Searches for new physics in precision atomic experiments

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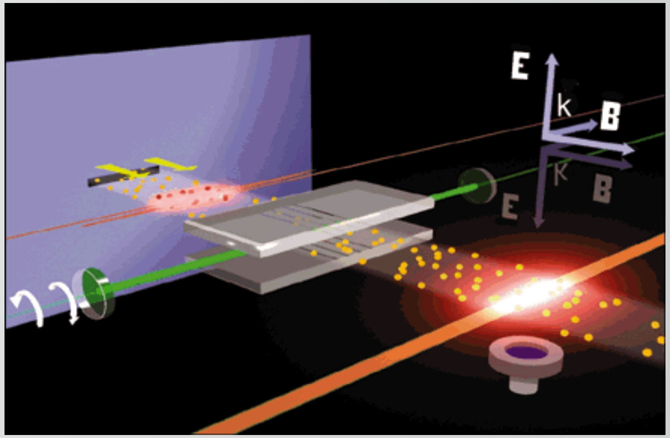
Australian Government
Australian Research Council



Canberra International Physics Summer School 2023 “Fields and Particles”

Plan

Lecture 1. How can atoms be used to test the SM and search for new physics?

- Atomic parity violation

Lecture 2. Time-reversal violating electric dipole moments

- Atomic EDMs, enhancement mechanisms

Lecture 3. Precision atomic theory

- Many-body methods, relativistic Hartree-Fock, QED in many-electron atoms

Lecture 4. Adventures at the intersection of atomic and nuclear physics

- Case study in the hyperfine structure

Lecture 4.
Adventures at the intersection of atomic and nuclear physics

Our precision atomic theory group at UQ — aim

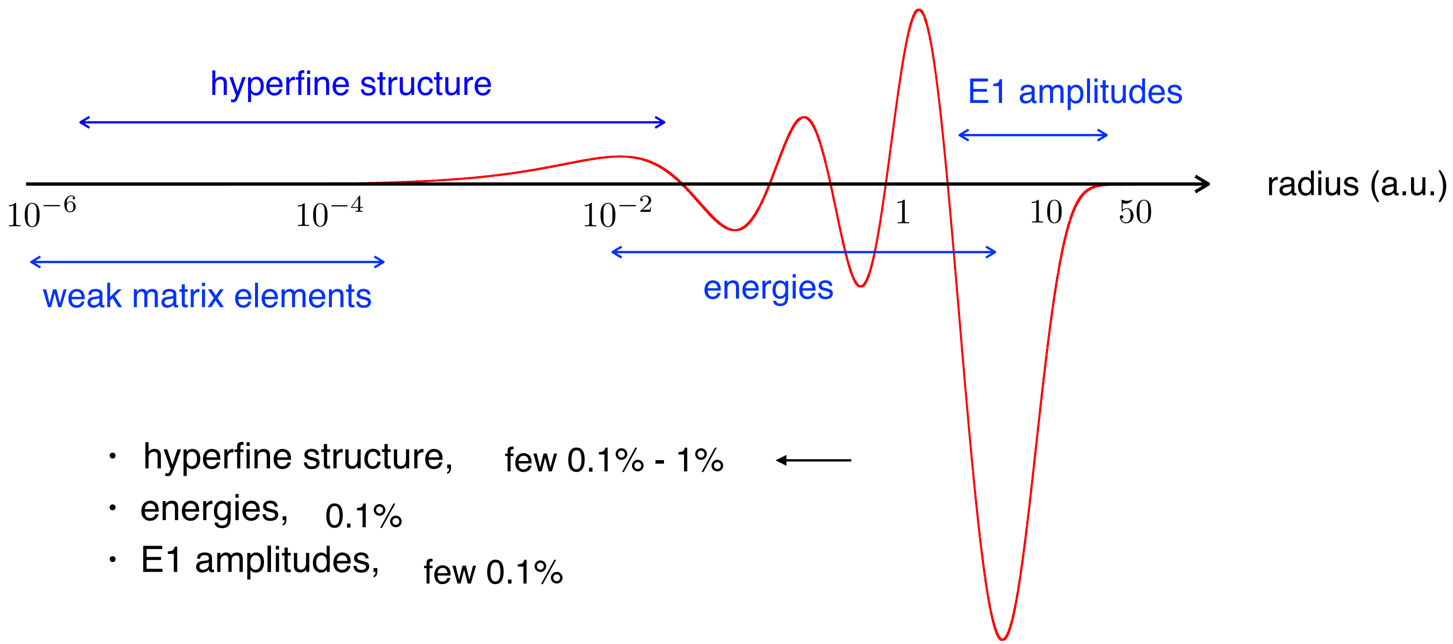
To maximise the discovery potential of precision atomic experiments

