SLAC-PUB-11010

A BRIEF REVIEW OF THE SEARCH FOR ISOLATABLE FRACTIONAL CHARGE ELEMENTARY PARTICLES

MARTIN L. PERL and ERIC R. LEE
Stanford Linear Accelerator Center, Stanford University
Stanford, California 94309, USA

DINESH LOOMBA
Department of Physics, University of New Mexico
Albuquerque, New Mexico 87131, USA

Since the initial measurements of the electron charge a century ago, experimenters have faced the persistent question as to whether elementary particles exist that have charges that are fractional multiples of the electron charge. In the standard model of particle physics the quarks are such particles, but it is assumed that quarks cannot be individually isolated, the quarks always being confined inside hadrons. This paper is a brief review of the present status of searches for isolatable fractional charge particles such as a lepton-like particle with fractional charge or an unconfined quark. There have been a very large number of searches but there is no confirmed evidence for existence of isolatable fractional charge particles. It may be that they do not exist, but it is also possible that they are very massive or that their production mechanisms are very small so that they have been missed by existing searches. Therefore the aim of this review is to urge (a) the invention of ways to substantially increase the range of known search methods and (b) to urge the invention of new search methods for isolatable fractional charge particles.

Keywords: Fractional electric charge; quarks.

1. Overview of Fractional Electric Charge Particles

1.1. *Definition of fractional charge particles*

This paper briefly reviews the present status of our knowledge of isolatable elementary particles with fractional electric charge. Our purpose is twofold, first to bring up-to-date the reviews of the 1970's and 1980's on fractional charge searches [1,2,3,4] and our own limited review of 2001.[5] Our second purpose is to emphasize the need for substantial improvements and inventions in the methods of searching for isolatable fractional charge particles.

We define a fractional electric charge to be $q = fe$ where f is *not* an integer and e is the magnitude of the electron's charge, 1.602×10^{-19} Culombs. Here f might be a simple fraction such as 1/2 or 3/2 that seems to have some significance or f might be an apparently arbitrary decimal such as 0.654 or 2.123. In the last several decades there has been a special interest in the existence of particles with charge close to zero, called millicharged particles.[6,7] Usually millicharged particles

Work supported in part by the Department of Energy Contract DE-AC02-76SF00515

Published in Mod.Phys.Lett.A19:2595-2610,2004

are taken to have $|q/e| \ll 0.1$.

1.2. *Status of searches*

In spite of a very large number of searches there is no confirmed evidence for the existence of isolatable, fractional charge particles. Yet, we cannot say that they do not exist. All the searches may have failed because the fractional charge particles may be very massive or their production mechanisms may be very small. Furthermore most searches have unexplored areas. For example, in most searches at accelerators the search is confined to charges with $f = 2/3$ or larger because it is difficult to experimentally identify smaller charges such as $f = 1/2$ or $f = 1/3$. Another example of an unexplored area is in our searches discussed in Sec. 4; in these searches in bulk matter we cannot look for fractional charge particles with f's within about 0.2 of an integer.

For those experimenters interested in finding isolatable fractional charge particles, the question is how to proceed. One might repeat old experiments with more care but in most cases the experimental apparatus and even the accelerator used for the experiment no longer exists. We think the right approach is to invent substantially improved ways to search for fractional charge particles. Therefore the emphasis in this review is to broadly describe the nature and range of the search techniques that have been used, so that we can see what has to be invented or at least see what search techniques have to be substantially improved.

1.3. *Quarks*

The concept of fractional charge elementary particles is tightly connected with our present understanding of the nature of quarks. In that present understanding the quarks have fractional charge f equal to 2/3 or $-1/3$ and the antiquarks have the opposite sign charges. This is the Gell-Mann-Zweig[8,9] assignment of quark charges. Therefore we might say that fractional charge particles already constitute an important sector of the world of elementary particles and that the goal of fractional charge searches is to find additional fractional charge sectors.

Before continuing with this discussion of quark charges we comment on an alternative assignment of quark charges, the Han-Nambu assignment.[10,11] In the Han-Nambu scheme the quarks have integer charges and it is only the average over the three colors that is fractional, for example the up quark has $f = 0, 1, 1$ so that the average over the three colors is 2/3. Thus if the Han-Nambu assignment was accepted there would be no known particles with fractional charge. However the present consensus[12] is that the Han-Nambu assignment is excluded by the results of experiments involving the interactions of two photons with hadrons.[13] Recently, Rindani[14] has questioned this consensus.

Accepting the consensus Gell-Mann-Zweig assignment of the quark charges we are still left with the basic questions about the connection of quark fractional charge with quark confinement in hadrons. The present consensus is that quarks are always confined within hadrons such as nucleons and mesons, the combination of quark charges being such that the hadron always has f integral.

- But are all quarks confined in hadrons or is there a very small fraction of quarks that are not confined?
- Another question, can some quarks become free in very high energy reactions?
- A more general question is whether the confinement of quarks is an indication that other classes of fractional charge particles are also always confined in integer charge, composite particles.

The first two questions have led to a substantial emphasis on looking for 2/3 and 1/3 charges in fractional charge particle searches. However, this seems to us to be a narrow viewpoint and where possible broader searches have been and should be conducted.

