University of Virginia Colloquium

ATOMIC CALCULATIONS FOR TESTS OF FUNDAMENTAL PHYSICS

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November 11, 2011

OUTLINE

- **Atomic physics tests of fundamental physics**
  - Parity violation
  - Search for permanent electric-dipole moment (EDM)
  - Variation of fundamental constants and atomic clocks
- **Atomic parity violation**
  - Theory: How to calculate APV amplitude?
  - Analysis of Cs experiment and implications for search for physics beyond the Standard Model
  - Nuclear spin-dependent APV effects and weak hadronic interactions

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]

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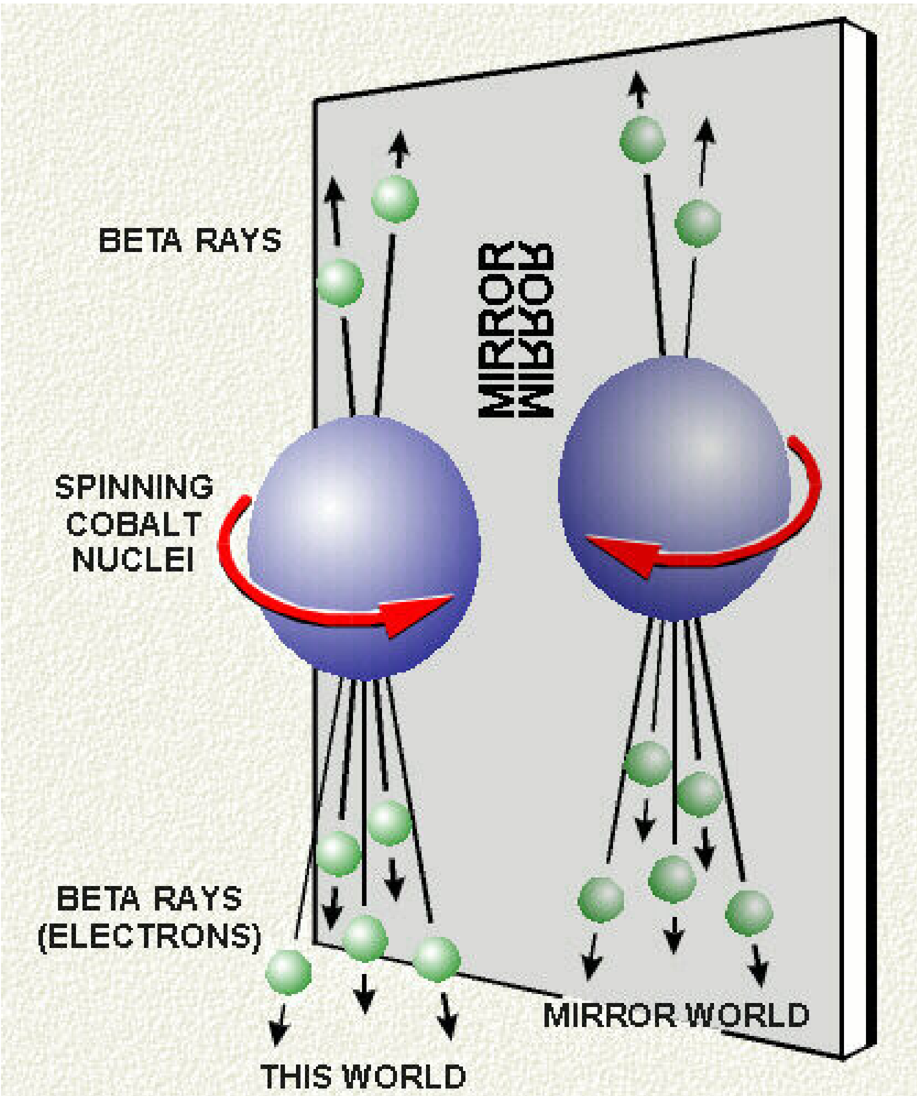
Parity Violation

$\vec{r} \rightarrow -\vec{r}$



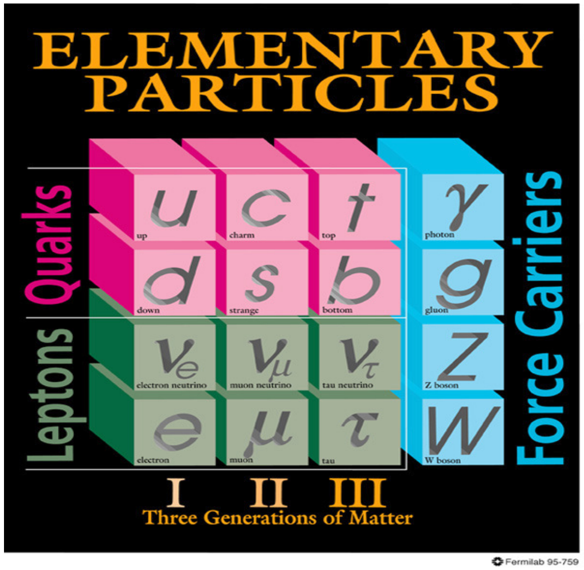
Parity-transformed world:

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

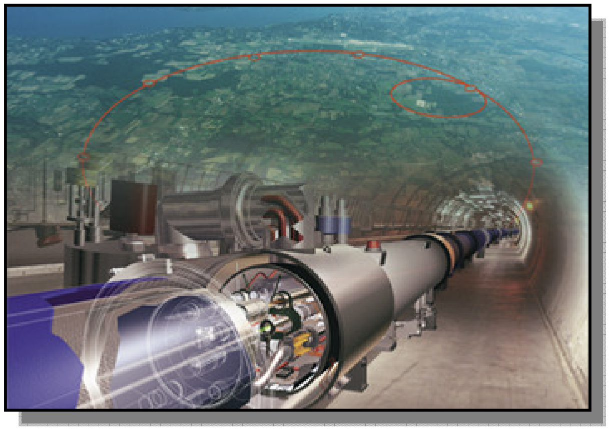
PROPERTIES OF THE INTERACTIONS

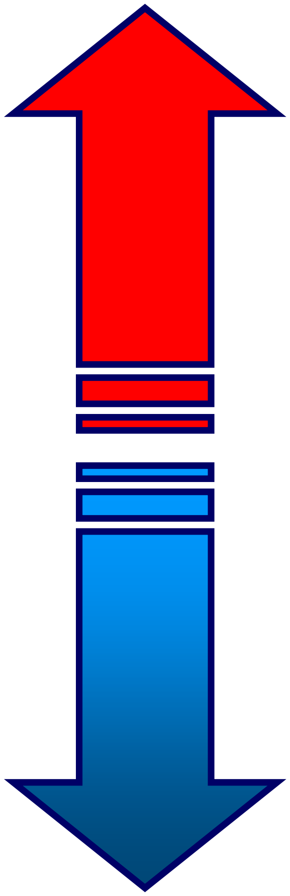
Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
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

Atomic Parity Violation

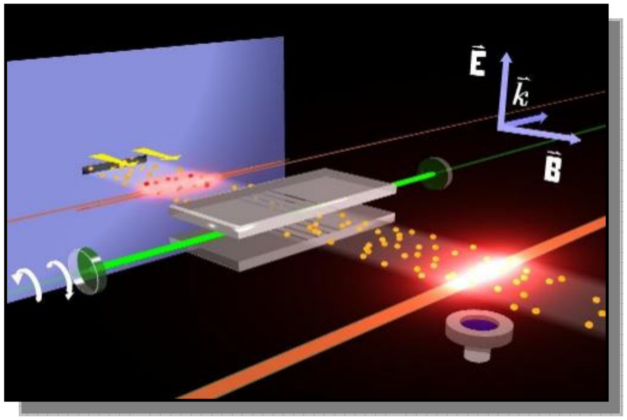
High energies

Instead of search for new processes or particles directly





Determine weak charge Q_W from atomic parity violation studies and compare the result with Standard Model prediction

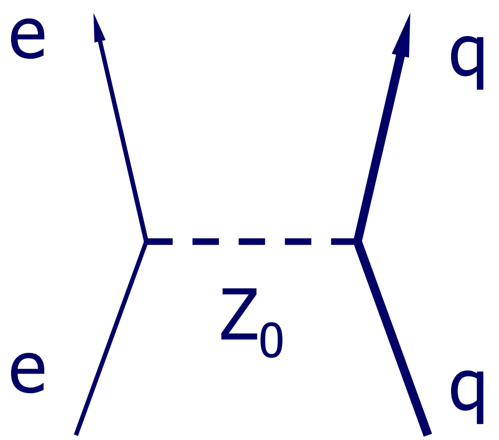


Low energies

http://public.web.cern.ch/, Cs experiment, University of Colorado

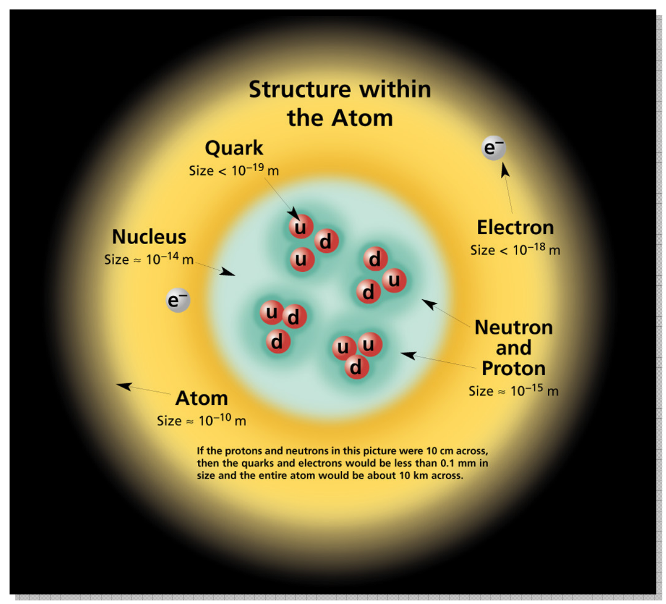
PARITY VIOLATION IN ATOMS

NUCLEAR
SPIN-INDEPENDENT
PNC:
SEARCHES FOR NEW PHYSICS
BEYOND THE
STANDARD MODEL



Weak Charge Q_W

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



Two sides of the atomic parity violation

NUCLEAR
SPIN-INDEPENDENT
PNC:
SEARCHES FOR NEW
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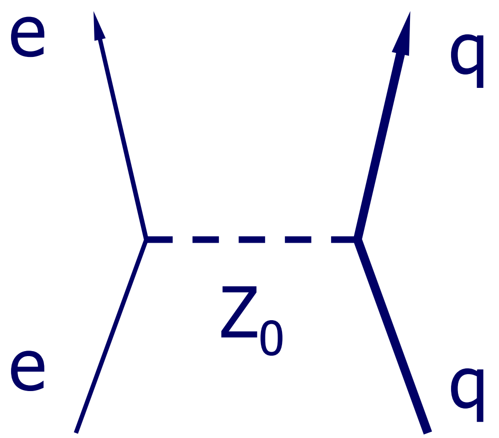