- ➤ 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

Benchmarking atomic theory

Upper radial component, Cs 6s:



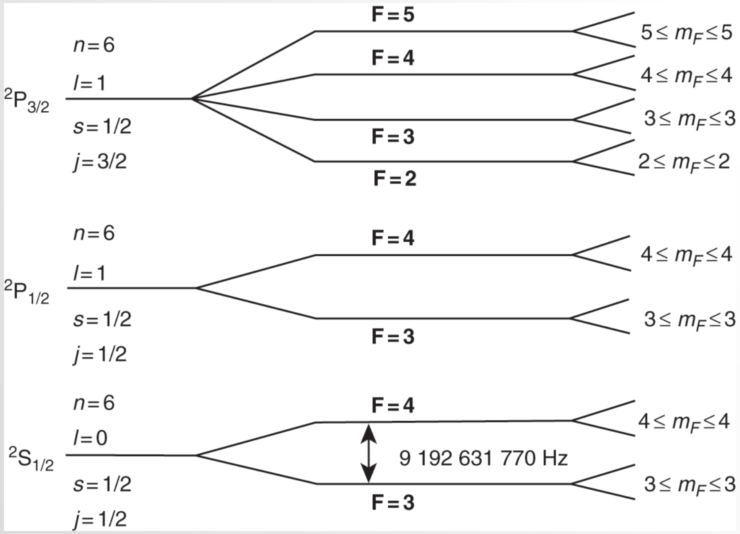
- hyperfine structure, few 0.1% - 1% ⟵
- energies, 0.1%
- E1 amplitudes, few 0.1%

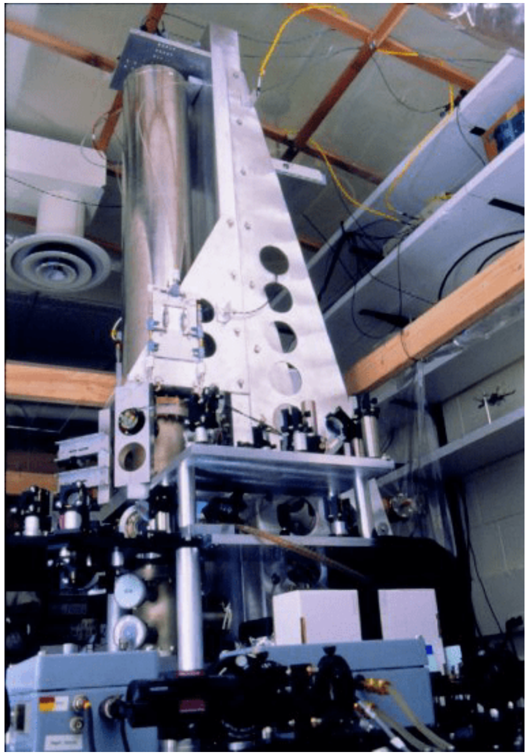
$$E_{\mathrm{PV}} = \sum_n \frac{\langle 7S_{1/2}|D|nP_{1/2}\rangle\langle nP_{1/2}|H_{\mathrm{PV}}|6S_{1/2}\rangle}{E_{6S_{1/2}} - E_{nP_{1/2}}} + \sum_n \frac{\langle 7S_{1/2}|H_{\mathrm{PV}}|nP_{1/2}\rangle\langle nP_{1/2}|D|6S_{1/2}\rangle}{E_{7S_{1/2}} - E_{nP_{1/2}}} = \xi Q_W$$

