A review of quark search experiments

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All of the experimental evidence for and against the existence of free, physical quarks from cosmic rays, particle accelerators, and stable matter is reviewed. There is no evidence for the existence of free quarks of fractional charge save for one recent report of niobium pellets of third-integral residual charge. The related searches for quarks of integral charge, for free magnetic monopoles, tachyons, dyons, and other postulated, stable elementary objects are also reviewed. Although some puzzling observations are noted, there is no firm evidence for any of these particles.

CONTENTS

I. INTRODUCTION

Physics research for almost two centuries has been probing progressively deeper into the structure of matter in order to seek at every stage the constituents of each previously "fundamental" entity. Thus a sequence proceeding from crystals through molecules, atoms, and nuclei to nucleons and mesons has been revealed. The energies required to dissociate each entity increase from thermal energies to GeV in proceeding from crystals to mesons. It is therefore only a logical extrapolation of past patterns to expect that hadrons—mesons and baryons—might be dissociated into more fundamental constituents if subjected to a sufficiently high energy. This vague prediction may have been insufficient as a basis for mounting an experimental search for constituents, but it may be responsible in large measure for the fertile ground on which the notion of quarks fell.

There were at least three factors which made a quark model plausible in the 1960s. First, the classic electron-proton elastic scattering experiments demonstrated that a proton has a finite form factor. Nonrelativistically, this is equivalent to a finite radial extent of the electric charge and magnetic moment distributions. It was plausible that the charge cloud which constitutes a proton is a probability distribution of some smaller, perhaps pointlike constituents, just as the charge cloud of an atom was learned to be a probability distribution of point electrons.

Second, the evolution in the late 1950s and early 1960s of hadron spectroscopy revealed an order and symmetry among the states of hadronic matter that could be interpreted in terms of representations of the SU(3) symmetry group. This in turn was interpreted by M. Gell-Mann, and independently by G. Zweig, as a consequence of the grouping of elementary constituents of fractional electric charge, christened "quarks" by Gell-Mann, in pairs and triplets to form the observed hadrons (Gell-Mann, 1964; Zweig, 1964). The general features of the quark model of hadrons have withstood the tests of time, and many of the static properties of hadrons are consistent with predictions of this model.

Third, the deep-inelastic scattering of electrons on protons revealed form factors corresponding to pointlike constituents of the proton. This is altogether consistent with the interpretation of the finite proton elastic form factor suggested above, in analogy to atomic electrons. J. D. Bjorken referred to these proton constituents as "partons" although from the beginning it was recognized that "partons" and "quarks" might be merely different manifestations of the same entities. R. P. Feynman also invoked the parton notion of proton structure to explain the scaling of inclusive secondary particle (pion) distributions in high-energy proton–proton collisions. The experimental search for quarks began with Gell-Mann's and Zweig's quark models in 1964 as a result of the explicit prediction of constituents of fractional charge. While no comprehensive review of the many theoretical quark models will be attempted here, it is useful to record the quantum numbers of the "classical" quarks. This basic quark set has been embellished subsequently in two important ways.

First, because quarks may be fermions (spin 1/2) but combine in identical states in some hadrons in violation of Fermi–Dirac statistics, it was necessary either to endow them with special statistical rules ("parastatistics") or to add another quantum number which may as-

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sume any one of three values to permit retention of conventional Fermi statistics. This new quantum number is the "color" quantum number, and there now may be at least three forms of each of the fundamental quarks—red, white, and blue varieties of u, d, and s quarks.

Second, physicists now add another quark, the "charmed" quark, to the list. The concept of charm was originally proposed to provide a mechanism (through cancellations) to inhibit the $K_L^\circ \to \mu^+\mu^-$ decay and other processes involving a change in strangeness with no charge change (Bjorken and Glashow, 1964; Glashow, Iliopoulos, and Maiani, 1970). The recent discoveries of massive, relatively long-lived particles, the ψ or J particles, has greatly stimulated enthusiasm for the concept of charm, as the most successful model for these particles considers them as states of the charmed quark–antiquark system, just as the φ is considered as $q_s\,\overline{q}_s$ state (Aubert *et al.*, 1974; Augustin *et al.*, 1974). More recent experiments have identified meson and baryon resonances having the theoretically predicted properties of hadrons containing charm (Goldhaber, 1976; Knapp, 1976). A postulated set of quark properties is reproduced in Table I.

While the fractional-charged quark model is appealing, it is not unique; Han and Nambu (1965) have proposed a scheme with integrally charged quarks which may also provide a self-consistent constituent model for fundamental particles. It is perhaps less widely accepted than the fractional-charge scheme, and quarks of integral charge would be more difficult to identify experimentally if they did exist as stable particles. Further, it is possible that, if massive, they would quickly decay to lighter hadrons. Quarks of fractional charge, on the other hand, would retain that signature by charge conservation until a rare chance encounter with another quark. On the other hand, if quarks of integral charge have fractional baryon number, again they may be stable (to the extent that baryon number is conserved). Both the Han-Nambu model, which proposed three sets to triplets (before the advent of the charm concept) and the somewhat related SUB model (Cabibbo, Maiani, and Preparata, 1967) in fact incorporated baryon number of $\frac{1}{3}$ as ingredients (Pati and Woo, 1971). In a later paper, Pati and Salam (1974) suggest that integral-charge quarks might exist but decay through second-order weak

TABLE I. Quark model: Quantum number assignments for four quarks of fractional charge.

Quarks symbol		u	d	s	c
Baryon number	B	1/3	1/3	1/3	1/3
Electric charge (in units of the proton charge)	q	2/3	−1/3	−1/3	2/3
Hypercharge	Y	1/3	1/3	−2/3	0
Isotopic spin	I	1/2	1/2	0	0
Third component of isotopic spin	I_3	1/2	−1/2	0	0
Strangeness	S	0	0	−1	0
Charm	C	0	0	0	1

processes, so that their lifetimes could be as long as 10^{-6} sec. An early appeal of the original quark model was its essential simplicity; only three fundamental entities were required. Now, with three colors and four "flavors" of quarks indicated, there are 12 fundamental entities, and simplicity is not an *a priori* virtue of the fractional-charge model over the Han-Nambu and related models.

Early searches for quarks were based on the assumptions that (1) they had fractional electric charge ($q = \pm 1/3, \pm 2/3$, (2) they were heavier than a nucleon, and (3) they could be produced if sufficient energy were provided either to dissociate an energetic hadron into its quark constituents or to produce them in pairs. The assumption that they were massive, perhaps several times the nucleon mass, seems to have been based on two considerations; first, that the mass splittings among members of observed multiplets could be understood as a perturbation on the very large quark-quark binding energy, and (more relevant) that they had not been previously detected.

It is not the purpose of this paper to review or even discuss the multitude of quark and quark–parton models that have flooded the literature in recent years. Nor will the arguments for the existence or nonexistence of physical quarks be discussed. Suffice it to say that wise men differ here; some feel that if the quark model is valid, quarks must exist as physical objects; others just as vigorously argue that they may be perfectly valid mathematical objects but be unobservable physically. As search experiments with negative results have multiplied, the latter point of view has gained popularity, and with it, the "mass" of these now virtual "u" and "d" quarks has been allowed to fall below a proton mass, with about 0.3 GeV/c^2 now a popular value (Drell and Johnson, 1972). Even though such a mass is a best fit for the characteristics of quarks bound in nucleons or mesons, it should be recalled that free quarks could in principle be much heavier, with the difference between free and bound masses equal to a large binding energy. It is currently popular to presume that quarks are real and light, but are bound by a force which increases with distance indefinitely, so that the physical isolation of quarks is impossible.

The purpose of this paper is to review the experiments and experimental data relating to the existence of physical quarks. Previous reviews have been published (Massam, 1968; Jones, 1970; Jones, 1971; Adair, 1972; Jones, 1973; Kim, 1973; Snow, 1974), and many of the experimental papers summarized previous searches in their respective domains. A brief summary also appears in the annual Review of Particle Properties by the Particle Data Group (Trippe *et al.*, 1976). In this paper "quark" is taken to include any particle which may be a constituent of known hadrons and is stable, i.e., with a lifetime greater than ~10^{-7} seconds. Besides quarks of fractional charge, the limits on massive quarks of integral charge are also discussed. To the extent that experimental data exist, dyons and other possible constituents are also noted (Schwinger, 1975; Yock, 1976). A particularly interesting set of papers is referenced on the searches for magnetic monopoles, but the subject is somewhat peripheral to the quark discussion and little space is devoted to it here.

Quark searches have been made among cosmic rays, with particle accelerators, and in stable matter. The most difficult task in relating these searches to one another and to the question of the possible existence of physical quarks is the relationship between quark mass and production cross section.

II. ASSUMPTIONS, KINEMATICS, AND MODELS

A. Kinematics of quark production

If quarks of fractional charge exist, they would be produced most probably in either of two ways: diffraction dissociation or pair production. In diffraction dissociation a hadron, for example a proton (the highest-energy hadron available in quantity, either from cosmic rays or from particle accelerators), incident on a target might be sufficiently excited to be broken into its constituents. If the proton mass is m_p and each quark mass is m_q, the binding energy of the quarks in the proton is

$$E_B = 3m_q - m_p . \tag{2.1}$$

(Here and throughout we will use units where $c=1$ and where energy, momentum, and mass are expressed in GeV).

If, in the collision of two protons, this binding energy is to be made available, then the total c.m. energy must be given by

$$E_{\text{c.m.}} \geq E_B + 2m_p = 3m_q + m_p . \tag{2.2}$$

In colliding beams, this is just twice the total energy in either of two protons of equal energy colliding head-on. For a proton incident on a stationary proton target, the required incident laboratory energy threshold is given by

$$E_L \geq (E^2_{\text{c.m.}}/2m_p) - m_p ; \tag{2.3}$$

$$E_L \geq \frac{(3m_q + m_p)^2}{2m_p} - m_p . \tag{2.4}$$

Actually, diffraction dissociation in hadronic processes is characterized by a cross section falling as exp (Bt) where $B \approx 10\ \text{GeV}^{-2}$, for reactions on protons. Depending on the mass change in the diffracted object, there is a minimum value of $|t|$ which is required kinematically. For this problem, in the limit where the incident energy is far above threshold,

$$E_L \approx \frac{(3m_q)^2 - m_p^2}{2|t|_{\min}} \tag{2.5}$$

For $|t| = 0.1$,

$$E_L \approx \frac{(3m_q)^2 - m_p^2}{2\times 0.316} . \tag{2.6}$$

The kinematic approximations here are violated as E_L approaches the kinematic limit of Eq. (2.4). In any case, close to threshold the minimum $|t|$ becomes relatively large and cross section for such dissociation would be expected to be quite small. However, far above threshold where $|t|_{\min}$ becomes quite small, this process could contribute.

A lower threshold energy would be relevant if quarks were more massive than nucleons and were produced in pairs, as are antinucleons with nucleons, electrons with positrons, etc. The c.m. and laboratory threshold energies for quark pair production in proton–proton interactions are given by

$$E_{\text{c.m.}} \geq 2m_q + 2m_p , \tag{2.7}$$

$$E_L \geq 2m_p \left(1 + \frac{m_q}{m_p}\right)^2 . \tag{2.8}$$

The same kinematic threshold pertains to a diffraction dissociation process wherein a proton would be dissociated into a proton and a quark pair, although the implied dynamics are different.

When a proton collides with a complex nucleus, the threshold energy for a given production process may be lower than for the corresponding free-proton collision. This may be considered either from the point of view of the Fermi momentum of the target nucleon or of the greater mass of the target. The dependence on energy of some numerical value of threshold cross section is found from the Fermi momentum distribution, while the ultimate kinematic limit is set by the mass of the target nucleus.

The Fermi momentum of a nucleon in a nucleus may be approximated by a momentum wave function of the form

$$\varphi(p) \cong \exp - (p/0.15)^2 .$$

The available center-of-mass energy between an energetic proton of energy E_L, momentum p_L and a nucleon with a colinear Fermi momentum p_z is given by

$$E^2_{\text{c.m.}} \cong 2p_L(m_p \mp p_z) + 2m_p^2 , \tag{2.9}$$

for $p_z \ll m_p$, and where the $\mp$ p_z refers to the relative directions of p_z and p_L. Hence, a component of Fermi momentum equaling $0.2\,m_p$ may increase $E_{\text{c.m.}}$ by about 10% or correspond to a 20% greater E_L colliding with a stationary nucleon. The exponential tail of the Fermi momentum distribution leads to a production cross section which falls exponentially with energy above that corresponding to a stationary target nucleon energy for a particular process. The relevance of this effect was demonstrated in experiments on the production of antiprotons and antideuterons versus energy by the Columbia group (Dorfan *et al.*, 1965a; 1965c).

It is useful to recall here some relationships between the various forms of cross section expressed by different authors. The cosmic-ray measurements which set limits on quark flux over broad ranges of momentum are sensitive to the total quark production cross section σ_q, or more accurately the cross section integrated over the primary cosmic-ray spectrum. Cascading within the atmosphere may add slightly to quark production, but due to the steeply falling primary spectrum, this is only an increase of 20% and is ignored here. Accelerator experiments on the other hand generally detect particles in a beam of average momentum p, solid angle $d\Omega$, and momentum interval dp. They thus determine directly limits on

$$d^2\sigma/d\Omega\,dp .$$

The most useful relativistic invariant is

$$Ed^3\sigma/dp^3.$$

The momentum is generally close to the direction of the incident particle, with $p_\perp \ll p$ so that

$$E\frac{d^3\sigma}{dp^3}=\frac{E}{p^2}\;\frac{d^3\sigma}{dp\,d\Omega}\cong\frac{d^3\sigma}{p\,dp\,d\Omega} \tag{2.10}$$

The Feynman x variable may also be used, where $x = (p/p_{\max})_{\rm c.m.}$. Then, in terms of p_T, x, and the c.m. energy of the produced particle,

$$E\frac{d^3\sigma}{dp^3}=\frac{E_{\rm c.m.}}{\pi(p_{\max}\;{\rm c.m.})}\frac{d^2\sigma}{dx dp_\perp^2}\quad . \tag{2.11}$$

This latter expression is most generally useful for expressing production parametrizations.

B. Production models

As it is uncertain whether quarks can exist as free particles, it is even less certain how they would interact, and less certain yet how to calculate the production cross sections. Consequently, all production models must be taken very lightly. Nevertheless, it is useful to develop a framework for discussion of experiments in order to interrelate quark searches using very different techniques. In the absence of better assumptions, it is usually assumed that quark behavior is similar to that of other hadrons, and that their interaction mean free path, for example, is the same as that for nucleons.

Adair and Price (1966) have proposed a useful, if somewhat arbitrary, model for estimating possible quark production. For lower-energy production of pions, kaons, and nucleons, they observe that the production cross section well above threshold may be approximately represented by

$$\sigma_q=\pi a_q^2, \tag{2.12}$$

with

$$a_q=\hbar/m_q. \tag{2.13}$$

Pal and Tandon (1965) independently proposed the same cross section dependence. To provide a smooth cross section rise between a threshold and a higher energy, possibly asymptotic value, Adair and Price propose as a recipe:

$$\sigma_q=\sigma_q^\circ\left(\left(\frac{E}{3E_t}\right)-\frac{1}{3}\right)^2,\ \text{for } E_t<E<4E_t, \tag{2.14}$$

$$\sigma_q=\sigma_q^\circ \text{ for } E>4E_t,$$

where $\sigma_q^\circ=\pi(\hbar/m_q)^2$, and E_t is the laboratory threshold energy of an incident hadron on a stationary hadron target. For quark masses of 5 and 10 GeV, the values of σ° are about 5×10^{-29} and 1.25×10^{-29} cm^2 in their flux calculations.

When quarks or any other particles are produced rarely in nucleon-nucleon collisions, the relevant quantity is often not σ_q but the production probability, e.g., the ratio of the production cross section to the total nucleon-nucleon inelastic cross section. At high energies, σ_{NN}(inelastic)$\sim$33mb and is probably nearly constant (a logarithmic rise is not consequential in the range of parameters and uncertainties here). Thus, defining

$$p_q=\sigma_q/\sigma_{NN}(\text{inel}), \tag{2.15}$$

the production probabilities for 5 and 10 GeV mass quarks would be 1.5×10^{-3} and 3.75×10^{-4}, respectively.

Chilton, Horn, and Jabbur (1966) have made a calculation based on an absorptive peripheral model and obtain cross sections for the process $N+N\to N+N+q+\bar{q}$ of 1 to 7×10^{-30}cm^2 for quark masses from 6 to 12 GeV/c^2 (respectively) at high energies (500–1000 GeV).

A different model altogether results from the statistical and thermodynamic approaches to particle production. Here the assumption is that a "fireball" of hadronic matter is heated to an asymptotic temperature of 160 MeV and that hadrons boil off from the fireball. These models give, for incident energies well above threshold, cross sections of the form

$$\sigma_q\propto\exp(-2m_q/T_0) \tag{2.16}$$

for pair-produced quarks, where T_0 is an asymptotic temperature of about 0.160 GeV. The exponential falloff of production cross sections with quark mass is more severe than any other model, amounting to over 5 decades per GeV increase in mass. Hagedorn (1968) and Maksimenko (Maksimenko *et al.*, 1966) have made statistical calculations of expected yields as functions of mass; their predictions, normalized to an antiproton cross section of 1 mb, have fit production data of antihyperons and antideuterons satisfactorily. Hagedorn has dealt explicitly with the quark production question (Hagedorn, 1968) and pointed out that under some circumstances the mass dependence of the cross section might approach exp $(-m/T_0)$ well above threshold, even for pair-produced quarks. The energy dependence of the production cross section near threshold was studied by Ranft (1970), and the parameters of the model were adjusted, including kinematic constraints, to provide good agreement with the 19.3- and 70-GeV data on production of pions, kaons, nucleons, and antinucleons. The ratio of antideuteron to antiproton production from various high-energy accelerators has remained in good agreement with the statistical prediction.

The advent of ψ/J particle production data (Snyder *et al.*, 1976) has made possible a new test of the statistical model. The results are in reasonable agreement if the ψ is not produced in pairs (Ranft, 1975), although the model prediction is somewhat below the experimental data. The disagreement may be significantly worse if the ψ/J must be produced in association with other charmed mesons, as suggested by Zweig's rule. However, recent data on direct production of two, three, or four muons by protons imply that ψ/J particles are produced neither in pairs nor in conjunction with other charmed mesons, in apparent contradiction to direct rigorous application of Zweig's rule.

The statistical model predicts further that the production of pairs of charmed mesons each of mass >2 GeV would be about three orders of magnitude below ψ production, and indeed such particles have not yet been observed. In hadron production there have been reports of a very massive object of over 6 GeV which decays leptonically (as does the ψ/J) and is produced with a cross section times branching ratio, $\sigma \cdot B$, greater than $10^{-4}\sigma \cdot B$ for the ψ/J (Hom *et al.*, 1976; Eartly, Giacomelli, and Pretzl, 1976). This particle, the Υ, would contradict the statistical model prediction by about four orders of magnitude if it exists; however, recent precise data on μ pair production have not confirmed its existence.

There are two ambiguities in the statistical model. First, while the temperature of normal hadronic matter is asymptotically below 170 MeV, particles which have no or very few excited states, i.e., are not part of the normal spectrum of hadronic matter, will be produced with a cross section two to three orders of magnitude above the prediction of Eq. (2.16). Such is the case with the antideuteron, for example. Second, if the energy is sufficiently far above threshold, pairs of particles may be produced with one in each of two primordial fireballs, in which case the production may go over to $\exp(-m_q/T_0)$ rather than $\exp(-2m_q/T_0)$. While it is not clear how far above threshold one must be for this more optimistic result to pertain, the authors (Ranft, 1975, 1976) do not believe that this mechanism is relevant for production of 2 GeV particles by 400 GeV protons, for example. Feinberg also notes that, if particles (quarks) are produced which have rather small cross sections in hadronic matter, they could escape a fireball before statistical equilibrium were established, thus also leading to a production in excess of the prediction of Eq. (2.16) (Feinberg, 1967).