Weak Charge Q_W

NUCLEAR
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STUDY OF PNC
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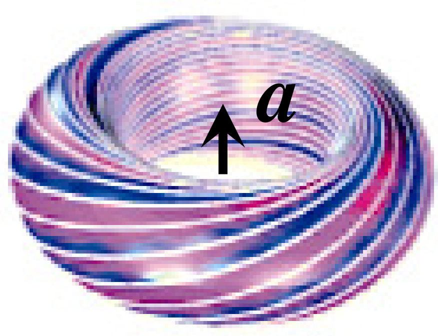

Nuclear anapole moment

Transformations and Symmetries

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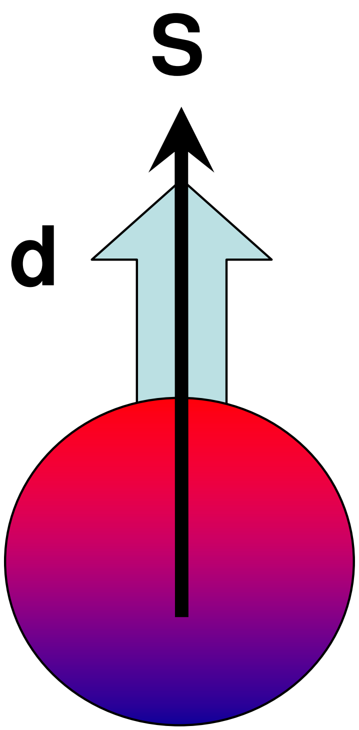
[CP]	
[CPT]	

PERMANENT ELECTRIC-DIPOLE MOMENT (EDM)

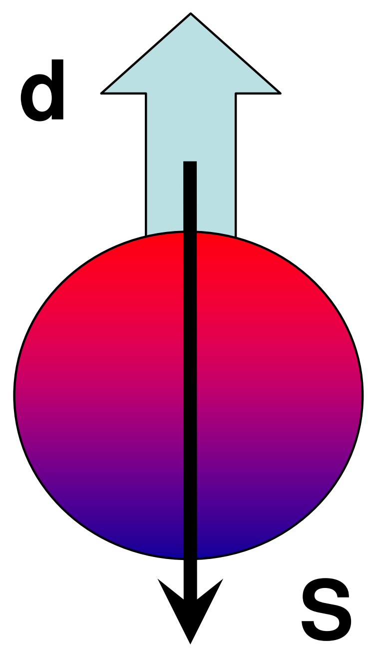
Time-reversal invariance must be violated for an elementary particle or atom to possess a permanent EDM.



$$t \rightarrow -t$$

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

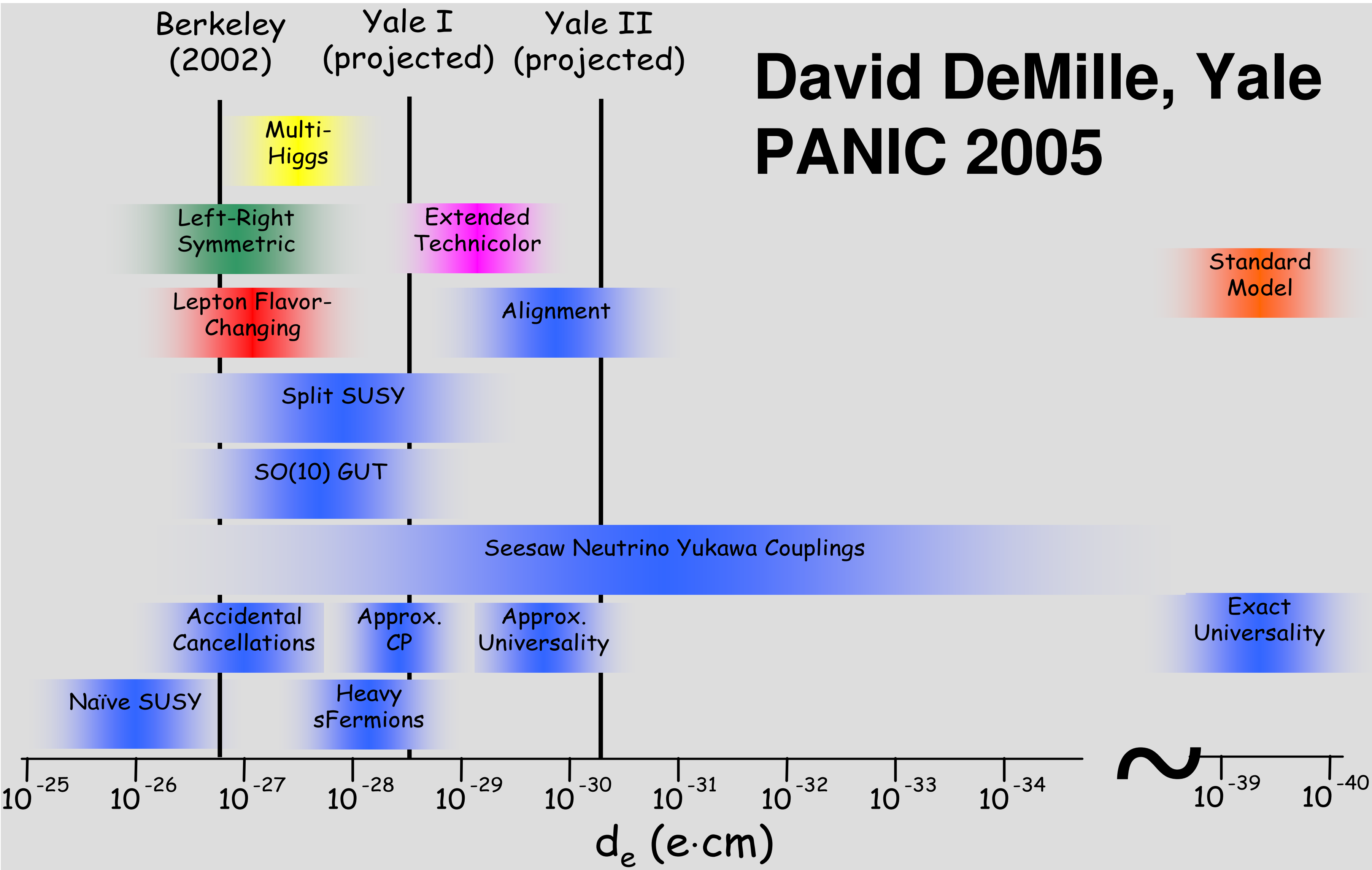
$$\vec{\mathbf{d}} \rightarrow \vec{\mathbf{d}}$$



$$\boxed{\begin{gathered} \vec{\mathbf{d}} = d\,\frac{\vec{\mathbf{S}}}{S} \\ d = 0 \end{gathered}}$$

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.

Theory is needed to calculate enhancement factors and search for new systems for EDM detection.

Recent new limit on the EDM of ^{199}Hg

$$| d(^{199}\mathrm{Hg}) | < 3.1 \times 10^{-29}\ e\ \mathrm{cm}$$

Phys. Rev. Lett.102, 101601 (2009)

Atomic calculations and variation of fundamental constants

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

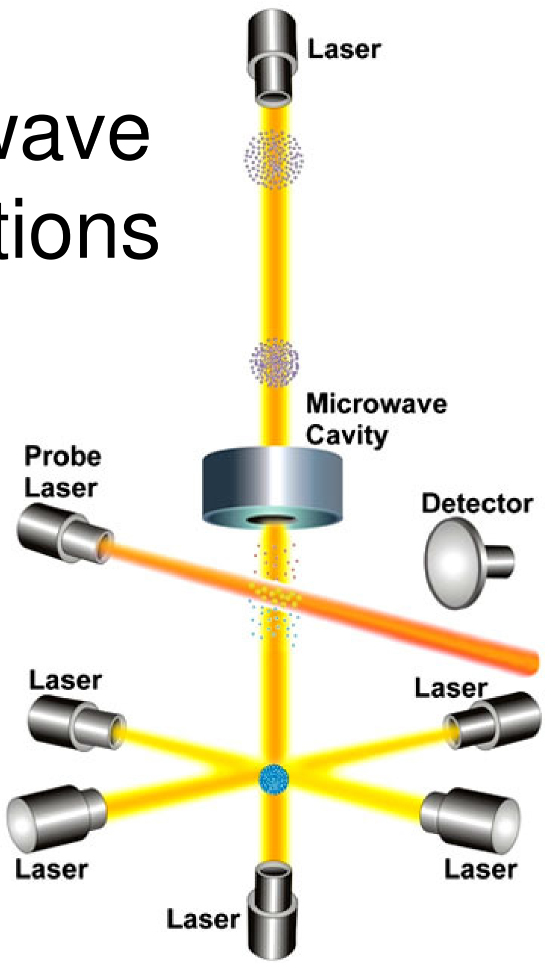
Atomic calculations: need to know isotope shifts
Changes in isotopic abundances mimic shift of α

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

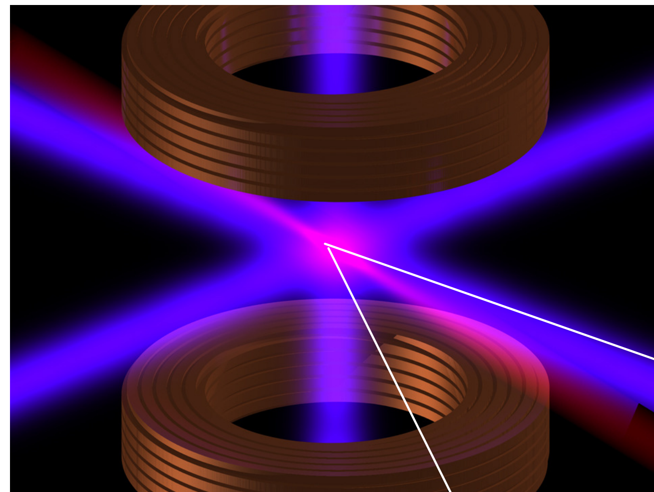
Need: dependence of transition frequency on α and ultra precise clocks!

