On the hyperfine anomaly and atomic parity violation

Jacinda Ginges

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

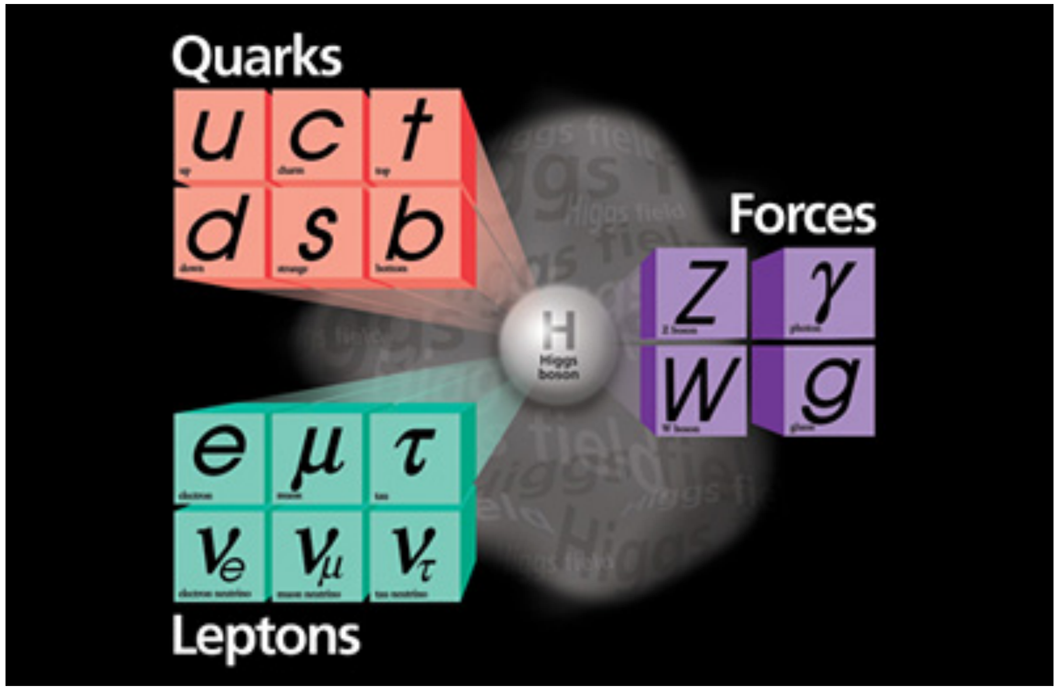
Australian Government
Australian Research Council

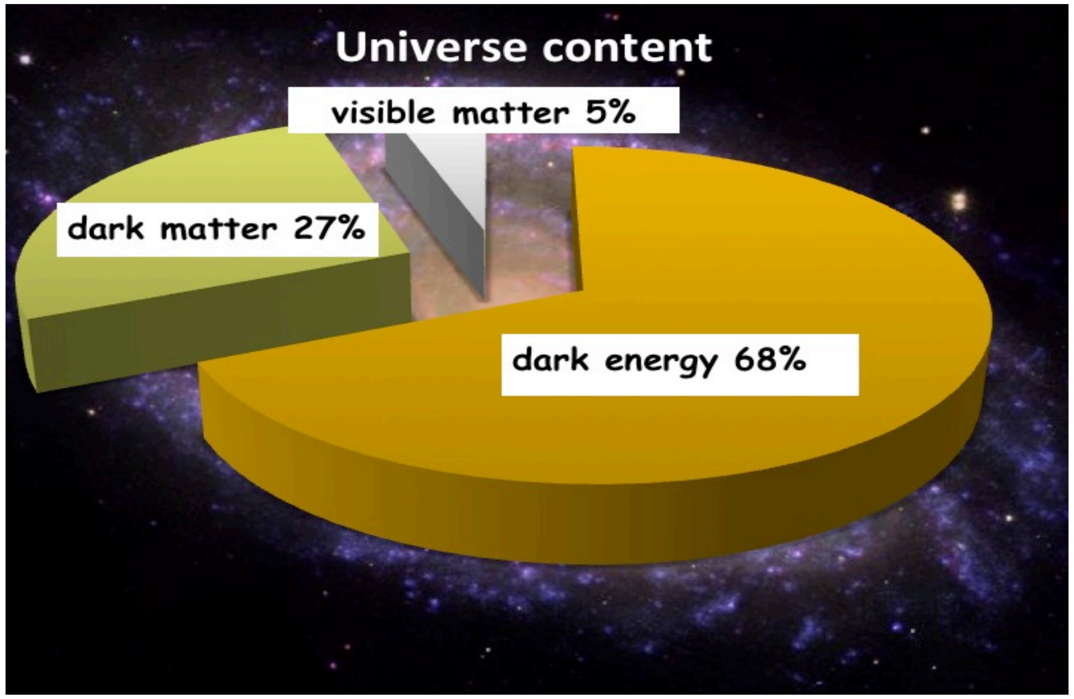
Students, collaborators

Ben Roberts (DECRA fellow)
Swaantje Grunefeld (postdoc)
Perry Ranclaud (student)
George Sanamyan (student)
Andrey Volotka (St Petersburg)
Stephan Fritzsche (Jena, Germany)
Magda Kowalska (CERN)
Jacek Dobaczewski (York)

Searching for new physics

Standard model particles





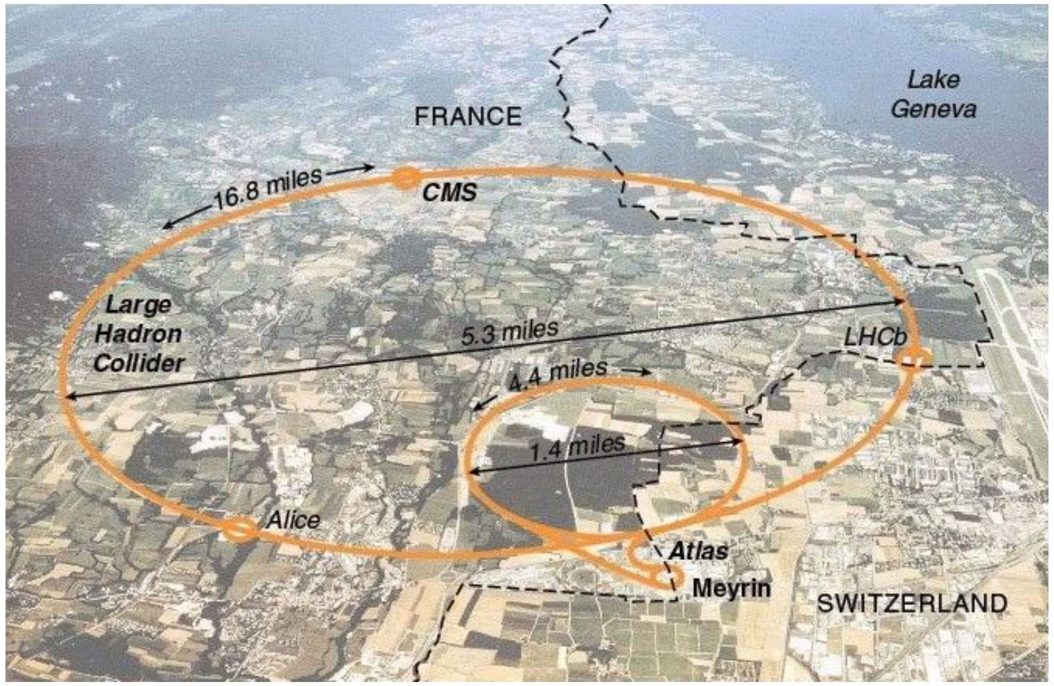
Dark matter?

Dark energy?

Matter-antimatter asymmetry of universe?

High precision vs high energy

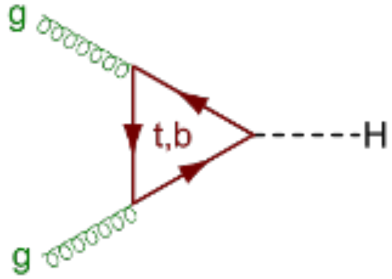
High energy



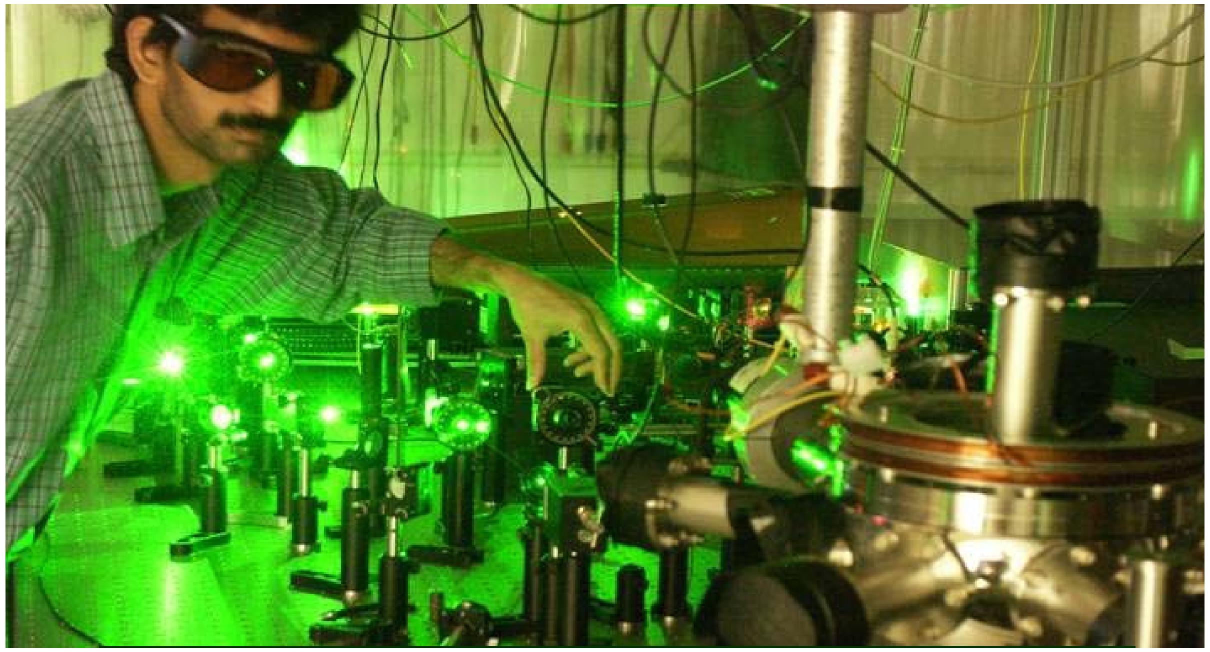
Large Hadron Collider, energies to 13 TeV

Produce particles *directly*

$$E = mc^2$$

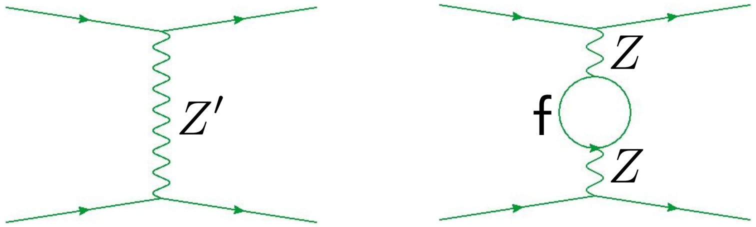


Low energy, high precision



Probe *virtual* processes, may reach >> TeV

$$\Delta E\,\Delta t \sim \hbar$$



Goal

To maximise the discovery potential of precision atomic experiments

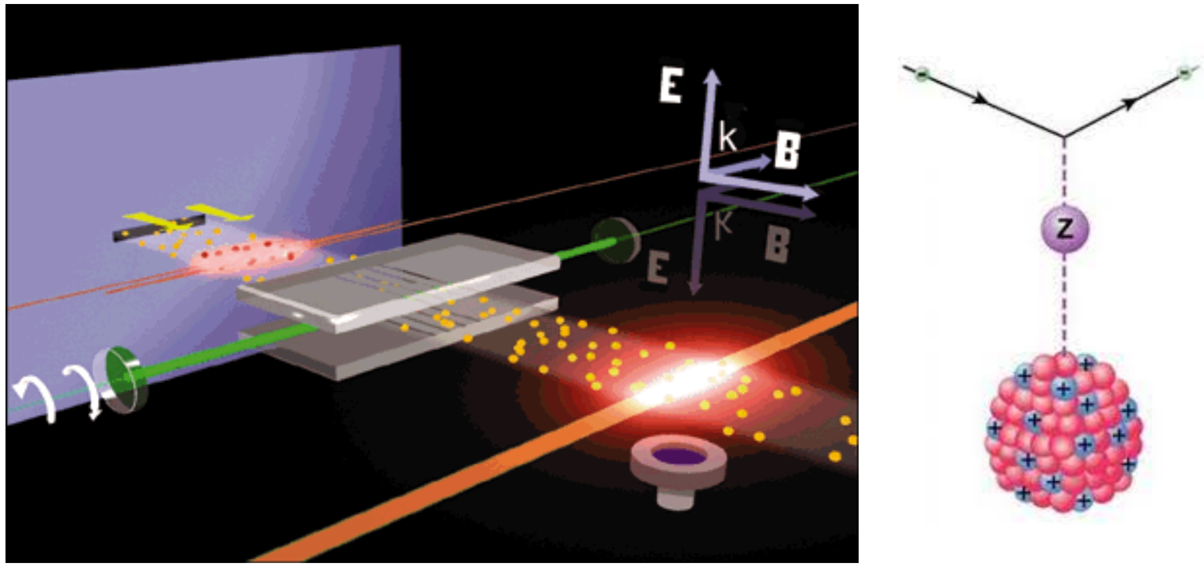
- Push state-of-the-art atomic calculations to 0.1% precision
  - Development of high-precision many-body methods
  - Improved benchmarking of atomic theory

Remove nuclear structure uncertainties that hinder tests of atomic theory

The need for precision atomic theory

Extraction of fundamental parameters and comparison to SM

Atomic parity violation (APV)



