THE QUARK HUNTERS' PROGRESS

T. Massam

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6. SUMMARY  

REFERENCES
1. INTRODUCTION

These lectures will be about the experiments which have been carried out in order to search for any particles which might belong to one of the sets of particles proposed as the basic constituents of the elementary particles. So, in spite of the title, particles with either fractional or integral charge and of any mass will be considered. The search is really for unknown particles with almost unknown properties.

The field has been very wide, and a critical examination of all the experiments would involve not only high-energy physics but also spectroscopy, physical chemistry, geophysics, and astrophysics. A list of the places searched sounds like a quotation from the Bible: they hunted them in the heavens above, in the earth beneath, and in those things in the waters and under the earth.

Table 1 is a summary of published experiments, and the grouping from left to right follows the plan of the lectures.

The most popular method of measuring the charge has been by specific ionization measurements in counter work and in bubble-density measurements in bubble chambers.

Velocity spectra have been measured in secondary beams from machines and in cosmic rays in order to detect anomalous mass values with integral or non-integral charges.

Direct charge measurements have been made using optical and mass spectroscopy, and also by the Millikan and the magnetic levitator methods. The latter method is particularly appealing because one has a piece of matter sitting there in the apparatus, suspended in a potential well in a magnetic field. Chance changes in its charge do not cause it to drift away and be lost, as in the Millikan apparatus. If there is a quark in it, no one can query the result. Sceptics could be invited to measure the charge for themselves. Certainly it would be exciting to be the first person to discover the quark, but think of the prestige of being the first to own one.

2. PROTON ACCELERATOR EXPERIMENTS

2.1 The production of secondary particles

2.1.1 Dependence on mass

Before describing the machine experiments, one should remember the general features of secondary particle production. Total cross-sections and differential cross-sections for the production of pions, kaons, antiprotons, and antideuterons are now carefully measured at several angles and energies.

Hagedorn, and Maksimenko et al. have used statistical models for the calculation of expected yields as a function of mass. Figure 1 illustrates their results.

We have normalized the predicted curves to an antiproton production cross-section of \(10^{-27} \text{ cm}^2\). The most important feature of these statistical model predictions is a decrease in cross-section by five orders of magnitude for every GeV increase in mass.

The details of the two predictions are slightly different. The Maksimenko group fit \(\bar{p}, \bar{\Xi}, \bar{\Upsilon}\) and \(\bar{\Lambda}\) with a unique curve. The low value of the \(\bar{\Lambda}\) cross-section makes the curve decrease rapidly for high mass. Hagedorn points out that there are two types of particles: a) those which are the ground states of a series of resonances, and b) those which are not.
Table 1
A summary of the techniques used in quark experiments published before January 1968

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Fig. 1
Statistical model predictions and experimental points for the reaction $p + p \to q + \bar{q} + \text{anything}$. Note the logarithmic vertical scale. The upper of the two Hagedorn curves is for particles which are the ground state of a series of resonances. The lower curve is for particles (e.g. the deuteron) which are not.

Excited states also compete in the production process, but they decay very rapidly and so contribute to the production of the ground-state particle. Thus Hagedorn draws two nearly-parallel curves, one through the antiproton point and one through the antideuteron. These curves have a lower slope than the Maksimenko curve by about a factor of seven for each GeV increase in mass.

Provided that the incident momentum is well above threshold, then the Hagedorn predictions vary very slowly with the primary energy, at most logarithmically. We may thus compare experiments done at different energies, on a unique curve, provided we remember that for each primary energy there is a kinematic limit to the range of masses. At mass values near this limit, the true cross-section will differ from the curve and will fall to zero for values above the limit.

We do not, of course, know which type of particle the quark is, and there is a factor of $\sim 10^3$ between the two types of curve.

2.1.2 Fermi motion

One may use the Fermi motion of nucleons in a nucleus to obtain a higher centre-of-mass energy for the production of secondary particles, and so extend the search to higher mass values for a given primary energy. The discussion will refer to the production process $p + p \to p + p + q + \bar{q}$. 
Dorfman et al. measured the production of antiprotons as a function of the primary energy and so obtained a probability distribution of the Fermi momentum.

Their result applied to the quark search is that the probability of there being a sufficiently high centre-of-mass momentum to produce a 5 GeV/c pair, when the maximum mass from a zero-momentum nucleon is 3 GeV, is $10^{-3}$. Thus if one is able to make a search for a mass equal to 3 GeV, one must be prepared to look $10^{14}$ times better for 5 GeV using this method (i.e. Fermi motion factor $\times$ expected decrease in production cross-sections).

2.1.3 Maximum mass as function of energy

Figure 2 shows the maximum mass which may be produced in particle-antiparticle pair production as a function of the primary energy.

![Graph showing maximum mass as a function of proton momentum]

This shows, as a function of the incident proton momentum, the maximum mass of the particle $q$ which may be produced in the reaction $p + p \rightarrow q + \bar{q} + p + p$.

We see that if a 70 GeV accelerator is used, the search can be extended up to 4.8 GeV/c, but one may have to do an experiment which is $10^8$ times more difficult.

2.1.4 Secondary particle momentum spectrum

Pion production spectra are well known and are available in machine users' handbooks as well as in the literature. The pions in a beam are perhaps the most reliable monitors for normalisation in the quark experiments. There is one feature which is interesting to state explicitly because it is one of these rare cases where one obtains, gratis, a reduction in background.

At a few degrees production angle, the pion spectra decrease with increasing beam momentum (Fig. 3).
If one searches for a quark of charge of, say, \( \frac{1}{3} \) and momentum \( p \), then the momentum of the pions transmitted by the beam is \( 3p \), where the pion intensity may be reduced by a factor of between 10 and 1000.

2.1.5 Estimation of the total cross-section

The laboratory differential cross-section is obtained either from the ratio of quarks to pions in the beam, or from the total number of primary protons which interact in the target.

The primary energy is known. Assumption of a value of quark charge defines the true beam momentum, and assumption of its mass defines its velocity. One then has a unique value for the Jacobian to transform the differential cross-section to the centre-of-mass system.

From here on, the calculation is model dependent. The usual method has been to assume

i) isotropic production; and

ii) four-body phase space for the momentum spectrum of the quark in the reaction:

\[ p + p \rightarrow p + p + q + q, \]

and hence calculate the total cross-section from the differential cross-section.

