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THE ELECTRONIC CONTROLS USED IN A SEARCH FOR FRACTIONAL CHARGES IN MERCURY DROPS *

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ABSTRACT

At San Francisco State University, we have developed an Automatic Millikan Device (AMD) for measuring the charge on small drops of Mercury. The device uses a standard atomic physics laboratory Millikan chamber, a piezoelectric driven ink-jet glass dropper, and a laser-photomultiplier system for tracking the motion of the drop. This paper describes the electronic control and error detection system used with the AMD. Signals from this system are sent to a microprocessor which controls the experiment. To this date (Dec 7, 1981), we have measured 175 micrograms of Hg and found no fractional charges in 1.05 x 10^{20} nucleons.

INTRODUCTION

Zweig and Gell-Mann (1) postulated in 1964 the existence of fractionally charged Quarks as the primary constituents of hardons. Since that time, there have been many searchs for free fractional charges. (2) To date, the various searches have produced either negative or at best, dubious results, with one exception: the Stanford experiments of Phillips, LaRue, Fairbank, and Hebard. (3) In the Stanford experiment, a superconducting Niobium sphere is levitated in a magneic field, and the charge is measured by varying the electric field and observing the motion of the sphere with a Squid (a sensitive magnetic field detector). Roughly one-third of the 90 microgram spheres measured showed fractional charges. Morpurgo and Marinelli (4) used a "Magnetic Levitaton Electrometer" to levitate steel spheres and found no fractional charge in the samples they measured. None of the studies to date have proven conclusively the existence or non-existence of free fractional charges. In 1978, our group decided to build an Automated Millikan Device (AMD) to measure the charges on drops of fluids injected into a Millikan device (6).

GENERAL OVERVIEW OF THE EXPERIMENT

The AMD (see Figure 1), in operation for over a year and a half, can measure the charge on up to 45 micrograms of Mercury per day. The light from the Argon laser illuminates drops of Mercury which are ejected from a glass dropper (7) into the region between two parallel capacitor plates spaced about 0.5 cm. apart. The drops are injected between the plates at a rate of close to 0.7 Hz. The laser light, scattered by the falling drops, passes through a side window and is focussed onto a series of 92 slits by a telescope. The light passing through the slits is monitored by three photomultiplier tubes. The signals from the tubes are used to check for error conditions and to determine the velocity at which the drop is falling. As the small sphere of Mercury drops, the voltage on the plates is changed three times in order to determine the charge on the drop.

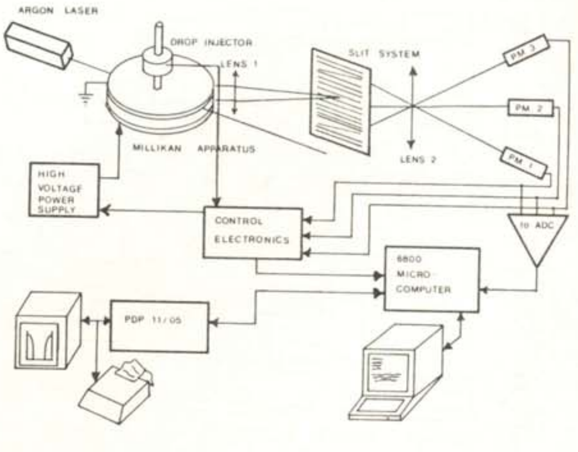

Figure 1
A general overview of the Automated Millikan Device.

The slit system is a glass photographic mask with ninety-two 100 μm wide slits which was made by an integrated circuit photoetching process at Stanford University (8). Phototubes one and three (PM 1 and PM 3) see the first set of two slits and the last set of two slits. These slits are guards for error conditions such as multiple drops in the region between the plates. The remaining central 88 slits are seen by phototube two (PM 2). The first and last of these slits are slightly diagonal and can be used with timing measurements to check for horizontal motions of the drop. The remaining center-most 86 slits are horizontal and parallel to each other. They are used to measure the velocity of the drop.