The statistical predictions for quark production at energies well above threshold may be summarized as follows. The cross sections may be normalized to the observed antiproton production of about 1 mb in the range $E_L \sim 10^{11}-10^{12}$ eV. Then

$$\sigma_q = 10^{-27} W_q \exp[-2(m_q - m_p)/T_0]\ \mathrm{cm}^2\ , \qquad (2.17)$$

where W_q is a factor which includes statistical weights (of order unity) and the quark excitation spectrum as discussed above (up to 10^3). Very far above threshold, this may grow to

$$\sigma_q = 10^{-27} W_q \exp[-(m_q - m_p)/T_0]\ \mathrm{cm}^2. \qquad (2.18)$$

Numerically, for 3 GeV quarks, Eq. (2.17) predicts $\sigma \sim 10^{-38}-10^{-36}$ cm^2, and Eq. (2.18) predicts $\sigma \sim 10^{-30}-10^{-28}$cm^2, but for 5 GeV quarks, even Eq. (2.18) predicts $\sigma \sim 10^{-35}-10^{-33}$cm^2 and Eq. (2.16) predicts $\sigma < 10^{-46}$ cm^2.

If the statistical model is totally correct, the upper limit on quark mass from all searches to date is no more than about 5 GeV, as repeatedly emphasized by Hagedorn and Feinberg.

A model has been developed by Gaisser and Halzen (Gaisser and Halzen, 1975; Gaisser, Halzen, and Kajantie, 1975; Halzen, 1976) which also fits $\bar{p}$, $\bar{\Lambda}$, and $\bar{K}$ data well and is a very good fit to ψ production data, including the Zweig rule. This model, which explicitly calculates the production of a high-mass cluster at the vertex of a double Regge exchange, provides a unified treatment of both kinematical and dynamical threshold behavior. The model scales in the variable $Q = (E_{\mathrm{c.m.}} - E^{\circ}_{\mathrm{c.m.}})/m_q$ (where $E^{\circ}_{\mathrm{c.m.}}$ is the threshold c.m. energy) such that

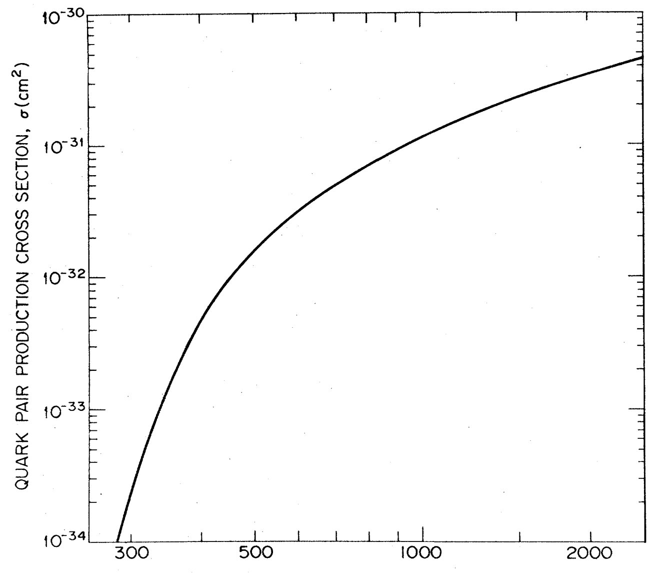


FIG. 1. The production cross section for 10 GeV mass quark pairs according to the model of Gaisser and Halzen (Gaisser, 1975; Halzen, 1976).

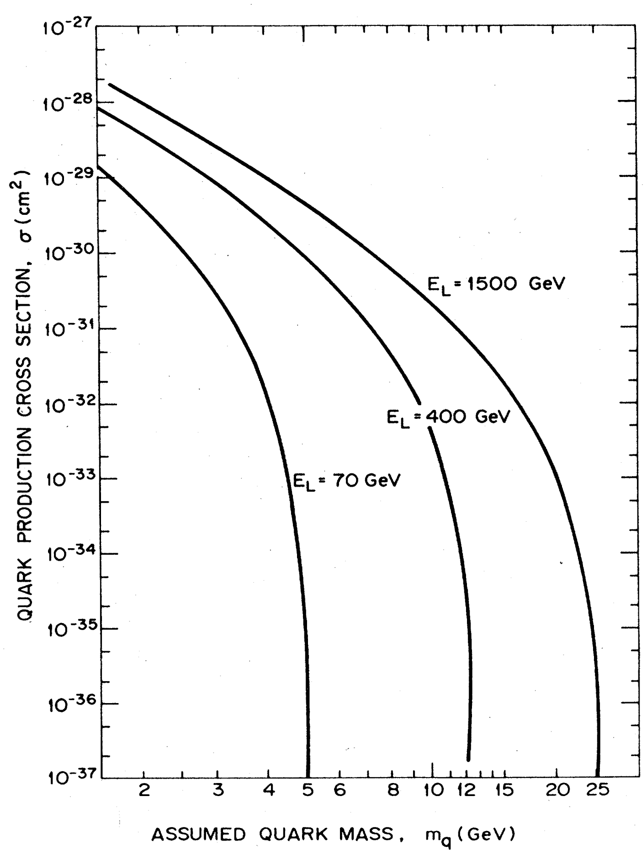


FIG. 2. The production cross section for quark pairs vs assumed quark mass for three different energies of incident protons on stationary nucleons according to Gaisser and Halzen (Gaisser, 1975; Halzen, 1976).

$$\sigma_q = 1.7\times10^{-28}(W_q/m_q^2)F(Q)\ , \tag{2.19}$$

where W_q is a statistical weight factor of order unity as in the statistical model, and $F(Q)$ is a numerical function evaluated by the authors. The model is as successful as any for the observed heavy particle production, and is considerably more optimistic concerning the production of massive particles than the statistical model. In Fig. 1 the production cross section of 10 GeV quarks pairs versus laboratory kinetic energy is plotted, and in Fig. 2 the production cross section is given versus quark mass for three incident proton energies, corresponding to particular particle accelerators.

C. Production spectrum

Quarks produced in nucleon–nucleon collisions may be produced with a center-of-mass distribution of momenta similar to that of antinucleons produced at the ISR. From kinematics, the average longitudinal quark momentum in the laboratory is given by

$$p_q \cong p_L(m_q+T_q)/(2m_p^2+2E_L m_p)^{1/2}\ , \tag{2.20}$$

where p_L is the momentum of an incident proton on a stationary proton, and T_q is the average kinetic energy of the quark in the c.m. From our knowledge of antideuterons, it is plausible that $T_q < m_q$ for $m_q \gg m_p$. With these assumptions and $p_L \gg m_p$,

$$p_q \simeq m_q(p_L/2m_p)^{1/2}. \tag{2.21}$$

Adair and Price also note the limiting values of possible quark momenta, assuming they are produced by diffraction-dissociation processes. For example, if $p \to p+q+\bar{q}$,

$$p_q \cong p_L m_q/(2m_q+m_p) \tag{2.22}$$

if the fast proton is dissociated. If the target proton were dissociated

$$p_q \cong m_q\left(\frac{m_q}{m_p}+\frac{1}{2}\right) \approx m_q^2/m_p \tag{2.23}$$

D. Propagation and interaction

Cosmic-ray searches depend on the propagation of quarks within the earth's atmosphere and in the earth (in some instances), as well as in thick detectors such as ionization calorimeters. It is generally assumed that the quark-nucleus inelastic interaction has the same cross section as the nucleon–nucleus interaction. However, the suggestion is made by Adair and Price (1966) and by Pal and Tandon (1965) that the inelasticity, or fraction of the incident hadron energy lost in an inelastic interaction, is smaller for a massive quark than for a nucleon. These authors assume that the average fraction of the quark energy lost in each interaction is $0.5/m_q$(GeV), so that the "inelasticity" η is given by

$$\langle\eta\rangle = 1-(0.5/m_q) \tag{2.24}$$

where $\eta = E_q/E_{0q}$, the fraction of the incident quark energy which is retained following a collision. In a nucleus where $\bar{\nu}$ interactions may occur within a single nucleus, the relevant inelasticity may be $\eta^{\bar{\nu}}$. Adair and Price use a similar argument, stating that the four-momentum transfer $|t|$ is generally also invariant with the type of collision and varies as

$$P(t) \propto \exp(-|t|^{1/2}/q_0)\ , \tag{2.25}$$

where q_0 is the order of m_π, or perhaps 0.5 GeV. They thus deduce that the inelasticity is effectively as given in Eq. (2.24) above.

While it is commonly assumed that quarks interact with cross sections characteristic of nucleons on nucleons (or nuclei), there are at least two reasons to suspect that $\sigma(q,N)$ might be substantially less than $\sigma(N,N)$. First, the simple factorization of the quark model which argues that $\sigma(\pi,N)$ is approximately $\frac{2}{3}$ of $\sigma(N,N)$ suggests that $\sigma(q,N)$ might be $\frac{1}{3}$ of $\sigma(N,N)$ or about 10–15 mb. Second, more massive, observed mesons appear to exhibit a smaller nucleon cross section than lighter mesons (deduced primarily from the photoproduction of these mesons on nuclei). Thus the cross section $\sigma(\psi,N)$ is perhaps only about one mb (Knapp *et al.*, 1975), or less than a tenth of the pion-nucleon cross section.

E. Ionization

The basis for the largest number of searches for quarks of fractional electric charge has been the careful determination of the ionization of relativistic charged particles. In view of its importance, a brief review of ionization properties is included below.

The average ionization of a charged particle is a function of energy and of the material through which it passes. In a gas at one atmosphere pressure or less, the ionization passes through a broad minimum for a value of energy $E\sim3m$ and then rises logarithmically for higher energies (Fig. 3). Condensed media, such as plastic or liquid scintillation counters, display a more limited relativistic rise in ionization as a consequence of the "density effect"; nevertheless, the average ionization does increase by about 70% above the minimum value. The average ionization in a sample of material is proportional to charge squared, so that quarks of charge

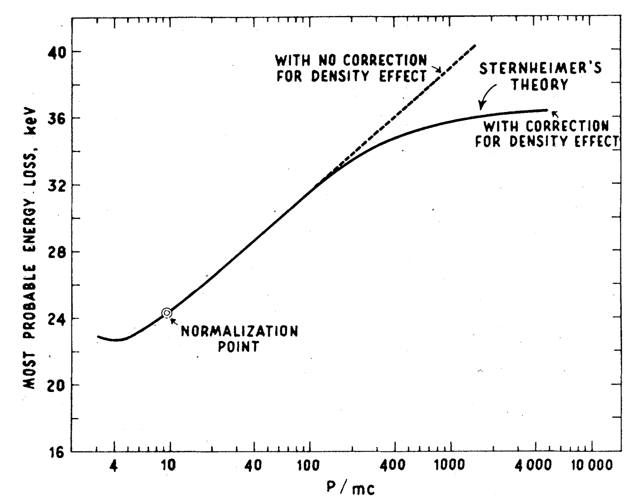


FIG. 3. The relativistic rise in ionization vs momentum (in units of mc). The density effect graphed here is for NTP argon (Ramana Murthy, 1968).

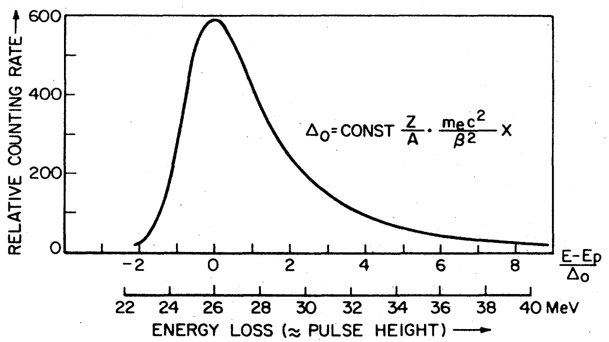


FIG. 4. The distribution of energy loss of energetic particles passing through a thin detector (Faissner, 1963).

$(2/3)e$ or $(1/3)e$ should produce ionization $\frac{4}{9}$ or $\frac{1}{9}$ that of a singly-charged particle of the same velocity. The energy loss of a charged particle passing through a thin sample of material follows a distribution of the form shown in Fig. 4, determined by Landau and modified by Symon. This energy loss appears as ionization. In a given slab of material the energy loss is not *a priori* identical to the ionization. The long, high-energy tail in the energy loss curve is due to infrequent elastic collisions with atomic electrons which are produced with a probability proportional to $(E)^{-1}$ at high energies. The more energetic electrons, or delta rays, may escape the material in which they are produced, but others produced upstream will generally enter the material so that the two effects may cancel. Hereafter, the two phenomena—energy loss and ionization—will not be distinguished. A feature of the Landau distribution is that the fractional width of the characteristic curve is nearly invariant with thickness, in contrast to predictions based simply on the statistics of ionization events. In order to make clean ionization measurements, most experiments have employed a series of successive independent ionization detectors. The signals from the separate detectors may be analyzed in a number of ways to test for the validity of a small number of quark signals. For example, a correlation function C may be evaluated for the pulses from n counters, where

$$C = \sum_{i=1}^{n} \frac{h_i - \langle h \rangle}{h_i} \frac{\sigma_i}{h_q}^2 , \qquad (2.26)$$

where h_i is the pulse height in counter i, $\langle h \rangle$ is the mean height for the n counters for that event, h_q is the pulse height expected for a quark, and σ_i is the standard deviation of pulse height expected for quarks. The correlation function is in effect a χ^2 distribution for n degrees of freedom, and a plot of numbers of events versus C should show a peak near $C = n$ if the data sample includes quarks.

III. COSMIC-RAY SEARCHES

A. Cosmic-ray flux

Energetic cosmic rays are mainly protons. The integral energy flux of all cosmic-ray hadrons over the energy range $10^{10} \sim 10^{15}$ eV is represented fairly well (Pal, 1967) by

$$\varphi(>E) = 2.08 \left(\frac{E}{E_0}\right)^{-1.67} \text{ particles } (\text{cm}^2 \text{sr sec})^{-1} , \qquad (3.1)$$

where E_0 is 1 GeV. The primaries are about half protons; most of the remaining primaries are He nuclei. The corresponding differential flux of nucleons, including nuclei, is

$$\frac{d\varphi_N(E)}{dE} = 2.35 \left(\frac{E}{E_0}\right)^{-2.67} \text{ nucleons } (\text{GeV cm}^2 \text{sr sec})^{-1}. \qquad (3.2)$$

An obvious consequence of this steeply falling spectrum is that the production of quarks according to models such as that of Eq. (2.12) would be peaked at proton energies not far from threshold. General reviews of cosmic rays, their fluxes, composition, energy spectra, and propagation in the atmosphere may be found in the literature (Greisen, 1960; Pal, 1967; Sitte, 1967; Hillas, 1975). Reviews of cosmic-ray data as they relate to high-energy particle physics are given by Feinberg (1972) and McCusker (1975). A running chronicle of the state of the art is found in the Proceedings of the Biennial International Cosmic Ray Conferences, in particular in the rapporteur papers. These proceedings have been reproduced by the host institutions (Munich, 1975; Denver, 1973; Hobart, 1971) or in journals of the host country (Acta Physica Academiae Scientiarum Hungaricae, 1970; Canadian Journal of Physics, 1968).

Due to interactions in the earth's atmosphere, the cosmic-ray nucleon flux falls off at angles away from the zenith according to $\exp(-z_0 \sec\theta/\lambda)$, where z_0 is the vertical depth in the atmosphere of a detector, λ is the primary proton attenuation mean free path in the atmosphere (about 120 g cm^{-2}), and θ the zenith angle. Quarks may be expected to be produced with transverse momenta of order of one GeV so that the direction of quarks would nearly parallel that of primary protons. However, quark attenuation in the atmosphere may be much less than that of nucleons; their energy may be degraded more slowly corresponding to a smaller inelasticity η (Eq. 2.24), and their charge would not be lost. Hence, the flux of energetic quarks would be peaked vertically, but slower quarks might be more abundant at large zenith angles.

The dominant flux of cosmic-ray particles at sea level are muons of a few hundred MeV momentum. Any small detector (e.g., a Geiger counter) will record about one muon per (cm^2 sr min) at sea level. This flux of relativistic muons provides both a primary background and a convenient source of calibration particles. For example, an experiment providing a limit to the quark flux of 10^{-10} (cm^{2}sr sec)$^{-1}$ must have rejected about 10^8 muons in the course of data collection.

B. Single-particle searches

The earliest and most numerous searches for quarks have been conducted using a set of detectors, most frequently scintillation counters, stacked vertically and operated in coincidence, with the individual pulse heights recorded in a manner sensitive to single cosmic-ray particles of anomalous ionization. One such experiment is illustrated in Fig. 5.

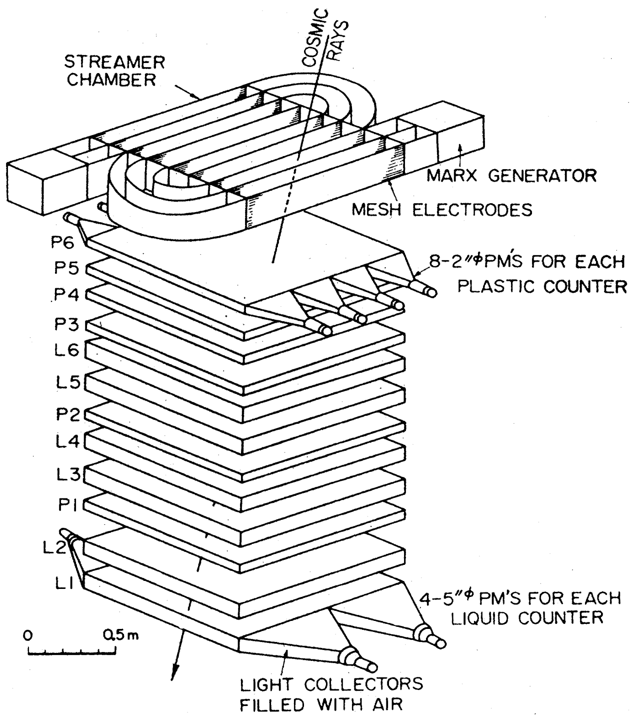
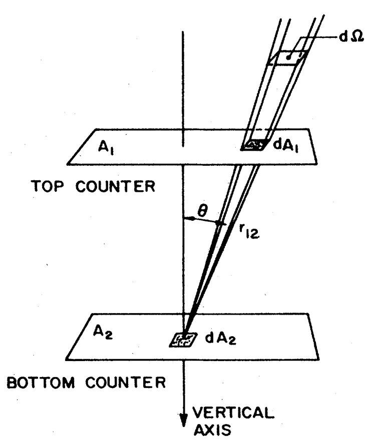


FIG. 5. A schematic drawing of a sensitive, single particle cosmic ray quark search. Layers labeled P1–P6 are plastic scintillation counters; those labeled L1–L6 are liquid scintillation counters (Fukushima, 1969).

The sensitivity of such a system may be expressed in terms of the "admittance" (often referred to as the "geometrical factor" in cosmic-ray literature) or the integrated solid angle-area product,

$$N=\int A\,d\Omega\ .$$

The geometrical problem is more clearly illustrated in Fig. 6 (taken from the Arizona group) for the practical



Counter geometry for $(A\Omega)$ calculation.

$$N=\int_{A_1}\int_{A_2} I r_{12}^{-2}\cos^2\theta\, dA_1 dA_2\,,$$

FIG. 6. The geometry of cosmic ray particle searches (Cox, 1972). Here N particles are detected for I incident particles per unit solid angle per unit area.

case where two large detectors spaced vertically define the aperture. When multiplied by the running time of the experiment, a negative result is simply related to the upper limit quark flux expressed in quarks $(\mathrm{cm}^2 \mathrm{sr\ sec})^{-1}$. Thus, for example, an apparatus with an admittance of 1 m^2 sr operated for 10^6 seconds (about 12 days) with no trace of a quark signal would establish a "limit" to the quark flux of $10^{-10}(\mathrm{cm}^2\mathrm{sr\ sec})^{-1}$. Actually, if the flux were of that value, the probability would be only 50% that a quark would have been seen. A more useful and more commonly employed index is the quark flux corresponding to a 90% confidence level of detection. For this example experiment, the upper limit quark flux would be determined to be 2.3×10^{-10} $(\mathrm{cm}^2\mathrm{sr\ sec})^{-1}$ to a 90% confidence level, meaning that if the quark flux were of this value, 9 out of 10 identical experiments run for 10^6 sec would have detected at least one quark.