If the answer to the third question is affirmative, then other classes of fractional charge particles could only be detected indirectly through the properties of the confining, integer charge, composite particle and this could be very hard to do. Therefore this review is limited to searches for unconfined, fractional charge particles, particles we designate as isolatable.

1.4. *Isolatable fractional charge elementary particles*

The designation of a fractional charge particle, F, as isolatable does not mean that the particle must be physically isolated from all other particles. This is a much too strict requirement. The practical requirements are:

- If a particle, F, has fractional charge q and the charge determination occurs when the particle is attached to additional charges Q, it is only necessary that Q total to an integer charge. Thus particle F might be bound to a nucleus with charge Q so that the total measured charge is $q + Q$. The existence of fractional charge will be proven even though the magnitude of q is not directly determined. Another example: in the bulk matter searches described in Sec. 4, F would be inside a small piece of ordinary matter, the net charge of the ordinary matter being Q so that the total charge is $q + Q$.
- Of course the particle F must be isolatable in the measuring apparatus long enough for the measurement to be carried out.

1.5. *Search methods*

There are three methods for searching for fractional charge particles:

- In Sec. 2 we summarize searches for fractional charge particles that are produced and detected using a particle accelerator or a particle collider. The advantage of such searches is that the fractional charge particle is produced directly and so definite limits on its production can be given. The disadvantage of this method is that we have no obvious model for the mass or the interaction properties of fractional charge particles, hence production limits have no deep meaning.

- In Sec. 3 we summarize searches for fractional charge particles coming from outside the earth and impinging on the earth. These might be cosmic ray particles themselves or they may have been produced by the interaction of cosmic ray particles in the atmosphere; or the fractional charge particles may be distributed throughout the galaxy, moving in random directions. This would be similar to the model usually assumed for dark matter particles.
- In Sec. 4 we describe searches for fractional charge particles in ordinary matter with the particles already existing in the matter and at rest. There are two different methods for carrying out such searches. One method uses modern technology versions of the Millikan oil drop experiment[15,16] of which the search of Lee *et al.*[17] is the most recent example. The other method is the levitometer method in which the total charge of a small piece of matter is measured by suspending it in an oscillating electric field using ferromagnetic levitation[2,4,18] or superconductor levitation.[19] The advantage of searches in bulk matter is that there is a large variety of materials that can be examined for fractional charge particles. The disadvantage is that even if fractional charge particles exist, as discussed in Sec. 4, there is no certain explanation for how they would come to be present in ordinary bulk matter. For example, a fractional charge particle might be present in bulk matter if it was produced in the very early universe and then mixed in with ordinary matter when our galaxy was formed; or fractional charge particles might be coming from outside the solar system and might stop in the ordinary matter of the system.

2. Searches for Fractional Charge Particles Using Accelerators and Colliders

2.1. *Searches using e^+e^- annihilation*

The most straightforward way to try to produce fractional charge particles, F, is to use pair production through e^+e^- annihilation:

$$e^+ + e^- \to F^+ + F^-, \tag{1}$$

with the cross-section in elementary particle units ($\hbar = c = 1$)

$$\sigma = \frac{2\pi\alpha^2}{3s}\beta(3-\beta^2)q^2\rho^2. \tag{2}$$

Here α is the fine structure constant, s is the square of the total energy, β is the velocity of F divided by the velocity of light, q is the charge of F in units of the electron charge, and ρ is a form factor if the F is not a point particle. Hence in this case there is a straightforward prediction when $\rho = 1$.

But there is also the more general F pair production process

$$e^+ + e^- \to F^+ + F^- + \text{other particles}. \tag{3}$$

In this case one simply searches for the F's but their absence leads to no conclusion unless one postulates a specific model.

The highest energy searches using e^+e^- annihilation have been carried out at LEP,[20,21,22] at a total energy of about 200 GeV, so that the F mass search extended to about 95 GeV/c^2.[21,22] No evidence for fractional charge particles was found with the search mass range extending from about 50 GeV/c^2 to about 95 GeV/c^2.

Using the OPAL Collaboration search[21] as an example, the search method looks for dE/dx ionization measurements that are either too small for $f < 1.0$ or too large for $f > 1.0$. The reaction in Eq. (1) is assumed. Upper limits on the cross-section are given for $f = 2/3, 4/3$, and 5/3 because the emphasis is on searching for free quarks. However the search limits apply to the range of f values 2/3 to 5/3. In this range for masses up to about 95 GeV/c^2, the upper limit on the cross-section is about 0.01 pb. Note that the production cross-section for muon pair production at 200 GeV is 2.0 pb. Therefore electromagnetic pair production Eq. (1), of fractional charge particles with masses in the range 50 to 95 GeV/c^2 and charge about 2/3 or greater is ruled out.

There have been searches using e^+e^- annihilation at the Z^0 [23,24] where the weak interaction dominates and perhaps provides for more general production mechanisms. Using the example of the search by the ALEPH Collaboration,[23] their assumed production process is that in Eq. (3) but they also allow the detection of just one of the F particles. Their search mass range is about 5 to 45 GeV/c^2 and they are able to search for charges as small as $f = 1/3$. The upper end of its f range is about 4/3. As in the OPAL Collaboration search[21] at higher energy, the essence of the search method is to look for particles with unusually small or unusually large ionization loss. No fractional charge particles were found and the upper limits on the production cross-sections is given in terms of the ratio:

$$R = \frac{\sigma(e^+ + e^- \to F^+ + F^- + \text{hadrons})}{\sigma(e^+ + e^- \to \mu^+ + \mu^-).} \tag{4}$$

The upper limits on R are of the order of 3×10^{-3}.