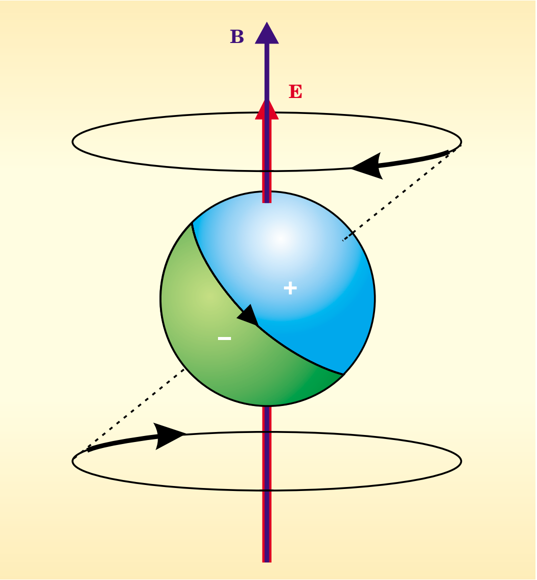
$$E_{\mathrm{PV}} = \xi\, Q_{\mathrm{W}}$$

from atomic structure theory

nuclear weak charge

Electric dipole moments (EDMs)

Parity- and time-reversal-violating



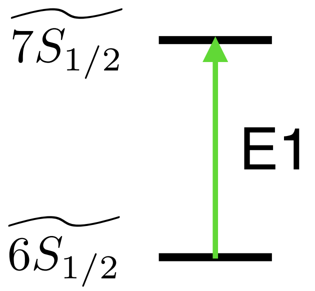
$$d_{\mathrm{atom}} = \zeta S + K d_{\mathrm{e}} + \ldots$$

from atomic structure theory

nuclear Schiff moment

electron EDM

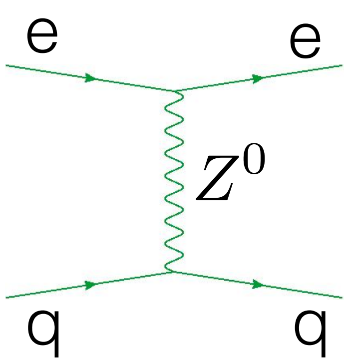
Cs atomic parity violation



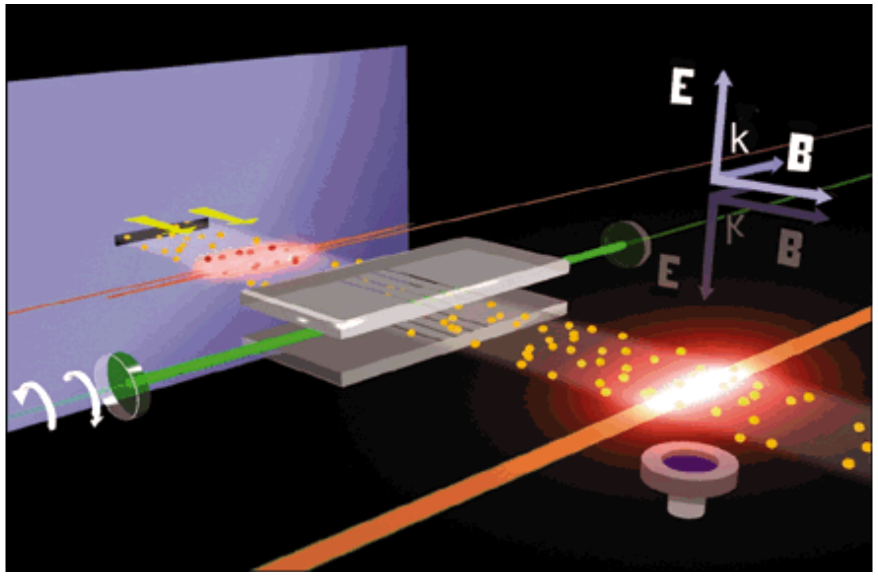
6S - 7S electric dipole transition amplitude E$_{\mathrm{PV}}$

Weak interaction mixes opposite-parity states,

$$\widetilde{S_{1/2}} \to S_{1/2} + \sum \zeta\, nP_{1/2}$$



Experiment, 0.35% uncertainty



Carl Wieman group

Wood et al., Science (1997)

Theory, 0.5% uncertainty

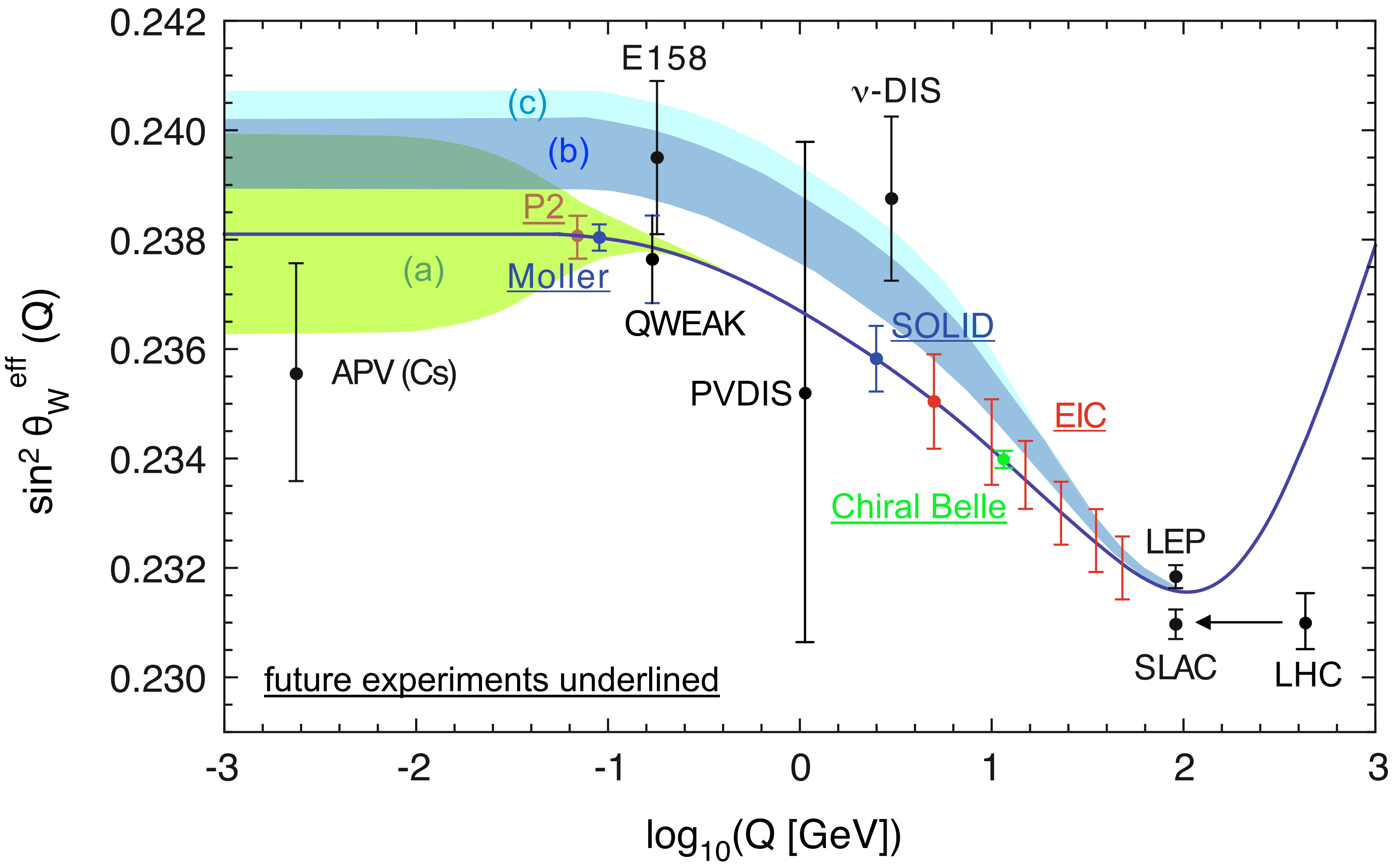
$$\begin{aligned} E_{\mathrm{PV}} &= \langle \widetilde{7S_{1/2}} | D_z | \widetilde{6S_{1/2}} \rangle \\ &= \sum_n \frac{\langle 7S_{1/2} | D_z | nP_{1/2} \rangle \langle nP_{1/2} | H_{\mathrm{PV}} | 6S_{1/2} \rangle}{E_{6S_{1/2}} - E_{nP_{1/2}}} + \ldots \\ &= \xi\, Q_W \end{aligned}$$

$\propto Q_W \rho(r) \gamma_5$

$\mathbf{D} = \sum_i e\mathbf{r}_i \qquad H_{\mathrm{PV}} = \sum_i (h_{\mathrm{PV}})_i \qquad$ Energies E

- Dzuba, Flambaum, Ginges, PRD (2002); Flambaum, Ginges, PRA (2005)
- Porsev, Beloy, Derevianko, PRL (2009); Dzuba, Berengut, Flambaum, Roberts, PRL (2012)

Running of Weinberg angle



Dark Z boson:
(a) 50 MeV;
(b) 15 MeV;
(c) 15 MeV, in tension with expt.

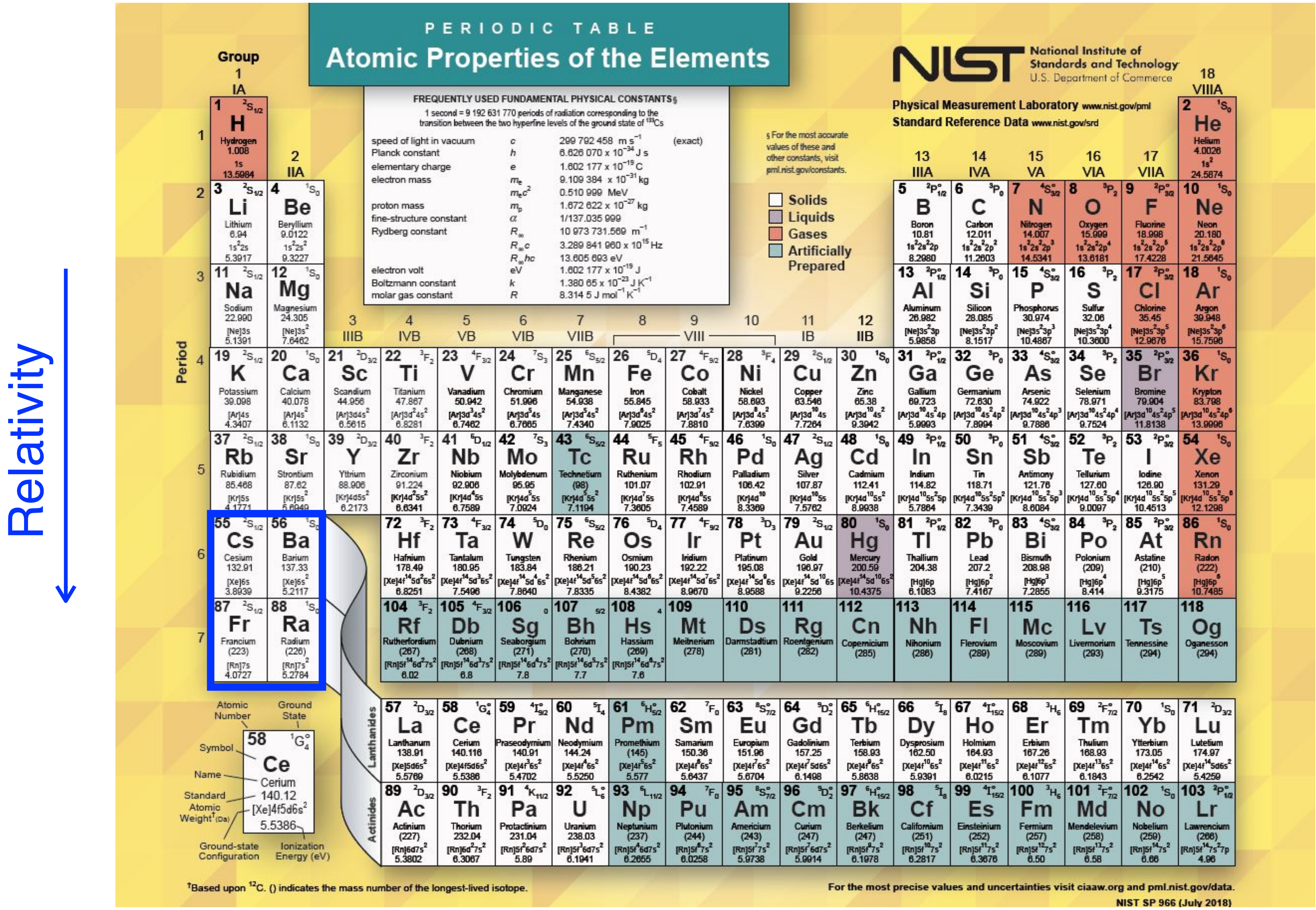
QWEAK: R. Young, talk (NUPP)

Figure from: Gwinner and Orozco, Quantum Sci. Technol (2022)

J. Hasted, poster → New result for vector polarizability shifts APV result: G. Toh et al., PRL (2019)

New value for W-boson mass shifts SM Q_W: Tran Tan and Derevianko, Atoms (2022)

