Electric Dipole moments
signature of time reversal violation

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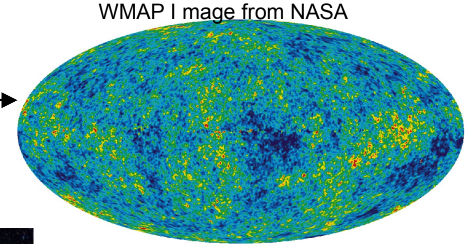
Physical Research Laboratory

11 January, 2010

International school and conference on cold ions and atoms

Science at different scales

WMAP I image from NASA



WMAP
Map of microwave background radiation of the Universe.

- 10^{26} — Farthest object → WMAP
- 10^{20} — Galaxy → Andromeda Galaxy
- 10^{15} — Light week
- 6.38×10^{6} → Earth
- 10^{-5} — Human cell
- 10^{-10} — Hydrogen atom → Nitrogen atom
- 10^{-15} — Proton → Large Hadron Collider

Image from HST

Andromeda Galaxy
~1000,000,000 stars.

Image from NASA website

Earth
Planetary and atmospheric sciences.

Nitrogen atom
Quantum world.

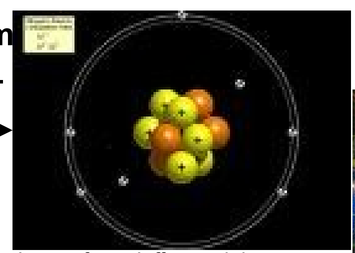


Image from Jafferson lab

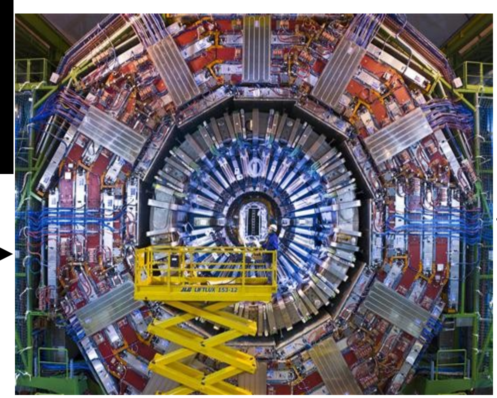


Image from CERN website

Large Hadron Collider
Elementary particles and their interactions.

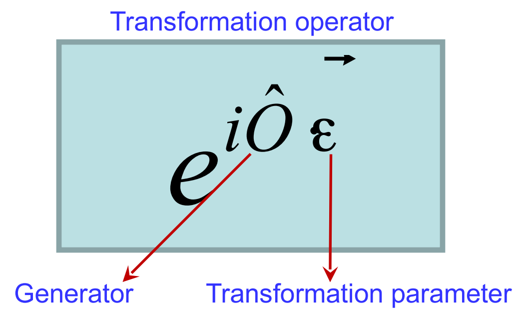
Length scales in meter

Symmetries in Nature
continuous and discrete

Continuous symmetries

Infinitesimal transformations are possible. Finite transformations are repeated operations.

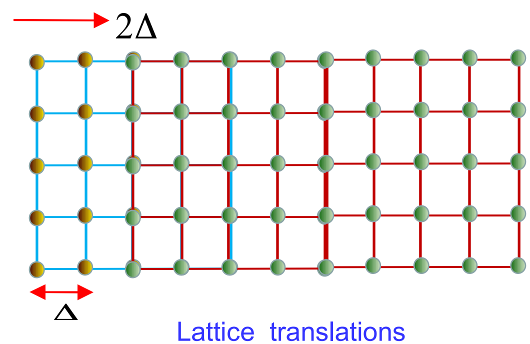
Examples: rotation, translation in space and time, etc



Discrete symmetries

Infinitesimal transformations are not defined. Transformations are discrete operations.

Examples: crystal symmetries, reflection, charge conjugation, time reversal, etc



Conservation laws

Dynamical variables which do not change under a symmetry transformation are conserved quantities.

Examples: rotation—angular momentum, translation—linear momentum, etc

CPT symmetries

charge conjugation, parity and time reversal

Charge conjugation

Transforms particle to antiparticle and leaves dynamical variables unchanged. Negates charge, baryon number, lepton number and strangeness.

Q, B, L, S, p, J, etc —Charge conjugation→ *-Q, -B, -L, -S, p, J*, etc

Charge *Q*, baryon number *B*, lepton number *L*, strangeness *S*, linear momentum *p*, angular momentum *J*, etc.

Parity/reflection

Mirror reflection about all the coordinates. Defines handedness of a system.

x, y, z —Partiy transformation→ *-x, -y, -z*

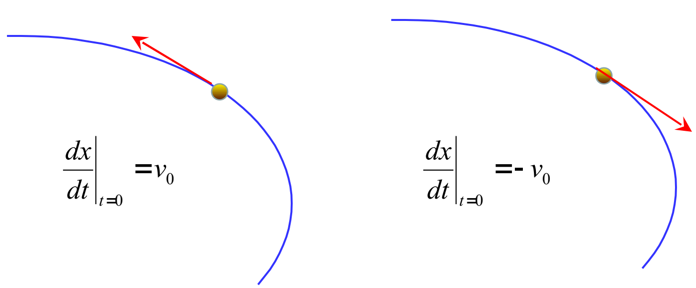
Coordinates undergo a change in sign and handedness changes.

Time reversal

Change in direction of time or motion reversal.

t —Time reversal→ *-t*

Time changes sign.



$$\left.\frac{dx}{dt}\right|_{t=0} = v_0 \qquad \left.\frac{dx}{dt}\right|_{t=0} = -v_0$$

Motion reversal without any dissipative forces.

Motion under potential

$$m\frac{d^2x}{dt} = -\nabla U \xrightarrow{\text{CPT}} m\frac{d^2x}{dt} = -\nabla U$$

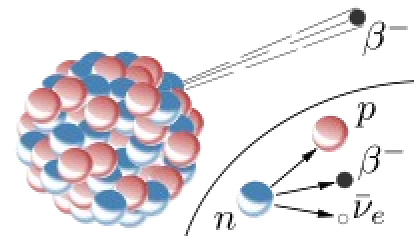
Newton's equation of motion remain unchanged under parity and time reversal transformations.

Parity violation in beta decay
equivalent to time reversal violation

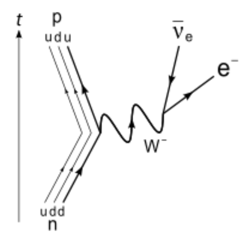
Parity violation in weak interaction

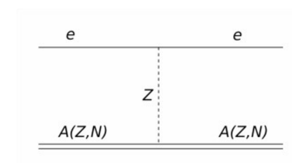
Weak interaction violates parity. First suggested to explain tau-theta puzzle and observed in beta decay of ^{60}Co

$$n \rightarrow p + e^{-} + \bar{\nu}$$

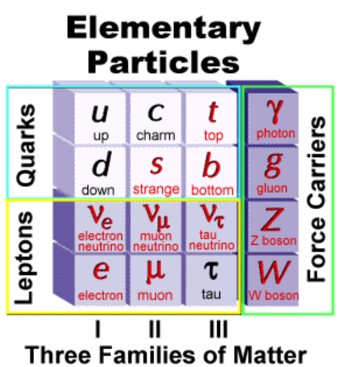


Arises from charged weak current interaction. Electroweak unification predicts a neutral weak current. Atoms are ideal candidate to observe neutral weak current.





Neutral weak currents induced parity nonconservation in atoms



Attention

D. Budker
Atomic and Molecular P- and P,T-Violation Experiments
18 Jan, 13:40 PM

B. K. Sahoo
Relativistic Many-Body Theory of Parity Nonconservation….
18 Jan, 14:30 PM

Lee, T. D., and C. N. Yang, Phys. Rev., 104, 254 (1956).,
C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, Phys. Rev. 105, 1413 (1957).

