Do Electrons in a Metal Have the Same Charge as Free Electrons in Vacuum?

- Neil Zimmerman, NIST Gaithersburg, MD, USA

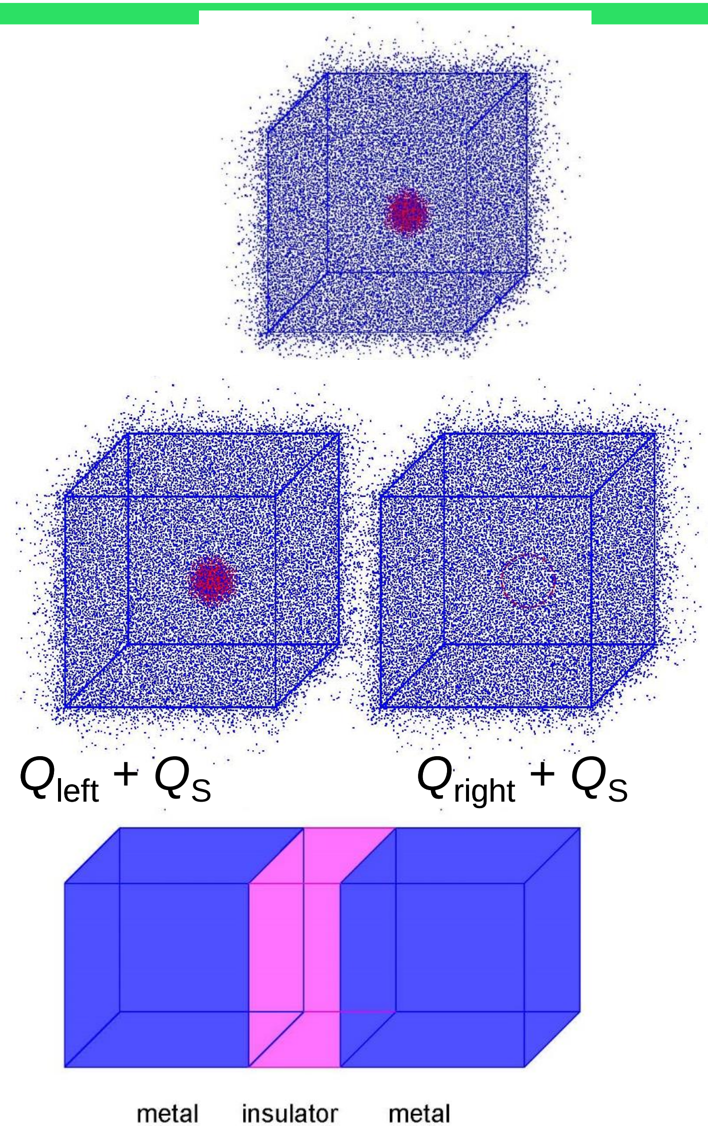
“I’d rather uncover less than cover more”

- Please ask questions

How can we measure (or even define) Q_S?

single "droplet" – can't
isolate single charge

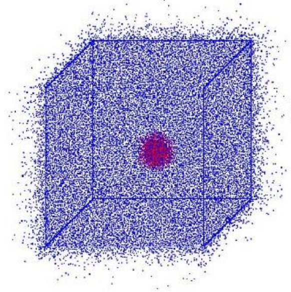
SET tunnel junction – can
define Q_S by motion



Theme of Experiment: What is Q_S?

[Do Electrons in a Metal Have the Same Charge as Free Electrons in Vacuum?]

piece of metal

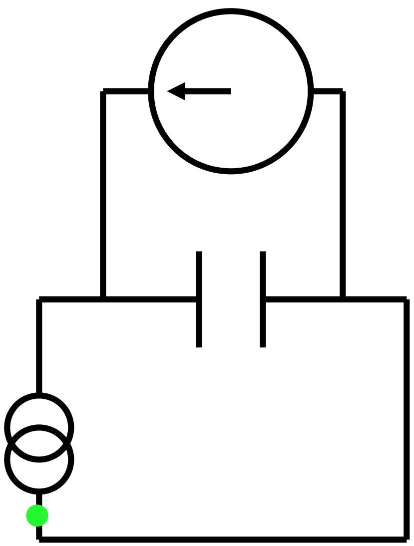


blue: piece of metal

red: “single” electron???

Q_S = 0.99 *e*, 1.00 *e*, 1.01 *e*?

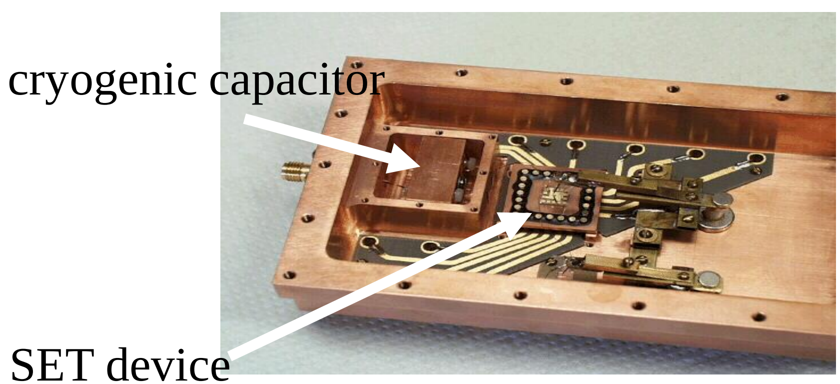
V = 0 V



0.99 *e*

- Define: Q_S = value of charge quantum
- ECCS: electron-counting capacitance standard

$$Q = CV = NQ_S$$



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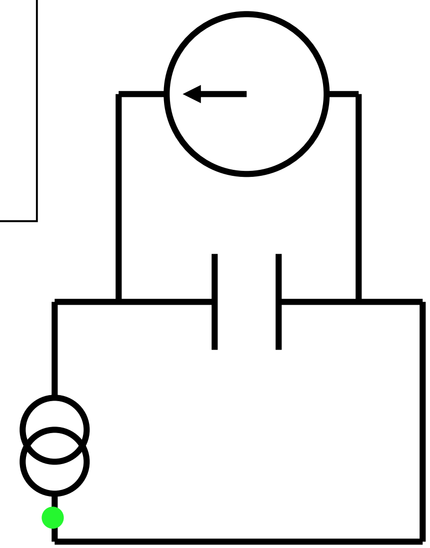


1.01 *e*

Outline

- Theme: pump charge quanta onto capacitor
- Introduction:
  - Why do we care if $Q_S = e$?
    - the SI system of units
  - SET devices – can move discrete charges
  - Can $Q_S \neq e$?
- Description of Experiment
  - Uncertainty Analysis
  - Result: $Q_S = e$?
- Future:
  - consistency check for Q_S – easier, better precision
  - Theory of Q_S.

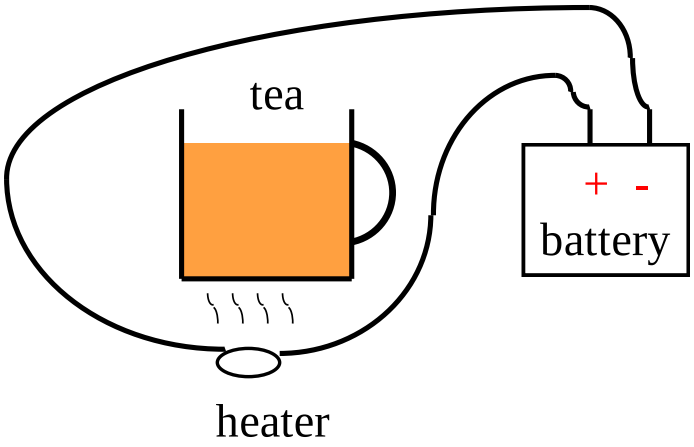
Why does NIST pay us to ask if $Q_S = e$?

- NIST (used to be the Bureau of Standards), the National Institute of Standards and Technology, is part of a worldwide effort to continually improve accuracy and reliability of standards
- We believe every electron has the same charge as every other electron (and always will), so that *e* is a fundamental constant. If we could base an electrical standard on *e*, it would be cool.
- That leads us to a discussion of the SI …

Some Questions About the SI

- Have you ever heard of the SI?
- Can you name some of the base units?
- What is the definition of the kilogram?
  - Why don't metrologists like this definition?
- What is the definition of the Ampere, volt, … ?
  - How is your voltmeter actually calibrated?
  - Why are metrologists uncomfortable about this situation?
- Can you suggest some changes to this situation?
  - The big "redefinition" …

Basic Idea of the SI System for Electrical Units



- We want our tea to be at the correct temperature for drinking!
- What does this mean for electrical standards and units?
  - It means that power or energy derived from thermal (heating the tea) and electrical (battery) standards must be **consistent**.
- In particular, the unit of power is W (the "Watt"):
  - Mechanical: 1 W = 1kg m^2/s^3.
  - Electrical: 1 W = 1 V^2/Ω.
- We want to calibrate V, Ω to enforce this consistency.