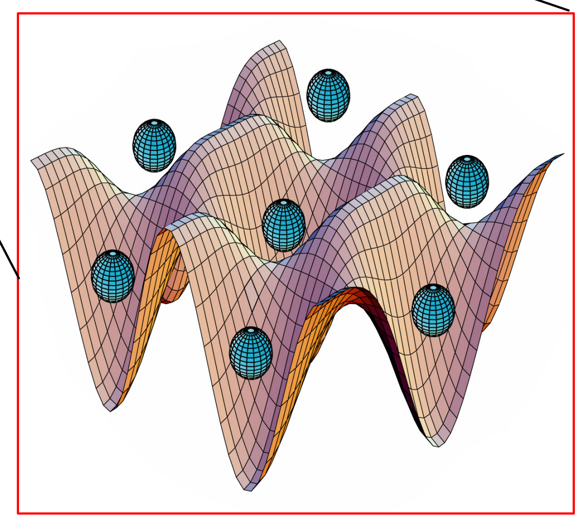
ATOMIC CLOCKS

Microwave Transitions



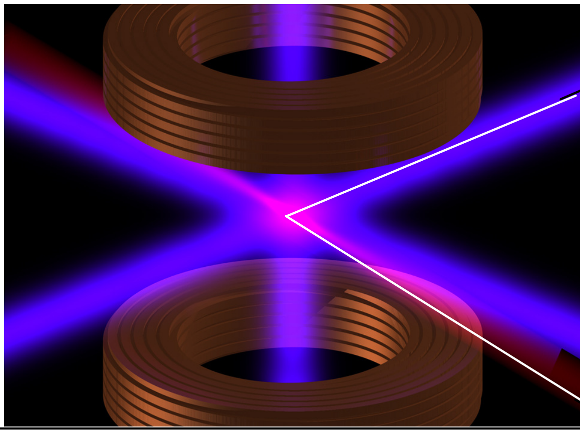
Optical Transitions



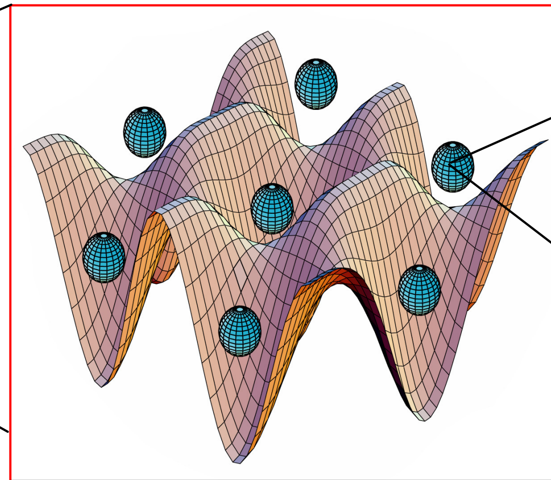


Blackbody Radiation Shifts and Theoretical Contributions to Atomic Clock Research, **M. S. Safronova, Dansha Jiang, Bindiya Arora, Charles W. Clark, M. G. Kozlov, U. I. Safronova, and W. R. Johnson, in press, Special Issue of IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control (2010).**

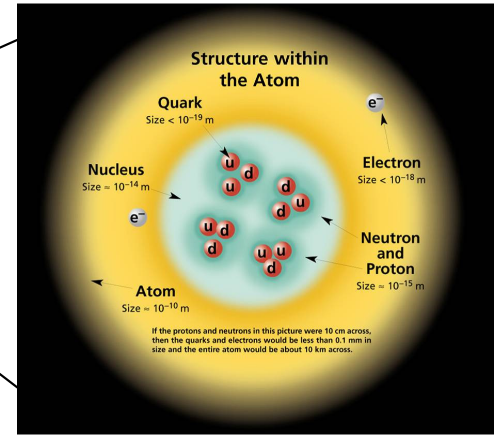
Motiation: Next Generation Atomic Clocks



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 Calculations & More Precise Clocks

(1)Prediction of atomic properties required for new clock proposals

New clock proposals require both estimation of the atomic properties for details of the proposals (transition rates, lifetimes, branching rations, magic wavelength, scattering rates, etc.) and evaluation of the systematic shifts (Zeeman shift, electric quadruple shift, blackbody radiation shift, ac Stark shifts due to various lasers fields, etc.).

(2)Determination of the quantities contributing to the uncertainty budget of the existing schemes.

In the case of the well-developed proposals, one of the main current uncertainty issues is the blackbody radiation shift.

ATOMIC PARITY VIOLATION

Two sides of the atomic parity violation

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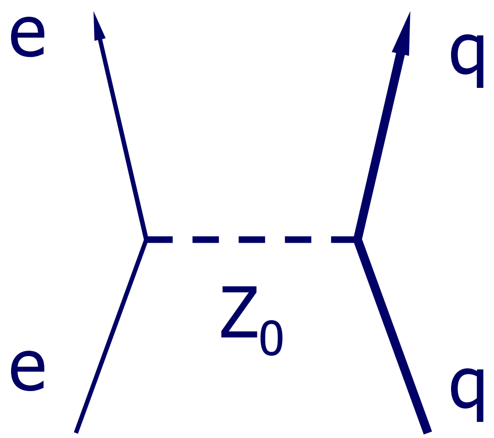

Weak Charge Q_W

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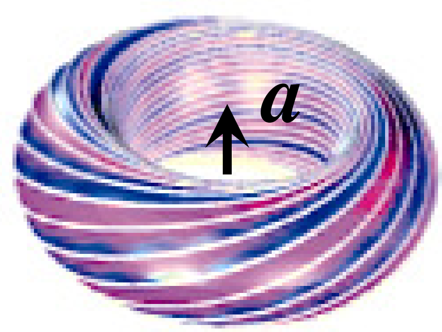
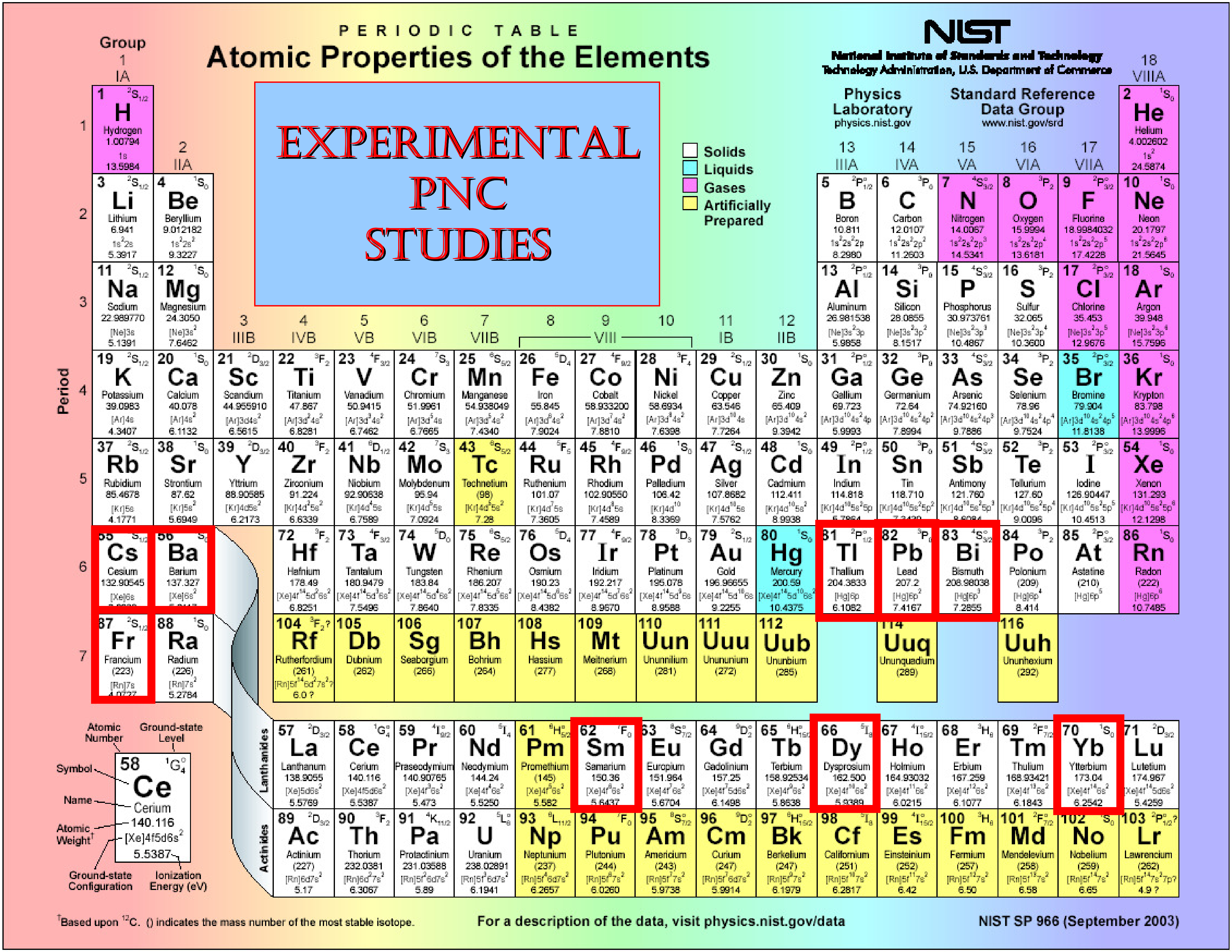
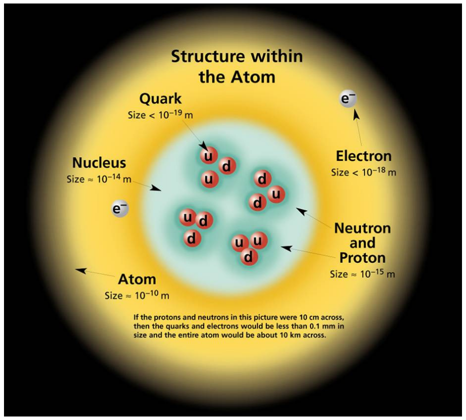


Nuclear anapole moment



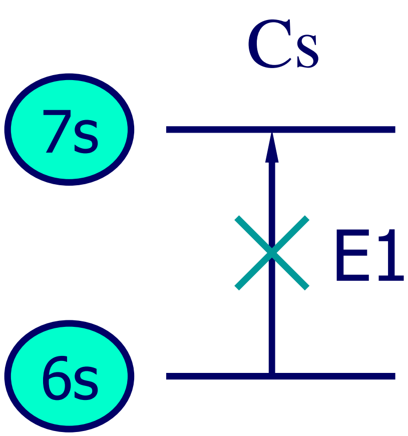
PERIODIC TABLE
Atomic Properties of the Elements
NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce
Physics Laboratory
physics.nist.gov
Standard Reference Data Group
www.nist.gov/srd
EXPERIMENTAL PNC STUDIES
Solids
Liquids
Gases
Artificially Prepared
Group
Period
Lanthanides
Actinides
Atomic Number
Ground-state Level
Symbol
Name
Atomic Weight
Ground-state Configuration
Ionization Energy (eV)
Based upon 12C. () indicates the mass number of the most stable isotope.
For a description of the data, visit physics.nist.gov/data
NIST SP 966 (September 2003)



Cesium: atom with single (valence) electron outside a closed core.

