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QUARK SEARCH EXPERIMENTS AT ACCELERATORS AND IN COSMIC RAYS

L. LYONS

Nuclear Physics Laboratory, Keble Road, Oxford, OX1-3RH, U.K.

"*... though a man labour to seek it out, he shall not find it*"
[*Eccl.* **8**, 17]

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L. LYONS

Nuclear Physics Laboratory, Keble Road, Oxford, OX1-3RH, U.K.

NORTH-HOLLAND – AMSTERDAM

Abstract:

The undoubted successes of the quark model in the fields of hadron spectroscopy and hard scattering processes have raised the question of whether free quarks exist. We review those recent experiments that have looked for quarks in experiments at accelerators, and in cosmic rays. The accelerator experiments include heavy ion reactions, $\bar{p}p$ and e^+e^- collisions, and deep inelastic scattering of leptons. Some of the cosmic ray experiments search for fractional charge, while others look for unusual mass particles, which need not necessarily be quarks; an example of the latter type is the delayed air shower search.

A brief mention is also made of stable matter searches, future experiments, and various ideas and speculations concerning quarks, which may be of relevance to the experimental search for them.

1. Introduction

Twenty years ago, high energy physics was a subject consisting of an enormous amount of seemingly unrelated phenomena. The advent of the quark model [1] succeeded in converting it to one in which a large body of data can be understood with relatively few additional assumptions. These successes occurred first in the field of non-strange and strange hadron spectroscopy [2], and then for hard scattering processes involving the so-called elementary particles (e.g., deep inelastic scattering of leptons [3]; electron–positron annihilations [4]; and in hadronic interactions, high transverse momentum reactions [5], the Drell Yan process of lepton pair production [6] and the production of intermediate vector bosons [7]) and for the spectroscopy of $c\bar{c}$ and $b\bar{b}$ systems [8].

Although the quark hypothesis, with its fractionally charged quarks, was initially regarded as simply a means of explaining the data and not necessarily as having any direct physical basis [9], the search for free quarks was soon started, and pursued with increasing interest both as the model gained wider acceptance and as larger accelerators and more sensitive techniques enabled the scope of experiments to be increased.

The early experiments have been summarised in various articles, culminating in the comprehensive review by Jones [11]. This was updated in 1981 by Lyons [12]. In several subsequent articles [13–17] and in a conference devoted to the subject [18], various aspects of quark search experiments have been discussed. In this article, we consider experiments searching for quarks either at accelerators or in cosmic rays; some of the searches in stable matter* are dealt with in refs. [16] and [17]. In particular we discuss developments that have occurred since the review of ref. [12]. The situation then was that a group at Stanford [87] had made 39 measurements of the charges on a set of 13 niobium balls; of these, 13 measurements on 5 different balls gave residual charges consistent with $\pm e/3$, and the remainder were consistent with zero. The only other experiment to claim evidence for fractional charge was a cosmic ray search for slow heavy particles [99].

In section 2, we discuss accelerator experiments; these consist of hadronic reactions (heavy ion collisions, $\bar{p}p$ and proton–nucleus reactions), deep inelastic scattering, and electron–positron annihilations. The cosmic ray studies described in section 3 include fractional charge searches, an interpretation of various cosmic ray phenomena in terms of quark globs, and searches for heavy particles. A brief mention of recent progress in stable matter searches is made in section 4, followed in section 5 by a summary of what results we can hope for in the near future. Some theoretical and phenomenological ideas relevant for quark search experiments are discussed in section 6.

* The categories of accelerator experiments or stable matter searches are not completely exclusive. Thus accelerator techniques have been used to look for quarks in matter, and there are other experiments which utilise the methods of stable matter searches in order to detect quarks that may have been produced by high energy beams.

All quark search experiments, be they at accelerators, in cosmic rays or in stable matter, require some significant signature for identifying quarks. The most characteristic is probably the colour triplet nature of quarks. Unfortunately no one has yet produced an unambiguous and practical suggestion of how it could be determined whether an observed particle is coloured or not. The second unusual property of quarks is their third-integral baryon number. Again this is in practice unusable, since in order to determine its value for a particle, it is necessary (and in general not even sufficient) to observe and identify the complete set of particles of the reaction in which the suspected quark is produced, or in which it decays. Quark search experiments at accelerators or in cosmic rays are far from achieving this, and by their very nature stable matter searches are insensitive to the way in which any interesting objects are produced.

Thus, most of the accelerator and stable matter experiments use third-integral charge as the significant characteristic for quark searches; a few cosmic ray experiments also are sensitive to the particle's charge. It is worth remembering, however, that some versions of the quark model have quarks of integral charge*, while there are also models in which fractional charge is associated with objects other than quarks (e.g., leptons; or hadrons composed of a mixture of fractional and integer charged quarks).

The other signature used is the mass of the free quark. This is of course unknown, but it is likely to be heavier than that of the proton or most other particles of long lifetime and small charge. Thus cosmic ray experiments, which often are unable to determine the charge of the relevant particle, have looked for unusual heavy masses; a few of the stable matter searches and accelerator experiments also use this technique. A convincing demonstration of such a heavy particle would of course be most interesting, but its nature would need confirming by other techniques.

2. Accelerator experiments

Each new accelerator facility has been an obvious hunting ground for the ever-elusive quark. Thus the new field of heavy ion reactions has provided two different types of experiments, which are discussed in section 2.1. With the operation of the proton–antiproton collider at CERN, hadronic reactions with "elementary" particles (section 2.2) have benefitted from an order of magnitude increase in the centre-of-mass energy. Another hadronic experiment uses the more conventional proton–nucleus collisions, but looks for heavy particles of unit charge and is sensitive to shorter lifetimes than were previous experiments. The deep inelastic scattering experiments of section 2.3 use high energy muon or neutrino beams, while the majority of the electron–positron annihilation experiments described in section 2.4 have been performed at the highest energy e^+e^- machines, PETRA and PEP.

2.1. Heavy ion reactions

In the last couple of years, increasing attention has been devoted to the idea that, as the density of nucleons in a system is increased, the quarks and gluons which were confined within individual nucleons may become capable of wandering around freely over the whole nuclear volume, and form a quark–gluon plasma [19]. Such a phase may have existed during the first millisecond of the Universe, but the most likely way to produce it now would be in heavy ion collisions. The currently favoured estimates for the energy density values required to produce this are such that accelerators larger than those presently in use (and which provide ~2 GeV/nucleon) would probably be required, but in the

* There may be problems in making integer-charged quark models compatible with experiment.

period while such higher energy experiments are being planned, the search is already in progress.

If such a plasma were formed, it is conceivable that either isolated quarks or nuclei containing an extra quark might escape (see, however, section 6.2). Hence there has been interest in the idea of searching for fractional charge production in heavy ion collisions. More specific motivation has come from the need to check whether "anomalons" contain extra quarks (see section 2.1.1), and from the suggestion of Slansky and Shaw that free diquark production may be favoured (see section 2.1.2).

2.1.1. *Are anomalons fractionally charged?*

For some 30 years, experiments with emulsions exposed to cosmic rays have suggested that some secondaries have larger than usual interaction cross sections. The initial observations consisted of the occasional production of chains of nuclear interactions from a single primary heavy ion, with the individual events close together [20]. More recently, the effect has been attributed to secondaries whose interaction cross section is enhanced near their production point. These became known as anomalons, and the same effect has now been observed with a heavy ion accelerator, in emulsion experiments [21,22] as well as with plastic sheet detectors [23] (see below), and also in a more recent analysis of cosmic ray data [24]. The magnitude of the effect varies from experiment to experiment. Indeed two recent searches [25] using Čerenkov techniques observe no anomalon effect, and another plastic scintillator experiment [26] reaches a similar conclusion. It is thus at present by no means clear that the anomalon effect is a real one. However, those experiments that do see a signal can typically be explained either by of order 6% of the secondaries having mean-free-paths λ a factor of ~ 4 smaller than the normal value λ_0, or by all secondaries having a mean-free-path of only $\sim 0.65\lambda_0$, but returning to λ_0 within 1–2 cm of their production point, or correspondingly in $\sim 10^{-10}$ s (although experiments looking for possible decays saw no effect [27]).

Various possible explanations of the phenomena have been proposed, including ideas such as nuclei with unusual shapes [28, 30], having a quasi-molecular structure [31], or containing π^- bound to an extended neutron rich region in the nuclear periphery [32]; longer range forces being associated with diquark structures within the nucleus [33] or with pion condensates [34]; nuclei with unusual spin couplings of the nucleons [35], in "isospin-stretched" states [179], with the 3 quarks within nucleons in colour octets [36], or with a 6 quark "angel deuteron" component [37]; and quark droplets [38]. Pshenin and Voinov [39] have suggested that the whole effect could be due to the statistical methods used to analyse the data, but the mechanism that they suggest has been shown [40] not to reproduce the anomalon effect. The field as of June 1983 is summarised in ref. [29].

2.1.1.1. Plastic detector experiment. Motivated by the suggestion that anomalons may be quark droplets, a Berkeley group [41] has measured the charges of secondaries in heavy ion collisions in order to determine whether they are occasionally third-integral*. The technique uses the fact that when particles of charge Z (and with velocity βc and angle of incidence θ both fixed) pass through a thin sheet of CR-39 plastic track detector, then the size of the subsequently produced etch pit is a monotonic function of Z. The resolution of a single measurement on Z is ± 0.23, so with successive measurements of 16 etch pits per track, a statistical accuracy of ± 0.06 is achieved. The detector was sensitive only to tracks with $Z > 9$.

The detector consisted of 400 sheets of plastic, each 640 μm thick. It was exposed to a beam of 1.85 GeV/nucleon argon ions from the Berkeley Bevelac. Some 1437 argon tracks were followed through the stack, which resulted in 248 projectile fragments of charges $10 \leq Z \leq 17$. With the

* Throughout this article, charges are quoted in units of the proton's charge.

assumption that the secondaries have the same velocity as the incident beam ions (which in general is expected to be essentially correct), the distribution of measured charges was consistent with a set of Gaussians centred on the integers and with the expected widths (see fig. 1(a)). All but one of the secondaries were within 4 standard deviations of an integer. The estimated charge for the remaining track was 11.23 ± 0.04; alternatively, it could have been 11 if its velocity was 2% lower than that of the beam.

To obtain a sample enriched in anomalons, a further 747 secondary tracks were measured within 1.7 cm of their primary interaction point. Again no third-integral charges were detected (see fig. 1(b)).

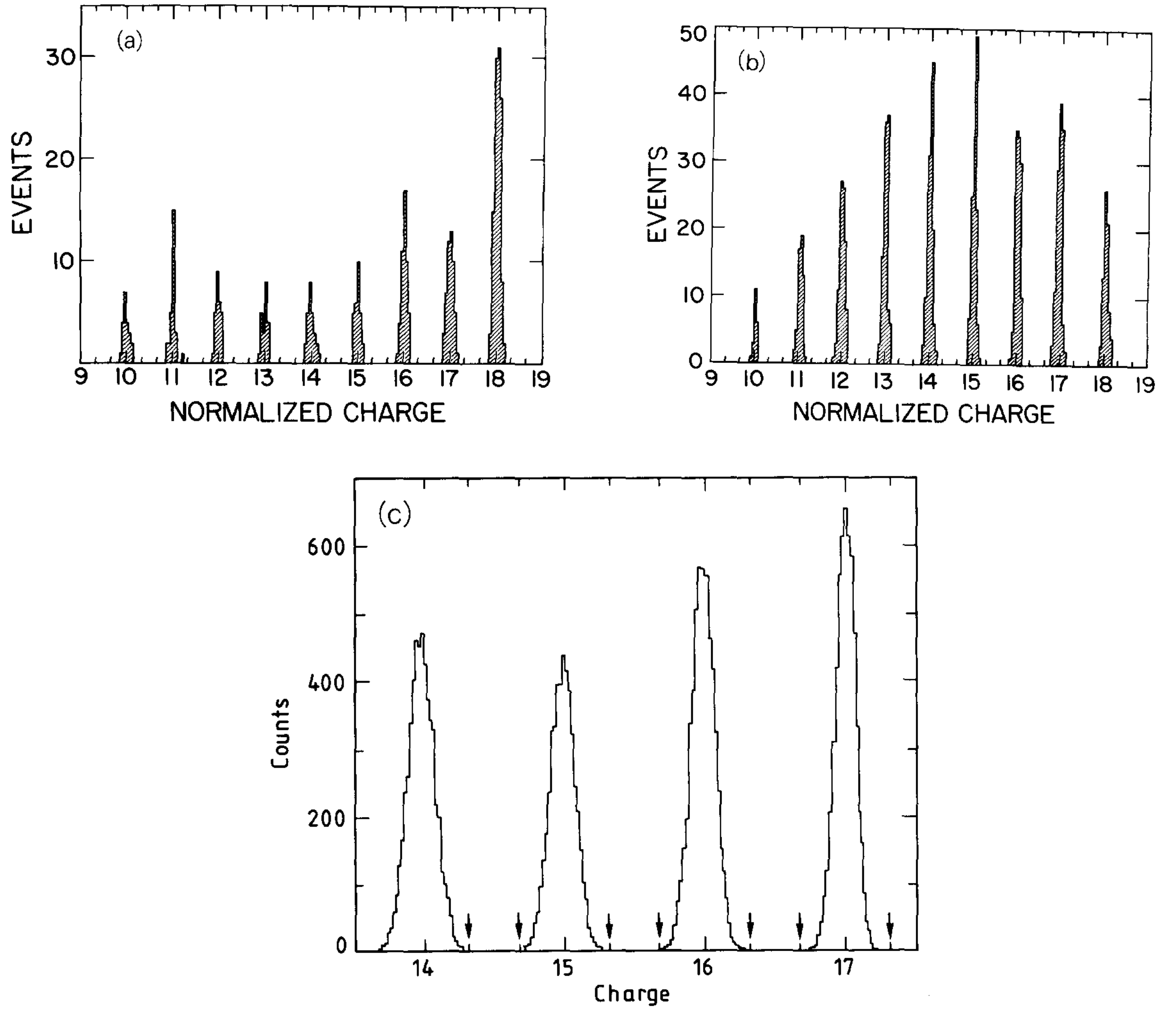


Fig. 1. The charges of projectile fragments from the interactions of 1.85 GeV/nucleon argon ions. In (a) and (b), the target/detector is a plastic track detector and the charges are estimated from the size of the etch pits on the surfaces of the plastic sheets. In (c), the target/detector is a Čerenkov system. (a) The results of measuring 248 projectile fragments of charges between 10 and 17 inclusive, plus 115 primary argon nuclei for calibration. The interactions had occurred up to 6.2 cm upstream of where the charges were measured. As discussed in the text, only 1 measurement lies outside the observed peaks at integer charges. (b) Results for 747 fragments, measured within 1.7 cm of their interaction point, plus 75 argon nuclei. (c) Results for 22000 fragments. The arrows show the positions of possible third-integrally charged fragments. The charge resolution of the peaks varies from 0.10 at $Z = 14$ to 0.07 at $Z = 17$.

Finally, and again without success, a search was made of 32 secondaries that in fact did interact a second time within ~1 cm of their original production point.

This experiment thus sets a 95% confidence limit of $<3\times10^{-3}$ for the fraction of secondaries having third-integral charge. A way for this experiment still to be consistent with fractionally charged anomalons would be for ≤6% of the secondaries to have such charges, and for their mean-free-path to be less than $\sim\frac{1}{2}$cm.

In a subsequent analysis of data from the same experiment, Tincknell et al. [23] observed a reduced mean-free-path at short distances, whose statistical significance was equivalent to about a 2 standard deviation effect. As already noted however, a Siegen group [26] with ~4 times the statistics claims to observe no effect (although their estimated mean-free-paths do seem to be reduced at both short and at larger distances).

The situation is unfortunately not clarified by the most recent results of Tincknell et al. [169]. Data on 875 charge-changing interactions of fragments with charges 10 to 24 produced by a ~1.7 GeV/nucleon iron beam in their plastic detector are unable to distinguish between the absence of an anomalon effect, or a 3.3% anomalon contribution with a 1.55 cm mean-free-path.

2.1.1.2. Čerenkov experiment. Barwick, Musser and Stevenson [167] have also looked for fractionally charged secondaries from the interactions of an argon beam at 1.8 GeV/nucleon. Their technique involves the use of a series of 14 Čerenkov detectors of thicknesses between 0.35 and 1.3 cm. Since the Čerenkov light output for particles above threshold is proportional to the square of their charge, this system can detect charge-changing interactions, and is then sensitive predominantly to the projectile fragment with the largest charge. The charge resolution of individual detectors for the argon beam varied from 0.15 to 0.25 for the thickest and thinnest counters. The observed resolution of the system for charge 17 secondaries was 0.07, increasing to 0.10 at charge 14. At even lower charges, the resolution became inadequate for detecting third-integral charges.

By demanding that the primaries interacted in one of the first two Čerenkovs, and that the leading secondary passed through the rest of the system without further interaction (which implies that its lifetime is greater than 10^{-10} s), Barwick et al. accepted 22 000 secondaries with charges 14 to $17\frac{2}{3}$. The distribution of observed charges is shown in fig. 1(c); none of them was found to lie beyond ±1/3 of the nearest integer. The 90% confidence limit on fractional charge production in this range of Z is thus less than 10^{-4}. If Čerenkov counters whose thickness was increased by 50% were used, the improved charge resolution should enable this limit to be reduced to about 10^{-6}.

It is worth remembering that this is one of the experiments [25] which saw no anomalon effect. Thus, while it places a stringent limit on fractional charge production in heavy ion collisions, it does not answer the question of whether anomalons (if they exist) are fractionally charged.

2.1.1.3. Emulsion experiment. In a similar study, Bloomer et al. [42] have looked for fragments of charge $\frac{4}{3}$, $\frac{5}{3}$, $\frac{7}{3}$ or $\frac{8}{3}$ among 1179 measured secondaries of charge 1 to 3 from interactions of a ~1.88 GeV/nucleon iron beam in an emulsion. The charges of the tracks were estimated to ±0.07 or better from their lacunarity. Those that were inconsistent with integral values were remeasured. leaving at most 1 candidate consistent with any of the third-integral values. If anomalons were produced among such low charges at the typical optimistic estimated rate of 6%, and if they had fractional charge, then 11 should have been observed in this study.

Our conclusion is that, although it is not clear that whether or not anomalons exist (despite the fact that there have already been 2 workshops devoted to their study), there is no evidence for them having fractional charge.

2.1.2. Limits on fractional charge production from stable matter search techniques

Shaw and Slansky [43] have suggested that colour SU(3) may be broken to SO_3 of "glow" (see section 6.2). Unconfined particles would then be glow singlets rather than colour singlets, and include such combinations as qq, $qq\bar{q}$ and qg. They consider that qq states may be the lightest, and that such diquarks may be most easily produced in heavy ion collisions rather than with elementary particle beams.

This provided the impetus for a series of searches at the Bevelac for fractional charge production, although they can be interpreted without specific reference to the Shaw and Slansky picture. The technique is to use the methods that have been developed for searching for quarks in matter, in order to look for fractionally charged objects produced in heavy ion collisions. The beam used for the main search so far has been iron at 1.9 GeV/nucleon, while the target assembly consisted mainly of lead, but also some indium and copper wafers, 10 g of mercury, and several hundred 0.1 mg steel balls. Most fragments with charge $\gtrsim 6$ would probably come to rest within the target, which was thus constructed in such a manner as to make it relatively easy to use the material in existing quark search apparatus. Fragments of lower charge in general would escape from the target assembly, and so behind it and within $\pm 30°$ of the straight through direction were placed 26 5-gallon containers of insulating liquid (carbon tetrachloride). It was estimated that the chance of a charge $\frac{1}{3}$ (or $\frac{4}{3}$) quark stopping in any given container was about 1% (or 8%).

From an exposure [44] with 3×10^{10} iron ions, two separate searches were performed using the San Francisco apparatus, which is a modified Millikan experiment in which the velocities of small liquid drops are measured in an electric field before and after a reversal of polarity; this had previously been used to look for fractional charges in mercury [45] and in water [46].

The first search was for quarks which may have stopped in the tanks of carbon tetrachloride. Each tank had a thin central wire, charged to +90 V or to −90 V with respect to the container, so that quarks (or quarked atoms or molecules) could drift towards and become attached to the wire. Two gold wires, one of each polarity, were then washed in a 10 mg drop of mercury (sample A) to remove the surface layer of the wire, and hopefully any quarks that might be there.

As it is possible that any quarks on the gold would not have been transferred to the mercury by the above technique, a second sample (B) was prepared by dissolving the 2 gold wires in 1.5 g of mercury from the target assembly. This search would thus be potentially capable of detecting either highly charged quark fragments stopping in the mercury, or low charged ones which reached the carbon tetrachloride bottles.

A total of 200 μg of sample A and 300 μg from B were investigated. A bias wire in the tip of the drop ejector was used to reduce the magnitude of the charge on the drops to $\lesssim 16$ (hopefully without disturbing any quarks in the mercury). Drops were rejected if they were seen to change charge during the course of a measurement (0.1%); further cuts at about the 5% level were used on drop size, etc. The charge on a drop could be measured to ± 0.035. Out of 260 000 drops tested, none had values of the residual charge between 0.2 and 0.75 (although 20 had such values before the cuts were imposed).

If it is assumed that any quarks attracted to the gold wire would have been dissolved in mercury with 100% efficiency, and using the 1% stopping probability for a charge $\frac{1}{3}$ object in a carbon tetrachloride tank, Lingren et al. deduce from the sample A search that at the 95% confidence level, the quark production rate is $<5\times10^{-7}$ per Fe–Pb collision. Otherwise sample B can be used to set this limit as $<5\times10^{-5}$. The lack of any signal for sample B can also be used to provide an estimate of $<1\times10^{-4}$ per interaction for the limit on the production of fractional charges that stop in the target assembly.

An earlier run [47] of 7×10^{12} silicon ions at 2.2 GeV/nucleon incident on a silicon target gave a limit of less than about 3×10^{-5} fractional charges per collision, based on measurements on 20 μg of mercury drops. This limit, which corresponds to the assumptions used for sample A in the iron–lead exposure, is somewhat model dependent, as the carbon tetrachloride was situated at a large production angle.