Experiments in preparation/progress

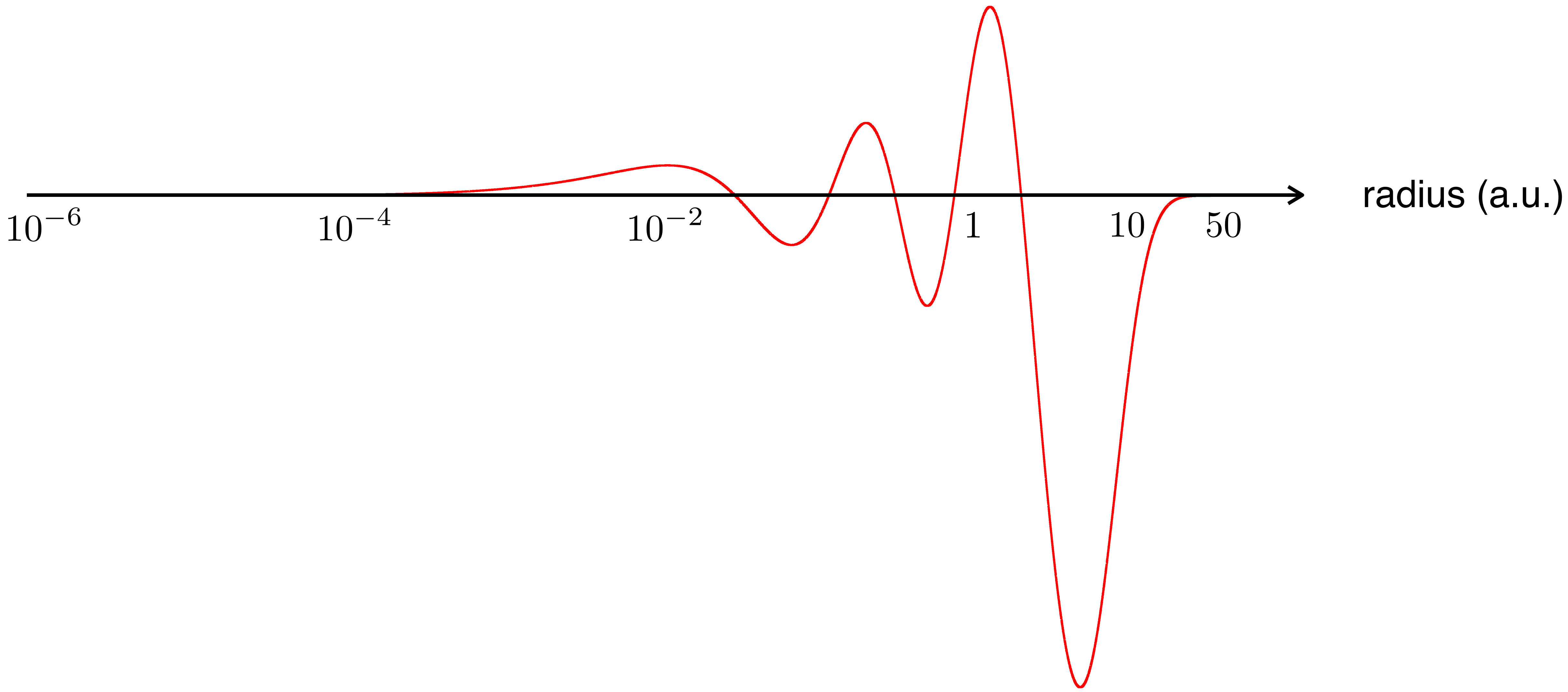


Neutral atoms: Cs (Purdue) ; Fr (TRIUMF; Tokyo)

Singly-ionized atoms: Ba+ (Seattle) ; Ra+ (Groningen)

Benchmarking atomic theory

Upper radial component, Cs 6s:



$$E_{\rm PV} = \sum_n \frac{\langle 7S_{1/2}|D|nP_{1/2}\rangle\langle nP_{1/2}|H_{\rm PV}|6S_{1/2}\rangle}{E_{6S_{1/2}} - E_{nP_{1/2}}} + \sum_n \frac{\langle 7S_{1/2}|H_{\rm PV}|nP_{1/2}\rangle\langle nP_{1/2}|D|6S_{1/2}\rangle}{E_{7S_{1/2}} - E_{nP_{1/2}}} = \xi Q_W$$

Benchmarking atomic theory

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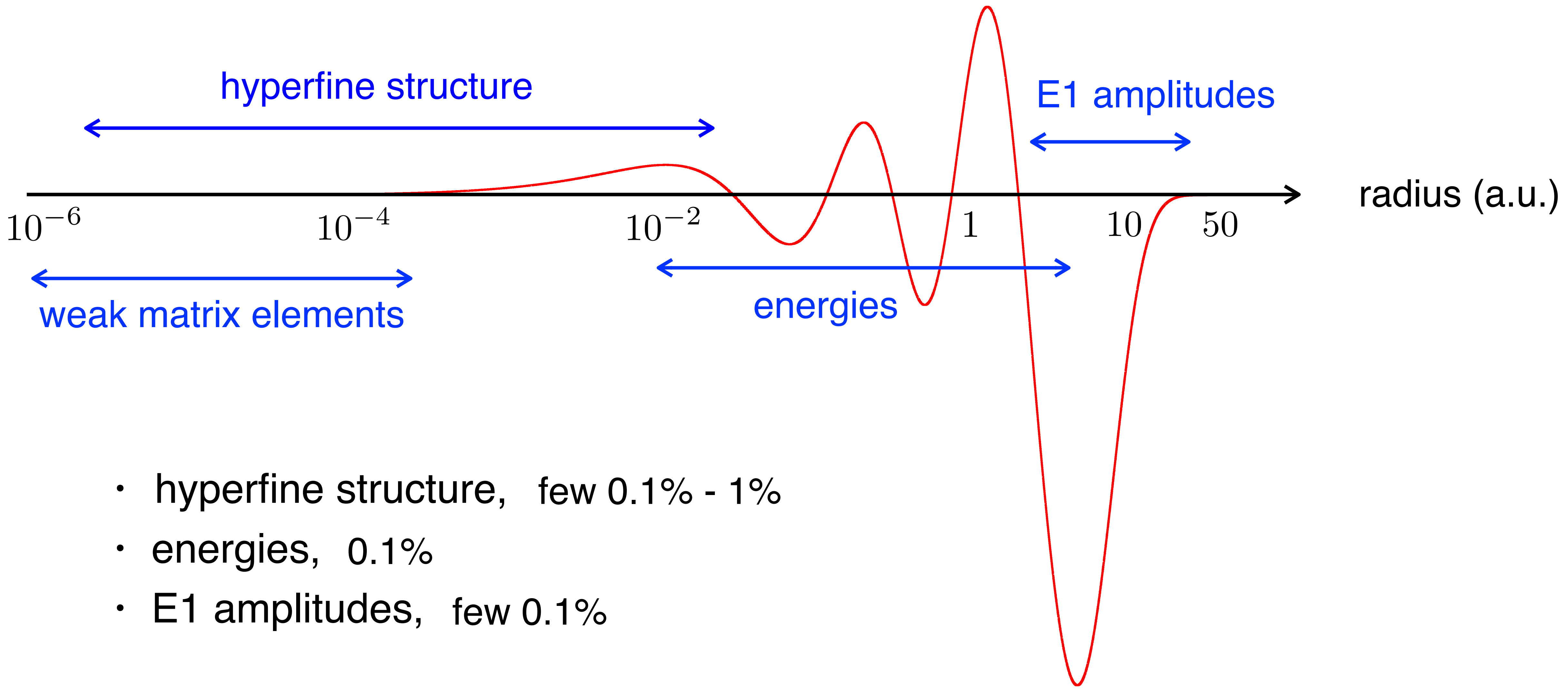

- hyperfine structure, few 0.1% - 1%
- energies, 0.1%
- E1 amplitudes, few 0.1%

$$E_{\mathrm{PV}} = \sum_n \frac{\langle 7S_{1/2}|D|nP_{1/2}\rangle\langle nP_{1/2}|H_{\mathrm{PV}}|6S_{1/2}\rangle}{E_{6S_{1/2}} - E_{nP_{1/2}}} + \sum_n \frac{\langle 7S_{1/2}|H_{\mathrm{PV}}|nP_{1/2}\rangle\langle nP_{1/2}|D|6S_{1/2}\rangle}{E_{7S_{1/2}} - E_{nP_{1/2}}} = \xi Q_W$$

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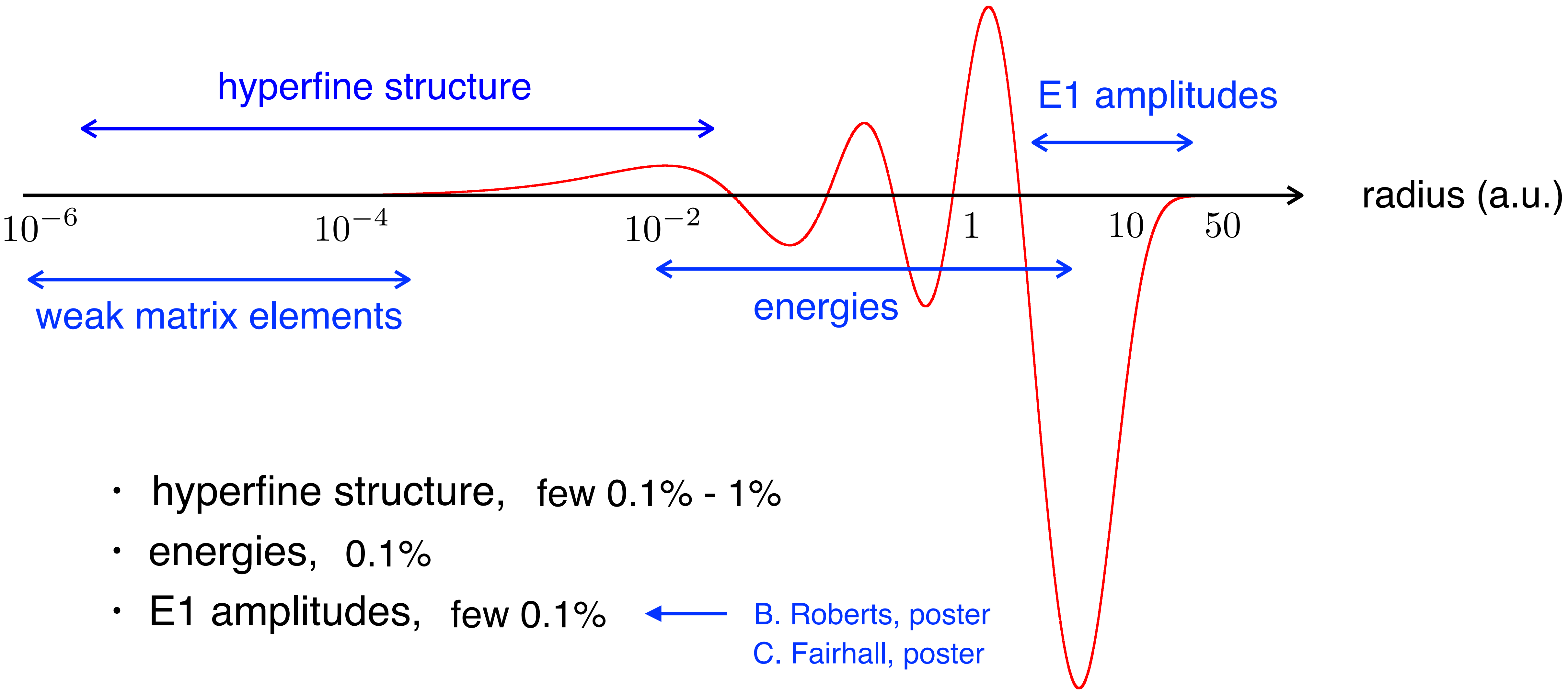
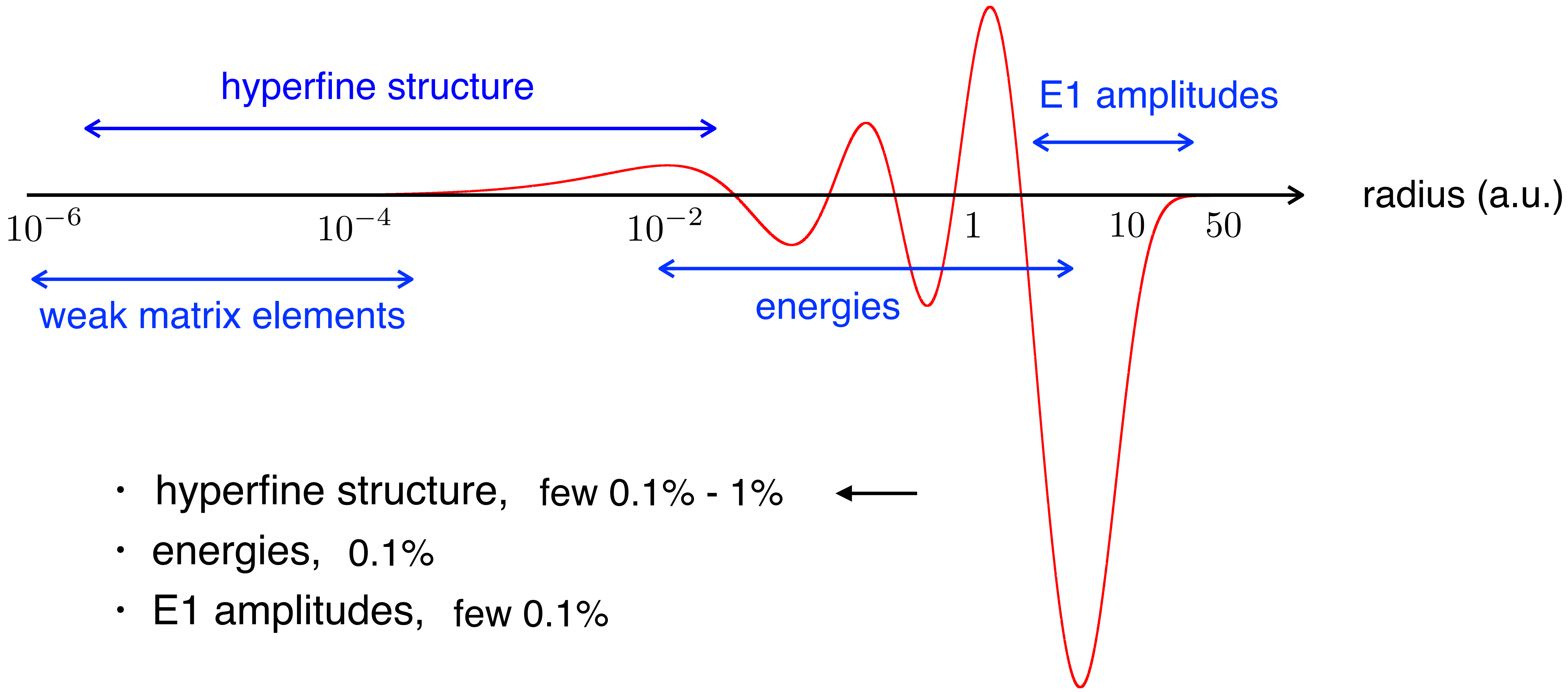


- hyperfine structure, few 0.1% - 1%
- energies, 0.1%
- E1 amplitudes, few 0.1% ← B. Roberts, poster
C. Fairhall, poster

$$E_{\rm PV} = \sum_n \frac{\langle 7S_{1/2}|D|nP_{1/2}\rangle\langle nP_{1/2}|H_{\rm PV}|6S_{1/2}\rangle}{E_{6S_{1/2}} - E_{nP_{1/2}}} + \sum_n \frac{\langle 7S_{1/2}|H_{\rm PV}|nP_{1/2}\rangle\langle nP_{1/2}|D|6S_{1/2}\rangle}{E_{7S_{1/2}} - E_{nP_{1/2}}} = \xi Q_W$$