Time reversal violations
genesis

Time reversal transformation

One dimensional time-dependent Schrodinger equation with real potential. Under time reversal transformation.

$$\left[-\frac{\partial^2}{\partial x^2} + V(\vec{r}) \right] \psi(\vec{r}) = i \frac{\partial}{\partial t} \psi(\vec{r})$$

Invariance

To preserve invariance of equation of motion (Schrodinger equation), time reversal transformation implies complex conjugation

$$\left[-\frac{\partial^2}{\partial x^2} + V(\vec{r}) \right] \psi(\vec{r}) = i \frac{\partial}{\partial t} \psi(\vec{r})$$

Time reversal violation

Complex potential, under time reversal transformation Schrodinger equation is modified. Classical analogue is dissipation.

$$e^{i\varphi} v(r,\theta) \xrightarrow{\text{time-reversal}} e^{-i\varphi} v(r,\theta)$$

Time reversal violation is associated with phase of interaction

CP violation in kaon decay
equivalent to time reversal violation

K^0 - **meson**

Bound state of down (d) and anti-strange ($\bar{s}$) quarks. Strangeness and parity eigenvalues are 1 and -1. K-mesons are isospin doublets.

$$[\bar{K}^0(s\bar{d}), K^-(s\bar{u})],\ [K^0(d\bar{s}), K^+(u\bar{s})]$$

Dominant decay channels, which conserve CP symmetry are:

$$|K_1^0\rangle \to \pi^0 + \pi^0; |K_1^0\rangle \to \pi^+ + \pi^-$$

$$|K_2^0\rangle \to \pi^0 + \pi^+ + \pi^-$$

CP violation

Decay products which changes CP eigenvalue.

$$|K_2^0\rangle \to \pi^+ + \pi^-$$

From CPT invariance, *CP violation implies time reversal violation*.

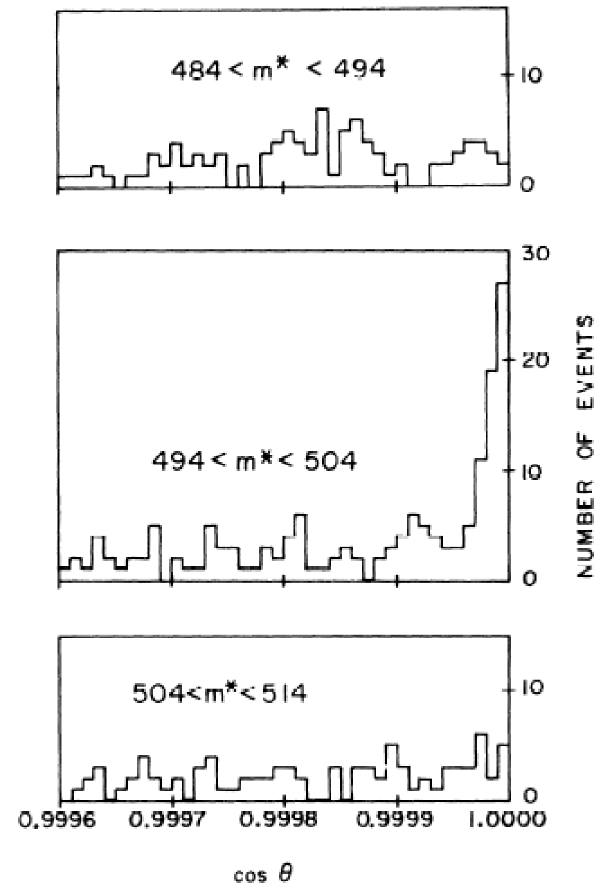


FIG. 3. Angular distribution in three mass ranges for events with $\cos\theta > 0.9995$.

J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Lett. 13, 138 (1964)

Importance of CP violation

time reversal violation

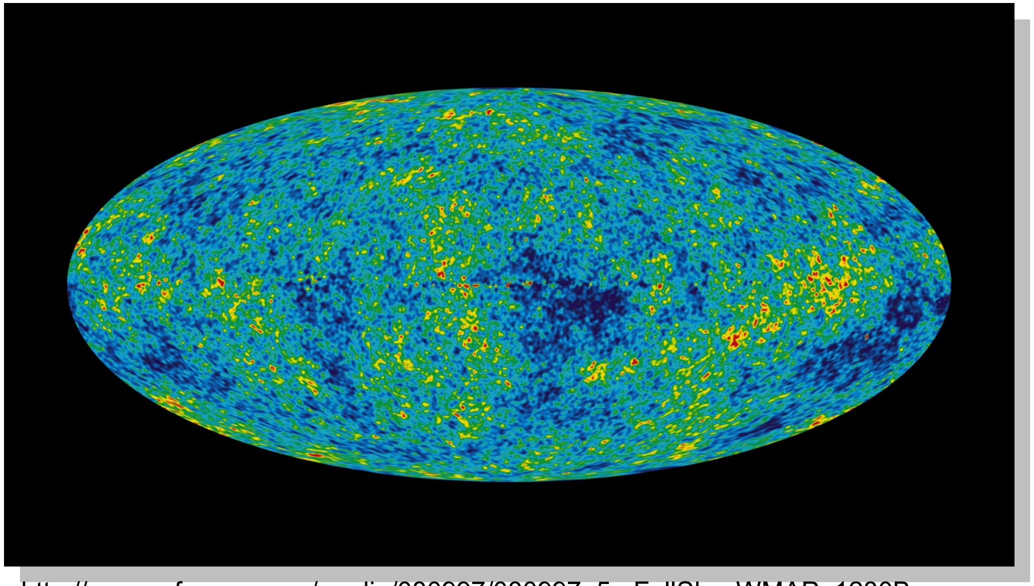
Important questions

•If Universe originates from big-bang, equal amounts of matter and antimatter are created. However, no signature of sizable antimatter presence is observed in the current epoch.

How and where antimatter vanished ?

•If the standard model of particle physics can be fine tuned with extensions or opt for alternatives. So that deficiencies or short comings of standard model can be fixed.

How to validate/check other models ?



http://map.gsfc.nasa.gov/media/080997/080997_5yrFullSky_WMAP_1280B.png

Key to finding a solution

Phenomenon providing clues to answering these questions is time reversal violation.

→

Observable signature

Observable signature of time reversal violation is intrinsic electric dipole moment.

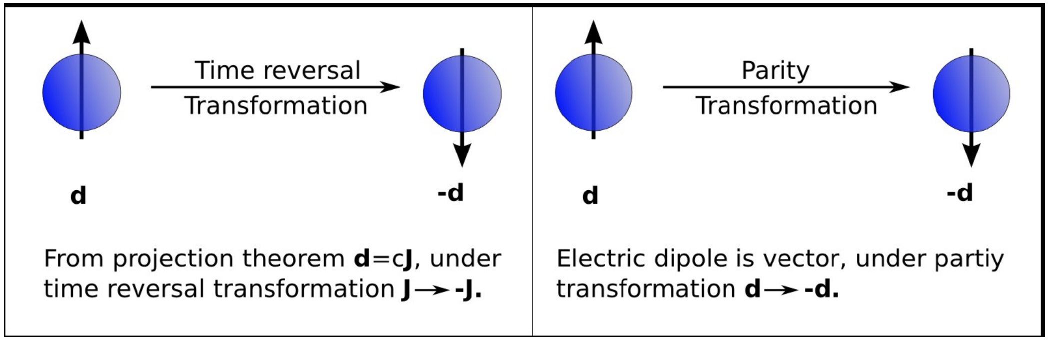
2006: *John C. Mather and George F. Smoot* awarded Nobel prize for CMBR studies

Observing time reversal violation
Electric dipole moments

P and T reversal transformations

Finite electric dipole moment of non-degenerate quantum system is signature of parity and time reversal violations.

Permanent EDM of molecules arise from degenerate opposite parity states.



Detecting electric dipole moments

EDM and magnetic moment couples to external static electric field and magnetic fields.