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The Definition of the kg – “Le Gran K”

- The prototype kg is kept in a safe in Paris, France; it has been used for dissemination three times in the last 100 years!

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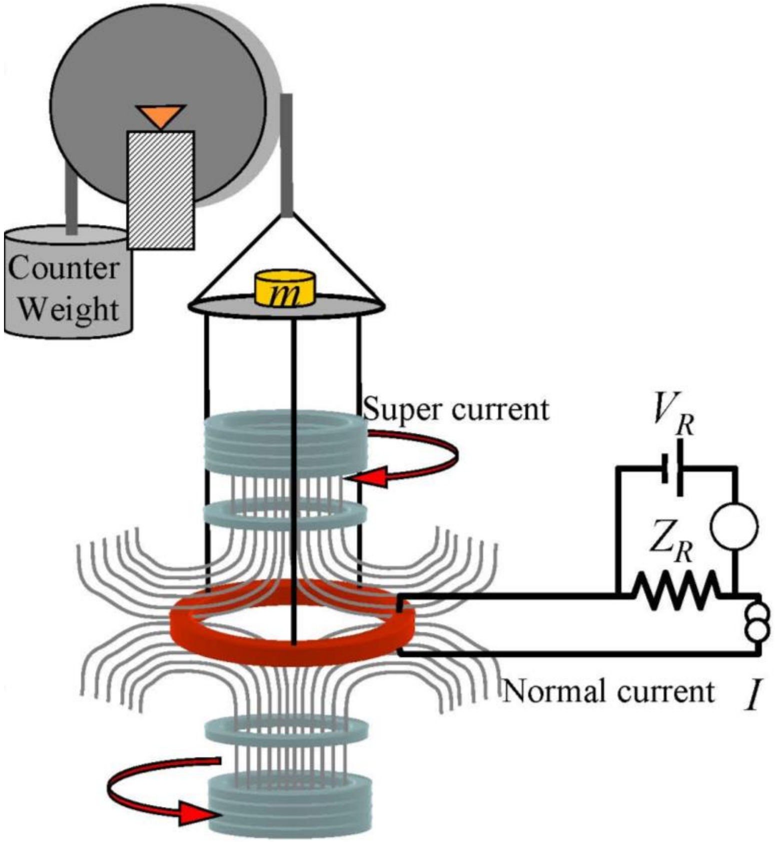
Link between mechanical and electrical: the "Watt balance"

- Watt balance: the modern version of Ampere's experiment
  - measures equivalence between mechanical power (electromagnetic coil moving in magnetic field)
  - electrical power: voltage and resistance $P = V^2/R$
- There are only about five in the world (as of 2014)!
- Best result: $\delta P/P \cong 1 \times 10^{-8}$
  - performed once/3 years or so



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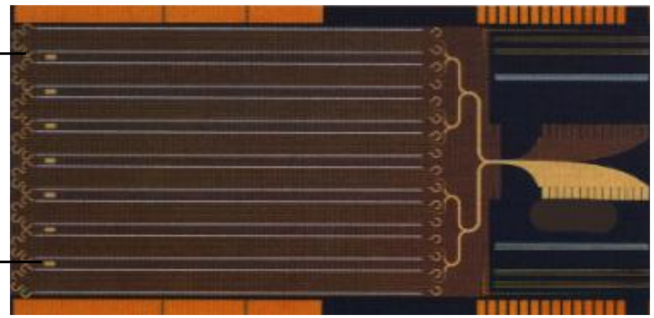
Example of quantum Standard: the Josephson voltage system

Microwave radiation at 80 GHz

About 100 exist around world

Can be run every week

$V_J = hf/2e$



Si chip with thin-film Devices (10 cm total)

NIST or K Tech

Tek 6320B Zener voltage standards

K Tech

Tek 6320B Zener voltage standards

Tek 6320B Zener voltage standards

Tek 6320B Zener voltage standards

...

K Tech

K Tech 3458 voltmeter

K Tech 3458 voltmeter

K Tech 3458 voltmeter

K Tech 3458 voltmeter

K Tech 3458 voltmeter

...

Why don't we like this situation?

- The kg prototype is an artifact, not a constant of nature
  - compare the standard of length or time.
- The electrical units, by virtue of the definition of the Ampere, are based on the kg
- Josephson voltage and quantum Hall resistance standards are much better practical standards:
  - easier, simpler, less expensive
  - much lower uncertainty: $|V_{J1} - V_{J2}|/V_J < 2 \times 10^{-17}$!!

  - But: V_J is **not** an SI volt.

(Joe metrologist)

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The proposed redefinition (electrical only)

- One possible outcome: make the values of h and e exactly defined.
  - Advantage: If V_J = hf/2e, Josephson V_J becomes a SI realization.
  - Advantage: If Q_S = e, SET I_{SET} becomes a SI realization of current.
  - Advantage: $\alpha = e^2/2\varepsilon_0 hc$ uncertainty now through only one constant.
    - doesn't reduce value of uncertainty, but allows easier communications with quantum mechanics.
  - Disadvantage: ε_0, μ_0 now have non-zero uncertainties.
  - Disadvantage: mass dissemination maybe more difficult (depends on, eg, V_J through Watt balance).

- What if $V_J \neq hf/2e$?
  - $V_J = hf/2e\,(1 + \varepsilon_J)$
  - Determinations of ε_J become crucial to supporting redefinition.

The proposed redefinition – effect of Q_S

- Current standard: $I = f\, Q_S = f\, e\,(1 + \varepsilon_S)$
  - value of Q_S determines validity of this fundamental current standard.

- Quantum Metrology Triangle: $V = IR$
  - V and R measured with respect to Josephson and quantum Hall standards
  - put bound on $\varepsilon_J + \varepsilon_K + \varepsilon_S$

Redux: Why does NIST pay us to ask if $Q_S = e$?

- NIST (used to be the Bureau of Standards), the National Institute of Standards and Technology, is part of a worldwide effort to continually improve accuracy and reliability of standards
- We believe every electron has the same charge as every other electron (and always will), so that *e* is a fundamental constant. If we could base an electrical standard on *e*, it would be cool.
- That leads us to a discussion of the SI …
- Answer: The possible redefinition of the SI would be strengthened if we were sure that $Q_S = e$, in part to have a fundamental current standard.

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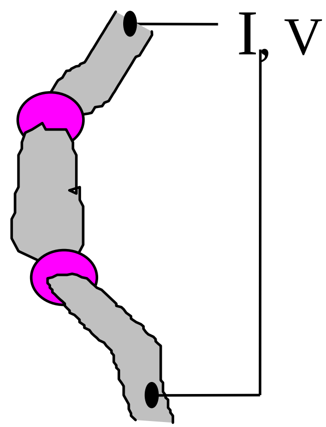
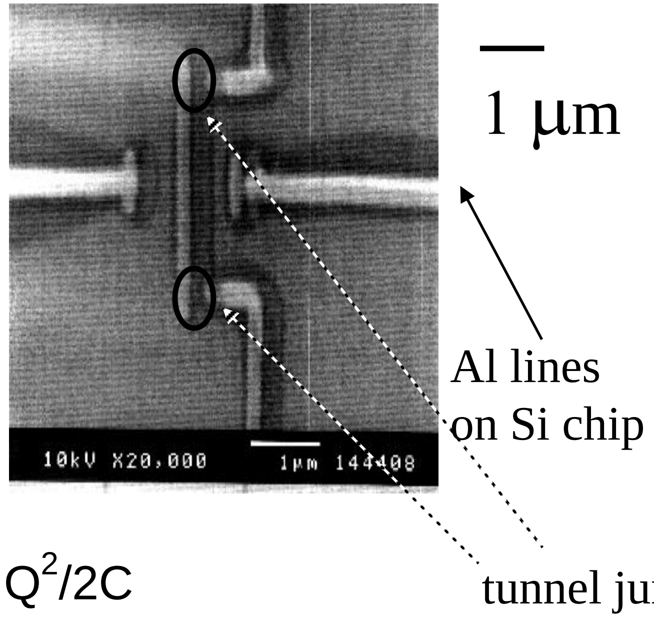
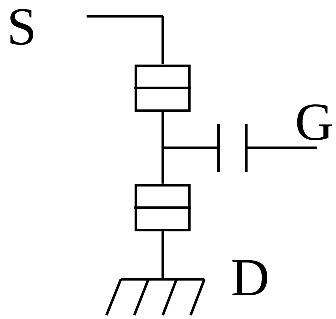
Basics of single electron tunneling (SET)devices: Coulomb Blockade



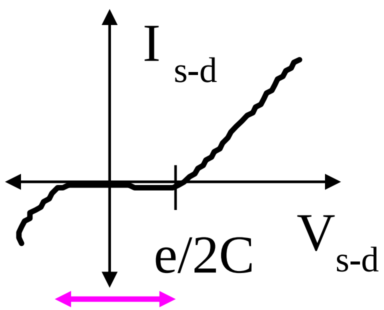


- Coulomb Blockade:
  - capacitor charging energy $Q^2/2C$
    - C is the total capacitance of the island
  - for lithographically-fabricated thin-film tunnel junctions, we can achieve $C < 10^{-16}$ F, or
  - $e^2/2C \sim 0.1$ meV ~ 1K.
  - Also need $R_{tunn} > h/e^2 \approx 26{,}000\ \Omega$.

