The Bohr-Weisskopf effect and atomic parity violation

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Australian Government

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Students, collaborators

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Motivation

To maximise the discovery potential of APV measurements

- Push state-of-the-art atomic calculations to 0.1% precision
 - Development of precision atomic theory
 - Improved benchmarking of atomic theory
- Remove *nuclear structure uncertainties* to enable atomic theory tests below 0.1%



Atomic parity violation

Cs 6S-7S APV amplitude, 0.35% uncertainty

Carl Wieman group (1997)





Parity-violating weak interaction,

 $E_{\rm PV} \propto Z^3$



mage: T. Andrews, University of Colorado



Atomic parity violation

Cs 6S-7S APV amplitude, 0.5% uncertainty

Most precise calculations:

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



Recent calculation: Sahoo and Das [Sahoo, Das, Spiesberger, PRD(L) (2021)]*

Working towards 0.1-0.2% precision:

- Precision Atomic Theory group @ UQ
- Derevianko's group [Tran Tan, Xiao, Derevianko, PRA (2022)]



Atomic parity violation

Experiments in preparation/progress include:

- Cs (Purdue)
- Fr (TRIUMF; Tokyo)
- Ba+ (Seattle)
- Ra+ (Groningen)

	G	roup 1 IA		At	omi	ic P	rope	erties	s of t	he E	leme	ents			N	5	Stand U.S. De	ards and 1 partment of	re of Technology Commerce	18 VIIIA
1	1 1 Hy	² S _{1/2} H (drogen 1.008	2		speed	FREQU 1 sec transit I of light in k constant	JENTLY USE cond = 9 192 63 ion between the vacuum	D FUNDAMEN 11 770 periods of two hyperfine le c h	Fradiation correst radiation correst evels of the grou 299 792 45 6.626 070 x	AL CONSTANT ponding to the ndistate of ¹³³ Cs 8 m s ⁻¹ (10 ⁻³⁴ J s	(exact)	s Fr valu	r the most accu ies of these and er constants, vis	rate I	Physical M Standard F 13	easureme Reference I 14	nt Laborato Data www.nis 15	D FY www.nist. t.gow/srd 16	gov/pml 17	2 'S ₀ He Helium 4.0026
2	2 3 2 3	15 3.5984 ² S _{1/2} Li ithium 6.94 15 ² 25 5.3917 ² S _{1/2}	IIA 4 19 Beryllium 9.0122 15 ² 25 ² 9.3227 12 19	δα δα	elemer electro proton fine-st Rydbe	elementary charge e electron mass m_e proton mass m_p fine-structure constant α Rydberg constant R_m $R_m c$ $R_m hc$ electron volt eV		e m _e c ² m _p α R _s c R _s c R _s hc eV	1.802 177 x 10 ⁻¹⁹ C 9.109 384 x 10 ⁻³¹ kg 0.510 999 MeV 1.872 622 x 10 ⁻²⁷ kg 1/137.035 999 10 973 731.569 m ⁻¹ 3.289 841 960 x 10 ¹⁵ Hz 13.605 693 eV 1.602 177 x 10 ⁻¹⁹ J			pmLnist.gov/constants. Solids Liquids Gases Artificially Prepared		IIIA 5 ² P [*] _{1/2} B Boron 10.81 1s ² 2s ² 2p 8.2980 13 ² P [*] _{1/2}	IVA 6 ³ P ₀ C Carbon 12.011 1s ² 2s ² 2 ² 11.2003 14 ³ P ₀	VA 7 ⁴ S ₃₇₂ N Nitrogen 14.007 1 ² 2 ² 2 ³ 14.5341 15 <u>4</u> S ₃₁₂	VIA 8 ³ P ₂ O 0xygen 15.999 13 ² 28 ² 29 ⁴ 13.0181 16 ³ P ₂	VIIA 9 ² P ₃₂ F Fluorine 18.998 18 ² 28 ² 29 17.4228 17 ² P ₃₂	18 ⁴ 24.5874 10 ¹ S ₀ Neon 20.180 18 ² 28 ² 29 21.5645 18 ¹ S ₀	
