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Efficient Bulk Search for Fractional Charge with Multiplexed Millikan Chambers*

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ABSTRACT

We outline the design of a fully automated Millikan droplet apparatus that could detect a single free fractional charge in several hundred grams of matter even without the use of a prefilter. This would constitute an improvement over current limits by about five orders of magnitude. The experiment achieves high material throughput and high background rejection through online processing which allows for a feedback system that can concentrate the measurement effort on anomalous droplets. The task is simplified by generating a monodisperse stream of droplets which will be preprocessed to let only a very narrow range of charges enter the Millikan chamber. Because the droplets can act as carriers of finely dispersed materials it is also possible to search for fractional charge in matter which has not undergone extensive refinement that may have excluded fractionally charged atoms from the sample. In a large refinery style operation many such Millikan chambers could be multiplexed to achieve extremely large material throughput.

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1. Introduction

The fundamental charge in Nature is $\frac{1}{3}e$. This has been well established experimentally and is a basic ingredient of the standard model of particle physics [1]. It is generally believed, that the standard model predicts the confinement of fractional charge. However, it is difficult to test this aspect of the model experimentally. Small changes to the standard model which are still in agreement with the body of experimental data would introduce stable, fractionally charged particles that can exist in isolation. For example, neither a slightly broken symmetry of color SU(3) [2], nor an electrically neutral, heavy member of a color triplet are ruled out by experimental evidence. Both variations on the standard model would imply the existence of isolated, fractionally charged particles. These particles would have formed in the early stages of the expanding universe and some would have survived to this day. However, most scenarios predict very low abundances of fractionally charged particles, so low that their discovery in past matter searches would have been unlikely. Whether fractionally charged particles can exist in isolation is a purely experimental question which still remains unanswered.

Here we describe an experimental technique for detecting fractional charges in bulk matter which is five to six orders of magnitude more sensitive than past experiments. Finding isolated fractional charges at this level, <1 per 10^{26} nucleons, would not only be of enormous scientific interest, but would also have significant practical applications. For example, one might obtain fractional charges in numbers sufficient for catalyzing fusion [3]. Even if this search does not lead to the discovery of fractional charges, it would set a reliable and much more stringent limit on the cosmic abundance of fractionally charged particles than is currently available. Such a limit would rule out or severely restrict the most natural models that predict free fractional charge.

The technique we describe is conceptually simple and has become possible by recent advances in computing technology. We automate the basic Millikan apparatus utilizing simple, real-time pattern recognition algorithms to measure the charge on a large number of drops simultaneously. Through feedback, the effort is concentrated on those drops which initially appear to have non-integer charge. This interactive approach allows for extremely high background rejection while keeping the average measurement time short. The Millikan-type charge measurement is simplified by generating streams of monodisperse droplets which are prefiltered in charge so as to allow only a narrow range of charges to enter the Millikan chamber. In a large, refinery style operation many such Millikan chambers could be multiplexed to achieve extremely large material throughput.

The simplicity of this table top experiment is its strongest advantage. By automating simple procedures measuring the charge on very small droplets, we can avoid the pitfalls of other bulk charge measurements. The difficulty of an individual measurement is minimal, interference of separate measurements is rare and detectable. Accuracy—and with it background rejection—is achieved through a feedback loop which allows one to take, if necessary, a second and third look at a drop, rather than through a highly accurate and therefore difficult single measurement. By using small drops which can be levitated in the electric field, and by performing all data analysis on-line and in real time, it is even possible to retain and collect drops if they pass all tests for fractional charge. In a sense, experimental difficulty has been traded for sophistication in on-line data analysis. The latter has become possible in recent years as computer power increased and pattern recognition algorithms have become more refined.

2. The Concepts

Matter searches for fractionally charged particles typically proceed by measuring the net charge on a sample of bulk material. A fractional net charge would indicate the presence of a fractionally charged particle. The classic example of an experiment determining the fundamental unit of charge in this way is the Millikan droplet experiment [4–6]. The experimental difficulty of matter searches for fractional charge stems from the need of processing large amounts of material.

In the past, experimenters have addressed this difficulty using two complementary approaches. The first, represented by e.g. Fairbank [7] and Morpurgo [8,9], attempts to maximize the mass of a sample whose charge is measured. This leads to difficult, time-consuming measurements. However, by measuring the charge of a single sample, a large amount of matter is processed. The major drawback is that the choice of the material investigated is largely determined by the constraints of the measuring method. Furthermore, impurities in the material have to be carefully eliminated because they can lead to spurious results. Fractional charges, being themselves impurities, are not likely to remain in these highly purified samples [10,11]. Indeed, it would be advantageous to enrich the sample in those impurities which are likely to carry fractionally charged objects with them.