At lower energies there have been numerous null searches in e^+e^- annihilation for fractional charge particles. Table 1 lists five examples.

Table 1. Some lower energy searches in e$^+$e$^-$ annihilation. No fractional charge particles were found. f is the ratio of the sought particle charge to the magnitude of the electron charge.

Total energy GeV	Mass range GeV/c^2	f range	Experimental reference
27-35	2-12	2/3 - 5/3	JADE[25]
29	1 - 13	1/3 - 2/3	TPC[26]
29	0 - 13	1/3 - 4/3	Free Quark[27]
10	0.1 - 4	1/3 - 4/3	ARGUS[28]
10.5	0.1 - 3.5	2/3	CLEO[29]

All of these searches depended upon finding particles with anomalously low or anomalously high ionization. The limits quoted in the papers refer to specific values of f such as 1/3 and 2/3 but because of the search method the limits apply to most of the f range between the smallest and largest values of f. Of course narrow nonsensitive ranges of f occur when changing from the search in the region of small ionization to the search in the region of large ionization.

The search by Guryn *et al.*[27] is particularly interesting because the apparatus was designed to detect fractional charge particles even if they had very large interaction cross-sections and so would not pass through ordinary detectors.

Summarizing, there have been many searches for fractional charge particles that might be produced in e^+e^- annihilation. None have been found in the mass range of 0-95 GeV/c^2 for f values in the range of about 1/3 to 5/3. Since the reactions in Eqs. (1) and (3) are so general, these null results argue that if fractional charge particles exist, they are more massive than about 95 GeV/c^2. However there are two ways to get around this conclusion. One way is for f to be less than 1/3 perhaps 0.2 or smaller. Then the fractional charge particle would not have been detected in these searches. Another way to get around the conclusion is to make the production cross-section very small, for example ρ in Eq. (2) could be very small. But in our view this is an unlikely possibility.

2.2. *Searches using proton-antiproton collisions*

One might think, given the enormous number of experiments using protons in accelerators or colliders that there would be extensive literature on searches for isolatable, fractional charge particles, F, using protons. Actually very little has been published and in fact, to our knowledge, very few of such searches have been done. If F's interact through the strong interaction, for example if they are free quarks, then there is certainly an advantage to searches using hadron-hadron collisions. Another advantage is that the highest mass region can be explored using proton-antiproton collisions in a collider. Of course, there is the usual disadvantage that the cross-section for F production through the strong interaction is not known, in contrast to the

$$e^+ + e^- \to F^+ + F^-, \tag{5}$$

production mechanisms. Therefore there is no established way to understand the theoretical basis for an upper limit on F production, one must use a speculative model.

Turning to the literature, the main searches for fractional charge particles have been carried out by the CDF Collaboration[30] using

$$p + \bar{p} \to F^+ + F^- + \text{other particles}, \tag{6}$$

at a total energy of 1.8 TeV at the Tevatron Collider. The experimenters searched for *slow* massive charged particles with anomalously high ionization, dE/dx, loss.

As in most of the e^+e^- searches the emphasis is on searches for f=1/3 and 2/3. But the search is more general and applies to most f from about 1/3 upwards. The search analysis was carried out for the mass range of 100 to 270 GeV/c^2. No evidence for fractional charge particles was found. As discussed earlier in this subsection, the significance of the null result depends upon the assumed production mechanism. For a particular strong interaction production mechanism the null result is significant up to an F mass of 200 GeV/c^2.

There are no other recent, published searches using $p\bar{p}$ interactions for fractional charge particles except for a previous search, also null, of the CDF Collaboration.[31] A 1982 null search by Banner *et al*,[32] looked for f values in the range of about 0.1 to 0.7 in a mass range up to about 3.0 GeV/c^2.

It seems to us unfortunate that the experimenters who carry out $p\bar{p}$ experiments pay so little attention to searches for isolatable fractional charge particles. We hope that some of those who use the Large Hadron Collider will give more time to F searches, and in particular, will search through a continuum of the f values, not restricting their attention to the quark charges of 1/3 and 2/3.

2.3. *Searches in nuclear collisions*

If one is specifically searching for free quarks then high energy collisions of nuclei are of interest. It might be possible for a quark to separate out from the mixture of quarks, gluons, and nucleons that exist during the collision. The quark might become attached to a nuclear fragment produced in the collision, that fragment would then have fractional charge $N/3$ where N is not a multiple of 3. If Z is the charge of the nuclear fragment, then

$$N = 3Z \pm 1 \text{ or } 3Z \pm 2. \tag{7}$$

In the last three decades there have been many searches for such fractional charge nuclear fragments.[33,34,35,36,37,38,39,40,41,42] These searches covered the Z range of 1 to about 15. No evidence has been found for nuclear fragments with charge Z deviating by at least 1/3 from an integer. These null results are strong evidence for quark confinement at the energies available in these searches.

