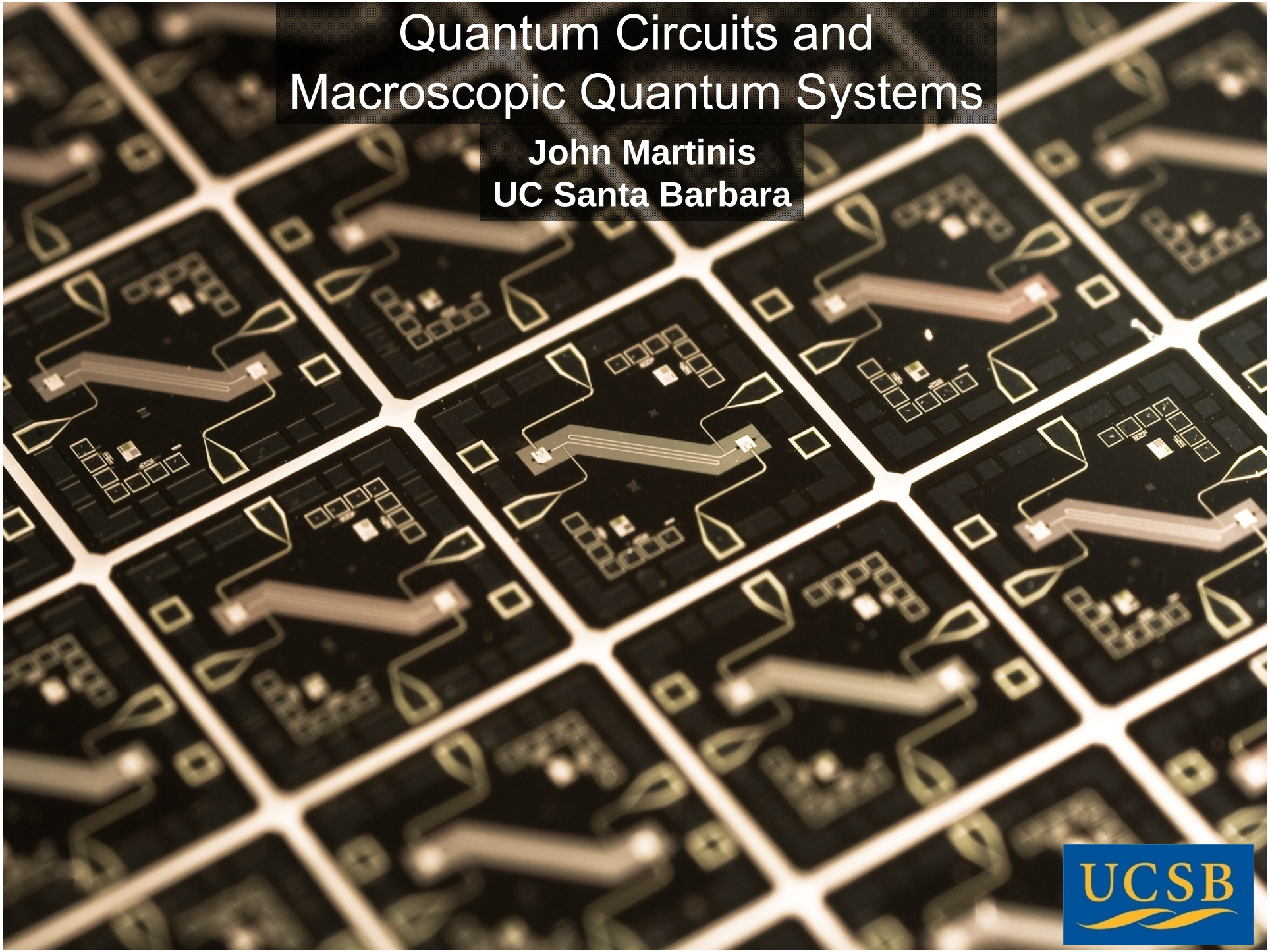
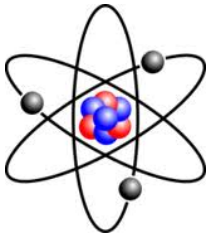
Quantum Circuits and Macroscopic Quantum Systems

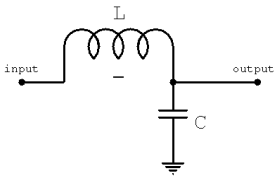
John Martinis
UC Santa Barbara



Outline



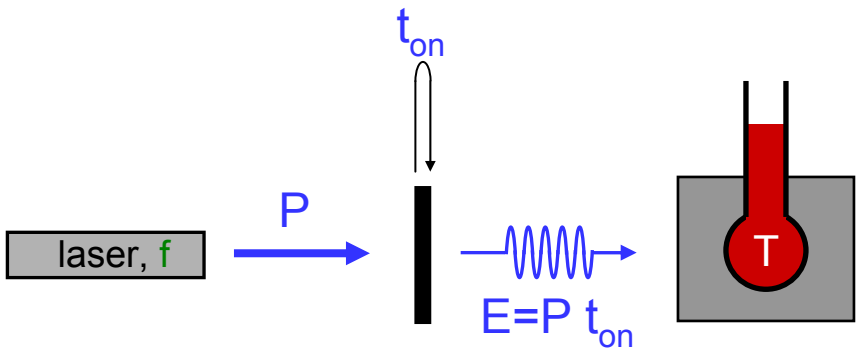
Quantum Light
Quantum mechanics & atoms
Periodic Table
Quantum tunneling

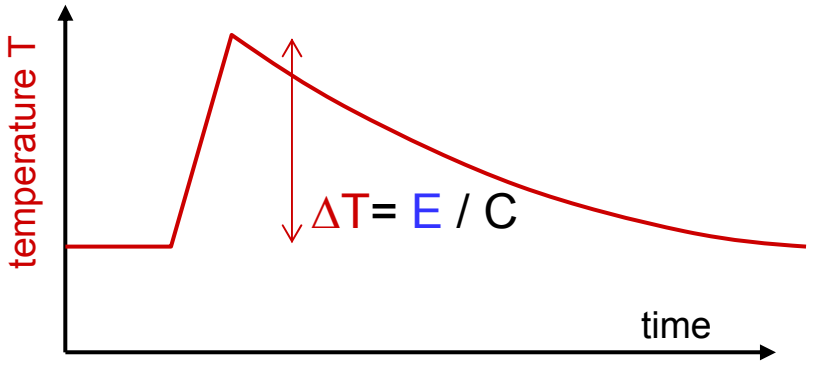


Quantum Circuits
Quantum Computation

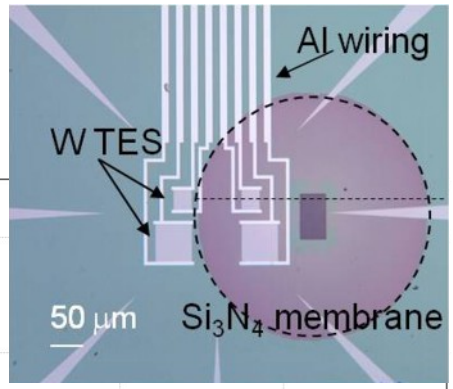
Quantum Light: E = n hf

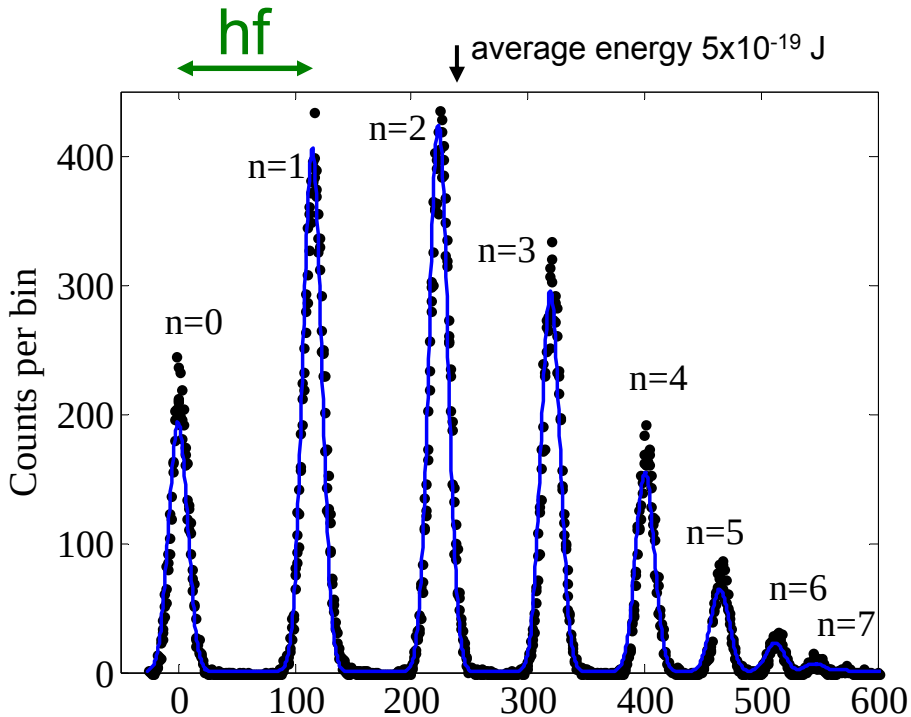
(modern version of blackbody radiation)