Instead of maximizing the size of a sample, the second approach minimizes the time for measuring the charge on an individual sample. Rather than measuring a few large samples, many small samples whose charges are much more easily determined are processed serially. Cylindrical liquid jet break-up technologies fall into this category [12]. The amount of material searched is controlled by the speed with which measurements can be accomplished. The difficulty of this approach is that background noise in the measurements must be carefully avoided. Since the number of measurements is large, it is crucial that the tails of the measured charge distributions do not extend to the fractional charges of interest. It is this accuracy requirement which limits the reduction in measurement time. In dropper type experiments the stringent requirements on the reproducibility in the drop generation lead to difficulties which ultimately limited the throughput. Nevertheless, the dropper experiment of Bland *et al.* [13,14] reached one of the highest sensitivities to fractional charges in a bulk matter search (cf. Table 1). Most importantly, this experimental technique was used for measurements on unprocessed materials.

Our method advances the second approach by allowing for multiple measurements on the same drop. We measure the charge of small drops in basically the same fashion as Millikan. By performing the data analysis on-line we can use the current best estimate of the charge to decide whether a further refinement of the charge measurement is warranted. This is the case if the apparent charge is compatible with a residual charge of $^1/_3\ e$ or $^2/_3\ e$. As a result, the average effort spent on a sample can be held low, while at the same time background noise can be suppressed to very low levels.

The mass of a droplet is chosen such that it can be levitated in the electric field and therefore can be observed for an indefinite amount of time. This makes it possible to concentrate a considerable effort on a single drop if it appears to have fractional charge. A hierarchy of more and more complex measurements, first eliminates statistical fluctuations and then detects systematic errors. The introduction of an interactive measurement

Table 1: Limits obtained in bulk matter searches. This table has been taken from Ref. [13]

Group	Material	Mass (mg)	fractional charge/nucleon
LaRue *et al.* [7]	niobium	1.1	2.1×10^{-20}
Morpurgo *et al.* [9]	iron	3.7	$<1.3 \times 10^{-21}$
Ziock *et al.* [15]	iron	0.72	$<6.9 \times 10^{-21}$
Smith *et al.* [16]	niobium	4.87	$<1.1 \times 10^{-21}$
Milner *et al.* [17]	niobium/tungsten		$<10^{-19} - 10^{-20}$
Joyce *et al.* [18]	sea water	0.05	$<9.8 \times 10^{-21}$
Savage *et al.* [13]	native mercury	2.0	$<2.9 \times 10^{-21}$

strategy which requires on-line, real time data analysis is a major improvement because it effectively eliminates the background as a problem in bulk matter searches. Another benefit of the automatization of the charge measurement is the ability to perform a large number of measurements in parallel.

The on-line analysis is made possible through an optical pattern recognition system which uses a charged coupled device to image and locate a large number of drops simultaneously and tracks them through a time varying electric field, thereby determining the mass and charge of a droplet. Individual measurements do not require extreme accuracy. Because the centroids of the peaks in the charge distribution provide a convenient reference, the system is self-calibrating, further reducing the effort required in an individual measurement.

The task for the pattern recognition algorithm is greatly simplified by using a droplet generator which generates monodisperse droplets with a variation in mass of less than one percent. Before entering the Millikan chamber these droplets are grossly segregated in an electric field according to their charge. Droplets entering the Millikan chamber, fall into a narrow charge range which in principle can be chosen such that it completely excludes integer charges. In this case the dominant contribution to the droplet stream is likely to be drops which changed charge during their fall time. Because the mass of the droplets varies very little, such a prefilter could increase the total efficiency of the system by three to five orders of magnitude. Since drops tend to have similar mass and charge, they move through the device at similar speeds minimizing the number of close approaches which complicate the pattern recognition problem.

The experimental design we have outlined improves on the state of the art in two ways. One is the staged design which leads to a multiplicative reduction of the experimental error and eliminates a large class of systematic errors. The stages are the prefilter, a series of Millikan oil drop measurements, consistency checks on the density, size, unit charge. Brownian motion of a drop, followed by the extraction of a fractionally charged droplet from the device. The second is the automated on-line measurement protocol which determines the level of effort invested into a droplet based on the outcome of earlier measurements

taken. It is this interactive process which makes it possible to perform most measurements with little effort while at the same time maintaining the high rejection rate of false positives which is necessary for extreme sensitivity.

3. The Millikan Chamber

To keep the design as simple as possible we use an air-filled Millikan chamber operating at room temperature and ambient pressure. The electric field is maintained between two horizontal, flat plates. The size of the plates and the spacing between them will follow from other design parameters and is of the order of centimeters. The bottom plate may be covered with a fluid to avoid complications from a build-up of droplet material. Alternatively droplets may fall through a narrow slit in the bottom plate. An additional set of plates may be used to move selected drops horizontally. A pulsed ultraviolet light source is used for inducing positive charge changes in droplets at appropriate times. The chamber is designed to minimize fluctuations in temperature, to avoid sudden pressure changes, and minimize air flow driven by heat convection or pressure gradients. These precautions facilitate the measurements. It is worthwhile pointing out, that these are not precision measurements. If gradual changes occur in temperature, in the electric field or even in the gas flow through the chamber, the measurements can account for these because of the effective calibration given by the large number of integer charge measurements which are continuously performed. One can view each measurement as a relative charge measurement against some other measurements which where done in a similar location and close in time.