The possibility of obtaining similar results from other groups analysing samples is mentioned later in section 5, as is the proposal to perform a similar experiment at Fermilab, using a beam of ~1 TeV protons.

2.2. Hadronic production

In this section, we discuss three other hadronic experiments. The first looks for fractionally charged particles in p̄p collisions, while the second searches for heavy particles of unit charge in proton–nucleus interactions. In the last one, a search is made for so called "white quarks" of low interaction cross section.

2.2.1. p̄p

Since the liberation of free quarks may require a large energy, the UA2 group has conducted a search at the p̄p collider. The centre-of-mass energy is 540 GeV, which is to be compared with the previous highest of 62 GeV. At that lower energy, a limit of $<2\times10^{-9}$ quarks/unit charged track was set [48] for quarks of charge $\frac{1}{3}$ and mass below 26 GeV, assuming the production mechanism gave an average transverse momentum of ~0.4 GeV/c. Somewhat better limits exist for the quark/unit charged particle ratio at 52 GeV [49] (including quarks of charge $\pm\frac{2}{3}$ [50]).

The UA2 experimental arrangement [180] consisted of 5 drift chambers followed by 7 scintillators (2 Ws and 5 Qs, see fig. 2), for 6 of which the pulse height was measured at each end. Veto counters were used to exclude tracks passing through the light guides of the scintillators, and giving spuriously low pulse heights. The whole array was at 90° to the p and p̄ beam direction.

The trigger required that at least 3 out of the 5 Q counters should have pulse heights greater than 5% of the minimum pulse height for a unit charged particle (henceforth denoted by I_0 throughout this article) and that the W_F signal should be greater than $0.03I_0$. Subsequent cuts removed events with no pulses in Q_1 or Q_5 (in order to reject tracks passing through the sides of the Q telescope), or where the drift chambers showed that there was more than 1 track in the telescope.

The pulse heights were corrected for the attenuation along the scintillators (of length ~1 m), and then normalised so that their distributions peaked at 1.0. The ionisation of a track was then found from the 6 pairs of corrected and normalised pulse height measurements by a maximum likelihood method. Tracks with too small a maximum likelihood were rejected as having inconsistent pulse height measurements. There remained 23 tracks with estimated ionisation less than $0.7I_0$. Of these 15 were rejected as having low pulse height in W_F or Q_5 only. None of the remaining 8 events had a corresponding track in the drift chambers. It was assumed that the 5 of these with estimated ionisation greater than $0.5I_0$ would have been at least 50% efficient in producing hits in the drift chambers if they had been genuine fractionally charged particles, and hence they were rejected as spurious. The efficiency for the 3 remaining events (with $<0.5I_0$ in the scintillators) could have been too low for them to produce recorded hits in the drift chambers. However, each had an electromagnetic shower in the

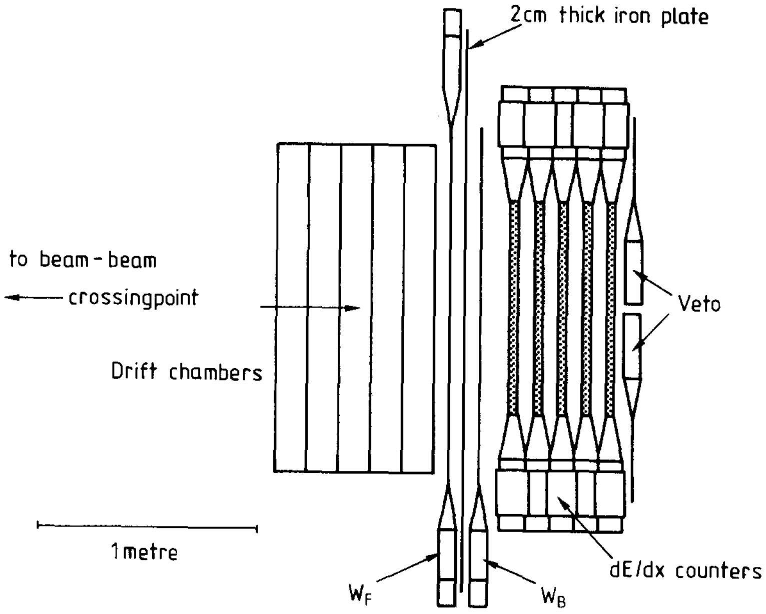


Fig. 2. The UA2 quark telescope. Quarks emerging from the beam intersection region traverse the 5 drift chambers, the scintillators W_F and W_B separated by an iron plate, and 5 further dE/dx counters (the Q_1 to Q_5 scintillators), which were each 1 m long, 30 cm wide and 4 cm thick. Both W_F and W_B consisted of a pair of counters 15 cm wide and 1 cm thick. The veto counters ensured that low pulses were not due to unit charged particles passing through the light guides of the W and Q scintillators.

lead glass blocks adjacent to the Q telescope. It was thus assumed that the low pulse heights were due to soft photons emerging from the lead glass, and hence these events were also rejected.

The detection efficiency for quarks was calculated with a Monte Carlo programme, assuming that the quark production in rapidity y and transverse momentum p_T is described by

$$d^2\sigma/dy\, dp_T \sim p_T \exp(-5m_T)\,,$$

where m_T is the transverse mass. For the 15062 charge particle triggers observed, the 90% confidence limit for the quark/unit charged particle ratio is $\sim 2\times 10^{-4}$ at low mass, but rises rapidly to $\sim 2.5\times 10^{-3}$ for quark masses of ~ 2 GeV for charge $\frac{2}{3}$, or ~ 3 GeV for charge $\frac{1}{3}$ (since heavier quarks would often be non-relativistic and hence give observed ionisations above the $0.7I_0$ cut). These limits do not allow for the possible absorption or scattering of quarks in the ~ 40 g/cm^2 of material in and before the telescope.

It is thus disappointing that despite the large centre-of-mass energy this experiment explores only the low mass range, and its sensitivity is much lower than obtained in earlier experiments. The restriction to lower masses arises directly from the track's momentum being unmeasured, thereby restricting possible quark candidates to being relativistic; the lower sensitivity is the result of (i) the lower luminosity at the $\bar{p}p$ collider, (ii) the small solid angle of the quark telescope, and (iii) the positioning of the quark telescope at 90° where the flux of relativistic particles is low.

Although the quark telescope has now been removed from the apparatus, more data (corresponding to ~ 300 times as many $\bar{p}p$ interactions as that used for the present study) is available and should be analysed soon. (See, Note added in proof.)

2.2.2. *Unit-charged heavy particles*

An experiment at Fermilab [172] has looked for heavy unit-charged particles in the mass range 4 to 12 GeV. A 400 GeV beam of protons was incident on a copper target 14.8 cm long. The spectrometer, in general tuned to negative secondaries of 87 GeV/c at zero transverse momentum, used bending magnets and Čerenkov detectors to obtain their momenta and velocities, and hence their masses. As the distance from the target to the end of the spectrometer was less than 20 m, useful limits could be obtained for lifetimes greater than $\sim 3 \times 10^{-9}$ s; this is one to two orders of magnitude smaller than was obtained in previous experiments of this type. Measurements on secondary antideuterons served to calibrate the system; its mass peak was centred on 1.88 GeV with a width of 0.19 GeV.

The apparatus is shown in fig. 3. The target is situated at the entrance to a 7 m 3.5 T magnetic channel with a momentum acceptance of ±7%, and which had previously been used in the Collaboration's hyperon beam experiments. The downstream spectrometer magnet, with the aid of the 4 sets of proportional wire chambers which were used to track particles through the system, enabled a momentum resolution of ±1% to be obtained. Particle velocities were determined from the radius of their Čerenkov ring in the counter C_2. The other 4 Čerenkov counters simply tagged particles as light or heavy. Thus C_4 rejected tracks below a mass of 3.75 GeV. The overall efficiency of the Čerenkov system for heavy particles was 84%.

No candidates passed the cuts, based on the Čerenkov signals, for negative heavy particles. The masses of particles between 4 and 6 GeV would have been measured by the Čerenkov ring radius in C_2; heavier particles would have given no Čerenkov signals. The kinematic upper limit on the mass of heavy particles was 12 GeV (or 11 GeV for pair production). Limits on their production cross section were obtained by comparison with the yield of $\sim 10^{10} \pi^-$ at the same secondary momentum, and assuming that the absorption of heavy particles in the target and spectrometer was the same as that for pions. These limits, shown in fig. 4(a), are sensitive to the lifetime of the heavy particles. The mass dependence of these limits reflects the fact that the lifetime in the laboratory system for particles of a given momentum depends inversely on their mass. However, while the spectrometer accepts 6 GeV particles

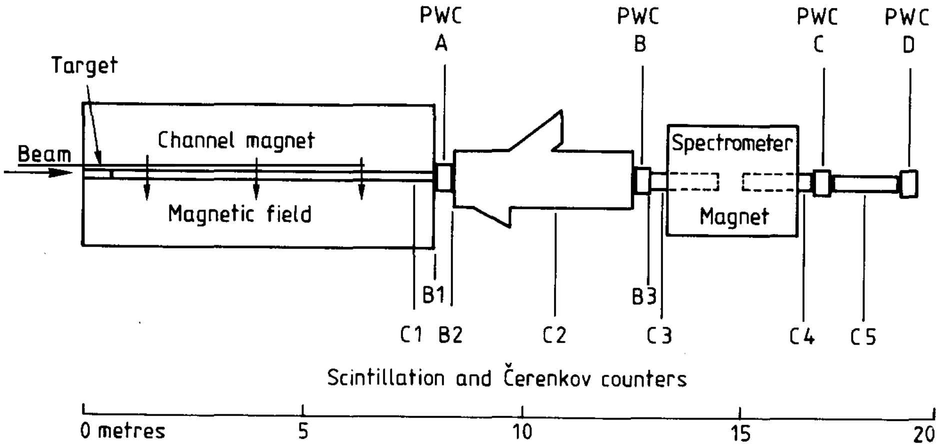


Fig. 3. The spectrometer of the Yale–Fermilab–Ames–Iowa Collaboration, used in their search for integrally charged heavy particles. The secondaries from the interactions of the 400 GeV proton beam are momentum selected by the magnetic channel and measured by the spectrometer magnet; the particles' trajectories are determined via the sets of proportional wire chambers (PWC A to D). Velocity information is obtained from the Čerenkov counters; C_2 provides a measurement of the velocity, while the others discriminate between high and low values.

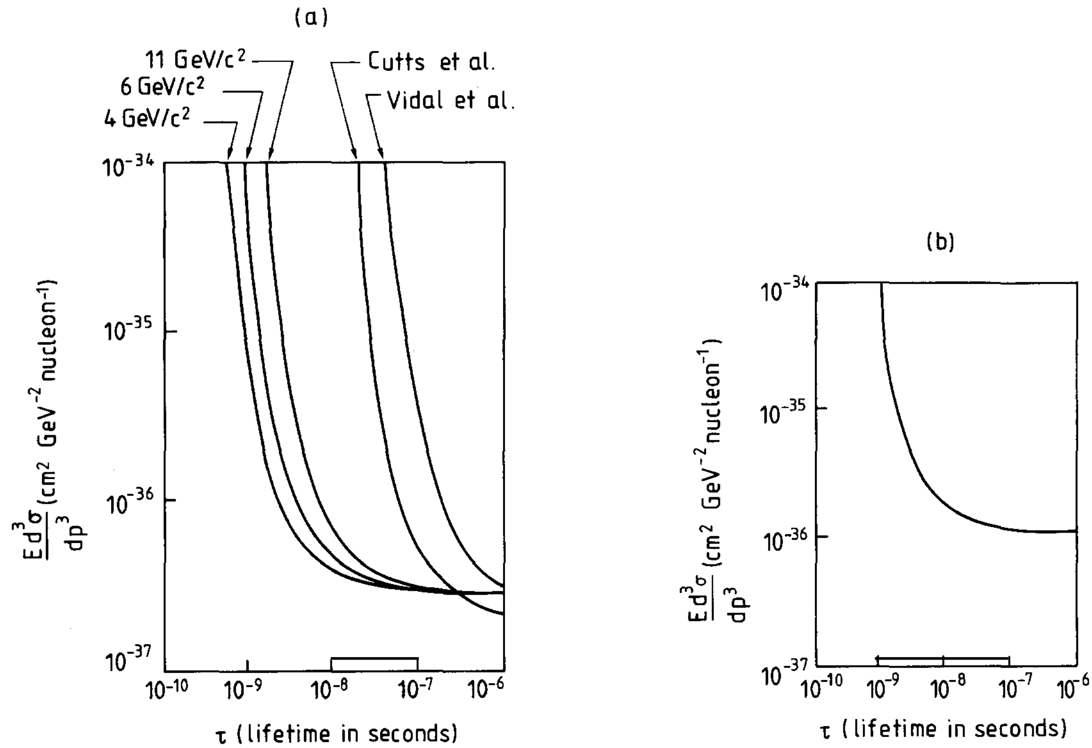


Fig. 4. (a) The cross section upper limits derived by Thron et al. for negative unit-charged secondaries of mass 4, 6 and 11 GeV, as a function of their assumed lifetime. Previous results of Cutts [173] and of Vidal [174] are shown. (b) The corresponding limit for positive secondaries of mass 6 GeV. The Thron curves are calculated for 1 observed event; the 90% confidence limits are obtained by multiplying those in (a) by a factor of 2.3, and that in (b) by 3.9.

which are produced at Feynman $x_F = 0$ and 4 GeV ones at slightly positive x_F, those of mass 11 GeV would have $x_F \sim -0.3$, where the expected cross section will in general be lower than that for central production.

Enthusiasts for quark discoveries will doubtless be excited by the few reported events that gave small signals in both the Čerenkov and scintillator ADCs (analogue to digital converters). If these were caused by particles passing through the detectors functioning properly, they could not have been integrally charged. Thron et al., however, point out that these could more mundanely be due to very occasional malfunctioning of the ADCs.

There was also a limited amount of running with a positive secondary beam. One possible event was found in the 4 to 6 GeV mass range. The limit on the production cross section for 6 GeV particles is shown in fig. 4(b).

2.2.3. *White quarks*

The CHARM group has recently published upper limits on the possible production of quarks [183]. Three different quark searches were performed, using their neutrino detector. This is a fine-grain calorimeter with 78 sequential sub-units of $3 \times 3\,\mathrm{m}^2$, surrounded by a magnetised iron frame, and followed by a muon spectrometer; each sub-unit consists of an 8 cm marble slab, 3 cm thick scintillators and a layer of proportional drift tubes. The energy losses of tracks were estimated by their pulse heights in the scintillators.

Motivated by the suggestion of Strikman [140] (see section 6.2), the CHARM group has looked for quarks of small interaction cross section ($\sim 10\ \mu b$), which could be produced by the 400 GeV proton beam in a copper beam dump. These would enter the detector, and appear as single, low ionisation tracks. A scan of tracks with apparent energy loss below $0.67 I_0$ removed those which passed close to scintillator edges, or which consisted of more than one event within the time acceptance gate; no candidates remained.

Because of energy loss in the shielding beyond the beam dump, quarks of charge $\frac{1}{3}$ (or $\frac{2}{3}$) would reach the detector only if they had energy above 45 (or 180) GeV. Corrections were applied for this and other acceptance and trigger cuts via a Monte Carlo programme. The resulting 90% confidence limits on the production of such quarks are somewhat mass dependent, but for masses below 12 GeV are less than $3\times10^{-40}\ \mathrm{cm}^2$ (or $2\times10^{-39}\ \mathrm{cm}^2$) for charge $\frac{1}{3}$ (or $\frac{2}{3}$) quarks. These are rather below other limits for quark production in hadronic reactions, but do require the assumption of low interaction cross section for the quarks.

The other two searches are for quark production in neutrino interactions, and are described in section 2.3.2.2.

2.3. Deep inelastic scattering

According to the successful parton model, deep inelastic scattering of leptons takes place via virtual photons or intermediate vector bosons interacting with quarks in the target nucleus. Although the struck quark in general hadronises to produce a jet of integrally charged particles, it is conceivable that occasionally it will actually be liberated as a free particle.

2.3.1. Incident muons

The European Muon Collaboration [51] has looked for quarks produced by 200 GeV/c muons incident on a berrylium target. The signature for a quark was provided by the pulse heights as measured in 6 pairs of scintillators. When one set of 6 scintillators all had their pulse heights below $0.68 I_0^*$, the other 6 pulse heights were examined; in no case did any track have more than one of these pulse heights below $0.75 I_0$. The scintillators were at the end of a spectrometer which was set to accept particles corresponding to momenta for particles of unit charge of 250 GeV/c for positives or for negatives, or 50 GeV/c for negatives†; the momentum bite was ±10%. The high value of the accepted momenta and the choice of geometry for the scintillators helped keep the background of low pulse heights small.

The lack of an observed signal is used, together with the calculated geometrical acceptance for free quarks of the chosen momenta and the estimated beam flux, to obtain limits on the quark production cross section. These in turn are converted to limits on the ratios R_q of the free quark production to that for bound quarks in the same momentum range, the latter being obtained from the calculated virtual photon spectrum, together with the assumption that the bound quarks have the same direction and momentum as the virtual photons. The limits on R_q are in the range 10^{-5} to 10^{-6} (see table 1), which the EMC group points out compare favourably with the corresponding limits for e^+e^- (see fig. 7) and for neutrino interactions [12,54].

* Provided that there was no drift in any of the relevant levels and that the width of their pulse height spectrum was as expected, this cut would have removed less than 1% of charge $\frac{2}{3}$ particles.

† The actual momenta for charge $\frac{1}{3}$ particles would be 83, or 17 GeV/c, respectively.

Table 1
EMC results: Upper limits on the production rate R_q (defined in the text) of free quarks of charge e_q and of momentum p_q, produced by a 200 GeV muon beam

e_q	p_q (GeV/c)	μ Flux ($\times 10^{11}$)	Acceptance	Upper limit on R_q ($\times 10^{-6}$)
+2/3	167 ± 17	4.6	20.4%	1.2
+1/3	83 ± 8	4.6	15.8%	1.5
−2/3	167 ± 17	1.6	20.4%	3.5
	33 ± 3	0.9	11.0%	12
−1/3	83 ± 8	1.6	15.8%	4.5
	17 ± 2	0.9	8.1%	16

Because of the production kinematics and the timing requirements on the counters, the experiment would not be sensitive to quarks heavier than 9 GeV for charge $\frac{2}{3}$ or 15 GeV for charge $\frac{1}{3}$. Quark lifetimes less than 10^{-8} s or large quark absorption cross sections would also have resulted in produced quarks not being detected.

2.3.2. Incident neutrinos

2.3.2.1. WA 44. The WA44 experiment is looking for quark production in neutrino or antineutrino interactions in a lead target 1.7 m thick (see fig. 5). A 0.4 Tm magnetic field is used to remove low momentum particles. Beyond it, a $2.35 \times 1.2 \times 0.6$ m^3 avalanche chamber [52] viewed by 3 cameras is used

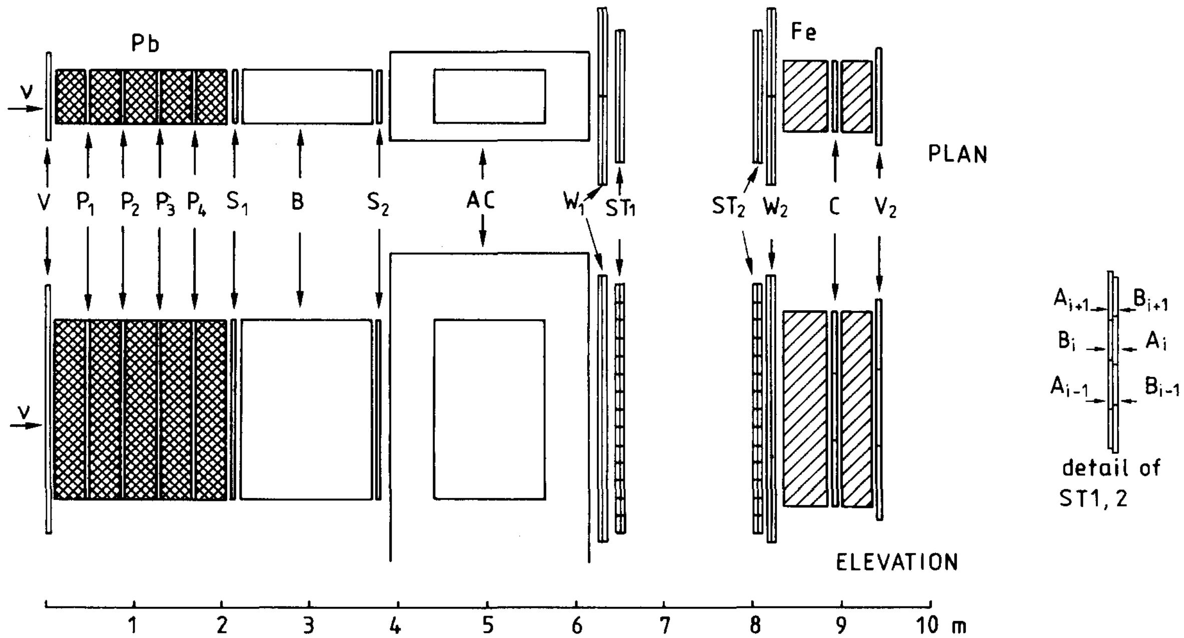


Fig. 5. Schematic plan and elevation of the WA44 apparatus, which looked for quark production by neutrinos. The elements of the detector are as follows: Pb is the lead target, V the veto counter, P_1 to P_4 and S_1, S_2 are scintillator counters for tagging neutrino interactions. B is the sweeping magnet, AC the avalanche chamber, W_1, W_2 the wire chambers, ST_1, ST_2 the scintillation hodoscopes for the low dE/dx trigger and C, V_2 the scintillation counters for the muon range telescope.

to estimate the primary ionisation of the secondaries. It was calibrated with muons of known momenta, and achieved a resolution σ of 13%.

