# The continuing search for quarks

The lack of positive evidence for physical particles with fractional charge has not halted attempts to find them with accelerators, in cosmic rays or in stable matter.

Lawrence W. Jones

**Cosmic-ray quark search.** This hut and trailer are at Echo Lake, Colorado, where experimenters from Michigan and Wisconsin have sought quarks in high-altitude cosmic rays.

The story of quarks really begins in the mid 1950's with the classical experiments on the proton's electromagnetic structure. This work, done by Robert Hofstadter and his group at Stanford, showed[1] that a proton has a finite size (a root-mean-square charge radius of 0.8 fermi), rather than being a point particle, as is an electron. In the early 1960's, the emerging spectra of mesons and baryons led theorists to organize hadrons according to various symmetry schemes. The most successful of these, then and to the present time, has been the so-called "SU(3)" scheme. In an attempt to provide a physical basis for the SU(3) symmetry, Murray Gell-Mann and George Zweig proposed the concept of quarks,[2] which were (are) presumed to be the physical manifestations of the SU(3) parameters and hence the structural constituents of hadrons.

Since that time, and despite strenuous efforts to find them, no firm positive evidence for these postulated particles has appeared. There have only been the occasional flurries of excitement, caused by particular observations. As we review the most recent generation of experiments, we may glimpse the excitement of the search.

### The symmetry scheme

An altogether self-consistent picture of known hadrons can be developed by considering three fundamental quarks with third-integral electric charge and baryon number, half-integral spin, and strangeness of zero or minus one. For each quark there is an antiquark, with exactly opposite values of all quantum numbers. Baryons are then composed of three quarks, antibaryons of three antiquarks, and mesons of a quark–antiquark pair. An embarrassing situation arises with the spin-1/2 quarks and the Pauli exclusion principle: One solution to this is to suggest that each quark is in turn a triplet with a "color" quantum number (say, red, white, or blue), so that there might be now nine fundamental quarks as well as their nine antiquarks.

Although there are still open questions, the SU(3) symmetry scheme and its attendant quark model have been remarkably successful in organizing the well established strongly interacting particles and resonances, as well as in understanding their magnetic moments and other properties, to the extent these are known.

A third stimulus to the notions of hadronic constituents has come about through deep inelastic scattering of electrons (and more recently of muons) on nucleons. The most attractive interpretation of these experiments suggests that the scattering is from pointlike constituents of the nucleons, at first called partons.[3] It has been understandably tempting to identify these partons with the quarks of SU(3).

Well, if quarks (or partons) exist as nucleonic or hadronic components, it seemed reasonable that it should be possible to find them as free particles, especially if the hadrons were struck hard enough. After all, physicists have learned to extract molecules from crystals, atoms from molecules, electrons from atoms, nucleons from nuclei and mesons from protons. In each case more energy was needed, of course. In the mid-1960's the quarks were presumed to be rather massive, with a rest mass of 5 to 10 GeV/$c^2$ (about five to ten times the nucleon mass). There were two reasons for this guess: It was tempting to ascribe the mass differences between hadronic multiplets, typically about 100 MeV/$c^2$, to a perturbation on a much greater binding energy. And (this I believe was much more relevant), since quarks had not shown up in experiments up to that time, sufficient energy had not been brought to bear on the hadrons to reach the "ionization potential" or to produce quarks in pairs.

In 1964 a rigorous series of experiments began searching for quarks with particle accelerators, in cosmic rays, and in stable matter. I will recall the most recent and most definitive of these searches here, together with limits they set to the mass and to the production cross section for quarks.[4] Briefly, to avoid needless suspense, I do not believe that there is currently any serious evidence for the existence of physical quarks.

### Accelerator quarks

Significant searches have been carried out at four of the most energetic accelerators in the world: the Brookhaven 30-GeV AGS (Alternating Gradient Synchrotron), the CERN 28-GeV proton synchrotron, the Serpukhov 76-GeV proton synchrotron, and the CERN Intersecting Storage Rings.

The basis for most quark searches is the ionization of charged particles passing through matter. The ionization of relativistic particles ($v \approx c$) is nearly independent of energy and is proportional to the square of electric charge $q$, hence the ionization of a $q = (1/3)e$ quark would be 1/9 that of any known singly charged particle. This ionization can be measured with scintillation counters, with gas detectors such as streamer spark chambers and gas proportional counters, or with cloud chambers. All have been used. A single scintillation counter cannot distinguish between the dominant unit charge particles and a possible 1/9 or 4/9 ionizing quark. The ambiguity results not only from the statistical fluctuations of the number of ion pairs produced, but more importantly from the intrinsic Landau fluctuation in ionization. This fluctuation, due to the occasional large energy losses from hard collisions with atomic electrons, significantly broadens the distributions of ionization.

Of course a solution to this problem is to use a set of several counters and to determine ionization independently from each of them for a single through-going particle. By combining the pulse-height data and using a maximum-likelihood calculation, for example, and of course by exercising sufficient care in a myriad of experimental details, one could find a possible quark at a level down to less than $10^{-10}$ of singly ionizing particles.

At CERN and Serpukhov, an added gimmick aided the search: a beam was set up (essentially a focussing magnetic spectrometer) tuned to accept secondary negative, singly charged particles of momentum about 20% greater than the maximum accelerator proton momentum. Naturally no such particles are produced in the accelerator, and only pathological (that is, slit-scattered or decay-in-flight) particles reach the detectors. However, as the deflection of particles in the magnets is proportional to the charge–momentum ratio, a $q = (1/3)e$ quark with a momentum 40% that of the primary proton momentum would happily traverse the channel.

