Searches for Fractionally Charged Particles

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Key Words
electric charge, quark, elementary particle

Abstract
Since the initial measurements of the electron charge were made a century ago, experimenters have faced the persistent question of the existence of elementary particles with charges that are fractional multiples of the electron charge. In this review, we discuss the results of recent searches for these fractionally charged particles.
1. THE PUZZLE OF UNIT ELECTRIC CHARGE

We cannot explain why the electric charges of the known elementary particles (Table 1) are zero, ±q, ±q/2, or ±q/3, where q is the magnitude of the electron's charge, 1.602 × 10⁻¹⁹ coulombs. (Here, we term q the unit of electric charge.) Furthermore, because quarks always combine into composite particles with charges nq, where n = 0, ±1, ±2..., all observable particles have zero or integer charge in terms of q. For example, there are no confirmed observations of elementary or composite particles with charge Q = rν, where r is a fraction such as ⅛ or
Table 1  The electric charges of the known or strongly predicted elementary particles

<table>
<thead>
<tr>
<th>Particle</th>
<th>Charge$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged lepton: $e$, $\mu$, $\tau$</td>
<td>$\pm 1^b$</td>
</tr>
<tr>
<td>Neutrino</td>
<td>0</td>
</tr>
<tr>
<td>Quark: $u$, $c$, $t$</td>
<td>$\pm \frac{2}{3}q$</td>
</tr>
<tr>
<td>Quark: $d$, $s$, $b$</td>
<td>$\pm \frac{1}{3}q$</td>
</tr>
<tr>
<td>Photon</td>
<td>0</td>
</tr>
<tr>
<td>$Z^0$</td>
<td>0</td>
</tr>
<tr>
<td>$W^\pm$</td>
<td>$\pm 1$</td>
</tr>
<tr>
<td>Graviton$^c$</td>
<td>0</td>
</tr>
<tr>
<td>Dark matter particle$^d$</td>
<td>0</td>
</tr>
</tbody>
</table>

$^a$The charges of the leptons, neutrinos, photons, $Z^0$, and $W^\pm$ were directly observed. The quark charges were deduced from the properties of hadrons and from interactions involving hadrons (1). Units are in $q = 1.602 \times 10^{-19}$ C.

$^b$Both particles and antiparticles are included.

$^c$The graviton is a hypothetical particle required in quantum mechanical treatments of gravity, but it has never been observed.

$^d$We expect dark matter to consist of neutral particles, but this has not been proven.

an irrational or transcendental number. We term these hypothetical particles fractional electric charge particles, even though the fraction $Q/q$ may be greater than 1, as in a particle with charge $Q = \pi q$. Throughout this review, we use $F$ to refer to a fractional electric charge particle.

Perhaps we physicists should be satisfied with such simple rules for particles’ electric charge, but we are not satisfied because we do not understand the natural law behind such amazing simplicity. Speculative experimenters and theorists have attempted to determine whether the simplicity is wrong and whether fractional charge particles exist. In this paper, we review results of searches for fractional charge particles, giving examples of the search methods and reproducing the results of the comprehensive searches. Section 2 gives an overview of this field, including a brief history and general remarks. In Sections 3 through 6, we discuss search results, which we organize into four classes corresponding to the four major experimental techniques: searches that use particle accelerators and fixed targets, searches that use particle colliders, searches in cosmic rays, and searches in bulk matter. A fifth class, discussed in Section 7, concerns searches for fractional charge particles with $Q$ very close to zero or $nq$, where $n = 0, \pm 1, \pm 2, \ldots$; in these cases, special search methods are required. In Section 8, we summarize the status of searches for fractional charge particles, as well as their prospects for the future.

2. OVERVIEW OF FRACTIONAL CHARGE PARTICLES AND SEARCHES

2.1. Early History

In about 1910, Robert Millikan (2) and Harvey Fletcher (3) elucidated the magnitude of the electron charge $q$. By the early 1920s, a value for $q$ of approximately $1.60 \times 10^{-19}$ coulombs was accepted, and scientists agreed that $q$ was the smallest electric charge that existed in nature. There were strong objections to these conclusions from the eccentric experimenter Felix Ehrenhaft (4), who claimed to have found particles with charges that were a fraction of $q$—findings that were never confirmed.
The identification of $q$ as the smallest electric charge was not challenged until the 1960s, when physicists adopted the view that quarks are real elementary particles. This view of quarks and the increasing use of particle accelerators led to many searches for particles with charge $\pm \frac{1}{3}q$, $\pm \frac{2}{3}q$, or higher fractions such as $\pm \frac{4}{3}q$.

