Searches for Fractional Charge Particles

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• Thales of Miletus (600 B.C.) Rubs amber with cat fur and picks up bits of feather. He concludes that amber has a soul!
• Thomas Browne (1646) First uses the word electricity derived from the Greek word *elektron* which means amber.
• B. Franklin (1752) Captures electric charge into a Leyden jar from lightning with a flying kite and a key. Installs lightning conductor in St. Paul Cathedral in 1769.
• M. Faraday (1833) From electrolysis studies suggests the existence of an elementary electrical charge.
• G.J. Stoney (1874) Names the “natural unit of electricity” electron and estimates its value of $0.3 \times 10^{-10}$ esu from electrolysis measurement.
• J.J. Thompson (1897) Discovers electron in cathode rays and from their deflection in electromagnetic field measures $e/m$.
• J.J. Thompson, H.A. Wilson (1903) Deduces the average elementary charge from the behavior of water or alcohol droplets in electrical field.
• R. Millikan (1909) Measures the electric charge of each water droplet.
• R. Millikan (1910) Repeats with silicone oil and obtains a value of $e = 4.891 \times 10^{-10}$ esu with a precision of 0.2%.
• R. Millikan (1916) Measures Planck’s constant $\hbar$ in photoelectric effect.

$$\alpha = \frac{e^2}{\hbar c} = \frac{1}{137}$$
ELECTRIC CHARGE IS A RELATIVISTIC INVARIANT

VALUE OF THE ELECTRIC CHARGE

\[ e = 4.803 \times 10^{-10} \text{ esu} = 1.602 \times 10^{-19} \text{ C} \quad \text{(uncertainty 39 ppb)} \]

Magnitude of Electron and Proton Charges are Equal

Net Charge of the Matter \( \rightarrow \) Expansion of Universe?

NO EVIDENCE OF FRACTIONAL CHARGE

RUNNING FINE STRUCTURE CONSTANT in QED

\[ \alpha (M_z) = 1 / 128 \]

Time Variation of the \( \alpha \) ?

Absorption measurement of the spectra of distant quasars indicate smaller value of the \( \alpha \) in the past

CHARGE QUANTIZATION \( \leftrightarrow \) MAGNETIC MONOPOLE

Conservation of Total Angular Momentum

Magnetic Charge \( g = (137/2) \, e \, n \) (Dirac Monopole)

\( e \) is the electric charge and \( n \) is an integer
WHERE TO LOOK FOR FRACTIONAL CHARGE

ACCELERATOR SEARCHES

Unknown production cross section
Limited mass range of the Frac. Charge Particle (FCP)
CDF Limit: $M > 250$ GeV
Possible loss of the FCP in the Detector components

COSMIC RAY SEARCHES

Require very high energy cosmic rays (Moving CM)
Low flux of high energy cosmic rays
Look for material exposed long time: Antarctic Ice

BULK MATTER SEARCHES

No limit on the mass range
Requires assumptions on how FCP got there
Absolute scale of abundance not known

TERRESTRIAL

Water, Silicone Oil, Mercury
Sediment Rocks: Clay, Shale, Limestone
Fluorapatite

Chemistry of Fractionally Charged Particles
K. Lackner and G. Zweig

EXTRATERRESTRIAL

Meteorite
Rocks from Moon and Mars
Asteroids
Levitometer

- Magnetically suspended sample oscillated in an electric field
- Tests magnetically reactive solids
- Test objects: ~ 0.2-0.3 mm dia. 10-100 µgm
- Days per charge measurement
- Measurements are labor intensive
- Samples can be saved and remeasured

Millikan

- Droplets falling in an oscillating electric field
- Test objects are fluid drops
- Drops ~1-10 µm dia. 0.001 - 0.0001 µgm
- Seconds per charge measurement
- Automation demonstrated
Fractional Charge Searches in Bulk Matter

