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A ROTOR ELECTROMETER FOR FRACTIONAL CHARGE SEARCHES*

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ABSTRACT

Work on a device for searching large samples of any composition for fractional charge is described. A resolution of 0.3 electron charges has been achieved for photo-induced charge changes.

MOTIVATION

"Are there objects with a charge other than an integral multiple of the electron charge?" is a fundamental physics question. The knowledge that such objects (quarks) very likely play a primary role in the interiors of elementary particles raises the question of whether they might exist in a free state. Many searches for fractional charge have been performed.[1,2] All existing direct searches use the motion of the test object due to an electric field to measure the charge. This limits the amount of material that can be searched since large samples result in small motions and large background forces. Furthermore most of these methods are very restricted in the composition of their samples. The apparatus described here does not have these fundamental limitations.

PRINCIPLE OF OPERATION

Imagine moving a sample rapidly back and forth between a grounded Faraday cup and one connected to the input of a high impedance amplifier. At the input of the amplifier an AC signal will appear which is proportional to the charge of the sample and inversely proportional to the total capacitance to ground at the amplifier input. Since the signal is synchronous with the sample movement, a lockin amplifier may be used to reduce the amplifier noise to arbitrarily low levels if one is arbitrarily patient.

In our electrometer the sample is stationary and suspended in a metal container on the end of a quartz glass fiber. The Faraday cups are approximated by copper pads plated on the periphery of a rotor. Every other pad is capacitively coupled to a high impedance amplifier, and the remaining pads are capacitively coupled to ground.

Any charge inside the metal sample holder will couple to the amplifier with a constant measurable efficiency. However charges on the suspension fibers will couple with an unknown and different efficiency. To determine the signal induced by the fibers and other background mechanisms the apparent charge of the empty sample holder is measured. The sample is then inserted and the charge remeasured. The fractional part of the difference is the desired quantity. This last step has not yet been done. Instead the response of the apparatus to photo-induced charge changes of a simple foil sample have been studied.

THE ROTOR ELECTROMETER

Figure 1 shows a cutaway view of the instrument. The rotor is a hollow polystyrene cylinder 18 cm long and 3 cm in diameter. A piece of annealed 4750 nickel iron is pressed into the top of the rotor and serves as part of a ferromagnetic bearing. The bearing is completed by a SmCo permanent magnet suspended in an oil bath and surrounded by a servo-coil. The bearing is passive horizontally and active vertically. The vertical position of the rotor is sensed by the LED and split photodiode and an appropriate current sent through the servo coil to maintain the rotor at the desired position.

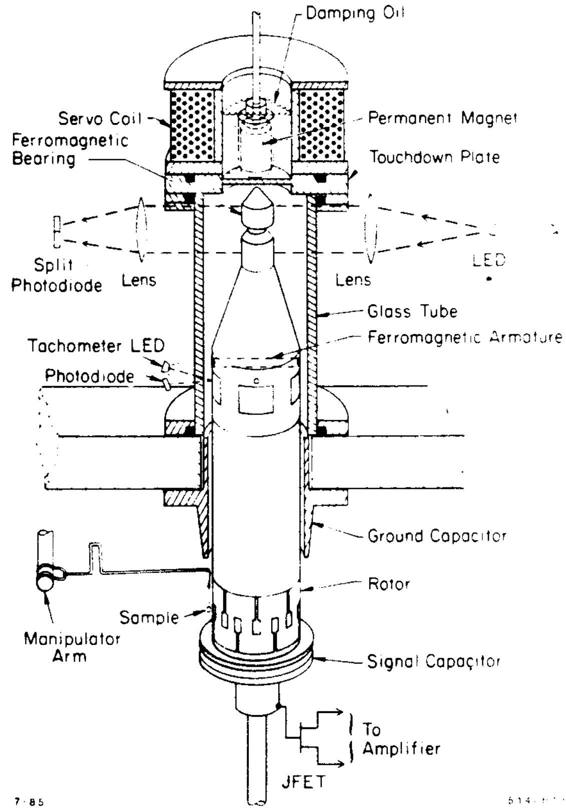

Figure 1. Cutaway view of the electrometer.

The rotor is spun by a simple reluctance motor consisting of the nickel iron armature in the rotor and a pair of drive coils. The drive coils are turned on and off synchronously with the rotor rotation at a 50% duty factor achieving an acceleration of 1 Hz/s. The tachometer LED and photodiode serve as a commutator for the motor during spin up and as a frequency reference during data acquisition. Once the operating speed of 900 Hz is reached the motor is turned off. The rotor slows less than .3 Hz per hour.

The pads, the coupling capacitors, and the tachometer reflectors are formed of copper plating. The ground coupling capacitor consists of the copper plated central portion of the rotor and a surrounding concentric cylinder of copper-plated

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aluminum which is fastened to the vacuum box. The signal coupling capacitor consists of the copper plated bottom surface of the rotor and a circular copper-plated aluminum disk which is supported by a quartz glass rod. The junction field effect transistor (JFET) which forms the first stage of the amplifier is connected to this disk by means of its gate lead.