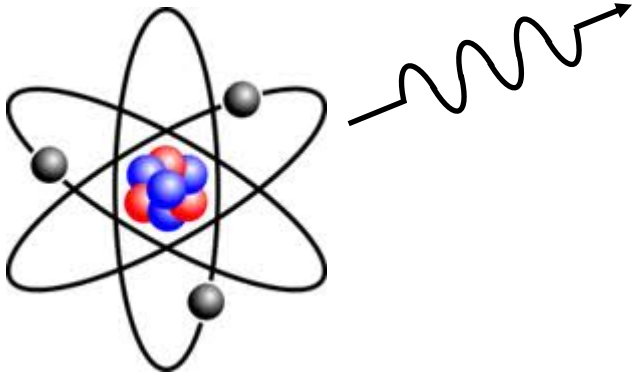
Microcalorimeter
(S. Nam, NIST)





(histogram of energy)

Why do Atoms have Size? – Quantum Mechanics



Nucleus and electrons attract
Can orbit (like planets)

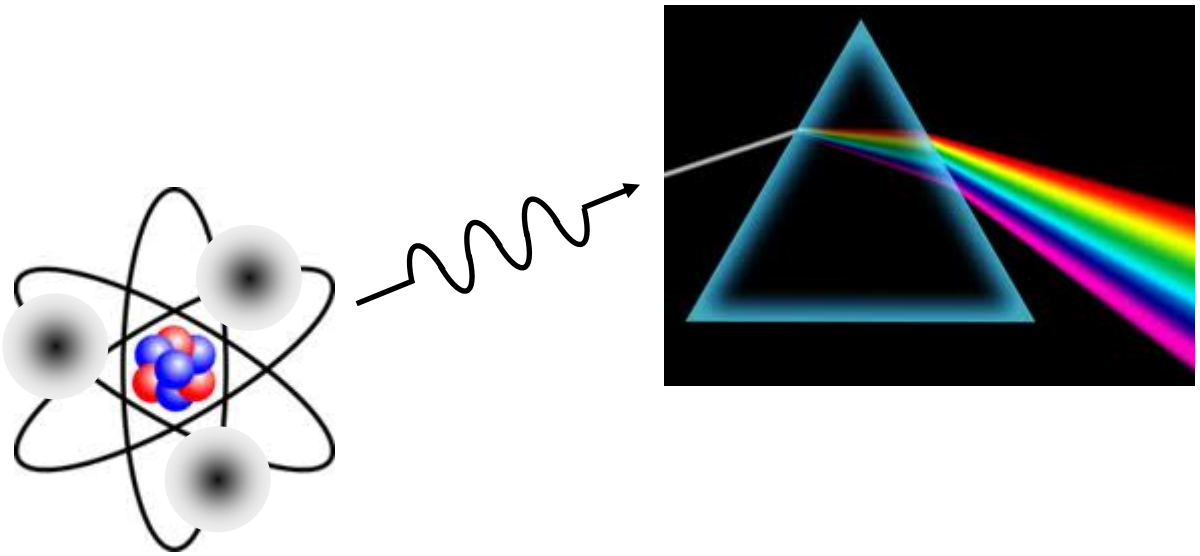
Shaking (accelerating) electrons emit light

Energy loss from light – electron would rapidly (10^{-12} s) spiral to nucleus

Electrons are not point objects

Example: Light bulb

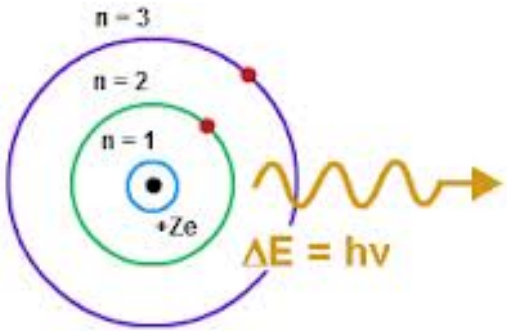
Are Electrons Fuzzy?



Fuzzy electrons
in orbit:
white light

Experiment:
distinct colors

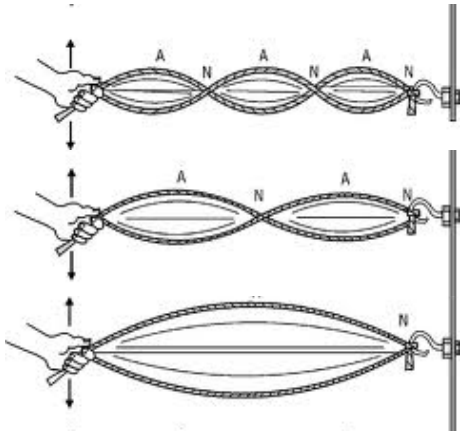
Picture: Bohr atom, distinct orbits



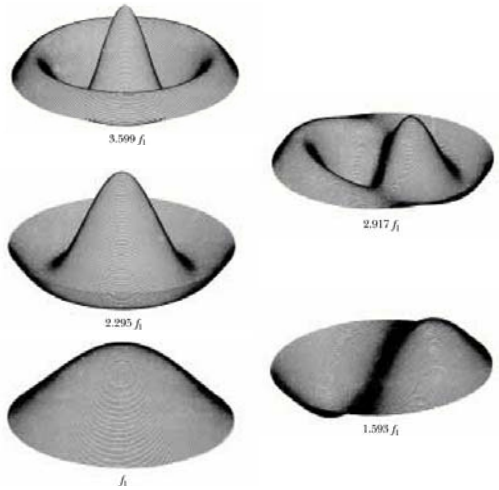
Example: Neon signs

Better Picture: Electrons form Standing Waves

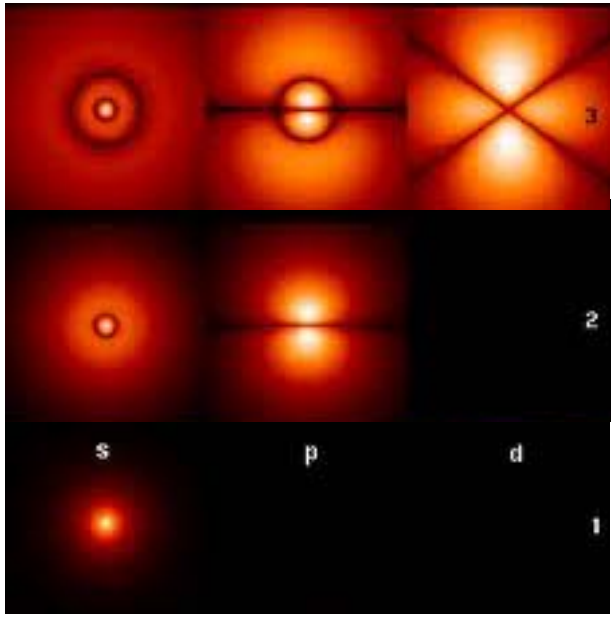
1D: string

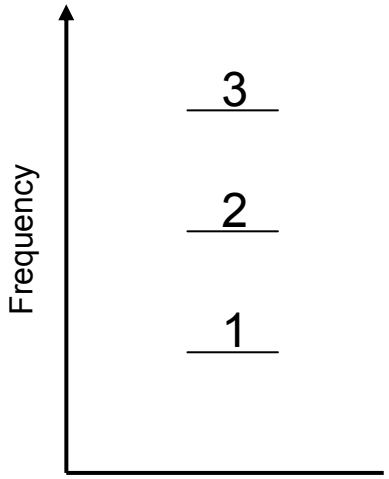


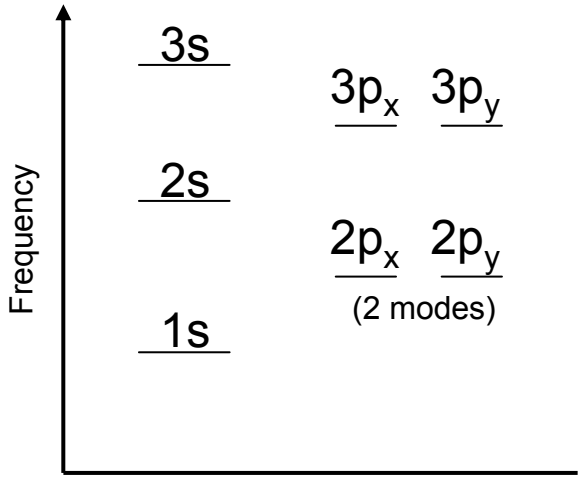
2D: drum

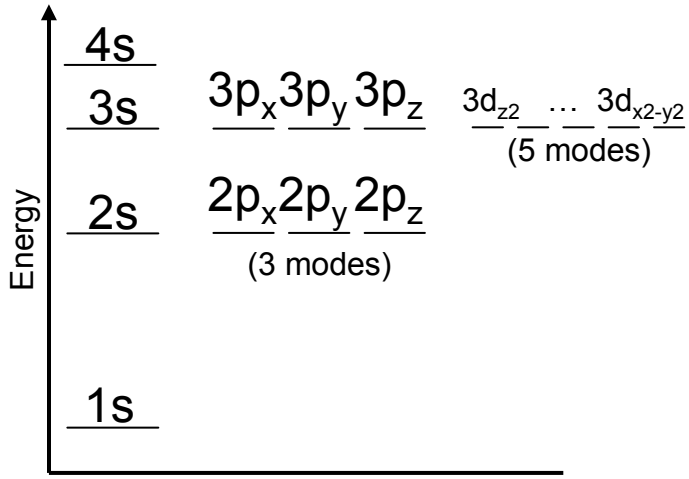


3D: H atom (QM)