Cs Z=55 ← **Need heavy atom for atomic PNC**

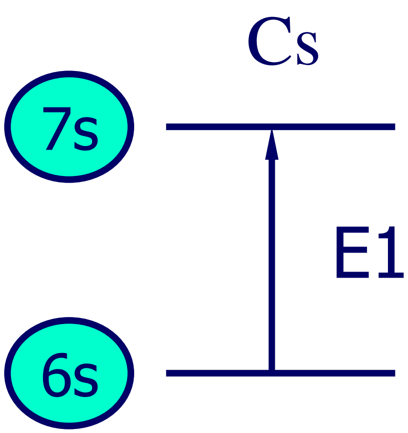
core → $1s^2 \ldots 5p^6$ | 6s ← valence electron



l=0 to *l*=0 electric dipole transition is forbidden by parity selection rules

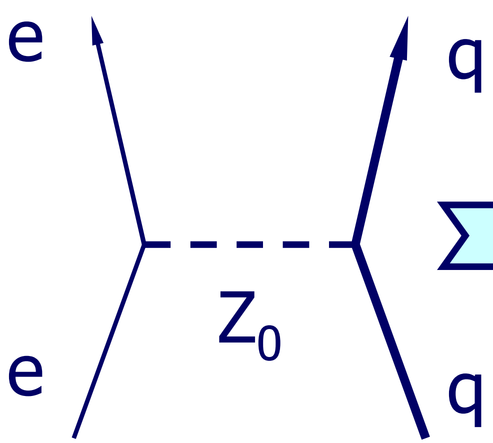
Atomic Parity Violation

$\vec{r} \rightarrow -\vec{r}$



Non-zero transition amplitude
PNC amplitude E_{PNC}

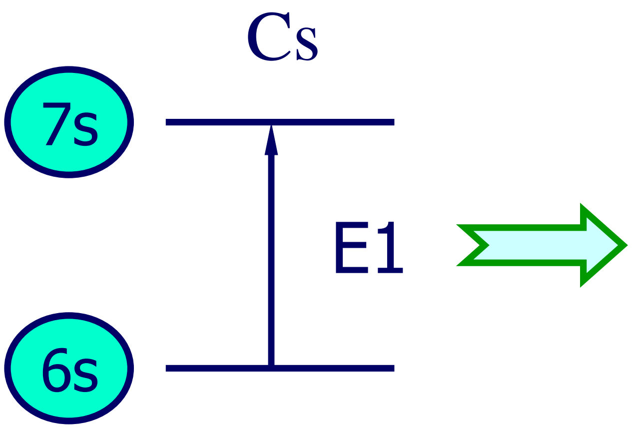
Both 6s and 7s states acquire an opposite-parity ($np_{1/2}$) admixture



Z_0 exchange: Laporte's rule is violated!

Atomic Parity Violation

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



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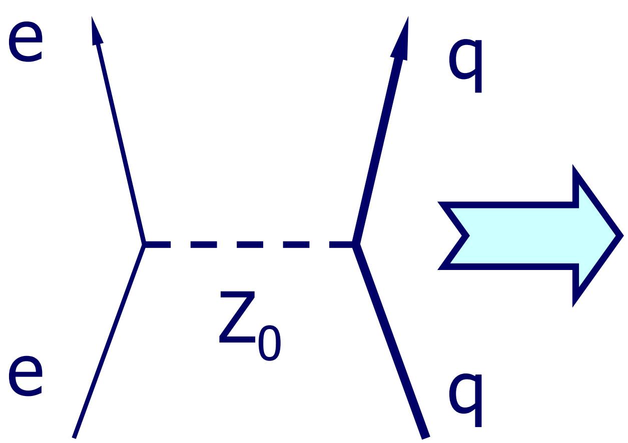


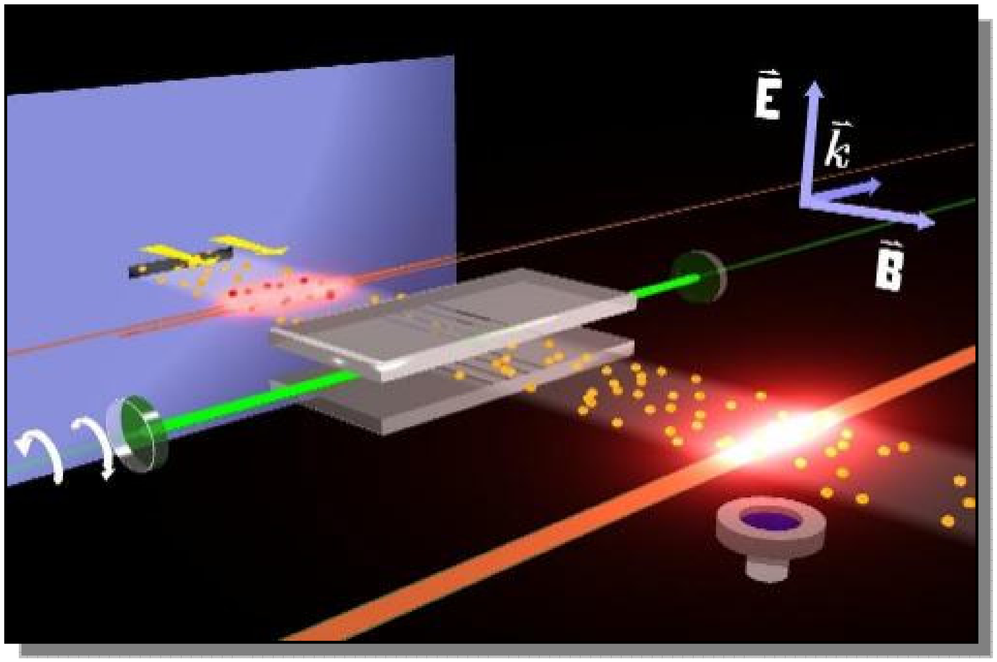
Z_0 exchange: Laporte's rule is violated!

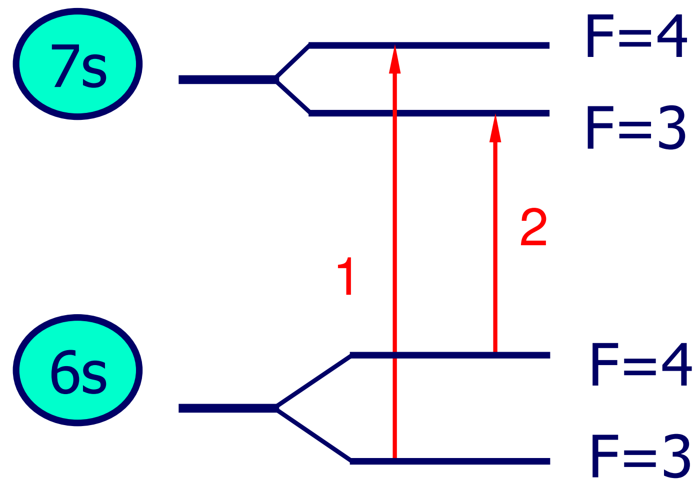
Note: it is really tiny effect !!! E_{PNC} ~$\mathbf{10^{-11}}$ atomic units

E1 amplitude for 6s – 6p transition is **4.5** atomic units

The most precise measurement of PNC amplitude (cesium)

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





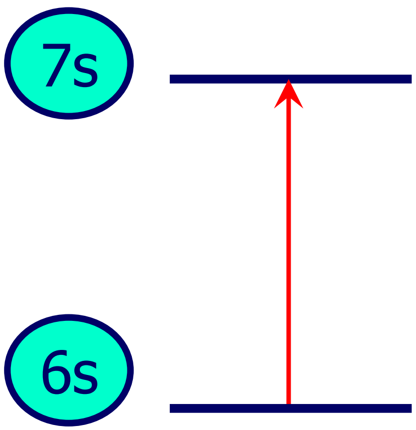
$$\frac{\mathrm{Im}\left(E_{\mathrm{PNC}}\right)}{\beta} = \begin{cases} -1.6349(80)\ {}^{\mathrm{mV}}\!/_{\mathrm{cm}} & 1 \\ -1.5576(77)\ {}^{\mathrm{mV}}\!/_{\mathrm{cm}} & 2 \end{cases}$$

0.35% accuracy

Stark interference scheme to measure ratio of the PNC amplitude and the Stark-induced amplitude β

Analysis of Cs PNC experiment

NUCLEAR SPIN-INDEPENDENT PNC

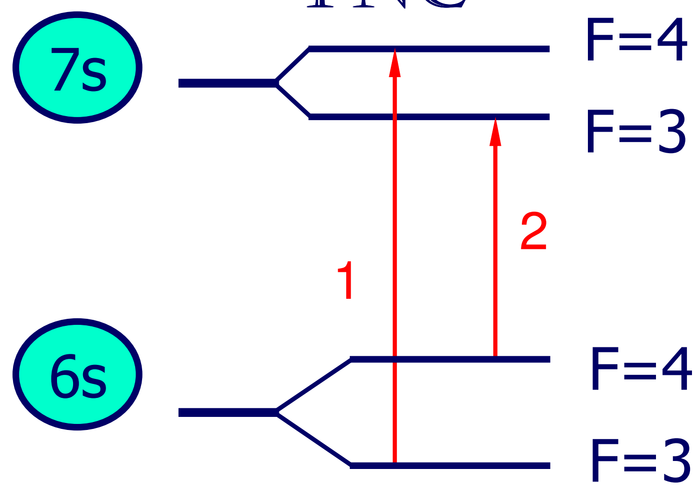


Average of 1 & 2

$$\frac{\mathrm{Im}\left(E^{\mathrm{si}}_{\mathrm{PNC}}\right)}{\beta} = -1.5935(56)\ {}^{\mathrm{mV}}\!/_{\mathrm{cm}}$$

Weak Charge Q_W

NUCLEAR SPIN-DEPENDENT PNC



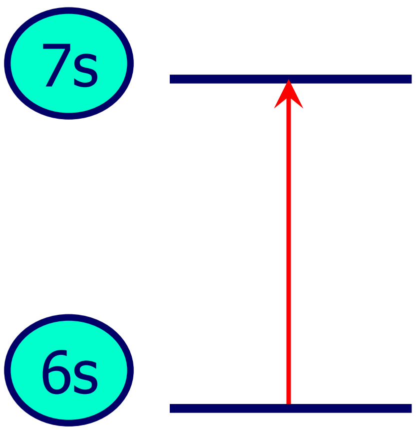
Difference of 1 & 2

$$\Delta\left[\mathrm{Im}\left(E^{\mathrm{sd}}_{\mathrm{PNC}}\right)/\beta\right]_{34-43} = -0.077(11)\ {}^{\mathrm{mV}}\!/_{\mathrm{cm}}$$

Nuclear anapole moment

Analysis of Cs PNC experiment

NUCLEAR SPIN-INDEPENDENT PNC

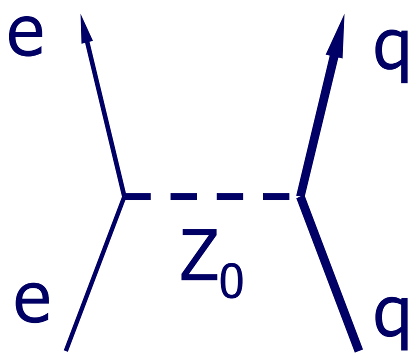


Average of 1 & 2

$$\frac{\mathrm{Im}\left(E_{\mathrm{PNC}}^{\mathrm{si}}\right)}{\beta} = -1.5935(56)\ {}^{\mathrm{mV}}\!/_{\mathrm{cm}}$$

Weak Charge Q_W

How to extract weak charge Q_w from Cs experiment?