Benchmarking atomic theory

Upper radial component, Cs 6s:



- hyperfine structure, few 0.1% - 1% ←
- energies, 0.1%
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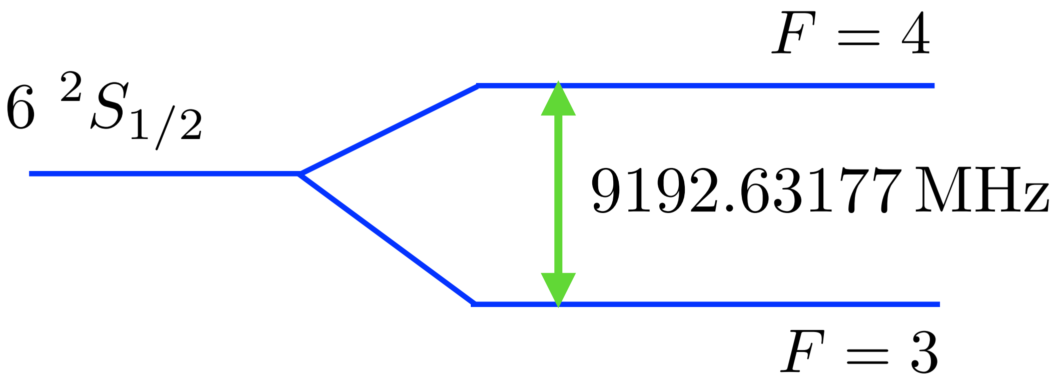
$$E_{\rm PV} = \sum_n \frac{\langle 7S_{1/2}|D|nP_{1/2}\rangle\langle nP_{1/2}|H_{\rm PV}|6S_{1/2}\rangle}{E_{6S_{1/2}} - E_{nP_{1/2}}} + \sum_n \frac{\langle 7S_{1/2}|H_{\rm PV}|nP_{1/2}\rangle\langle nP_{1/2}|D|6S_{1/2}\rangle}{E_{7S_{1/2}} - E_{nP_{1/2}}} = \xi Q_W$$

Hyperfine structure

NIST-F2 Atomic clock

Primary standard for the SI unit for time, the *second*

Hyperfine splitting in cesium

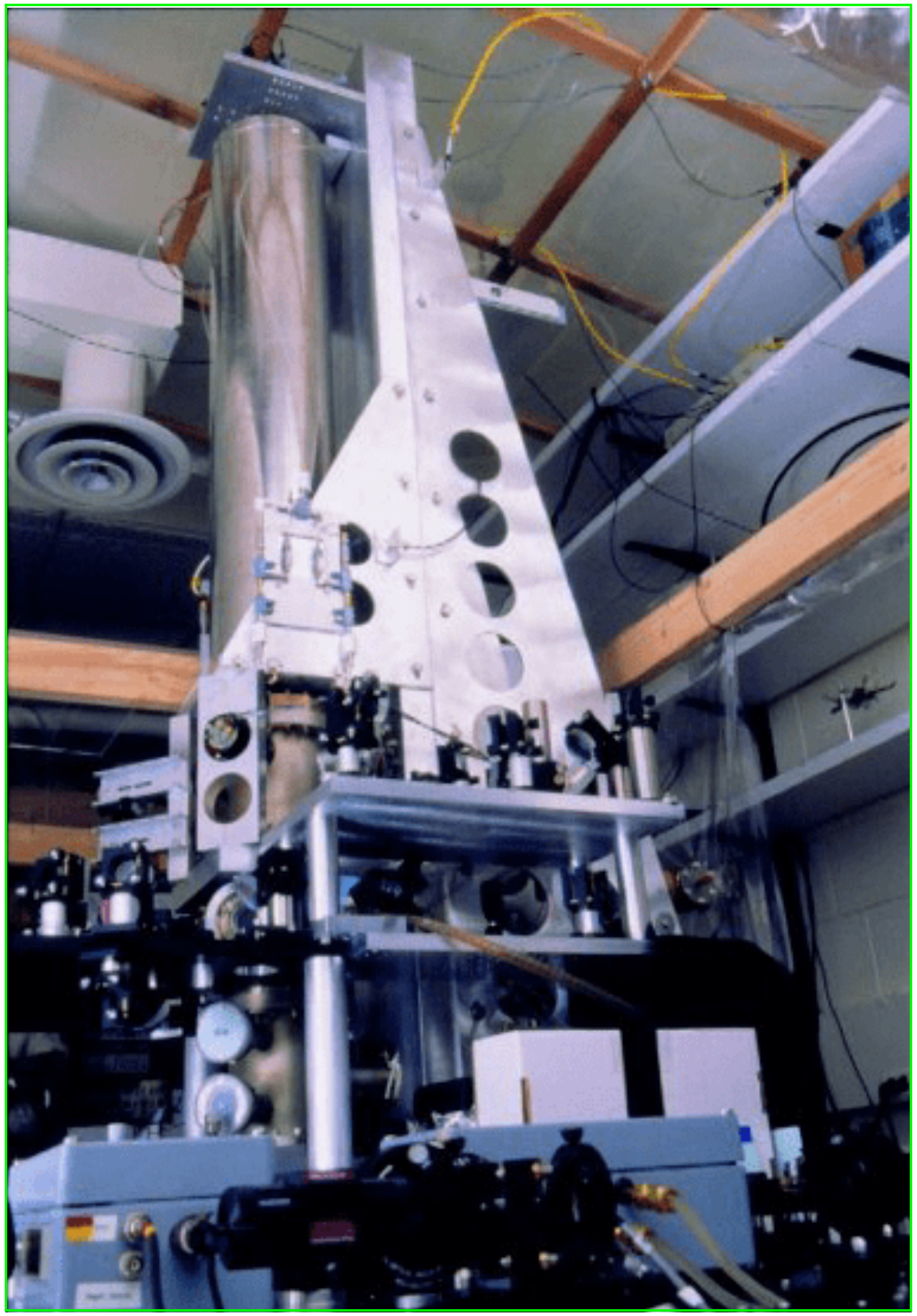


$F = 4$

$6\ ^2S_{1/2}$

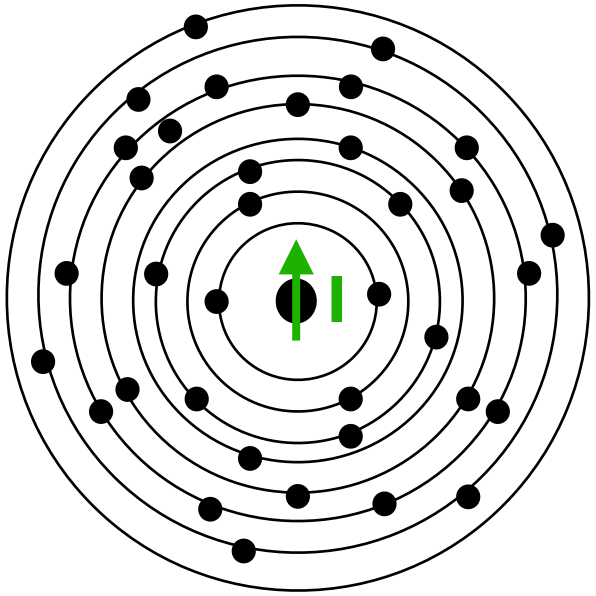
$9192.63177\,\mathrm{MHz}$

$F = 3$

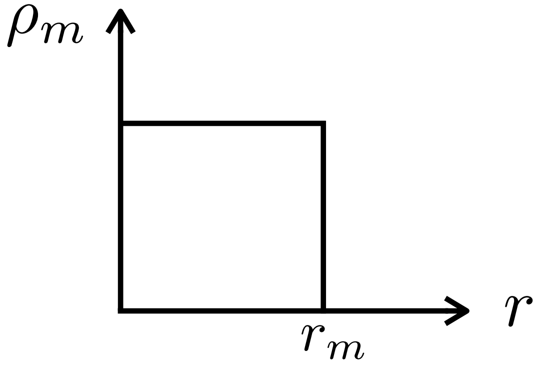


Modelling the hyperfine structure

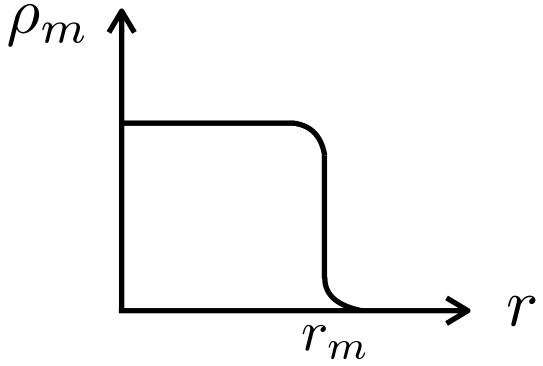
Interaction $$h_{\mathrm{hfs}} = \frac{1}{c}\frac{\boldsymbol{\mu}\cdot(\mathbf{r}\times\boldsymbol{\alpha})}{r^3}F(r)$$



Ball, $F(r) = (r/r_m)^3$



Fermi distribution



Standard ways to model *F(r)*, until recently

Hyperfine splitting quantified by hyperfine constant *A*

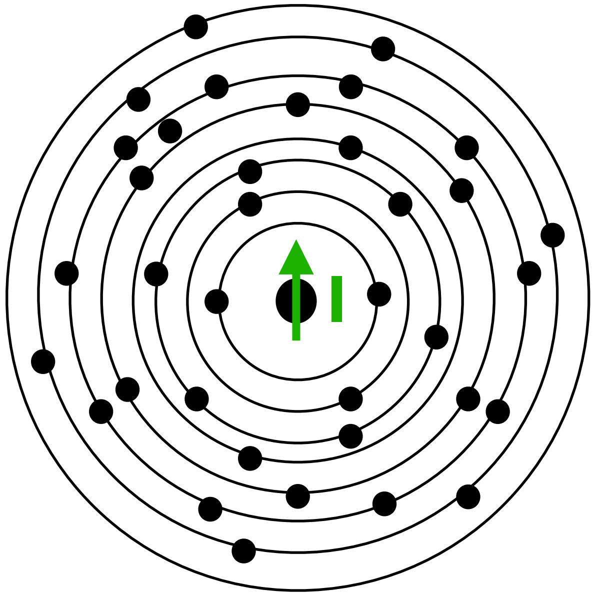
$$A = A_0(1+\epsilon) + \delta A^{\mathrm{QED}}$$

Modelling the hyperfine structure

nuclear magnetic moment

$\boldsymbol{\mu} = \mu \mathbf{I}/I$

Interaction $$h_{\text{hfs}} = \frac{1}{c} \frac{\boldsymbol{\mu} \cdot (\mathbf{r} \times \boldsymbol{\alpha})}{r^3} F(r)$$



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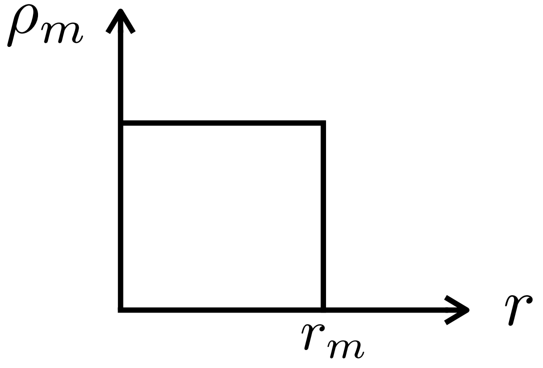

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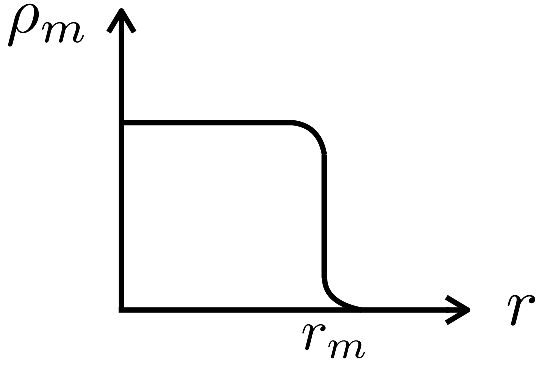


Standard ways to model *F(r)*, until recently

Hyperfine splitting quantified by hyperfine constant *A*

$$A = A_0(1 + \epsilon) + \delta A^{\text{QED}}$$

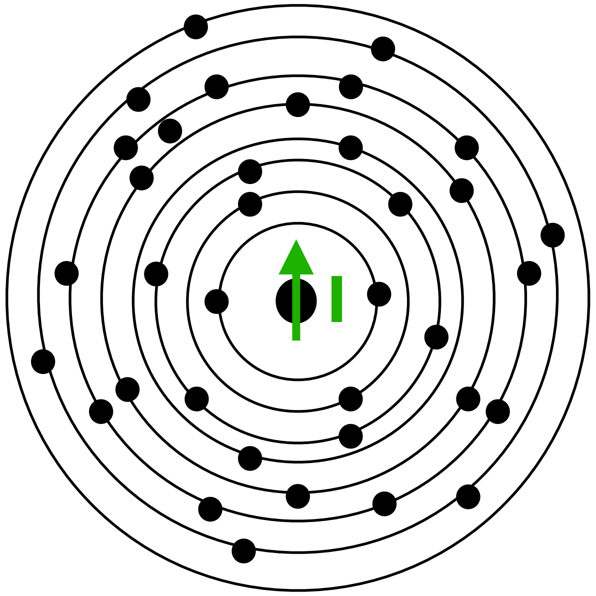
Modelling the hyperfine structure

nuclear magnetic moment

$\mu = \mu\mathbf{I}/I$

Interaction $$h_{\text{hfs}} = \frac{1}{c}\frac{\boldsymbol{\mu}\cdot(\mathbf{r}\times\boldsymbol{\alpha})}{r^3}F(r)$$

describes radial distribution of μ; point-nucleus, $F(r) = 1$



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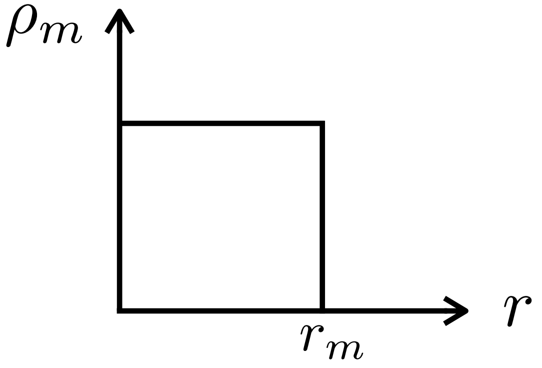