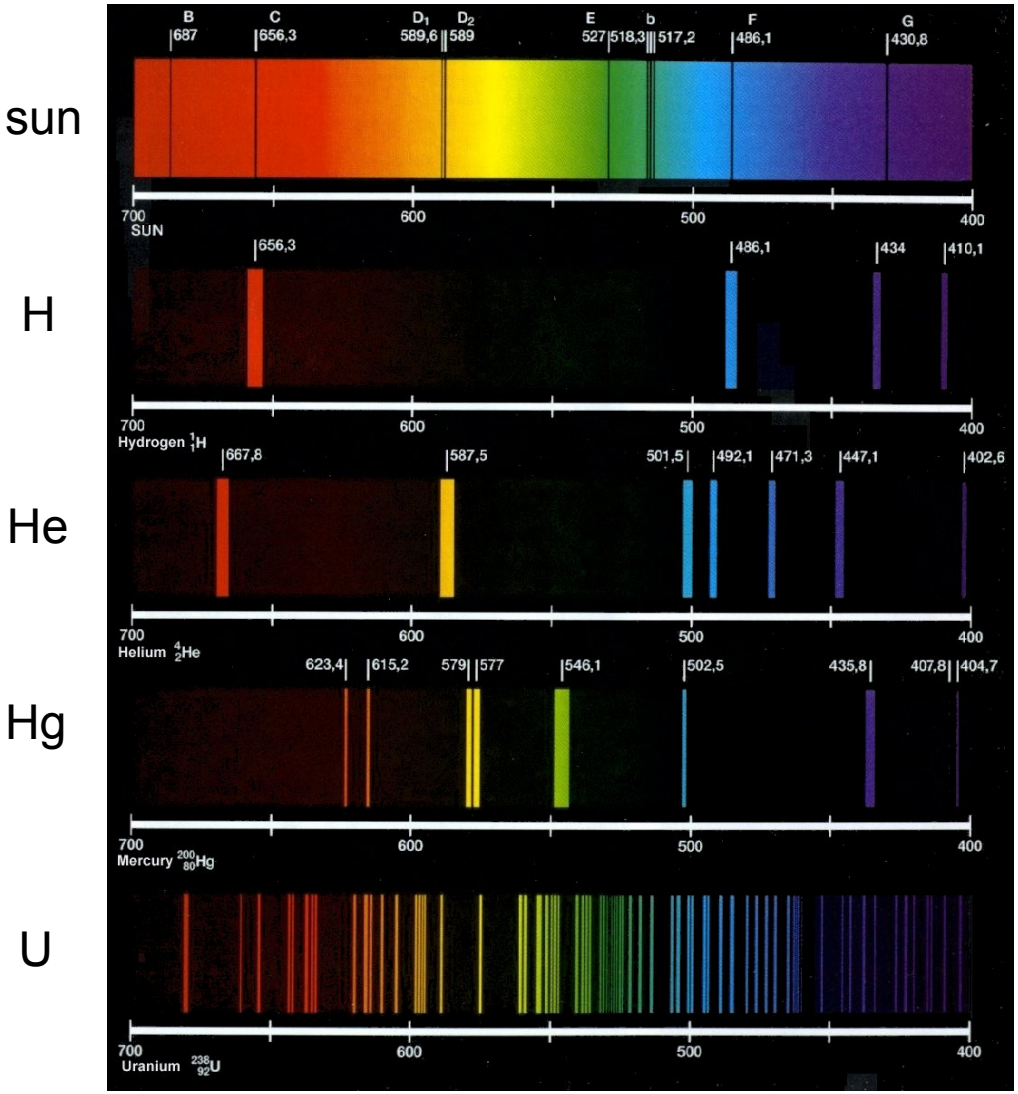






Photon Color Set by Energy Level Transitions

Each atom has different series of energy levels, gives unique spectrum of colors



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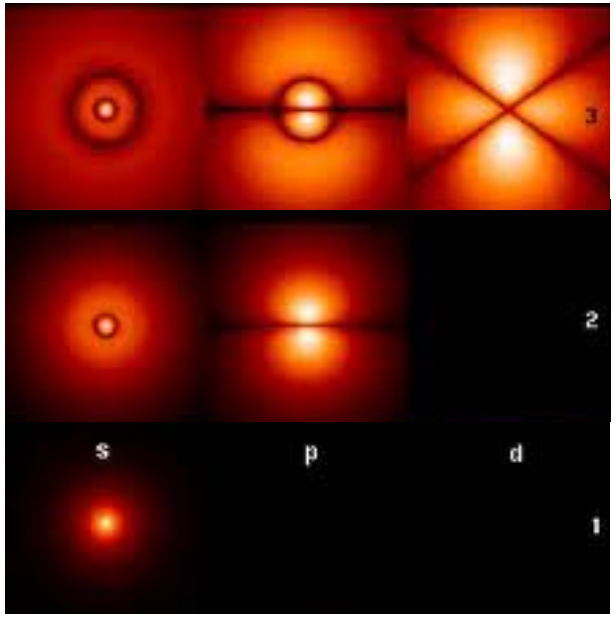
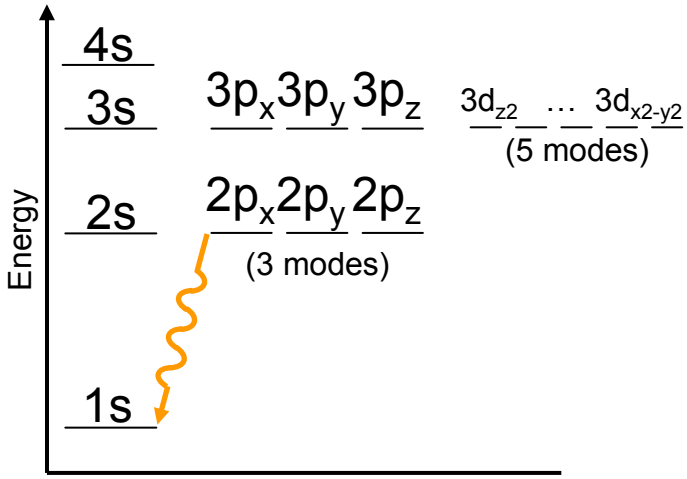




Pauli Exclusion Principle

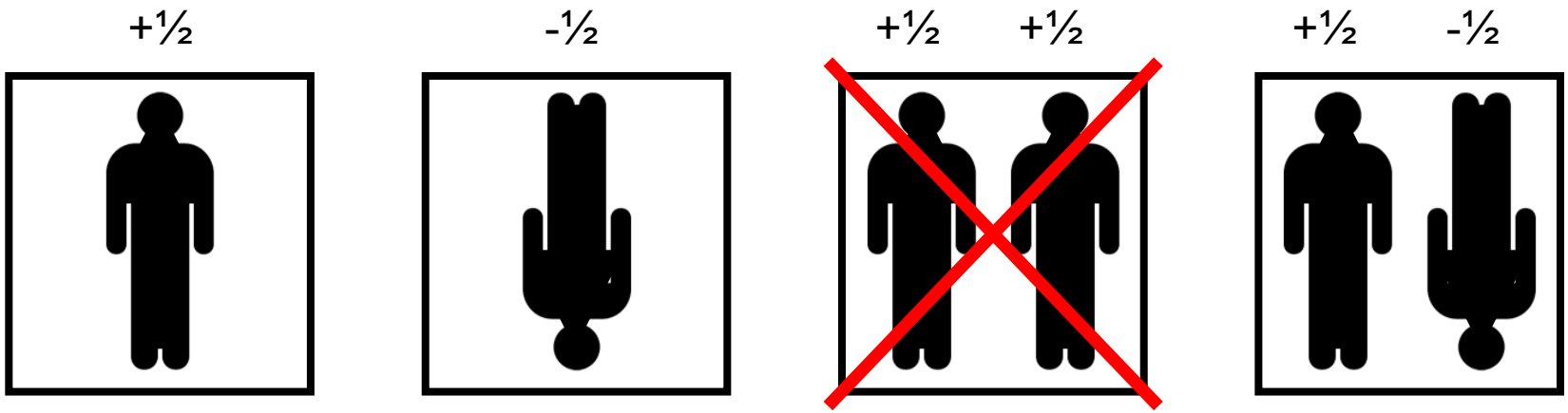
Periodic table of elements be understood qualitatively
from Hydrogen energy levels