2.2 Bubble chamber experiments

2.2.1 Principle

The compression cycle of a bubble chamber is phased with the accelerator so that a short (~100 \( \mu \)sec) burst of particles enters the chamber during that part of the cycle corresponding to a plateau of sensitivity.
The bubble density depends on the number of $\delta$ rays produced in the few keV region, and is proportional to the (charge)$^2$. A typical density is 20/cm with a variation of ±5/cm from one chamber to another. For a small chamber showing 30 cm track length, the total number of bubbles in the track will be:

<table>
<thead>
<tr>
<th>Charge</th>
<th>Total bubbles</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{1}{2}$</td>
<td>70</td>
</tr>
<tr>
<td>$\frac{3}{2}$</td>
<td>280</td>
</tr>
<tr>
<td>1</td>
<td>600</td>
</tr>
</tbody>
</table>

so fractional charges will be clearly recognized.

2.2.2 Background

There is one very important precaution against spurious events. The bubble density as a function of time looks roughly as shown in Fig. 4:

![Bubble density graph]

This figure shows the variation in bubble density as a function of time; $t_0$ is the centre of the plateau of sensitivity in the bubble chamber pressure cycle.

Some particles may spill out of the accelerator between 1 and 2 msec before the nominal time $t_0$ and so simulate fractional charges. There are several methods of recognizing this background:

i) Tagging of events: The best method is to use scintillation counters to detect the incident particles and to display, on an oscilloscope, the time of arrival of the beam particles together with the bubble chamber pressure cycle. Using this method, Blum et al.\(^7\) were able to say that of the nineteen low-density events observed by them, all were accompanied by an early beam particle, and that these beam particles were the only ones which arrived between 1 and 2 msec before $t_0$. 

\(^7\) Blum et al.
ii) δ rays: A cross-check is to make a bubble count on long δ rays. Average pictures in a 2 m hydrogen bubble chamber show two δ rays, each long enough for bubble-density measurement. In this way, Hagopian et al. rejected some 14 events which had low bubble-density but were not recorded on their oscilloscope. Two low-density events without δ rays were rejected on the basis of the probability of finding a track with no δ rays.

iii) Bubble size: A third possible method of identifying early tracks is to look at the bubble size — early bubbles will have grown larger by the time the photograph is taken. This is difficult in a large chamber where the image size is determined mainly by diffraction effects, but Morrison used this method in the analysis of 30 cm chamber pictures.

iv) Cosmic rays: These may also cross the chamber when it is partly sensitive, but they may be recognized by their direction.

2.2.3 The experiments

There have been four bubble chamber experiments: three at CERN and one at Brookhaven.

The first two results were the analysis of existing bubble chamber photographs in the CERN 30 cm hydrogen chamber [Morrison9] and in the CERN heavy liquid chamber [Bingham9].

The last two experiments, by Hagopian10 et al. at Brookhaven and by Blum11 et al. at CERN, were designed to detect quarks and so the electronic detection of early particles was used.

2.2.4 Results

Table 2 shows the results quoted by the authors and also includes the parameters of each experiment. A more general comparison of the results will be made after describing the counter experiments.

2.3 Counter experiments

The two types of experiments which have been made with counters are:

i) $dE/dx$ measurements;

ii) velocity measurements.

$dE/dx$: The techniques used here are the same as in many of the cosmic-ray experiments. In fact, the first of the series of cosmic-ray experiments at CERN used a telescope which had been designed for a machine experiment.

2.3.1 Typical counter performance

Remember (Fig. 5) that the mean pulse height $h_0$ is proportional to the square of the charge, and the width of the distribution $\Delta$ is proportional to the absolute value of the charge. Typical values of $\Delta/h_0$ are 20% to 30%, depending on the light collection efficiency and counter thickness.

If one makes an electronic cut $h_0$ to reject singly-charged particles, one may obtain (for example, in a five counter telescope) 80% efficiency for $Q = 3/2$ for a contamination of 2% of charge $Q = 1$.

Calibration of the efficiency for fractional charges is usually done by simulation, using optical attenuators or masks over the photocathode.
### Table 2a
The experimental parameters of the bubble chamber experiments

<table>
<thead>
<tr>
<th>Authors</th>
<th>Ref.</th>
<th>Target</th>
<th>Primary energy GeV</th>
<th>Secondary beam angle mrad</th>
<th>Nominal momentum GeV</th>
<th>$\Delta\Omega$ sr</th>
<th>$\Delta p$ GeV/c</th>
<th>Bubbles/frame cm</th>
<th>Tracks/Frame</th>
<th>Number of pictures</th>
<th>Chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morrison</td>
<td>8</td>
<td>Al</td>
<td>26.8</td>
<td>70</td>
<td>10.7</td>
<td>10^{-7}</td>
<td>0.33</td>
<td>25</td>
<td>10^6</td>
<td>30 cm Hg</td>
<td>30 cm Hg</td>
</tr>
<tr>
<td>Bingham et al.</td>
<td>9</td>
<td>Cu</td>
<td>21.0</td>
<td>77</td>
<td>16.0</td>
<td>1.2 x 10^{-6}</td>
<td>0.32</td>
<td>15</td>
<td>10^6</td>
<td>1 x 1/2 x 1/2 m^2</td>
<td>C_2H_5Cl</td>
</tr>
<tr>
<td>Hagopian et al.</td>
<td>10</td>
<td>W</td>
<td>31.0</td>
<td>120</td>
<td>8.5</td>
<td></td>
<td></td>
<td>30</td>
<td>10^6</td>
<td>80° Hg</td>
<td>80° Hg</td>
</tr>
<tr>
<td>Blum et al.</td>
<td>7</td>
<td>Cu</td>
<td>27.5</td>
<td>76</td>
<td>20.0</td>
<td>product = 6.9 x 10^{-6}</td>
<td>20</td>
<td>11</td>
<td>1.4 x 10^6</td>
<td>81 cm Hg</td>
<td>81 cm Hg</td>
</tr>
</tbody>
</table>