The experimental problems in such searches lie in discriminating against pathological sources of anomalously lightly ionizing radiation. For example, an air shower incident on the side of the system might give small pulses from low-energy, stopping electrons in each of several scintillators, simulating a subnormal ionizing particle. This type of problem is resolved by increasing the number of independent detectors, and the same solution likewise improves the statistical rejection against the low pulse height tail of the Landau ionization profile of normal particles.

For the same reasons, many later experiments have employed track detectors such as spark chambers or multiwire proportional chambers to insure that the event candidates were indeed single, well-behaved particles.

In Table II the results of many of these single-particle cosmic-ray experiments are tabulated, and the most relevant parameters of each experiment are listed. As time progressed, the experiments became more elegant and also were operated in more varied sites. Thus, Bowen and his co-workers operated their apparatus on a mountain in view of the possibility that quarks might be attenuated in the earth's atmosphere. Others operated their detectors deep underground on the assumption that quarks might interact only weakly and thus be found with muons as the only survivors of primary cosmic-ray events in such locations.

If these searches can be considered as independent and equivalent, the results of Table II may be combined to give overall flux limits for each charge assumption. The results are: $\varphi \leq 1.1\times10^{-11}$ $(\mathrm{cm}^2\ \mathrm{sr\ sec})^{-1}$ (90% C.L.) for $\frac{1}{3}e$, and $\varphi\leq 2.4\times10^{-11}$ $(\mathrm{cm}^2\ \mathrm{sr\ sec})^{-1}$ (90% C.L.) for $\frac{2}{3}e$.

Besides seeking quarks of charge $\frac{1}{3}e$ and $\frac{2}{3}e$, some searches have sought particles of $\frac{4}{3}e$, on the chance that such a charge might result from a bound state of a quark and an integrally charged meson (or baryon) and might be a lower energy, more stable configuration than a free quark. Such searches are more difficult for two reasons. First, the Landau energy loss distribution is asymmetric with a long tail on the high side, thus making searches for anomalously high ionization more difficult than those for anomalously low ionization. Second, slower particles of high rest mass but integral charge

TABLE II. Cosmic ray single particle ionization measurements.

Group	Reference	Detectors [b]	Elevation above sea level (m) [a]	Admittance (m^2 sr)	Data collection time (hr)	Quark flux limits (90% C.L.) $\phi \times 10^{-10}$ (cm^2 sr sec)$^{-1}$ $\pm 1/3e$	$\pm 2/3e$	$\pm 4/3e$
BNL	Sunyar, 1964	7 scint.	S	0.0011	720	2000		
Arizona	Bowen, 1964	5 liquid scint.	2750	0.033	237	160		
CERN	Massam, 1965		S	0.0054			500	
Arizona	Delise, 1965	6 liquid scint.	2750	0.024	1100	87	180	
Yale–BNL	Kasha, 1966	3 plastic scint., 3 liquid scint.	S	0.065	2500	26		
					900		21	
CERN	Buhler–Brohlin, 1966	6 plastic scint., 2 spk. chm.	S	0.11	850	15	14	
Argonne	Lamb, 1966	2 gas counters, 2 plastic scint., 4 liquid scint.	S	0.40	1750	4.5	16	
Cal. Tech.	Gomez, 1967	8 plastic scint., 2 spk. chm.	S	0.15	3300	1.7	3.4	
CERN	Buhler–Brohlin, 1967a	6 plastic scint., 2 spk. chm.	S	0.11	2605	4.5	1.7	
Yale–BNL	Kasha, 1967	7 scint.	S	0.060	2000		20	
Yale–BNL	Kasha, 1968a	8 layer hodoscope [c] each of 6 scint.	S	1.0	1100		1.2	
Yale–BNL	Kasha, 1968b		S	1.0	1000			1.3
Osaka	Hanayama, 1968	5 plastic scint., 16 spk. chm.	S	0.52	800	3.1		
Tokyo	Fukushima, 1969	12 scint., 1 streamer chamber	S	0.20	3500	0.5	7.5	
Arizona	Krider, 1970	6 scint., 4 spk. chm., 1 shower det. 1 range ch.	750	0.95	1160	0.98	1.6	
Aachen	Faissner, 1970	6 gas counter layers [c]	S	0.428	1580	1.9		
Osaka	Chin, 1971	6 scint., 16 spk. ch.	S	0.38	2050	1.3		
			2770		5500	0.57		
Arizona	Cox, 1972	6 liquid scint. 2 wide gap spk. chm.	2750	0.63	1500	0.83	0.96	
Arizona	Beauchamp, 1972	6 liquid scint., 2 wide gap spk. chm.	2750	0.63	1500			4.1
Case	Crouch, 1972	5 liquid scint., 2 flash tube trays	S	0.51	1159		2.2	
Tokyo	Kifune, 1974	6 layer hodoscope each of 4 scint.	S	0.65	556	3.0		

[a] All entries with S were experiments at or near sea level.
[b] "Scint." refers to organic plastic or liquid scintillation counters; "spk. chm." refers to spark chambers.
[c] Sensitive to 2 or 3 particles.

TABLE IIa. Cosmic ray single particle ionization measurements. Shielded or buried detectors.

Group	Reference	Detectors	Depth below sea level ($g\,cm^{-2}$)	Admittance	Data collection time (hr)	Quark flux limits (90% C.L.) $\phi\times10^{-10}$ $(cm^2\,sr\,sec)^{-1}$ $\pm1/3e$	$\pm2/3e$	$\pm4/3e$
London	Barton, 1966	1 scint.	220 000	1.0	1840		1.4	
London	Barton, 1967	6 liquid scint.	6 000	0.51	1600		1.4	
CERN	Buhler-Brohlin, 1967b	6 plastic scint., 2 spk. chm.	790	0.11	12			1600
M.I.T.	Garmire, 1968	2 plastic scint., 1 liquid scint., 2 prop. ctr.	~300 [b]	0.52	...	0.66 [c]	0.88 [c]	
Torino–CERN	Briatore, 1968	6 scint.	6 300	0.010	4170	1.8	1.8	
					770			110 [a]

[a] Not 90% C.L., uncertain by ±180.
[b] One meter concrete.
[c] 95% confidence level.

will have sufficient range to penetrate a thick detector, and may have ionization comparable to $(4/3)^2$ times minimum ionization. In particular, the experiment of the Arizona Group (Beauchamp *et al.*, 1972) observed such particles and identified them as cosmic-ray deuterons, and these particles effectively set the limit to the detectable upper limit flux of $q=(4/3)e$ quarks.

Searches of this sort for quarks, while setting the most sensitive limits to possible quark production by proton–nucleus collisions for incident protons in the energy range of 10^{12}–10^{14} eV, have one significant weakness. The apparatus typically is "blind" to events wherein two charged particles enter the sensitive volume simultaneously. The ionization, as measured by a pulse height, is generally recorded for an entire detector layer, and the simultaneous passage of a normal particle renders that reading insensitive to a second, coincident particle of subnormal ionization. As detector areas are typically of order of magnitude one square meter, implicitly these searches really search only for quarks among showers of particles less dense than about one particle per square meter. One assumes that quarks would be produced in the collision of a primary proton with an air nucleus high in the atmosphere along with other secondary mesons, and an air shower would be initiated so that at sea level any quarks would probably be accompanied by shower particles, mostly electrons and positrons, of the order of 100 MeV energy. The theory and experimental study of such cascades is well developed, so that one may in principle evaluate the limits that such showers place on particle detection in the class of events described above. As an independent class of experiments has searched for quarks among air showers (Sec. II.C, below) to comparable sensitivity limits, the value of such a complex calculation is questionable and will be foregone here.

Some experimenters have provided for modest accompanying air showers in the "single-particle" searches; for example, the effective area of each element of the detector of Kasha *et al.*, 1968a, 1969b) is one sixth the total, and a few accompanying shower particles would not reduce the stated limits. The Aachen group (Faissner *et al.*, 1970) quotes separate, somewhat less sensitive upper limit quark fluxes for particles accompanied by one and two additional tracks in their detector, where wire proportional chambers separate the tracks. The Durham detector (Ashton, 1968) contained a hodoscope of 1 cm diameter neon flash tubes, to achieve the same result. As most shower particles are electrons, a few radiation lengths of lead filter out a large fraction, and some experiments have used such shielding.

Searches deep underground are tabulated separately (Table IIa), as they are quite insensitive to electron shower accompaniment but do presume significantly lower quark interaction cross sections.

If the question of accompanying shower particles is ignored, the negative results of a single-particle search may be related to the limits on the production cross section of quarks of a given mass using the kinematical thresholds and relationships given in Eq. (2.8). Because of the steeply falling primary spectrum, the production of a massive particle will be dominated by cosmic-ray

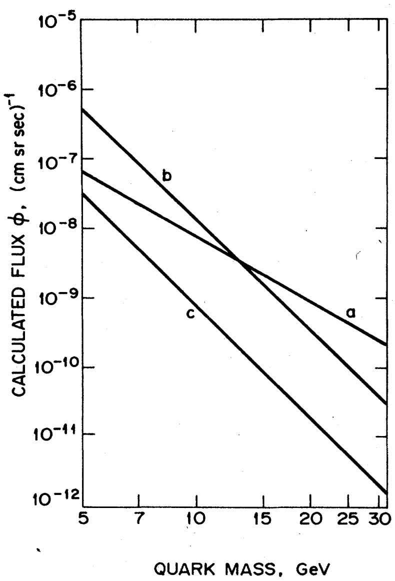


FIG. 7. Calculated quark fluxes vs quark mass from cosmic rays according to the model of Adair and Price (Adair, 1966) with an assumed constant quark production cross section of 10^{-30} cm^2 (curve a), according to this model with $\sigma=\pi(\hbar/m_q)^2$ (curve b), and according to the model of Gaisser and Halzen (Gaisser, 1975) (curve c).

protons not far from threshold. If it is further assumed that quarks are not attenuated in the atmosphere, then the spectrum of Eq. (3.1) and the production cross section model of Eq. (2.14) may be folded to give the following relationship between quark flux φ_q, quark production probability $P_q=\sigma_q/\sigma_{NN}$, and energy for threshold quark production E_T (for an incident primary nucleon on a stationary laboratory nucleon)

$$\varphi_q=0.267\ P_q E_T^{-1.67}(\text{cm}^2\ \text{sr sec})^{-1}\ . \tag{3.3}$$

This simple formulation may be further elaborated by approximating the threshold energy as

$$E_T\simeq 2m_q^2/m_p \tag{3.4}$$

giving

$$\varphi_q\simeq 0.075\ P_q\ m_q^{-3.33}\ (\text{cm}^2\ \text{sr sec})^{-1} \tag{3.5}$$

Adair and Price have carried out a Monte Carlo calculation using this production cross section behavior and the primary cosmic-ray spectrum, and considering subsequent interactions of the cosmic-ray protons in the atmosphere. Their results, for an assumed production cross section of 10^{-30} cm^2, are replotted in Fig. 7. If it is further assumed that

$$\sigma_q^\circ=\pi(\hbar/m_q)^2\ \text{(Eqs. 2.12, 2.13).} \tag{3.6}$$

then

$$\varphi_q\simeq 3\times 10^{-3} m_q^{-5.33}(\text{cm}^2\ \text{sr sec})^{-1} \tag{3.7}$$

This simple, approximate expression is also presented on Fig. 7. It may be convenient in relating cosmic-ray quark searches to accelerator experiments to rewrite Eq. (3.7) in terms of quark production cross sections σ_q°, in cm^2 (where m_q is large compared to m_N):

$$\varphi_q\cong 2.3\times 10^{24}\sigma_q^\circ(m_q)^{-3.33}(\text{cm}^2\text{sr sec})^{-1}\ , \tag{3.8}$$

$$\sigma_{q_0}^\circ\cong 4.4\times 10^{-25}\varphi_q(m_q)^{+3.33}\ \text{cm}^2\ .$$

If alternatively the rise in σ_q above threshold is ignored and the quark production cross section is assumed to follow the step functions

$$\sigma_q=0;\ E<E_t,$$

$$\sigma_q=\sigma_q;\ E\geqslant E_t,$$

then

$$\varphi_q\cong 1.3\times 10^{25}(m_q)^{-3.33}\sigma_q(\text{cm}^2\text{sr sec})^{-1}\ ,$$

and (3.9)

$$\sigma_q\cong 7.5\times 10^{-26}(m_q)^{+3.33}\varphi_q\,\text{cm}^2.$$

The more recent model of Gaisser and Halzen discussed in Sec. II above permits similar numerical calculations. Here, for example, the folding of the cosmic-ray spectrum with the production cross section gives a maximum contribution to quark production from cosmic-ray primaries of about three times the threshold energy. Numerically, the Gaisser and Halzen model predicts a cosmic-ray quark flux φ_q versus quark mass given by

$$\varphi_q=8\times 10^{-10}\ (m_q/10)^{-5.33}\ (\text{cm}^2\text{sr sec})^{-1}, \tag{3.10}$$

or

$$\varphi_q=1.7\times 10^{-4}m_q^{-5.33}(\text{cm}^2\text{sr sec})^{-1}\ . \tag{3.11}$$

The flux from Eq. (3.11) is also plotted on Fig. 7.

In this model also, $\sigma\propto m_q^{-2}$, and the cosmic-ray quark flux may be expressed in a manner similar to Eqs. (3.8) and (3.9) in terms of the production cross section at the cosmic-ray energy where the yield of quarks would be greatest (three times the threshold energy for this particular model). Such an artifice is useful for reference as the production cross section continues to rise with energy. Again, in limits where the nucleon mass may be neglected

$$\varphi_q=1.4\times 10^{25}\ m_q^{-3.33}\sigma_q(\text{cm}^2\text{sr sec})^{-1}\ , \tag{3.12}$$

$$\sigma_q=7\times 10^{-26}m_q^{+3.33}\varphi_q\,\text{cm}^2.$$

If, further, the upper limit cosmic-ray flux of quarks is taken to be 10^{-11} (cm^{2}sr sec)$^{-1}$, the limits on quark production cross section versus mass are given by

$$\sigma_q\cong 7\times 10^{-37}m_q^{+3.33}\ . \tag{3.13}$$

From this model, using the cross section values of Eq. (2.19) and an upper limit quark flux of 10^{-11} (cm^{2}sr sec)$^{-1}$, the lower limit quark mass would be about 22.5 GeV. Here the cross section is for the production of quark pairs, and the flux limit refers to detection of single quarks.

The statistical model predicts very much smaller quarks fluxes for every case with $m\lesssim 10$ GeV. If the most optimistic set of assumptions is adopted, the quark flux φ_q would be given by

$$\varphi_q\simeq 2\times 0.075\ m_q^{-3.33}\exp(-m_q/0.16)(\text{cm}^2\text{sr sec})^{-1} \tag{3.14}$$

using

$$P_q=2\exp(-m_q/0.16). \tag{3.15}$$

This results in flux values of 6×10^{-17} ($m_q=5$ GeV), 6×10^{-31} ($m_q=10$ GeV), or 1.5×10^{-44} ($m_q=15$ GeV) in units of $(\text{cm}^2\text{sr sec})^{-1}$.

C. Air shower studies

The greatest excitement in the history of quark searches was generated by the report of McCusker's group in Sydney, Australia that quarks had been observed in air showers using cloud chamber detectors (Cairns et al., 1969; McCusker, Peak, and Rathgeber, 1969). McCusker had been studying air shower phenomena over a long period, and had been impressed by departures from expectations in transverse shower distributions (McCusker and Cairns, 1969; Bakich, McCusker, and Winn, 1970). Specifically, his data suggested phenomena in energetic showers (initiated by primary cosmic rays of over 10^5 GeV) which corresponded to anomalously large transverse momenta. The quark concept suggested a mechanism for generation of such phenomena, and he thus set out to search for quarks. He further reasoned that the high electron density near the core of a shower might have masked any quark signals in the single-particle telescope searches (Table I). Before describing his experiment and others it is useful to recall some features of extensive air showers. Useful reviews of air showers have been given by various authors (Greisen, 1960; Pal, 1967; Hillas, 1975).

A single proton at the top of the atmosphere in the energy range of 10^3 to 10^7 GeV will generate an electromagnetic cascade producing at sea level (an atmospheric depth of about ~1000 g cm^{-2}) an average number of electrons very approximately equal to the energy in GeV divided by 10. A primary proton will interact in the atmosphere to produce π°'s and hence γ's. At high energies approximately one sixth of the primary interaction energy will appear as γ's so that ultimately a majority of the energy of the primary will appear in the electromagnetic cascade. The lateral density distribution falls with distance from the core axis, so that in a shower of 10^6 electrons at sea level (about 10^7 GeV), the central density may exceed 10^4 e/m^2 but fall to 1 e/m^2 at a radius of 200 m. At sea level, Greisen notes, a good approximation to the electron number density in the interval $1<r<200$ m from the shower axis is given by

$$\rho(N,r)=(aN/r)\exp(-r/b)\ , \qquad (3.16)$$

where ρ is the density in electrons per m^2, N is the total number of the electrons, $a=2\times10^{-3}$, r is in meters, and $b=60$ m.

At any height the average density at a given r increases about linearly with energy. Thus, while a primary of 10^3 GeV will seldom produce more than 1 electron shower particle/m^2 at sea level, even near the axis, a primary of 10^5 GeV will on the average produce 10 to 100/m^2 within 1m of the axis.

The consequence of this argument for quark searches is that a counter telescope of about one square meter area at sea level, which is sensitive only if no more than one particle strikes it within its time resolution (typically about 10^{-7} second), would be adequately sensitive to quarks produced by 10^3 GeV protons, but virtually insensitive to quarks produced by primaries of 10^5 GeV, assuming that quarks generally lie in the core.

If it is assumed that quarks are produced with $\langle p_\perp\rangle \simeq 0.5$ GeV/c and quarks are produced at only very high energies, then the approximate average production angle and distance from the shower axis at sea level may be found as functions of assumed quark mass and energy. The earlier equations [Eqs. (2.3), (2.8)] may be approximated by letting $m_q \cong \frac{1}{2}E_{\text{c.m.}}\ m_N \cong 1$ GeV, and $\gamma_q \cong E_0/2$ for quark production at threshold. Then

$$E_q=\gamma_{\text{c.m.}}m_q \simeq E_0/2 \qquad (3.17)$$

and

$$\theta_q \simeq 1/E_0 \simeq \tfrac{1}{2}m_q^2\ . \qquad (3.18)$$

Since the first interaction takes place in the atmosphere at an altitude of about 3×10^4m, the sea level lateral displacement of quarks from the shower axis may be very approximately

$$r_q \simeq 3\times10^4\,\theta_q\,(\text{meters}) \qquad (3.19)$$

or

$$r_q \sim \frac{1.5\times10^4}{m_q^2\,(\text{GeV}^2)}\ (\text{meters}). \qquad (3.20)$$

Numerically, a quark of 10 GeV rest mass, produced by a 200 GeV proton, would lie about 100 m from a shower "core" (although at such low energy the core itself would be largely gone), while a 100 GeV-mass quark may well lie only a meter from a core. Quarks produced above threshold would have an appreciable distribution of longitudinal momentum as well as a distribution in transverse momentum, so that the spatial distributions of any quarks would vary widely about these average values.