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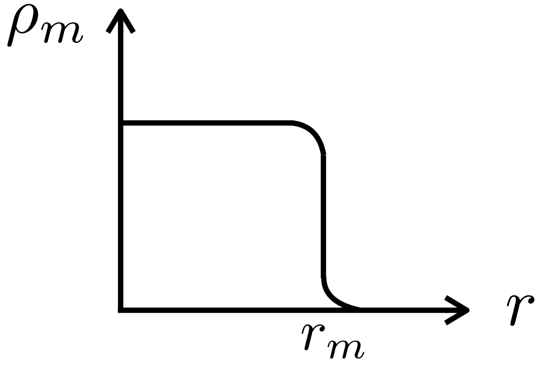

Standard ways to model *F(r)*, until recently

Hyperfine splitting quantified by hyperfine constant *A*

$$A = A_0(1+\epsilon) + \delta A^{\text{QED}}$$

Modelling the hyperfine structure

nuclear magnetic moment

$$\boldsymbol{\mu} = \mu \mathbf{I}/I$$

Interaction

$$h_{\mathrm{hfs}} = \frac{1}{c}\frac{\boldsymbol{\mu}\cdot(\mathbf{r}\times\boldsymbol{\alpha})}{r^3}F(r)$$

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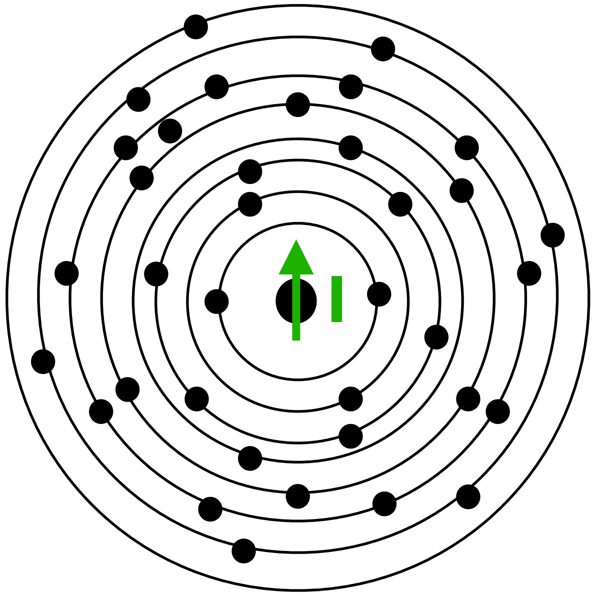

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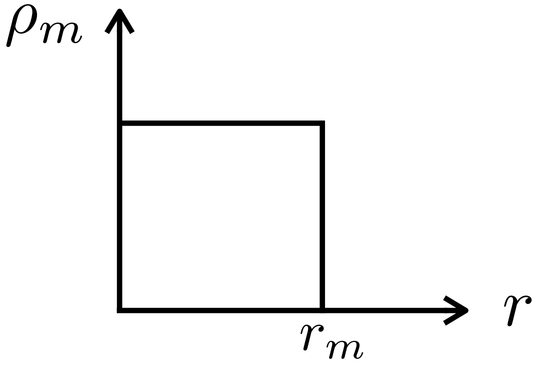

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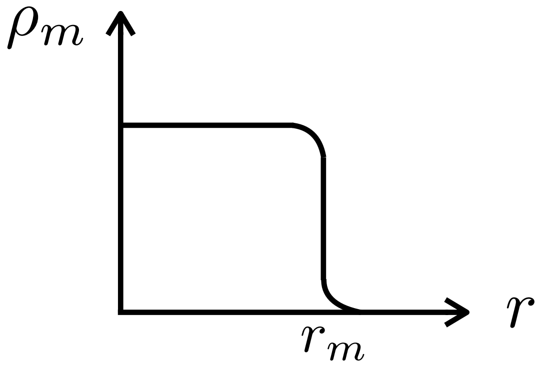

← Standard ways to model *F(r)*, until recently

Hyperfine splitting quantified by hyperfine constant *A*

$$A = A_0(1+\epsilon) + \delta A^{\mathrm{QED}}$$

↑

Many-body result,
finite nuclear charge effect included

Modelling the hyperfine structure

nuclear magnetic moment

$\boldsymbol{\mu} = \mu \mathbf{I}/I$

Interaction $$h_{\mathrm{hfs}} = \frac{1}{c}\frac{\boldsymbol{\mu}\cdot(\mathbf{r}\times\boldsymbol{\alpha})}{r^3}F(r)$$

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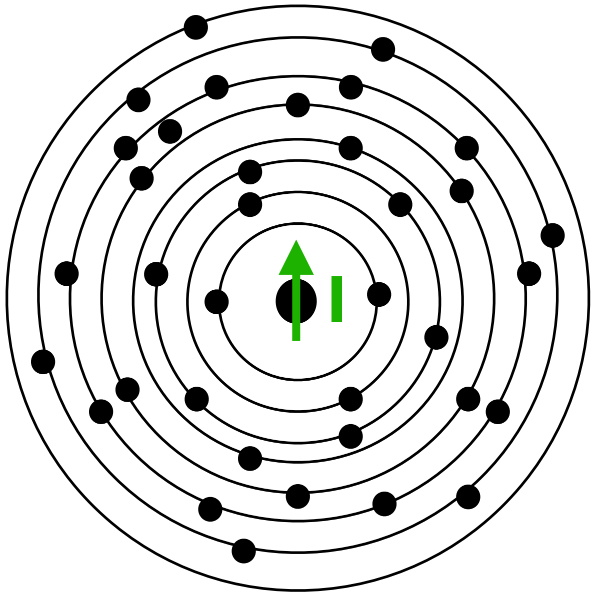

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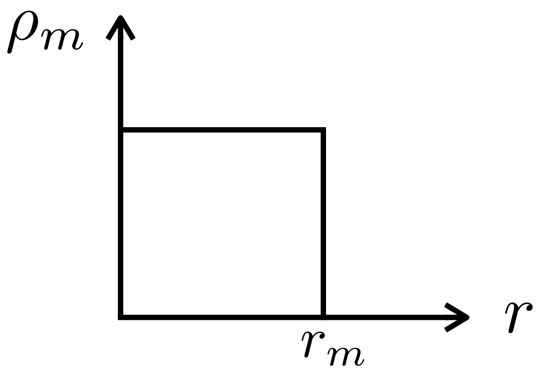
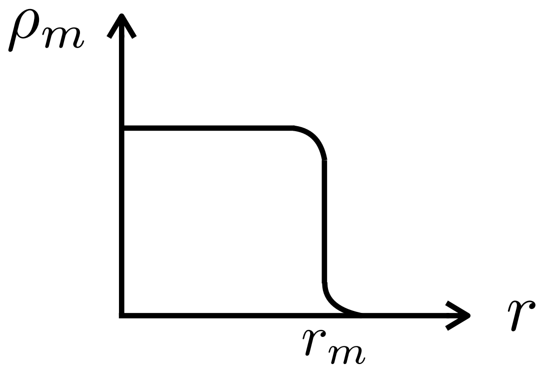


Fermi distribution



← Standard ways to model *F(r)*, until recently

Hyperfine splitting quantified by hyperfine constant *A*

$$A = A_0(1+\epsilon) + \delta A^{\mathrm{QED}}$$

Bohr-Weisskopf (BW) effect or *magnetic hyperfine anomaly* — finite nuclear magnetization contribution

Modelling the hyperfine structure

nuclear magnetic moment

$\boldsymbol{\mu} = \mu \mathbf{I}/I$

Interaction $$h_{\mathrm{hfs}} = \frac{1}{c}\frac{\boldsymbol{\mu}\cdot(\mathbf{r}\times\boldsymbol{\alpha})}{r^3}F(r)$$

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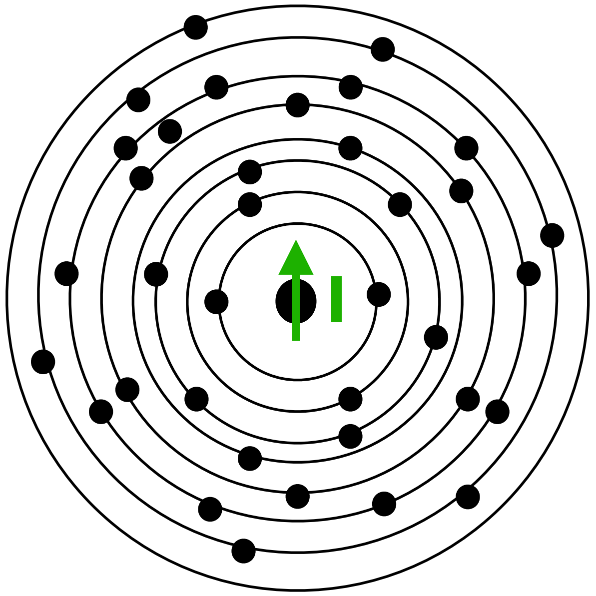

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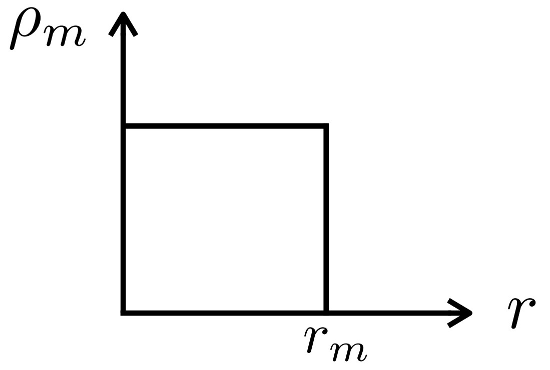

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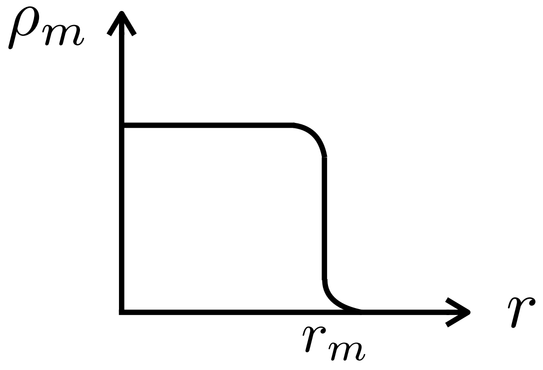

← Standard ways to model *F(r)*, until recently

Hyperfine splitting quantified by hyperfine constant *A*

$$A = A_0(1+\epsilon) + \delta A^{\mathrm{QED}}$$

Quantum electrodynamics radiative correction

Modelling the hyperfine structure

nuclear magnetic moment

$\mu = \mu \mathbf{I}/I$

Interaction
$$h_{\mathrm{hfs}} = \frac{1}{c}\frac{\boldsymbol{\mu}\cdot(\mathbf{r}\times\boldsymbol{\alpha})}{r^3}F(r)$$

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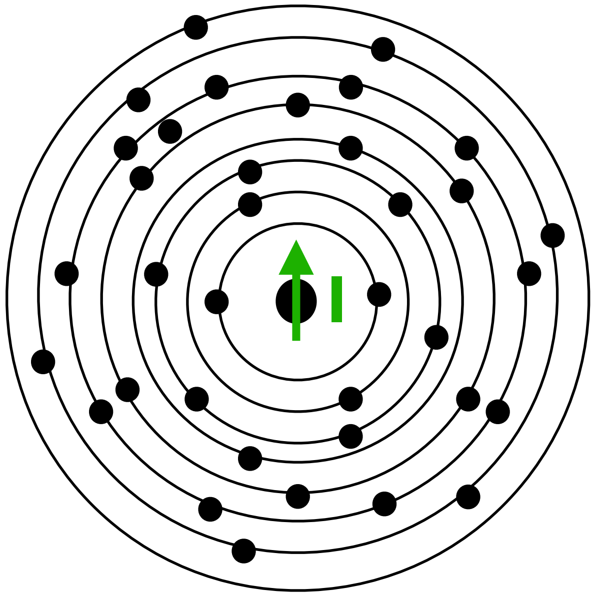

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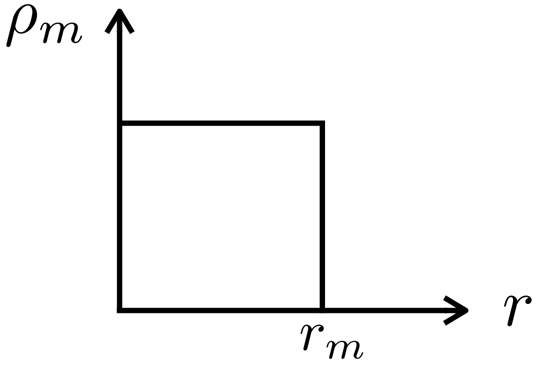

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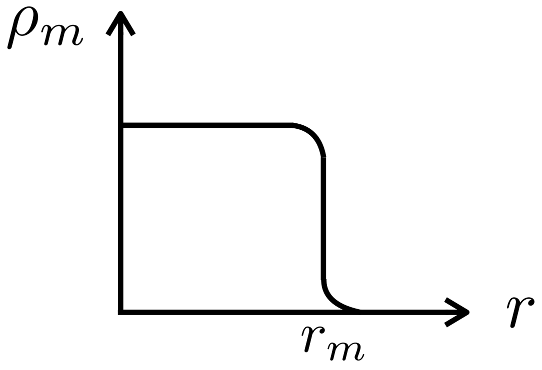

← Standard ways to model *F(r)*, until recently

Hyperfine splitting quantified by hyperfine constant *A*

$$A = A_0(1+\epsilon) + \delta A^{\mathrm{QED}}$$

contains factor μ

Hyperfine comparisons

$$A^{\mathrm{expt}} \;\longleftrightarrow\; A_0(1+\epsilon) + \delta A^{\mathrm{QED}}$$

Provides test of atomic many-body theory in the nuclear vicinity *only if* the following properties/contributions are known well (< 0.1% uncertainty):

- ➤ QED radiative corrections δA^{QED}
- ➤ Nuclear magnetic moments μ
- ➤ Bohr-Weisskopf effect ϵ

