Laser Cooling of Ra ions for Atomic Parity Violation

CERN-INTC-2017-069

CERN, June 27, 2017

Lorenz Willmann

university of groningen / faculty of mathematics and natural sciences / van swinderen institute for particle physics and gravity

CERN-INTC-2017-069

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Laser Cooling of Ra ions for Atomic Parity Violation

May 31, 2017

L. Willmann[1], K. Jungmann[1], N. Severijns[2], K. Wendt[3]

[1] *Van Swinderen Institute, FSE, University of Groningen, The Netherlands*
[2] *University of Leuven, Belgium*
[3] *Johannes Gutenberg University Mainz, Germany*

Spokesperson: [Lorenz Willmann] [l.willmann@rug.nl]
Contact person: [Lorenz Willmann] [l.willmann@rug.nl]

Abstract: The observation of weak interactions in atomic systems have played a mayor role in the acceptance of the Standard Model of the electroweak unification. In particular atomic parity violation (APV) is the only route to investigating contribution of the weak interactions at low momentum transfer and ions of the alkaline earth metal

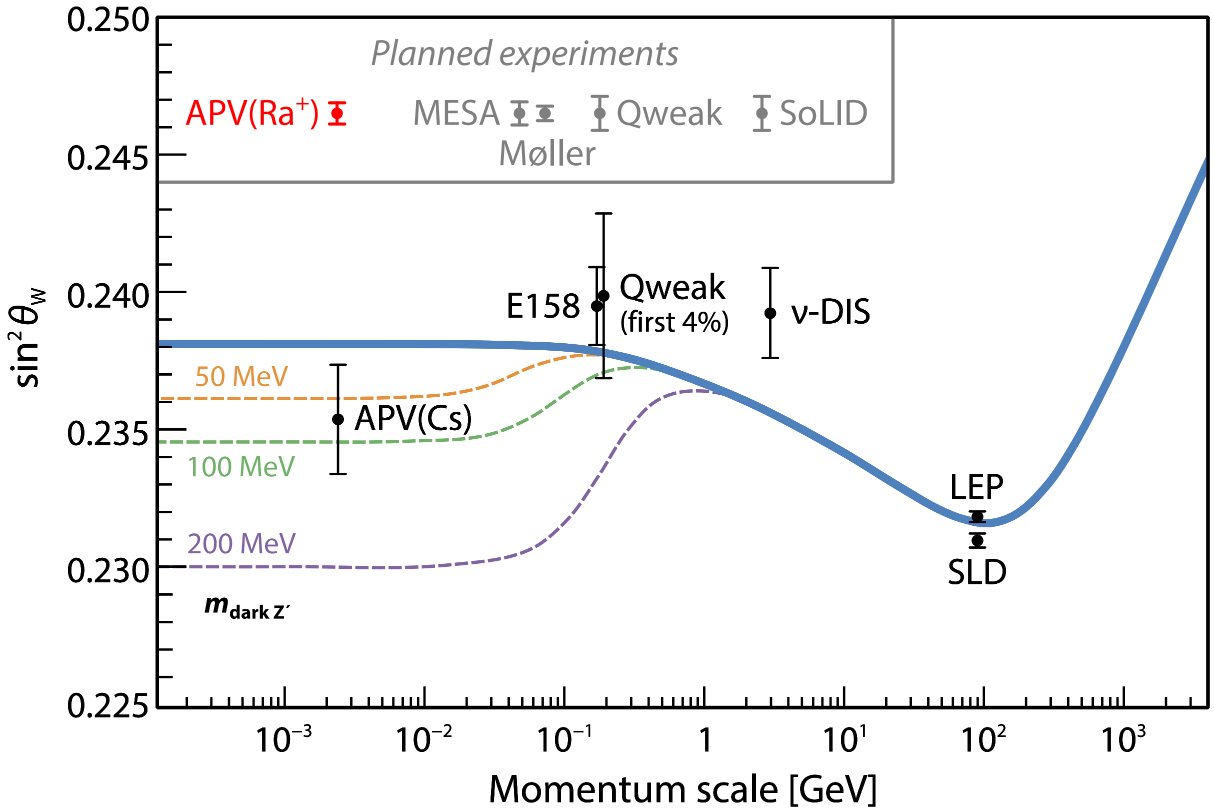
Atomic Parity Violation

THE WEINBERG ANGLE

Atomic parity violation (APV)

