

# On the hyperfine anomaly and atomic parity violation

**Jacinda Ginges**



**THE UNIVERSITY  
OF QUEENSLAND**  
AUSTRALIA



**Australian Government**  

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**Australian Research Council**



A large, leafy tree stands in the center of a grassy field. In the background, a large, multi-story building with many windows is visible. A group of people is sitting on the grass under the tree's shade.

# Students, collaborators

Ben Roberts (DECRA fellow)

Swaantje Grunefeld (postdoc)

Perry Ranclaud (student)

George Sanamyan (student)

Andrey Volotka (St Petersburg)

Stephan Fritzsche (Jena, Germany)

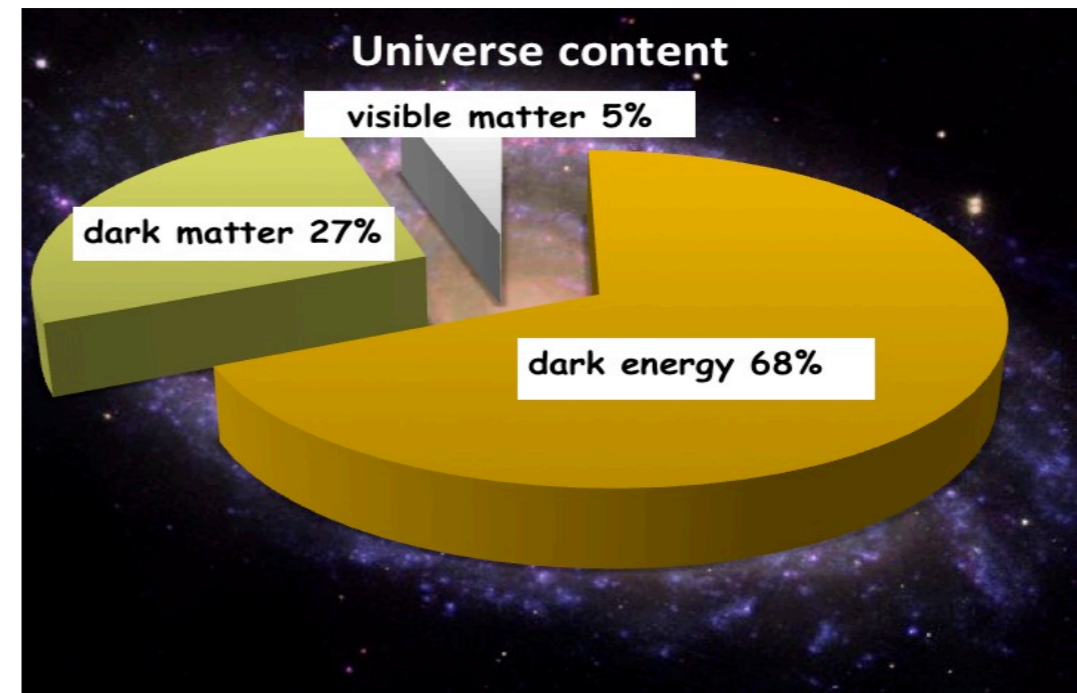
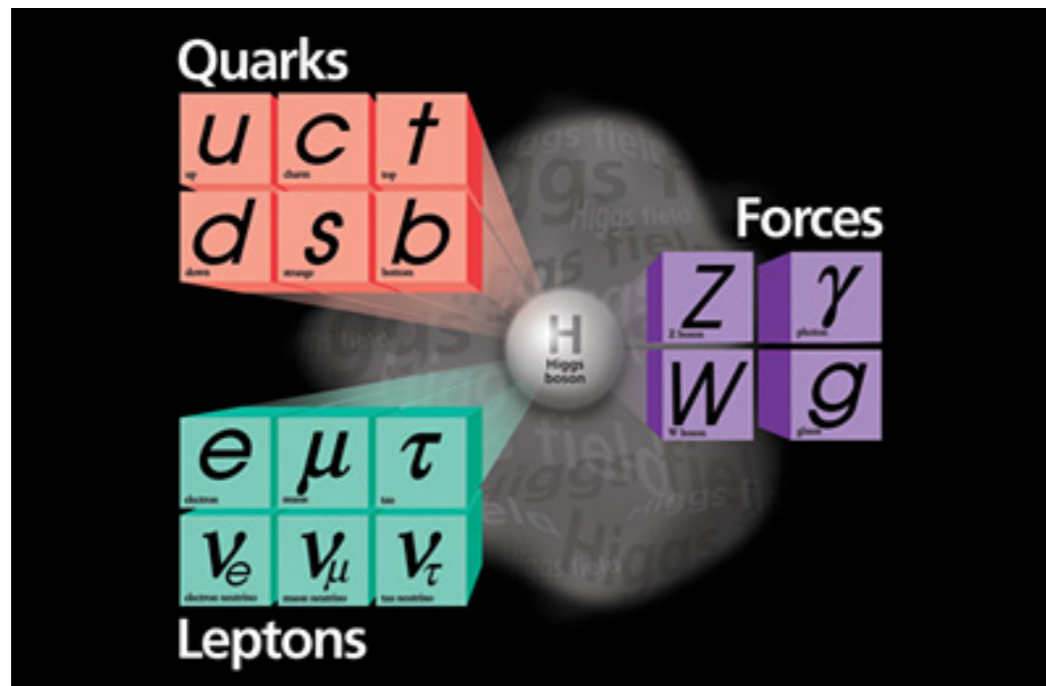
Magda Kowalska (CERN)

Jacek Dobaczewski (York)



# Searching for new physics

Standard model particles



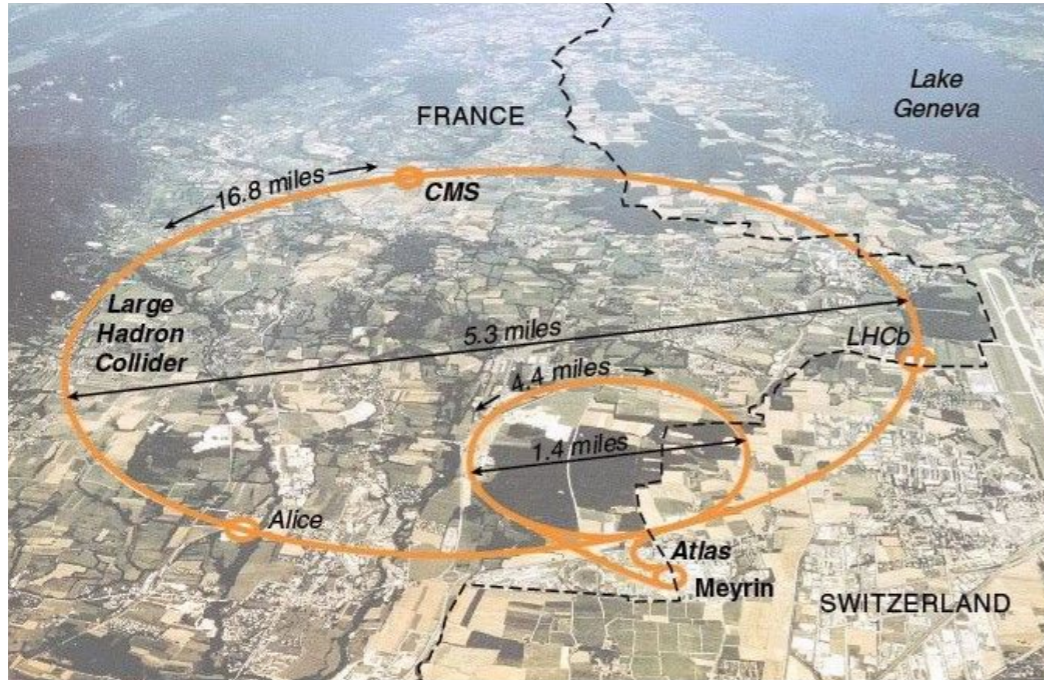
Dark matter?

Dark energy?

Matter-antimatter asymmetry of universe?

# High precision vs high energy

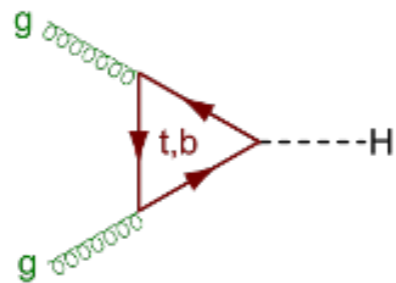
High energy



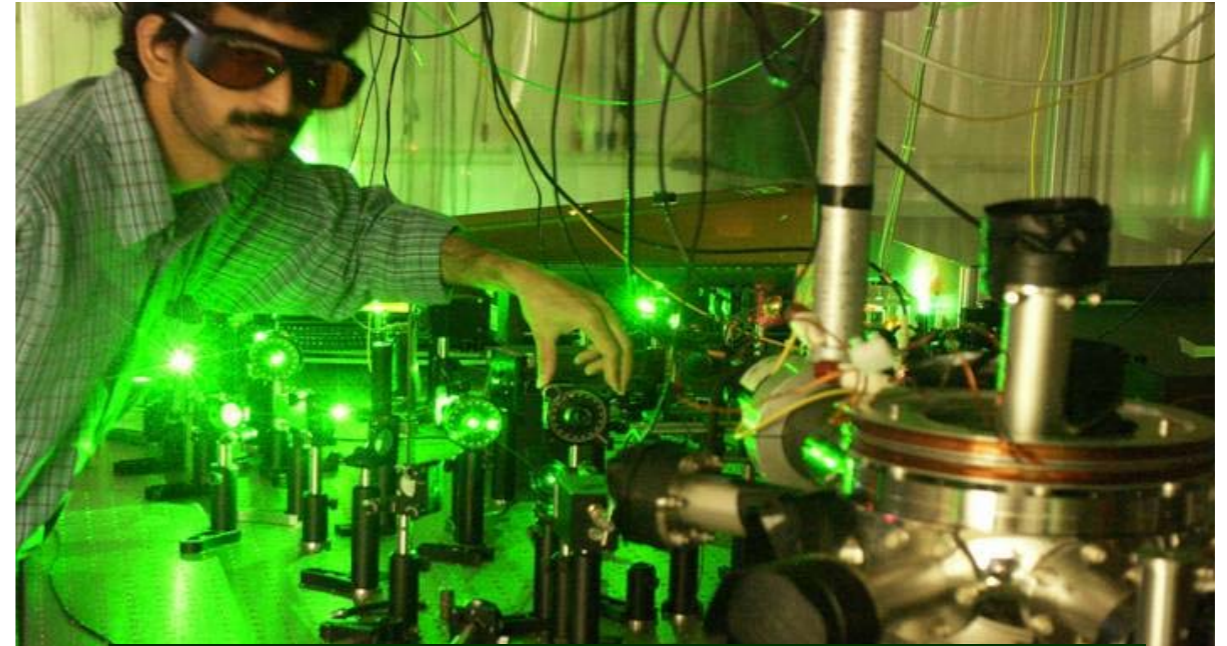
Large Hadron Collider, energies to 13 TeV

Produce particles *directly*

$$E = mc^2$$

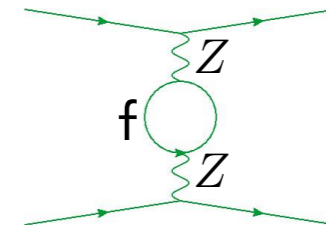
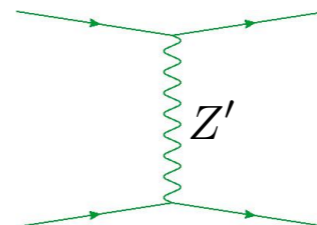


Low energy, high precision



Probe *virtual* processes, may reach  $\gg$  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



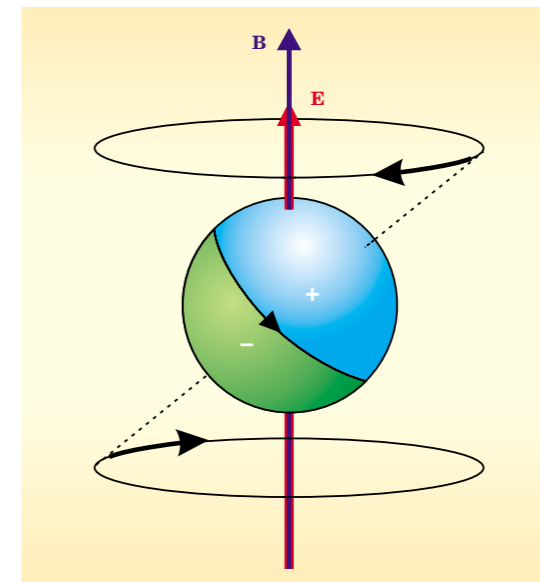
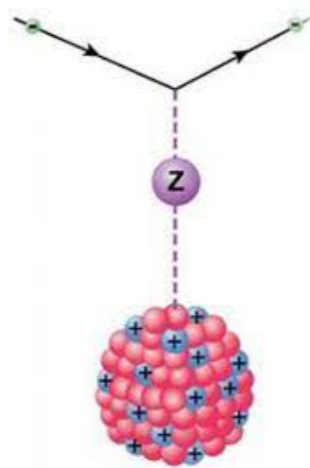
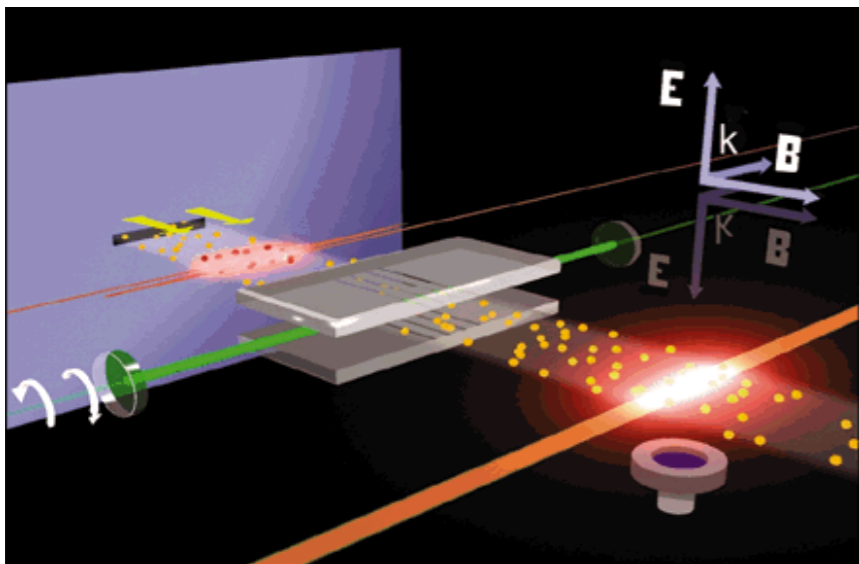
# The need for precision atomic theory