2.2. Free Quarks and Free Quark Searches

Thus, beginning in the 1960s, fractional charge particle searches emphasized searching for free quarks, isolated particles with charge $\pm \frac{1}{3}q$ or $\pm \frac{2}{3}q$. Researchers speculated that isolated quarks might occasionally break free in high-energy interactions. This possibility has not been realized, and the absence of free quarks has become enshrined in the theory of quark confinement inside quantum chromodynamics (QCD) (1). This theory holds that the attractive strong force between quarks becomes stronger as the quarks separate more and that the energy stored in the attraction is eventually converted into additional pairs of quarks, but never into a single quark. The acceptance of quark confinement has led searchers for fractional charge particles to look more broadly for particles with any charge.

2.3. General Searches for Isolatable Fractional Charge Particles

Most modern searches for fractional charge particles look for any deviation from the rule $Q = nq$, where $n = 0, \pm 1, \pm 2, \ldots$. It is important to recognize that present search technology requires that the particles be isolated during the charge measurement. Our inability to directly measure quark charges extends to any unknown fractional charge particle bound with related particles inside an elementary or composite particle. Thus, all past and present searches are limited to particles, $F$, that are or can be isolated at the elementary-particle level from their antiparticles or from other related particles.

2.4. Hypothetical Properties of Fractional Charge Particles

There are two unknowns in the search for fractional charge particles beyond the question of their existence. First, how do they interact with ordinary particles? Is the interaction strong, electromagnetic, weak, or a not yet discovered force? This interaction uncertainty affects the searches in two ways: (a) The production cross section depends on the interaction, and (b) the detection of the particle also depends on the interaction. For example, if $F$ has a large cross section with ordinary matter, it may not get through the apparatus (5).

Second, because we do not know the mass of $F$ ($m_F$), searches that use accelerators, colliders, or cosmic rays become broader as the energy increases, hence the emphasis on energy in the below discussions of those search methods. However, sensitivity of searches in bulk matter are independent of $m_F$.

2.5. Other Reviews

This review emphasizes modern and future searches. The 1977 review by Jones (6) and the 1985 review by Lyons (7) mostly focus upon searches that used accelerators or cosmic rays. The 1982 review by Marinelli & Morpurgo (8) and the 1989 review by Smith (9) emphasize searches in bulk matter. We wrote a brief review (10) in 2004.
3. SEARCHES THAT USE PARTICLE ACCELERATORS AND FIXED TARGETS

3.1. Fractional Charge Particle Production in Accelerator–Fixed Target Searches

Possible $F^{+q}$ production processes in accelerator–fixed target searches are

1. $p + N \rightarrow F^{+q} + X,$
2. $\bar{p} + N \rightarrow F^{+q} + X,$
3. $e + N \rightarrow F^{+q} + X,$
4. $\mu + N \rightarrow F^{+q} + X,$ and
5. $\nu + N \rightarrow F^{+q} + X,$

where $N$ is a proton or a neutron and where $X = F^{-q}$ plus other known particles.

In particle accelerator–fixed target searches, the choice of method depends partly on the available beam and detection equipment and partly on the experimenter’s hypothesis as to the properties of $F$. For example, the $p + N$ and $\bar{p} + N$ in Equations 1 and 2 are most suitable for searching for an $F$ that interacts strongly. The disadvantage is that the production cross section for ordinary particles is huge, so the fractional charge particle must be found within an almost overwhelming background of ordinary particles. The usual search method is to look for a high-energy particle physically isolated from particle jets.

The impetus for using electrons or muons is that $F$ interacts electrically, perhaps providing a direct channel to $F$ production. In addition, the background from ordinary particle production is smaller. Almost all searches based on this hypothesis use electrons because of their availability in direct accelerator beams and in electron-proton colliders.

If one supposes that $F$ has some property related to the lepton nature of the $e$, $\mu$, or $\nu$, then the use of such beams is appropriate. However, in the past two decades the number of muon- and neutrino-beam facilities has dwindled, and in earlier decades very few $F$ searches were carried out through the available facilities.

The maximum mass reach of a search is given by

$$m_{F,\text{max}} \approx (2m_N E)^{\frac{1}{2}},$$

where $m_N$ is the nucleon mass and $E$ is the beam energy. However, because the process in Equations 1–5 involves the quarks in $N$, the full beam energy usually is not available in the collision, in which case Equation 6 should be replaced by

$$m_{F,\text{max}} \approx (2 f m_N E)^{\frac{1}{2}},$$

where the factor $f$ is less than one.