Electron-quark parity violating interaction
(exchange of virtual Z_0 boson)

$$H_W = \frac{G_F}{\sqrt{2}}\left(\bar{e}\gamma_\mu\gamma_5 e\right)\left\{C_{1u}\bar{u}\gamma^\mu u + C_{1d}\bar{d}\gamma^\mu d\right\} + \ldots$$

Neutron density function

Electronic sector: $$H^{(1)}_{PNC} = \frac{G_F}{2\sqrt{2}} Q_W \gamma_5 \rho(r)$$

Extraction of weak the charge:

Theoretical calculation of PNC amplitude

Measured value → $$E_{PNC} = E^{theory}_{PNC} Q^{\text{inferred}}_W$$

Calculation of PNC amplitude

1. Main part – Coulomb interactions

Electric-dipole matrix elements

$$E_{\mathrm{PNC}}^{theory} = \sum_{n=2}^{\infty} \frac{\langle 7s|d|np_{1/2}\rangle\langle np_{1/2}|H_{\mathrm{PNC}}|6s\rangle}{E_{6s}-E_{np_{1/2}}} + \sum_{n=2}^{\infty} \frac{\langle 7s|H_{\mathrm{PNC}}|np_{1/2}\rangle\langle np_{1/2}|d|6s\rangle}{E_{7s}-E_{np_{1/2}}}$$

Energies

PNC matrix elements

Sum is separated to main part, n = 6 - 9 and the tail

2. Other small corrections:

Breit, QED, Neutron skin, e – e weak interaction

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 $\longrightarrow$ **55-fold excitations to get exact wave function**

Even for 100 function basis set $\longrightarrow$ 100^{55}

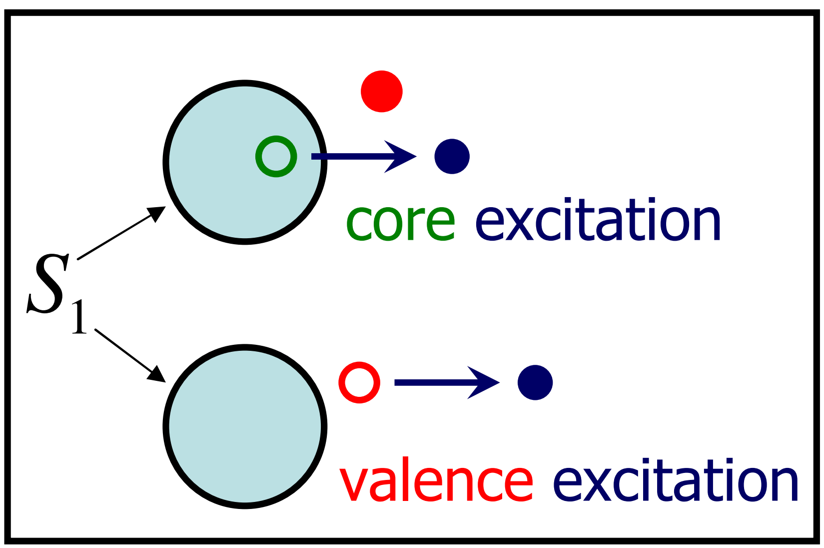
Approximate methods: perturbation theory does not converge well,
Need to use all-order methods (coupled-cluster method and correlation potential method)

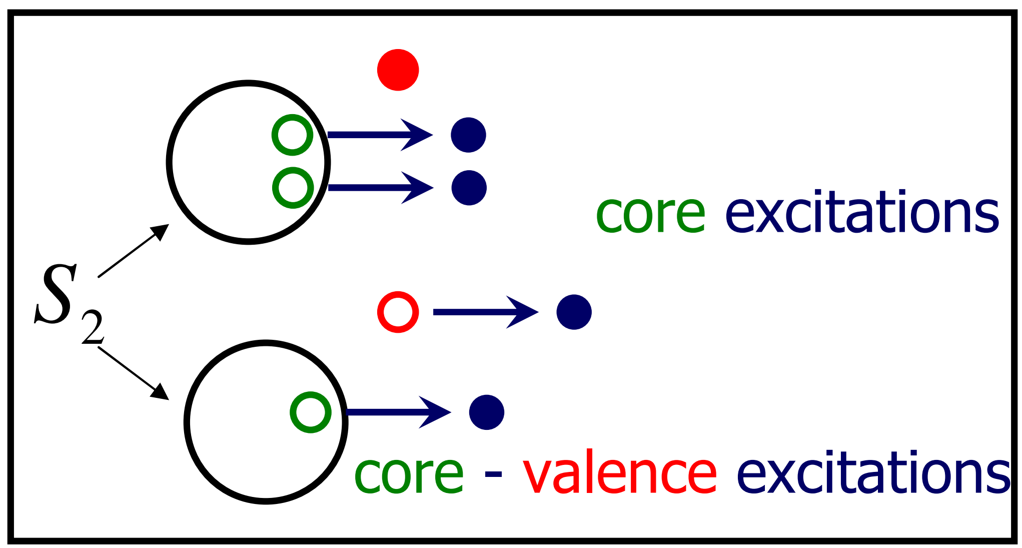
Coupled-cluster method (CCSD)

$$\left|\Psi_v\right\rangle = \Omega\left|\Psi_v^{(0)}\right\rangle = \exp(S)\left|\Psi_v^{(0)}\right\rangle \Rightarrow$$ **DHF wave function**

$$\exp(S_1 + S_2)$$ **CCSD single-double coupled-cluster**

$$S_1 + S_2$$ **LCCSD coupled-cluster**

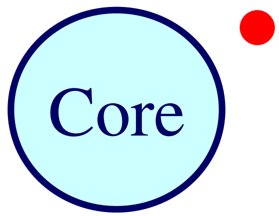




LCCSD ATOMIC WAVE FUNCTION

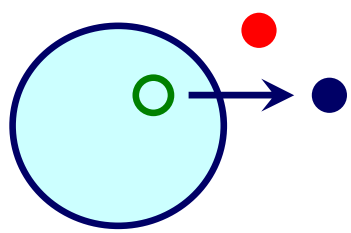
- core
- valence electron
- any excited orbital

Lowest order

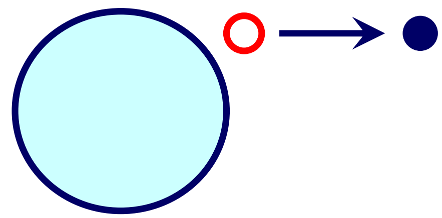


$$\left|\Psi_v^{(0)}\right\rangle$$

Single-particle excitations

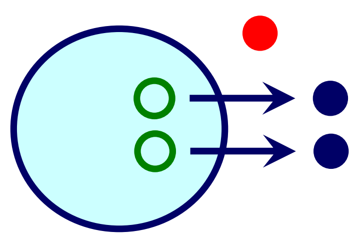


$$\sum_{ma} \rho_{ma}\, a_m^{\dagger} a_a \left|\Psi_v^{(0)}\right\rangle$$

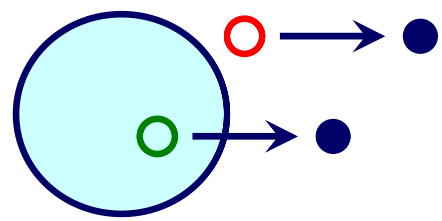


$$\sum_{m\neq v} \rho_{mv}\, a_m^{\dagger} a_v \left|\Psi_v^{(0)}\right\rangle$$

Double-particle excitations



$$\frac{1}{2}\sum_{mnab} \rho_{mnab}\, a_m^{\dagger} a_n^{\dagger} a_b a_a \left|\Psi_v^{(0)}\right\rangle$$



$$\sum_{mna} \rho_{mnva}\, a_m^{\dagger} a_n^{\dagger} a_a a_v \left|\Psi_v^{(0)}\right\rangle$$

Actual implementation: problem 1

There are some many equations!

Need very accurate (large) basis sets for parity violation.

$\boxed{\rho_{mnab}}$

Cs: a,b = $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10} 5s^2 5p^6$

m,n : *finite basis set* $= (35 \times 13) \times (35 \times 13)$

Total actually $15412 \times 35 \times 35 \sim 19\,000\,000$ equations

to be solved iteratively!

Our implementation of the coupled-cluster is different from quantum chemistry – new sets of codes were developed.

Actual implementation: problem 2

These are really complicated equations !!!

- "Quadruple" term:

$$\sum_{rs} g_{mnrs}\rho_{rsab}$$

a,b core
(17 shells)

Indices ***mnrs*** can be **ANY** orbitals

Basis set: n_{max}=**35**, l_{max}=6

17x17x(**35**x13)^4=5 x 10^{12}!

- Program has to be exceptionally efficient!

How to improve accuracy of CCSD?

1. Add more terms to the all order wave-function

Non-linear terms — **Triple excitations**

$$\frac{1}{2}(S_1^2+2S_1S_2+S_2^2)$$
$$+\frac{1}{6}(S_1^3+3S_1^2S_2)+\frac{1}{24}S_1^4$$

$$S_3$$

2. Restore complete 4th order for matrix elements

Non-linear terms

$$\frac{1}{2}S_2^2$$

Contract operators by Wick's theorem

$$H\frac{1}{2}S_2^2|\Psi_v^{(0)}> \rightarrow \overbrace{\underbrace{:a_i^+a_j^+a_la_k:a_m^+a_n^+a_r^+a_s^+a_da_ca_ba_aa_v^+:}}|0_c>$$

Non-linear terms

$$\frac{1}{2} S_2^2$$

$$H \frac{1}{2} S_2^2 \mid \Psi_v^{(0)} > \rightarrow \overbrace{: a_i^+ a_j^+ a_l a_k : a_m^+ a_n^+ a_r^+ a_s^+ a_d a_c a_b a_a a_v^+}^{\text{Contract operators by Wick's theorem}}_{\underbrace{\qquad\qquad}_{\text{800 TERMS!}}} : \mid 0_c >$$

Codes that write formulas

The derivation gets **really complicated** if you add triples and non-linear terms!