$\sin^2(\theta_W) = (1 - (M_W/M_Z)^2) + \text{rad. corrections} + \text{New Physics}$

Standard Model

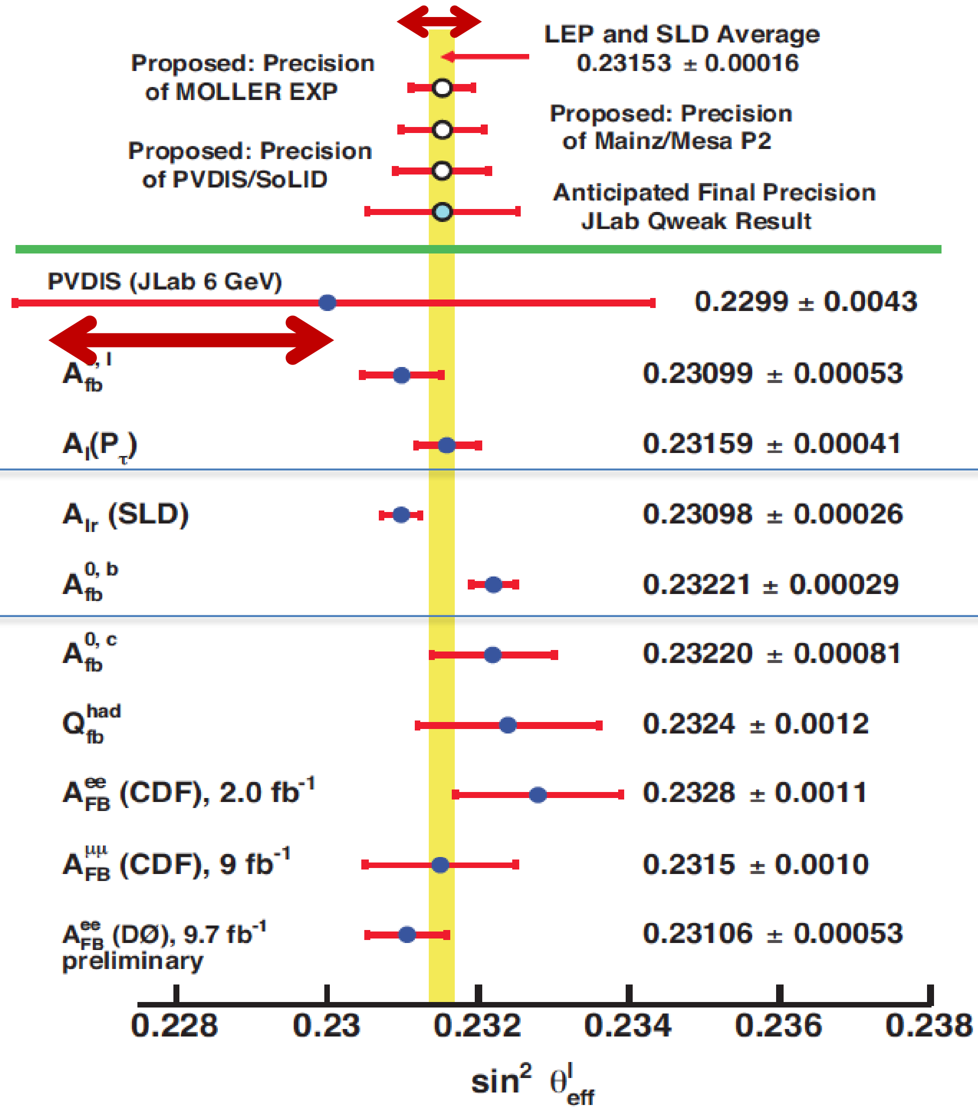


Kumar, Marciano, Annu. Rev. of Nucl. Part. Sci. **63,** 237 (2013)
Davoudiasl, Lee, Marciano, Phys. Rev. D **89**, 095006 (2014); Phys. Rev. D **92**, 055005 (2015)