(1) Electrons come in two states: spin up (+½) and down (-½)

(2) Not possible for two electrons to be in same state

Example: two identical twins can't be in same room

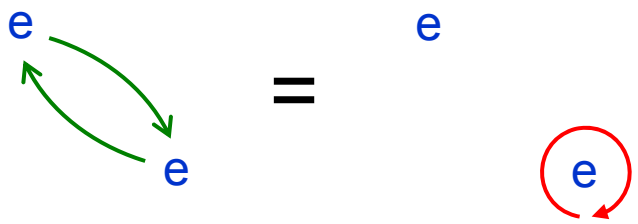
two identical electrons can't be in same state



Spin-Statistics Theorem

(1) All electrons are identical, so no change in physics when exchange

(2) Exchange of 2 electrons = rotate by 360°



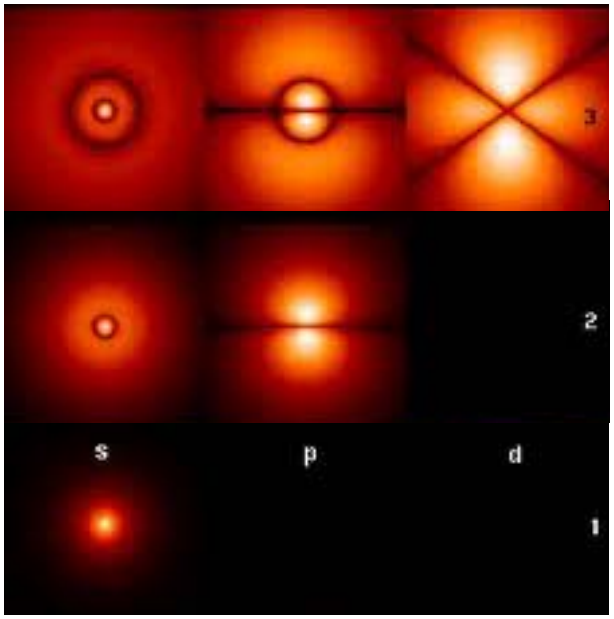
(3) When rotate

Boson: photon: $X \rightarrow X \exp[\, i\, 2\pi\, (\, 1\,)\,] = +X$

Fermion: electron: $X \rightarrow X \exp[\, i\, 2\pi\, (1/2)\,] = -X$

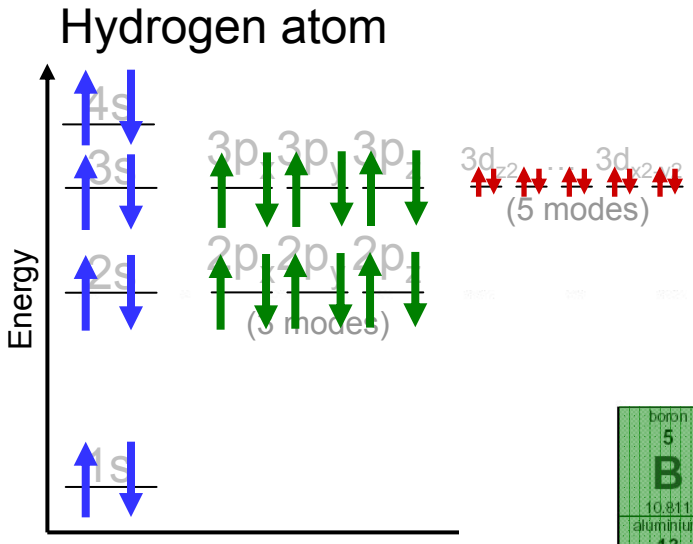
spin statistics

(4) Statistics: Solution of X = -X is X=0
corresponds to no state



Building the Periodic Table

Electrons will interact with each other, but fills mostly according to energy of H atom

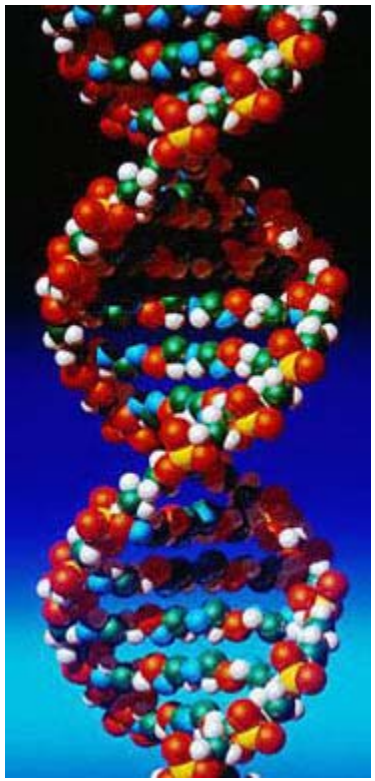


hydrogen 1 H 1.0079																	helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122											boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305											aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078	scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62	yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 ✶	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 ✶ ✶	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	ununnium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]			

Why is Natural World so Rich in Structure?

Quantum mechanics gives atoms size

Wide variety of chemical bonds

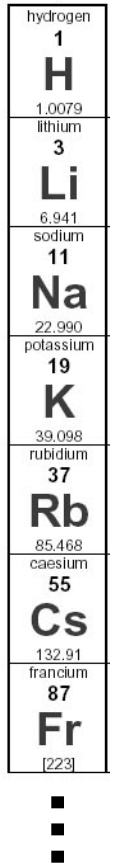


Electric force is only radial ($1/r^2$)
Where did directionality of chemical bonds come from?

Exclusion principle forces population of states
in p, d …, gives directional (rich) bonding properties

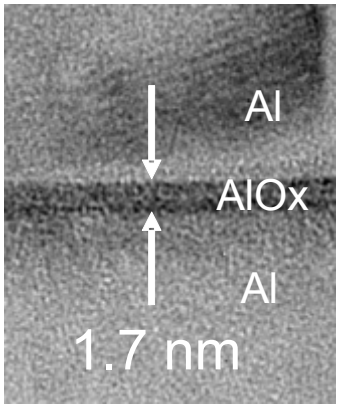
Without exclusion principle:

All states would be 1s, only H type chemistry

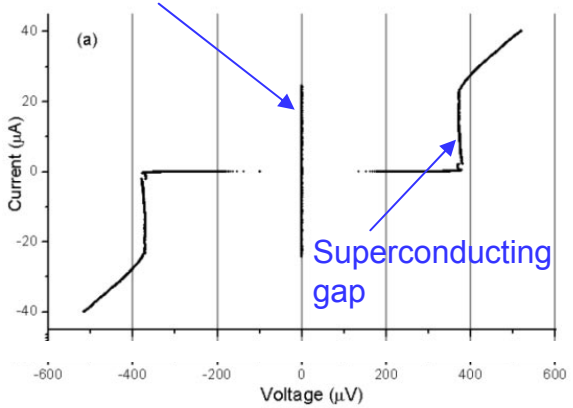


Quantum in Electronics: Tunneling

Tunnel junction:

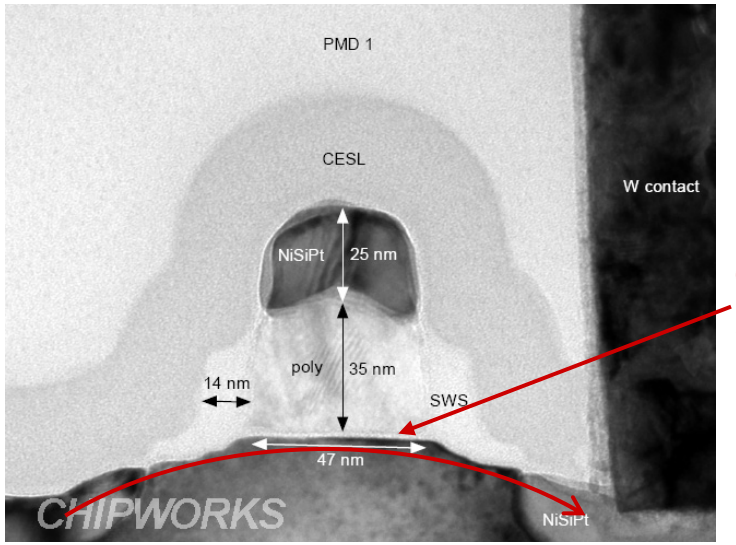


Current flow
without resistance



1973 Nobel Prize:
Esaki, Giaever, Josephson

Modern Transistor:



gate
capacitor

current flow

Quantum mechanics describes physics of silicon

Suppress quantum tunneling thru gate with high K insulators

Quantum Mechanics

Fundamental particles (quarks, electrons)
Nuclei (protons, neutrons)
Atoms
Molecules
Metals
Crystals
Superconductors

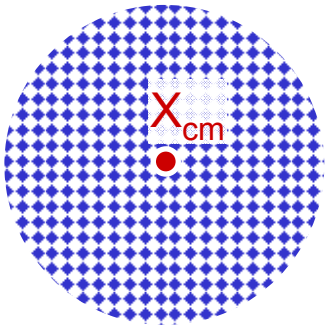
} QM observable on macro scale

A.J. Leggett (1980):
Do macroscopic variables obey quantum mechanics?