The trigger was provided by scintillator hodoscopes beyond the avalanche chamber, which could be set to correspond to look for one track of low ionisation; or by scintillators beyond the target, which selected either high multiplicity events, or alternatively could select all neutrino interactions. Altogether some 200 000 triggers were obtained. The initial analysis [53], which was already mentioned in ref. [12], was restricted to events with a low pulse height in one of the scintillator hodoscope elements, and hence was sensitive only to "isolated" quarks, not accompanied by a nearby jet of hadrons. The limits obtained then were $<3\times10^{-5}$ or $<7\times10^{-5}$ quarks per interaction (for ν or $\bar{\nu}$ beams respectively), and assumed that the quark absorption in the target corresponded to only $\frac{1}{3}$ of a hadronic cross section; the sensitivity of the experiment decreases significantly for larger cross sections.

The current analysis [54] makes use of data from all the triggers. About 100 000 avalanche chamber photographs have been scanned in order to look for inclusive quark production; this has yielded 3 quark candidates. One of these has been rejected as being in an unsuitable region of the chamber; the other 2 are still being investigated. The sensitivity of this inclusive search is again in the few times 10^{-5} range. As before, this new limit will require the assumption that any quarks are not strongly absorbed in the lead target.

2.3.2.2. CHARM. In addition to looking for white quarks produced in hadronic reactions (see section 2.2.3), the CHARM collaboration has also searched for such quarks which could have been produced by neutrino or antineutrino interactions in the upstream CDHS apparatus, and detected by CHARM. For 1.2×10^{18} protons on the target and an estimated 8×10^{6} neutrino interactions in the CDHS apparatus, 10^{5} single tracks were detected by CHARM, of which 956 had energy loss less than $0.67I_0$. None of these survived a visual check. The geometrical acceptance was calculated in Monte Carlo fashion, and for an assumed quark mass of 2 GeV yielded limits for charge $\frac{1}{3}$ or $\frac{2}{3}$ quark production in ν or in $\bar{\nu}$ beams in the range 1–3×10^{-5} quarks per interaction. These are similar to the limits of the WA44 experiment [54] discussed above.

The final search was for ordinary quarks produced in ν or $\bar{\nu}$ interactions. These were looked for in exposures of the CHARM detector to wide band beams. Here the neutrinos interacted in CHARM, and the signature of quark production would be a low-ionising secondary which either did or did not interact again within the apparatus. From some 2.6×10^{5} neutrino and 1.0×10^{5} antineutrino events, no quark candidates with energy loss below $0.75I_0$ were found.

Again the detection efficiency was obtained by a Monte Carlo method, and depended on the quark mean-free-path λ_q and its mass M_q, and to a lesser extent on its assumed fragmentation function. The resulting limits are shown in table 2.

Table 2
The CHARM Collaboration 90% confidence limits (in units of 10^{-5} quarks per interaction) on the production of ordinary quarks of mass M_q in ν and $\bar{\nu}$ interactions

		$M_q = 1$ GeV		$M_q = 10$ GeV	
	$\lambda_q/\lambda_\pi =$	1	5	1	5
$q = 2/3$ from ν	Reinteracting	13	4	200	25
	Not reinteracting	60	5	400	30
$q = 1/3$ from $\bar{\nu}$	Reinteracting	16	4	300	50
	Not reinteracting	60	6	700	60

2.4. Electron–positron annihilation

The bulk of hadronic production in electron–positron annihilation is well described in terms of fig. 6; the intermediate virtual photon couples to a quark–antiquark pair which then produces jets of hadrons as a result of the (probably) confining QCD interaction between the quarks. Neglecting higher order QCD effects (e.g., extra jet production due to gluon bremsstrahlung), the ratio R_h of the cross section for this process to that for muon pair production is

$$R_h = 3 \sum q_i^2 ,$$

where q_i is the charge of the ith flavour of quark, and the factor of 3 arises from the number of colours for each flavour. For energies below the $t\bar{t}$ threshold, we expect $R_h = 11/3$. We thus have some sort of yardstick with which to compare any experimental limit on free quark production. Assuming we are above the threshold for free quarks, an experimental upper limit below 11/3* can thus be interpreted as providing a lower limit on the extent to which confinement effects reduce free quark production.

Electron–positron annihilation has thus proved to be a popular hunting ground for quarks, which could be pair produced either alone (exclusive production) or together with other particles (inclusive production), which would be mainly integrally charged hadrons.

2.4.1. Mark II

A search for quarks of unit charge or of charge $\frac{2}{3}$ has been performed using the Mark II detector at SPEAR [55].

The integer-charge search was performed by using momentum and time-of-flight measurements to determine the mass of a particle producing a track. A sample of 10^6 events (with two-prong collinear events excluded) at centre-of-mass energies in the range 3.9 to 7.4 GeV was used. The observed mass spectrum for positive tracks showed peaks at the deuteron and triton masses, assumed to arise from beam–gas interactions. These were not visible in the negative tracks' spectrum, which was then used to establish limits on the inclusive production† of negative particles of unusual mass (and which include

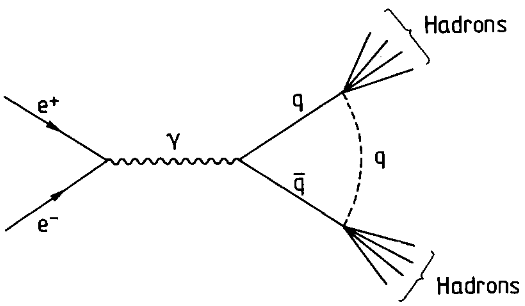


Fig. 6. Hadronic production in electron positron annihilation. The virtual photon couples to a quark pair, which subsequently hadronise. The exchanged quark (dashed line) is required to enable the coloured fractionally charged produced quarks (solid lines) to become colourless integrally charged hadrons; this effect is first mentioned in ref. [182].

* This is the expected cross-section ratio for producing *all* types of quarks, but it is likely that heavier flavours would decay rapidly into the *lightest* one.

† The limit is not quite for inclusive production, since the two-body exclusive reaction ($e^+e^- \to q\bar{q}$) is excluded. The term "inclusive" is used in this sense throughout this article.

possible integrally charged quarks). For the mass ranges 1.7 to 2.3 and 2.3 to 3 GeV, the 90% confidence limits* on R are respectively $<3\times10^{-4}$ and $<2\times10^{-3}$. These values required an estimate of the efficiency for observing the hypothesised quarks, which was obtained by assuming that the production of quarks of energy E was given by

$$E\,\mathrm{d}^3\sigma/\mathrm{d}p^3 \sim \mathrm{e}^{-4.5E}\,.$$

To obtain the corresponding limit on the inclusive production of charge $-\frac{2}{3}$ quarks, the same data sample was used, but the extra information from the pulse heights of the scintillators was utilised. The calibration of these counters was determined from $\mu^+\mu^-$ pairs and from Bhabha electrons; the resolution on pulse height was then 20%. A track was retained for further study if its pulse height was between 0.2 and 0.65 of I_0, if it was consistent spatially with coming from a beam–beam interaction and if its estimated mass (assuming charge $-\frac{2}{3}$) was greater than 0.85 GeV. For each of several quark masses, the number of tracks consistent within $\pm2\sigma$ with that mass was determined; here σ was the estimated mass resolution, and was mass dependent. After performing a background subtraction and allowing for the model dependent efficiency of ~0.5, Weiss et al. calculate the upper limit on R for inclusive

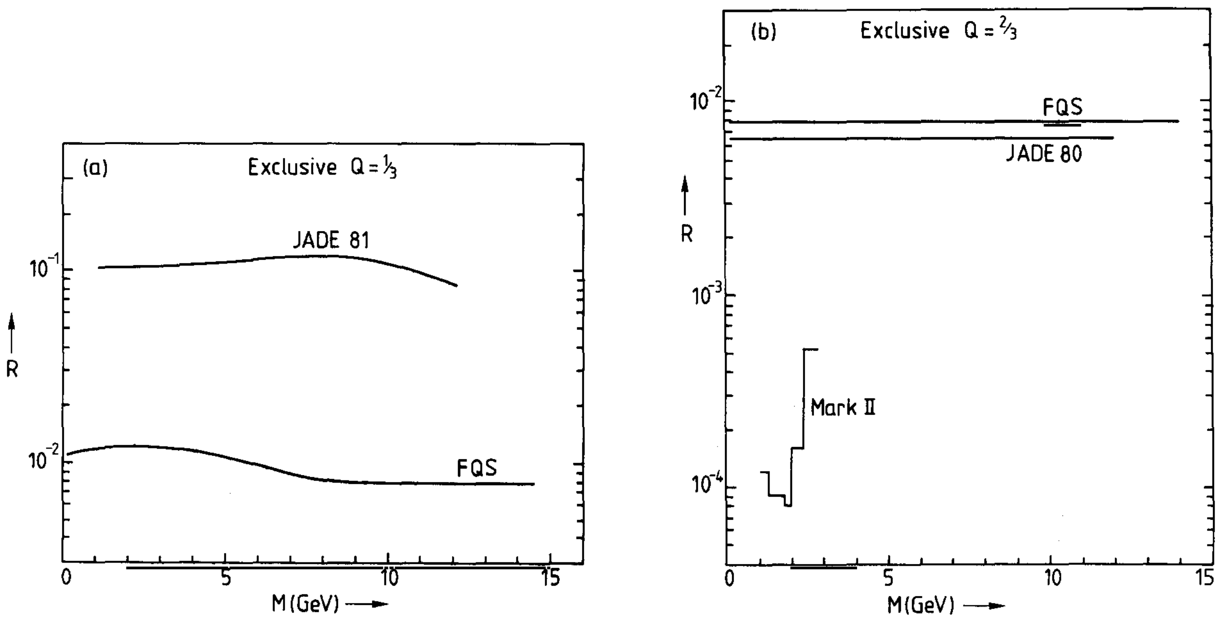
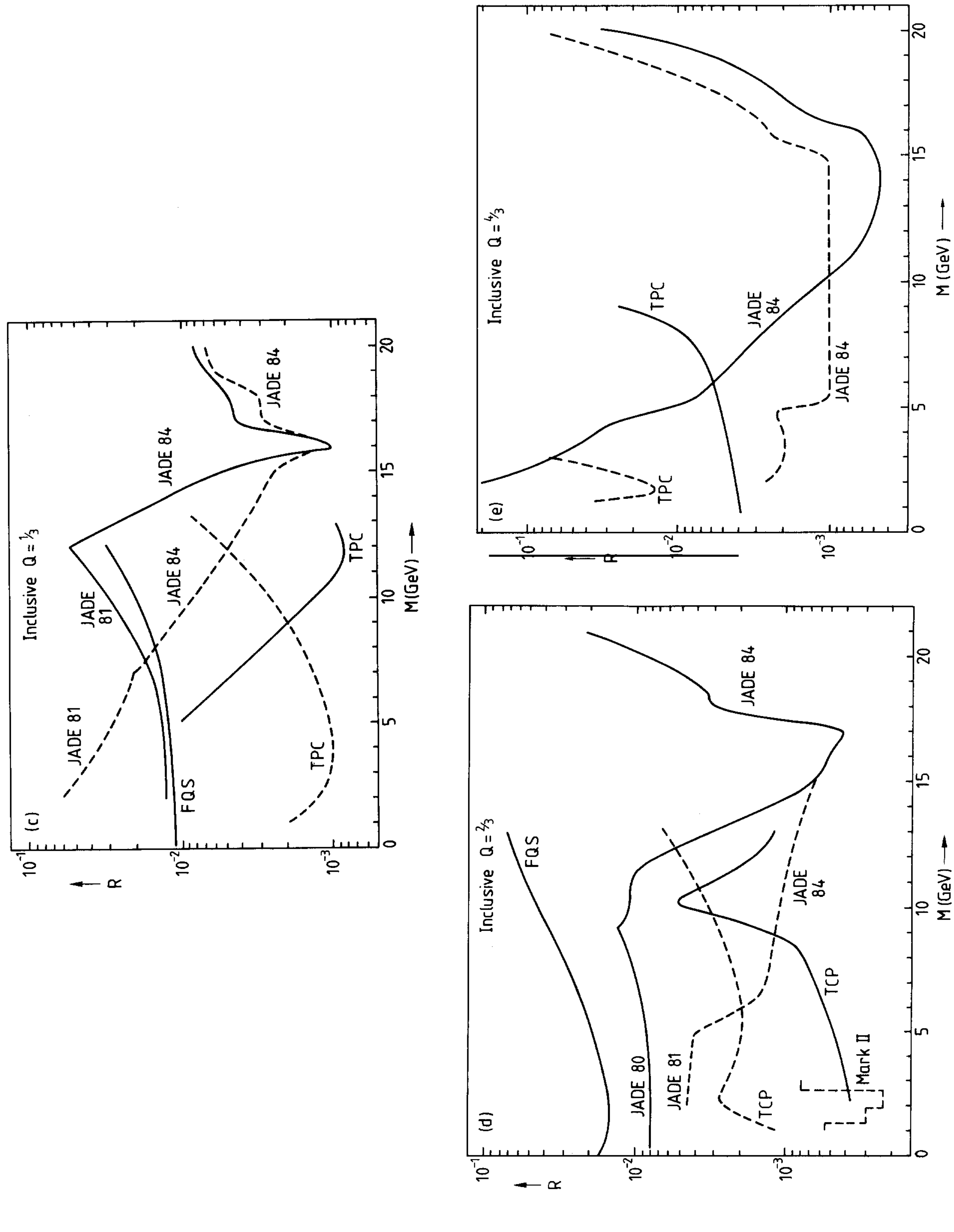


Fig. 7. Limits on the ratio R for quark production in e^+e^- annihilations as a function of the hypothesised quark mass. R is defined as the ratio of the quark production cross section to that for muon pairs. The various diagrams are for (a) exclusive production of charge 1/3 quarks; (b) exclusive charge 2/3; (c) inclusive production of charge 1/3 quarks; (d) inclusive charge 2/3; and (e) inclusive charge 4/3. The curves show the limits obtained from the following sources: Mark II, ref. (55); JADE 80, ref. (56); JADE 81, ref. (129); JADE 84, ref. (130); FQS, ref. (60) in fig. 7(a) and (b), ref. (59) in fig. 7(c) and (d); TPC, ref. (128) in fig. 7(c) and (d), ref. (58) in fig. 7(e). For clarity, where the various JADE limits cover the same mass range, only the lower one is shown. The inclusive limits are in general dependent on the production model assumed; those shown as solid lines refer to $E\,\mathrm{d}^3n/\mathrm{d}p^3$ being taken as constant, while the dashed ones are for an exponential form (taken as $\exp(-3.5E)$ by JADE and TPC, and as $\exp(-4.5E)$ by Mark II).

* Throughout this article, R denotes the ratio of the cross section (either inclusive or exclusive) for free quark production in e^+e^- reactions to that for muon pairs.


(c)
Inclusive Q = 1/3
JADE 81
JADE 81
JADE 84
JADE 84
JADE 84
FQS
TPC
TPC
R
M(GeV)
(d)
Inclusive Q = 2/3
FQS
JADE 80
JADE 81
TCP
TCP
Mark II
JADE 84
JADE 84
R
M(GeV)
(e)
Inclusive Q = 4/3
TPC
TPC
JADE 84
JADE 84
R
M(GeV)

production of charge $-\frac{2}{3}$ quarks. For masses over the range 1 to 3 GeV, these vary from 2.3×10^{-4} to 8×10^{-4} (see fig. 7(d)).

Finally in order to search for exclusive production of quark pairs, a sample of 4×10^5 collinear two-prong events was used. Here the cut of between 0.2 and 0.65 of I_0 was imposed on both the tracks of each event. Tracks with curvature more than twice those of $\mu^+\mu^-$ events were excluded. No event satisfied these restrictions, and the upper limits on R for the exclusive production of quark pairs of charge $\pm\frac{2}{3}$ and of mass 1 to 2.8 GeV varied from 0.8×10^{-4} to 5.2×10^{-4}.

The exclusive limits obtained here are one to two orders of magnitude lower than the corresponding values [56, 60] obtained in other e^+e^- experiments, but are of course for a much restricted mass range (see fig. 7(b)).

2.4.2. Time projection chamber (TPC)

The TPC [57] has been used to search for charge $\frac{4}{3}$ objects* produced in multihadron e^+e^- annihilations at 29 GeV at PEP [58]. It is a cylindrical detector with its axis along the e^+e^- beam directions. It contains an 80/20 argon–methane mixture at 8.5 atm pressure. Ionisation produced by the tracks drifts at ~5 cm/μs in an electric field of 75 kV/m parallel to the axis. The momenta of tracks are determined via the measurement of 15 space points in a 4 kG magnetic field, which is also parallel to the axis, while 183 measurements of their energy loss dE/dx help in identifying them; the dE/dx resolution is 3.9%.

The event selection criteria required at least 5 visible charged tracks pointing to the interaction vertex; restrictions were also imposed on the total energy of the charged tracks and on their momentum balance. In order to distinguish charge $\frac{4}{3}$ particles of unknown mass from other particles, it was required that the estimated dE/dx should be larger than both (i) 1.2 times the expected dE/dx for an electron, and (ii) the expected dE/dx for a particle of unit charge and mass 1.8 GeV. It was further restricted to be less than 3.5 times minimum ionising, in order to avoid saturating the electronics (see fig. 8(a)).

The effect of these cuts on the efficiency for detecting charge $\frac{4}{3}$ particles is dependent on the assumed production model. Two different hypotheses were used for the momentum distributions of all charged particles viz.

$$E\,d^3n/dp^3 \sim \text{constant}\,, \qquad E\,d^3n/dp^3 \sim e^{-3.5E}\,.$$

Other cuts on the tracks were employed to ensure: (a) good dE/dx and momentum resolution; and (b) that they came from the interaction vertex, and were not too close, either to the edges of the TPC sector boundaries, or to other tracks.

From 7137 events satisfying the event selection criteria, no tracks were accepted as candidates for charge $\frac{4}{3}$. The data sample used contained 22 events/pb.

More recently, limits have been obtained for the inclusive production of charge $\frac{1}{3}$ or charge $\frac{2}{3}$ quarks [128]. The 29094 hadronic events used correspond to an integrated luminosity of 77 events/pb. The region of the energy loss against apparent momentum plot used for looking for quarks is shown in fig. 8(b). It was established that the detector would have been fully sensitive to tracks with energy loss as low as 4 keV/cm ($0.33I_0$), the lower cut on the lower acceptance region. Below this, noise became a problem. This meant that the apparatus was sensitive only to non-relativistic charge $\frac{1}{3}$ quarks.

With similar track acceptance criteria to those used for the charge $\frac{4}{3}$ search, no tracks were found in

* In models where quarks have charges of $\frac{2}{3}$ and $-\frac{1}{3}$, these could be diquarks [43] or quark-hadron bound states [62].

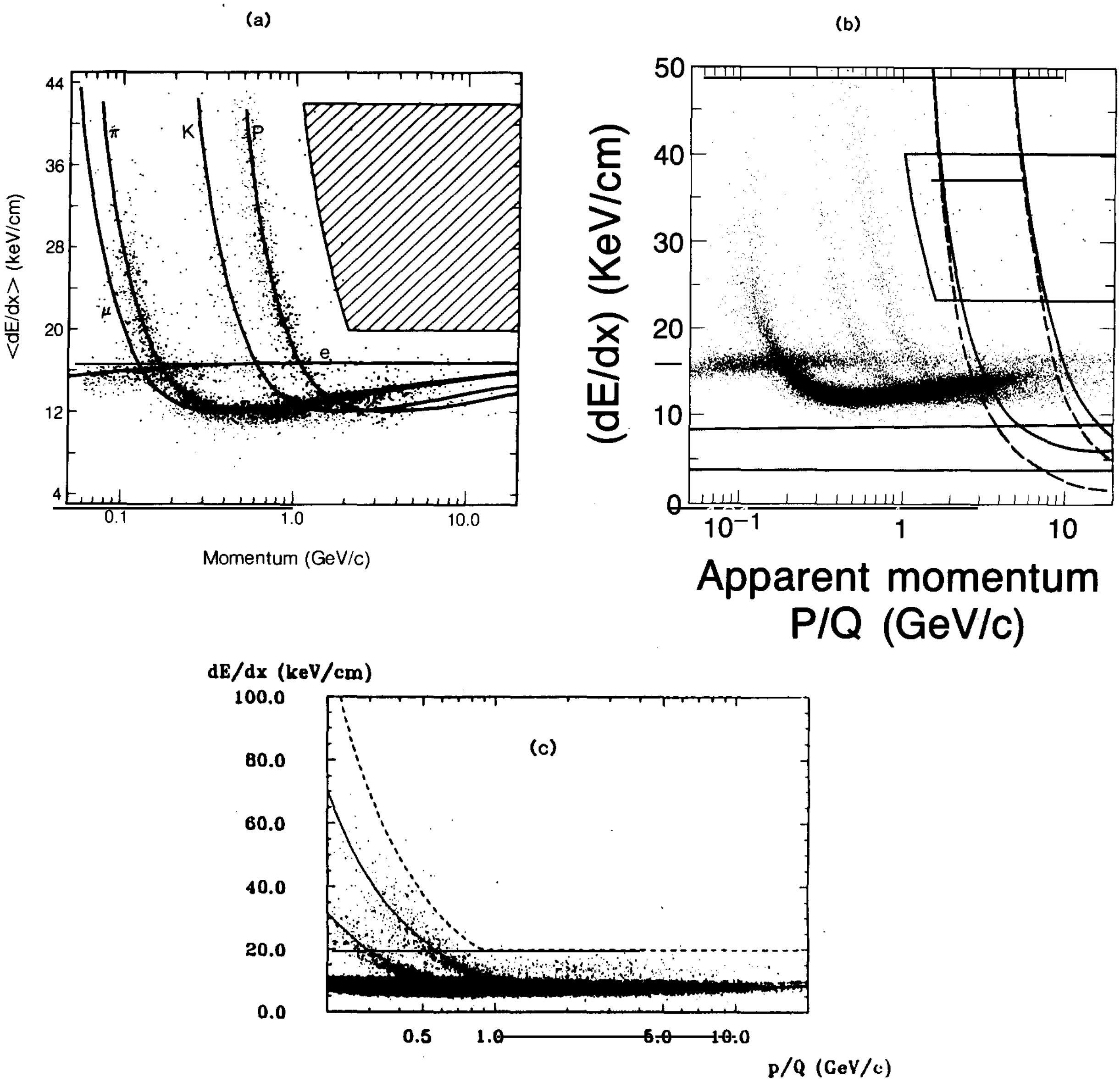


Fig. 8. Diagrams showing the selected regions used for the search for the inclusive production of quarks, on a plot of measured energy loss against apparent momentum p/q. The various diagrams are for: (a) TPC search for charge 4/3 quarks [58]; (b) TPC search for charge 1/3 or 2/3 quarks [128]; the bands of points due to electrons, π, K and protons are clearly visible; and (c) JADE's 1984 search for charges 1/3 to 5/3 [130]. The bands are for π, K and $\bar{p}$. Only negatively charged tracks appear in this plot.

the lower region, and 96 in the upper one. All of these, however, were removed by a cut designed to exclude overlapping tracks which may have simulated a single track of high energy loss in the detector.