### Table 2b
The results of the bubble chamber experiments

<table>
<thead>
<tr>
<th>Authors</th>
<th>Charge</th>
<th>$n_{\pi}/n_{\nu}$</th>
<th>Total incident particles $\sigma_{\text{e}}^a$</th>
<th>Mass assumed for $\sigma_{\text{total}}$ calculation</th>
<th>$\sigma_{\text{total}}$ cm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morrison</td>
<td>-3/2</td>
<td>-3/2</td>
<td>8 x 10^{-34} in the lab. system</td>
<td>0.5 to 2.0 GeV/c^2</td>
<td>$&lt; 6.0 \times 10^{-34}$</td>
</tr>
<tr>
<td>Bingham et al.</td>
<td>-3/2</td>
<td>$&lt; 5 \times 10^{-9}$ c)</td>
<td>$&lt; 5 \times 10^{-9}$ to $&lt; 4 \times 10^{-34}$ in the centre of mass</td>
<td>1.0 to 2.0 GeV/c^2</td>
<td>$&lt; 5.0 \times 10^{-34}$</td>
</tr>
<tr>
<td>Hagopian et al.</td>
<td>+3/2</td>
<td>$0/10^3 + b)$</td>
<td>$3 \times 10^3$</td>
<td>1.0</td>
<td>$&lt; 6.5 \times 10^{-35}$ d)</td>
</tr>
<tr>
<td>Blum et al.</td>
<td>-3/2</td>
<td>0/1.5 x 10^3 b)</td>
<td>1.5 x 10^6 in the lab. system</td>
<td>2.0</td>
<td>$&lt; 2.0 \times 10^{-35}$</td>
</tr>
</tbody>
</table>

a) Units are cm$^2$ (or GeV/c)$^{-1}$.
b) Ratio in the beam.
c) Ratio calculated at the same true momentum.
d) These numbers are for the two assumptions of the quark mass. The results for the two charge states are similar.

* indicates 90% confidence. Otherwise normalisation is per event.
2.3.2 Experiments

The unique machine experiment which used $dE/dx$ measurements is that of Leipuner et al.\textsuperscript{11}, and this experiment was not made under the easiest of experimental conditions.

There were seven counters (Fig. 6) alternating as coincidence and anticoincidence, the anti being larger than the coincidence counters. In this way, the anticounters can veto singly-charged particles and showers, and can be used as an unbiased measure (for very low pulse heights) of the particles which trigger the coincidence counters. This reduces counter edge effects.
The coincidence counters were 5 cm thick × 5 cm × 15 cm, and the anticounters were 2 to 5 cm larger. The search was restricted to charge \( \pm \frac{1}{2}e \).

The experiment was done in two parts:

1. **\( 0^\circ \) measurement:** In this measurement, the telescope was set at zero degrees relative to the internal accelerated beam, but there were 1.6 kg of magnet and shielding wall between the internal target and the telescope. The limit to the cross-section was obtained by comparison with the muon flux outside the shielding, and refers to quarks which interact weakly.

2. **\( 10^\circ \) measurement:** In the second part of the experiment, the counters were placed in an \( 10^\circ \), 4.5 GeV/c beam. At this angle, the maximum quark mass observable (in the pair production model) was 1.8 GeV.

### 2.4 Velocity measurements

This way of looking for new particles is as old as the accelerators [Conconi (1960), Pitch (1962), Schwarzschild (1963), and Amaldi (1963)]. The only difference is that nowadays any stable massive particle would be considered as a quark candidate. Between 1960 and 1963, experiments have been made to detect deuterons, tritons, and antiprotons using time-of-flight and electrostatic separator techniques. The background level between these peaks may be considered as a limit to the cross-section for producing quarks. The limit was reduced, during this period, from \( 10^{-30} \text{ cm}^2 \) to \( 4 \times 10^{-30} \text{ cm}^2 \). The use of more sophisticated electronic selection has now produced a further gain of \( 10^4 \) in the limits. It is interesting to note that the time-of-flight accuracy of a little better than 1 nsec over 100 metres is still the same in the present experiments as it was six years ago. This resolution is to be compared to the separation in time between a pion and a 3 GeV particle, which is 17 nsec (in Franzini et al., below).

#### 2.4.1 Separation and time-of-flight

Franzini et al. used a combination of electrostatic separator and time-of-flight measurements. The mass slits in the beam were set very wide so as to accept a mass bite of 1 GeV, and for the low mass run the separator was set in such a way that pions and antiprotons were just not accepted; thus the timing electronics would not be overloaded. Three runs were made so as to scan a mass range of 2.5 GeV. The counter thresholds were set to accept charges \( \pm \frac{1}{2}e \).

To give an indication of what can be done with a separator, Fig. 7 shows a separator curve taken in a beam where a simple three-counter telescope was timed to accept antideuteron velocities.

With more sophisticated time-of-flight measurements, Franzini gives a background level which is \( 10^3 \) better than this.

#### 2.4.2 Time-of-flight selection alone

Dorfan et al. did not use a separator, but instead used a more sophisticated counter system and electronic logic consisting of:

- 5 bending magnets
- 2 momentum slits
- 13 scintillation counters
- 1 Pitch Čerenkov counter, and
- 1 threshold gas Čerenkov counter.
An electrostatic particle-separator scan in the region of the antideuteron peak. A rough time-of-flight selection was made in the telescope used to detect the beam.

They summarize their selection criteria as follows:

i) An event "must have a momentum established via its trajectory, narrowly defined through four bending magnets by eleven counters;

ii) "must not be accompanied by particles spraying into the guard counters";

iii) "must be separated in time from any $\beta = 1$ particle by greater than $\pm 35$ nsec";

iv) "must not trigger any of the five pairs of $\beta = 1$ coincidence circuits;

v) "must not give a pulse in the 10 m gas Cerenkov counter";

vi) "must have a velocity between 0.81 and 0.96 as determined both by delayed coincidences and by the angular cone of the radiation produced in the Fitch counter"; and

vii) "must have the same velocity to $\pm 1\%$ in three different flight intervals".

Events which satisfied these criteria had the times-of-flight between counters 1 and 10, and 2 and 9, printed out in digital form.

The above quotation needs little clarification. It is sufficient to point out that: in (ii) the guard counters formed 'halos' about the beam to veto events with multiple particle transmission or interactions in earlier counters; condition (iii) served a similar purpose and reduced randoms; the circuits in (iv) were five independent, 4 nsec resolution, 99% efficient, coincidences circuits to supplement the threshold Cerenkov rejection; (v) was to veto
$\beta = 1$ particles, i.e. $\pi$, $e$, and $\mu$; and in (vi) a velocity window was selected to accept particles of mass between 3 and 7 GeV for charge $\neq \frac{3}{2}$.

To illustrate the method, it is well worth while showing the results obtained with the same system in the search for antideuterons (see Figs. 8 and 9).

**Fig. 8**

The time-of-flight spectrum obtained by Dorfan et al. in calibration runs with deuterons and tritons.