Droplets are back-lit and are imaged on a charged coupled device (CCD). In order to minimize the rate of light induced charge changes, the light source should be strobed, which would also lead to an improvement in the timing accuracy of a measurement. Furthermore, the light source should be limited to a narrow spectral bandwidth which is near the maximum sensitivity of the recording device. A system of lenses is used to obtain the optimal resolution and the enlargement may differ in the horizontal and vertical direction. A large array CCD camera may generate an image of about 4000×4000 pixels. The CCD is read out at approximately $30 - 200\,\mathrm{Hz}$ and the information is processed to obtain charge measurements. In normal operation, the electric field is switched between $E_{\max}$ and $-E_{\max}$.

Using Stoke's law which relates the radius R of a droplet, its velocity $\vec{v}$ relative to the ambient gas, and the viscosity η of the gas to the force $\vec{F}$ on the droplet,

$$\vec{F} = 6\pi\eta R\vec{v},$$

one can calculate its mass and charge from the trajectory in a time varying electric field. In our case the mass of the drop is already known. Its measurement mainly serves as a consistency check. But by determining the actual droplet mass more accurately, one may also refine the charge measurement.

The three most important parameters describing the operation of this Millikan chamber are the maximum strength of the electric field, the size of the droplet and the accuracy requirement for a charge measurement. Together, these parameters determine the layout of the chamber and determine its serial throughput. As we will show later, they also

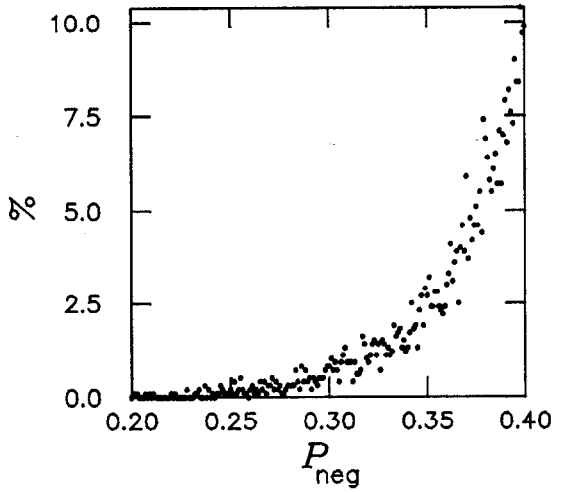

Figure 1: Monte Carlo estimate of the percentage of droplets which will eventually fall below a charge of $15\,e$ as function of the probability of an individual charge change to be negative. Random charge changes were applied to a droplet of an initial charge of $20\,e$. Droplets were followed until they either dropped below $15\,e$, exceeded $60\,e$ or had not left this interval after 1000 charge changes.

set the maximum number of simultaneous observations in a Millikan chamber and thus the maximum possible throughput through a single chamber. In order to determine the potential of this approach, we present in the remainder of this section estimates of these parameters which would govern the layout of a near optimal design. Clearly, an initial attempt would start with a smaller system then the one discussed here.

The electric field intensity in a Millikan chamber is limited by the breakdown characteristics of the gas in the chamber and by the electrohydrodynamic droplet emission from liquid coated surfaces in the chamber. At high field strengths, liquid surfaces distort and form points of liquid from which small highly charged droplets are emitted into the chamber space. An electric field intensity of about $10000\,\mathrm{V/cm}$ can be maintained if care is taken to minimize liquid layers on electrode surfaces. Such voltages have been demonstrated in Ref. 13. In the following we shall assume this to be the maximum amplitude $E_{\max}$ of the electric field.

If one measures the droplet charge to 0.5% accuracy, a good choice for the nominal droplet charge is $20e$. In this case, a residual charge of $^1/_3\,e$ or $^2/_3\,e$ differs by three standard deviations from the nearest integer charge. The size of the droplet is chosen such that it is possible to levitate a somewhat smaller charge. This is necessary since droplets in the Millikan device may occasionally change charge. Charge changes may also be induced artificially in order to obtain a consistency check on a measurement. Since induced charge changes are obtained through the emission of photoelectrons we assume that the average charge change is biased in favor of positive ones. Therefore, the initial charge on a droplet should be $+20\,e$. Even if the ratio of positive to negative charge changes has a bias of only 65 : 35, Monte Carlo calculations show that only about two percent of droplets will ever drop below a charge of $15\,e$ (cf. Figure 1). In the following we will assume that the electric field is strong enough to just levitate a charge of $15\,e$. Then the mass of a droplet is limited to $M = 2.4 \times 10^{-10}\mathrm{g}$ or 1.5×10^{14} nucleons.

