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A SEARCH FOR FRACTIONAL CHARGE

The Ohio State University

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A SEARCH FOR FRACTIONAL CHARGE

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree doctor of Philosophy in the Graduate
School of the Ohio State University

By
Ronald Edward Turner, B.S., M.S.

*****

The Ohio State University
1984

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VITA

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Attempts to measure the value of the fundamental unit of electric charge have been conducted ever since it was believed that matter existed in discrete form. The most comprehensive early measurements were made by Robert Millikan in his celebrated Oil Drop Experiment. His conclusion was that all matter carries integral multiples of $1.6 \times 10^{-19}$ coulombs, the magnitude of the charge on an electron or proton. These experiments were performed around 1910. In the first half of this century, refinements were made in his procedure allowing more precise measurements of this quantity, but the basic tenet was unchallenged. Around 1960 Gell-Mann and Zweig independently proposed that protons were made up of smaller particles now called quarks. They found that all of the particles catalogued at that time fell into a pattern predicted by a model that assumed they were made from three new fundamental particles that carried charges with one third or two thirds of the value of an electron's charge. As the quark theory was developed, its predictions were so
successful that by the 1970's the existence of quarks was no longer doubted by the physics community.

In the meantime, however, a new generation of very sensitive searches had been made specifically looking for fractionally charged particles, all of which were either inconclusive or negative. These searches were performed using everything from standard high purity elements to such exotic sources as meteorites, sea water, oysters, and peanut oil. Later searches expanded into lunar soil and antifreeze. However, even before this new wave of data had begun to look convincing, it was found that theory seemed to imply a quirk called "confinement". This new development asserted that one could not, even in principle, isolate a single quark. All quarks had to exist in combinations that had a net zero or integral charge.

Thus the experimentalists and theorists would be in agreement to this day were it not for a series of experiments conducted by Fairbank and collaborators and published between 1977 and 1981. They claim\textsuperscript{1,2,3} to have found fractional charges at a concentration of one in 10\textsuperscript{20} nucleons in very tiny niobium spheres using a sophisticated version of the Millikan Oil Drop Experiment. Since this is the only conflicting claim against a seemingly massive body of corroborating experiments, why not simply discount Fairbank's result as somehow flawed? There are many good reasons.
First, Fairbank's technique has survived six years of very intense scrutiny. Any result as controversial as this naturally invites the best minds to analyze it. Invariably, experimentalists and theorists come away from such a study empty handed. So far no flaw has been found, nor has any alternate explanation been proposed. It is a very sound experiment. While it may be wrong, no one to date could say why.

Second, inevitably all searches for fractional charges have caveats that could preclude detection of existing fractional charges. Attempts to produce free quarks in very high energy accelerators have only explored free quark masses of 25 GeV/c² or less. Pure confinement predicts an infinite, and thus unattainable, mass for free quarks. Searches for fractionally charged objects among cosmic rays typically are restricted to one-third or two-thirds charged objects. If a fractional charge tends to accrue even one additional integer charge, it would not be detected by such searches. Finally all bulk matter searches suffer two major failings. One is that they may be looking in the wrong place. Geologically, the fractional charges will have had plenty of time to have been selectively deposited where their chemistry says is most favorable. This is the "you find gold in gold mines" argument. Furthermore, even if you pick the right sample initially you may, in preparing your sample, separate out the
very thing you are looking for. The fact is, very little is known about the chemistry of fractionally charged objects.

There is still one more reason why Fairbank's result should be taken seriously. There is nothing in his conclusion that contradicts the unproven but strongly suggested notion of confinement. As Fairbank himself is very careful to point out, he has found evidence for the existence of fractional charge, not free quarks. While fractional charge searches are colloquially called "quark searches", a fractional charge could actually fit into a variety of modern theories. It could be a fractionally charged lepton (a class of particles not made up of quarks). It could be a new type of quark with no charge bound to two normal quarks giving a particle in which all the quarks are confined, but resulting in a particle with a net fractional charge. It could even be evidence for a new type of hypothetical particle that is proposed to be a building block of quarks and leptons. It remains for the experimentalists to unravel this puzzle. Their aim is twofold. First, is Fairbank right? Do free fractional charges exist? Second, what are their basic properties? For example, what is their mass? Also, Fairbank's experiment can only measure net charge, and thus it can only determine that the fractionally charged object carries a charge that is a multiple of one-third. For
example, a negative one-third, a positive two-thirds, and two one-third charged particles would all give the same result.

Thus it is clear that fractional charge searches are essential to extend our understanding of fundamental physics. If they exist, a detailed description of their properties would be a powerful clue to the microscopic structure of matter. In addition, they may provide the answers to a number of questions about physics on a grand scale, the evolution of stars. Very tiny amounts of fractional charges may have a profound influence on the nuclear burning of matter in stars such as our sun.

This paper discusses a search for fractionally charged matter in air, assuming the fractional charges exist in neutral form as chemically inert molecules of fractionally charged atoms. The format is as follows. A background is provided covering theoretical models first, then the possible implications of fractionally charged nuclei on stellar burning, and finally a discussion of previous fractional charge searches. Next, experimental technique is described in two parts, one covering sample selection and preparation, and a second part describing the apparatus used to actually detect the fractional charges. The next chapter presents the data, and discusses how limits on sensitivity were attained. Finally, a concluding chapter summarizes the results and proposes future modifications to the procedure.
Fractional charge searches are typically called "quark searches" for a very good reason. Quarks are the only known, well studied entities that exist with charges a fraction of the "fundamental" unit of charge, e. They come in flavors that carry charges of plus or minus one- or two-thirds e. The catch of course is that the standard model of quark behavior, Quantum Chromo Dynamics, QCD, seems to require that quarks exist in very specific clusters called "color singlets", which exhibit only net integral or zero charge. While this property called confinement has never been proven, it does appear to be very strongly suggested. This effect can be expressed in a very simple and elegant fashion. The entities colloquially called quarks are broken down into two sets, true quarks and antiquarks. The quarks carry charges of plus two-thirds e or minus one-third e, while the antiquarks are minus two-thirds e or plus one-third e. A true quark also carries one of three colors, call them red, yellow, and blue. Each antiquark carries one of the colors anti-red, anti-yellow, and anti-blue. The rule is that each
observable quark combination must be colorless. That is, one quark of each primary color, red + blue + yellow, with net color white, or one antiquark of each primary anti-color giving anti-white, or one color from a quark, plus the opposing anti-color from an antiquark. Of course all of this is merely jargon used to add life to a formal set of rules laid out by a mathematical formalism called group theory. However, the fact remains that the basic theory and its recent expansion that unified three fundamental forces (weak, electromagnetic, and strong) has been an incredibly successful theory. So much so, in fact, that the theorists are loath to introduce the complications that would allow observable particles to exist with fractional charge. Nevertheless, the remainder of this section will discuss various scenarios that have been published that do permit fractionally charged objects in the particle spectrum.

The most well known example of a theory that admits fractionally charged objects was published in 1978 by A. De Rujula, R. Giles, and R. Jaffe (hereafter DJG)\(^5\). Because the qualitative features of this model are similar to some other models and will be important to latter sections of this work, it will be treated in slightly more detail than most subsequent references. Essentially, they modified the standard QCD theory by giving a small mass to the gluons, the mediator of the color force that binds quarks. For small
values of gluon mass, the low-lying particle spectrum is unchanged. However, at some mass in the spectrum (inversely proportional to the gluon mass) free quarks will appear. As the gluon mass tends to zero, the free quark mass will tend to infinity, which is the tendency implied by confinement. As an example, a gluon mass of eighteen MeV corresponds to a free quark mass of ten GeV. Another important property of the model is the unscreened color force of the bare quark will attract nucleons. These nucleons will then dissolve into the bare quark until the quark has reached its "appetite". The quark-nucleon binding energy may vary over a range of from a few to several hundred MeV. After appetite, the complex will continue to attract nucleons, but on a scale more like normal nuclear attractions. The natural tendency for the bare quark to bind strongly to nucleons will be an important feature in subsequent considerations.

In a model proposed by Slansky, Goldman and Shaw the eight gluons are broken into two subsets, three massless gluons and five which acquire mass, $m$. While the model of DGJ does not explicitly break the color symmetry, this one does. The key result of the model is that the fractionally charged physical particles are bound quark pairs called "diquarks". Other models of broken QCD include works by Saly, Sundaresan, and Watson (in which four gluons are massless, and four acquire mass, $m$) and Shaw and Slansky.
Chaplin made a study of properties of bare color models. In particular he concluded that the fractionally charged particles will bind strongly to nucleons, as described above in the discussion on the model of DGJ.

Not all models which admit fractionally charged particles go to the extreme of breaking QCD. Currently several popular mechanisms allow fractionally charged color singlets. Caldi and Nussinov introduce a color triplet of massive, electrically neutral scalar particles which can bind with quarks giving color singlet fractionally charged hadrons. Wagoner, Schmitt, and Zerwas constructed a similar model, and referred to the entities as electrically neutral quarks. In 1974, Georgi and Glashow described how quarks could be united with leptons in a single cover group. The model successfully unites the strong force of hadrons with the weak leptonic force and the electromagnetic force (Grand Unified Theory). Each becomes a different manifestation of the same interaction. Subsequently, many of the color singlet models seek to enlarge the cover group further to allow for fractionally charged particles. For example, Zee describes a model in which each colored quark has a color singlet companion of the same charge. The color singlet quarks are referred to as "echo quarks". In the language of group theory, \( \text{SU}(3)_{\text{color}} \) was expanded to \( \text{SU}(4) \). Georgi and Glashow embedded the color group in \( \text{SU}(5) \) to unify
the fundamental forces. Typically the cover group to allow fractional charges is chosen to be $SU(7)^{14,15,16}$. Other cover groups are not uncommon, however $^{17,18,19}$.

Two recent experiments spurred considerable theoretical effort on the nature of fractional charges. The most dramatic was that of Cabrera$^{20}$ which produced results that could be interpreted as evidence for the existence of magnetic monopoles. A characteristic common among grand unified theories is the prediction of extremely massive magnetic monopoles. Several such models also allow fractionally charged particles in the spectrum$^{21,22,23,24,25}$. The other experimental result was a claim$^{26}$ that, following energetic heavy ion bombardment of target atoms in an emulsion, certain fission fragments had an anomalously short mean free path. Although the very existence of these "anomalons" is in doubt$^{27}$, and while it is also presently clear that the fragments are integrally charged$^{28,29}$, many theoretical models have been presented to explain them. Most relevant to this paper are conjectures that the anomalons are manifestations of bare color$^{9,30}$.