Observable signature, energy difference under reversal of electric field.

$$H_{int} = -d_a \cdot E - \mu \cdot B$$

$$\Delta E = 2d_a \cdot E = \omega$$

$$d_a = \frac{\omega}{2E}$$ **Electric dipole moment**

Attention
D. Budker
Atomic and Molecular P- and P,T-Violation Experiments
18 Jan, 13:40 PM

Measuring electric dipole moments not any particles

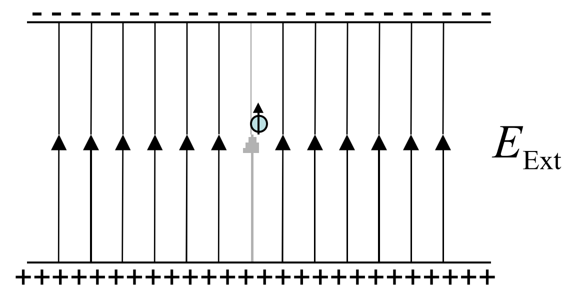
Particles with EDM

Intrinsic EDM of electron and quarks are signature of fundamental physics. It probes phenomena at the high energy scales. For charge particles

$$\vec{F} = q\vec{E}_{\text{ext}}.$$

Particle accelerates away. Neutron is an exception.

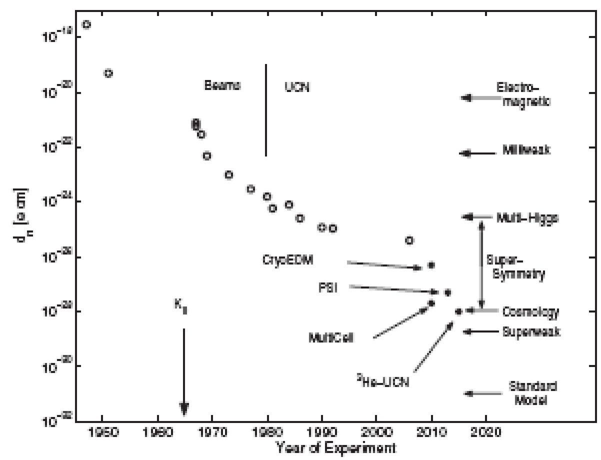
Charge particles with EDM in external fields



Neutrom EDM

Current limit on neutron EDM.

$$|d_n| < 2.9 \times 10^{-26}\ e\,\text{cm}.$$



EDM of charged particles

To measure EDM of electron, composite charge neutral systems like atoms and molecules are ideal. These do not experience Coulomb force.

C. A. Baker, et al., Phys. Rev. Lett **97,** 131801 (2006),

S. K. Lamoreaux and R. Golub, . Phys. G: Nucl. Part. Phys. **36 ,** 104002 (2009).

Atomic electric dipole moments
Can we measure it ?

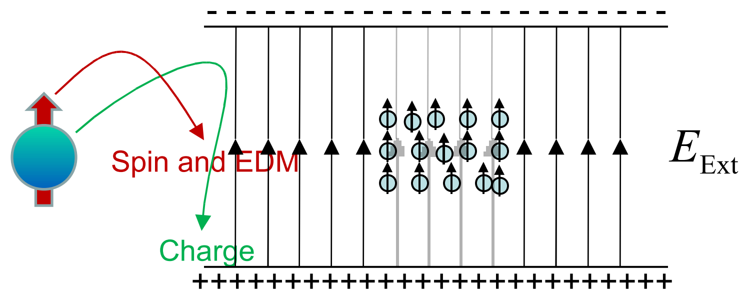
Schiff theorem

Non-relativistically, collection of point particles with electric dipole moments (EDMs) realigns to shield applied external electric field. This renders observable EDM to zero.

Interaction of EDMs with external/internal electric field.

$$H_{\mathrm{EDM}} = \sum_i - d_i \sigma_i \cdot E_i$$

Charge particles with EDM in external fields



$$H_0 = \sum_i \frac{p_i^2}{2m_i} + \sum_{i \neq j} \frac{q_i q_j}{2r_{ij}} + \sum_i q_i V(\mathrm{r}_i)$$

External/internal electric field

$$\vec{E}_i = \vec{\nabla}_i \left[\sum_j \frac{q_j}{2r_{ij}} + V(\mathrm{r}_i) \right]$$

$$H_{\mathrm{EDM}} = \left[\sum_i \frac{d_i}{q_i} \vec{\sigma} \cdot \vec{\nabla}_i, H_0 \right]$$

EDM of the system

$$W_{\mathrm{EDM}} = \langle \psi | \left[\sum_i \frac{d_i}{q_i} \vec{\sigma} \cdot \vec{\nabla}_i, H_0 \right] | \psi \rangle = 0$$

Exceptions

EDM is observable due to

- Relativistic effects,
- Finite size of particles,
- Non-electrostatic interactions.

L. I. Schiff, Phys. Rev. **132**, 2194 (1963),

P. G. H. Sandars, Contemporary Physics **42**, 97 (2001).

Defying Schiff theorm I
relativistic effects

Relativistic description

Relativistic Hamiltonian of an electron in central potential

$$H_D = \beta mc^2 + c\alpha \cdot p - eV(r).$$

Can be nuclear potential as well.

Covariant form of electron EDM and external field interaction

$$H_{\mathrm{EDM}} = - d_e \beta \sigma \cdot E.$$

In terms of total Hamiltonian

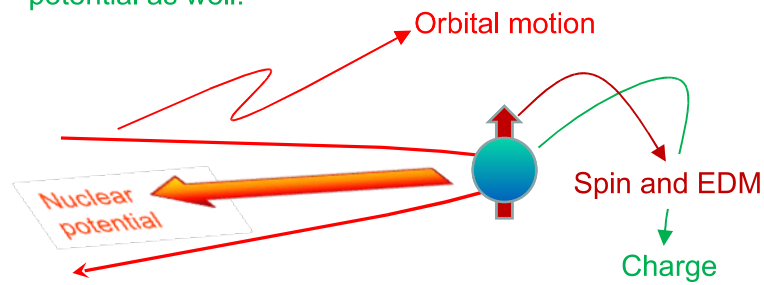
$$H_{\mathrm{EDM}} = \left[- d_e \beta \vec{\sigma} \cdot \vec{\nabla}, H_D \right] + 2i \frac{d_e}{e} c \beta \gamma_5 p^2.$$

Expectation of second term is non zero

$$\langle \psi | \left[\frac{d_e}{e} \beta \vec{\sigma} \cdot \vec{\nabla}, H_D \right] | \psi \rangle = 0,$$

$$\langle \psi | 2i \frac{d_e}{e} c \beta \gamma_5 p^2 | \psi \rangle > d_e$$

P. G. H. Sandars, Phys. Lett. **14**, 194 (1965)



Enhancement

Derivation can be extended to atoms higher Z and there is an enhancement of atomic EDM.

$$D_A \propto Z^3 \alpha^2,$$

Incomplete cancellation arises from the spin-orbit coupling (magnetic interaction)

$$2i \frac{d_e}{e} c \beta \gamma_5 p^2.$$

Defying Schiff theorm II
finite size effects

Schiff moment

Emerges when charge and electric dipole moment distributions are different within the nucleus. Then

$$W_{\text{EDM}} = - D_N \sigma_N \cdot \int d^3x (\rho_d - \rho_c) \langle \psi | E(x) | \psi \rangle$$

The above dipole interaction energy is zero if nuclear charge and dipole distributions are the same. Unequal distributions can arise from

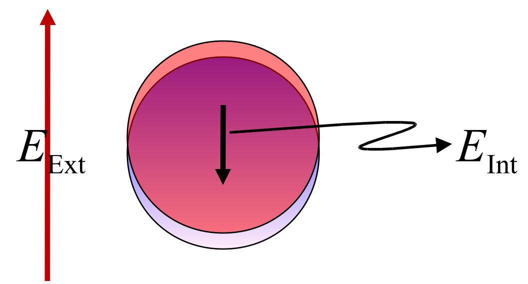
- Electric dipole moment of quarks,
- CP violating quark-quark interactions.

It is also referred to as the local dipole moment of the nucleus.

$$W_{\text{EDM}} = - eS \cdot \left| \nabla, \delta(r_e) \right|$$

This is point nucleus limit. More precise treatment is to consider finite nucleus.

