Петербургский Университет, Петергоф, НИИФ, Кафедра квантовой механики

Fundamental Symmetries, Atomic Clocks and Quantum Computers

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NSF

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Applications of Atomic Calculations

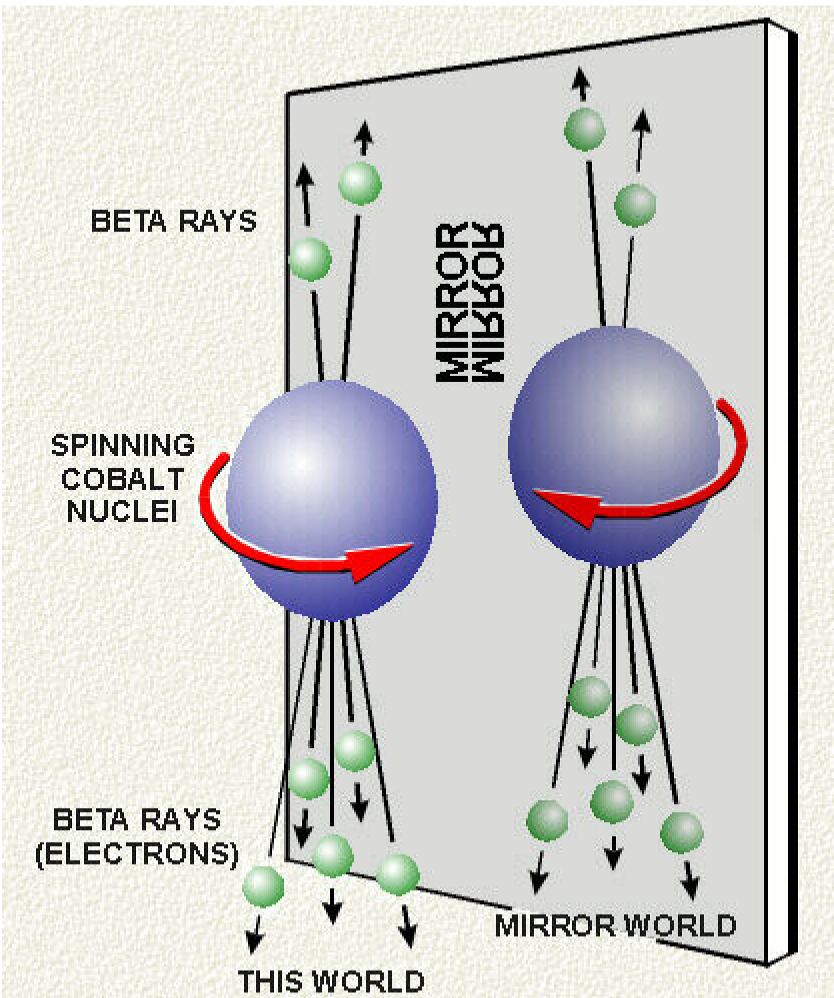
- **Study of fundamental symmetries with atoms**
  - **Parity violation: tests the of Standard Model**
  - **Parity violation: study of weak hadronic interactions**
  - **Search for permanent elector electric-dipole moment**
  - **Search for variation of fundamental constants**
- **Atomic clocks**
- **Quantum computers**
- **Development of high-precision atomic methodologies**
- Web site: www.physics.udel.edu/~msafrono

Transformations and Symmetries

Translation	→	Momentum conservation
Translation in time	→	Energy conservation
Rotation	→	Conservation of angular momentum
[C] Charge conjugation	→	C-invariance
[P] Spatial inversion	→	Parity conservation (P-invariance)
[T] Time reversal	→	T-invariance
[CP]		
[CPT]		

Parity Violation

$$\vec{r} \to -\vec{r}$$



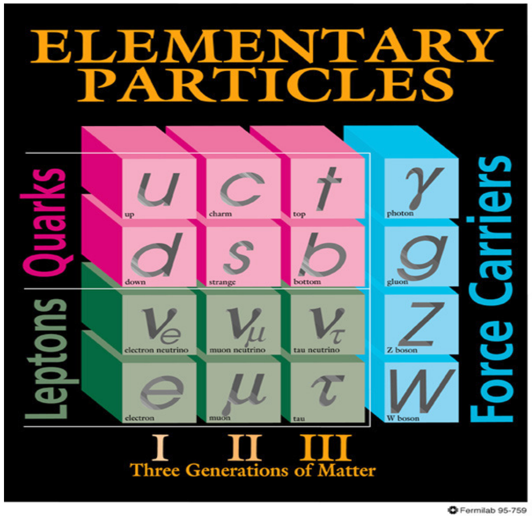
Parity-transformed world:

Turn the mirror image upside down.

The parity-transformed world is not identical with the real world.

Weak (Electr
Flavor
Quarks, Leptons
W^+ W^- Z^0
0.8
10^{-4}
10^{-7}

⇒ Parity is not conserved.



STANDARD MODEL

viewed as the exchange of mesons

PROPERTIES OF THE INTERACTIONS

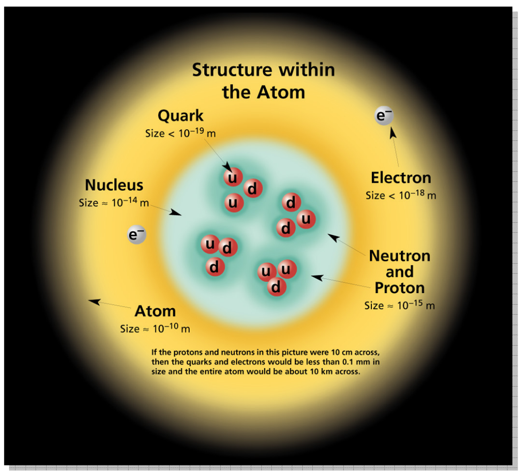
Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

PARITY VIOLATION IN ATOMS: PART 1

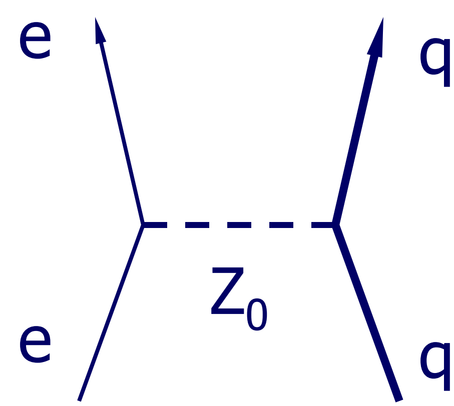
Searches for new physics beyond the Standard Model

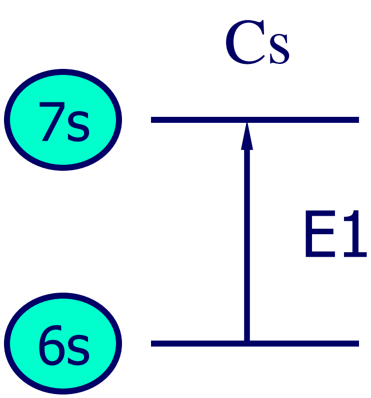
Weak Charge Q_W

$$Q_W = -N + Z(1 - 4\sin^2\theta_W)$$



Q_W quantifies the strength of the electroweak coupling between atomic electrons and quarks of the nucleus.