A typical density of the droplet fluid is $\rho = 1\,\mathrm{g\,cm^{-3}}$. This number may vary somewhat for different experiments. Based on this density, the droplet radius becomes,

$R = 3.9\,\mu$. In air which under ambient conditions has a viscosity of $\eta = 182\,\mu$poise (1.82×10^{-4}g cm^{-1} s^{-1}), the fall velocity is given by Stoke's law

$$v_{\text{fall}} = \frac{2\rho g R^2}{9\eta} = 1.8\,\text{mm/s}\,,$$

where $g = 980\,\text{cm}\,\text{sec}^{-2}$ is the gravitational acceleration.

The Brownian motion of the droplet puts a limit on the accuracy with which the drop velocity can be measured. To estimate this effect we calculate the mean thermal velocity of a droplet in the vertical direction

$$v_{\text{brownian}} = \sqrt{\frac{kT}{M}} = 0.13\text{mm/s}$$

The relaxation time follows from Stoke's law

$$\dot{v} = \frac{9\eta}{2\rho R^2} v\,,$$

and is given by

$$\delta t = \frac{2\rho R^2}{9\eta} = 1.8 \times 10^{-4}\text{s}.$$

In effect the droplet performs a random walk around its average position with an average stepsize of $\delta t\, v_{\text{brownian}}$ and a mean time between steps of δt [19]. The same time constant δt also applies to the transient occurring at a change in the electric field.

The Brownian motion limits the accuracy of a velocity measurement. If the measurement time Δt is large compared to the relaxation time, the thermal velocity fluctuation is given by

$$\Delta v = v_{\text{brownian}} \sqrt{\frac{\delta t}{\Delta t}}\,.$$

If Δt is of order δt or less, the uncertainty simply becomes the Brownian velocity.

In order to achieve a measurement accuracy which is 0.5% of the fall velocity, the measurement time must be sufficiently long to average out over the fluctuations caused by the Brownian motion. This implies

$$\Delta t = \left(\frac{\Delta v}{v_{\text{fall}}}\right)^{-2} \left(\frac{v_{\text{brownian}}}{v_{\text{fall}}}\right)^{2} \delta t = 0.038\,\text{s}.$$

The corresponding fall distance is 0.07 mm or only 9 drop diameters. A positional accuracy of 0.3 μ is required for velocity measurements at the 0.5% level. This accuracy is close to the diffraction limit but not impossible to achieve. It requires a pixel resolution of 0.3 μ/pixel. A frame rate of 30 Hz would be barely sufficient for the measurements. However, we will show below that it is possible to reduce the frame rate, thereby reducing the rate at which measurements are taken on a single drop, and still maintain the same throughput by increasing the number of drops processed in parallel. This would not only reduce the basic

data rate from the CCD camera but also reduce the required magnification and therefore would avoid operating near the diffraction limit.

The measurement accuracy is not necessarily limited by Brownian motion. Other effects can also introduce uncertainties in the measurements. In particular, the effects due to the dipole moments induced by the electric field on the droplets must be carefully controlled [20]. The dipole moment of a dielectric sphere in a constant electric field is given by

$$\vec{P} = 4\pi\epsilon_0 \left(\frac{\epsilon - 1}{\epsilon + 2}\right) R^3 \vec{E}\,.$$

It should be noted that for our choice of parameters and a typical value of the dielectric constant ϵ which is not close to one, the induced dipole charge is much larger than the net charge on the droplet. The dipole charge on the drop is given by

$$Q_D = 3\pi\epsilon_0 \left(\frac{\epsilon - 1}{\epsilon + 2}\right) R^2 E\,.$$

For materials considered here, the factor $(\epsilon - 1)/(\epsilon + 2)$ is on the order 1/4 to 1, the latter corresponding to a conductor which would carry a dipole charge of 8000 e.

Since the induced dipole of a droplet will interact with electric field gradients, gradients for example due to the droplet entrance hole must be minimized in the region of measurement. In our case however, an additional 0.5% error would require a relatively large gradient of about 250 (V/cm)/cm. In the parameter range discussed here, the more likely error source are droplet-droplet interactions. The effective droplet-droplet potential is given by

$$\frac{1}{4\pi\epsilon_0}\left(\frac{\vec{P}\cdot\vec{P}}{r^3} - 3\frac{(\vec{P}\cdot\vec{r})^2}{r^5}\right).$$

At a distance of about 30 radii, the dipole-dipole correction to the total force is about 0.5%. Furthermore, in the vertical direction the force is attractive, and if one wants to avoid collisions between drops one must maintain a minimum distance between them. To make the shortest time of approach at least one hundred seconds would require about 45 radii between drops. Thus, the minimum droplet spacing is about 50 radii. This distance may not entirely result from vertical spacing but may indeed be dominated by lateral spacing.

