Atomic Physics and Search for Variation of Fundamental Constants

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Motivation

Theoretical arguments for fundamental constants to vary:

- **Extra space dimensions** (Kaluza-Klein theories, Superstring and M-theories, etc). Extra space dimensions is a common feature of theories unifying **gravity** with other interactions. Any change in size of these dimensions would manifest itself in the 3D world as variation of fundamental constants.
- **Scalar fields** (Bekenstein theory, etc.). Fundamental constants appear as expectation values of some scalar fields which don’t have to be stationary in the non-stationary Universe.

Search for variation of fundamental constants

- Big Bang Nucleosynthesis

$|\Delta c|>0$?

- Cosmic Microwave Background Radiation

$|\Delta c|>0$?

✓

- Quasar Absorption Spectra [1]

$|\Delta c|>0$?

- Oklo natural nuclear reactor
- Analysis of meteorite data

✓

- Atomic clocks [1]

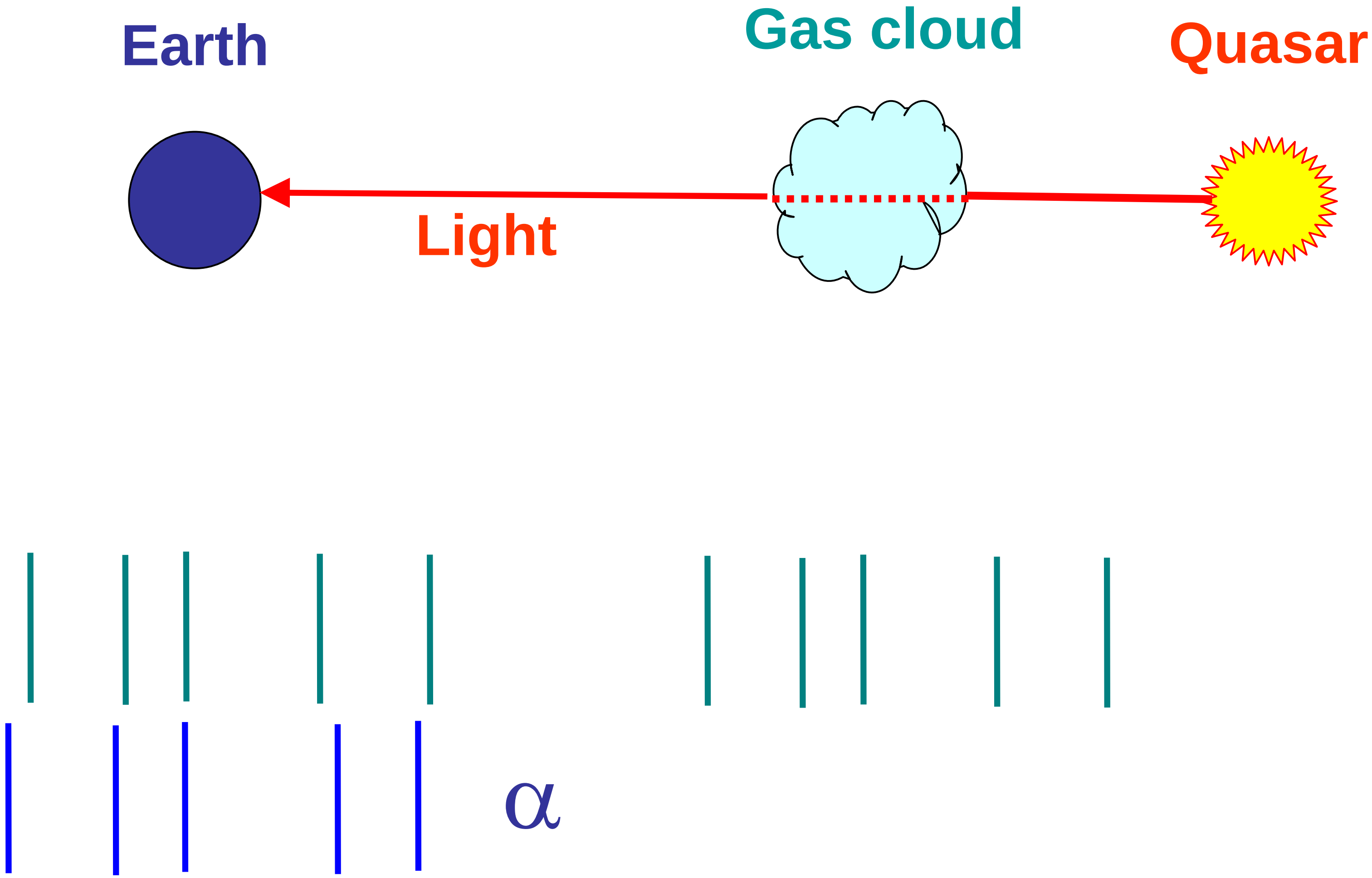
[1] *Based on analysis of atomic spectra*

Which Constants?

- Since variation of **dimensional** constants cannot be distinguished from variation of **units**, it only makes sense to consider variation of **dimensionless** constants.
- Quasar absorption spectra depends on the fine structure constant $\alpha = e^2/hc = 1/137.036$
- Atomic clocks:

Optical transitions	α
Microwave transitions	$\alpha,\ m_{e\ ,q}/\Lambda_{QCD}$

Quasar absorption spectra



Earth

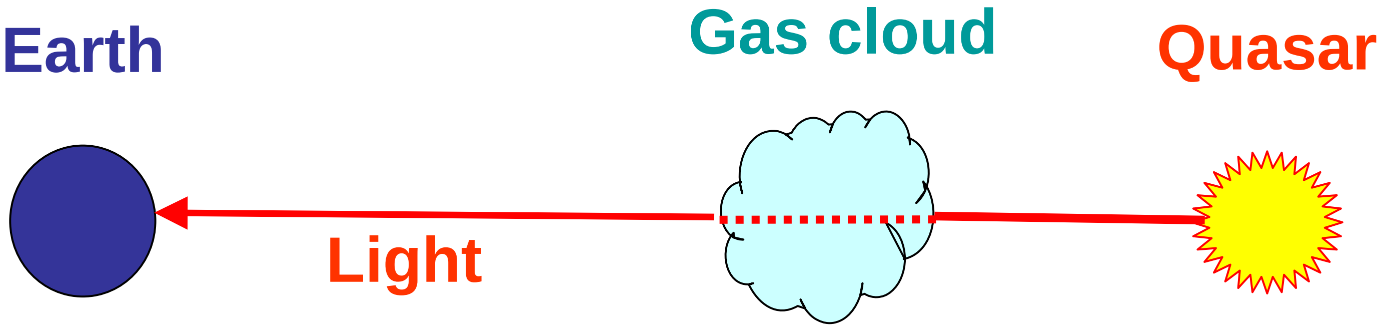
Gas cloud

Quasar

Light

α

Quasar absorption spectra

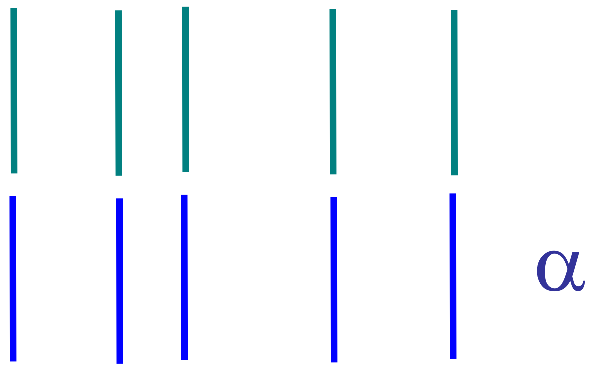


Earth

Gas cloud

Quasar

Light



α

One needs to know *$E(\alpha^2)$* for each line to do the fitting

Alkali Doublet Method

(Varshalovich, Potekhin, Ivanchik, et al)

Fine structure interval

$$\Delta_{FS} = E(p_{3/2}) - E(p_{1/2}) = A(Z\alpha)^2$$

If Δ_Z is observed at red shift Z and Δ_0 is FS measured on Earth then

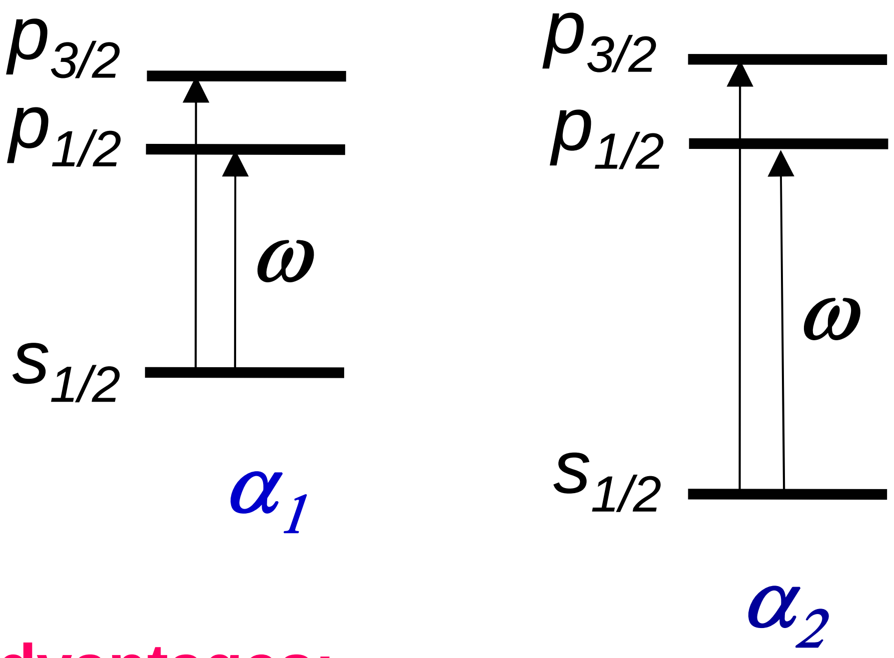
$$\frac{\Delta\alpha}{\alpha} = \frac{1}{2}\left(\frac{\Delta_Z}{\Delta_0} - 1\right)$$

Ivanchik *et al*, 1999: **$\Delta\alpha/\alpha = -3.3(6.5)(8) \times 10^{-5}$.**

Murphy *et al*, 2001: **$\Delta\alpha/\alpha = -0.5(1.3) \times 10^{-5}$.**

Many Multiplet Method

(Flambaum, Webb, Murphy, et al)



$$\delta\omega >> \delta\Delta_{FS}\,!$$

Advantages:

- **Order of magnitude gain in sensitivity**
- **Statistical: all lines are suitable for analysis**
- **Many opportunities to study systematic errors**

Complication: no simple formula for $\omega(\alpha)$.

Solution: use atomic calculations!