Macroscopic Variables

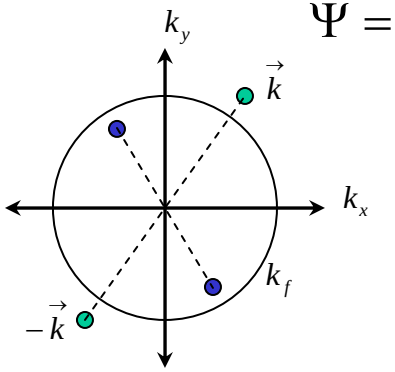
Single degree of freedom describing state of macroscopic number of atoms/electrons

Center of mass of ball
(single variable describes position)



Would ball tunnel through wall?

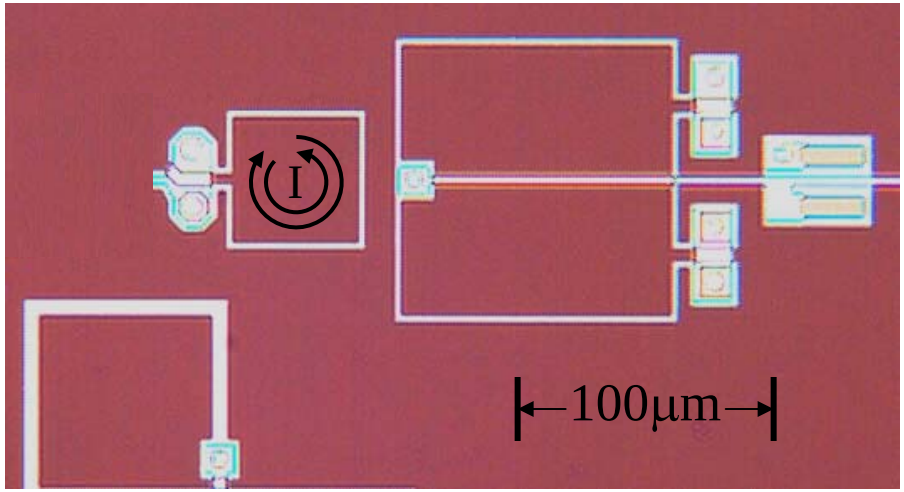
Phase of superconductor
(Single phase for all Cooper pairs)



$$\Psi = \prod_k \left(u_k + v_k e^{i\phi} c_k^+ c_{-k}^+ \right) \left| \Psi_0 \right\rangle$$

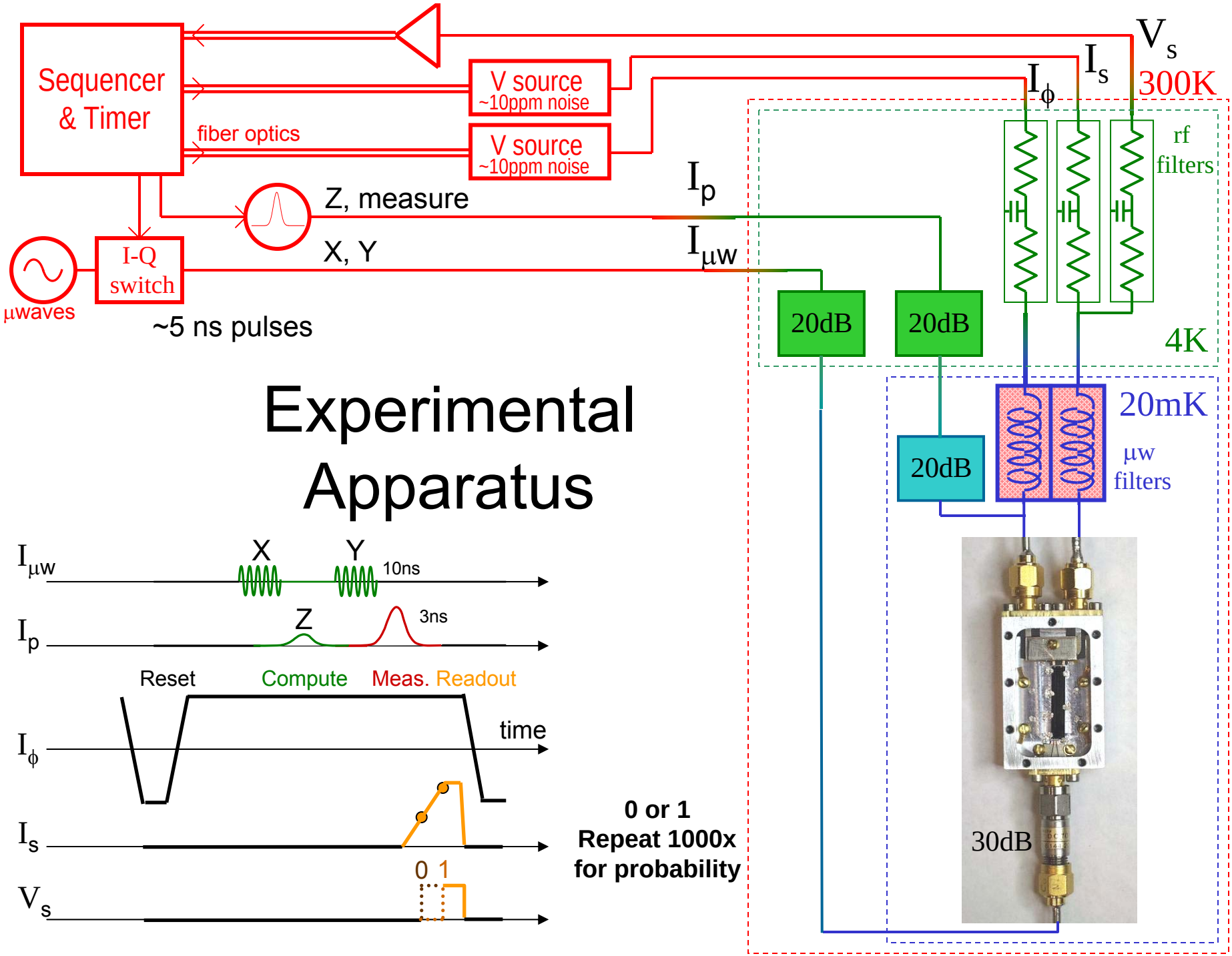
$$I \propto \nabla \phi$$

Single variable sets current

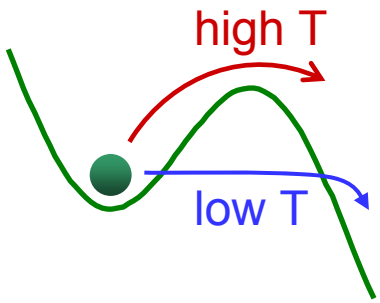


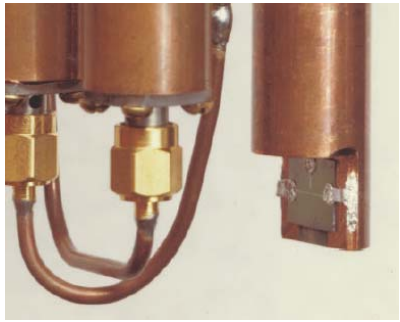
Quantum circuit:
I described by QM

Experimental Apparatus

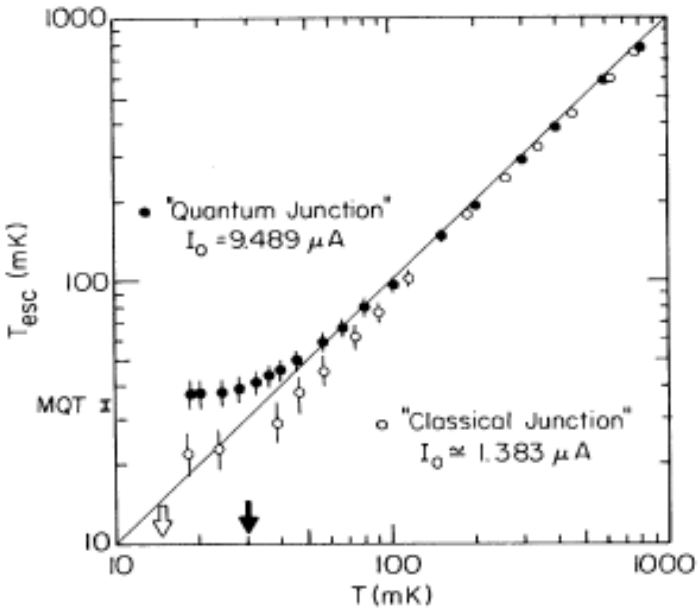


Demonstration of Macroscopic Quantum Mechanics





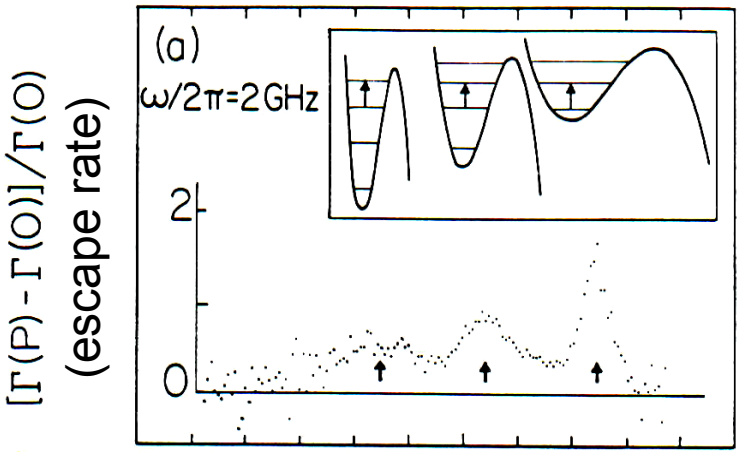
Quantum Tunneling



Quantized Energy Levels

Inject microwave photons

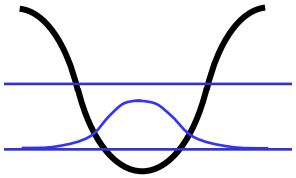
UC Berkeley: Martinis, Devoret, Clarke;
PRL **55**, 1543 (1985)



