

Physics of Quantum Information: qubits, entanglement, measurement & decoherence



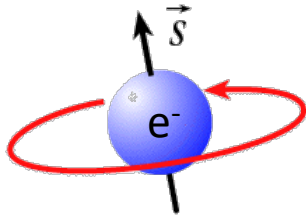
Antoine Browaeys
LCF, Institut d'Optique



Thomas Ayrat
CPHT, Ecole Polytechnique

Quantum theory = a precisely-tested theory...

Magnetic moment of the electron



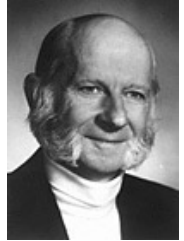
$$\frac{\mu_{\text{exp}}}{2\mu_B} = 1.001\,159\,652\,180\,\underline{73}(28)$$

$$\frac{\mu_{\text{theo}}}{2\mu_B} = 1.001\,159\,652\,153\,\underline{4}(240)$$



1989

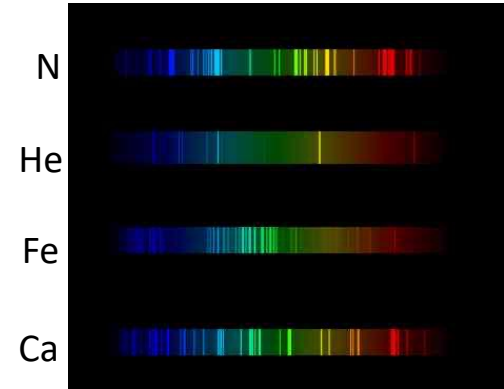
H. Dehmelt



Spectroscopy of atoms

Ex: Hydrogen $f_{1s-2s}^{\text{exp}} = 2\,466\,061\,413\,187\,\underline{018}(11)$ Hz

$$f_{1s-2s}^{\text{theo}} = 2\,466\,061\,413\,187\,\underline{103}(46)$$
 Hz



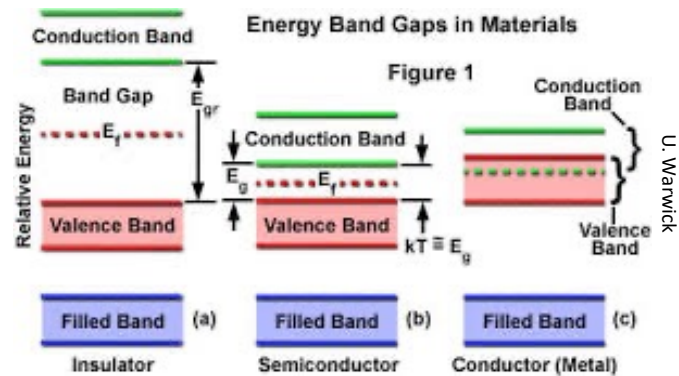
International system of units

$$\hbar = 6.62607004 \times 10^{-34} \text{ kg.m}^2/\text{s} \quad \text{now exact (2019)!}$$

Nucleus

1 H Hydrogen 1.00794																	2 He Helium 4.002602																		
3 Li Lithium 6.941	4 Be Beryllium 9.012182																	5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00643	8 O Oxygen 15.999	9 F Fluorine 18.998403	10 Ne Neon 20.1797												
11 Na Sodium 22.98976928	12 Mg Magnesium 24.304	13 Al Aluminum 26.9815385	14 Si Silicon 28.08558	15 P Phosphorus 30.9737615	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.948											19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.630	33 As Arsenic 74.9216	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90584	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium 98	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.9055	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.757	52 Te Tellurium 127.6	53 I Iodine 126.905	54 Xe Xenon 131.29																		
55 Cs Cesium 132.90545196	56 Ba Barium 137.327	57 La Lanthanum 138.90547	58 Ce Cerium 140.12	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.242	61 Pm Promethium 144.9127	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92532	66 Dy Dysprosium 162.50015	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.967	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.222	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.9804	84 Po Polonium 209	85 At Astatine 210	86 Rn Radon 222				
87 Fr Francium 223	88 Ra Radium 226	89-103 Actinides																104 Rf Rutherfordium 261	105 Db Dubnium 262	106 Sg Seaborgium 266	107 Bh Bohrium 264	108 Hs Hassium 277	109 Mt Meitnerium 268	110 Ds Darmstadtium 271	111 Rg Roentgenium 272	112 Cn Copernicium 285	113 Uut Ununtrium 284	114 Fl Flerovium 289	115 Uup Ununpentium 288	116 Lv Livermorium 293	117 Uus Ununseptium 294	118 Uuo Ununoctium 294			

