STANDARD AND UNCONVENTIONAL EXPERIMENTS IN LEPTON PHYSICS *

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Contents of Lecture 1

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1. The Present Landscape in Lepton Physics

a. The Known Leptons

In 100 years six leptons have been discovered in the universe of elementary particles. Three - the electron (e), muon (μ), and tau (τ) - have electric charge $\pm q$ where $q=1.6 \times 10^{-19}$ coulombs; the other three, the neutrinos (ν's) have zero electric charge, Table 1.

Table 1. The properties of the charged leptons and their associated neutrinos. The generation number 1, 2, 3 gives the historical order of discovery of the charged leptons, that is also the order of the masses of the charged leptons. The first generation in no known way is more fundamental than the second or third generation.

Generation	1	2	3
Charged lepton name	electron	muon	tau
Charged lepton symbol	e	μ	τ
Charged lepton mass in units of MeV/c^2	0.51	106.	1777
Charged lepton lifetime in seconds	stable	2.2×10^{-6}	2.9×10^{-13}
Associated neutrino name	ν_e	ν_μ	ν_τ
Upper limit on neutrino mass in MeV/c^2	about 1.5×10^{-5}	0.17	about 20.

The masses of the charged leptons are well known, although we have absolutely no understanding of why the μ mass is about 200 times the e mass and the τ mass is about 17 times the μ mass. We only have measured upper limits for the neutrino masses. Therefore at present the neutrinos are only distinguished from each other by their associated charged lepton. The upper limits come from the limited precision of the technology of the experiments used to measure the neutrino mass. Unfortunately in all these three cases the limited measurement precision of the energy and momentum of the particles combined with other experimental problems has defeated the experimenter.

It is important to find out if neutrino masses are zero or non-zero. Suppose that the neutrinos have zero mass like the photon. The zero mass of the photon is related to a basic invariance property of the electromagnetic field. Similarly a zero mass for the neutrinos should signify something basic, but what? Alternatively suppose neutrinos have non-zero mass. We already know that the ratio of the ν_e mass to the e mass is less than 3×10^{-5}; what is the significance of such a small number? In quark pairs the smallest mass ratio is that of the bottom quark mass to the top quark mass, about 3×10^{-2}.

b. Are There More Leptons: Accelerator Searches?

Since the discovery of the tau and the deduction of the discovery of the tau neutrino twenty years ago[1] there have been many, many searches for additional leptons. Yet no more have been found. I am as surprised as anyone. When my colleagues and I in the 1960's started thinking about looking for charged leptons more massive than the muon I was motivated[2] by my sequential lepton model. I thought there was a long series of charged leptons and associated neutrinos:

$$
\begin{array}{ll}
e & \nu_e \\
\mu & \nu_\mu \\
L & \nu_L \\
L' & \nu_{L'} \\
. & . \\
\end{array}
$$

with the neutrino much less massive than the charged lepton. When we discovered the tau in the 1970's this model seemed even more reasonable.

Since the 1970's the powerful method used to discover the tau at SPEAR

$$e^+ + e^- \rightarrow \tau^+ + \tau^-$$

has been used at ever increasing energies to search for the next charged lepton. In the reactions

$$e^+ + e^- \rightarrow \textit{virtual photon} \rightarrow L^+ + L^-$$
$$e^+ + e^- \rightarrow \textit{virtual } Z^0 \textit{ or real } Z^0 \rightarrow L^+ + L^-$$

when the e^+ and e^- have the same energy E and collide head on, the search can be made up to a lepton mass $m(L) = E/c^2$. As I write the LEP 2 electron-positron collider at CERN has been used to search up to E of about 85 GeV. But no additional charged lepton has been found. Therefore if L exists $m(L) > 45\ m(\tau)$; a larger ratio gap than exists between the τ and the μ.

Searches for neutral leptons are more difficult since the reaction

$$e^+ + e^- \rightarrow \textit{virtual } Z^0 \rightarrow \nu + \bar{\nu}$$

cannot be directly detected. However it can be indirectly detected when the reaction is carried out through a real Z^0,

$$e^+ + e^- \rightarrow real\ Z^0 \rightarrow \nu + \bar{\nu}\ ,$$

because this reaction broadens the decay width of the Z^0. Of course $m(\nu)$ must be less than $m(Z^0)/2$. Since $m(Z^0)$, the mass of the Z^0, is about 91 GeV/c^2, there are no additional neutrinos with mass less than about 45 GeV/c^2.

These lower bounds for $m(L)$ of about 85 GeV/c^2 and for $m(\nu)$ of about 45 GeV/c^2 apply not only to leptons that follow the sequential lepton model, but also to hypothetical leptons with different properties. For example we can considered a charged lepton L that has no associated neutrino, or a charged lepton L whose associated neutrino is more massive, $m(\nu) > m(L)$. If the lepton number of L is conserved it will be stable, if it is not conserved then the L could decay to one or more of the known leptons. Searches for these sorts of leptons have also been fruitless up to a mass of about 85 GeV/c^2. Similarly there have been speculations about a massive stable neutrino, N , not associated with any charged lepton, or N might be stable because it is associated with a more massive charged neutrino, or the decay of N might violate lepton conservation. Once again nothing has been found, and the lower limit on $m(N)$ is 45 to 85 GeV/c^2 depending on the model used in the speculation.

c. Are There More Leptons: Non-Accelerator Searches?

I speculate in Sec. 3 that accelerator searches may not be the best way to look for new leptons. Two examples:

- If a new lepton has fractional electric charge then a search can be conducted up to very large masses using the Automated Millikan Liquid Drop experiment I describe in my second lecture.

- There have been several searches[3] for atoms containing stable charged lepton λ^+. One of the technologies involves using mass spectrometry to look for a very heavy nucleus that contains the λ^+. In a typical search experiment the researchers look for very heavy hydrogen in water, that is look for $\lambda_2 O$. Although the basic apparatus is a mass spectrometer, the sample is sometimes first enriched using techniques such as electrolysis. So far such experiments have had no success, a 1993 search[4] covered λ masses up to about 1500 GeV/c^2 and set a concentration upper limit of 10^{-16} λ's per hydrogen atom in deep sea water.

I am sure there will be other non-accelerator techniques that can and will be used to serch for massive leptons.

2. What We Think We Want to Know in Particle Physics

a. Grand But Standard Questions

- Are there additional elementary particles?
- Are there other fundamental forces?
- Are the elementary particles composites of more fundamental particles?
- What are the equations or laws or rules that set the sizes of the coupling constants and masses and mixing angles?
- What is the significance of the violation of time reversal invariance?
- Do neutrinos have non-zero mass, and if so, do neutrinos change their lepton number?
- How exact is lepton number conservation?
- Is there non-baryonic dark matter, and if so, what is its nature?

b. Very Grand Questions

- What is the correct quantum theory of gravitation?
- Is there a unified theory of all the forces?
- Does time or space have unknown properties such as a fundamental unit of time or length?

c. Experimenting to Answer These Questions

Experiments in particle physics fall into three classes, Fig. 1.