Several investigators have studied the survival of fractionally charged particles following the Big Bang. Using a model of broken QCD, Wagoner and Steigman$^{31}$ concluded that the abundance of free quarks varied exponentially with the mass of the quark. A free quark mass of ten GeV would result
in an abundance of \(1 \times 10^{-14}\). Higher masses give lower abundances. Kolb, Steigman, and Turner\(^3\) did a calculation varying the mass of the gluon. They noted that a very small fluctuation of the gluon mass (roughly five MeV) could affect the expected abundance by forty orders of magnitude (from \(1 \times 10^{-10}\) to \(1 \times 10^{-50}\)). In a subsequent report, Kolb and Turner\(^3\) found that primordial color fluctuations could similarly have an enormous range of impact on the resultant abundance. Taken together, these studies demonstrate that there are no astrophysical arguments against abundances less than \(1 \times 10^{-14}\).

The two most critical caveats imposed on most fractional charge searches are the particle's mass, and its chemistry. A comprehensive study of the chemistry of fractionally charged atoms has been carried out by Zwieg and collaborators\(^4\). He has made a systematic study of the addition of one-third and two-third charges to each element of the periodic table. An estimate of a property such as electronegativity for a nucleus with charge \(z\) plus one-third, for example, is obtained by interpolating between the electronegativity of an atom with nuclear charge \(z\) and \(z\) electrons and an atom with nuclear charge \(z\) plus one and \(z\) electrons. In this manner the electronegativity and electron affinity of four species of fractionally charged atoms were tabulated: those with \(z\) electrons and \(z\) plus and minus one-
and two-thirds charge on the nucleus. Fractionally charged atoms are found to range in properties from super-alkalines to super-halides. Only rarely is a fractionally charged atom a very close match with a normal atom. In general it is certainly true that if a fractional charge is added to an element, the new atom will not be similar chemically to the original element. Each of these observations is at least qualitatively true. However, for Zwieg's work to be quantitatively accurate as well, the isoelectronic interpolation scheme must be valid as well. In at least some specific instances it can be shown to fail drastically\textsuperscript{35}. The alternative to such a general program is to specifically calculate the properties atom for atom. Such was done, for example, by Rashid and Fricke\textsuperscript{36} on atomic systems with a sodium nucleus for the core. They calculated the atomic energy levels using relativistic self-consistent field procedures. Clearly the problem with this program is the magnitude of work (and computer time) necessary for a thorough investigation. Some work has also been done on atomic systems involving fractionally charged atoms. A simple example is provided by the work of Gupta and Singh\textsuperscript{37}, who studied molecules made of combinations of bare one-, two- and four-thirds charged nuclei. Of critical importance to this report is a similar, though more comprehensive, study performed by Schaad, Hess, Wikswo, and Fairbank\textsuperscript{38}. Stuctures
of molecules containing low z, fractionally charged atoms were examined via a self-consistant-field approximation. In addition to energy levels and molecular geometries, formation reaction rates in solutions of very low concentration were tabulated. At concentrations on the order of $1 \times 10^{-19}$ it was determined that for a very modest binding energy (thirty kcal/mole), over geological time scales fractionally charged atoms will tend to bind together to form neutral molecules. At more typical binding energies (100 to 200 kcal/mole) essentially all fractionally charged atoms will be bound in neutral molecules.

In summary, several mechanisms that could produce observable fractionally charged particles were presented. At this time, however, it is still not clear if fractionally charged particles even exist. Moreover, if they do exist, not enough information is known about them to discriminate between these widely different theories. The status of our limited understanding of the chemistry of fractionally charged atoms was reviewed. Also, it was shown that there exist no hard astrophysical constraints to their existence at reasonable levels. The following chapter details how the sun, in fact, may be providing clues to the existence of low z fractionally charged nuclei.
CHAPTER THREE
SOLAR BURNING AND FRACTIONAL CHARGES

Energy is produced in the sun by converting four hydrogen atoms into one helium atom. The dominate mode of conversion is a sequence of nuclear reactions called the pp chain, shown in figure 1. To a much smaller extent, an alternate mode uses carbon as a catalyst. This is the CNO cycle. Together they form the Standard Solar Model, SSM, which was believed to provide a complete accounting for the major solar processes. In 1964, Ray Davis proposed an experiment to test the model by detecting the neutrinos given off as protons are converted to neutrons in the various nuclear reactions of both modes. His experiment is predominately sensitive to the high energy neutrinos produced in one step of the pp chain ($^8\text{B}$ decays to $^8\text{Be} + \text{positron} + \text{neutrino}$). His data so far indicate that the neutrino flux from the sun is four times smaller than is predicted by the SSM.

Several attempts have been made to explain the discrepancy. Some parameters in the SSM can be adjusted, but there is no self consistent way for the model to explain both
Figure 1.

Sequence of reactions in the p-p chain
the neutrino flux and other experimentally measured characteristics, such as the sun's luminosity. The assumptions behind Davis's experiment have been scrutinized and found to be valid. So it is not unreasonable to expect that a more exotic phenomenon may be responsible. For example, it has been proposed that neutrinos may oscillate between two forms\textsuperscript{41}. In this scenario, Davis's experiment is sensitive to one form but not the other. This could account for a factor of two or three in the discrepancy.

It is well known that lowering the temperature of the sun's core from 15.5 to 14.5 million degrees Kelvin will give the "right" answer for Davis's experiment. However, this results in a twenty percent reduction in hydrogen burning by the SSM, so this cannot be the whole answer. If one could invoke a mechanism to take up the slack without introducing more high energy neutrinos, then the whole picture could again be self consistent. Small amounts of strongly interacting free fractional charges may catalyze the helium production much as the CNO cycle does, but at a much higher rate. This work is detailed in references 42 and 43, and a short summary of the key features follow.

The model is not particularly sensitive to the identity of the fractional charge. For this chapter only, to be consistent with references 42 and 43, "quark" will be used as the general phrase, up quark, u, as a two-thirds charge.
particle, and down quark, d, as a negative one-third charge particle. The minimum requirements are that the particles bind strongly to nuclei, but not so strongly that the nuclei lose their identity, and that the nuclear radius is reduced slightly. In this manner properties of nuclei with an embedded fractional charge, q-nuclei, can be inferred from the properties of the analogue nucleus. This has been shown to be roughly true in studies of hypernuclei, where particles such as lambdas and sigmas are added to normal nuclei.

One such case of particular interest is the addition of a lambda to $^5\text{He}$ which produces a baryon stable hypernucleus. Ultimately, of course, the lambda will decay, destroying the complex. The lightest quark, however, will have to be absolutely stable due to conservation of electric charge. So a quarked $^5\text{He}$ has the potential to be a stable, long lived q-nucleus. This is important because the lack of a stable mass five nucleus is a severe blockade to normal stellar nucleosynthesis.

If stable five nucleon q-nuclei exist, then the cycle indicated in figure 2 may compete with pp burning in our sun. The figure illustrates an analogue of the CNO cycle, but based on much lower $z$ nuclei. For notational purposes, a superscript q, u, or d to the right of an element's chemical symbol represents the addition of the indicated particle to the nucleus of the element. For example, $^6\text{Li}^u$ stands for a
Q-nuclear cycle based on the addition of two-thirds charge to low z nuclei. Dominate cycle indicated with heavy arrow, branches indicated with light arrow.

Figure 2.
$^6$Li nucleus with an embedded up quark.

For this cycle to run as indicated, certain physical requirements must be met. The additional binding energy must be large enough to bind $^5$He$^u$ and $^5$Li$^u$, but not so strong as to prohibit a $(p,\alpha)$ reaction on $^7$Li$^u$ to restart the cycle. Within these bounds the nuclear structures of the q-nuclei suggest the reactions indicated in figure 2.

A problem is posed by the branch starting with the $(p,\gamma)$ reaction on $^7$Be$^u$. A high energy neutrino would most likely be emitted in the decay of $^8$Be$^u$. Since such high energy neutrinos would have been readily detected by Davis's experiment, this branch must be avoided. To do so the beta decay rate of $^7$Be$^u$ must be sufficiently fast that the $(p,\gamma)$ reaction rarely takes place.

To investigate these restrictions on binding energy and beta decay rates the q-nuclear potential was approximated first by a $1/r$ potential, which proved to be too restrictive, then by a square well. Shown in figure 3 are the binding energy and nuclear rms radius for several well depths and a core of charge 3, mass 6. From the rms radii one can calculate the energy available for beta decay. From this energy an estimate of the beta decay rate can be made, as shown in figure 4.

The conclusion reached is that a well depth of 100 MeV and radius of 1.6 fermi gives a nuclear rms radius of 1.66
Figure 3.

Binding energy versus nuclear rms radii for a square well potential with a core of charge 3 and a mass of 6 amu.
Figure 4.

Beta decay rate as a function of energy available for beta decay.
fermi and a binding energy of 2.83 Mev. This in turn allows the $^{7}\text{Li}^4(p,\alpha)$ reaction to proceed kinematically and gives a $^{7}\text{Be}^4$ beta decay lifetime of approximately one thousand seconds. That is sufficient to avoid the $(p,\gamma)$ reaction on $^{7}\text{Be}^4$.

The next step is to calculate the reaction rate of the slowest step in the cycle, $^{6}\text{Li}^4(p,\gamma)$, Without experimental data on $q$-nuclei, the best course presently open to calculate reaction rates is the statistical formalism of Woosley, Fowler, Holmes and Zimmerman. Normally this formalism fails for low $z$ nuclei, as it relies on a fairly high density of states. How seriously it fails for $q$-nuclei is a matter of conjecture. However, the model successfully treats coulomb barrier penetration, and it is that feature that dominates thermonuclear reaction rates at temperatures like that of our sun. Shown in figure 5 are the calculated $q$-nuclear reaction rate, and for comparison, the weak decay rate mediating the pp chain, and the rate for the $^{6}\text{Li}(p,\gamma)$ reaction given by Fowler, Caughlan and Zimmerman. Note that the $q$-nuclear rates vary from 13 to 15 orders of magnitude faster than the pp rates.

These reaction rates were used as input in a solar evolution model, performed by Craig Joseph at Ohio State. Shown in figure 6 are the fraction of energy production accounted for by $q$-nuclear burning, and the neutrino count
Figure 5.

$^{6}\text{Li}(p,\gamma)$ reaction rate at solar temperatures, and for comparison the weak rate mediating the pp chain and the rate of $^{6}\text{Li}(p,\gamma)$ reaction.
Fraction of energy production accounted for by q-nuclear burning, and the neutrino count rate expected to be observed by Davis's solar neutrino detector.
rate expected to be detected by Davis's solar neutrino
detector.