Atoms & chemistry



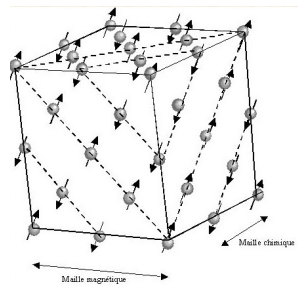
Band structures



superfluidity



superconductivity



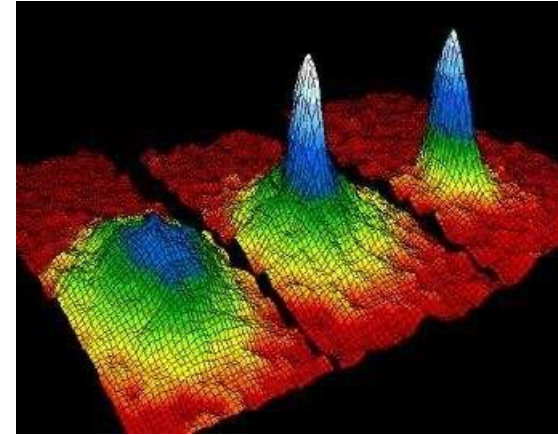
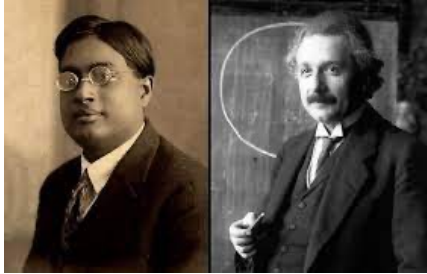
magnetism



neutron star

With predictive power...

Bose-Einstein condensate: prediction 1924 / experiment 1995

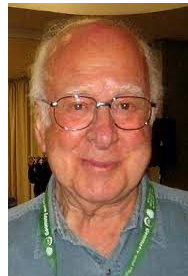


Existence of the Higgs boson

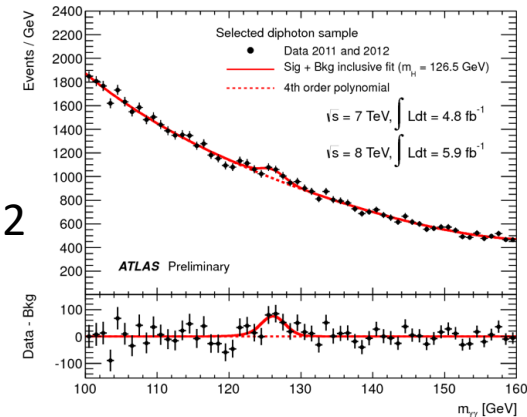
Predicted 1960's



2013



CERN
2011-2012



And with many, many, many... applications...

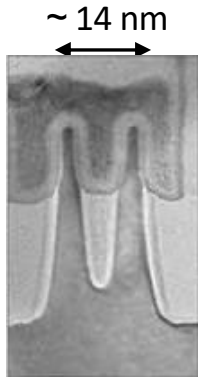


laser

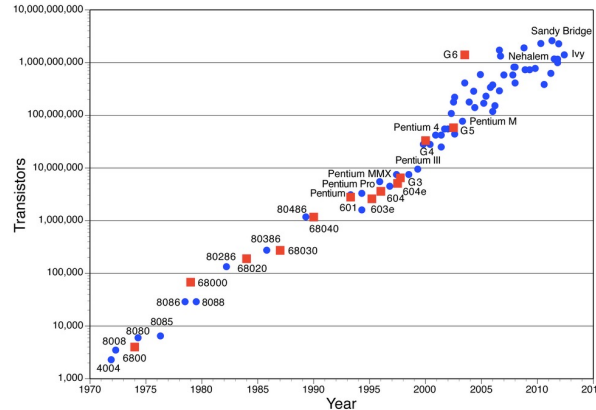


Information world

Transistors



Intel
2015



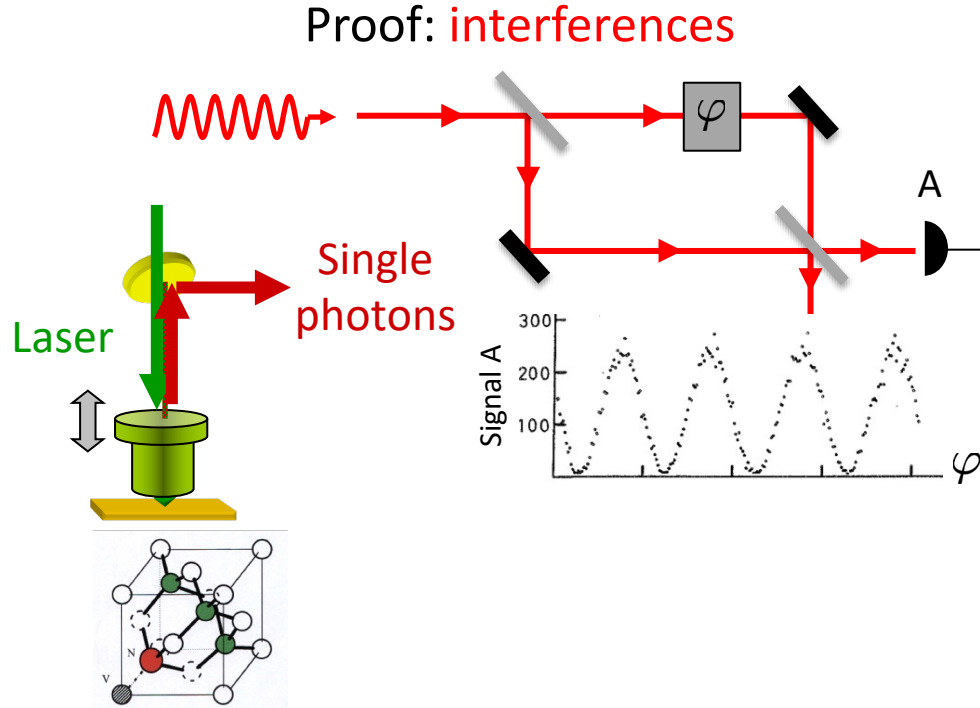
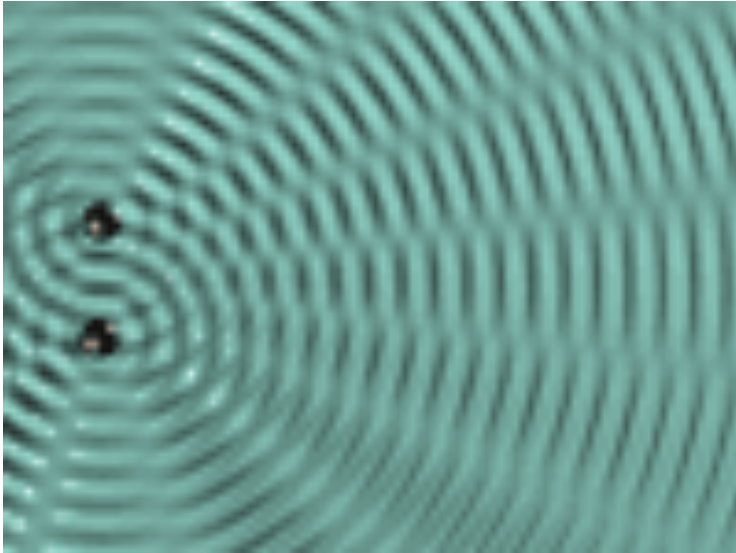
NMR