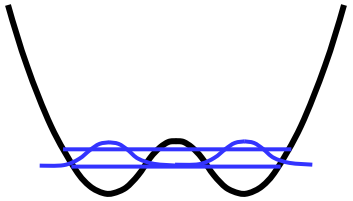
junction bias current

Period Table of SC Qubits

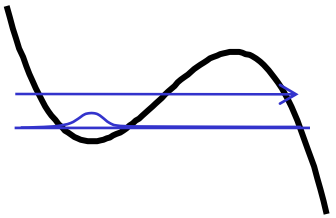
Charge

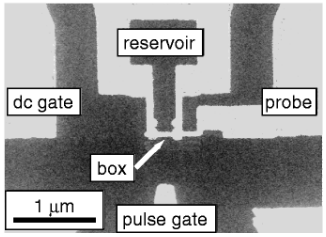


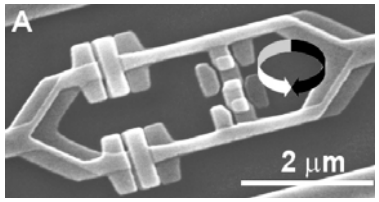
Flux

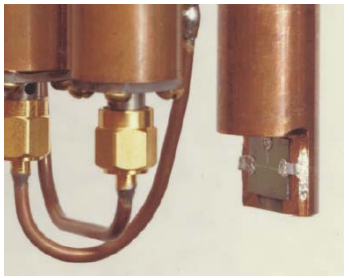


Phase

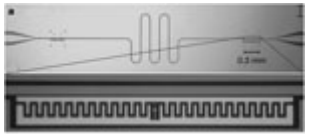






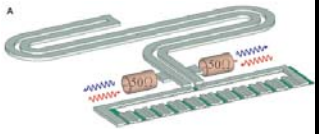


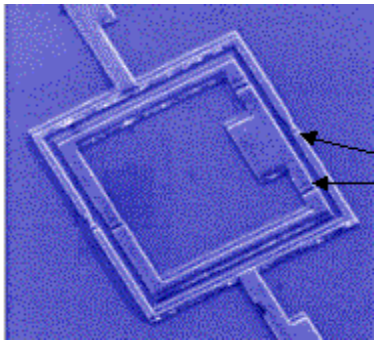
Tr
transmon

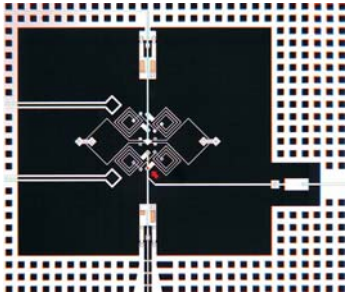


Qu
quantronium

Fx
fluxonium





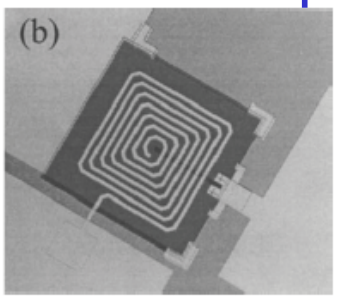


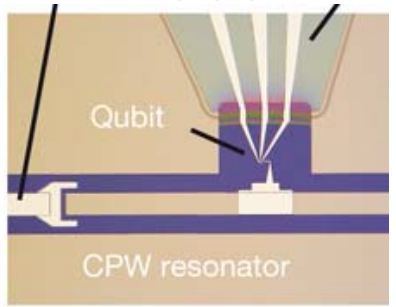
Quantum Integrated Circuits

Photonics

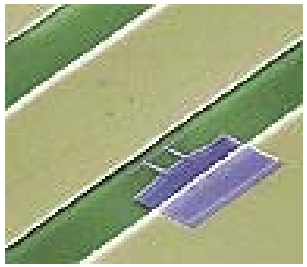
Q-limit amp

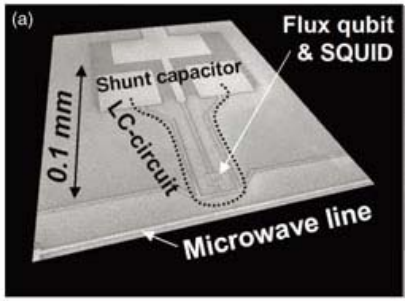
Maser

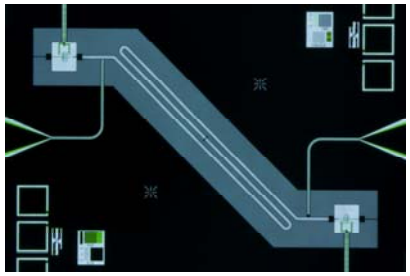




Resonator

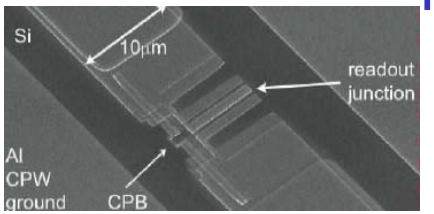


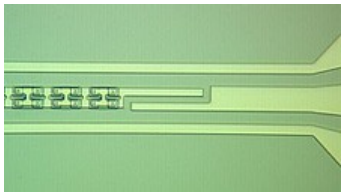




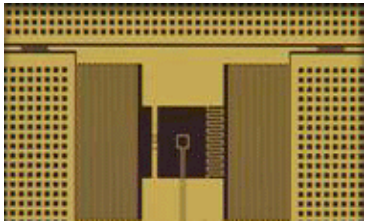
Bifurcation-amp

Paramp

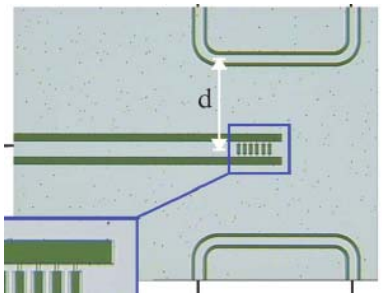


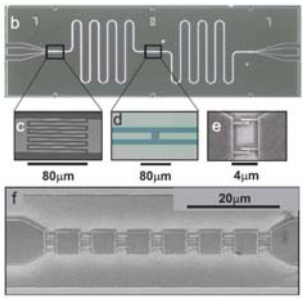


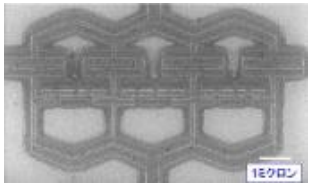
"Molecules"