If a charge measurement on a droplet is compatible with a residual charge of $^1/_3\,e$ or $^2/_3\,e$, the measurement must be repeated. One out of a few thousand drops will have to be measured twice simply because of statistical fluctuations. A charge change during a measurement would also necessitate additional measurements on a droplet. With a vertical viewing distance of 4000 pixels, ten consecutive pairs of measurements can be taken on the same drop without changing the voltage protocol. The number of pixels necessary in the vertical direction could be reduced by using an electric field which on average pulls droplets upward. After ten iterations a measurement of a residual charge of $^1/_3\,e$ or $^2/_3\,e$ cannot be explained by a statistical fluctuation.

Because spontaneous charge changes increase the effort necessary to establish the charge of a droplet, their likelihood should be minimized. However, charge changes may

be induced intentionally in certain regions of the Millikan chamber in order to determine the apparent size of the charge quantum. To rule out that a simple distortion of the charge scale (e.g. because of an anomalous density) is the cause of an apparently fractional charge, the size of a charge change is measured with a an accuracy sufficient to rule out such a distortion. For a single charge change this requires about ten measurements. For multiple charge changes it can be done with less data. By inducing charge changes with a pulsed light source every few measurement cycles one can determine the charge scale during the time the droplet moves through the field of view. With a total of ten measurements one can then expect a sufficiently accurate measurement of the residual charge on a drop.

Only if the apparent charge on the droplet is still fractional after it has fallen close to the bottom of the chamber is the standard measurement protocol interrupted. Further measurements deal exclusively with this anomalous drop and will apply an electric field of different magnitude and time variation in order to rule out other causes of an apparently fractional charge. For an optimized design this down time should be minimized. One way to achieve this would be to extract these special drops from the chamber and process them elsewhere.

We now consider the ultimate limit to which a single automatic Millikan device of this type could be pushed. The obvious limitations arise from the number of droplets which can be observed simultaneously. Vertical spacing between droplets should be large enough to avoid complicated, intertwined and intersecting trajectories. For pattern recognition, a spacing of maybe 10 diameters would be sufficient. In this case more than half of the average displacement between droplets required for controlling dipole-dipole interactions would have to result from horizontal spacing between droplets. Parallel streams of drops should also not interfere with each other physically nor in the pattern recognition process. For a very large CCD, 4000 by 4000 pixels, this would lead to a limit on the order of 20000 drops simultaneously in the field of view. With a fall time on the order of one second this would correspond to 20000 drops/s.

The next limit stems from the data processing requirement. at twenty thousand drops per second the average drop can only get 1/20000 of a cpu-second of attention from the dataprocessing system. A top of the line workstation with parallel processing capabilities may be rated at about 2000 MIPS which would leave 10^5 machine instructions for the average drop. This seems to be a rather tight but not impossible budget within which to program the pattern recognition algorithms. Note that most droplets can be eliminated after one or two measurements.

Finally, the probability that a droplet will pass all preliminary tests and thereby become a candidate for exclusive attention by the processing system sets another limit on the total rate of drops which can be processed by the system. If the device will be blocked for a time t_{excl} if such a candidate shows up, it can be shown that the throughput through the device is optimized if the average time between such candidates is equal to the exclusion time t_{excl}. If the probability of a droplet to be such a candidate is P_{cand} then the optimal drop rate D for the device is given by

$$D = \frac{1}{P_{\mathrm{cand}}\, t_{\mathrm{excl}}}$$

Table 2: Parameters of Millikan Chamber

Parameter	Value
Plate Spacing	$1-2\,\mathrm{cm}$
Plate Radius	$10-20\,\mathrm{cm}$
Observed Fall Distance	$0.14\,\mathrm{cm}$
Vertical Image Resolution	$0.35\,\mu$/pixel
Vertical Image Size	4000 pixel
Frame Rate	$20-200\,\mathrm{Hz}$
Electric field strength	$10000\,\mathrm{V/cm}$
Switching frequency	$20-30\,\mathrm{Hz}$
Drop size	$3.9\,\mu$
Drop density	$1\,\mathrm{g/cm^3}$
Fall velocity	$0.18\,\mathrm{cm/s}$
Transient response time	$1.8\times10^{-4}\mathrm{s}$
Maximum number of tracks	$\sim$1000
Horizontal Image size	4000 pixel
Maximum throughput	20 drops/track/sec

If we assume that only one in 10^5 droplets will need such special treatment, $P_{\mathrm{cand}} = 10^{-5}$. and if such a droplet takes on average 5 s to be either processed or to be moved out of the Millikan chamber, we obtain again a limiting drop rate of 20000 drops/s. We note, however, that the probability P_{cand} is currently unknown. It will depend on a number of variables concerning the reproducibility of the droplet generation, the suppression of dust particles and other causes for background. On the other hand our estimates are reasonably close to what has been achieved in previous dropper experiments [13,14].