The signals from the photomultipliers go to an electronic control system which determines the switching time for the high voltage on the bottom plate of the AMD, checks for error conditions, and combines the three signals for analog-to-digital conversion and analysis by the microcomputer. The computer then calculates the drop's velocity in the three regions of different voltage. From this information, the drop's radius, mass, and charge (as well as change in charge) are determined.(6) A hardware error condition or an error discovered in analysis will cause the rejection of the event. If there are no error conditions, the computer stores the values of charge, radius, and the change in charge in its memory. After a run of up to four-thousand good events has occured, the data stored in the microcomputer is transferred to the PDP 11/05 for final analysis of the run.

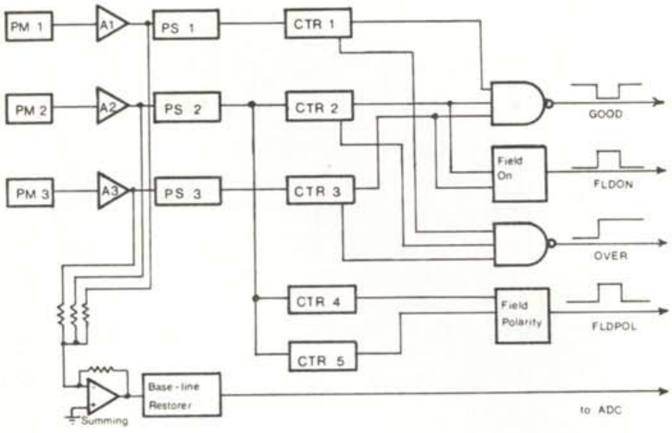

Figure 2
The control electronics. The block diagram includes the photomultiplier tubes (PM), their amplifiers (A), counters (CTR), and the peak-squarers (PS)

CONTROL ELECTRONICS AND SUMMING CIRCUIT

The control electronics (Figure 2) generate various output signals that are sent to the microcomputer and are used to determine if an event is good or bad. As the image of the drop moves across the slit system, the phototubes send an output pulse whenever the scattered laser light falls on the transparent part of the slit. The signals from the photomultipliers are inverted, amplified, and conditioned in a series of peak-squarers. The three counters (CTR 1, CTR 2, CTR 3) count the pulses from their corresponding photomultiplier tube. Logic circuits are used to determine if the correct number of signals were sent by each phototube: two from the first, 88 from the central tube, and 2 more from the last tube. If each of the counters indicate the correct number of pulses, a $\overline{\text{GOOD}}$ (the level rests high and when the condition is met, it drops to low) is sent to the computer. The signal from PM 2 (which monitors the middle 88 slits) controls when and what polarity high voltage is placed on the bottom plate

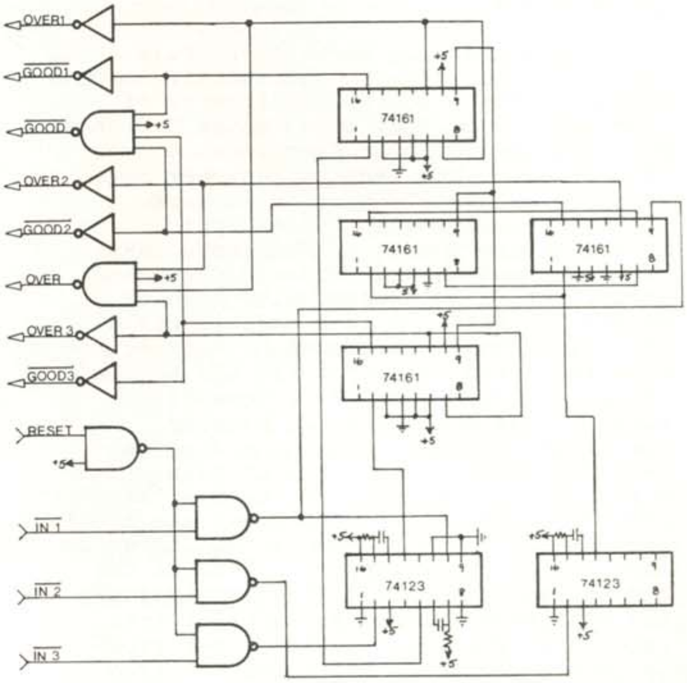

Figure 3
The error detection circuit consists of two 4-bit counters (CTR 1 and CTR 3) and an 8-bit counter (CTR 2). The 74123's are monostable multivibrators used to condition the signals as the come into they counter circuit.

