Effects of variation of fundamental constants and violation of symmetries P, T, CPT in nuclei and atoms

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Astrophysical evidences for space-time variation of fundamental constants and proposals of laboratory tests

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Dimensionless Constants

Since variation of **dimensional** constants cannot be distinguished from variation of **units**, it only makes sense to consider variation of **dimensionless** constants.

- Fine structure constant $\alpha = e^2/2\varepsilon_0 hc = 1/137.036$
- Electron or quark mass/QCD strong interaction scale, $m_{e,q}/\Lambda_{QCD}$

  $\alpha_{strong}(r) = const/\ln(r\,\Lambda_{QCD}/ch)$

Electron-to-proton mass ratio=const m_e/Λ_{QCD}

Search for variation of fundamental constants

- Big Bang Nucleosynthesis **evidence?**
- Quasar Absorption Spectra [1] **evidences?**
- Oklo natural nuclear reactor
- Atomic clocks [1]
- Enhanced effects in atoms [1], molecules[1] and nuclei
- Dependence on gravity

[1] Based on atomic and molecular calculations

Evidence for spatial variation of the fine structure constant α

Quasar spectra

Webb, King, Murphy, Flambaum, Carswell, Bainbridge, PRL2011,MNRAS2012

$$\alpha(x)= \alpha(0) + \alpha '(0)\, x + \ldots$$

$x=r\cos(\phi)$, $r=ct$ – distance (t - light travel time, c - speed of light)

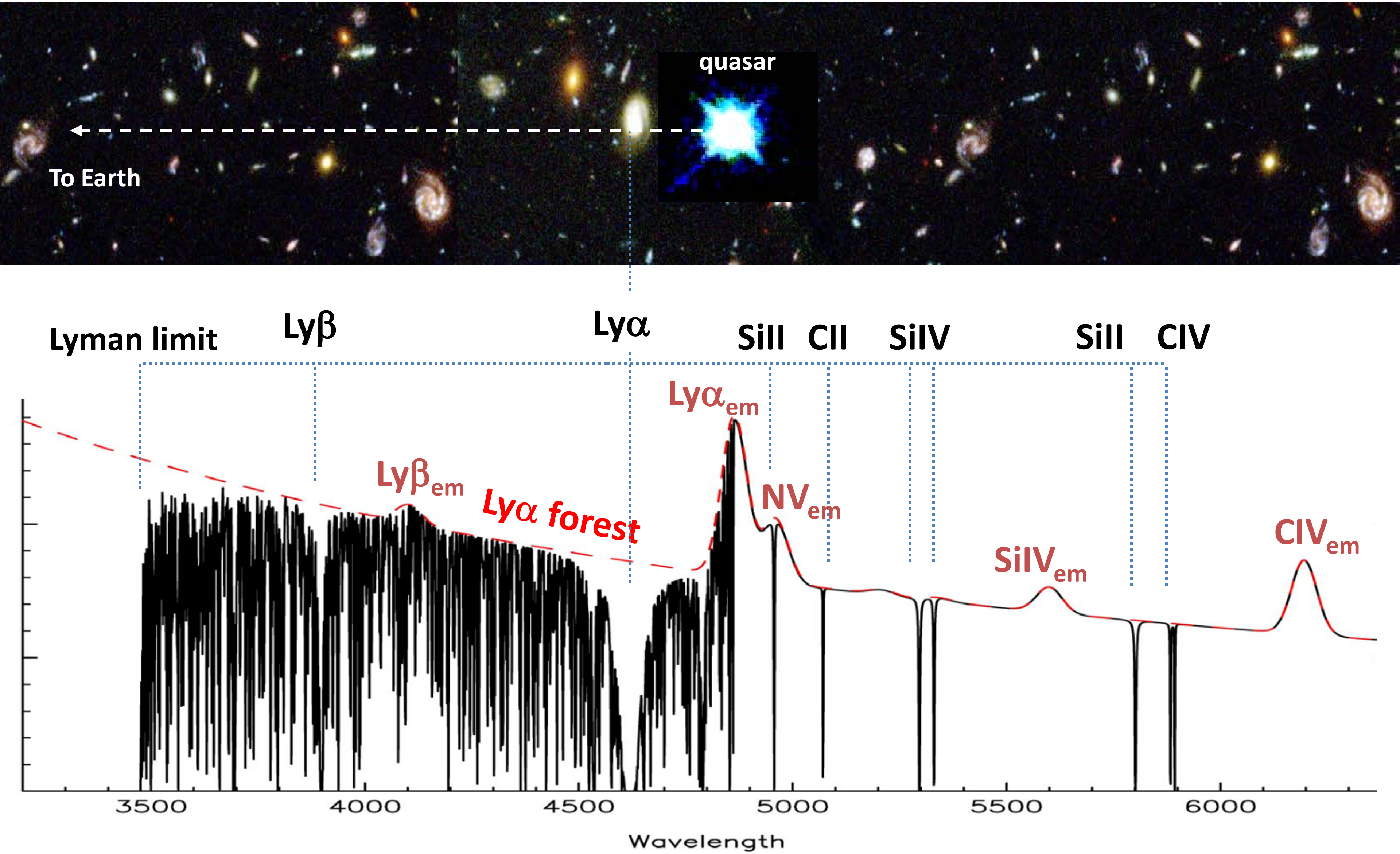
Reconciles all measurements of the variation

“ Fine tuning” of fundamental constants is needed for life to exist. If fundamental constants would be even slightly different, life could not appear!

Variation of coupling constants in space provide natural explanation of the “fine tuning”: we appeared in area of the Universe where values of fundamental constants are suitable for our existence.

There are theories which suggest variation of the fundamental constants in expanding Universe.

Quasars: physics laboratories in the early universe



Use atomic calculations to find $\omega(\alpha)$.

For α close to α_0 $\quad \omega = \omega_0 + q(\alpha^2/\alpha_0^2 - 1)$

q is found by varying α in computer codes:

$$q = d\omega/dx = [\omega(0.1) - \omega(-0.1)]/0.2, \quad x = \alpha^2/\alpha_0^2 - 1$$

$\alpha = e^2/2\varepsilon_0 hc = 0$ corresponds to non-relativistic limit (infinite c). Dependence on α is due to relativistic corrections.

Methods of Atomic Calculations

N_{ve}	Relativistic Hartree-Fock +	Accuracy
1	All-orders sum of dominating diagrams	0.1-1%
2-6	Configuration Interaction + Many-Body Perturbation Theory	1-10%
2-15	Configuration Interaction	10-20%

These methods cover all periodic system of elements

They were used for many important problems:

- Test of Standard Model using Parity Violation in Cs,Tl,Pb,Bi
- Predicting spectrum of **Fr (accuracy 0.1%)**, etc.

Results of calculations (in cm^{-1})

Anchor lines

	Atom	ω_0	*q*
	Mg I	35051.217	86
	Mg II	35760.848	211
	Mg II	35669.298	120
	Si II	55309.3365	520
	Si II	65500.4492	50
	Al II	59851.924	270
	Al III	53916.540	464
	Al III	53682.880	216
🔵	Ni II	58493.071	-20

Also, many transitions in Mn II, Ti II, Si IV, C II, C IV, N V, O I, Ca I, Ca II, Ge II, O II, Pb II,Co II,…

Different signs and magnitudes of q provides opportunity to study systematic errors!