Extraction of fundamental parameters and comparison to SM

Atomic parity violation (APV)

Electric dipole moments (EDMs)

Parity- and time-reversal-violating



$$E_{PV} = \xi Q_W$$

from atomic structure theory

nuclear weak charge

$$d_{\text{atom}} = \zeta S + K d_e + \dots$$

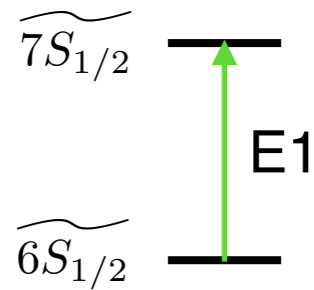
from atomic structure theory

nuclear Schiff moment

electron EDM

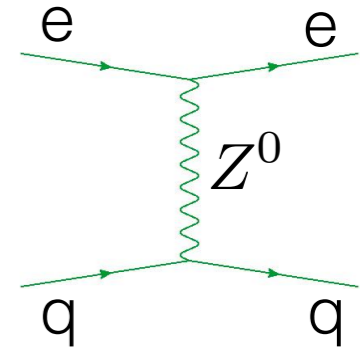


# Cs atomic parity violation

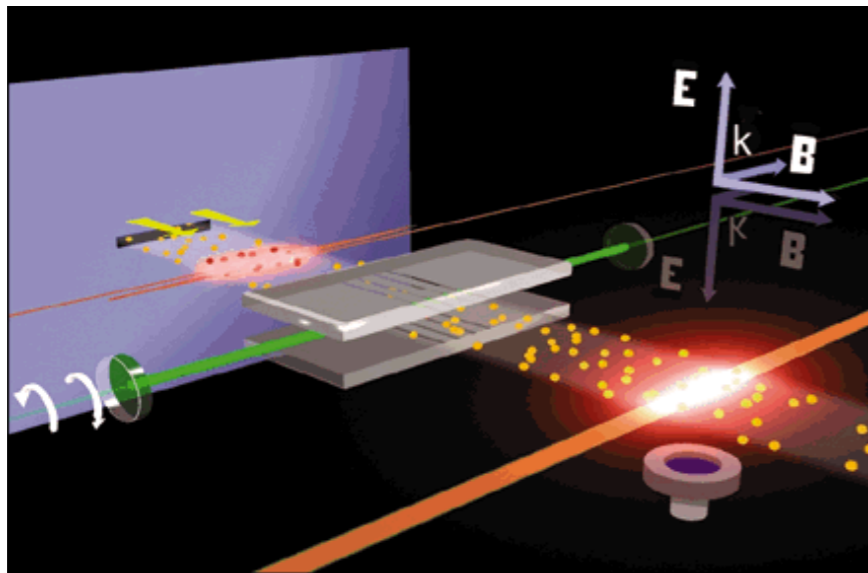


6S - 7S electric dipole transition amplitude  $E_{PV}$   
 Weak interaction mixes opposite-parity states,

$$\widetilde{S}_{1/2} \rightarrow S_{1/2} + \sum \zeta nP_{1/2}$$



Experiment, 0.35% uncertainty



Carl Wieman group

Wood et al., Science (1997)

Theory, 0.5% uncertainty

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

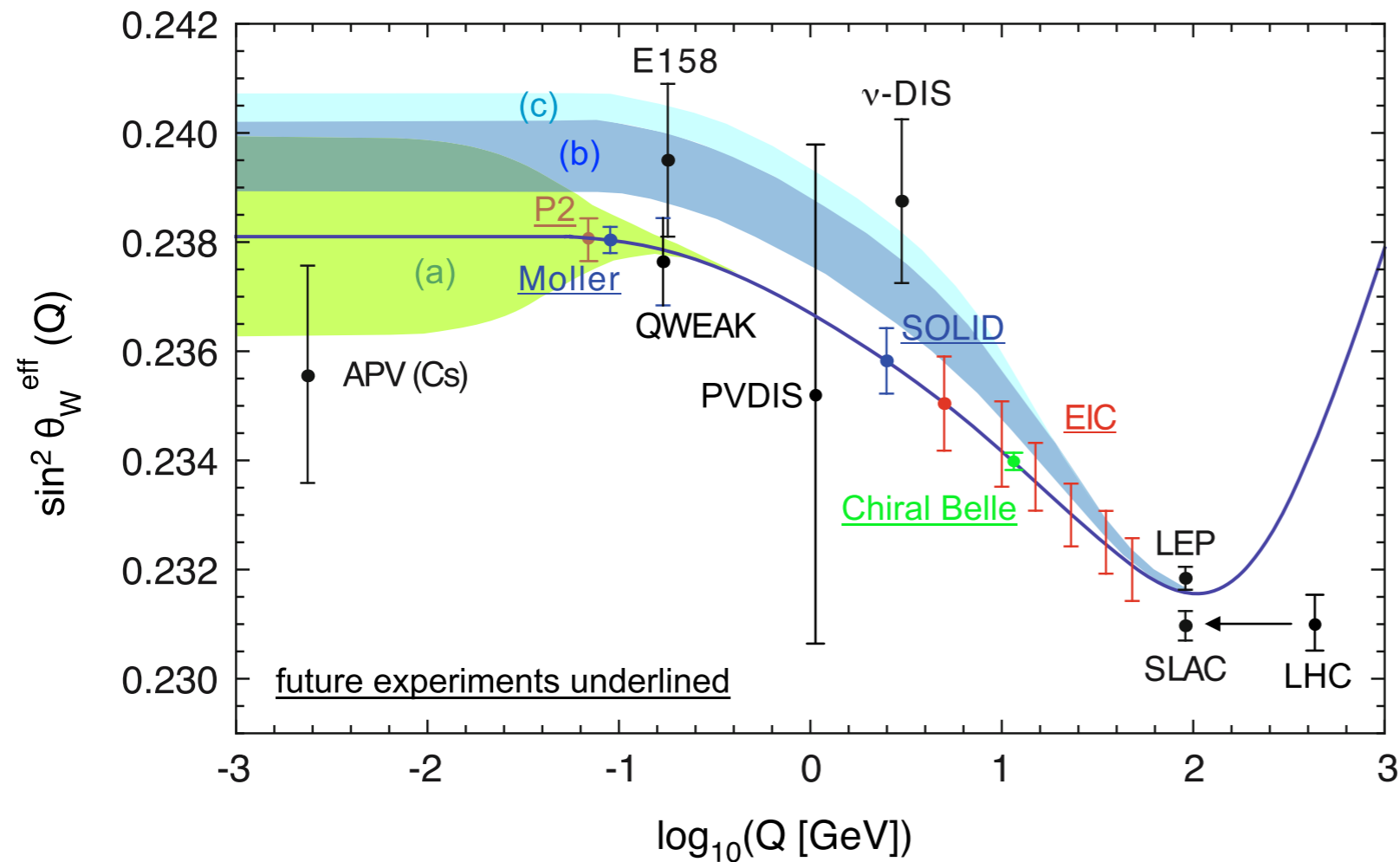
$$\mathbf{D} = \sum_i e \mathbf{r}_i \quad H_{PV} = \sum_i (h_{PV})_i \quad \text{Energies } E$$

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

- 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  $\longrightarrow$  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