The essence of quantum physics: superposition

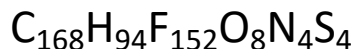
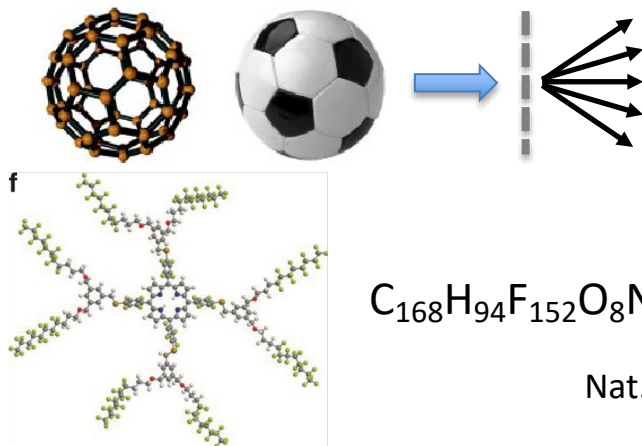
Quantum objects can be in
several states at the same time...

$$\psi = \psi_1 + \psi_2$$



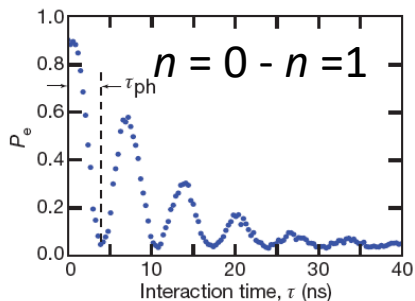
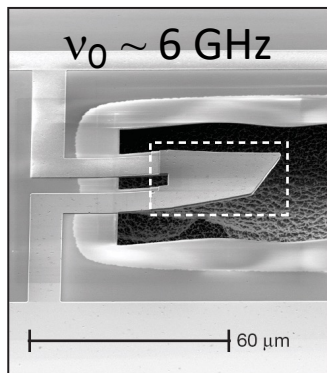
Tests of the superposition principle: examples

Atoms, molecules...



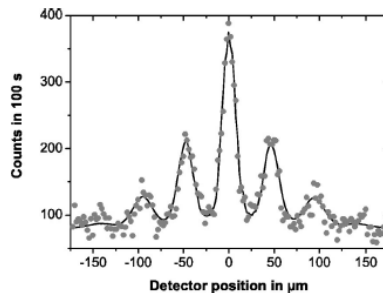
Nat. Comm. 2013

Nanomechanical resonator



Nature **464**, 697 (2010)