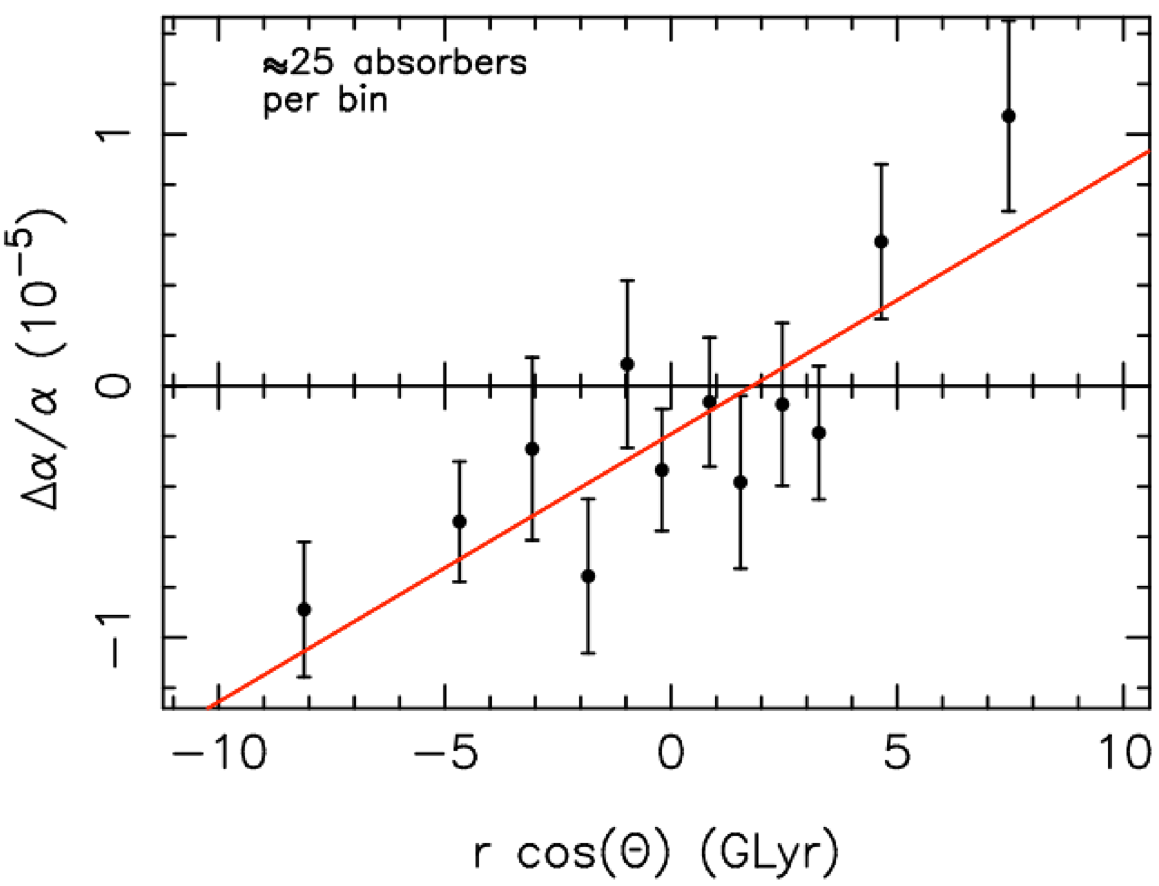
Negative shifters

Atom	ω_0	*q*	
Ni II	57420.013	-1400	🔵
Ni II	57080.373	-700	🔵
Cr II	48632.055	-1110	
Cr II	48491.053	-1280	
Cr II	48398.862	-1360	
Fe II	62171.625	-1300	🔴

Positive shifters

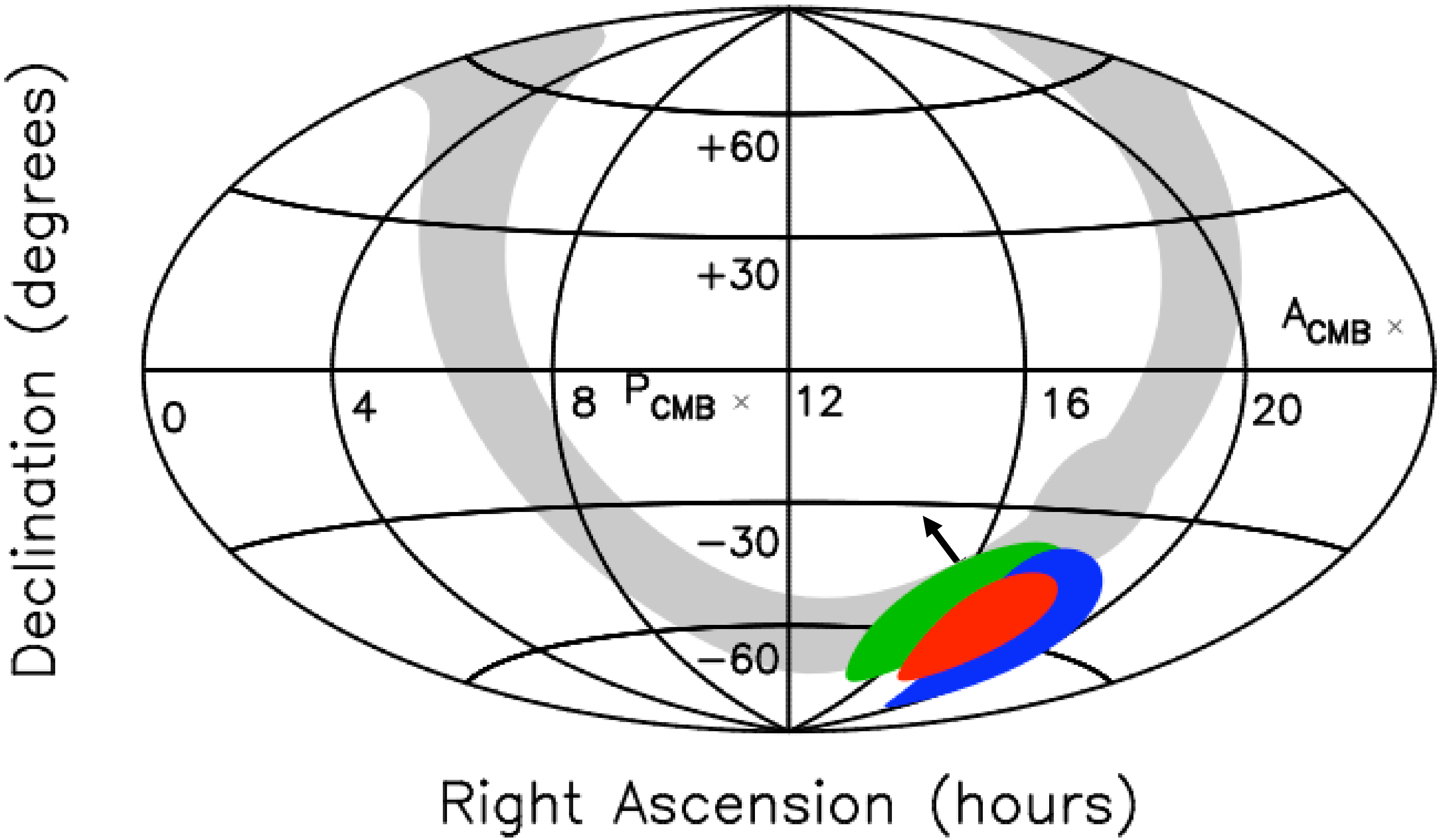
Atom	ω_0	*q*	
Fe II	62065.528	1100	🔴
Fe II	42658.2404	1210	🔴
Fe II	42114.8329	1590	🔴
Fe II	41968.0642	1460	🔴
Fe II	38660.0494	1490	🔴
Fe II	38458.9871	1330	🔴
Zn II	49355.002	2490	
Zn II	48841.077	1584	

Distance dependence



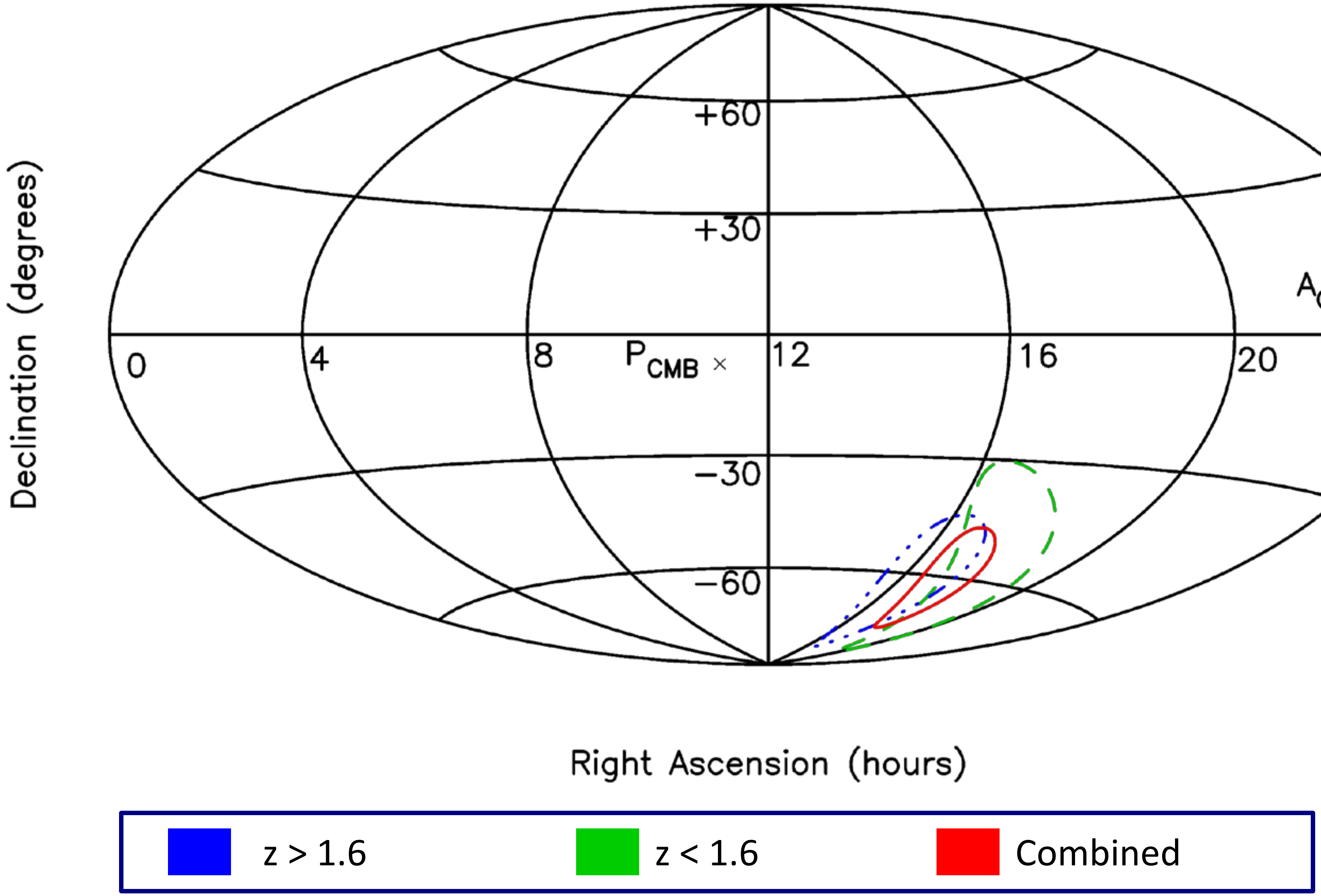
Δα/α vs BrcosΘ for the model Δα/α=BrcosΘ+m showing the gradient in α along the best-fit dipole. The best- fit direction is at right ascension 17.4 ± 0.6 hours, declination −62 ± 6 degrees, for which B = (1.1 ± 0.2) × 10^{-6} GLyr^{-1} and m = (−1.9 ± 0.8) × 10−6. This dipole+monopole model is statistically preferred over a monopole-only model also at the 4.1σ level. A cosmology with parameters (H_0 , Ω_M , Ω_Λ) = (70.5, 0.2736, 0.726).