3.2. Results of Accelerator–Fixed Target Searches

As reviewed in detail by Jones (6) and Lyons (7), no accelerator–fixed target search has found evidence for the existence of fractional charge particles. The mass range of the searches that used $p$, $\bar{p}$, and $e$ have been exceeded by the equivalent collider searches described in Section 4; therefore, the relevant mass range discussion can be found in Section 4.

Among searches that used muons and neutrinos, the highest-energy search that used muons (11) had a muon beam of 200 GeV, yielding $m_{F,\text{max}} = 19$ GeV/$c^2$. The experimenters only searched for particles with $\pm \frac{1}{4}q$ or $\pm \frac{1}{3}q$; none were found.
Although high-energy neutrino beams have been available, the largest mass range search that used neutrinos (12) employed a neutrino beam averaging 21 GeV and searched for $\pm \frac{1}{3}q$ particles; none were found.

### 3.3. Searches That Use Nucleus-Nucleus Collisions

It is an interesting possibility that fractional charge particles could be produced in high-energy nucleus-nucleus collisions where quark confinement may not hold perfectly. We cite Huntrup et al. here (13):

"In theoretical considerations it has been speculated that QCD might be slightly broken, i.e., quarks could in principle be unconfined. Within this framework it is assumed that the production of free quarks in high energy particle interactions, ... is strongly suppressed, since the energy which is put into the gluon field by the separation of the quarks is used for the creation of quark-antiquark pairs out of the vacuum. These combine with the separated quarks to form particles with an integer charge.

However, in nucleus-nucleus collisions it could be much more likely to produce fractionally charged particles. Due to a hypothetical reduction of the color field in nuclear matter by polarization of the nucleons, it might be possible to separate quarks and bind polarized nucleons without producing quarks out of the vacuum. As a consequence, fractionally charged fragments with high baryon numbers could be produced in high energy heavy ion collisions. It has been estimated that these quark-nuclear complexes, QNCs, could bind up to 20 nucleons and could have a mean free path which is reduced up to a factor of 2 in comparison to that of normal nuclear fragments with the same mass. If these QNCs are formed in high energy heavy ion collisions and their lifetime is not too short, they should be observable as an admixture to the normal nuclear fragments."

This is an intriguing idea, but unfortunately no fractional charge nuclear fragments have been found. See Table 2 for a list of recent experiments.

### 4. SEARCHES THAT USE PARTICLE COLLIDERS

#### 4.1. Fractional Charge Particle Searches That Use Electron-Positron Colliders

High-energy electron-positron colliders provide the most definitive search method among accelerator and collider searches for fractional charge particles; hence, we begin by summarizing electron-positron collider search results.

4.1.1. Fractional charge particle production in electron-positron colliders. The beauty of searches that use electron-positron colliders is that the cross section $\sigma$ for the production process

$$e^+ + e^- \rightarrow F^+ Q + F^- Q$$

is

<table>
<thead>
<tr>
<th>Beam</th>
<th>Target</th>
<th>Energy</th>
<th>Charge sought</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{32}$S</td>
<td>Pb</td>
<td>200 GeV/nucleon</td>
<td>$\frac{1}{3}$ or more from integer</td>
<td>13</td>
</tr>
<tr>
<td>$^{197}$Au</td>
<td>Pb</td>
<td>10.6 GeV/nucleon</td>
<td>$\frac{1}{3}$ or more from integer</td>
<td>13</td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>Emulsion</td>
<td>60 GeV/nucleon</td>
<td>?</td>
<td>14</td>
</tr>
<tr>
<td>$^{28}$Si</td>
<td>Pb, Cu</td>
<td>14.5 GeV/nucleon</td>
<td>$\frac{2}{7}, n = 23...28$</td>
<td>15</td>
</tr>
</tbody>
</table>
Table 3  The highest-energy fractional charge particle searches in electron-positron colliders. No evidence for fractionally charged particles was found

<table>
<thead>
<tr>
<th>$E_{\text{total}}$</th>
<th>Charges sought ($q$ units)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>130–209</td>
<td>$\frac{3}{7}, \frac{4}{7}$</td>
<td>16</td>
</tr>
<tr>
<td>130–136, 161, 172</td>
<td>$\frac{1}{7}$</td>
<td>17</td>
</tr>
<tr>
<td>91.2 (at $Z^0$)</td>
<td>$\frac{3}{7}, \frac{4}{7}$</td>
<td>18</td>
</tr>
<tr>
<td>91.2 (at $Z^0$)</td>
<td>$\frac{1}{7}$</td>
<td>19</td>
</tr>
</tbody>
</table>

*aTotal energy in gigaelectronvolts.

is known precisely, if $F$ is a pointlike particle:

$$\sigma = \left( \frac{2\pi \alpha^2}{3s} \right) \beta (3 - \beta^2) \left( \frac{Q}{q} \right)^2.$$  

Here, $\alpha$ is the fine structure constant and $\beta$ is the velocity of $F$ divided by the velocity of light. If $F$ is assumed not to be a point particle, then the right side of Equation 9 must be multiplied by the square of a form factor. If the collider beams have equal energies, $E_{\text{beam}}$, the mass reach is

$$m_{F_{\text{max}}} = E_{\text{beam}},$$

where $E$ is the energy of either beam.