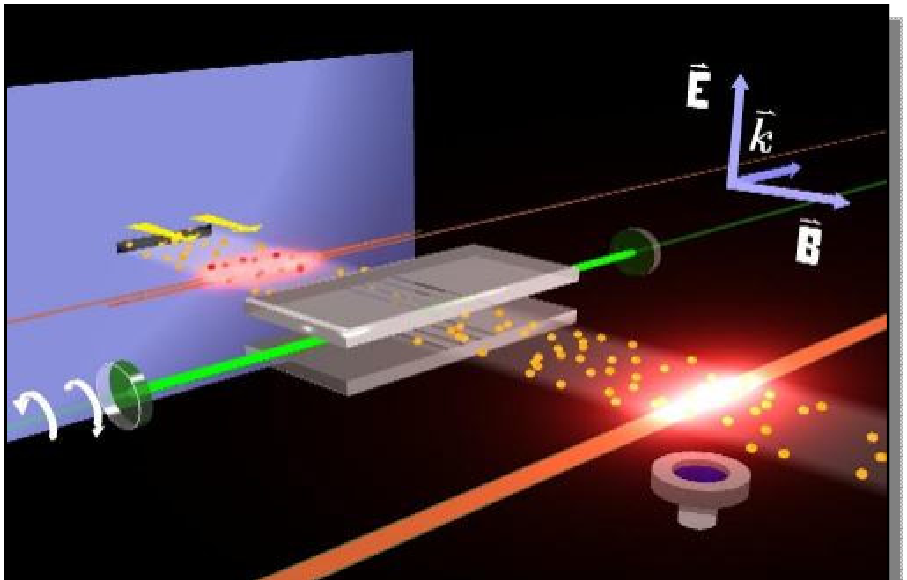




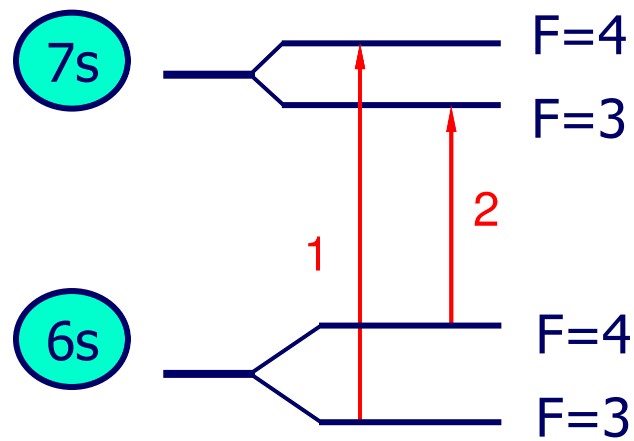
Non-zero transition amplitude
PNC amplitude E_{PNC}

The most precise measurement of PNC amplitude (in cesium)

C.S. Wood et al. Science 275, 1759 (1997)



0.3% accuracy



$$\frac{\mathrm{Im}\left(E_{\mathrm{PNC}}\right)}{\beta} = \begin{cases} -1.6349(80)\ \mathrm{mV/cm} & 1 \\ -1.5576(77)\ \mathrm{mV/cm} & 2 \end{cases}$$

NEED ATOMIC THEORY TO GET Q_W FROM THE EXPERIMENT

Reducing theory uncertainty: Why is it so difficult?

$$\left|\Psi_v\right\rangle = \Omega\left|\Psi_v^{(0)}\right\rangle$$

Exact wave function

Many-body operator,
describes excitations from lowest-order

Dirac-Hartree-Fock
wave function (lowest order)

Cs: 55 electrons → **55-fold excitations to get exact wave function**

Even for 100 function basis set → 100^{55}

Approximate methods: perturbation theory does not converge well,
Need to use all-order methods (coupled-cluster method and correlation potential method)

Atomic physics tests of the standard model, Cs nucleus

Standard Model $Q_W = -73.16(3)$

1999 analysis of Cs experiment showed 2.5σ deviation from the Standard Model

Most current result:

Atomic physics [1] $Q_W = -73.16(29)_{exp}(20)_{th}$

[1] S. G. Porsev, K. Beloy and A. Derevianko, PRL 102, 181601 (2009)

Confirms fundamental "running" (energy dependence) of the electroweak force over energy span 10 MeV → 100 GeV

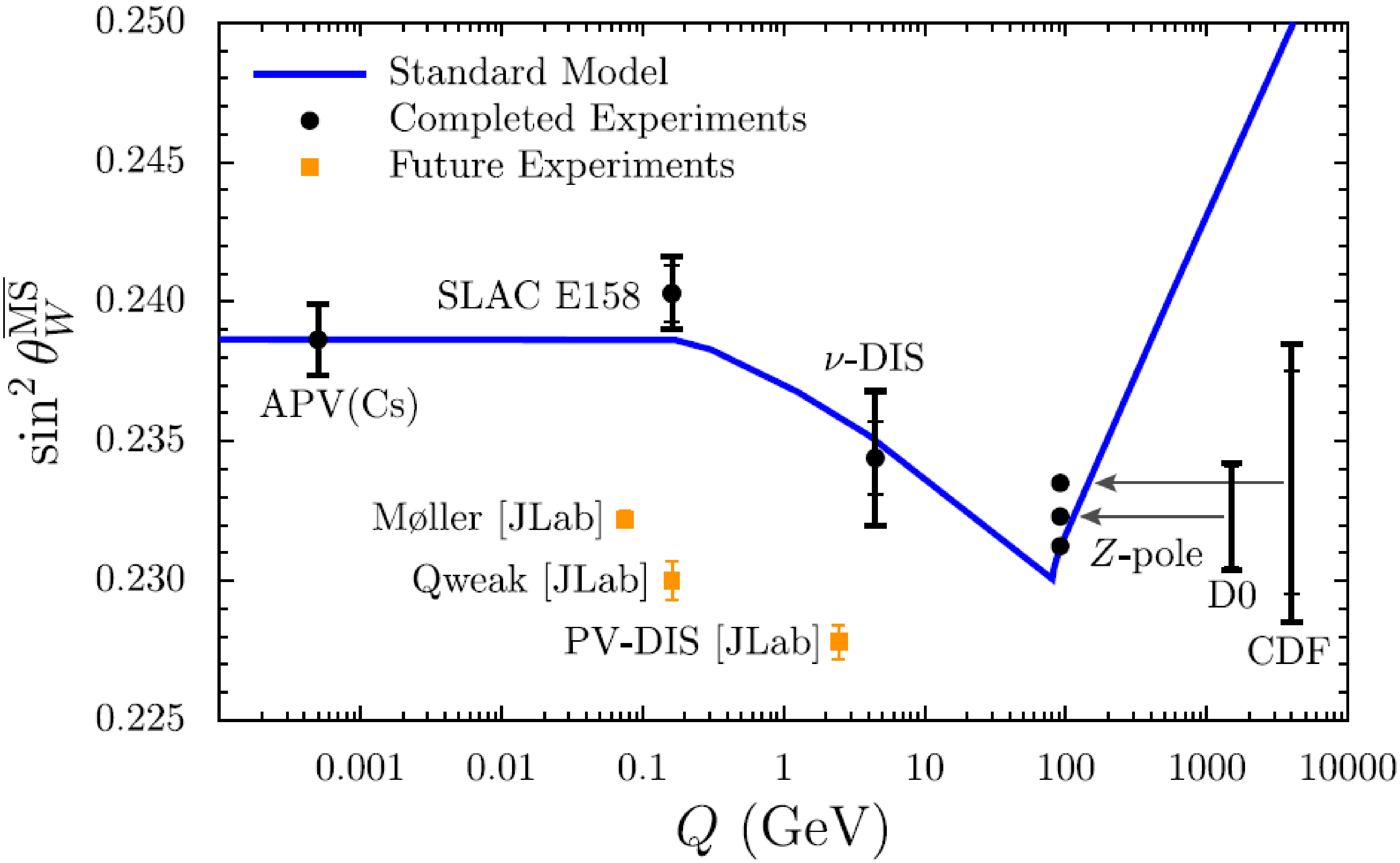
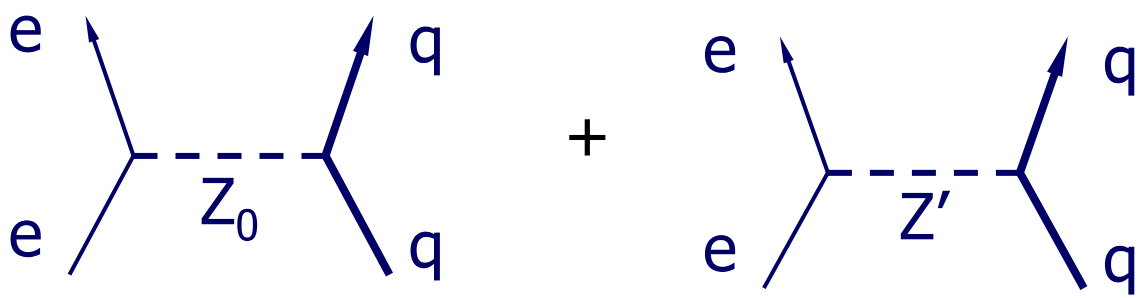