Theoretical estimates using the SSM have predicted a
count rate of $7.5 \pm 1.5 \text{SNU}^{39}$, while Davis has been reporting
a value of $1.8 \pm 0.2 \text{SNU}^{40}$. (A SNU is $1 \times 10^{-36}$ events per
target nucleus per second) A q-nuclear mole fraction of $1.6 \times 10^{-15}$ will give the observed neutrino flux assuming the
q-nuclear cycle does not produce any high energy neutrinos.
At this abundance the q-nuclear cycle accounts for 65 percent
of the sun's energy production.

The q-nuclear cycle will produce essentially the same
number of low energy neutrinos as predicted by the SSM.
However, the energy distribution will most likely be
sufficiently different that the next generation of solar
neutrino detectors could provide further evidence for or
against the existence of this cycle.

This model has more to its credit than solving the
solar neutrino problem. A discussion by Joseph\textsuperscript{48} points out
that an additional source of energy in the sun, such as the
q-nuclear cycle, could solve several long-standing problems
with the SSM. One such problem is that the SSM's prediction
of the original helium abundance in the sun is consistent
with the primordial helium abundance, in spite of the fact
that our sun is not a first generation star and hence the
helium abundance should have been higher than the primordial abundance. In addition, there is a discrepancy in the $^6$Li abundance in the sun which can be accounted for nicely with this new model. A more detailed accounting of these and other problems can be found in the reference cited.

This concludes an overview of the effect of positive two-third particles added to nuclei. If negative one-third particles are added instead, the resulting effect on our sun is less dramatic. Since the nuclear charge is decreased by one-third, the capture reactions will proceed much more quickly. In fact, too quickly for the beta decay of $^7$Be$^d$ to restart the same cycle run by up quarked q-nuclei. However, by the time the q-nuclei have reached a $z$ of six to eight, the reaction rates will be comparable to those of normal nuclei, and the result would be a down-quarked version of the CNO cycle.

In conclusion, it appears that reasonable values for q-nuclear densities and properties allow the q-nuclear cycle to compete with the pp chain in energy production in our sun, and also presents a plausible solution to the solar neutrino problem. If this cycle does exist as described, it would have the following impact on fractional charge searches. First, it would provide an astrophysical guide to the abundance of fractionally charged particles in nature. Second, it would provide a clue as to where to look in
terrestrial searches. Since the longest lived member of the cycle is $^6\text{Li}^u$, searches should concentrate on low $z$ nuclei, particularly nuclear charges of three and two-thirds.
Several comprehensive reviews of fractional charge search experiments have been published. Nevertheless, it is important to summarize in this report the various types of searches that have been performed, specifically with regard to their bearing on this particular search. The discussion will cover three broad categories: accelerator searches, cosmic ray searches, and bulk matter searches.

The most model dependent way to look for free fractional charges is to attempt to produce them in energetic-particle collisions via very high energy accelerators. A positive result in an experiment of this type could provide a very detailed description of the nature of the fractionally charged particle.

However, accelerator searches are limited in general by three major factors: total center of mass energy, production cross section, and detector efficiency. Detector efficiency is determined not only by such factors as solid angle and a ratio of particles producing signals to particles passing through the detector, but also by the type of electronic
windows placed on events for analysis. Two examples will serve to demonstrate this caveat. If a fractional charge leaves a track similar to a normal-particle event, it would be lost in the background. More about this will be examined in the discussion of cosmic ray searches. A second example would be the case of a fractional charge producing such an anomalous signal that it would be rejected as noise or a multiple particle event. An example would be the case of a bare quark rapidly accruing nucleons as it moves through the detector, thus appearing to be a particle growing in mass and charge. Another example would be a particle producing such a small energy loss signal that the signal is lost in the detector noise.

Accelerator searches are also limited by production cross sections. Theoretical cross section estimates are very model dependent. While proton-proton and proton-nucleus colliders would be appropriate for production mechanisms involving strong interactions, electron-positron and electron-positron-positron colliders are perhaps best suited for investigating weak and electromagnetic mechanisms. Other experiments include high energy heavy ion collisions, and muon-nucleon interactions. The highest mass limits were attained by Fabjan, in an experiment that was sensitive to masses up to 25 GeV. Typically, however, mass limits are 10-15 GeV.
Cosmic ray flux measurements are limited by practical considerations of detector size and run time to sensitivities on the order of $10^{-12}$ cm$^{-2}$sr$^{-1}$s$^{-1}$, or more typically, $10^{-11}$ cm$^{-2}$sr$^{-1}$s$^{-1}$, roughly $10^{-11}$ cm$^{-2}$sr$^{-1}$yr$^{-1}$. Since the total primary nucleon cosmic ray flux for energies above one GeV is roughly $10^{-12}$ cm$^{-2}$sr$^{-1}$s$^{-1}$, (ref. 57), this gives a ratio of fractionally charged particles to nucleons of $1 \times 10^{-12}$. Even this sensitivity may be overstated. The reason is that most cosmic ray searches, such as that of Cox et al. and Marini et al. explicitly assume particles with nuclear charges of one- or two-thirds. These experiments are based on the fact that minimum ionization produced by a particle in matter depends almost exclusively on the square of the particle's charge at very high energies, hence a one- or two-thirds charge particle produces, on average, one- or four-ninths the ionization of unit charge particles. Some experiments, such as that of Beauchamp have searched for four-thirds charge particles, which produce sixteen-ninths the ionization of minimally ionizing unit charge particles. Unfortunately, the distribution of ionization produced by a particle of given charge has a small tail extending upward from the minimum amount. For experiments with a large flux of integrally charged particles this effect can produce a considerable background. Such a background problem exists, for example, in sea-level cosmic ray searches (from the massive amounts of
muons) and in some accelerator searches. One way around this problem is to search the cosmic ray spectrum for very massive particles\textsuperscript{61,62,63}. Once again, however, note the practical limitation of these searches to roughly $1 \text{ m}^{-2} \text{sr}^{-1} \text{yr}^{-1}$.

In addition to accelerator and cosmic ray searches, one can attempt to identify fractionally charged contaminates of normal matter. The most noteworthy examples of such a search are the experiments of Fairbank et al.\textsuperscript{1,2,3} discussed briefly in the introduction. In these experiments ninety microgram samples of niobium, annealed on a tungsten substrate, are cooled to superconducting temperatures and levitated by a combination of electric and magnetic fields. The oscillation rate of the spheres as the electric field is varied is measured by a Super Conducting Quantum Interference Device (SQUID). This rate of oscillation depends on the residual charge residing on the spheres. Out of 39 measurements, 14 were interpreted to have had residual fractional charge. If all the charges observed were distributed in the niobium, this would correspond to a concentration of 1 in $10^{20}$ nucleons. If instead, the charges actually were related to the tungsten substrate, the concentration could be much higher. Only a few monolayers of tungsten are deposited on the niobium during the annealing process, but the technique could be preferentially extracting the fractional charges from the tungsten and depositing them on the niobium. The
reasons for suspecting the tungsten are 1) only niobium spheres annealed on the tungsten substrate demonstrate the effect of residual fractional charge, and 2) the charge observed on a single sphere often changes after they have been handled. For example, one ball changed charge 9 times out of 13 measurements during the several experiments.

Experimenters have tested many hypotheses regarding where the fractional charges actually reside. Searches have been done on niobium\textsuperscript{64}, tungsten\textsuperscript{65}, helium\textsuperscript{66}, (the atmosphere inside the chamber was helium at roughly ten torr) and even that very mobile fractional charges are trapped cryogenically on the spheres\textsuperscript{67}. To date, none of these experiments has produced a positive result.

Other searches have been performed in different media. Particularly relevant to the experiment described in this work are searches involving air and sea water. Chupka\textsuperscript{68} searched for fractional charges in air that passed through a region of a strong electric field. Joyce et al.\textsuperscript{69} ran a Millikan type experiment looking for residual fractional charges in sea water. Chupka\textsuperscript{68} also searched for fractional charges in sea water. Although sensitivities in these experiments run as high as three fractional charges per $10^{29}$ nucleons (ref. 68) each would have missed any fractional charges bound in neutral molecules. Stevens et al.\textsuperscript{70} searched a specific deep ocean sediment, iron-manganese
nodules, on the assumption that the fractional charges precipitate out of solution and are concentrated there. Rank searched in sea water salt, seaweed, oysters, and plankton at a level of 1 part in $10^{18}$, on the assumption that one or another of these substances may concentrate the fractionally charged particles.

This is not a comprehensive listing of samples or methods of searching. More such details can be located in the reviews cited earlier. However, it is important to point out that the sensitivity of any search in any particular sample depends critically on the specific chemical properties of the fractionally charged particles, the chemical history of the sample investigated, and the enhancements and depletions assumed in preparing the sample and detecting the particles.

In conclusion, it is not at all unreasonable to assume that Fairbank and the host of null results are compatible. Accelerator searches may not have attained sufficiently high energies to produce them, or fractional charge production may be suppressed relative to production of other forms of matter. Cosmic ray flux measurements are not sufficiently sensitive to rule out even one- or two-thirds charged particles, and higher nuclear charges are lost in the background. Finally, there is one apparently successful bulk matter search, in spite of the fact that all such searches suffer severe chemical caveats.
We chose to concentrate our efforts on the assumption that the fractionally charged particles exist as a neutral component of the atmosphere. Given a geological time span, and a medium that allows mobility Schaad et al. have shown that even in concentrations less than 1 in $10^{20}$ fractionally charged atoms would tend to form neutral molecules. This combination most likely would not take place in the atmosphere. The reason is that many mechanisms exist to sweep single fractionally charged particles out of the air. For example, they would tend to be trapped by dust particles and water droplets. However, once removed from the atmosphere and deposited in the ocean, single fractionally charged particles would be in a very favorable environment for combination reactions. Once in neutral form, an equilibrium would be expected to be established between the ocean and the atmosphere.

Can an estimate be offered for what concentrations to expect in air given their existence? Only in a very limited way. The first question pertains to their origin on earth.
The fractionally charged particles could be 1) primordial, that is, already mixed with the matter that formed the earth, 2) extra-terrestrial, brought in as a component of the cosmic ray flux, 3) created, formed by interactions of very high energy cosmic rays with terrestrial matter, or 4) a combination of the above. Given an upper limit on each model, the next question would be how are the fractionally charged particles distributed in the earth? For the most part this means what fraction of all fractionally charged particles are trapped in the earth's crust, and what fraction is freely dissolved in the ocean. Finally, given a concentration estimate in sea water, what concentration would one expect in air?

Consider first the least quantitative possibility: the fractionally charged particles were present when the earth was formed. Since the earth did not have a primitive atmosphere, the fractionally charged particles must first out-gas from the matter that formed the earth and dissolve into developing oceans. But this line of evolution is too strongly chemistry dependent to place numerical bounds. Even if astrophysical studies gave a bound on solar abundances, the resulting fractionally charged particles could have been depleted in the atmosphere by orders of magnitude due to retention mechanisms or they could have been enhanced considerably by very high solubility. In view of this
extreme caveat, one must rely on the astrophysical values detailed in an earlier chapter that vary typically from $10^{-16}$ to $10^{-22}$.