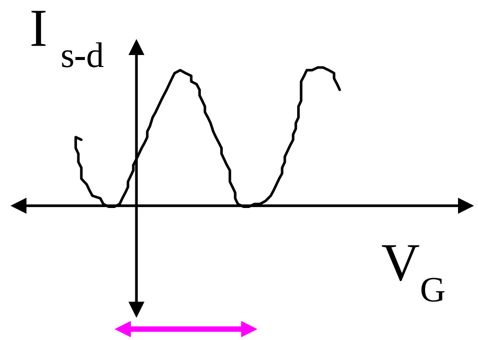
Basics of single electron tunneling (SET) devices: SET transistors.



Three-terminal device
(two junctions)



blockaded
region

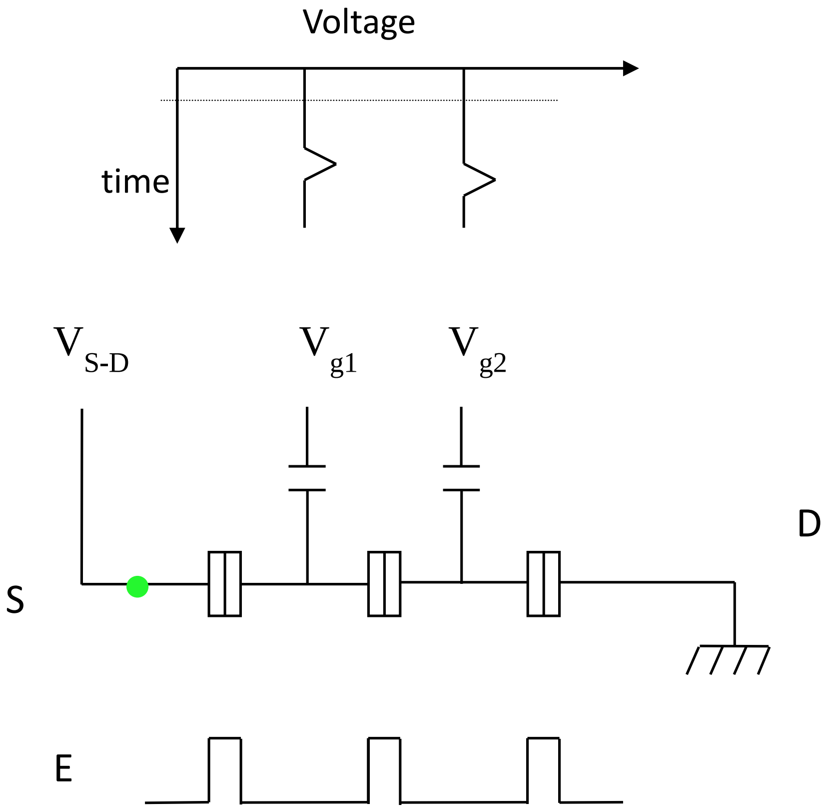


e/C_g - sensitive to
10^{-3} or 10^{-6} e charge change

With two junctions, we can monitor single electrons.

With three junctions, ...

Basics of SET devices: Pumps.



- One and only electron (usually) passed each T_{rep}…

  $\Rightarrow I = fQ_S$
- To be useful for metrology:
  - we need $< 10^{-7}$ error rate.
  - We can achieve this with seven-junction pump.
  - maximum freq about 10 MHz ->

    max I = 1 pA.

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Can $Q_S \neq e$?

- The classic answer is: No!
  - based on the Millikan oil drop experiment, and modern analogues
  - also based on highly accurate measurements of charge neutrality of atoms ($Q_{electron} = -Q_{proton}$).
- Example: where do we get the value of *e*?
  - $e = (2\alpha h/\mu_0 c)^{1/2}$
  - μ_0 and c are defined
  - single value of h comes from Watt balance, assuming $\varepsilon_J = 0$.
  - α comes from repeated atomic physics experiments.

$\Rightarrow$ constancy of *e* results from constancy of electron charge in atoms.

Can $Q_S \neq e$?

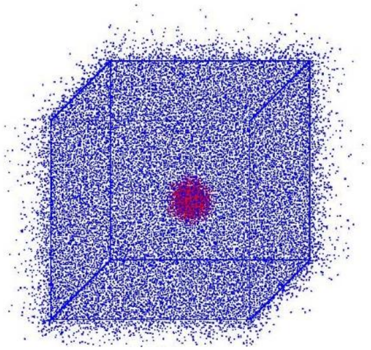
- An SET device is different:
  - In a solid, electrons are not “free” – they are highly modified by the lattice of positive ions, and by the Coulomb interaction with other electrons
  - $\rightarrow$ effective mass, quasiparticles
  - not like atoms – not free charge.
  - not like oil drop experiment

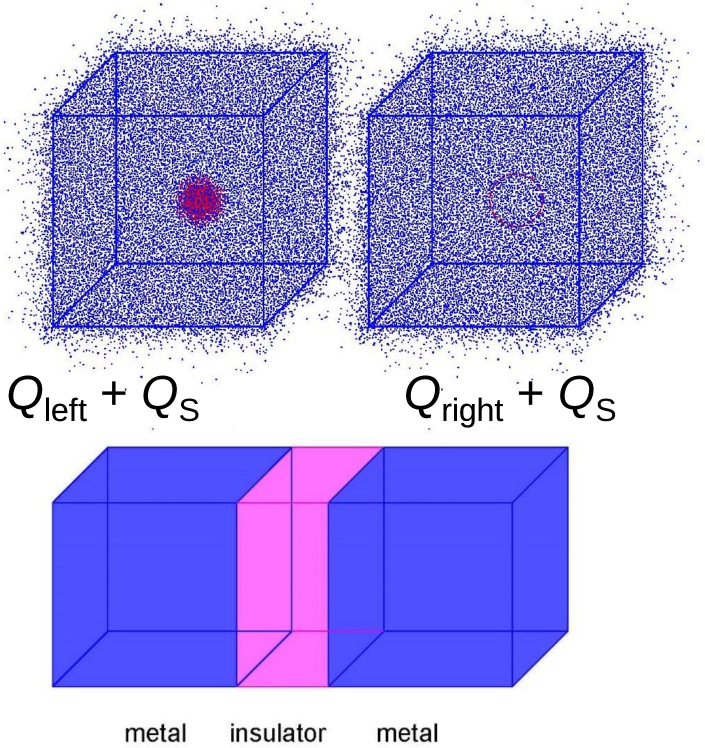
    – two “drops” are coupled.

How can we measure (or even define) Q_S?

single "droplet" – can't
isolate single charge

SET tunnel junction – can define Q_S by motion





Can $Q_S \neq e$?

- The classic answer is: No!
- Electrons in an SET device may be different.
- At this time, there is no well-established proof pro or con, but it seems plausible to ask: is there a condensed-matter correction to *e* at 10^{-6}, 10^{-8}, …?

- So let's do the experiment and see!

