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A Fractional Charge Search*

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Abstract

A device to search for fractional charge in matter is described. The sample is coupled to a low-noise amplifier by a periodically varying capacitor and the resulting signal is synchronously detected. The varying capacitor is constructed as a rapidly spinning wheel. Samples of any material in volumes of up to 0.05 ml may be searched in less than an hour.

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Principle of Operation

We are building a machine with which we plan to search for fractional charge in large samples of material of arbitrary composition. The principle of operation of the device is illustrated in figure 1. The sample is rapidly moved back and forth between two Faraday cages. One cage is connected to a high impedance amplifier and the other is grounded thus serving as a shield. The charge of the sample (Q) moving in and out of the first cage produces an rms signal voltage $V = Q/(2\sqrt{2}C)$, where C is the total capacitance of the cage and amplifier input to ground. Using synchronous technique , i.e. a "lock-in" amplifier, this signal can be measured to an accuracy limited only by the time over which the sample charge can be kept constant.

Apparatus

In practice the sample cannot be moved without changing its charge. In our apparatus the sample is placed in a holding device which is suspended by a quartz glass fiber. Three sided Faraday cups mounted on the periphery of a rotating wheel move past the sample. Every other cup is connected to the amplifier and the remainder are grounded. Some of the charge on the glass fiber will be seen by the Faraday cups and can appear to have a fractional part. To overcome this problem runs are made with no sample, and the fractional part of the apparent charge of the sample holder is measured. The sample is then put into the holder, and the fractional part of the charge of the combination is measured. The difference between the two measurements is the fractional part of the charge of the sample. The difficult aspect of the procedure is clear:

the apparent charge of the sample holder must remain unchanged during the measurement cycle.

Figure 2 is a drawing of the first version of the machine. The outer box is both a vacuum and an electrostatic enclosure. The 1.5 cm diameter steel shaft is surrounded by a plastic insulator. Around the insulator are two identical aluminum rings into which the Faraday cups have been machined. The ring nearest to the left edge of the figure (the shield rotor) is electrically connected to the shaft which in turn is grounded. The other ring (the signal rotor) is surrounded by a concentric nonrotating aluminum cylinder which serves to capacitively couple the signal to the amplifier. The diameter of the rotors is 10 cm. The vacuum enclosure is completed by another box, approximately the same size as the one shown, which contains the sample support and manipulation equipment. The sample holder hangs so that it nests inside the Faraday cups as they pass underneath it. Table I gives the parameters of this device as well as those of a second, upgraded device we are currently building.

Noise

Since the impedance of the signal source is an almost pure capacitance, the main source of noise is the amplifier. Figure 3 shows the equivalent noise circuit of the device connected to an amplifier which has a junction field effect transistor (JFET) input stage. V_n is the JFET input noise voltage in $V/\sqrt{Hz}$ and I_n is the input noise current in $A/\sqrt{Hz}$. At the relevant frequencies (2 to 10 kHz) V_n and I_n are approximately independent of frequency for a good JFET. Typical values are 3 nV/$\sqrt{\text{Hz}}$ and 1 fA/$\sqrt{\text{Hz}}$. The signal is:

$$V_s = Q/(2\sqrt{2}C)$$

where C is the total input capacitance. The total equivalent input noise is given by:

$$V_{nt} = (V_n \langle+\rangle I_n/(\omega C))\sqrt{B}$$

where ω is radial frequency of the signal, B is the equivalent noise bandwidth of the detection scheme in Hz, and <+> indicates quadrature addition. From these formulae we deduce the rms charge measurement error:

$$Q_{en} = 2\sqrt{2}(V_nC \langle+\rangle I_n/\omega)\sqrt{B} \quad .$$

Using "lock-in" detection and averaging the output of the "lock-in" amplifier for a period T gives B=1/(2T) and thus

$$Q_{en} = 2(V_nC \langle+\rangle I_n/\omega)/\sqrt{T}$$

where T is in seconds. To reduce Q_{en} one reduces the bandwidth B, i.e., one averages longer. For the machine we are currently building (version 2 with C_{device} = 15 pf and f = $\omega/(2\pi)$ = 8 kHz) coupled to an amplifier[1] whose input JFET is cooled to 150 K, Q_{en} will be less than 1 e/$\sqrt{T}$. This means reliably determining the integer part of the charge (99% C.L.) will take less than 25 seconds, and determining the fractional charge to 0.03 e will take less than 17 minutes.