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

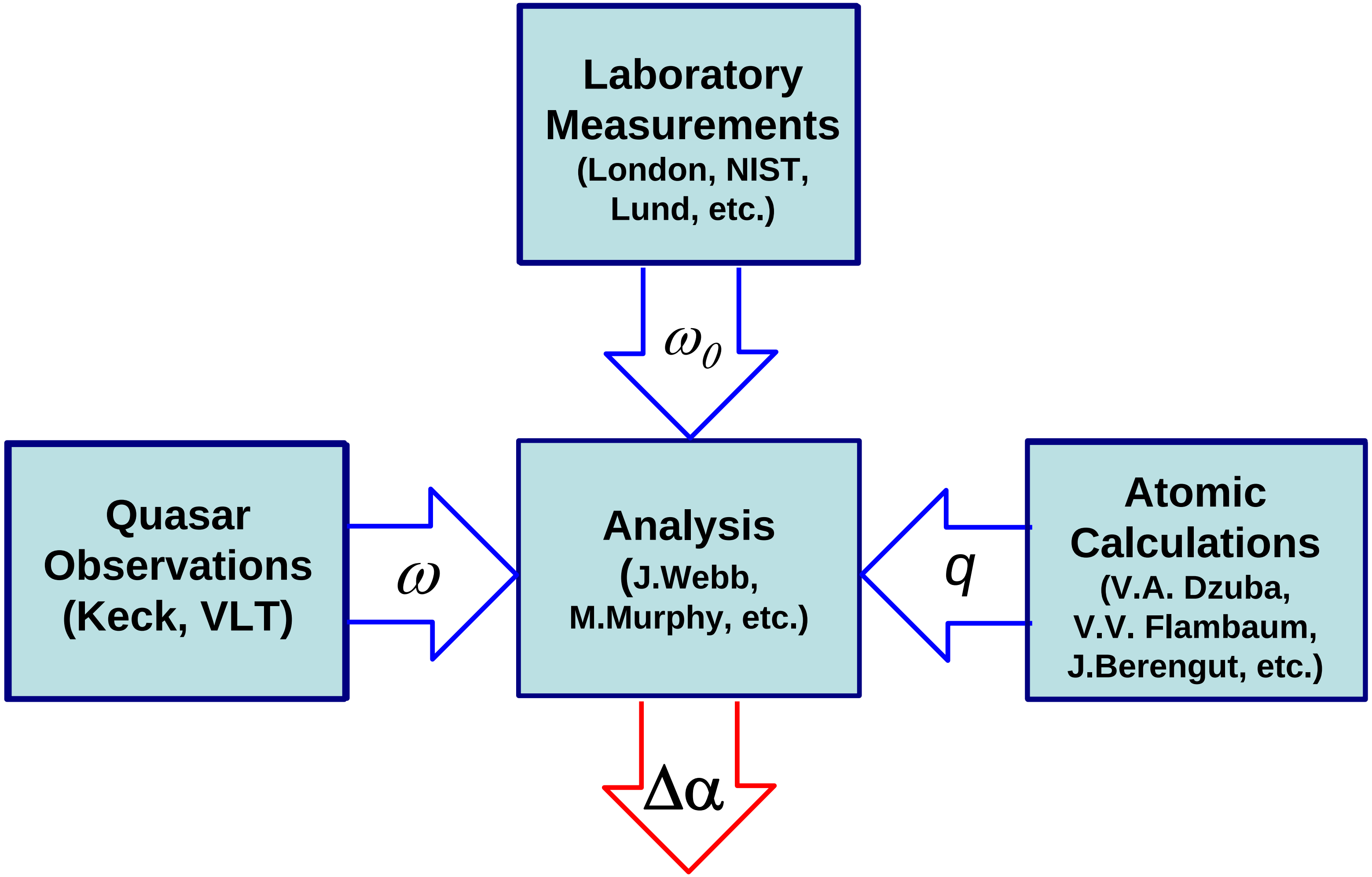
q is found by varying α in computer codes:

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

In atomic units $e=1$, $h=1$, $\alpha=1/c$

Variation of α corresponds to variation of <u>speed of light</u> and $\alpha=0$ corresponds to non-relativistic limit!

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



Laboratory Measurements
(London, NIST, Lund, etc.)

ω_0

Quasar Observations
(Keck, VLT)

ω

Analysis
(J.Webb, M.Murphy, etc.)

q

Atomic Calculations
(V.A. Dzuba, V.V. Flambaum, J.Berengut, etc.)

$\Delta\alpha$

Atoms of interest

Z	Atom / Ion	Transitions	N_{ve}[1]
6	C I, C II, C III	*p-s*	4, 3, 2
8	O I	*p-s*	4
11	Na I	*s-p*	1
12	Mg I, Mg II	*s-p*	2, 1
13	Al II, Al III	*s-p*	2, 1
14	Si II, Si IV	*p-s*	3, 1
16	S II	*s-p*	4
20	Ca II	*s-p*	1
22	Ti II	*s-p, d-p*	3
24	Cr II	*d-p*	5
25	Mn II	*s-p, d-p*	1
26	Fe II	*s-p, d-p*	7
28	Ni II	*d-p*	9
30	Zn II	*s-p*	1

[1] N_{ve} – number of valence electrons

Methods of Atomic Calculations

N_{ve}	Method	Accuracy
1	Correlation Potential Method	0.1-1%
2-6	Configuration Interaction + Many-Body Perturbation Theory	1-10%
2-15	Configuration Interaction	10-20%

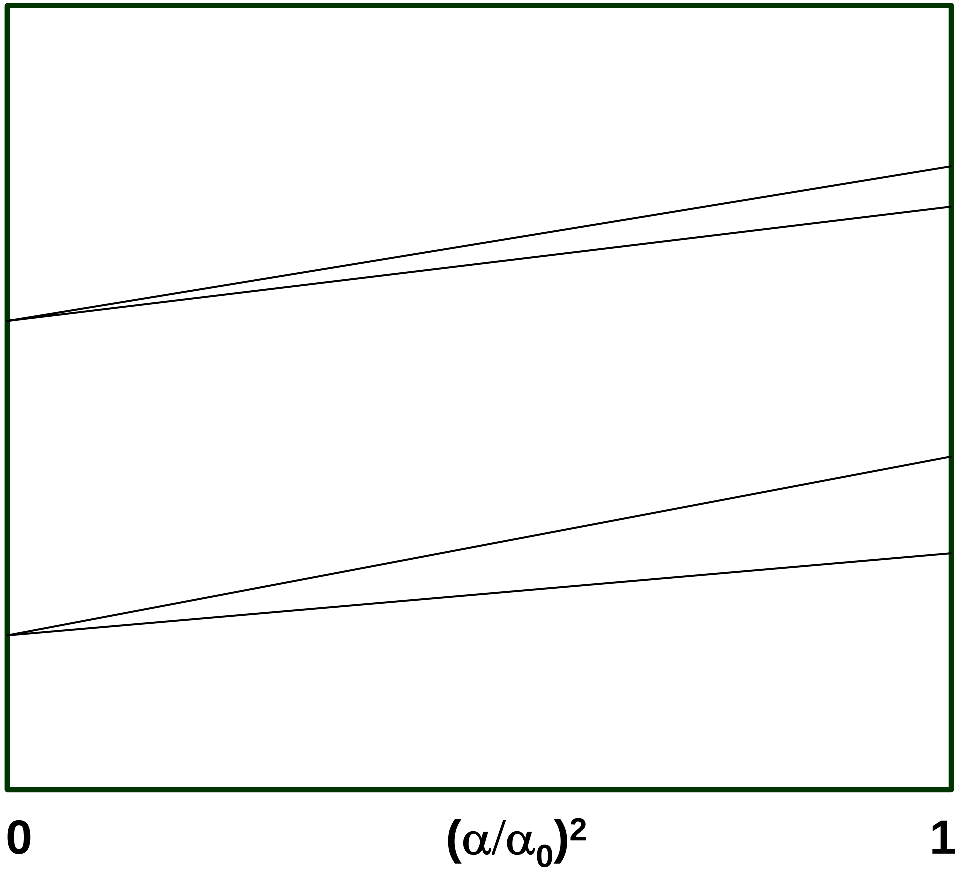
These methods cover all periodic system of elements