Charge distribution gradient within nucleus



$$\phi(\vec{R}) = - \frac{3\vec{S} \cdot \vec{R}}{B} \rho_N(R)$$

Schiff potential

$$B = \int \rho_N(R) R^4 dR$$

Nuclear Schiff moment

C.-P. Liu, M. J. Ramsey-Musolf, W. C. Haxton, R. G. E. Timmermans, and A. E. L. Dieperink, Phys. Rev. C **76**, 035503 (2007).

Atomic electric dipole moments
choosing one

Elementary particles to atoms

Atomic EDM arise from parity and time reversal phenomena at elementary particle physics level. These could be

•Quark or electron electric dipole moments,

•Quark-quark, quark-electron, electron-electron P and T odd interactions,

Choice of atoms

Different atoms are sensitive to parity and time reversal violations in various sectors

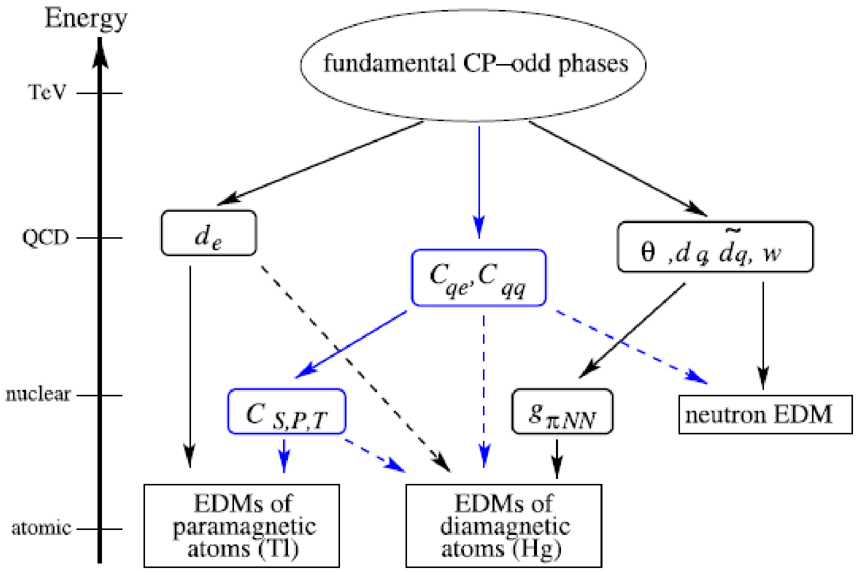
•Paramagnetic atoms—leptonic sector,

•Diamagnetic atoms—leptonic and hadronic sectors,

Electron electric dipole moment

Standard model predictions

$$d_e < 10^{-38}\,\mathrm{e\,cm}$$



C. Jarlskog, Phys. Rev. Lett. **55**, 1039 (1985),

W. Bernreuther and M. Suzuki, Rev. Mod. Phys. **63**, 313 (1991).

M. Pospelov , A. Ritz , Ann. Phys. 318 , 119 (2005).

Electron electric dipole moment limits

Current limit

Thallium experimental results provide the best limit on electron EDM.

•Atomic beam experiment,

•Enhancement factor is -585,

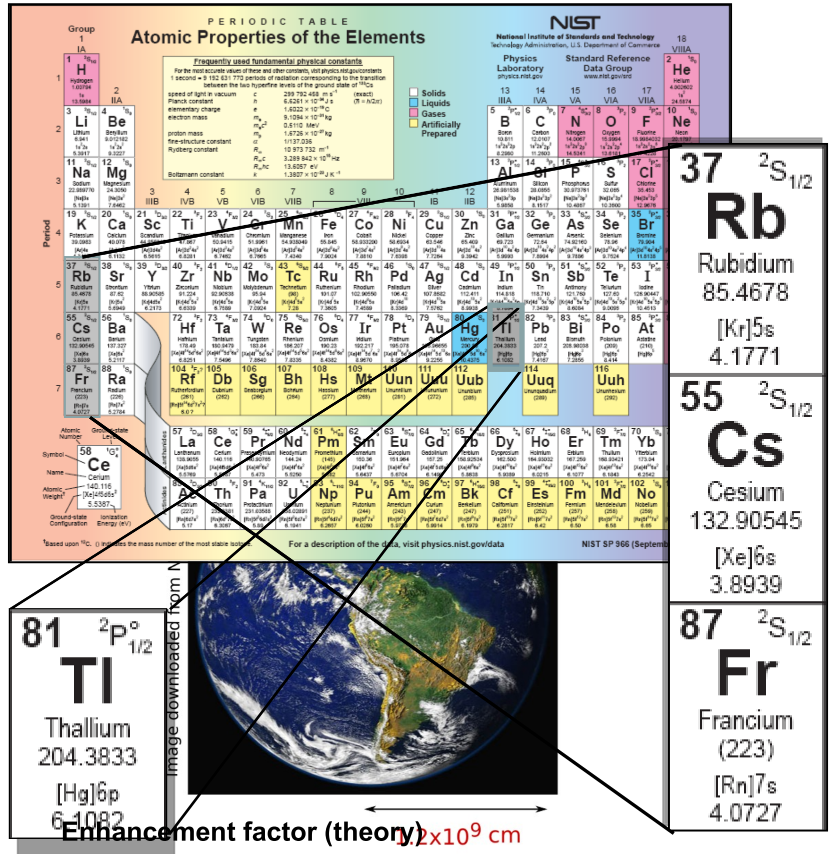
•Main systematic error is motional magnetic field.

$$d_e = (6.9 \pm 7.4) \times 10^{-28}\, e\,\mathrm{cm}$$

Equivalent to the upper limit

$$|d_e| < 1.6 \times 10^{-27}\, e\,\mathrm{cm}$$

B. C. Regan, E. D. Commins, C. J. Schmidt, D. DeMille, PRL **88**, 071805 (2002) .



Other atoms

Theoretically, alkali metal atoms have less complications and are preferred choice.

Atom	Experimental result	Enhancement factor (theory)
Rb	------------------------	25.74
	J. M. Amini, et al , PRA 75, 063416 (2007)	H. S. Nataraj, et. Al. PRL 101, 033002 (2008)
Cs	d_e=(-1.5±5.5±1.5)×10^{-26} *e* cm	120.53
	S. A. Murthy, et al , PRL **63,** 965(1989)	H. S. Nataraj, et. Al. PRL 101, 033002 (2008)
Fr	------------------------	910±~5%
	Z-T. Lu, et. al, PRL 79, 994 (1997)	T. M. R. Byrnes, et al Phys. Rev. A 59, 3082 (1999) ,

CP violation parameters
Hadronic sector

CPT theorem

Combined discrete symmetries CPT is a good symmetry.
Result obtained from local field theory.

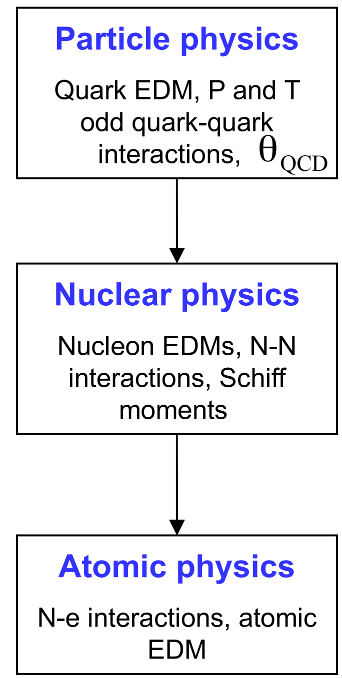
T reversal violation, then *imply CP violation*.

Current experiments

Diamagnetic or closed-shell atoms like Yb, Hg, Xe, Ra and Rn are candidate atoms to probe CP violation in hadronic sector.

Estimating CP violation parameter

CP violation parameters are obtained after combining the experimental results with the theoretical results.