Summary: Measurements of $\sin^2\theta_{W(effective)}$

Ra⁺

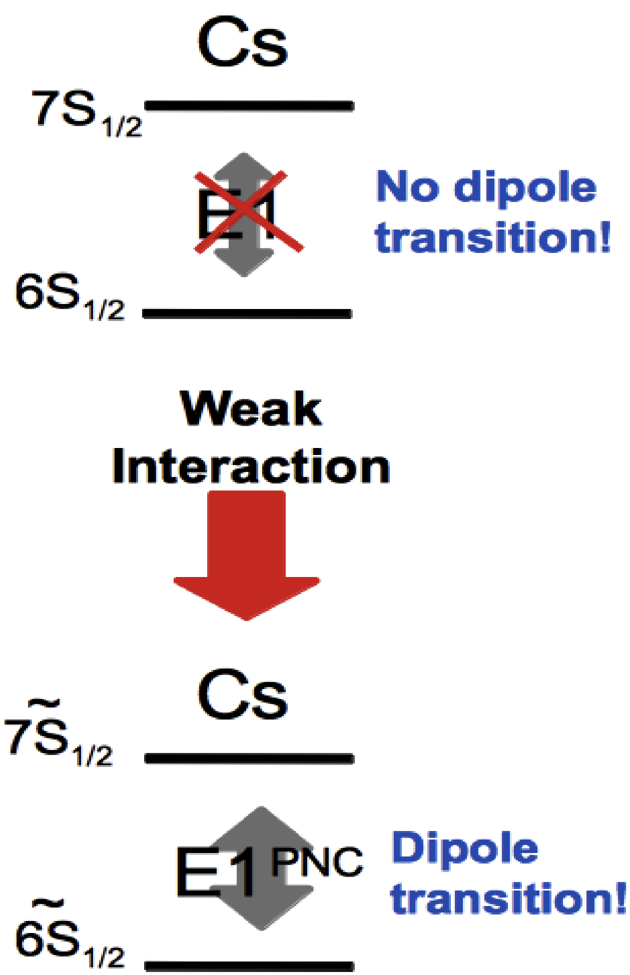
Cs

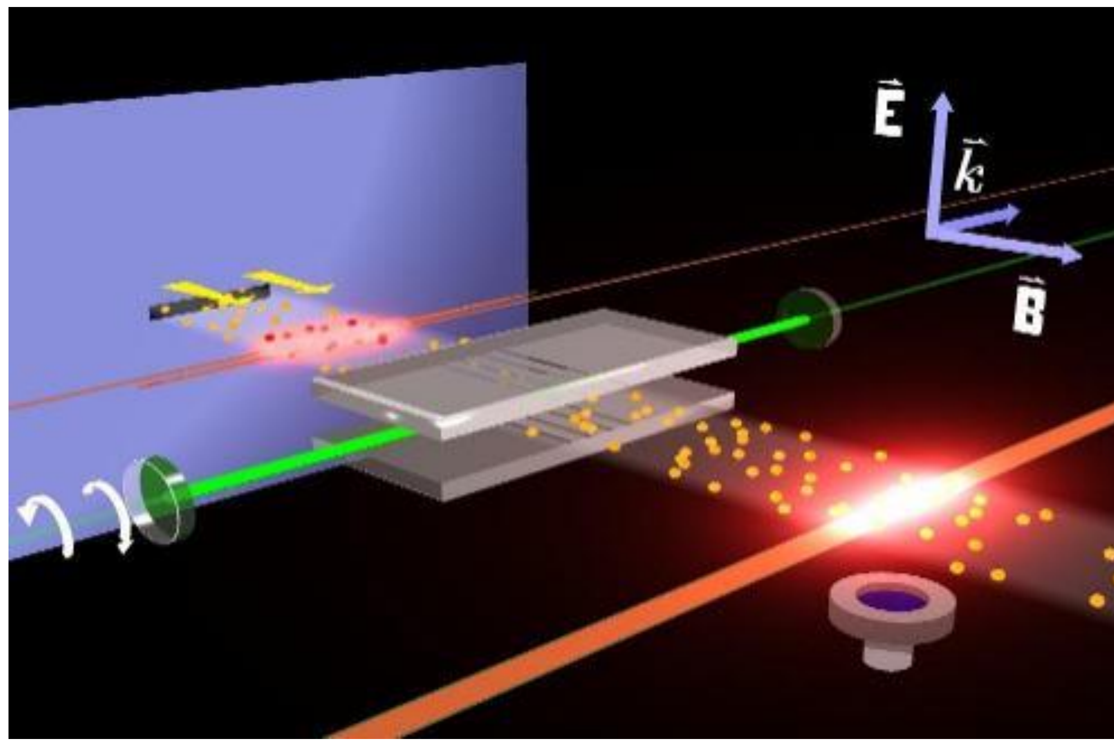


F. Maas, PSI2016

Cs Atomic Parity Violation

Stark induced forbidden transition
(C. Wieman et al. 1985-1996)