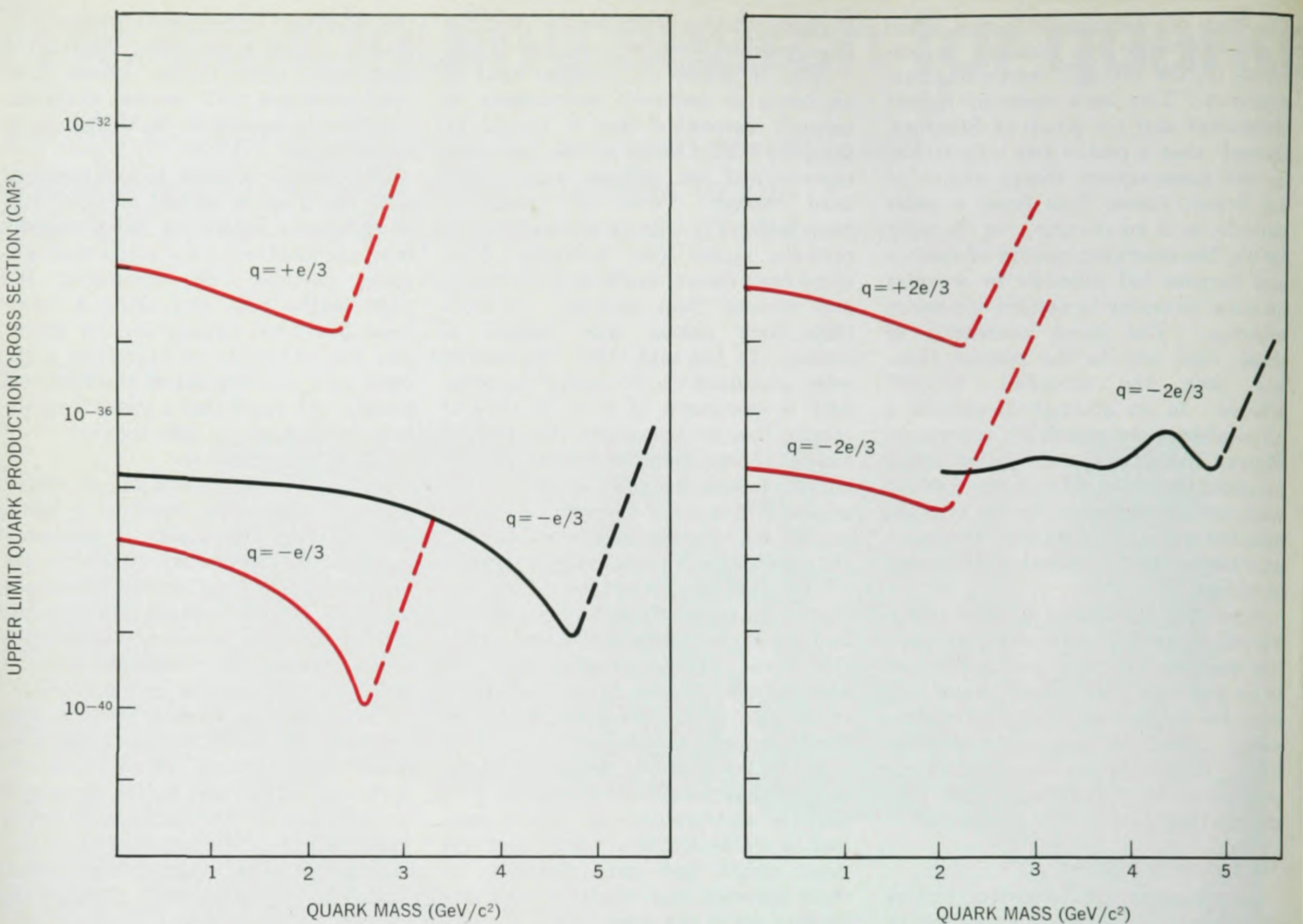
The upper limits to the possible cross section for quark production in proton–proton collisions found from the CERN and Serpukhov proton-synchrotron experiments are seen in figure 1. Apparently, quarks of rest mass below 5 GeV/$c^2$ are not produced.[5] Although some statistical models predict production cross sections below $10^{-40}$ cm$^2$ for 5 GeV/$c^2$ quarks, it must be recalled that these numbers are now well within the range of weak interaction cross sections and are $10^{-10}$ to $10^{-14}$ of the total p–p cross section.

Last year the first search for quarks from the new CERN ISR was published, corresponding to p–p interactions of 52-GeV center-of-mass energy (equivalent to a 1500-GeV proton on a stationary target).[6] Although the cross-section limits are a few orders of magnitude less sensitive than the proton-synchrotron limits, they extend up to possible quark masses of 25 GeV/$c^2$. Two experiments, scheduled for the 300-GeV National Accelerator Laboratory, will extend the searches up to about 10 GeV/$c^2$ with a sensitivity of less than about $10^{-38}$ cm$^2$.

### Cosmic-ray detection

Some of the earliest quark search experiments were with cosmic rays, and

Lawrence W. Jones is professor of physics at the University of Michigan, Ann Arbor.