Figure is from Bentz *et al. Phys. Lett.* ***B693***, 462 (2010).

Probing new physics: extra Z bosons

Z'_χ in SO(10) GUT, Marciano & Rosner



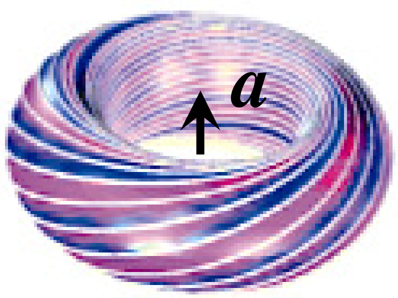
Cs result [1] implies $M_{Z'_x} > 1.3 \mathrm{TeV}/c^2$

Direct search at Tevatron collider [2]

$$M_{Z'_x} > 0.82 \mathrm{TeV}/c^2$$

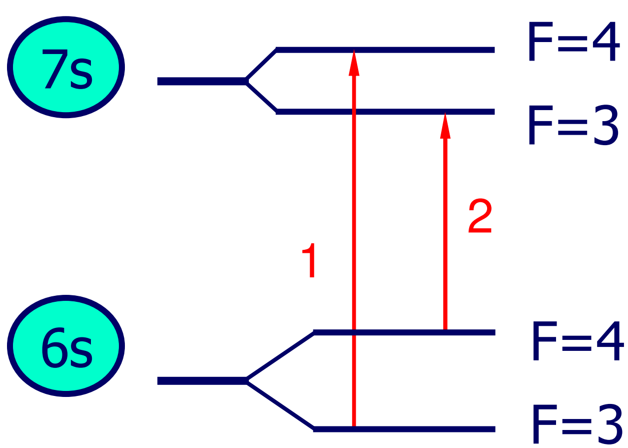
[1] S. G. Porsev, K. Beloy and A. Derevianko, PRL 102, 181601 (2009)
[2] T. Aaltonen et al., Phys. Rev. Lett. 99, 171802 (2007)

Parity violation in atoms: Part 2
Study of Weak Hadronic Interactions



Parity-violating nuclear moment

Valence nucleon density

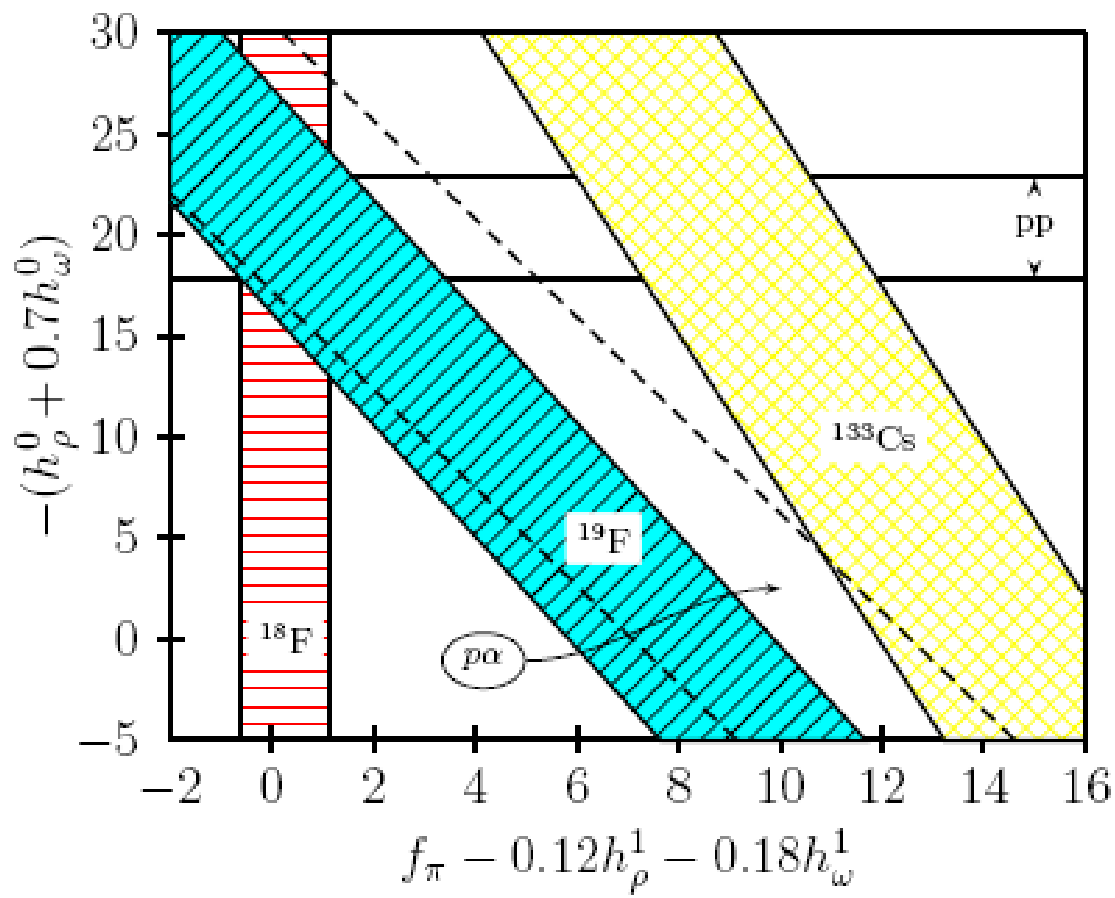


$$H^{(a)}_{\mathrm{PNC}} = \frac{G_F}{\sqrt{2}} \kappa_a \, \boldsymbol{\alpha} \cdot \mathbf{I} \; \rho_v(r)$$

Anapole moment

Nuclear anapole moment is parity-odd, time-reversal-even E1 moment of the electromagnetic current operator.

Constraints on nuclear weak coupling contants



W. C. Haxton and C. E. Wieman, Ann. Rev. Nucl. Part. Sci. 51, 261 (2001)

Nuclear anapole moment: Test of hadronic weak interations

The constraints obtained from the Cs experiment were found to be inconsistent with constraints from other nuclear PNC measurements, which favor a smaller value of the ^{133}Cs anapole moment.

All-order (LCCSD) calculation of spin-dependent PNC amplitude:

$k = 0.107(16)$* [1% theory accuracy]

No significant difference with previous value $k = 0.112(16)$ is found.

NEED NEW EXPERIMENTS!!!