Keck & VLT dipoles independently agree, p=4%



🟦 VLT 🟩 Keck 🟥 Combined

Low and high redshift cuts are consistent in direction. Effect is larger at high redshift.



Hints that this result might be real

Two internal consistencies:

1 Keck and VLT dipoles agree. Independent samples, different data reduction procedures, different instruments and telescopes.

2 High and low redshift dipoles also agree - different species used at low and high redshift – and different transitions respond differently to the same change in α.

300 absorption systems, 30 atomic lines

Plank satellite Cosmic Microwave Background data 2013:
Universe is not symmetric!
CMB fluctuations are different in different directions.

Limits on dependence of alpha on gravity from white dwarf spectra
Fe4+,Ni4+ 4.2(1.6) 10^{-5}. Accurate laboratory spectra needed.

Variation of strong interaction

Grand unification suggests coefficient R

$$\frac{\Delta\left(m/\Lambda_{QCD}\right)}{m/\Lambda_{QCD}} = R\frac{\Delta\alpha}{\alpha}$$

1. Proton mass $\mathrm{M_p} = 3\Lambda_{QCD}$, measure m_e/M_p
2. Nuclear magnetic moments

$$\mu = g\,e\hbar/4M_p c, \quad g = g\left(m_q/\Lambda_{QCD}\right)$$

3. Nuclear energy levels and resonances

Dependence on quark mass

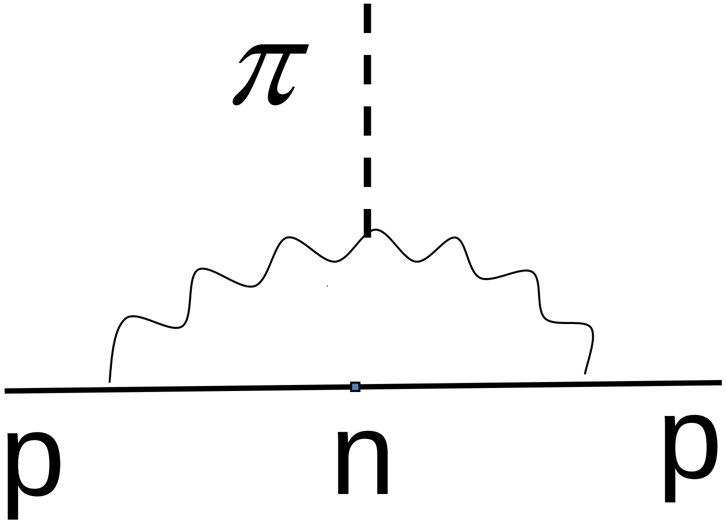
- Dimensionless parameter is m_q/Λ_{QCD} . It is convenient to assume Λ_{QCD} =const, i.e. measure m_q in units of Λ_{QCD}
- m_π is proportional to $(m_q\Lambda_{QCD})^{1/2}$
  $\Delta m_\pi/m_\pi=0.5\Delta m_q/m_q$
- Other meson and nucleon masses remains finite for $m_q=0$. $\Delta m/m=K\,\Delta m_q/m_q$

Argonne: K are calculated for p,n,ρ,ω,σ.

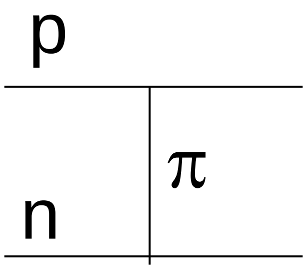
$$m_q=\frac{m_u+m_d}{2}\approx 4\,MeV,\ \Lambda_{QCD}=220\,MeV\rightarrow K=0.02-0.06$$

$$\text{Strange quark mass } m_s=120\,MeV$$

Nuclear magnetic moments depends on π-meson mass m_π



Nucleon magnetic moment



Spin-spin interaction between valence and core nucleons

Nucleon magnetic moment

$$\mu = \mu_0 (1 + a m_\pi + \ldots) = \mu_0 (1 + b\sqrt{m_q} + \ldots)$$

Nucleon and meson masses

$$M = M_0 + a m_q$$

QCD calculations: lattice, chiral perturbation theory,cloudy bag model, Dyson-Schwinger and Faddeev equations, semiempirical.

Nuclear calculations: meson exchange theory of strong interaction. Nucleon mass in kinetic energy $p^2/2M$

m_e / M_p limit from NH_3

Inversion spectrum: exponentially small“quantum tunneling” frequency

ω_{inv}=W exp(-S(m_e / M_p))

ω_{inv} is exponentially sensitive to m_e / M_p

Laboratory measurements proposed (Veldhoven et al)

Astrophysics - -2 systems containing NH_3

Flambaum,Kozlov PRL 2007

First enhanced effect in quasar spectra

Δ(m_e / M_p)/ (m_e / M_p)=-0.6(1.9)10^{-6} No variation

z=0.68, 6.5 billion years ago, -1(3)10^{-16} /year

More accurate measurements

Murphy, Flambaum, Henkel,Muller. Science 2008 -0.74(0.47)(0.76)10^{-6}

Henkel et al AA 2009 z=0.87 <1.4 10^{-6} 3 σ

Levshakov,Molaro,Kozlov2008 our Galaxy 0.5(0.14)10^{-7}

Metanol

Hydrogen molecule - 4 systems

$\Delta(m_e / M_p)/(m_e / M_p) =$

$3.3(1.5)\ 10^{-6}\ r\cos(\phi)$

gradient direction 16.7(1.5) h, -62(5)°

consistent with α gradient direction 17.6(0.6) h, -58(6)°

If we assume the same direction

$2.6(1.3)\ 10^{-6}\ r\cos(\phi)$ 4% by chance

Big Bang nucleosynthesis: dependence on quark mass

- Flambaum, Shuryak 2002
- Flambaum, Shuryak 2003
- Dmitriev, Flambaum 2003
- Dmitriev, Flambaum, Webb 2004
- Coc, Nunes, Olive, Uzan,Vangioni 2007
- Dent, Stern, Wetterich 2007
- Flambaum, Wiringa 2007
- Berengut, Dmitriev, Flambaum 2010
- Bedaque, Luu, Platter 2011
- Berengut,Eppelbaum,Flambaum,Hanhart,Meissner, Nebreda, Pelaez 2013

Deutron binding energy is sensitive to the variation of the quark mass

- Shallow level : small variation of the potential leads to large variation of the binding energy.
- Virtual level in (n+p) is even more sensitive, and it influences the deuterium formation rate.
- BBN is exponentially sensitive to the deuteron binding energy E, exp(-E/T)

Deuterium abundance – 7 points

Big Bang Nucleosynthsis data give direction of the gradient in the deuterium abundance consitent with the direction of the α gradient. However, the amplitude of the relative spatial variation 0.0045(35) is not statistically significant. This would result in relative variation of $X=m_q/\Lambda_{QCD}$