Note, that if the system operates in this limit, the cycle frequency of the experiment does not affect the throughput. The throughput is only affected by the size of the field of view, the processing power of the computer hardware, the effort required for each droplet and the frequency of droplets which passed all tests for fractional charge. Longer measuring times for individual droplets are compensated for by a larger number of droplets which are simultaneously under observation. Therefore it may be possible to relax the high rate of data taking somewhat without compromising the eventual throughput of the system. If the observation time of the average droplet becomes too long, the large fall distances between measurements will complicate the drop identification and therefore increase the effort in the pattern recognition.

The parameters governing such an optimal device are listed in Table 2. Running continuously, it could handle 10000 drops or 1.5×10^{18} nucleons per second, or 1.3×10^{23} nucleons in a day. An additional increase in effective throughput can be obtained with the prefilter we discuss in the next section. Since the experiment is fully automated, it is also possible to run many such Millikan chambers in parallel.

4. Droplet Generation and Prefiltering

The technology for generating a monodisperse stream of droplets is well established [21–26]. Hendricks [26] describes a single jet device which generates 10^6 droplets of $R = 5\,\mu$ per second. The uniformity of the droplets is excellent at a fractional standard deviation in radius of about 10^{-3}. The particle mass rate of a single jet is $\sim$1 mg/sec. This exceeds the processing rate in the Millikan chamber by four orders of magnitude. Even higher rates, grams per second, were achieved with multiple jets. The advantage of the single jet is the ability to control the charge of individual droplets within narrow margins. The size of the charge fluctuations is limited by thermal fluctuations

$$\left| \frac{q\,\Delta q_{\rm therm}}{4\pi\epsilon_0 R_0} \right| = kT \qquad \text{or} \quad \Delta q_{\rm therm} = 3.5\,e$$

In principle, it is possible to include in the liquid a fine dispersion of other materials as long as the grain size is significantly smaller than the droplet radius. Methods for including such grains have been studied in the past [27]and others are currently under investigation. The ability to use the droplets as carrier of solid materials which may have undergone only very minimal processing allows one to test a wide variety of materials and one can translate an upper limit of the fractional charge occurring in the sample into a meaningful upper limit on their cosmic abundance.

For the drop generator we propose a linear array of jets which break up inside a charging electrode that sets the mean charge of the droplets to approximately $20\,e$. Each jet corresponds to one of the tracks observed in the Millikan chamber. After the jets break up into droplets, these droplets fall through a transverse electric field which deflects their trajectory by an angle proportional to the charge on the drop. Since the mass of the droplets is known very accurately it is possible to completely separate the different integer charges. The droplets enter the Millikan chamber through a small entry hole or slit. This entry hole is sufficiently narrow to only allow entry of drops within a fraction of a charge. The deflecting electric fields can be tuned through a feedback mechanism such that the window completely excludes the trajectories of particles of integer charge. E.g., only droplets with an effective charge between $20.2\,e$ to $20.8\,e$ may enter the Millikan chamber. We expect that the majority of droplets which satisfy this criterion have changed charge in flight. The probability of this to occur can be kept quite low. As a result, this first filter can greatly enhance the effective throughput. Without having actually built such a prefilter it is difficult to estimate its efficacy. However, the mass accuracy would easily allow for a mass reduction by a factor of 10^3. Other effects due to charge changes or dipole-dipole interactions should also allow a prefilter of such an efficiency. The charge separation employed in the prefilter has a rate of false positives which used by itself would be far too high for a fractional charge search, but by using it as a prefilter, it provides a multiplicative factor in the total material throughput of the system. It may, however, increase the fraction of false positives in the Millikan chamber. It will be necessary to weigh these factors against each other.

The droplets enter the Millikan chamber in well defined points, each marking the beginning of an individual track. The timing of the droplets is by necessity random because

only a very small fraction of the initially formed droplets will pass the prefilter stage of the droplet generator. The droplets are highly uniform in mass and vary only little in their initial charge. This uniformity makes the pattern recognition task manageable. It also allows for a strong suppression of background due the accidental introduction of other materials into the droplet stream.

5. Pattern Recognition

The optical system generates a raster image of the droplets in the Millikan chamber. For the design considered here, a droplet image covers approximately 20 raster points. This complicates pattern recognition on the one hand, because the position of the droplet must be deduced from its extended image. On the other hand, it greatly decreases the chance of two droplet images overlapping within the time of a measurement and therefore reduces the effort in the drop identification algorithm. It also may allow for a certain amount of subpixel resolution. Furthermore, the apparent droplet size and image intensity, which varies in a predetermined manner across the diameter of the droplet, provides another consistency check a droplet has to pass before its charge measurement is considered anomalous. At a frame rate of 180 Hz, a droplet moves by about its own diameter in a single frame update. By assumption the mean separation is about 10 diameters or 200 pixels. A more likely practical frame rate is around 20 to 30 Hz.

