PROPOSED MEASUREMENT OF THE FINE STRUCTURE CONSTANT USING A COULOMB-BLOCKADE CHARGE PUMP*

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Abstract

We propose a new experiment to measure the fine structure constant α. The experiment uses an electron pump to transfer a countable number of electrons onto a cryogenic capacitor. Given a definite number of electrons on this capacitor, we can obtain a value for α by measuring the voltage in terms of the Josephson effect and the capacitance in terms of the calculable capacitor.

Introduction

With the advent of devices made from ultra-small tunnel junctions [1], it is now possible to measure charge by counting electrons. The turnstile and pump devices [2,3], which allow the passage of a single electron with each oscillation of a gate bias, have already demonstrated that electrons can be counted with an experimental uncertainty of about 0.1%, and highly accurate counting is thought to be possible. We describe here the effort at NIST to use such devices for measuring the fine structure constant in a fundamentally new way. Theoretical calculations and recent experimental results make us optimistic that an experiment with metrological accuracy can be achieved.

In response to a gate bias of frequency f_g, typically a few MHz, the turnstile and pump produce an accurate current $I = ef_g$ on the order of 1 pA. Because this current is so small, we believe the best strategy for initial metrological applications is to use these devices to count electrons rather than to create a current standard. In particular, electron counting could be used in combination with the ac Josephson effect to calibrate a capacitor. When combined with an independent calibration based on the calculable capacitor, this procedure yields a new approach to measuring the fine structure constant.

Figure 1 shows a schematic diagram of the electron counting experiment. Here, a charge pump constructed with ultra-small tunnel junctions is used to pump a known charge $q = ne$ onto a cryogenic capacitor C. The voltage across the pump is measured with an infinite-input-impedance voltmeter (electrometer), while a voltage source V defines the potential across the series combination of the capacitor and the pump. A feedback loop (not shown) controls the voltage source to maintain the pump voltage as sensed by the electrometer at the optimum value for error-free electron counting. After counting is complete, this feedback circuit can be used to set the pump voltage to zero. If V is then measured by the ac Josephson relationship through $V = mfh/2e$, the capacitance can be calculated as $C = 2(n/mf)/(h/e^2)$.

Fortunately, a cryogenic capacitor of about 1 pF, which can be compared directly with a capacitance defined by the calculable capacitor, is nearly ideal for the counting experiment. If the charge pump is operated at 10 MHz, for example, the cryogenic capacitor would charge to 10 V in about 6 s.

In the following, we discuss our progress in designing and testing the charge pump and the electrometer, two key components of the proposed experiment.

The Charge Pump

Figure 2 shows the design of a charge pump based on a series array of five ultra-small tunnel junctions. The operating principle is an extension of that for the three-junction pump [3], with five junctions used to reduce errors from cotunneling [4]. Figure 2 also shows the voltage waveforms that must be applied to the gate capacitors to cause an electron to tunnel sequentially through all five of the junctions.

Calculations have been made to understand the dominant error processes in the pump device [5]. We have extended these calculations to create a computer program that can calculate the average pump current to about 1 part in 10^{12}. The accuracy of this program was confirmed by developing approximate analytic formulas which predict the error rate in certain limiting cases. Figure 3 shows the computed deviation from the nominal current $I = ef_g$ for a charge pump with parameters that we believe are experimentally attainable. An error rate of less than 1 part in 10^9 is found over a voltage range of about 80 μV at a gate frequency of 20 MHz. These results show that metrological accuracy should be achievable with charge pump devices.

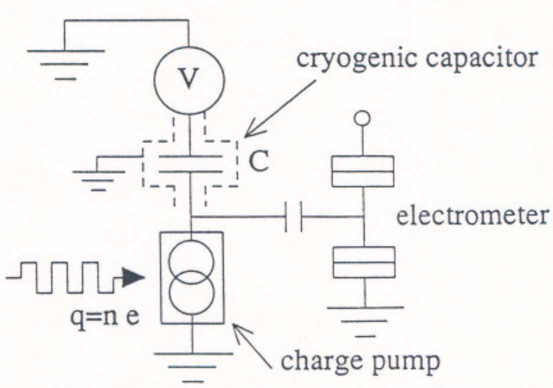

Figure 1. Circuit used to measure the cryogenic capacitor C. The charge pump puts a charge $q = ne$ onto this capacitor. The electrometer measures the voltage at the pump and controls the voltage source V.

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The Coulomb-Blockade Electrometer

Although the charge pump is the crucial device that enables this new metrological standard, the development of an electrometer to measure the pump voltage is also important for the success of the experiment. The Coulomb-blockade electrometer [1] is well suited to this task because it is highly sensitive and because its input impedance is capacitive and roughly matches the output capacitance of the pump. The required sensitivity can be estimated by considering the case in which the cryogenic capacitor is charged to 10 V and a measurement accuracy of 0.1 ppm is sought. In this case, the electrometer noise referred to the input must be less than about 1 μV in a measurement time of a few seconds.