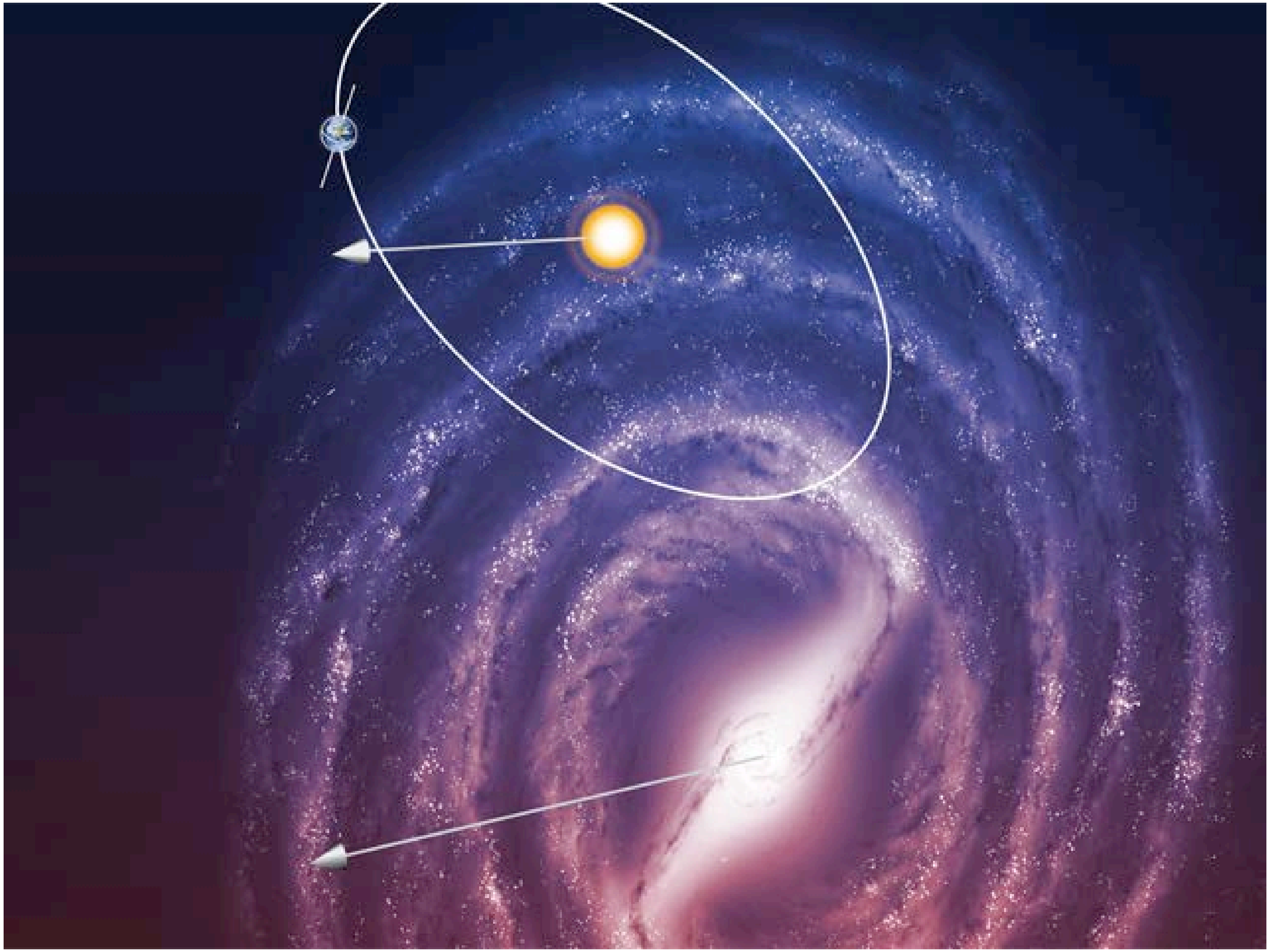
$\Delta X/X = 0.0013(10)\ r\cos(\phi)$

$\Delta\alpha/\alpha = 0.003(3)\ r\cos(\phi)$

Compare with QSO

$\Delta\alpha/\alpha = 1.10(0.25)\ 10^{-6}\ r\cos(\phi)$

Gradient α points down



Oklo natural nuclear reactor

n+^{149}Sm capture cross section is dominated by E_r =0.1 eV resonance.
Shlyakhter-limit on $\Delta\alpha/\alpha$ two billion years ago

Our QCD/nuclear calculations
ΔE_r = 10 Mev$\Delta X_q/X_q$ - 1 MeV $\Delta\alpha/\alpha$
$X_q = m_q/\Lambda_{QCD}$, enhancement 10 MeV/0.1 eV=10^8

Galaxy moves 552 km/s relative to CMB, cos(ϕ)=0.23
Dipole in space: ΔE_r =(10 R - 1) meV

Fujii et al $|\Delta E_r|$<20 MeV
Gould et al, -12 < ΔE_r <26 meV
Petrov et al -73< ΔE_r <62 meV

Consequences for atomic clocks

- Sun moves 369 km/s relative to CMB $\cos(\phi) = 0.1$

  This gives average laboratory variation

  $\Delta\alpha/\alpha = 1.5\ 10^{-18}\ \cos(\phi)$ per year

- Earth moves 30 km/s relative to Sun-

  $1.6\ 10^{-20}\ \cos(\omega t)$ annual modulation

Atomic clocks:

Comparing rates of different clocks over long period of time can be used to study time variation of fundamental constants

Optical transitions: α

Microwave transitions: $\alpha, (m_e, m_q)/\Lambda_{QCD}$

Calculations to link change of frequency to change of fundamental constants:

Optical transitions: atomic calculations (as for quasar absorption spectra) for many narrow lines in Al II, Ca I, Sr I, Sr II, In II, Ba II, Dy I, Yb I, Yb II, Yb III, Hg I, Hg II, Tl II, Ra II , ThIV

$$\omega = \omega_0 + q(\alpha^2/\alpha_0^2 - 1)$$

Microwave transitions: hyperfine frequency is sensitive to nuclear magnetic moments and nuclear radii

We performed atomic, nuclear and QCD calculations of powers κ ,β for H,D,Rb,Cd^+,Cs,Yb^+,Hg^+

$$V=C(Ry)(m_e/M_p)\alpha^{2+\kappa}\ (m_q/\Lambda_{QCD})^{\beta}\ ,\quad \Delta\omega/\omega=\Delta V/V$$

Cs: $\beta=0$, m_e/M_p measurement! Not magnetic moment.
Rydberg contstant in SI units=Cs hyperfine=$(m_e/M_p)\alpha^{2.83}$

We performed atomic, nuclear and QCD calculations

of powers κ ,β for H,D,He,Rb,Cd$^+$,Cs,Yb$^+$,Hg$^+$…

$V=C(Ry)(m_e/M_p)\alpha^{2+\kappa}\ (m_q/\Lambda_{QCD})^{\beta}$, $\Delta\omega/\omega=\Delta V/V$

^{133}Cs: $\kappa=0.83,\ \beta=0.002$

Cs standard is insensitive to variation of m_q/Λ_{QCD}!

^{87}Rb: $\kappa=0.34,\ \beta=-0.02$

^{171}Yb+: $\kappa=1.5,\ \beta=-0.10$

^{199}Hg+: $\kappa=2.28,\ \beta=-0.11$

^{1}H: $\kappa=0,\ \beta=-0.10$

Complete Table in Phys.Rev.A79,054102(2009)

Results for variation of fundamental constants

Source	$Clock_1/Clock_2$	$d\alpha/dt/\alpha (10^{-16}\ \mathrm{yr}^{-1})$
Blatt *et al*, 2007	Sr(opt)/Cs(hfs)	-3.1(3.0)
Fortier *et al* 2007	Hg+(opt)/Cs(hfs)	-0.6(0.7)[a]
Rosenband *et al*08	Hg+(opt)/Al+(opt)	-0.16(0.23)
Peik *et al*, 2006	Yb+(opt)/Cs(hfs)	4(7)
Guena *et al*, 2012	Rb(hfs)/Cs(hfs)	3(2)[a]

[a] assuming $m_{q,e}/\Lambda_{QCD} = Const$

Combined results: $\frac{d}{dt} \ln\alpha = -1.6(2.3) \times 10^{-17}\ \mathrm{yr}^{-1}$

$\frac{d}{dt} \ln(m_q/\Lambda_{QCD}) = 7(4) \times 10^{-15}\ \mathrm{yr}^{-1}$

m_e/M_p or m_e/Λ_{QCD} $-1.5(3.0) \times 10^{-16}\ \mathrm{yr}^{-1}$

Largest q in multiply charged ions, narrow lines

q increases as $Z^2\,{}^{(}Z_i+1)^2$

To keep frequencies in optical range we use configuration crossing as a function of Z. Projected accuracy 10^{-19}

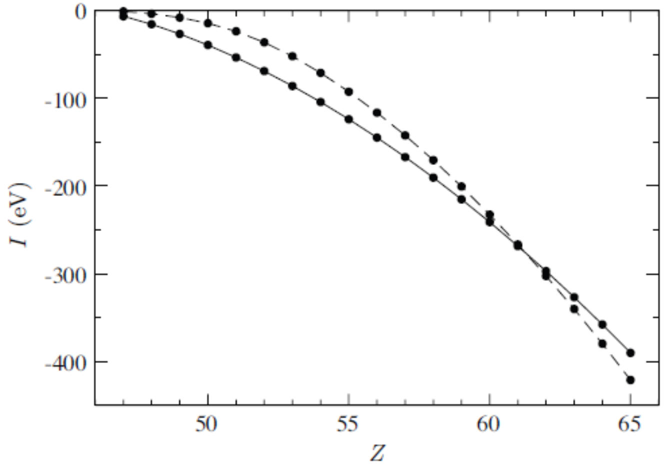


FIG. 2. Dirac-Fock ionisation energies of $5s$ (solid) and $4f_{7/2}$ (dashed) levels for the Ag isoelectronic sequence.