Fine and hyperfine structure

Fine and hyperfine splitting of levels in ^{133}Cs

Nuclear spin $I = (7/2)^+$,
total angular momentum $\mathbf{F} = \mathbf{I} + \mathbf{J}$

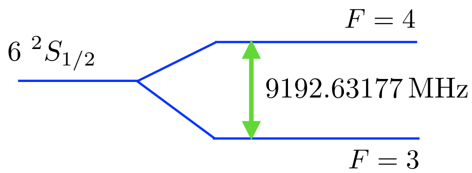




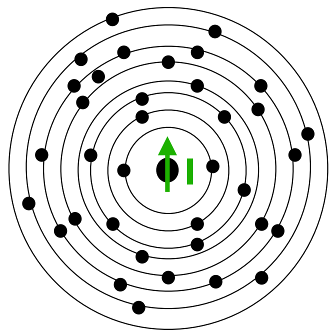
NIST-F2 Atomic clock

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

Hyperfine splitting in cesium



Modeling the hyperfine structure

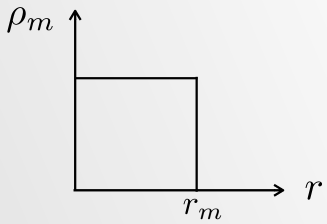


nuclear magnetic moment $\boldsymbol{\mu} = \mu \mathbf{I}/I$

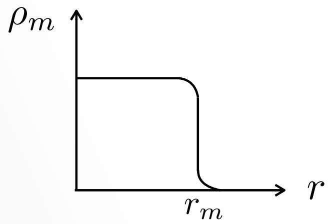
Interaction $h_{\rm hfs} = \frac{1}{c}\frac{\boldsymbol{\mu}\cdot(\mathbf{r}\times\boldsymbol{\alpha})}{r^3}F(r)$

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

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



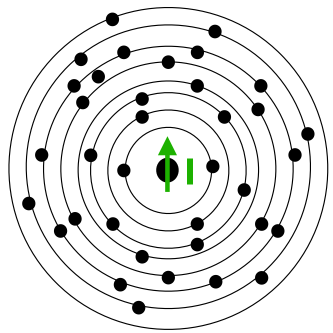
Fermi distribution



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

Hyperfine splitting quantified by hyperfine constant *A*, $A = A_0(1+\epsilon) + \delta A^{\rm QED}$

Modeling the hyperfine structure



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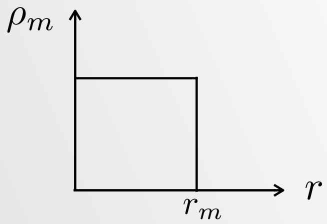
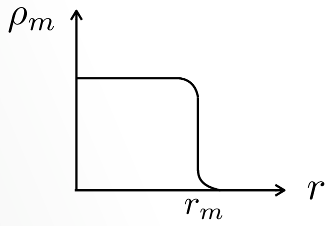


Fermi distribution

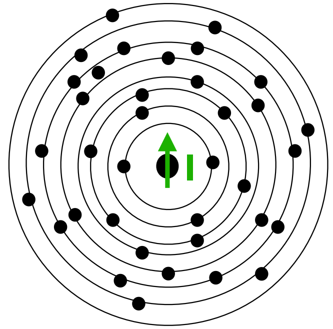


Standard ways to model *F(r)*, until recently

Hyperfine splitting quantified by hyperfine constant *A*, $A = A_0(1+\epsilon) + \delta A^{\mathrm{QED}}$