Next consider the second possibility, that the fractionally charged particles arrive as cosmic rays. Recalling the cautions cited earlier that one must apply to cosmic ray flux measurements, it is not unreasonable to use $1\text{ m}^{-2}\text{sr}^{-1}\text{yr}^{-1}$ for an order of magnitude estimate. This then gives $1.4 \times 10^{25}$ fractionally charged particles incident on the earth's surface over 4.5 billion years. If all of these find their way into the ocean, the ratio fractionally charged particle/water molecule would be $3.7 \times 10^{-23}$. Aside from the uncertainty in cosmic ray flux, many other factors could tend to reduce this value. One obvious factor is the ratio of ocean surface area to total surface area integrated over the life of the earth. However, if the range in matter of the average cosmic-ray fractionally charged particle is less than the depth of the atmosphere, 1030 gms/cm$^2$, this ratio may be mitigated by the effects of weather and weathering. On the other hand, if the range is larger than the combined depth of the atmosphere and the ocean, typically $3.3 \times 10^5$ gm/cm$^2$, the fractionally charged particles may be trapped deep in the earth's crust. In this extreme case, essentially none of the fractionally charged particles would be expected to be dissolved in the oceans. It is not likely that the range
would be so large, as that corresponds to protons with energies of $10^3$ Gev., or less than $10^{-5}$ times the total proton flux. A much more serious problem with this estimate lies, as usual, with the chemistry of the fractionally charged particle. There may be a host of depletion mechanisms that will remove them from solution before neutralization can take place, or at least trap them in a way that makes the combination reaction much less probable. It was this line that led experimenters to test ocean sediment and even oysters for evidence of fractional charges. Keeping in mind then that this estimate is an upper bound, a cosmic flux of $1 \text{ m}^{-2}\text{sr}^{-1}\text{yr}^{-1}$ would result in a sea water mole fraction of $3.7 \times 10^{-23}$.

Since cosmic ray searches cannot differentiate between a fractionally charged particle that was created in the atmosphere and one that was a component of the original flux, it appears that the arguments presented above also give terrestrial limits on fractionally charged particles due to production mechanisms. This is true if the overall production cross section favors creation in the first 1000 gms/cm$^2$. However, the ocean averages over 300 times deeper than that, so a more careful investigation must be attempted. The number of fractionally charged particles produced, $N$, is given approximately by:
\[ 1) \quad N = \int_0^{E_{\text{max}}} s(E) A M \left( \frac{dE}{dx} \right) \left( \int_{E_{\text{max}}}^{E'} F(E') dE' \right) + \int_{E_{\text{max}}}^{\infty} F(E') dE' \times s(E') R \]

\[ F(E) = \text{total number of cosmic ray protons incident on the earth with energy } E \]

\[ \Phi(E) = \text{flux of cosmic rays with energy } E \]

\[ a = \text{earth's surface area} \]

\[ t = \text{earth's age} \]

\[ s(E) = \text{production cross section for fractionally charged particles} \]

\[ E_{\text{max}} = \text{Energy of proton with range equal to the combined earth-sea depth} \]

\[ R = \text{air-ocean depth (active range)} \]

\[ A = 6.023 \times 10^{23} \text{ AMU/gm} \]

\[ M = \text{average atomic mass of air and ocean penetrated} \]

Both cosmic ray searches and accelerator searches argue that \( s(E) \) is zero or very small for energies less than 10 GeV. Equation 1 can be used to find what average cross section is required for a production mechanism to compete with primordial cosmic rays as a source of fractionally charged particles on earth. The values used in equation 1 are:
\[ N = 1.4 \times 10^{25} \]
(taken so that the number of fractional charges produced matches the number deposited by a flux of 1 m\(^{-2}\)sr\(^{-1}\)yr\(^{-1}\))

\[ \Phi(E) = 6 \times 10^{-4} E^{-2.67} \text{cm}^{-2} \text{sec}^{-1} \text{GeV}^{-1} \]
(ref 57)

\[ s(E) = \begin{cases} 0 & \text{if } E < 10 \text{ GeV} \\ s & \text{if } E > 10 \text{ GeV} \end{cases} \]

\[ E_{\text{max}} = 1000 \text{ GeV} \]

\[ R = 3.3 \times 10^5 \text{ gms/cm}^2 \]

\[ \frac{dE}{dx} = 0.002 \text{ GeV/ gm/cm}^2 \]

These values indicate that for production mechanisms to account for a significant concentration in sea water, the average cross section would have to be on the order of 5 \times 10^{-11} \text{ barn}. This number is sensitive to the production threshold, as if \( s \) is zero up to one Tev, the necessary average cross section would increase to 5 \times 10^{-9} \text{ barns}.

So far only concentrations in sea water have been described. It is straightforward to estimate atmospheric concentrations. Clearly it must vary directly with sea water concentrations.

2) \[ P = k n \]

Here \( P \) is the partial pressure of the vapor, \( n \) is the molar concentration in solution, and \( k \) is the empirical constant of
proportionality. From an examination of Noble gas concentrations in air and sea water a value for $k$ can be estimated. If a phenomenological mass dependence is factored out, a particularly simple form results. The values in the following table have been organized such that $k$ is in units that give the molar concentration in air instead of the partial pressure.

Table I. Air and seawater concentrations of noble gases

<table>
<thead>
<tr>
<th>GAS</th>
<th>SEAWATER* MOLARITY</th>
<th>ATMOSPHERIC* MOLARITY</th>
<th>$k$ (DIMENSIONLESS)</th>
<th>MxK (MASS IN AMU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEON</td>
<td>$3 \times 10^{-7}$</td>
<td>$1.8 \times 10^{-3}$</td>
<td>$6 \times 10^4$</td>
<td>$1.2 \times 10^6$</td>
</tr>
<tr>
<td>ARGON</td>
<td>$3 \times 10^{-11}$</td>
<td>$9.3 \times 10^{-5}$</td>
<td>$3.1 \times 10^4$</td>
<td>$1.2 \times 10^6$</td>
</tr>
<tr>
<td>KRYPTON</td>
<td>$7 \times 10^{-11}$</td>
<td>$1.1 \times 10^{-6}$</td>
<td>$1.6 \times 10^4$</td>
<td>$1.3 \times 10^6$</td>
</tr>
<tr>
<td>XEON</td>
<td>$1.5 \times 10^{-11}$</td>
<td>$8.7 \times 10^{-8}$</td>
<td>$5.8 \times 10^3$</td>
<td>$0.8 \times 10^6$</td>
</tr>
</tbody>
</table>

Hence the simple estimates:

3) $n_{\text{air}} = (1 \times 10^6 / \text{Mass in AMU}) n_{\text{sea water}}$

4) $n_{\text{air}} = (1 \times 10^4) n_{\text{sea water}}$

The second equation may be more reasonable if the mass trend exhibited by the noble gases is not universally valid. At any rate a rough estimate from the earlier sea water values gives a concentration in air of $1 \times 10^{-19}$.

Two approaches were used to collect fractionally charged particles. One method relies on the assumption that
a molecule containing the fractionally charged particles is heavier than xenon and hence will be concentrated in gas mixtures derived from air which are rich in heavy noble gases. A second scheme involved ionizing air, allowing a short recombination period, and then collecting all remaining ions on titanium disks for subsequent analysis.

If the neutral molecule composed of fractionally charged particles is chemically inert and more massive than xenon, then the same process that is used to collect xenon should also concentrate the fractionally charged particles. With this in mind it was thought that a good source may be bottled xenon gas. However, in collaboration with several chemical engineers for the Linde division of Union Carbide, it was determined that an even more promising source would be the residue gas usually thrown away at the next-to-last stage of xenon purification. To collect xenon, air is allowed to pass through several columns, each selecting successively lower vapor pressure components. As the vapor pressure generally decreases with increasing mass, this scheme concentrates high mass components of the atmosphere. At the next-to-last stage, the "c-5 column", the gas consists of xenon and everything heavier than xenon, largely hydrocarbons. At this point the xenon is allowed to proceed, but the lower vapor pressure residue is trapped. Normally this residue is recycled until it is thrown away. However,
special arrangements were made to tap into this gas to supply us with a sample. Since xenon normally exists at the level of 1 part in \(10^7\), a rule of thumb would suggest that the fractionally charged particles would thus be enhanced in this residue by seven or eight orders of magnitude, if its mass is sufficiently large. In addition, xenon is a particularly nice vehicle for this study since it essentially does not form negative ions, and hence will produce very little background from the type of injector to be used (see chapter six). The second major component, hydrocarbons, can also be selected against, giving a potential for a very clean background. For details on overall sensitivity, refer to chapter seven.

The second concentration scheme is mass independent. It assumes that the fractionally charged particle are bound together as a neutral molecule, but once the molecule is split the components would require more than a few seconds to find one another and recombine to reform the neutral molecule. This is obviously consistent with the assumption that the original neutralization takes place over a geological time span. To take advantage of this property, air is fed into a volume at a low pressure. An RF field, as is used to produce ions for a Van de Graaff accelerator, is applied to ionize this air. A short period of time is provided for the ions to recombine. A bias potential is then
applied to disks at opposite ends of the volume, collecting all residual ions. The volume is then evacuated and subsequently refilled to start the procedure over. Figure 7 schematically illustrates the apparatus.

In more detail, the operation proceeds as follows. Solenoid valve V1 opens, filling a reservoir with air to atmospheric pressure. The volume of the reservoir is adjustable to provide control over the pressure in the active volume. Next valve V2 opens and the active volume is filled from the reservoir. The RF field is then applied. It was found that the RF field could consistently light the gas at a pressure of approximately six torr. It is not assumed that at any one instant the ionization was one hundred percent. It is only assumed that over the life of the RF field, one second, every molecule will have dissociated at least once. Since the characteristic time is roughly given by the collision frequency, or a few hundred microseconds, this is a good assumption. For the next second, the ions are allowed to recombine. In this phase essentially all normal ions will neutralize. However, the fractionally charged particles will have something like $10^{19}$ more normal ions with which to combine than partner fractionally charged particles. Thus the fractionally charged particles will be trapped in charged, rather than neutral, molecules. At this point a potential gradient is applied across the active volume. This
Schematic of apparatus to ionize, and then collect fractionally charged particles in air
is accomplished by applying a bias of 300 volts between the titanium disks at each end of the pyrex tube enclosing the active volume. One second of collection time is allowed to attract the residual ions to these disks. Once on a disk, the fractionally charged particle will migrate along a surface defect line until it encounters a junction of defect lines. At this point the fractionally charged particle will be trapped. Finally, with the bias maintained, the active volume is evacuated to approximately 100 millitorr by opening valve V3. V3 is then closed, the bias is removed, and the cycle is ready to repeat. The evacuation is the most time consuming step of the operation. It is this phase that determined the value of the applied bias, since ionization must be avoided in a very pressure sensitive regime. If the density of defect line junctions is smaller than the number of fractionally charged particles collected, then these sites provide a mechanism by which the fractionally charged particles may recombine and escape the metal surface. If, further, the escape takes place during the evacuation phase, they will be lost from the sample. That they should be so numerous is clearly unlikely. If, however, migration on the time scale of one week allows considerable recombination, then that introduces a storage problem after the apparatus is shut down.