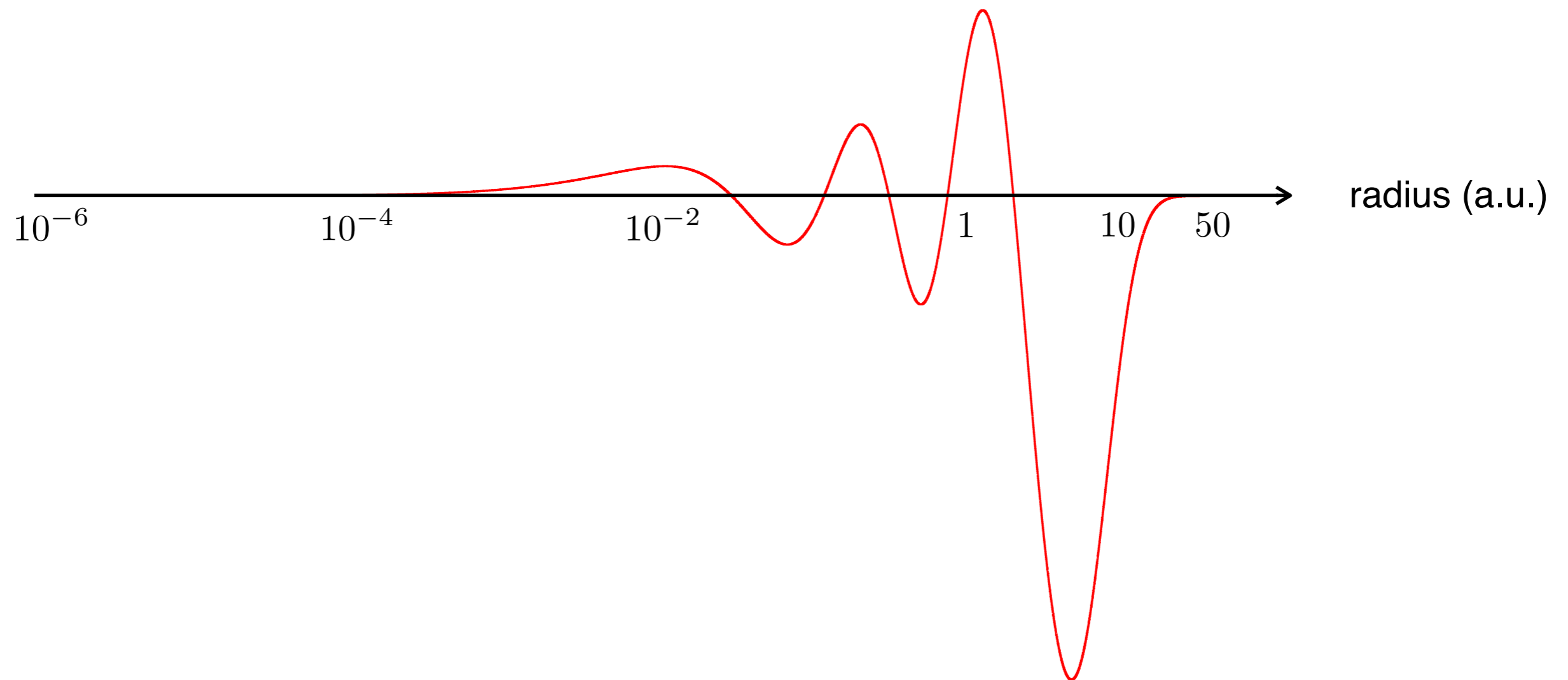
Relativity ↓

PERIODIC TABLE																																																																																		
Atomic Properties of the Elements																																																																																		
<p><b>FREQUENTLY USED FUNDAMENTAL PHYSICAL CONSTANTS<sup>§</sup></b></p> <p><sup>§</sup> 1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of <sup>133</sup>Cs</p> <table border="0"> <tr> <td>speed of light in vacuum</td> <td><i>c</i></td> <td>299 792 458</td> <td>m s<sup>-1</sup></td> <td>(exact)</td> </tr> <tr> <td>Planck constant</td> <td><i>h</i></td> <td>6.626 070 × 10<sup>-34</sup></td> <td>J s</td> <td></td> </tr> <tr> <td>elementary charge</td> <td><i>e</i></td> <td>1.602 177 × 10<sup>-19</sup></td> <td>C</td> <td></td> </tr> <tr> <td>electron mass</td> <td><i>m<sub>e</sub></i></td> <td>9.109 384 × 10<sup>-31</sup></td> <td>kg</td> <td></td> </tr> <tr> <td></td> <td><i>m<sub>e</sub>c<sup>2</sup></i></td> <td>0.510 999</td> <td>MeV</td> <td></td> </tr> <tr> <td>proton mass</td> <td><i>m<sub>p</sub></i></td> <td>1.672 622 × 10<sup>-27</sup></td> <td>kg</td> <td></td> </tr> <tr> <td>fine-structure constant</td> <td><i>α</i></td> <td>1/137.035 999</td> <td></td> <td></td> </tr> <tr> <td>Rydberg constant</td> <td><i>R<sub>∞</sub></i></td> <td>10 973 731.569</td> <td>m<sup>-1</sup></td> <td></td> </tr> <tr> <td></td> <td><i>R<sub>∞</sub>c</i></td> <td>3.289 841 960 × 10<sup>15</sup></td> <td>Hz</td> <td></td> </tr> <tr> <td></td> <td><i>R<sub>∞</sub>hc</i></td> <td>13.605 693</td> <td>eV</td> <td></td> </tr> <tr> <td>electron volt</td> <td>eV</td> <td>1.602 177 × 10<sup>-19</sup></td> <td>J</td> <td></td> </tr> <tr> <td>Boltzmann constant</td> <td><i>k</i></td> <td>1.380 65 × 10<sup>-23</sup></td> <td>J K<sup>-1</sup></td> <td></td> </tr> <tr> <td>molar gas constant</td> <td><i>R</i></td> <td>8.314 5</td> <td>J mol<sup>-1</sup> K<sup>-1</sup></td> <td></td> </tr> </table> <p><sup>§</sup> For the most accurate values of these and other constants, visit <a href="http://pml.nist.gov/constants">pml.nist.gov/constants</a>.</p>																		speed of light in vacuum	<i>c</i>	299 792 458	m s <sup>-1</sup>	(exact)	Planck constant	<i>h</i>	6.626 070 × 10 <sup>-34</sup>	J s		elementary charge	<i>e</i>	1.602 177 × 10 <sup>-19</sup>	C		electron mass	<i>m<sub>e</sub></i>	9.109 384 × 10 <sup>-31</sup>	kg			<i>m<sub>e</sub>c<sup>2</sup></i>	0.510 999	MeV		proton mass	<i>m<sub>p</sub></i>	1.672 622 × 10 <sup>-27</sup>	kg		fine-structure constant	<i>α</i>	1/137.035 999			Rydberg constant	<i>R<sub>∞</sub></i>	10 973 731.569	m <sup>-1</sup>			<i>R<sub>∞</sub>c</i>	3.289 841 960 × 10 <sup>15</sup>	Hz			<i>R<sub>∞</sub>hc</i>	13.605 693	eV		electron volt	eV	1.602 177 × 10 <sup>-19</sup>	J		Boltzmann constant	<i>k</i>	1.380 65 × 10 <sup>-23</sup>	J K <sup>-1</sup>		molar gas constant	<i>R</i>	8.314 5	J mol <sup>-1</sup> K <sup>-1</sup>	
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Group 1 IA	Group 2 IIA	Groups 3-10 IIIB, IVB, VB, VIB, VIIB, VIIIB, VIII, IB, IIB										Group 11 IIIB	Group 12 IIB	Group 13 IIIA	Group 14 IVA	Group 15 VA	Group 16 VIA	Group 17 VIIA	Group 18 VIIIA																																																															
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5 Rb Rubidium 85.468 [Kr]5s <sup>2</sup>	6 Sr Strontium 87.62 [Kr]5s <sup>2</sup>	7 Y Yttrium 88.906 [Kr]4d <sup>1</sup> 5s <sup>2</sup>	8 Zr Zirconium 91.224 [Kr]4d <sup>2</sup> 5s <sup>2</sup>	9 Nb Niobium 92.906 [Kr]4d <sup>4</sup> 5s <sup>1</sup>	10 Mo Molybdenum 95.96 [Kr]4d <sup>5</sup> 5s <sup>1</sup>	11 Tc Technetium (98) [Kr]4d <sup>5</sup> 5s <sup>2</sup>	12 Ru Ruthenium 101.07 [Kr]4d <sup>7</sup> 5s <sup>1</sup>	13 Rh Rhodium 102.91 [Kr]4d <sup>8</sup> 5s <sup>1</sup>	14 Pd Palladium 106.42 [Kr]4d <sup>10</sup>	15 Ag Silver 107.87 [Kr]4d <sup>10</sup> 5s <sup>1</sup>	16 Cd Cadmium 112.41 [Kr]4d <sup>10</sup> 5s <sup>2</sup>	17 In Indium 114.82 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>1</sup>	18 Sn Tin 118.71 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>2</sup>	19 Sb Antimony 121.76 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>3</sup>	20 Te Tellurium 127.60 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>4</sup>	21 I Iodine 126.90 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>5</sup>	22 Xe Xenon 131.29 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>6</sup>																																																																	
6 Cs Cesium 132.91 [Xe]6s <sup>2</sup>	7 Ba Barium 137.33 [Xe]6s <sup>2</sup>	8 La Lanthanum 138.91 [Xe]5d <sup>1</sup> 6s <sup>2</sup>	9 Ce Cerium 140.116 [Xe]4f <sup>1</sup> 5d <sup>1</sup> 6s <sup>2</sup>	10 Pr Praseodymium 140.91 [Xe]4f <sup>3</sup> 6s <sup>2</sup>	11 Nd Neodymium 144.24 [Xe]4f <sup>4</sup> 6s <sup>2</sup>	12 Pm Promethium (145) [Xe]4f <sup>5</sup> 6s <sup>2</sup>	13 Sm Samarium 150.36 [Xe]4f <sup>6</sup> 6s <sup>2</sup>	14 Eu Europium 151.96 [Xe]4f <sup>7</sup> 6s <sup>2</sup>	15 Gd Gadolinium 157.25 [Xe]4f <sup>7</sup> 5d <sup>1</sup> 6s <sup>2</sup>	16 Tb Terbium 158.93 [Xe]4f <sup>9</sup> 6s <sup>2</sup>	17 Dy Dysprosium 162.50 [Xe]4f <sup>10</sup> 6s <sup>2</sup>	18 Ho Holmium 164.93 [Xe]4f <sup>11</sup> 6s <sup>2</sup>	19 Er Erbium 167.26 [Xe]4f <sup>12</sup> 6s <sup>2</sup>	20 Tm Thulium 168.93 [Xe]4f <sup>13</sup> 6s <sup>2</sup>	21 Yb Ytterbium 173.05 [Xe]4f <sup>14</sup> 6s <sup>2</sup>	22 Lu Lutetium 174.97 [Xe]4f <sup>14</sup> 5d <sup>1</sup> 6s <sup>2</sup>																																																																		
7 Fr Francium (223) [Rn]7s <sup>2</sup>	8 Ra Radium (226) [Rn]7s <sup>2</sup>	9 Ac Actinium (227) [Rn]5f <sup>1</sup> 7s <sup>2</sup>	10 Th Thorium 232.04 [Rn]6d <sup>2</sup> 7s <sup>2</sup>	11 Pa Protactinium 231.04 [Rn]5f <sup>2</sup> 6d <sup>1</sup> 7s <sup>2</sup>	12 U Uranium 238.03 [Rn]5f <sup>3</sup> 6d <sup>1</sup> 7s <sup>2</sup>	13 Np Neptunium (237) [Rn]5f <sup>4</sup> 6d <sup>1</sup> 7s <sup>2</sup>	14 Pu Plutonium (244) [Rn]5f <sup>6</sup> 7s <sup>2</sup>	15 Am Americium (243) [Rn]5f <sup>7</sup> 7s <sup>2</sup>	16 Cm Curium (247) [Rn]5f <sup>7</sup> 6d <sup>1</sup> 7s <sup>2</sup>	17 Bk Berkelium (247) [Rn]5f <sup>9</sup> 7s <sup>2</sup>	18 Cf Californium (251) [Rn]5f <sup>10</sup> 7s <sup>2</sup>	19 Es Einsteinium (252) [Rn]5f <sup>11</sup> 7s <sup>2</sup>	20 Fm Fermium (257) [Rn]5f <sup>12</sup> 7s <sup>2</sup>	21 Md Mendelevium (258) [Rn]5f <sup>13</sup> 7s <sup>2</sup>	22 No Nobelium (259) [Rn]5f <sup>14</sup> 7s <sup>2</sup>	23 Lr Lawrencium (260) [Rn]5f <sup>14</sup> 6d <sup>1</sup> 7p <sup>1</sup>																																																																		

Neutral atoms: Cs (Purdue) ; Fr (TRIUMF; Tokyo)  
Singly-ionized atoms: Ba<sup>+</sup> (Seattle) ; Ra<sup>+</sup> (Groningen)

# Benchmarking atomic theory

Upper radial component, Cs 6s:

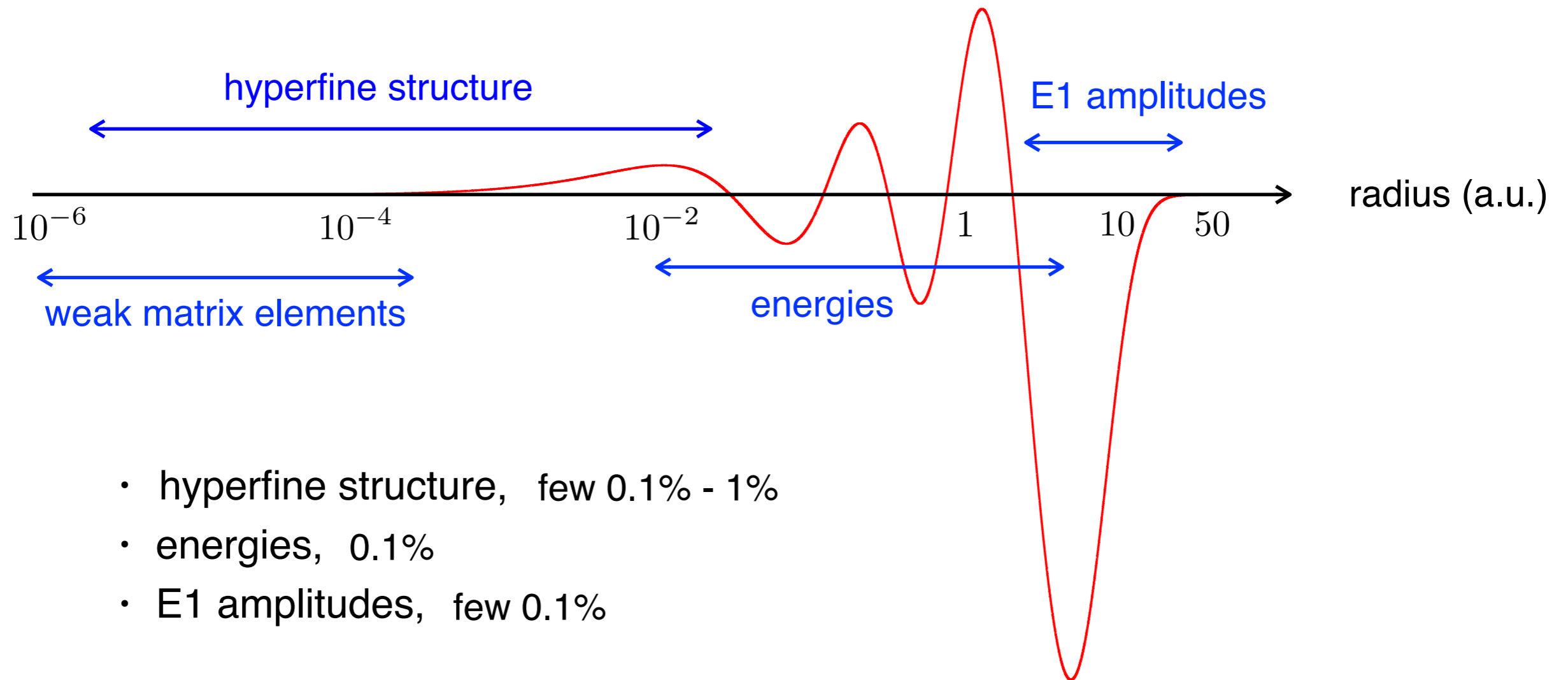


$$E_{\text{PV}} = \sum_n \frac{\langle 7S_{1/2} | D | nP_{1/2} \rangle \langle nP_{1/2} | H_{\text{PV}} | 6S_{1/2} \rangle}{E_{6S_{1/2}} - E_{nP_{1/2}}} + \sum_n \frac{\langle 7S_{1/2} | H_{\text{PV}} | nP_{1/2} \rangle \langle nP_{1/2} | D | 6S_{1/2} \rangle}{E_{7S_{1/2}} - E_{nP_{1/2}}} = \xi Q_W$$



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Upper radial component, Cs 6s:

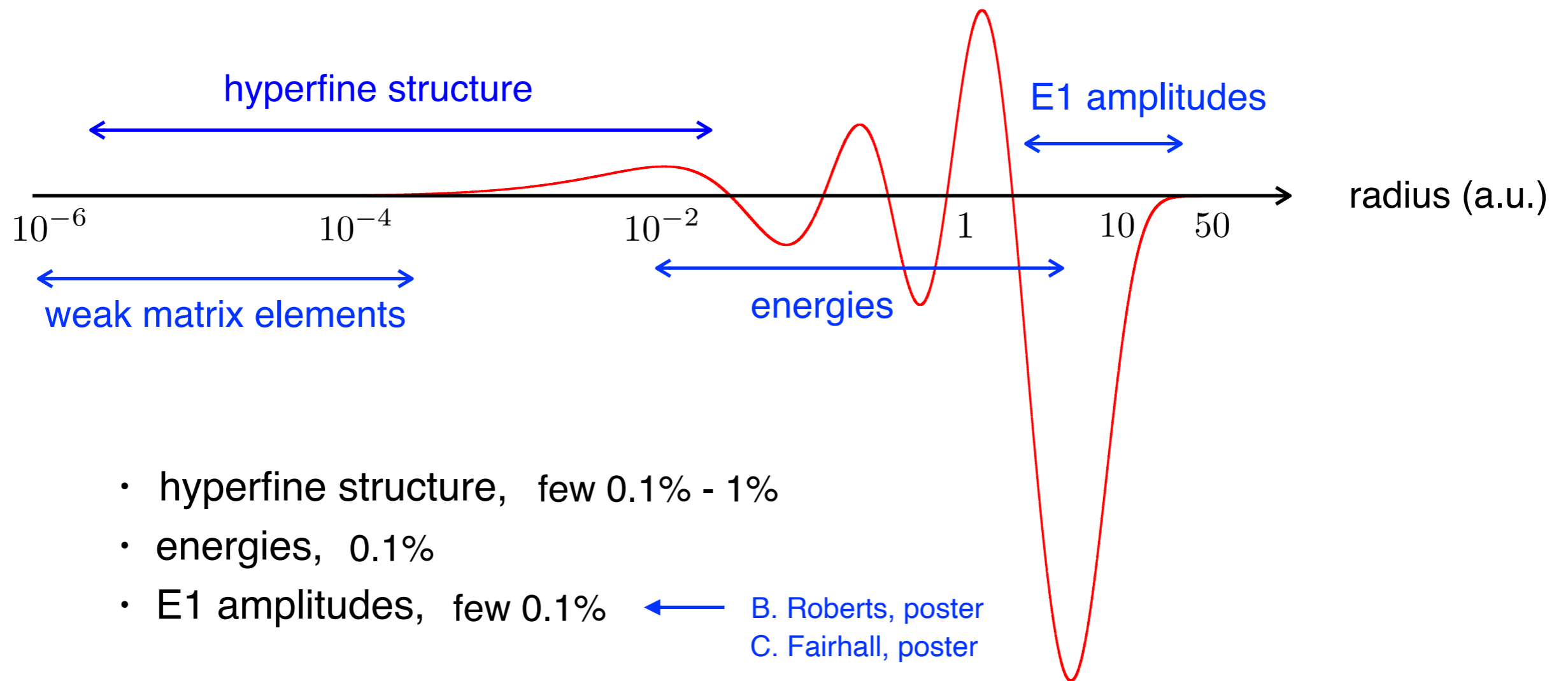


- hyperfine structure, few 0.1% - 1%
- energies, 0.1%
- E1 amplitudes, few 0.1%

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

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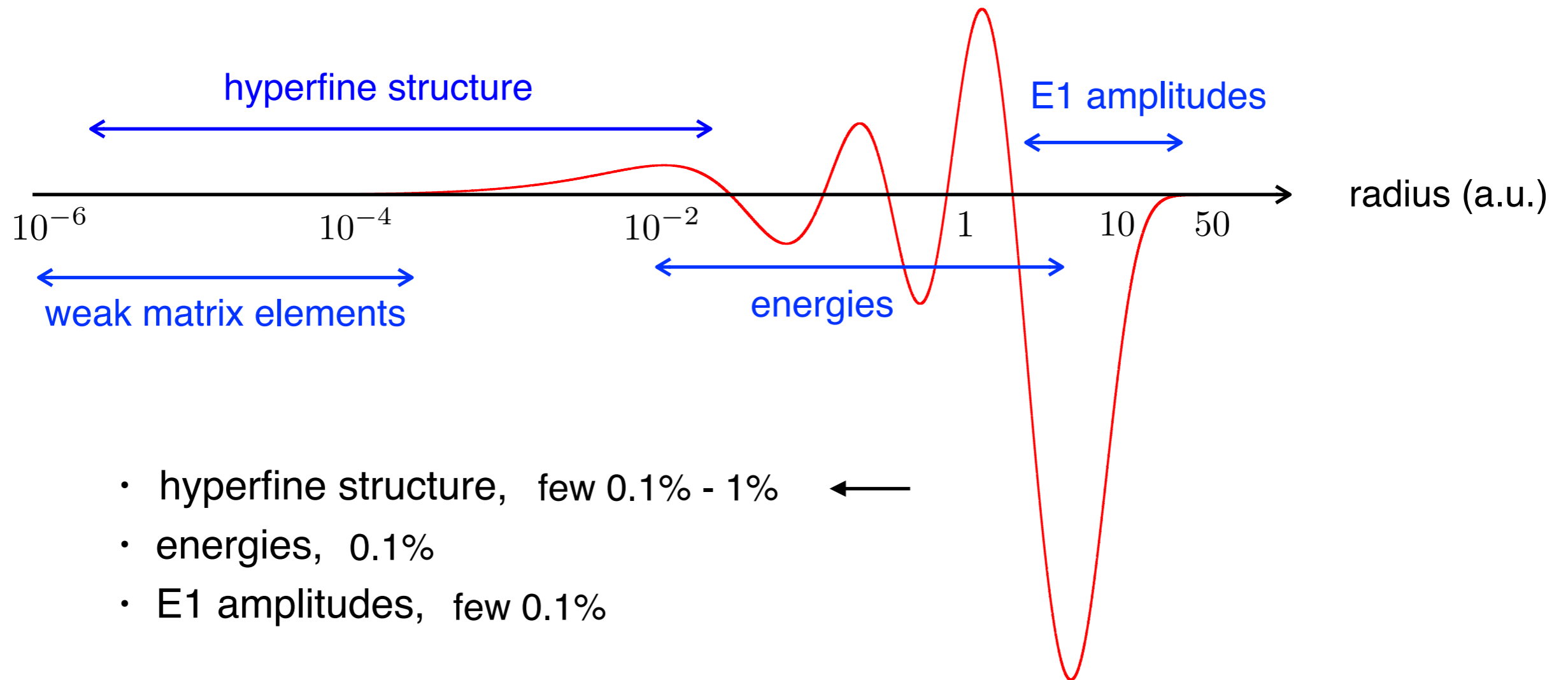
← B. Roberts, poster  
C. Fairhall, poster

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



# Benchmarking atomic theory

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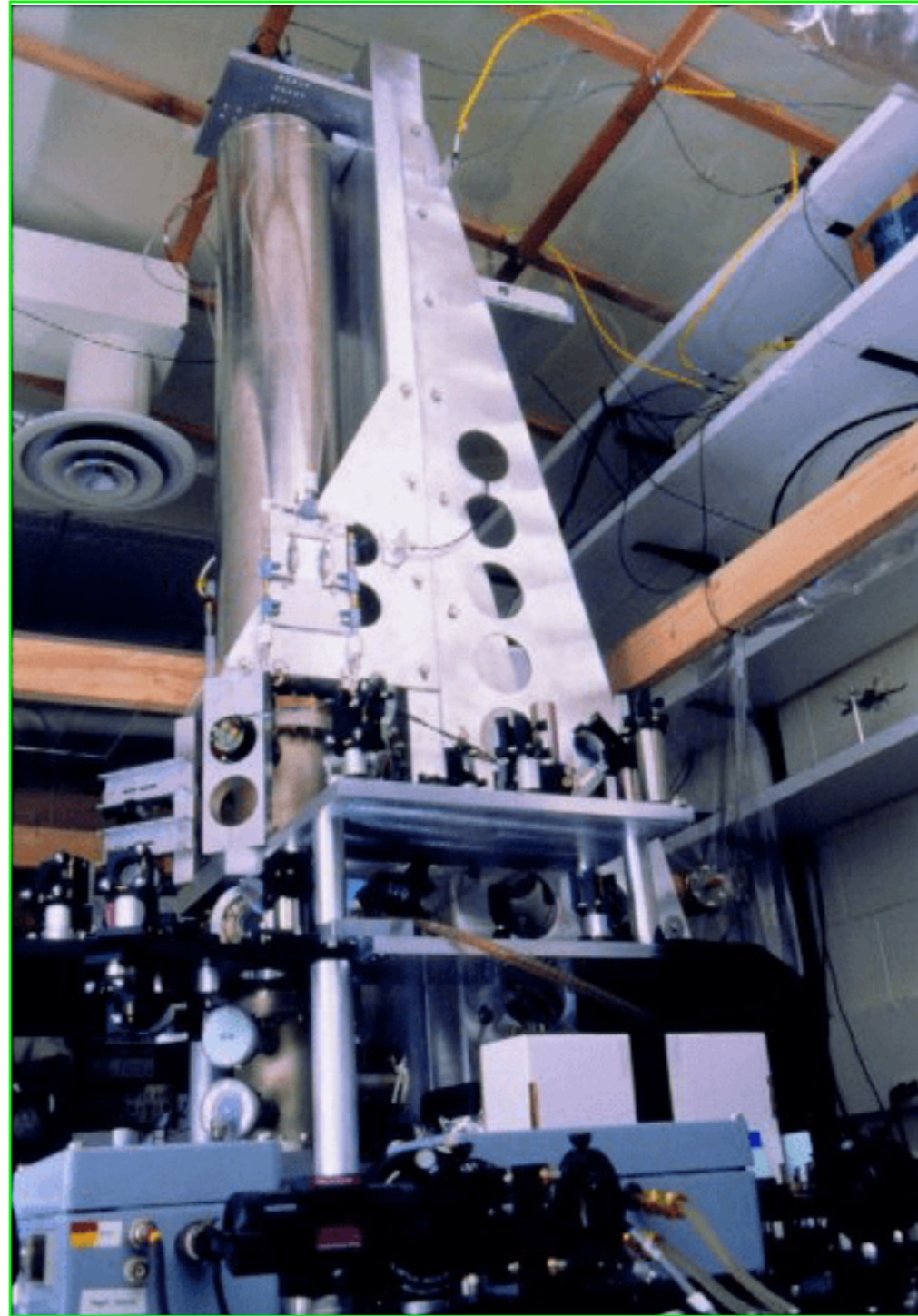
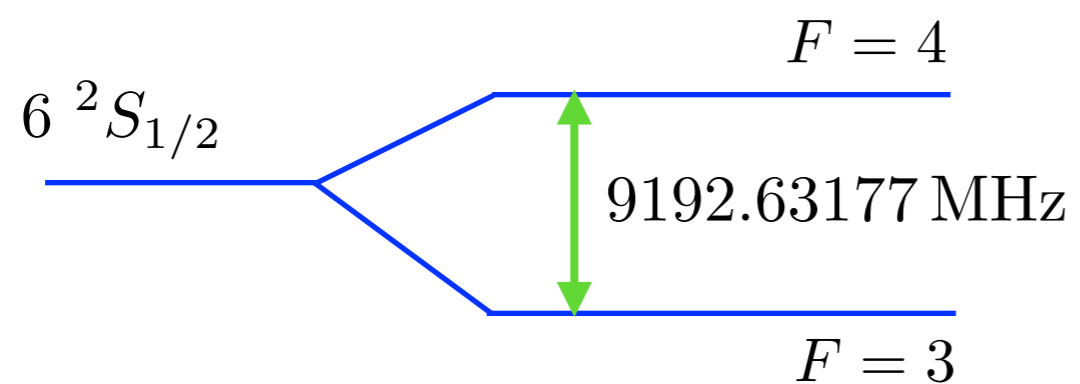
$$E_{\text{PV}} = \sum_n \frac{\langle 7S_{1/2} | D | nP_{1/2} \rangle \langle nP_{1/2} | H_{\text{PV}} | 6S_{1/2} \rangle}{E_{6S_{1/2}} - E_{nP_{1/2}}} + \sum_n \frac{\langle 7S_{1/2} | H_{\text{PV}} | nP_{1/2} \rangle \langle nP_{1/2} | D | 6S_{1/2} \rangle}{E_{7S_{1/2}} - E_{nP_{1/2}}} = \xi Q_W$$

# Hyperfine structure

NIST-F2 Atomic clock

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

Hyperfine splitting in cesium

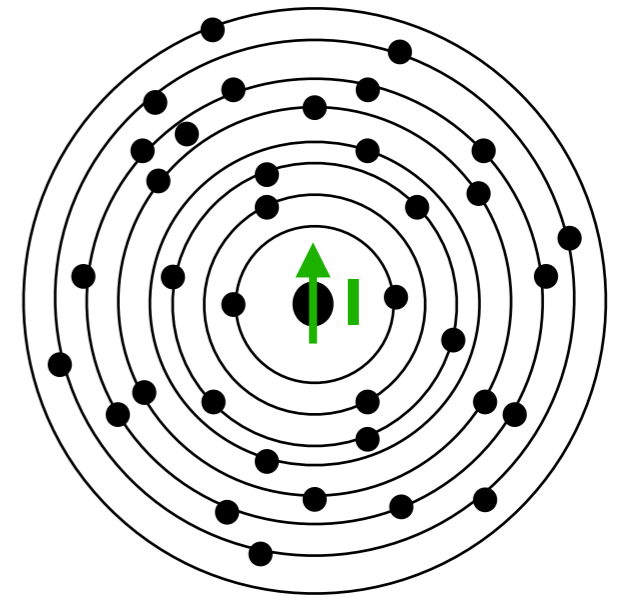




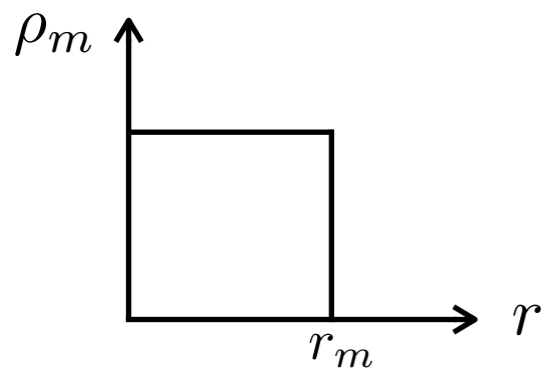
# Modelling the hyperfine structure

Interaction

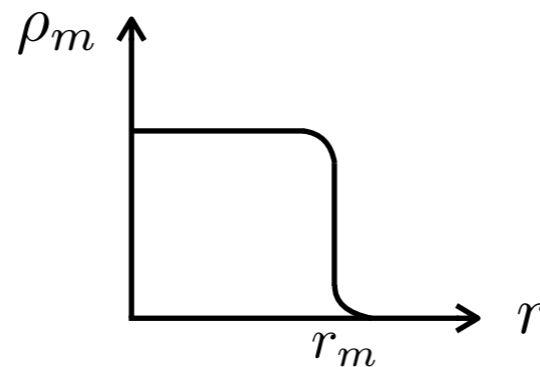
$$h_{\text{hfs}} = \frac{1}{c} \frac{\boldsymbol{\mu} \cdot (\mathbf{r} \times \boldsymbol{\alpha})}{r^3} F(r)$$