<table>
<thead>
<tr>
<th>Group</th>
<th>Material</th>
<th>Technique</th>
<th>Mass (mg)</th>
<th>σq</th>
</tr>
</thead>
<tbody>
<tr>
<td>LaRue et al. (1981)</td>
<td>Niobium</td>
<td>Levitometer</td>
<td>1.1</td>
<td>0.010-0.093</td>
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<tr>
<td>Marinelli et al. (1982)</td>
<td>Iron</td>
<td>Levitometer</td>
<td>3.7</td>
<td>0.013-0.129</td>
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<tr>
<td>Liebowitz et al. (1983)</td>
<td>Iron</td>
<td>Levitometer</td>
<td>0.72</td>
<td>~0.001</td>
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<tr>
<td>Smith et al. (1985)</td>
<td>Niobium</td>
<td>Levitometer</td>
<td>4.87</td>
<td>0.02-0.05</td>
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<tr>
<td>Jones et al. (1989)</td>
<td>Meteorite</td>
<td>Levitometer</td>
<td>2.8</td>
<td>0.03-0.07</td>
</tr>
<tr>
<td>Hodges et al. (1981)</td>
<td>Mercury(refined)</td>
<td>Millikan</td>
<td>0.6</td>
<td>0.035-0.40</td>
</tr>
<tr>
<td></td>
<td>Mercury(native)</td>
<td>Millikan</td>
<td>0.115</td>
<td></td>
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<tr>
<td>Joyce et al. (1983)</td>
<td>Sea Water</td>
<td>Millikan</td>
<td>0.05</td>
<td>0.037</td>
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<tr>
<td>Lindgren et al. (1983)</td>
<td>Mercury</td>
<td>Millikan</td>
<td>0.5</td>
<td>0.035</td>
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<tr>
<td>Savage et al. (1986)</td>
<td>Mercury</td>
<td>Millikan</td>
<td>2.0</td>
<td>0.040</td>
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<tr>
<td>Mar et al. (1996)</td>
<td>Silicon Oil</td>
<td>Millikan</td>
<td>1.07</td>
<td>0.025</td>
</tr>
<tr>
<td>Halyo et al (2000)</td>
<td>Silicon Oil</td>
<td>Millikan</td>
<td>17.4</td>
<td>0.020</td>
</tr>
</tbody>
</table>

1 mg = 6 x 10^{20} Nucleons
I. SEARCH FOR FRAC. CHARGE IN SILICONE OIL

Traditional Millikan Oil Drop Experiment with High Throughput
Drop size 8-10 microns
Double column, 4 Hz

Search for free fractional electric charge elementary particles,

II. SEARCH FOR FRAC. CHARGE IN SILICONE OIL WITH HORIZONTAL E FIELD

Single Column at 1 Hz
Larger Drop Size (22 microns)
Air Flow to slow down the drops
Horizontal E Field

A new method for searching for free fractional charge particles

III. SEARCH FOR FRAC. CHARGE IN METEORITE

Difficulties in Suspending Heavy Particles
Successful Preliminary Run for Feasibility Test
Ready for New Run with Improved Setup
Stoke’s Law

$$F = 6 \pi \eta \ r \ V$$

$V$ = terminal velocity
$\eta$ = viscosity of air
$r$ = radius of drop

Drops reach terminal velocity in milliseconds
Millikan’s Method

\[ mg + E_d q = 6\pi \eta r \, v_d \]
\[ mg - E_u q = 6\pi \eta r \, v_u \]
\[ v_g = \frac{1}{2} (v_d + v_u) \]
\[ v_e = \frac{1}{2} (v_d - v_u) \]

\[ q \propto v_e \sqrt{v_g} \]
Original Millikan Apparatus (1910)

- Drops generated with an atomizer
- Drops observed with a telescope
- Timed with a stop watch
- Manually operated knife switch
- Hand recorded & calculated results

- rate ~ 1 drop/day
- ~ 100 drops total
- mass throughput ~ 1 nanogram
Multiplexed Millikan Experiment

- SLAC 1996 - 1999
- 42 million fluid drops
- $1/50 \text{e}$ accuracy
- 17.4 milligrams silicone oil
- 1 anomalous fractional charge event
Drop on Demand Fluid Ejector

- Flexible Tubing
- Manometer Tubing
- Glass Tube
- Fluid
- Piezoelectric Disk
- Manometer Tubing
- Enlarged View of Micromachined Orifice Plate
- 0.5 mm
Data Acquisition

- AC Line monitor
- Vibration Sensor
- Temperature
- E Field Polarity
- A/D, DIO Board
- Framegrabber
- Digital CCD Camera
- 100 Mbit Ethernet
- DAQ Machine
- Analysis Machines
- Local Disk
- CD/DVD Archiving
- Results!
Imaging Hardware

Captured image with enhanced contrast

Strobed LED array

Lens

Active region of CCD

~1m

6.4mm

4.8mm
Image Processing
Tracking Algorithm Performance
The Three Data Sets

<table>
<thead>
<tr>
<th>DATA SET</th>
<th>DIAMETER (µm)</th>
<th>MASS SAMPLE (mg)</th>
<th>$V_g$ (mm/s)</th>
<th>$V_e$ (mm/s)</th>
<th>DROPS NUMBER</th>
<th>$\sigma_q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>7.6</td>
<td>1.35</td>
<td>1.54</td>
<td>0.19</td>
<td>$6.42 \times 10^6$</td>
<td>0.016</td>
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<tr>
<td>II</td>
<td>10.4</td>
<td>10.13</td>
<td>2.88</td>
<td>0.16</td>
<td>$1.88 \times 10^7$</td>
<td>0.020</td>
</tr>
<tr>
<td>III</td>
<td>9.4</td>
<td>5.92</td>
<td>2.34</td>
<td>0.18</td>
<td>$1.49 \times 10^7$</td>
<td>0.019</td>
</tr>
</tbody>
</table>
Cuts