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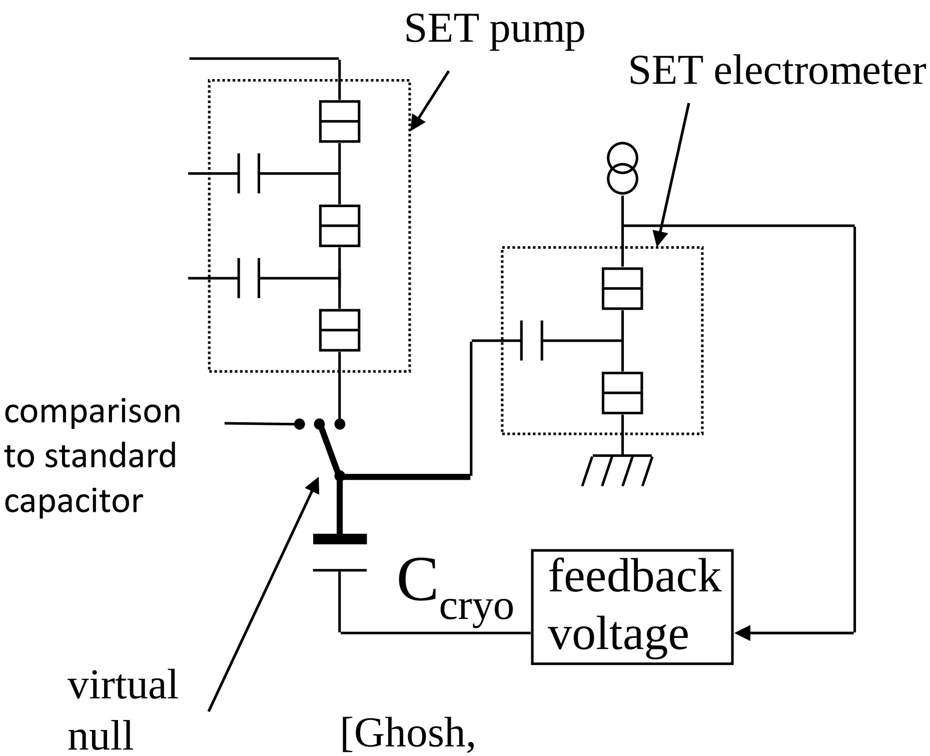
How best to use a single electron pump?

- The simplest way is via the "Quantum metrology triangle": $V = IR$
  - V ~ 10 V, R ~ 10 kΩ, I ~ 1 pA – Difficult!

- Use capacitor as integrator:
  - $Q = CV = NQ_S = It$, $V = It/C$ ~ (1 pA) (100 s) / 10 pF ~ 10 V.
  - This is a more powerful test than the full QMT: tests only $\varepsilon_J + \varepsilon_S$, rather than $\varepsilon_J + \varepsilon_K + \varepsilon_S$

Basic Circuit for the Electron-Counting Capacitance Standard (ECCS)



[Ghosh, Martinis, Williams, JR NIST 1992]

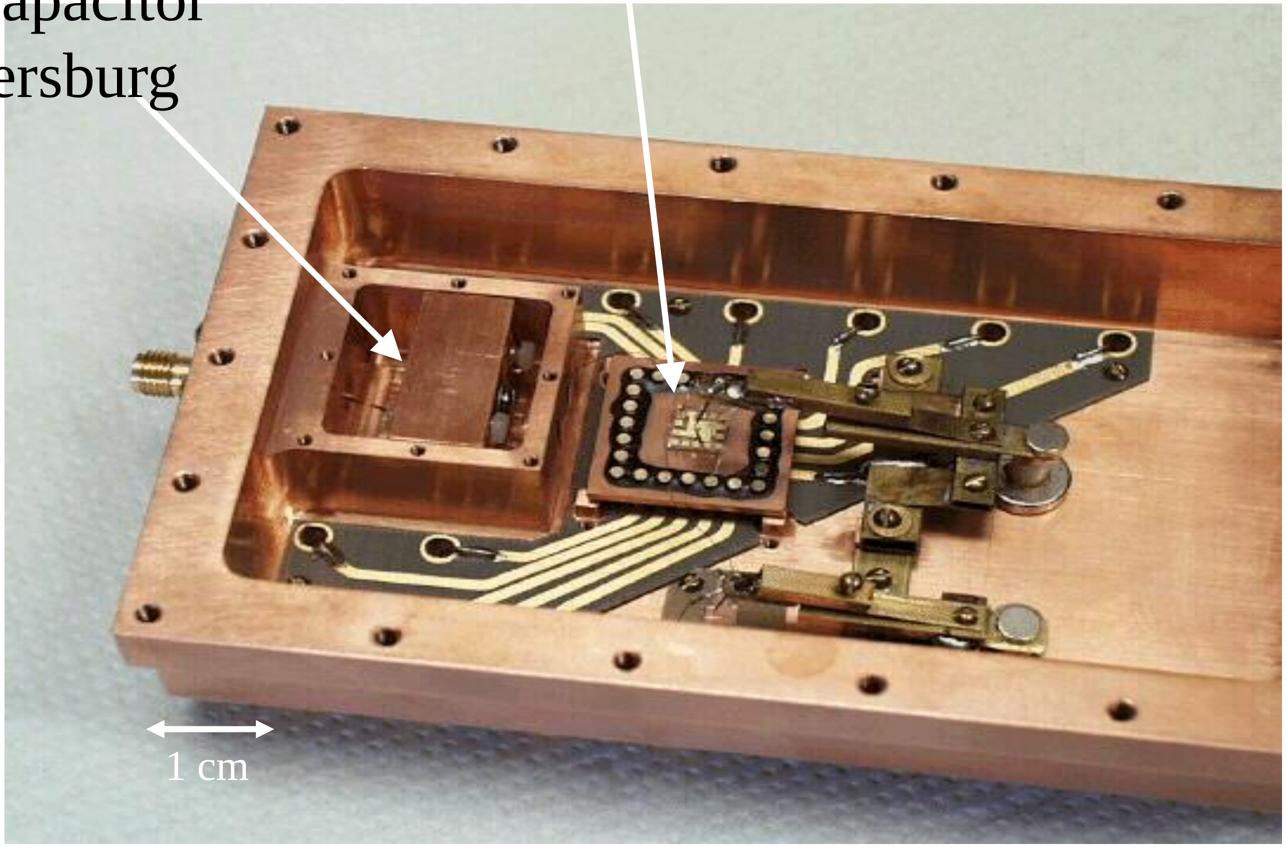
- Experiment cycle: calibrate C, run pump, stop and measure +V, reverse pump stop and measure -V, ...

Critical Elements of the ECCS Experiment

- SET pumps: error rate maximum one extra or less electron per 10^8 pumped.
  - achieved: 2×10^{-8} [Keller, Martinis, Zimmerman, Steinbach, APL]
- SET electrometers: null detector sensitivity 10^{-8}.
  - achieved: 1×10^{-7} [Clark, Zimmerman, Williams, Amar, Song, Wellstood, Lobb, APL; Keller, Eichenberger, Martinis, Zimmerman, Science]
- cryogenic capacitors: stable, low frequency and voltage dependence, low dissipation.
  - $\Delta C(V)/C \cong \Delta C(\text{time})/C \leq 10^{-8}$.
  - leakage $R > 10^{21}\ \Omega$. [Zimmerman, IEEE TIM; Eichenberger, Keller, Martinis, Zimmerman, JLTP].
  - dispersion $\Delta C(f)/C \leq$ **2 X** 10^{-7} [Zimmerman Simonds, Wang, Metrologia]

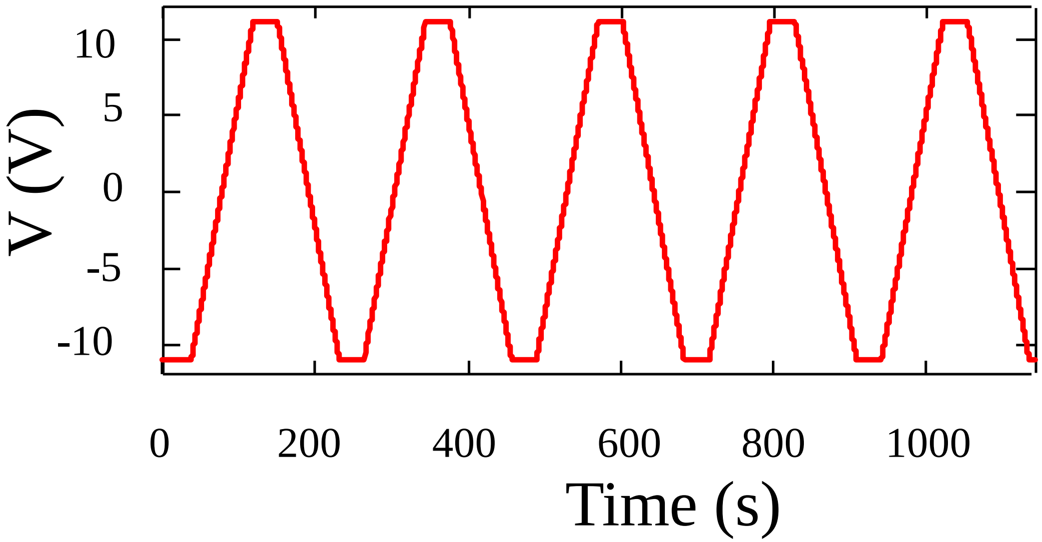
SET device from Boulder,
in Boulder cryostat