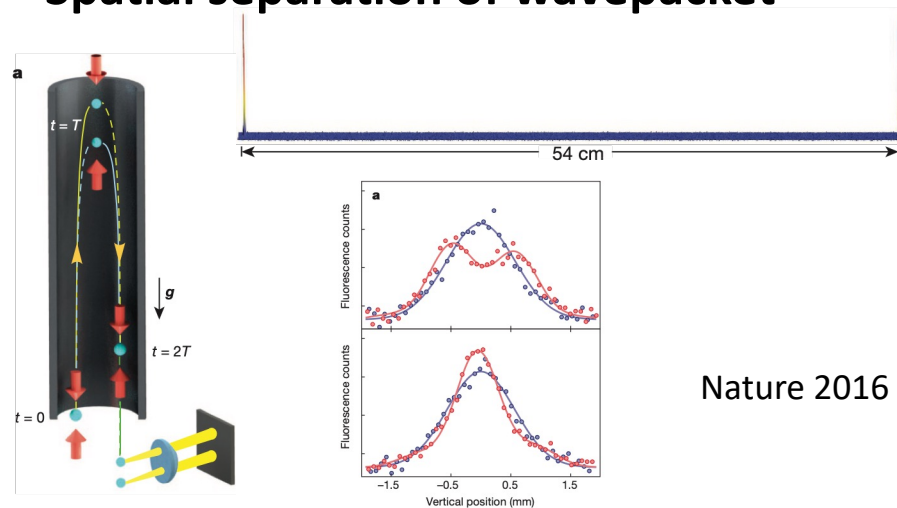
Nature 1999



Electrons



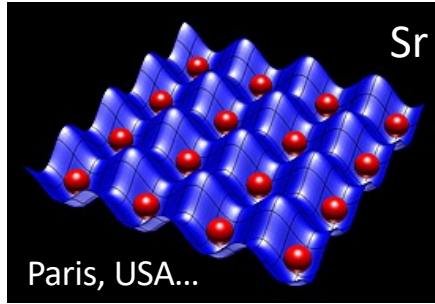
Spatial separation of wavepacket



Nature 2016

The superposition principle in our daily lives...

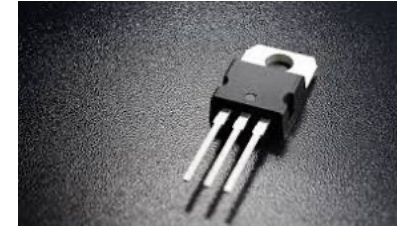
Atomic clock



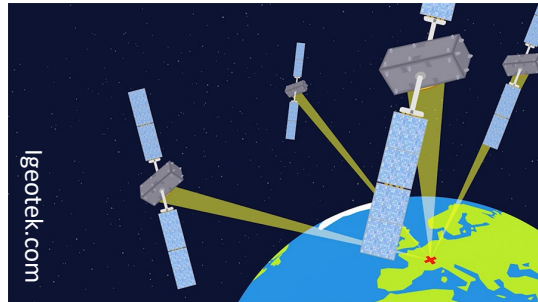
Magnetic resonance
imaging



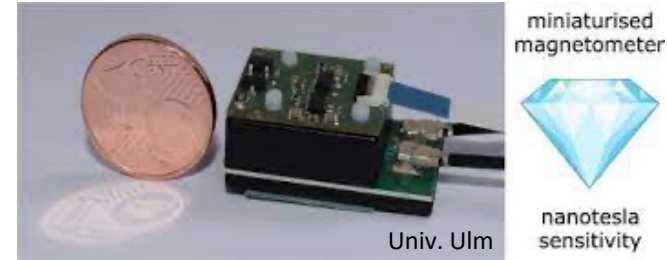
transistors



GPS

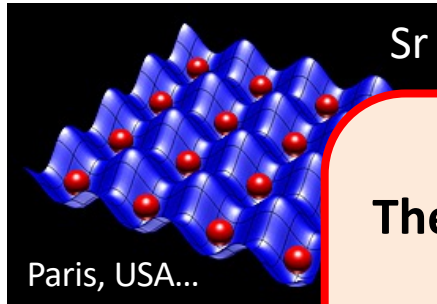


Sensors: gravity, rotation, magnetic field...



The superposition principle in our daily lives...

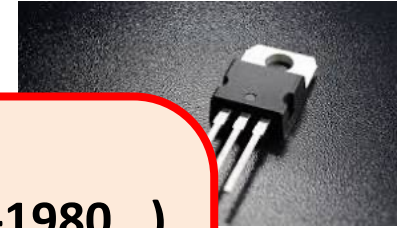
Atomic clock



Magnetic resonance
imaging



transistors



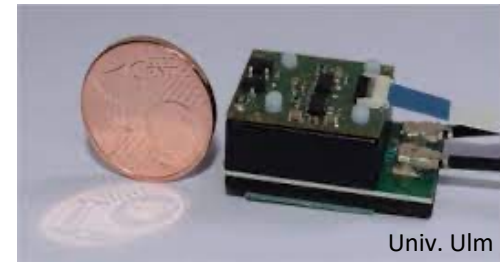
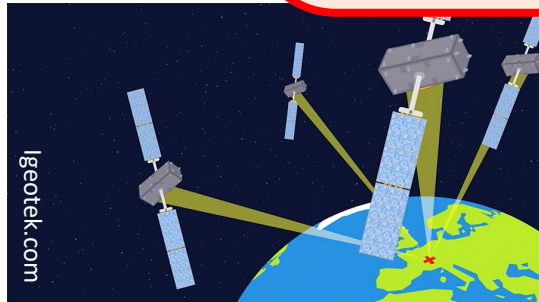
The First Quantum Revolution (1920-1980...)

SUPERPOSITION

(at the individual particle level...)