Crossing of 5f and 7s

Th IV: q_1=-75 300

Crossing of 4f and 5s

Sm15+, Pm14+, Nd 13+

Difference $q=q_2 - q_1$ is 260 000

5 times larger than in Hg II/Al II

Relative enhancement up to 500

In Sm+14 there are narrow transitions and E1 transitions in the laser range, for cooling,

Holes in filled shells: 13 times larger q than in Hg II/Al II

Cf: 23 times larger than in Hg II/Al II

New accurate calculations of energy levels and electromagnetic amplitudes

Atomic clocks with highly charged ions

Highly charged ions have small size, r = const $/Z_{ion}$

Narrow E2 transitions, r^2

Greatly reduced coupling to external perturbations:
Polarizability r^3
Small balck body radiation shift
Suppressed quadrupole shift, etc

Precision at the level 10^{-19}

Derevianko, Dzuba, Flambaum 2012; Berengut, Dzuba, Flambaum, Ong 2012

Plus enhanced sensitivity to α variation : potential for 2-3 order of magnitude improvement in laboratory measurements of α variation

Enhancement of relative effect

Our proposal and calculations:

Dy: $4f^{10}5d6s$ E=19797.96… cm^{-1} , q= 6000 cm^{-1}

$4f^{9}5d^{2}6s$ E=19797.96… cm^{-1} , q= -23000 cm^{-1}

ω_0 = 10^{-4} $\mathrm{cm}^{-1.}$ Relative enhancement $\Delta\omega/\omega_0 = 10^8\,\Delta\alpha/\alpha$

Measurement Berkeley **$d\ln\alpha/dt$ =-6(7)x 10^{-17} yr^{-1}**

Different signs of ω_0 in different isotopes: cancellation of errors!

Limits on dependence of α on gravity, Lorentz invariance and equivalence principle violation, parity violation

Close narrow levels in molecules

Nuclear clocks

Peik, Tamm 2003: UV transition between first excited and ground state in ^{229}Th nucleus Energy 7.6(5) eV, width 10^{-3} Hz. Perfect clock!

We made specific clock proposals : Th+, Th+3. Projected accuracy 10^{-19}

Flambaum 2006: Nuclear/QCD estimate- Enhancement **10^5**

He,Re; Flambaum,Wiringa; Flambaum,Auerbach,Dmitriev;

Hayes,Friar,Moller;

Litvinova,Feldmeier,Dobaczewski,Flambaum;

$\Delta\omega = \mathbf{10^{19}}$ Hz $(\Delta\alpha/\alpha + 10\ \Delta X_q/X_q)$, $X_q=m_q/\Lambda_{QCD}$,

Shift 10-100 Hz for $\Delta\alpha/\alpha=10^{-18}$

Compare with atomic clock shift 0.001 Hz

Enhancement is due to cancellation of large contributions of strong and electromagnetic interactions, $\omega =$ **S+Q=100 KeV**-100 KeV

^{235}U nucleus, 76 eV transition, laser build by Jun Ye group.

Variation effect is larger than in ^{229}Th

Dependence on α

$\Delta\omega = Q\, \Delta\alpha/\alpha$

- Total Coulomb energy 10^9 eV in ^{229}Th
- Difference of moments of inertia between ground and excited states is 4% (?)
- If difference in the Coulomb energy would be 0.01%, Q=100 KeV, estimate for the enhancement factor

$Q/\omega_0 = 10^5 \text{ eV} / 7 \text{ eV} = 1.4\ 10^4$

Sensitivity to $\Delta\alpha$ may be obtained from measurements

$\Delta\omega = Q\, \Delta\alpha/\alpha$

Berengut,Dzuba,Flambaum,PorsevPRL2009

$Q/\mathrm{Mev} = -506\, \Delta\langle r^2\rangle/\langle r^2\rangle + 23\Delta Q_2/Q_2$

Diffrence of squared charge radii $\Delta\langle r^2\rangle$ may be extracted from isomeric shifts of electronic transitions in Th atom or ions

Diffrence of electric quadrupole moments ΔQ_2 from hyperfine structure

^{229}Th: Flambaum,Wiringa 2007 Sensitivity to quark mass

$\omega = E_{pk} + E_{so} + Q = 7.6$ eV **huge cancellations!**

$E_{so} = \langle V_s\, L\, S \rangle$=spin-orbit=-1.04 MeV

E_{pk} =potential+kinetic=1 MeV

Extrapolation from light nuclei

$\Delta E_{pk}/E_{pk} = -1.4\, \Delta m_q/m_q$

$\Delta E_{so}/E_{so} = -0.24\, \Delta m_q/m_q$

$\Delta\omega/\omega_0 = 1.6\ 10^5\ \ \Delta X_q/X_q$

Nuclear clocks ^{229}Th3+: 19 digits precision

In stretched states $F=F_z=I_{nucleus}+J_{electron}$ the ion wave function is a product of electron and nuclear wave functions. Electronic shifts produced by external perturbations in the ground and excited nuclear states are equal and cancel out.

Nuclear size is very small. Nuclear polarizability, black body radiation shift and other shifts are very small.

Campbell, Radnaev, Kuzmich, Dzuba, Flambaum, Derevianko PRL 2012

Potential to improve sensitivity to variation of the fundamental constants by 7 orders of magnitue

Electron bridge mechanism to excite nuclear transtions

Excitation of atomic electrons which transfer energy to nucleus.

Calculations in Th+ and Th3+

Th3+ Porsev, Flambaum PRA 2010, PRA 2010

Th+ Porsev, Flambaum, Peik, Tamm PRL 2010

Exponential increase of energy level density in atoms: Th ,Th+. Dzuba, Flambaum PRL2010

Close nuclear and atomic energy levels

Conclusions

- Spatial gradient of alpha from quasar data, 4.2 sigma, Keck and VLT data agree, low and high red shift data agree, no contradictions with other groups.
- It provides alpha variation for atomic clocks due to Earth motion at the level 10^{-18} and 1 meV shift in Oklo resonance. One-two orders of magnitude improvement in the measurement accuracy is needed. Three orders for meteorites.
- Very weak indications for the spatial variation in H_2 quasar spectra and BBN abundance of deuterium. The same direction of the gradient!

New systems with higher absolute sensitivity include:

- transitions between ground and metastable states in highly charged ions. Frequencies are kept in laser spectroscopy range due to the configuration crossing phenomenon. An order of magnitude gain.
- ^{229}Th nucleus – highest absolute enhancement (10^5 times larger shift), UV transition 7eV.
- Many systems with relative enhancement due to transition between close levels: Dy atom, a number of molecules with narrow close levels,…

- Search for anisotropy in CMB, expansion of the Universe, structure formation

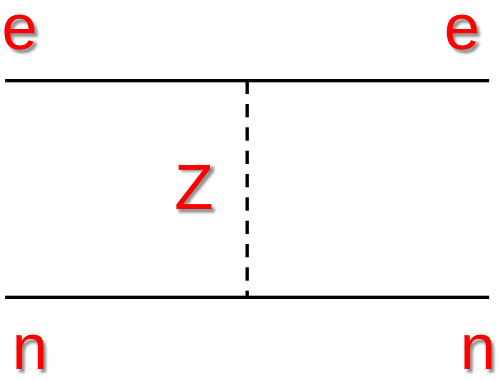
Parity and time reversal violation in atoms, molecules and nuclei and search for physics beyond the Standard Model

Victor Flambaum

Co-authors: I.Khriplovich, O.Sushkov, V.Dzuba, P.Silvestrov, N.Auerbach, Spevak, J.Ginges, M.Kuchiev, M.Kozlov, A.Brown, A.Derevianko, S.Porsev, J. Berengut, B. Roberts, A. Borschevsky, M.Ilias, K.Beloy, P.Schwerdtfeger

Atomic parity violation

- Dominated by Z-boson exchange between electrons and nucleons



$$H = \frac{G}{\sqrt{2}}\left[C_{1p}\bar{e}\gamma_\mu\gamma_5 e\bar{p}\gamma^\mu p + C_{1n}\bar{e}\gamma_\mu\gamma_5 e\bar{n}\gamma^\mu n\right]$$

Standard model

$$C_{1p} = \tfrac{1}{2}\left(1 - 4\sin^2\theta_W\right) \;\; ; \quad C_{1n} = -\tfrac{1}{2}$$

- In atom with Z electrons and N neutrons obtain effective Hamiltonian parameterized by “nuclear weak charge” Q_W

$$h_{PV} = \frac{G}{2\sqrt{2}} Q_W \rho(r)\gamma_5$$

$$Q_W = 2(NC_{1n} + ZC_{1p}) \approx -N + Z(1 - 4\sin^2\theta_W) \approx -N$$

- PV amplitude $E_{PV} \propto Z^3$ [Bouchiat,Bouchiat]

Discovered in 1978 Bi; Tl, Pb, Cs –accuracy 0.4-1%

Our calculations in 1975-1989 Bi 11%,Pb 8%,Tl 3%,Cs1%

Cs: accuracy of experiment and theory 0.4%, agreement with the standard model, limits on new physics.