They were used for many important problems:

- Saving Standard Model from PNC in Cs.
- Predicting spectrum of **Fr**, etc., etc., etc.

Fine structure anomalies and level crossing

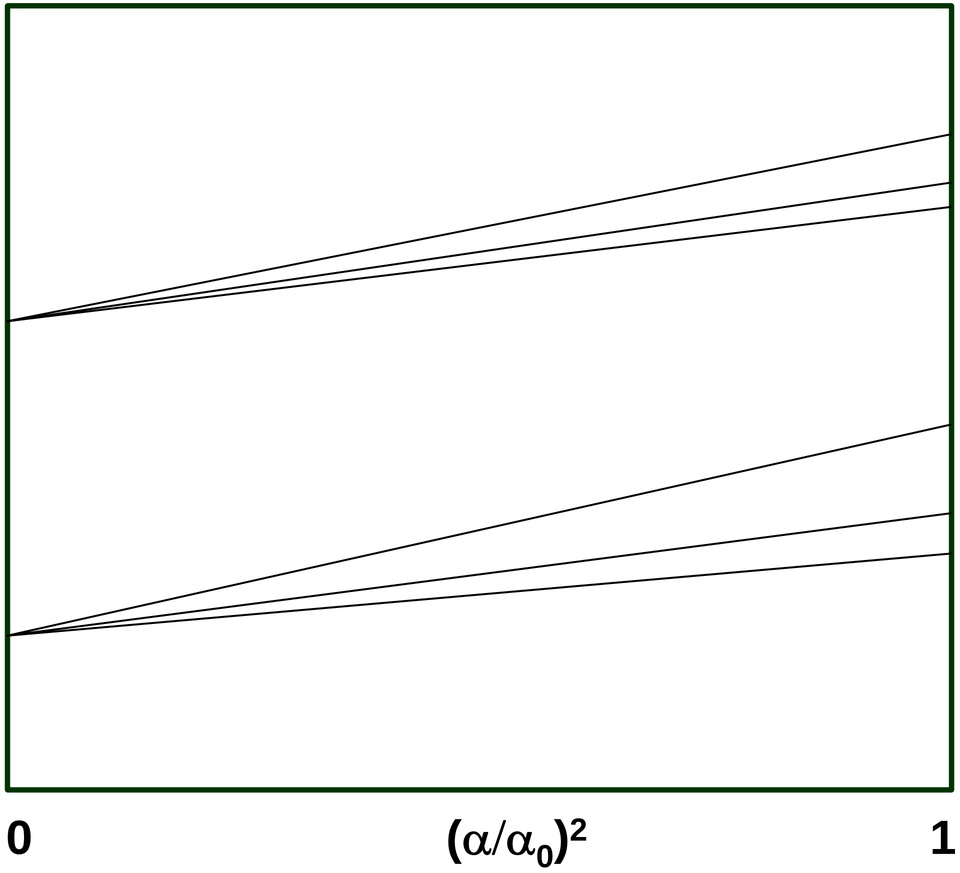
Energies of "normal" fine structure doublets as functions of α^2



$$\Delta E = A(Z\alpha)^2$$

Fine structure anomalies and level crossing

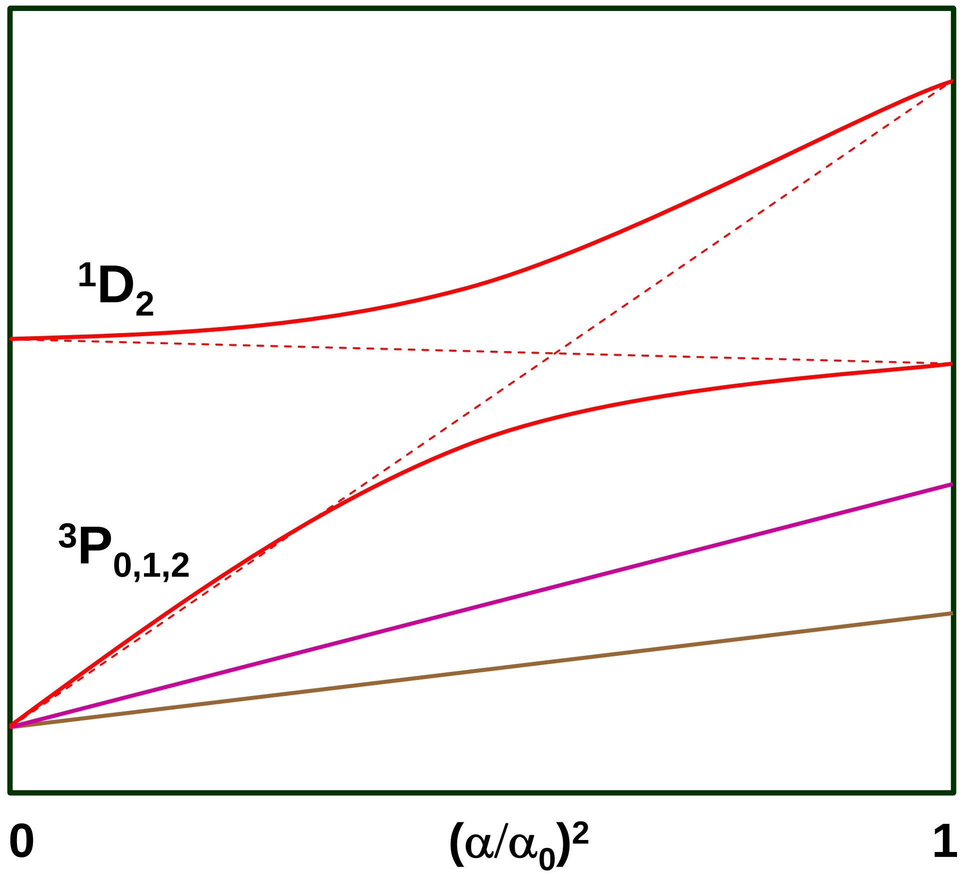
Energies of “normal” fine structure triplets as functions of α^2