There is also the general production process

$$e^+ + e^- \rightarrow F^+Q + X,$$  

where $X = F^0$ plus other known particles, but where the general cross section is not known. However, no high-energy searches using this process have taken place.

If $F$ can occur in $Z^0$ decays, another possibility is the process

$$e^+ + e^- \rightarrow Z^0 \rightarrow F^+Q + F^-Q,$$

where $m_F = m_Z/2$. This mass reach is less than that in Equation 11 because the value of $E_{\text{beam}}$ up to $\sim 100$ GeV was attained at the LEP (Large Electron-Positron) collider, whereas the peak energy of the process in Equation 12 is $E_{\text{beam}} = 91$ GeV.

4.1.2. Search results from electron-positron colliders. In collider searches for fractional charge particles based on the event type given in Equation 8, there is a lower limit to the magnitude of $Q$. If $Q$ is too small, the ionization in a detector is too small to meet the criterion for triggering or for track identification and fitting. For example, the OPAL collaboration at LEP (16), using $130 < E_{\text{beam}} < 209$, could not look for $Q = \frac{1}{7}q$ particles but could look for $Q = \frac{2}{7}q$ particles and for larger $Q$ particles.

Table 3 lists the highest-energy searches in electron-positron colliders. No evidence for fractionally charged particles was found.

4.2. Fractional Charge Particle Searches That Use Proton-Proton Colliders

We do not know of any searches for fractional charge particles that utilized the Intersecting Storage Ring proton-proton collider, which was in use at CERN from 1971 to 1984. The total energy of the Intersecting Storage Ring was 63 GeV.

The Large Hadron Collider now beginning operation at CERN is a proton-proton collider with a total energy ($E_{\text{total}}$) of 14 TeV. However, not all of this total energy is available for fractional charge particle searches because (a) the basic interaction is quark on quark and (b) the available
Table 4 The highest-energy fractional charge particle searches in proton-antiproton colliders. No evidence for fractionally charged particles was found

<table>
<thead>
<tr>
<th>$E_{\text{tot}}$a</th>
<th>Charges sought ($q$ units)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8</td>
<td>$\frac{2}{7}, \frac{4}{7}$</td>
<td>20</td>
</tr>
<tr>
<td>1.8</td>
<td>$\frac{1}{7}, \frac{2}{7}$</td>
<td>21</td>
</tr>
</tbody>
</table>

*aTotal energy in teraelectronvolts.

energy is of the order of $\frac{1}{4} E_{\text{tot}}$ or less; thus, $m_{F_{\text{max}}} \approx 5 \text{ TeV}/c^2$. Nevertheless, this is substantially more available energy than was available in searches that used proton-antiproton colliders (Section 4.3). In Section 8, we discuss the importance of searches that use the Large Hadron Collider.

4.3. Fractional Charge Particle Searches That Use Proton-Antiproton Colliders

Searches that use proton-antiproton colliders have reached larger masses than searches that use electron-positron colliders, but the former are less distinctive.

4.3.1. Fractional charge particle production in proton-antiproton colliders. The basic production mechanism is

$$\text{quark} + \text{antiquark} \rightarrow F^+Q + F^-Q,$$

but the observed process is

$$p + \bar{p} \rightarrow F^+Q + X,$$

where $X = F^-Q$ plus other known particles.

4.3.2. Search results in proton-antiproton colliders. Table 4 lists the higher-energy searches in proton-antiproton colliders. No evidence for fractionally charged particles has been found. The search made with the CDF detector operating at the Tevatron collider (21) reached a particle mass of about $250 \text{ GeV}/c^2$; this is the highest-mass search performed to date.

4.4. Fractional Charge Particle Searches That Use Electron-Proton Colliders

There exists only one electron-proton collider, HERA. No results from searches for fractional charge particles using HERA have been published; indeed, there is no motivation for such searches because (a) we expect no connection between an electron and a fractional charge particle and (b) higher masses can be reached in proton-antiproton colliders.