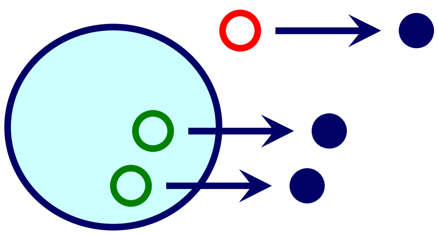
Solution: develop analytical codes that do all the work for you!

Input: ASCII input of terms of the type

$$\sum_{mnrab} \sum_{ijkl} g_{ijkl} \rho_{mnrvab} : a_i^\dagger a_j^\dagger a_l a_k : : a_m^\dagger a_n^\dagger a_r^\dagger a_b a_a a_v : \left| \Psi_v^{(0)} \right\rangle$$

Output: final simplified formula in LATEX to be used in the all-order equation

Triple excitations



- core
- valence electron
- any excited orbital

$$\sum_{mnrab} \rho_{mnrvab}\, a_m^\dagger a_n^\dagger a_r^\dagger a_a a_b a_v \left| \Psi_v^{(0)} \right\rangle$$

Problem 1: too many excitation coefficients ρ_{mnrvab}

Problem 2: increased complexity of equations .

Triple excitations

Problem: too many excitation coefficients ρ_{mnrvab} .

Doubles:

$\boxed{\rho_{mnab}}$ Cs: a,b = $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10} 5s^2 5p^6$

$$m,n : \textit{finite basis set} = (35 \times 13) \times (35 \times 13)$$

Smallest required basis set:

Need total about 300 MB (+extra 150MB file)

Extra index r gives at least a factor (35×13) : over 130GB!

The complexity of the equations also increases.

Problem with all-order extensions:
TOO MANY TERMS

Solution: automated code generation !

Codes that write formulas

Codes that write codes

Input: list of formulas to be programmed
Output: final code (need to be put into a main shell)

Features: simple input, essentially just type in a formula!

Results for Alkali-Metal Atoms: E1 Matrix Elements (a.u.)

	Na $3p_{1/2}$-$3s$	**K** $4p_{1/2}$-$4s$	**Rb** $5p_{1/2}$-$5s$	**Cs** $6p_{1/2}$-$6s$	**Fr** $7p_{1/2}$-$7s$
All-order	3.531	4.098	4.221	4.478	4.256
Experiment	3.5246(23)	4.102(5)	4.231(3)	4.489(6)	4.277(8)
Difference	0.18%	0.1%	0.24%	0.24%	0.5%

Experiment Na,K,Rb: U. Volz and H. Schmoranzer, Phys. Scr. T65, 48 (1996),

Cs: R.J. Rafac et al., Phys. Rev. A 60, 3648 (1999),

Fr: J.E. Simsarian et al., Phys. Rev. A 57, 2448 (1998)

Theory M.S. Safronova, W.R. Johnson, and A. Derevianko, Phys. Rev. A 60, 4476 (1999)

Monovalent systems: very brief summary of what we calculated with all-order method

Properties

- Energies
- Transition matrix elements (E1, E2, E3, M1)
- Static and dynamic polarizabilities & applications
  - Dipole (scalar and tensor)
  - Quadrupole, Octupole
  - Light shifts
  - Black-body radiation shifts
  - Magic wavelengths
- Hyperfine constants
- C_3 and C_6 coefficients
- Parity-nonconserving amplitudes (derived weak charge and anapole moment)
- Isotope shifts (field shift and one-body part of specific mass shift)
- Atomic quadrupole moments
- Nuclear magnetic moment (Fr), from hyperfine data

Systems

Li, Na, Mg II, Al III, Si IV, P V, S VI, K, Ca II, In, In-like ions, Ga, Ga-like ions, Rb, Cs, Ba II, Tl, Fr, Th IV, U V, other Fr-like ions, Ra II

http://www.physics.udel.edu/~msafrono

1989 – 2003: Summary of the PNC calculations

-0.902, -0.908 (-0.905 average) Blundell et al. (1992)
-0.908 Dzuba et al. (1989)

-0.909 Safronova & Johnson (1999)
-0.905 Kozlov et al. (2001)
-0.908 Dzuba et al. (2002) **0.5% uncertainty**

Units: $i|e|a_B(-Q_W / N)\times 10^{11}$

-0.6% Breit correction
-0.2(1)% neutron skin correction
+0.4% vacuum polarization
-0.8% radiative corrections

← **(Several works for all corrections)**

Determination of Q_W : 1997 - 2003

Wood et al. (1997) $\mathrm{Im}(E_{PNC})/\beta$	$-72.11(29)_{expt}(89)_{theor}$	1σ
Bennett & Wieman (1999) Measurement of β	$-72.06(29)_{expt}(34)_{theor}$	2.5σ
Derevianko (2000,2002) Calculation of Breit correction	$-72.61(29)_{expt}(34/73)_{theor}$	$1.3\sigma/0.7\sigma$
Dzuba et al. (2000) Calculation of Breit correction	$-72.42(29)_{expt}(74)_{theor}$	1.5σ/no dev.
Kozlov et al. (2001) Calculation of E_{PNC}, Breit correction	-72.5(7)	no deviation
Johnson et al. (2001) Calculation of vacuum pol. corr.	$-72.12(29)_{expt}(34/74)_{theor}$	$2.2\sigma/1.2\sigma$
Milstein & Sushkov (2002) Calculation of vacuum pol. corr.		2.2σ
Vasilyev et al. (2002) Measurement of 6s-7p trans., β	-72.65(49)	1.1σ
Dzuba et al. (2002) E_{PNC}	$-72.16(29)_{expt}(36)_{th}$	2σ
Flambaum & Kuchiev (2002)	$-72.71(29)_{expt}(36)_{th}$	no deviation
Milstein et al. (2003) self-energy & vertex corr.	$-72.81(29)_{expt}(36)_{th}$	0.6σ

Summary of the PNC amplitude calculations

Coulomb interaction		Porsev et al., PRL 102, 181601 (2009)
Main part, n = 6 - 9	0.8823(18)	
Tail	0.0175(18)	
Total	0.8998(25)	
Corrections		
Breit	-0.0054(5)	Derevianko, PRL 85, 1618 (2000)
QED	-0.0024(3)	Shabaev et al., PRL 94, 213002 (2005)
Neutron skin	-0.0017(5)	Derevianko, PRA 65, 012016 (2000)
e-e weak interactions	0.0003	Blundell et al., PRL 65, 1411 (1990)
Final	**0.8906(26)**	Porsev et al., PRL 102, 181601 (2009)

Units: $i|e|a_B(-Q_W / N)\times 10^{11}$

Cs PNC: Comparison with the standard model

Standard Model [1] : $$Q_W^{\mathrm{SM}} = -73.16(3)$$

Most current result for Cs PNC Expt/Theory:

Atomic physics [2] :

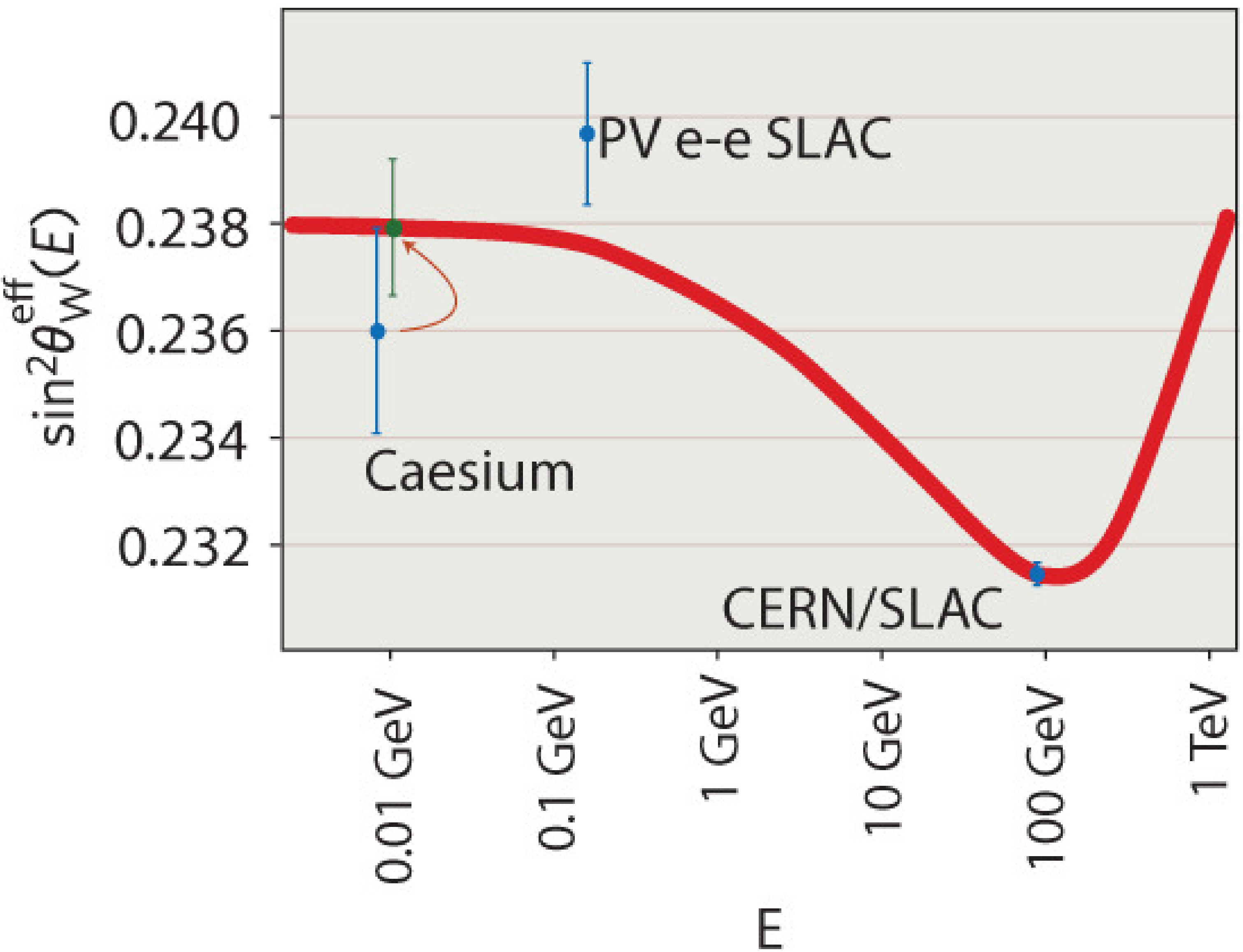
$$Q_W^{\mathrm{inferred}} = -73.16(29)_{\mathrm{expt}}\,(20)_{\mathrm{theory}}$$

No deviation from the Standard Model

[1] C. Amsler et al. (Partical Data Group), Phys. Lett. B 667, 1 (2008)
[2] S. G. Porsev, K. Beloy and A. Derevianko, PRL 102, 181601 (2009), Phys. Rev. D **82**, 036008 (2010)

IMPLICATIONS FOR PARTICLE PHYSICS

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



Adopted from Czarnecki & Marciano, Nature (2005)

Probing new physics

New physics can be phenomenologically described by weak isospin - conserving S and isospin - breaking T parameters [1].