The central point is that, if quarks of $m_q \lesssim 10$ GeV exist, single-particle cosmic-ray searches are a sensitive, useful technique for seeking them. On the other hand, if they are five times more massive (or if for some reason their production threshold energy is much higher), they would most often be found accompanied by a dense flux of shower particles. In this sense, McCusker introduced a new perspective on quark searches and stimulated a line of investigation which has subsequently led to the most stringent limits on the existence of very massive quarks ($m_q \gtrsim 25$ GeV).

McCusker's experiment utilized a trigger consisting of three arrays of Geiger counters each of 110 cm^2 effective area arranged in a horizontal equilateral triangle 2 m on a side. This should provide an efficient trigger for air shower cores corresponding to primary cosmic-ray energies in excess of 10^6 GeV. Based on other data, the mean primary energy for showers triggering this array was about 5×10^6 GeV. The four cloud chambers, each with a cylindrical illuminated volume 5-cm deep by 30-cm diameter were oriented with their cylindrical axes horizontal and positioned between and below the trigger counters. In several months of operation, 5500 useful air shower events were photographed and analyzed, resulting in five quark candidates among about 60 000 tracks (McCusker, Peak, and Rathgeber, 1969; Cairns *et al.*, 1969).

In terms of the flux units employed in Table II, these five quark candidates corresponded to a flux of 5.5 $\times 10^{-10}$ (cm^{2}sr sec)$^{-1}$ for quarks of $(2/3)e$ charge. McCusker suggested that these results were not incompatible with single quark limits if the production threshold were quite high ($>10^6$ GeV) and if the production cross section were so large above threshold that several quarks were produced in each interaction.

Following discussion and publication of the Sydney results many questions were raised. The droplet count along the normal tracks was anomalously low, leading some to question technical details of the cloud chamber operation, and the statistical basis for the conclusions was questioned. There were also concerns expressed about the relativistic rise in ionization and other physical effects. These questions are discussed in several papers which closely followed McCusker's initial publication (Rahm and Louttit, 1970; Kiraly and Wolfendale 1970; Frauenfelder, Kruse, and Sard, 1970). Adair (Adair and Kasha, 1969) also questioned whether the Sydney results were compatible with earlier single-particle searches. Thus, if the Sydney results were taken at face value, a primary of 10^6 GeV would produce 10 quarks, so that the threshold would be below 10^5 GeV. At that energy, counter telescope experiments would not have missed quarks for any set of plausible production assumptions. Given the importance of the question, the most meaningful check of the experiment appeared to be a repeat of it with a similar but improved technique. This was done by four groups, all with negative results.

The Sydney group continued to run their apparatus, presumably with somewhat improved technique, for an additional 1.3 times the original data run, and no quarks were subsequently reported. Although the original claims were never officially retracted, it appears significant that, in a 1975 review paper on cosmic-ray hadronic interactions, McCusker does not mention his earlier quark results (McCusker, 1975).

A search was made by a British group using a 140 cm^2 high-pressure helium-filled cloud chamber (Evans *et al.*, 1971). Using a counter trigger array to select showers with local particle densities >60 m^{-2} at sea level ($E_0 \gtrsim 10^5$ GeV), 1200 showers were studied for lightly-ionizing tracks, and no candidates were found. The authors set an upper limit of 4×10^{-9} (cm^{2}sr sec)$^{-1}$ (95% confidence level) to the possible flux of $q=(1/3)e$ quarks.

W.E. Hazen, first at the University of Michigan (Hazen, 1971) and later in collaboration with A. L. Hodson and others at the University of Leeds (Hazen *et al.*, 1975), has carried out a program of cloud chamber studies seeking quarks in air showers. By operating the large 3 m^2 Leeds cloud chamber horizontally and using an illuminated depth of 30 cm, the group has been able to search more sensitively for $q=(1/3)e$ (one-ninth minimum ionization) particles. They have triggered the system on about 7200 showers. Their latest published results quote upper limits of 1.2×10^{-11} (cm^2 sr sec)$^{-1}$ for quarks of $(1/3)e$ charge. About one third of the data was taken with a 250g cm^{-2} absorber of lead and concrete over two chambers. Hazen had earlier set limits of 10^{-10} (cm^2 sr sec)$^{-1}$ on the flux of quarks of $(2/3)e$ charge using a smaller cloud chamber at the University of Michigan.

In another cloud chamber experiment, a group at the Lawrence Livermore Laboratory under the direction of A. F. Clark operated a set of eleven 44-cm diameter cylindrical cloud chambers with 10-cm deep illuminated region triggered in a manner similar to the Sydney experiment (Clark *et al.*, 1971; 1974). As in the case of the Leeds experiment, the Livermore group took care to be certain that individual droplets were recorded on film. They also occasionally superimposed on the film computer-generated simulated quark tracks. This gave the scanners positive evidence to report, and provided a quantitative check on the scanners' efficiency in detecting any possible real quarks. (Such artificial quarks were also planted on the film in the later Leeds experiment.) The experiment included 200 000 chamber stereo photographs containing 10^6 cosmic-ray tracks. The negative results set a limit of 2 $\times 10^{-11}$ (cm^2 sr sec)$^{-1}$ for flux of particles with $q=(2/3)e$ and somewhat poorer limits for other charge assignments. These results, together with those from Leeds, Sydney, and elsewhere are tabulated in Table III.

In each of these experiments a lead shield was used to screen out soft electrons for some of the data. The lead shields permitted searches closer to the shower core than would be possible with unshielded detectors. The data collected in these experiments is difficult to interpret in terms of simple flux limits from a particular primary energy, as the triggers generally respond to a minimum local shower density and not to a particular threshold energy. Thus showers initiated by very energetic particles with cores incident far from the detector may trigger the system, but only those lower energy primaries resulting in cores close to the trigger counters will be studied.

An experiment at the University of Durham employed a hodoscopic array of neon flash tubes with a delayed pulse so that the flash efficiency was a steep and known function of specific ionization (Ashton *et al.*, 1968, 1969, 1973a, 1973b, 1975). Again an air shower trigger was used, and the technique is sensitive to moderately high particle densities. The apparatus was shielded with 15 cm of lead, and triggers were operated at different times corresponding to different minimum shower particle densities.

The Aachen group (Bohm *et al.*, 1972) extended their proportional counter array, used earlier in a single-particle search (Faissner *et al.*, 1970), and placed it below a 15-cm thick lead shield with air shower trigger counters above. In over 2000 hours of operation, over 500 000 triggers were obtained; no quarks of $(1/3)e$ or $(2/3)e$ charge were detected to about 1×10^{-10} (cm^2 sr sec)$^{-1}$ (90% confidence limit). If 3% of the shower particles penetrate the lead, the experiment is sensitive to incident particle densities less than 600 m^{-2}.

One other experiment which reported positive results from a search for quarks presumably accompanying air showers was published by an Ohio State University group (Chu *et al.*, 1970). They scanned film taken from the 1-m diameter Michigan-Argonne heavy liquid bubble chamber and studied the accidentally occurring cosmic-ray tracks. Two tracks which they identified as

TABLE III. Quark flux limit from cosmic ray air shower experiments.

Group	Reference	Detector and area	Absorber	Shower energy	Shower density (particles m^{-2})	Number triggers	Number of tracks studied	Upper limit[a] quark flux $\varphi \times 10^{-10}$ $(cm^2\ sr\ sec)^{-1}$ 1/3e	2/3e	Other
Sydney	Cairns, 1969; McCusker, 1969	3 cloud chambers, each 120 cm^2	15 cm Pb	$\sim 4 \times 10^6$ GeV	$100-5 \times 10^4$	5 500	55 000		5.5[c]	
		1 cloud chamber, 120 cm^2	unshielded			~12 000			2.4[c]	
Ohio	Chu, 1970	1 m diam. bubble chamber	1 200g cm^{-2} Fe and Cu			10 000[d]			1 000[c]	
Edinburgh	Evans, 1971	High pressure, cloud chamber, 140 cm^2		$>10^5$ GeV		1 200	12 000	40[b]		
Michigan	Hazen, 1971	Cloud chamber 0.15 m^2	10 cm concrete, 1.25 cm Al plate in chamber	$>10^6$ GeV		3 200	~100 000		1	
Aachen	Bohm, 1972	1 m^2 proportional counters	15 cm Pb	10^5-10^6 GeV	$\lesssim 600$	523 724	107 500	1	1	
Durham	Ashton, 1973a, Ashton, 1973b, Ashton, 1975	Neon flash tube hodoscope array	15 cm Pb		>250 >80 >20	1 217 4 516 12 057		0.43 0.55 0.80		
Livermore	Clark, 1974	11 cloud chambers, each 44 cm diam. × 9 cm deep	Half under 10 cm Pb	$\gtrsim 10^6$ GeV	$\gtrsim 86$ $\lesssim 5\,000$	~20 000 (200 000 chamber photographs)	1 000 000	0.8	0.2	7(1/4e) 1 000(1/6e) 100(4/9e)
Leeds	Hazen, 1975	Cloud chamber 3 m^2 (horizontal)	20g cm^{-2} 250g cm^{-2}	$\sim 5 \times 10^6$ GeV	$\lesssim 500$	5 000 2 250		0.12		

[a] 90% Confidence level.
[b] 95% Confidence level upper limit.
[c] Quark candidates reported (see text).
[d] 10 000 bubble chamber photographs studied with no *a priori* requirement of coincident cosmic rays.

$q=(2/3)e$ quarks were found in their scanning. The structure of the bubble chamber magnet placed an overburden of 1200 grams per cm^2 of iron and copper over the sensitive region of the chamber, effectively shielding out almost all air shower electrons. If quarks, these events corresponded to a flux of 10^{-7} (cm^2 sr sec)$^{-1}$. However their identification depends critically on the correlation between track age and bubble size, a correlation the authors only calculated but did not measure for the relevant set of chamber operating conditions. Their interpretation has been sharply challenged by the Argonne bubble chamber group (Allison *et al.*, 1970) and by the Michigan physicists who designed and built the chamber (Sinclair, 1970). Their flux is in sharp disagreement by orders of magnitude with many convincing negative results.

The recent air shower experiments with cloud chambers now appear to set the most significant upper limits to the production cross sections for very massive quarks. The Durham results add to the confidence in these results by varying the triggering conditions. As noted in Table III, these various upper limits are 90% confidence level values. Again, as with Table II, the negative results in this table may be combined statistically. The consequent quark flux limits are then: $\varphi \leq 0.71\times10^{-11}$ (cm^2 sr sec)$^{-1}$ (90% C. L.) for $q=\frac{1}{3}e$, and $\varphi \leq 1.4\times10^{-11}$ (cm^2 sr sec)$^{-1}$ (90% C. L.) for $q=\frac{2}{3}e$.

Hazen *et al.* (1975a) noted that as the cosmic-ray hadrons cascade down through the atmosphere they effectively probe production possibilities over the range of energies below the primary initiating particle. In this way the production cross section by cosmic rays is effectively studied over the continuous range of energies between earlier single-particle searches and the initiating shower energy.

In view of the design of later single-particle searches using lead shielding and sensitive to several simultaneous particles in the meter-square detector, there is now convincing evidence against the existence of fractionally-charged cosmic-ray quarks at flux levels above about 10^{-11} (cm^2 sr sec)$^{-1}$.

D. Time delay searches

An independent technique for seeking particles of large rest mass in cosmic rays has been employed in several experiments. Here the relative delay of a massive particle behind the relativistic component of an air shower is studied. If a particle (e.g., quark) of rest mass m_q and Lorentz factor $\gamma=E_q/m_q$ is produced at a height y above a detector, it will arrive at the detector delayed by a time Δt behind the shower front (the particles with $v\simeq c$) given by

$$\Delta t \cong y/2\gamma_q^2 c, \quad \gamma_q \gg 1. \tag{3.21}$$

Thus a quark of mass 10 GeV with an energy of 100 GeV ($\gamma_q=10$) produced 10 km above a detector would arrive 160 nsec behind the shower front (see Fig. 8). A simultaneous measurement of time delay and total energy of the delayed particle then sets limits on possible masses and production heights.

The method is limited, however, to values of γ below 70, given the 30-km height of the atmosphere, as the relativistic component of showers is spread (by path length straggling) over about 6 nsec, and a reasonable time resolution limit for large counters (including this spread) is perhaps 10 nsec. For quarks produced near threshold, $m_q\simeq\gamma_q$ (where m_q is expressed in nucleon masses or GeV), so the method is sensitive up to quark masses of about 70 GeV rest mass. Although particles produced in the backward cm hemisphere above threshold may have $\gamma<70$ for greater masses, the sensitivity of the method will decrease for $m_q>70\, m_N$.

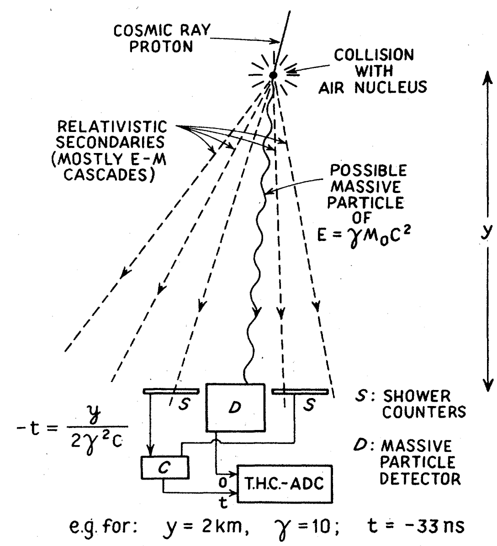


FIG. 8. The principle of cosmic ray experiments seeking quarks or other massive particles through the study of pulses delayed relative to air showers.

Early discussion of this approach is contained in papers by the Copenhagen group (Damgaard *et al.*, 1965; Bjørnboe and Koba, 1966). It is characteristic of such search methods that they are sensitive to massive particles of fractional or integral charge—or indeed zero charge in some cases. However it is required that they are produced in interactions of cosmic-ray primaries with air nuclei and that they do not decay in their passage through the atmosphere. It is also assumed that their energy loss within the atmosphere leaves them with substantial kinetic energy ($\gamma\gg1$) at the detector.

The Echo Lake group (Jones *et al.*, 1967) employed an ionization calorimeter, a large spark chamber, proportional counters, and an air shower array of about 10 m^2 to explore the energy and time delay of hadron signals in the calorimeter relative to showers. The apparatus was located at an altitude of 3230 m, or an atmospheric depth of 715 g cm^{-2}. The experimental solid angle, area, and running time corresponded to a sensitivity of 2.3×10^{-11} (cm^2 sr sec)$^{-1}$. The apparatus is represented schematically in Fig. 9. With a 10 GeV hadron threshold, 3×10^5 events were studied. One anomalous event was detected with an energy of 36 GeV and a time delay of 45 nsec. The event could possibly have been a nucleon surviving from an interaction from the top of the atmosphere ($y\cong30$ km), and there was also a 6% probability that it was an accidental coincidence between a

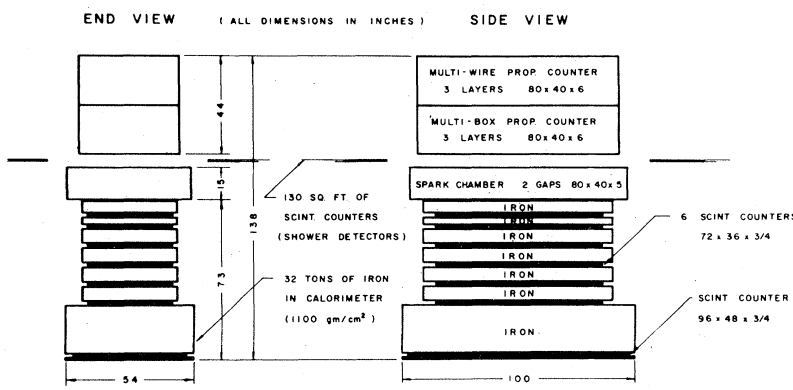


FIG. 9. Schematic drawing of the Echo Lake quark search experiment (Jones, 1967).

hadron and an unrelated shower. No separate ionization data on the candidate was obtained due to the density of the shower. Taking into account a 3% instrumental uncertainty, the authors do not regard the event by itself as evidence of quarks. In such an experiment only a characteristic distribution of a number of events would be convincing evidence for a quark.

The Copenhagen group (Bjornboe *et al.*, 1968) carried out two experiments. In the first experiment a counter telescope on the surface of the ground (at sea level) signaled an arriving air shower, and delayed pulses (> 2 times minimum) were sought in a detector of 1.6 tons of liquid scintillator at a depth of 3.6×10^3 g cm^{-2} of rock. A uniform time distribution of delayed particles was seen, numerically compatible with chance coincidences. The second experiment was a modification of the first wherein a delayed event was required to be accompanied by a second delayed pulse from a π-μ-e decay. In other words, events were sought corresponding to a massive, penetrating hadron delayed behind a shower and interacting to produce stopping π^+ mesons. Again no signals were observed over a random background. These two experiments set limits to the flux of such "plutons" (as the authors referred to their sought-for massive particles) less than 1 to 3×10^{-10} (cm^2 sr sec)$^{-1}$.

White and Prescott reported a less sophisticated search wherein a small air shower array was used in conjunction with two other counters, one unshielded and one shielded by 274 g cm^{-2}, to study possible delayed particles (White and Prescott, 1970). The shower array triggered when the particle density exceeded about 535 particles m^{-2}. The possible quark flux upper limit was set at 4×10^{-10} (cm^{2}sr sec)$^{-1}$ (90% confidence level).

The cosmic-ray group of the Tata Institute in Bombay has operated a detector system at Ootacamund, a mountain laboratory at 800 g cm^{-2} atmospheric depth (Tonwar, Naranan, and Sreekantan, 1972). Twenty scintillation counters arranged in an 80 m diameter array surrounded a 1.44 m^2 ionization calorimeter. The system was triggered on showers of electron numbers $6.7\times10^4 < N_e < 1.8\times10^6$ with the shower core within 20 m of the cloud chamber and direction within 30° of the zenith. About 65 000 showers were studied. The time delay between the air shower front and hadrons detected in a calorimeter was determined. From the initial operation a number of nucleons in excess of expectations based on results from 30 GeV accelerator data was reported. This is now more plausible in view of the rising antinucleon production seen at the CERN Intersecting Storage Rings. Indeed a number of delayed energetic particles were also detected, which correspond to a flux of approximately 1 to 2×10^{-9} (cm^2 sr sec)$^{-1}$. However these formed the tail of a continuous distribution of events in a pulse height-delay matrix of hadron signals; about 42 hadrons with $E > 20$ GeV and delay > 28 nsec were recorded. There are two arguments against these constituting a "quark" signal. First, as part of a smooth, continuous distribution, there is no evidence that they are a separate group with a greater mass; the only argument of the authors is that they are too frequent to be readily explained as nucleons. Second, McCusker (1975) suggests that they might be accidental coincidences between air showers with uncorrelated hadrons.

Subsequently, a large multiplate cloud chamber was added, and with a scintillator near its center to provide timing information, cleaner data were obtained (Tonwar, Sreekantan, and Vatcha, 1976). Two events have been seen in 2800 hours of operation; one of 110 GeV delayed 41 nsec, and the other of 80 GeV delayed 25 nsec behind their respective shower fronts. Although the cloud chamber photogtaphs show clean, impressive jets, the interpretation is not clear. First, the one scintillator layer in the cloud chamber, on which the energy measurement was based, provides a very uncertain measurement of the hadron energy; the authors state that the energies, if interpreted as electron–photon cascades, would be 36 and 28 GeV, respectively. Second, the noise levels were such that, in this running time, 0.1 accidental events would have been expected. If the energies are as low as 30 GeV, the particles could be surviving nucleons from interactions near the top of the atmosphere. If the results are taken serious-

TABLE IV. Cosmic ray quark search time delay experiments.