As an example of a search method, consider one of the 1996 experiments of Hüntrup *et al.*,[42] where a 200 GeV/nucleon ^{32}S beam collides with a lead target. The produced nucleon fragments then pass through a series of CR-39 plastic foils making tracks in the plastic. The foil is then etched and the size of the etch pits determines the ionization loss of the nuclear fragment in the foil. Measurements of the pit sizes for the fragment as it passed through the series of foils gives Z with an error in f of 0.05. Another search method by Ghosh *et al.*[41] used a 60 GeV/c per nucleon ^{16}O beam in collision with a nuclear emulsion target, the emulsion also serving to measure the Z of the produced nuclear fragments.

3. Searches for fractional charge particles coming from outside the earth

In the 1960's through the 1980's there were numerous searches for fractional charge particles coming from outside the earth. These may be the traditional cosmic ray particles, either primary particles or particles produced by the interaction of the primary particles in the atmosphere. Or these fractional charge particles may be halo particles trapped in the galaxy. For convenience we refer to all these particles as cosmic ray particles. There are two incentives for searches in cosmic ray. First, very high energy primary cosmic ray particles are available for producing very high energy collisions in the atmosphere, but with the advent of $\mathrm{p\bar{p}}$ colliders this incentive has been lost. The second incentive is that some primary cosmic ray particles could themselves have fractional charge, these particles being produced outside the solar system or having been produced in the very early universe. The 1977 review of Jones[1] and the 1985 review of Lyons[3] have thoroughly described searches in cosmic rays in this time period. None of these searches led to *confirmed* evidence for the existence of fractional charge particles in cosmic rays.

However it is interesting to recall the claim of McCusker and Cairns[43,44] for the presence of an $f = 2/3$ particle in a cloud chamber picture of the core of an air shower; the $f = 2/3$ being determined from the relatively low number of drops along the track. If this were a fractional charge particle its flux would be about $3{\times}10^{-12}\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$. But this claim has never been confirmed.[1,3]

Since the 1980's there have been three extensive but null searches for fractional charge particles in cosmic rays.[45,46,47] These searches used modern detectors deep underground, the overburden of earth and rock in terms of water equivalents ranging from 2700 m to 5000 m. These large overburdens unfortunately limit these searches in two ways. First, the fractional charge particle, F, cannot be strongly interacting. Therefore these are not searches for free quarks. Second, the F must have sufficient energy to get through the overburden.

Aglietta *et al.*,[45] used the LSD liquid scintillator detector under Mont Blanc to look for relativistic fractional charge particles. The authors report 90% confidence level upper limits on the flux, Φ of $f = 1/3$ or $2/3$ particles

$$\Phi(1/3) \leq 2.3 \times 10^{-13}\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}, \tag{8}$$

$$\Phi(2/3) \leq 2.7 \times 10^{-13}\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}. \tag{9}$$

Looking at the data figures in this paper, it appears that all other f values in the range of about 1/3 to 2/3 are also excluded with about the same upper limits.

Mori *et al.*,[46] used the Kamiokande II water Cerenkov detector to search for F's. They give 90% confidence level upper limits for $f = 1/3$ and $2/3$

$$\Phi(1/3) \leq 2.1 \times 10^{-15}\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}, \tag{10}$$

$$\Phi(2/3) \leq 2.3 \times 10^{-15}\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}. \tag{11}$$

We were not able to estimate flux limits for other f values from this paper.

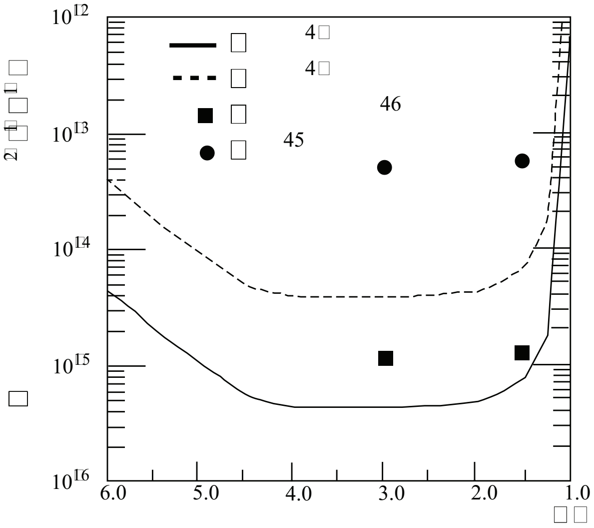

Fig. 1. 90 percent confidence level[47] upper limits on the flux of fractional charge particles in terms of $e/q = 1/f$. The solid and dotted lines are from the results of Ambrosio *et al.*[47] using the MACRO detector and from previous MACRO limits.[48] The previously noted flux upper limits from the LSD search[45] and the Kamiokande search[46] are also given.

The most complete and most sensitive search has been carried out by Ambrosio, *et al.*,[47] using the MACRO detector's streamer tube and scintillator systems. The search covered the range of $f = 1/6$ to 1 and the 90% confidence level upper limit on the flux is given in Fig. 1. For the center of the search region the upper limit is about $6 \times 10^{-16}\text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1}$.