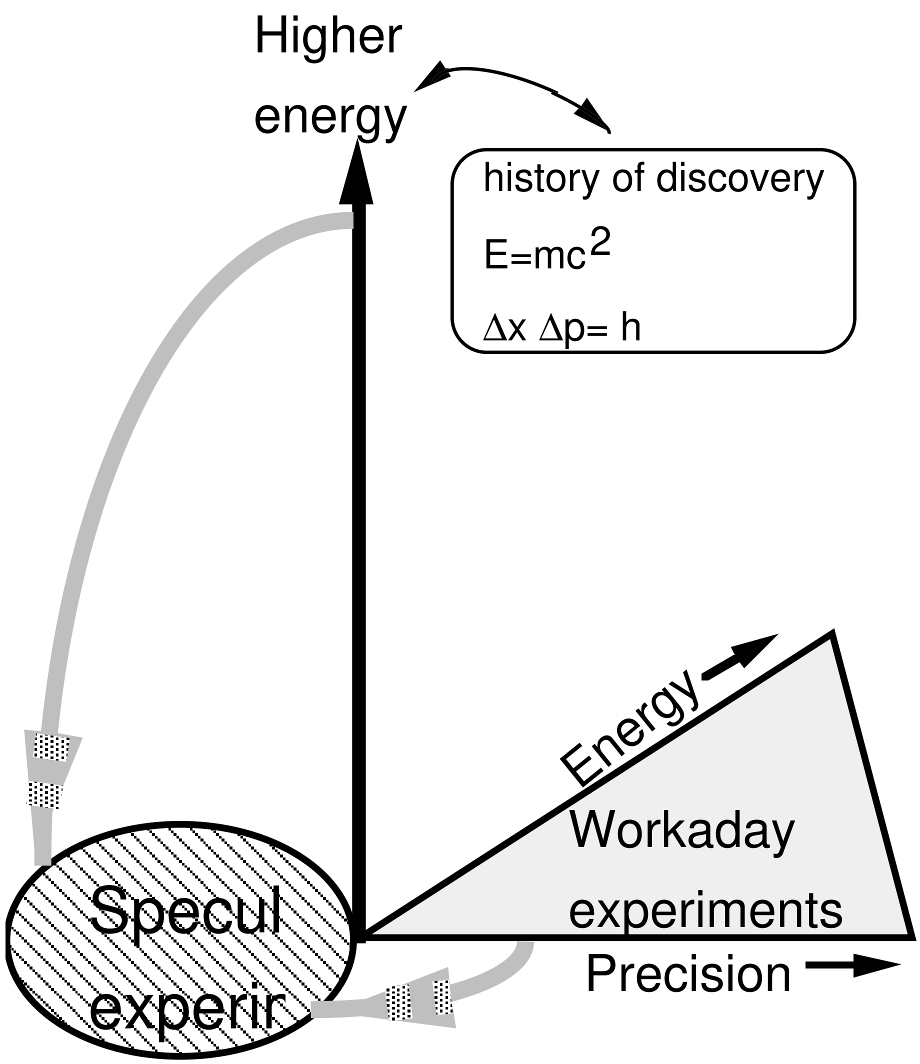

Fig. 1

The history of discoveries in particle physics, E=mc^2, and the uncertainty principle all argue for higher and higher energies being the way to find answers to the grand and very grand questions. For example, as shown in Fig. 2, higher energy electron-positron collisions are a straightforward way to search for leptons, quarks, and bosons of higher mass.

Future e^+-e^- Searches

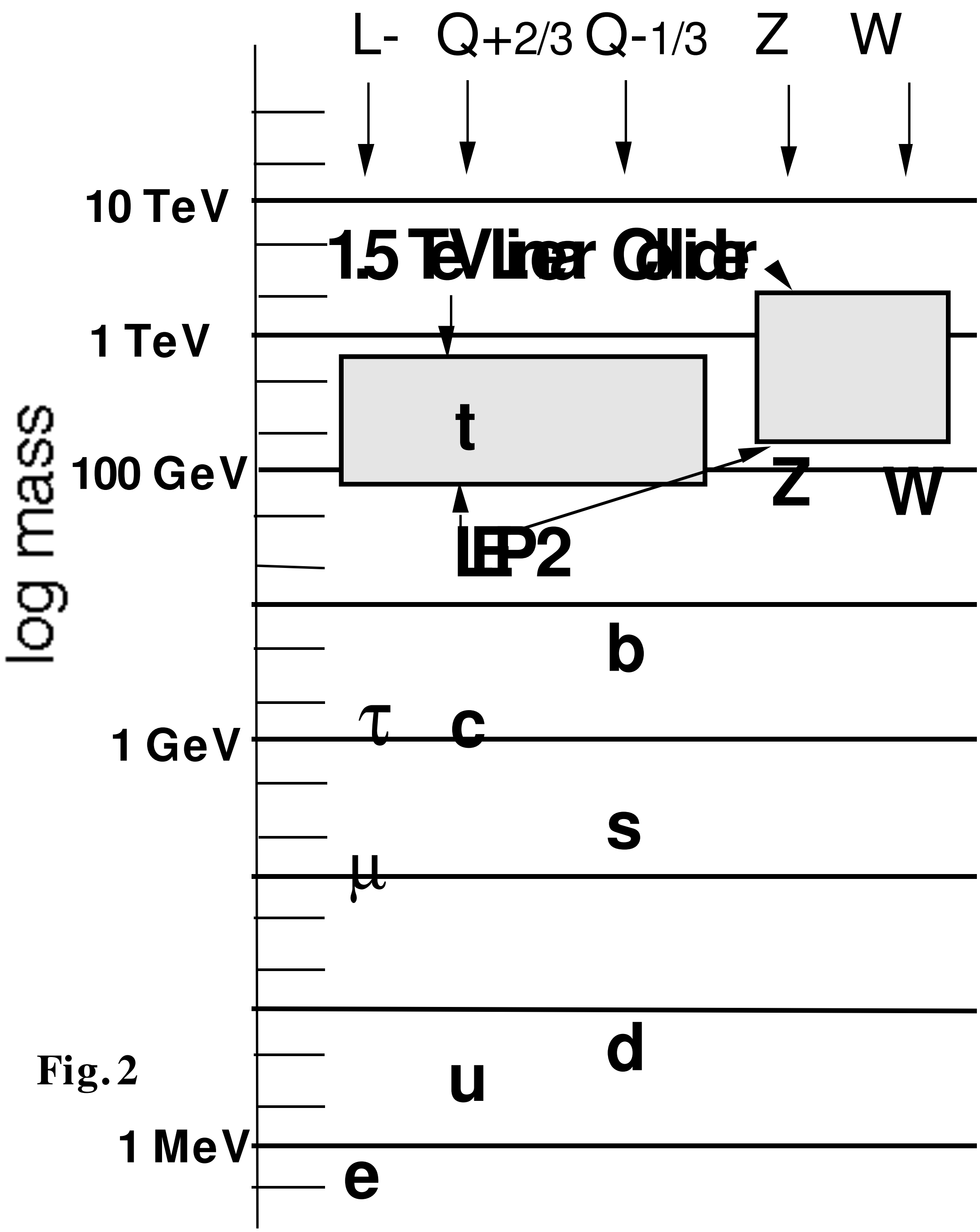

Fig. 2

d. Workaday Experiments

Looking again at Fig. 1, we researchers in particle physics spend a good deal of time on workaday experiments such as the following:

- Detailed measurements of quark decays.
- Detailed measurements of lepton decays.
- Detailed measurements of quark and gluon interactions.
- Searches for odd hadronic matter such as glueballs

We always maintain the hope that one of these workaday measurements will show an anomaly leading to an answer to one of the grand questions.