The resulting limits on R for the inclusive production of charge $\frac{1}{3}$, $\frac{2}{3}$ or $\frac{4}{3}$ quarks are shown as a function of quark mass in figs. 7(c), (d) and (e) respectively, where they are compared with the corresponding limits obtained in other e^+e^- experiments.

2.4.3. JADE

The earlier results of the JADE Collaboration working at PETRA [56] had already been mentioned in ref. [12]. They corresponded to an exposure of 3.3 events/pb at around 30 GeV centre of mass energy, and were for quarks of charge $\frac{2}{3}$, 1, $\frac{4}{3}$ or $\frac{5}{3}$. They were subsequently complemented with limits for charge $\frac{1}{3}$, and updated to a sample of 12 events/pb for charge $\frac{2}{3}$ [129].

The newer results [130] on inclusive production come from a sample of 86 events/pb. The region of the dE/dx against apparent momentum plot used for selecting potential quark candidates is shown in fig. 8(c), i.e., it is the region of high ionisation, and for quarks of charge less than 1 is sensitive only to non-relativistic particles. These latest limits are shown in fig. 7(c)–(e) as JADE84. Analysis of the low ionisation region is currently in progress, and should substantially improve their limits for charge $\frac{1}{3}$ and charge $\frac{2}{3}$ quarks.

2.4.4. *The free quark search (FQS) experiment*

A series of searches have been performed by the FQS group at PEP. The apparatus (see fig. 9) consists of 2 identical spectrometers at right angles to the e^+e^- beams; each subtends a solid angle of $4\pi/6$.

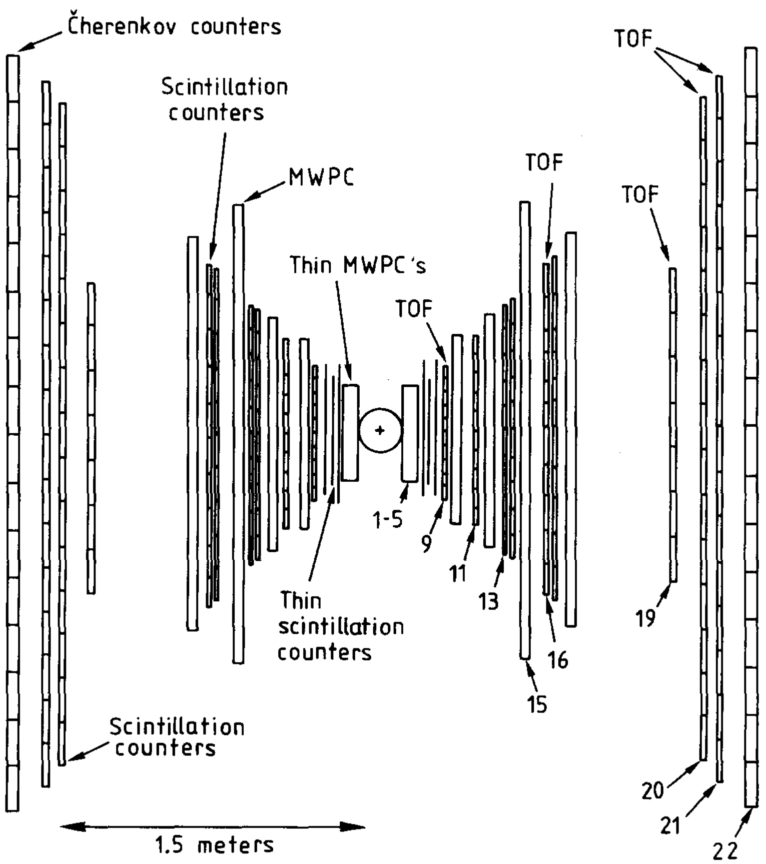


Fig. 9. Schematic diagram of the FQS apparatus. The two identical arms each consist of 9 multiwire proportional chambers, 12 scintillation counter hodoscopes and 1 lucite Čerenkov hodoscope. The 5 scintillation layers labelled TOF are equipped for time-of-flight measurement.

The principle of the method is to determine the charge of a track from its energy loss dE/dx and speed (βc). This is preferable to the combination, for example, dE/dx and the apparent momentum p/e, since in that case the estimated charge depends on the assumed mass of the particle. Then it is in principle not necessary to exclude large regions of phase space from the acceptance region (contrast fig. 8), and the resulting limits on inclusive quark production are insensitive to the form of the production mechanism for the quarks. Thus the aim is to measure pulse heights and time-of-flight. The energy loss dE/dx was estimated by calculating the truncated mean of the pulse heights.

Each arm of the spectrometer contained 12 planes of scintillator hodoscopes, with the counters equipped with photomultipliers at both ends. Five of the planes also measured the time-of-flight of the track, with a resolution of ~150 ps for cosmic rays. Six planes consisted of 10 counters arranged in roads projecting radially out from the interaction region, and which were used as part of the trigger; there was no magnetic field. Each arm also contained 9 layers of multiwire proportional chambers to define the particles' trajectories, and which were determined to be ≥97% efficient to particles of charge $\frac{1}{3}$. Finally there was a Čerenkov counter plane (with a threshold $\beta \sim 0.7$) to provide a check on the velocity measurement from time-of-flight.

The modifications of the apparatus used for the searches for highly interacting quarks or for quarks in cosmic rays are described in the individual sections below.

2.4.4.1. Inclusive quark search [59]. In order to obtain an event sample for inclusive production of quarks of charge $\frac{1}{3}$ or $\frac{2}{3}$, the trigger required that at least 5 out of the six counters defining a road on either side of the spectrometer were hit and had pulse heights of at least $0.05I_0$. Further off-line cuts required ≥3 reconstructed tracks in the spectrometers, with at least 2 of them having energy loss $\geq 0.25I_0$.

A plot of energy loss against $1/\beta$ (see fig. 10) has 1 event below the expected curve for $q = \frac{1}{2}$ (i.e. a candidate for $q = \frac{1}{3}$) and 16 below the $q = \frac{3}{4}$ curve (i.e., candidates for $q = \frac{2}{3}$). The $q = \frac{1}{3}$ candidate was eliminated because its pulse in the Čerenkov counter was inconsistent with its large time-of-flight. The

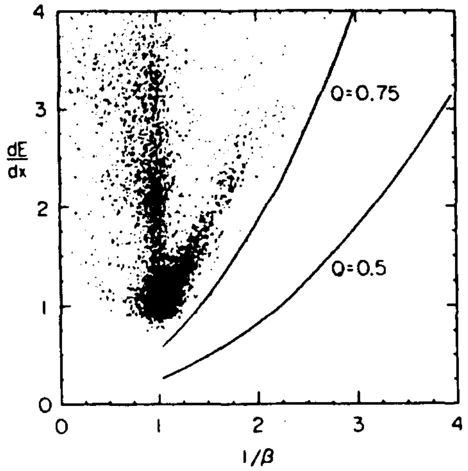


Fig. 10. The FQS scatter plot of dE/dx (measured in units where a minimum ionising unit charged particle has dE/dx equal to unity) against $1/\beta$, which is proportional to the time-of-flight. The curves are the predictions for particles of charge 3/4 and 1/2. The band due to unit charged particles, with its maximum intensity at $\beta \sim 1$, is clearly visible. Values of $1/\beta$ significantly below 1 are due to accidental tracks; high dE/dx at $\beta \sim 1$ is caused by 2 or more close tracks being taken as a single one.

$q = \frac{2}{3}$ possibilities were rejected by raising the threshold for pulse heights to $0.2I_0$, or by removing tracks which passed close to counter edges.

The efficiency of the apparatus for observing quarks was calculated in a Monte Carlo two-jet programme, in which two of the pions were replaced by quarks. The cuts (including the requirement of ≥ 3 detected tracks, whose effect becomes significant at large quark masses, the possibility of low-ionising particles not producing a recognised track, the absence of other tracks in the road of the pulse height counters, and the removal of tracks close to counter edges) result in an overall efficiency of a few percent for quarks of mass less than 12 GeV. The resulting limits on R are shown in fig. 7(c) and (d). No allowance has been made for the possible interactions of the quarks in the 30% of a hadronic collision length of material in a spectrometer arm; a separate search was made for possible quarks with very large interaction cross sections (see below).

2.4.4.2. Exclusive quark search [60]. This analysis started with the same sample of events as produced by the on-line road trigger used for the inclusive search described above. The extra requirements that the event contained only 2 tracks, which were consistent both spacewise and timewise with coming from the beam intersection region and were collinear to within ±8° in azimuth and in dip, reduced the sample to 13000 events. When these are plotted on a scatter diagram showing the estimated charge of each of the 2 tracks of an event, a strong concentration around (1, 1) is clearly evident, and there are no events in which both charges are measured as being below 0.8.

The corrections used in extracting upper limits on quark production include the trigger efficiency (~75% for lightly ionising low mass quarks of charge $\frac{1}{3}$, rising to ~100% at $m_q \sim 8$ GeV); the geometrical acceptance, taking into account the expected production angular distribution of the exclusive reaction; radiative corrections; and the 5% loss of signal of quarks of charge $\frac{2}{3}$ because of the requirement on the measured quark charges being both below 0.8. The experiment was sensitive to quark masses up to 14 GeV, beyond which the quarks would not have enough range to reach the outer layers of the detector. Again no allowance is made for possible quark absorption within the detector.

The limits on R are <0.8% for charge $\frac{2}{3}$ and <1% for charge $\frac{1}{3}$. They are displayed in figs. 7(a) and (b), where the results of similar searches in other experiments are also shown. The limit for exclusive charge $\frac{1}{3}$ production is seen to be an order of magnitude better than the only other measurement to date.

2.4.4.3. Quarks with large cross sections [61]. One possible reason why quarks have not yet been observed in accelerator experiments is that their cross section is much larger than that for ordinary hadrons [62], and that they interact in the target or beam pipe, or in the surrounding apparatus before they are detected. The FQS group has thus modified their apparatus so as to have a better chance of detecting such highly interacting quarks.

A thinner beam pipe was used, and in front of each spectrometer arm was placed an additional detecting system consisting of 5 thin multiwire proportional chambers (MWPCs) and 3 1.5 mm thick scintillators. The total thickness of material encountered by a particle traversing this system was only 0.7% of a standard hadron interaction length. The previous thinnest detector was JADE [56], which identified quarks in 8% of a collision length.

The trigger for the accepted events still required at least 5 hits in the 6 standard scintillators, equivalent to 20% of an interaction length. For inclusive quark production this could have been caused by any of the associated hadrons, but for the exclusive reaction, it would have had to be either the highly interacting quark itself, or one of the secondaries produced by its interaction earlier in the spectrometer or in the beam pipe. No allowance for any losses from this requirement was made in the efficiency calculations. A total of 1.1×10^6 triggers was obtained.

Relativistic quarks were recognised by their energy loss in the thin MWPCs, whose thresholds were set at $0.02I_0$. A minimum ionising particle of unit charge produced 47 primary collisions in such a chamber. The value of the particle's dE/dx was calculated as the average of the lowest 4 pulse heights. This procedure gave a distribution with a 55% full width at half height for a unit charged minimum ionising particle.

Tracks were rejected if they had less than 4 measurements of pulse height (5% rejected), more than 1 overflow (23% expected for charge $\frac{2}{3}$), or an unlikely distribution of pulse height measurements (10% for charge $\frac{1}{3}$). To reduce the background from noise, tracks with less than 3 pulse heights above $0.06I_0$ were also rejected (10% for charge $\frac{1}{3}$), as well as tracks which were not well separated from neighbouring hits (34% of Monte Carlo tracks rejected). There remained 4600 events containing at least one track with estimated dE/dx below $0.6I_0$, which selection is expected to keep 91% of any tracks of charge $\frac{2}{3}$.

There were no two-prong events in which both tracks had estimated ionisation below $0.6I_0$. This enabled limits to be set on exclusive quark production of either charge $\frac{1}{3}$ or $\frac{2}{3}$. These limits were derived as functions both of the quark mass and of the assumed quark interaction cross section σ_q. These are displayed in fig. 11 for values of σ_q equal to the hadronic cross section, or to 100 times as large.

To study inclusive production of such quarks, only one quark track was required to be observed, and so to reduce backgrounds, only charge $\frac{1}{3}$ inclusive production was studied, from a sample of 29 tracks having dE/dx less than $0.25I_0$. A further condition required pulse heights of greater than $0.05I_0$ in at least 2 of the 3 thin scintillator hodoscopes behind the MWPCs. These correspond to another 0.9% of an interaction length, but such pulses could have been produced by either the quark itself or by its

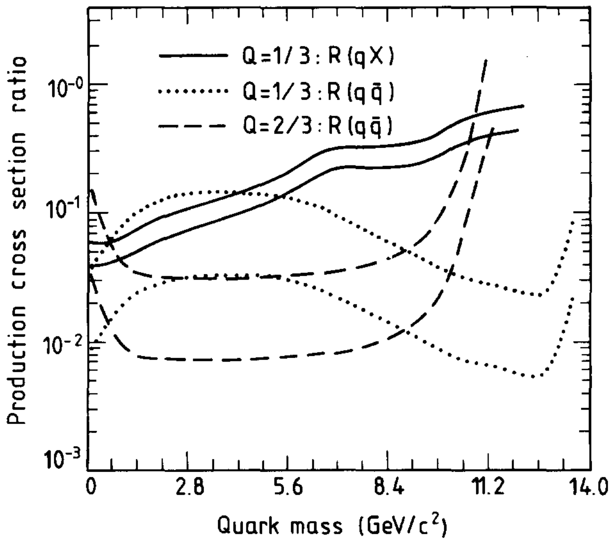


Fig. 11. The FQS 90% confidence level upper limits on the cross-section ratio R for the production of highly interacting quarks, as a function of their hypothesised mass. The solid lines are for inclusive production of charge 1/3, while the dotted and dashed curves are for exclusive production of quarks of charge 1/3, or 2/3, respectively. They thus correspond to the ordinary searches for quarks as shown in figs. 7(c), (a) and (b), respectively. For each type of search, the upper curve corresponds to quarks whose interaction cross section is assumed to be 100 times geometrical; the lower one is for a geometrical cross section.

Table 3
(A) FQS limits on quark production in e^+e^-

Quark interaction σ	Quark production		Limit on R		Other experiments
Ignored	Inclusive	$q = \pm 1/3$	<1–3%	$M < 12$	See fig. 7(c)
		$q = \pm 2/3$	<2–8%	$M < 12$	See fig. 7(d)
	Exclusive	$q = \pm 1/3$	<1%	$M < 14$	<10%, $M < 12$ [129]
		$q = \pm 2/3$	<0.8%	$M < 14$	<0.6%, $M < 12$ [56]
$\sigma = 100\sigma_0$	Inclusive	$q = \pm 1/3$	<6–50%	$M < 11$	-
		$q = \pm 2/3$	-		-
	Exclusive	$q = \pm 1/3$	<2.5–15%	$M < 13$	-
		$q = \pm 2/3$	<3–14%	$M < 10$	-

(B) FQS limits on cosmic ray quark flux Φ (in $cm^{-2}\,s^{-1}\,sr^{-1}$)

Quark signature	Limit on Φ	Previous limit or value
$q = \pm 1/3$	$<3 \times 10^{-10}$, $\beta > 0.1$	Similar for $\beta \sim 1$, $\theta < 45°$ [131]
$q = \pm 2/3$	$<3 \times 10^{-10}$, $\beta > 0.1$	$<5 \times 10^{-8}$ for $\beta = 0.5$–0.9, $\theta \sim 84°$ [132] $<2 \times 10^{-8}$ for $\beta \sim 1$, $\theta > 75°$ [133]
$M \sim 4.2$ GeV	$<10^{-9}$, $\beta \sim 0.5$ $<10^{-8}$, $\beta = 0.4$–0.7	$(2 \pm 1)10^{-9}$, $\beta = 0.55$, $\theta = 0°$ [64]

interaction secondaries; again this effect was not allowed for in the efficiency calculations. Of the remaining 12 tracks, all but 2 were rejected as having too many spurious low pulses in the MWPCs. The last 2 did not look like quark tracks, but were not rejected so that the inclusive limit was based on a production rate corresponding to ≤5.3 events (at the 90% confidence level). This was converted to a limit on R via the two-jet Monte Carlo programme described earlier, again allowing for different possible interaction cross sections (see fig. 11).

This is thus the only experiment to date which would have been capable of detecting quarks even if their interaction cross section was hundreds of barns.

The various results of the FQS experiment are summarised in table 3, while table 4 contains a summary of all the accelerator experiments.

3. Cosmic ray experiments

There is a long tradition of looking for new particles in the cosmic rays. Such experiments can claim the successes of having discovered the positron, the muon and the pion, and strange particles. Thus it is not surprising that quark searches have been performed in cosmic rays as well. Here the quarks could either be part of the primary cosmic ray flux, or else they could be produced as secondaries in the interactions of very high energy cosmic rays with the upper atmosphere.

Three of the cosmic ray experiments described below were capable of measuring the charge of any incident quarks. These are the FQS experiment (section 3.1), which made use of the same apparatus as

Table 4
Summary of accelerator searches

First author or collaboration	Ref.	Exp. type	Beam + target	Quark identification	Quark's charge[(a)]	Quark's mass[(b)]	Results	Comments
Price	[41]	Anomalons	1.8A GeV Ar on plastic detector	Etch pits in plastic detector	$n/3$		$<3\times10^{-3}$ fr.ch./int	
Barwick	[167]	Anomalons	1.8A GeV Ar on Č detector	Č signal	$n/3$		$<10^{-4}$ fr.ch./int	No anomalon effect
Bloomer	[42]	Anomalons	1.9A GeV Fe on emulsion	Lacunarity of emulsion track	$n/3$		$<3\times10^{-3}$ fr.ch./int	Secondaries of charge 1–3
Bland	[44]	Heavy ion	1.9A GeV Fe on lead	Millikan	$n/3$		$<5\times10^{-7}$ or $<5\times10^{-5}$ q/int	Somewhat model dependent
Bland	[47]	Heavy ion	2.2A GeV Si on silicon	Millikan	$n/3$		$<3\times10^{-5}$ q/int	More model dependent
UA2	[180]	Hadronic	p̄p at $\sqrt{s}$ of 540 GeV	Pulse height	{1/3 2/3	<3 <2}	$<2\times10^{-3}$ q/unit ch	
E-497	[172]	Hadronic	400 GeV/c p on copper	Mass from Č ring radius	1	See fig. 4	See fig. 4	
CHARM	[183]	Hadronic	400 GeV p on copper	dE/dx	1/3 2/3	<12 <12	$\sigma<3\times10^{-40}$ cm^2 $\sigma<2\times10^{-39}$ cm^2}	White quarks
EMC	[51]	D.I.S.	200 GeV/c muons on berrylium	Pulse height	{1/3 2/3	<15 <9}	$<10^{-5}$–10^{-6} free q/virtual q	
WA44	[54]	D.I.S.	Wideband ν and $\bar{\nu}$ on lead	Avalanche chamber	1/3, 2/3		$<10^{-4}$ q/int	Includes q within jets Ignores absorption in target
CHARM	[183]	D.I.S.	Wideband ν and $\bar{\nu}$ on CDHS	dE/dx	1/3, 2/3	2	<1–3×10^{-5}q/int	White quarks
			Wideband ν and $\bar{\nu}$ in CHARM	dE/dx	1/3, 2/3		See table 2	Ordinary quarks
Mark II	[58, 128]		e^+e^-	p and dE/dx	1 Inc 2/3 Inc 2/3 Exc	1.7–3 1–3 1–2.8	$R<2\times10^{-3}$ $R<8\times10^{-3}$ (fig. 7(d)) $R<5\times10^{-4}$ (fig. 7(b))	SPEAR
TPC	[57]		e^+e^-	p and dE/dx	1/3 Inc 2/3 Inc 4/3 Inc	<14 <13 <9	(fig. 7(c)) (fig. 7(d)) (fig. 7(e))	PEP
JADE	[130]		e^+e^-	p and dE/dx	1/3-2 Inc	<20	(fig. 7(c)–(e))	PETRA
FQS	[59–61]		e^+e^-	TOF and dE/dx	1/3, 2/3 Inc 1/3, 2/3 Exc 1/3 Inc 1/3, 2/3 Exc	<14 <12	(fig. 7(c), (d)) (figs. 7(a), (b)) (fig. 11) (fig. 11)	PEP Large σ quarks Large σ quarks

[(a)]The symbol $n/3$ refers to searches for quarks of third-integral charge. The e^+e^- experiments are labelled "Inc" or "Exc" for inclusive or exclusive searches respectively.
[(b)] Masses are given in GeV.

had been used to look for quarks in e^+e^- annihilations; a Japanese experiment (section 3.2) whose main purpose was to look for magnetic monopoles; and the Auckland experiment (section 3.5), which triggered on slow particles. The Auckland apparatus was also sensitive to heavy particles, as were the delayed air shower searches of section 3.4. We also include (section 3.3) a summary of the evidence put forward by McCusker for a quark component in the cosmic rays; this is based on a variety of cosmic ray phenomena, including his own old observation of a cloud chamber track of low ionisation.

3.1. FQS

In order to look for quarks in cosmic rays, the FQS apparatus [63] was run with the PEP storage rings turned off. A total exposure of 2.3×10^6 s was obtained; for about $\frac{1}{3}$ of the data, the apparatus was in the PEP shielding tunnel (~250 g/cm^2 thick) while for the remainder it was outside but adjacent to the tunnel. Because of the configuration of the spectrometer arms, the apparatus was sensitive to cosmic rays at zenith angles of 45° to 90°.