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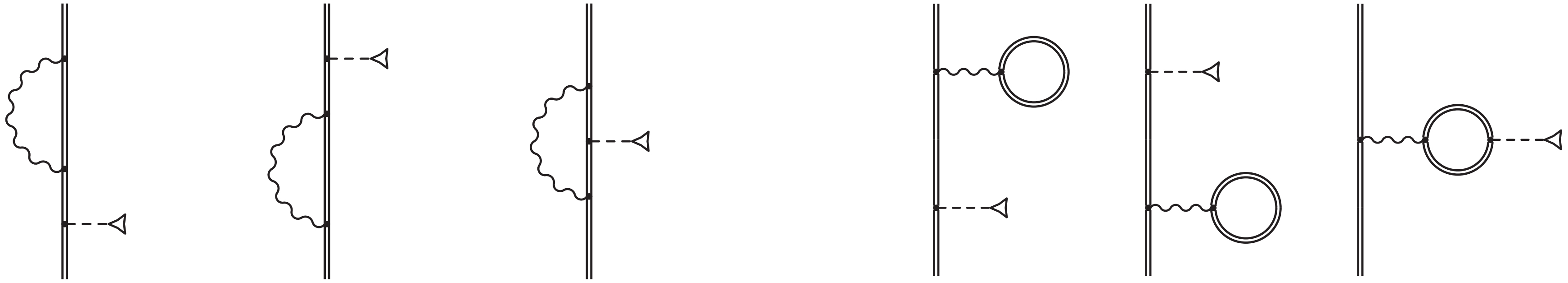


self energy

vacuum polarization

Cs	Ba+	Fr	Ra+	Reference
-0.38(6)	-0.37(4)	-0.60(1)	-0.55(8)	Ginges, Volotka, Fritzsche, PRA (2017)
-0.42		-0.6		Sapirstein and Cheng, PRA (2003)

QED corrections to g.s. hyperfine constants (%)

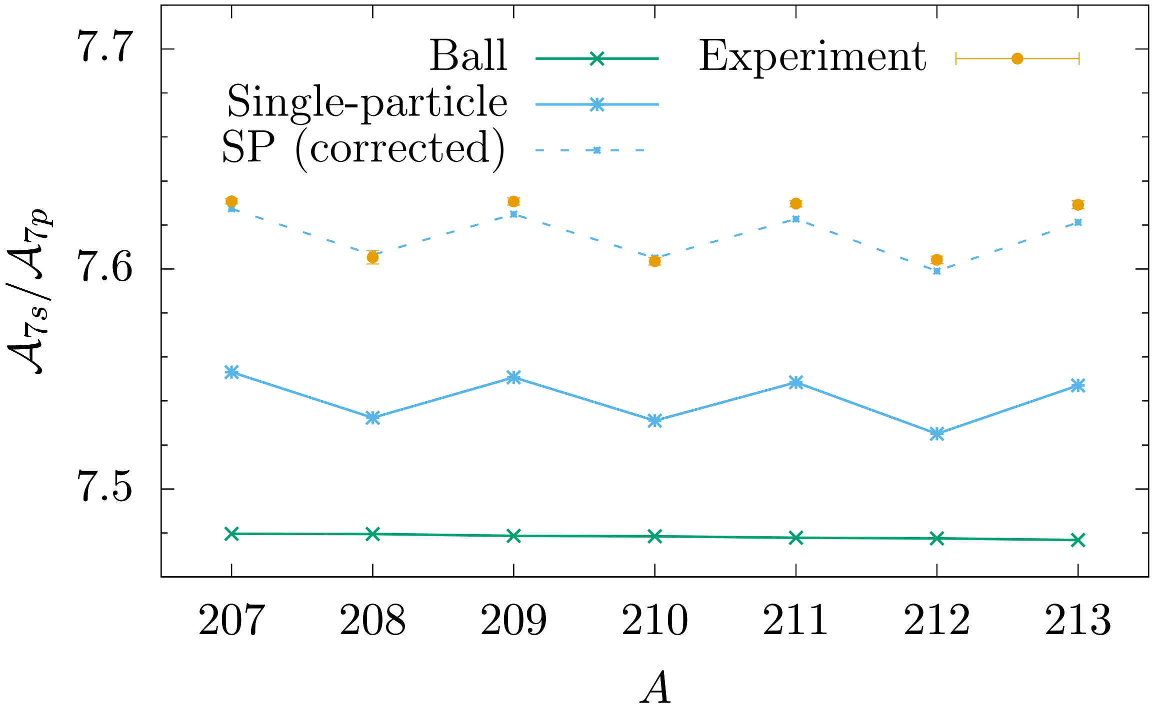
Hyperfine comparisons

$$A^{\rm expt} \;\longleftrightarrow\; A_0(1+\epsilon)+\delta A^{\rm QED}$$

Provides test of atomic many-body theory in the nuclear vicinity *only if* the following properties/contributions are known well (< 0.1% uncertainty):

- ➤ QED radiative corrections $\delta A^{\rm QED}$
- ➤ Nuclear magnetic moments μ
- ➤ Bohr-Weisskopf effect ϵ

A(*7s*)/*A*(*7p*$_{1/2}$) vs atomic mass for francium



Known with 1-2% uncertainty for Fr isotopes. We can do better!

$$A^{\rm expt} \;\longleftrightarrow\; A^{\rm th}(\mu_{\rm th})(\mu/\mu_{\rm th})$$

Found μ with 0.5% uncertainty

Roberts and Ginges, PRL (2020)

Hyperfine comparisons

$$A^{\mathrm{expt}} \;\longleftrightarrow\; A_0(1+\epsilon) + \delta A^{\mathrm{QED}}$$

Provides test of atomic many-body theory in the nuclear vicinity *only if* the following properties/contributions are known well (< 0.1% uncertainty):

- ➤ QED radiative corrections δA^{QED}
- ➤ Nuclear magnetic moments μ
- ➤ Bohr-Weisskopf effect ϵ

SP model: $F(r) = \left(\frac{r}{r_m}\right)^3 \left[1 - 3\ln\left(\frac{r}{r_m}\right)\frac{\mu_N}{\mu}\left(-\frac{2I-1}{8(I+1)}g_S + \frac{2I-1}{2}g_L\right)\right]$ for *I*=*L*+*1/2*

BW corrections (%) to hyperfine constants

nuclear model	^{133}Cs	^{135}Ba$^+$	^{211}Fr	^{225}Ra$^+$
ball	-0.71	-0.74	-2.7	-2.8
single-particle (SP)	-0.21	-1.0	-1.3	-2.8
SP (WS, spin-orbit)	-0.19(14)	-1.3(4)	-1.4(5)	-4.3(13)

Difference **0.5%** **1.3%**

Expression for F(r):
Volotka *et al.,* PRA (2008)

Ginges, Volotka, Fritzsche , PRA (2017)

Total hyperfine intervals

Calculations of hyperfine intervals and comparison with experiment. Units: MHz

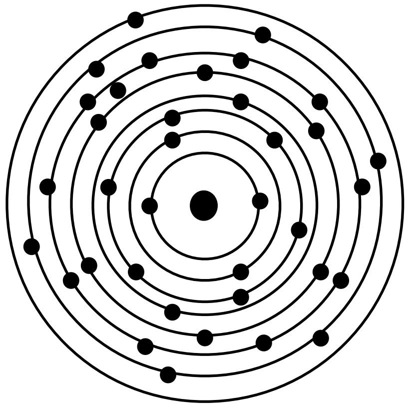
	^{133}Cs	^{135}Ba^{+}	^{211}Fr	^{225}Ra^{+}
Many-body	9229.5	7286.8	45374	-29113
BW	-17.0(131)	-91.8(275)	-641(244)	1267(380)
QED	-35.1(58)	-27.1(30)	-273(56)	159(23)
Total theory	9177.4	7167.9	44460	-27687
Experiment	9192.6	7183.3	43570	-27731
Difference	-15.2	-15.4	890	44
Difference (%)	-0.17(16)	-0.21(38)	2.0(6)(20)	-0.2(14)

Ginges, Volotka, Fritzsche, PRA (2017)

Many-body methods — all-orders correlation potential: Dzuba, Flambaum, Sushkov (1989)

Extraction of Ra^{+} BW effect, -4.7%: Skripnikov, J. Chem. Phys. (2020)

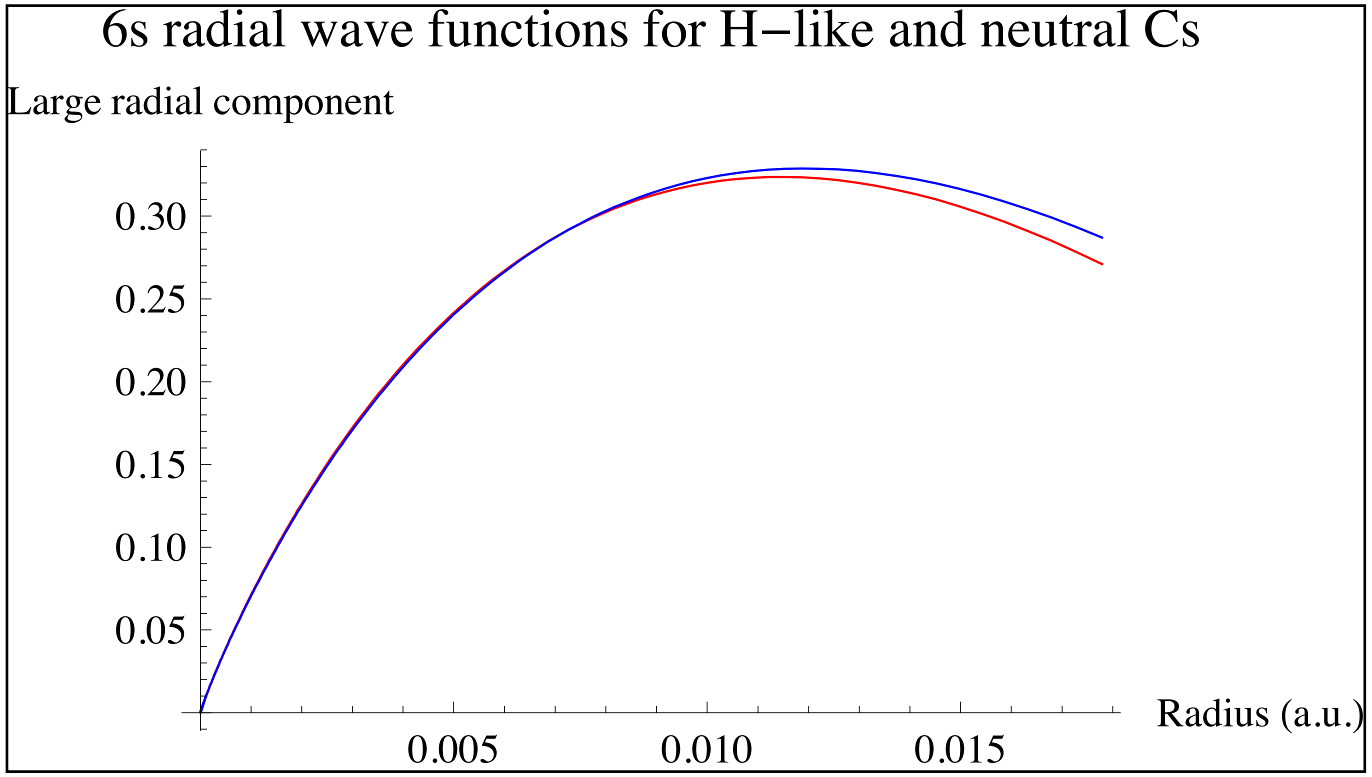
BW effect: properties



Relative BW correction $$\epsilon = \frac{\int_0^{r_m} dr f(r) g(r) [F(r) - 1]/r^2}{\int_0^{\infty} dr f(r) g(r)/r^2}$$

- In the nuclear region, the electrons see the unscreened Coulomb field of the nucleus
- Since the binding energies $\varepsilon \ll V(r)$, wave functions with the same angular dependence are proportional.

$$\begin{bmatrix} V(r) - \varepsilon & c(\kappa/r - \partial_r) \\ c(\kappa/r + \partial_r) & V(r) - \varepsilon - 2c^2 \end{bmatrix} \begin{bmatrix} f_{n\kappa} \\ g_{n\kappa} \end{bmatrix} = 0$$



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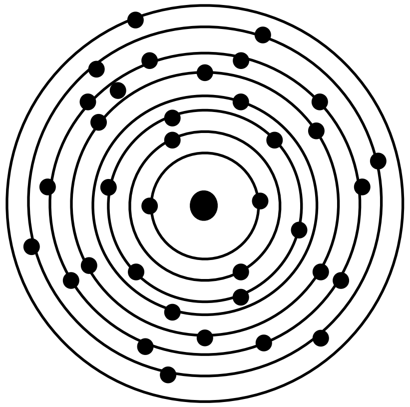