An example is the workaday experiment of Xiaofan Zhou and myself working in the CLEO Collaboration and using the 10 GeV CESR electron-positron collider at Cornell University. We are studying the radiative decays of the tau lepton such as

$$\tau^- \rightarrow \mu^- + \nu_\tau + \overline{\nu}_\mu + \gamma$$

Figure 3 shows the three processes that are expected to contribute to this decay, with radiation from the μ dominating because its mass is smallest.

$$\boxed{\tau^- \rightarrow \mu^- + \nu_\tau + \bar{\nu}_\mu + \gamma}$$

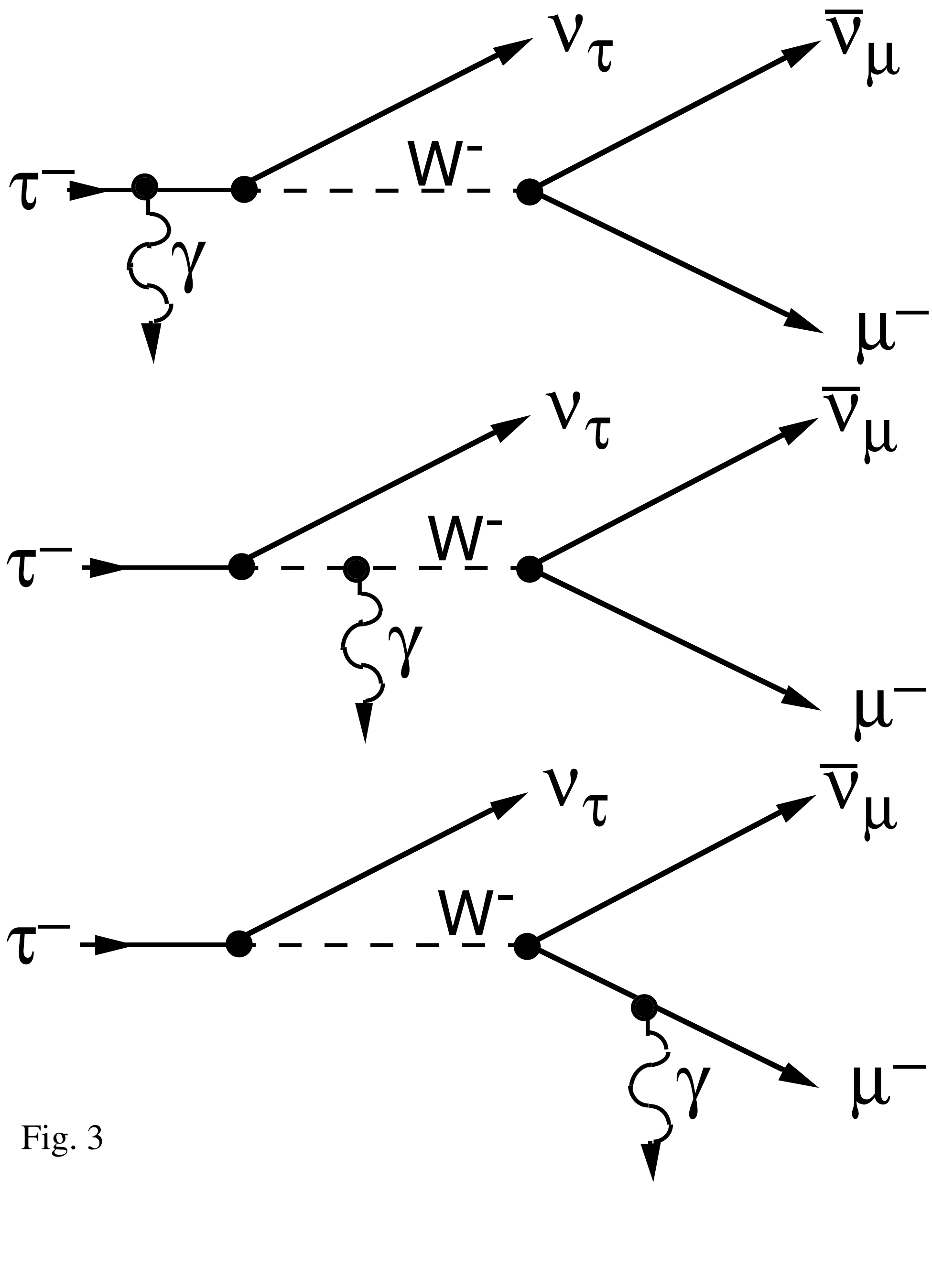

Fig. 3

My dream is that a sufficiently precise measurement might reveal an unexpected contribution to the radiative decay, perhaps a contribution coming from a previously unknown decay process, such as that in Fig. 4.

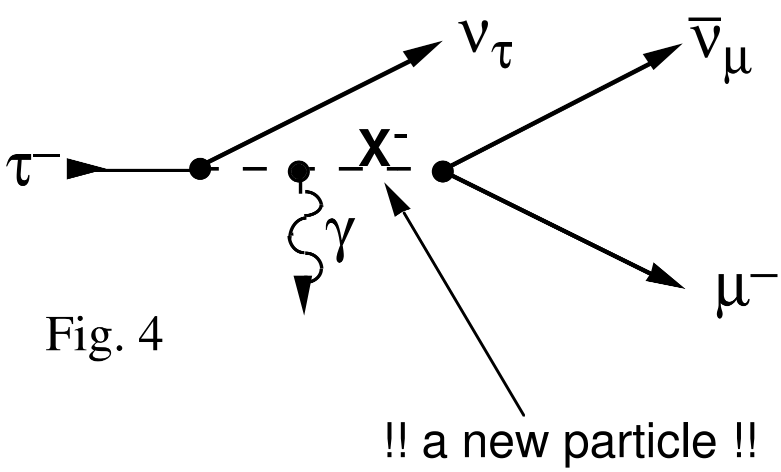

Fig. 4

e. Speculative Experiments

The third class of experiments, Fig. 1, consists of speculative research directed to answer questions such as:

- Are there isolated elementary particles with fractional electric charge:
    - a. isolated quarks with 1/3 q or 2/3 q?
    - b. particles with 1/2 q or -1.5 q or π q or ...?
    - c. particles with very small, but non-zero, charge such as 10^{-6} q?

- Are the electron and proton stable?

- Are there very massive stable particles

- Do magnetic monopoles exist?

- Does strange matter exist?

- Is there a "fifth force"?