**Production cross sections for quarks** of charge $\pm(1/3)e$ (left) and $\pm(2/3)e$ (right). These upper limits are from proton–proton experiments at the CERN 28-GeV proton-synchrotron (colored curves) and the 76-GeV Serpukhov synchrotron (black curves). The actual curves depend somewhat on the production model assumed but, apparently, quarks with rest mass below 5 GeV/$c^2$ are not produced. Figure 1

many groups in at least ten countries have contributed to this literature.[4,7] Typical cosmic-ray searches involve a vertical stack of counters, each about a meter square, often interspersed with other detectors such as spark chambers. The ionization of single cosmic rays is then recorded as in accelerator experiments. The sensitivity of such experiments is measured as the flux of particles per ($cm^2$ second steradian). This flux depends in turn on the running time of the experiment, and on the "geometry factor" or "admittance" of the system, expressed in $cm^2$ steradians.

Typically experiments have areas of about a square meter and an admittance of about $10^3$ $cm^2$ sterad. Such an apparatus running continuously for four months ($10^7$ sec) and detecting no quarks would establish an upper-limit quark flux of $2.3 \times 10^{-10}$ per ($cm^2$ sec sterad) to a 90% confidence level. This means that, if the flux were $2.3 \times 10^{-10}$, nine out of ten such experiments would count at least one quark.

A typical experiment is seen in figure 2. Flux limits set by several of the later experiments are noted in Table 1. It is apparent that the flux of quarks is no greater than about $5 \times 10^{-11}$ per ($cm^2$ sec sterad) from the best experiments. To interpret these limits in terms of upper limits on quark mass and production cross section in p–p collisions, three factors are necessary: information on the primary cosmic-ray proton spectrum, assumptions concerning the behavior of the quark production cross section as a function of quark mass and proton energy, and assumptions about the propagation of quarks through the atmosphere.

The primary cosmic-ray spectrum is known reasonably well, and is given by the expression $N(>E) \simeq 1.4\ E^{-1.67}$ where $N(>E)$ is the number of primary nucleons of energy greater than $E$ per ($cm^2$ sterad sec) and $E$ is in GeV. The variation of quark production cross section with mass and energy is of course much more speculative, but one guess is that quarks are produced in a process such as $p + p \rightarrow p + p + Q + Q^*$, with a cross section rising from threshold to a constant value with increasing proton energy. This energy-independent cross section is estimated to be reached at an energy of two to four times that threshold energy. Robert Adair and Nancy Price have developed a specific, somewhat arbitrary, but altogether sensible and self-consistent model along these lines.[8] It is also plausible to guess that energetic quarks produced high in the atmosphere arrive at sea level (or indeed underground) still with relativistic velocities and (of course) fractional charge, in spite of inelastic nuclear interactions and ionization in the intervening atmosphere. Again, although this is plausible, it is a weak point, and a factor that would make mountain-top quark searches more sensitive than those near sea level.

With these assumptions, calculations and spectrum appropriately considered, then, the upper limit $q = (1/3)e$ cosmic-ray quark flux of $5 \times 10^{-11}$ per ($cm^2$ sec sterad) can be compared with the results of accelerator searches for $q = (1/3)e$ quarks, as in figure 3. Here, for clarity, only the three most sensitive accelerator searches (in these energy ranges) are shown, together with the best cosmic-ray value.

Some experiments have also set limits to the flux of $q = (4/3)e$ particles in cosmic rays. The best limits here are from the University of Arizona group. The rationale for these searches is the possibility that a quark–nucleon or quark–meson compound state may be more stable (lower mass) than a free quark, and that this may have nonintegral charge greater than unity.

### Delayed particles and air showers

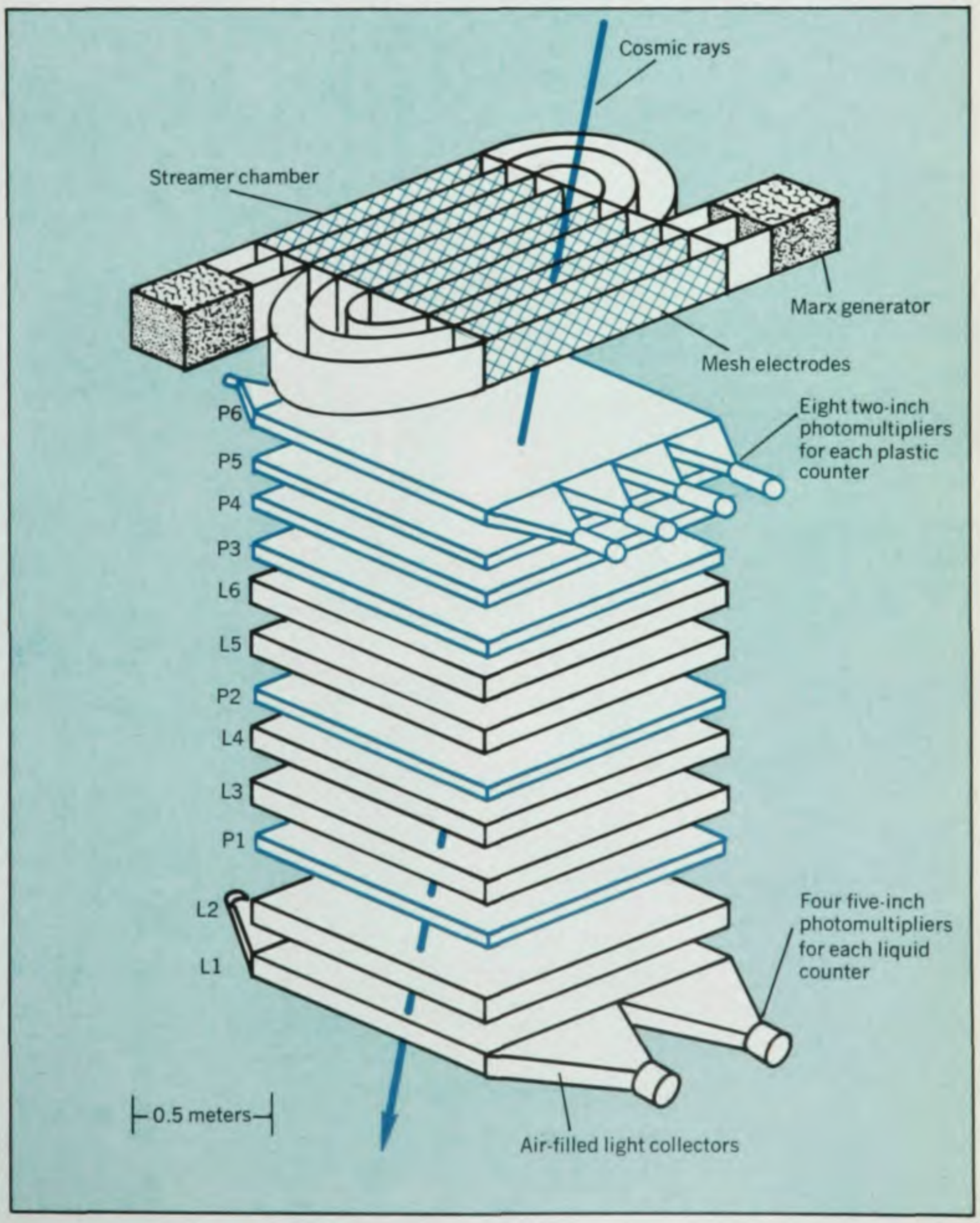
Two other methods of seeking quarks in cosmic rays have been pursued. One seeks to find energetic particles delayed behind relativistic particles produced in the same primary interaction. A particle known to be very energetic but "slow" must be massive. In such experiments little information comes from a single event, but distributions of energies and time delays should reveal massive constituents of secondary cosmic rays. The massive-particle detector may be an ionization calorimeter, a multiplate cloud chamber or a range-ionization detector system. A virtue of this method is its insensitivity to charge; any massive, strongly interacting particle could be found.