4	19 4	Na iodium 12.990 [Ne]3s 1.1391 ² S _{1/2} K	Magnesiu 24.305 [Ne]35 ² 7.6462 20 19	3 50 21	molar B ² D _{3/2} 22	4 IVB 2 ³ F ₂	5 VB 23 ⁴ F ₃₂	6 VIB 24 ⁷ s ₃	8.314 5 J m 7 VIIB 25 ⁶ S ₅₂ Mn	26 ⁵ D ₄	9 VIII 27 ⁴ F ₉₂	10 28 ³ F ₄ Ni	11 IB 29 ² S _{1/2}	12 IIB 30 ¹ %	Al Aluminum 26.982 [Ne]3s ² 3p 5.9858 31 ² P _{1/2} Ga	Silicon 28.085 [Ne]3s ² 3p ² 8.1517 32 ³ P ₀ Ge	Phosphorus 30.974 [Nei3s ² 3p ³ 10.4867 33 ⁴ S _{3/2} As	S Sulfur 32.06 [Ne]35 ² 39 ⁴ 10.3800 34 ³ P ₂ SP	Cl Chlorine 35.45 [Ne]35 ² 3p ⁵ 12.9878 35 ² P ^o ₃₂ Br	Ar Argon 39.948 [Ne]35 ² 39 ⁶ 15.7598 36 ¹ S ₀ Kr
	Po 3 4 37	Atassium 19.098 [Ar]4s 1.3407 2S ₁₁₂ Rb	Calcium 40.078 (Ar]4s ² 6.1132 38 ¹ 5 Sr	Scani 44.9 [Ar]3: 0.56	lium T 56 4 μs ² [Α 15 6 ² D _{3/2} 40	itanium 47.887 1/33 ² 45 ² 8.8281 0 ³ F ₂ Zr	Vanadium 50.942 [Ar]3d ³ 4s ² 6.7462 41 ⁶ D _{1/2} Nb	Chromium 51.996 [Argad ⁵ 4s 6.7085 42 ⁷ S ₃ MO	Manganese 54.938 [Ar]3d ⁵ 4s ² 7.4340 43 ⁵ S _{5/2} TC	lion 55.845 [Arj3d ⁴ 4s ² 7.9025 44 ⁵F₅ RU	Cobait 58.933 [Ar]33 ⁷ 45 ² 7.8810 45 ⁴ F _{5/2} Rh	Nickel 58.693 [Ar]3d ⁴ 4s ² 7.6399 46 ¹ S ₀ Pd	Copper 83.548 [Ar]3d [®] 4s 7.7284 47 ² S _{1/2} Ag	Zinc 65.38 [Ar]3d ¹⁰ 45 9.3942 48 ¹ S ₀ Cd	Gallium 69.723 [Ar]3d [®] 45 ² 4p 5.9993 49 ² P ₁₂ In	Germanium 72.630 [Art]3d ¹⁹ 45 ² 4p ² 7.8904 50 ³ P ₀ SN	Arsenic 74.922 [Ar]3d ¹⁹ 4s ² 4p ³ 9.7886 51 ⁴ S ^o ₃₂ Sb	Selenium 78.971 (Ar)3d ¹⁰ 4s ² 4p ⁴ 9.7524 52 ³ P ₂ TC	Bromine 79.904 [Ar]3d ¹⁰ 4s ² 4p ⁵ 11.8138 53 ² P ₃₂	Knypton 83.798 [Arj3d ¹⁰ 4s ² 4p ⁶ 13.9998 54 ¹ S ₀ Xe
e	55 55	ubidium 35.468 [Kr]5s 1771 ² S _{1/2} CS Sesium	Strontium 87.62 [Kr]55 5.6949 56 849 Barjum	Yttri 88.9 [Kr]44 6.2	um Zi 06 9 155 ² 1K 173 6 72	irconium 91.224 1rj4d ² 55 ² 8.6341 2 ³ F ₂ Hf	Niobium 92.906 [K144 ⁴ 55 6.7589 73 ⁴ F _{3/2} Ta	Molybdenum 95.95 [Kr]4d ⁵ ss 7.0924 74 ⁵ D ₀ W Tungsten	Technetium (98) [Krj4d 55 ² 7.1194 75 ⁶ S ₅₂ Re Bhenium	Ruthenium 101.07 [Kr)4d ⁷ 5s 7.3605 76 ⁵ D ₄ OS Osmium	Rhodium 102.91 [Kr]4d ⁸ 5s 7.4589 77 ⁴ F _{9/2} [r kridium	Palladium 106.42 [Kr)4d ¹⁰ 8.3369 78 ³ D ₃ Pt Platinum	Silver 107.87 [Kr]4d ¹⁰ 55 7.5762 79 ² S _{1/2} AU Gold	Cadmium 112.41 [Kr]4d ¹⁰ 5s ² 8.9938 80 ¹ S ₀ Hg Mercury	Indium 114.82 [Kr]4d ¹⁰ 5s ² 5p 5.7884 81 ² P ^o _{1/2} Thallium	Tin 118.71 [Kr]4d ¹⁰ 5s ² 5p ² 7.3439 82 ³ P ₀ Pb Lead	Antimony 121.76 [Kr]4d ¹⁰ 55 ² 5p ³ 8.6084 83 ⁴ S _{3/2} Bi Bismuth	Tellurium 127.60 [Kr]4d ¹⁰ 5s ² 5p 9.0097 84 ³ P ₂ PO Polonium	lodine 128.90 [Kr]4d ¹⁰ 5s ² 5p ⁵ 10.4513 85 ² P ^o ₃₂ At Astatine	Xenon 131.29 [Kr]4d ¹⁰ 55 ² 59 ⁰ 12.1298 86 ¹ S ₀ Rn Badon