Experiment result $d_a = \frac{\omega}{2E}$

Theoretical result $d_a = \lambda\eta$

$\rightarrow$ $\lambda = \frac{\omega}{2E\eta}$ CP violation parameter

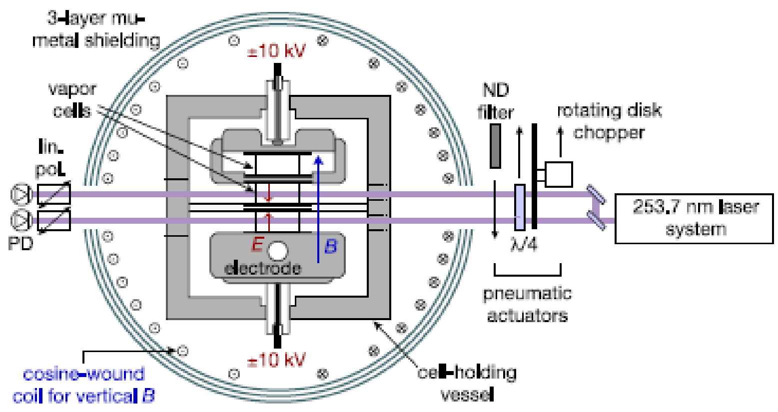
G. Luders, Ann. Phys. (N.Y.) 281, 1004-1018 (2000)

Mercury EDM experiment
recent results

Most precise EDM experiment

Hg EDM experiment results is the best result so far. Result from the current generation is

$$d\left({}^{199}\mathrm{Hg}\right) = \left(0.49 \pm 1.29_{\mathrm{stat}} \pm 0.76_{\mathrm{syst}}\right) \times 10^{-29}\ \mathrm{e\ cm}$$



Limit from this experimental result is

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

CP violation parameter bounds

Bounds on CP violation parameters obtained after combining the experimental data with earlier theoretical results.

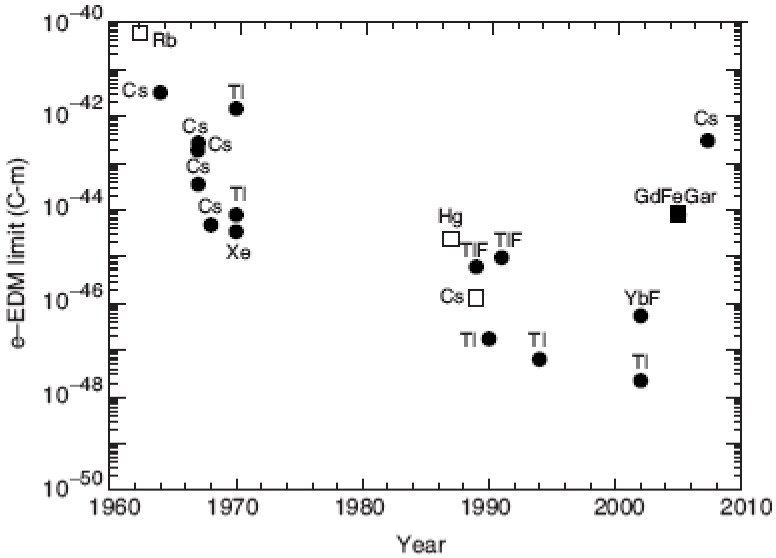
Parameter	^{199}Hg bound	Hg theory	Best alternate limit	
$\tilde{d}_q$(cm) [a]	6×10^{-27}	[15]	n: 3×10^{-26}	[3]
d_p(e cm)	7.9×10^{-25}	[16]	TlF: 6×10^{-23}	[17]
C_S	5.2×10^{-8}	[18]	Tl: 2.4×10^{-7}	[19]
C_P	5.1×10^{-7}	[18]	TlF: 3×10^{-4}	[1]
C_T	1.5×10^{-9}	[18]	TlF: 4.5×10^{-7}	[1]
$\bar{\theta}_{QCD}$	3×10^{-10}	[20]	n: 1×10^{-10}	[3]
d_n(e cm)	5.8×10^{-26}	[16]	n: 2.9×10^{-26}	[3]
d_e(e cm)	3×10^{-27}	[21, 22]	Tl: 1.6×10^{-27}	[18]

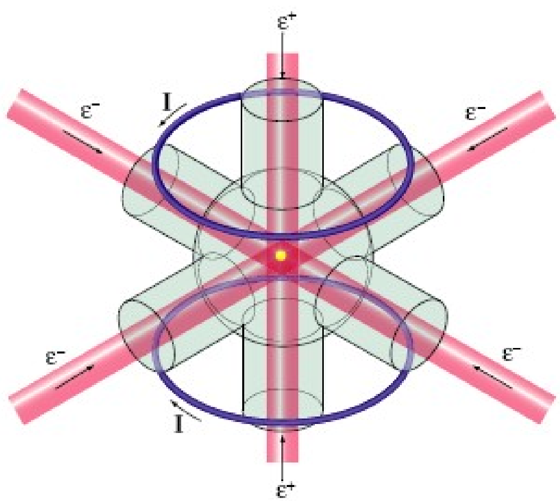
[a] For ^{199}Hg: $\tilde{d}_q = (\tilde{d}_u - \tilde{d}_d)$, while for n: $\tilde{d}_q = (0.5\tilde{d}_u + \tilde{d}_d)$.

Our recent calculations provide new bounds

W. C. Griffith, M. D. Swallows, T. H. Loftus, M. V. Romalis, B. R. Heckel, and E. N. Fortson, Phys. Rev. Lett. **102**, 101601 (2009)

Ultracold atomic gases
next generation experiments





Ultracold atoms

Low atomic velocities reduce the systematic error from motional magnetic field

$$\vec{B}_{\text{mot}} = \frac{v \times E}{c^2}.$$

It couples to the magnetic moment of atom and mimics EDM signal. Recall

$$H_{\text{int}} = -d_a \cdot E - \mu \cdot B.$$

Interaction of motional magnetic field with atom

$$-\vec{\mu} \cdot \frac{v \times E}{c^2},$$

Changes sign when electric field E is reversed like the EDM interaction term.

Measurement scheme

There are various propsed schemes

•Quantum non-demolition measurement of cold atoms (Yb),

•Measurement using a cold atom fountain (Cs),

•Optical lattices (Cs, Rb).

Candidate atoms
and where

Proposed experiments

Atom	Proposed Lab
Rb	Penn State University
	F.Fang and D.S. Weiss, OL **34,** 169 **(**2009 **).**
Cs	LBNL
	J. M. Amini, et al , PRA 75, 063416 (2007).
Yb	Kyoto University
	M. Takeuchi M, et. al, PRA **75**, 063827 (2008).
	IISc
	V. Natarajan, EPJD **32**, 33 (2005).
Fr	RCNP, Osaka Univesity
	Sakemi et. al.
	JILA
	Z-T. Lu, et. al, PRL 79, 994 (1997).

What to expect

For Cs and Rb atoms trapped in a one dimensional, 1.064 \mum, optical lattice.

•No of atoms—Cs 5×10^{8} and Rb 10^{10} ,

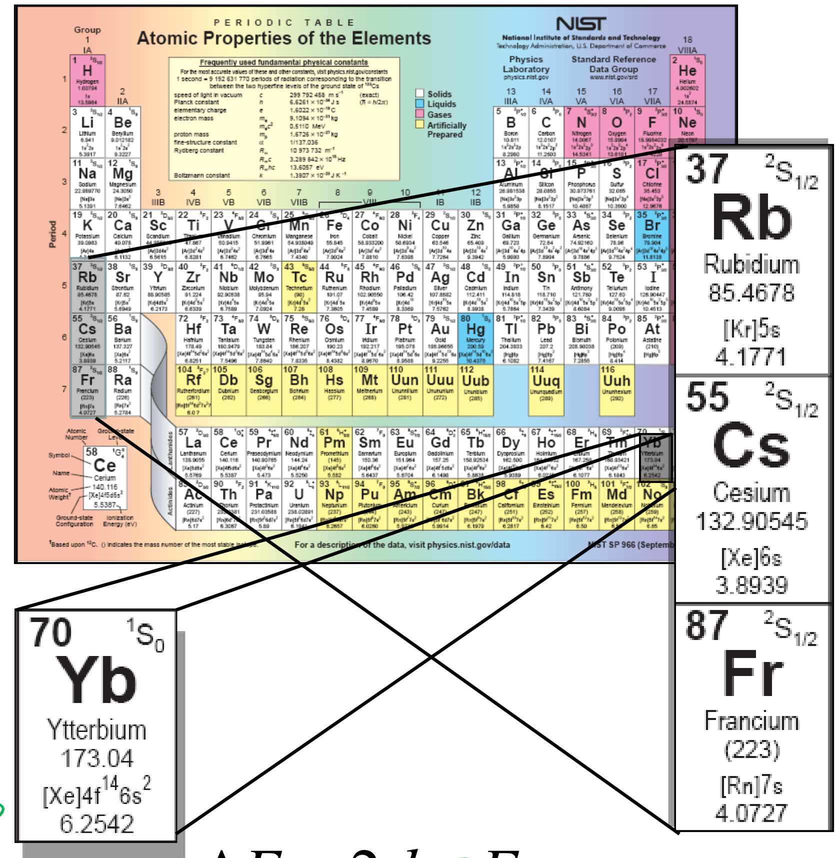
•External field—exceeding 10^{5} V/cm,

•Integration time—approx 100 hours,

•Precision—less than 5×10^{-30} e-cm.