Calculations and experiments in Cs analogues

Our calculations and calculations of other groups

Ba+

Fr, Ra+ , Ac+2, Th+3 PNC effects 15 times larger

Experiments in Seattle (Ba+),

TRIUMF (Fr), Groningen (Ra+)

PV : Chain of isotopes

Dzuba, Flambaum, Khriplovich

Rare-earth atoms:

- close opposite parity levels-enhancement
- Many stable isotopes

Ratio of PV effects gives ratio of weak charges. Uncertainty in atomic calculations cancels out. Experiments:

Berkeley: Dy and Yb; PV amplitude 100 x Cs!

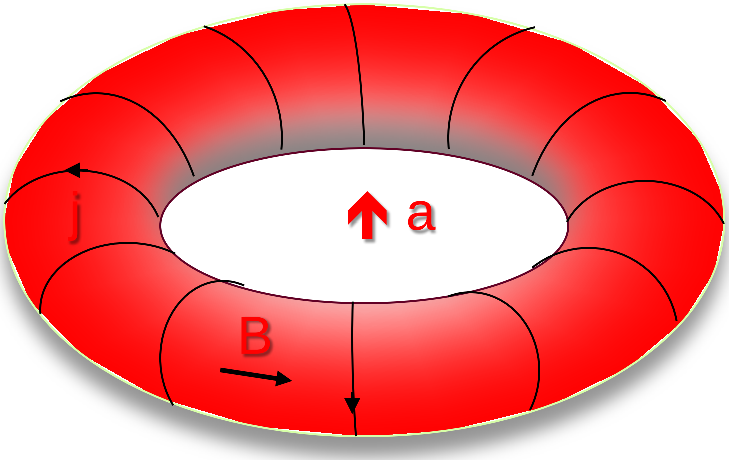
Ra^+ - Groningen, Fr- TRIUMF

Fortson,Pang,Wilets Test of Standard model or neutron distribution?

Brown, Derevianko,Flambaum 2009. Uncertainties in neutron distributions cancel in differences of PV effects in isotopes of the same element. Measurements of ratios of PV effects in isotopic chain can compete with other tests of Standard model!

Nuclear anapole moment

- Source of nuclear spin-dependent PV effects in atoms
- Nuclear magnetic multipole violating parity
- Arises due to parity violation inside the nucleus



- Interacts with atomic electrons via usual magnetic interaction (PV hyperfine interaction):

$$h_a = e\alpha\cdot A \propto \kappa_a \alpha\cdot I\rho(r)\ , \quad \kappa_a \propto A^{2/3}$$

[Flambaum,Khriplovich,Sushkov]

$E_{PV} \propto Z^2 A^{2/3}$ measured as difference of PV effects for transitions between hyperfine components

Cs: |6s,F=3> – |7s,F'=4> and |6s,F'=4> – |7s,F=3>

Probe of weak nuclear forces via atomic experiments!

Nuclear anapole moment is produced by PV nuclear forces. Measurements +our calculations give the strength constant g.

- Boulder Cs: g=6(1) in units of Fermi constant

  Seattle Tl: g=-2(3)

New accurate calculations Flambaum,Hanhart; Haxton,Liu,Ramsey-Musolf; Auerbach, Brown; Dmitriev, Khriplovich,Telitsin:

problem remains.

Experiments and proposals: Fr (TRIUMF),

10^3 enhancement in Ra atom due to close opposite parity state; Dy,Yb,…(Berkeley)

Enhancement of nuclear anapole effects in molecules

10^5 enhancement of the anapole contribution in diatomic molecules due to mixing of close rotational levels of opposite parity. Theorem: only nuclear-spin-dependent (anapole) contribution to PV is enhanced (Labzovsky;Sushkov,Flambaum 1978). Weak charge can not mix opposite parity rotational levels and Λ–doublet.

Ω=1/2 terms: $\Sigma_{1/2}$, $\Pi_{1/2}$. Heavy molecules, effect $Z^2 A^{2/3} R(Z\alpha)$

YbF,BaF, PbF,LuS,LuO,LaS,LaO,HgF,…Cl,Br,I,…BiO,BiS,…

Cancellation between hyperfine and rotational intervals-enhancement.

Interval between the opposite parity levels may be reduced to zero by magnetic field – further enhancement.

Molecular experiments : Yale, Groningen, NWU.

New calculations for many molecules and molecular ions: Borschevsky,Ilias,Beloy,Dzuba,Flambaum,Schwerdtfeger 2012

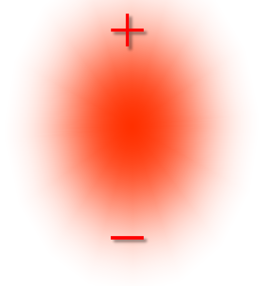
Accurate molecular calculations and proposals by other groups

- RaF: T.A.Isaev, S. Hoekstra, R.Berger.
- BaF: M.G.Kozlov, A,V.Titov, N.S. Mosyagin, P.V. Souchko. M.N.Nayak,B.Das, …

Experimental proposals:

- DeMille et al
- T.A.Isaev, S. Hoekstra, R.Berger.

Atomic electric dipole moments



- Electric dipole moments violate parity (P) and time-reversal (T)

$d \equiv r \propto J$

- T-violation ≡ CP-violation by CPT theorem

CP violation

- Observed in K^0, B^0
- Accommodated in SM as a single phase in the quark-mixing matrix (Kobayashi-Maskawa mechanism)

However, not enough CP-violation in SM to generate enough matter-antimatter asymmetry of Universe!

→ Must be some non-SM CP-violation

- Excellent way to search for new sources of CP-violation is by measuring EDMs
  - SM EDMs are hugely suppressed

  → Theories that go beyond the SM predict EDMs that are many orders of magnitude larger!

e.g. electron EDM

Theory	d_e (e cm)
Std. Mdl.	$< 10^{-38}$
SUSY	$10^{-28} - 10^{-26}$
Multi-Higgs	$10^{-28} - 10^{-26}$
Left-right	$10^{-28} - 10^{-26}$

Best limit (90% c.l.): $|d_e| < 1.6 \times 10^{-27}$ *e cm* Berkeley (2002)

- Atomic EDMs $d_{atom} \propto Z^3$ [Sandars]

Sensitive probe of physics beyond the Standard Model!

Atomic EDMs

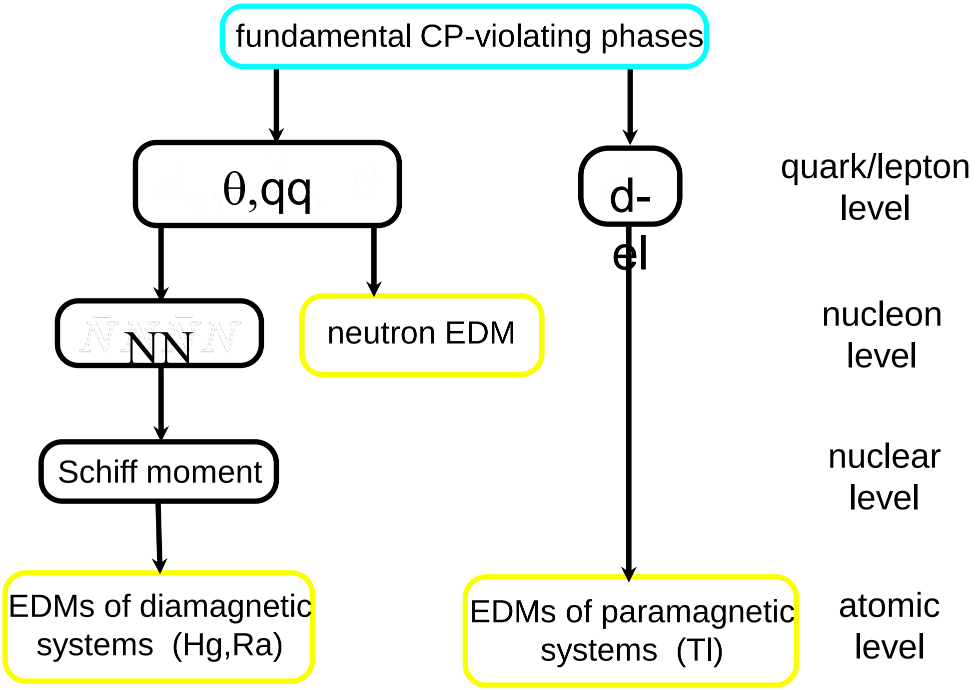
Best limits

$|d(^{199}\mathrm{Hg})| < 3 \times 10^{-29}\ e$ cm
(95% c.l., Seattle, 2009)

$|d(^{205}\mathrm{Tl})| < 9.6 \times 10^{-25}\ e$ cm
(90% c.l., Berkeley, 2002)
YbF, London 2012