Fr, Yb, Ra^+

*M.S. Safronova, Rupsi Pal, Dansha Jiang, M.G. Kozlov, W.R. Johnson, and U.I. Safronova, Nuclear Physics A 827 (2009) 411c

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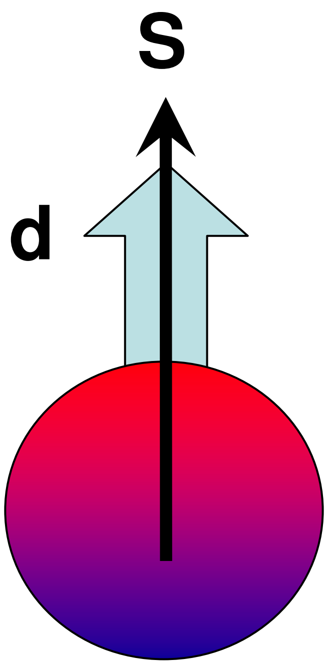
Permanent electric-dipole moment (EDM)

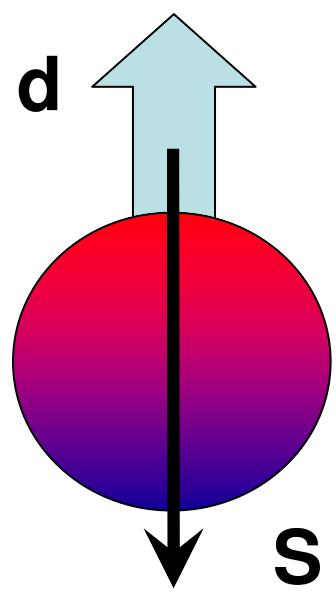
Time-reversal invariance must be violated for an elementary particle or atom to possess a permanent EDM.



$$t \to -t$$

$$\vec{\mathbf{S}} \to -\vec{\mathbf{S}}$$

$$\vec{\mathbf{d}} \to \vec{\mathbf{d}}$$

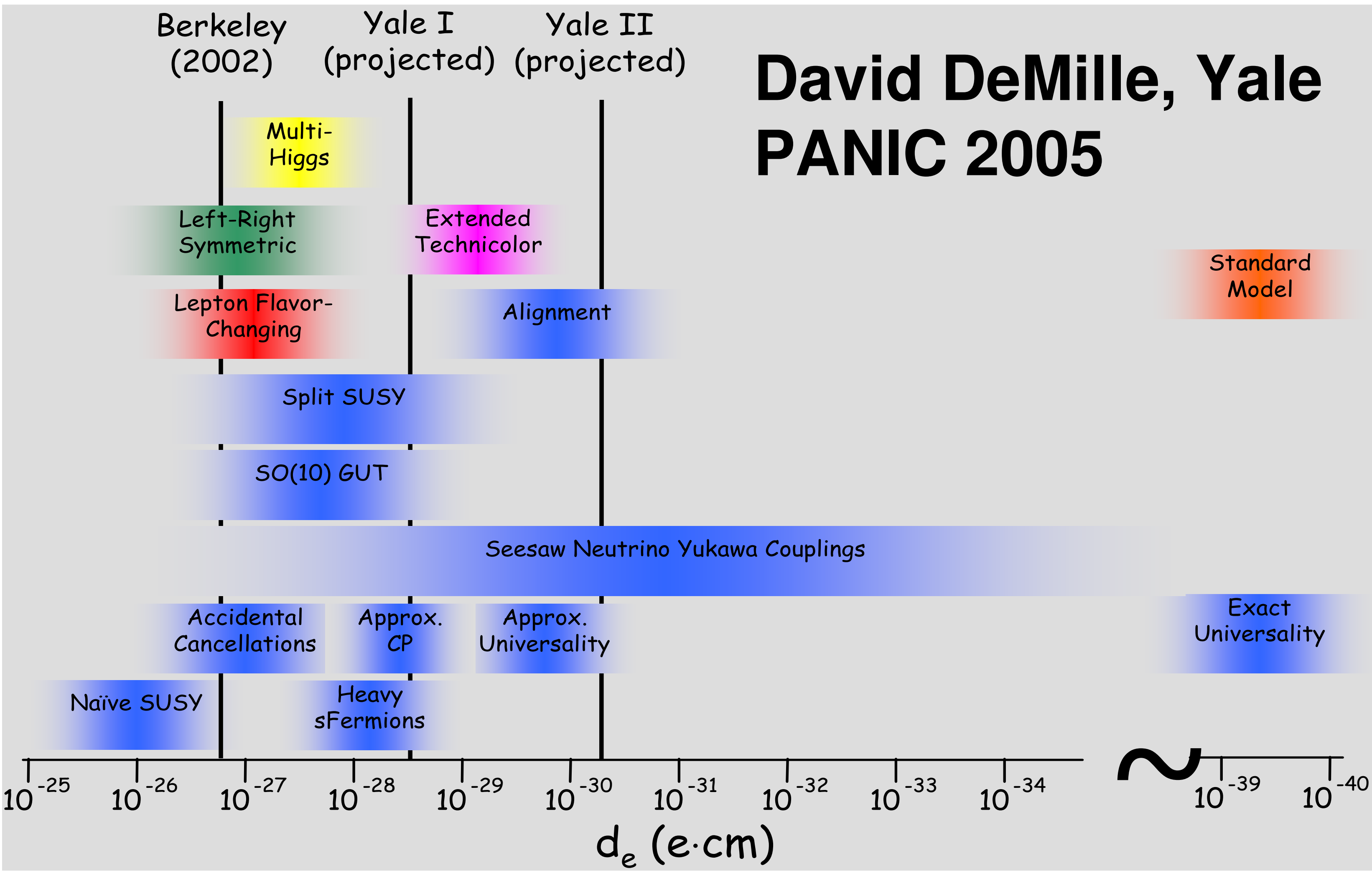


$$\vec{\mathbf{d}} = d\,\frac{\vec{\mathbf{S}}}{S}$$

$$d = 0$$

EDM and New physics

Many theories beyond the Standard Model predict EDM within or just beyond the present experimental capabilities.



Atomic calculations and search for EDM

EDM effects are enhanced in some heavy atoms and molecules.

Limits on the electron EDM

Tl atom: $|d_e| < 1.6 \times 10^{-27}$ *e* cm

Regan et al., Phys. Rev. Lett.88, 071805 (2002)

YbF molecule: $|d_e| < 1.05 \times 10^{-27}$ *e* cm

Hudson et al., Nature 473, 493 (2011)

Both results crucially depend on the calculated values of the effective electric field on the valence electron. In the case of Tl this effective field is proportional to the applied field E_0,
$E = K E_0$ and $d(^{205}\mathrm{Tl}) = K d_e$, ***K = - 585***

Summary: Tl EDM enhancement factor

Z. W. Liu and H. P. Kelly, PRA 45, R4210 (1992).

K = - 585 (30-60)

V.A. Dzuba and V. V. Flambaum, PRA 80, 062509 (2009)

K = - 582 (20)

H. S. Nataraj, B. K. Sahoo, B. P. Das, and D. Mukherjee, PRL 106, 200403 (2011)

K = - 466 (10)

S. G. Porsev, M. S. Safronova, and M. G. Kozlov, arXiv:1201.5615, Phys. Rev. Lett, in press, April 2012

K = - 573 (20) - several calculations carried out

Atomic calculations and variation of fundamental constants

(1) **Astrophysical constraints** on variation of α:
Study of quasar absorption spectra: **4σ variation!!!**

Atomic calculations: need to know isotope shifts
Changes in isotopic abundances mimic shift of α