5. SEARCHES FOR FRACTIONAL CHARGE PARTICLES COMING FROM OUTSIDE THE EARTH

5.1. Possible Sources of Fractional Charge Particles Coming from Outside the Earth

There are three possible sources of fractional charge particles coming from outside the Earth:

1. The particles may have been produced in the early universe and may be a stable component of the present material in the universe;
Table 5  High-sensitivity searches for fractional charge particles coming from outside the Earth.

No evidence for fractionally charged particles was found

<table>
<thead>
<tr>
<th>Detector name</th>
<th>Charges sought (q units)</th>
<th>Flux sensitivity (cm$^{-2}$ sr$^{-1}$ s$^{-1}$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSD</td>
<td>$\frac{1}{3}$, $\frac{2}{3}$</td>
<td>$\sim 10^{-11}$</td>
<td>26</td>
</tr>
<tr>
<td>Kamiokande</td>
<td>$\frac{1}{3}$, $\frac{2}{3}$</td>
<td>$\sim 10^{-11}$</td>
<td>27</td>
</tr>
<tr>
<td>MACRO</td>
<td>from $\sim \frac{1}{3}$ to $\sim 1$</td>
<td>$\sim 10^{-15}$ to $\sim 10^{-15}$</td>
<td>28</td>
</tr>
</tbody>
</table>

2. The particles may be produced in the present era through violent astrophysical processes; or
3. The particles may be produced through the interaction between ordinary cosmic rays and the Earth's atmosphere.

These possibilities are intriguing, but the variety of production conditions means that the search range for $m_F$ is unknown. Therefore, search sensitivity is usually given in terms of the incoming flux, with units of cm$^{-2}$ sr$^{-1}$ s$^{-1}$.

5.2. Early Searches for Fractional Charge Particles Coming from Outside the Earth

Between the 1960s and the early 1980s, researchers carried out many searches for fractional charge particles (where $Q < q$) in cosmic rays through use of expansion cloud chambers (6, 7). The signature for a fractional charge particle was a cloud chamber track with a track drop density of less than normal. (The drop density is proportional to $Q^2$.) All searches were negative except for those reported by McCusker & Cairns (22, 23); in these reports, the authors claimed several small drop density tracks that corresponded to $Q = \frac{2}{7} q$. However, these claims were not verified by other searches, such as that performed by Hazen (24). There are several instrumental reasons for low density tracks; for example, tracks formed at the end of the chamber expansion have smaller drop densities.

An interesting search at the end of the early period was carried out by Marini et al. (25), who employed a large multipurpose detector that had originally been used at an electron-positron collider. Even with a flux sensitivity of $\sim 10^{-10}$ cm$^{-2}$ sr$^{-1}$ s$^{-1}$, the best sensitivity of the early period, no particles with $Q = \frac{2}{7}$ or $\frac{1}{3}$ were found.

5.3. Modern Searches for Fractional Charge Particles Coming from Outside the Earth

Table 5 lists the three modern high-sensitivity searches for fractional charge particles coming from outside the Earth. All results were negative. The search that used the MACRO detector (28) was the most extensive. The limits of each search are given in Figure 1.

6. SEARCHES FOR FRACTIONAL CHARGE PARTICLES IN BULK MATTER

6.1. Possible Sources of Fractional Charge Particles in Bulk Matter

The possible sources of fractional charge particles in bulk matter are the same as two of the possible sources of such particles in cosmic rays: The particles may have been produced (a) in the early universe or (b) through the interaction between ordinary cosmic rays and the Earth’s
atmosphere. As in cosmic ray searches, the search range for $m_F$ is unknown. A negative fractional charge particle, $F$, could be held in bulk matter by the coulomb attraction of a nucleus; being heavy, $F$ could be in a low Bohr orbit. This orbit may be so small that the nucleus and $F$ form a compact object. A positive $F$ may itself act as a nucleus, collecting electrons and being held in the solid by molecular forces. We do not assume special forces between $F$ and nuclei or electrons.

6.2. The Most Suitable Bulk Matter for Fractional Charge Particle Searches

This section outlines the considerations involved in selecting the best materials to use in searches for fractional charge particles.

6.2.1. Solar System considerations. Fractional charge particle searches in bulk matter require grams of material for preparation of the search samples, although most searches have used less than a gram of material for the search itself. Therefore, any particular bulk matter must be available in grams. Three such sources of bulk matter are available: terrestrial material, material brought back to Earth from the surface of the Moon, and meteoritic material from asteroids. Terrestrial matter is, of course, the most abundant and has been used for most searches. However, some suitable material may lie far below the Earth’s surface, given that $m_F$ is probably heavier than the nuclei of ordinary matter and that during the course of the Earth’s geological history, most fractional charge particles would have descended deep within the Earth.
No searches have been carried out on material from the Moon because of the scarcity of such material. Also, there is no strong reason to expect material from the Moon’s surface to be particularly rich in fractional charge particles. However, meteorites that come from asteroids may be a particularly rich source of fractional charge particles for several reasons. These meteorites form out of asteroidal surface material that comes loose when asteroids collide. During the formation of the Solar System, asteroids had chemically and electrically active surfaces that may have attracted fractional charge particles. Additionally, many asteroids, once formed, are chemically and thermally stable; thus, fractional charge particles collected on an asteroid’s surface would remain on that surface.