A total of $\sim 10^7$ triggers were obtained with the requirement that there was at least 1 hit of pulse height greater than $I_0/30$ in two specified scintillator planes in either spectrometer arm; about 85% of these corresponded to single tracks. The charge resolution was ±3.5%, and tracks with measured charge of less than 0.8 were regarded as candidates for quarks; there were 271 of these during the first third of the exposure. After a series of cuts to remove various backgrounds, however, there was no evidence for particles of either charge $\frac{1}{3}$ or of charge $\frac{2}{3}$. The resulting 90% confidence limit on the flux of quarks of either charge $\pm\frac{1}{3}$ or $\pm\frac{2}{3}$ in cosmic rays is $3 \times 10^{-9}\,\mathrm{cm^{-2}\,sr^{-1}\,s^{-1}}$, and is compared with the results of previous experiments at large zenith angles in table 3.

With the detector outside the tunnel, a search was also made for heavy unit charged particles. An earlier cosmic ray experiment [64] had reported a few vertical tracks with mass 4 to $4\frac{1}{2}$ GeV (see section 3.5).

To identify such particles, a 30 g/cm^2 steel absorber was inserted in the middle of the FQS detector. Heavy particles were those which, given their measured time-of-flight, slowed down too little to be protons, deuterons or tritons. About 1300 tracks were found with β less than 0.8, of which 230 were not consistent with being protons. Of these 90% were rejected as not being genuine slow particles, and the remainder were consistent with a deuteron assignment.

The sensitivity of this search procedure is a function of the mass and velocity; at a low mass-dependent velocity, the particles would not penetrate the apparatus, while at large velocities, heavy particles could not be distinguished from hydrogen isotopes. The upper limit as a function of β for a cosmic ray component of 4.2 GeV is presented in fig. 12, where the Yock value for such vertical particles is also shown.

The FQS collaboration emphasises that, in contrast to several other cosmic ray experiments, their apparatus has sufficient redundancy to distinquish background effects from potential quark candidates. In a simpler apparatus, the background would not have been identified as such and could have been mistakenly accepted as a genuine quark signal.

3.2. Japanese magnetic monopole experiment

A group from Tokyo [65] has operated a cosmic ray telescope 250 m underground, to look for magnetic monopoles or for fractionally charged particles by measuring the velocities and energy losses for isolated tracks. The telescope consists of 3 pairs of layers of crossed scintillators, with effective

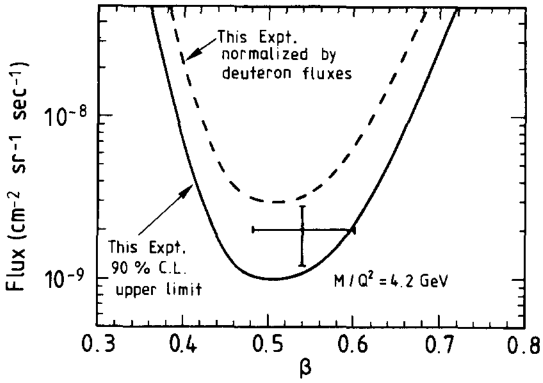


Fig. 12. The 90% confidence level upper limit as derived by the FQS experiment on the flux of unit charged particles of mass 4.2 GeV in cosmic rays at zenith angles above 45° as a function of their velocity βc. The cross is the value of the flux as deduced by Yock, for vertical tracks. If these particles are assumed to have the same dependence on zenith angle as do deuterons, and the experiments are normalised to each other by their observed deuteron fluxes, then the upper limit increases (dashed curve), and the experiments are no longer inconsistent.

cross-sectional area 2.5 m × 2.5 m. The depth of the apparatus is 80 cm, and together with iron supporting plates corresponds to a thickness of 3.5 radiation lengths.

Each scintillator was viewed by photomultipliers at each end. A truncated mean of the 6 pulse heights was used to obtain dE/dx estimates for tracks. The requirements for accepted pulses restricted the sensitivity of the experiment to $dE/dx > 0.2$. The timing resolution of ±0.3 ns enabled the particles' velocities to be determined via their times-of-flight, and a distinction to be made between downward and upward going tracks. The latter could have been caused by particles traversing 13 000 kms of earth*. For non-relativistic particles to do this, their mass must be $\gtrsim 10^{10}/\beta^4$ MeV. Mashimo et al. point out that candidates for such heavy fractionally charged particles include not only quarks but also subquarks or preons [66].

The apparatus ran for 2361 h. Events with more than 1 track were rejected. The majority of the 3×10^6 accepted tracks were consistent with being relativistic muons (see fig. 13). The curves shown in the diagram correspond to the calculated [67] energy loss of particles of different charges, and for monopoles.

If these estimates are correct, then the sensitivity of the experiment is such that a limit of 6×10^{-13} particles $cm^{-2}\,sr^{-1}\,s^{-1}$ for β in the range 3.5×10^{-4}–0.4 for particles of charge $\frac{2}{3}$ (or from 6×10^{-4} to 0.4 for charge $\frac{1}{3}$) is obtained. They also provide a limit of 2×10^{-12} particles $cm^{-2}\,sr^{-1}\,s^{-1}$ for relativistic charge $\frac{2}{3}$ particles†. All these values include in the calculated acceptance of the apparatus the possibility of upward going particles being detected, as well as downward ones.

3.3. The McCusker analysis

McCusker [68] has collected various pieces of data on extensive air showers (EAS), which he claims could possibly be explained as being evidence for free quarks (or possibly quark globs [69], or quarks clothed with a covering of nucleons [62]), and from which he estimates the quark flux. McCusker then says that the hypothesis of the existence of free quarks in cosmic rays is corroborated by the fact that his

* In fact 6 upward going tracks with $\beta \sim 1$ were observed, but could come from more prosaic sources.
† No corresponding limit can be obtained for relativistic charge 1/3 particles, as their expected energy loss is too small.

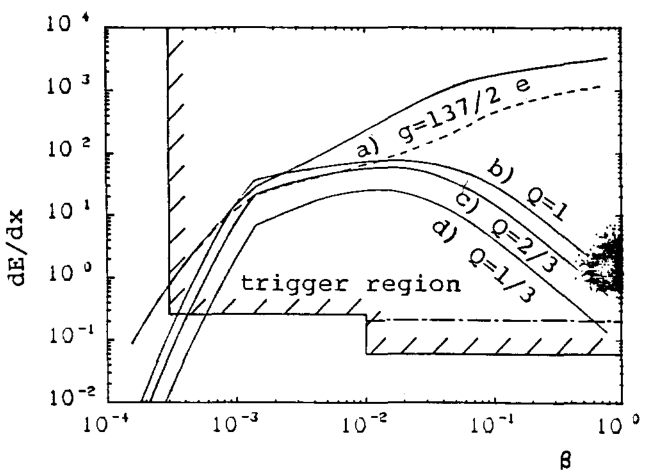


Fig. 13. Measured values of dE/dx (in units of I_0) plotted against β, for tracks in the Japanese magnetic monopole experiment. The expected curves for particles of charge 1/3, 2/3 and 1 are shown, as well as for a monopole; the dashed line is the expected light output for a monopole, taking into account the saturation of the scintillator. The dashed area shows the limit of the selected trigger region; the dot–dash line is the lower limit on dE/dx imposed by software cuts. The observed tracks congregate strongly around $\beta = 1$ and $Q = 1$.

various estimates more or less agree, and that several of these phenomena appear to set in at energies of around 1000 TeV.

The experimental observations he uses and his flux estimates are as follows.

3.3.1. *The McCusker event*

Many previous experiments which failed to observe quarks in cosmic rays were sensitive only to isolated quarks unaccompanied by other particles. McCusker has argued that the best place to look for quarks may be close to the cores of EAS.

A cloud chamber photograph of an EAS, and showing a low ionisation track, was published in 1969 [70]. This quark candidate had 16.2 ± 2.5 drops/cm while 3 other more or less parallel tracks gave a drop density of 40.7 ± 1.0. Criticism of the suggestion that this was evidence for a quark of charge $\frac{2}{3}$ included the following:

(i) The statistical error on the droplet densities had been underestimated, and the effect was due to a large fluctuation.

(ii) The track in question could have been a minimum ionising track with $\gamma \sim 3.5$, while the others could have been on the plateau of the relativistic rise.

(iii) The photographs may have been sensitive only to overlapping droplets rather than to single droplets, which would change the expected ratio of measured drop densities.

(iv) Only poor information was available concerning when the particles entered the cloud chamber. Thus either the low droplet count could be explainable in terms of the low sensitivity of the cloud chamber for that entry time; or the positive and negative ions had separated so far by the time the picture was taken that only half the initiating centres for droplets were in view.

(v) The "quark" track does not appear to be parallel to the other cosmic ray tracks in the picture, and hence may not be part of the shower.

(vi) The result of this experiment is inconsistent with those of others looking for quarks in cosmic rays.

McCusker has now answered most of these criticisms, but the suspicion remains that it is possible to observe the occasional odd tracks in a cloud chamber, and in an apparatus without many redundancy checks on the data, it may not be apparent what the cause of the phenomena is.

3.3.2. Other cosmic ray searches

Other searches for quarks in EAS and quoted by McCusker are those performed by the groups from Edinburgh [71] (0.0019), Michigan [72] (0.073), Leeds [73] (1.37), Livermore [74] (0.77) and Durham [75] (2.82), where the figures in brackets are the exposures of the data collection, expressed in metre^2 years; the corresponding figure for the experiment that yielded the McCusker event was 0.18. None of these other groups claimed to observe quarks. However, the Durham experiment, which utilised an array of neon flash tubes as detector, observed two tracks with low flash rate and which had an estimated probability of 7% for being due to out-of-time muons.

To estimate the quark flux from all these experiments, McCusker on the one hand accepts the 2 Durham tracks as fractional charge candidates; and on the other excludes the Leeds experiment, which would have been insensitive to quarks within 2 or 3 m of the core of the shower, and also reduces the Durham exposure by a factor of 2, to allow for the fact that quarks would have been difficult to detect in events which produced hadrons in the lead shield above the neon tube hodoscope. His estimate of the quark flux is then 0.5 to 2/m^2 yr.

3.3.3. Centauros

The Centauro and mini-Centauro events observed by the Brazilian–Japanese collaboration [76] provided the motivation for the Bjorken–McLerran quark glob picture, although such a multiquark glob would not necessarily have to have fractional charge. Of the 5 Centauro and 13 mini-Centauro events, McCusker accepts 4 as being inconsistent with Monte Carlo simulations of normal nuclear events. With an assumed glob mean-free-path as long as 200–300 g/cm^2* (which is necessary in order for globs to penetrate through the atmosphere to the apparatus, and which Bjorken and McLerran hypothesise is due to the small size of the tightly bound glob) and assuming that the primary interactions of the globs could only be detected if they occurred not more than 500 m above the apparatus, McCusker obtains an estimated flux of 0.7 to 4.8/m^2 yr for the objects responsible for the Centauro phenomena.

An accelerator search for Centauros in $\bar{p}p$ collisions at a centre of mass energy of 540 GeV yielded no candidates in 2600 interactions [83]. In the spring of 1985, the search is to be extended to an energy of 900 GeV and a sample of 10^5 events [84]. Of course, if the Centauros are due to quark glob interactions, there is no necessity for them to be seen in $\bar{p}p$ interactions.

3.3.4. Long flying component

A Russian experiment [77] using an ionisation calorimeter has observed that there appears to be less attenuation for large bursts than for smaller ones. The measured attenuation length increases by a factor of about 2 as the energy of the secondary hadrons increases from 70 to 700 TeV. There thus seems to be a "long flying" component which becomes more prominent as the energy is raised. If the corresponding shower energy is taken to be ~10 times that of the hadrons, then the corresponding flux of particles producing this phenomenon is ~3/m^2 yr. McCusker notes that this is comparable to his

* See footnote to section 3.3.4.

earlier estimates of quark fluxes, and assumes that this phenomena as well could be caused by quark globs*.

3.3.5. *Horizontal air showers*

The flux of air showers drops rapidly as a function of zenith angle until about 70°, beyond which the dependence is much shallower [78]. McCusker attributes the "extra" flux beyond 70° as being due to quark globs which, because of their lower interaction cross section, can more easily penetrate the thicker atmosphere at these larger angles. To estimate this flux, McCusker assumes that the globs are responsible for showers with more than about 2200 particles, there appearing to be a change in shape of the size spectrum at that value [79] (but which could alternatively be simply an instrumental effect or a fluctuation). Then the glob flux is estimated as $3.1/\mathrm{m}^2\,\mathrm{yr}$. This value is, however, sensitive to the choice of the minimum shower size N, varying like N^{-3}.

It is not clear, however, that this large angle flux cannot be interpreted conventionally in terms of muon bremsstrahlung [78, 168] – at high energies, cosmic ray primaries at large angles of incidence interact high up in the low density region of the atmosphere, with the result that the secondary pions can decay rather than interact; this should result in an increasing flux of high energy muon-induced showers at large zenith angles.

3.3.6. *Comparison of phenomena*

Since the 4 estimates of the quark flux (0.5–2, 0.7–4.8, 3 and $3.1/\mathrm{m}^2\,\mathrm{yr}$) are reasonably consistent, McCusker claims that the assumption of a common origin is supported. Thus, since his own experiment appears to give evidence for fractional charge, the other phenomena (i.e., Centauros, long flying component and horizontal air showers) which do not measure the charge of whatever is responsible for them, are interpreted as supporting the free fractional charge hypothesis.

It is possible to argue, however, that the fluxes of $\sim 3/\mathrm{m}^2\,\mathrm{yr}$ correspond to very few events in any typical experiment, and, as commented by the FQS group, apparatus without sophisticated redundancy checks may have difficulty in rejecting various spurious sources of background. It would also be reassuring to observe the charges of the primaries responsible for the phenomena which are claimed to be evidence for quark globs.

3.3.7. *Other effects*

Finally McCusker quotes various other experiments as being consistent with the idea of free quarks or quark globs of $\sim 10^3$ TeV energy.

(a) *The Yunnan track* [80]. This is a cloud chamber track of >40 GeV/c and with 21 ± 1 drops/cm, as opposed to 33 ± 1 drops/cm for relativistic tracks. While the authors suggest that this may be caused by a unit charged particle of mass greater than 12 GeV near the minimum of the ionisation-against-velocity curve, McCusker repeats a remark by Jones [11] that it could be a charge $\frac{2}{3}$ particle of somewhat more than minimum ionisation.

(b) *Various air shower data.* In the development of air showers as they come down through the atmosphere, there is a depth at which there will be a maximum number of particles. This depth increases with energy and can be compared with the expected depth, assuming that the primaries are either (i) protons, or (ii) iron nuclei. In general the data lie between these predictions, except for a point

* It is amusing to note that here a phenomenon with an unexpectedly *long* mean-free-path is associated with quarks. In the anomalon effect (see section 2.1.1), it is a *short* mean-free-path which has given rise to the suggestion that free quarks may be involved.

in the neighbourhood of 10^4 TeV [81]. This McCusker interprets as possible evidence for quarked globs of longer interaction mean-free-path. (At larger energies, however, the data returns towards the proton prediction.)

At a similar energy range, the proportion of multicore (as opposed to single core) showers increases [82], rising from 50% at 1000 TeV to 95% at 10^4 TeV. This is, not surprisingly, accompanied by an increase in the average transverse momentum.

Finally the overall energy spectrum of cosmic rays [88] sharpens from $E^{-2.6}$ below 3×10^3 TeV to $E^{-3.4}$ above it (but flattens again to E^{-3} above 10^5 TeV).

McCusker concludes that "the hypothesis that superdense quarked globs appear in the cosmic radiation at ~500 TeV and become dominant at ~10^4 TeV . . . accounts for all these effects qualitatively and some quantitatively".

Not included in McCusker's evidence for quarks are the experimental data of Yock (see section 3.5), since his own more extensive experiments failed to reproduce the effects; and the various claims of delayed heavy particles (see section 3.4) since it is not clear that they are observing the same phenomena. The reported fluxes in these experiments are also much larger than the McCusker estimate of the quark glob flux. On the other hand, he does note that Millikan [85], Garris and Ziock [86] and Fairbank [87] have observed fractional charges in their searches in stable matter (although only Fairbank claims that the effect is real); and in experiments on pp collisions at the CERN Intersecting Storage Rings, Basile [48] and Fabjan [89] have had 3 quark candidates which they were unable to reject (but which they took simply as limiting their ultimate sensitivity).

McCusker's quark flux of ~$3/\mathrm{m}^2$ yr (or ~$10^{-11}/\mathrm{cm}^2$ s) is somewhat below most of the limits quoted by Jones [11] in his review of experiments searching for unaccompanied quarks in cosmic rays. Using Jones pessimistic estimate of the concentration of quarks that such a flux would produce on earth, McCusker notes that it is a factor of ~10^5 below that required to reproduce the density of quarks needed to explain the Stanford observations, and that such a concentration factor is not untypical for geophysical processes with some ordinary chemical species on Earth.

3.4. Delayed air showers

Very energetic cosmic ray primaries interact high up in the atmosphere, and the resulting electromagnetic cascade can reach down to sea level. Since the electrons and photons are ultra and completely relativistic, respectively, the various parts of the shower arrive virtually simultaneously, with a spread of ~5 ns coming mainly from path length differences of a couple of metres due to different path lengths for electrons scattered in the atmosphere. If, however, at some stage between the primary interaction and the shower detection there has been produced a heavy particle of mass M, this would lag behind the shower front, and the subsequent detection of this particle (or of any secondaries that it produced by interaction or decay) would be delayed by a time interval τ with respect to the shower front, where

$$\tau \sim L/2\gamma^2 c\,,$$

with L being the distance over which the heavy particle travelled with relativistic dilation factor γ, assumed to be much larger than unity.

Thus experiments looking for delayed particles in showers are sensitive to the production of heavy particles, whose charge could be fractional, integer or perhaps even zero. These types of searches thus do not rely on fractional charge as the signature for a quark. On the contrary, the detection of a heavy particle of course does not confirm that quarks have been discovered. Indeed the authors of one experimental paper have suggested that their possible signal could be due to heavy leptons, to hadrons containing a new flavour of quark, or to preons.

Jones [11] and Lyons [12] have discussed early experiments of this type. Jones has emphasised that the mere observation of events with large delay ($\gtrsim$20 ns) and large hadronic energy ($\gtrsim$5 GeV) in itself is not really sufficient to establish the existence of a significant effect. What is required is that a group of clean events should be seen, which are clearly distinguished from the tail of the observed distribution of time delays, especially at the lower energies, and preferably which allow a mass determination to be made. Since the observed events of this type occur at a very low rate, there is also the question of whether all sources of background have been successfully removed, which can be a serious difficulty in apparatus without a high degree of redundant information. Finally there is the problem that hadronic energies are usually determined with poor accuracies in these experiments. Thus there is the danger that an uninteresting low energy delayed hadron can be accidentally accepted as being of high energy at the same delay, which could be the signature of something interesting.

Clearly, experiments are needed with a high rejection factor against backgrounds, the ability to measure times and especially energies accurately, well understood errors and sufficient redundancy.

3.4.1. Sakuyama and Watanabe

Out of a total of 6000 EAS, Sakuyama and Watanabe [90] have observed some tens of showers in which the hadronic component has measured energy greater than 5 GeV and is delayed with respect to the shower front by 20 to 120 ns. Their apparatus consists of an assembly of some 40 plastic scintillators of 1 m^2 area spread out over 300 m $\times$ 300 m in order to measure the EAS, and a fast timing scintillator, also of 1 m $\times$ 1 m, below 1 m of concrete and 3 cm of lead. The methods of obtaining the time delays and of estimating the energy are not described in detail.

For such large delays to be caused by protons produced within 1 mean-free-path ($\sim$1 km of air) from the detector, their energy would have to be below about 3 GeV. The higher observed energies are inconsistent with this, and thus Sakuyama and Watanabe invoke heavier particles. To explain the delayed signals for EAS of energies 10^3 to 10^4 and of 10^5 to 10^6 TeV, two different heavy particles ξ and σ (of masses 40–60 GeV and 1–14 TeV, and each of lifetime $\sim 10^{-6}$ s) are then required. From the spectrum of the delay times, scatter plots of delay times against x (the distance from the core axis) and the particle densities as a function of x, Sakuyama and Watanabe conclude that the favoured explanation is one in which new hadrons, containing quarks of new flavours, are produced copiously high up in the atmosphere. These decay to their corresponding charged and neutral leptons, and the delayed signals are produced when the heavy charged or neutral leptons eventually decay low down in the atmosphere. The long lifetimes of the heavy leptons are due to very small couplings [90], or to small neutrino mixings [92].

Sakuyama and Watanabe also believe that the above type of mechanism could be used to explain the frequency of horizontal air showers, the large transverse momenta at high energies and the anomalous bursts observed underground.

This experiment appears to have little redundancy or protection against spurious effects. Especially in view of the history of the analysis of other experiments looking at delayed particles, it may well be worthwhile to withold judgement on the significance of this effect, which in any case is not claimed to be evidence for free quarks.

3.4.2. *Inoue et al.*

A Japanese–Bolivian collaboration [93] has also looked for delayed hadrons, by using 9 scintillators each of 4 m^2 and shielded by 380 g/cm^2 of material. The detector is situated 5200 m above sea level on Mount Chacaltaya.

The system was triggered by at least 6 relativistic particles passing through the scintillators, whose signals were fed to a 100 MHz oscilloscope. Delayed bursts were required to contain more than the equivalent of 15 relativistic particles, and to have a time resolution as measured on the oscilloscope of better than 8 ns. The range of incident energies studied in this experiment is 10^4 to 10^6 TeV.

Among 9000 showers with more than 10^6 electrons, 15 bursts at delay times larger than 100 ns (including 2 at $\sim$300 ns) were observed. When Inoue et al. attempt to explain their hadron bursts with delays of $>$30 ns in terms of nucleon or antinucleon production, the results at energies above 10^5 TeV suggest that the incident nuclei are iron rather than protons. Because of their low statistics for very large delays and with large delay burst sizes, it is not clear whether these events require a more exotic explanation. More data is being accumulated.