Many-body result,
finite nuclear charge effect included

Modeling the hyperfine structure



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

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

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

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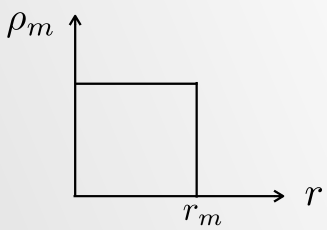
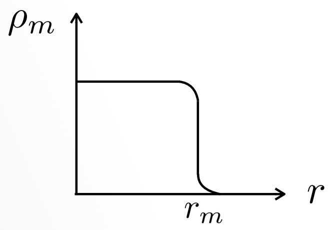


Fermi distribution



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

Hyperfine splitting quantified by hyperfine constant *A*, $A = A_0(1+\epsilon) + \delta A^{\rm QED}$

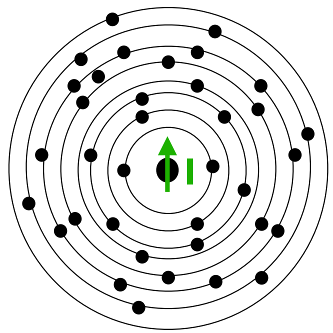
Bohr-Weisskopf (BW) effect or *magnetic hyperfine anomaly*
— finite nuclear magnetisation contribution

Modeling the hyperfine structure

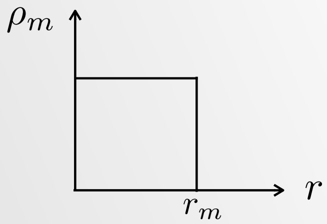
nuclear magnetic moment $\mu = \mu \mathbf{I}/I$

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

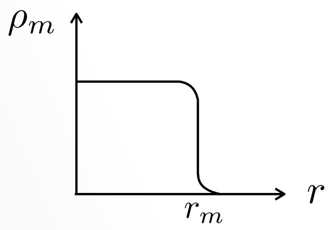
describes radial distribution of µ ;
point-nucleus, $F(r) = 1$



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



Fermi distribution

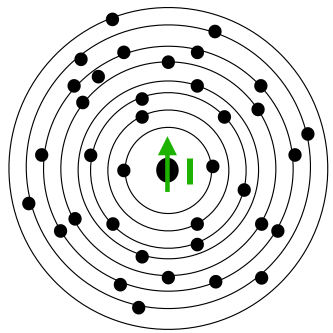


Standard ways to model *F(r)*, until recently

Hyperfine splitting quantified by hyperfine constant *A*, $A = A_0(1+\epsilon) + \delta A^{\text{QED}}$

Quantum electrodynamics
radiative correction

Modeling the hyperfine structure

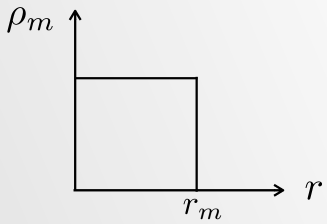


nuclear magnetic moment $\boldsymbol{\mu} = \mu \mathbf{I}/I$

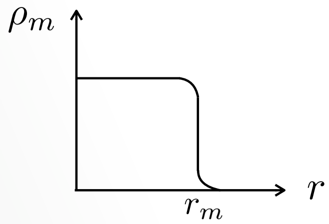
Interaction $h_{\rm hfs} = \frac{1}{c}\frac{\boldsymbol{\mu}\cdot(\mathbf{r}\times\boldsymbol{\alpha})}{r^3}F(r)$

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

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



Fermi distribution



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

Hyperfine splitting quantified by hyperfine constant *A*, $A = A_0(1+\epsilon) + \delta A^{\rm QED}$