of the AMD. A correct count in CTR 4 sets a flip-flop (FLDPOL) that controls the field polarity between the plates. A correct count in CTR 5 clears FLDPOL. If any of the counters over-count, an OVER signal is sent to the front panel for display purposes and to the field-on (FLDON) circuit to cut off the voltage on the bottom plate.

While the counters in the control electronics are checking for errors in the number of peaks detected, a summing circuit combines the signals from the three photomultiplier tubes. This signal goes through a base-line restorer which maintains the output base line at ground. This signal is then sent to an analog-to-digital converter in the microprocessor. The digitized signal from the photomultiplier tubes is used to caluclate the speed at which the drops are traveling. This information, coupled with the size of the electric field, allows the computer to calculate the charge on the drop.

Signal conditioning circuits

The signal from each of the photomultiplier tubes is sent to a peak-squarer (Figure 3) to be converted into a square pulse for counting. The first op-amp acts as an AC-coupled buffer amplifier which couples the signal to a false ground of 2.5 volts. The second op-amp is used as Schmitt trigger with a variable threshold. After the peak-squarers, the signals are further conditioned by a 74123 monostable multivibrator. This sets the proper length to the digital signal needed for input into the counters.

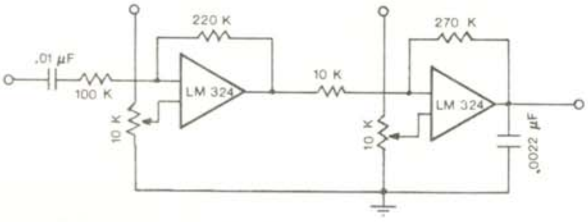

Figure 4
The peak-squarer circuit contains 2 op-amps. The first is used as a buffered input and the other as a Schmitt trigger. Both op-amps have a small gain to condition the signal for input to the counters.

Error detection circuit

CTR 1, CTR 2, and CTR 3 in the error detection circuit (Figure 3) are used to search for error conditions that can arise from a number of sources. CTR 1 and CTR 3 are 4-bit binary counters (74161 chips) and CTR 2 is an 8-bit binary counter (two 74161 chips in series). The counters are initialized by a reset pulse generated when the dropper is pulsed to inject a drop in the chamber. This reset pulse loads a predetermined number into the counters: 13 for CTR 1 and CTR 3, and 167 for CTR 2. When two pulses are counted by CTR 1 or CTR 3, or 88 pulses by CTR 2, the overflow pin in the counter will go high and the most significant bit of the counters will go low. This is the signal that the counter received the correct number of counts. The $\overline{\text{GOOD}}$ signal is generated by putting the three overflow signals through a 3 input NAND gate. The signal that indicates that the counter had over-counted is generated by examining the overflow pin the the most signifcant bit. If both go low, the OVER goes high and $\overline{\text{GOOD}}$ remains high. If any counter under-counts, the overflow pin remains low ($\overline{\text{GOOD}}$ is high) and the most significant bit remains high (OVER is low). There is a $\overline{\text{GOOD}}$ and OVER for each counter.

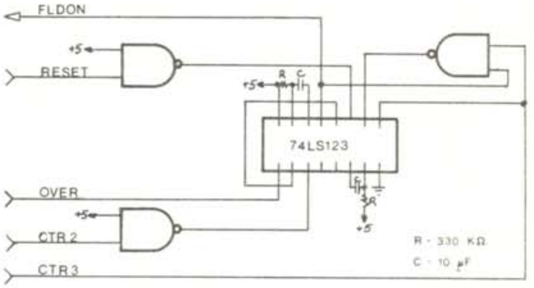

Figure 5
The FLDON circuit shown above is cleared by a reset pulse which is generated at the beginning of each event. The FLDON signal goes high when a pulse from PM 2 is received through IN 2. The electric field remains on until either the signal from PM 2 stops coming in, or the signal from PM 3 is received.