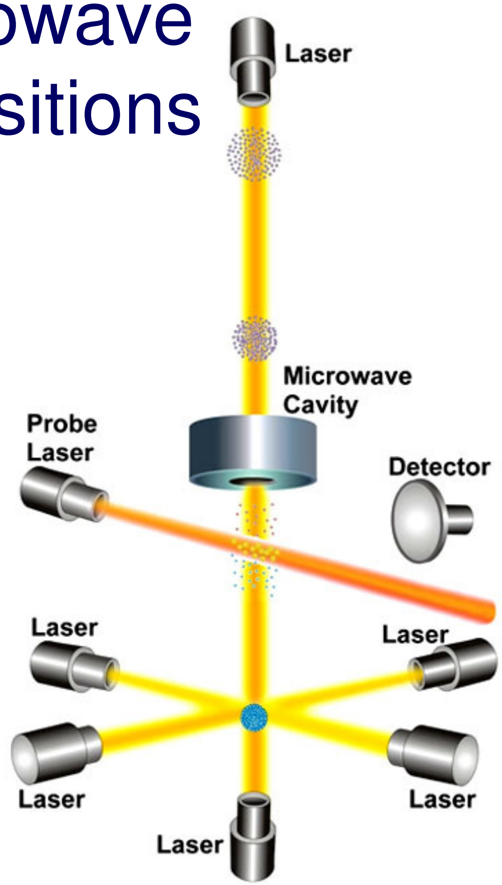
(2) **Laboratory atomic clock experiments**:
compare rates of different clocks over long period of time to study time variation of fundamental constants

Need: dependence of transition frequency on α and ultra precise clocks!

ATOMIC CLOCKS

Atomic frequency standards

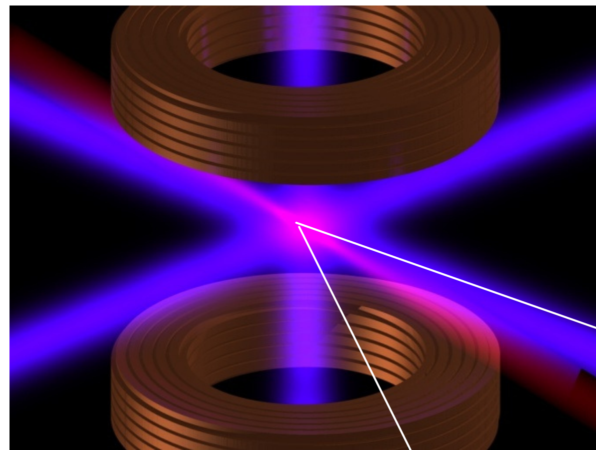
Microwave Transitions

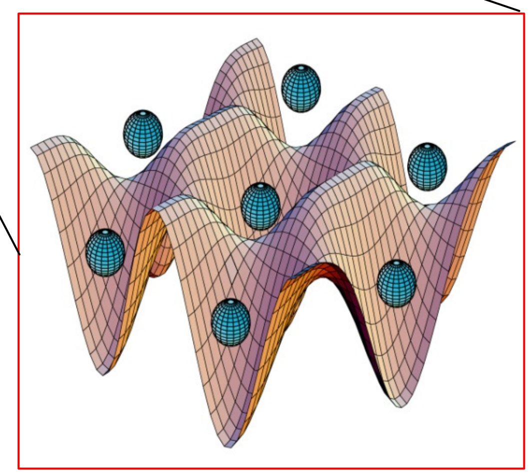


Cs: 4×10^{-16}

M. A. Lombardi, T. Heavner, and S. Jefferts, Measure: J. Meas.Sci. 2, 74 (2007).

Optical Transitions





Neutral atoms in optical lattices

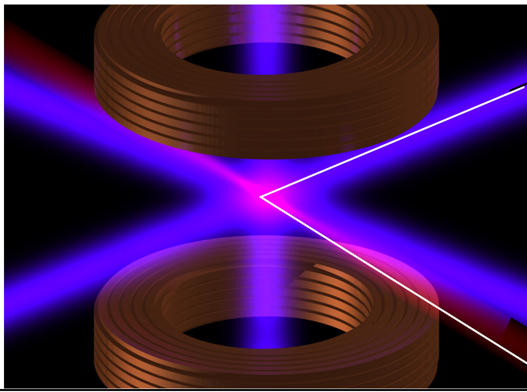
Single ion

Th: nuclear clock?

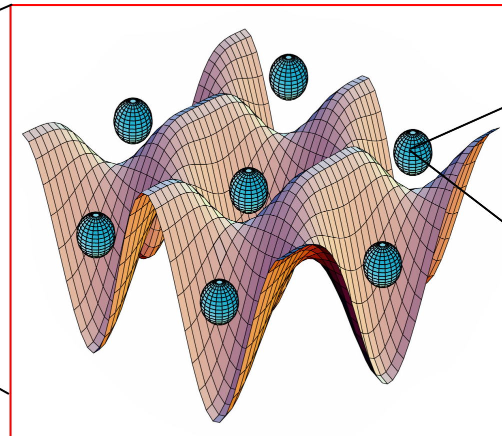
Al^{+}: 8.6×10^{-18}

C. W. Chou et al., Phys. Rev. Lett. 104, 070802 (2010).

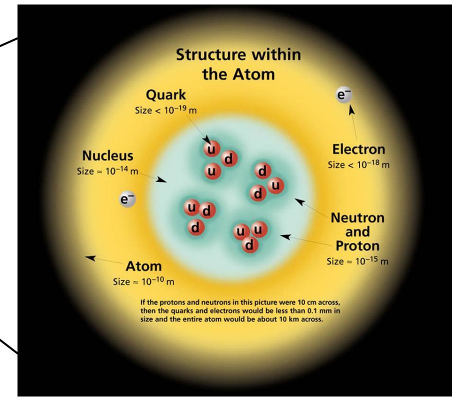
Motivation: next generation atomic clocks



Next - generation ultra precise atomic clock



Atoms trapped by laser light



http://CPEPweb.org

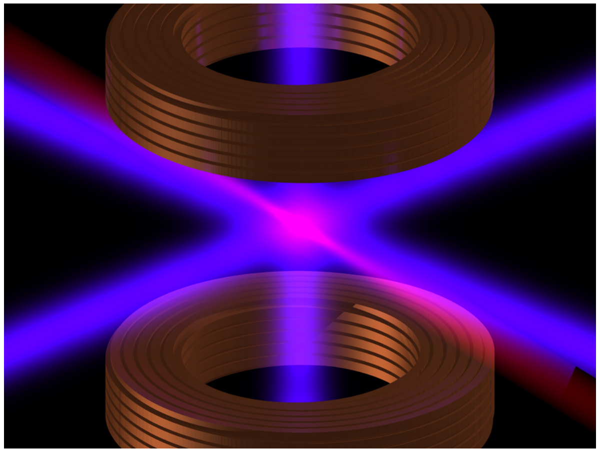
The ability to develop more precise optical frequency standards will open ways to improve global positioning system (GPS) measurements and tracking of deep-space probes, perform more accurate measurements of the physical constants and tests of fundamental physics such as searches for gravitational waves, etc.