There seem to be fewer speculative experiments these days. I don'think it is because we know so much, rather it is the result of tight funds and the drain of the cost of the massive experiments.

3. The Discovery of the Leptons and Experimental Technology

a. Brief History

The reactions

$$e^+ + e^- \rightarrow L^+ + L^-$$
$$e^+ + e^- \rightarrow \nu + \bar{\nu}$$

may not be the best way to search for some kinds of new leptons, they are certainly not the only way. Look back at the history of lepton discovery.

In the late nineteenth century research of William Crookes, Eugen Goldsmith, Heinrich Hertz, Walter Kaufman, Philipp Lenard, Joseph Thomson, Emil Weichert that led to the discovery of the electron, the cathode ray tube was the primary apparatus. Working with the cathode ray tube required understanding the late nineteenth century technologies of gas discharges and vacuum pumps. Indeed one of Thomson's major contributions[5] was his recognition that a good vacuum is required to produce an electrostatic field inside the tube, a field that can electrically deflect the electrons making up the cathode ray, Fig. 5. This accomplishment of Thomson resolved the long standing puzzle of why a cathode ray was deflected in a magnetic field but appeared not to be deflected in an electric field.

The muon was discovered in cosmic rays[6] by following the mystery of penetrating radiation - particles that passed through the atmosphere with little interaction - compared to the interactions expected from electrons or protons. The penetrating radiation puzzle began in the 1920's. But it was not until the 1930's and early 1940's that the new technologies of triggered cloud chambers and coincidence circuits finally led to the identification of the muon; and its separation from the pion[7].

The discovery of the electron antineutrino[8] by Frederick Reines and Clyde Cowan required still different technology. They showed that the electron antineutrino existed using a nuclear reactor and large liquid scintillation counters. For that period in the history of nuclear physics, the liquid scintillation counter apparatus was immense, Fig. 6.

The first use of accelerators in the history of lepton discovery occurred in the early 1960's when Melvin Schwartz and Bruno Pontecorvo independently proposed the use of high energy neutrinos to study the interaction of neutrinos with matter. Schwartz with his colleagues exposed thick plate optical spark chambers to a ν_μ beam, Fig. 7, from the Brookhaven National Laboratory AGS proton accelerator. The interaction of the ν_μ's with the spark chamber material led to muon production, but not electron production, thus showing that the ν_e and ν_μ are different[9] and giving another demonstration of lepton flavor conservation.

The next use of accelerators, and the last use in which a new lepton was found, was our discovery[1,2] of the tau using the SPEAR electron-positron circular collider. But that was not the only new technology, we also used one of the first large solid angle particle detectors, Fig. 8. This detector built by my colleagues from the Stanford Linear Accelerator Center and the Lawrence Berkeley Laboratory consisted of a central magnetostrictive wire spark chamber surrounded by sandwiches of plastic scintillation counters and lead plates, these sandwiches allowing us to detect photons and identify electrons. Then came the coil producing an axial magnetic field, and outermost layers of iron and spark chamber for muon identification.

b**. Lessons from this History**

And so each lepton was discovered using a different experimental technology. Perhaps this was simply because the discoveries stretched over eighty years; or perhaps leptons are so elusive that a new technology is required for each discovery. Perhaps the next charged lepton, is so massive that it is beyond the energy reach of present or near future $e^+ + e^- \rightarrow L^+ + L^-$ search technology, The mass need only be above several 1000 GeV/c^2 to be out of reach. Then methods such as those summarized in Sec. 1C must be used. there are two lessons that we experimenters keep learning and then forgetting:

☞ To improve results you must improve the engineering and the technology of the experiment.

☞ To make a discovery it is often necessary to use or to invent a new technology.

4 Reflections on Experimenters, Experiments and Theory

I conclude this lecture with reflections[10] on experimenters, experiments, and theory in elementary particle physics.

a. Experimenters

☞ The researcher must take account of her or his personality and temperament in choosing experiments. Decide if you like experiments with a few simple results or experiments with many complicated results. Do you like to spend much of your time on inventing, designing, and building equipment; or would you rather concentrate on data analysis and interpretation. Are you happier with standard very high energy experiments, workaday experiments or speculative experiments?

☞ It is best to use your own ideas for, and in, experiments. Unfortunately this is often impossible in today's very large experiments. In that case at least choose a unique topic for data analysis, don't join the hundred other experimenters looking for the hypothetical particle sanctified this year by a hundred theory papers.

☞ You don't have to know everything, you can learn a subject when you need it. Indeed it is best to keep your mind uncrowded. Doing experimental research is not the same as taking examinations in graduate school.

☞ You don't have to be a fast thinker.

b. Colleagues

☞ Try to choose colleagues in research who are smarter than you are. They will be able to help you through difficulties. And if there is a disagreement as to how to do something it is safe to do it their way.

☞ But avoid potential colleagues who are fast talkers and are overbearing. They will kill your ideas before you have time to develop them. With time, thought and helpful colleagues, bad ideas can be transformed into good ideas.

c. Experiments

☞ The feelings of experimenters for their experimental equipment are complicated.

☞ It is very helpful to be interested, even enchanted, by some of the technology.

☞ The experimenter must be prepared to learn in new areas of engineering and instrumentation.

☞ The experimenter may dislike, even dread, some of the technology of the experimenter. Be prepared to have to troubleshoot and rebuild the technology you dislike or dread.

☞ The experimenter must be fond of the apparatus but not in love with it.

☞ If you are in love with your apparatus you become obsessed with using it beyond its capability and usefulness. You must know when to abandon an apparatus or a technique.

d. Theory

☞ Theory should be a good companion to the experimenter, sometimes leading, sometimes following, always helping.

☞ The experimenter must not let theory set the fashion, must not let theory dictate what is important.

Lecture 2: The Search for Free Particles with Fractional Electric Charge

1. Introduction

2. Models for Particles with Fractional Electric Charge

3. Motivation for the Automated Millikan Liquid Drop Search Method

4 Accelerator Searches for Fractional Charge Particles

5. Cosmic Ray Searches for Fractional Charge Particles

6. General Principles of Fractional Charge Particle Searches in Bulk Matter

7. The Levitometer Method in Bulk Matter Searches

8. Our Automated Millikan Liquid Drop Experiment: First Results, Technical Progress, and Search Plans

1. INTRODUCTION

For the past few years we have been engaged in a new search[11] for isolated elementary particles with fractional electric charge - particles such as free quarks not bound in mesons or baryons.[12,13] By fractional electric charge I mean a charge *rq* where *q* is the magnitude of the electric charge (1.602×10^{-19} coulombs) and *r* is a non-integer such as +1/3 or -2/3 or 0.01 or 2.5 or π.

There is *no* confirmed evidence for the existence of *isolated* elementary particles with fractional electric charge and our current theory of the physics of elementary particles does *not* require the existence of such particles. In particular current theory holds that quarks, whose charge is $\pm 1/3\ q$ or $\pm 2/3\ q$, cannot be isolated, Sec. 2. Thus this is a speculative experiment, we are either searching for particles not presently required or we are hoping to demonstrate that isolated quarks can exist.