200-fold improvement over the current experimental limit.

D. S. Weiss, F. Fang, J. Chen, BAPS J.008 (2003).



$$\Delta E = 2 d_a \cdot E = \omega$$

Attention

Y. Takahashi

Quantum simulator Using ytterbium

18 Jan, 11:50 PM

Atomic theory calculations
enhancement factor

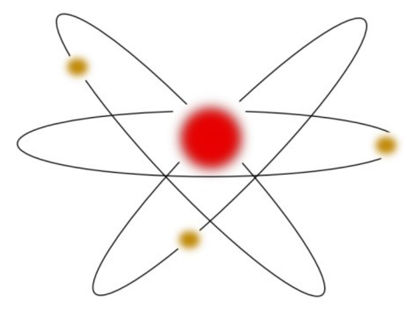
Atomic EDM from Schiff moment

Electrons within atoms interact with the nuclear Schiff moment and induces finite atomic EDM.

Atomic EDM arising from the nuclear Schiff moment

$$d_a = 2\sum_I \frac{\langle \Psi_0 | D | \Psi_I \rangle \langle \Psi_I | H_{\mathrm{PTV}} | \Psi_0 \rangle}{E_0 - E_I} = S\eta$$

$$H_{\mathrm{PTV}} = -\phi(\vec{R}) = \frac{3S \cdot R}{B} \rho_N(R)$$



Though this be madness, yet there is method in it.
(Hamlet)

Atomic theory

Considerations for accurate calculations

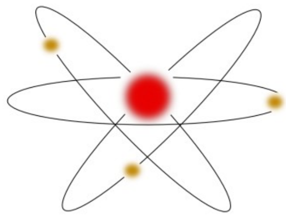
•Dipole—dominant contribution from large *r*,
•Schiff moment—significant at small *r*,
•Energy—contribution all radial ranges.

Accurate wavefunction at all *r* ranges

Key points

•Complexity—multiple perturbations,
•Route to bounds—atomic-nuclear-particle,
•Many-body physics—heavy atoms,

Atomic wavefunctions mean field



Atomic orbitals

For atoms with high nuclear charge relativistic effects are important. Dirac-Hamiltonian is an appropriate choice,

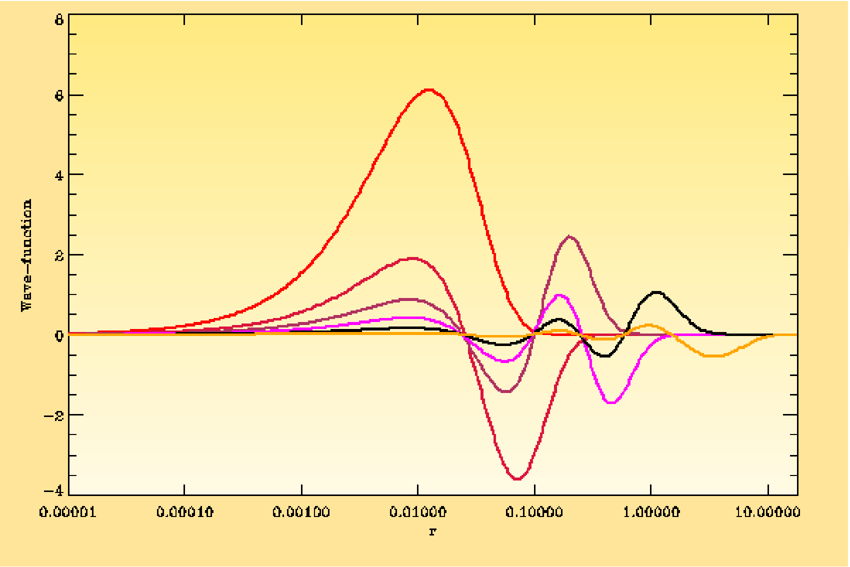
$$H_{\mathrm{DC}} = \sum_{i} \left[\alpha_i \cdot p_i + \beta c^2 - V_n(r_i) \right] + \sum_{i<j} \frac{1}{\left| r_i - r_j \right|}$$

Challenge

Accurate description of the electron-electron correlations

$$\sum_{i<j} \frac{1}{\left| r_i - r_j \right|}$$

Starting point is the mean field calculations, Dirac-Fock for the present calculations. Then obtain many electron wavefunctions as direct product.



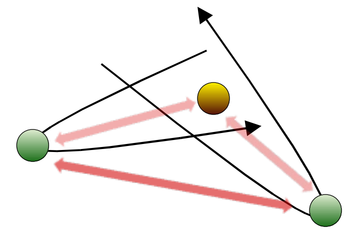
Single electron radial wave functions (1-6s) of atomic Ytterbium.

Many body perturbation theory diagrammatics

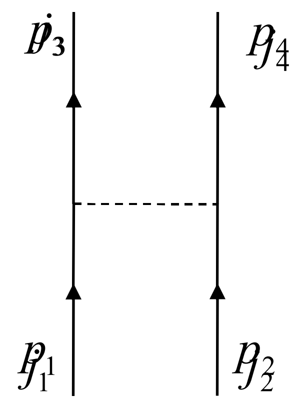
Residual Coulomb interaction

Consider Helium atom, which has two electrons.

$$H = \sum_{i=1}^{2} \frac{p_i^2}{2m} + \frac{2}{r_i} + \frac{1}{r_{12}}$$



Where, linear momentum states are eigenstates for free particles; angular momentum are eigen states with the nuclear potential.



In actual many-body calculations, residual Coulomb interaction

$$\sum_{i<j} \frac{1}{|r_i - r_j|} - \sum_i U_{DF}(r_i)$$

Is the perturbative interaction.

Complications in EDM calculations

Two more perturbative Hamiltonians: CP violating interaction Hamitonian and electric dipole moment coupling to external field

$$H_{PTV} \quad \text{and} \quad D.E_{ext}$$

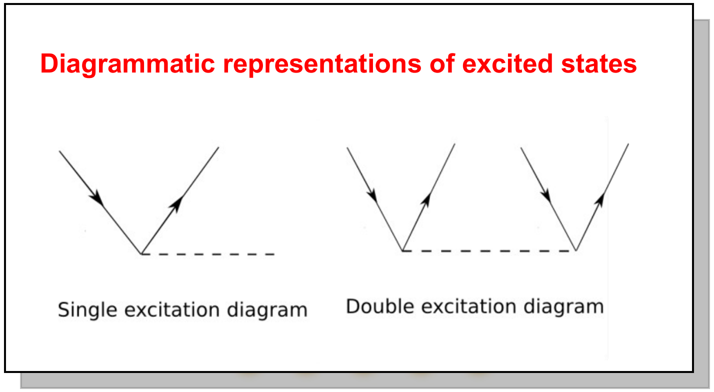
Correlations effects
many-body effects

Electron-electron correlation effects

To define Hilbert space, single particle states are separated into core and virtual.