Group	Reference	Detector	Location	Showers studied	Candidates	Upper limit[a] quark flux φ $\times 10^{-10}$ (cm^2 sr sec)$^{-1}$
Copenhagen	Bjorneboe, 1968	1.6 ton liquid scintillator	Sea level plus 3.6×10^3 g cm^{-2}		Background of accidential events	1–3[d]
Echo Lake	Jones, 1967	Ionization calorimeter	715 g cm^{-2}	3×10^5	1	0.23 0.90[c]
Calgary	White, 1970	Scintillator counters	Sea level plus 274 g cm^{-2} Pb			4
Tata	Tonwar, 1972	Ionization calorimeter	800 g cm^{-2}	1.4×10^4	42	10–20[b]
Tata	Tonwar, 1976	Cloud chamber	800 g cm^{-2}		2	1[b]
Torino	Dardo, 1972	Scintillator counters	Sea level plus 7×10^3 g cm^2			300[b]
Torino	Briatore, 1975	Counters and spark chambers	Sea level plus 7×10^3 g cm^{-2}	719		12.5[d]

[a] 90% confidence level.
[b] Positive result reported (see text).
[c] One event observed, not claimed as evidence for quark.
[d] Delayed events detected compatible with background.

ly, the two events would correspond to a quark flux of about 1×10^{-10} (cm^2 sr sec)$^{-1}$. Although no charge determination of the interesting particles could be made, the results are of interest and subsequent similar experiments will warrant attention.

An experiment by a Torino–Freiburg group (Dardo *et al.*, 1972) studied the relative delay of pairs of particles underground under 7×10^3 g cm^{-2} of earth. An air shower would be manifested at such a depth as a few muons. If quarks were penetrating, they might be detected following muons in underground detectors. While early results suggested positive evidence for delayed particles with anomalously low ionization at a flux level of about 3×10^{-8} (cm^{2}sr sec)$^{-1}$, the most recent report of the group gave a negative result and withdrew the earlier claim (Briatori *et al.*, 1975). The results of these time delay experiments are summarized in Table IV.

E. Other cosmic-ray searches

Time delay experiments are sensitive to quarks of integral (including zero) charge produced in air showers for favorable values of quark velocity. Cloud chamber searches for fractional ionization within dense air showers are independent of time delay. However these experiments might miss quarks of integral charge among the primary cosmic-ray flux and not *a priori* produced in air showers. Several experiments have studied the spectrum of massive particles in cosmic rays, detecting combinations of range, ionization, and momentum.

Kasha and Stefanski (1968) employed a magnetic, time-of-flight mass spectrometer at sea level, inclined 75° from the vertical, to set a limit of 2.4×10^{-8} (cm^2 sr sec)$^{-1}$ on the intensity of hypothetical massive particles.

Franzini and Schulman (1968) used a three-element, nearly horizontal cosmic-ray telescope together with an absorber to measure range and velocity of cosmic rays incident at large zenith angles. By exploring velocities in the range $0.5\lesssim\beta\lesssim 0.9$ with 195 g cm^{-2} of aluminum absorber, the authors could select particles with $m > m_p$. The mean zenith angle of the telescope was 84°, so that, as with the Kasha spectrometer, air showers accompanying a candidate particle would have largely died out and possible quarks slowed down. No events were seen to a flux limit of 4.9×10^{-8} (cm^{-2}sr sec)$^{-1}$ (90% confidence limits). Hicks, Flint, and Standil (1973) operated a horizontal telescope of six scintillation counters with anticoincidence "tunnels" to veto air showers, in order to look for unaccompanied quarks of fractional charge. The minimum zenith angle of 75° corresponds to a minimum atmospheric overburden of 4 kg/cm^2, so that most accompanying air showers would be filtered, essentially as in underground single-particle searches. No evidence for particles of fractional charge was observed, corresponding to a quark flux upper limit of 1.7×10^{-8} (cm^2 sr sec)$^{-1}$ (90% C.L.) for either $q=\frac{1}{3}e$ or $q=\frac{2}{3}e$.

The Arizona group (Barber *et al.*, 1975) have also recently set up a magnetic spectrometer together with time-of-flight counters and have set upper limits to the flux of massive particles of 5 to 10 GeV rest mass of $\lesssim 10^{-6}$ (cm^{-2}sr sec)$^{-1}$.

A small experiment by Yock in Auckland, New Zealand (Yock, 1974) sought to repeat aspects of the Torino experiment using optical spark chamber, absorbers, and a set of six scintillation counters at a depth of 600 g cm^{-2} underground at sea level. The system was triggered on signals corresponding to $\beta < 0.69$, while the absorber assured that muons of $\beta<0.88$ were stopped and the spark chambers permitted rejection of stray tracks and accidental coincidences. The results indicate a flux of 6×10^{-9} (cm^{-2} sr sec)$^{-1}$ of particles with integral charge and mass greater than the deuteron. Although the apparatus was biased to select masses equal to or greater than 6 m_p, the author does not exclude the possibility that the particles observed may be tritons. A Sydney University group has set up a larger detector array to pursue this lead (McCusker, 1975).

The Durham group has operated a large vertical telescope to look for massive particles of integral charge through velocity and range measurements (Ashton, Edwards, and Kelly, 1969). Two thick water Cherenkov counters were used to veto particles with $\beta>0.8$, steel slabs provided the principle absorbers, several layers of neon flash tubes delineated the particle paths, and six scintillation counter layers determined timing and pulse heights. Two particles of integral charge and mass about 2 GeV were detected and ascribed to deuterons. The absence of other candidates sets a limit to the flux of quarks of integral charge, $\beta<0.8$, and mass greater than the deuteron to 4.9×10^{-10} (cm^{-2} sr sec)$^{-1}$ (90% confidence level). This experiment would probably not have been sensitive to quarks within dense air showers.

A rather similar system was assembled and operated by a Soviet group (Galper *et al.*, 1971), using spark chambers rather than neon flash tubes, together with solid plastic Cherenkov counters, iron absorbers, and scintillators in a vertical telescope to select particles within range and velocity limits. Operating both at sea level and at mountain elevations (3340 m), they set an upper limit of 3×10^{-8} (cm^2 sr sec)$^{-1}$ to the flux of single particles of $m>m_p$ and a velocity at the detector $\beta<0.67$.

An interesting experiment directed at a different astrophysical question, the possible existence of antimatter, has been reported by the Berkeley cosmic-ray group (Smoot, Buffington, and Orth, 1975). Using a balloon-borne superconducting magnetic spectrometer, they have looked for primary cosmic rays with $Z\leqslant-2$ with a momentum-to-charge ratio in the range from 4 to 100 GeV/c. For the lower part of this range, they have set limits on the ratio of antinuclei to nuclei of less than 8×10^{-5} (95% confidence level). This limit is relevant to the quark discussion perhaps only in the context of primary objects such as dyons, magnetic monopoles, or Yock's subnucleons.

One possibly related phenomenon was observed in a magnetic-field cloud chamber operated by the cosmic-ray group of Yunan Institute of Atomic Energy. They reported an event of anomalously low ionization (0.88 ± 0.11 times minimum) and high momentum (>48 GeV/c) (Yunan, 1972). There are three possibilities: it could be a $q=(2/3)e$ quark of large mass, a particle of integral charge but $M>12$ GeV (to be near the minimum of ionization), or a cloud chamber anomaly. Chamber illumination, vagaries of droplet formation, and other "quirks" are sources of continued concern with cloud chambers. Although the event merits interest, it also cannot of itself be taken as evidence for a new phenomenon.

An earlier report by a Leeds, England group (Baruch, Brooke, and Kellerman, 1973) of evidence for a new particle of mass 40–70 GeV has not been confirmed. This suggested particle, dubbed the "Mandella," was sought by other groups with negative results (Dardo *et al.*, 1975; Gopalakrishnan and Sreekantan, 1975; Barrows *et al.*, 1975). At the Munich Cosmic Ray Conference, the original authors announced that they had discovered an error in their analysis and withdrew their original claim (Kellerman, 1975). The neutrino group working in the Indian Kolar Gold Fields at depths of 3655 ft. and 7600 ft. have reported five unusual events (Krishnaswamy *et al.*, 1975). In about ten years of operation they have found evidence for 20 neutrino interactions. Of these five appear to show evidence for the decay in flight of a particle between the rock wall of the mine tunnel and the spark chamber detector. Evidence for two or three decay particles is seen, but it is uncertain whether the parent particle is charged or neutral, as the detectors could easily have missed one or more charged decay prongs. The authors state that the average path length in air for decay of these particles is 70 cm; from this and characteristics of the decay they state that $\tau>10^{-9}$ sec, $m>2$ GeV, and σ (production) $>10^{-37}$ cm^2. As the mean neutrino energy is about 7 GeV, the frequency of occurrence seems to preclude a mass above 5 GeV. It is tempting to criticize the technique and the data interpretation, although the group has proven technically sound in the past. DeRujula, Georgi, and Glashow (1975) suggested that these events could be explained by the production of a new lepton, L^-, in primary cosmic-ray interactions in the atmosphere. If L^- decayed promptly to L° and L° decayed only weakly ($10^{-3}>\tau>10^{-6}$ sec), it might produce the observed decays as reported. However, in this case the same particle should be seen in experiments at Fermilab, either in the 15 ft bubble chamber or in the electronic experiments. One of the groups working there reported negative results of a search for such particles (Benvenuti *et al.*, 1975), either produced by neutrino interactions in matter or in proton cascades as suggested by DeRujula and Georgi. With a higher mean neutrino energy (20 GeV) they should have detected about 600 of the decay-in-flight events in their experiment, whereas only two candidates were observed, as expected from the small amount of residual material in their decay volume. They thus exclude particles of $2<m<5$ GeV decaying in flight and produced in either neutrino reactions or in proton cascades as reported by Krishnaswamy. Thus if the cosmic-ray observations are not spurious, their source must in some way involve phenomena not present in the 300 GeV proton interactions.

It is outside the scope of this review to discuss evidence for unstable particles of very short lifetimes ($<10^{-10}$ sec) reported from cosmic-ray experiments. These may have some bearing on searches for particles with charm quantum numbers or other massive hadron states. They are not presumed to be relevant to quark searches.

In summary then, cosmic-ray experiments have set significant upper limits to the flux of quarks of $(1/3)e$ and $(2/3)e$ charge. At the same time, there are some continuing suggestions of unusual phenomena such as massive particles in cosmic rays, although there is no evidence that they would be of fractional charge. No one experiment is yet convincing, even to its authors (from this author's personal perceptions), as evidence for $Z \geq 1$ anomalous objects, and the different experiments with positive suggestions do not indicate the same phenomenon.

It does not seem profitable to group these miscellaneous searches in a table; they are too disparate and unique in their parameters. They nevertheless add a further dimension to the negative results from cosmic-ray searches, especially with regard to possible quarks of integral charge.

F. Magnetic monopoles

Magnetic monopoles are somewhat peripheral to a discussion of quarks, but as postulated stable, elementary particles, they deserve some attention here. If magnetic monopoles exist, it can be simply shown that electric charge is quantized. The Dirac monopole should have a magnetic "charge" given by $g_D = 137e/2$ (Dirac, 1931), and possible real monopoles have been sought for various values of n, where $n = g/g_D$. The ionization produced by a relativistic monopole of magnetic charge g passing through matter would be $g^2 = 4700\ n^2$ times that of a singly charged electric particle. This very large anomalous ionization forms the basis for many monopole searches using emulsions, scintillation counters, and etched plastic detectors. The fact that a monopole passing through a solenoid would induce a direct current signal has been used by Alvarez and his co-workers as a basis for a detection device (Eberhard *et al.*, 1971). Monopoles would be accelerated along magnetic field lines, and various experiments have used solenoids in conjunction with ionization detectors to seek monopoles in targets of particle accelerators and in geological samples. Monopoles might also be expected to concentrate on magnetic materials, such as iron meteorites and magnetite iron ore.

Magnetic monopoles have been sought with particle accelerators, in cosmic rays, and among stable matter, just as have quarks of fractional electric charge. Among particle accelerators, searches have been carried out at the CERN PS (Amaldi *et al.*, 1963) and the Brookhaven AGS (Purcell *et al.*, 1963), at Serpukhov (Gurevich *et al.*, 1970; Barkov *et al.*, 1972; Gurevich *et al.*, 1972), at the Fermilab 300–400 GeV synchrotron (Carrigan, Nezrick, and Strauss, 1973; 1974; Eberhard *et al.*, 1975), and at the CERN ISR (Giacomelli *et al.*, 1975). The upper limit monopole masses are of course limited by kinematics with each accelerator (as are quark searches) assuming pair production of monopoles. The upper limits to monopole production in proton–nucleon collisions has been set at about 10^{-40} cm^2 (30 GeV), 10^{-43} cm^2 (70 GeV), 10^{-43} cm^2 (300 GeV), and 10^{-36} cm^2 (1500 GeV) (where the figures in parentheses are the proton energies). Carrigan (Carrigan and Nezrick, 1975) also searched CERN heavy-liquid bubble chamber film for monopole signals and set upper limits of 10^{-39}–10^{-37} cm^2 for production by neutrinos of 1–8 GeV. The most sensitive accelerator limit (Eberhard *et al.*, 1975) corresponds to monopole production in proton–nucleon interactions of less than 10^{-18} per interaction.

Monopoles moving along magnetic field lines from cosmic-ray production, or perhaps as primordial cosmic rays, have been sought by Carithers using spark chambers, scintillation counters, and emulsions (Carithers, Stefanski, and Adair, 1966) and by Fleischer (Fleischer, Price, and Woods, 1969; Fleischer *et al.*, 1970; 1971) seeking tracks in Lexan and in geological samples of mica and obsidian. These experiments set upper limits to the cosmic-ray monopole flux of about 3×10^{-19} (cm^2 sr sec)$^{-1}$.

By "extracting" monopoles from geological samples with a strong magnetic field and seeking an ionization signal upper limit, monopole concentrations in stable matter may be set. This has been done by various experiments (Goto, Kolm, and Ford, 1963; Petukhov and Yakimenko, 1963; Fleischer *et al.*, 1969**a**, **b**; Kolm, Villa, and Odian, 1971). The more direct search method of placing samples (rocks, lunar soils, etc.) in a device wherein they are circulated through a coil in which a direct current signal is sought is perhaps most easily interpreted (Eberhard *et al.*, 1971; Ross *et al.*, 1973). The lunar soil yielded negative results, corresponding to an upper limit monopole concentration of 2×10^{-28} monopoles per nucleon (95% confidence level), corresponding to a monopole flux upper limit of about 10^{-18} (cm^2 sr sec)$^{-1}$. The less direct searches have set comparable flux and concentration limits. The terrestrial limits of Fleischer have also been reanalyzed assuming cosmic-ray neutrinos would produce monopoles (Carrigan and Nezrick, 1971). Upper limit monopole production cross sections for $\nu + N \to$ magnetic monopole are $\sigma < 10^{-39}\, E_T^2$ cm^2, where E_T is the monopole production threshold energy in GeV.

Considerable excitement was generated when Price announced that a magnetic monopole had been detected (Price *et al.*, 1975). The detector consisted of a stack of Lexan foils together with a layer of nuclear emulsion and a second photographic film to serve as a Cherenkov detector. The array was exposed in a balloon flight for the purpose of studying the flux of primary cosmic-ray heavy ($Z > 28$) nuclei. The observed event would correspond to a monopole flux of 3.4×10^{-13} (cm^2 sr sec)$^{-1}$, based on Price's analysis. Several other investigators have subsequently criticized the monopole interpretation of that event, contending rather that the candidate was probably a heavy nucleus ($Z \simeq 69$) which experienced one or more nuclear interactions in the detector stack (Alvarez, 1975; Fowler, 1975; Friedlander, 1975; Fleischer and Walker, 1975). It was further argued that a flux of primordial monopoles as great as 10^{-16} (cm^2 sr sec)$^{-1}$ would lead to decay of the galactic magnetic fields (Parker, 1970). On the other hand, the large mass and low velocity ($\beta \simeq 0.5$) deduced from Price's observation preclude the candidate from being a product of a primary cosmic-ray interaction in the upper atmosphere (Badhwar *et al.*, 1976; Wilson, 1975; Hungerford, 1975). A summary by Ross concludes that, if the monopole flux were as great as stated by Price, other experiments would have detected 10^4–10^6 monopoles where none were seen, the exact limit dependent on the assumed mass, magnetic charge, and kinetic energy of the monopole (Ross, 1976). In a recent paper, Price notes that indeed the monopole interpretation of the event may not be unique, but argues (on the basis of emulsion evidence) that the other interpretations involve truly exceptional nuclear objects, such as an antinucleus of $Z \cong -82$, a nucleus of $Z \gtrsim +116$, or a nucleus of $Z \sim 96$ but a rest mass of thousands of atomic mass units (Price, Shirk, and Osborne, 1976).

At least at this time, it seems that the weight of evidence against the monopole interpretation of the Price event is sufficiently convincing that it should not yet stand as evidence for the discovery of a free Dirac magnetic monopole.

On the other hand, there appears to be no theoretical reason why they should not exist as physical objects. One suggestion has been advanced (Ruderman and Zwanziger, 1969) that monopoles might be pair-produced in high-energy interactions but that they would reannihilate with nearly 100% probability in spite of their intrinsic stability because of the very strong, long-range force predicted from the Dirac theory. The consequence of such reannihilations would be anomalous γ-ray events produced in cosmic rays or at high-energy particle accelerators. Some years ago cosmic-ray physicists indeed reported several unusual γ-ray events in nuclear emulsions (Schein, Haskin, and Glaisser, 1954; Debenedetti *et al.*, 1954, Koshiba and Kaplan, 1955; Silva *et al.*, 1956). Recently a search was made for such events at the Fermi National Accelerator Laboratory and none were observed to a level of 10^{-2}, the cross section required to account for the cosmic-ray observations (Burke *et al.*, 1975). Whatever the explanation for these cosmic-ray observations, there is no reason at this time to ascribe them to magnetic monopoles.

G. Tachyons

It has been observed that Einstein's equations relating mass to energy, velocity, and other kinematic variables in principle permit the existence of particles with velocities greater than the velocity of light (Bilaniuk, Deshpande, and Sudarshan, 1962; Feinberg, 1967; Recami and Mignani, 1974; Feldman, 1974). Such particles would speed up as they lose energy and would never be observed with $v \leq c$. Should they exist, they should not only be observable through their ionization in conventional particle detectors, they should also produce Cherenkov radiation in vacuum.

A number of experiments were carried out looking for evidence of tachyons between 1968 and 1971, all with negative results (Alvager and Kreisler, 1968; Davis, Kreisler, and Alvager, 1969; Baltay *et al.*, 1970; Danburg *et al.*, 1971; Ramana Murthy, 1971). In the experiment of Ramana Murthy, a signal was sought corresponding to a charged particle preceding the relativistic front of an air shower.

A similar technique was employed by Clay and Crouch (1974) and a positive result was reported. Other groups sought to repeat this experiment and subsequently reported negative results (Fegan *et al.*, 1975; Hazen *et al.*, 1975; Emery *et al.*, 1975). Meanwhile a careful re-examination of the Clay and Crouch data revealed an artifact of the apparatus which contributed to the original apparently significant result (Prescott, 1975). Consequently, it appears safe to assume that no significant positive evidence for tachyons exists at this time.

IV. ACCELERATOR SEARCHES

A. Searches for particles of fractional charge in hadronic reactions

Particle accelerators have provided the strongest negative evidence for quarks through the energies accessible to them. A series of sensitive experiments have been carried out at every high-energy accelerator above 20 GeV. Very soon after the suggestion of the existence of physical quarks, bubble chamber physicists rescanned earlier film to search for tracks with anomalous ionization (Morrison, 1964; Bingham *et al.*, 1964; Hagopian *et al.*, 1964). Subsequently the CERN 81 cm bubble chamber was operated with auxilliary detectors in a beam optimized for the presumed production kinematics of quarks (Blum *et al.*, 1964). Other counter experiments were also instrumented to search for quarks in various ways. Franzini used an electrostatic velocity selector in a bubble chamber beam to search for quarks (Franzini *et al.*, 1965), while Adair's group considered that quarks might be penetrating and looked for fractional-charged particles which penetrated 1.5 m of concrete at the Brookhaven Alternating Gradient Synchrotron (AGS). Other searches used time-of-flight and momentum analysis primarily, and obtained limits on massive particle production independent of charge (Dorfan *et al.*, 1965b). These searches are summarized separately in Sec. IV. C below. Lederman's group emphasized the fact that the kinematic limit for quark production is extended by virtue of the Fermi motion of target nucleons (as discussed in Sec. II. A above), and demonstrated the point by experiments on $\bar{p}$ production below 6 GeV (Dorfan *et al.*, 1965a) and antideuteron production at the Brookhaven AGS (Dorfan *et al.*, 1965c). This point was important in the 1960s; however, at this time the CERN Intersecting Storage Ring (ISR), a proton–proton colliding-beam storage ring system, provides the highest accelerator energy and overlaps the kinematic threshold extensions of fixed-target accelerators.