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

Hyperfine comparisons

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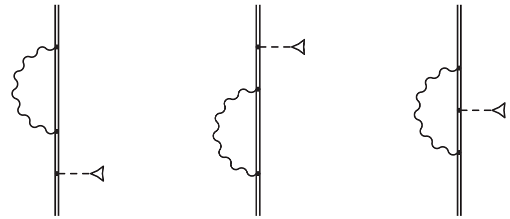
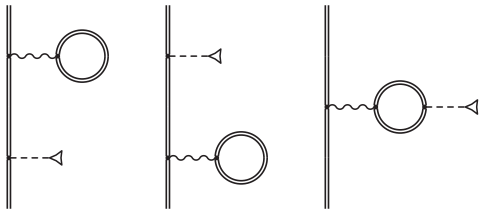
self energy





vacuum polarization

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

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)

Hyperfine comparisons

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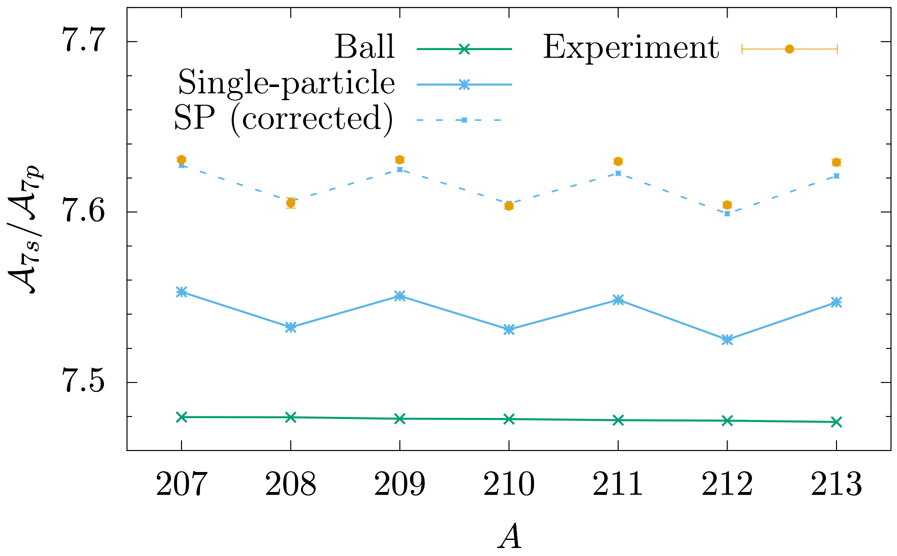
- ➤ QED radiative corrections δA^{QED}
- ➤ Nuclear magnetic moments μ
- ➤ Bohr-Weisskopf effect ϵ

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

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

Found μ with 0.5% uncertainty

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



Roberts and Ginges, PRL (2020)

Hyperfine comparisons

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- ➤ Nuclear magnetic moments μ
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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%**	

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)

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

BW effect — properties

Relative BW correction

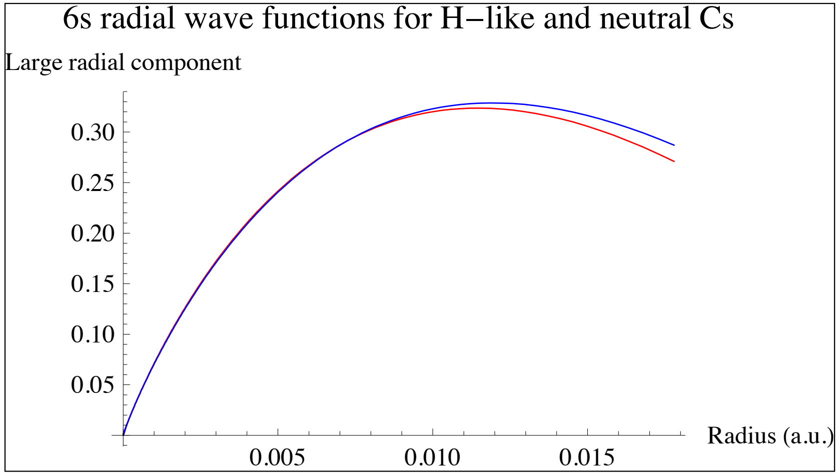
$$\epsilon = \frac{\int_0^{r_m} dr f(r) g(r) [F(r) - 1]/r^2}{\int_0^{\infty} dr f(r) g(r)/r^2}$$

- 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.