•Core: states occupied in reference/unperturbed state,
•Virtual: states not occupied in reference/unperturbed state.

Hilbert space consist of reference and occupied replaced with virtual states.



Size extensivity

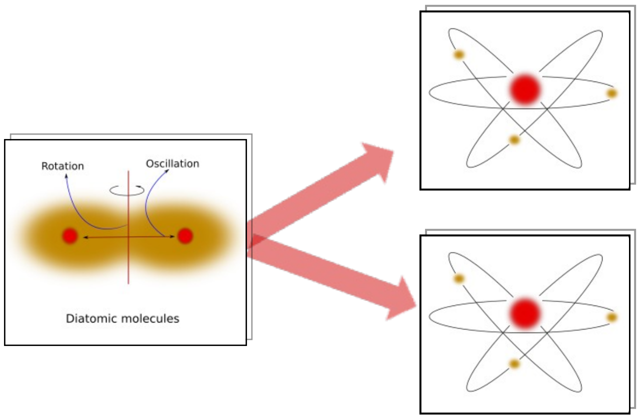
A key point in many-body theory is: total energy of the system depend linearly dependent on number of constituent particles.

$$E(n) \propto n$$

Which implies

$$E(N) = \sum_i E(n_i) : \quad \sum_i n_i = N$$

Coupled-cluster theory satisfies this condition.



$$E(2N) \qquad E(N) + E(N)$$

Coupled-cluster theory
accurate many-body theory

Many-body perturbation to Coupled-cluster

Order by order calculation with many-body theory, even with diagrams, is tedious beyond third order. Number of diagrams runs into thousands.

Coupled-cluster theory is equivalent to selected summation or grouping of diagrams to all orders.

Wave operator is an exponential.

Further, it couples excitations of various orders.

Working equations are coupled Nonlinear equations

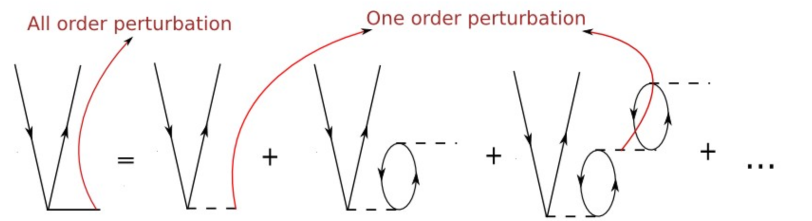
$$|\Psi\rangle = e^{T}|\Phi_0\rangle$$

Coupled-cluster equations

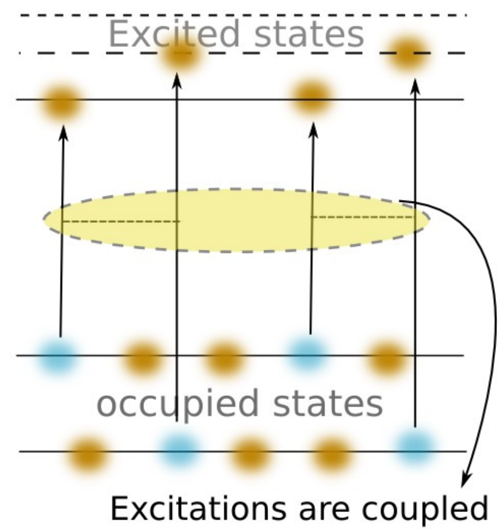
$$\langle \Phi_a^p | H_N + [H_N, T] + [H_N, [H_N, T]] + \cdots | \Phi_0 \rangle = 0$$

$$\langle \Phi_{ab}^{pq} | H_N + [H_N, T] + [H_N, [H_N, T]] + \cdots | \Phi_0 \rangle = 0$$

T. J. Bartlett and M. Musial, Rev. Mod. Phys. 79, 291 (2007).



Coupled-cluster singles



Attention
B. K. Sahoo
Relativistic Many-Body Theory of Parity Nonconservation….
18 Jan, 14:30 PM

Perturbed Coupled-cluster theory
accurate many-body theory

Perturbing coupled-cluster wave function

Electric dipole moment expression consist of summing over a set of intermediate atomic states

$$d_a = 2\sum_I \frac{\langle \Psi_0 | D | \Psi_I \rangle \langle \Psi_I | H_{\mathrm{PTV}}^{\mathrm{Schiff}} | \Psi_0 \rangle}{E_0 - E_I} = S\eta$$

Reframe or modify the expression in terms of perturbed atomic state

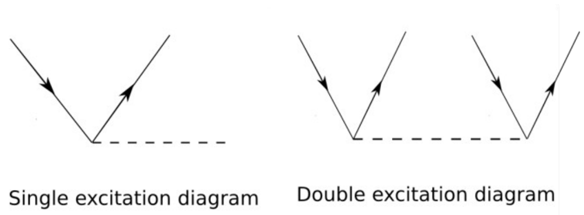
$$d_a = 2\langle \tilde{\Psi}_0 | D | \tilde{\Psi}_0 \rangle$$

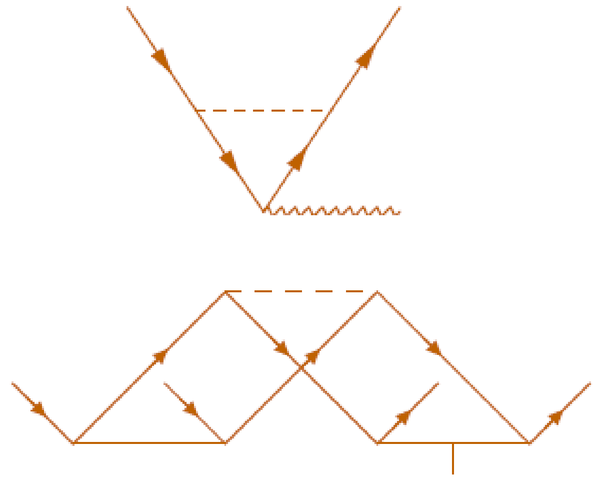
$$|\tilde{\Psi}_0\rangle = \sum_I \frac{|\Psi_I\rangle \langle \Psi_I | H_{\mathrm{PTV}}^{\mathrm{Schiff}} | \Psi_0 \rangle}{E_0 - E_I}$$

Perturbed coupled-cluster expression

$$|\tilde{\Psi}_0\rangle = e^{T^{(0)} + \lambda T^{(1)}} |\Phi_0\rangle$$

Diagrammatic representations of excited states





K. V. P. Latha, D. Angom, R. K. Chaudhuri and B. P. Das, J. Phys. B 41, 035005 (2008)

Particle physics implications
parameter bounds

Route via nuclear physics

Connecting atomic physics results to nuclear physics parameters

- Method—Skyrme potential, pion dominated interaction,
- Many-body effects—core-polarization,

Key points

- Least contribution—iso-vector component,
- Dominant contribution—iso-tensor component,
- Perturbation—P and T violating.

$$S\left({}^{199}\mathrm{Hg}\right) = g_{\pi NN}\left|0.01\bar{g}^{(0)}_{\pi NN} + 0.007\bar{g}^{(1)}_{\pi NN} + 0.02\bar{g}^{(2)}_{\pi NN}\right| \mathrm{e\ fm}^3$$

J. H. de Jesus and J. Engel, Phys. Rev. C 72, 045503 (2005)

θ_{QCD} bound

Consider iso-scalar contributes maximally then [R. J. Crewther, P. Di Vecchiaa, G.Venezianoa and E. Witten, Phys. Lett. B 88, 123 (1979)]

$$\bar{g}^{(0)}_{\pi NN} = 0.027\theta_{\mathrm{QCD}}$$

$$\theta_{\mathrm{QCD}} < 1.7\times 10^{-10}$$

$\left(\tilde{d}_u - \tilde{d}_d\right)$ bound

Consider iso-vector contributes maximally then [M. Pospelov, Phys. Lett. B 530, 123 (2002)]