Most of the experiments at accelerators employed a telescope of several scintillation counters in a secondary beam with pulse height analysis of each, as indicated schematically in Fig. 10. As searches pressed to lower limits, more auxilliary devices were added. Thus the early experiments used only scintillation counters (Leipuner *et al.*, 1964), while later, streamer chambers (Allaby *et al.*, 1969), Cherenkov counters (Antipov *et al.*, 1969), time of flight, and multiwire proportional chambers (Fabjan *et al.*, 1975) were included to improve the rejection of integral-charge particles and various false signal sources.

The solid angle subtended by each beam and telescope system was small enough so that the question of accompanying particles from the primary interaction was not important. A particularly clean experiment is pos-

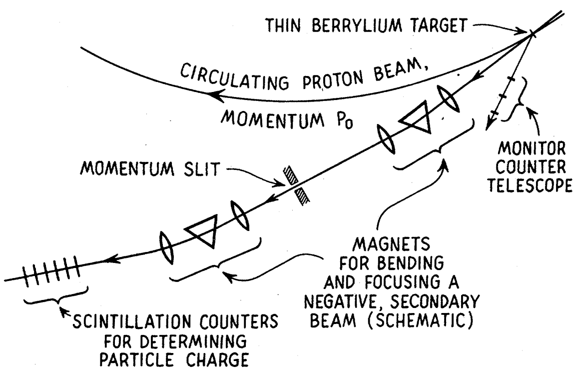


FIG. 10. Greatly simplified diagram of the typical quark search experiments at high energy proton accelerators.

sible in searching for particles of charge of $(1/3)e$. Here the secondary beam may be tuned to bend and focus particles of integral charge of greater than the incident proton momentum (e.g., 1.2 p_0), although kinematically allowed quarks (e.g., of 0.4 p_0) would be transmitted. The only particles transmitted are those from slit scattering or other accidental effects, and they are readily discriminated against by ionization. The CERN experiment (Allaby *et al.*, 1969), the Serpukhov experiment (Antipov *et al.*, 1969), and one of the FNAL experiments (Nash *et al.*, 1974) employed this technique in their searches. However, the other FNAL experiment (Leipuner *et al.*, 1973) used no magnetic analysis, and thus accepted a continuous momentum range.

An elaborate experiment was done at the CERN ISR where a set of six scintillation counter telescopes was employed to simultaneously sample several ranges of production angle. This experiment, reported in preliminary form in 1972 (Bott-Bodenhausen *et al.*, 1972), and in final form in 1975 (Fabjan *et al.*, 1975), used no magnetic analysis and, as it spanned a range of production angles (through 0°), it was less sensitive to production model assumptions than most other searches. The apparatus is sketched in Fig. 11. It suffered in sensitivity from the luminosity available from the ISR, equivalent to a proton beam of 10^5–10^6 per pulse on a stationary target. However, the production cross-section limits set are still orders of magnitude lower than cosmic-ray searches even up to masses of about 25 GeV, corresponding to operation at an equivalent laboratory energy of almost 1500 GeV. The quark flux upper limits measured at the ISR are not expressed in units of $d^2\sigma/d\Omega dp$, but in terms of ratios of the fractional-charge flux to the flux of integral-charge particles.

The results of experiments at the Brookhaven 33-GeV Alternating Gradient Synchrotron (AGS), the 28-GeV CERN Proton Synchrotron (PS), the 70 GeV Serpukhov Proton Synchrotron, the Fermilab 200–400 GeV Proton Synchrotron, and the CERN ISR are summarized in Table V. The data are first in terms of an upper limit quark flux per interacting proton at particular production angle and momentum ranges. These fluxes, in terms of double differential cross sections $d\sigma/d\Omega dp\,[\mathrm{cm^2 sr^{-1}(GeV}/c)^{-1}]$, may then be related to production cross sections using various assumptions concerning the production distributions through expressions such as Eqs. (2.10)–(2.11). For example, the BNL AGS, CERN PS, and the Serpukhov experiments assumed an isotropic (cm) final state quark distribution with momenta distributed according to the phase space of two nucleons and two quarks. This is probably overly conservative, based on production processes for other massive particles ($\bar{p}$, ψ, etc.). The Fermilab experiments considered production models now known to be more typical for such heavy particles. The Yale–BNL group (Leipuner *et al.*, 1973) assumed

$$d^3\sigma/dp^3 = C \exp(-Ax)\exp(-p_\perp^2/p_0^2),$$

where x is the ratio of longitudinal momentum to its maximum value and $p_\perp$ is the transverse momentum. They found their observed flux limits could be interpreted in terms of production cross sections with little sensitivity to the assumed values of A and p_0 over the ranges $2 < A < 12$ and $0.4 < p_0 < 2.0$ GeV/c. The Yale–BNL group extended their search beyond the data published from 300-GeV interactions by operating their apparatus with 400 GeV protons incident on the production target. The unpublished negative results of this search set less significant quark flux limits than the published 300 GeV data (Leipuner, 1976). The other Fermilab group (Nash *et al.*, 1974) used a modified four-body phase space calculation constrained by a multiplicative factor of $\exp(-6p_\perp)$. They also compare predictions based on this model with those based on the unrestricted four-body phase space model, isotropic in the center of mass. For the mass corresponding to the most sensitive cross-section limit, the isotropic model limits are about two orders of magnitude greater (less sensitive) than the limits from the model with damped transverse momentum. Zaitsev and Landsberg (1972) have also recalculated the cross-section limits corresponding to a differential cross section parametrization matching antiproton production at Serpukhov. Their limits are lower (more sensitive) than the isotropic limits for $q = \frac{1}{3}e$ by about an order of magnitude, but higher (less sensitive) for $q = \frac{2}{3}e$, in both cases converging toward the isotropic limits at 4.8 GeV, the kinematic upper limit quark mass. The CERN ISR experimenters used a model similar to that of Nash (Nash *et al.*, 1974), and tabulated results for both four-body isotropic phase space and phase space restricted

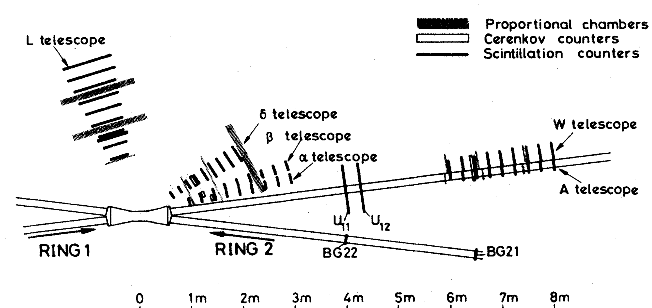


FIG. 11. Schematic drawing of the quark search experiment at the CERN ISR (Fabjan, 1975).

TABLE V. Accelerator searches for quarks of fractional charge.

Accelerator	Reference	Detector system	Proton beam momentum (GeV/c)	Beam angle (mrad)	Quark beam momentum (GeV/c)	Charge
CERN PS	Morrison, 1964	30 cm hydrogen bubble chamber	24.8	70	5.3	−1/3
					10.7	−2/3
CERN PS	Bingham, 1964	1 m freon bubble chamber	24.8	77	5.3	−1/3
					10.7	−2/3
BNL AGS	Hagopian, 1964	2 m hydrogen bubble chamber	31	120	2.83	+1/3
					5.67	+2/3
CERN PS	Blum, 1964	81 m hydrogen bubble chamber	27.5	77	6.7	−1/3
					13.3	−2/3
BNL AGS	Leipuner, 1964	7 pulse height scintillation counters	29	~0	...[f]	±1/3
				314	1.5	−1/3
BNL AGS	Franzini, 1965	Electrostatic mass separator, time-of-flight	31	120	4.7	−2/3
BNL AGS	Dorfan, 1965b	Time-of-flight, momentum	31	76	6.0	−2/3
CERN PS	Allaby, 1969	6 pulse ht. scint. ctrs.	27.2	0	10.9	−1/3
		6 triggers ctrs.	26.4	0	21.4 }	
		2 threshold Cherenkov ctrs.		6.5	14.7 }	−2/3
				6.5	13.3 }	
		1.1 liter isotropic spark chm.		44	6.7	+1/3
				44	13.3	+2/3
SERPUKOV	Antipov, 1969a	10 pulse ht. scint. ctrs.	70	0	13.3 }	−1/3
	Antipov, 1969b	2 threshold Cherenkov ctrs., time-of-flight, wide gap spark chamber-magnetic spectrometer			16.7 }	
					21.5 }	−2/3
					26.7 }	
					26.6 }	
					33 }	
					43 }	
					53.3 }	
FNAL	Leipuner, 1973	8 pulse ht. scint. ctrs.	300	6.5	...[f]	±1/3
					...[f]	±2/3
		2 threshold Cherenkov ctrs.		6.5	80	−4/3
FNAL	Nash, 1974	8 pulse ht. scint. ctrs.	200	1	90	−1/3
		2 Cherenkov ctrs.,			69	−1/3
		muon identifier			50	−1/3
			300		90	−1/3
					69	−1/3
					50	+1/3
			200		180	−2/3
					138	−2/3
					100	+2/3
			300		180	−2/3
					138	−2/3
					100	+2/3
CERN ISR	Fabjan, 1975	6 telescopes; each with 9 pulse ht. scint. ctrs.,	1500 h	9–24[i]	...[f]	±1/3
				20–62		±2/3
				104–170		
		3 multiwire prop chambers,	1100	190–255		±1/3
				390–555		±2/3
		1 plastic Cherenkov ctr., time-of-flight	2000	1040–1330		±2/3
						±2/3

[a] Cross section derived from flux values assuming $N+N \rightarrow N+N+q+\bar{q}$, isotropic phase space of four-body final state, unless otherwise stated.
[b] Not quoted by authors, inferred from flux data.
[c] Values are 90% confidence level flux upper limits.
[d] This measurement included 1.5m concrete in the beam path to search for quarks with 3 mb.
[e] Values differ by ±15% depending on assumed interactions of quarks with beam material. Figures here assume $\sigma(\text{quark}) \equiv 1/2\ \sigma(\text{pion})$.

Upper limit quark flux $\frac{d^2\sigma}{d\Omega dp}\left(\frac{\text{cm}^2}{\text{sr GeV}/c}\right)$	Quarks per pion	Quark mass range (GeV/c^2)	Quark mass at maximum sensitivity (GeV/c^2)	Quark production cross section [a] (cm^2)
4.8×10^{-34}	10^{-5}	0.5–2.46	2.0	4×10^{-34}
			2.0	8×10^{-34}
1×10^{-36}	10^{-6}	0.5–2.46	1.6	3×10^{-35} [c]
2×10^{-36}			1.6	6×10^{-35} [c]
	10^{-5}	0.5–2.5	2	8×10^{-34}
		0.5–3		10^{-33} [b]
9.5×10^{-36}	6×10^{-6}	0.5–2.5	2	2×10^{-35}
	3×10^{-8}			2×10^{-35}
				1×10^{-34} [d]
	$5\times10^{-10}(\mu)$			
	2×10^{-9}	2–3	2.8	2×10^{-35} [b]
1.5×10^{-36}	2.5×10^{-11}	<3.0		10^{-36}
7.2×10^{-39}			2.7	3.2×10^{-39} [c]
5.2×10^{-38}			2.4	5.5×10^{-38} [c]
2.6×10^{-35}			2.5	1.8×10^{-35} [c]
1.3×10^{-35}			2.5	1.0×10^{-35} [c]
{ 4.9×10^{-34} 1.4×10^{-35} } [e]		2–5	4.7	1×10^{-39} [c]
(3.6×10^{-37} 7.1×10^{-38} 2.8×10^{-34} 7.7×10^{-36} 2.1×10^{-37} 4.1×10^{-38}) [e]		2–5	4.9	2×10^{-37} [c]
10^{-35}	7×10^{-10}	1–12	11	1×10^{-35} [g]
		1–12	11	1×10^{-35} [g]
	10^{-5}	2–12	11	5×10^{-31} [g]
5.6×10^{-36} 5.6×10^{-35} 8.0×10^{-35} 5.1×10^{-34} 1.0×10^{-34} 4.8×10^{-33}		2–10	8.8	6×10^{-38} 10^{-39} [g]
2.8×10^{-36} 2.8×10^{-35} 4.0×10^{-35} 2.5×10^{-34} 5.0×10^{-35} 2.4×10^{-33}		2–12	11	2×10^{-37} 3.5×10^{-39} [g]
	7.18×10^{-10}	1–24	20	4×10^{-35} 8×10^{-35} [g]
	4.36×10^{-9}	1–19	15	2.3×10^{-34} [b] 4.6×10^{-34} [b]
	1.07×10^{-6}	1–29	25	6×10^{-32} [b] 1.2×10^{-31} [b]

[f] Neutral beam channel, no magnetic deflection.
[g] Cross sections derived from flux assuming limited transverse momentum distributions (see text).
[h] Colliding proton beams; storage rings tuned to 26.6 GeV/c, 22.3 GeV/c, and 31 GeV/c to give $s=2830$ GeV^2, 2080 GeV^2, and 3844 GeV^2. Values listed are equivalent beam momenta on a stationary target.
[i] Each set of six telescopes operated at all three ISR momentum settings.

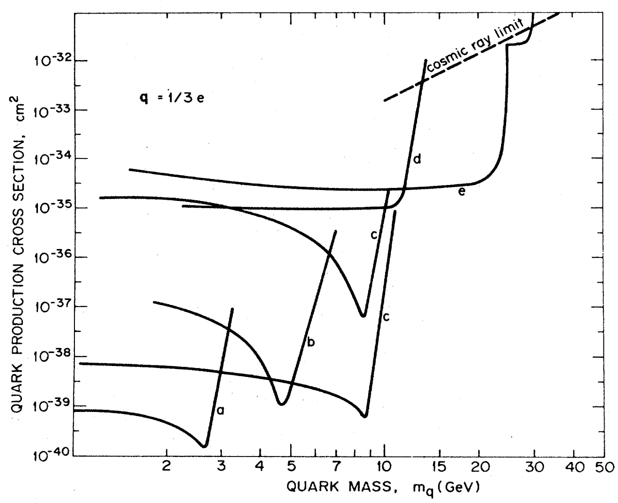


FIG. 12. The 90% confidence level upper limit quark production cross sections from various accelerator experiments for quarks of charge $q=1/3e$. The various curves are from cited references as follows: a (Allaby, 1969), b (Antipov, 1969), c (Nash, 1974), d (Leipuner, 1973), e (Fabjan, 1975). The two curves c represent two production models applied to the same flux data. The dashed line represents the corresponding production cross section limit set by cosmic ray experiments, assuming an upper limit quark flux of 10^{-11} (cm² sr sec)$^{-1}$ and Eq. 3.13.

to follow a Gaussian transverse momentum distribution with $\langle p_\perp \rangle = 0.4$ GeV/c. Because of the angular coverage of the several telescopes, the isotropic assumption leads to less sensitive cross-section limits by only one order of magnitude compared with the restricted transverse momentum assumption.

The various groups considered thresholds and cross sections for quark pair production

$$N+N \to N+N+q+\bar{q} \tag{4.1}$$

and for quark triplet production by diffraction dissociation

$$N+N \to N+q+q+q. \tag{4.2}$$

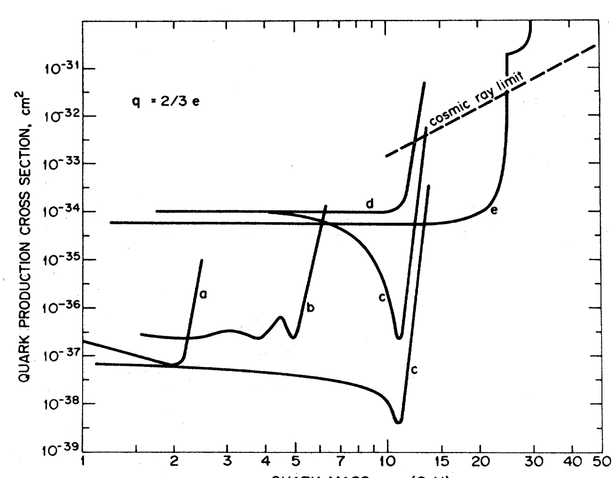


FIG. 13. The 90% confidence level upper limit quark production cross sections from various accelerator experiments for quarks of charge $q=2/3e$. The curves are labeled as in Fig. 12.

For a given assumed quark mass, the threshold for pair production is lower than for triplet production. As there is no *a priori* wisdom concerning the relative cross sections for the two processes, the comparison between various experiments and the upper limit production cross sections in this section is based on the pair production cross section Eq. (4.1), with energetics as noted in Eqs. (2.7), (2.8).

The production cross sections of the most sensitive searches from each range of accelerator energies is given in Fig. 12 for $q=\pm(1/3)e$ quarks and in Fig. 13 for $q=\pm(2/3)e$ quarks. Earlier searches at the Brookhaven AGS and the CERN PS are not represented on the figure as the later experiments comfortably exceed the earlier sensitivity. Isotropic limits and limits which constrained $p_\perp$ are presented on the graphs, according to the form in which the data has been presented by the authors, except for the Fermilab data of Nash where both are shown. Also noted on the graph is a cosmic-ray limit corresponding to a quark flux of less than 10^{-11} particles per (cm² sr sec) according to the Gaisser and Halzen calculation of Eq. (3.13).

B. Electromagnetic searches

A discrete class of experiments was carried out searching for quarks produced electromagnetically, i.e., through pair production, at electron accelerators. If quarks are point particles, then electromagnetic pair production should be calculable from the Bethe–Heitler formula dependent only on charge and mass of the quarks. This is rigorously true only if such particles are also only weakly coupled to other fields. Quark pair production could be suppressed below the Bethe-Heitler prediction through radiation of mesons (via the strong interaction) leading to a strong radiation damping. The Bethe–Heitler formula is nevertheless the basis for the calculated quark mass limits referenced in these experiments. There have been three searches reported: A search at the Deutsches Electron Synchrotron (DESY) using a 6 GeV electron beam (Bathow *et al.*, 1967), a search at the Cambridge Electron Accelerator (CEA) using a 6 GeV bremsstrahlung beam (Foss *et al.*, 1967), and a search at the Stanford Linear Accelerator Center (SLAC) using a 12 GeV electron beam (Bellamy *et al.*, 1968).

The 6 GeV searches were restricted to truly leptonic quarks, as there were large quantities of absorber in the beam (to reject e^+e^- pairs). At CEA, there were 200 radiation lengths, or about 10 nuclear mean free paths, of material ahead of their first counter, and 14 r.l. of lead between each of eight counters. The DESY search used 90 r.l. of lead and 30 r.l. of concrete ahead of the counter system. If quarks were non-strongly interacting, the CEA experiments excluded the existence of quarks of $q=(1/3)e$ with: 0.5 MeV $\leq m_q \leq$ 780 MeV and of $q=(2/3)e$ with: 2.0 MeV $\leq m_q \leq$ 840 MeV.