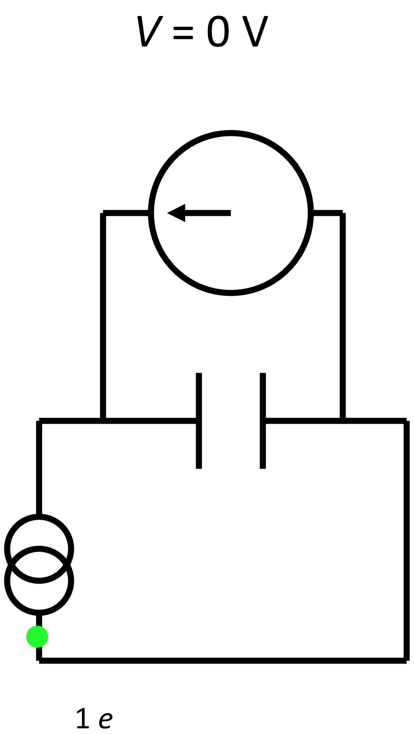
cryogenic capacitor
from Gaithersburg



Capacitor Charging

Actual data (not simulated) N = 251 658 240 (3) electrons





- $Q_S = CV/N$, $\varepsilon_S = Q_S/e - 1$

- Fundamental equation: $\varepsilon_S = CV/Ne - 1$
  - Identify CV as SI charge, Ne as charge in "SET units".

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Uncertainty Budget

- type A: noise of SET electrometer
- accuracy of C: largest uncertainty, dominates total
  - from commercial bridge measurement
  - future: improve by at least factor of 5 by local calibration
- Voltmeter accuracy: link to Josephson standard and ε_J

Source	Quantity	Rel. Stand. Uncer.
Type A	$\delta\{\Delta U\}_{90}/\{\Delta U\}_{90}$	1.3×10^{-7} (run A) 2.1×10^{-7} (run B) 1.9×10^{-7} (run C)
Type B		
loading (cable corrections) accuracy of C voltage dependence of C frequency dependence of C	$\delta C/C$ (pF/pF)	3.1×10^{-7} 8.5×10^{-7} 9×10^{-8} 2×10^{-7}
voltmeter accuracy	$\delta\{\Delta U\}_{90}/\{\Delta U\}_{90}$	5×10^{-8}
capacitor leakage pump error rate	$\delta N/N$	4×10^{-8} 1.0×10^{-8}
fundamental constant	$\delta R_K/R_K$	3.3×10^{-9}
fundamental constant	$\delta\epsilon_J$	8×10^{-8}
All others		8×10^{-8}
Total type B		9.4×10^{-7}

The Result

- $\varepsilon_S = (-0.5 \pm 9.2) \times 10^{-7}$ ($k = 1$).
- A null result: we see no reason to believe the charge quantum Q_S is not identical to the free electron (at 0.92 ppm).

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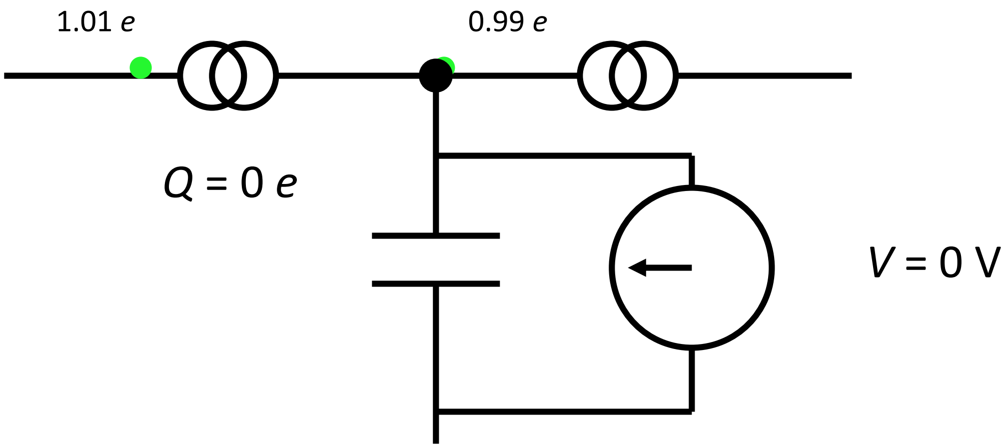
Future: Fundamentally, does $Q_S = e$?

- Theory:
  - we solicit help in developing a theoretical basis!
- Experimental: consistency checks (much easier than 10-year accuracy measurement – whew!)
  - run two identical pumps, check for difference.
  - run two different pumps (eg, metal and Si-based), check for difference.



Collaborators

- NIST Boulder:
  - Mark Keller
  - Joe Aumentado
  - John Martinis
  - Ali Eichenberger
- NIST Gaithersburg
  - Yicheng Wang
  - Brian Simonds

Advertisement

- Postdoc positions:
  - NRC (National Research Council) postdocs are prestigious, well-paid fellowships awarded (from a competion run by the NRC) by a number of US gov't research labs.
    - US citizens only
    - deadlines February and August 1
  - JQI postdocs open to citizens and non-citizens, no deadlines
- Graduate Student Positions: study at U. Maryland, work at U MD or at NIST through JQI (Joint Quantum Institute)
- Undergraduate Students: summer internships at NIST paid for by NSF
  - citizens and non-citizens
  - housing and large stipend provided
- If any of the foregoing (not just SET-related) or working in other areas at NIST interests you, please contact me.

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"19) Redux: Why does NIST pay us to ask if Q
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"41) Future: Fundamentally, does QS = e?"
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"42) Collaborators"

Future: value of Q_S

- One prediction for a condensed-matter correction [Nordvedt 70]:
  - considers correction to screening due to virtual excitations from Dirac sea of negative energy states
  - $\delta e/e \sim \alpha\ (p_F/mc)^2 \sim 10^{-9}$

(Coulomb energy/rest mass energy) (Fermi energy/rest mass energy) ~

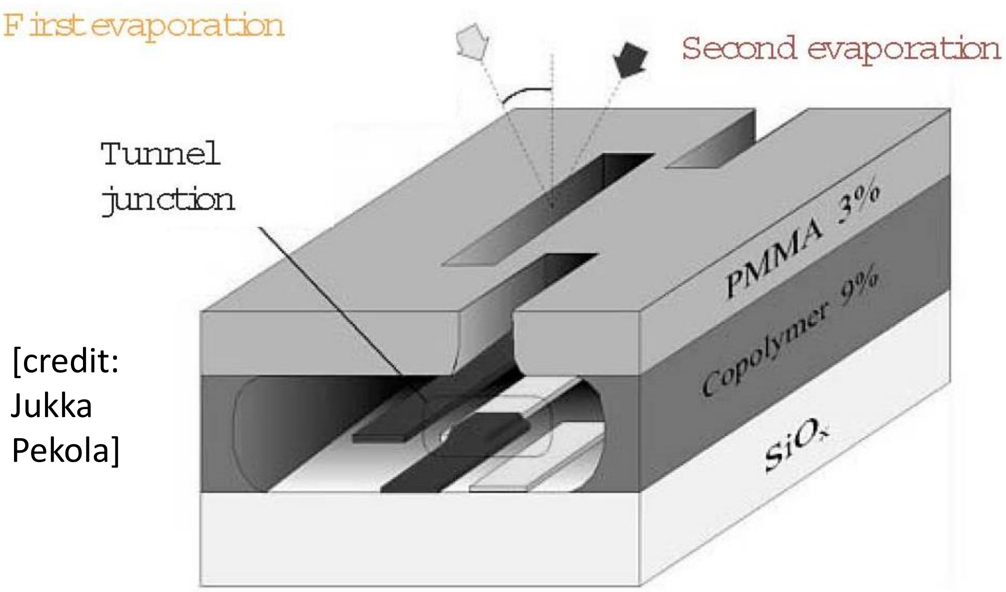
relative screening X relative phase space