3.4.3. *Bhat et al.*

A search for delayed particles in showers has been conducted over the period 1978–81, with timed scintillators inside and near the Ooty multiplate cloud chamber [94] (see fig. 14). The use of 2 scintillators S_3 and S_4 within the chamber to time the hadrons was an improvement over earlier experiments, where hadron timing was provided by a single counter. Another feature was that, for part of the run, the counters S_3 and S_4 were timed at 2 different output signal levels; this enabled delayed hadrons to be recorded in the presence of prompt hadrons giving a smaller signal. The shower front was timed by 6 scintillators above the cloud chamber. The timing resolution was said to be $\pm$3 ns.

The experiment collected data for 8 800 h with the apparatus as shown in fig. 14, and for a further 2 800 h with S_4 moved to be just above S_3. The cloud chamber, whose purpose was to provide a picture of the type of shower and to give an improved measurement of the hadron energy, was unfortunately not operational for most of the data taking. The estimate of the hadronic energy was thus obtained simply from the number of particles in S_3 and S_4 (with a conversion factor of 1 GeV per hadron), which

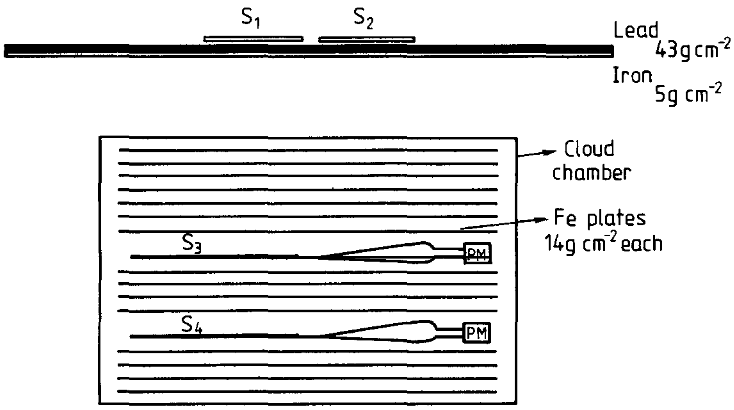


Fig. 14. Schematic diagram of the Ooty multiplate cloud chamber detector. Within the cloud chamber are a series of iron plates and two hadron timing scintillators S_3 and S_4. These are shown in their position for the first part of the experiment; later S_4 was directly above S_3 in place of one of the iron plates. The shower front was timed by the two scintillators S_1 and S_2 each of area 0.5×0.5 m^2. Four liquid scintillators (not shown) of area 1 m^2 each were placed at distances of $\sim$10 m from the cloud chamber, and their timing measurements of the shower front were used to deduce the shower direction. A further 20 plastic scintillators spread over distances up to 40 m helped determine the shower size and its core position.

in turn was derived from the pulse heights. Bhat et al. estimate that this lead to an uncertainty in energy of a factor of ~2.

Events were classified as types A, B or C, depending on whether the two times from S_3 and S_4 agreed, disagreed or whether only one of the counters provided any pulse. No events of type A with more than 40 particles at delays of more than 20 ns were observed; there were 20 such events of types B and C, of which 16 were obtained before S_4 was moved.

The lack of delayed hadron events giving consistent times in S_3 and S_4 lead Bhat et al. to place a 99% confidence level upper limit of $2\times 10^{-11}\,\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$ on the flux of heavy particles in cosmic rays. Because of the similarity of their events of types B and C with those from other experiments which do not have redundancy in their timing information, they also suggest that the earlier data on delayed hadrons should not be regarded as evidence for the existence of such heavy particles.

3.4.4. Maryland

Another interesting result is a Monte Carlo calculation of the Maryland group [95]. They had observed 3 events with energetic delayed hadrons in an earlier experiment [96], and had suggested that a new particle of mass greater than about 5 GeV could have been responsible for producing them.

They have now measured the response of their hadron calorimeter in an accelerator beam, and find that the fluctuations in the output signal are much larger than they had previously assumed. Their Monte Carlo calculation now includes the measured response of the calorimeter, and they find that their events of large energies and delays can probably be explained as normal low energy delayed hadrons which, due to a fluctuation, occasionally appear to have a larger energy.

Their conclusion is that their earlier data is not evidence for the existence of heavy particles. A new experiment has been operational for 2 years at sea level. The analysis of this should be completed shortly*, and the sensitivity will be of order 10^{-12} heavy particles $\mathrm{cm^{-2}\,sr^{-1}\,s^{-1}}$ [97].

3.5. The Auckland cosmic ray telescope

For several years, a small cosmic ray telescope has been operating in New Zealand. It consists of 3 scintillators above an absorber and 3 below it. The incident particle's velocity, charge and mass are determined by measuring the pulse heights above and below the absorber, and the time-of-flight. The results of 3 runs, each of 4000 h, have already been published, and also reviewed in ref. [12]. The first run provided 3 possible examples of fractional charge [99], while in the last 2 there were 6 examples of integrally charged particles of mass $\sim 4.5 M_p$ [64].

Further results are now available from 4000 h of exposure with a slightly improved arrangement [98]. The timing accuracy is claimed to be ±0.2 ns, and pulse heights determine $\mathrm{d}E/\mathrm{d}x$ to an accuracy of ±8%. The trigger is set to select particles with $\beta < 0.65$, since at larger velocities, heavy particles would not be distinguishable from tritons.

For those tracks whose ionisation increases by more than 20% in passing through the absorber, the mass resolution is about $0.3 M_p$. Peaks are observed at positions corresponding to the deuteron and the triton, and there are 2 tracks with measured masses of 4–$5 M_p$. There are 7 other events whose ionisation increases by less than 20%. Because of the worse mass resolution, only lower limits on the mass are quoted. Again two tracks have masses greater than $4 M_p$ (and unit charge). Yock does not believe that these 4 tracks are tritons as they are ~2 to 3 standard deviations from the triton mass, with only about 23 tritons being observed.

Accepting these tracks as being heavy particles, Yock estimates the flux of slow single charged

* See, Note added in proof.

particles of mass greater than $4M_p$ and falling approximately vertically in Auckland at sea level as of order $10^{-9}\,cm^{-2}\,s^{-1}\,sr^{-1}$. Data from a further 1000 h running should be available shortly. The earlier fractionally charged candidates [99] are assumed to be due to spurious effects connected with multitrack events in the telescope.

As with many other cosmic ray experiments, it would clearly be desirable to have a more sophisticated apparatus in order to check that the observed effects are genuine. It is also imperative to obtain a measurement of the mass of interesting tracks, rather than just a lower limit.

3.6. Charge $\frac{4}{3}$ particles

A small cosmic ray telescope has been operated at zenith angles of 31° to 49° by a Japanese group [184] in order to look for charge $\frac{4}{3}$ particles. The particle's charge is estimated via its energy loss, which is obtained from the mean and the minimum pulse heights in 8 layers of proportional drift chambers. The cell structure of the detector helped in rejecting tracks which entered through or left the sides of the detector, and events with more than one track. Slow, heavily ionising particles were excluded by $253\,g/cm^2$ of absorber above the lower trigger counter.

From around a million clean single cosmic ray tracks, 7 were between the defined acceptance regions of pulse height corresponding to charge 1 tracks and to an unresolved pair of tracks. Although it is by no means clear that they represent a genuine signal, the flux of charge $\frac{4}{3}$ tracks is deduced as $(4.0 \pm 1.5)10^{-9}\,cm^{-2}\,sr^{-1}\,s^{-1}$.

The lack of tracks in the regions for charge $\frac{1}{3}$ or $\frac{2}{3}$ corresponds to 90% confidence limits of 9×10^{-10}, and $6 \times 10^{-10}\,cm^{-2}\,sr^{-1}\,s^{-1}$, respectively.

This experiment is being continued with an improved telescope and at other zenith angles [185].

All the above cosmic ray results are summarised in table 5.

4. Brief survey of stable matter searches

Although this review is devoted to quark search experiments at accelerators and in cosmic rays, we here include a brief survey of recent progress concerning experiments looking for quarks in stable matter.

The Stanford group [87] has published no new results since those quoted in ref. [12]. Two major runs (starting in September 1980 and in January 1982) have been completed since then and have yielded some 15 new measurements; a detailed account of this work is to be found in Phillips' thesis [100]. These new results, however, do not display the feature of the older data of yielding values of the residual charge which are consistent with zero or $\pm\frac{1}{3}$ only. The spread of results is ascribed at least in part to a misalignment of the magnetic field axis with the vertical by 17 mrad. It is planned for future runs to eliminate the spurious effects that this could produce by spinning the balls during the measurements.

The September 1980 run also included a "blind" measurement in which a random number was added to the ball's charge, so that the experimentalists had to calculate the residual charge without knowing what final correction still had to be removed; this was to eliminate the possibility that unconscious biasses may be introduced by the experimentalists (either through the way runs were accepted or rejected, or in the manner in which corrections were applied) via preconceived ideas of what would be a satisfactory answer. The value obtained for the residual charge was +0.189, but as other results from these runs were also unsatisfactory, this one was not regarded as being of negative significance.

Table 5
Cosmic ray results

First author or collab.	ref.	Quark identifn.	Quark's charge + mass	β	Result[(a)]	Comment
FQS	[63]	dE/dx + TOF	{1/3, 2/3	>0.1	$\phi < 3 \times 10^{-9}$	Uses FQS apparatus for PEP
			{1, 4.2 GeV	0.4–0.7	See fig. 12	
Mashimo	[65]	dE/dx + TOF	{2/3	~1	$\phi < 2 \times 10^{-12}$	Magnetic monopole search
			{1/3, 2/3	6×10^{-4}–0.4	$\phi < 6 \times 10^{-13}$	ϕ includes upward particles
Sakuyama	[90, 91]	Delayed air showers	? ~50 GeV and ~10 TeV	Just below 1	2 particles claimed to exist	
Inoue	[93]	Delayed air showers	?	Just below 1	Could be due to N and $\bar{N}$	
Bhat	[94]	Delayed air showers	?	Just below 1	$\phi < 2 \times 10^{-11}$	No events with consistent times
Mincer	[95]	Monte Carlo on delayed air showers			Previous results *not* evidence for heavies	Fluctuations on estimated energies can be large
Yock	[98]	dE/dx + TOF	Integral, ≥4 GeV	<0.65	$\phi \sim 10^{-9}$	Previous evidence for fractional charges now discounted.
Wada	[184]	dE/dx	4/3		$\phi = 4 \times 10^{-9}$	Zenith angles 31–49°
			1/3, 2/3		$\phi < 9 \times 10^{-10}$	
McCusker	[70]	Various (see section 3.3)	Fractional?		$\phi \sim 10^{-11}$	Claims evidence for quark globs close to shower cores

[(a)] The flux ϕ is quoted in particles $cm^{-2}\,s^{-1}\,sr^{-1}$.

Since the Stanford experiment is the only one to date to have a positive result in the search for quarks in matter, it is obviously of the utmost importance for more data to be accumulated by this apparatus, especially in view of the outcome of the last two runs. Future "blind" measurements will also be awaited with interest, as will some planned comparative tests with the Rutherford group on a new batch of niobium samples (see below).

The future plans of the Stanford group [101] also include the development of a room temperature levitometer in which balls exposed to the Bevelac heavy ion beam (see section 2.1.2) can be measured. Currently the level of radioactivity of these balls is such that charge changes occur too frequently for reliable measurements to be made; by the time the apparatus is ready, the radioactivity may have decayed to an acceptable level. A crude mass spectrometer is also planned, so that if fractional charges are detected, some information on the mass of these objects can be obtained.

An account, largely from the point of view of the criteria of acceptability used by the scientific community for judging the validity and significance of experimental results, of this series of experiments and its relation to those of the Genoa group (see next paragraph) has been given by Pickering [102].

Marinelli and Morpurgo [103] have reported the final results of their ferromagnetic levitation experiment. They have measured 70 spheres of diameter 0.2 and 0.3 mm, typically with errors of ~ 0.04 on the residual charge. Excluding 8 of the larger size balls which did not discriminate sufficiently between residual charges of zero or $\pm\frac{1}{3}$, and 4 more which were measured alone and hence could not have their residual charge compared directly with that of another ball, they are left with 3.7 mg of iron with no observed fractional charge. At the 90% confidence level, this corresponds to $<10^{-21}$ quarks per nucleon in their steel. The magneto-electric effect that they observed in their measurements has since been explained [104] as arising from the balls' magnetic moments being tilted by the effect of the applied electric field on their electric dipole moments.

Liebowitz, Binder and Ziock [105] have looked for quarks in steel balls from the same manufacturer who supplied Morpurgo. They measure the residual charge by determining the amplitude of the alternating component of the vertical magnetic field required to levitate the ball when a 2 Hz vertical electric field is applied. Their experiment differs from that of Marinelli and Morpurgo principally in having the electric and magnetic fields parallel. This arrangement, together with rapid spinning of the balls, eliminates the spurious magneto-electric force mentioned above. The values of the residual charge on 24 balls peaked at zero, with no value larger than 0.15 (although individual measurements seem to have a random error of about ± 0.01). The amount of material tested is 0.72 mg, as compared with Morpurgo's 3.7 mg.

Because they believe that unrefined water is a likely source of quarks, the San Francisco group has used water samples from a variety of sources in their modified Millikan experiment [106]. The charge on a 15 μm drop can be measured to an accuracy of ± 0.035. After rejecting about 50% of the drops as having too large an initial charge (>12), or for apparently changing charge while dropping through the apparatus, they obtain a residual charge distribution which, except for two measurements at a charge of ~ 0.74, is consistent with a Gaussian of width 0.037 centered on zero; the two curious values are regarded as being produced by instrumental effects. Then the 90% confidence level upper limit for these water samples is 0.7×10^{-19} quarks per nucleon.

In an earlier experiment [107] with this apparatus, 0.06 mg of refined mercury and 0.115 mg of native mercury were tested, again with no sign of a quark signal.

This apparatus is the one that was subsequently used for the San Francisco group's search for quarks produced in heavy ion collisions (see section 2.1.2).

A limit of less than 5×10^{-14} fractional charges per nucleon has been measured in ultrapure germanium [108], although it is admitted that the chemical purification processes, zone refining and crystal growth techniques to which the germanium was subjected may not have been conducive to retaining any primordial quarks that it may have contained. The technique used is photothermal ionisation spectroscopy, which requires a measurement of the change in conductivity of a sample (cooled to ~1 K) as it is illuminated with monochromatic radiation; electrons attached to impurities of fractional charge Z should be ionised at a threshold lower by a factor of Z^2 than for those attached to unit charges. Van de Steeg et al. claim that this type of experiment should be able to reach a sensitivity of $\sim 10^{-19}$ quarks per nucleon.

An Argonne group [109] has looked for positively charged quarks trapped in niobium at 4 K, in order to test whether this was the crucial feature that resulted in the Stanford group's observation of fractional charge [149]. They can heat their niobium to several hundred degrees within a second, and then accelerate any released quarks by a 700 kV Cockroft Walton accelerator (which is an injector for the Fermilab large machine). The energies of the accelerated particles were measured by silicon surface barrier detectors, in front of which were two thin stripper foils and an electrostatic deflector, in order to reduce backgrounds in the energy region of interest. The experiment was sensitive to particles of mass greater than 10 MeV (below which they would have been deflected by residual magnetic fields) and below about 100 GeV (above which they would have been too slow to be observed in the silicon detector)*.

No excess of particles with either $\frac{1}{3}$ or $\frac{2}{3}$ of the energy of a unit charged particle was seen in the few seconds after heating, compared with a background counting rate of ~2 per minute. The size of the niobium source was such that Kutschera et al. expected at least 100 fractionally charged particles to be released, if the hypothesis of quark trapping by niobium at low temperatures was correct.

Sea water as well as ocean sediments and volcanic lava have been used as potential sources of quarks by Ogorodnikov et al. [120]. Any quarks in the sample are hopefully extracted by thermal desorption and accumulated on electrodes at ±100 V, which are then used as ion sources with an accelerating voltage of 20 kV. The ions were identified by either mass spectrometry or by using an electric gate. The sample sizes varied from 2 kg of lava to 84 kg of water. The upper limits obtained for possible quark densities varied from 10^{-25} to 5×10^{-28}.

Sea water had also been investigated by Mitsuhashi et al. [111]. They attempted to concentrate any quarks by ion exchange chromatography and evaporation. The enriched sea water was sprayed into a Millikan apparatus, where the water evaporated, leaving salt grains, whose charges were measured. They argue that (a) terrestrial quarks are likely to accumulate in sea water; (b) ion chromatography works for fractionally charged ions in the expected manner; and (c) any quarks in sea water would remain in the salt grains. No third-integral charges were observed in 696 grains, which weighed 1.5 μg and corresponded to an original mass of sea water of 4.5 mg. This experiment thus sets a limit of less than 10^{-21} quarks per nucleon.

Finally in this section, we mention three experiments which have looked for heavy particles, rather than those of fractional charge.

Motivated by a suggestion of Dover, Gaisser and Steigman [175] (see section 6.3), Middleton et al. [176] have used a tandem accelerator to look for anomalous integrally charged isotopes of oxygen. The mass range scanned was 20 to 54 amu (i.e., 4 to 36 GeV for any unusual heavy particles) with a resolution of ≤0.2 amu. Peaks were observed at some integral masses, corresponding to conventional nuclei. Even including these, the upper limit on the heavy particle/nucleon ratio is always better than

* Lewin and Smith [166] are currently studying the mass dependence of the sensitivity of quark search experiments like this one.

10^{-16}, and for much of the range is 10^{-18} to 10^{-19}. Middleton et al., however, point out that oxygen has undergone considerable chemical and biological cycling, which could result in a separation of isotopes of different masses.

Dick, Greenlees and Kaufman have looked for heavy isotopes of sodium [177], which could contain integrally charged or neutral heavy particles. Their technique involved looking for an isotopic mass shift in the D2 atomic transition in an atomic beam of sodium. Such a shift is proportional to $1/M$ (where M is the mass of the isotope), and the method is sensitive to all masses from ~100 GeV up to ~10^6 GeV. The relevant part of the spectrum contained 3 peaks, which disappeared when the temperature was raised; this was consistent with their being due to rotational-vibrational levels in molecules of diatomic sodium in the beam. The negative result of the search is converted to a limit of $<5\times10^{-12}$ heavy particles/nucleon; this assumes that the nuclear size effect for the heavy isotope is negligible, and that its hyperfine splitting is at least half that of normal sodium-23. The authors point out that the overall cosmic abundance of heavy particles could differ from this because of (i) nucleosynthesis effects being different from that of normal nuclei, and (ii) fractionation effects that may occur between normal and heavy sodium in the earth's crust, in the manufacture of the sodium sample used, or in the production of the atomic beam. A future experiment is planned with an atomic beam of lithium, which is thought to be predominantly primordial rather than produced by nucleosynthesis.

A Rutherford Laboratory team has looked for anomalous heavy particles of integral charge, by performing mass analysis of ions produced from enriched samples of heavy water (D_2O). Thus 1.2×10^8 litres of natural water yielded 6000 litres of heavy water, which were concentrated by a further factor of 3×10^7 by electrolysis. It is assumed that any anomalous heavy particles would be retained in the

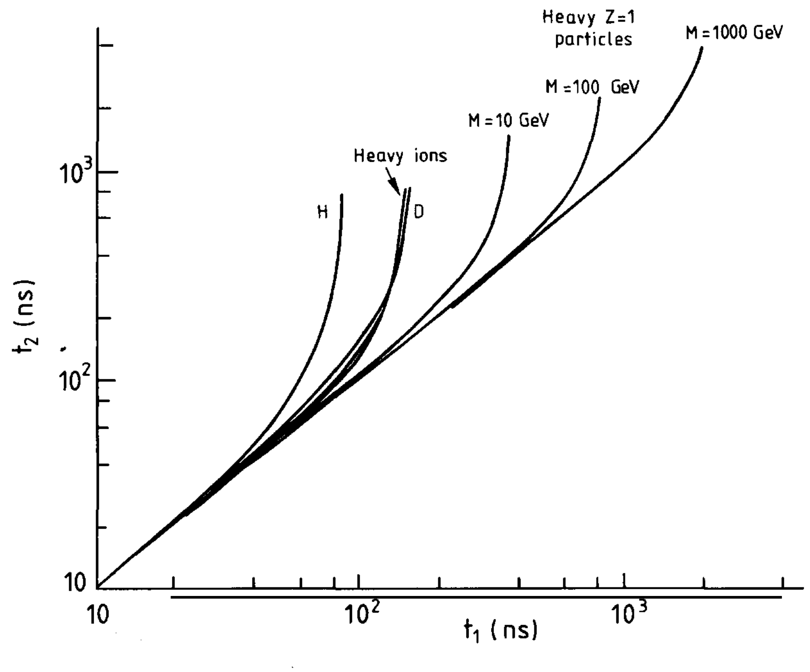


Fig. 15. Calculated curves of t_1 against t_2 for particles passing through the spectrometer of Smith et al. [135]; these are the times-of-flight between the first and second carbon foil, and between the second and third respectively. The time t_2 is larger than t_1 because the ions slow down in the central foil; the curves are calculated assuming the most probable energy loss. Those for unit charged particles of mass greater than 10 GeV are well separated from those of normal light or heavy ions.

Table 6
Summary of stable matter searches

Lab or first author	Ref.	Method	Material	Result[a]	Comments
Phillips	[100]	Supercond. levitn.	Niobium	No new results yet	Previously obtained positive signal ($\rho \sim 10^{-20}$)
Marinelli	[103]	Ferromag. levitn.	Iron	$\rho < 10^{-21}$	
Liebowitz	[105]	Ferromag. levitn.	Iron	$\rho < 6 \times 10^{-21}$	
San Francisco	[106]	Millikan	Water	$\rho < 7 \times 10^{-20}$	
	[107]	Millikan	Mercury	$\rho < 2 \times 10^{-20}$	
Van de Steeg	[108]	Photothermal ionisation spectroscopy	Germanium	$\rho < 5 \times 10^{-14}$	
Chang	[116]	Accelerator + charge exchange	Gallium	$\rho < 10^{-14}$	Residual charge $+\frac{1}{3}$
Kutschera	[109]	Accelerator	Niobium	$\rho < 10^{-21}$	Looks for positive quarks
Ogorodnikov	[120]	Thermal desorption, collection and acceln.	Water, etc.	$\rho < 10^{-25}$–5×10^{-28}	Uses concentration techniques
Mitsuhashi	[111]	Ion chromatography + Millikan	Water	$\rho < 10^{-21}$	Requires assumptions about quark chemistry
Smith	[135]	TOF spectrometer	Water	$\rho < 10^{-28}$–10^{-29}	Uses enriched heavy water $M \sim 10$–1000 GeV
Dick	[177]	Isotope shift	Sodium	$\rho < 5 \times 10^{-12}$	Assumes similar hyperfine effect; negligible radius effect. $M \sim 10^2$–10^5 GeV
Middleton	[176]	Accelerator	Oxygen	$\rho < 10^{-16}$–10^{-19}	$M \sim 4$–36 GeV

[a] The results are presented as ρ, the quark density per nucleon in the sample tested. The last three rows refer to searches for integrally-charged heavy quarks; the others have looked for fractional charges.

residue; a check on this is afforded by monitoring the increase in the tritium concentration during the process.