**Fig. 9**

The scatter diagram of two independent time-of-flight measurements obtained by Dorfan et al. in a search for antideuterons.
The background level reached in this experiment in a search for antitrions may be used as the production limit for quarks in the mass range 2-3 GeV.

Table 3 gives the parameters of these experiments.

2.5 Summary of the proton machine situation

We will summarize the results of the machine experiments by comparing them with the statistical model predictions (Fig. 10). This was not always easy because of the different forms in which results were given. Where total cross-sections were not calculated, they have been estimated by comparison with the quark/pion limits given in papers where the total cross-section was calculated.

![Graph showing the comparison of experimental limits on quark production in proton accelerators with those of statistical model predictions. The lower line through the p point is the prediction of Maksimenko et al. The upper line is drawn so as to pass half-way between the two Hagedorn predictions at 3.0 GeV/c². The vertical lines are the maximum mass values which are kinematically possible in the reaction pp → q+q+p+p. The horizontal lines are the experimental upper limits of the cross-section. Points are labelled with the charge value. The sloping cross-hatched line shows the way in which Fermi motion of the target nucleons extends the experimental limit to higher mass values.]

The meaning of the symbols ' in Fig. 10: the horizontal line indicates the cross-section limit; the vertical limit indicates the maximum mass which can be produced at that angle and beam energy if it is produced in the reaction p+p → p+p+q+q, without any Fermi motion. The extension of the mass limit by Fermi motion can be approximated in a line of slope 10²⁻³/GeV as indicated on the Dorfan results, part of which were done entirely in the Fermi motion region (shaded line).
Table 3a
The experimental parameters of counter experiments at proton accelerators

<table>
<thead>
<tr>
<th>Authors</th>
<th>Ref.</th>
<th>Target</th>
<th>Machine energy GeV</th>
<th>Secondary beam angle sr</th>
<th>Beam momentum GeV</th>
<th>ΔΩ sr</th>
<th>Δp GeV/c</th>
<th>Number of counters</th>
<th>Length used in time-of-flight feet</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leipuner et al.</td>
<td>11</td>
<td>Be</td>
<td>28.0</td>
<td>0</td>
<td>All</td>
<td>3.14</td>
<td>4.5</td>
<td>7</td>
<td></td>
<td>ΔE/dx behind 1.6 kg shielding wall ΔE/dx in a beam.</td>
</tr>
<tr>
<td>Fransini et al.</td>
<td>16</td>
<td>W</td>
<td>30.0</td>
<td>120</td>
<td>7.0</td>
<td>4.8 × 10⁻⁶</td>
<td>190</td>
<td>Separator + time-of-flight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dorfan et al.</td>
<td>18</td>
<td>Be, Fe</td>
<td>30.0</td>
<td>76</td>
<td>9.0, 10.0</td>
<td>0.2</td>
<td>15</td>
<td>210</td>
<td>Time-of-flight</td>
<td></td>
</tr>
</tbody>
</table>

Table 3b
The results of counter experiments at proton accelerators

<table>
<thead>
<tr>
<th>Authors</th>
<th>Charge</th>
<th>nq/νσ</th>
<th>Total incident particles</th>
<th>d²e/ dΩ dp . cm² sr GeV/c</th>
<th>σtotal cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leipuner et al.</td>
<td>5/3 e</td>
<td>10⁻¹⁰ a)</td>
<td>3 × 10⁷ mesons</td>
<td>&lt;10⁻³⁴ cm²</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1/3 e</td>
<td>10⁻⁸ a)</td>
<td>10⁸ pions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fransini et al.</td>
<td>negative</td>
<td>2 × 10⁻⁹ b)</td>
<td>5 × 10⁸ pions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dorfan et al.</td>
<td>negative</td>
<td>2.5 × 10⁻¹¹</td>
<td>2.4 × 10⁸ pions</td>
<td>≤1.5 × 10⁻³⁶ / Be nucleus</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.6 × 10⁸ pions</td>
<td>≤3.0 × 10⁻³⁶ / Fe nucleus</td>
<td></td>
</tr>
</tbody>
</table>

a) Ratio in the beam.
b) Ratio calculated at the same true momentum.
The relevant questions are:

i) Can we say that all the experimental limits which have been established are significantly below theoretical predictions -- the answer is no.

ii) Has a complete search been made? Answer: definitely not.

Summarizing the situation for each possible charge state:

$+\frac{3}{2}$: The limit is a factor of $10^3$ above the theoretical curve at a mass of 2.5 GeV. This is the only charge $+\frac{3}{2}$ experiment.

$+\frac{1}{2}$: In the best case, the limit is just equal to the predictions, assuming full detection efficiency up to the kinematically maximum mass. Note that as this experiment was done behind 1.5 kg of absorber, it is not valid if quarks interact strongly.

$-\frac{1}{2}$, $-\frac{3}{2}$, $-1.0$: The best experiments are just equal to the predictions at the maximum mass.

$+1.0$: The best limits which I have found are those (2% of the deuteron peak) which were found six years ago, before anyone heard of quarks, and a limit of about $10^{-3}$ of the deuteron production between a mass of 2 and 3 GeV which may be deduced from the calibration curves of Dorfan et al. in Fig. 8.

$\frac{1}{2}$: If we assume quarks to be heavy, fractionally charged particles with large binding energy, then we may speculate that there may exist a quark-quark state which has a lower mass than the quark itself$^{19,20}$. Such a particle would then be stable. It would be possible to have reactions such as

a) $p + p \rightarrow p + \text{quarks}$

b) $p + n \rightarrow p + \text{quarks}$.

Possible quark combinations have the following charges:

<table>
<thead>
<tr>
<th>States</th>
<th>Charges</th>
<th>Charges</th>
</tr>
</thead>
<tbody>
<tr>
<td>a $(p_0p_0)$</td>
<td>$n_0$</td>
<td>$+\frac{3}{2}$, $-\frac{1}{2}$</td>
</tr>
<tr>
<td>$p_0$</td>
<td>$(p_0n_0)$</td>
<td>$+\frac{3}{2}$, $-\frac{1}{2}$</td>
</tr>
<tr>
<td>b $(n_0n_0)$</td>
<td>$p_0$</td>
<td>$-\frac{3}{2}$, $+\frac{1}{2}$</td>
</tr>
<tr>
<td>$n_0$</td>
<td>$(p_0n_0)$</td>
<td>$-\frac{1}{2}$, $+\frac{3}{2}$</td>
</tr>
</tbody>
</table>

An objection to a search for charge $-\frac{3}{2}$ might be that it is always accompanied by charge $-\frac{1}{2}$, which has already been investigated. However, if the $-\frac{1}{2}$ quark were unstable with a lifetime of about $2 \times 10^{-6}$ sec, it would only have a small probability ($-10^{-5}$) of surviving to the end of a typical beam transport system.