The negative searches are less sensitive than the single-particle telescopes discussed previously, but nicely supplement them. Two experiments, one by the Tata Institute group in India[9] and one by the Torino group in Italy,[10] seemed to give positive results. However I regard both as inconclusive; the Indian result awaits confirmation by a rebuilt, more elaborate detector at the same site, and the Italian result appears sharply inconsistent with single-particle telescope searches for quarks underground at the same depth. In both cases the flux values appear higher than upper limits set by other searches (see Table 1).

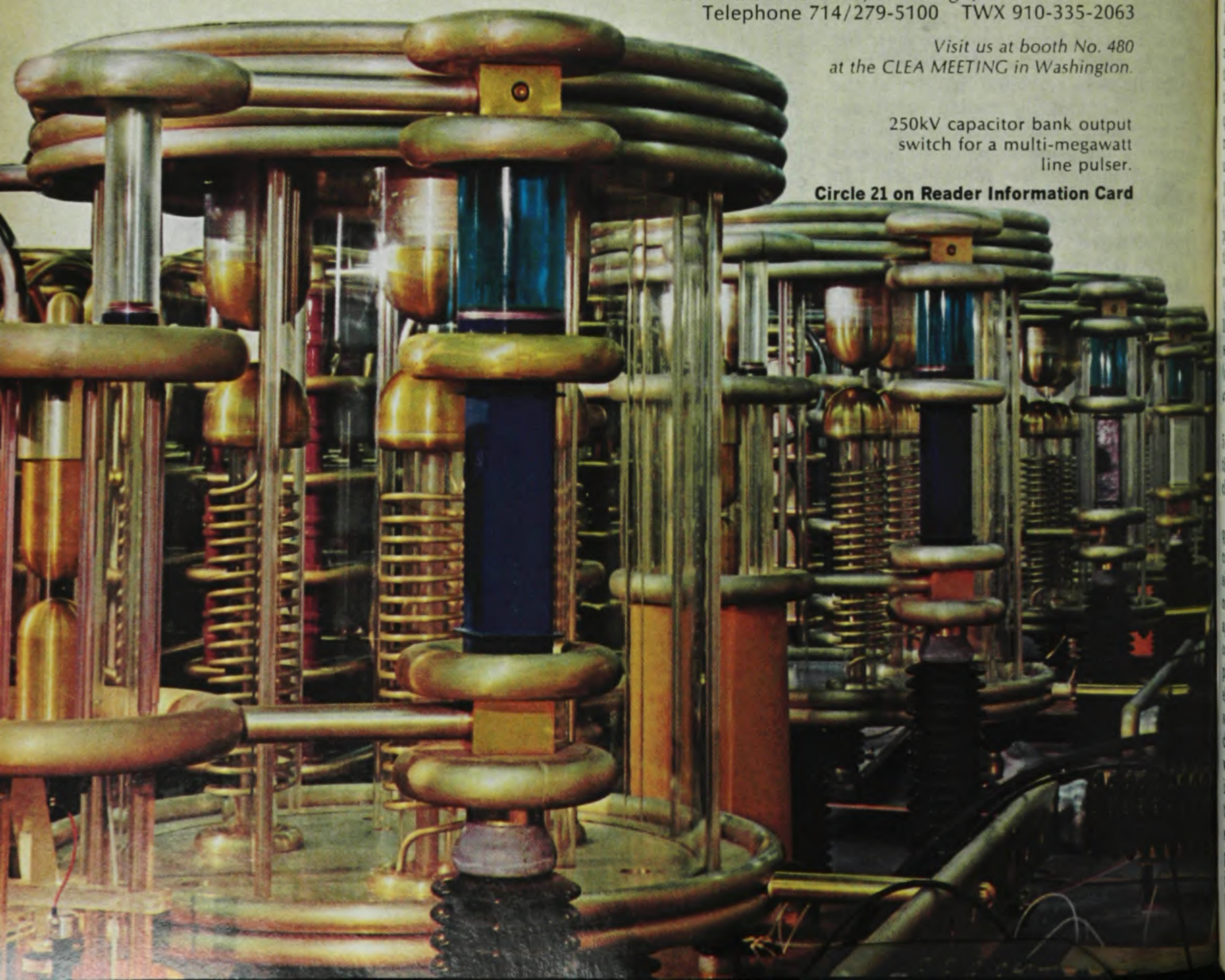
The other cosmic-ray approach is to look for quarks within the cores of extensive air showers. If quarks were only produced at very high energies (say, $10^{14}$ eV and above) they might be too fast to find with a time-delay experiment and among too dense an electron shower at sea level to be detected through subnormal ionization in a large counter telescope. Thus C.B.A. McCusker and his group at the University of Sidney set up a group of cloud chambers triggered on energetic air showers and scanned the resulting chamber photographs for lightly ionizing tracks. In 1969 this group reported five such events, corresponding to a flux of about $5.5 \times 10^{-10}$ quarks per ($cm^2$ sec sterad).[11] Although these papers were greeted with healthy skepticism concerning statistical questions and details of the cloud chamber operation and photography, nevertheless it may have been possible that this method of searching was more or less orthogonal to other experiments and therefore not in direct contradiction with any prior experiment. (Adair and Henry Kasha have questioned even this.[12])