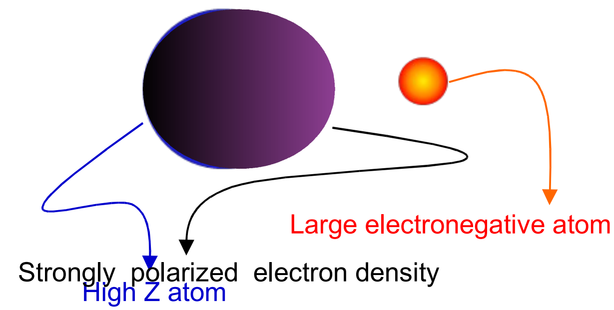
$$g^{(1)}_{\pi NN} = \frac{2\left(\tilde{d}_u - \tilde{d}_d\right)}{10^{-14}}$$

$$(\tilde{d}_u - \tilde{d}_d) < 3.2\times 10^{-27}\ \mathrm{e\ cm}$$

Experiments with polar molecules
larger polarization

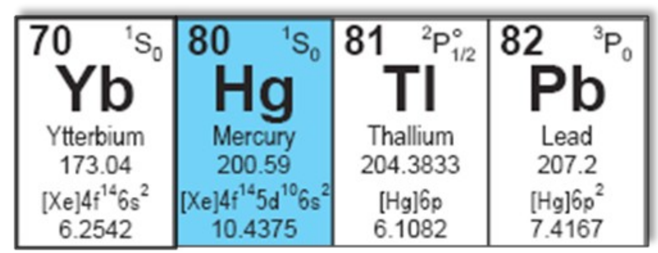
Diatomic polar molecules

Electronic clouds of heavy atoms like Pb, Tl, Yb and Hg are strongly polarized/distorted when it form molecules with Flourine or Oxygen.



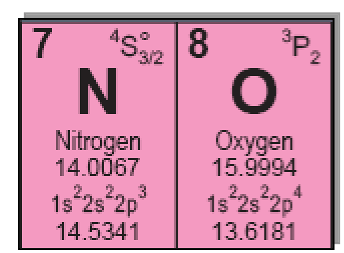
$$\frac{\langle W_{\mathrm{EDM}}\rangle_{\mathrm{molecule}}}{\langle W_{\mathrm{EDM}}\rangle_{\mathrm{atom}}} \approx \frac{5\times10^{8}}{E_{\mathrm{ext}}}$$

For moderate field of 5000 kV/cm, molecular interaction energy is 100,000 time larger. A huge gain.



Candidate molecules

Molecule/ion	Results or ongoing experiments
PbO	Yale
	D. DeMille, et al, Phys. Rev. A 61, 052507 (2000) .
YbF	University of Sussex
	J. J. Hudson, et al, PRL 89, 023003 (2002).
HfF^+, HfH^+,	JILA
PtH^+	Russell Stutz, Eric Cornell , BAPS J1.047 (2004)



Attention **E. A. Cornell**
How round is the electron? Looking for an asymmetry of 10^{-15} femtometers
20 Jan, 9:30 AM

Atomic/molecular physics
probing cosmos

The Universe

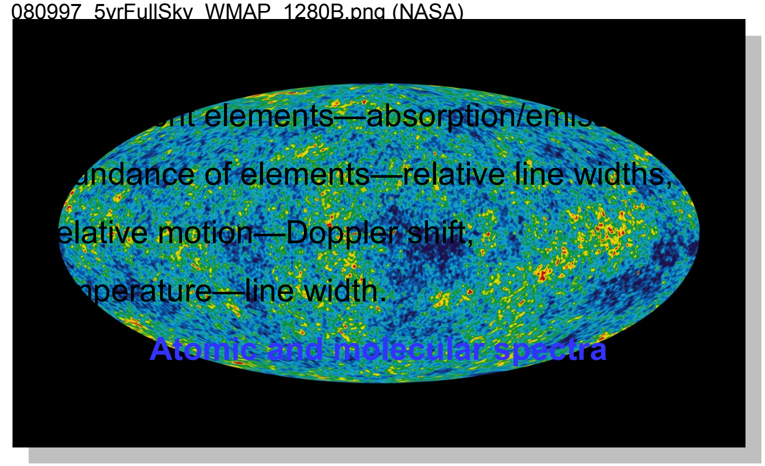
•~13,700,000,000 yrs young,

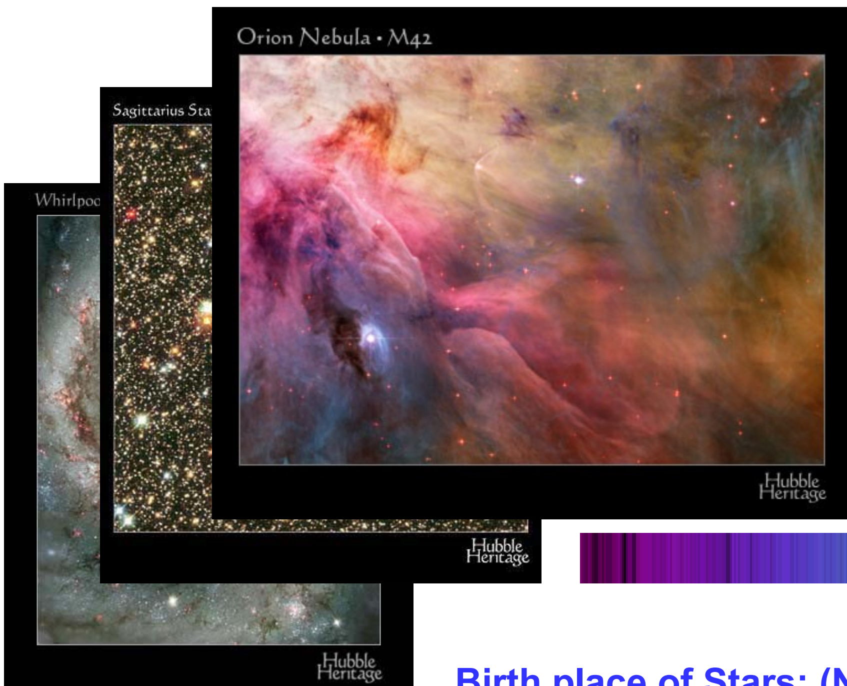
•~80,000,000,000 galaxies,

•Stable protons ~3 minutes after Big-bang,

•Molecular clouds and stars (galaxies) observable components.

080997_5yrFullSky_WMAP_1280B.png (NASA)





Implications: Helium discovery

•Pierre Janssen—16 August1868,

•Solar spectra during eclipse—He absorption line,

•Observation location—Guntur, India,

•Name—derived from Helios, Greek sun god.

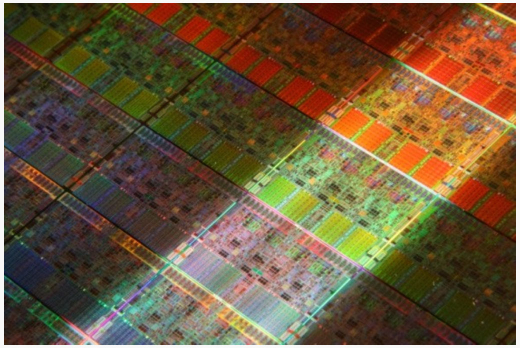
Unique signature of elements and molecules

Birth place of Stars: (Not bollywood) Spectacular molecular clouds

A revolution

what one PC can do

Intel i7 940 processor



Latest Intel processor
•2.93GHz clock frequency,
•Quad core,
•8 processing threads,
•SPECfp2006 31.3

Average performance
~ 5.8 x 10^9 FLOPS

Quantum many-body calculations

Performance required

Solving ~10^7 nonlinear equations

↓

Each term require ~10^7 integrations

↓

One iteration ~48 hours

↓

Complete calculation ~560 hours (40 days)

Cluster computing

Solution
Harness the power of several processors and parallelize applications. Possible options are shared memory, distributed memory and hybrid of these two.

Conclusions
implications of atomic EDMs

- Energy range—higher than achievable with LHC,
- Physics—sensitive to a wide variety of CP violation phenomena,
- Neutral systems—atoms and molecules are the only systems,
- Complimentarity—atomic EDMs explore slightly different parameter space

Thank you