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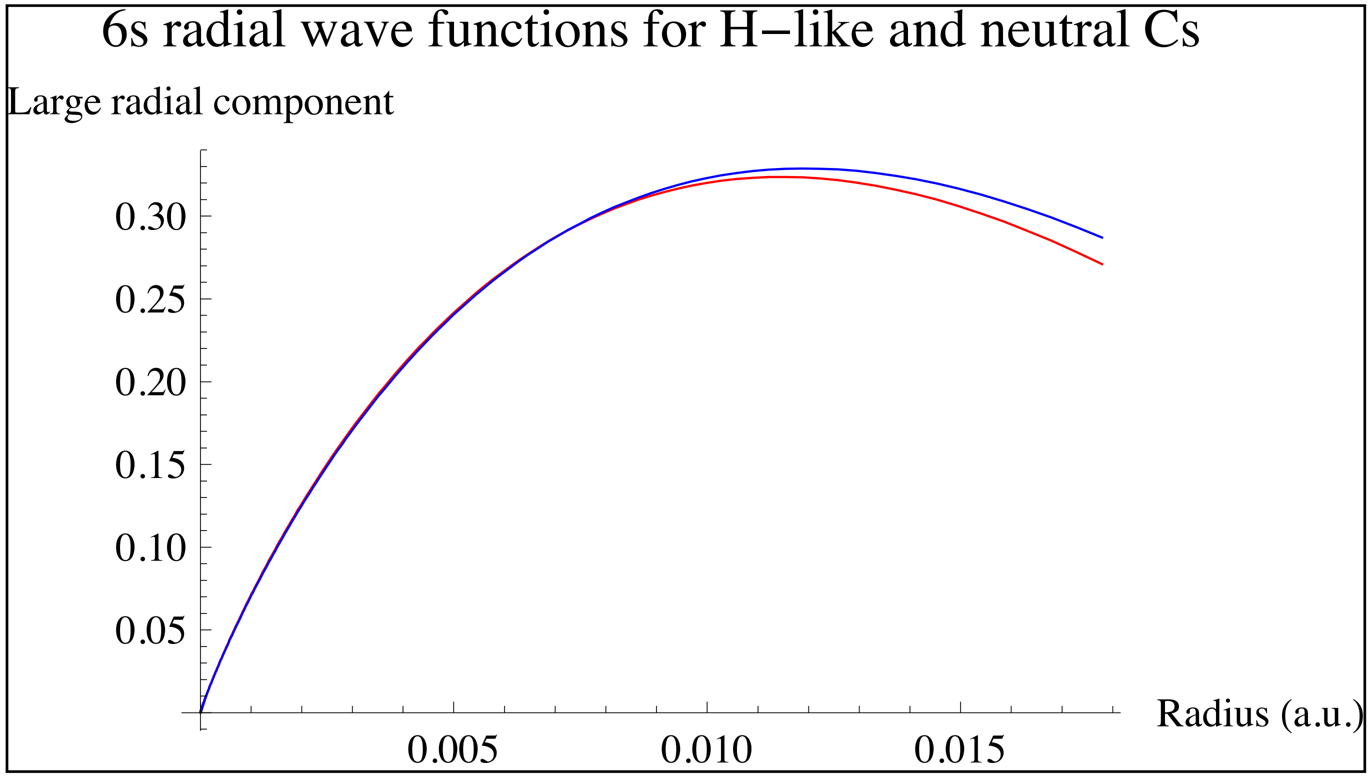
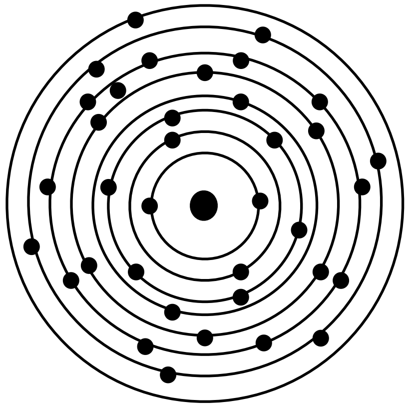


BW effect is independent of principal quantum number!

$$\Rightarrow \quad \epsilon_{n\kappa} = \epsilon_{n'\kappa}$$

BW effect: properties



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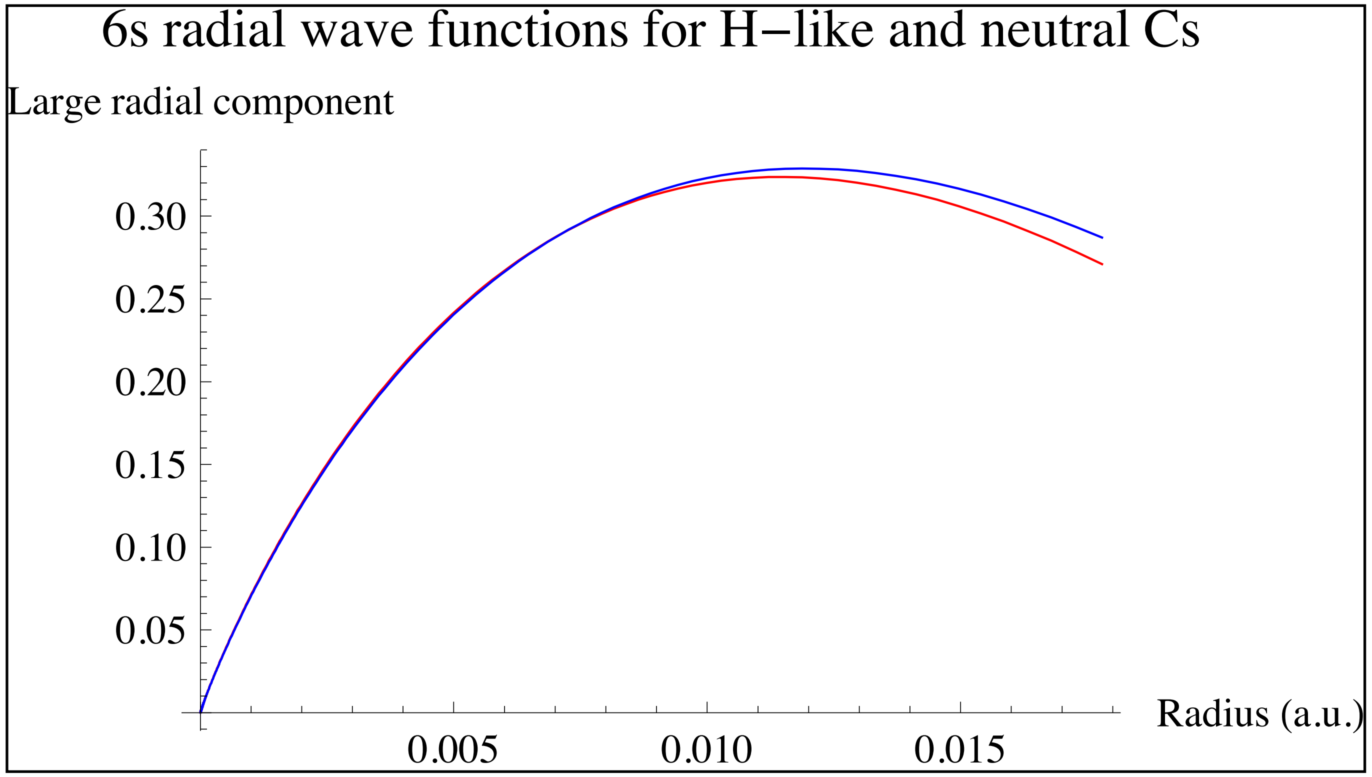


6s radial wave functions for H−like and neutral Cs

BW effect is independent of principal quantum number!

$$\Rightarrow \quad \epsilon_{n\kappa} = \epsilon_{n'\kappa}$$

Also, in the nuclear region, for heavy systems:

$$f_{s_{1/2}} \propto g_{p_{1/2}} \quad , \quad g_{s_{1/2}} \propto f_{p_{1/2}}$$

BW effects in atoms related to BW matrix element for *1s* state of H-like ion

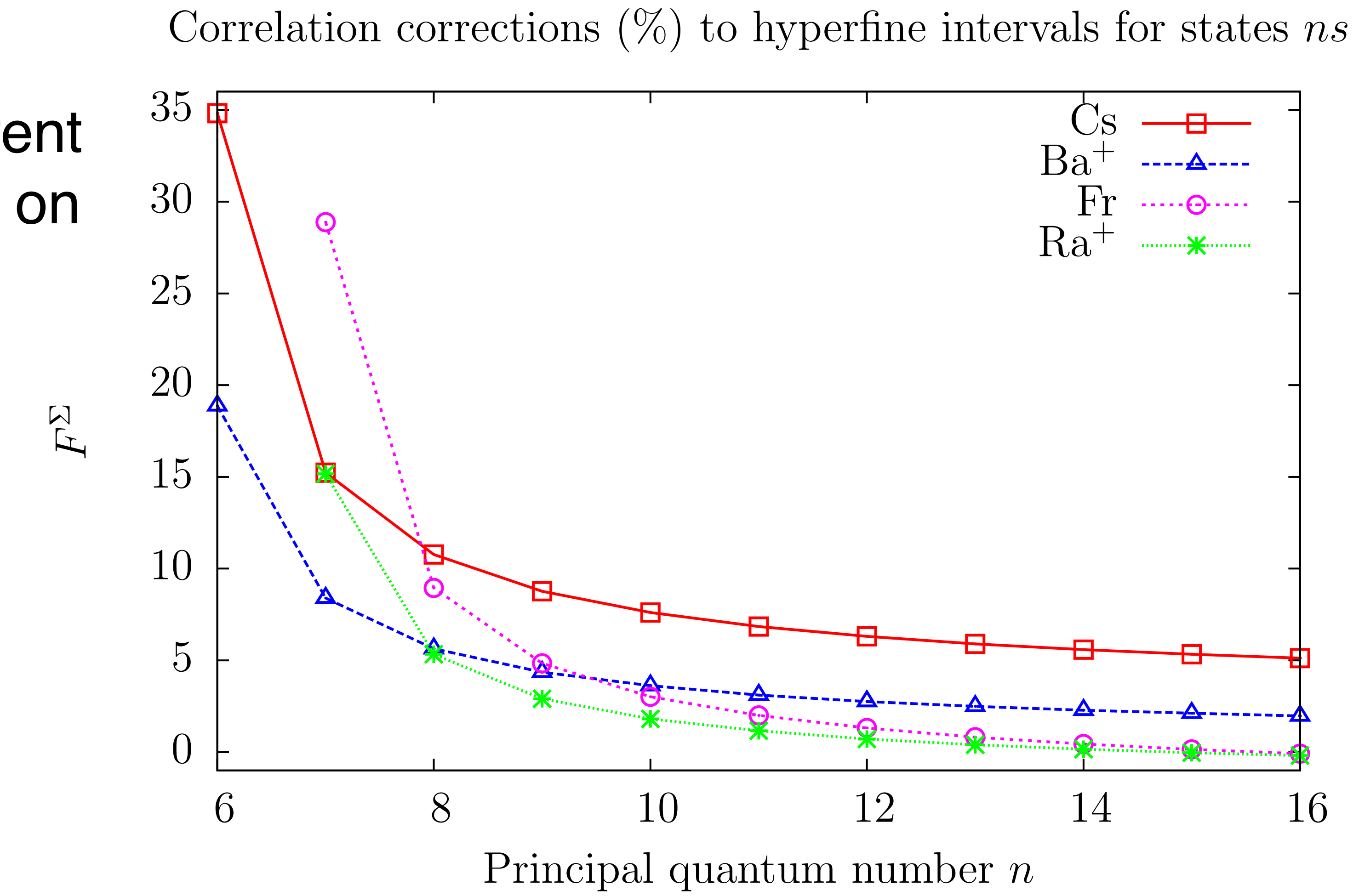
Shabaev et al., PRL (2001)
Skripnikov, J. Chem. Phys. (2020)
Roberts and Ginges, PRA (2022)

BW effect: ratio method

By taking a ratio of two states with different principal quantum number, dependence on BW effect may be removed!

$$A^{\mathrm{th}}_{n\kappa} = A_{0,n\kappa}\left(A^{\mathrm{exp}}_{n'\kappa}/A_{0,n'\kappa}\right)$$

May be used to make high-precision predictions of the hyperfine constants!



Ratio method: Ginges and Volotka, PRA (2018)

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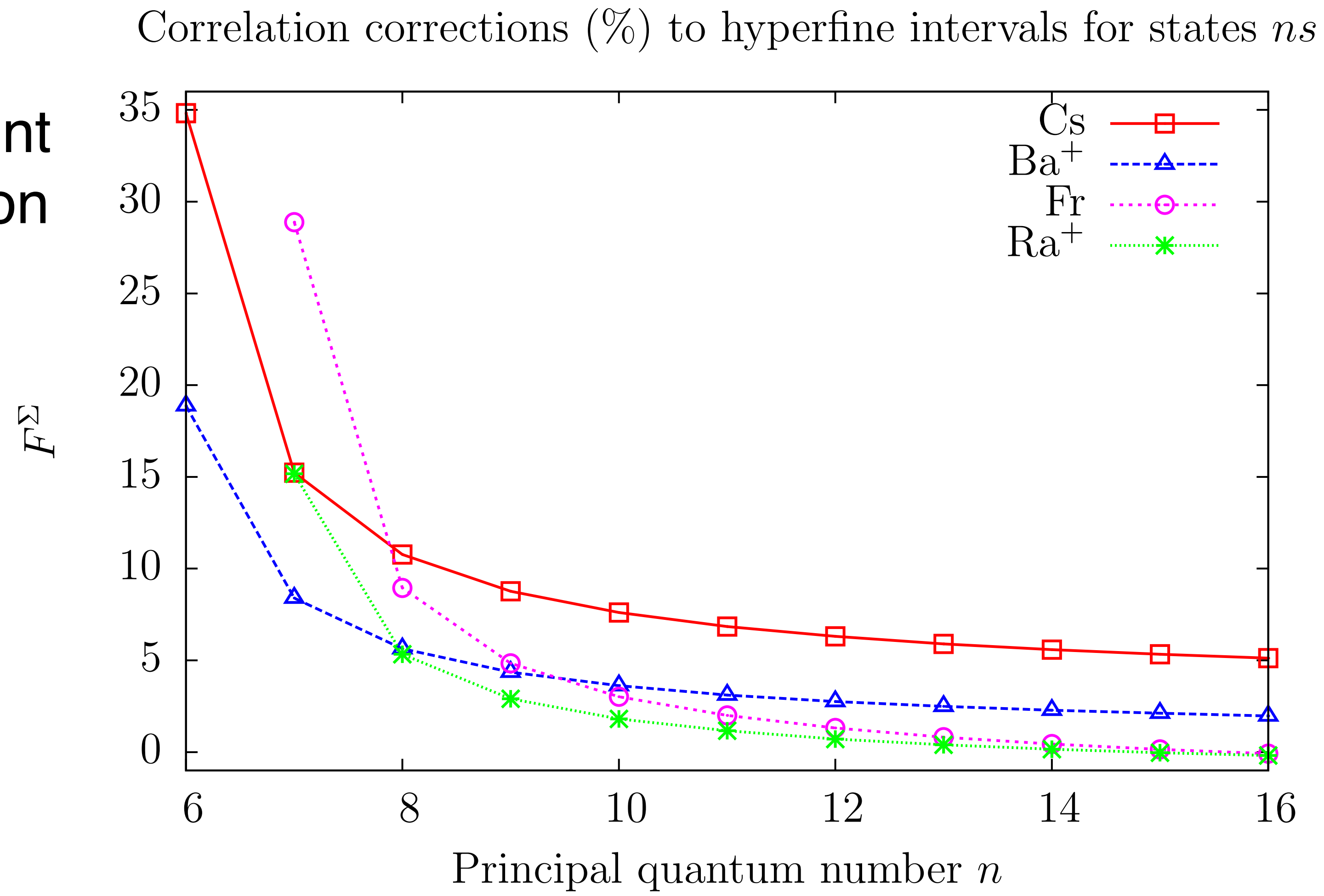