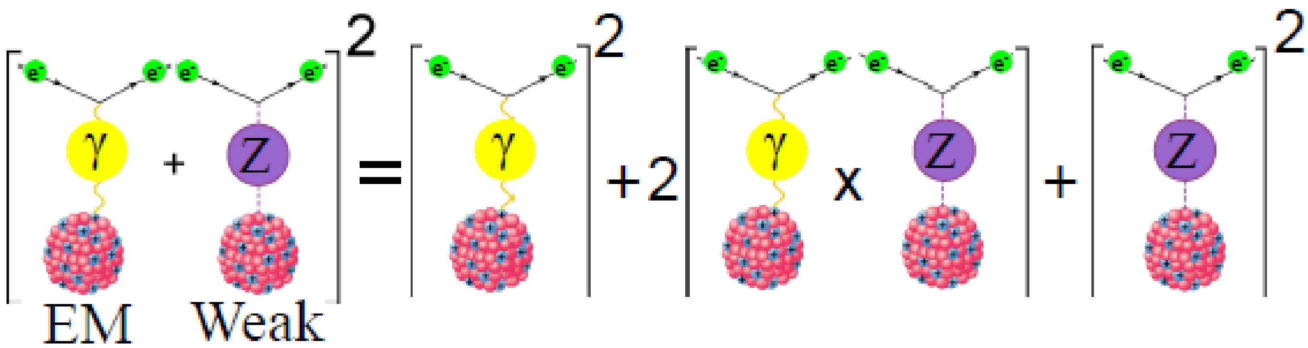


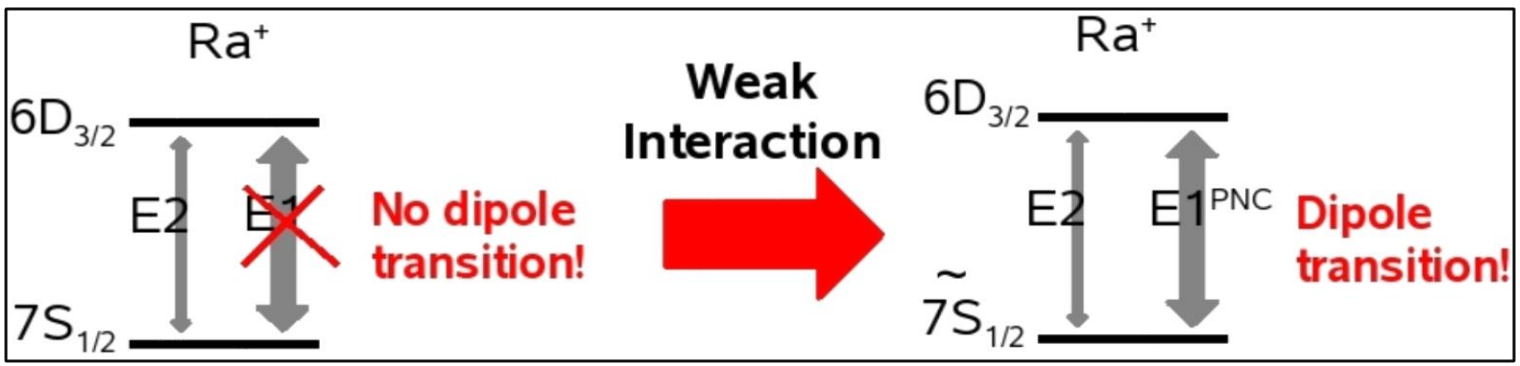
Experimental Method

SINGLE ION APV

Weak Interaction in Atoms

Interference of EM and Weak interactions





$$E1_{PNC} = K_r \; Z^3 \, Q_w = K_r \; Z^3 \, (- N + Z \, (1\text{-}4\sin^2 \theta_W))$$