$$\Delta E = A(Z\alpha)^2$$

Fine structure anomalies and level crossing

Energies of strongly interacting states as functions of α^2



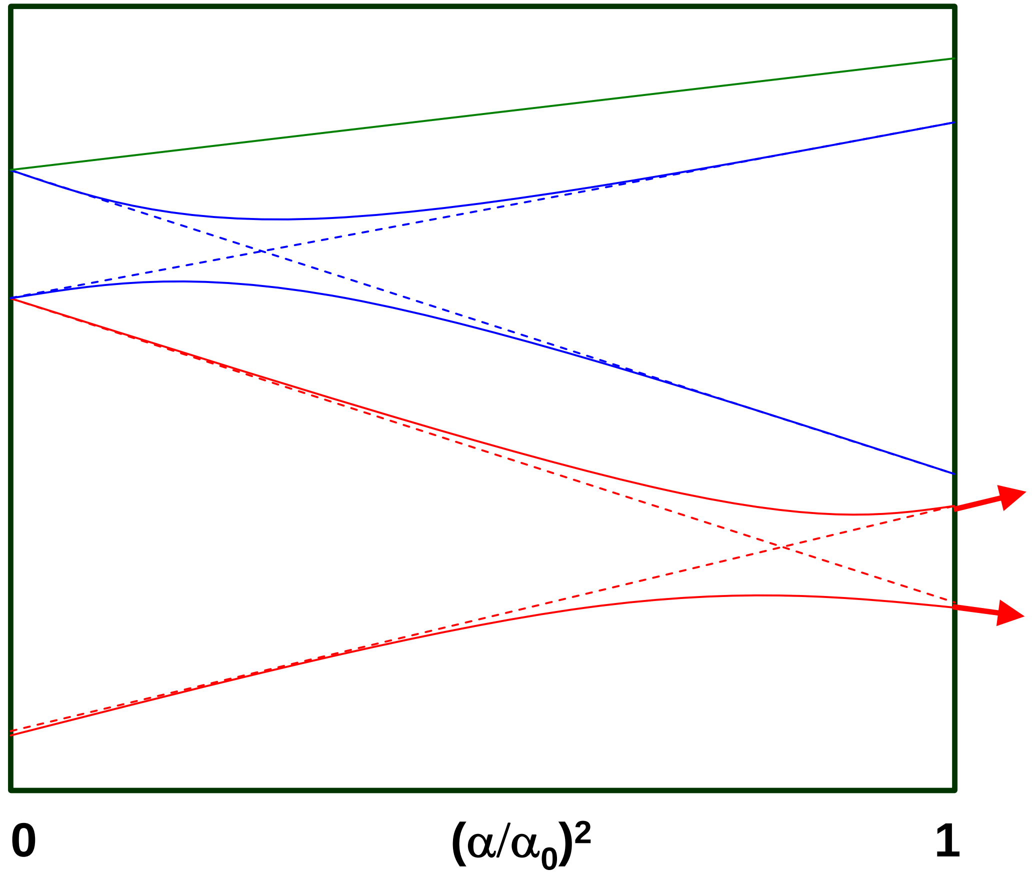
$$\xcancel{\Delta E = A(Z\alpha)^2}$$

Implications to study of α variation

- Not every fine structure interval can be used in the analysis based on formula $\Delta E=A(Z\alpha)^2$ (not good!).
- Strong enhancement is possible (good, but for atomic clocks only).
- Level crossing may lead to instability of calculations (bad!).