Now if you are faced with a startling new result from an experiment, a result that you suspect is correct and wish to confirm, the most convincing *confirmation* would be from an experiment as different as possible from the original. However if you are skeptical, the most convincing *refutation* of that result would be a negative result from a new experiment very similar to but better than the original. In late 1969 Wayne Hazen at the University of Michigan and Arnold Clark at the Lawrence Livermore Laboratory undertook to set up cloud chambers triggered by air showers as were McCusker's. However their chambers had a greater admittance, and their chamber operation and photography were optimized in view of the concerns over McCusker's techniques.[13] In addition, Clark employed the extensive computer capability of Livermore to generate artificial 4/9 and 1/9 ionizing tracks, which were photographically superimposed on the real events without knowledge of the film scanners. Hence the scanners were kept "honest" by occasionally discovering a lightly ionizing track, and the physicists were able to appraise quantitatively the efficiency of their scanning operation. Meantime, McCusker improved his own apparatus and continued to run, to a total of 2.3 times his original (published) sensitivity. In view of the subsequent unanimously negative cloud-chamber results it appears that the 1969 quarks reported by McCusker were spurious.

Clark is currently extending the scanning of his film to set upper limits to the flux of $q = e/4$, $e/5$ and perhaps $e/6$ particles. These are of course even harder to detect, but with properly constructed artificial tracks, again the




**Detector configuration for a recent cosmic-ray quark search.** This "telescope" consists of six plastic and six liquid scintillators (P1–P6 and L1–L6) and a streamer spark chamber. Results from the best such cosmic-ray experiments indicate that the quark flux is no greater than about $5 \times 10^{-11}$ per ($cm^2$ sec sterad). From reference 17. Figure 2



250kV capacitor bank output switch for a multi-megawatt line pulser.

sensitivity of the search can be quantitatively verified. Some theorists have interpreted the deep-inelastic electron-scattering experiments in terms of partons with smaller fractional charge; however the results of Clark's searches are thus far negative.