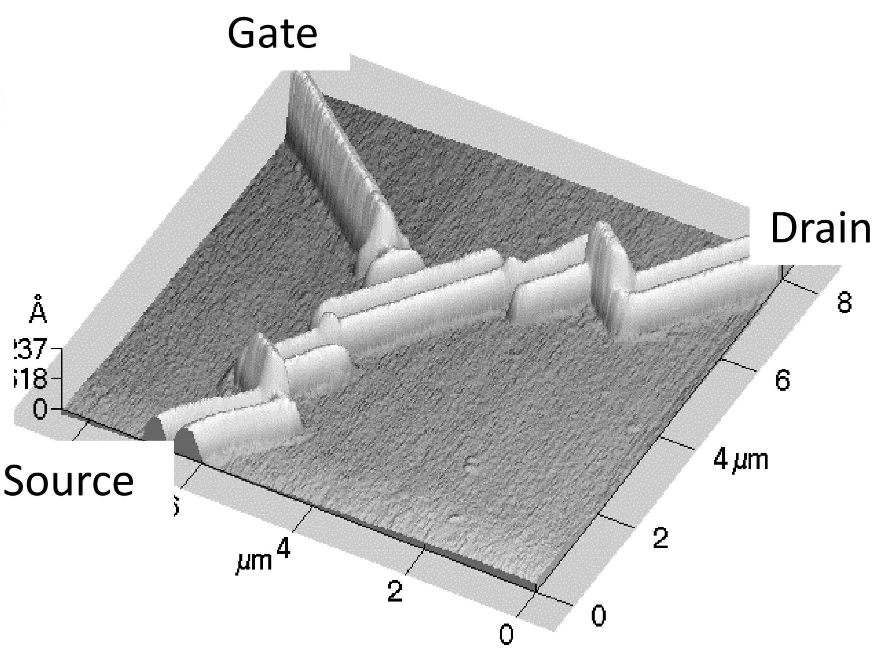
- Later work cast some doubt on this idea
- We do not expect to reach 10^{-9} with ECCS, but
- We may be able to reach with QMT, if we can get a much larger-value current standard.
  - At that level, we could test the basic physics of this conjecture.

Basics of SET Devices: Fabrication

- Made using thin-film lithography and fabrication techniques (much simpler than CMOS).
- Al lines, AlO_x tunnel junctions on Si substrate:

[credit: Jukka Pekola]



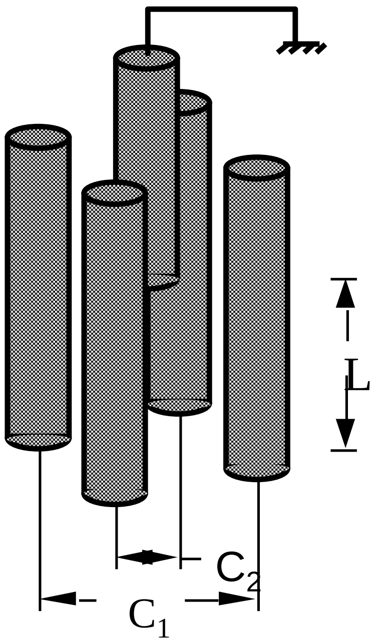


Some Questions About the SI

- Have you ever heard of the SI?
- Can you name some of the base units?
- What is the definition of the kilogram?
  - Why don’t metrologists like this definition?
- What is the definition of the Ampere, volt, … ?
  - How is your voltmeter actually calibrated?
  - Why are metrologists uncomfortable about this situation?
- Can you suggest some changes to this situation?
  - The big “redefinition” …

Link between mechanical and electrical: the "calculable capacitor"

- The calculable capacitor experiment is a lynchpin experiment: mechanical $\rightarrow$ electrical units.
  - based on Coulomb's Law
- There are only two or three in the world (yikes!).
- $\delta C/C \cong 2 \times 10^{-8}$.
  - performed once/year or so



- $\Delta C_1/\Delta L = \varepsilon_o \ln 2/\pi$
  - » ε_o is a defined quantity (no uncertainty).
  - » $\Delta L \sim 25$ cm
  - » $\Delta C = 1/2$ pF

Reminder: what defines fine-structure constant α?

- Historical:
  - split lines in atomic spectra and Stern-Gerlach experiment $\Rightarrow$ spin
- Semi-classical (Bohr atom) approximation
- Spin-orbit interaction $E_{so} = - \mu_{spin} \bullet B_{proton}$
  - $\mu = q/2m\ L \sim e/m\ h$
  - from Biot-Savart for circular current, $B = \mu_0 I/2r \sim \mu_0 ef/r = \mu_0 eE_0 / hr$
    - from $e^2/4\pi\varepsilon_o r^2 = mv^2/r$ and $L = mvr = h$,
    - $r = a_0 = 4\pi\varepsilon_o h^2/me^2$

  $\Rightarrow B \sim \mu_0 eE_0 / h\ (me^2/4\pi\varepsilon_o h^2) = \pi\mu_0 e^3 m/\varepsilon_o h^2\ E_0$

  $\Rightarrow E_{so} \sim \mu_0 e^4/\varepsilon_o h^2\ E_0 = e^4/\varepsilon_o{}^2 h^2 c^2\ E_0 = \alpha^2\ E_0$
- $\alpha = e^2/2\varepsilon_o hc$ is useful in electrical metrology because:
  - it is unitless
  - e^2/h is the von Klitzing conductance quantum

An example of the importance of electrical metrology to fundamental physics: test of QED

- Similar to Josephson voltage standard, quantum Hall resistance : for two-dimensional electron gas in high magnetic field, all the electrons are condensed into Landau levels, and the transverse Hall resistance is believed to be dependent on fundamental constants only:
  - $R_K = h/e^2$.
- Fine-structure constant $\alpha = e^2/2\varepsilon_0 hc = 1/2\varepsilon_0 c R_K$.
  - some of the most accurate values for α come from R_K, **if** measured in SI units (as low as 2×10^{-8}).
- QED: eg, electron magnetic moment anomaly $a_e = C_e^2(\alpha/\pi) + C_e^4(\alpha/\pi)^2 + \ldots + a_e$ (weak) + a_e(hadronic).
  - theory now up to 6^{th} order in QED (thousands of Feynman diagrams)
  - a_e can be measured with unc. as low as 4×10^{-9}.
  - $\Rightarrow$ test of accuracy (truth) of QED theory.

The Future - ε_S, the SI, redefinition

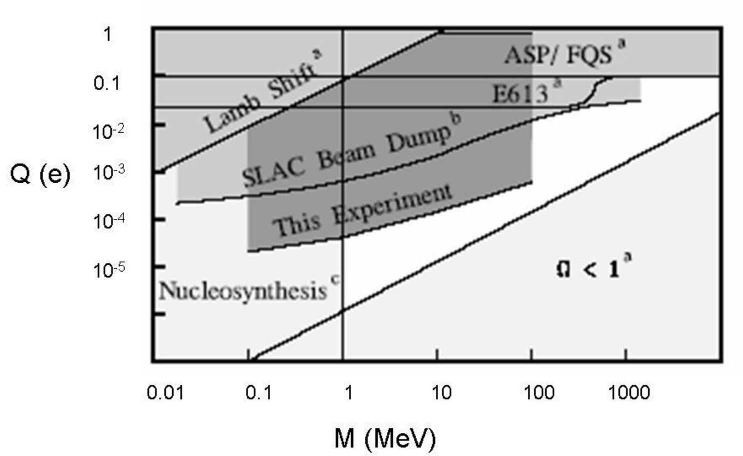
- Near-term:
  - ECCS: we can reduce the uncertainty to about 3 X 10^{-7}. At this level, we can help refine the next derivation of ε_J.
- Medium-term:
  - ECCS: with more work (several years), we believe we can reduce uncertainty to about few X 10^{-8}. At this level, we can help support the redefinition, removing the last artifactual realization (the kg) in the SI.
  - QMT: we are working on developing high-value current standards (Si, passive counting, …). If we can achieve 100 pA (factor of 100 increase), we can test all three legs of Ohm's Law with quantum standards. This will also support the possible redefinition.