The plan of this paper is the following. In Sec. 2 I develop some models for fractional charge particles, while reviewing the known elementary particles· In Sec. 3 I give the motivation for our experimental method: a search for fractional charge particles in *bulk* matter using an automated Millikan liquid drop technique. Very different search methods using accelerators and cosmic rays, searches not in bulk matter, are discussed in Secs. 4 and 5. I return to the general principals of bulk matter searches in Sec. 6. A brief description of the magnetic levitometer search method in bulk matter is given in Sec. 7. A general description of an automated Millikan liquid drop search method is given in Sec. 8 along with our first results, technical progress and plans. In this paper I use the symbol *f* to represent a fractional electric charge particle that can be isolated.

There have been two comprehensive reviews on searches for fractional charge particles, Jones[2] in 1977 and Lyons[3] in 1985.

2. MODELS FOR PARTICLES WITH FRACTIONAL ELECTRIC CHARGE

a. Free Quark Model, f_{quark}

The presently accepted theory of quark properties and behavior, called quantum chromodynamics, states that the strong force which acts on quarks and antiquarks prevents the existence of isolated quarks or antiquarks. The theory holds that quarks or antiquarks only exist bound together in pairs in mesons and in triplets in baryons. For example, a π^+ meson consists of an up quark with charge +2/3 *q* and an antidown quark with charge +1/3 *q*, giving a total charge of +1 *q*. A proton consists of two up quarks with total charge +4/3 *q* and one down quark with charge -1/3 *q*, giving a total charge of +1 *q*. (The entire system of quark charges and allowed quark configurations inside hadrons has, of course, been set to fit the observation that all known hadrons have integer charge.)

I speculate, and am not the first to do so,[2,3] that quarks may exist that are not bound in hadrons, or it may be possible to produce isolated quarks. Then just as Newtonian mechanics is a restricted sector of relativistic mechanics, so quantum chromodynamics might be a restricted sector of a more general theory of the strong interactions. Our speculative search for free quarks must then reach outside the present experimental boundaries which are the foundation of quantum chromodynamics.

I use the symbol f_{quark} for a free quark, we expect the charge to be ±1/3 *q* or ±2/3 *q* as for bound quarks. But I do *not* require or even expect the masses to be those of the bound quarks.

b. Free Diquark Model, $f_{diquark}$

Slansky et. al[14] have described the possibility that pairs of quarks might more easily occur in an isolated state. For example, a free diquark

$f_{diquark}$ might consist of two up quarks and have a charge 4/3 q or of two up antiquarks and have a charge of -4/3 q.

c. Fractional Charge Lepton Model, f_{lepton}

Suppose there are fractional charge leptons, f_{lepton}, with charges such as 1/2 q for example. Since leptons do not partake of the strong force, it is straightforward to understand how they might be produced, Sec. 3.

d. Electromagnetic Model, f_{em}

An even simpler model consists of a fractional charge particle, f_{em}, that only interacts through the electromagnetic and gravitational force.

e. Millicharge Particle Model, $f_{millicharge}$

The recent experimental work of J. Jaros and his colleagues[15] has revived interest in the possible existence of particles with very small electric charges, such as 10^{-2} q and smaller. The search methods discussed in this paper are not sensitive to such small charges.

3. MOTIVATION FOR THE AUTOMATED MILLIKAN LIQUID DROP SEARCH METHOD

a. Selection of a search method for fractional charge particles.

There are three ways to look for *f*'s, fractional charge particles:

<u>Produce *f*'s in an accelerator experiment</u>

For example use electron-proton annihilation, Sec. 4:

$$e^{+} + e^{-} \rightarrow f^{+Q} + f^{-Q} \tag{1}$$

<u>Search in cosmic rays</u>

The *f* might be contained in the cosmic ray flux coming from outside the earth's atmosphere or the *f* might be produced in a cosmic ray collision in the earth's atmosphere, Sec. 5.

<u>Search in bulk matter</u>

An *f* might exist in bulk matter on or near the earth's surface. The *f* might have been produced by a cosmic ray collision at the earth's surface sometime during the history of the earth. Or the *f* may have been produced in the early universe and come to the earth, perhaps during the formation of the earth or perhaps later by a meteorite landing on the earth.

For the reasons given in Secs. 4 and 5 further searches in accelerator experiments or in cosmic rays were not attractive to me. But to search for *f*'s in bulk matter was and is attractive to me. Indeed very attractive because we have developed such a beautiful method to search for *f*'s in bulk matter.

As for possible sources of *f* particles on the earth's surface I am very partial to the speculative concept that the *f* particles we seek were produced in the early universe, and our experiment is designed with this concept playing a dominant role in our thinking. This probably seems far fetched to many readers; they think to themselves that surely accelerator searches are more straightforward. To explain my thoughts and my passion I will take the reader through the alternate choices of accelerator searches, cosmic ray searches, and the bulk matter levitometer method. However before doing so I give a brief description of our technique.

b. Automated Millikan Liquid Drop Method

Our method, Fig. 1, was developed from the technique used in fractional charge searches at San Francisco State University[16,17,18,19] which in turn were modern versions of the original work of Millikan.[20,21,22] Two flat, horizontal, circular, metal plates about 1 cm apart have small diameter holes along their central axis. The plates are in air and there is a vertical, uniform, electric field E between the plates. The direction of E changes every 0.2 s, alternating between E_{up} and E_{down}. Very small liquid drops, about 7 μ in diameter, are produced periodically by the drop generator and fall along the axis of the plates under the influence of gravity.

The air resistance leads to drops without charge falling with a constant terminal velocity v_{term}, given by Stoke's law:

$$mg = 6\pi\eta r v_{\mathrm{term}} \qquad (2)$$

Here mg is the gravitational force, η is the viscosity of air, m is the drop mass and r is the drop radius. For our drops $v_{term} \approx 1.4\ mm/s$. When a drop has a charge Q, there are two different terminal velocities, v_{up} and v_{down}, given by

$$\begin{aligned} mg + QE_{down} &= 6\pi\eta r v_{down} \\ mg - QE_{up} &= 6\pi\eta r v_{up} \end{aligned} \qquad (3)$$

As the drop falls repeated measurements are made of v_{down} and v_{up} using the stroboscopic light source, the CCD video camera, and a computer. Since we know the density ρ of the liquid and $m = 4\pi r^3\rho/3$, the measured values of v_{down} and v_{up} give the charge Q of the drop.

If the drop does not contain a particle with fractional charge then Q will have, within measurement error, one of the values...0, $\pm 1\ q$, $\pm 2\ q$...; depending on whether the drop contains an equal number of protons and electrons, or there is an excess of protons or electrons. If, to our great pleasure, the drop contained say a free quark of charge 1/3 q then Q would have one of the values +1/3 q, +4/3 q, +7/3 q... or -2/3 q, -5/3 q, ... depending on the proton - electron balance in the drop.
This was Millikan's method[10-12] and this is our method eighty years later[23]. Millikan studied a few hundred drops, we have studied almost 10^7 drops[1] and will soon study 10^8 to 10^{10} drops. Our improvement over Millikan is made possible by the use of modern technology, Sec. 8, piezoelectric drop generators, CCD video cameras, image processing electronics, and computers.