Correlation corrections (%) to hyperfine intervals for states ns

	A_{hfs} (MHz)			
	Experiment		Theory	
State	This work	Prior expt.	Ref. [37]	Ref. [16]
12s	26.318 (15)	26.31 (10) [24]	26.28	26.30 (2)
13s	18.431 (10)	18.40 (11) [25]		18.42 (1)

from Quirk et al., PRA (2022)

Ref. [16] : Grunefeld, Roberts, Ginges, PRA (2019)

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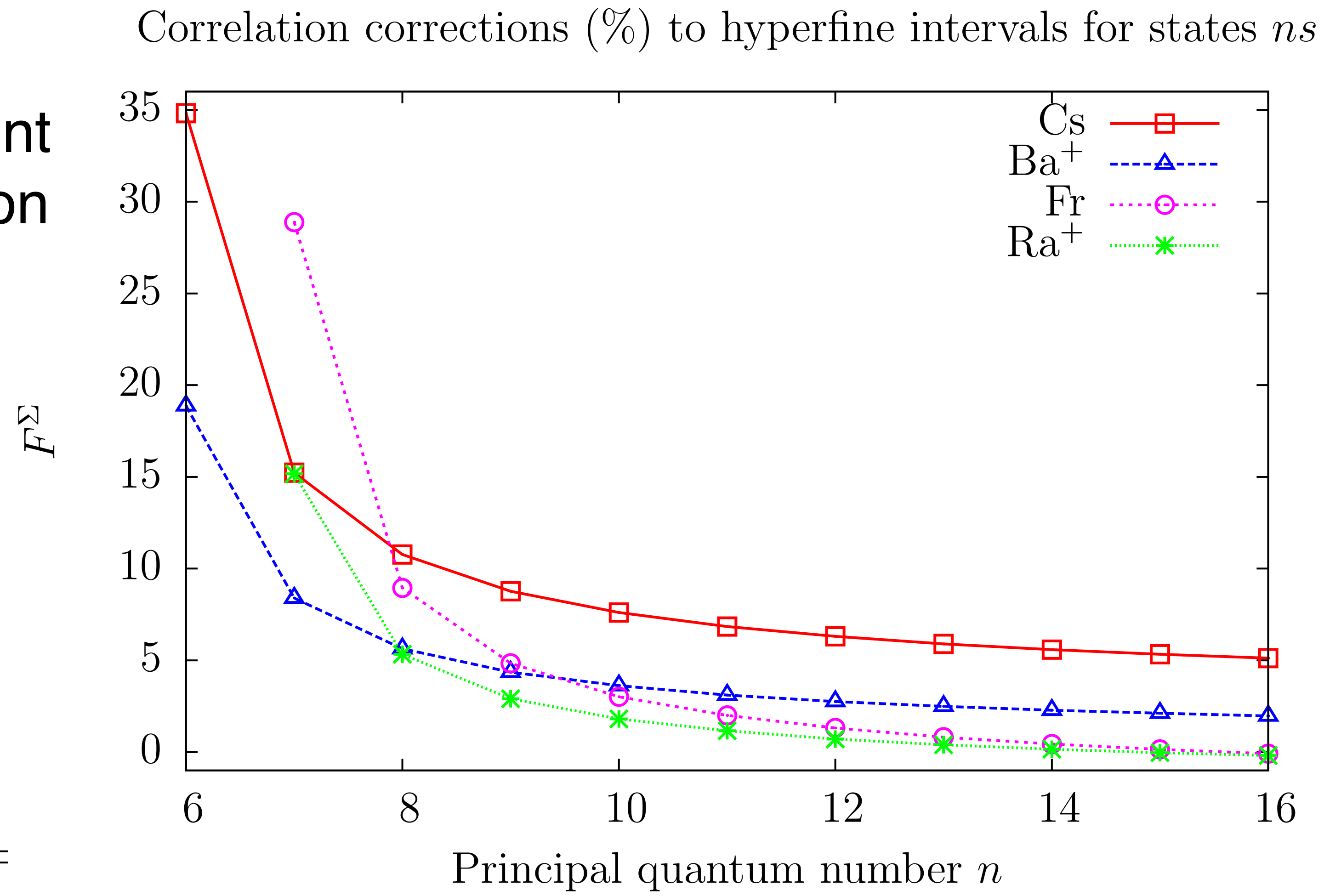

A_{hfs} (MHz) for $8p_{1/2}$

A	Source
Experiment	
42.97 (10)	Tai *et al.*, 1973 [40]
42.92 (25)	Cataliotti *et al.*, 1996 [48]
42.95 (25)	Liu & Baird, 2000 [49]
42.933 (8)	This work
Theory	
42.43	Safronova *et al.*, 1999 [46]
42.32	Tang *et al.*, 2019 [47]
42.95 (9)	fit method, Grunefeld *et al.*, 2019 [34]
42.93 (7)	ratio method, Grunefeld *et al.*, 2019 [34]

from Quirk et al., arxiv (2022)

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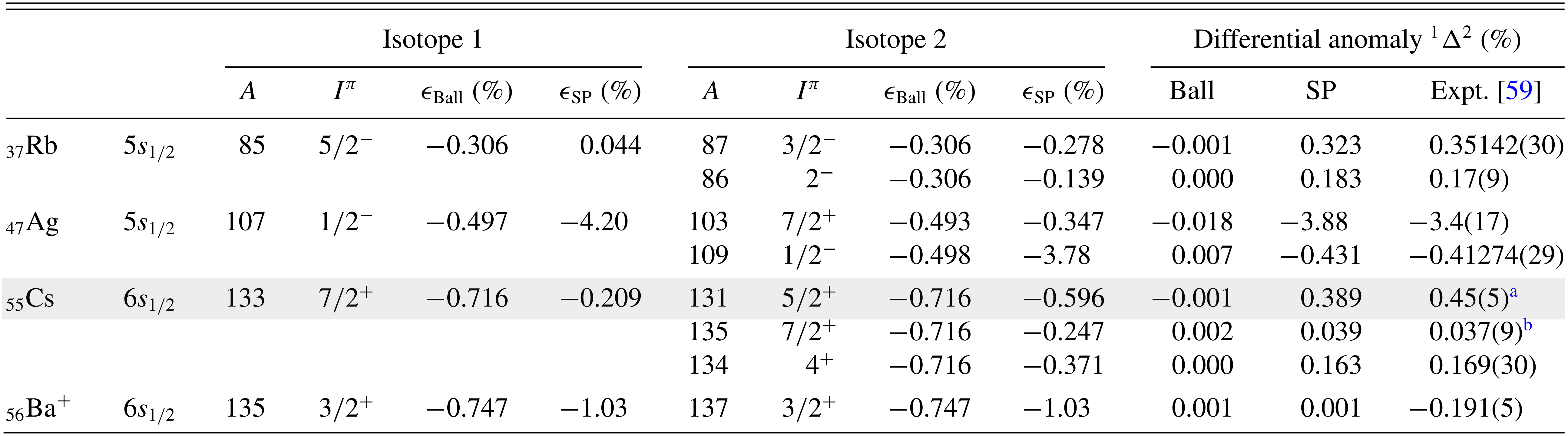
BW effect: differential anomaly

Ratio of hyperfine constants of different isotopes of same element:

$$\mathcal{A}^{(1)}/\mathcal{A}^{(2)} = g_I^{(1)}/g_I^{(2)}(1 +^1 \Delta^2)$$

Typically for nuclei of different spin: $^1\Delta^2 \approx \epsilon^{(1)} - \epsilon^{(2)}$

→ Gives *difference* in BW effect for different isotopes



		Isotope 1				Isotope 2				Differential anomaly $^1\Delta^2$ (%)		
		A	I^π	$\epsilon_{\rm Ball}$ (%)	$\epsilon_{\rm SP}$ (%)	A	I^π	$\epsilon_{\rm Ball}$ (%)	$\epsilon_{\rm SP}$ (%)	Ball	SP	Expt. [59]
$_{37}$Rb	$5s_{1/2}$	85	$5/2^-$	−0.306	0.044	87	$3/2^-$	−0.306	−0.278	−0.001	0.323	0.35142(30)
						86	2^-	−0.306	−0.139	0.000	0.183	0.17(9)
$_{47}$Ag	$5s_{1/2}$	107	$1/2^-$	−0.497	−4.20	103	$7/2^+$	−0.493	−0.347	−0.018	−3.88	−3.4(17)
						109	$1/2^-$	−0.498	−3.78	0.007	−0.431	−0.41274(29)
$_{55}$Cs	$6s_{1/2}$	133	$7/2^+$	−0.716	−0.209	131	$5/2^+$	−0.716	−0.596	−0.001	0.389	0.45(5)[a]
						135	$7/2^+$	−0.716	−0.247	0.002	0.039	0.037(9)[b]
						134	4^+	−0.716	−0.371	0.000	0.163	0.169(30)
$_{56}$Ba$^+$	$6s_{1/2}$	135	$3/2^+$	−0.747	−1.03	137	$3/2^+$	−0.747	−1.03	0.001	0.001	−0.191(5)

Roberts and Ginges, PRA (2021)

Expt. data from: Persson, At. Data Nucl. Data Tables (2013)

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Collaboration with M. Kowalska (CERN-ISOLDE) and J.Dobacewski (U. York) on radioactive isotopes

Roberts and Ginges, PRA (2021)

Expt. data from: Persson, At. Data Nucl. Data Tables (2013)

BW effect: from H-like ions and muonic atoms

BW effect from H-like ion experiments:

$$\mathcal{A}_{\rm expt}^{\rm 1s} = \mathcal{A}_0^{1s}(1+\epsilon^{1s}) + \delta\mathcal{A}_{\rm QED}^{1s}$$

BW effect with $\sim 1\%$ uncertainty from
H-like ^{203,205}Tl, ^{207}Pb, ^{209}Bi

H-like Tl experiments: Beiersdorfer et al., PRA (2001)

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H-like ion result may be used to find
BW effect in many-electron atoms!

$$\mathcal{A} = \mathcal{A}_0(1 + \underset{\substack{\uparrow \\ \text{electronic} \\ \text{screening factor}}}{x_{\rm scr}}\,\epsilon^{1s}) + \delta\mathcal{A}_{\rm QED}$$

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x_{scr} *independent of the nuclear model!*

s states: $x_{\mathrm{scr}} \approx 1$, negligible uncertainty

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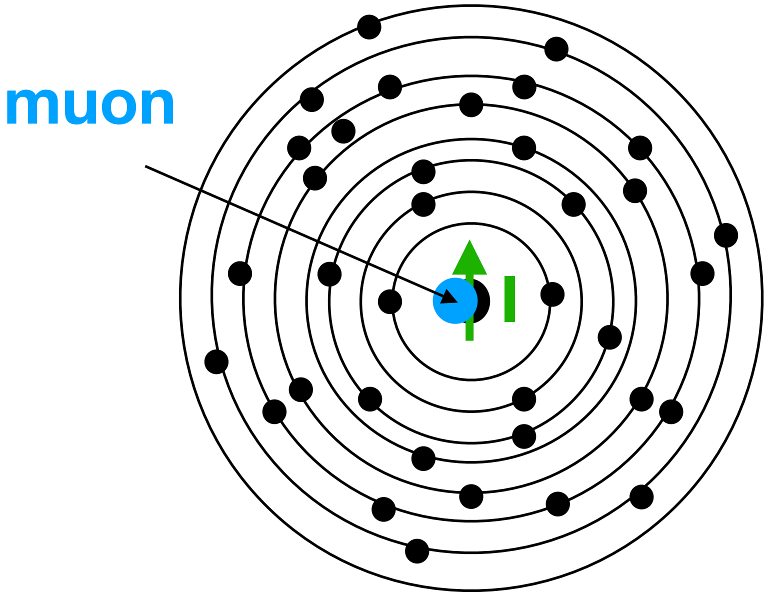
G. Sanamyan, next talk



Sanamyan, Roberts, Ginges, arxiv (2022)

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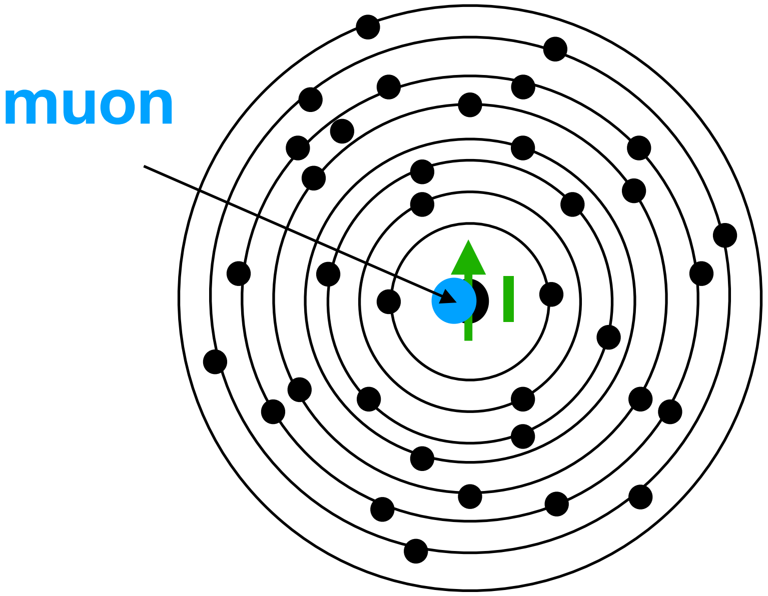

SP model: -0.21%

SP(WS) model: -0.19(14)%

“ball”/fermi model: -0.7%

Empirical result for ^{133}Cs s states, ε =….

Sanamyan, Roberts, Ginges, arxiv (2022)

Summary

Accurate modelling of the finite magnetization distribution in atomic nuclei is important for

- ➤ Hyperfine comparisons
  - Tests of atomic wave functions in the nuclear region
  - Reducing APV theory uncertainty to 0.1%
- ➤ Nuclear structure theory
- ➤ Determination of nuclear moments
- ➤ Probing the neutron distribution
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New! Postdoc position opening in our group soon
New! PhD stipend available