Problem: level pseudo crossing

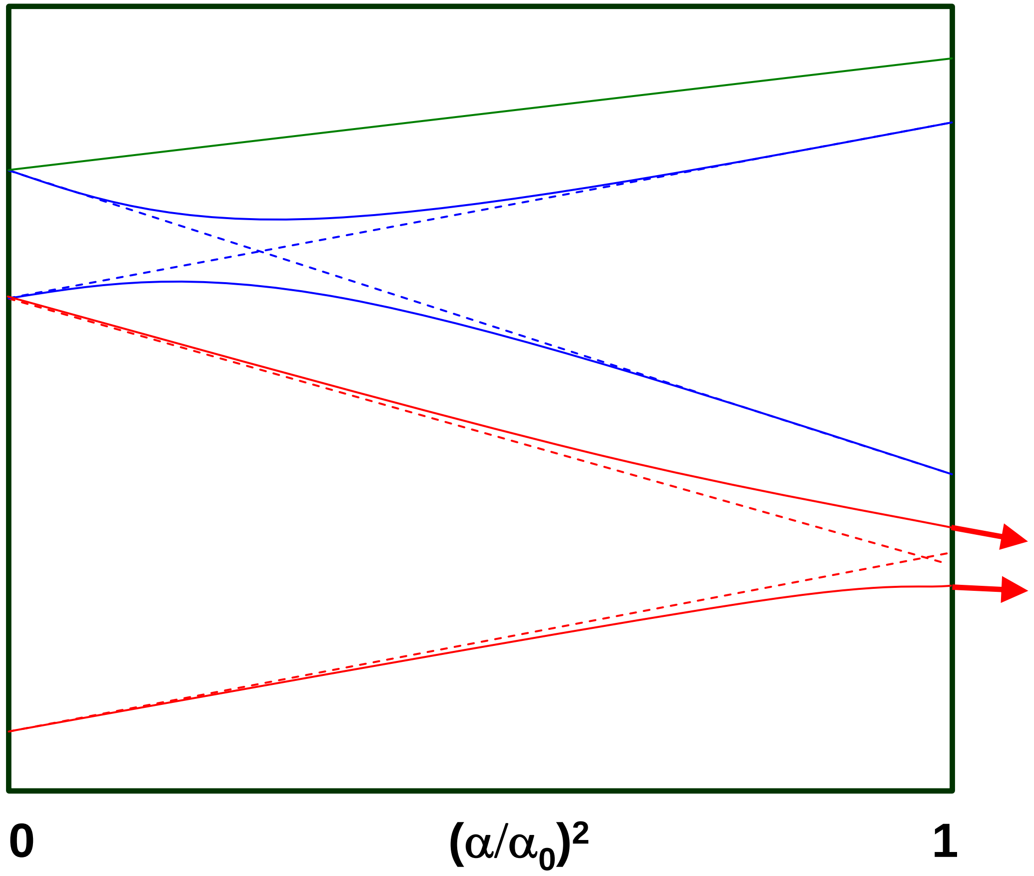
Energy levels of Ni II as functions of α^2



Values of *$q=dE/d\alpha^2$* are sensitive to the position of level crossing

Problem: level pseudo crossing

Energy levels of Ni II as functions of α^2

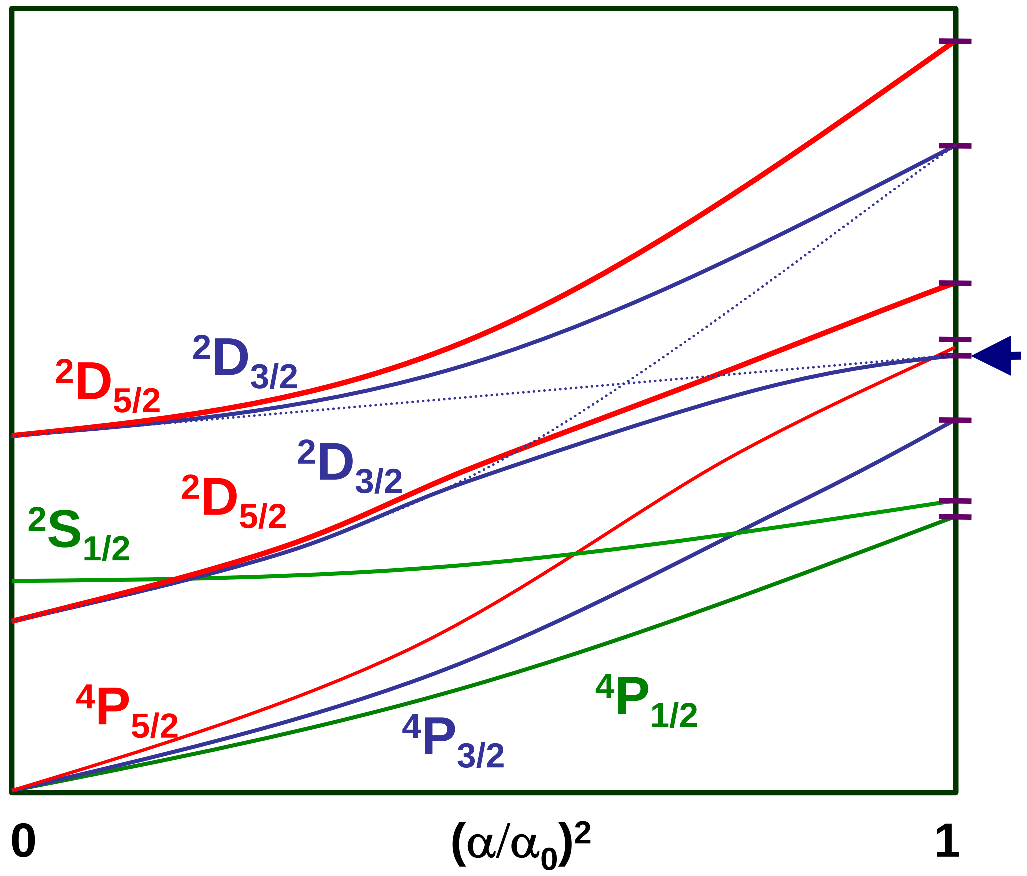


Values of $q=dE/d\alpha^2$ are sensitive to the position of level crossing

Solution:
matching experimental *g*-factors

Pb II: g-factors don't help

Energy levels of Pb II as functions of α^2



Two $^3D_{3/2}$ states are strongly mixed, but g-factors do not depend on mixing.

Solution: perform calculations with extremely high accuracy.

Results of calculations

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**

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**	

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

Complicated behaviour of atomic spectra provides opportunity to study systematic errors!