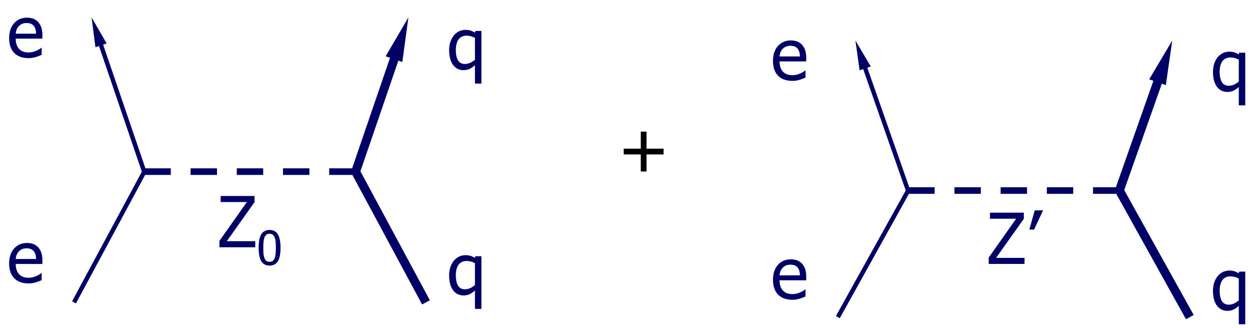
$$\Delta Q = Q_W^{\text{inferred}} - Q_W^{\text{SM}} = -0.800S - 0.007T$$

Present result [2]: $$|S| < 0.45$$

Parameter S is important for indirect constraint on the mass of Higgs particle [1].

[1] J.L. Rosner, PRD 65, 073026 (2002)
[2] S. G. Porsev, K. Beloy and A. Derevianko, PRL 102, 181601 (2009), Phys. Rev. D **82**, 036008 (2010)

Probing new physics: extra Z bosons



Atomic parity violation is uniquely sensitive to Z′

Z'$_X$ in SO(10) GUT, Marciano & Rosner

$$\Delta Q = Q_W^{\text{inferred}} - Q_W^{\text{SM}} \approx \left(\frac{0.736\ \text{TeV}/c^2}{M_{Z'_x}} \right)^2$$

Probing new physics: extra Z bosons

Z'$_\chi$ in SO(10) GUT, Marciano & Rosner

$$\Delta Q = Q_W^{\text{inferred}} - Q_W^{\text{SM}} \approx \left(\frac{0.736\ \text{TeV}/c^2}{M_{Z'_x}} \right)^2$$

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

Direct search at Tevatron collider [2]

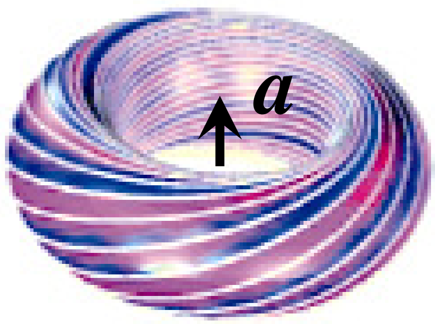
$$M_{Z'_x} > 0.82\text{TeV}/c^2$$

[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

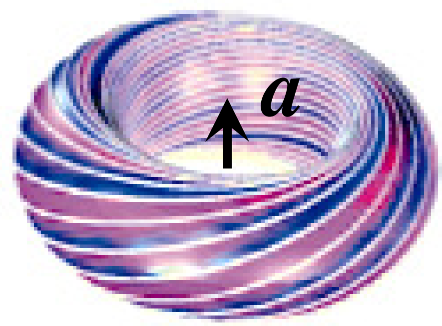
The other part of the story

NUCLEAR
SPIN-DEPENDENT
PNC:
STUDY OF PNC
IN THE NUCLEUS



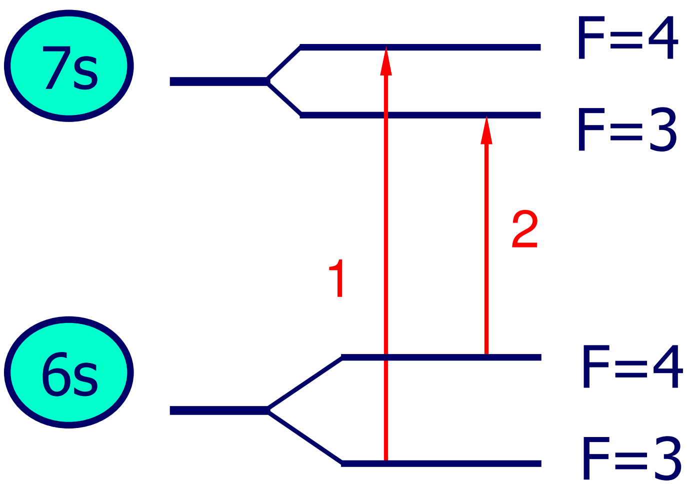
Nuclear anapole moment

Spin-dependent parity violation: Nuclear anapole moment



Parity-violating nuclear moment

Valence nucleon density

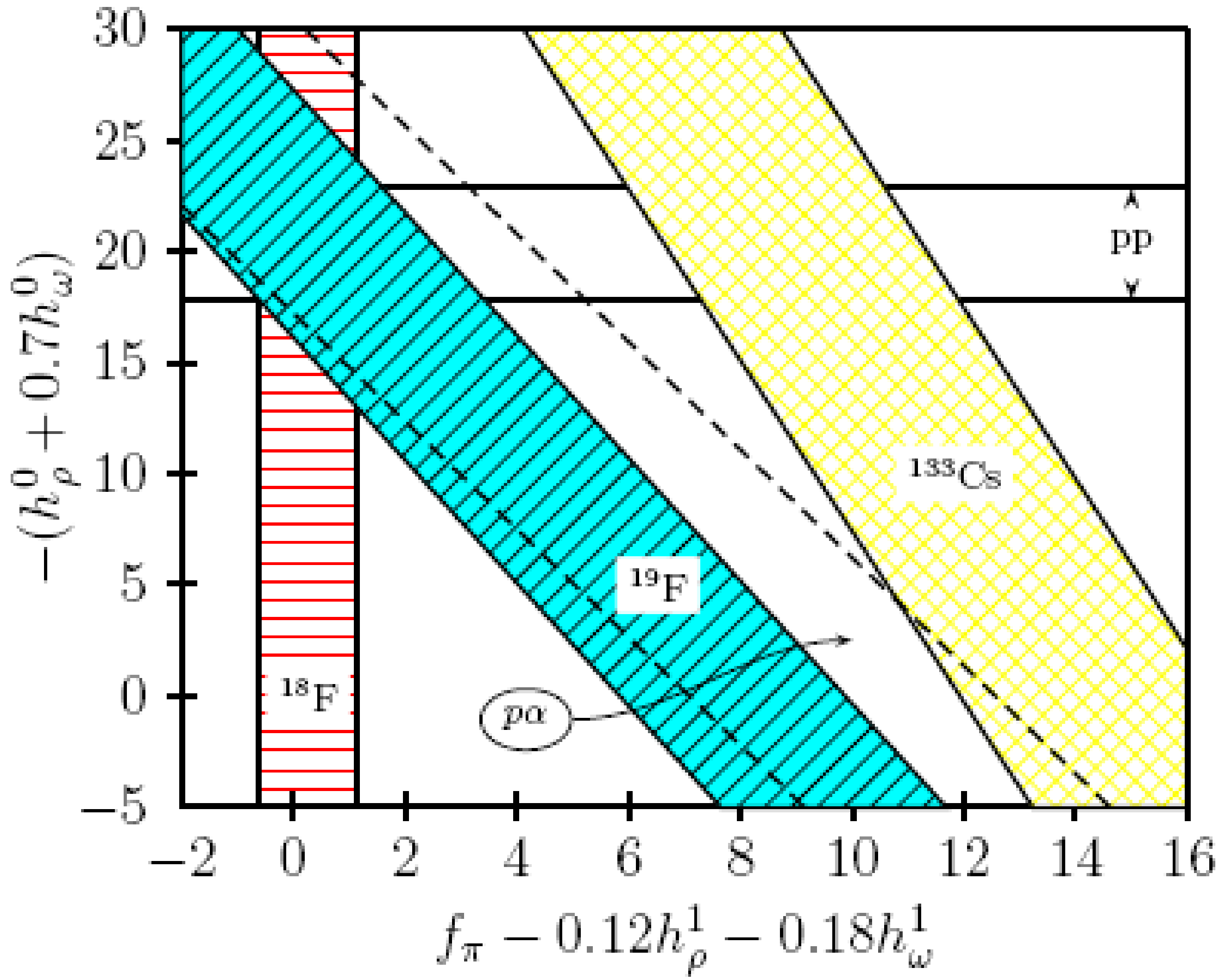


$$H_{\mathrm{PNC}}^{(a)} = \frac{G_F}{\sqrt{2}} \kappa_a \, \boldsymbol{\alpha} \cdot \mathbf{I} \; \rho_v(r)$$

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?

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.

Possible atomic calculation solution?

$\kappa = 0.117(16)$

Incomplete correlation calculation of spin-dependent PNC amplitude?

More spin-dependent PNC effects

$$\kappa = \kappa_a + \kappa_2 + \kappa_{\mathrm{hf}}$$

(V_e,A_N) interaction

Weak-hyperfine interference term

Same Hamiltonian as anapole moment term with $\kappa_a \Rightarrow \kappa_2$

This term does not reduce to the same interaction but "effective" constant κ_{hf} can be calculated.