6.2.2. Chemical considerations. A fractional charge particle in solid matter forms an atomlike entity whose nucleus consists of either the fractional charge particle alone or the fractional charge particle bound to an ordinary nucleus. Lackner & Zweig (29, 30) have shown that these entities may have unusual chemical properties. For instance, an entity with a fractional charge nucleus $Q = +\frac{1}{3}q$ and one electron in orbit has chemical properties similar to those of fluorine. The authors therefore argue that minerals containing fluorine are good materials in which to perform a particular fractional charge search.

6.2.3. Range of $m_F$ in bulk matter searches. A powerful incentive to search for fractional charge particles in bulk matter is that the upper limit to $m_F$ may be very large. If the particle was produced in the early universe before inflation, its mass may be as large as $10^8\text{ GeV}/c^2$ (31). If the particle was produced after inflation, its mass may be as large as $10^{15}\text{ GeV}/c^2$ or larger (32). However, there is an upper limit to the mass of a charged particle in bulk matter that can be held by the coulomb force of a nucleus against the pull of gravity on the Earth’s surface (33). This upper limit is $\sim 10^{15}\text{ GeV}/c^2$ when $Q/q = -1$, decreasing proportional to $Q^2$.

6.2.4. Modulus $q$ problem in bulk matter searches. In bulk matter searches, the sought particle $F$ is always part of a sample of solid or liquid matter; thus, the total sample charge is $Q + nq$, where $n = 0, \pm 1, \pm 2 \ldots$ is the sum of the charges from ions or electrons that are not neutralized. Therefore, the $Q$ measurement has modulus $q$.

6.3. Searching for Fractional Charge Particles in Bulk Matter Using the Levitometer Method

Levitometer searches for fractional charge particles use unique and beautiful experimental technology (briefly described in this section).

6.3.1. The principles of the levitometer method. The levitometer method, described in detail by Marinelli & Morpurgo (8) and Smith (9), is shown schematically in Figure 2. Here, a sample that may contain a fractional charge particle (typically a sphere with a 0.2-mm diameter) is magnetically suspended in vacuum. An oscillating electric field is applied to the sample, and the resulting motion is observed and measured.

One experiment whose sample consisted of a superconducting niobium ball (34) made use of diamagnetic levitation. All other experiments performed to date have used ferromagnetic levitation, which requires a feedback system to keep the sample levitated. This requirement is a disadvantage, but ferromagnetic levitation does allow a variety of samples to be tested. The sample need not be pure iron; it may be an iron ball coated with the material to be sampled, or it may consist of the sample coated with a layer of iron.
6.3.2. Results of searches that used ferromagnetic levitation. The first five entries in Table 6 are the results of ferromagnetic levitometer searches for fractional charge particles in bulk matter. All these searches reported null results. In Table 6, the total mass of the samples used in each search is given in milligrams, and the equivalent number of nucleons is listed. For example, the authors of the first search studied a total of 3.7 mg of steel, equivalent to $2.4 \times 10^{21}$ nucleons. The lack of a signal sets a limit on the abundance of fractional charge particles that is of the order of only a few in material containing $2.4 \times 10^{21}$ nucleons.

6.3.3. Results of searches that used superconducting levitation. Although Larue et al. (34) claim to have found $\frac{2}{3}q$ charges on niobium spheres, others (6) have failed to find such charges in the larger niobium sample using the ferromagnetic levitometer method. There has been some controversy over this contradiction because the senior member of the former experiment, William Fairbank, claimed that the presence of the $\frac{2}{3}q$ charges on the superconducting niobium ball was contingent upon the process used to prepare the balls. The consensus is that the conclusions drawn by Larue et al. were wrong.