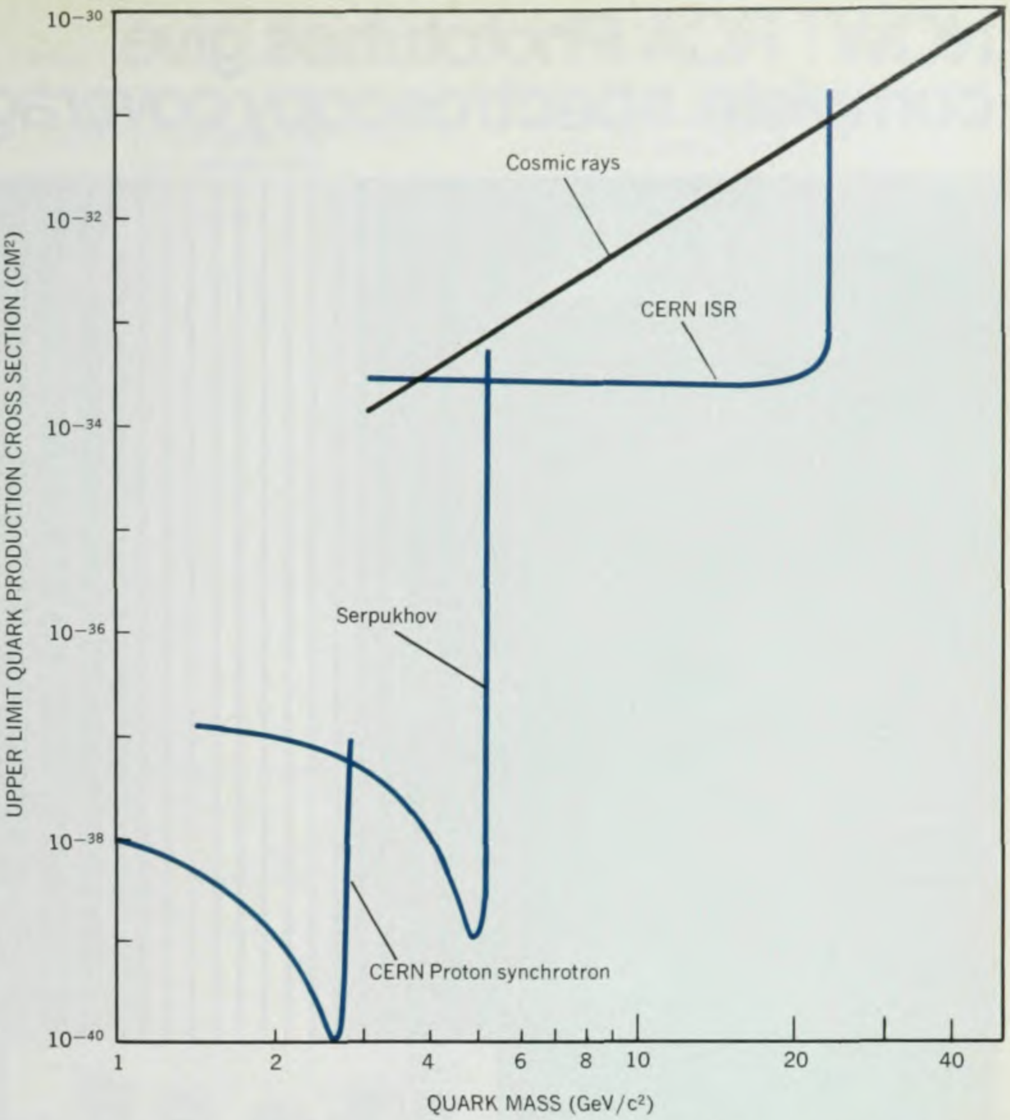
Hazen, A. L. Hodson and others at Leeds have been operating a large (3 square-meter area) horizontal cloud chamber to observe the ionization of air-shower particles and have recently reported a new, low limit for $e/3$ quarks from this apparatus.[14] The group at Aachen has operated a proportional-counter array under a lead shield and trigger-counter array to seek quarks in air showers with electronic detectors.[15] The present upper limits to the quark fluxes, set by the Aachen, Leeds, Livermore and Michigan groups, are about 2-10 $\times 10^{-11}$ quarks per (cm$^2$ sec sterad) for $q = \pm(1/3)e$ or $\pm(2/3)e$.

### Stable-matter searches

Finally, it is possible to seek quarks in stable matter: Material samples with other than integral electric charge would indicate their presence. If quarks have rained down on the surface of the Earth (produced by cosmic rays) during the life of the Earth, and if they are mixed through the top two km of Earth's crust (the oceans, primarily), it is possible to relate simply the quark flux from cosmic rays, $\varphi$ particles per (cm$^2$ sec sterad), to the quark density in matter ($\rho$ quarks per nucleon or $\rho N$ quarks per gram). Let us take the age of the earth $T$ as $5 \times 10^9$ years ($1.5 \times 10^{17}$ sec). Then $\rho = (\pi T/yN)\varphi$, (where $y$ is the depth in gm per cm$^2$ corresponding to two km and the factor $\pi$ comes from integrating over the isotropic incident flux) and $\rho$ (quarks per nucleon) is about $4 \times 10^{-12}$ $\varphi$ [cosmic-ray quarks per (cm$^2$ sec sterad)]. Correspondingly, $\rho N$ (quarks per gram) is about $2.4 \times 10^{12}$ $\varphi$.

For example, if $\varphi$ is less than about $5 \times 10^{-11}$ quarks per (cm$^2$ sec sterad), then $\rho \leq 2 \times 10^{-22}$ quarks per nucleon, or $\rho N \leq 120$ quarks per gram.

Several methods of searching for quarks have been tried; mass spectroscopy, optical spectroscopy, refined versions of the Milliken oil drop and magnetic levitometers. Most spectroscopic approaches involve in some way "concentrating" the quarks from the sample, by passing vapor through a strong electric field, for example. Now if such a concentration scheme gave evidence of quarks, the concentration would have been successful. However, if the search were negative, either there are no quarks or the experimenter was unlucky in guessing the quark properties. For this latter reason, I believe that it is well to treat upper-limit quark concentrations from such experimental methods with a certain skepticism.




**Comparison of accelerator and cosmic-ray results.** The production cross-section upper limits refer here to $q = (1/3)e$ quarks. Limits for the cosmic-ray studies, deduced from the model of Robert Adair and Nancy Price (see reference 8), correspond to a 90% confidence level upper-limit flux of $5 \times 10^{-11}$ per (cm$^2$ sec sterad). Figure 3

The most impressive stable-matter experiments to me are the magnetic levitometers. Here, a diamagnetic pellet is suspended in a static magnetic field and exercised with various electric fields. The pellet may either be graphite or (better) a superconductor such as niobium. From its motion under applied dc or ac fields, the net charge may be found as in the oil-drop experiments. The results of some searches are noted in Table 2. The Michigan and Genoa results have been negative. Arthur Hebard and William Fairbank have mounted the most elegant search of this genre at Stanford, and ultimately they will have the best limits in terms of quarks per nucleon as well as sensitivity to fractional charges of $e/6$ and smaller.

One 70-microgram pellet appeared to have a charge of $(-0.37 \pm 0.03)e$, and results of this measurement were reported at a cryogenic conference in 1970 and in Hebard's doctoral thesis. However Hebard and Fairbank emphasize the great difficulties in measurements of this sort, due to polarization effects and so on, and do not consider this first measurement as firm evidence for a quark. If our calculations here are approximately correct, the stable-matter searches are still considerably less sensitive than the cosmic-ray experiments.