Thus these underground searches have set severe upper limits on the flux of fractional charge particles in the f range of 1/6 to 2/3 that are impinging on the earth, providing such particles are not stopped or absorbed by the overburden.

4. Searches for Fractional Charge Particles in Bulk Matter

4.1. *Searches in bulk matter using the Millikan liquid drop method*

This bulk matter search method uses modern technology versions of the original Millikan method of determining the electron's charge.[15] The essence of the method is that small liquid drops, 5 to 30 μm in diameter depending on the experiment, fall through an oscillating electric field in air.[49,50] The motion of the drops due to the field measures the charge and the net vertical velocity measures the drop mass.

The basic equation is Stokes' Law

$$F = 6\pi\eta r\nu. \tag{12}$$

Here ν is the terminal velocity of a spherical drop of radius r, η is the viscosity of

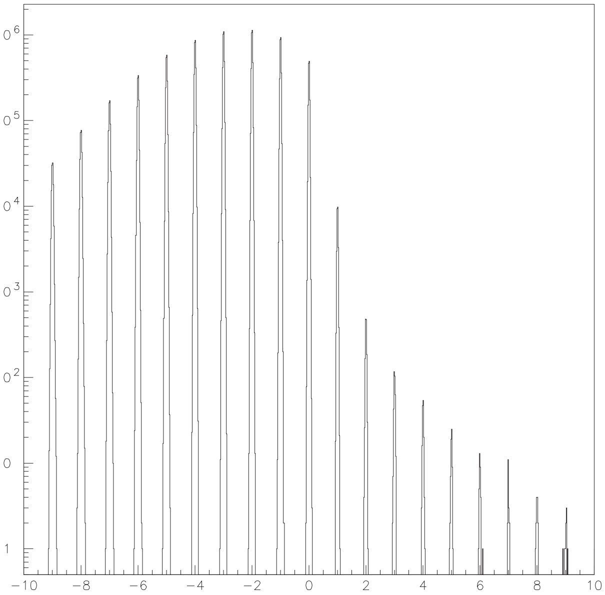

Fig. 2. The f charge distribution in 70.1 mg of silicone oil. [17]

air and F is the force on the drop. A small correction for very small drops has been ignored. In our present experiments,[17] the electric field, E, is horizontal so that

$$EQ = 6\pi\eta r\nu_{horizontal}, \tag{13}$$

where Q is the drop charge. The vertical terminal velocity is given by

$$mg = 6\pi\eta r\nu_{vertical}, \tag{14}$$

where m is the drop mass and g is the acceleration of gravity. Knowing the drop density ρ connects the two equations since

$$m = 4\pi r^3\rho/3. \tag{15}$$

In our most recent experiment, Lee *et al.*,[17] we searched through 70.1 mg of 20.6 μm diameter drops of silicone oil. Figure 2 shows the f charge distribution of the drops. To look for fractional values of f between the integer peaks we define a residual charge distribution f_r where

$$f_r = f - n, \tag{16}$$

and n is the largest integer less than f. Figure 3 shows the f_r distribution; the use of f_r leading to superposition of the valleys between the integer peaks. There are no drops with f_r values in the range of 0.18 to 0.82. In this f_r range the 95% confidence level upper limit on the existence of fractional charge particles in silicone oil is 1.17 $\times 10^{-22}$ particles per nucleon.

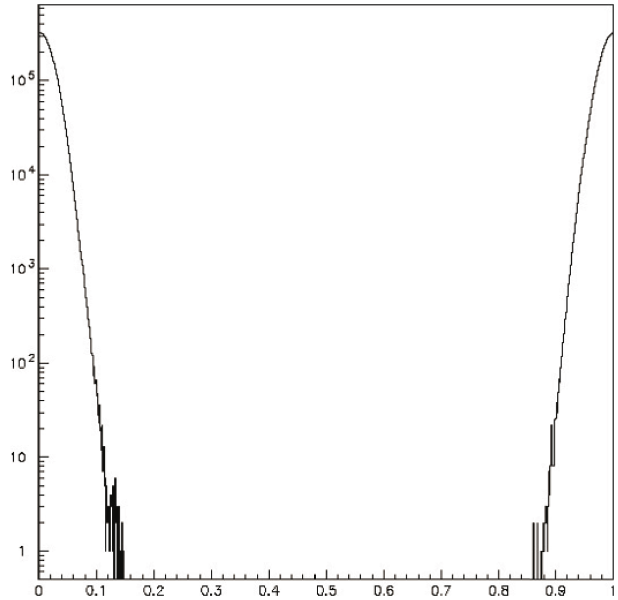

Fig. 3. The f_r charge distribution in 70.1 mg of silicone oil.[17] The use of f_r superimposes the valleys between the integer peaks. There are no drops with f_r values between 0.18 and 0.82.

Table 2 lists the major searches for fractional charge particles using the Millikan liquid drop method. Thus all liquid drop searches in bulk matter have been null.

Table 2. Searches for fractional charge particles in bulk matter. All experimenters reported null results except LaRue *et al.* See text. There are 6.4×10^{20} nucleons in a milligram.