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



Fermi distribution



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

Hyperfine splitting quantified by hyperfine constant  $A$

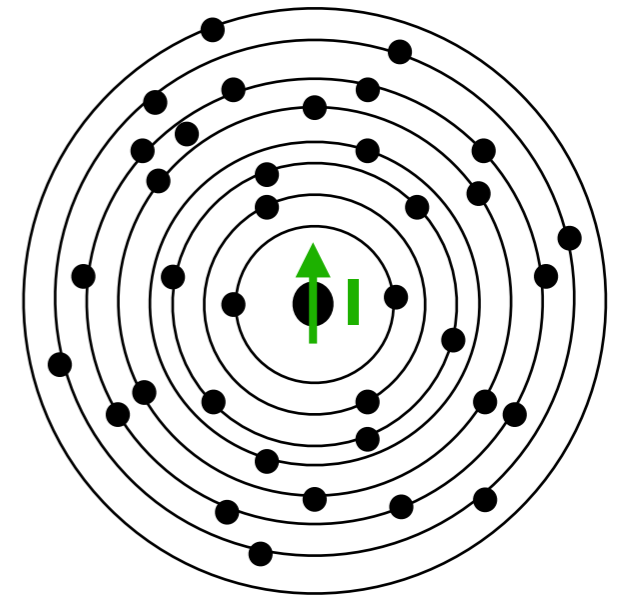
$$A = A_0(1 + \epsilon) + \delta A^{\text{QED}}$$

# Modelling the hyperfine structure

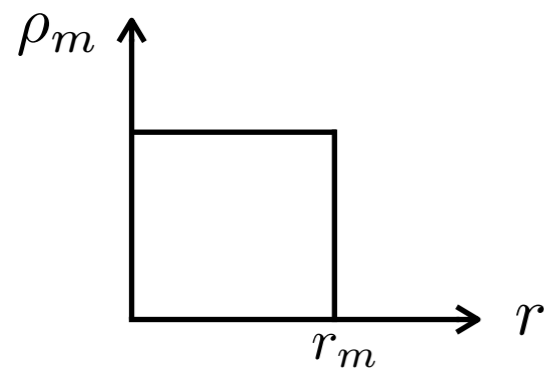
Interaction

nuclear magnetic moment  
 $\mu = \mu \mathbf{I} / I$

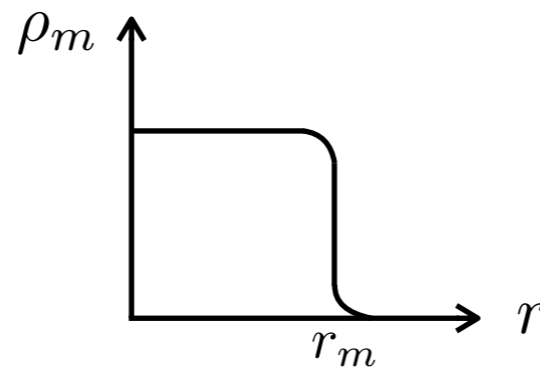
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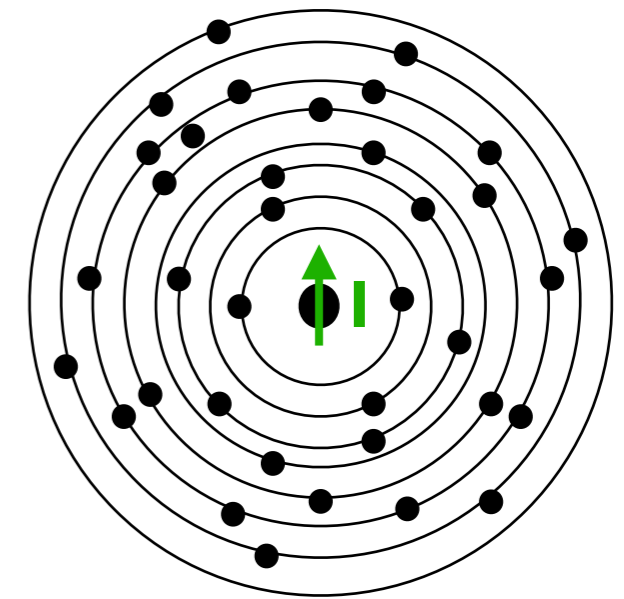
Interaction

nuclear magnetic moment

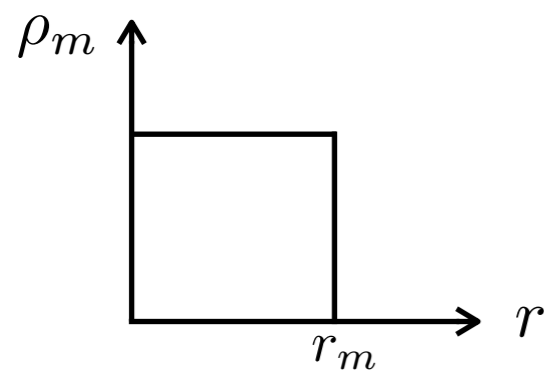
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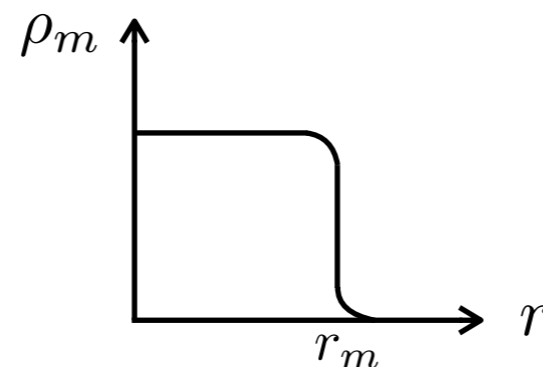
describes radial distribution of  $\mu$ ; point-nucleus,  $F(r) = 1$



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



Fermi distribution



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

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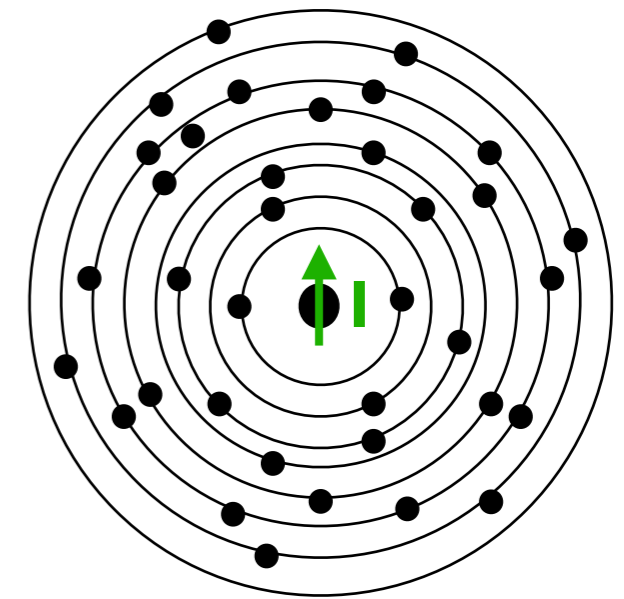
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Interaction

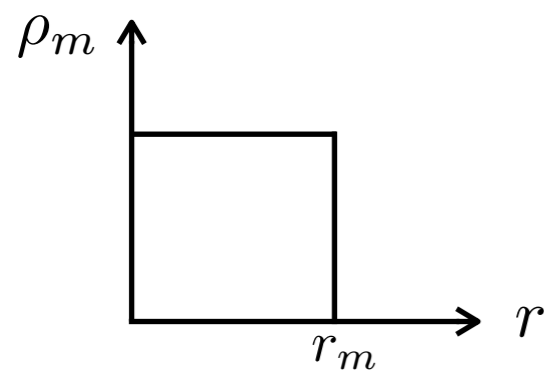
$$h_{\text{hfs}} = \frac{1}{c} \frac{\mu \cdot (\mathbf{r} \times \boldsymbol{\alpha})}{r^3} F(r)$$

nuclear magnetic moment  
 $\mu = \mu \mathbf{I} / I$

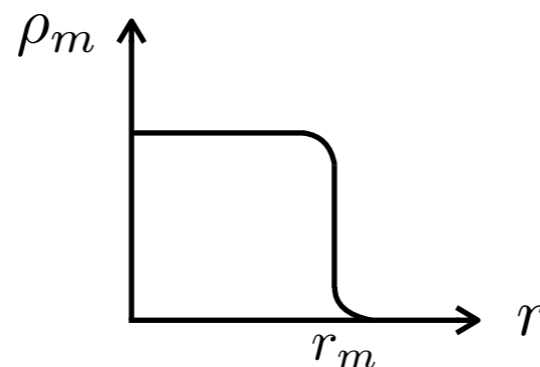


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Fermi distribution



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

Hyperfine splitting quantified by hyperfine constant  $A$

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↑  
Many-body result,  
finite nuclear charge effect included

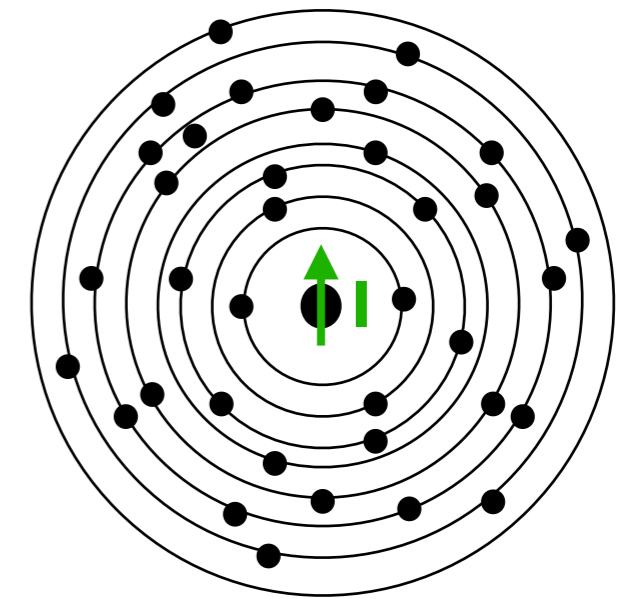
# Modelling the hyperfine structure

Interaction

nuclear magnetic moment

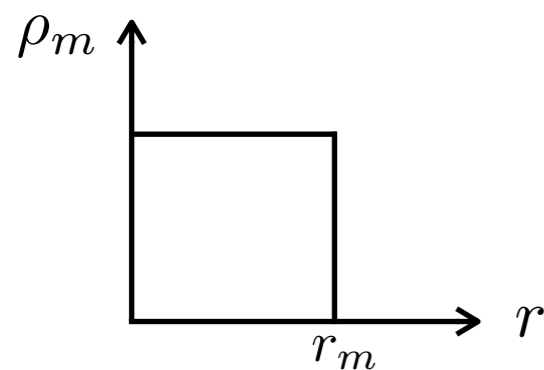
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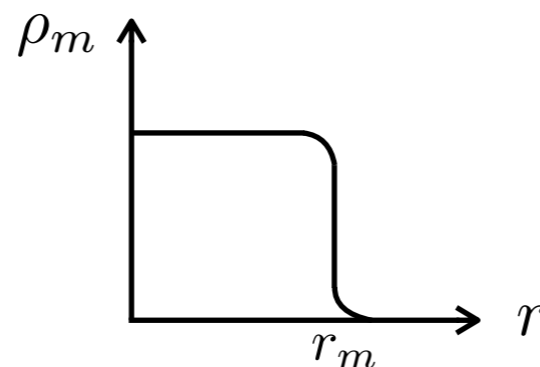