The number of fractionally charged particles collected
in this manner is determined by the volume of air processed, the density of fractionally charged particle in air, and the apparatus efficiency. The volume of air is given by the volume of a collection unit, 25.8 cm$^3$, times the number of cycles completed, or run time divided by cycle time. Since the collection time was fifteen days with a cycle time of six seconds, a total of $5.6 \times 10^6$ cm$^3$ was processed. For $3 \times 10^{19}$ molecules per cm$^3$ at one atmosphere, this means $1.3 \times 10^{24}$ air molecules passed through the apparatus. Hence, for a mole fraction, $n$, the number of fractionally charged particles collected, $N$, is given by:

$$5) \quad N = 1.3 \times 10^{24} \times n \times e$$

where $e$ is the apparatus efficiency. This efficiency is given by

$$6) \quad e = e_1 \times (1-e_2) \times e_3$$

with $e_1$ given by:

$$e_1 = \text{ionization efficiency}$$

$$e_2 = \text{neutralization efficiency}$$

$$e_3 = \text{collection efficiency}$$
As noted earlier, $e_1$ should be close to one, and $e_2$ should be near zero. The final parameter, $e_3$, depends in part on the mobility of the ions. Typically, drift velocities for heavy ions are on the order of 1000 cm/sec, so at first glance one may expect that $e_3$ would also be order unity. However, the long recombination period, during which there is no applied field, also gives the fractionally charged particle the opportunity to stick to any available surface. So, conservatively, $e_3$ is taken to be the ratio of active surface area to total surface area in the active region, or 0.17. Folding this back in, the number of fractionally charged particles collected is given by:

7) \[ N = 2.2 \times 10^{23} \times n \]

8) \[ N = 2.2 \times 10^4 \quad (\text{at } n = 1 \times 10^{-19}) \]

The number of fractionally charged particles actually collected will depend on the efficiency of the detection system, detailed in a later section.

In summary, our samples employ two completely different concentration schemes. The underlying assumptions for each are that fractionally charged particles exist in neutral molecules, and these molecules are a trace component of the atmosphere. The ionization scheme further assumes these molecules are not so tightly bound that an RF field will not
dissociate them. The air separation scheme assumes that the net molecular mass is high, the vapor pressure is low, and processing performed prior to the vapor pressure separation did not already remove the fractionally charged particle. While the former method relies on fewer assumptions as will be seen shortly its potential sensitivity is not quite as great.
CHAPTER SIX
EXPERIMENTAL TECHNIQUE

The samples described in the preceding chapter were analyzed at the Nuclear Structure Research Laboratory at the University of Rochester, Rochester, New York. Figure 8 shows a schematic diagram of the system used in this search. There are four major elements involved: the source, the accelerator, the electrostatic analyser, and the detectors. In this chapter, first each of these elements will be described in general, then the specific configurations for the experiments performed will be described. The following chapter will present details on the data collected and discuss the sensitivity achieved.

A cesium sputter source is used to inject a low energy negative ion beam into the tandem accelerator. A beam of energetic cesium ions is focused onto the surface of a source target. The resulting collisions break off the surface layer of atoms, some of which sputter off as negative ions. These ions are accelerated to roughly one hundred KeV and are electrostatically focused into the entrance of the
Figure 8.

Schematic of the University of Rochester system for detecting fractional charges
The amount of beam produced can be monitored with a Faraday cup located between the source and the accelerator. While the target typically is a small amount of some solid, a gas can also be used. By feeding gas into the sputter chamber, collisions between the cesium ions and the gas will produce some negative ions from the gas sample. The efficiency for focusing these negative ions into the accelerator will be a function of where the ions were produced. Further, most of the gas will be pumped from the chamber without interacting with the cesium beam.

The low energy beam is injected into an MP Tandem Accelerator. The ends of the machine are at ground potential, while the terminal at the center can have a potential voltage as high as twelve million volts. The negative ions entering the low energy end are accelerated toward the high potential at the terminal. In the terminal the negative ions lose electrons in either a thin carbon foil or a small region with a low pressure gas. The now positively charged ions are further accelerated toward the grounded high energy side of the machine. The total energy of the resulting beam is given by \((Q_1 + Q_2)V + E_i\), where \(Q_1\) is the negative ion charge, exclusively negative one for normal elements, \(Q_2\) is the positive ion charge, \(V\) is the terminal voltage, and \(E_i\) is the injection energy.

The electrostatic analysis of the beam is performed by
three elements: electrostatic lenses for focusing, electric dipole fields for specific energy-to-charge selection, and stripper gas or foils to enhance the yield to the selected state.

There are several focusing elements throughout the beam line. An einzel lens is located immediately after the source. The next focusing element is an electrostatic quadrapole triplet, which focuses the beam into the accelerator. At the entrance of the accelerator there is a lens to counter the strong focusing properties of the accelerating region. Finally, there are two electrostatic quadrapole doublets on the high energy side of the Van de Graaff. One is located at the exit of the accelerator, but just before the first electrostatic selection element, while the second is located after the second electrostatic selection element.

In addition to the focusing elements, the beam line contains several locations that consist of attenuators, foils, or slits. These are indicated in Figure 8. The attenuators are nickel foils with small holes. Combinations of these foils can attenuate the beam by products of factors of ten. There are two locations for strippers. One is at the terminal, and was described above. The second is located at the high energy side of the beam line between the electrostatic selectors.
The energy-to-charge selection (hereafter E/Q) is accomplished with two independent elements. The first consists of two parallel plates. The force on a charged particle passing between the plates is given by

\[ \text{Force} = F = \frac{VQ}{D} \]

where \( V \) is the potential drop across the plates, \( D \) is the plate separation, and \( Q \) is the ion charge. The displacement, \( d \), of an ion with energy \( E \), mass \( m \), and charge \( Q \) after passing plates of length \( L \) is given by

\[ d = \frac{at^2}{2} = \frac{1}{2} \frac{F}{m} \frac{L^2 m}{2E} = \frac{1}{2} \frac{VQ}{D} \frac{L^2}{2E} \]

Or, simply, the deflection depends on E/Q, but not mass. The focusing element and collimators are positioned to select those ions that are deflected approximately 1.3 degrees. The second element to select E/Q consists of two curved plates producing a radial electric field. An ion that travels directly through the center of the two plates will trace a circular trajectory. Since this is along an equipotential line, it will not gain energy from the element. The radius of curvature, \( r \), of the trajectory is given by

\[ \frac{m_v^2}{r} = F = \frac{VQ}{D} \]

or
12) \( r = \frac{2DE}{VQ} \)

Again, the element selection is mass independent. This selection element is set up to deflect the desired beam by twenty degrees.

The detector system is illustrated in figure 9. Essentially, it consists of two units, a time of flight (TOF) system and a gas ionization detector. The TOF system provides the ion's velocity while the gas ionization detector provides information on the ion's energy and energy loss profile. Between the two of them, the ion's mass and charge can be determined.

The start and stop signals for the TOF system are produced by two units such as the one shown in figure 10. These units are on loan to the University of Rochester from Los Alamos National Laboratory and are described in detail by Bowman and Heffner\(^7\). The essential elements of each unit are a carbon foil of a few microgram per square centimeter thickness, a channel plate electron multiplier, and a combination electric and magnetic field for electron transport. The magnetic field is provided by permanent magnets not shown in the figure. As an ion passes through the foil, it knocks out electrons from the foil. The
Figure 9.

Detector arrangement
Figure 10.

Detail of time of flight system start and stop signal generator, on loan from Los Alamos National Laboratory.
electric field accelerates the electrons, and the magnetic field directs the electrons toward the channel plate. The efficiency for collecting electrons is approximately seventy five percent\(^7\). A single electron incident on the channel plate is sufficient to produce a signal. However, the efficiency for ions to produce electrons in the foil is a function of the energy loss of the ion in the foil. An ion that loses very little energy in the foil produces very few electrons.

The gas ionization chamber is illustrated in figure 11. It follows the design described in detail by Shapira et al.\(^7\)\(^8\). Basically, the chamber is filled to some pressure, typically fifty to one hundred torr, with isobutane. As an ion passes through the chamber, it ionizes the gas. The electrons produced are attracted to the positively biased plates (the \(dE\) plates). The positive charges left behind induce an image charge on the negatively biased cage surrounding the active region. The induced charge is proportional to the total energy deposited in the active region. The amount of negative charge collected by one of the \(dE\) plates is proportional to the energy the ion lost while passing the plate. Figure 12 is a detail of the entrance to the detector. It is possible to fill the area in front of the
Figure 11.

Schematic of gas ionization detector
Figure 12.

Detail of entrance to gas ionization detector.
detector with gas, thus producing a variable thickness absorber. However, a side effect of this can be to produce an additional signal to the total energy. Electrons produced in the region of the absorber that is labeled "active region" in figure 5 will be drawn toward the front of the absorber, as the entrance to the detector is negatively biased, but the front of the absorber is at ground potential. The positive charge left behind will contribute to the image charge induced on the cage. Thus it is possible for an ion to produce an energy signal without producing a signal on the first dE plate.

An event recorded by the detector system consists of six signals: a time-of-flight signal generated by a start and stop signal delivered to a Time to Amplitude Converter (TAC), an Energy signal proportional to the energy deposited in (or near, see above) the detector, and four Energy Loss signals, taken from individual or combination dE plates. These six signals can be recorded together so that a history of each event can be recalled off line at any time. In addition, each of the six signals are separately histogramed. This histogramming can be done in several individual sets, with different sets requiring different operator-controlled gates. Finally, the data can be stored in two different two-parameter plots, such as TOF versus Energy or the first dE versus Energy. These two dimensional plots can come from
either a gated set of spectra or from the raw ungated spectra.