W.R. Johnson, M.S. Safronova and U.I. Safronova, Phys. Rev. A 67, 062106 (2003)

New all-order (CCSD) calculation of spin-dependent PNC

Electric-dipole matrix elements

$$E_{\mathrm{PNC}}^{(2,a)} = \mathcal{A}_1 \sum_{j \neq v} \frac{\langle 7s \| d \| j \rangle \langle j \| H_{\mathrm{PNC}}^{(2,a)} \| 6s \rangle}{E_{6s} - E_j} + \mathcal{A}_2 \sum_{j \neq w} \frac{\langle 7s \| H_{\mathrm{PNC}}^{(2,a)} \| j \rangle \langle j \| D \| 6s \rangle}{E_{7s} - E_j}$$

PNC matrix elements

First four terms in the sums are replaced by
all-order matrix elements
1% accuracy is expected

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.

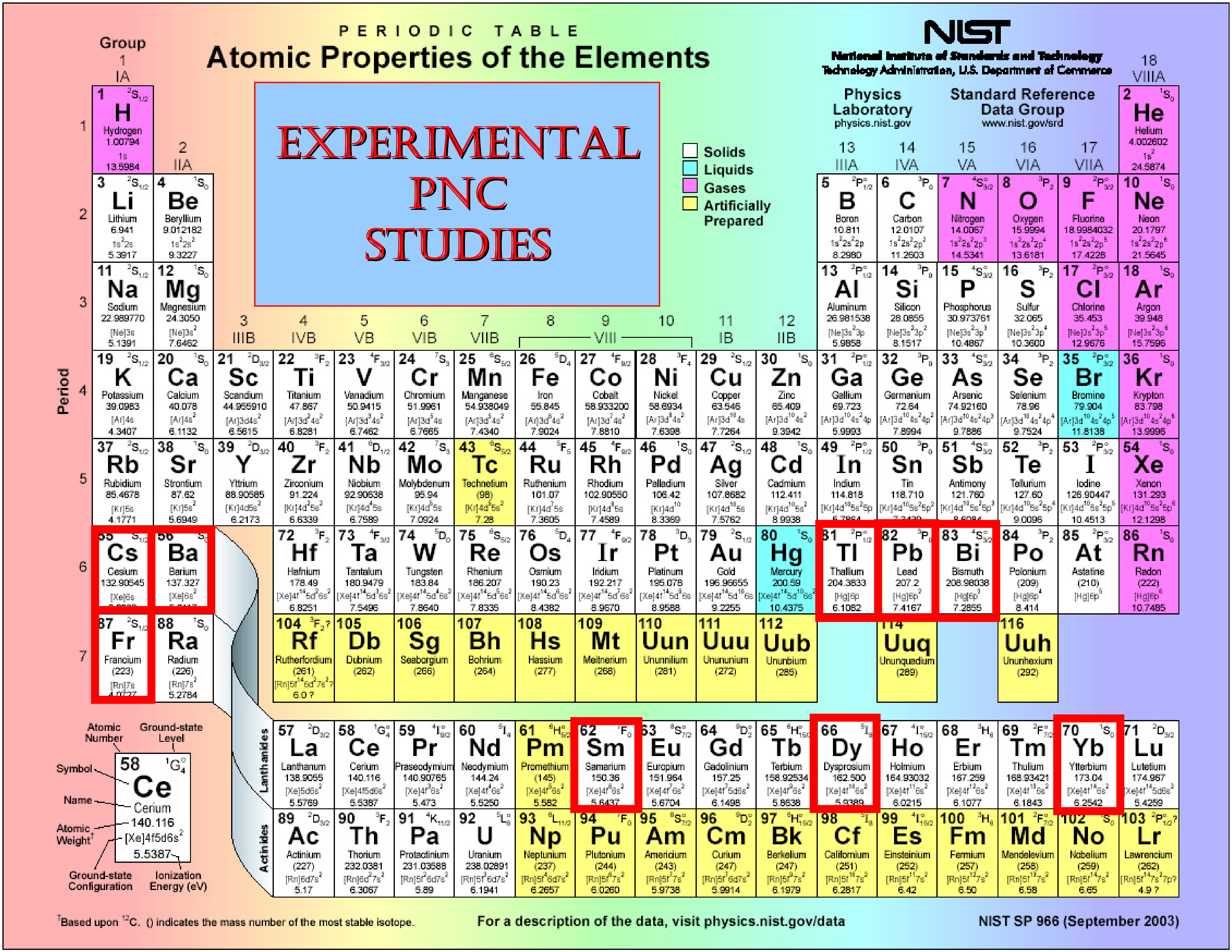
NEED NEW EXPERIMENTS!!!

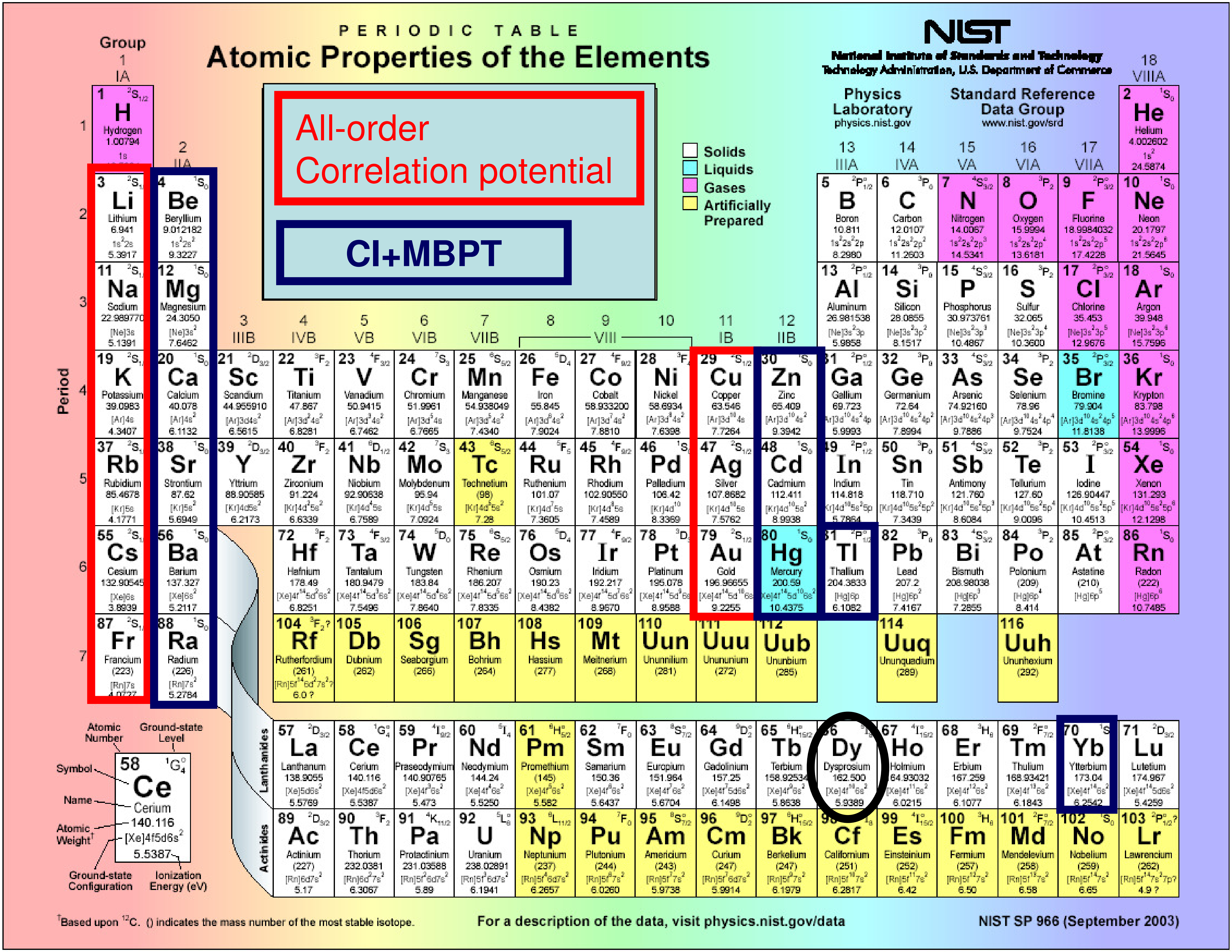
Fr, Yb, Ra$^+$

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

NEED NEW EXPERIMENTAL PNC STUDIES

WANTED!


PERIODIC TABLE
Atomic Properties of the Elements
NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce
Physics Laboratory
physics.nist.gov
Standard Reference Data Group
www.nist.gov/srd
EXPERIMENTAL PNC STUDIES
Solids
Liquids
Gases
Artificially Prepared
Group
Period
Lanthanides
Actinides
Atomic Number
Ground-state Level
Symbol
Name
Atomic Weight†
Ground-state Configuration
Ionization Energy (eV)
58 Ce Cerium 140.116 [Xe]4f5d6s2 5.5387
†Based upon 12C. () indicates the mass number of the most stable isotope.
For a description of the data, visit physics.nist.gov/data
NIST SP 966 (September 2003)


PERIODIC TABLE
Atomic Properties of the Elements
NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce
Physics Laboratory
physics.nist.gov
Standard Reference Data Group
www.nist.gov/srd
All-order Correlation potential
CI+MBPT
Solids
Liquids
Gases
Artificially Prepared
Lanthanides
Actinides
Atomic Number
Ground-state Level
Symbol
Name
Atomic Weight†
Ground-state Configuration
Ionization Energy (eV)
†Based upon 12C. () indicates the mass number of the most stable isotope.
For a description of the data, visit physics.nist.gov/data
NIST SP 966 (September 2003)

PROSPECTS FOR THEORY IMPROVEMENT

Fr and Ra^+: 1-3% at present
0.5% possible with CCSDT (same as Cs)

Yb: 9% at present
Significant improvement should be be possible with
CI + coupled-cluster, especially if triples are implemented

Dy: ? Previous: no signal within 2 orders of magnitude from prediction. The problems appears to be somewhat understood at this time. Significant improvement possible if CI+MBPT could be implemented.

Tl, Bi, Pb – improvements to 1% should be possible

Conclusion

A: New analysis of atomic PNC experiment is Cs: Nuclear spin-independent part:

(1) Provided most accurate to-date test of the low-energy electroweak sector of the SM.

(2) Confirmed fundamental “running” (energy dependence) of the electroweak force.

(3) Placed constraints are on a variety of new physics scenarios beyond the SM.

B: New analysis of atomic PNC experiment is Cs: Nuclear spin-independent part (anapole moment)

(1) New calculations, accurate to 1% - essentially the same result.

(2) Constraints on nuclear weak coupling constants are still inconsistent with nuclear physics experiments.

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Matt Simmons

*Graduated with a Ph.D.

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Ephraim Eliav, Tel Aviv University, Israel
Walter Johnson, University of Notre Dame