The sample is hung by one or more quartz glass fibers on one side of the rotor. For the data presented here the sample was a square of indium ($\sim 1\,\mathrm{mm} \times .5\,\mathrm{mm} \times .2\,\mathrm{mm}$) pinched onto a $3\,\mu\mathrm{m}$ fiber. The fiber is attached to its support by a small strip of latex rubber which serves to damp sample motion. A smaller piece of indium is squeezed onto the fiber 4.3 mm above the sample. By adjusting the charges on the sample and this auxiliary piece, the sensitivity of the instrument to relative motion in the vertical and radial directions can be nulled.

The rotor, sample and coupling capacitors are contained within an aluminum box which serves as both vacuum vessel and electrostatic shield. The box is evacuated to a pressure less than 10^{-6} Torr by a diffusion pump and liquid nitrogen trap.

ELECTRONIC ANALYSIS

The rms signal at the amplifier input is $\epsilon q/(2\sqrt{2}C)$, where ϵ is the charge coupling efficiency (~ 0.3), q is the charge of the sample, and C is the sum of the capacitance of the ensemble of signal pads to ground (2.8 pF) and the input capacitance of the amplifier (1.5 pF). The amplifiers's noise spectral density referred to the its own input (S_n) is observed to be $(8.8\mathrm{nV})^2/\mathrm{Hz}$ at the signal frequency of 7200 Hz (8 pairs of pads times the rotation frequency). If we average the output of the lockin amplifier for a time T then the noise bandwidth is $1/2T$. The resolution in units of electron charge is

$$\sigma_e = \frac{2C}{\epsilon q_e}\sqrt{\frac{S_n}{T}} = 1.5 \times \sqrt{\frac{1\,\mathrm{sec}}{T}}$$

if the amplifier is the only noise source. For the difference of two measurements multiply this by $\sqrt{2}$.

PERFORMANCE

With the rotor spinning and no sample in the machine, no noise in excess of that due to the amplifier is seen. With a sample present the amplifier noise is dominant at frequencies above 3 mHz (from here on we refer to frequencies at the output of the lockin amplifier, i.e., to the difference between the frequency of interest and the signal frequency). Below this frequency there is an excess noise whose spectral density rises approximately as $1/f^2$. The source of this excess noise is not yet understood. Most of it is not due to either sample motion or spontaneous charge changes. The combination of this excess noise with the spectrally flat amplifier noise results in an optimum averaging time of 200 s. To calibrate the electrometer we flashed a light source on the sample every 200 s. The differences of the averages of adjacent 200 s periods are histogrammed in Fig. 2. Peaks corresponding to 0, 1, 2, and 3 electrons ejected from the sample are clearly seen. The peak separation is 4.7 nV, and the occupation of the peaks closely follows a Poisson distribution. To study the noise we acquired and processed data in an identical manner but did not actually flash the light. The result is shown in Fig. 3. The rms deviation of the peak is 1.5 nV. Thus the resolution of the instrument for a charge change is 0.32 e.

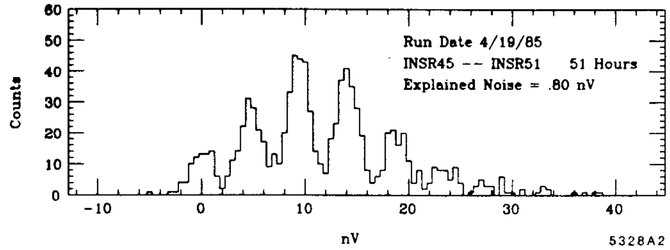

Figure 2. Charge differences—light flashing.

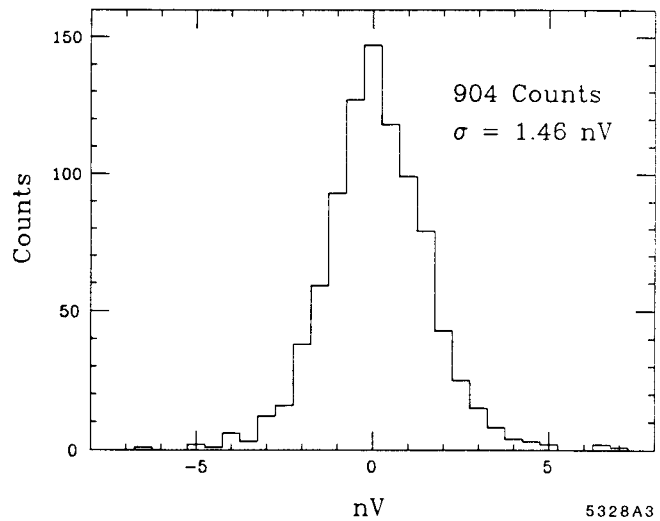

Figure 3. Charge differences—light off.

PROSPECTS

To look for quarks a resolution of less than 0.05 e is needed. Careful optimization of the design and cooling the input JFET to near $150K$ could reduce the amplifier noise as much as a factor of 2. This would serve mainly to reduce the averaging time unless the excess noise can be eliminated. Since this excess low frequency noise has not yet been studied carefully, it is not known if it is serious problem. In any case the error can be reduced by repeated measurements of the same sample.

The major remaining task is the design of a sample holder and sample changing mechanism which will change samples quickly and leave the background charge unchanged. This task becomes rapidly more difficult as the sample holder becomes larger. Nevertheless, we know of no reason why it cannot be done.

For a complete description of this work see John Price's thesis.[3] For a description of a similar device see Williams and Gillies.[4]

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