There is a clear need for a programme of greatly improved experiments. Probably, in view of the uncertainty in the predicted cross-sections one should aim for a limit $10^7$ times lower than any theoretical predictions, i.e., about $10^{-30}$ cm$^2$. This corresponds to a limit of one quark per $5 \times 10^{13}$ pions.
3. ELECTRON MACHINE EXPERIMENTS

3.1 Leptonic quarks

If there exist quarks which are purely leptonic\textsuperscript{21),} their production in proton machines is depressed relative to strongly interacting particles. The reason is that they will be produced predominantly in pairs via the electromagnetic interaction.

For a quark mass of only 1.25 GeV/c\textsuperscript{2}, the square of the four-momentum transfer is 6.25 (GeV/c)\textsuperscript{2}.

The investigation of proton-antiproton annihilation into lepton pairs\textsuperscript{22,23) has shown that time-like photons of this four-momentum transfer are rare, and that cross-sections are depressed by a factor of at least 500 relative to those expected if nucleons were point-like particles.

With respect to proton-antiproton production, one might expect cross-sections which are lower by a factor

\[ q^2 \cdot q^2 \cdot \frac{1}{500} \cdot \text{(phase space factor)} = 10^{-7} q^2 \cdot \text{(phase space factor)} \]

\((\alpha = 1/3; q = \text{the charge of the quark; for particles heavier than the nucleon, the phase space factor would be less than unity}).\)

Such cross-sections could not have been observed in recent proton machine experiments. The obvious place to look for this type of particle would be at an electron accelerator, where photons are plentiful.

3.2 Calculation of production rates

If the particles are point-like leptons (spin \(1/2\) Dirac particles), then the events rate is directly calculable using Bethe-Heitler theory and including the effects of nucleon and nuclear form factors for the incoherent and coherent pair production\textsuperscript{24).}

The only uncertainty is the possibility that the quarks themselves have form factors which would depress the production.

The results of the proton machine experiments could be conveniently expressed in terms of limits to the production differential or total cross-section. In the electron machines, the situation is much more complicated. The incident beam consists of bremsstrahlung radiation, the spectrum of which is modified as it crosses the target. The most convenient way is to calculate the expected events rate, by Monte Carlo methods, and then to compare the observed and expected events rate.

The methods of calculation were verified with 20\% accuracy in the experiments, by comparing the observed and calculated flux of muons.

3.3 Experiments

There have been three experiments so far:

i) Batzow et al.\textsuperscript{25}, at DESY, using a 6 GeV electron beam incident on a lead target;
ii) Foss et al.\textsuperscript{26}, at Cambridge, using a 6 GeV bremsstrahlung beam on a carbon target;
iii) Bellamy et al.\textsuperscript{27}, at Stanford, using a 12 GeV electron beam on a Cu plus Be target.
Background: The serious background in these experiments is electron pair production at small angles.

Bathow et al. and Foss et al. restricted their search to truly leptonic quarks, and so were able to put large quantities of absorber in their beam. Foss et al. had 200 radiation lengths of material before the first counter, and then 14 radiation lengths of lead between each of the eight counters. Bathow et al. used 90 radiation lengths of lead and about 30 radiation lengths of heavy concrete before the first counter, as well as a sweeping magnet which further reduced the background (Fig. 11).

![Fig. 11](image)

The experimental arrangement in the search for pair production of leptonic quarks at an electron accelerator (Bathow et al.).

Bellamy et al. used only 16 radiation lengths of target (copper followed by beryllium), and so could also give limits on strong-quark production. This target was that of a 90 m long muon beam. The beam transport was set for a momentum of 12.5 GeV/c; 0.5 GeV/c above the incident electron momentum so as to transmit predominantly the fractionally charged particles. Further reduction of the electron background was made by placing two radiation lengths of lead at the first focus of the beam.

A point of particular technical interest in this experiment is that the authors were not content with common plastic scintillator. Their five counters were thick (~13 cm) sodium iodide crystals, which had a resolution of ±5% for 1 MeV energy release. The experiment was sensitive to the production of charges as low as e/25.

The detailed results of this experiment are shown in Fig. 12, where the 90% confidence mass limit is expressed as a function of charge.

The curve labelled 'stable leptonic' was derived from the Bethe-Heitler type of calculation mentioned above. The \( r = 10^{-10} \) sec curve shows the effect of decay-in-flight of the quarks with a mean life of \( 10^{-10} \) sec. Finally, the curve 'stable strong' is the result of an estimation of the detection probability for strongly interacting quarks.

3.4 Summary of electron accelerator results

Figure 13 shows the rate of expected events as a function of mass, and may be used to compare the three experiments. The short lines for the experiment of Bellamy et al. show the 90% confidence limits which they quote.
It is interesting to see how the mass limits change if one puts a form factor reduction of 50% in cross-section as observed in strong interactions. The limits of 1.5 GeV for charge $\frac{2}{3}e$ and 1.0 GeV for charge $\frac{1}{3}e$ would become 1.1 and 0.65 GeV, respectively.

![Graph showing mass limits and lifetime](image)

**Fig. 12**
The mass limits, as a function of charge, obtained in a search for quarks in electromagnetic pair production (Bellamy et al.). The three curves are for stable leptonic quarks, for leptonic quarks with a mean-life of $10^{-10}$ sec, and for stable quarks which interact strongly and so are attenuated in the target and in the beam telescope.

![Graph comparing mass limits](image)

**Fig. 13**
A comparison of the mass limits established for fractionally charged particles at electron machines. Note: these limits are valid only for the assumption that the quark does not have a form factor. The presence of a form factor would decrease the mass value at which the curves cross the 2.5 event, 90% confidence, limit.
4. COSMIC-RAY EXPERIMENTS

4.1 Introduction -- possible rates

This type of experiment investigates both the existence of quarks in the primary cosmic radiation and their production by it.