Atomic clocks:
Black-body radiation (BBR) shift

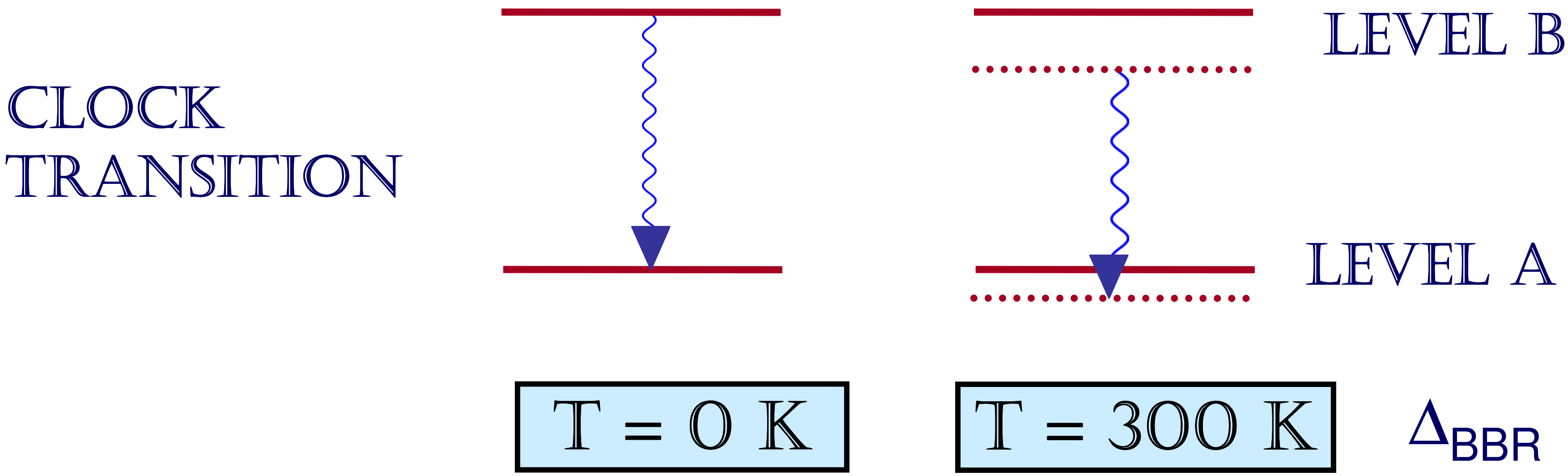
REALLY HARD TO MEASURE OR GET RID OF!

BBR shift gives large contribution into uncertainty budget for some of the atomic clock schemes.

Accurate calculations (or measurements) are needed to achieve ultimate precision goals at room temperature.



Blackbody Radiation Shifts



Transition frequency should be corrected to account for the effect of the black body radiation at T=300K.

Summary of the fractional uncertainties $\Delta\nu/\nu_0$ due to BBR shift and the fractional error in the absolute transition frequency induced by the BBR shift uncertainty at T = 300 K in various frequency standards

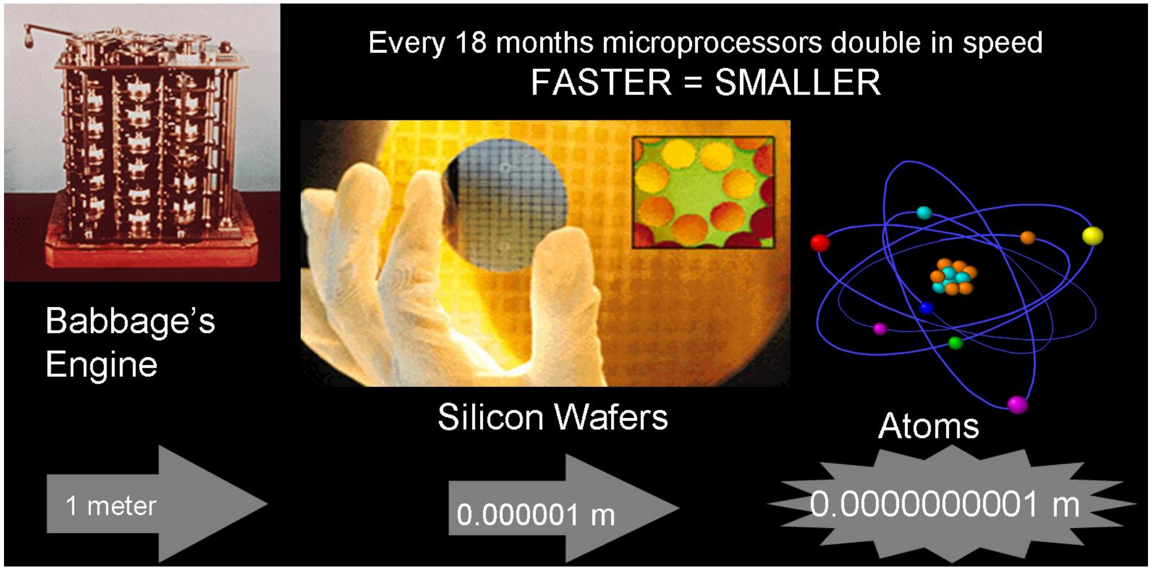
Atom	Clock transition	$\Delta\nu/\nu_0$	Uncertainty	Reference
Rb	5s (F=2 - F=1)	-1.25×10^{-14}	4×10^{-17}	Safronova et al. 2010
Cs	6s (F=4 - F=3)	-1.7×10^{-14}	3×10^{-17}	Simon et al. 1998
Ca^+	$4s - 3d_{5/2}$	9.2×10^{-16}	1×10^{-17}	Safronova et. Al, 2011
Sr^+	$5s - 4d_{5/2}$	5.6×10^{-16}	2×10^{-17}	Jiang et al. 2009
Yb^+	$6s - 5d\ ^2D_{3/2}$	-5.3×10^{-16}	1×10^{-16}	Tamm et al. 2007
Yb^+	$6s - 4f^{13}\ 6s^2\ ^2F_{7/2}$	-5.7×10^{-17}	1×10^{-17}	Hosaka et al 2009
Mg	$3s^2\ ^1S_0 - 3s3p\ ^3P_0$	-3.9×10^{-16}	1×10^{-17}	Porsev et al. 2006
B^+	$2s^2\ ^1S_0 - 2s2p\ ^3P_0$	1.42×10^{-17}	1×10^{-18}	Safronova et al. 2011
Al^+	$3s^2\ ^1S_0 - 3s3p\ ^3P_0$	-3.8×10^{-18}	4×10^{-19}	Safronova et al. 2011
In^+	$5s^2\ ^1S_0 - 5s5p\ ^3P_0$	-1.36×10^{-17}	1×10^{-18}	Safronova et al. 2011
Tl^+	$6s^2\ ^1S_0 - 6s6p\ ^3P_0$	-1.06×10^{-17}	1×10^{-18}	Zuhrianda et al. 2012
Sr	$5s^2\ ^1S_0 - 5s5p\ ^3P_0$	-5.5×10^{-15}	7×10^{-17}	Porsev et al. 2006
Yb	$6s^2\ ^1S_0 - 6s6p\ ^3P_0$	-2.6×10^{-15}	3×10^{-16}	Porsev et al. 2006
Hg	$6s^2\ ^1S_0 - 6s6p\ ^3P_0$	-1.6×10^{-16}		Hachisu et al. 2008