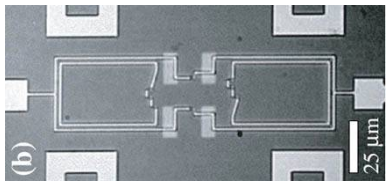


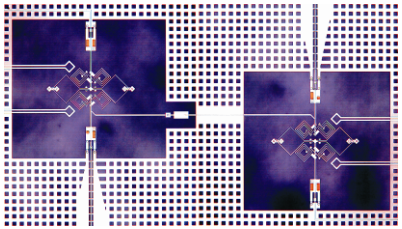
Tunable resonator

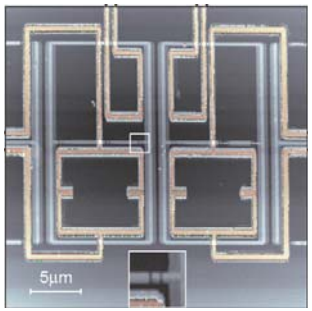


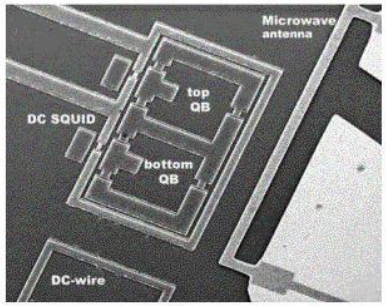


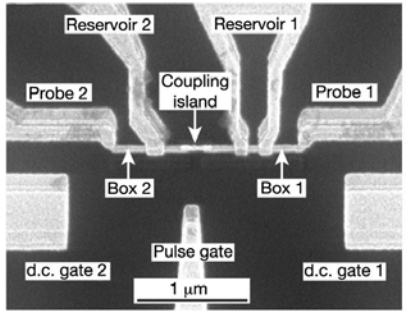


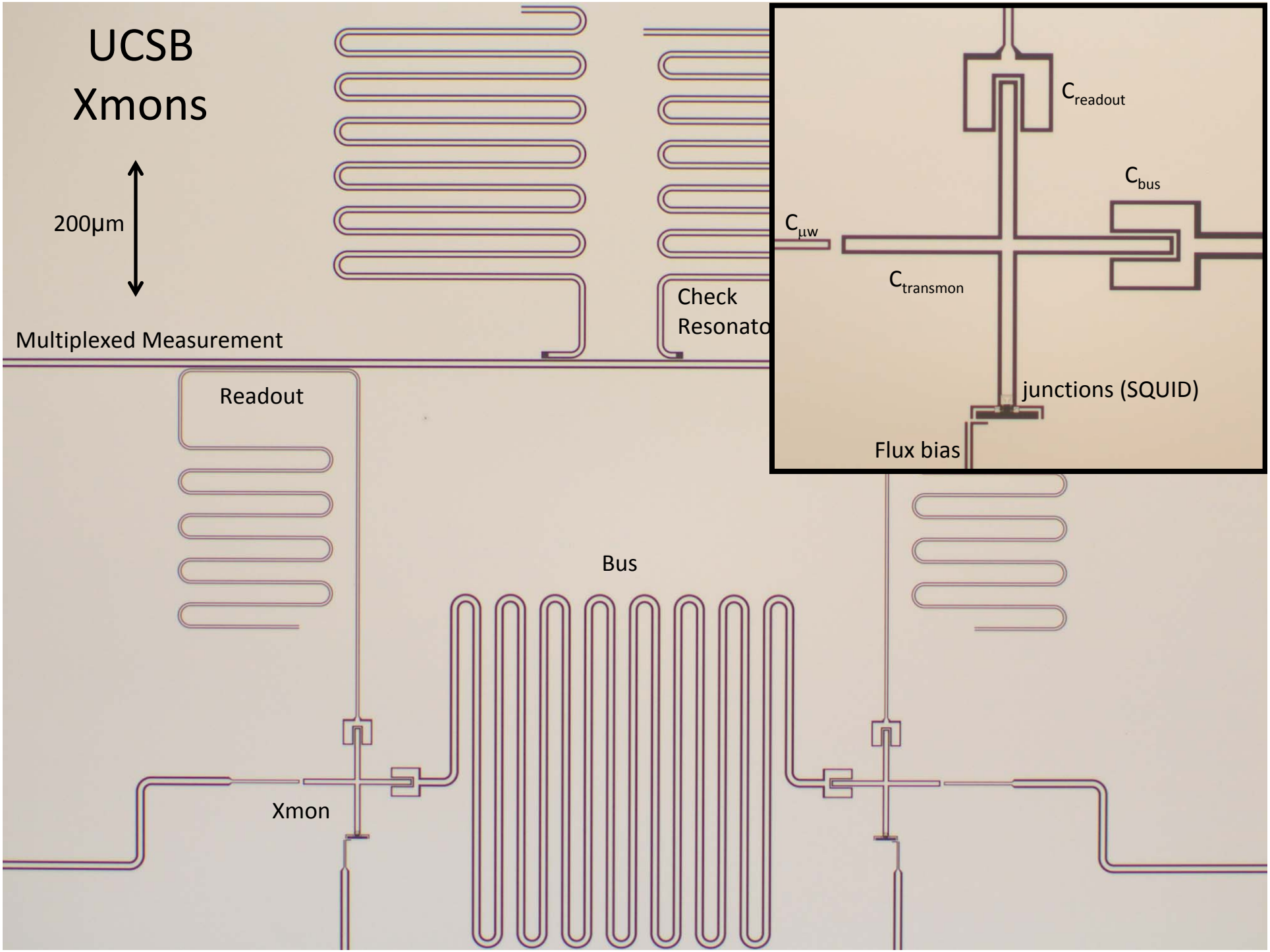











UCSB
Xmons
200μm
Multiplexed Measurement
Check
Resonato
Readout
Bus
Xmon
$C_{readout}$
C_{bus}
$C_{\mu w}$
$C_{transmon}$
junctions (SQUID)
Flux bias

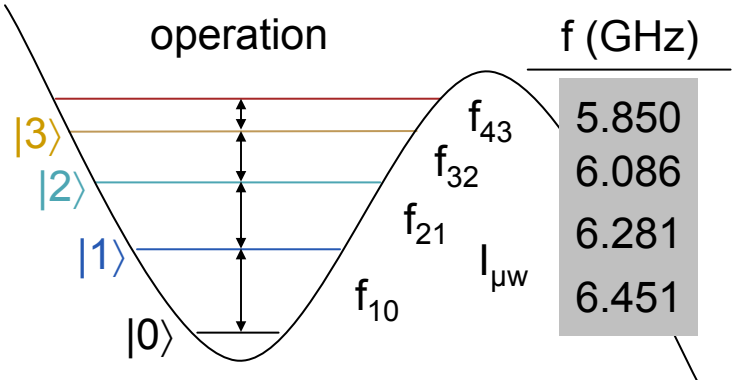
Emulation of Spins with a Quantum Circuit

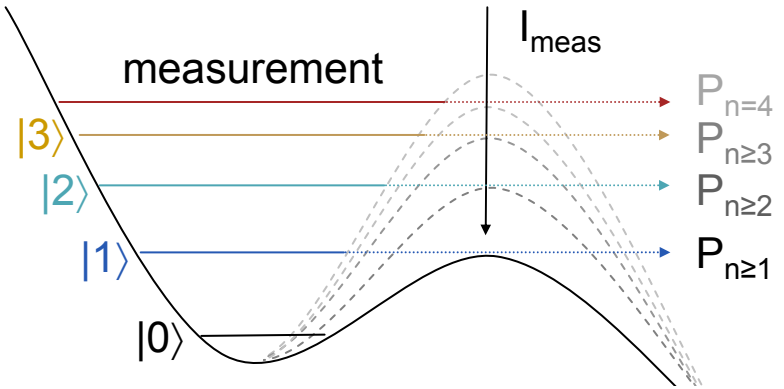
Hardware can emulate higher spin number (transitions at unique frequencies)

(1) Demonstrate spin rotation

(2) Measure spin parity (2π rotation)

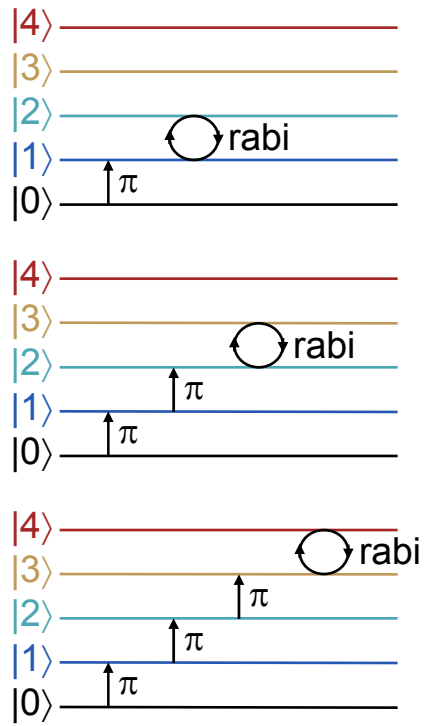
States	Number	Spin	Statistics	Parity
$\|0\rangle,\|1\rangle$	2	1/2	"Fermion"	-1
$\|1\rangle,\|2\rangle$	2	1/2	"Fermion"	-1
$\|0\rangle,\|1\rangle,\|2\rangle$	3	1	"Boson"	+1
$\|1\rangle,\|2\rangle,\|3\rangle$	3	1	"Boson"	+1
$\|1\rangle,\|2\rangle,\|3\rangle,\|4\rangle$	4	3/2	"Fermion"	-1