In summary, a very complete system exists to perform fractional charge searches. A fractional charge can be sputtered from a wide range of sources, either solid or gas. The negative ions produced in this manner are then focused electrostatically into the tandem accelerator. A specific E/Q is selected from the beam and passed through a foil which produces a new set of charge states. Another E/Q selection is made, and the beam is delivered to the detectors. In the detectors, a detailed profile of each event is produced. Specific examples of how the E/Q selections are determined, and a discussion of the types of background that exist will be detailed in the following chapter.
CHAPTER SEVEN
EXPERIMENTAL RESULTS

This chapter will detail the results obtained from four runs using two different experimental set-ups searching for fractional charge. Each of the experiments assumed the nuclear charge of the fractionally charged atom has the form of a low integral number, $z$, plus two-thirds. In the first configuration the sensitivity was maximized for a nuclear charge of three and two-thirds. In configuration two, it was assumed that the fractionally charged particle has an anomalously long range in matter, for example by being very massive.

In general, each experiment consists of the following steps: 1) select and install a sample, 2) select a scenario for ion charge in each region of the beam line: low energy side of the terminal, high energy side of the terminal, and following the second stripper, 3) set both electrostatic selectors and the Van de Graaff terminal voltage, 4) tune on a "contaminant" beam, which has an E/Q equal to that of the given scenario, but composed of a normal element, 5) perform a transmission efficiency measurement on the tuned
contaminant, 6) run the sample. The high mass experiment has an additional step inserted before or after step five: fill the absorber region just before the detector to a pressure high enough to drop the count rate in the gas detector to an acceptable level by stopping most contaminant beams.

Initially, several scenarios were to be tested. Runs were planned searching for nuclei with low z and one- and two-thirds charge added and also for high z nuclei with one- and two-thirds charge added. However, extremely high background rates precluded the high z search, and ultimately a lack of time forced a postponement of the search for low z nuclei with an additional one-third charge.

The first scenario actually tested assumed that the ion charge was negative one-third out of the source, stripping to positive two and two-thirds at the terminal, and finally stripping to positive three and two-thirds at the final foil stripper. Since the first electrostatic selector was well calibrated at an E/Q of ten MeV (note that in all cases the charge is in units of the electron charge), the terminal voltage was set to produce an energy of 26.6 MeV (8.89 MV minus injection potential of roughly one tenth of an MV). The second electrostatic selector was tuned to an E/Q of 7.27 MeV. With these settings, normal elements that leave the source in charge state negative one, strip at the terminal to charge state eight, and finally strip at the second stripper
to charge state eleven, also were focused into the detector. The advantage of this configuration was that elements with a 
z lower than eleven could not make it directly to the detector. Since oxygen is a common contaminant with a very 
high count rate, it was hoped that this scenario would give a reasonably clean spectrum. As will be seen shortly, such was 
not the case.

The sample used in this run was a positively biased 
titanium disk from the ion collector described in chapter 
five. (To prevent contamination of the disks during the one 
to two weeks prior to scanning, the tubes containing them 
were stored sealed in an argon environment.) The cesium beam 
was focused on the outer edge of the disk, and remained there 
for several hours while transmission tests were run on a 
chlorine beam from vapor from a sample of carbon 
tetrachloride. Chlorine was chosen because of its 
accessibility, its efficiency for producing negative ions in 
the source, and because of its intermediate mass.

After these transmission tests, the carbon 
tetrachloride was flushed from the system, and a background 
spectrum was taken without moving the cesium beam from the 
now-clean edge spot of the disk. A two-parameter plot of 
these data are shown in figure 13. The figure shows counts 
collected versus energy lost in the detector and energy 
deposited over the first dE plate. Labels on the figure
Figure 13.

Background spectrum from surface of a titanium disk removed from ion collector. Number of counts is represented by the density of dots. "dE1" is the energy deposited on the first dE element, "Energy" is the energy deposited in detector.
identify the various peaks, determined by correlating them with corresponding peaks in the TOF detector. A more detailed description of the structure of this spectrum will follow shortly. To produce a spectrum as sharp as this, it was necessary to attenuate the beam by up to five orders of magnitude, using the nickel foil attenuators. The limiting factor in count rate was the gas ionization detector. It performed well up to $10^3$ counts per second. However, by $3 \times 10^3$ counts per second, pile-up began to disrupt the spectra. By $10^4$ counts per second, the gas began to saturate (the ions produced from one event would not clear from the active region before the subsequent event began). The TOF detector, meanwhile, continued to give reliable data up to several times $10^5$ counts per second.

After the background run was completed, a scan of the disk was begun. Scanning was done by moving the disk such that the cesium beam etched successively larger squares on the disk surface. An entire scan requires on the order of ten minutes. The scan was done in two stages due to a failure in the scanning routine after roughly sixty percent of the scan was completed. Figure 14 shows the result of the first phase of the scan, and figure 15 shows the result of the rest of the scan. In figure 14, the increased background at low values of $dE$ was due to pile-up during intermitent bursts from the disk. In this run the attenuation was
Figure 14.

Start of first scan of titanium disk searching for integer + 2/3 nucleus, in first configuration. Heavy line indicates primary region of interest.
Figure 15.

Spectrum from conclusion of first scan.
accomplished with a 1200-times attenuator located just before the detectors, and also by closing down the slits just after the 1.3 degree electrostatic selector. Figure 15 appears cleaner than figure 14 because an additional two orders of magnitude attenuation was added in the low energy beam line.

A more detailed understanding of the structure of figures 1-3 requires a more complete description of the processes by which an ion will make it to the detectors. The actual resolution of the first electrostatic selector was measured to be roughly three percent at full-width half-maximum. This was determined by varying the plate voltage and monitoring the detector count rate. Thus, a wider range of charge states can pass this gate than previously implied. The twenty degree selector, however, was measured to have a resolution of better than 0.2 percent. The figures show that over-all the dominate peaks were the anticipated charge states. The continuum that tails back from these peaks is largely due to ions that lost energy in the residual gas in the beam line and also consists of ions that small-angle scattered off of various elements in the beam line. Some additional peaks are due to molecules that break up at the terminal, and acquire the correct E/Q to be selected. The result of the distribution of energies and charge states is a detailed mapping of the energy loss curve of the more abundant contaminant beams. The multiple
intermediate mass lines merge into a single straight line at the point where all of the energy is lost over the first $dE$ plate. The higher $z$ elements, such as titanium, are shifted to the left relative to aluminum due to their greater energy loss in the entrance window. Oxygen and other light elements are shifted to the left of aluminum because their range is so great they do not lose all of their energy in the detector active region.

The region enclosed by heavy lines in figure 14 is where the fractionally charged particle would show up, assuming standard energy loss mechanisms. In most of this region there are one or no counts per channel. The next step, then is to convert this result into a lower limit on our sensitivity. Because of the many factors involved, this will be a long, and in some cases tedious, discussion. Some of the details will not be completely covered until later in this chapter, as the subsequent runs will point out additional considerations. Nevertheless, the starting point will be a general over-view of the basic equation for calculating sensitivity, along with a careful definition of the basic terms. If there are $N$ fractionally charged particles, denoted by "f", on the surface of the disk, the number of counts, $C(f)$, expected is given by:

$$C(f) = N A e_i(f) e_{cs}(q_j,f,E) e_t(f,E)$$

where the additional terms are defined as:
\[ A \quad = \text{fraction of disk area actively scanned (including the effect of detector dead time),} \]

\[ e_i(f) \quad = \text{efficiency for sputtering off of the source in a negative charge state (injection efficiency),} \]

\[ e_{cs}(q,f,E) \quad = \text{efficiency for scattering into the correct charge states, } q_i, \text{ in each of the two strippers, hence typically a product of two such efficiencies at two energies, } E, \]

\[ e_t(f,E) \quad = \text{transmission efficiency through the system including all effects other than those indicated explicitly.} \]

The most difficult term to assign a quantitative value is the transmission efficiency, which includes such effects as attenuators, tuning, and losses due to small angle scattering and charge exchange in the accelerating region. In this run \( e_t(f) \) could be replaced by using the titanium peak and a separate run with a chlorine source. This was accomplished by first noting that the number of chlorine counts, \( C(Cl) \), is given by:

\[ 14) \quad C(Cl) \quad = \quad Cu(Cl^-) \quad t \quad e_{cs}(Cl) \quad e_t(Cl) \]

with:

\[ Cu(Cl^-) \quad = \text{particle current of chlorine into the low energy faraday cup,} \]

\[ t \quad = \text{active run time of the normalization run} \]

and the arguments of the remaining terms simplified for
clarity. Meanwhile, the run time is directly proportional to
the number of titanium counts observed.

15) \[ t = C(Ti) k \]

If \( e_t(f) \) is then expressed as a product of \( e_t(Cl) \) and another
function, \( d \), which represents principally the effect of mass
on the transmission efficiency, equation 13 could be
rearranged with the factors \( k \) and \( d \) as the chief obstacles.

16) \[ e_t(f) = e_t(Cl) d \]

Finally, even \( k \) can be removed by taking the ratio of \( C(f) \) to
\( C(Ti) \). The result of these manipulations is:

17) \[ \frac{C(f)}{C(Ti)} = \frac{A N e_i(f) e_{cs}(f)}{e_{cs}(f)} \frac{C(Cl)}{C(Ti) Cu(Cl^-) e_{cs}(Cl)} d \]

The terms in the bracket are measured separately, as
described above. To convert this into an estimate of
sensitivity, recall equation 7 from chapter five, which gives
the number of fractionally charged particles on the disk as a
function of number density in air. Using this information
and rearranging equation 16 gives:

18) \[ n = \frac{1}{2.2 \times 10^2} \frac{C(f)}{C(Ti)} A e_i(f) e_{cs}(f) d \]
\[ \times \frac{t}{C(Ti) Cu(Cl^-) e_{cs}(Cl)} \]
The only remaining step is to substitute appropriate values for each of the terms. Starting with the terms in the bracket, the chlorine current was measured in the low energy faraday cup to be 190 nanoamps, or $1.1 \times 10^{12}$ particles per second. While this current measurement actually measures all species in the faraday cup, the chlorine component was determined to be the dominate beam by comparing currents with the gas line open and closed, and by observing TOF and gas detector spectra. The fraction of chlorine beam to strip to charge state eight at approximately nine MeV in a carbon stripper foil is roughly thirty percent. At eighty Mev roughly three percent strip to charge state eleven. These values were taken from a table assembled by Chaki and Elmore\textsuperscript{79}, which is based on semi-empirical formulas published by Dmitriev and Nikolaev\textsuperscript{80}. The net value of $e_{cs}(\text{Cl})$ is the product of these two yields, or 0.009. The ratio of chlorine counts to titanium counts was 4000 to 20 or 200.