The SLAC experiment used much less absorber; instead, an existing muon beam was employed and tuned

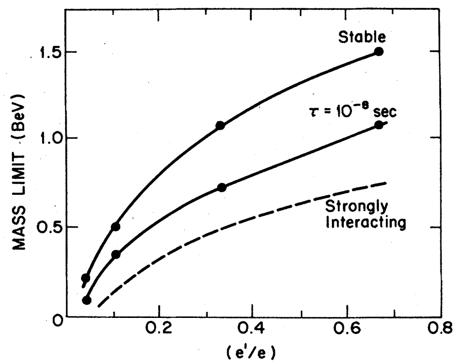


FIG. 14. Limits to the mass and charge of possible quarks produced electromagnetically set by the SLAC experiment (Bellamy, 1968).

to 12.5 GeV/c for particles of integral charge. The electron target was 16 r.l. of Cu, a 2 cm filter was placed at the first focus, and the counters used were five large NaI(Tl) crystals, four of them 12.5 cm thick. Hence even here there was significant attenuation of any strongly interacting particle. The mass limits on the existence of stable quarks, assuming and not assuming strong interactions, are summarized in Figure 14, where the values plotted refer to 95% confidence limits. If quarks are extended, e.g., if they have a form factor like the nucleon, the sensitivity of the experiment is reduced correspondingly. Although these limits do not bear strongly on the existence of massive quarks ($m_q > m_N$), they represent perhaps the most convincing evidence against the existence of free, pointlike quarks with masses close to $\frac{1}{3}\, m_N$, as no production assumptions beyond well-established electromagnetic theory are involved. There have been three classes of searches for new leptons of integral charge using particle accelerators: neutrino beams, electron-positron collisions, and proton beams have all been used. Although the latter will be included under Sec. IV. C below, the leptonic searches are summarized here. A heavy lepton with the same quantum numbers as the μ and decaying weakly into ν_μ + hadrons or alternative leptonic decays was the subject of a search in the CERN Gargamelle neutrino exposure film (Asratyan *et al.*, 1974). No evidence for such particles was found setting a mass lower limit of 1.8 GeV (90% C. L.). Three experiments have looked for evidence for a massive lepton with the same quantum number but opposite charge of a muon (Eichten *et al.*, 1973; Barish *et al.*, 1973, 1974). Mass limits have been pushed up to 8.4 GeV (90% C. L.) for such an object.

Benvenuti *et al.*,(1975a) have observed muon pairs produced in nuclear interactions by ν_μ and $\bar{\nu}_\mu$ interactions at Fermilab. They favor the interpretation that these events are evidence for charmed hadron production, although they state that production of a heavy neutral lepton cannot be ruled out.

Experiments at the Frascati e^+e^- colliding-beam facility have looked for evidence for production of heavy leptons, perhaps with new quantum numbers. As in the case of searches for leptons of fractional charge, the production cross sections should be accurately predictable from quantum electrodynamics. Bacci *et al.* (1973) looked for $e^+e^- \to e^\pm e^{\mp *}$ with $e^{\mp *} \to e^\mp + \gamma$. They have excluded the existence of such heavy electrons for $0.6 < m_{e^*} < 2.2$ GeV to 95% confidence level. They also looked for $e^+e^- \to \mu^\pm e^\mp$ + neutrals, where the final state leptons would be the weak decay products of a new lepton with new quantum numbers; e.g., $U^+ \to \mu^+ + \nu_\mu + \bar{\nu}_U$; or $U^+ \to e^+ + \nu_e + \bar{\nu}_U$ (Alles-Borelli, *et al.*, 1970; Bernardini *et al.*, 1973; Orito *et al.*, 1974). The more recent experiments set lower limits of 1.0–1.4 GeV (95% C.L.) on the masses of new leptons.

There has recently been a report from the Stanford electron-positron colliding-beam facility of the discovery of a massive lepton (Perl *et al.*, 1976). The data indicate a mass of about 1.8 GeV for such leptons, which are presumably produced in pairs and decay into the observed charged leptons. The signature observed is a muon-electron pair of opposite charge which is noncoplanar and unaccompanied either by charged or (less assuredly) neutral hadrons or γ's. This result has not been confirmed and should be regarded as tentative at this time.

C. Integral-charge experiments

Free stable quarks might exist with unit charge, charge of $(4/3)e$, or perhaps even greater, as mentioned in the Introduction and in the discussion of cosmic-ray quark searches. Accelerator experiments have been performed to search for stable particles more massive than the proton over the range of masses scanned in the fractional-charge searches. The basis for all of these experiments is a simultaneous measurement of energy or momentum and velocity or time of flight.

As noted in Sec. III. D [Eq. (3.21)], the time delay Δt of a massive particle relative to one with $v = c$ is given by

$$\Delta t \cong L/2\gamma_q^2 c,$$

where L is the flight path between timing counters. For $\gamma \gg 1$,

$$\Delta t \cong L m_q^2/2cp_q^2 \cong L m_q^2/2cE_q^2 .$$

These experiments have identified antideuterons produced at each of the accelerators with $E > 25$ GeV, and have established the ratio of antideuteron to antiproton production. The first detailed experiment in this group was carried out at Brookhaven (Dorfan *et al.*, 1965c) and was discussed in Section IV. A. Other early experiments, also discussed in Section IV. A and tabulated in Table V, were as sensitive to integral charge as to fractional charge (Franzini *et al.*, 1965). Antideuterons were also studied at Serpukhov (Binon *et al.*, 1969; Antipov *et al.*, 1971a, b) and upper limits set to the production of other negative particles of integral charge. At Fermilab the Yale-BNL group also set limits on the production of more massive particles by time of flight, although the primary emphasis was on fractional charge (Leipuner *et al.*, 1973). More recently, the Columbia group made a specific search for particles of unit charge or greater, and studied antideuteron pro-

TABLE VI. Accelerator searches for massive, stable particles of integral charge.

Accelerator	Reference	Detector	Proton beam momentum (GeV/c)	Quark momentum per unit charge GeV/qc	Quark charge (in units of e)
BNL AGS	Franzini, 1965	Electrostatic separator time-of-flight	31	7	−1
BNL AGS	Dorfan, 1965b,c	Momentum, t.o.f.	31	4–10	−1
Serpukov	Binon, 1969	Momentum, t.o.f., 6 threshold Cherenkov ctr.; disc Cherenkov ctr	70	25 31.4 39	−1 −1
Serpukov	Antipov, 1971a; Antipov, 1971b	Momentum, t.o.f. Cherenkov ctrs. pulse ht.	70	13.3	−4/3
Serpukov	Antipov, 1971c	Momentum, t.o.f. Cherenkov ctrs. pulse ht.	70	10	−2
FNAL	Leipuner, 1973	Ionization momentum, t.o.f. r.f. structure	300	... [b] 60	±4/3 1
FNAL	Appel, 1974	Momentum t.o.f. Cherenkov ctr. r.f. structure	300	25–35 75 150 50 75 150	−1 −1 −1 +1 +1 +1
FNAL	Gustafson, 1976	Ionization calorimeter r.f. structure	300	$7 < \gamma$ 16 [c]	0
CERN ISR	Alper, 1973	Momentum time-of-flight	1500	>9 ($0.2 < \beta < 0.65$)	−2/3 −1 −4/3
CERN ISR	Jovanovich, 1975	Momentum dE/dx energy of stopped particles, t.o.f.	1500 1000		2/3 4/3 2
CERN ISR	Albrow, 1975	Momentum, t.o.f. Cherenkov ctrs. wire spark chms.	1500	4–10	±1 ±4/3 ±2

[a] Quark production cross section generally deduced from $\bar{d}$ production cross section or calculated as noted in Table V.
[b] No momentum analysis.
[c] Neutral beam; time-of-flight range sensitive to the range of $a = E_q/m_q c^2$ from 7 to 16.
[d] Quark production cross sections derived from pion production by multiplying quarks/pion ratio by 60×10^{-27} cm^2, the p-p inelastic cross section times the average multiplicity. If quarks were produced more centrally than pions this would be an underestimate.
[e] Quark production derived assuming quarks produced with the same p and x distributions as ψ/J particles.

duction as well (Appel *et al.*, 1974). Three experiments have been carried out at the CERN ISR (Alper *et al.*, 1973; Jovanovich *et al.*, 1975; Albrow *et al.*, 1975) to search for massive particles with $|q| \geq (2/3)e$.

Three experiments with proton accelerators have sought massive, penetrating particles, assuming they are charged and have lifetimes of the order of 10^{-9} sec or longer. A Serpukhov search (Golovkin *et al.*, 1972) using a 0° secondary beam tuned to 25 GeV/c with 6750 g/cm^2 of iron and glass in the beam path established an upper limit of 1.6×10^{-37} cm^2 sr^{-1} GeV^{-1} for $d^2\sigma/d\Omega\, dp$ (90% C.L.) for such particles. If production proceeds as predicted by the Drell-Yan model (Drell and Yan, 1970) the experiment sets a lower limit of 4.25 GeV to the mass of such leptons. Two Fermilab groups (Bintinger *et al.*, 1975; Cronin *et al.*, 1974) have reported

Upper limit quark flux $\frac{d^2\sigma}{d\Omega dp}\left(\frac{\mathrm{cm}^2}{\mathrm{srGeV}/c}\right)$	Quarks per pion	Quark mass range (GeV/c^2)	Upper limit quark production cross section (cm^2)[a]	$\bar{d}$ momentum (GeV/c)	$\bar{d}/\pi^-$ ratio	$\bar{d}$ Production cross section (cm^2)
	2×10^{-9}	2–3	2×10^{-35}			
1.5×10^{-36}	10^{-11}	3–5	10^{-35}	5	5.5×10^{-8}	
	5×10^{-9}	1–1.8	3×10^{-34}	25	6.0×10^{-7}	1.4×10^{-34}
	1×10^{-9}	2–3	6×10^{-35}	31.4	2.5×10^{-7}	3.0×10^{-35}
				39.1	5.0×10^{-8}	3.0×10^{-36}
1.6×10^{-36}	1.4×10^{-11}	1.9–2.3	$\sim 2 \times 10^{-36}$	10	1.4×10^{-6}	
3.8×10^{-36}	6.2×10^{-11}	2.7–4.4				
		2.3–2.7		13.3	3.5×10^{-6}	
1.2×10^{-35}	10^{-10}	2.2–3		20 ($\overline{\mathrm{He}}^3$)	2×10^{-11} ($\overline{\mathrm{He}}^3/\pi^-$)	
		2–11	5×10^{-31}			
		3–11	10^{-31}			
3.6×10^{-31}	3.6×10^{-7}	1.2–3.2	2×10^{-32}[d]			
1.0×10^{-31}	2.7×10^{-7}	3.2–7.0	1.6×10^{-32}	24.5	4.0×10^{-6}	
2.4×10^{-32}	2.2×10^{-7}	5.6–18.7	1.3×10^{-32}	34.2	11.0×10^{-6}	
4.4×10^{-30}	6.1×10^{-6}	2.5–4.6	4.0×10^{-31}			
3.5×10^{-31}	4.7×10^{-7}	3.2–7.2	2.8×10^{-32}			
1.0×10^{-31}	7.5×10^{-8}	5.5–14	4.5×10^{-33}			
2.8×10^{-31}		2	1.4×10^{-31}[e]			
7.7×10^{-32}		4	9.0×10^{-33}			
1.4×10^{-32}		10	1.5×10^{-34}			
4.0×10^{-34}[m]		2	2.0×10^{-34}			
5.1×10^{-34}[m]		4	6.0×10^{-35}			
1.2×10^{-34}[m]		8	2.8×10^{-36}			
	1.4×10^{-8}	1.5-25	10^{-32}[f]		5.0×10^{-5}	
		5–22	10^{-32} to 3.0×10^{-33}[g]			
2.0×10^{-33}	$5.5 \times 10^{-8}(+)$	2.4–20				
1.6×10^{-33}	$7.8 \times 10^{-8}(-)$		10^{-32} to 10^{-33}[h]		7.6×10^{-6}	
1.1×10^{-33}						

[f] Assumes quark production isotropic in c.m. with momentum distribution $d\sigma/d|p| = p^2 \exp(-bp)$ with $1.2 < b < 2.0$ $(\mathrm{GeV}/c)^{-1}$.
[g] Statistical model predictions; nearly isotropic for large m_q.
[h] Assume either same x and p distribution as pions or assumes $\exp(-ap_T)$ with values of a between 2 and 4 $(\mathrm{GeV}/c)^{-1}$.
[k] 90% confidence level upper limits.
[m] 980 gcm^{-2} Fe absorber in beam. Limit for quark-nucleon $\sigma \sim 1$ mb.

negative results of searches for penetrating particles of larger $p_\perp$ in secondary beams. The Bintinger *et al.* experiment established an upper limit flux, $Ed^3\sigma/dp^3$, of 6.4×10^{-35} $\mathrm{cm^2GeV^{-2}}$ for $m > 0.6$ GeV and somewhat lower for $m > 1.0$ and 1.4 GeV. The transverse momenta corresponded to 1.0 to 2.25 GeV. There were 17 mean free paths of iron in the beam path. The Cronin *et al.* experiment, sensitive over $1.0 < m < 6.8$ GeV at $p_\perp = 2.38$ GeV, set an upper limit on $Ed^3\sigma/dp^3$ of 5.4×10^{-39} cm^2 (90% C. L.). There were 1130 g cm^{-2} of tungsten in the beam path, providing an attenuation factor of 334 for π^-. No events were detected among $1.28 \times 10^9 \pi^-$.

It is conceivable that the most stable (lowest-energy) state of quarks with integral charge would be electrically neutral (Okun and Zeldovich, 1976). Among the cosmic-ray experiments, only some of the time delay studies of hadrons accompanying air showers would have been sensitive to neutral, massive hadrons (Jones *et al.*, 1967; Bjørnboe *et al.*, 1968; Tonwar, Naranan, and Sreekantan, 1972). There has recently been a corresponding search carried out at Fermilab with 300 GeV primary energy (Gustafson *et al.*, 1976). In this experiment, as in the experiment of the Columbia group (Appel *et al.*, 1974), the fact that the extracted proton beam at the Fermilab accelerator may be bunched by the rf to one-nanosecond bursts spaced by 18 nsec is used to provide a time base. In the charged-particle beam, a flight path L of 1.1 km was used, and momentum was determined with the conventional magnetic deflection and focusing of a secondary beam transport system. The neutral particle search used a flight path L of 0.59 km and an ionization calorimeter to measure the energy. The calorimeter enabled identification of energy-time delay contours corresponding to neutrons and neutral kaons; however, no evidence for more massive states was observed.

For part of this experiment an iron absorber of 960 g cm^{-2} was inserted into the beam line, and the apertures of other defining collimators in the beam were opened. Should massive, neutral particles exist in the beam and interact with a nuclear cross section much less than that of a neutron, the transmitted beam would be considerably enriched by such particles. For example, neutrons are attenuated by a factor of about 3000, but particles with a cross section of 1 mb per nucleon, such as the ψ, would be attenuated by less than a factor of two. The results of this part of the experiment are summarized in Fig. 15, where the 90% confidence level upper limit invariant production cross section, $E\,d^3\sigma/dp^3$, is plotted versus the assumed total cross section of the massive neutral particle for typical mass assumptions. The curves display a minimum

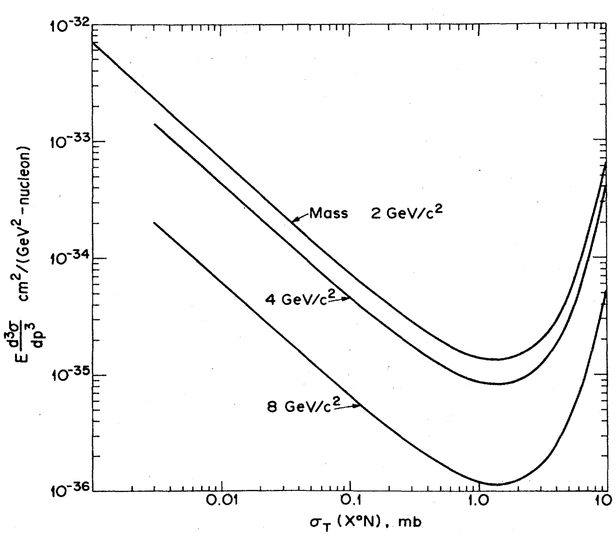


FIG. 15. Upper limits (90% confidence level) to the differential production cross section of massive, neutral, stable particles of representative masses 2, 4, and 8 GeV vs assumed interaction cross section on nucleons from the FNAL experiment of Gustafson *et al.*, (Gustafson, 1976).

near 1 mb, as the detection probability in the ionization calorimeter would be less for smaller cross section.

The limits on the existence of massive particles are tabulated in Table VI together with antideuteron fluxes where observed.

None of the experiments have detected massive particles other than known light nuclei and antinuclei. Besides deuterons and antideuterons, one triton was detected (Alper *et al.*, 1973), and five reported antihelium-3 (Antipov *et al.*, 1971c).

While this class of experiments has not reached the sensitivity of fractional-charge searches, particles with production cross sections comparable to that for the ψ/J particle ($m=3.1$ GeV/c^2) would have been observed. Particles with integral charge and $\gamma\cong 10$ would not have been detected in most of these experiments if they had a decay lifetime much less than 10^{-7} sec.

As with the charged-particle searches, each of these studies has looked in different secondary momentum ranges and at different c.m. production angles, and each group has interpreted the flux limits obtained in terms of quark production cross section limits with somewhat different models. It appears difficult, however, to see how the cross sections stated could be in error by more than perhaps two orders of magnitude for any sensible model. The range of production cross sections plotted in Fig. 12 and 13 for the Fermilab data (Nash *et al.*, 1974) may represent extreme limits.

V. SEARCHES IN STABLE MATTER

There is evidence from meteorites and rocks from the moon's surface that the cosmic-ray flux has been reasonably constant over the age of the earth, or about 4×10^9 years (1.2×10^{17} sec). Due to plate tectonic activity and crustal subsidence, most crustal material has been mixed to a depth y of perhaps 200 km or 5×10^7 g cm^{-2} over the age of the earth. If quarks were produced by cosmic rays and stopped in matter of the earth's crust, there should be an accumulated density of quarks in crustal matter simply related to the cosmic-ray quark flux. Again φ is the quark flux in cosmic rays in quarks (cm^2 sr sec)$^{-1}$, ρ is the quark density in stable matter in quarks per nucleon, and N is Avogadro's number. Then:

$$\rho=\frac{\pi\varphi t}{Ny}\;;\;\varphi=\frac{Ny\rho}{\pi t}\;. \tag{5.1}$$

The results are that

$$\rho\cong10^{-14}\,\varphi\text{ quarks/nucleon,} \tag{5.2}$$

and, correspondingly,

$$\rho\cong6\times10^{9}\,\varphi\text{ quarks/gm .} \tag{5.3}$$

The assumption of a 200 km depth may be extreme; some rock samples may have lain closer to the surface for an appreciable fraction of the earth's age. A more favorable estimate (from the standpoint of stable matter searches) may be made by assuming that the oceans are 3×10^9 years old and 3 km deep (on the average), so that $y=3\times10^5$ g cm^{-2}. This gives

$$\rho=1.6\times10^{-12}\,\varphi\text{ quarks/nucleon.} \tag{5.4}$$

An extreme assumption may be made by assuming a minimum y value from a presumed quark range and neglecting all erosion, sedimentation, and other geologic effects. This could lead to a value of ρ as great as

$$\rho = 2\times10^{-10}\ \varphi \text{ quarks/nucleon.} \qquad (5.5)$$

Unfortunately, it does not seem possible to sharply identify the age-depth ratio of most of the samples used in the experiments summarized below, and the uncertainty remains in relating these search upper limits to those from cosmic rays. Moon rock samples probably provide limits closer to the latter (Stevens, Schiffer, and Chupka, 1976).