4. ACCELERATOR SEARCHES FOR FRACTIONAL CHARGE PARTICLES

The principle behind accelerator searches for fractional charge particles is straightforward. The experimental apparatus must be sensitive to the production in collision of a particle f with charge $Q \neq Nq$, where N is integer. Examples are proton-proton collisions:

$$p + p \rightarrow f^{+Q} + f^{-Q} + other\ particles; \qquad (4a)$$

and positron-electron annihilation:

$$e^{+} + e^{-} \rightarrow f^{+Q} + f^{-Q} + other\ particles; \qquad (4b)$$

$$e^{+} + e^{-} \rightarrow f^{+Q} + f^{-Q}\ . \qquad (4c)$$

The conservation of electric charge requires the production of the f^{+Q}, f^{-Q} pair, but the experimenters need only detect one f. Of course one may speculate that charge need not be conserved in f production:

$$p + p \rightarrow f^{\pm Q} + other\ particles \qquad (5a)$$

$$e^{+} + e^{-} \rightarrow f^{\pm Q} + other\ particles. \qquad (5b)$$

Indeed this is what was done in almost all accelerator searches. Thus Banner et al.[24] looked at 540 GeV total energy proton-antiproton collisions

$$p + \overline{p} \rightarrow f + \ other\ particles \qquad (6)$$

searching for an f produced at 90° to the antiproton beam direction. The search was sensitive to f charges as small as 1/3 q and f masses as large as 3.5 GeV/c^2. No f's were found and the upper limit on f production is this experiment was defined using

$$\mathrm{R}_f = \frac{\sigma_f(90^0)}{\sigma_{any\ particle}(90^0)} \qquad (7)$$

Here σ_f (90°) is the sought cross section for *f* particles at 90° and $\sigma_{any\ particle}$ (90°) is the measured cross section for the production of any charged particle, a charged pion or proton for example, at 90°. The experimenters found[16]

$$R_f \leq 10^{-3} \text{ to } 2 \times 10^{-4} \tag{8}$$

depending on the mass and charge of the sought *f*.

This illustrates two of the problems or weaknesses in accelerator searches.

i. The available energy puts an upper limit on the mass of the *f*.

ii. The significance of R_f in Eqs. 7 and 8 is obscure. The denominator in Eq. 7 is a strong interaction cross section, is $R_f < 10^{-4}$ a loose limit or a tight limit on *f* production $\bar{p}p$ collisions?

The significance of an accelerator experiment determined limit is a little clearer in the simplest electron-proton annihilation search method since the reaction

$$e^+ + e^- \to f^{+Q} + f^{Q} \tag{9}$$

can occur through the mechanism in Fig. 2. It is customary to compare the cross section for high energy $e^+ + e^-$ annihilation reactions to the cross section for

$$e^+ + e^- \to \mu^+ + \mu^- \tag{10}$$

a copious and completely understood process. Thus

$$R_f = \frac{\sigma\left(e^+ + e^- \to virtual\,\gamma \to f^{+Q} + f^{-Q}\right)}{\sigma\left(e^+ + e^- \to virtual\,\gamma \to \mu^+ + \mu^-\right)} \tag{11}$$

is defined.

If $Q = rq$ and the *f*'s are leptons, hence not affected by the strong interaction, then

$$R_f = r^2 \times T \tag{12}$$

The threshold factor, T, depends on E, the total energy, and M, the f mass. For example if the f has spin 1/2

$$T = \frac{1}{2}\left[1-\left(\frac{2M}{E}\right)^2\right]^{\frac{1}{2}}\left[2+\left(\frac{2M}{E}\right)^2\right] \tag{13}$$

so that $T = 1$ for $E >> 2M$ and $T = 0$ at $E = 2M$.

W. Guryn et al.[25] have carried out such a search at $E = 29$ GeV. The experiment was sensitive to charges, Q, as small as 1/3 q and masses, M, as large as 14 GeV/c^2. No f's were found. The 90% confidence level upper limits on R_f of Eq. 11 were

$$\begin{aligned} &R_f \leq 3 \times 10^{-2} \text{ for } Q = 1/3\, q \text{ and } M \leq 10 \text{ GeV/c}^2 \\ &R_f \leq 10^{-2} \text{ for } Q = 2/3\, q \text{ and } M \leq 10 \text{ GeV/c}^2 \end{aligned} \tag{14}$$

Thus if the f's are leptons, the limits in Eq. 14 have clear significance. However, if the f's partake of the strong interaction there is a serious impediment to a clear understanding of the limits on R_f. Eq. 12 must be replaced by

$$R_f = r^2 \times T \times F_{SI} \tag{15}$$

where F_{SI} takes account of the strong interactions between the f's; $F_{SI} \leq 1$ and may be zero. Consider Fig. 3, a picture of how present strong interaction theory describes the process

$$e^+ + e^- \rightarrow x(quark) + \bar{x}(antiquark). \tag{16}$$

In (a) the x and $\bar{x}$ are moving apart, the field lines show schematically the strong force between the x and $\bar{x}$, the force carried by gluons. In (b) the x and $\bar{x}$ are further apart, but more of the energy E of the collision is now in the strong force field. In (c) this field energy changes into additional quark-antiquark pairs. Finally in (d) the quark-antiquark pairs change into pions, there are no separate quarks left, and F_{SI} in Eq. 15 is zero.

It may be that if the x and $\bar{x}$ could get far enough apart without additional $x\bar{x}$ production, they might break free and then $F_{SI} \neq 0$. But we don't know how much energy would be required or how small the probability would be. Of course, the theory of quantum chromodynamics states quarks can never break free, that F_{SI} always equals zero. This brings us to the third problem in accelerator searches for *f*'s.

iii. If the *f* partakes of the strong force we don't know the effect of the strong force on R_f.

The presence of the strong force raises a second problem in accelerator searches.

iv. The *f* may interact and stop in the walls of the accelerator, target or detecting apparatus, hence it may be produced but not found. The positron-electron search just discussed considers this problem.[17]

Points i, ii, iii, and iv have turned me away from working on accelerator searches for fractional charge particles.

My turning away from accelerator searches does not mean that I think further accelerator searches are pointless. Indeed I believe searches for *f*'s should be made at present high energy accelerators: the Tevatron with proton-proton collisions at almost 2 TeV and LEP with electron-proton collisions at 190 GeV/c. And certainly *f* searches should be made at the future Large Hadron Collider with a design energy of 14 TeV.

5. COSMIC RAY SEARCHES FOR FRACTIONAL CHARGE PARTICLES

There have been no confirmed discoveries of fractional charge particles. The reviews of Lyon[3] and particularly Jones[2] give many details. Cosmic ray searches have the same problems as accelerator searches if we hope that the f is produced by cosmic ray collisions in the atmosphere. As in point i of Sec. 4 the available energy puts an upper limit on the f mass. There are very high energy cosmic rays, but their flux is very small. And as in points ii and iii the f production mechanism is obscure.