Moving to values taken from the actual fractional charge search run, approximately sixty percent of the disk area was covered in the first run. This run lasted seven minutes, but the very high count rate resulted in a dead time over ninety percent. So the active time was roughly forty seconds. Part of this dead time was due to the fact that an intermediate buffer between the detector and the computer can
only store 1000 counts per second, and events after the first 1000 are lost. During the run, twenty titanium counts were collected, and in the most sensitive region, there were zero or one background counts. For a ninety five percent confidence interval, zero background counts is consistent with fewer than three real events. The remaining terms, \( e_i(f), e_{CS}(f), \) and \( d \), are inherently model dependent. Up to these terms, the status is given by:

\[
19) \quad n < 2.2 \times 10^{-15} \frac{1}{e_i(f) e_{CS}(f) d}
\]

Since each of these terms is critical to establishing the limit to the sensitivity of this experiment they will be dealt with separately in detail.

The first term, \( e_i(f) \), is the efficiency for sputtering off of the disk in a negative charge state. This term is the most chemistry dependent. Among naturally occurring elements \( e_i \) varies typically from better than 0.2 to less than \( 1 \times 10^{-4} \). For some elements, such as most noble gases, \( e_i \) is essentially zero. Nonetheless, the most reasonable guess for this term applied to fractionally charged atoms would be a value on the order of 0.1. The reason for this assignment goes as follows. Very electronegative elements such as fluorine or chlorine will produce up to twenty percent or more atoms in a negative charge state. Many other elements, such as carbon and oxygen, also produce ten percent or more
negative ions. The addition of some fractional charge to a nucleus will result in a nuclear charge of $z$ plus some positive fractional number. The resulting element should be more electronegative than the natural element with nuclear charge, $z$, and hence at least as efficient at producing negative ions as carbon.

The next term, $e_{cs}(f)$, is very mass dependent. Estimates of the yield to various charge states were obtained by modifying the computer code used to obtain the tables cited earlier. Essentially, the modification was to allow non-integral nuclear charge, and to allow the mass to be an input parameter. The basic equations give the equilibrium charge state, $q^*$, the probability distribution for charge $q$, $P(q)$, and the standard deviation of the distribution, $d$.

\begin{align}
20) \quad q^* &= \frac{z \log(11.2 \ (E/m)^{0.5} z^{0.1})}{\log(5.0 \ z^{0.6})} \\
21) \quad P(q) &= \frac{1}{d \ (2\pi)^{0.5}} \exp\left(-\frac{(q-q^*)^2}{2 \ d^2}\right) \\
22) \quad d &= 0.38 \ z^{0.4}
\end{align}

Two values of stripper yields are required to give a complete estimate of $e_{cs}(f)$. The total yield is the product of the yield to charge state 2.67 at three MeV and the yield to charge state 3.67 at 26.7 MeV. For a nuclear charge of 3.67 and mass of nine GeV, the first yield is approximately...
thirty percent, and the second yield is essentially one hundred percent, giving a net of thirty percent. If the mass is increased to ninety GeV, the first yield drops to twenty percent, and the second yield drops to sixty percent, giving a net yield of roughly ten percent. The qualitative features that are important are 1) with low mass, high energy, all of the yield is to the fully stripped configuration, and 2) with high mass, all of the yield is to the lower charge states. The first property is why this experiment was primarily sensitive to a z of 3.67. The second property limited the overall sensitivity of this experimental configuration. Experimental configuration number two, however, will take advantage of the high mass yield to low charge states. This will be explained in more detail shortly.

The final term in equation 19 represents the mass dependence of the transmission yield. In many respects this term represents the greatest uncertainty in determining overall sensitivity. The problem is a multitude of contradicting effects come into play. While an all electrostatic beam handling system is advertised to be mass independent, this idealized environment is impossible to achieve in practice. Ultimately, a compromise must be made, particularly while selecting a contaminant to tune with.

Early in the setting up phase of the experiment an attempt was made to test the "mass" dependence of the system.
Three elements were mass-analyzed from a source identical to the one used in the fractional charge search. The analysis measured beam intensities out of the source of carbon, chlorine, and gold. The sample disk was transferred to the actual source, and currents were measured at the detector. The relative transmission, normalized to source output and charge state yield, indicated a two order of magnitude decrease in transmission in going from carbon to gold. Experience with various samples had led the operators to expect roughly one order of magnitude decrease. The discrepancy was believed to be due to a poor vacuum in the low energy beam line, the result of a faulty pump on that portion of the line. The argument was that one mass effect is the velocity dependence of charge exchange in a residual gas. Nevertheless, sufficient additional effects became apparent that once the vacuum in that beam line improved, that particular test was not repeated.

A major contribution to mass effect may have been a magnet between the source and the accelerator. A gauss meter was inserted between the magnet poles, and a current was applied to the magnet to counter the residual fields at the probe. However, residual fields away from the probe may have been sufficient to cause a tune for one mass to detune others. Since the effect of the field is greater for smaller masses, early tunes concentrated on intermediate mass contaminants.
Late in the experiment, it was noted that small changes in the twenty degree selection element resulted in large changes in relative yields of various elements. Figure 16 shows the count rates of oxygen and chlorine as a function of voltage applied to the plates in the electrostatic selector. It was believed that this effect was primarily due to the different energy losses of different elements in the stripper foils. Since experiments involving the second configuration were to look for very penetrating particles, which would lose very little energy in the foils, oxygen was selected as the contaminant to tune with.

In summary, then, the major sources of mass effects are 1) different rates of charge exchange in residual gas, 2) stray magnetic (and higher order electric) fields, and 3) energy losses in residual gas and stripper foils. Whether the net result is major or minor is not clear, and d will be left as a parameter.

Folding in the "best" guesses for $e_i (0.1)$ and $e_{cs} (0.2)$ gives a sensitivity estimate

$$23) \quad n < 1 \times 10^{-13} \ (1/d).$$

This pertains to the cleanest region of the spectrum of figure 14. This sensitivity is much less than had been hoped for. The major problem was the count rate limitation of the gas detector. Many orders of magnitude attentuation were
Count rate of oxygen and count rate of chlorine as a function of voltage on 20° electrostatic selector.
required to produce an acceptable count rate. It was clear, further, that to achieve a reasonable sensitivity a major shift in procedure was required. For this reason it was decided to shift the emphasis to an assumption of highly penetrating particles.

It was assumed in each of the following runs that the fractionally charged ion would leave the source with a net charge of negative one-third, strip at the terminal to a charge of positive two-thirds, and remain charge two-thirds through to the detector. The terminal voltage was set to give the ion an energy of 6.67 MeV, which resulted in an E/Q of ten MeV for each of the electrostatic selectors. The contaminant beam would be composed primarily of elements that stripped from charge state negative one in the low energy end of the accelerator to charge state two at the terminal, and remained charge state two through to the detector. To reduce background, a foil stripper was inserted between the electrostatic selectors. The first sample was the positively biased titanium disk from tube two of the ion collector.

Before beginning the actual run, pure oxygen was delivered to the source to provide a contaminant to tune with. Care was taken to insure that the tuned element was in fact oxygen by consulting the spectra from the gas detector and the TOF detector. Next, the pressure in the gas absorber was increased until the oxygen peak disappeared from the
spectrum. At this point the pressure in the absorber was approximately fifty torr, and the pressure in the detector was approximately thirty torr. Using the TOF system to give the count rate of oxygen through the beam line, and measuring the oxygen current in the low energy faraday cup, the oxygen transmission was measured with the second stripper in and out. For the latter measurement, a 1200-times attenuator was necessary just in front of the detector.

The oxygen was purged from the gas line to the source, and two successive scans of the titanium disk were performed. The results of the first scan are shown in figures 17 and 18, the second scan in figures 19 and 20. After the scans were completed, oxygen was again added to the source, and the transmission figures were checked. Next, the oxygen was again purged, and the xenon gas sample was fed into the source. The current from the source was periodically monitored, and data were collected for approximately one hour. The results of this run are shown in figures 21 and 22. Finally, the oxygen calibration was again tested. The only additional spectrum that will be important was a run taken with the beam prevented from reaching the detector. This was taken to examine a peculiar source of background that became evident when this experiment began. The background is shown in figure 23. A detailed discussion of each of these runs will follow shortly.
Figure 17.

First scan of titanium disk using second configuration. Counts vs dE and Energy.
Figure 18.

First scan of titanium disk using second configuration. Counts vs dE and TOF
Second scan of titanium disk. Counts vs dE and Energy
Figure 20.

Second scan of titanium disk. Counts vs dE and TOF
Figure 21.

Results of one hour run of xenon gas sample, 
Counts vs dE and Energy.
Figure 22.

Results of one hour run of xenon gas sample, Counts vs dE and TOF
Figure 23.

Noise spectrum
For the titanium disk runs, the number of counts expected is given by equation 13. The subsequent procedure employed with the first run cannot be repeated here, however, since the normalization contaminants are prohibited from reaching the detector. As a result, a simpler procedure was devised. As in equation 16, the transmission efficiency of the fractional charge can be expressed in terms of the transmission efficiency of oxygen:

\[ 24) \ e_t(f) = e_t(0) \ d \]

Meanwhile, the transmission efficiency of oxygen is given by an equation analogous to equation 14:

\[ 25) \ \frac{C(0)}{t} = \frac{C(0^-)}{e} \ c_s(0) \ e_t(0) \]

The resulting equation, analogous to equation 18 is then:

\[ 26) \ n = \frac{1}{2.2 \times 10^{23}} \ \frac{C(f)}{A \ e_i(f) \ e_c(f) \ d} \ \frac{C(0^-)}{e} \ c_s(0) \]

The gas sample must be treated slightly differently in the initial equations. The number of fractional charges observed will be given by:

\[ 27) \ C(f) = N_s(f) \ e_i(f) \ e_c(f) \ e_t(f) \]

When a gas is delivered to the source, most of it is simply pumped away, and never gets near the cesium beam. \( N_s(f) \) represents the number of fractional charges that pass through the cesium beam in a region where ionized atoms will ultimately be focused into the accelerator. Notice that the ratio \( N_s(f)/N_s(\text{Carbon}) \) will be equal to the ratio of
fractionally charged particles to carbon atoms in the gas. Using this, and the observation

\[ 28) \quad N_S(C) e_i(C) = Cu(C^-) t, \]

allows one to write:

\[ 29) \quad C(f) = \frac{N(f)}{N(C)} Cu(C^-) t \frac{e_i(f)}{e_i(C)} e_{cs}(f) e_t(f) \]

Next, the ratio of fractional charges to carbon atoms has to be related to the original density in air:

\[ 30) \quad n = \frac{1}{K} \frac{N(f)}{N(C)}, \]

where \( K \) is the enhancement factor achieved. Finally, then, the result is:

\[ 31) \quad n = \frac{C(f)}{K Cu(C^-) t} \frac{1}{e_i(f)} e_{cs}(f) e_t(0) d \]

All that remains is to substitute appropriate values into equations 26 and 31. The transmission efficiency is given by equation 24 once the transmission efficiency of oxygen is derived from equation 25. Crucial to this equation is the charge state yield of oxygen to charge state two at 6.67 MeV and 20 MeV. The lower energy yield can be estimated fairly reliably to be \( 1 \times 10^{-3} \). However, the higher energy yield is so far from the equilibrium charge state that an estimate is difficult to ascertain. To correct for this, the second foil was removed and an attenuator was inserted as described above. In this mode, the oxygen current was three
hundred nanoamps and the counts per second in the TOF was $2 \times 10^5$. These figures give a transmission efficiency of thirteen percent. With the foil replaced, and the attenuator removed, the number of oxygen counts per second was stable at 300/sec. A similar run with the foil stripper in place implies an oxygen charge state two yield at twenty Mev of $1 \times 10^{-5}$.