6.4. Searching for Fractional Charge Particles in Bulk Matter Using the Millikan Liquid Drop Method

The liquid drop method of searching for fractional charge particles has a hundred-year history of technological improvements. Unfortunately, space constraints do not allow us to describe this special history here.
Table 6  Searches for fractional charge particles in bulk matter

<table>
<thead>
<tr>
<th>Method</th>
<th>Material</th>
<th>Sample (mg)</th>
<th>Nucleons</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferromagnetic levitometer</td>
<td>Steel</td>
<td>3.7</td>
<td>$2.4 \times 10^{21}$</td>
<td>35</td>
</tr>
<tr>
<td>Ferromagnetic levitometer</td>
<td>Tungsten</td>
<td>3.0</td>
<td>$1.4 \times 10^{21}$</td>
<td>36</td>
</tr>
<tr>
<td>Ferromagnetic levitometer</td>
<td>Niobium</td>
<td>6.5</td>
<td>$4.2 \times 10^{21}$</td>
<td>37</td>
</tr>
<tr>
<td>Ferromagnetic levitometer</td>
<td>Meteorite</td>
<td>2.8</td>
<td>$1.8 \times 10^{21}$</td>
<td>38</td>
</tr>
<tr>
<td>Ferromagnetic levitometer</td>
<td>Seawater solutes</td>
<td>See Reference 39</td>
<td>See Reference 39</td>
<td>39</td>
</tr>
<tr>
<td>Superconducting levitometer</td>
<td>Niobium</td>
<td>1.1</td>
<td>$7 \times 10^{20}$</td>
<td>34</td>
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<tr>
<td>Liquid drop</td>
<td>Seawater</td>
<td>0.05</td>
<td>$3.2 \times 10^{19}$</td>
<td>40</td>
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<tr>
<td>Liquid drop</td>
<td>Mercury</td>
<td>2.0</td>
<td>$1.3 \times 10^{21}$</td>
<td>41</td>
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<tr>
<td>Liquid drop</td>
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<td>17.4</td>
<td>$1.1 \times 10^{22}$</td>
<td>42</td>
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<tr>
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<td>70.1</td>
<td>$4.5 \times 10^{22}$</td>
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<tr>
<td>Liquid drop</td>
<td>Mineral oil</td>
<td>259</td>
<td>$1.7 \times 10^{23}$</td>
<td>44</td>
</tr>
<tr>
<td>Liquid drop</td>
<td>Meteorite</td>
<td>3.9</td>
<td>$2.51 \times 10^{21}$</td>
<td>44</td>
</tr>
</tbody>
</table>

6.4.1. The principles of the liquid drop method. The most recent basic design of the liquid drop method is shown in Figure 3. A liquid drop with a radius $r$ ranging from 3 to 15 μm falls under the influence of gravity through a measurement region containing still or precisely regulated flowing gas, usually air. The measurement region also contains a horizontal, alternating electric field $E$. Within a few milliseconds, the drop reaches its vertical, downward terminal velocity, $v_{\text{vert-term}}$. This term is defined by Stokes’ law,

$$v_{\text{vert-term}} = \frac{mg}{6\pi \eta r}$$

Figure 3
Schematic of the modern Millikan liquid drop method used to search for fractional charge elementary particles (43).
where \( m \) is the drop mass, \( g \) is the gravitational acceleration, and \( \eta \) is the viscosity of the gas. Given the liquid density \( \rho \), and with \( m = \frac{4}{3} \pi \rho r^3 \), the drop radius \( r \) can be calculated from \( v_{\text{vert-term}} \). The alternating electric field \( E \) causes the drop to have an alternating, horizontal, terminal velocity, \( v_{\text{horiz-term}} \), which is given by

\[
v_{\text{horiz-term}} = \frac{EQ}{6\pi \eta r}.
\]

Thus, the drop charge \( Q \) is given by \( v_{\text{horiz-term}} \) once \( r \) is known.

### 6.4.2. Results of searches that used the liquid drop method

The modern use of the liquid drop method was initiated and developed by experimenters at San Francisco State University (40, 41). The authors tested milligram-range quantities of fluids ranging from mercury to seawater for fractional electric charge. All results were negative. Building on this foundation, experimenters at the Stanford Linear Accelerator Center embarked upon a research program to develop a much higher mass throughput Millikan apparatus to test fluid suspensions of meteoric material. Using silicon oil as the test fluid, the authors constructed automated Millikan-based charge-measurement systems of increasingly high mass throughput. Although each system operated for less than one year, the technologies developed and tested in these experiments met a number of desired criteria: (a) completely automated long-duration operation, (b) real-time machine-vision tracking of fluid microdrops, (c) the ability to perform simultaneous charge measurements of multiple drops in the same field of view, and (d) the use of regulated laminar airflow to slow the fall speed of fluid drops, allowing accurate charge measurement of large-diameter fluid droplets. The charges of 63 million silicon oil drops (88.6 mg) were measured in these developmental runs, but no evidence of fractional charge was found (43). The final experiment, which utilized the technology perfected in the three prior apparatuses, searched for fractional charge in a 1.5%-by-mass suspension of carbonaceous chondrite meteorite dust in light mineral oil. This experiment ran continuously for three years and detected no fractional charge in 42.5 million fluid drops with a total mass throughput of 259 mg of mineral oil and 3.9 g of meteoritic material (Figures 4 and 5) (44).