Performance Requirements

The first requirement is that the integer part of the charge be determined in a time short compared to the mean time between integer charge changes so that these changes can be isolated. This allows the fractional part to be averaged over long periods and prevents false fractional values due to including different integer values in the average. The primary mechanism for integer charge changes is expected to be cosmic rays passing through the sample. Charge changes due to this source should occur less than once every 20 minutes.

The second requirement is that the sample holder charge not change more than 0.03 e during a cycle (sample out, sample in, sample out). Such a cycle might consist of 2 minutes in each mode plus sample manipulating time, say 8 minutes altogether. A complete measurement would consist of 8 such cycles. The sample holder charge drift would then have to be less than 10^{-4} electrons per second.

Status (June 1982)

We have been working with the version 1 device for a year. With a room temperature amplifier, the lowest Q_{en} that has been achieved is $2.5\ e/\sqrt{T}$. This will be lower in version 2 because C_{device} will be half as large. Use of a low temperature amplifier will further reduce Q_{en}.

We have consistently achieved signal drifts less than 0.1 e/s. This drift appears to be associated with heating due to the rotating shaft vacuum seals. Version 2 uses a magnetic drive to avoid this heat source. In addition, the version 1 Faraday cup structure "sees" nearby nonrotating, noncylindrical surfaces. The version 2 cup structure will be shielded from nonrotating surfaces.

Conclusion

A factor of 10^3 reduction in signal drift is necessary before fractional charge can be measured. Improvements embodied in the second version of the apparatus are expected to take us a long way toward this goal.

Acknowledgment

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REFERENCES

1. F. Bordoni et al., Rev. Sci. Instrum. 52, 1079 (1981).

Table I

Apparatus Parameters

	version 1	version 2	
rotor diameter	10	5	cm
sample size	0.15	0.05	ml
rotation speed	8 000	30 000	rpm
#cells	16	16	
signal frequency	2.1	8.0	kHz
motor	electric	air turbine	
drive	belt	magnetic	
vacuum	$< 5\times10^{-5}$	10^{-6}	torr
capacitance	30	15	pf

FIGURE CAPTIONS

1. Principle of operation of fractional charge search device.
2. View from above of the machine (version 1) with the sample handling box removed. Parts indicated are: A insulator; B shield rotor; C signal rotor; D coupling capacitor.
3. Noise equivalent circuit of the machine connected to a JFET input amplifier.