High voltage control circuits

The FLDON and FLDPOL circuits for the high voltage are controlled by the signal from PM 2. When the image of the drop reaches the third slit, the voltage on the bottom plate is set to +10,000 V. The drop then falls past 39 horizontal slits, and when the drop reaches the 40th slit, the field polarity is reversed to -10,000 V. After passing 34 more slits, the field polarity is again changed to +10,000 V for the final 14 slits. The electric field takes a few milliseconds to stabilize during each switch. The micropocessor can check for changes in the charge of the drop, since the drop velocity must be the same in the same electric field.

The FLDON (Figure 5) signal to the high voltage supply is controlled by a TTL 74123 chip. As long as the signal from PM 2 is coming in, and the OVER pulse is not received, FLDON remains high. When the signal from PM 2 is no longer received, FLDON goes low after 1/2 second. When the signal from PM 3 starts to come in, flip-flop B goes low, clearing flip-flop A and FLDON goes low, turning off the high voltage on the bottom plate of the AMD.

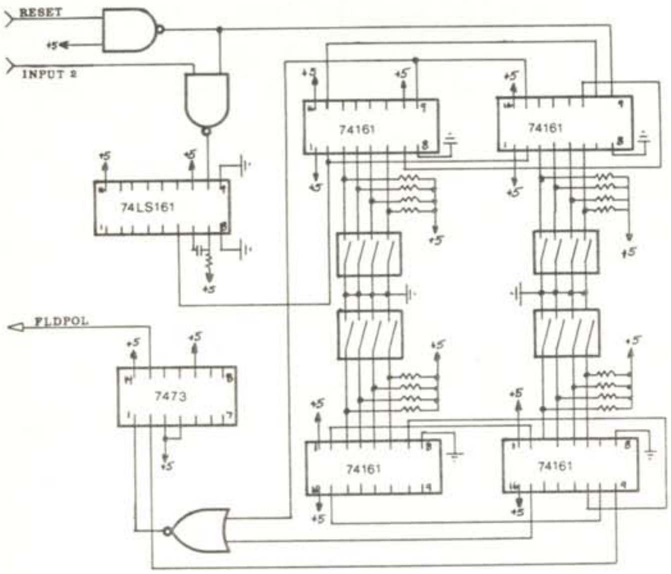

Figure 6
The FLDPOL counters (CTR 4 and CTR 5) generate the signals that control the reversal of the electric field. CTR 4 controls the first reversal, and CTR 5 controls the second one.

The FLDPOL circuit (Figure 6) is controlled by CTR 4 and CTR 5 which count the pulses from PM 2. The number of pulses between each reversal of the field is controlled by two sets of eight DIP switches, set to 215 and 180 respectively. The FLDPOL flip-flop (a 7473 chip) is set by the overflow pulse from CTR 4 for the first reversal and cleared by the overflow pulse from CRT 5 for the second reversal.

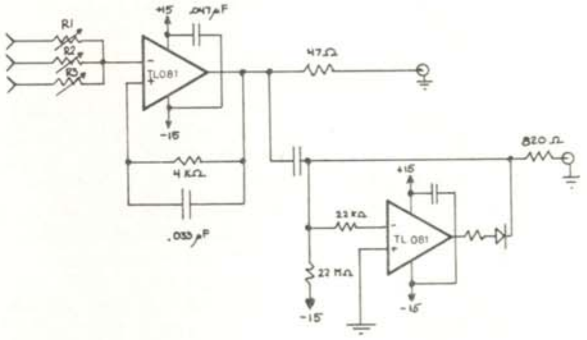

Figure 7
The summing circuit and base line restorer. This signal is sent to the ADC in the microprocessor to determine the speed of the falling drop.