Results of the analysis

- Murphy et al, 2003: **Keck telescope,** 143 systems, 23 lines, 0.2<z<4.2

$$\Delta\alpha/\alpha = -0.543(116) \times 10^{-5}$$

- Quast et al, 2004: **VLT telescope,** 1 system, Fe II, 6 lines, 5 positive *q*-s, one negative *q*, z=1.15

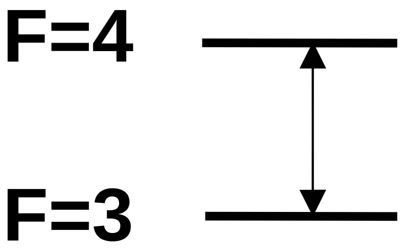
$$\Delta\alpha/\alpha = -0.4(1.9)(2.7) \times 10^{-6}$$

- Srianand et al, 2004: **VLT telescope,** 23 systems, 12 lines, Fe II, Mg I, Si II, Al II, 0.4<z<2.3

$$\Delta\alpha/\alpha = -0.06(0.06) \times 10^{-5}$$

Atomic clocks

Cesium primary frequency standard:



HFS of 6s:

F=4

F=3

$\nu = 9\ 192\ 631\ 770$ Hz

Also: Rb, Cd^+, Ba^+, Yb^+, Hg^+, etc.

E.g. $\nu(Hg^+) = 40\ 507\ 347\ 996.841\ 59(14)(41)$ Hz

(D. J. Berkeland *et al*, 1998).

Optical frequency standards:

Z	Atom	Transition	Frequency	Source
20	Ca	$^1S_0$-$^3P_1$	455 986 240 494 144(5.3) Hz	Degenhardt et al, 2005
38	Sr^+	$^1S_0$-$^3P_1$	434 829 121 311(10) kHz	Ferrari et al, 2003
49	In^+	$^1S_0$-$^3P_0$	1 267 402 452 899 920(230) Hz	von Zanthier et al, 2005
70	Yb^+	$^2S_{1/2}$-$^2F_{7/2}$	642 121 496 772 300(600) Hz	Hosaka et al, 2005

Also: Al^+, Sr, Ba^+, Yb, Hg, Hg^+, Tl^+, Ra^+, etc.

Accuracy about 10^{-15} can be further improved to 10^{-18}!

Opportunities:

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: α, $\boldsymbol{m_e, m_q/\Lambda_{QCD}}$

Advantages:

- Very narrow lines, high accuracy of measurements.
- Flexibility to choose lines with larger sensitivity to variation of fundamental constants.
- Simple interpretation (local time variation).

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

Microwave transitions: analytical formula or atomic calculations.

$$A_s = A_0 \alpha^2 F(\alpha Z)$$

Optical transitions: atomic calculations (as for quasar absorption spectra).

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

Results for variation of fundamental constants

Source	$\text{Clock}_1/\text{Clock}_2$	$d\alpha/dt/\alpha(10^{-15}\,\text{yr}^{-1})$
Marion *et al*, 2003	Rb(hfs)/Cs(hfs)	$0.05(1.3)^a$
Bize *et al*, 2003	Hg+(opt)/Cs(hfs)	$-0.03(1.2)^a$
Fisher *et al*, 2004	H(opt)/Cs(hfs)	$-1.1(2.3)^a$
Peik *et al*, 2004	Yb+(opt)/Cs(hfs)	$-0.2(2.0)$
Bize *et al*, 2004	Rb(hfs)/Cs(hfs)	$0.1(1)^a$

[a] assuming $m_q/\Lambda_{QCD} = Const$

Combined results: $d/dt \ln\alpha = -0.9(2.9) \times 10^{-15}\ \text{yr}^{-1}$

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

Search for enhancement

If $\omega = \omega_0 + \mathbf{q}(\alpha^2/\alpha_0^2 - 1)$ then $\Delta\omega/\omega_0 = 2\mathbf{q}/\omega 0\, \Delta\alpha/\alpha$

$K = 2\mathbf{q}/\omega_0$ is an enhancement factor.

For a transition between excited states:

$$K = 2\Delta\mathbf{q}/\Delta\omega$$

We should look for sufficiently different states (large Δq) separated by small energy interval!

For atomic clocks $K = 1 - 2$ (no enhancement!).

Dysprosium miracle

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}

Interval $\Delta\omega = 10^{-4}\ \mathrm{cm}^{-1}$

Enhancement factor **$K = 10^{8}$** (!), i.e. $\Delta\omega/\omega_0 = 10^{8}\,\Delta\alpha/\alpha$

Preliminary result (Budker *et al*, Berkeley)

$|d\ln\alpha/dt| < 4.3 \times 10^{-15}\ \mathrm{yr}^{-1}$

Problem: states are not narrow!

We have:

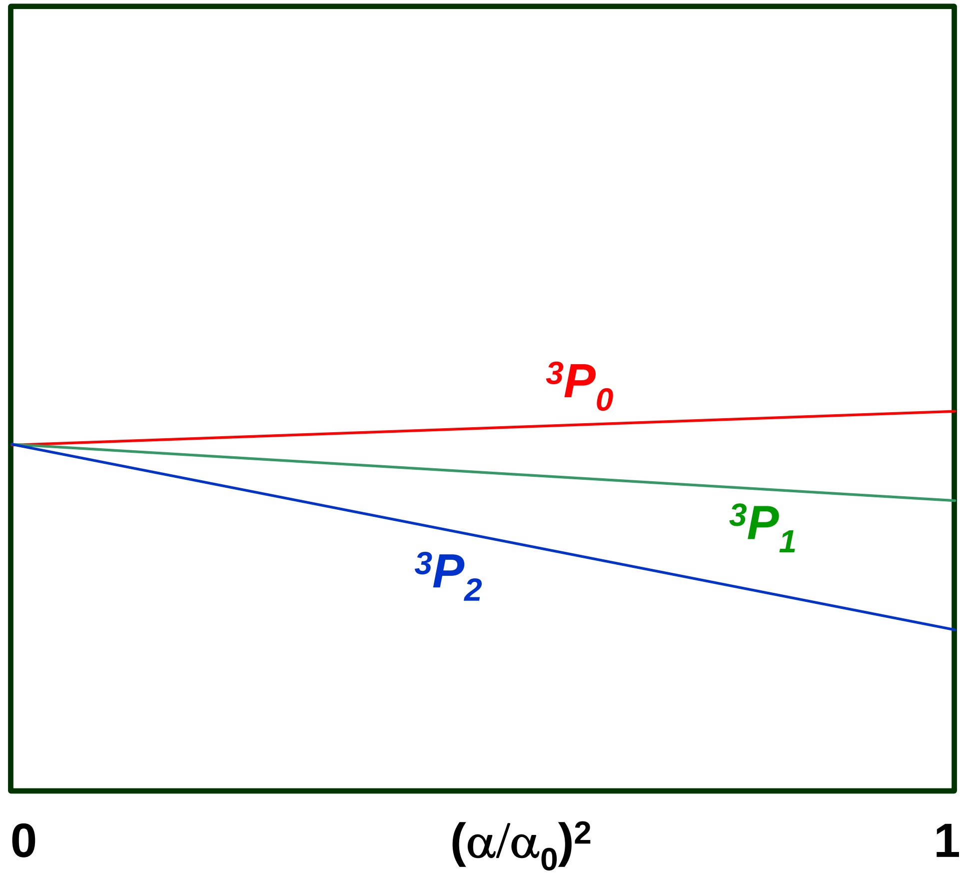
- Atomic clocks: narrow states (good!),
  no enhancement (bad!).