Chernavsky, Feinberg and Sissakian estimate that the abundance of quarks in cold objects in the universe could be as high as $10^{-9}$ relative to nucleons, and Zel'dovich, Okun' and Pikel'ner estimate an over-all concentration of between $10^{-9}$ and $10^{-10}$ of the nucleons. The higher estimate is encouragingly near to present experimental limits in cosmic rays.

With regard to the production by the primary cosmic rays, if the mass is low, then the machine experiments would produce a greater yield, and if the mass is large, then the flux is probably negligible. This is roughly illustrated as follows:

$$\frac{\text{Number of quarks}}{\text{Number of muons}} < \frac{\sigma(p + p \rightarrow p + p + \text{quarks})}{\sigma(p + p \rightarrow p + p + \text{pions})}$$

(the 'less than' sign is because pion multiplicity has been neglected). Take the cross-section for pion production to be 40 mb; use statistical model results to extrapolate from proton-antiproton production (1 mb, with a factor $10^{-5}$ for each 1 GeV increase in mass); take into account the integral cosmic-ray spectrum $N(E) = 1.4 \times 10^{-6}/\text{cm}^2/\text{sr/sec}$; and note that the threshold for quark production is

$$2m_p \left(1 + \frac{m_q}{m_p}\right)^3.$$ 

So the number of primary protons available for producing quarks with mass $m_q$ is (roughly)

$$N(m_q) \approx \frac{0.7}{(1 + m_q)^3}.$$ 

These factors are given in Table 4.

Table 4

<table>
<thead>
<tr>
<th>Mass</th>
<th>$\sigma_{\text{quark}}/\sigma_{\text{pion}}$</th>
<th>$N(m_q)/N(m_p)$</th>
<th>$\frac{\sigma_{\text{quark}}}{\sigma_{\text{pion}}}$</th>
<th>$\frac{N(m_q)}{N(m_p)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_p$</td>
<td>1</td>
<td>1.0</td>
<td>$2.5 \times 10^{-2}$</td>
<td>$2.5 \times 10^{-2}$</td>
</tr>
<tr>
<td>$2m_p$</td>
<td>$10^{-5}$</td>
<td>0.3</td>
<td>$2.5 \times 10^{-7}$</td>
<td>$7.5 \times 10^{-8}$</td>
</tr>
<tr>
<td>$3m_p$</td>
<td>$10^{-10}$</td>
<td>0.13</td>
<td>$2.5 \times 10^{-12}$</td>
<td>$3.5 \times 10^{-13}$</td>
</tr>
</tbody>
</table>

Thus for 3 GeV quarks, which is the upper limit which may be produced by a 30 GeV proton machine, the quark flux is expected to be less than $3 \times 10^{-13}$ of the muon flux. This is $10^{-8}$ of the detectable rate of the most sensitive cosmic-ray experiment so far performed.

4.2 Experiments

Although the specific ionization types of experiment are similar to those performed at accelerators, some extra care is needed to compensate for the fact that there is not a collimated momentum-analysed beam. In cosmic-ray experiments, every extra counter improves the rejection against unit-charge particles, but the solid angle decreases as $1/(\text{Number of counters})^2$. 

The main sources of background are soft $\gamma$ showers for charge $\frac{q}{2}$ and the tail of the $q = 1$ spectrum (finite photomultiplier resolution) for charge $\frac{q}{2}$.

Two methods have been used to improve the analysis.

4.2.1 The use of a correlation function

For example,

$$ C = \sum_{i=1}^{n \text{ counters}} \left( \frac{h_i - h_{av}}{h_i} \right)^2 \left( \frac{\sigma_i}{h_q} \right)^2, $$

$h_i =$ pulse height in counter $i$;

$h_{av} =$ mean pulse height of the $n$ counters for that event;

$h_q =$ pulse height expected for the quark (the mean pulse heights of the $n$ counters are equalized in calibration measurements);

$\sigma_i =$ standard deviation of the pulse-height distribution expected for quarks in counter $i$.

This should be a $\chi^2$ distribution for $n$ degrees of freedom. It tests if the event is compatible with being produced by one unique particle crossing all the counters with the same mean specific ionization in each counter.

Kasha et al. have used this analysis on a five counter system (Fig. 14).

![Graph](image)

**Fig. 14.**

The distribution of the correlation function $C$ used by Kasha et al. to enrich their sample of events. $C$ is a function of the observed pulse-heights and the resolutions of the counters. The upper curve shows the distribution for good events and the lower curve the distribution for background events.

The upper curve of Fig. 14 obtained with simulated fractional charges is the frequency distribution of $C$ for good events.

Random pulse heights in all counters would give the lower curve. The observed events were distributed in the same way as the latter.
This analysis was used to enrich the sample of events by rejecting all events with \( C > 4 \). In this way, at the cost of a factor of two in the efficiency for good events, a factor of two in the ratio of efficiency for good events to efficiency for background events was obtained.

4.2.2 The use of spark chambers\(^{31}\)

The clearest way of removing ambiguities due to showers or strange multiparticle events is to include a spark chamber system in the telescope. Simply by scanning the pictures to select clean single tracks one can gain a factor of five in background rejection. There is, of course, the extra advantage that one may correct the pulse heights for obliqueness of the incident particle and for non-uniformity of the counters.

A particular type of event which is rejected is that in which a shower passes through the light-guides of all the counters without giving a charged track in the spark chambers. This suggests a lower order background in which this type of event is accompanied by an earlier cosmic-ray muon within the sensitive time of the spark chambers. To protect against this, each event of this type, with up to 100 \( \mu \)sec between the muon and the shower, is detected by auxiliary electronics and is marked on the film with a light.

Further use of the chambers is to provide an independent charge measurement, provided that they have not been filled with argon to get a high efficiency. The broken line of Fig. 15 shows a typical efficiency curve for an eight-gap, 6 mm gap-width He-Ne chamber.

![Fig. 15](image)

The distribution of the number of spark chamber gaps which trigger per event. The broken curve is the typical distribution for minimum ionizing particles. The solid curve is that expected for fractional charges.

The solid curve shows the distribution expected for charge \( \frac{1}{2} \).

The stability of the chambers to time-jitter in trigger and gas impurity is indicated in Fig. 16.
Fig. 16

The variation in spark chamber efficiency with the delay between the particle traversal and the triggering of the chamber. This is used to show the insensitivity of the spark count distribution to gas impurities and to time-jitter of the trigger.