$|d(\mathrm{n})| < 2.9 \times 10^{-26}\ e$ cm
(90% c.l., Grenoble, 2006)

Leading mechanisms for EDM generation



fundamental CP-violating phases

θ,qq

d-
el

NN

neutron EDM

Schiff moment

EDMs of diamagnetic systems (Hg,Ra)

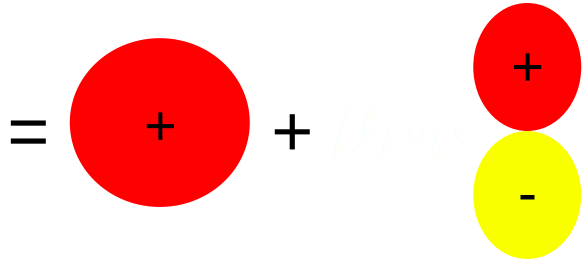
EDMs of paramagnetic systems (Tl)

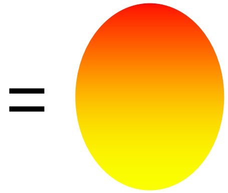
quark/lepton level

nucleon level

nuclear level

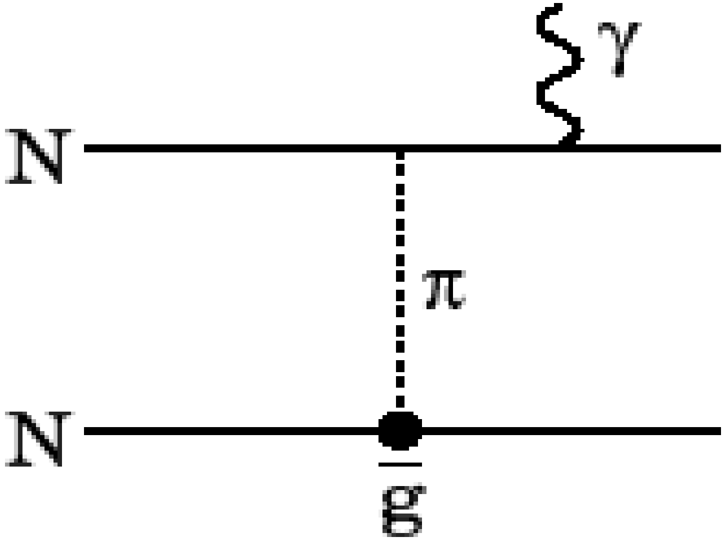
atomic level

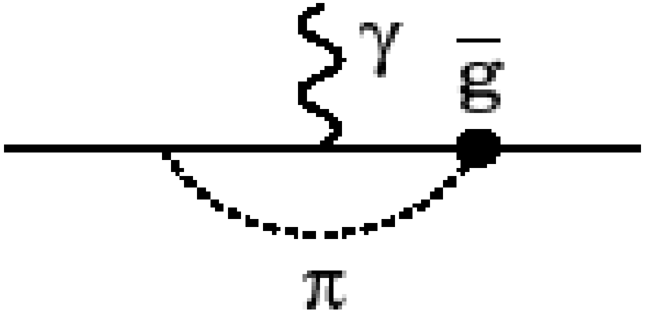




Nuclear EDM:
T,P-odd NN interaction gives 40 times larger contribution than nucleon EDM

Sushkov, Flambaum, Khriplovich
1984





T,P-odd NN interaction

Khriplovich, Sushkov, Flambaum 1984,1986

- Calculations of nuclear EDM and Schiff moments
- Calculations of atomic EDM
- Calculation of T,P-odd π NN and nucleon-nucleon interaction in the Standard model. NN interaction strength 0.3 10^{-8} G. Current limit from atomic EDM 10^{-4} G.
- We need physics beyond Standard model
- Or new enhanced effects.

Nuclear EDM-screening: d_N E_N

- Schiff theorem: $E_N=0$, neutral systems
- Extension for ions and molecules: Flambaum, Kozlov

Ion acceleration $a= Z_i\, eE/M$

Nucleus acceleration $a=Z\, eE_N/M$

$$E_N=E\, Z_i/Z$$

In molecules screening is stronger:

$a= Z_i\, eE/(M+m)$, $E_N= E\, (Z_i/Z)(M/(M+m))$

Schiff moment dominates in molecules!

Diamagnetic atoms and molecules
Source-nuclear Schiff moment

SM appears when screening of external electric field by atomic electrons is taken into account.

Nuclear T,P-odd moments:

- EDM – non-observable due to total screening (Schiff theorem)

Nuclear electrostatic potential with screening (our 1984 calculation following ideas of Schiff and Sandars):

$$\varphi(\mathbf{R}) = \int \frac{e\rho(\mathbf{r})}{|\mathbf{R}-\mathbf{r}|} d^3r + \frac{1}{Z}(\mathbf{d}\bullet\nabla)\int \frac{\rho(\mathbf{r})}{|\mathbf{R}-\mathbf{r}|} d^3r$$

d is nuclear EDM, the term with **d** is the electron screening term

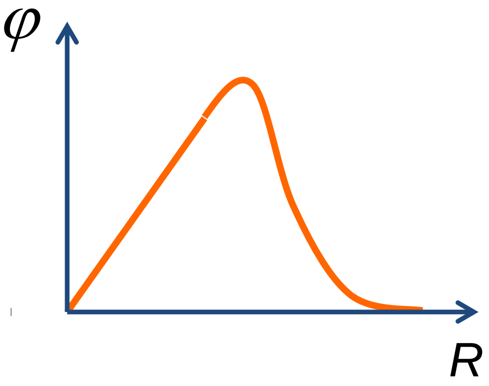
$\varphi(\mathbf{R})$ in multipole expansion is reduced to $$\varphi(\mathbf{R}) = 4\pi\mathbf{S}\bullet\nabla\delta(\mathbf{R})$$

where $\mathbf{S} = \frac{e}{10}\left[\langle r^2\mathbf{r}\rangle - \frac{5}{3Z}\langle r^2\rangle\langle\mathbf{r}\rangle\right]$ is Schiff moment.

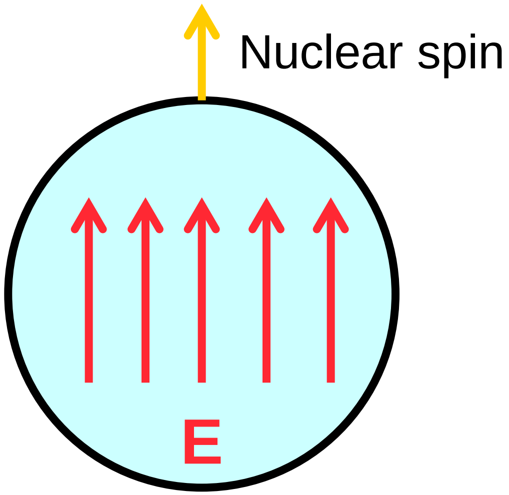
This expression is not suitable for relativistic calculations.

Flambaum,Ginges:
L=S(1 – c Z^2 α^2)

$$\phi(\mathbf{R}) = -\frac{3L\bullet\mathbf{R}}{B}\rho(R)$$ where $$B = \int \rho(R)R^4 dR$$



Electric field induced by T,P-odd nuclear forces which influence proton charge density



This potential has no singularities and may be used in relativistic calculations.
SM electric field polarizes atom and produces EDM.
Calculations of nuclear SM: Sushkov,Flambaum,Khriplovich ;Brown et al,Flambaum et al Dmitriev et al,Auerbach et al,Engel et al, Liu et al,Sen’kov et al, Ban et al.
Atomic EDM: Sushkov,Flambaum,Khriplovich; Dzuba,Flambaum,Ginges,Kozlov.
Best limits from Hg EDM measurement in Seattle –
Crucial test of modern theories of CP violation (supersymmetry, etc.)

Atomic EDM induced by Schiff moment rapidly increases with nuclear charge, $Z^2 R(Z\alpha)$

- We perfomed accurate many-body calculations for heavy atoms:Xe,Yb,Hg, Rn,Ra; Measurements for Xe (Seattle,Ann Arbor) and Hg (Seattle).
- In molecules there is an additional enhancement suggested by Sandars: internal electric field of polarised molecule is orders of magnitude larger than applied external field

Calculations and measurements in TlF (Hinds)

Enhancement in nuclei with quadrupole deformation

Close level of opposite parity

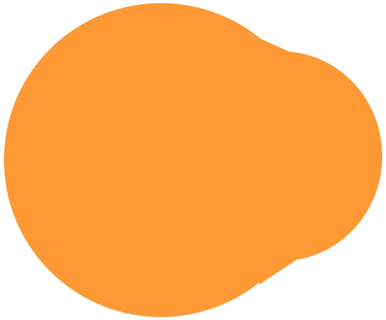
- Haxton, Henley –EDM, MQM
- Sushkov, Flambaum, Khriplovich –Schiff moment
- Flambaum - spin hedgehog and collective magnetic quadrupole are produced by T,P-odd interaction which polarises spins along radius

Enhancement factor does not exceed 10

Nuclear enhancement

Auerbach, Flambaum, Spevak 1996

The strongest enhancement is due to octupole deformation (Rn,Ra,Fr,...)