QUANTUM COMPUTERS

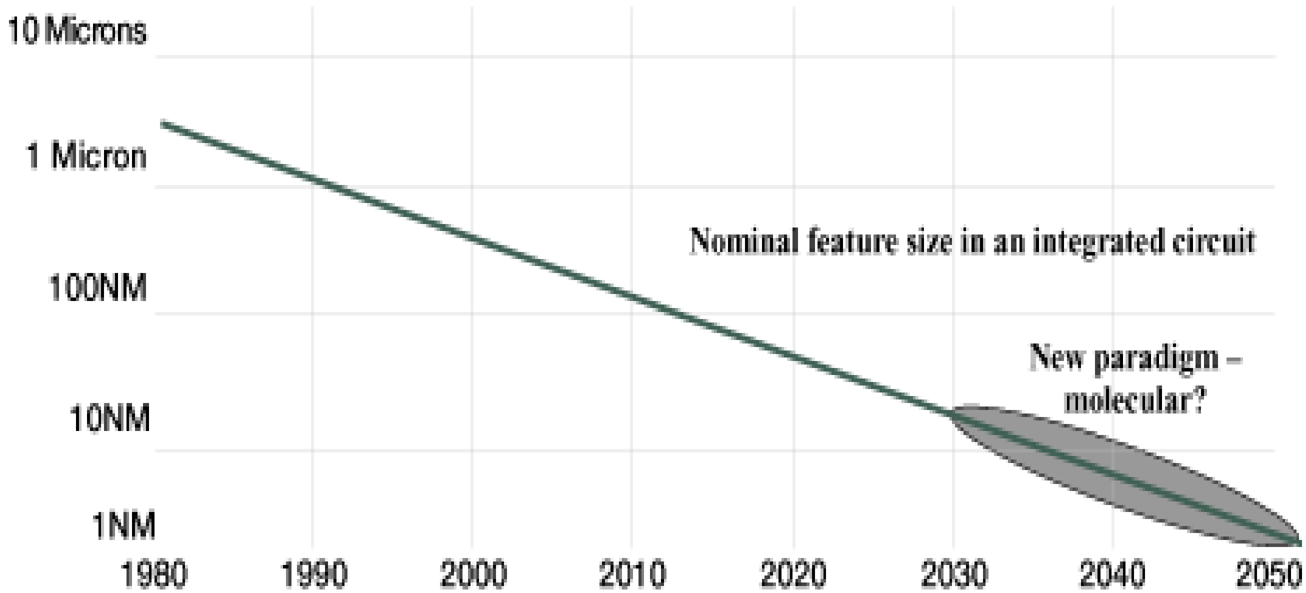
Why quantum information?

Information is physical!
Any processing of information
is always performed by physical means

Bits of information obey laws of classical physics.



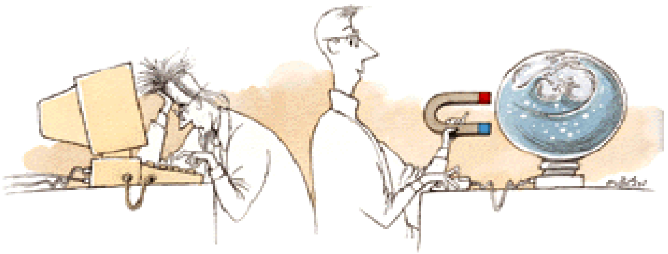
Why Quantum Computers?



Computer technology is making devices smaller and smaller…

…reaching a point where classical physics is no longer a suitable model for the laws of physics.

Bits & Qubits



Fundamental building blocks of classical computers:

BITS

STATE:

Definitely

0 or 1

Fundamental building blocks of quantum computers:

Quantum bits

or

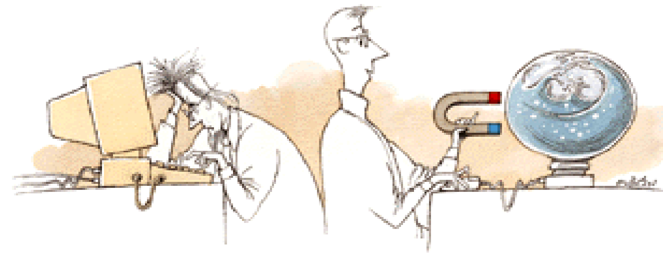
QUBITS

Basis states: $|0\rangle$ and $|1\rangle$

Superposition:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

Bits & Qubits



Fundamental building blocks of classical computers:

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Quantum bits

or

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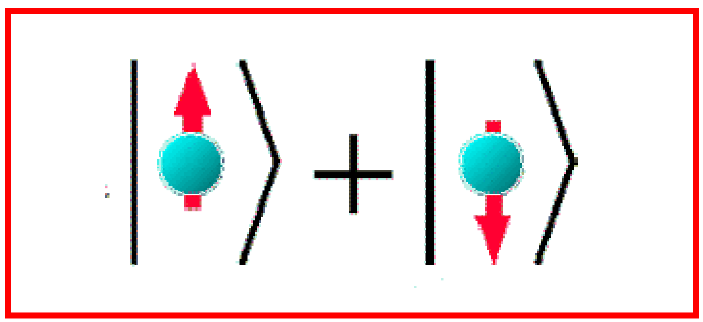


Hilbert space is a big place!

- Carlton Caves

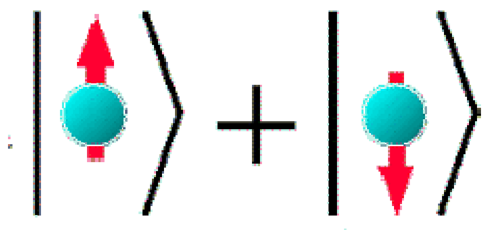
Multiple qubits

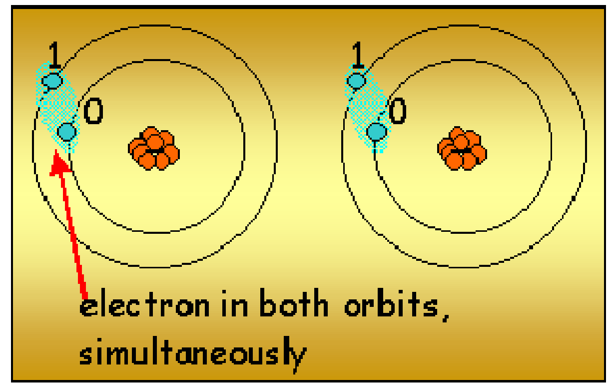
- Two bits with states 0 and 1 form four definite states 00, 01, 10, and 11.
- Two qubits: can be in superposition of four computational basis set states.

$$|\psi\rangle = \alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle$$

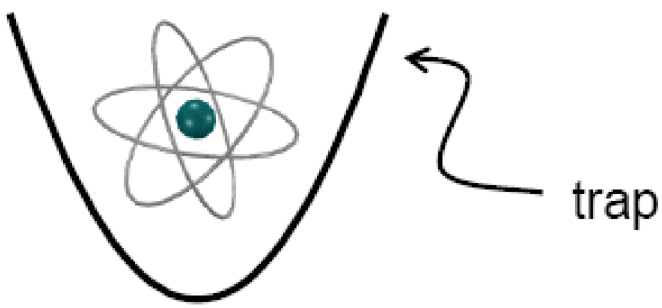
2 qubits	4 amplitudes
3 qubits	8 amplitudes
10 qubits	1024 amplitudes
20 qubits	1 048 576 amplitudes
30 qubits	1 073 741 824 amplitudes
500 qubits	**More amplitudes than our estimate of number of atoms in the Universe!!!**

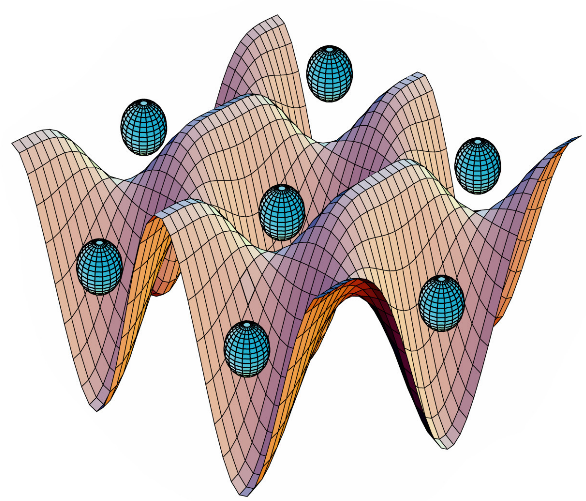
Qubit: any suitable two-level quantum system