Point iv in Sec. 4, the worry about the f interaction and stopping before detectors, also applies in cosmic ray searches, whether the f has come from outside the solar system or is produced in the atmosphere.

The upper limit[2] on the existence of fractional charge particles with $Q \geq 1/3\ q$ is about 10^{-10} *particles*/(cm^2 *sr s*). This can be compared with the total flux of cosmic rays of energy greater than 1 GeV, namely 2 *particles*/(cm^2 *sr s*). Thus, the searches have been heroic. It is difficult to substantially improve the sensitivity of f searches in cosmic rays unless special selection criteria are used, for example f's might be sought only in very high energy cosmic ray events.

6. GENERAL PRINCIPLES OF FRACTIONAL CHARGE PARTICLE SEARCHES IN BULK MATTER

Finally I get to searches for *f's* in bulk matter, the levitometer method described briefly in Sec. 7 and our experiments in Sec. 8. "But," the reader may be thinking, "you have been so hard on searches using accelerators or cosmic rays, emphasizing the uncertainties, surely expecting to find a rare particle produced in the early universe is also an uncertain enterprise."

My hope is that:

(a) Fractional charged particles, *f*'s, were produced in the very early universe along with photons, leptons and quarks.

(b) As the universe cools some of these *f*'s were not annihilated, but remained in the H and He gas of the early universe.

(c) Next some of the *f*'s along with the H, He and other light nuclei collected into stars.

(d) Eventually some of these stars disintegrated as supernova ejecting the *f*'s, the light nuclei and the heavier nuclei made in the stars.

(e) Finally some of the material from supernovas along with the *f*'s became our solar system, the asteroids and meteors of that system, and our earth.

If you think about it, this sequence is not so fantastic, it is the sequence which produced the carbon, oxygen, nitrogen, iron, and uranium of our world.

There are several general principles for fractional charge particle searches in bulk matter.

i The sensitivity of a search depends in part upon the amount of bulk matter examined. Table 1 shows the amount presently achieved. Note, 1 mg contains about 6×10^{20} nucleons. If we ignore the claims of LaRue et al.[26] to have found *f*'s, then no *f*'s have been found in material containing about 10^{21} nucleons.

Table 1. Published searches for free fractional electric charge in bulk matter. The mass is in mg. 1 mg contains about 6×10^{21} molecules.

Method	Experimenters	Material	Mass (mg)
levitometer	LaRue *et al*. [16]	niobium	1.1
levitometer	Marinelli & Morpurgo [18]	iron	3.7
levitometer	Liebowitz *et al*. [19]	iron	0.7
levitometer	Smith *et al*. [20]	niobium	4.9
levitometer	Jones *et al*. [21]	meteorite	2.8
Millikan liquid drop	Hodges *et al*. [6]	mercury	0.1
Millikan liquid drop	Lindgren *et al*. [8]	not relevant	
Millikan liquid drop	Savage *et al*. [9]	mercury	2.0
Millikan liquid drop	Joyce *et al*. [9]	sea water	0.05
Millikan liquid drop	Mar *et al*. [1]	silicone oil	1.1

ii But, and this is a large but, the physics and chemistry of atoms with a fractional charge at the nucleus has a substantial influence on the probability that a particular material sample contains *f*'s.[27]

Consider the example of an atom with a total nucleus charge of +4/3 q. As shown in Fig. 4 this can occur in three ways. With one electron in the atom, the electronegativity of the atom is large[17] and the atom behaves chemically like fluorine, and *not like hydrogen*. Therefore if one wants to search for *f*'s of the type in Fig. 4, it is best to look in material which naturally contains compounds of fluorine.

Another consequence of quark chemistry concerns iron being the largest mass samples in Table 1. Metallic iron is smelted from iron ores such as hematite, Fe_2O_3, and magnetite, Fe_3O_4. These ores have been concentrated in small volumes at the earth's surface through complicated geochemical processes. It is unlikely that iron atoms containing *f*'s would have participated in the concentration processes, hence iron may not be a good place to look for *f*'s.

General principle iii for bulk matter searches is another argument against further searches in terrestrial iron for *f*'s.

iii It is less likely that *f*'s will be found in highly refined materials; the *f* or *f* containing atom is likely lost in many refining processes because of the unneutralized charge.

Principle iii is an argument against further study of niobium, nevertheless the claims of La Rue et al.[16] impel further study of niobium.

In Sec. 8 I give our choices for the materials which I believe are the most likely sources for fractional charge particles.

7. THE LEVITOMETER METHOD IN BULK MATTER SEARCHES

In the levitometer method a small object such as a spherical ball is magnetically suspended, an oscillating electric field is applied to the object, and the charge on the object is determined by measuring the amplitude of the forced oscillation. The magnetic suspension may be accomplished using diamagnetic material, ferromagnetic material, or superconducting material for part or all of the object. Here I briefly and qualitatively describe the ferromagnetic levitation method[28,29,30,31]. The ferromagnetic ball in Fig. 5 is supported against gravity by the magnetic field of a coil. An optical feedback system measures the vertical position of the ball and adjusts the coil current so that vertical position of the ball is fixed. An additional magnetic field, not shown in Fig. 5, has a local maximum in field strength in the horizontal plane, the local maximum being along the coil axis. This produces a harmonic restoring force, βx pushing the ball horizontally toward this axis. A motion damping mechanism $\alpha\dot{x}$, not shown, is also provided. The equation for free horizontal oscillation of the ball of mass m is

$$m\ddot{x} + \alpha\dot{x} + \beta x = 0 \qquad (17)$$

The ball is put into forced oscillation by a horizontal, uniform, oscillating electric field, $E \cos \omega t$. If the ball has charge Q, the equation of motion is

$$m\ddot{x} + \alpha\dot{x} + \beta x = QE\cos\ \omega t \qquad (18)$$

At resonance the amplitude of the forced oscillation is

$$x_0 = QE/\alpha\omega \qquad (19)$$

Since E, α, and ω are known, Q is determined from x_o.

The ferromagnetic levitometer method has been highly developed and effectively used by Marinelli and Morpugo[18], Liebowitz et al.[19], and Smith et al.[20]. As demonstrated by Jones et al. [21], a non-ferromagnetic material can be used by plating the material with iron.