The pattern recognition task is best summarized as extracting from the time sequence of raster images the trajectory of the droplets whose charge is currently measured. From the trajectory of a droplet its mass and charge can then be determined. The raw image can be reduced to obtain the size, the brightness and the vertical position of the droplet. Size and brightness are expected to be constant within the accuracy of the device, they also have to be within the established margins for the average drop. If these parameters fall outside this regime or fluctuate, the droplet is considered anomalous and measurements are rejected. Otherwise we use the fall velocity to update the charge and mass estimate for the droplet.

For a single droplet in the field of view this task is quite simple. Applying a predictor corrector algorithm, we use the current position of the droplet to predict its position in the next frame. If the change in position exceeds a prespecified distance, and the droplet is not found at a predicted position within one or two more frames, the droplet is considered lost. The precise number of frames one is willing to wait will depend on the accuracy to which its parameters were already known and on the background noise which must be determined empirically.

After the actual droplet position has been determined it is used to update the current best estimate of charge and mass. We assume that both are known from the beginning with an experimental error which is described by an error ellipse in the (q, R) space. A single measurement will tighten this error ellipse in one specific direction. Once this error ellipse has shrunk to the point that a residual charge of $^1/_3\, e$ and $^2/_3\, e$ can be ruled out, the droplet can be abandoned. If the charge of the droplet comes out incompatible with prior measurements, a charge change is assumed. Previous data points are kept so that the trajectory can be recalculated under the assumption of a charge change. The largest

difficulty in developing this aspect of the algorithm is the proper identification of rare multiple charge changes within a few frames.

Track crossings in which droplet images overlap pose another problem to the pattern recognition algorithms. Again we rely on the predictor/corrector method. As two droplets approach each other, the predictor method is used to assure the identity of the two droplets. The prediction may attempt to include the dipole-dipole interaction which is, however, difficult to estimate because only the projection of the droplet distance into the plane of view is measured. If the two droplets stay close for more than a predetermined time or after separation follow trajectories which disagree with the predicted ones, the droplets are considered lost. Note, that partial occultation still allows the tracking of one of the two droplet edges which helps in preventing the loss of a droplet. The point at which a drop is considered lost depends on the precision to which its parameters are known. Hence a drop which has been measured many times may be tracked through a much longer encounter than could be done for a droplet whose measurements had just begun. The physical merger of two droplets is not considered likely. If it were to happen the resulting droplet could still be levitated but its fall velocity would have greatly increased.

Track crossings, particularly in the later stages are further complicated by the fact that not all droplets in the field of view are tracked. It is therefore necessary to define a local protected area around a tracked droplet which is considered its own "air space." If another droplet enters this space, its will also be tracked in order to prevent losing the first droplet in a close encounter. This protected area is larger for droplets which have undergone multiple measurements. In the case that normal measurements are suspended and a single drop is tracked exclusively, a large fraction of the available processing power is used in tracking potentially close encounters. It may even be possible to avoid such collisions by appropriately tuning the electric field.

The purpose of the global pattern recognition algorithm is to measure the charge on a large number of droplets simultaneously. Assuming that processing power for additional droplets is available, the global pattern recognition algorithm searches for currently untracked droplets near the start of all vertical tracks at the beginning of a cycle in which the electric field drives the droplet downward. Droplets which have velocities more than 10% different from the nominal standard are immediately discarded and if possible are replaced by others. These outliers may be handed over to a special subprocessor dealing with tracks likely to intersect many other tracks. The remaining drops are tracked to the end of the next upward drive. All drops whose charge measurement resulted within one standard deviation of an integer charge are discarded. The remaining ones are tracked through a second stage and possibly even more stages until their charge is considered to be integer. Charge changes are recorded and if $\Delta q/q$ is integer, the droplet is discarded. If a droplet is followed to the bottom of the field of view and still appears to have a fractional charge, the electric field is changed to levitate this drop back into the center of the apparatus.

Such a droplet may then be subjected to a number of further tests. First one finds out whether the response to an arbitrary electric field which also may have a horizontal component are consistent with the predictions from Stokes law and previous measurements. Secondly one could measure Brownian motion and test whether it is compatible with its expected value. Finally one checks that the measurements of all induced charge changes