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Fermi distribution



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

Hyperfine splitting quantified by hyperfine constant  $A$

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

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



# Modelling the hyperfine structure

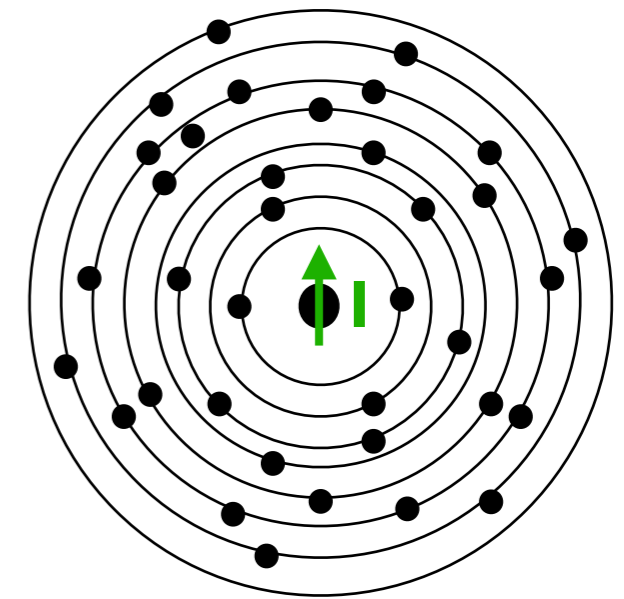
Interaction

nuclear magnetic moment

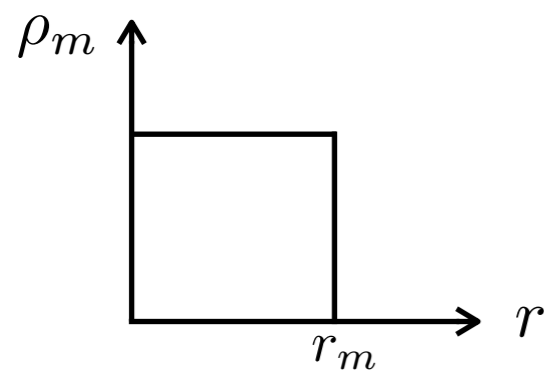
$$h_{\text{hfs}} = \frac{1}{c} \frac{\mu \cdot (\mathbf{r} \times \boldsymbol{\alpha})}{r^3} F(r)$$

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

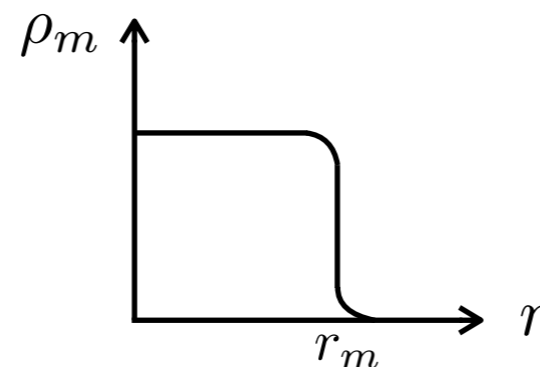
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Ball,  $F(r) = (r/r_m)^3$



Fermi distribution



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

Hyperfine splitting quantified by hyperfine constant  $A$

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

↑  
Quantum electrodynamics  
radiative correction

# Modelling the hyperfine structure

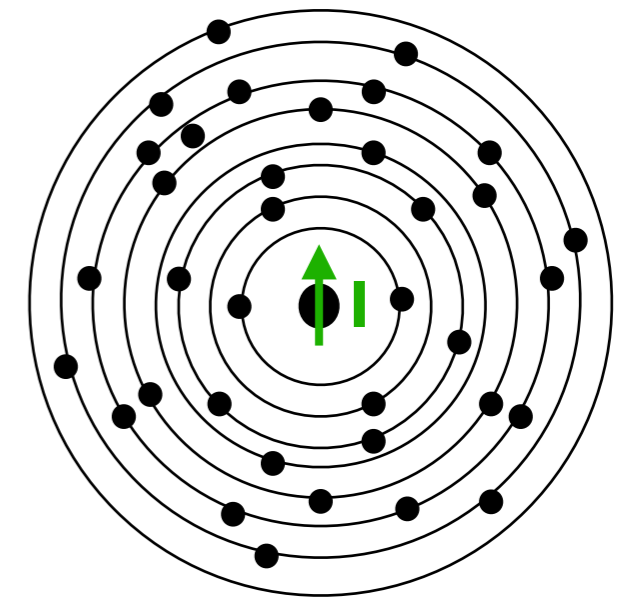
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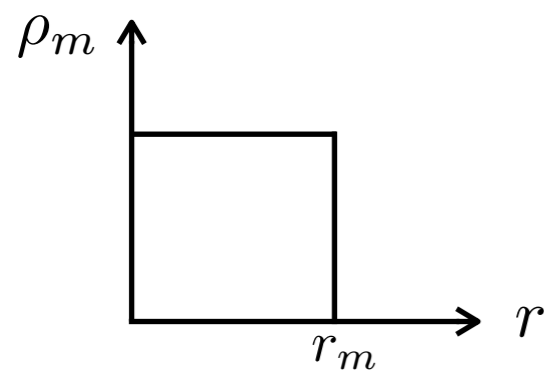
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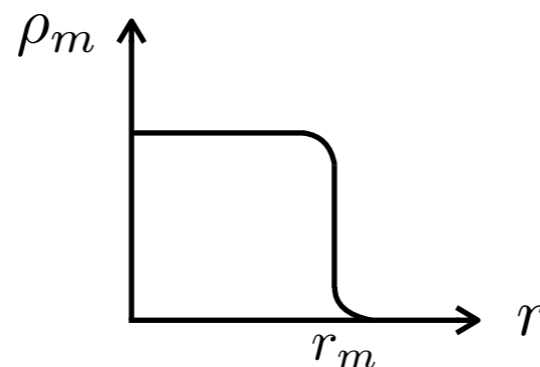
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Fermi distribution



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

Hyperfine splitting quantified by hyperfine constant  $A$

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

↑—————↑  
contains factor  $\mu$

# Hyperfine comparisons

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

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  $\delta A^{\text{QED}}$
- ▶ Nuclear magnetic moments  $\mu$
- ▶ Bohr-Weisskopf effect  $\epsilon$

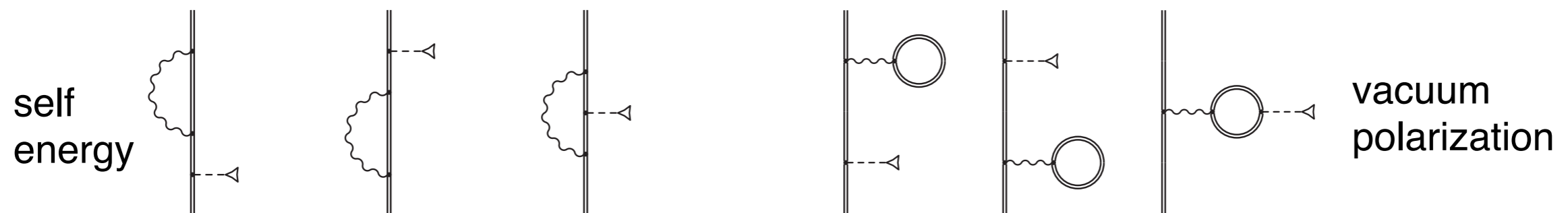


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- ▶ Bohr-Weisskopf effect  $\epsilon$



Cs	Ba <sup>+</sup>	Fr	Ra <sup>+</sup>	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 (%)

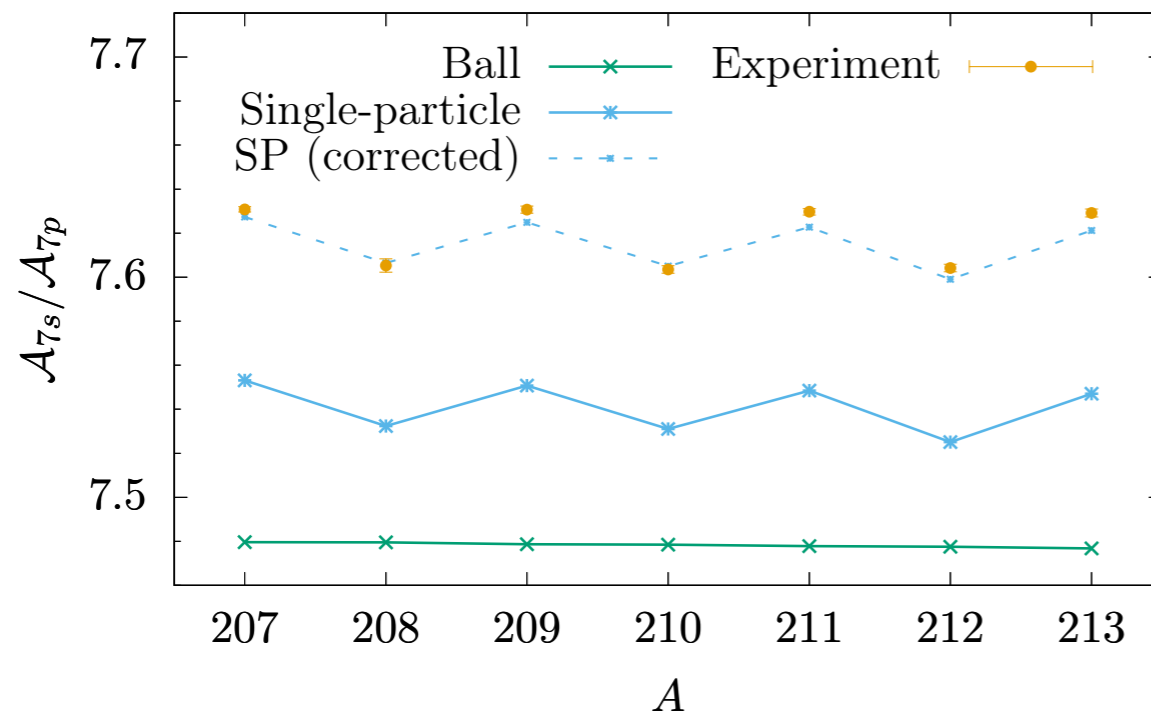
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$A(7s)/A(7p_{1/2})$  vs atomic mass for francium



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

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

Found  $\mu$  with 0.5% uncertainty

# Hyperfine comparisons

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

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  $\delta A^{\text{QED}}$
- ▶ Nuclear magnetic moments  $\mu$
- ▶ Bohr-Weisskopf effect  $\epsilon$

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

BW corrections (%) to hyperfine constants

nuclear model	<sup>133</sup> Cs	<sup>135</sup> Ba <sup>+</sup>	<sup>211</sup> Fr	<sup>225</sup> Ra <sup>+</sup>
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

	$^{133}\text{Cs}$	$^{135}\text{Ba}^+$	$^{211}\text{Fr}$	$^{225}\text{Ra}^+$
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)

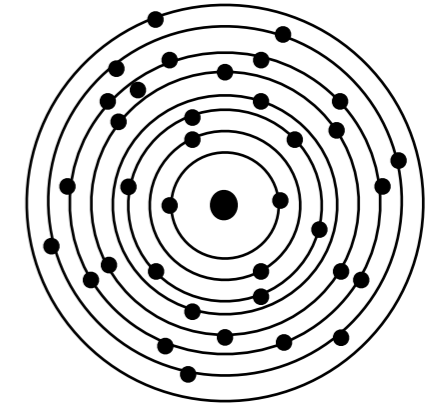
Ginges, Volotka, Fritzsche, PRA (2017)

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

Extraction of  $\text{Ra}^+$  BW effect, -4.7%:

Skripnikov, J. Chem. Phys. (2020)

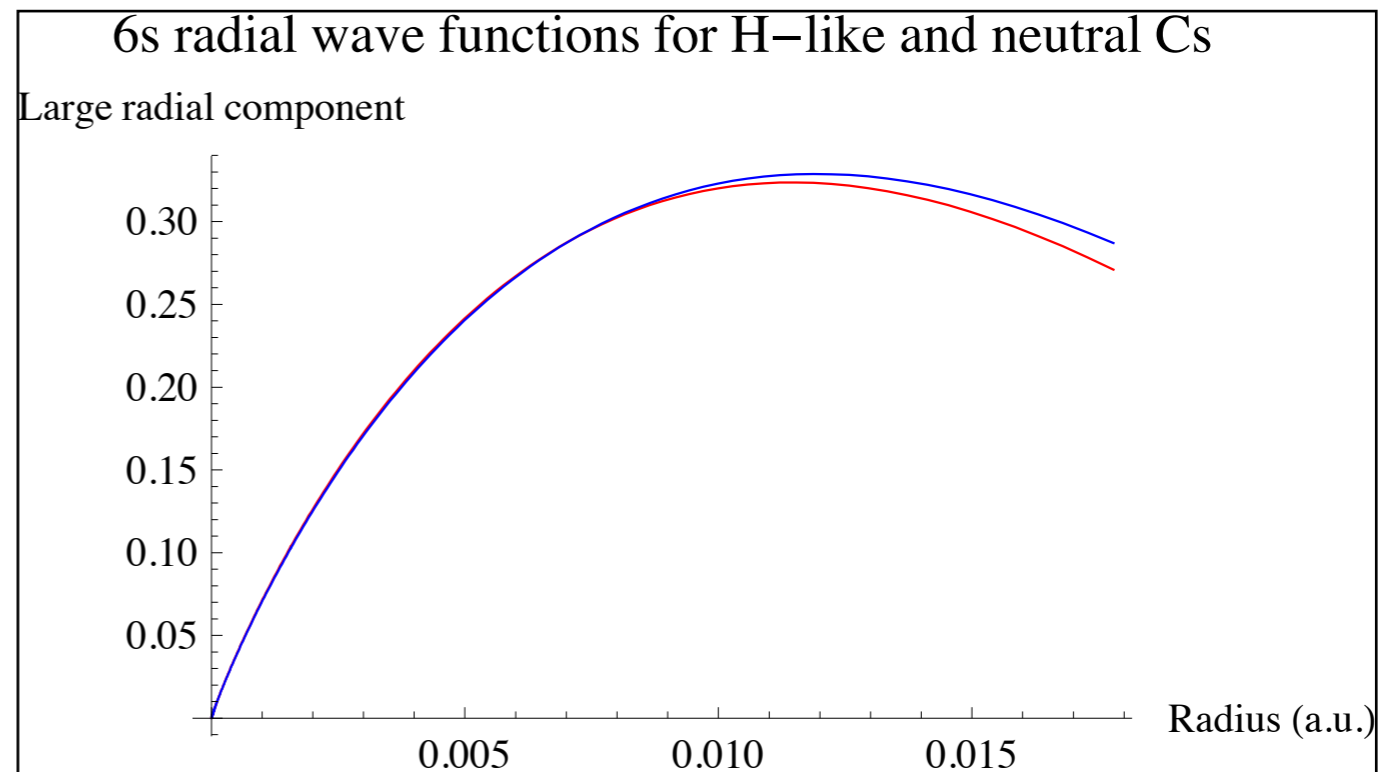
# BW effect: properties



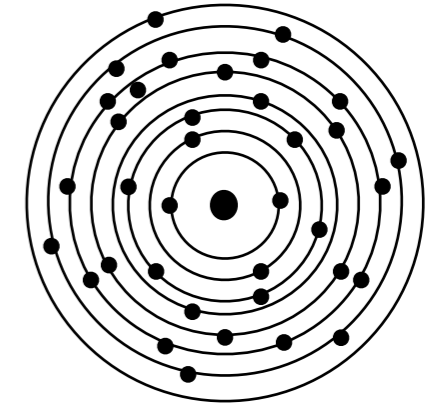
Relative BW correction  $\epsilon = \frac{\int_0^{r_m} dr f(r)g(r)[F(r) - 1]/r^2}{\int_0^\infty dr f(r)g(r)/r^2}$