Here the mean efficiency is plotted as a function of the delay between the event and the trigger for zero clearing field. If the loss of ions by electronegative gas impurity and by drift is an exponential with decay time $\tau$, and $N_0$ is the number of ions produced in the gap, then the efficiency $\epsilon$ is given by

$$\epsilon = 1 - \exp \left[-N_0 \exp \left(-\frac{t}{\tau}\right)\right].$$

This curve is shown for charge $e$ and charge $e/3$. Typically, one triggers the chambers within 0.5 $\mu$sec, so even a factor of two variation in gas purity will not invalidate the method.

A list of cosmic-ray counter experiments is shown in Table 5. To summarize, the present limit for the flux of quarks in the cosmic radiation is

<table>
<thead>
<tr>
<th>Charge</th>
<th>Flux limit</th>
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<tbody>
<tr>
<td>$e/3$</td>
<td>$1.2 \times 10^{-10}$ (cm$^{-2}$ sr$^{-1}$ sec$^{-1}$)</td>
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<tr>
<td>$2e/3$</td>
<td>$1.7 \times 10^{-10}$ (cm$^{-2}$ sr$^{-1}$ sec$^{-1}$)</td>
</tr>
<tr>
<td>$4e/3$</td>
<td>$1.3 \times 10^{-10}$ (cm$^{-2}$ sr$^{-1}$ sec$^{-1}$)</td>
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</table>
### Table 5
A summary of the parameters and results of cosmic-ray experiments on fractional charges

<table>
<thead>
<tr>
<th>Author</th>
<th>Ref.</th>
<th>Surface density above apparatus kg/cm²</th>
<th>Density of apparatus e/cm²</th>
<th>Area m²</th>
<th>Solid angle x area m² sr</th>
<th>Counters</th>
<th>Charge sensitivity</th>
<th>Efficiency</th>
<th>Time hours</th>
<th>Number of incident mesons</th>
<th>Number of triggers</th>
<th>90% Confidence limits</th>
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<td>min max</td>
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<td></td>
<td>flux x 10⁻¹⁴ cm⁻² s⁻¹ g⁻¹</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- coinc. = coincidence counter
- gas = proportional counter
- plastic = plastic scintillator
- liquid = liquid scintillator
- sp.ch. = spark chambers

* These results were published after the lectures were given.
4.3 Velocity measurements in cosmic rays

The experiments described above were sensitive only to relativistic (minimum ionising) fractionally-charged particles. Bangaard et al.\cite{32} have shown that because of the rapid decrease in the primary proton spectrum with increasing energy, most quarks would be produced just above threshold, and so would have velocities measurably less than c. This may be demonstrated in a simple way as follows:

For the production process

\[ p + p \rightarrow p + p + q + q, \]

at threshold,

\[ p_q = \frac{m_q}{m_q + m_p} \cdot \frac{p_{\text{in}}}{2} \quad \text{(zero momentum in the centre-of-mass system)} \]

where

- \( p_q \) = laboratory momentum of the quark,
- \( p_{\text{in}} \) = primary proton momentum,
- \( m_q \) = mass of the quark,
- \( m_p \) = mass of the proton;

the threshold momentum is:

\[ p_{\text{in}}^2 = 4 \cdot m_q \cdot m_p \left( 1 + \frac{m_q}{m_p} \right)^2 \left( 2 + \frac{m_q}{m_p} \right) \]

\[ p_q^2 = m_q^2 \cdot \left( \frac{m_q}{m_p} \right)^2 \left( 2 + \frac{m_q}{m_p} \right). \]

Hence the quark velocity is

\[ \beta_q = \frac{1}{\sqrt{1 + \frac{m_q}{m_p} \left[ \frac{m_q}{m_p} \left( 2 + \frac{m_q}{m_p} \right) \right]}} \]

\[ \approx 1 - \frac{m_q}{m_p} / [2m_q(2 + m_q/m_p)]. \]

Thus, for a quark of mass 10 GeV/c\(^2\), \( \beta_q = 1 - 0.004 \), and the difference in time-of-flight of a quark and a relativistic particle is 0.012 nsec/metre.

The height of the atmosphere is 7 km (1000 g/cm\(^2\)) and we assume most of the quarks are produced near the top, so the time lag of the quarks is 84 nsec.

Detailed calculations show that no known particle, with total energy greater than 5.5 GeV can be delayed by greater than 20 nsec relative to the front of an extensive air shower.

The experimental arrangement is shown schematically in Fig. 17.

The quark telescope consisted of three scintillation counters subtending 0.25 m\(^2\) sr, with one metre of iron absorber between the counters to provide an energy threshold. Adjacent counters, placed in coincidence, detected the front of the shower and opened a 1 \( \mu \)sec gate for the triples.
Fig. 17

The counter arrangement of Damgaard et al. The shower counters detect an air shower. The telescope ABC is then used to search for a time delay of energetic particles. The iron imposes the energy threshold.

The parameters of the experiment were:

Mean rate of muons = 400/minute
Total operating time = 30,000/week \times 1 \mu s
Expected randoms = 2/week
Observed rate = 2/day.

The high rate is not understood. If taken as an upper limit, it gives a flux less than $10^{-8} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$.

5. CONCENTRATION OF FRACTIONAL CHARGES IN MATTER

It is not intended to make a detailed discussion about the difficult problem of predicting the concentration of quarks, but I will summarise the classification of concentrations which was made by Nir$^{33}$). This illustrates well the range of values which can be obtained and the difficulties of the calculation.

Nir used quark production distributions and spectra from cosmic-ray interactions, which were calculated by Adair and Price$^{34}$), to calculate a factor of merit

$$M = TV/D$$

for several materials, where

T = the time T during which matter is irradiated; this is large for meteorites and small for the surface of the ocean.
E = enrichment in collection. This is largest in the aerosols in the stratosphere, where the dust is only $3 \times 10^{-11}$ by weight of the stratosphere. The total mass of the stratosphere is useful for producing quarks. Arguments are given that the quarks concentrate on the (charged) aerosol particles, and so give an enrichment factor of $3 \times 10^{10}$.

D = dilution by non-irradiated matter. For example, if in the ocean the quarks are produced in the top layer (4 kg/cm$^2$) then since the total depth is about 400 kg/cm$^2$, $D = 10^{-7}$.

The predictions and some experimental limits are given in Table 6 below.