Method	Experiment	Material	Sample mass (mg)
liquid drop	Joyce *et al.*[51]	sea water	.05
liquid drop	Savage *et al.*[52]	mercury	2.0
liquid drop	Halyo *et al.*[53]	silicone oil	17.4
liquid drop	Lee *et al.*[17]	silicone oil	70.1
superconducting levitometer	LaRue *et al.*[19]	niobium	1.1
ferromagnetic levitometer	Marinelli *et al.*[2]	iron	3.7
ferromagnetic levitometer	Smith *et al.*[54]	tungsten	3.0
ferromagnetic levitometer	Smith *et al.*[55]	niobium	6.5
ferromagnetic levitometer	Jones *et al.*[56]	meteorite	2.8

4.2. *Searches in bulk matter using the levitometer method*

In the levitometer method a small sample of ordinary matter is magnetically suspended in vacuum using either superconductivity[19] or ferromagnetism.[2,4,18] The sample may be, but need not be spherical. Masses in the range of 0.03 to 0.1 mg were used. The charge q on the sample is determined by applying an alternating electric field while the movement of the sample is damped magnetically. The amplitude of the damped oscillation so produced is proportional to q. To ensure that there is not an offset problem, a series of different charges ranging from up to about $+6e$ to down to about $-6e$ is placed on the sample using ultraviolet light and radioactive sources; q being measured for each charge setting.

Table 2 also lists five important levitometer searches for fractional charge particles. The only report of evidence for the existence of fractional charge particles in either liquid drop or levitometer experiments is that of LaRue *et al.*[19] They claim to have found $f = \pm 1/3$ charges on niobium spheres using their superconductor levitometer method. This claim created extensive interest in the early 1980's but was never confirmed by other experimenters using ferromagnetic levitation[4,55] and the claim is not accepted at present.

Therefore in spite of searches in a variety of bulk matter materials there is no confirmed evidence for the existence of fractional charge particles in bulk matter. But as shown in Table 2 most searches used less than 10 mg of material, only the searches using silicone oil used larger amounts of material. In Sec. 6 we discuss the possibility of investigating much larger amounts of material.

4.3. *Comparison of bulk matter search materials and methods*

Table 2 shows that a wide variety of materials have been examined in bulk matter searches for a fractional charge particle, F. Although we have no certain criterion as to which materials provide the most sensitive search sources, we have some general notions as to the relative sensitivities. In highly processed materials such as silicone oil, iron, and niobium there is a higher probability that even if the material originally contained F's, the F's may be lost in the processing through chemical processes, adherence to the walls of the processing equipment, or other loss mechanisms. The use of highly processed materials came about for special reasons. In the Millikan method, silicone oil allowed the most reliable and uniform drop formation, thus enabling the large sample of Ref. 17 to be achieved. In the case of niobium the superconducting levitometer method required its use[19] and the discovery claims of that experiment stimulated further searches.[55]

Materials not artificially processed such as unpurified mercury offer a better chance that the F's are not lost, although of course mercury deposits occur through geological processing.

However, the most hopeful materials are those for which there has been a minimum of natural processing and no artificial processing, the best example to our knowledge are meteorites from asteroids such as studied in Ref. 56. The asteroids, formed about 5 billion years ago as the solar system was forming, could have been good collectors of rare stable particles including *F*'s. Meteorites are produced when the asteroids collide so that the natural processing of the produced meteorites is minimal, being simply the heating and breakup effects as the meteorite passes through the earth's atmosphere and hits the earth.

The authors of this paper have begun a search for fractional charge particles using the Millikan method with drops consisting of powdered meteorite suspended in silicone oil.

This application of the Millikan method to suspensions may be applied to any solid that can be powdered and suspended in a suitable, drop-friendly, liquid. But there is a throughput limitation in that the mass fraction of the suspended solid will be less than about 6%. However, the ferromagnetic levitometer method can also be applied to any room temperature solid as in Ref. 55. Some iron is necessary for levitation but the mass fraction of the arbitrary solid may be as high as 80%.[55] Hence it may be that in the future the ferromagnetic levitometer method is best for large throughput, fractional charge particle searches in arbitrary solids.

5. Searches for Millicharge Particles

All the search methods previously discussed are insensitive to particles with small f values, the boundary being about $f = 0.1$. In the techniques relying on particle ionization in a detector, $f \leq 0.1$ does not give a sufficient detection signal. In the bulk matter searches using the liquid drop method the tails of the $f = 0$ peak would overwhelm a signal at $f \leq 0.15$, Fig. 2.[17] In the bulk matter searches using the levitometer method the statistical error on f is of the order of 0.01, so in this technique one might detect fractional charge particles with f as small as 0.06.

Thus special techniques are needed to detect fractional charge particles with values of f smaller than those discussed in the preceding paragraph, values as small as 10^{-3} and smaller.[6] Such particles are called millicharged[6,57,58,59] although Davidson *et al.*[7] use the term to refer to all fractional charge particles with $f < 1$. We use the first definition in accordance with the experimental work of Prinz *et al.*,[6] the only direct search for millicharged particles.

Prinz *et al.*[6] looked for millicharged particles that might be produced in a tungsten-rhenium target by 29.5 GeV electrons. (This was the positron production target for the SLAC Linear Collider.) No millicharged particles were found. The search extended from about 0.1 MeV/c^2 to 100 MeV/c^2. The 95% confidence upper limits on f range from about 2×10^{-5} to 6×10^{-4} depending on the mass.