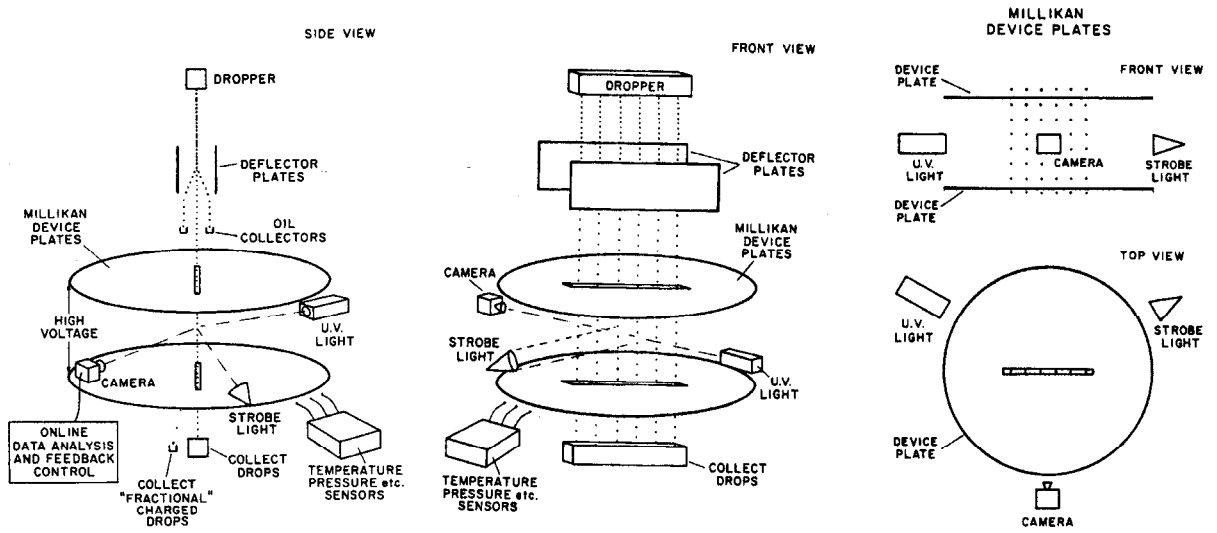

Figure 2: Sketch of the automated Millikan apparatus as seen from three different orientations.

are consistent with an integer charge and do not appear to vary with the charge on the droplet. If a droplet passes all these tests and possible additional ones that could be added to this list, it is considered a fractional charge and is maneuvered into a special holding tank. For this last step to be effective, one may have to prevent droplets form entering the Millikan chamber and let all other charges drop out of sight.

An important issue in the automatic processing is the self-calibration of the device. The nearly continuous set of measurements together with the constraint that charge distributions must peak at integer values provides a calibration which can be used to correct the measured charge. The correction may be a function of both position and time. This can be done by breaking the field of view into regions and in each region a calibration is determined from the data. If the corrections vary to rapidly in time or are larger than a predetermined limit, the system is taken off line.

To obtain a good estimate of the necessary processing power requires a simulation of the complete Millikan device which we are in the process of doing.

6. Discussion

We have outlined the design of an automated Millikan apparatus and discussed the issues surrounding its optimization. A sketch of our design is presented in Figure 2. The choice of droplet radius and charge and the rate of droplet flow represents a compromise between errors due to Brownian motion and dipole-dipole interactions. It is likely that for a specific implementation with its own particular constraints the optimization will vary somewhat from the choices given here.

To estimate the sensitivity of an automated Millikan apparatus we can combine the sensitivity of the different stages of the system. The first stage, which prepares uniform drops within a narrow charge change is relatively inefficient. Only a small number of

drops will be in the proper charge range. For a continuous charge distribution no more than 1 : 5 could fall into the allowed range of $20.2\,e$ to $20.8\,e$. This ratio is based on the thermodynamic limit, other effects may widen the charge distribution and therefore lower the ratio. To be specific we will assume that 1 : 20 may fall into the allowed range. However, since charge is quantized and the allowed range is less than one unit of charge, the effect on integer and fractional charges differs and varies with the position of the window. If random fluctuations in the drop deflection can be held to 0.5% of the total, fractionally charged droplets could be enriched in the sample by about a factor of better than 1000. Added to this is another component of a non-gaussian background stemming from in-flight charge changes. If one achieves an enrichment by a factor of 1000, the total rate of droplet production must exceed the throughput through the Millikan apparatus by a factor of 20000. Hence the droplet generation for a very large automated Millikan apparatus requires droplet generation at a rate of $4 \times 10^8\,\mathrm{sec}^{-1}$ or about 0.1g/s. This would be achievable by multiplexing about 400 of the current droplet generator designs [26]. Note, however, that we already assume a multiplexing by a factor of 1000 in order to produce the parallel streams entering the Millikan chamber.

Under these assumptions, of the total number of fractionally charged droplets approximately one in twenty would reach the Millikan chamber where its detection probability is high, its theoretical maximum for a fully occupied Millikan chamber being 50%. At this rate the effective mass probed becomes 2.4×10^{-3} g/sec or 1.5×10^{21} nucleons/sec. With a year of running time such a device could establish an upper limit on the order of one part in 5×10^{28} on the abundance of fractionally charged particles. In comparison to other methods of searching for fractionally charged particles the potential of this method stands out by more than 6 orders of magnitude. Even an initial experiment using a much smaller start-up version of the apparatus could reach a respectable material throughput and could also demonstrate the feasibility of testing unprocessed materials finely dispersed in the oil for fractional charges.

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