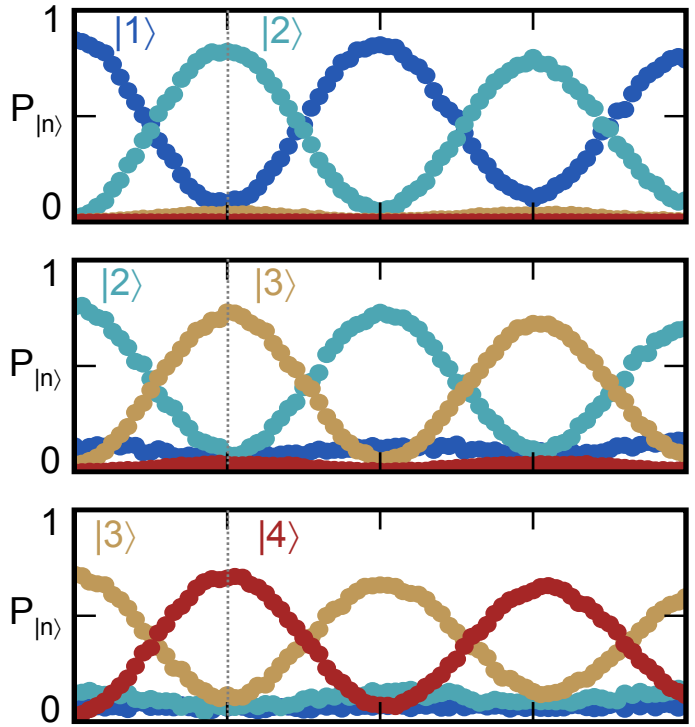




State Rotations

Calibration

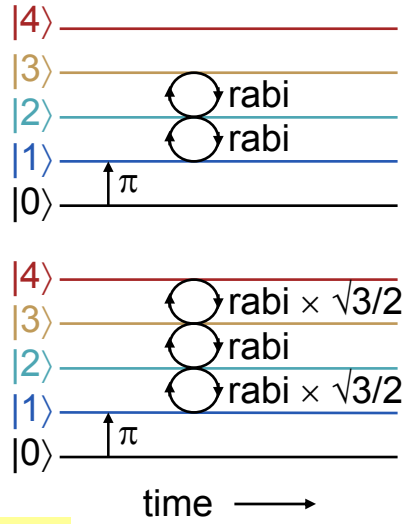


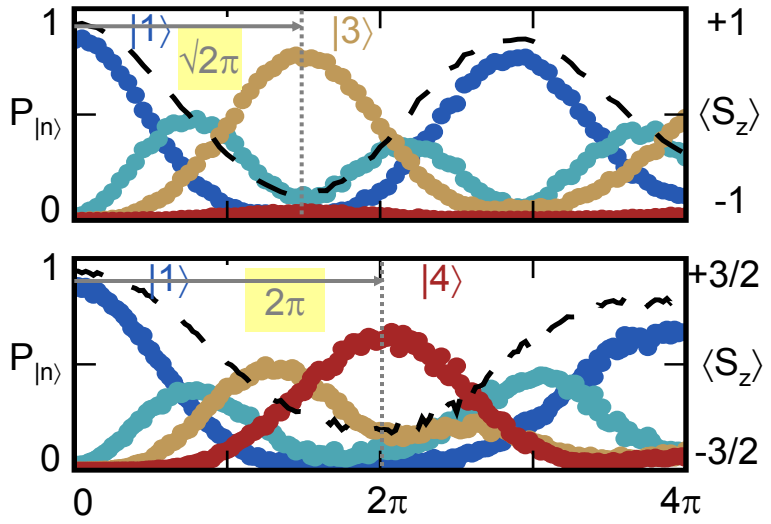


Emulation

S = 1

S = 3/2





Rotation rate agrees with theory

Measurement of Parity from 2π Rotation

π/2 ← Ramsey fringe → π/2

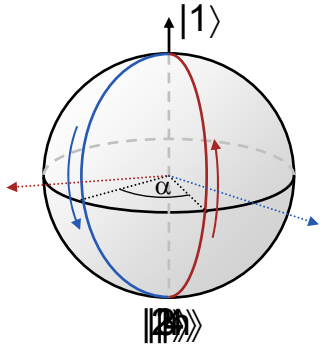
$|0\rangle \rightarrow |0\rangle + |1\rangle$

$+1: \ |0\rangle + |1\rangle \rightarrow |1\rangle$

$-1: \ |0\rangle - |1\rangle \rightarrow |0\rangle$

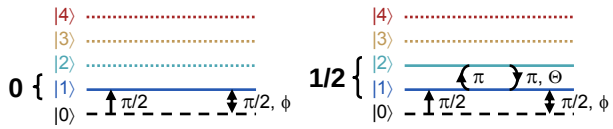
phase reference

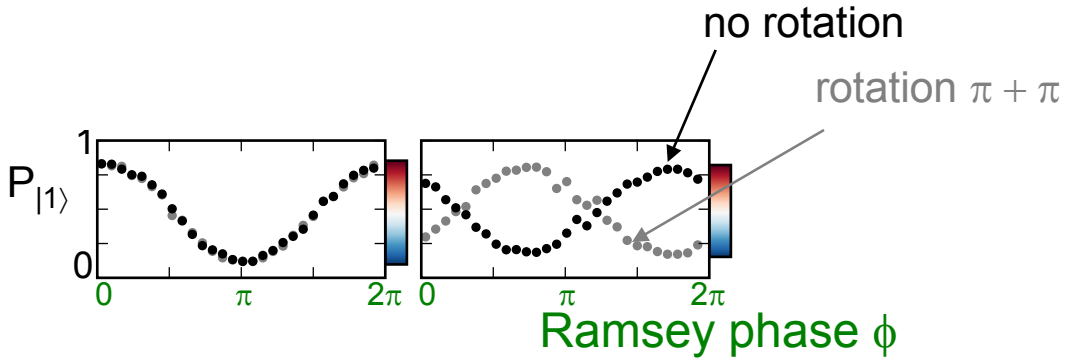
2π rotation



S = 0 (check)

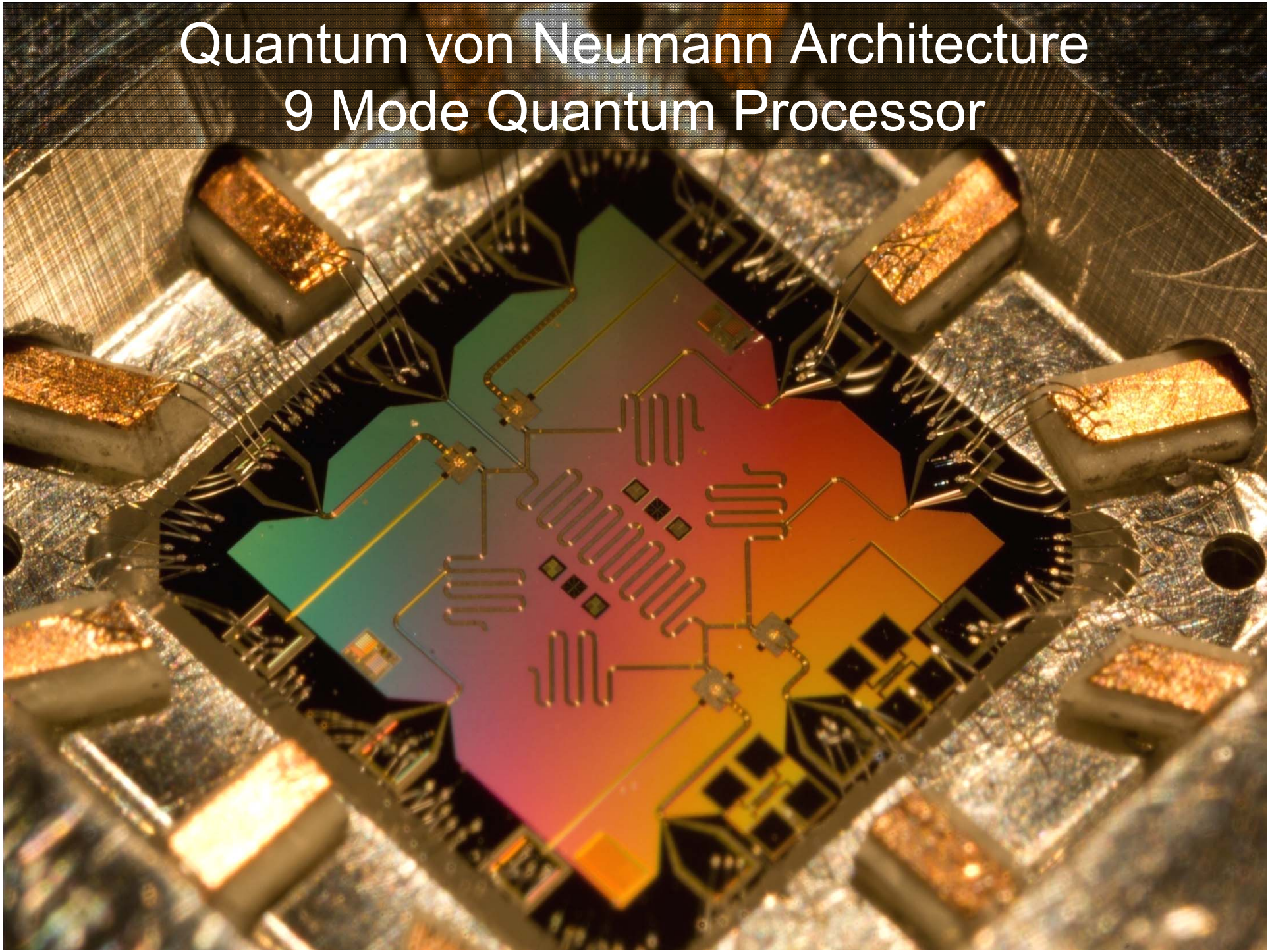
S = 1/2





Parity: (+1) -1

Quantum von Neumann Architecture
9 Mode Quantum Processor



Quantum Behavior of Mechanical Resonators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