- **The first cut** removes drops with charges higher than $4.5\,e$ percentage removed 3.056 %
- **The second cut** removes drops with less than 6 positions percentage removed 0.215 %
- **The third cut** checks the consistency of the charge within a drop, we choose the $\Delta q <0.2e$ percentage removed 0.342 %
- **The fourth cut** eliminates drops with residual larger than $8\sigma_{br}$ percentage removed 0.039 %

These criteria removed 3.653% of the total drops
Residual charge is defined \( q_s = |q| - N_s \)
## Contributions to measurement error $\sigma_q^2$

<table>
<thead>
<tr>
<th>Sources of Errors</th>
<th>Set I</th>
<th>Set II</th>
<th>Set III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brownian Motion</td>
<td>57.0 %</td>
<td>40.9 %</td>
<td>42.1 %</td>
</tr>
<tr>
<td>Position measurement</td>
<td>36.2 %</td>
<td>47.8 %</td>
<td>48.2 %</td>
</tr>
<tr>
<td>E field non uniformity</td>
<td>6.8 %</td>
<td>11.4 %</td>
<td>9.7 %</td>
</tr>
</tbody>
</table>
Horizontal E-Field Millikan Experiment

- SLAC 2000 - ?
- $1/50 \, e$ accuracy
- currently taking data
The electric field is produced by parallel plates embedded directly in the chamber walls, and is limited by the breakdown value in dry air.
Laminar Airflow

The airflow profile across the chamber cross section is determined by the solution to Poisson’s equation.

\[ u(x, y) = 1 - \frac{y^2}{b^2} + \frac{32}{\pi^3} \sum_{n=1,3,5}^{\infty} \frac{(-1)^{2n-1}}{n^3} \frac{\cosh\left(\frac{n\pi x}{2b}\right) \cos\left(\frac{n\pi y}{2b}\right)}{\cosh\left(\frac{n\pi b}{2b}\right)} \]
Measured Velocity vs. z

operating region

Velocity (mm/s)

Height (mm)
The current run has accumulated 70 mg of silicone oil, and is working towards a target of 100 mg.
METEORITE DROPS

ALLENDE METEORITES

Allende, Mexico  Feb. 8, 1969 covering 130 sq. miles
Carbonaceous chondrite meteorite
Contains un-refined Early Solar system materials
   (4.6 billion years old)

Discovery of Fullerene (C-60) molecules
   → High concentration of He 3 gas trapped inside!

PREPARATION OF METEORITE MATERIAL

Grind to micron size in Jet Pulveriser.
Suspend in mineral oil with 5% Castrol 5W30 engine oil

After 3 months, large particles settle out and remaining solution near the top has 1 micron size meteorites with 6% mixture by weight.
PRELIMINARY EXPERIENCE WITH METEORITE DROPS

Colloidal suspension of meteorite STABLE

Drop operation requires retuning every 3-4 days

Dropper stops in 1-2 weeks due to jamming.

→ Go with a larger drop size (25-30 microns)

Drops have very large negative charge:  \( Q = -600 \text{ e} \)

Use \(^{90}\text{Sr}\) radioactive source to produce \( \text{N}_2^+ \) and \( \text{O}_2^- \) in air

Successfully positioned the mean to zero with potential strips shaping the ion distributions.

Failed to reduce the width of charge distribution: \( \sigma = 15 \text{ e} \)

Observed large Dipole effect due to the E-field plates

→ Forced to tilt the air tube to compensate the lateral dipole force

→ New symmetric HV switching system
NEW EXCITING METEORITE DROP RUN WILL START SOON

NEW SYMMETRIC E-FIELD SWITCHING

LARGER CCD CAMERA (1300 x 1000 pixels) WITH FAST READOUT (400Mb/sec)

ONE YEAR RUN WILL REPRESENT THE LARGEST SAMPLE OF METEORITES STUDIED
FUTURE PLANS

Finish the silicone oil experiment: 100 mg

First real data run with Meteorite drops

Alternate material suitable for Frac. Charge Search
e.g., fluorapatite, which collects fluorine-like elements

New approaches:

Magnetic suspension of ferromagnetic fluids

Search for very massive particles with mass spectrometer

Ultimate Dream Experiment

Zero gravity experiment on the surface of an Asteroid!