- Is there anything in between?
  (narrow states + strong enhancement ?)

- Dysprosium: broad states (bad!),
  HUGE enhancement (good!).

Fine structure anomaly in Te I

Normal ^3P_J fine structure multiplet for the p^4 configuration as functions of α^2

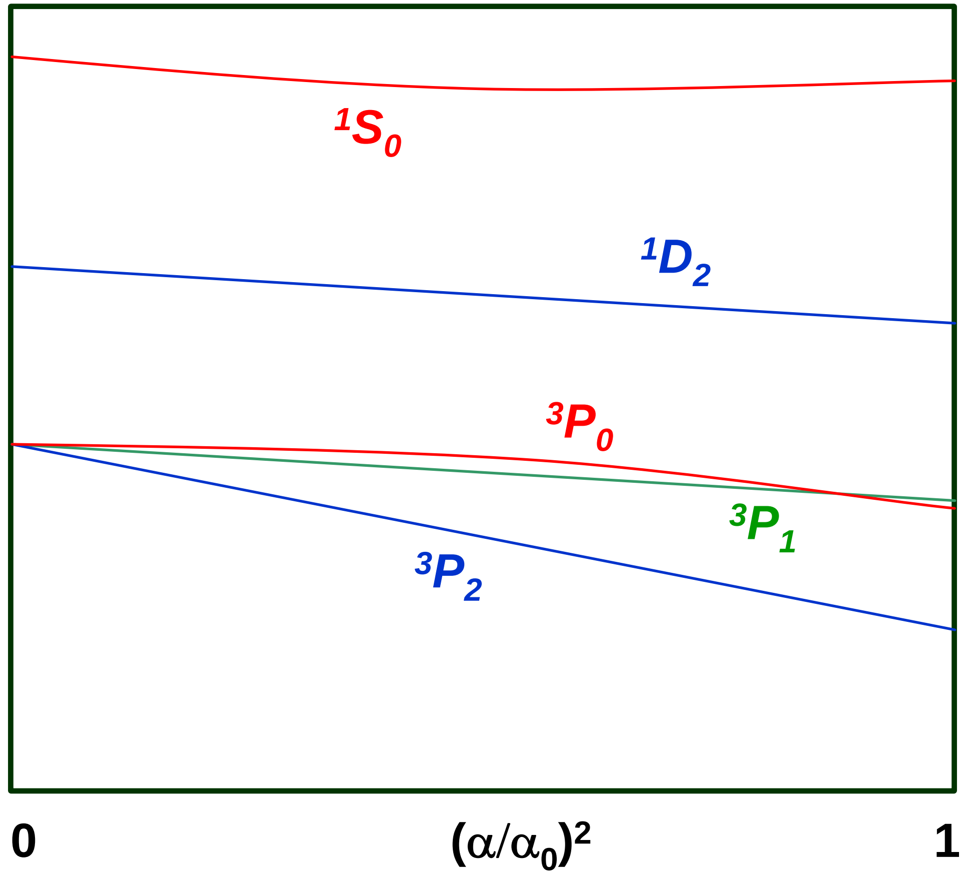


For a “normal” multiplet:

- Lande rule: $\Delta E_{J,J1} = AJ$
- $A < 0$, if $n_e > n_p$
- $A = c(Z\alpha)^2$

Fine structure anomaly in Te I

Real energy levels of the p^4 ground state configuration of Te I as functions of α^2



$E(^3P_1) - E(^3P_0) = 5\ \mathrm{cm}^{-1}$!

Enhancement factor

$K = 100$

i.e. $\Delta\omega/\omega_0 = 100\ \Delta\alpha/\alpha$

Also, all states are metastable!

More suggestions …

Atom	**State$_1$**		**State$_2$**		**K**
Ce I	$^5H_3$	2369.068	$^1D_2$	2378.827	2000
	$^3H_4$	4762.718	$^3D_2$	4766.323	13000
Nd I	$^5K_6$	8411.900	$^7L_5$	8475.355	950
Nd I	$^7L_5$	11108.813	$^7K_6$	11109.167	10^5
Sm I	$^5D_1$	15914.55	$^7G_2$	12087.17	300
Gd II	$^8D_{11/2}$	4841. 106	$^{10}F_{9/2}$	4852.304	1800
Tb I	$^6H_{13/2}$	2771.675	$^8G_{9/2}$	2840.170	600

E. J. Angstmann *et al*, to be published in J. Phys. B

Conclusion

- Analysis of **quasar absorption spectra** indicate that α might be smaller in early epoch. However, discrepancy between different groups must be resolved.
- Comparing the rates of different **atomic clocks** puts strong constraints on the variation of fundamental constants. Fast progress in the field promises new interesting results.
- All results involving **optical** atomic transitions were obtained using our calculations.

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