7	87 7 Fr	132.91 (Xe)6s 3.8939 ² S _{1/2} Fr ancium	137.33 [Xej65 ² 5.2117 88 ¹ 5 Ra Radium	. Y	Diagonal dia	178.49 4f ¹⁴ 5d ² 65 ² 8.8251 4 ³ F ₂ Rf herfordium	180.95 [Xej4f ⁴⁵ sd ³ 6s ² 7.5498 105 ⁴ F ₃₂₂ Db Dubnium	183.84 [Xe]4 ^{4*} 5d ⁴ 6s ² 7.8040 106 0 Seaborgium	186.21 [Xe]4f ⁴⁵ d ⁵ 6s ² 7.8335 107 sr2 Bh Bohrium	190.23 [xej4f ⁴⁵ 5d ⁶ 65 ² 8.4382 108 4 HS Hassium	192.22 [Xe]4f ^M 5d ⁷ 65 ² 8.9670 109 Mt Meitnerium	195.08 [Xe]4f [*] 5d [*] 6s 8.9588 110 DS Darmstadtium	196.97 [xe)4f ⁴⁵ 5d ¹⁰ 65 9.2256 111 Rg Roentgenium	200.59 [Xej4f ⁴⁵ 5d ¹⁰ 65 10.4375 112 Cn Copernicium	204.38 [Hg]6p 6.1083 113 Nhonium	207.2 [Hg]6p ² 7.4167 114 Fl Flerovium	208.98 [Hg]6p ³ 7.2855 115 MC Moscovium	(209) [Hg]6p 8.414 116 LV Livermorium	(210) [Hg]6p ⁵ 9.3175 117 TS Tennessine	(222) [Hg]6p 10.7485 118 Og Oganesson
	Ate Nur	(223) Rn]7s 1.0727 omic mber	(220) [Rn]7s ² 5.2784 Ground State		sahides	⁽²⁰⁷⁾ ⁽²⁰⁷⁾ ⁽¹⁾ ⁽²⁾	(2007) (Fini)5f ¹⁴ 6d ³ 7s ² 8.8 58 ¹ G [*] ₄ Ce	(271) [Rn]5t ¹⁴ 6d ⁴ 75 ² 7.8 59 ⁴ T ₉₂ Pr	(270) [Rn]5f ¹⁴ 6d ⁵ 75 ² 7.7 60 ⁵I₄ Nd	(2009) [Rn]51 ¹⁴ 6d ⁴ 7s ² 7.8 61 ⁶ H ₅₂₂ Pm	62 ⁷ Fa Sm	63 ^s _m	64 ³ D ² Gd	(285) 65 ຳຕ _{ຳ522} Tb	(280) 66 ⁵ I ₈ Dy	(289) 67 ⁴ 1°52 HO	⁽²⁸⁹⁾ 68 ³ н ₆ Er	(283) 69 ² F ^o ₇₇₂ Tm	(294) 70 ¹ S ₀ Yb	(294) 71 ² 0 ₃₂ Lu
N Itar Ato	Symbo lame ndard omic ght [†] (Da		Cerium 140.12 e]4f5d6s ²		inides Lanth	nthanum 138.91 (e)5d65 ² 5.5789 ² D _{3/2}	Cerium 140.116 [Xe]4f5d6s ² 5.5388 90 ³ F ₂ Th	Praseodymium 140.91 [Xe]44 ³ 65 ² 5.4702 91 ⁴ K _{11/2} Pa	Neodymium 144.24 [xe]4f ⁴ 6s ² 5.5250 92 ⁵ L ^o U	Promethium (145) [Xe]4f ⁵ 65 ² 5.577 93 ⁶ L _{11/2} Np	Samarium 150.36 [xe)4 ⁷ 6s ² 5.6437 94 ⁷ F ₀ PU	Europium 151.96 [Xe]4 ⁷ 65 ² 5.6704 95 ⁸ S ^o _{7/2} Am	Gadolinium 157.25 [Xe]44 ⁷ 5d6s ² 6.1498 96 ⁹ D ₂ ² Cm	Terbium 158.93 [Xe)4f ⁶ 6s ² 5.8838 97 ⁶ H ⁶ 152 Bk	Dysprosium 162.50 [Xe]4t ¹⁰ 65 ² 5.9391 98 ⁵ L ₈ Cf	Holmium 164.93 [Xe)4f ¹⁶ 5 ² 6.0215 99 ⁴ T [*] ₁₅₂ ES	Erbium 167.26 [Xe]4t ¹² 6s ² 6.1077 100 ³ H ₆ Fm	Thulium 168.93 [Xe]4f ¹³ 6s ² 6.1843 101 ² F _{7/2} Md	Ytterbium 173.05 [Xe]4f ¹⁴ 65 ² 6.2542 102 ¹ S ₀ NO	Lutefium 174.97 [Xe]4f ⁴⁵ d6s ² 5.4259 103 ² P _{1/2} Lr
0	Groun	d-state	lonizat	on	TO V IR	(227) Rn]6d7s ²	232.04 [Rn]6d ² 7s ²	231.04 [Rn]5f ² 6d7s ²	238.03 [Rn]5f ³ 6d7s ²	(237) (Rn)5f ⁴ 6d7s ²	(244) (Rn)5/ ⁶ 75 ²	(243) (Rn)5f ⁷ 75 ²	(247) (Rn)5f ⁷ 6d7s ²	(247)	(251) [Rn]5f ¹⁰ 7s ²	(252) (Rn)5f ¹¹ 7s ²	(257) (Rn)5f ¹² 7s ²	Mendelevium (258) [Rn]5f ¹³ 75 ²	(259) (Rn)5f ¹⁴ 7s ²	(266) (Rn)5f ¹⁴ 7s ² 7p