...magnetic field...



miniaturised
magnetometer

nanotesla
sensitivity

Superposition principle for 2 objects $\Rightarrow$ entanglement



MAY 15, 1935

PHYSICAL REVIEW

VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

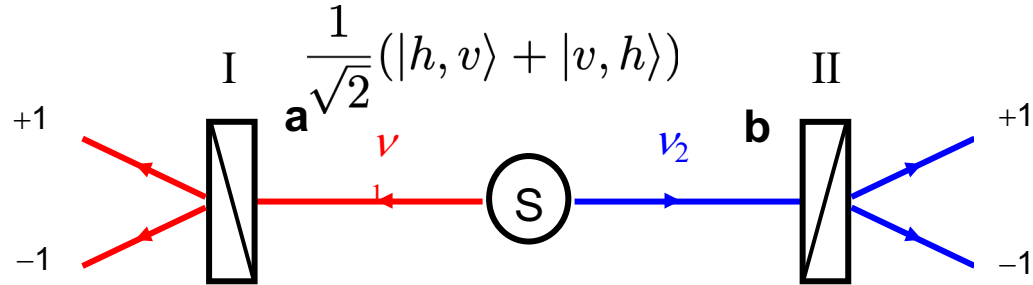
A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)



1964

J. Bell



Strong quantum correlations!!



2022

VOLUME 49, NUMBER 25

PHYSICAL REVIEW LETTERS

20 DECEMBER 1982

Experimental Test of Bell's Inequalities Using Time-Varying Analyzers

Alain Aspect, Jean Dalibard,^(a) and Gérard Roger

Institut d'Optique Théorique et Appliquée, F-91406 Orsay Cédex, France

(Received 27 September 1982)

« There is plenty of room at the bottom ...»



R.P. Feynman

“There's Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics”

R.P. Feynman, Caltech (1959)

Problem: exponential complexity

2 d. of freedom (spin...) $\psi_i = \begin{pmatrix} a \\ b \end{pmatrix}$

Many-body wavefunction: $\Psi = \Psi(1, 2, \dots, N) \Rightarrow \Psi$ requires 2^N numbers

Record *ab-initio* calculation (2026) $N \sim 50 \Rightarrow 2^{50} \sim 10^{15} = \text{1000 Tb RAM !!}$

Worldwide computer memory (2026): 10 zetabytes (10^{22}) $\Rightarrow N \sim 70 !!$

Huge challenge to calculate complex quantum systems

BUT... opportunity if properly harnessed

Isolating & manipulating single quantum particles

The point of view of a founding father...

In the first place it is fair to state that we are not *experimenting* with single particles, anymore than we can raise Ichtyosauria in the zoo.

...., this is the obvious way of registering the fact, that we **never** experiment with just **one** electron or atom or (small) molecule. In thought-experiments we sometimes assume that we do; this invariably entails **ridiculous** consequences.



E. Schrödinger
British Journal of the Philosophy
of Science III (10), (1952)

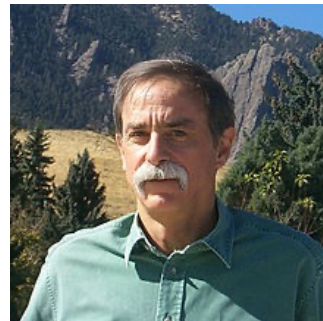
60 years later...



2012



S. Haroche (France)

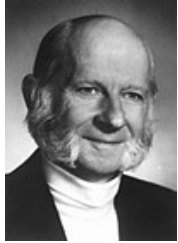


D. Wineland (USA)

"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"

Trapping individual particles: the early days...

H. Dehmelt

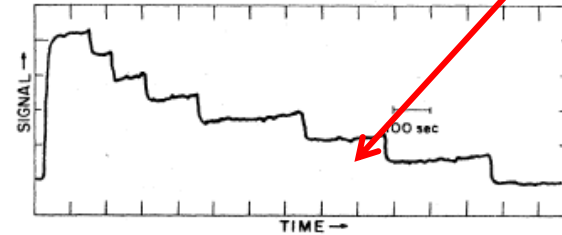


1989

VOLUME 31 19 NOVEMBER 1973 NUMBER 21

Monoelectron Oscillator

D. Wineland, P. Ekstrom, and H. Dehmelt
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 13 August 1973)



Single electron

W. Paul: ion trapping techniques



1st single ion

PHYSICAL REVIEW A

VOLUME 22, NUMBER 3

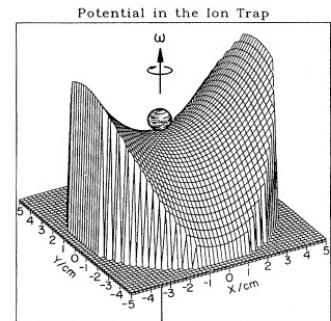
SEPTEMBER 1980

Localized visible Ba^+ mono-ion oscillator

W. Neuhauser, M. Hohenstatt, and P. E. Toschek
Institut für Angewandte Physik I der Universität Heidelberg, D-69 Heidelberg, Federal Republic of Germany

H. Dehmelt

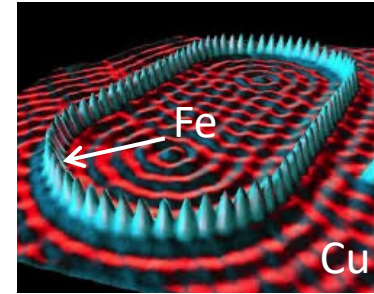
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 11 September 1979)