Unfortunately there have been no other direct searches for millicharged particles. There are various limits on their existence from astrophysical calculations and other considerations,[7,57,58,59,60] however the discussions in this paper are limited to direct experimental searches.

6. Summary and Looking Ahead

Although a very large number of searches for isolatable fractional charge particles have been carried out using a variety of techniques, there is no confirmed evidence for the existence of such particles. Perhaps the conclusion is that there are *no* isolatable fractional charge particles. Indeed almost all physicists seem to have come to this conclusion as demonstrated by the very small interest by experimenters these days in searching for isolatable fractional charge particles.

An alternative conclusion, but not in our view a very useful conclusion, is that isolatable fractional charge particles do exist, but the masses of fractional charge particles are so large or that their production mechanisms are so small that they were not produced in the early universe; and furthermore, that they cannot be produced now by ongoing natural processes in the universe or by existing accelerators or colliders.

In our view the most useful conclusion is to recognize that the searches so far carried out, while extensive, were bounded by the technique and the technology. And to further recognize that with new technology and new inventions, the range of search parameters can be extended. We conclude with examples and questions of how search ranges might be extended.

- The obvious example is to make careful searches for isolatable fractional charge particles at the Large Hadron Collider that will be in operation at CERN in a few years. In such searches it is important that the experimenters look for particles with all values of $f = q/e$ for which the apparatus is sensitive *not* just f values corresponding to quark charges such as 1/3 and 2/3.
- In the three modern searches for isolatable fractional charge particles impinging on the earth's surface,[45,46,47] Sec. 3, the detectors were all deep underground. Is it possible to conduct a significantly sensitive search on the earth's surface or will the search apparatus be overwhelmed by the background from cosmic ray hadrons, electrons, and photons?
- The amount of matter examined in the bulk matter searches, Table 2, has been limited by the technology and the time allotted to the search by the experimenters. Looking at Table 2 we see that the amount of material examined by any one experiment ranges from several mg to about 70 mg, leading to the conclusion that in the examined materials there are no isolatable fractional charge particles in sample sizes containing on the order of 10^{22} nucleons. There is no general theoretical significance to upper limits of the order of 10^{-22} fractional charge particles per nucleon. The limit comes from the search technology. The question is how to improve the technology or invent a new bulk matter search technology. The obvious way to increase the sample size is to build a very large number of bulk matter search devices and operate them simultaneously,[49] for example a hundred searches could be conducted in parallel. Present day automation and computing technology makes this feasible. The problem of course is the cost. The devices need not be completely separate but could share some systems. Also

other improvements in search rate might be made. For example, in the Millikan liquid drop method, the CCD camera used to record the motion of the drops could be upgraded to one having more pixels and thus allowing a larger field of view with more than 1 drop per second being studied.[61] As another example, the data acquisition rate might be increased by a factor of ten in the ferromagnetic levitometer method,[62] perhaps by physically scaling up the apparatus to handle larger diameter test samples. Another direction for future bulk matter searches would be to look at other materials. For example terrestrial minerals such as fluorapatites that concentrate rare impurities might be studied.[63,64]

Acknowledgment

We are very grateful to our colleagues who have worked with us in the past on searches for fractional charge particles: Klaus Lackner, Gordon Shaw, Charles Hendricks, Peter Kim, Valerie Halyo, Nancy Mar, and Howard Rogers. We are very grateful to Melodi Masaniai for her crucial work in preparing and formulating this paper.This work was supported by Department of Energy contract DE-AC02-768F00515.

References

1. L. W. Jones, *Rev. Mod. Phys.*, **49**, 717 (1977).
2. M. Marinelli and G. Morpurgo, *Phys. Rep.*, **85**, 161 (1982).
3. L. Lyons, *Phys. Rep.*, **129**, 225 (1985).
4. P. F. Smith, *Ann. Rev. Nucl. Part. Sci.*, **39**, 73 (1989).
5. M. L. Perl, *et al.*, *Int. J. Mod. Phys.*, **A16**, 2137 (2001).
6. A. A. Prinz *et al.*, *Phys. Rev. Lett.* **81**, 1175 (1998).
7. S. Davidson, S. Hannestad and G. Rafelt, *J. High. Ener. Phys.* **5**, 3 (2000).
8. M. Gell-Mann, *Phys. Lett.* **8**, 214 (1964).
9. G. Zweig, CERN Reports TH401, TH412 (1964).
10. M. Y. Han and Y. Nambu, *Phys. Rev.* **B139**, 1006 (1965).
11. B. Iijima and R. L. Jaffe, *Phys. Rev.* **D24**, 177 (1981).
12. P. Roy and S. Brodsky, private communication.
13. The experiment usually cited is that of E. Auge *et al.*, *Phys. Lett.* **B182**, 409 (1986), on deep ineleastic Compton scattering.
14. S. D. Rindani, hep-ph/0210054.
15. R. A. Millikan, *Philos. Mag.*, **19**, 209 (1910).
16. R. A. Millikan, *Phys. Rev.*, **32**, 349 (1911).
17. I. T. Lee *et al.*, *Phys. Rev.*, **D66**, 012002 (2002).
18. M. Marinelli and G. Morpurgo, *Phys. Lett.*, **B137**, 439 (1984); G. Morpugo, *et al.*, *Nucl. Instrum. Meth.*, **79**, 95 (1970).
19. G. S. LaRue *et al.*, *Phys. Rev. Lett.*, **46**, 967 (1981).
20. K. Ackerstaff *et al.*, *Phys. Lett.*, **B433**, 195 (1998).
21. G. Abbiendi *et al.*, *Phys. Lett.*, **B572**, 8 (2003).
22. P. Abreu *et al.*, *Phys. Lett.*, **B396**, 315 (1997).
23. D. Buskulic *et al.*, *Phys. Lett.*, **B303**, 198 (1993).
24. R. Akers *et al.*, *Z. Phys.*, **C67**, 203 (1995).
25. W. Bartel *et al.*, *Z. Phys.*, **C6**, 295 (1980).