![Figure 4](image-url)

**Figure 4**

The \( Q \) charge distribution in units of \( q/e \). Note the narrow peaks in the distribution at integer values of \( \frac{Q}{q} \) (44).
Figure 5
The $Q_i$ residual charge distribution in units of $q/e$ (44). $Q_i = Q - N_C$, where $N_C$ is the signed integer closest to $Q$.

7. SEARCHES FOR PARTICLES WITH CHARGE CLOSE TO ZERO OR $\pm q$

7.1. Motivation and Speculation

The past three decades have seen substantial interest in the existence of elementary particles with charge $Q$ below $\sim 0.1 q$, even as small as $10^{-15} q$ (45). A motivation to search for such particles comes from models of dark matter that consider mirror particles (46), photon analogs with very small charge. Another motivation is that astronomical and cosmological measurements give limits on the existence of small-mass and small-charge particles (45, 47, 48). In contrast, there is very little to learn from astronomical and cosmological measurements pertaining to the more general theoretical problem of the existence of fractional charge particles with $Q \geq 0.1 q$.

7.2. Direct Searches for Millicharged Particles

Intertwined with the considerations described in the previous section is the long-held interest in finding axions in searches that consist of a beam of photons, $\gamma$s, passing through a strong magnetic field, $H$. It is thought that the $\gamma H$ interaction converts the $\gamma$ into an axion (Figure 6). This concept has been extended to the possible production of other small-mass exotic particles, including millicharged particles (49). Of course, in the conversion of a photon to a millicharged particle, charge conservation is violated. There is no evidence for exotic particle production, and when these null results are applied to the concept of millicharged fermions, the upper limits in Figure 7 are reached.

The easiest way to search for millicharged particles is to use real or virtual photoproduction because charge conservation is obeyed. Then

$$\gamma + N \rightarrow F^+Q + F^-Q + X,$$

where $N$ is a nucleon or nucleus and $X$ is one or more ordinary particles. Golowich & Robinett (50) considered this production process 20 years ago as applied to beam-dump searches. In the applicable searches, the experimenters looked for the appearance of an event in a dense particle...
Figure 6
Schematic of a typical experimental setup used to search for conversion of photons to axions, paraphotons, or millicharged particles.

Figure 7
Regions of mass-charge space ruled out for millicharged particles (45). The solid and dashed lines apply to the model that includes a paraphoton; the solid and dotted lines apply in the absence of a paraphoton. Abbreviations: AC, accelerator experiments; Op, search for the invisible decay of ortho-positronium; SLAC, the SLAC millicharged particle search (51); L, the Lamb shift; BBN, big bang nucleosynthesis; RG, plasmon decay in red giants; WD, plasmon decay in white dwarfs; DM, dark matter searches; SN, Supernova 1987A.
Prinz et al. (51) carried out a beautiful, unique, dedicated search for millicharged particles approximately a decade ago using the process given in Equation 17. The photons came from a 20-GeV/$c^2$ particle interacting in a thick target. The detector searched for lightly ionizing particles but found none (Figure 8).

8. THE EXISTENCE OF FRACTIONAL CHARGED PARTICLES: STATUS AND PROSPECTS

After nearly 50 years of searches for fractional charged particles, we have found nothing. The search methods have been ingenious and varied, the experimenters have been persistent, and there has been a tremendous amount of clever, solid theoretical work. Perhaps fractional charge particles, like unicorns, do not exist. Perhaps they do not interact in any way with ordinary matter, but this is unlikely: Because they are charged, it must be possible to photoproduce them in pairs with sufficient energy. Perhaps they are so massive that known search-production processes have too little energy to locate them.

We make the following suggestions for future searches:

1. Extend the millicharged particle search of Prinz et al. (51) to higher energy and larger statistics.
2. Search for fractional charge particles at the Large Hadron Collider. This will not be easy because most events have large multiplicity.
3. Extend searches in bulk matter using the levitometer method developed by Marinelli & Morpurgo (8), Smith (9), and Jones (6). We believe that meteoritic material from asteroids will be the best choice for future examination.

DISCLOSURE STATEMENT

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LITERATURE CITED

4. Ehrenhaft F. Philos. Sci. 8:403 (1941)
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Errata

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