Benchmarking atomic theory





Benchmarking atomic theory



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



Benchmarking atomic theory



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



NIST-F2 Atomic clock

Primary standard for the SI unit for time, the second

Hyperfine splitting in cesium









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

$$\begin{tabular}{l} \begin{tabular}{l} \end{tabular} \\ \end{tabular} Many-body \ result, \\ \end{tabular} finite \ nuclear \ charge \ effect \ included \end{tabular}$$





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

$$\uparrow$$
Bohr-Weisskopf (BW) effect –
finite nuclear magnetization contribution





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

$$\uparrow$$
Quantum electrodynamics
radiative correction







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

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

are known well (contributing < 0.1% uncertainty to hyperfine constants)



QED corrections

Self-energy and vacuum polarisation corrections evaluated for:

- lowest states of alkali-metal atoms;
- ground-states of Rb, Cs, Fr, Ba+, Ra+



QED corrections (%) to ground state 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)



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	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)	

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



7.7

7.6

7.5

207

208

209

 $\mathcal{A}_{7s}/\mathcal{A}_{7p}$

Nuclear magnetic moments

Our atomic theory uncertainty is better \Rightarrow can find $\mu(Fr)!$

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

Test/control BW effect using:

- ratios of A for different states
- Empirical BW value extracted from H-like ²⁰⁹Bi

Determined µ with an uncertainty of 0.5%

211



210

A



212

213









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!

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

Also, in the nuclear region, for heavy systems:

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



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



To remove or extract?

Ratio method

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

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

Correlation corrections (%) to hyperfine intervals for states ns



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

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



Ratio method:Ginges and Volotka, PRA (2018)Ref. [16]Grunefeld, Roberts, Ginges, PRA (2019)Experiment:Quirk et al., PRA (2022)

Differential hyperfine anomaly

Ratio of hyperfine constants of different isotopes of the same element,

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

and typically for nuclei of different spin,

$$^{1}\Delta^{2} \approx \epsilon^{(1)} - \epsilon^{(2)}$$

Gives the difference in the BW effect for different isotopes.

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

From H-like experiments to heavy atom calculations

Accurate empirical BW effect from H-like ion measurements,

 $\mathcal{A}_{\mathrm{expt}}^{\mathrm{1s}} = \mathcal{A}_{0}^{\mathrm{1s}}(1 + \epsilon^{\mathrm{1s}}) + \delta \mathcal{A}_{\mathrm{QED}}^{\mathrm{1s}}.$

BW effect with $\sim 1\%\,$ precision from measurements with H-like $^{203,205}{\rm TI}$, $^{207}{\rm Pb}$, $^{209}{\rm Bi}$.

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

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

screening factor

For s states, $x_{\rm scr} \approx 1$, the uncertainty is negligible, and $x_{\rm scr}$ is independent of the nuclear model!

Nuclear structure uncertainty is entirely removed from atomic calculations!





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
- Tests of quantum electrodynamics