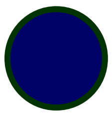
single trapped atom:



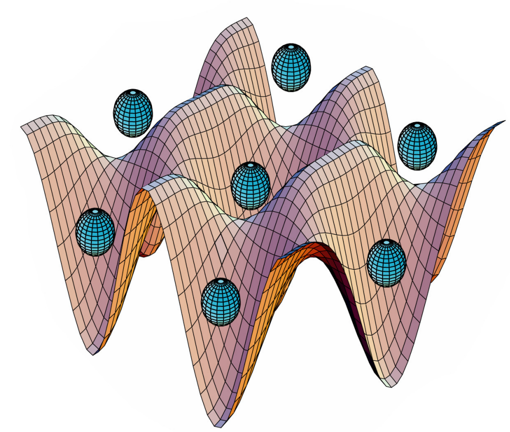


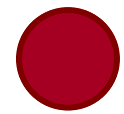
ATOMIC CALCULATIONS & QUANTUM INFORMATION

(1) Need information for various cooling and trapping schemes (for example, magic wavelength)



Atom in state A sees potential U_A





Atom in state B sees potential U_B

Magic wavelength λ_{magic} is the wavelength for which the optical potential U experienced by an atom is independent on its state

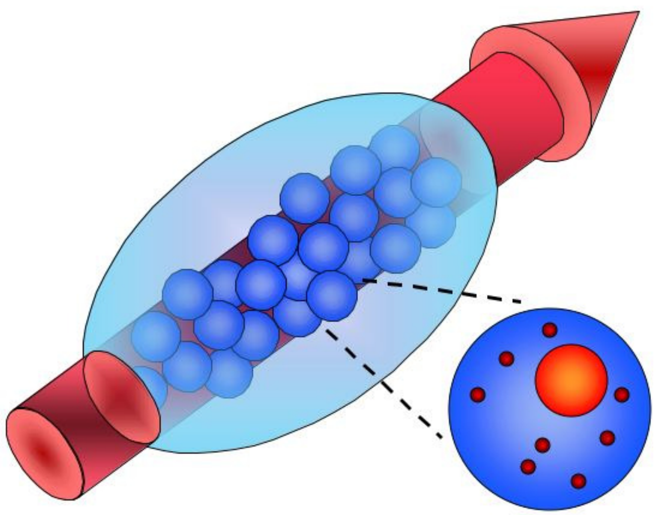
$$U \propto \alpha(\lambda)$$

ATOMIC CALCULATIONS & QUANTUM INFORMATION

(2) Need information to minimize decoherence during quantum gate operation.

(3) Need to know various atomic properties for quantum information proposals.

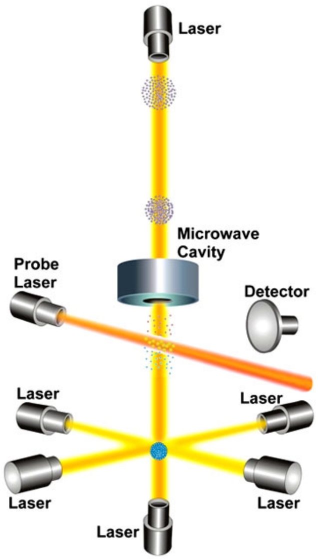
Example: Quantum gate schemes using dipole blockade via Rydberg excitations



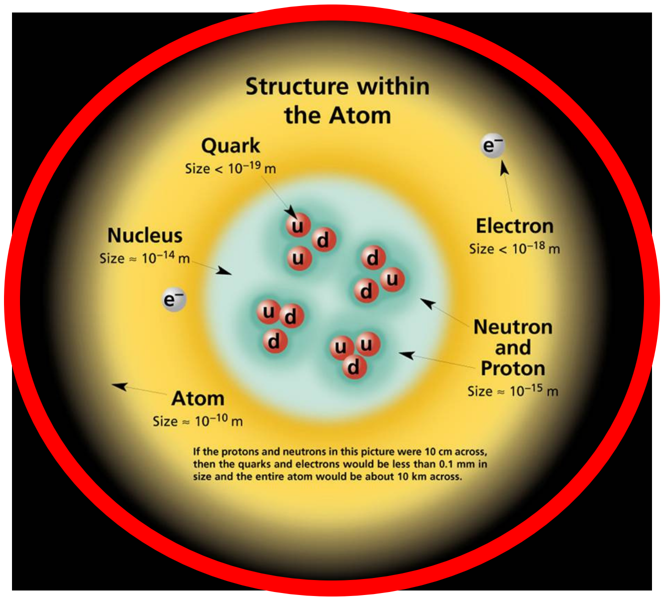
Excitations to Rydberg states are suppressed due to a dipole-dipole interaction or van der Waals interaction

http://www.physics.uconn.edu/~rcote/

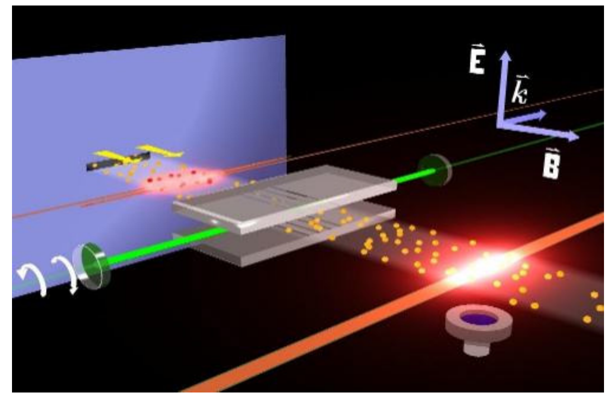
QUANTUM MECHANICS APPLICATIONS

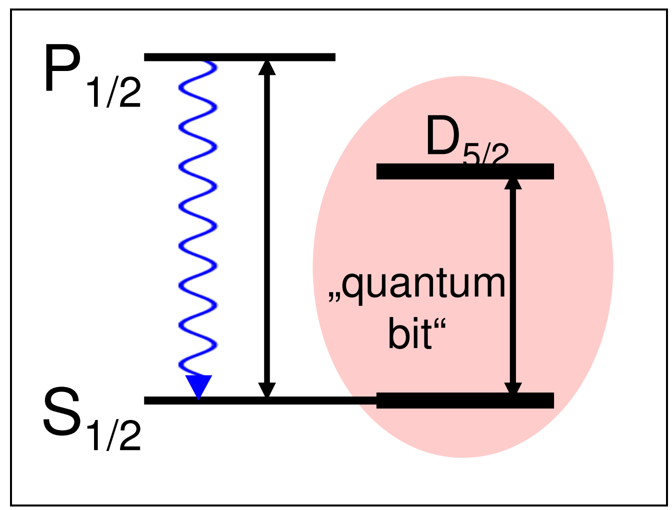


Atomic Clocks

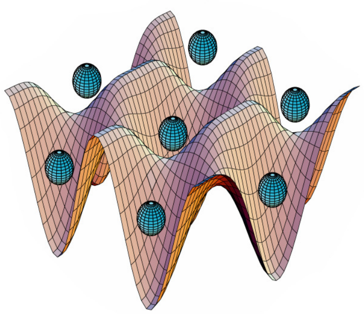


Parity Violation





Quantum information



NEED ATOMIC CALCULATIONS