Future: Goals and Necessary Improvements

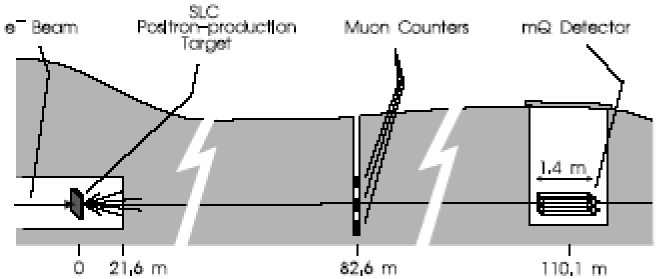
- Near-term:
  - By doing local calibrations of commercial bridge, we can reduce the uncertainty in *C* to about 2 X 10^{-7}.
  - Also need modest improvements in cable corrections
  - At this level, we can help refine the next derivation of ε_J.
- Medium-term:
  - New model for *C(f)* to reduce one order of magnitude.
  - Replace cables with triaxial.
  - Measure *C* directly against calculable capacitor.
  - $\rightarrow$ we believe we can reduce uncertainty to about few X 10^{-8}.
  - At this level, we can help support the redefinition, removing the last artifactual realization (the kg) in the SI.

Search for fractional charges – high energy

- Theory and experimental tests
- Example: PRL 81, 1175 (98)
  - 30 GeV electrons hit metal target
  - 100 meters of sandstone filter out all other charged particles.
  - electromagnetic interaction assumed ⇒ yield $\propto Q^2$, depending on mass.
  - Null result leads to exclusion $M \in [0.1, 100]$ MeV/c^2, $Q > 10^{-4}$ e.



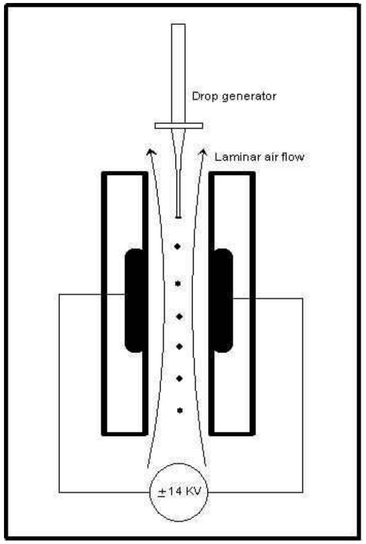
"This experiment" (SLAC)



Search for fractional charges – Millikan oil drop

- Original: 1910. Total throughput ~ 100 drops
- SLAC: decade-old project
  - automated (millions of drops)
  - four versions over 12 years
  - one result [PRD 66, 12002] –

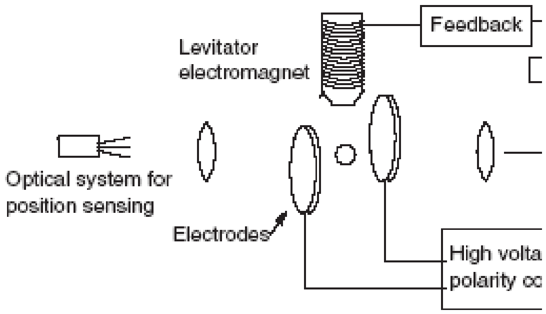
    < 1.2 X 10^{-22} /nucleon, 0.18 e < Q < 0.82 e
  - most recent:
    - 25 micron diameter target drops from a suspension of carbonaceous chondrite meteoric material.
    - Search for fractional electric charge in primordial material that has not undergone geologic, biological or industrial processing.



Search for fractional charges: charge neutrality $q_p = -q_e$, $q_n = 0$.

- $\eta \equiv (q_p + q_e)/e = q_n/e$
- Theory:
  - standard model: no constraint
  - GUT's: $\eta = 0$, or theory very wacky.
  - Cosmological constraints: expansion of universe, pulsar decay, anisotropy of CMBR.
- Experiments:
  - Example: levitation: $\rightarrow$ AC electric field

Unnikrishnan, Metrologia 2004



Gas efflux (CO_2)	Piccard and Kessler 1925 [11]	$\pm 5 \times 10^{-21}$
Gas efflux (Ar, N_2)	Hillas and Cranshaw 1958 [9]	$(1 \pm 3) \times 10^{-20}$
Gas efflux (H_2, He)	King 1960 [28]	$(2.5 \pm 1.5) \times 10^{-20}$
Acoustic resonator (SF_6)	Dylla and King 1973 [13]	1.3×10^{-21}
Millikan (silicone oil)	Perl and Lee 1997 [25]	6×10^{-17}
Levitator (iron)	Stover *et al* 1967 [27]	8×10^{-20}
Levitator (steel)	Marinelli and Morpurgo 1984 [23]	$(0.8 \pm 0.8) \times 10^{-21}$
Atomic beam (Cs)	Zorn *et al* 1962 [30]	5×10^{-19}
Atomic beam (Cs, K)	Hughes *et al* 1988 [12]	$(0.9 \pm 2) \times 10^{-19}$
Superfluid ^{4}He	Burke and Newman 1989 [32]	$(-1.1 \pm 1.5) \times 10^{-21}$
Neutron beam	Gahler *et al* 1982 [33]	$(1.5 \pm 2.2) \times 10^{-20}$
Neutron beam	Bauman *et al* 1988 [34]	$(-0.4 \pm 1.1) \times 10^{-21}$

Uncertainty Details I

- Others (smaller):
  - thermal voltages,
  - ground loops,
  - cable leakage,
  - microphonics,
  - effects of switch motion.

Source	Quantity	Rel. Stand. Uncer.
Type A	$\delta\{\Delta U\}_{90}/\{\Delta U\}_{90}$	1.3×10^{-7} (run A)
		2.1×10^{-7} (run B)
		1.9×10^{-7} (run C)
Type B		
loading (cable corrections)	$\delta C/C$ (pF/pF)	3.1×10^{-7}
accuracy of C		8.5×10^{-7}
voltage dependence of C		9×10^{-8}
frequency dependence of C		2×10^{-7}
voltmeter accuracy	$\delta\{\Delta U\}_{90}/\{\Delta U\}_{90}$	5×10^{-8}
capacitor leakage	$\delta N/N$	4×10^{-8}
pump error rate		1.0×10^{-8}
fundamental constant	$\delta R_{\mathrm{K}}/R_{\mathrm{K}}$	3.3×10^{-9}
fundamental constant	$\delta\epsilon_J$	8×10^{-8}
All others		8×10^{-8}
Total type B		9.4×10^{-7}

Uncertainty Details II

Source	Quantity	Rel. Stand. Uncer.
Type A	$\delta\{\Delta U\}_{90}/\{\Delta U\}_{90}$	1.3×10^{-7} (run A)
		2.1×10^{-7} (run B)
		1.9×10^{-7} (run C)
Type B		

- Type A (statistical uncertainty):
  - three sets of pumping data – 7, 12, 3 individual V(t)
    - each V(t) has 10 – 20 ramps, each of 50 – 200 million electrons.
    - individual ramp: $\delta\Delta U/\Delta U$ ~ 2 X 10^{-7} to 2 X 10^{-6}.
    - each set uncertainty of mean ~ 1 - 2 X 10^{-7}.

Uncertainty Details III

Type B		
loading (cable corrections)	$\delta C/C$ (pF/pF)	3.1×10^{-7}

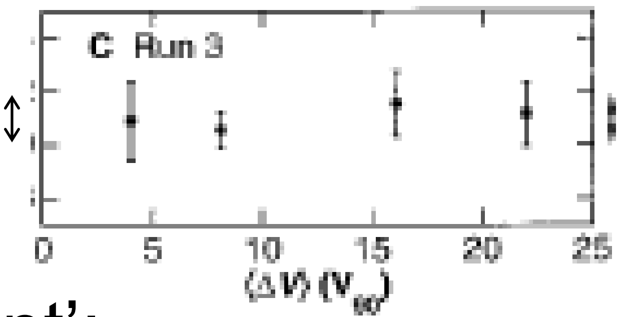
- Type B (systematic uncertainty):
  - loading (cable corrections) δC, ΔC
    - Typically due to parasitic series R and L, stray C
    1. Measure R, L, C – calculate $\Delta C \propto f^2$.
    2. Measure C(f) = constant + f^2 term
       - Leads to correction by ΔC = 0.8 ppm.
    3. Also measure ΔC upon addition of discrete R, L, C at various places (above and below cryogenic filters, top plate, sample).
    4. Also measure ΔC upon permutation of leads.

    $\Rightarrow$ high voltage side 2.4 X 10^{-7}, null side 2 X 10^{-7}, total 3.1 X 10^{-7}.