**Table 6**

<table>
<thead>
<tr>
<th>Material</th>
<th>Range of Values of E</th>
<th>Results (quarks/nucleon)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea water</td>
<td>$10^6$ to $10^7$</td>
<td>$5 \times 10^{-27}$</td>
<td>55</td>
</tr>
<tr>
<td>Stratospheric aerosol</td>
<td>$10^9$ $10^{10}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tropospheric aerosol</td>
<td>$10^5$ $10^6$</td>
<td>$3 \times 10^{-27}$ to $10^{-33}$</td>
<td>55</td>
</tr>
<tr>
<td>Rock</td>
<td>$10^6$ $10^8$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marine sediments</td>
<td>$10^6$ $10^8$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meteorites</td>
<td>$10^5$ $10^8$</td>
<td>$10^{-17}$</td>
<td>55</td>
</tr>
<tr>
<td>Graphite</td>
<td></td>
<td>$10^{-16}$</td>
<td>26</td>
</tr>
</tbody>
</table>

*) see the text for description of the method.

***) i.e. dirt out of the air filters.

Concerning the behaviour of quarks in matter, one finds strongly conflicting predictions in the literature, but these do not have great relevance to the experimental results since the technique seems to have been to try everything and to try all conditions.

5.1 The method of Chupka, Schiffer and Stephens

The sample in gaseous form was passed through an electric field so that fractional charges could collect on the electrodes. These were concentrated onto a small platinum electrode, which was at a low positive voltage in order to retain the quarks. This was next heated to 600°C for 10 sec to drive off impurities, and then a 15 kV accelerating potential was applied to accelerate the quarks into a photomultiplier or a mass spectrometer.

Meteorites were vaporized directly in the ion source of a 100° mass spectrometer.
Air sampled at sea level was investigated, the search being for atoms of argon with a quark. The air was allowed to blow between the bars of a type of electric fence in order to collect quarked atoms.

Dust from air filters was examined.

Sea water was investigated, both the water and the residual salt being vaporised and treated as described above.

The method of detecting quarks was to search for an anomalous loss of charge from the platinum electrode when the accelerating field was removed.

The results were often difficult to interpret, and are shown in Table 6.

5.2 The Millikan method

Chupka et al. also did the Millikan experiment using 5μ diameter polyethylene spheres which had been exposed to likely sources of quarks. A total of 1000 spheres were measured corresponding to a limit of less than 1/3 x 10¹⁴ quarks/nucleon.

5.3 The magnetic levitometer method

This method was described by Becci, Gallinaro and Morpurgo and has been used by Gallinaro and Morpurgo, and by Braginskii. The two experiments are very similar.

The apparatus of Becci et al. is described below.

5.3.1 The apparatus

A small piece of diamagnetic substance P (graphite) floats in a potential well in a magnetic field, produced by shaped pole-pieces as shown in Fig. 18.

---

The principle of the magnetic levitometer of Morpurgo et al. A groove with constant radius of curvature is cut in the circular pole-piece of a magnet. P is a particle of diamagnetic material suspended in the field. The end view shows how two small plates A and B are positioned to measure the charge by balancing the electric force on the particle against the small component of the gravitational force tangential to the magnetic equipotential surface.
The equipotentials in the planes YOZ and YOZ are shown in Fig. 19. The equipotentials in the plane XOZ are very nearly circular.

![Diagram of equipotentials in YOZ and XOZ planes]

Fig. 19
The equipotential surfaces for a diamagnetic particle in the apparatus of Fig. 18.

Two small plates, A and B, supply an electric field of 1 kV/cm.

The graphite particle is viewed through a microscope, and typical displacements for a singly-charged particle are 250 μ.

5.3.2 Experimental method
The displacement Δ is given by

\[ \Delta = \frac{qE}{mg} \cdot R \]

where
- \( q \) is the electric charge
- \( E \) is the applied electric field strength
- \( m \) is the mass of the particle
- \( g \) is the acceleration due to gravity
- \( R \) is the radius of curvature of the equipotentials.

A radioactive source may be used to change the charge so that one may determine the charge of the particle which corresponds to the position nearest the equilibrium position with no electric field present. This must then be a fractional charge if there is a quark present in the particle.

At present, 70 grains have been measured, corresponding to \( 10^{17} \) nucleons.

The application of an alternating electric field with frequency near the natural frequency of the particle, at low pressure in order to reduce damping, gives an amplified displacement. At present, amplification factors of 200 have been observed.

The aim of the authors is to reach a sensitivity of one quark/\( 10^{21} \) nucleons.
5.4 Comparison of the charge composition of matter with cosmic-ray results

Our unit of flux is \(10^{-10} \text{ cm}^{-2} \text{ sr}^{-1} \text{ sec}^{-1}\). Such a flux, incident for \(10^6\) years and stopped in the first kilometre of the earth's crust, gives 100 quarks/cc, that is, \(10^{-22}\) quarks/nucleon. So roughly, the magnetic levitometer and the cosmic-ray search appear comparable in sensitivity.

The results of the Chupka experiment look much better than this, but the uncertainties in the concentration factors and the difficulty in interpreting some of their experimental results indicates great caution before abandoning any other methods.

5.5 Search in optical spectra

This seems a particularly difficult way of finding quarks. The experiments which have been done have value as pioneer experiments. The principle is that an atom with a quark will have shifted energy levels and spectra.

Bocaletti et al.\(^{39}\) suggest the possibility that the red shift of spectral lines in quasars may be due to a very high quark concentration rather than to a source motion. Unfortunately, there is some difficulty in identifying the unshifted lines which should also exist.

Sinanoglu et al.\(^{40}\) studied the far ultraviolet spectrum of the sun, and found two predicted quark lines. Bennett\(^{41}\) has pointed out that there may be many weak dipole transitions, and has used a computer to make a systematic prediction of spectral lines from normal, unquarked atoms. In this way, he found a total of 21 predicted lines within the line-widths observed by Sinanoglu et al.

Vainshtein et al.\(^{42}\) have made a search for lines predicted for quarked calcium and magnesium. They have also found hitherto unidentified lines.

6. SUMMARY

Conclusions drawn from published works have been given at the end of each group of experiments. To summarize:

i) experiments on proton machines have not been extended to the highest mass limits kinematically possible from the present machines;

ii) for several of the possible quark charge states, statistics are inadequate;

iii) in order to have results which are clearly below statistical median predictions, experiments need to be up to 1000 times better;

iv) cosmic rays are useful mainly as existence experiments: in production experiments, they do not compare well with either present or proposed accelerators;

v) if the experiments on the charge content of matter can be shown to be correct and can be fully understood, then these methods are able to give the best limit on existence.
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