We have performed experiments to understand the noise performance of the electrometer at the low frequencies (0.1 to 1 Hz) that are applicable to this experiment. Figure 4 shows the frequency dependence of the measured noise of the electrometer referred to an equivalent charge noise at the gate. We believe the measured noise is not intrinsic to the electrometer circuit but arises from thermally activated motion of charges between pinning sites in the electrometer dielectric. Its magnitude is about 4×10^{-3} e/$\sqrt{\text{Hz}}$ at 1 Hz.

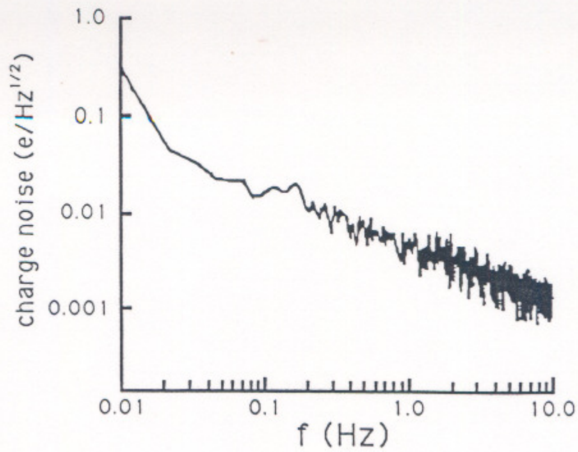


Figure 4. Measured charge noise versus frequency for a Coulomb-blockade electrometer with junction capacitances of 0.085 fF and gate capacitance of 0.014 fF.

The electrometer to be used in the electron counting experiment would require a gate capacitance larger than what we have initially fabricated. For a value of 1 fF, the experimentally measured charge noise translates into a voltage sensitivity of about 0.6 μV/$\sqrt{\text{Hz}}$ at 1 Hz. Thus, the Coulomb-blockade electrometer meets the requirements of the electron counting experiment.

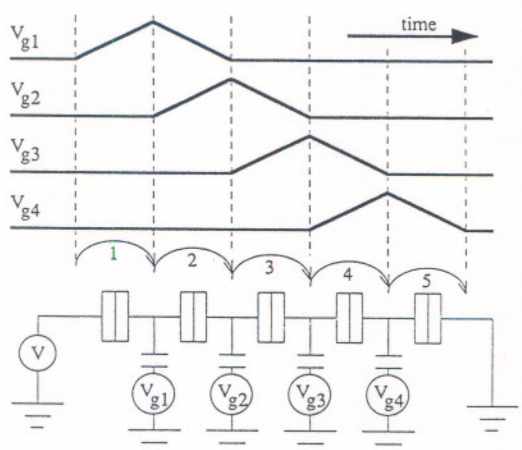
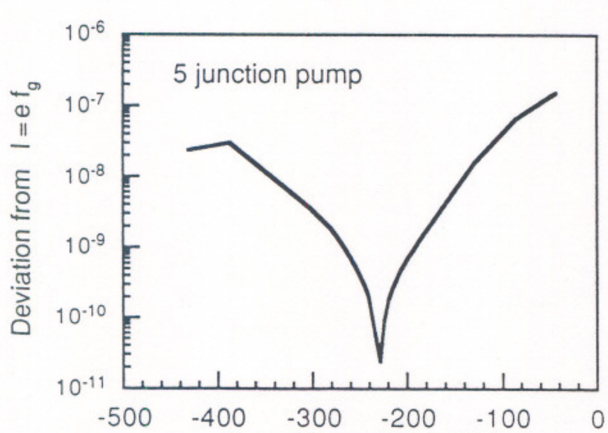


Figure 2. Schematic representation of the charge pump based on five ultra-small tunnel junctions represented by boxes. A sequence of voltage pulses V_{g1}, V_{g2}, V_{g3}, and V_{g4} causes an electron to tunnel across the junctions sequentially in time.

Conclusions

We believe that the charge pump will allow a new, highly accurate measurement of the fine structure constant. Two crucial elements of the experiment, the charge pump and the Coulomb-blockade electrometer, are presently thought to have sufficient performance to make the experiment possible. Computer simulations of the charge pump show that the error rate is in principle small enough to enable measurements with metrological accuracy.



pump with parameters that are experimentally attainable. The junction capacitances and resistances are 0.186 fF and 500 kΩ. The temperature and gate frequency are 50 mK and 20 MHz.

References

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