There has been a recent and generally complete summary of quark searches in terrestrial matter (Kim, 1973). In view of this, the discussion here may be brief. If a fractionally charged quark combines with atomic matter, the resulting atom (or molecule) will not be electrically neutral, and it should be possible to exercise it with electric fields. This property of quarked matter is the basis of several enrichment schemes. For example, water may be boiled and the steam passed between parallel-plate charged electrodes. The electric field would presumably drive the quark-containing atoms onto one of the electrodes. These electrodes may then be used in the arc source of an optical spectrometer (Rank, 1968) or the ion source of a mass spectrometer (Chupka, Schiffer, and Stevens, 1966). Quarked atoms may have extreme chemical properties so that they may be concentrated in certain biological materials such as kelp or oyster shells. Conversely, they may be removed by chemical refining techniques. Had quarks been discovered as a result of enrichment schemes, these would have proven of obvious validity. However the negative results might mean either that no quarks exist or that they do not behave in stable matter in the manner assumed by the experimenters. The entries in Tables VII and VIII distinguish between results employ-

TABLE VII. Stable matter quark searches. Oil drops, levitometer, electrometer.

Reference	Technique	Source material	Sample mass (gm)	No. of samples	Quarks per nucleon ρ	Corresponding quark flux upper limits [d] ϕ (cm^2 sr sec)$^{-1}$
Millikan, 1910	Oil drop	Water	10^{-11}	~100	$<10^{-13}$	
Hillas and Cranshaw, 1959	Electrometer, bulk gas	Argon, nitrogen			$<10^{-22}$	$10^{-8}-10^{-11}$
Chupka, Schiffer, and Stephens, 1966	Oil drop	Sea water, [a] air	6×10^{-11}	1000	$<10^{-14}$ [b]	
Gallinaro and Morpurgo, 1966	Diamagnetic levitometer	Graphite	10^{-9}	70	$<10^{-18}$	$10^{-4}-10^{-7}$
Stover, Moran, and Trischka, 1967	Ferromagnetic levitometer	Iron	10^{-6}	2	$<10^{-19}$	$10^{-5}-10^{-8}$
Rank, 1968	Oil drop	Mineral oil, soy bean oil, cod liver oil, peanut oil	10^{-10}	46 45 17 20	$<10^{-20}$ [b]	$10^{-6}-10^{-9}$
Braginskii *et al.*, 1968	Diamagnetic levitometer	Graphite and sample mixed	10^{-8}	36	$<10^{-17}$	$10^{-3}-10^{-6}$
Johnston, 1969	Superconducting levitometer	Niobium	9×10^{-6}	2	$<10^{-19}$	$10^{-5}-10^{-8}$
Morpurgo, Gallinaro, and Palmieri, 1970	Diamagnetic levitometer	Graphite	5×10^{-7}	75	$<5\times10^{-19}$	$5\times10^{-5}-5\times10^{-8}$
Hebard and Fairbank, 1971	Superconducting levitometer	Niobium	7×10^{-5}	2	2×10^{-20} [e]	$2\times10^{-6}-2\times10^{-9}$
Garris and Ziock, 1974	Ferromagnetic levitometer	Iron	3×10^{-5}	12	5×10^{-20} [f]	$5\times10^{-6}-5\times10^{-9}$
LaRue, Fairbank, and Hebard, 1977	Superconducting levitometer	Niobium	9×10^{-5}	8	2×10^{-20} [g]	$2\times10^{-6}-2\times10^{-9}$
Gallinaro, 1977	Ferromagnetic levitometer	Iron	2×10^{-4}	3	$<3\times10^{-21}$	$3\times10^{-7}-3\times10^{-10}$

[a] Sample "rubbed" on spheres of polyethylene to transfer quarks to spheres.
[b] An enrichment factor is included in this figure.
[c] Values given are upper limits except last three entries.
[d] Flux values given assuming Eq. (5.2) ($y=5\times10^7$ g cm^{-2}) as well as a smaller value of y, smaller than that corresponding to the existing oceans ($y=5\times10^4$ g cm^{-2}).
[e] One pellet of $q=1/3\ e$ reported, although systematic uncertainties precluded quark claim.
[f] Most pellets appeared to show residual $|q|\cong 1/3\ e$, although systematic uncertainties precluded quark claim.
[g] Two pellets of residual charge $q=(+0.337\pm0.009)\ e$ and $q=(-0.331\pm0.070)\ e$ reported. Positive evidence for existence of fractional charge on matter claimed.

TABLE VIII. Stable matter quark searches other techniques. All involve transferring or enriching samples with uncertain or unknown efficiency.

Reference	Technique	Source material	Sample size	Upper limit[a] concentration (quarks per nucleon)	Effective thickness $y(g/cm^2)$	Accumulation time t(sec)	Upper limit flux $\phi(cm^2\ sr\ sec)^{-1}$
Elbert, 1970	Mass spectrometer range, solid state detector	Air, limestone, sea water, He, N, O		10^{-15}			
Rank, 1968	Optical spectrometer	Sea water	20 l	10^{-18}	3×10^5	1×10^{17} [b]	6×10^{-7}
		salt, oysters, seaweed, plankton	1 kg each	10^{-17}			
		lake water	20 l	10^{-18}	3×10^4	3×10^{13} [c]	2×10^4
Bennett, 1966	Optical spectrometer	Solar spectrometer		10^{-10}			
Chupka, 1966	Mass spectrometer, Electrometer	Meteorites	10^{-3} g	10^{-17}	3×10^3	1×10^{16} [d]	6×10^{-7}
		Air 25°C,	10^{10}–10^{11} l	10^{-33}	1×10^3	1×10^6 [f]	2×10^{-13}
		air 200°C		10^{-30}	1×10^3		
		Dust 200°C		2×10^{-20} g			
		Sea water 25°C,	20 l	5×10^{-27}	3×10^5	1×10^{17} [b]	3×10^{-15}
		sea water 400°C	20 l	3×10^{-24}			
Cook, 1969	Electron gun, solid state detector	Lava	32 g	4×10^{-23}			
			50	2×10^{-22}			
			50	2×10^{-23}	1×10^4	3×10^{13}	3×10^{-9}
		Limestone	30	4×10^{-23}			
			65	6×10^{-23}			
		Grand Canyon	45	5×10^{-23}			
		Rock	100	2×10^{-23}	1×10^4	3×10^{13}	1×10^{-9}
		Australian rock	31	3×10^{-22}			
		Sea water	3000	1×10^{-24}	3×10^5	1×10^{17}	6×10^{-13}
			3000	9×10^{-25}			
		Lava	300	3×10^{-23}			
			500	1×10^{-23}	1×10^4	3×10^{13}	6×10^{-10}
Stevens, 1976	Wien mass spectrometer,	Deep ocean sediment	160	1×10^{-21}	0.75	3×10^{13} [e]	2×10^{-11}
	Electronic multiplier	Lunar soil	15 g	2×10^{-22}	3×10^3	1×10^{16} [d]	1×10^{-11}

[a] Numbers quoted are author's stated values including enrichment factors. All numbers are rounded to one significant figure.
[b] Average ocean depth is 3000 m; assumed ocean age is 3×10^9 yr.
[c] Assumed lake depth is 300 m; lake water age is 10^6 yr.
[d] Assumed range of cascade due to primary cosmic ray, galactic cosmic ray exposure age of 3×10^8 yr.
[e] Assumed accumulation rate of 3 mm per 10^6 yr of ferromanganese modules.
[f] Assuming standard atmosphere residence of 10 days.
[g] Taken from Stevens 1976 reference to the earlier work by the same group.

ing enrichment schemes and those which do not.

The most straightforward search method has been a repeat of the classical Millikan oil drop experiment. [Indeed, authors are fond of noting an observation of Millikan in 1910 of a fractional charge of 30% on one droplet, which he later rejected as not reproducible (Millikan, 1910)]. Here the net charge on a droplet of oil (or other solid or liquid) is determined by its motion under the influence of gravity and electric fields in the presence of viscous drag.

The Genoa group (Becchi, Gallinaro, and Morpurgo, 1965) suggested that the oil drop technique could be improved by levitating a diamagnetic particle in a suitably shaped magnetic field, and then applying electric fields to determine the charge (Gallinaro and Morpurgo, 1966: Braginskii *et al.*, 1968; Morpurgo, Gallinaro and Palmieri, 1970). It is possible to use a "perfect" diamagnet, a sphere of superconducting niobium (Hebard, 1972; Johnson, 1969). A variation of the technique makes use of a ferromagnetic pellet (Stover, Moran, and Trischka, 1967). In this case the magnetic force, proportional to $H\partial H/\partial z$, is attractive, so that a magnet (or magnets) above the pellet support it against the force of gravity. As the equilibrium is unstable, a feedback scheme is necessary to maintain the pellet in a fixed horizontal plane. Garris and Ziock (1974) have developed this approach further, working with steel spheres 0.2 mm in diameter ($33\,\mu$g). Gallinaro, Marinelli, and Morpurgo are also now pursuing this approach with iron spheres of 200 μg.

Hebard and Fairbank, (1971) initially reported a positive result, a niobium sphere of net charge $\frac{1}{3}e$; and Garris and Ziock noted a clumping of the residual charges on their 12 spheres about values of $\pm\frac{1}{3}e$. However both groups noted various systematic difficulties that damped their confidence and suppressed any loudly proclaimed discovery of quarks.

If quarks form analogues to the hydrogen atom, it is straightforward to calculate the spectral lines which would result and, if candidate lines had been found, to further determine the quark mass. Such spectroscopic searches have been carried out with terrestrial materials (Rank, 1968), and in the solar spectrum (Bennett, 1966).

A cosmological debate concerning the exact equality of the magnitude of the electron and proton electric charges led to experiments which sought to determine the net electric charge in a tank of compressed gas with an electrometer. Although the experiments predated the quark model, in retrospect they may be classed as quark searches (Hillas and Cranshaw, 1959).

Finally, molecular beam techniques have been used. These experiments appear to make the strongest sets of assumptions concerning quark properties, although each assumption is indeed plausible. The Argonne group (Chupka, Schiffer, and Stevens, 1966) passed a sample in gaseous form through an electric field so that fractional charges could collect on the electrodes. These were then concentrated onto a small platinum filament held at a low positive voltage in order to retain the quarks. The platinum was next heated to 600° for 10 sec to drive off impurities, and then a 15 kV accelerating potential was applied to accelerate the quarks into an electron multiplier or a mass spectrometer. Some materials, e.g., meteorites, were evaporated directly in the ion source of a 254 cm mass spectrometer. The Illinois group (Cook *et al.*, 1969) examined 6000 cm^3 of sea water and ten rock samples using a molecular beam electrometer system. These rock samples were known to be within a few tens of meters of the earth's surface for about one million years. Charged particles were extracted from the samples through cation exchange columns and condensed out onto LiN_3 pellets. The LiN_3 pellets were then evaporated onto a Ta foil in vacuum, and finally, the Ta foil was heated inside an electron gun. An accelerating potential of 50 kV was then applied between the gun and a solid-state detector, and the energy spectrum of arriving ions was examined for 16 and 33 keV energy signals. The authors note that the electric field of the earth may effectively reduce the integration time for quarks in air or sea water to the order of years (McDowell and Hasted, 1967; Axford, 1968). They consequently regard their rock determinations as the most significant. It should be noted that their rock samples correspond to values of t/y used in Eq. (5.2).

The most recent experiments of this sort, not included in Kim's survey, have been reported by the Argonne group (Stevens, *et al.*, 1976a). In this experiment the authors explored lunar soil samples and ferro-manganese mineral nodules from deep ocean sediments. A crossed-field Wien mass analyzer was used for the lunar soil samples (Figure 16). Samples were first heated in a crucible to over 1100°C and any negative particles extracted with a 15 kV potential. The negative particles were implanted on a rhenium filament which was then used as the negative ion source for the mass spectrometer. About 15 g of lunar soil was studied over several different runs. The procedure with the deep ocean sediments was slightly different: powdered sample material was heated to 800°C and argon flowed over it to a P_t collecting filament held at a positive potential which was subsequently used as the source in a simpler Wien-filter mass spectrometer.

Table VIII includes data from these searches together with those from earlier searches. Of the many indirect searches (i.e., those involving enrichment and transfer schemes), the limit using lunar material is the most readily interpretable, in view of the known age of the lunar surface. For the quoted limits, the authors assumed a mixing depth y of 3 kg/cm^2 and an integration time of 3×10^8 yr. The depth is determined more from the penetration of the cosmic rays than from stirring, and the age t comes from the measurement of spallation induced isotopes.

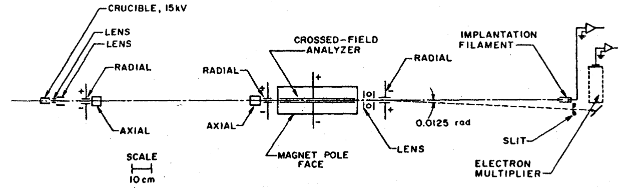


FIG. 16. Diagram of the Wien spectrometer used in the analysis of lunar soil samples by the Argonne group (Stevens, 1976).

The heterogeneous group of experimenters contributing to stable matter searches have not uniformly quoted their limits in terms of simple absence of quarks, 90% confidence level limits, or any other single criterion. However, these questions are small compared to uncertainties in the enrichment techniques and in the age/depth ratio.

If the enrichments are accepted as stated by the authors, and if the material samples lay close to the surface of the earth for the earth's lifetime, then the stable matter searches put more sensitive limits to quarks' existence than cosmic-ray experiments. On the other hand, a great mixing depth y or less efficient quark concentration than advertised leave cosmic-ray limits as more sensitive. It is remarkable that the latest and most clean-cut of the enrichment measurements, that based on lunar soil samples, gives a limit to quark flux entirely comparable to the cosmic-ray results, $\varphi \sim 10^{-11}$ $(\text{cm}^2\,\text{sr}\,\text{sec})^{-1}$.

Zeldovich and Okun (1965) have noted that quarks might exist at small concentrations in stable matter, not from cosmic-ray production but as primeval quarks left over from a cosmological "Big Bang." They have calculated a concentration ρ of 10^{-9} to 10^{-18} quarks per nucleon depending on various assumptions. Feinberg notes that observations of the 3°K blackbody radiation may constrain this estimate to 10^{-10} to 10^{-13} quarks per nucleon (Feinberg, 1967).

Clearly the stable matter searches set the most stringent limits on the existence of such quarks. The single-particle cosmic-ray quark searches are also relevant if it is assumed that primeval quarks would also be components of the material which is accelerated in the astrophysical processes which give rise to primary cosmic rays. From Eq. (3.1), the total primary cosmic-ray flux above the geomagnetic cutoff (a few GeV) is of the order of $10^{-1}(\text{cm}^2\,\text{sr}\,\text{sec})^{-1}$. If primary cosmic-ray quarks are not attenuated in the atmosphere, then the cosmic-ray flux limit corresponds to an upper limit quark concentration among primary cosmic rays of $\rho \lesssim 10^{-10}$ quarks/nucleon.

Two other searches in stable matter relate to quarks of integral charge, although neither is yet published. The Alvarez group (Muller *et al.*, 1977) has used the LBL 88-inch cyclotron as a high-energy mass spectrometer, together with a particle identifier telescope to seek quarks over the mass range up to 8.2 a.m.u. down to a sensitivity of 2×10^{-19} quarks per hydrogen atom (for $m>1$ a.m.u.).

A second group from Purdue, Chicago, Fermilab, and ANL are studying target materials exposed to the 400 GeV proton beam of the FNAL synchrotron with a mass spectrograph. They hope to set limits of 10^{-35} cm^2 to the production cross section for integral-charged quarks of $m_q > 1.2$ GeV (Stevens *et al.*, 1976b).

Following completion of this manuscript, a report was circulated by Fairbank's group at Stanford (LaRue, Fairbank, and Hebard, 1977) which declares positive, reproducible data for fractional charge on two niobium pellets, each of 9×10^{-5} g. The technique is a refinement of the previously published Hebard experiment (Hebard, 1973), and the authors argue that all systematic effects are now understood. If this result is confirmed and validated, there are a large number of apparent contradictions, both with free quark (cosmic-ray and accelerator experiments) and with other stable matter experiments. These contradictions might be resolved if (a) unpaired quarks may not exist except within a nucleus, and (b) "quarked" matter is tightly bound into a solid or liquid phase, and hence may not be found in ion beams as needed in the concentration schemes of searching in stable matter. Such conjectures are awkward but not impossible.

VI. CONCLUSIONS

Save for the very recent Stanford results with niobium pellets, there is no other experimental evidence for the existence of free quarks of fractional electric charge.

The experiments at particle accelerators have set impressive limits to the flux of, and production cross sections for, quarks so that, based on a current phenomenological model, quarks would have been detected if their rest masses were less than 20 GeV. The accelerator experiments set upper limit production cross sections below 10^{-34} cm^2 for masses up to 20 GeV, and about 10^{-38} cm^2 for masses below 10 GeV. On the other hand, if quarks exist and are produced in accord with some predictions of the statistical model, they may have escaped detection if their masses exceeded about 5 GeV. Cosmic-ray experiments which had given published positive evidence for quarks have been repeated with greater sensitivity and negative results. The cosmic-ray flux upper limits correspond to about 10^{-11} quarks per $(\text{cm}^2\,\text{sr}\,\text{sec})$ for either unaccompanied quarks or quarks among air showers for charge assignments of either $\frac{1}{3}$ or $\frac{2}{3}$ the electronic charge. While it is difficult to relate cosmic-ray limits to accelerator limits and to production models, the attempt included here again sets a quark mass limit of somewhat over 20 GeV, unless the statistical model prediction is considered.

Quarks or other stable hadrons of integral charge have not been found, either with accelerators or in cosmic rays. The limits on flux and production cross section for quarks (or other peculiar, massive hadrons) of integral charge is less sensitive than that for fractional charge by two to four orders of magnitude. Nevertheless, the observation of deuterons, antideuterons, tritons, and even antihelium-3 nuclei indicates the sensitivity that these searches have achieved. Three cosmic-ray experiments have unexplained events which have interpreted by their authors in each case as possibly a particle of large mass; however, each of the three (Yock, Tonwar, and the Chinese group) see something different, and the interpretation in each case is not clear. Other experiments which had earlier reported positive signals have now retracted their claims.

Searches for quarks in stable matter complement the other searches; the recent negative result based on lunar soil samples is interpreted in terms of a flux quite equivalent in sensitivity to the cosmic-ray searches, corresponding to a quark flux of no greater than 10^{-11} $(\text{cm}\,\text{sr}\,\text{sec})^{-1}$. The new Stanford results which claim positive evidence for quarks at a level of one quark per 10^{20} nucleons in niobium are in contradiction with the cosmic-ray (and, for masses below 20 GeV, the accelerator) results by at least two orders of magnitude, and with stable matter searches using enrichment techniques by two to four orders of magnitude. These contradictions might be circumvented if quarks behaved in matter in unusual ways, with free quarks still precluded outside nuclei.

In spite of earlier reports, at this time it seems that neither magnetic monopoles nor tachyons have been detected. It was noted that there is positive evidence from the Stanford electron-positron storage rings for a new, heavy lepton. Should this discovery be confirmed, it will indeed revise established concepts of leptons. However these particles, if they exist, are not stable (they decay through the weak interaction into leptons with lifetimes no longer than about 10^{-10} sec).

Experimental searches for quarks have been tapering off in number, although the recent Stanford result with niobium pellets will revive interest and stimulate new experiments, especially in stable matter.

Of course each new step upward in energy available with particle accelerators will bring on a new series of searches for free quarks.

Until the report of the Stanford result, it was possible to say that there remained no serious evidence for the existence of quarks (other than as hadronic constituents). The issue must now be regarded as still open, and serious ambiguities and contradictions must now be resolved between this positive result and the large body of earlier, published negative evidence.

Note added in proof. A recent paper from the Genoa group (Gallinaro, Marinelli, and Morpurgo, 1977) reports a negative result from a fractional charge (quark) search in stable matter using cylindrical iron samples suspended in a magnetic levitometer. The search reports no fractional charge among three samples, each of 2×10^4 g, corresponding to $\rho<3\times10^{-21}$ quarks per nucleon. This upper limit lies somewhat below the reported ρ from the recent Stanford result, albeit in a different sample material. Those results are included in Table VII.

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