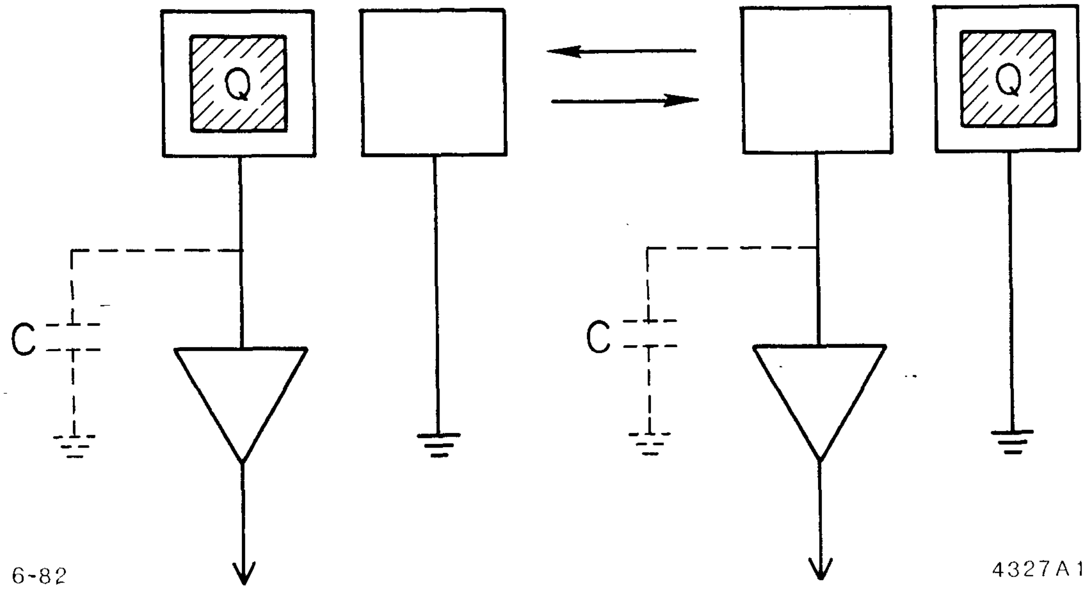

Fig. 1

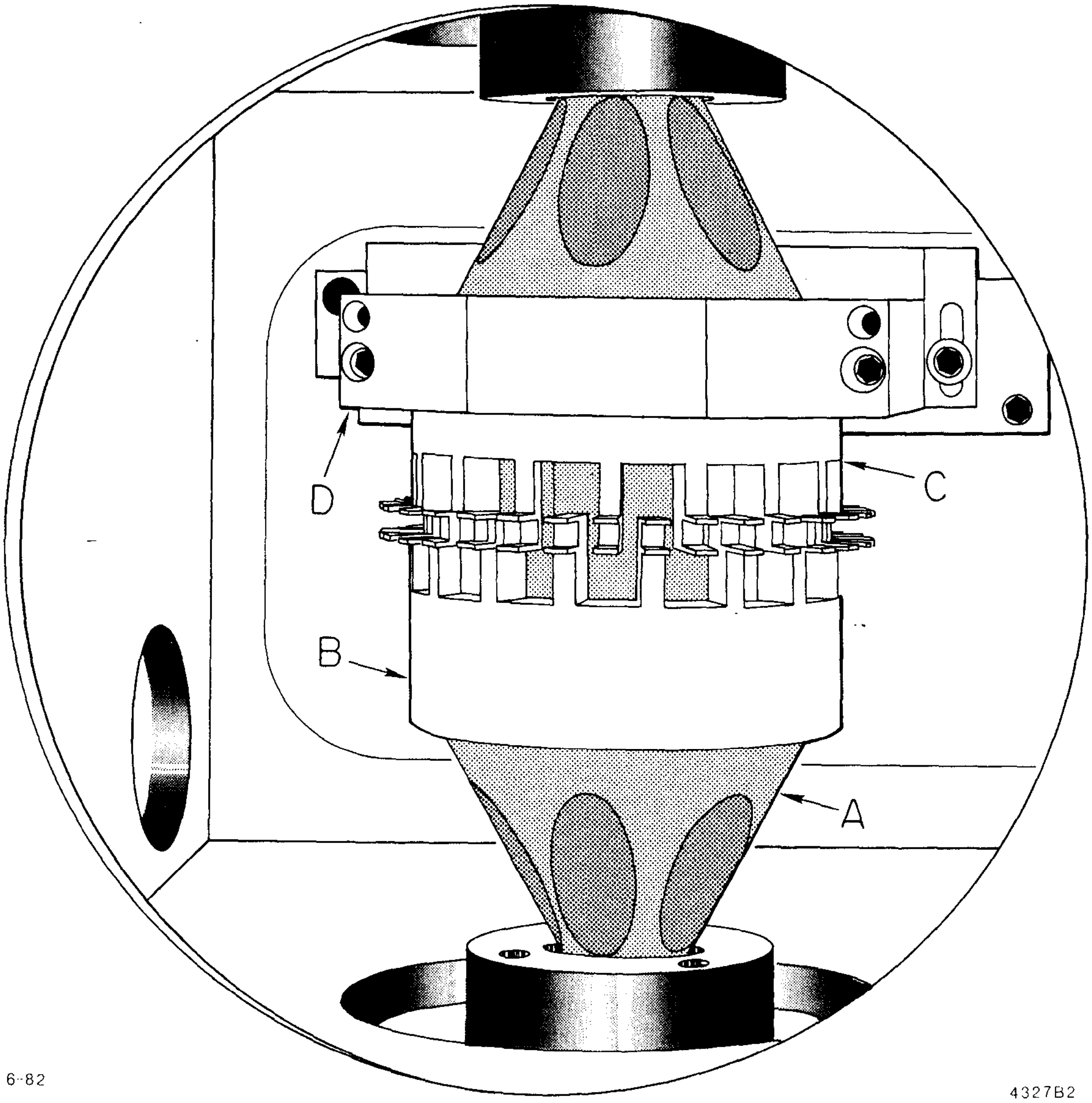

Fig. 2

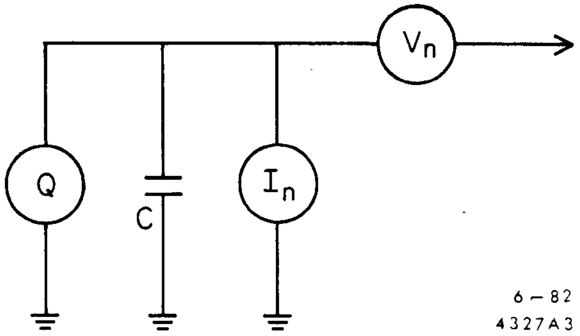

Fig. 3