We should remind ourselves that comparisons between search methods depend strongly on model assumptions.

Now I have cited four experiments with tentatively positive evidence for quarks, and in each case I have downgraded their importance. In some cases (say, the Sidney experiments) subsequent, more sensitive experiments failed to confirm the earlier results; however in others (say, the Stanford experiments) there is simply a lack of subsequent confirmation. It seems to me that if an experimenter reports something as dramatic and important as a quark after several months of operation of a new experiment but then produces no subsequent, confirmatory evidence over a period of a couple of years, the original work should be regarded with a certain skepticism. Therefore I would conclude at this

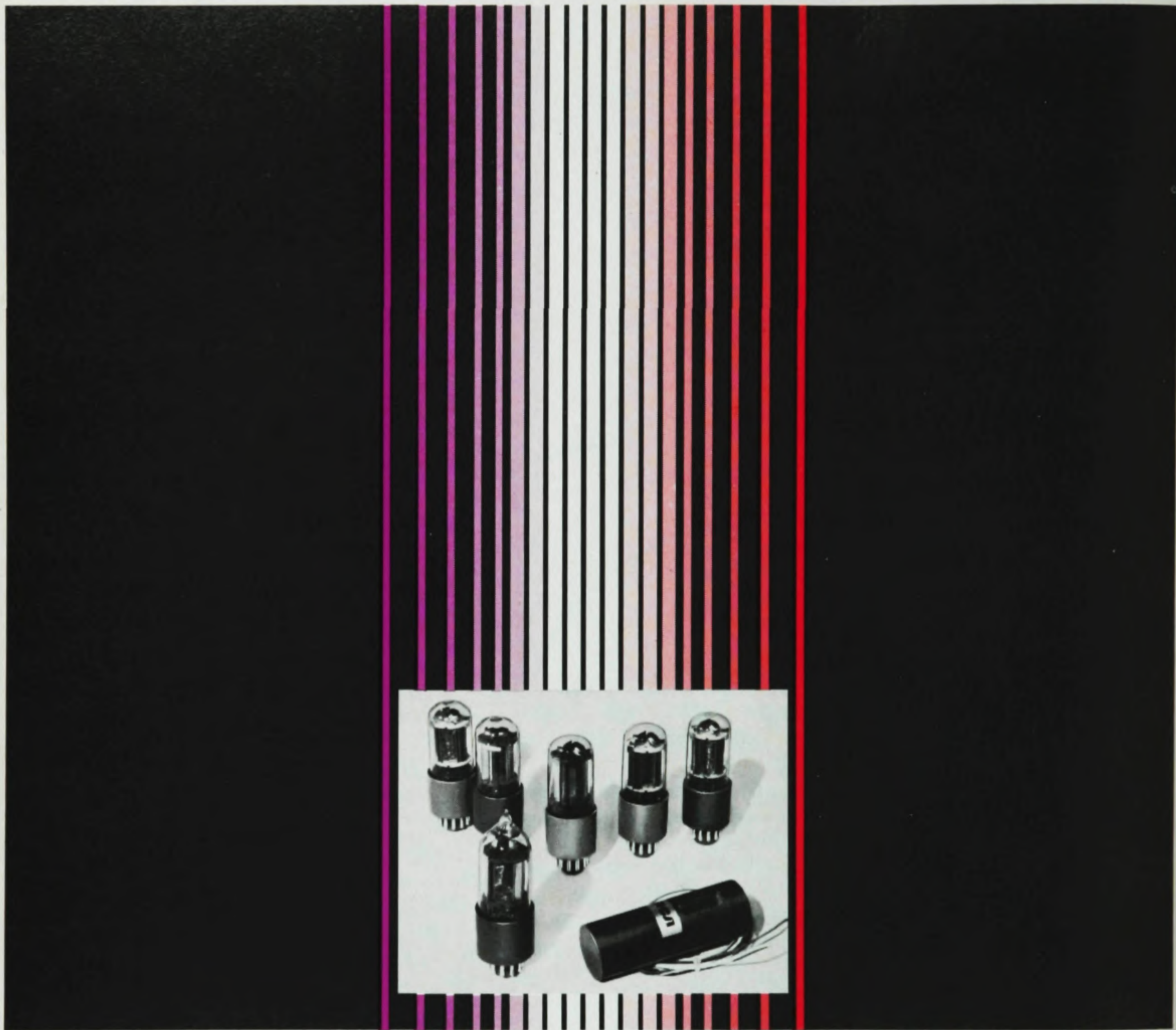


**Table 1. Upper-Limit Quark Fluxes from Cosmic-Ray Ionization**

| Group | Altitude | Quark flux* particles $\times 10^{-10}$ per (cm$^2$ sec sterad) | | |
|---|---|---|---|---|
| | | $e/3$ | $2e/3$ | $4e/3$ |
| Arizona | 2750 m | 0.83 | 0.96 | 4.1 |
| Osaka | 2770 m | 0.57 | | |
| Aachen | Sea level | 1.0 | 1.0 | |
| Brookhaven | Sea level | | 1.2 | |
| Case | Sea level | | 2.2 | |
| Tokyo | Sea level | 0.5 | 7.5 | |
| Osaka | Sea level | 1.3 | | |
| Durham | Sea level | 1.15 | 0.8 | 19 |
| Durham | Underground | | 1.4 | |