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

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



# BW effect: properties



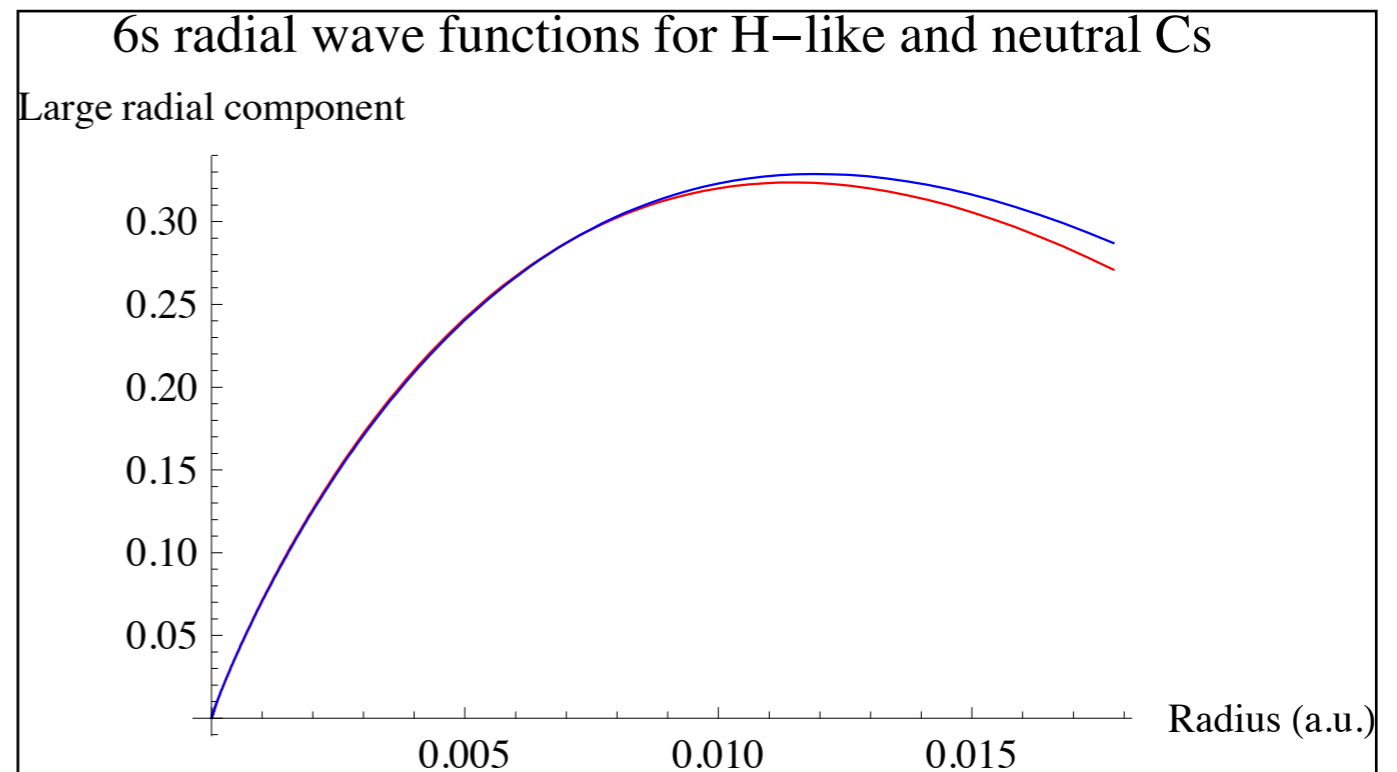
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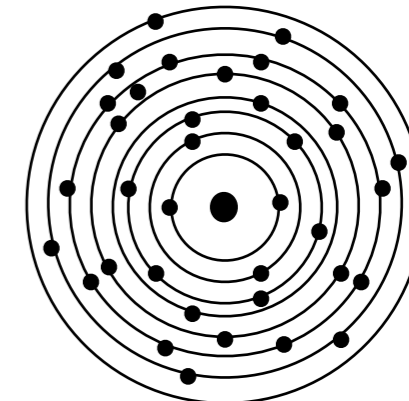
BW effect is independent of principal quantum number!

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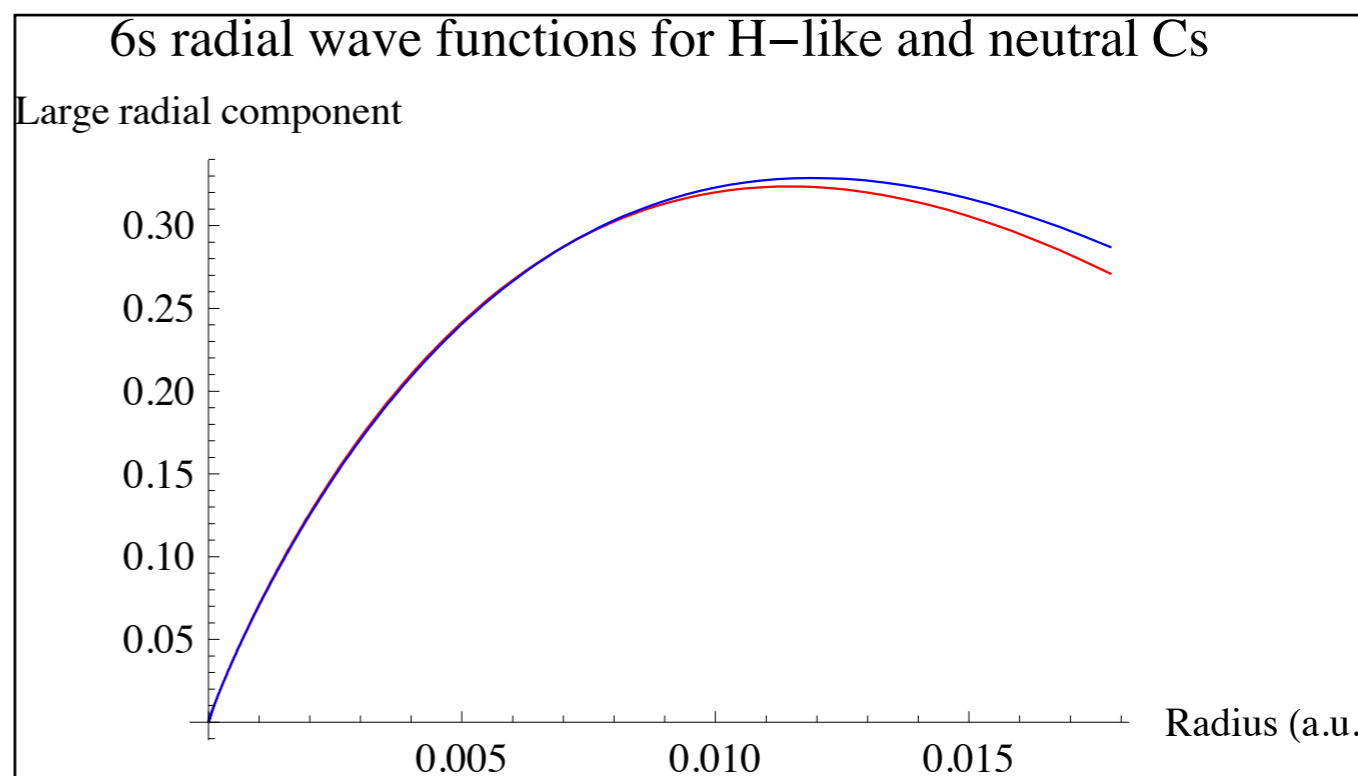
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Also, in the nuclear region, for heavy systems:

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



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

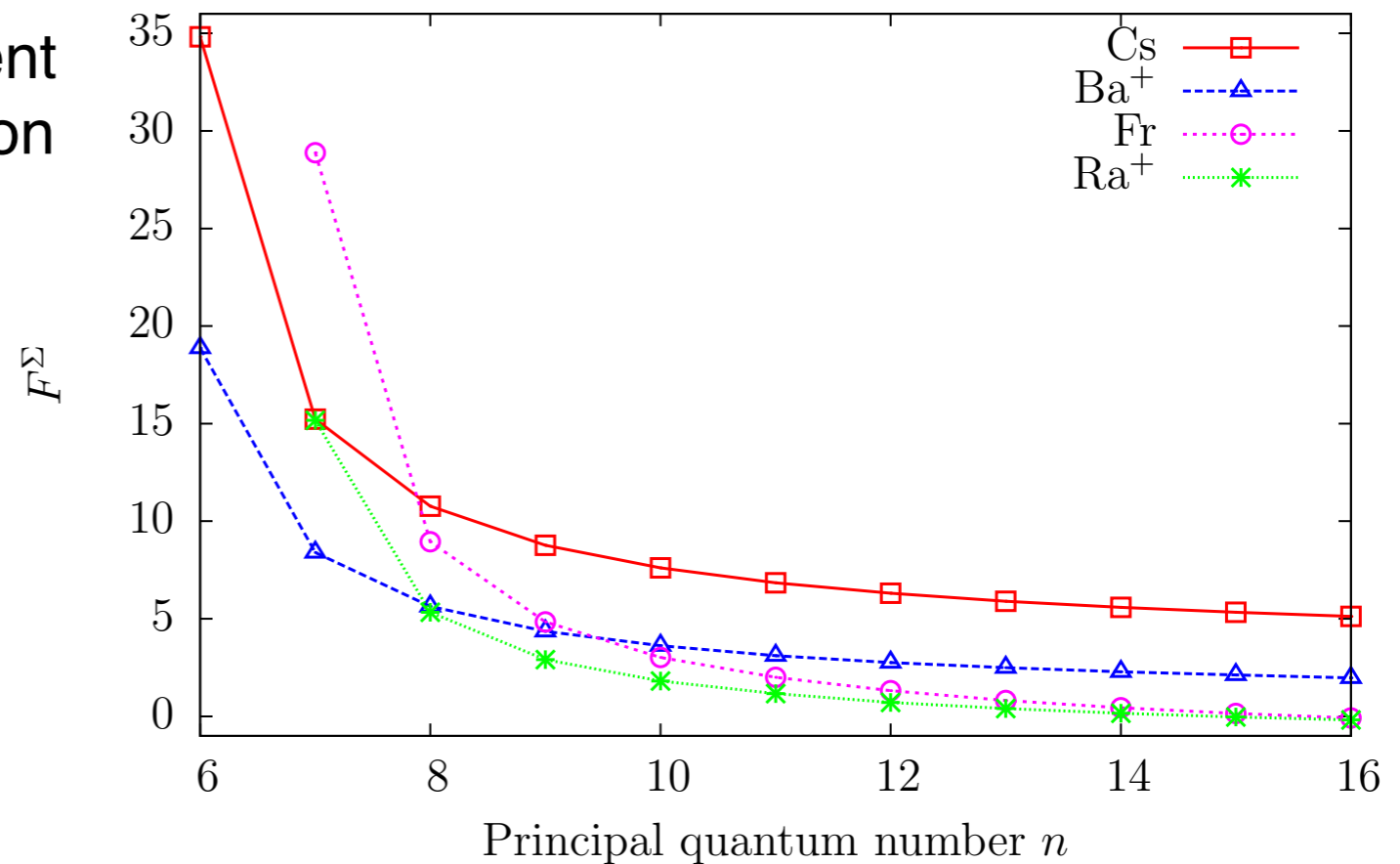
# BW effect: ratio method

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

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

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

Correlation corrections (%) to hyperfine intervals for states  $ns$



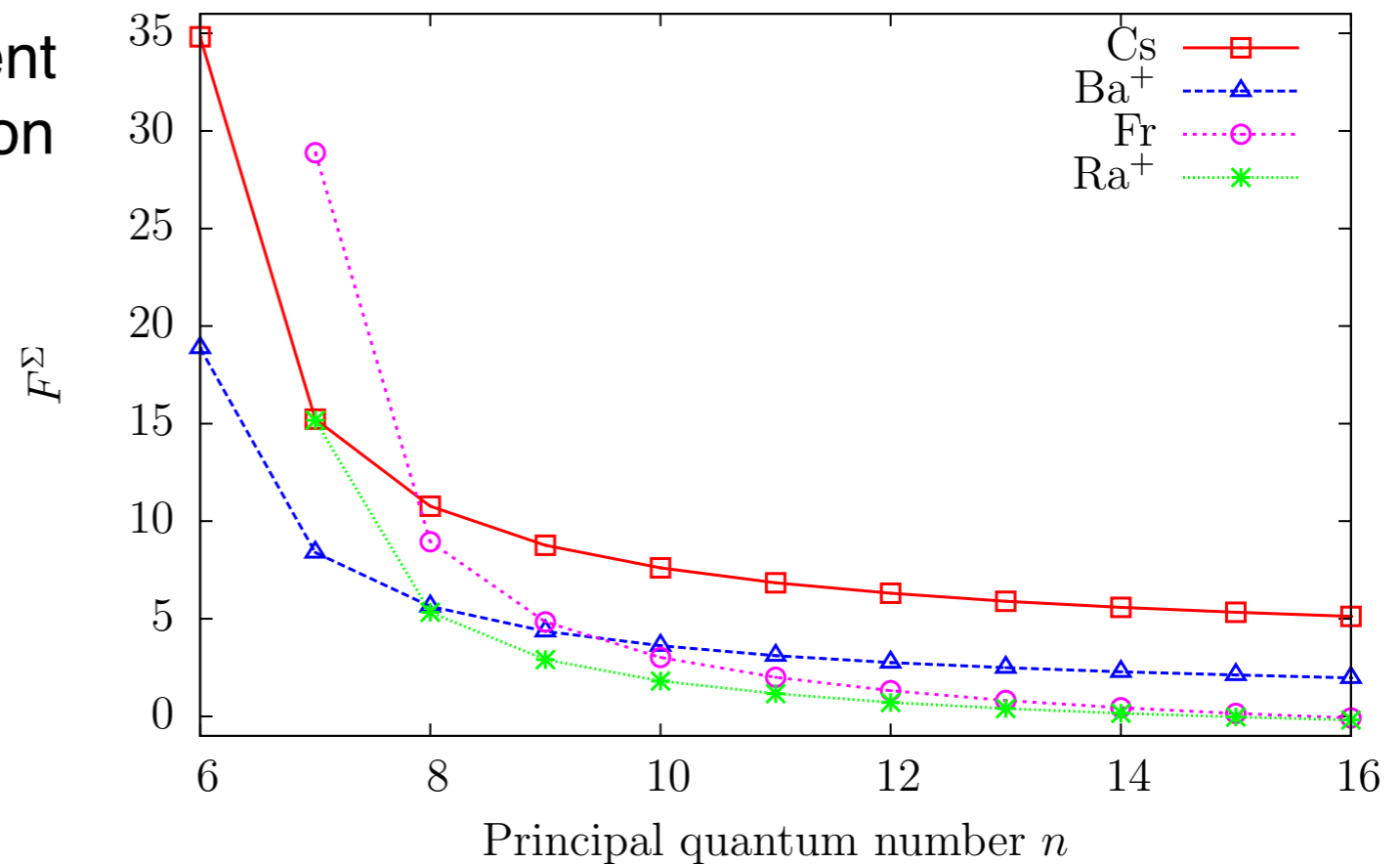
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State	$A_{\text{hfs}}$ (MHz)			
	Experiment		Theory	
	This work	Prior expt.	Ref. [37]	Ref. [16]
12s	26.318 (15)	26.31 (10) [24]	26.28	26.30 (2)
13s	18.431 (10)	18.40 (11) [25]		18.42 (1)

from Quirk et al., PRA (2022)

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

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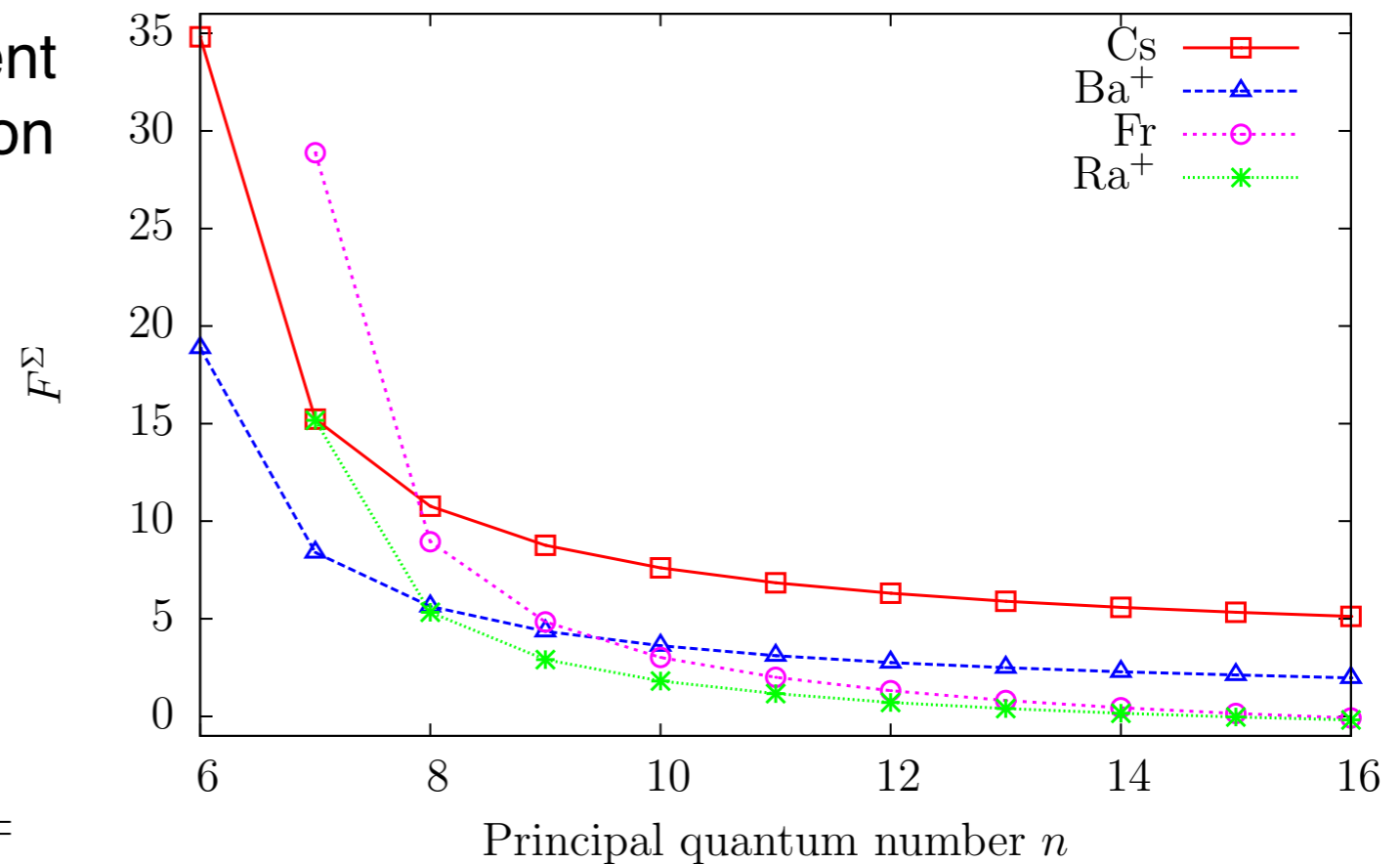
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$A_{\text{hfs}}$  (MHz) for  $8p_{1/2}$

$A$	Source
Experiment	
42.97 (10)	Tai <i>et al.</i> , 1973 [40]
42.92 (25)	Cataliotti <i>et al.</i> , 1996 [48]
42.95 (25)	Liu & Baird, 2000 [49]
42.933 (8)	This work
Theory	
42.43	Safronova <i>et al.</i> , 1999 [46]
42.32	Tang <i>et al.</i> , 2019 [47]
42.95 (9)	fit method, Grunefeld <i>et al.</i> , 2019 [34]
42.93 (7)	ratio method, Grunefeld <i>et al.</i> , 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 ${}^1\Delta^2$ (%)		
		<i>A</i>	<i>I</i> <sup>π</sup>	ϵ <sub>Ball</sub> (%)	ϵ <sub>SP</sub> (%)	<i>A</i>	<i>I</i> <sup>π</sup>	ϵ <sub>Ball</sub> (%)	ϵ <sub>SP</sub> (%)	Ball	SP	Expt. [59]
<sup>37</sup> Rb	5 <i>s</i> <sub>1/2</sub>	85	5/2 <sup>-</sup>	-0.306	0.044	87	3/2 <sup>-</sup>	-0.306	-0.278	-0.001	0.323	0.35142(30)
						86	2 <sup>-</sup>	-0.306	-0.139	0.000	0.183	0.17(9)
<sup>47</sup> Ag	5 <i>s</i> <sub>1/2</sub>	107	1/2 <sup>-</sup>	-0.497	-4.20	103	7/2 <sup>+</sup>	-0.493	-0.347	-0.018	-3.88	-3.4(17)
						109	1/2 <sup>-</sup>	-0.498	-3.78	0.007	-0.431	-0.41274(29)
<sup>55</sup> Cs	6 <i>s</i> <sub>1/2</sub>	133	7/2 <sup>+</sup>	-0.716	-0.209	131	5/2 <sup>+</sup>	-0.716	-0.596	-0.001	0.389	0.45(5) <sup>a</sup>
						135	7/2 <sup>+</sup>	-0.716	-0.247	0.002	0.039	0.037(9) <sup>b</sup>
						134	4 <sup>+</sup>	-0.716	-0.371	0.000	0.163	0.169(30)
<sup>56</sup> Ba <sup>+</sup>	6 <i>s</i> <sub>1/2</sub>	135	3/2 <sup>+</sup>	-0.747	-1.03	137	3/2 <sup>+</sup>	-0.747	-1.03	0.001	0.001	-0.191(5)

Roberts and Ginges, PRA (2021)

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

Roberts and Ginges, PRA (2021)

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# BW effect: from H-like ions and muonic atoms

BW effect from H-like ion experiments:

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

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↑  
electronic  
screening factor

Roberts and Ginges, PRA (2022)

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



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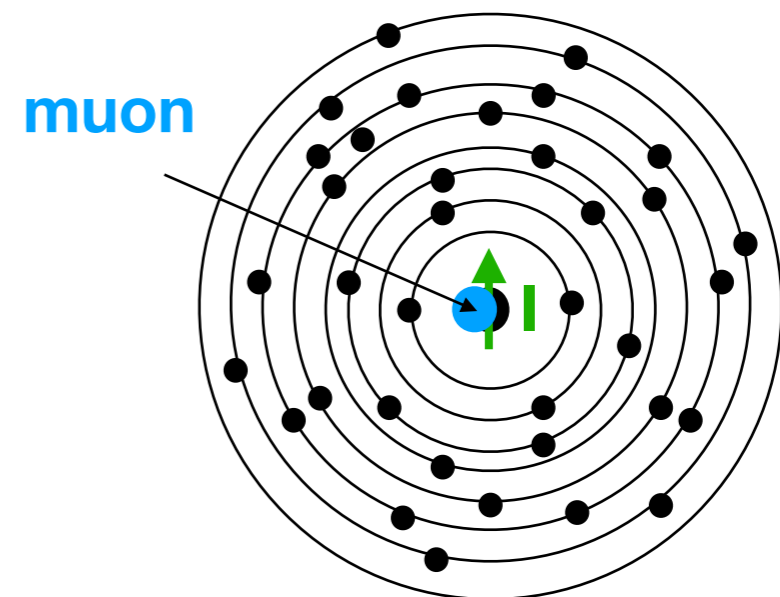
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G. Sanamyan, next talk



Sanamyan, Roberts, Ginges, arxiv (2022)

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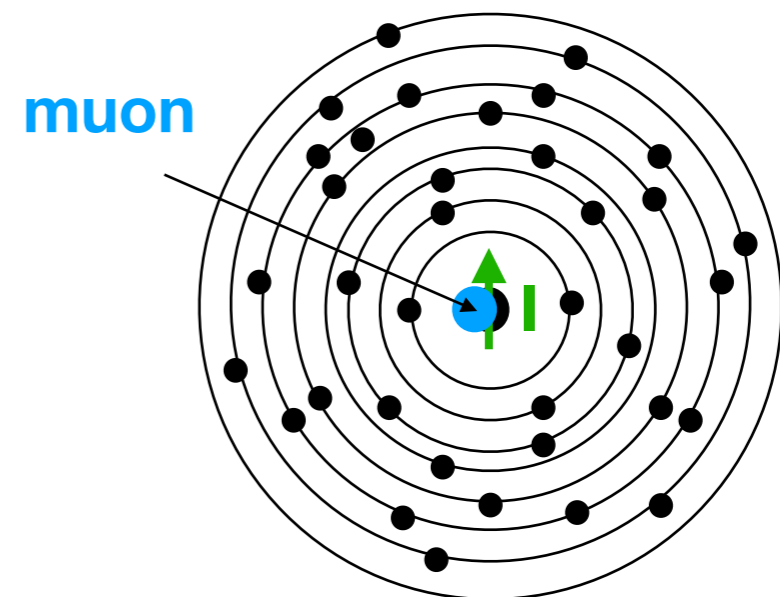
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SP model: -0.21%

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

“ball”/fermi model: -0.7%

Empirical result for  $^{133}\text{Cs}$  s states,

$\epsilon = \dots$

Sanamyan, Roberts, Ginges, arxiv (2022)

# Summary

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

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  - Tests of atomic wave functions in the nuclear region
  - Reducing APV theory uncertainty to 0.1%
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