The first analysis [134] of 0.012 ml of D_2O used a mass spectrometer to obtain a limit of 10^{-21} to 10^{-22} heavy particles per hydrogen atom in the original water source, for masses in the range $6M_p$ to $350M_p$. The sensitivity was limited by the low efficiency of the ion source, and by the necessity to scan the accessible mass range.

A second search [135], with 0.016 ml of D_2O, utilised a time-of-flight system in which ions were first accelerated to 130 kV. Uninteresting low masses were removed magnetically, and high Z ions by a carbon foil. The remaining beam passed through three 10 μg/cm² carbon foils at 10 cm separations, which provided timing signals. Because ions of different masses and/or charges slow down differently in passing through the foils, a scatter plot of the 2 time differences enables heavy singly charged ions to be isolated (see fig. 15). No counts were observed in the region of interest, yielding a limit 10^{-16} to 10^{-17} heavy particles per deuteron of the enriched heavy water, or correspondingly 10^{-28} to 10^{-29} per hydrogen atom for the original source; the experiment was sensitive to masses of $12M_p$ to $1200M_p$.

The various limits on quark densities in stable matter are set out in table 6.

5. Future possibilities

A proposal [110] is being submitted for a Tevatron experiment, which would be an extension of the Bevalac search described in section 2.1.2. The new experiment would use a proton beam on a target of indium and lead wafers, followed by mercury. Downstream from the target would be 10 tanks filled with freon-113, each containing two wires of opposite electrical polarity. Both the wires and the target material would be available for the various groups who perform stable matter searches. It is hoped that the ultimate sensitivity of such experiments could be of order 10^{-13} fractional charges per collision.

A similar type of experiment could be envisaged for LEP, in order to search for quarks with large interaction cross sections* and/or higher masses than have been investigated previously. The basic idea is to place some material near a beam intersection region and *within* the beam pipe, and then subsequently to investigate whether it contains any quarks.

At the energy of the Z°, the design luminosity should produce 10^5 hadronic events per day. In the absence of confinement effects, a small amount of material 8 cm from an intersection would be subjected to a flux of 200 quarks $cm^{-2}\, day^{-1}$. Thus, for example, if 10^4 250 μm diameter steel balls were placed there, 1000/day would be hit by quarks (although not all of these would necessarily stop within the balls). If they could be tested at a long-term rate of 1 every hour, all 10^4 balls could be investigated in about one year. Alternatively, 200 quarks per day would be incident on a 1 cm cube of liquid; this could be tested, for example, in one of the planned liquid drop experiments within a few days running.

A group from the University of Rochester [112] has been developing an ultrasensitive mass spectrometer by using a 12 MV tandem accelerator. The ion source uses a cesium primary beam to convert the sample to negative ions. As with the arrangement of the Argonne group [109], the analysis system is entirely electrostatic in order to avoid the mass dependence that magnetic deflection introduces. The background to a charge $-\frac{2}{3}$ signal would arise from charge exchanges in the residual gas in the system, and would limit the sensitivity of the search to 10^{-16} to 10^{-18}. The plan is to use this system to analyse samples from a Bevelac exposure [113] (see section 2.1.2). Initial tests of the system

* Compare refs. [62] and [199].

[186] have involved looking for (i) berrylium ions of mass greater than 100 GeV; and (ii) fractional charges recombined into neutral molecules [152], in the gaseous residue of a xenon fractional distillation process.

An example of the earlier work of this group is their search for integrally charged quarks of mass below $1.75\,M_p$ [114].

Another all-electrostatic spectrometer is being used by a Toronto group [115]. The principle of the method is to accelerate ions by a 3 MV tandem accelerator, and to measure their energy afterwards. Backgrounds from integrally charged sources are significantly reduced by electrostatic filters before and after the charge of the ions are changed in passing through an alkali-metal vapour cell (see fig. 16). A time-of-flight technique at the end of the spectrometer could be used to measure the mass of any quark candidates.

Since molecules tend to get dissociated in this type of apparatus, it would be capable of detecting quarks in neutral molecules consisting of pairs of quarked atoms, as suggested by Schaad et al. (see section 6.4).

At present, the apparatus has achieved a sensitivity of better than 1 fractional charge in 10^{14} gallium atoms, for masses between M_p and $100\,M_p$, and for charges below 100 [116]. This technique should be capable of some 4 orders of magnitude improvement in sensitivity [115], and may be used to test specimens from the Bevelac and Tevatron exposures [117].

A liquid drop experiment is in progress at Livermore [118]. Drops of down to 10 μm diameter and which have been deflected by an electrostatic field have their transverse position measured optically. The system is designed to have a charge resolution of 0.01, and a throughput of ~1 litre per day. It is also possible to test solids, which have been ground to sizes of ~1 μm, and which are suspended in the liquid. This arrangement can be used to test Bevelac and Tevatron samples.

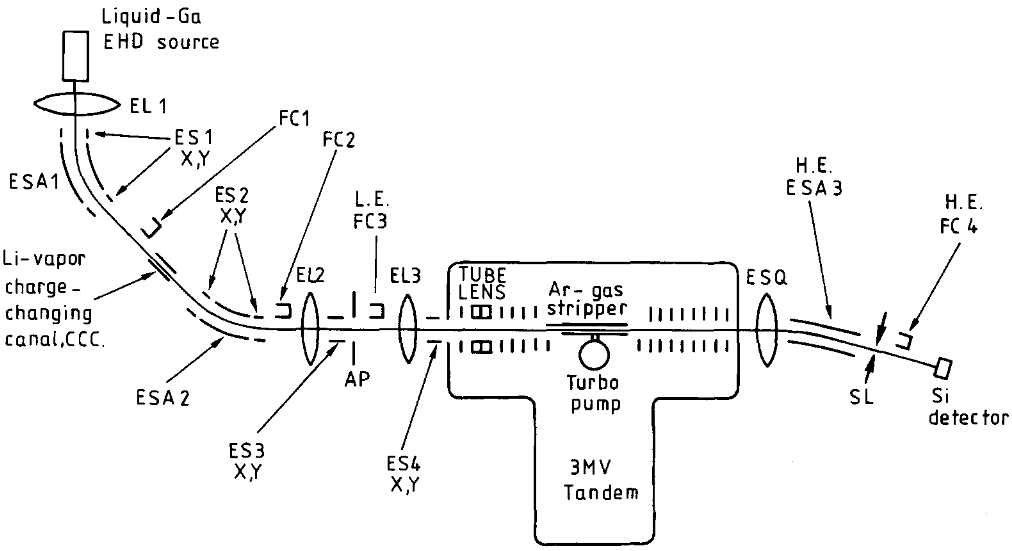


Fig. 16. The University of Toronto Isotrace Laboratory's all electrostatic apparatus for a fractional charge search. The gallium source provides positive ions, which pass through a series of electrostatic lenses (EL), steerers (ES) and analysers (ESA). They are converted to negative ions in the charge-changing canal, which contains lithium vapour, and then accelerated by the 3 MV tandem. A second charge change in the argon gas stripper, followed again by electrostatic analysis, provides further rejection against integrally charged backgrounds. The energies of the particles emerging from the system are measured by a silicon surface barrier detector.

The Argonne liquid jet experiment [119], in which drops fall down a 20 m tower, is not yet operational. There are no plans to analyse accelerator-produced samples.

A new ferromagnetic levitation apparatus at the Rutherford Laboratory [121] has just started operating. Measurements of the charge on $\frac{1}{4}$ mm diameter iron balls have a statistical accuracy of $\pm 0.3/\sqrt{t}$, where t is the measurement time in minutes, and systematic errors of less than 0.05. A complete measurement of a ball takes several hours. Both iron and iron-coated niobium balls are currently being measured*. It is also planned to exchange samples with the Stanford group so that they can be measured by both groups [121]. Other possibilities include the electrostatic extraction of any fractional charges from large quantities of air or water, and then concentrating them onto the surface of the iron balls to be tested.

An alternative method of estimating the charge on a sample is to suspend it on a very high resistance fibre, to rotate a series of capacitor plates past it, and to measure the induced alternating voltage on the plates. This type of approach has the advantages of being applicable to almost any type of material, and not requiring low temperatures. To obtain sufficient accuracy on the charge determination, it is necessary to measure the alternating voltage over a long enough time, which implies that the charge must remain constant over this period; this can be a problem owing to the charge fluctuations on the suspension and sample holder.

In the first version of such an apparatus [122], the best performance achieved was an accuracy on the charge of $\pm 0.3/\sqrt{t}$, where t is the measurement time in minutes. Thus to obtain an accuracy of ± 0.05 would take 40 min; but the rate of charge drift of the sample container and suspension (without a sample present) was about 0.1/s, which is orders of magnitude too large.

A second version [123] has yielded accuracies of ± 2 on the charge measurements. A third one is currently being assembled; the hoped for precision is $\pm 0.05/\sqrt{t}$, which would require a 1 min measurement with a much improved background drift rate in order to identify a fractionally charged sample.

Two experiments are currently being set up to look for heavy relics from the Big Bang, which although not specifically quarks could include them. In one of these experiments [124], the spontaneous fission of californium is studied. If a californium nucleus contained a heavy particle which remained bound in one of the fragments after fission, the latter's recoil energy would be small and hence, assuming that the fission energy were typical, the other fragment would have an anomalously large range. The sample is placed at the centre of a low pressure time projection chamber [125] (TPC), which enables the range, energy and ionisation of the fission fragments to be measured. By using a source of 10^5 distintegrations per second, this experiment hopes to reach a sensitivity of 10^{-13} relics/nucleon, for relic masses in the range 10 to 10^6 GeV.

The other experiment [126] is similar in spirit. It looks for backward elastic scatters at energies beyond the kinematic limit for scattering off normal nuclei. Tests have been performed with 160 MeV bromine ions on a gold target, and the background is small. The actual experiment plans to use a uranium beam on a target specially chosen as being geologically more likely to contain heavy relics, or perhaps on meteorities from outside the solar system. The range of masses that can be explored is above about 100 GeV.

Charge $\frac{1}{3}$ quarks in large air showers are to be looked for in an experiment planned by a Leeds–Nottingham collaboration [127]. By using the Leeds cloud chamber (of cross-sectional area 3 m^2 and useful depth 40 cm), they hope to be able to see any quarks close to the shower centre, which is where McCusker suggested they may be found. The chamber is shielded by 15 cm of lead and 25 cm of

* See, Note added in proof.

concrete, above which is a 7 m × 5 m array of discharge tubes, and also plastic scintillators. The trigger rate for showers of above 10^{15} eV energy is ~1/h, yielding ~120 showers per year passing through the cloud chamber. For events with not too high a density of tracks in the chamber, the lower ionisation of a charge $\frac{1}{3}$ particle should be apparent. It is hoped to run this experiment for 2 to 3 yr.

The future plans of experiments already in progress have been mentioned earlier in this article where relevant.

6. Assorted suggestions concerning quarks

Here we mention briefly various ideas that may be of some relevance to quark search experiments. These include the question of whether or not quarks are confined; the possibility that any observed fractional charge may be due not to coloured quarks but to other types of colourless objects; phenomenological suggestions concerning quarks, including their expected abundance as relics from their production in the early Universe; and the expected chemistry of quarks and quarked atoms, which could be of the utmost importance in deciding where and how to search for quarks in stable matter.

6.1. Confinement

The most significant fact would be if quarks are permanently confined [181], and hence that it is impossible to detect a single free quark, Despite much effort, no proof of confinement has been produced. If such a proof were to be forthcoming, then, depending on one's viewpoint, the experimental search for free quarks would be either a complete waste of time, or would be of even greater significance. Our own opinion of this hypothetical situation is that, especially in view of assumptions that would almost inevitably be involved in any proof, the search should and would continue.

Most of the activity in this field has been in the lattice gauge theory approach, with either analytic [136] or Monte Carlo techniques [137] being employed. In order to investigate whether the quark–quark potential is confining, the overall size of the lattice should be much larger than a typical hadron, while the lattice spacing needs to be small (and eventually tend to zero in order to yield the continuum limit). As currently used lattices in Monte Carlo calculations have no more than 16 sites in each dimension, these inequalities are difficult to satisfy simultaneously.

Since gauge theories almost automatically result in confinement for strong coupling, the question is whether there is a deconfining phase transition with decreasing coupling constant as the continuum limit is approached. The present state of the art seems to be that by using these techniques, one can obtain "insight into" or "indications suggestive of" confinement*.

Several comprehensive reviews of this subject have appeared recently [138].

This is not the only approach to the question of confinement. Thus, within the context of perturbative QCD, Kamenshchik and Sveshnikov [139] have shown that a self-consistency condition in scattering theory leads to the result that there are no free quarks. Other suggestions can be found in refs. [202–204].

Clearly this is a field in which continued activity can be expected in the future.

* Two physicists working on confinement were asked to predict the result of a horse race involving N horses. The first did extensive analytic and Monte Carlo calculations, and came back months later with the solution to the problem, provided the horses were spherical. The second had found a unique solution, but only in the limit that $1/(N-1)$ tended to infinity.

6.2. Non-confinement

Within the conventional QCD approach, there is widespread agreement that, even if a theory has a confining phase at low temperatures and densities, at higher values there should be a transition to an unconfined quark–gluon plasma. This is generally calculated as occurring at a temperature in the neighbourhood of $\sim$200 MeV [19].

It is, however, by no means clear whether such a deconfined phase implies that one could observe free quarks. If we assume that, for example, a quark gluon plasma can be created in a heavy ion collision at a suitable energy, the unconfined quarks which can move freely in the hot central region must pass through cooler, low density regions before travelling any macroscopic distance; in these outer regions, the normal phase is expected to be a confined one, and so the quarks may well recombine to form colourless hadrons before they can be directly detected. Similar arguments could apply to quarks which had been produced in the early stages of the Universe.

We thus now turn to other ideas which have been suggested as means of escaping from confinement.

Following an idea of Gribov, Strikman [140] considers the possibility that the vacuum may screen the colour charge, but not the electric charge, of quarks. Then it may be possible to detect "white quarks", which are colourless but which possess fractional charge and baryon number. If the mass of the white up and down quarks were $\sim$4 GeV with the down quark being heavier than the up quark by $\sim$2 MeV, the free white down quark would be unstable with a lifetime of the order of ten seconds. It could, however, be stabilised when orbiting a heavy nucleus by the Coulomb binding. Strikman suggests that this may explain the observation of fractional charges in niobium, but not in the lower-Z iron.

It is possible that white antiquarks in matter would be absorbed by the process

$$\bar{q}_w + N \to (qq)_w + \pi ,$$

since Strikman feels that the white diquark $(qq)_w$ may be of similar mass to the white quark itself.

According to Strikman, a good place to look for white quarks is in a modified beam dump experiment. He expects them to escape from the target because (a) he estimates that their hadronic cross section is of order 10^{-3} times a typical hadronic one; (b) their large mass implies that their energy loss per collision is small; and (c) their energy loss due to ionisation is small, because of their charge being $\frac{1}{3}$.

The CHARM collaboration's searches for white quarks in hadronic and in neutrino interactions have been described in sections 2.2.3 and 2.3.2.2 respectively.

Although the one-gluon exchange contribution to the quark–antiquark force leads to a potential that rises linearly with their separation r, Arbuzov [141] claims that it is not impossible that the effect of multigluon exchange may make the potential fall off like $1/r$ at large enough r (see fig. 17). The lower limit that he sets on the height of the potential barrier (from the non-observation of quarks at PETRA, after allowing for quark masses and for the radiation of quarks and gluons) is only $\gtrsim$8 GeV. Combined with the slope of the quark potential as determined from the charmonium spectrum, this determines $r_0 \gtrsim 10^{-12}$ cm. This radius is taken to imply that the quark cross section with matter is $\gtrsim 6 \times 10^{-24}\,\text{cm}^2$.

Since an anomalon mean-free-path of $\sim$1.5 cm would imply a cross section of this order of magnitude, Arbuzov subscribes to the idea that anomalons contain free quarks (see, however, section 2.1.1).

He also suggests that if the Stanford estimate of the quark concentration in matter and if his assumptions of the quark–hadron cross section are correct, it may be possible to perform an experiment

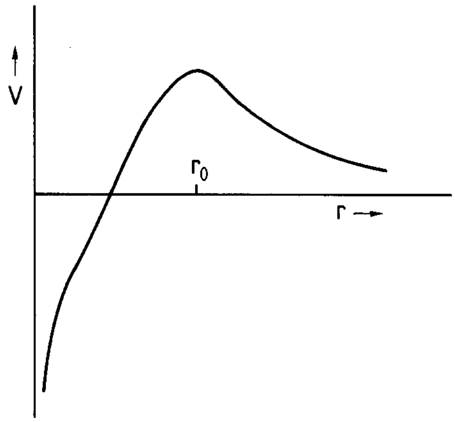


Fig. 17. The quark–quark potential, as assumed by Arbuzov [141]. At short distances it rises linearly, but then reaches a maximum at $r = r_0$, and at much larger distances falls like $1/r$.

in which pre-existing quarks are knocked out of a small target of dense material by an intense proton beam. Thus a 70 GeV beam of 10^{13} protons per second incident on a 2 cm target might yield 1 quark/day (which would have to be distinguished from the other $\sim 10^{18}$ reaction products), with a hoped-for increase in rate from the production of anomalons by the beam.

The possibility of colour SU(3) being broken to "glow" SO(3) has been suggested by Shaw and Slansky [43]. This would leave 3 gluons massless, but the other 5 acquire a mass μ, which is a measure of the $SU(3)_c$ breaking.

Quarks and gluons in this picture both carry glow. Observable particles are now glow singlets, and this includes a diquark system. Other glow singlets include qg and $qq\bar{q}$, but Shaw and Slansky think that these will be heavier than the diquark. If the difference in mass between the diquark and the qg system is less than the nucleon mass, then processes of the form

$$(\bar{q}\bar{q}) + N \rightarrow (qg)[+ \gamma s + \pi s]$$

are possible. Otherwise anti-diquarks would be stable in matter.

It is further suggested that diquark production in heavy ion reactions may be favoured as compared with either pp or e^+e^- interactions, since in the latter cases (a) the diquark form factor suppresses their production, and (b) for distances of separation larger than $1/\Lambda_{QCD}$ but smaller than $1/\mu$, the confinement mechanism of QCD will reorganise the system predominantly into colour singlets. This has provided the motivation for the experiments looking for fractional charge production with heavy ion beams at the Bevelac (see section 2.1.2). Their production at a reasonable rate requires the formation of a quark–gluon plasma, for which the Bevelac energy may be somewhat low; and for the parameter μ to be large enough* ($\sim$50–100 MeV) in order for the diquarks to be light ($\sim$1 GeV).

Okun and Shifman [142] have discussed models in which quarks can be unconfined because of a broken local colour symmetry. For the model of de Rujula et al. [62], they conclude that either assymptotic freedom would be violated in a way that would have been detectable by now, or else there

* In an earlier model of broken $SU(3)_c$, de Rujula, Giles and Jaffe [62] took $\mu < 15$ MeV. Shaw and Slansky, however, claim that the suppression factors that are operative in pp or in e^+e^- reactions for their own model result in a larger value of μ being possible.

should exist new fractionally charged hadron-like objects with masses around 1 GeV. They regard these as at best serious difficulties, and perhaps insuperable. The de Rujula approach had earlier been discussed by Bjorken [143] and by Georgi [144].

Some models keep quarks confined, but allow other objects to be fractionally charged and free. Thus, in order to reconcile the (possible) observations of fractional charge [87] and of a magnetic monopole [145], Barr et al. [153] suggest that there exists a new quantum number called peculiarity, and that the stable lowest mass peculiar particle has charge $\frac{1}{3}$. The expected level of peculiar matter in the Universe is also discussed.

Other possibilities include the extension of the Grand Unified group SU(5) to allow colour singlets of unusual charges [163]. Some models are also designed to accommodate both fractional charges and magnetic monopoles [157, 165, 171]. Thus Li and Wilczek [164] have considered SU(7), which can contain leptons of third-integral charge, and integrally charged quarks (which can combine with ordinary quarks to produce fractionally charged hadrons). They expect the new particles to be below a few hundred GeV in mass, and perhaps to be as light as ~40 GeV, in which case they could soon be produced in e^+e^- machines. The predicted value of $\sin^2\theta_w$ is too low, but could be adjusted to be in better agreement with experiment by a suitable form of symmetry breaking. Goldberg, Kephart and Vaughan [154] have also considered SU(7), and discuss the problems of this approach (the value of $\sin^2\theta_w$, the abundance of relic leptons, etc.). They too expect exciting new physics to appear in the 100–1000 GeV range. SU(7) is also the group used by Frampton and Kephart [155] in the context of supersymmetry. They overcome the problem of $\sin^2\theta_w$ being too small by the introduction of fractional charges, which they claim could be detected in stellar spectra, or be produced in collider experiments in the near future if their masses are in the 100 GeV region.