**Values are 90% confidence level upper limits*

**Table 2. Searches for Particles of Fractional Charge in Stable Matter**

| Group | Method | Upper limit (quarks per nucleon) |
|---|---|---|
| Argonne | Mass spectrometer | $1 \times 10^{-17}$–$3 \times 10^{-29}$ |
| Michigan | Optical spectrometer | $10^{-18}$ |
| Michigan | Oil drop | $10^{-20}$ |
| | Magnetic levitometers | |
| Genoa | Graphite pellet | $5 \times 10^{-19}$ |
| Michigan | Superconducting niobium pellet | $1.1 \times 10^{-19}$ |
| Stanford | Superconducting niobium pellet | $2.4 \times 10^{-20}$* |

**Possible quark candidate*

time that there is no strong evidence for the physical existence of fractionally charged elementary particles. Still, I am watching the ongoing searches with considerable interest. Of course it only takes one capricious experimental result to keep the field alive. As in the case of the search for the Loch Ness Monster, things may quiet down for a time, but only one fuzzy photograph can set everyone off again.

Well what if no quarks are found? In the first place, it is my understanding that theorists now favor quarks of rest mass of about 0.3 GeV/$c^2$ (about a third of a nucleon mass or twice a pion mass), and in fact they would be somewhat embarrassed if 10 GeV/$c^2$ quarks were now discovered and had to be built into their models. It is difficult to understand why quarks should be so light but still not be observable as discrete particles. Perhaps the nature of strong interactions simply conspires to produce them only in pairs (as mesons). Perhaps they are only mathematical entities, a theoretical convenience, and have no physical separate existence: The Dirac magnetic monopole may be another example of this same class. Or perhaps laws of quantum mechanics quantize electric charge of observable, stationary states to integral values. One is reminded here of the conjecture that everything not expressly forbidden by the laws of physics exists. Are quarks forbidden? Do they exist? Or is this conjecture wrong?

In any event, the experimental searches for quarks go on: Cosmic ray searches are continuing at Leeds and Durham (UK), Torino (Italy), Auckland (New Zealand), and in India. The Stanford experiments are continuing with niobium pellets, and accelerator searches are now being undertaken at Batavia.

I do not expect quarks of the 1964 variety to be found experimentally. However I strongly suspect that we will be surprised by the nature of hadronic matter as we now enter a new energy regime. From many cosmic-ray experiments above a few TeV there are tantalizing hints that the qualitative nature of strong interactions may change with energy.

In any event, the internal structure and constituents of the nucleon and of other hadrons remain among the more fascinating and most fundamental problems in science today.

* * *

*This article is adapted from a talk presented at the annual meeting of The American Physical Society in New York this past January. The work was supported by the National Science Foundation.*

## References

1. R. Hofstadter, "Nuclear and Nucleon Scattering," Benjamin, New York (1963).
2. M. Gell-Mann, Phys. Lett. **8**, 214 (1964); G. Zweig, CERN Report No. 8419/TH 412 (1964).
3. W. T. Toner, *Proceedings* of the Fourth International Conference on High Energy Collisions, Oxford, (1972), RHEL-72-001, page 1; H. Kendall, *Proceedings* of the 1971 International Symposium on Electron and Photon Interactions at High Energies, Cornell (1972), page 247.
4. T. Massam, CERN Report No. 68-24 (1968); L. W. Jones in "Symmetries and Quark Models," (R. Chand, ed.) Gordon and Breach (1970), page 225; *Proceedings* of the 12th International Conference on Cosmic Rays, Hobart, 1971, University of Tasmania, Invited and Rapporteur Papers, page 125.
5. Yu. M. Antipov and others, Phys. Lett. **30B**, 576 (1969).
6. M. Bott-Bodenhausen and others, Phys. Lett. **40B**, 693 (1972).
7. A. J. Cox, W. T. Beauchamp, T. Bowen, R. M. Kalbach, Phys. Rev. **D6**, 1203 (1972); M. F. Crouch, K. Mori, G. R. Smith, Phys. Rev. **D5**, 2667 (1972).
8. R. K. Adair, N. J. Price, Phys. Rev. **142**, 844 (1966).
9. S. C. Tonwar, S. Naranau, B. V. Sreekautan, J. Phys. **A5**, 569 (1972).
10. K. Sitte and others, *Proceedings* of the 12th International Conference on Cosmic Rays, Hobart, 1971, University of Tasmania (1971), Vol. 3, 1137, 1145, 1149, and 1150.
11. I. D. Cairns, C. B. A. McCusker, L. S. Peak, R. L. S. Woocott, Phys. Rev. **186**, 1394 (1969); C. B. A. McCusker, I. D. Cairns, Phys. Rev. Lett. **23**, 658 (1969).
12. R. K. Adair, H. Kasha, Phys. Rev. Lett. **23**, 1355 (1969).
13. D. E. Smith, N. E. Hansen, H. F. Finn, A. F. Clark, Bull. Am. Phys. Soc. **17**, 603 (1972); A. F. Clark and others, Phys. Rev. Lett. **27**, 51 (1971); W. E. Hazen, Phys. Rev. Lett. **26**, 582 (1971).
14. W. E. Hazen, A. L. Hodson, D. Winterstein, O. Keller (to be published in Phys. Rev. Lett.).
15. A. Böhm and others, Phys. Rev. Lett. **28**, 326 (1972).
16. G. Morpurgo, G. Gallinaro, G. Palmieri, Nucl. Instr. and Meth. **79**, 95 (1970); E. W. Johnson, Univ. of Michigan PhD thesis (1969); A. F. Hebard, Stanford Univ. PhD thesis (1970).
17. Y. Fukushima and others, Phys. Rev. **178**, 2059 (1969). □