The balls or other objects used in these levitometer experiments had linear dimensions of 0.2 to 0.3 mm and masses of 0.03 to 0.1 mg. The study of the charge on one object generally took one or more days. The levitometer search method is attractive but I feel our automated Millikan liquid drop method, discussed in the next section, will handle larger quantities of material.[13]

8. OUR AUTOMATED MILLIKAN LIQUID DROP EXPERIMENT: FIRST RESULTS, TECHNICAL PROGRESS, AND SEARCH PLANS.

As described at the end of this section we plan to search through a number of specific solid materials, and we need to suspend or immerse these materials in powder form in an inert stable, low vapor pressure liquid of low or moderate viscosity. We chose for the liquid Dow-Corning 200, 5-cs silicone oil. Liquids such as water or alcohol have much too high a vapor pressure, and many oils have too large a viscosity. As discussed in Sec. 4, we do not expect to find fractional charge particles in such a refined, synthetic material as silicone oil, however we began our search with this oil to develop our technique.

a. First results

In our first search[1] we used 7.1 μ diameter drops of silicone oil produced by the drop generator in Fig. 6. A drop was pushed out of the 8 μ diameter hole in the bottom of the dropper every time a voltage pulse about 1 us wide and about 150 volts in amplitude was applied. In the first search we used a 486/66 class personal computer with a first generation image capture card and a commercial grade CCD camera to locate the drops and to obtain the terminal velocities. Only one drop at a time was allowed to be in the imaged region between the plates. This was because limitations in the processing speed of our computer system did not allow us to extract velocities in real time from an image that contained multiple drops. Thus we limited the drop production rate to 0.6 Hz to assure that two drops never appeared simultaneously in the field of view of the camera. In our early work there were also problems with the drop ejector that rendered drop production unstable if production rates exceeded a few hertz.

We required in general four measurements of the drop charge, Q1, Q2, Q3, Q4, during the fall of each drop. We further required that the maximum spread of Q1, Q2, Q3, Q4 be less than 0.15 q. This eliminated the small fraction of the drops that during their fall either picked up an ion or were hit by a cosmic ray; such occurrences could give a false fractional charge. We then used the average value of the four measurements to calculate the charge Q of the drop.

Fig. 7 gives the distribution of the charge of the 6 x 10^6 drops used in the first search. We see that most of the drops have zero charge with the remaining drops having charges that extend out to about $\pm 10\ q$. To look for fractional charge, we define

$$Q_f = |Q|/q - N_f \quad (20)$$

were N_f is the largest non-negative integer less than $|Q|/q$. The graph of Q_f in Fig. 8 shows there were no fractional charge particles in the intervals between the integer charge peaks in this 1.07 mg of silicon oil. These intervals are

0.2 q to 0.8 q
1.2 q to 1.8 q
. .
-0.2 q to -0.8 q
-1.2 q to -1.8 q
. .

We have achieved a root mean square error in the charge measurement of 0.025q; a fortieth of the charge on an electron. The large number of drops observed brings the tail of the charge measurement distributions out to 0.2 q limiting our ability to search for small fractions charges close to the integer peaks. In searching for fractional charges near 1/3 and 2/3 q the measurement distribution is sufficiently narrow that false detections are not a problem. We are pleased with the small root mean square error; more than half of which is caused by the Brownian motion of the drop in the air. We are also pleased by the cleanliness of the technique, the interval between the integer charge peaks has no background. A few f's forming a peak of events at some fractional charge should show up easily if we search through the right material.

b. Technical progress

In the year since we completed the first search we have made good progress in being able to search through material at a much greater rate. A reconfiguration of the drop generator assembly and a change in the dropper excitation waveforms allows drop ejection now in the hundreds of hertz range.

A method of producing two dimensional arrays of drops with purely electronically programmable vertical and horizontal separations was developed, Fig. 9. This was accomplished by ejecting the drops horizontally and sequencing the excitation through a discrete set of different values such that the ejected drops would fall in different columns. The number and spacing of the columns are determined by the number and magnitudes of discrete excitation values that are sequenced through. The number of drops in each column is determined by the ejection rate. The vertical spacing is defined by drop production rate and drop terminal velocity. The advantages of this method are that it can utilize existing single channel drop ejectors and, that it allows us to vary at will the drop distributions in computer's field of view in order to maximize the throughput commensurate with minimum drop to drop measurement interference.

A new measurement chamber and optical platform have been designed and built. Computer simulations predicted that electric field plates of half the diameter of the original main electric field plates could be used without an increase in error from E field non uniformity. The entire apparatus scaled down in size with this decrease in electric field plate size. This made practical placing cameras at right angles to each other to view the measurement region. A dual camera system makes instrument calibration and alignment much easier and allows the detection of out of focal plane drops that can potentially give false fractional charge indications.

The measurement electronics were also upgraded. Both digital CCD cameras and low cost desktop computers have increased in performance since our initial automated Millikan experiment was performed. With our new digital cameras and higher speed computers we believe that it is possible to calculate the charges of multiple drops simultaneously present in the field of view of the camera in real time. If the drops are generated in the pattern of a regular two dimensional array, on the order of a hundred drops can fit in the field of view of the camera before their mutual interactions start to degrade measurement accuracy. This represents a very large potential enhancement of our ability to do fractional charge searches through much larger quantities of test material in the same amount of time.

c. Plans

Finally as promised at the end of Sec. 6, our plans for the material we will examine. First we will use this enhanced hardware to search through 10 or 20 mg of silicone oil to set a baseline for the searches and establish that the computer algorithms for extracting drop charges from images containing multiple drops are fully operational and accurate. Next we will suspend within this silicone oil materials that we believe are likely to contain or at least not have actively suppressed fractionally charged particles bound to normal atoms. Since the chemical processes mentioned in Sec. 7 may remove atoms with bound free quarks via difficult to predict geochemical processes, primordial material that has not participated in significant amounts of terrestrial chemical reactions are the test materials of choice. Examples of materials of this type include Moon rocks and the cores of fallen meteorites believed to be of cometary or asteroidal origin. Terrestrial materials such as flourapatites which concentrate chemical impurities from the surrounding rocks are also likely target materials. Since the masses and nuclear binding properties of free quarks are unknown, we plan on testing about a dozen different test fluid suspensions. Each colloidal suspension will correspond to an optimized fluid for one particular theory of free quark properties.

The measurement apparatus is also intended to be continuously upgraded as the experiment progresses. The most critical enabling technologies for this experiment are the digital imaging and analysis hardware. Due to demands from the consumer, industrial and military sectors, the capabilities of such hardware for a given price has been increasing rapidly and will almost certainly continue to do so over the next decade. Our Millikan technique based fractional charge search experiment has been designed to exploit this technological trend by being built in a modular fashion to allow new imaging hardware to be incorporated as it becomes available.

As an example, we anticipate that it will initially take multiple paralleled computers to process the image in real time of the hundreds of drops contained in a single frame. Each computer will be programmed at first to handle analysis of a single column containing ten or twelve falling drops out of the ten total columns of drops in the camera's field of view. Five years ago, a similarly priced single computer was able to only track a single falling drop. Each of these computers will be linked to a central computer whose job will be to continually process and archive the data collected in real time. As computer power and digital camera pixel density increases increase the physically imaged field of view will be expanded which will increase measurement throughput. We simultaneously anticipate the computational power per dollar available on desktop computers to increase even faster which will reduce the cost of the image analysis hardware required to run the experiment.

The ultimate goal is to make a fractional charge search experiment that can run totally autonomously for extended periods of time. If the cost of the measurement hardware is low and the need for human operator interaction is minimal, then throughput can be increased by simply building and running multiple copies of the measurement chamber. This designed-in ease of replication at low cost is also important in an experiment of this kind, so that the apparatus can be readily reproduced at low cost by other research groups should fractional charge events be detected.

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