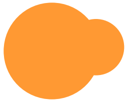


Intrinsic Schiff moment:

$$S_{\text{intr}} \approx eZR_N^3 \frac{9\beta_2\beta_3}{20\pi\sqrt{35}}$$

$\beta_2 \approx 0.2$ - quadrupole deformation

$\beta_3 \approx 0.1$ - octupole deformation



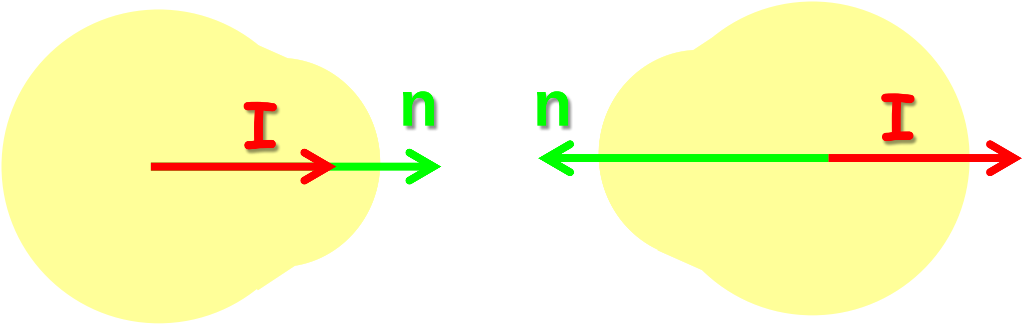
No T,P-odd forces are needed for the Schiff moment and EDM in intrinsic reference frame

However, in laboratory frame S=d=0 due to rotation

In the absence of T,P-odd forces: doublet (+) and (-)

$$\Psi = \frac{1}{\sqrt{2}}\left(\left|IMK\right\rangle + \left|IM-K\right\rangle\right)$$

and $\langle \mathbf{n} \rangle = 0$



T,P-odd mixing (β) with opposite parity state (-) of doublet:

$$\Psi = \frac{1}{\sqrt{2}}\left[(1+\beta)\left|IMK\right\rangle + (1-\beta)\left|IM-K\right\rangle\right]$$

and $\langle \mathbf{n} \rangle \propto \beta \mathbf{I}$

EDM and Schiff moment

$$\langle d \rangle, \langle \mathbf{S} \rangle \propto \langle \mathbf{n} \rangle \propto \beta \mathbf{I}$$

Simple estimate (Auerbach, Flambaum, Spevak):

$$S_{lab} \propto \frac{\langle + | H_{TP} | - \rangle}{E_+ - E_-} S_{body}$$

Two factors of enhancement:

1. Large collective moment in the body frame
2. Small energy interval (E_+-E_-), 0.05 instead of 8 MeV

$$S \approx 0.05 e \beta_2 \beta_3^2 Z A^{2/3} \eta r_0^3 \frac{\text{eV}}{E_+ - E_-} \approx 700 \times 10^{-8} \eta e \text{fm}^3 \approx 500 S(\text{Hg})$$

^{225}Ra,^{223}Rn, Fr,… -100-1000 times enhancemnt

Engel, Friar, Hayes (2000); Flambaum, Zelevinsky (2003):
Static octupole deformation is not essential, nuclei with soft octupole vibrations also have the enhancement.
Nature 2013 Measurements of octupole deformation

EDMs of atoms of experimental interest

Z	Atom	[*S*/(e fm3)]*e* cm	$[10^{-25}\,\eta]$ *e* cm	Expt.
2	^{3}He	0.00008	0.0005	
54	^{129}Xe	0.38	0.7	Seattle, Ann Arbor, Princeton
70	^{171}Yb	-1.9	3	Bangalore,Kyoto
80	^{199}Hg	-2.8	4	Seattle
86	^{223}Rn	3.3	3300	TRIUMF
88	^{225}Ra	-8.2	2500	Argonne,KVI
88	^{223}Ra	-8.2	3400	

Standard Model $\eta = 0.3\ 10^{-8}$ $d_n = 5 \times 10^{-24}\ e\ \mathrm{cm}\ \eta$, $d(^{199}\mathrm{Hg})/\ d_n = 10^{-1}$

RaO molecule

Enhancement factors

- Biggest Schiff moment
- Highest nuclear charge
- Close rotational levels of opposite parity

(strong internal electric field)

Largest T,P-odd nuclear spin-axis interaction κ(I n), RaO= 200 TlF

Flambaum 2008; Kudashov, Petrov, Skripnikov,Mosyagin, Titov, Flambaum 2013

Sandars: Enhancement of electron EDM in heavy atoms and molecules

- Flambaum: Atomic enhancement $=3Z^3 \alpha^2 R(Z\alpha)$

Tl enhancement $d(Tl)= -585\ d_e$

Experiment – Berkeley

- Sushkov,Flambaum 1978 Molecules –close rotational levels, additional enhancement M/m_e

Ω –doubling – huge enhancement of electron EDM

$\Omega=1/2$	10^7	YbF	London
$\Omega=1$	10^{10}	PbO	Yale
		HfF^+	Boulder
		ThO	Harvard, Yale

Weak electric field is enough to polarise the molecule. Molecular electric field is several orders of magnitude larger than external field (Sandars). Accurate calculations available.

Extra enhancement in excited states: Ra

$$d_{atom}(1) = 2\sum_N \frac{\langle 1|D_z|N\rangle\langle N|H_{PT}|1\rangle}{E_1 - E_N}$$

- Extra enhancement for EDM and APV in metastable states due to presence of close opposite parity levels

[Flambaum; Dzuba,Flambaum,Ginges]

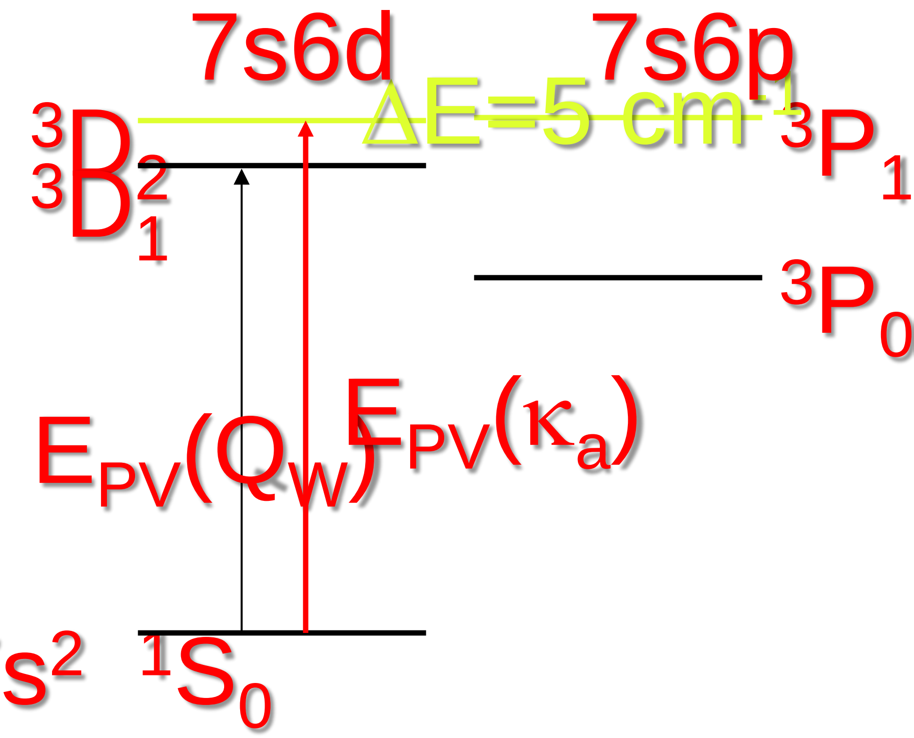
$d(^3D_2) \sim 10^5 \times d(\mathrm{Hg})$

$E_{PV}(^1S_0\text{-}^3D_{1,2}) \sim 100 \times E_{PV}(\mathrm{Cs})$

Comparison of even Ra isotopes

anapole moment: ~10^3 E_{PV} (Cs)

Strongly enhanced


7s6d

7s6p

$\Delta E = 5\ \mathrm{cm}^{-1}$

$^3D_2$

$^3D_1$

$^3P_1$

$^3P_0$

$E_{PV}(Q_W)$

$E_{PV}(\kappa_a)$

$7s^2$ $^1S_0$

Summary

- Atomic and molecular experiments are used to test unification theories of elementary particles

Parity violation

  - Weak charge: test of the standard model and search of new physics
  - Chain of isotopes method can compete with other methods to search for physics beyond the Standard model and measure difference of neutron skins

  - Nuclear anapole, probe of weak PV nuclear forces

Time reversal

  - EDM, test of physics beyond the standard model.

1-3 orders improvement may be enough to reject or confirm all popular models of CP violation, e.g. supersymmetric models

- A new generation of experiments with enhanced effects is underway in atoms, diatomic molecules, and solids