Yamamoto [156] investigates an SO(14) model which can accommodate fractionally charged leptons. Yu [165] considers SU(8), which contains quarks and leptons with a variety of fractional charges. The proton is chosen to be stable but other baryon and lepton non-conserving processes may take place. In Yu's model, fractional charges occur only accompanying 2 normal generations. Dong et al. [157] discuss SU(8) and SO(18). The latter is selected in order to accommodate 3 generations, magnetic monopoles and leptons of half-integral charge; it includes "peculiar" photons, whose experimental signatures are discussed. The SU(10) model of Kancheli and Chkareuli [163] predicts a second narrow Z^0 of mass below 87 GeV. They remark that the present abundance of the new leptons and/or hadrons could be consistent with observational limits if the expansion and temperature evolution of the Universe shortly after the Planck time were modified from the Big Bang predictions. They also suggest that centrifuging the Stanford spheres may succeed in dislodging the fractionally charged particles, if they are bound by ~1 eV and have masses above 10^{12} GeV. Wu and Li [158] discuss the abnormal families of particles that would be produced as a consequence of fractionally charged colour singlets.

Gupta and Kabir [159] also explain the possible observation of fractional charge in terms of either fractionally charged colourless particles without strong interactions, or by quarks with unusual (possibly integer) charge producing fractionally charged composite colourless hadrons.

6.3. Phenomenological suggestions

The cosmological consequences of fractionally charged leptons [154] have been investigated by Goldberg [160]. He considers the necessary mechanisms by which the predicted abundance could be reduced sufficiently to be consistent with current observations.

Wagnor, Schmitt and Zerwas [161] have studied the cosmological consequences of uncharged quarks (compare ref. [158]). They find that, within the context of the Big Bang model and of QCD, a cosmic abundance of $\gtrsim 7\times10^{-12}$ fractionally charged particles per nucleon would be required. Because of possible chemical and molecular effects for fractionally charged ions (see section 6.4), they do not consider such a limit to be inconsistent with current experiments. The production of such quarks at accelerators and by cosmic rays is also considered.

The production of fractional charge in the early Universe and by cosmic rays is also considered by Kolb et al. [162]. They use the broken SU(3) model of Slansky et al. [43], and assume that the scale breaking parameter μ is less than Λ_{QCD}. Because of their exponential dependence on the parameters of the model, the predicted abundances can range from enormous to insignificant.

The implications of heavy colour-sextet quarks of charge $\frac{1}{3}$ have been considered by Dover, Gaisser and Steigman [175]. Such quarks could be bound to a pair of ordinary antiquarks to produce colourless heavy hadrons H. The lightest of these, which they argue will be electrically neutral, could be stable, and bind with nuclei to produce heavy isotopes. This has motivated the search for such unusual nuclei, which are however neither fractionally charged nor coloured. The Dover et al. scenario is that, with the H abundance being due to $H\bar{H}$ production in the very early Universe and with the nucleon density being as observed (and $\sim10^{10}$ larger than that expected for nucleon pair production in a Universe with net baryon number zero), the H abundance per nucleus of mass A could be $\sim10^{-10}A$. (See, however, the experiments mentioned at the end of section 4.)

The suggested values for the lifetime of a proton [146] are such that the probability for the decay of a proton in the time since the Big Bang is not far from the estimate of the quark density per nucleon as derived from the Stanford experiments [87]. This has motivated Jones [147] to suggest that the observation of fractional charge may be due to proton decays leaving two nucleons with fractional charge by a process such as that shown in fig. 18. Jones correctly remarks that such an explanation still requires confirmation of the existence of both proton decay and free fractional charges.

Orear [148] investigates the possibility that some free quarks were left over from the Big Bang. If the u quark is the lightest and only colour singlet combinations are confined, then within ~1 hr of the Big Bang, the quark content of the Universe consists of ū bound electromagnetically to helium nuclei, and of free u quarks.

Orear goes on to suggest that the quarks within the earth would consist of such a mixture, together with less than 1% of negative quarks orbiting heavier nuclei (which came from supernovae). This would be of relevance to experiments that set out to search for quarks in matter. He emphasises that the chemical refining processes almost always involved in the production of a pure sample are very likely to

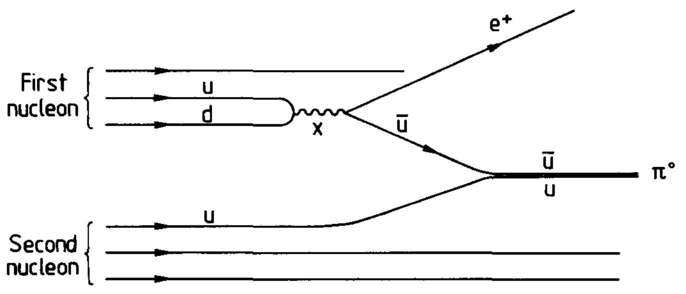


Fig. 18. Process suggested by Jones [147] as being responsible for proton decay. The ū from X-decay combines to form a pion with a u quark from a second nucleon, rather than with the remaining quark from the original nucleon. With such a mechanism, hydrogen would not undergo nucleon decay, but heavier nuclei would.

have removed any quarks that may have accumulated there. He finally suggests that the hydrogen-like properties of small quarked atoms and the large affinity for hydrogen of tungsten and more especially of niobium could explain the fractional charge signal seen by Fairbank et al. and that the observed changes in charge could be due to the fact that the balls heat treated on tungsten initially contained several quarks*, and can lose one or more between measurements.

Schiffer [149] has noted that a charge $+\frac{1}{3}$ quark would be bound electromagnetically to an electron by only ~1.5 eV, and to nothing else more strongly. He surmises that such a quark–electron structure may be able to diffuse readily through matter, and hence may be attached to matter rather weakly and only at low temperatures. This may then explain why the Stanford low temperature experiment detected fractional charges (which changed fairly often between measurements), while room temperature experiments did not. Schiffer also remarks that the excess of $+\frac{1}{3}$ residual charge measurements compared with $-\frac{1}{3}$ is consistent with more of the balls containing a single charge $\frac{1}{3}$ quark than those containing 2 such objects (which would give an apparent residual charge of $-\frac{1}{3}$). Since his previous search [150] for charge $+\frac{1}{3}$ quarks was a high temperature experiment, he pointed out the need to seek confirmation of the Stanford results in a new low temperature experiment. This he has now done [109], without finding any evidence for fractional charges (see section 4).

6.4. Quark chemistry

Lackner and Zweig [151] have embarked on an ambitious programme of predicting the chemical properties of atoms containing quarks (either bound by strong interactions to the nucleus, or circling it in a very small Bohr orbit). The initial phase consists of calculating electronegativities, co-ordination numbers and radii of such quarked atoms. This they do largely by interpolating from the known properties of sequences of different normal ions but with the same number of electrons as the quarked atom in question. This enables them to find analogues from among ordinary ions for specific quarked ones. The ultimate aims of such an approach are to suggest where quarked atoms may be found, to have a better appreciation of enrichment procedures used for concentrating quarks (and conversely of processes which are likely to deplete the tested sample of any quarks that may have been there), and to find ways of isolating quarked atoms. They comment that such ideas could be tested by comparing their similar predictions concerning non-quarked atoms.

Two examples should illustrate this approach. They claim that a quarked atom consisting of a proton-plus-a-quark nucleus and an electron should resemble a fluorine ion from the viewpoint of ionic radius and co-ordination number, and is even more electronegative than fluorine. They could thus well substitute fluorine ions in a suitable crystal lattice. Secondly, this quarked atom could perhaps bind to xenon, which is known to react only with the most electronegative substances. This selectivity could form the basis of a quark enrichment process.

Their studies to date lead them to criticise several previous quark search experiments (as well as some earlier reviews). Thus they comment that any quarked atoms in gases or in non-polar liquids are likely to be attracted to the walls of the containing vessel; they would be bound to molecules of polar liquids so that attempts to evaporate them would fail; they are likely to be swept out of the atmosphere by the electric fields there; and many substances used in quark search experiments may well have had their quarks removed by either geochemical or by technological purification processes.

* This would require there to be almost equal probabilities for the balls having residual charges of 0, $+\frac{1}{3}$ or $-\frac{1}{3}$. Schiffer [149], however, wanted more $\frac{1}{3}$ than $-\frac{1}{3}$. Morgan and Barnhill also note that the Stanford data are consistent with a large number of fractional charges per ball [170].

Like Orear, they suggest that most of the quark remnants of the Big Bang are likely to be bound to light nuclei, while some may be found among heavier nuclei which have resulted from nucleosynthesis in stars.

Based on their investigation of quark chemistry, they have made several specific suggestions concerning which materials should be subjected to future searches for quarks.

Schaad et al. [152] also point out that a knowledge of where to search for free quarks would be helped by an understanding of quark chemistry. They have thus investigated the properties of molecules made of atoms containing bound quarks (and give a list of references to earlier such studies). Over the lifetime of the Universe, it is possible that such quarked atoms would have come together to form neutral molecules, although the approach to equilibrium could be very slow.

The nuclear chemistry of isotopes containing integrally charged heavy particles has been discussed by Cahn and Glashow [178]. They concentrate on approaches that could be used for identifying them.

7. Conclusions

We have seen that there has been continued activity in the search for quarks at accelerators. This has included the new field of heavy ion reactions. Such experiments have shown that anomalons, if they exist, do not appear to be fractionally charged. Another experiment has been motivated by the suggestion that diquark production via the formation of a quark gluon plasma may be enhanced in heavy ion reactions. Such a search would probably benefit from increased energy.

The centre-of-mass energy range investigated in hadronic reactions has been increased by a factor of 10; unfortunately the possible mass range studied and the experiment's sensitivity were both low, and there are no plans for further running.

A muon deep inelastic scattering experiment has provided good upper limits on quark production, but the largest number of new experiments have involved e^+e^- annihilations. Limits have been provided for the inclusive production of quarks of charges from $\frac{1}{3}$ to $\frac{5}{3}$, for the exclusive production of charges $\frac{1}{3}$ or $\frac{2}{3}$, and for quarks with very large interaction cross sections. Again no evidence exists.

In experiments involving cosmic rays, direct searches have found no evidence for fractional charge. The other experiments in this field have involved looking for heavy particles, which may (or may not) be quarks. The Auckland results on slow particles are not yet conclusive. The situation concerning delayed particles in extensive air showers appears to be confusing – even when different experiments appear to be similar insofar as their results are concerned, their conclusions can be very different. It would be desirable to have a higher degree of redundancy in the information from the typical experimental arrangements involved in this type of work, in order to exclude various possible backgrounds. The role of fluctuations in the measurements is also not clear.

Unusual phenomena in cosmic rays have been collated by McCusker, who has interpreted them in terms of a quark or quark glob flux of $\sim 10^{-11}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}$. In most cases, however, it is not clear what is the nature of the incident particle initiating the phenomenon (or in some cases even whether the effect may not be an experimental quirk rather than a physical quark).

Thus there is still no evidence for the production of free quarks at accelerators, nor for their existence in or production by cosmic rays.

Recent searches in stable matter also have provided only upper limits on possible quark densities. Because of the lack of any new data from Stanford, the excitement generated by their original results has dwindled.

On the theoretical side, popular opinion is for quarks being confined at normal temperatures and densities, but forming a quark–gluon plasma under conditions such as prevailed in the early Universe, or perhaps may be attainable in heavy ion collisions at higher energies. There exists, however, no proof of confinement, and even if there were such a demonstration, it is not clear that it would affect the experimental search for quarks.

Because of the prejudice in favour of confinement, there has been speculation that, if the fractional charge effect observed by the Stanford group is real, it may be due to colour singlet objects rather than quarks.

Other calculations involve the production of quarks in the early Universe and their expected current abundances. A start has also been made on calculating the chemical and molecular properties of quarked atoms, which should be useful for designing quark search experiments in stable matter.

Our final conclusion is that the race between experimentalists endeavouring to discover a free quark and theoreticians intent on demonstrating that this is impossible is still very much open.

Acknowledgements

I would like to thank everyone who has provided me with their latest results, and to those experimentalists and theoreticians who have communicated with me concerning their work. I am particularly indebted to John Barrow, Paul Frampton, John Lloyd, Nigel Parsons and Peter Smith for advice and comments concerning various parts of this review, and to Daphne Pollard for her accurate and efficient typing.

Note added in proof (July 1985)

We here make brief mention of some recent results that have appeared since the main text of this article was written.

The UA2 collaboration [193] has now analysed the data collected during 1982, which corresponded to an integrated luminosity of some 2 orders of magnitude larger than for their 1981 run, reported in the text (see section 2.2.1). Their quark telescope was augmented by 3 further sets of scintillators, 2 of which could be incorporated in their ionisation estimating algorithm. The method of analysis is similar to that described for their earlier data. No tracks surviving the trigger and off-line selection criteria were observed with ionisations below $0.7I_0$.

Again limits are presented on the ratio of quark production to that for unit charged particles. As before, these apply to quarks of mass below 3 GeV, of normal hadronic interaction cross section, and unaccompanied by other tracks in the quark telescope. The improvement in sensitivity as compared with the earlier data is about 2 orders of magnitude for quarks of charge $\frac{1}{3}$, but less than a factor of 4 for charge $\frac{2}{3}$.

Penetrating neutral or integrally charged particles have been looked for by the NA3 collaboration [195], using a 300 GeV/c π^- beam incident on a beam dump. Two-body decays to identified pairs of particles (including electrons, muons, K^0 and Λ^0, as well as the usual $\pi^\pm$, $K^\pm$ and $p^\pm$) were investigated in the mass range from 1 to 5 GeV, and no signals were seen. The limits on σB, the production cross section per nucleon times the branching ratio for the given decay mode, are in the range 1 pb to 1 nb for lifetimes 10^{-10} to 10^{-6} s. The sensitivity of the experiment is reduced by a factor of 3500, however, if the sought-for particles have interaction cross sections of 5 mb/nucleon.

The OLYA detector [187] has been used at the VEPP-2M collider to search for the exclusive production of charge $\frac{2}{3}$ quark pairs, at centre-of-mass energies in the range 1 to 1.4 GeV. The pulse heights of each track in collinear events were recorded in three scintillators; none of the 10^5 observed events had the sum of the average pulse heights below $1.6I_0$. The resulting limit on R is $<10^{-4}$ for quark masses below 350 MeV. Any absorption of quarks in the detector, whose thickness up to the last trigger counter was 0.14 of a hadronic absorption length, was ignored.

The ARGUS collaboration [194] has performed a search for the inclusive production of free quarks in e^+e^- annihilations in the upsilon region (i.e. at centre-of-mass energies of around 10 GeV). Their detector contains a cylindrical drift chamber in a 0.7 T magnetic field. With an integrated luminosity of 84.5 events/pb, they have studied 0.7 million events with ≥ 3 detected prongs, and 0.9 million 2 prong events; the latter had survived a series of cuts to suppress the number of elastic scatters.

As with the Jade and TPC experiments, potential quark tracks were selected according to their measured energy loss dE/dx and apparent momentum. Candidates were required to have dE/dx either below that of an electron, or above that for a particle of 1.4 GeV mass and of unit charge. In the large dE/dx region, only negative tracks were accepted, in order to remove background from beam-gas and beam-wall interactions. The numbers of tracks satisfying these criteria for the dE/dx regions were zero and 25, respectively. The latter were interpreted as containing 6 antideuterons; 18 examples of $e^+e^- \to e^+e^-\gamma$, $\gamma \to e^+e^-$ with the two electrons unresolved in the detector; and 1 example of overlapping hadrons.

The calculation of the efficiency of quark detection includes consideration of the trigger, the apparatus geometry, track reconstruction and selection criteria. The Monte Carlo calculation of efficiency makes use of the 2 usual production assumptions concerning the quarks, and yields limits on R as shown in table 7.

Price [189] has reinterpreted his previous exposures [190] of CR-39 plastic track detectors to cosmic rays in order to provide a limit of $<10^{-13}\,\mathrm{cm^{-2}\,sr^{-1}\,s^{-1}}$ for the flux of charged particles X^+or X^- with velocities in the range $3\times10^{-5}c$ to $0.05c$. The masses of such particles would be greater than 2×10^5 GeV, in order to penetrate the atmosphere.

The Japanese experiment referred to in section 3.2 has now run for 5200 h [196], looking for charge $\frac{1}{2}$ or $\frac{2}{3}$ relativistic particles. The upper limits set on their fluxes are 8×10^{-13} and $10^{-12}\,\mathrm{cm^{-2}\,sr^{-1}\,s^{-1}}$, respectively; the latter improved by a factor of 2 their previous limit [65]. The number of apparently upward particles is now 31.

The results of the Maryland experiment referred to in section 3.4.4 have now been published [200]. Their detector contains calorimeter modules, each with at least 4 layers of scintillators, separated by mainly iron shielding. During 9266 h running, none of their large pulse height/large delay events produced a signal in the lowest layer of scintillators, which is shielded by ~50 cm of iron. If the events were due to energetic delayed particles (which would then have to be heavy), a significant fraction

Table 7
Summary of ARGUS limits on inclusive quark production.

Quark charge		1/3	2/3	4/3
Production mechanism				
$E\dfrac{d^3\sigma}{dp^3} \sim \text{const}$	Mass (GeV)	1–4	0.1–4	0.1–4
	R	$<2\times10^{-2}$–6×10^{-4}	$<6\times10^{-5}$–9×10^{-4}	$<7\times10^{-5}$–10^{-4}
$E\dfrac{d^3\sigma}{dp^3} \sim e^{-3.5E}$	Mass (GeV)	0.4–4	0.1–4	0.1–4
	R	$<4\times10^{-3}$–10^{-4}	$<3\times10^{-5}$–2×10^{-4}	$<3\times10^{-3}$–8×10^{-5}

would have been expected to penetrate to the lowest scintillators. This supports their suggestion, based on Monte Carlo calculations incorporating experimentally determined cascade fluctuations, that the apparently large energy delayed events observed in experiments of this type (see, for example, the next paragraph) arise from pulse height fluctuations from low energy conventional hadrons, rather than being the signature of new particles. The limit they set on heavy, long-lived particles is $1.4 \times 10^{-12}\,\mathrm{cm^{-2}\,sr^{-1}\,s^{-1}}$.

Meanwhile, an experiment with the Kobe EAS array [205] has looked at the pulse profiles in arrival time of EAS particles in 2 to 4 scintillators. During 3647 h running, 6162 showers were collected, including 4 classified as "delayed subshowers", characterised by double-peaked profiles with the secondary peak delays being consistent in 2 or 3 of the scintillators. Yoshida et al. discuss these in terms of a heavy incident particle.

Whereas delayed air shower experiments tend to claim the need for new heavy particles, a possible signal for a new light particle comes from recent cosmic ray data. The Soudan I [206] and NUSEX [207] proton decay experiments both report an enhancement in the flux of muons from the general direction of Cygnus X-3, and which have a phase $\phi \sim 1.5\pi$ with respect to the minimum of the X-ray signal in the Cygnus binary cycle period of 4.8 h. (This is, however, not yet confirmed by the IMB [211], Frejus [208] or Harvard–Pennsylvania–Wisconsin [209] groups.) The effects are claimed to be significant at the $\sim 10^{-4}$ confidence level. These numbers, however, refer to the probability of the null hypothesis that the *one* histogram shown is consistent with being flat; both experiments, however, have optimised their angular acceptance region in order to maximise the effect. Soudan I thus uses a cone of 3° half-angle, centred about 3° away from Cygnus, while NUSEX has an angular aperture of $10° \times 10°$, as compared with their angular resolution of $\lesssim 1°$.

It is thus by no means clear that the effect is real. If it is, then several features of the incident particles producing the observed muons follow [210]: they must be neutral, energetic, long-lived and are probably light (less than a few GeV). Of the conventional particles, photons and neutrons are almost certainly ruled out, and probably neutrinos as well. One suggestion is that hadrons with a relatively high strange quark content (e.g. a $\Lambda\Lambda$ bound state) could be responsible. Other possibilities include light neutral quarks or statistical fluctuations.

Turkevich et al. [188] have looked for superheavy isotopes of the type suggested by Cahn and Glashow [178]. In particular, they have searched for X^- particles of mass below 10^5 GeV, bound to nitrogen nuclei, which would thus resemble heavy carbon nuclei. Their approach is to use the reaction

$$n + (N^{14}X^-) \to p + (C^{14}X^-)$$

and then to look for the expected β decay of $(C^{14}X^-)$, which chemically resembles boron. A 30 gram graphite sample irradiated by neutrons in a reactor over a period of 4–5 yr, and then treated by radiochemical techniques to extract boron-like material, gave a count rate of <0.01/min above background. This in turn yielded a limit of $<2 \times 10^{-15}$ X^- particles per nucleon, subject to the assumptions made about nuclear and chemical properties of any such superheavy isotope.

Ion beams sputtered from niobium and from tungsten samples were examined for fractional charge by a group from Cal Tech, who used an all electrostatic acceleration and deflection system [197]. Background from integrally charged particles was reduced by using a stripper to convert the original negative ions to positive ones; this is the technique already described in section 5 for the Toronto experimental arrangement.

The experiment was sensitive to fractionally charged particles, of charge $\frac{2}{3}$, $\frac{5}{3}$ or $N + \frac{1}{3}$ (where N is an integer). Ions emerging from the apparatus had their energy losses and their energies measured in a gas ionisation chamber and in a silicon surface barrier detector respectively. Charges of ions are determined from their trajectories in the electrostatic system (which depend on their energy divided by their charge) and their energies.

For each source material, separate searches were made, corresponding to various fractional charges and to different assumptions about their ability to form the relevant ions. No positive signals were seen, corresponding to limits of the order of 10^{-19} fractional charges per nucleon in niobium, and about an order of magnitude larger in tungsten. These limits are dependent on the estimates of transmission efficiencies and the sputter rates of fractionally charged ions, which are thought to be reliable to within a factor of about 2.

The Rutherford Laboratory group (see section 5) has now looked for fractional charges on 46 niobium spheres of 280 μm diameter, coated with a 10 μm layer of iron [198]. None of the accepted measurements was consistent with third-integral residual charge (although a couple, rejected for other reasons, were), leading to an upper limit of $<10^{-21}$ quarks per nucleon at the 95% confidence level. The sensitivity of this experiment is greater than that of the Stanford one. The main differences are in the treatment of the niobium balls before measurement, and the nature of the levitation techniques.

Additional suggestions for fractionally charged particles have been made by Wu and Li [191], using $SO(10) \times SO(5)$; with an SU(7) model by Park et al. [192]; and in the context of superstrings by Wen and Witten [201], whose fractionally charged colourless particles are expected to be of about the Planck mass.

Our conclusion remains, perhaps even somewhat strengthened, that we are still awaiting convincing evidence for the existence of free quarks.

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