The three signals from the photomultiplier tubes are added together using a TL081 op-amp (Figure 7). The amplitudes of the input signals from the tubes are individually controlled by varying the resistors R1, R2, and R3. The output from ths summing circuit goes to a Tektronix 2600 plug-in module and to the base-line restorer. This pulse is then sent to the microprocessor to calcuate the velocity and hence the charge on the drop.

RESULTS

We have measured (as of December 7, 1981) a total of 175 micrograms of Mercury. 60 micrograms were triply distilled lab Mercury and 115 micrograms were native Mercury (unpurified) from the Socrates Mine in Northern California. Figures 8 and 9 show data from different evolutionary states of the experiment. These histograms show the residual charge, the charge remaining after the integer part is subtracted, vs the number of drops of Mercury detected. Figure 8 shows data from earlier runs, where charge changes were rejected only if the change in charge on the drop was in the range between 0.25 and 0.75 electron charges. The statistical tails on the integral-charge peaks probably are due to charge changes. Figure 9 shows runs where all charge changes were rejected as bad events.

Our experiment has measured the largest sample of Mercury (175 micrograms) and of any element heavier than Niobium on the periodic table. We follow the Morpurgo et. al. experiment which examined 3.4 milligrams, and the Fairbank et. al. experiment which used 1.2 milligrams. We found no fractional charges in the 175 micrograms of Mercury measured to date. This sets an upper limit on the concentration of fractionally charges at 1 in 1.05×10^{20} nucleons.

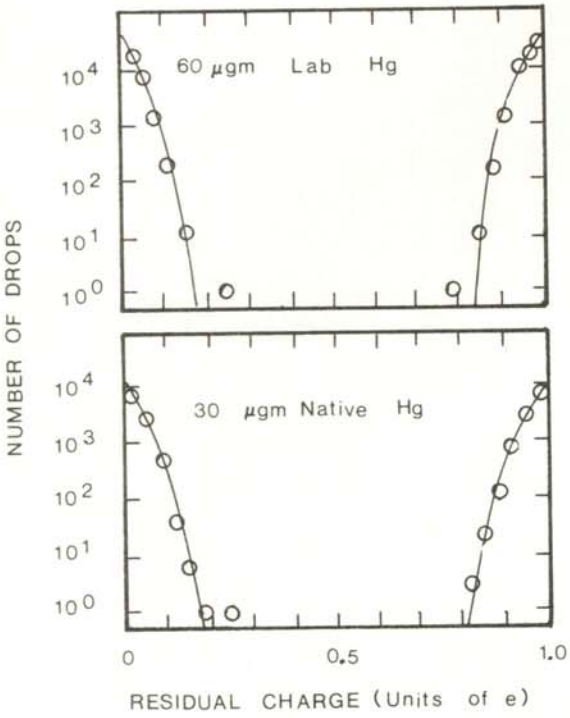

Figure 8
The first results of the search. These data include events where the charge changed on the drop.

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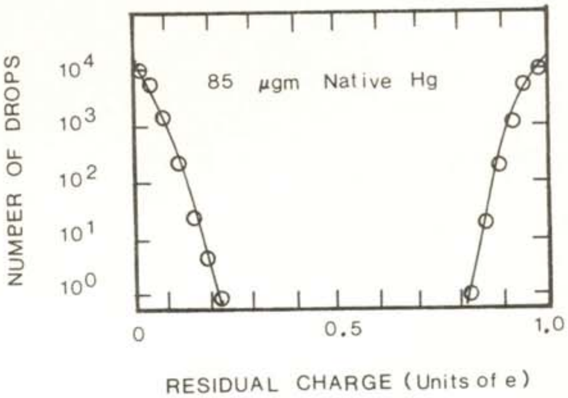

Figure 9
The latest results (as of Dec 7, 1981). In this sample of native Mercury, we detected no fractionally charged drops. In these events, we rejected any runs where the charge on the drop changed.

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