Today, we can « see » atoms

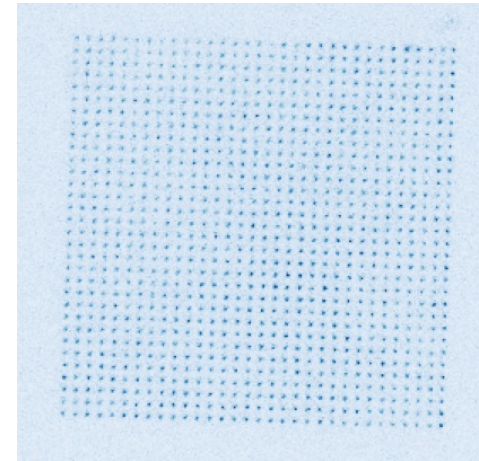
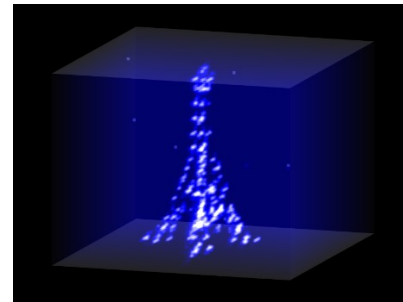
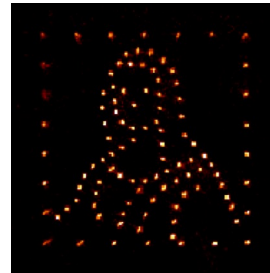
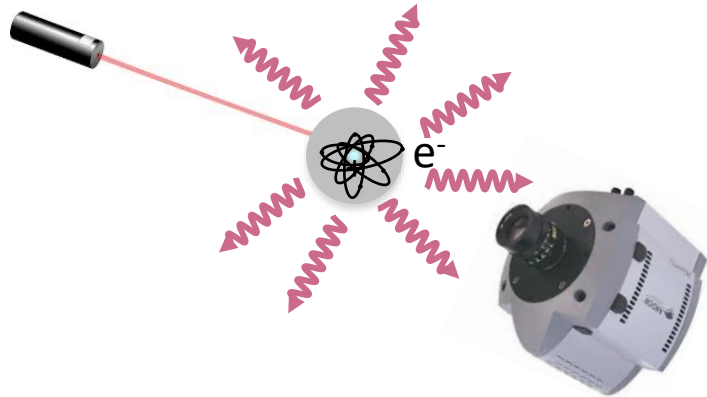
Scanning tunnel microscope (IBM, 1981)

« see » electronic cloud



 Pasqal

Light scattered by a **single atom**: see directly...



1024 atoms

The second Quantum Revolution (1990 - ...)

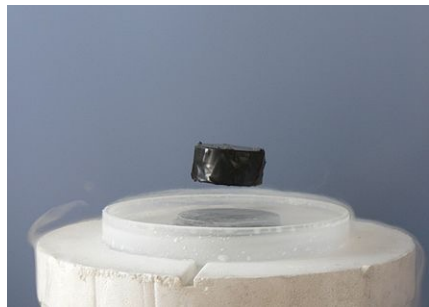
Entanglement

+

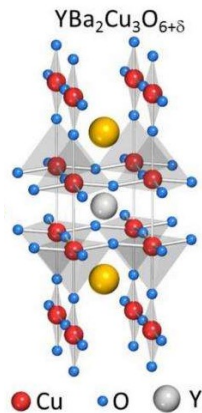
Manipulation of individual
quantum systems

Quantum state engineering: create controlled quantum states

Quantum Simulation



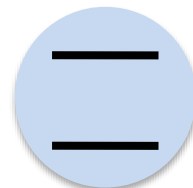
YBaCuO



Quantum metrology



^{133}Cs



F=4

F=3

1 sec = 9 192 631 770 cycles

$$\frac{\Delta\nu}{\nu_0} \propto \frac{1}{\sqrt{N}} \xrightarrow{\text{qu. states}} \frac{\Delta\nu}{\nu_0} \propto \frac{1}{N}$$

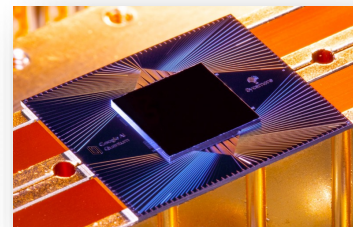
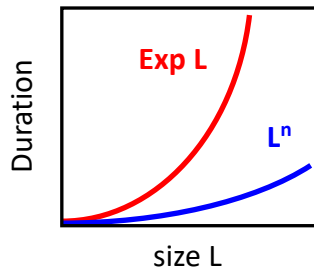
Quantum Communication



Message

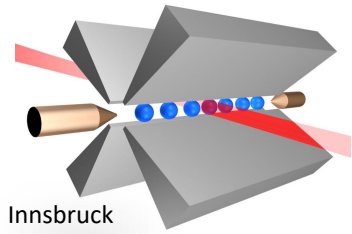


Quantum Computation

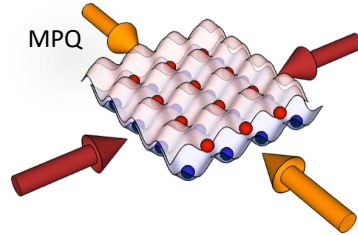


Sycamore processor, Google Inc.