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

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)

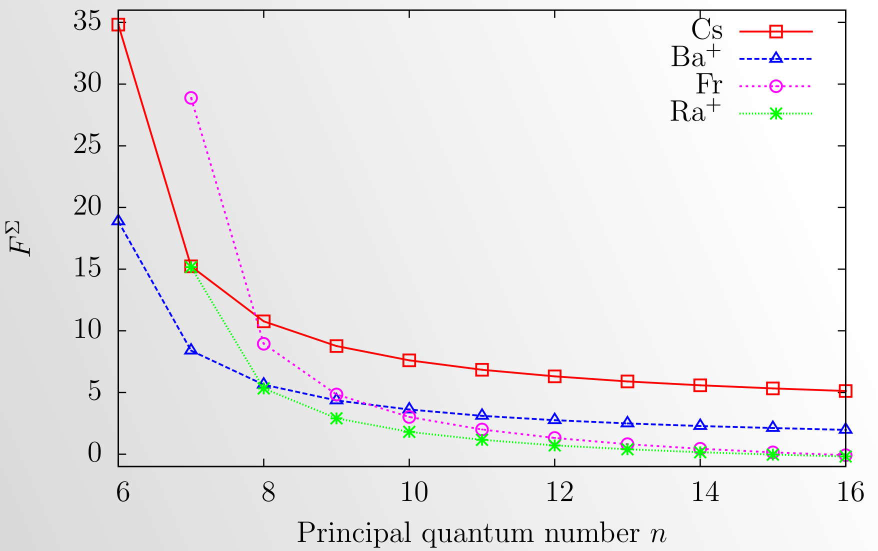
BW effect: ratio method

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

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

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

Correlation corrections (%) to hyperfine intervals for states ns



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

from Quirk et al., arxiv (2022)

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

$A_{\rm hfs}$ (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., PRA (2022)

Ratio method: Ginges and Volotka, PRA (2018)

Differential hyperfine 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)

BW effect: from H-like ion

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

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

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

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

electronic screening factor

$x_{\rm scr}$ *independent of the nuclear model!*

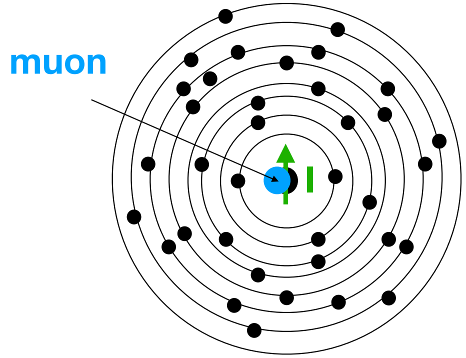
s states: $x_{\rm scr} \approx 1$, negligible uncertainty

Nuclear structure uncertainty is entirely removed from atomic calculations!

Roberts and Ginges, PRA (2022)

from muonic atom experiment

There is historical data on muonic hyperfine structure for Cs! Propose and implement method to extract the BW effect in muonic Cs and translate it to Cs atom



SP model: -0.21%
SP(WS) model: -0.19(14)%
“ball”/fermi model: -0.7%

Empirical result for ^{133}Cs s states,
ε = -0.24(18)%

Sanamyan, Roberts, Ginges, PRL (2023)

Bohr-Weisskopf effect summary

Accurate modelling of the finite magnetisation 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

➤ Tests of quantum electrodynamics

Summary

Lecture 1. How can atoms be used to test the SM and search for new physics?

- Atomic parity violation

Lecture 2. Time-reversal violating electric dipole moments

- Atomic EDMs, enhancement mechanisms

Lecture 3. Precision atomic theory

- Many-body methods, relativistic Hartree-Fock, QED in many-electron atoms

Lecture 4. Adventures at the intersection of atomic and nuclear physics

- Case study in the hyperfine structure

New! Postdoc position opening in our group soon
New! PhD stipend available