Uncertainty Details IV

accuracy of C	8.5×10^{-7}
voltage dependence of C	9×10^{-8}

1 ppm ↕

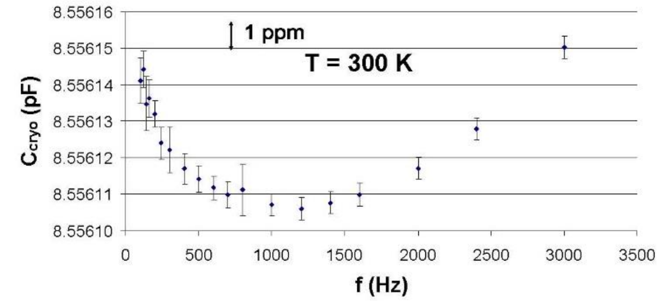


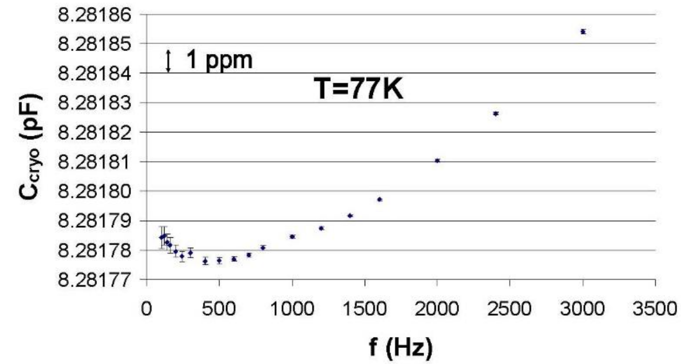
- Type B (systematic uncertainty), cont':
  - accuracy of C:
    - Andeen-Hagerling 2500A – E option manual → $\delta C/C = 3.3 \times 10^{-6}$ (k = 4) ⇒ $\delta C/C = 8.5 \times 10^{-7}$ (k = 1), after internal calibration
    - Internal cal's done within a few weeks of any meas't, drift < 10^{-7}.
    - One calibration to NIST 10 pF standard → $\delta C < 4 \times 10^{-7}$.
    - ⇒ $\delta C/C = 8.5 \times 10^{-7}$ (k = 1).
  - C(V): run ECCS for different N, (ΔU/N) varies by 9×10^{-8}.

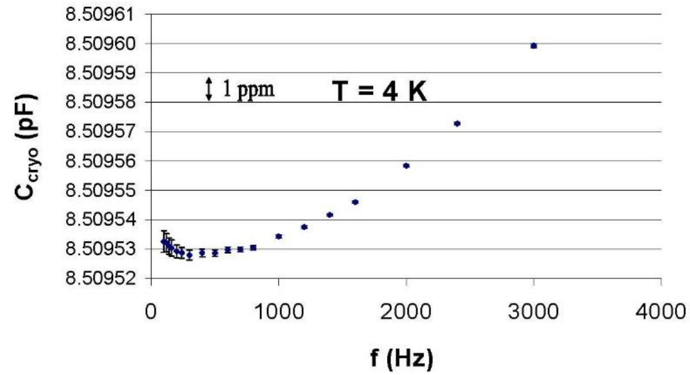
Uncertainty Details V

frequency dependence of C		2×10^{-7}

- Type B (systematic uncertainty), cont':
  - C(f) – Metrologia 2006.
    - Model surface insulators at low temperature:
      - dispersion $\delta\varepsilon(f)$ and dissipation ε'' both decrease rapidly with T.
      - calculate $|C(1000\text{ Hz}) – C(0.01\text{ Hz})|/C < 2 \times 10^{-7}$ for $T < 4$ K.
      - Experimental support: measure $C \in$ [100 Hz, 1000 Hz] at 300, 77, 4 K. Dispersion falls off rapidly, $DC/C < 10^{-6}$.
    - $\Rightarrow \delta[\Delta C(f)]/C = 2 \times 10^{-7}$.







Uncertainty Details VI

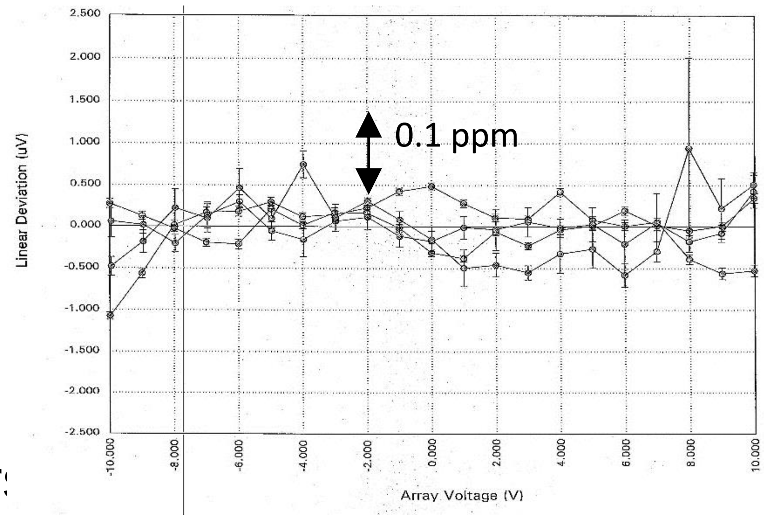
voltmeter accuracy	$\delta\{\Delta U\}_{90}/\{\Delta U\}_{90}$	5×10^{-8}
capacitor leakage	$\delta N/N$	4×10^{-8}

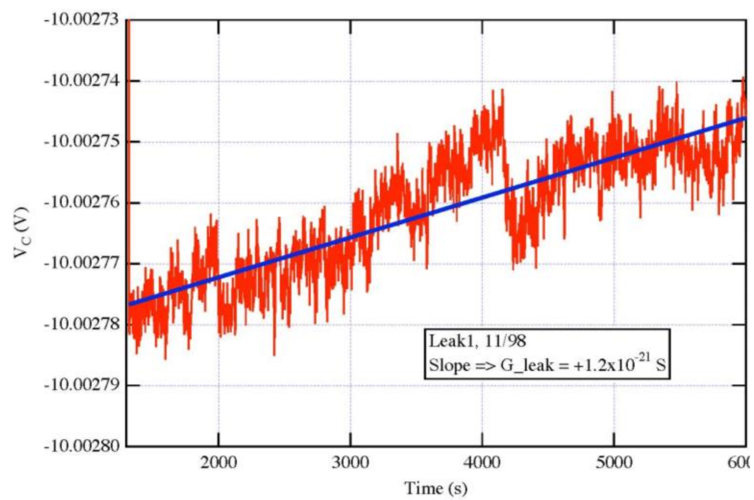
- Type B (systematic uncertainty), cont':
  - Voltmeter accuracy: calibrated against 10 V JVS.

  $\Rightarrow \delta\Delta U/\Delta U = 5 \text{ X } 10^{-8}$.
  - Capacitor leakage: measure drift in ECCS feedback voltage over two hours

  1. $\Delta U \rightarrow$ 450 electrons leaked in 6000 sec
  2. 200 million electrons in 200 seconds

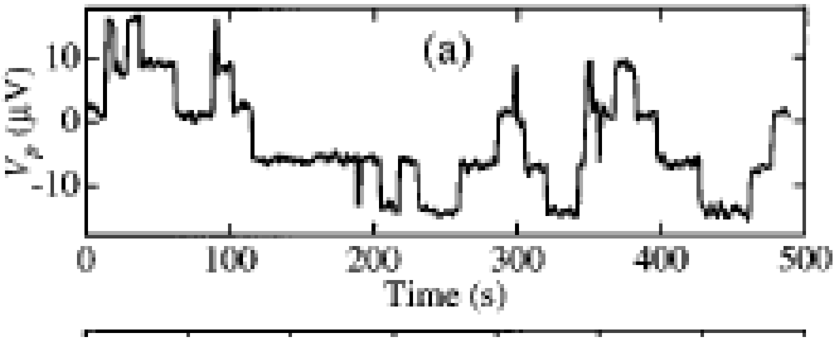
  $\Rightarrow \Delta N/N \sim 15 \text{ e}/2 \text{ X } 10^8 \sim 8 \text{ X } 10^{-8}$.





Uncertainty Details VII

pump error rate		1.0×10^{-8}
fundamental constant	$\delta R_K / R_K$	3.3×10^{-9}
fundamental constant	$\delta \epsilon_J$	8×10^{-8}



- Type B (systematic uncertainty), cont':
  - pump error rate - APL 96:
    1. "shuttle" one electron repeatedly on and off of capacitor, C ~ 20 fF.
    2. $\Delta V = e/C \sim 10\ \mu V$ – easily measured.
    3. 37 errors/(500 s)(5 MHz) $\Rightarrow$ $\Delta N/N \sim 1.5 \times 10^{-8}$.
  - fundamental constants:

RMP 2005.