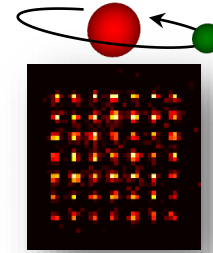
Engineering with individual quantum systems



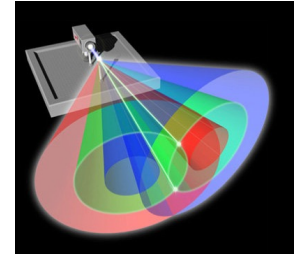
Trapped ions



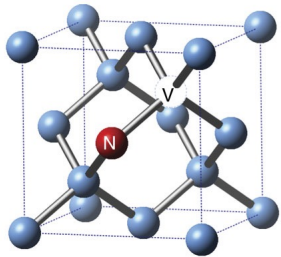
Cold atoms & molecules



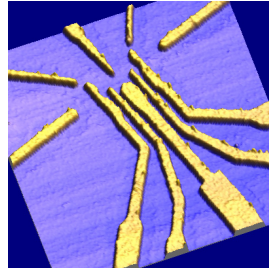
Rydberg atoms



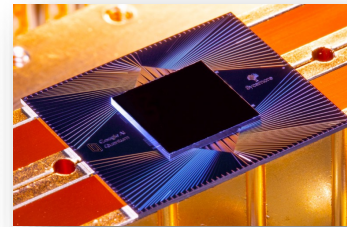
Photons



NV center, SiV

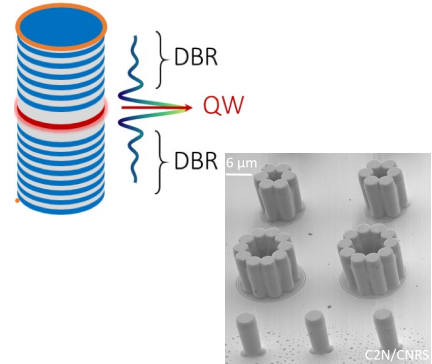


Quantum dots



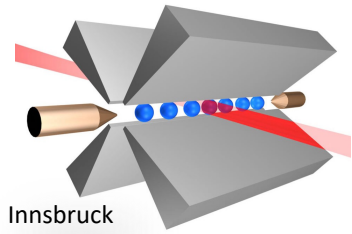
Sycamore processor, Google Inc.

Superconducting circuits

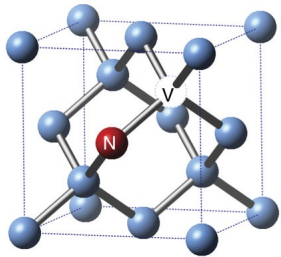


Polaritons in semiconductors

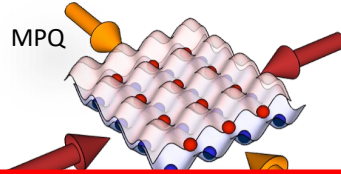
Engineering with individual quantum systems



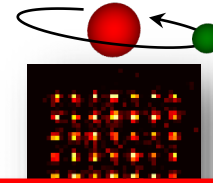
Trapped ions



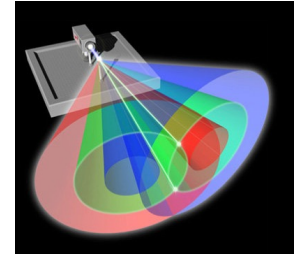
NV center, SiV



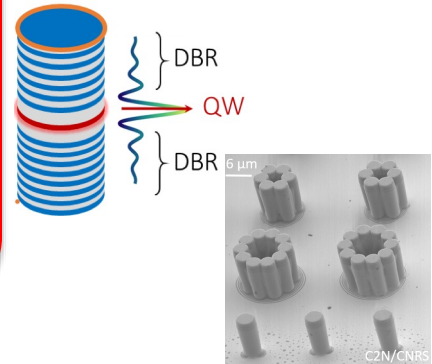
Quantum dots



Superconducting
circuits



Photons

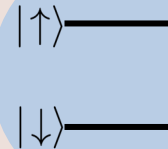


Polaritons in semi-
conductors

Two-level systems to encode a spin:

Cold atoms &
molecules

Rydberg atoms

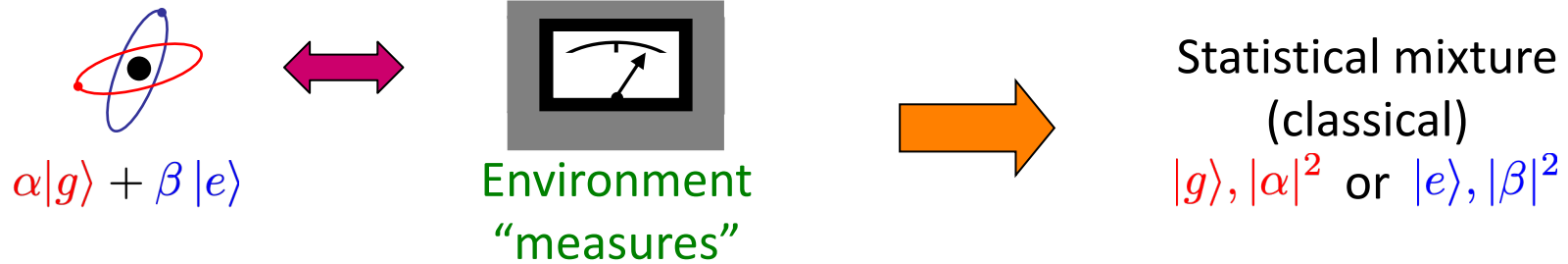


Addressable + **controlled** interactions

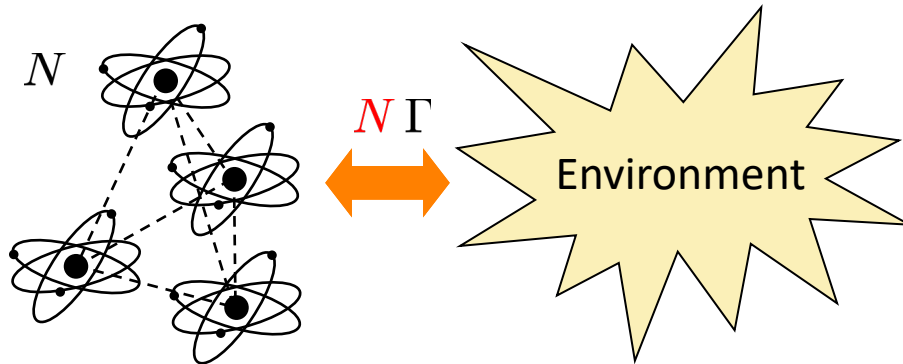
Sycamore processor, Google Inc.

Why is it so difficult?

Quantum superposition = **very fragile!!** Decoherence



The larger, the more decoherence...

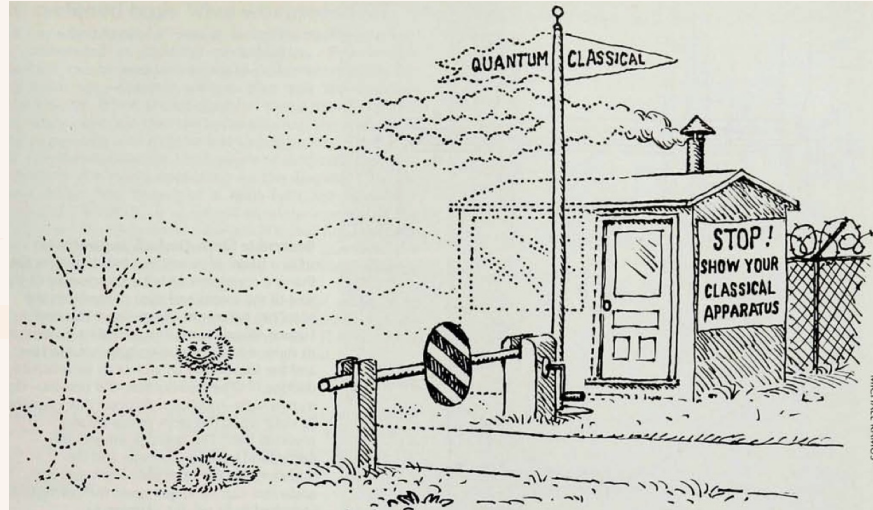
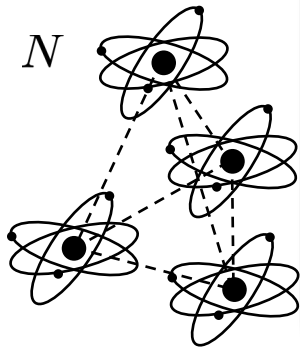


Why is it so difficult?

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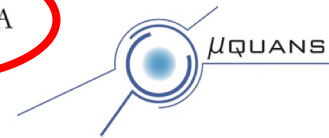
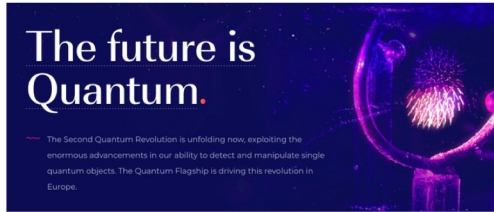
Transition quantum / classical ?



Zurek, Physics Today 1991



Academia, many industrial players and startups



Many job opportunities for you...!

Objectives of this course

Understand the **concepts** of the Second Quantum Revolution
= **modern presentation** of quantum physics

Discuss recent experiments using **quantum technologies**
= understand opportunities, challenges and... “dreams”...

Main topics:

- Qubits and harmonic oscillators in practice
- Entanglement and its characterization
- Measurements in quantum physics
- Description of open quantum systems
- Decoherence and transition to classicality
- Stochastic wavefunction methods

Warning note: what this course is *not* about...

Not a course on Quantum Information:

No discussion of quantum algorithms

No discussion of error correction codes

No profound discussion on information theory...

More details in specialized courses (semester 2)

Experimental Quantum Computing & QEC
Quantum communication & cryptography, Ultra-cold atoms
and quantum simulation,
Manipulation of simple quantum systems

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