The values for $e_{cs}(f)$ were obtained by extrapolating the stripper yield formulas as described earlier. The general trend toward low charge states is certainly clear enough. A precise quantitative value is slightly more dubious. For example, at mass 90, nuclear charge 3.67, the equilibrium charge state is estimated for 3 MeV to be 0.9, or roughly eighty percent to the lowest positive charge state. At 6.67 MeV the equilibrium charge state climbs to roughly 1.5, leaving approximately thirty percent to the lowest positive charge state. Higher masses will increase this yield until the equilibrium charge state becomes low enough to preferentially populate the lowest lying negative charge state. For an order of magnitude estimate, an average value of fifty percent at each energy covers a wide range of masses and nuclear charges. A better estimate would be valuable, but very difficult to obtain. Combining the two yields gives a net estimate of 0.25 for $e_{cs}(f)$.

As described earlier, $e_{i}(f)$ will be approximately the same as $e_{i}(C)$, or roughly 0.1.
The last parameter common to both equations 26 and 31 is the number of counts produced by the fractional charges. At this point, a more detailed description of the spectra is in order. Since most contaminants are stopped in the gas absorber, a clean spectrum is produced. The key features of the plots showing counts versus dE and energy are 1) a long diagonal line from carbon ions not stopped in the absorber, 2) a broad noise region, as shown in figure 23, and 3) isolated peaks not obviously related to the noise or the carbon.

The line labeled carbon was identified by the occasional coincidences with the carbon peak in the TOF. If the coincidences had been accidental, they would have occurred much more frequently in conjunction with the very strong oxygen peak in the TOF. Nevertheless it is troublesome that the TOF versus energy plots reveal that there is a very poor efficiency for coincidences between energy signals and TOF signals, an important result that will be returned to shortly. The fact that the carbon line in the dE versus energy plot is straight is a simple result of the fact that all of the energy lost in the detector is deposited over the first dE. The great extent of the line in this case is due principally to the energy straggle in the detector window and absorber. The width can be accounted for by a straggle of roughly two MeV, through an absorber at a
pressure of fifty torr. The critical feature of the carbon line is that the intercept on the energy axis is greatly shifted to the right. The shift is due to the additional energy deposited on the total energy signal from a region of the absorber outside the actual detector cavity, as described in chapter six and shown in figure 12. The important point is that this shift will be different for each element, and for each incident energy. The exact magnitude of the shift could be calculated only if the pressure in the absorber were known precisely, which was not the case. Similarly, the exact magnitude of the straggle, estimated as two MeV, requires more precise information on the pressure in the absorber.

The second important feature of the dE versus energy plots is the broad noise region along the center of the energy axis, and very low in dE. This feature became apparent after the pressure in the detector was lowered to thirty torr to enhance the range of low energy ions. These signals typically are coincident on two or three of the first three dE plates. It is believed that these signals are produced by low level activity from an americium source that contaminated the detector some time ago. Naturally, these signals are never coincident with a real TOF signal. If the efficiency for coincidences between TOF and energy signals were large, that would be sufficient to reject the noise.
Finally, isolated peaks appear in a few locations on several of the dE versus energy plots. There is a prominent peak visible to the right of the carbon line in figures 17 and 19, and it even appears in a greatly reduced way in figure 21. The very high energy eliminates this peak from consideration as a possible candidate. (The carbon contaminant is twenty MeV, but a fractional charge would only have 6.67 MeV.) The small extent of the peak suggests that the ion responsible lost relatively little energy in the window and the dead region of the absorber, suggesting either a very light ion, or a very energetic heavy ion.

In the gas-sample spectrum, figure 21, a small peak is apparent above and to the right of the main carbon line. Again, this peak seems to be too high in energy to be considered a candidate.

Just above the left edge of the noise in figure 21 are approximately eleven events that deserve a brief mention. Three similar events are apparent in figure 17, the first scan of the titanium disk. Corresponding events are not readily apparent on the noise spectrum or the second scan of the titanium disk. These events are located along the right edge of the energy region in which the fractional charges are most likely to be found. Each of these events is accompanied by a signal on dE2 about half as large as the signal on dE1. Since there is a sharp cutoff of the noise below these
events, and since each event has a dE2 signal, and since none of the events have an associated TOF, it is most likely that these are artifacts of the noise. However, these arguments are not compelling, and further investigation of this region is warranted on future runs.

With the exception of the noise region, which is mostly to the right of the area in which fractionally charged events are expected to lie, the spectra are clean enough to conclude no candidates for fractionally charged particles were found. For the limit on sensitivity, a value of three for C(f) would again be appropriate for equations 26 and 31.

At this point, all the parameters common to equations 26 and 31 have been discussed. To conclude the evaluation of sensitivity from the titanium disk run, the area scanned was roughly sixty percent. This results in an ultimate sensitivity of:

\[ 32) \quad n < 1 \times 10^{-20} \text{ (1/d)} \]

In the case of the gas run, a few additional parameters are involved. Since the carbon to xenon ratio is roughly one for the gas sample, the enhancement factor can be taken conservatively to be \(10^7\). The current in the low energy faraday cup was 200 nanoamps, or \(1 \times 10^{12}\) particles per second. The run time was approximately one hour, with very little dead time. Folding all of this into equation 19 gives a sensitivity limit for the gas sample of:

\[ 33) \quad n < 1 \times 10^{-21} \text{ (1/d)} \]
A discussion of these limits, including caveats to them, and a discussion of possible improvements to the procedure taken here, will be covered in the final chapter.
CHAPTER EIGHT
CONCLUSION

This final section will consist of three parts: a summary, a discussion of implied caveats, and suggestions for future fractional charge searches.

It was assumed that fractionally charged particles exist in air bound together to form neutral molecules. Two distinct enhancement techniques were employed. One version assumes the vapor pressure of the neutral molecules is lower than that of xenon and hence can be collected from a process that produces pure xenon from air. A second enhancement technique involved ionizing air, allowing a short recombination period, and collecting all remaining ions on the surface of titanium disks. Each of the samples was examined at the University of Rochester with an "all-electrostatic" system to produce ions, accelerate them, and deliver them to a detection system that measures both velocity and energy. Ultimately, a maximum sensitivity on the order of $1 \times 10^{-20}$ fractionally charged particles per air molecule was attained.

More precisely, the sensitivities attained were $1 \times$
$10^{-20} \times (1/d)$ for the ionized air sample (where it is assumed that there are $n \times 10^{23}$ fractional charges per titanium disk, with $n$ being the concentration of fractional charges in air) and $1 \times 10^{-21} \times (1/d)$ for the xenon gas sample (assuming the gas enhances the concentration by seven orders of magnitude). In both cases the term "$(1/d)$" represents the effect of mass and nuclear charge on the transmission efficiency through the entire beam line.

Early in the run, an attempt to deduce $1/d$ gave the result that the transmission varied inversely with the square of the particle's mass, while it had been anticipated that the effect would be more like simply the inverse mass. Further investigation indicated that the term may depend more on the energy loss characteristics of the particle. In that case, the previous measurements were more a study of the effect of nuclear charge than particle mass. Clearly, a more careful study of transmission efficiency is required. The most disconcerting aspect of this study may turn out to be that the resolution of the apparatus is too high. As figure 16 shows, a tune on any specific contaminant beam may actually deflect the fractionally charged particles away from the detector. Clearly, the null result obtained in this experiment is not a definitive answer.

This study is important because it is the first systematic study of the possibility that fractionally charged
particles exist but have evaded detection because they are bound in neutral molecules. Nevertheless, it is important to note the caveats that would have precluded the observation of fractional charges at concentrations considerably above those indicated. Obviously, first of all, the premise may be wrong. It could well be that mechanisms exist that trap the fractional charges and prevent neutralization. Assuming that the premise is correct, however, the fractional charges could have been lost in any of the following steps: collection, transmission, or detection.

The enhancement techniques may have failed. Particularly suspect is the xenon gas sample. Since the gas is refined in multiple steps prior to the point from which the sample used here was collected, the fractionally charged particles may have been removed. The ionization technique is more secure. However, if the molecules are too tightly bound, they may not have been broken up. Or, recombination may have occurred on the disk surface, for example at defect line junctions.

Second, the fractional charges may have existed in either or both of the samples, but were not delivered from them to the detector. The transmission efficiency was already discussed. At least two other mechanisms may have depleted the beam. Since the disk was heated by the cesium beam throughout the transmission tests, the fractional
charges may have outgassed from this sample prior to the run. Finally, the fractionally charged particles may have been stopped in the absorber prior to the detector. This depends on the range of the particles, which is strongly charge and mass dependent. Due to the uncertainty in the pressure in the absorber, it is difficult to make an estimate on the mass cutoff. Roughly, for a nuclear charge less than five, the least massive particle that could penetrate the gas at fifty torr would have a mass greater than fifty GeV. This figure is a guideline, not a hard estimate. A more precise estimate, made by extrapolating energy loss from measured mass and charge dependence can be attempted.

Finally, the fractionally charged particles may have reached the detector and gone unnoticed. This would be particularly possible if they happened to lie under the carbon peak or in the noise. Recall that not all peaks have been clearly identified.

What remains for the future?

In the short term, the identical experiment should be repeated. This time, care must be taken to increase the efficiency of coincidences between the TOF and the gas detector. Also, the noise peak should be removed or understood. (It is highly likely that this step has already been taken. A radioactive contaminate was cleaned from the interior of the detector after these runs were completed.)
Finally, modifications must be done to allow precise measurements of the gas pressure in the absorber and the detector. In addition to the xenon gas sample, a new set of titanium disks, cooled in the source, should be examined. One of these disks should have collected ions from the xenon gas, in the same way the current experiment looked at ionized air.

In the long term, more efficient means could be devised to examine the possibility that the fractionally charged particles exist in neutral form in air or in sea water.

In conclusion, the experiment described in this work can be used as a starting point for future, similar, studies. In all such works it is important to note the caveats, implied and explicit. It should be clear at this point that the existence, or lack, of fractionally charged particles at fairly high abundances is still very much an open question.
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