Measurement

Atomic Theory

Heavy System

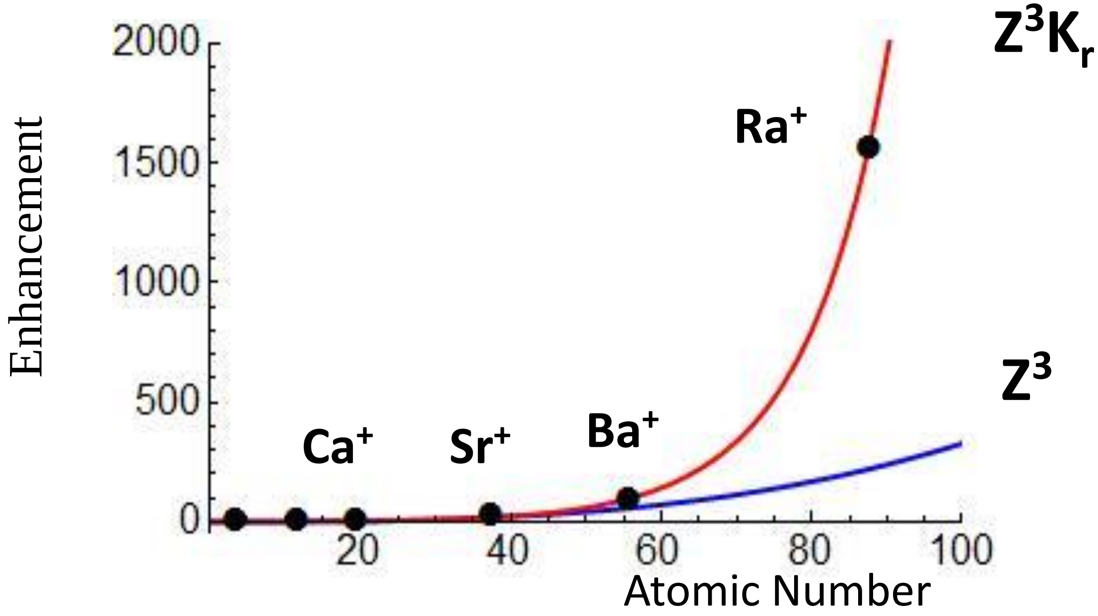
Scaling of the APV

$\langle nS_{1/2} | H_W | nP_{1/2} \rangle \propto K_r Z^3$

increase faster than Z^3

K_r relativistic enhancement factor

(Bouchiat & Bouchiat, 1974)



Ra+ effects larger by:

20 (Ba+)

50 (Cs)

L.W. Wansbeek *et al*., Phys. Rev. A **78**, 050501 (2008)

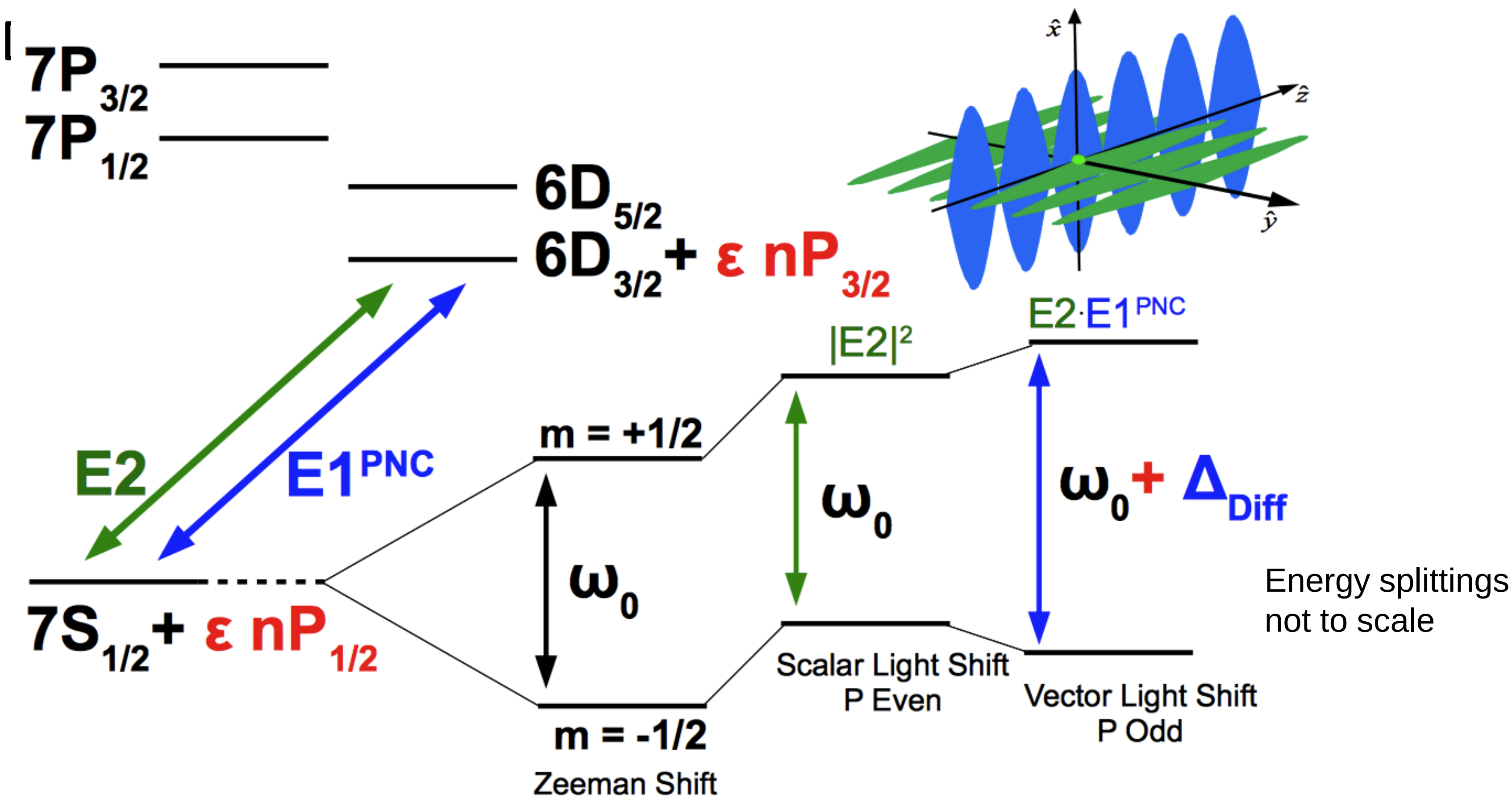
Relativistic coupled-cluster (CC) calculation of $E1_{APV}$ in Ra^+