26. H. Aihara *et al.*, *Phys. Rev. Lett.*, **52**, 2332 (1984).
27. W. Guryn *et al.*, *Phys. Lett.*, **B139**, 313 (1984).
28. H. Albrecht *et al.*, *Phys. Lett.*, **B156**, 134 (1985).
29. T. Bowcock *et al.*, *Phys. Rev.*, **D40**, 263 (1989).
30. D. Acosta *et al.*, *Phys. Rev. Lett.*, **90**, 131801-1 (2003).
31. F. Abe *et al.*, *Phys. Rev.*, **D46**, R1889 (1992).
32. M. Banner *et al.*, *Phys. Lett.*, **B121**, 187 (1983).
33. M.A. Lindgren *et al.*, *Phys. Rev. Lett.*, **51**, 1621 (1983).
34. P.B. Price *et al.*, *Phys. Rev. Lett.*, **50**, 566 (1983).
35. S.W. Barwick *et al.*, *Phys. Rev.*, **D30**, 691 (1984).
36. M.A. Bloomer *et al.*, *Phys. Lett.*, **B138**, 373 (1984).
37. G. Gerbier *et al.*, *Phys. Rev. Lett.*, **59**, 2535 (1987).
38. A. Hoffmann *et al.*, *Phys. Lett.*, **B200**, 583 (1988).
39. D. Calloway *et al.*, *Phys. Lett.*, **B232**, 549 (1989).
40. Y.D. He and P.B. Price, *Phys. Rev.* **C44**, 1672 (1991).
41. D. Ghosh *et al.*, *Fizika*, **B5**, 2 (1996).
42. G. Hüntrup *et al.*, *Phys. Rev.*, **C53**, 358 (1996).
43. C.B.A. McCusker and I. Cairns, *Phys. Rev. Lett.*, **23**, 658 (1969).
44. B. McCusker, *The Quest for Quarks*, (Cambridge University Press, Cambridge, 1983).
45. M. Aglietta *et al.*, *Astropart. Phys.*, **2**, 29 (1994).
46. M. Mori *et al.*, *Phys. Rev.*, **D43**, 2843 (1991).
47. M. Ambrosio *et al.*, e-Print Archive hep-ex/0402006 (2004).
48. M. Ambrosio *et al.*, *Phys. Rev.*, **D62**, 052003-1 (2000).
49. C.D. Hendricks *et al.*, *Meas. Sci. Technol.*, **5**, 337 (1994).
50. M.L. Perl and E.R. Lee, *Am. J. Phys.*, **65**, 698 (1997).
51. D.C. Joyce *et al.*, *Phys. Rev. Lett.*, **51**, 731 (1983).
52. M.L. Savage *et al.*, *Phys. Lett.*, **B167**, 481 (1986).
53. V. Halyo *et al.*, *Phys. Rev. Lett.*, **84**, 2576 (2000).
54. P.F. Smith *et al.*, *Phys. Lett.*, **B197**, 447 (1987).
55. P.F. Smith *et al.*, *Phys. Lett.*, **B171**, 129 (1986); see also P.F. Smith *et al.*, *Phys. Lett.*, **B181**, 407 (1986); and P.F. Smith *et al.*, *Phys. Lett.*, **B153**, 188 (1985).
56. W.G. Jones *et al.*, *Z. Phys.*, **C43**, 349 (1989).
57. E. Golowich and R.W. Robinett, *Phys. Rev.*, **D35**, 391 (1987).
58. M.L. Dobroliubov and A.Yu. Ignatiev, *Phys. Rev. Lett.*, **65**, 679 (1990).
59. S.L. Dubovsky *et al.*, *JETP Lett.*, **79**, 1 (2004).
60. R. Foot, *Shadowlands: Quest for mirror matter in the universe*, (Universal Publishers, Boca Raton, 2002).
61. E.R. Lee *et al.*, *Metrologia*, to be published.
62. Private communication from W.G. Jones.
63. K.S. Lackner and G. Zweig, *Phys. Rev.*, **D28**, 1671 (1983).
64. K.S. Lackner and G. Zweig, *Novel Results in Particle Physics*, (Vanderbilt, 1982), eds. R. S. Panvini, S. Alam, and S. E. Csorna (AIP, New York, 1982), p.1.