicted from cosmic rays
Alvager & Naumann
95% c.l.
67% c.l.
This experiment
Quark to Proton ratio (q/p)
Quark mass (amu)
10 -8
10 -10
10 -12
10 -14
10 -16
10 -18
10 -20
0
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Fig. 2

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