$$\mathbf{E1_{APV} = 46.4(1.4) \cdot 10^{-11}\, iea_0\, (-Q_w/N)} \quad \textbf{(3\% accuracy)}$$

Other results:

$45.9 \cdot 10^{-11}\, iea_0\, (-Q_w/N)$ (R. Pal *et al.,* Phys. Rev. A **79**, 062505 (2009), Dzuba *et al.*, Phys Rev. A **63**, 062101 (2001).)

Experiment requires Trapping



$$|\Omega|^2 = |\Omega^{E2}_{m'm} + \Omega^{PNC}_{m'm}|^2 \sim |\Omega^{E2}_{m'm}|^2 + 2Re|\Omega^{PNC}_{m'm}\Omega^{E2}_{m'm}|$$

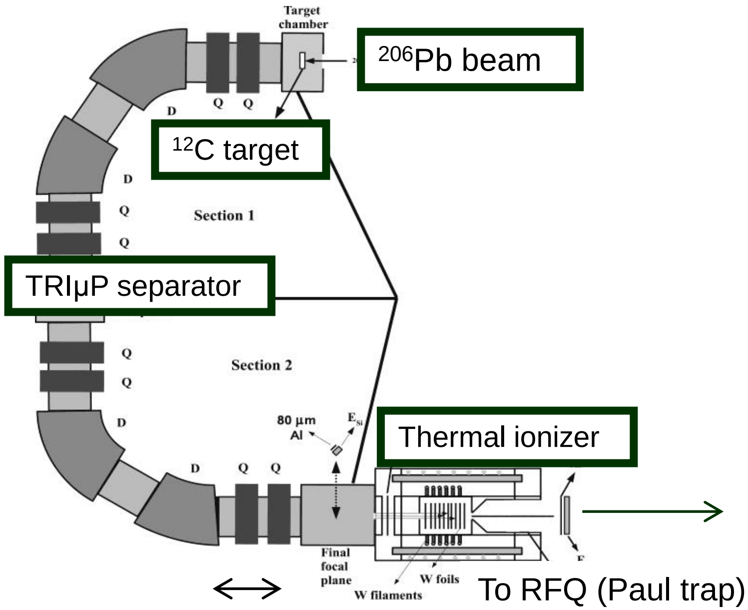
N. Fortson, Phys. Rev. Lett. 70, 2383-2386 (1993)

Previous Work

TRAPPING RA ION

Radium Isotopes

$^{206}Pb + ^{12}C \rightarrow {}^{A}Ra + (218\text{-}A)\ n$



To RFQ (Paul trap)
Rate after $5 \times 10^4/s$

^{225}Ra

extraction from ^{229}Th source (ANL)
Long lived ^{229}Th source in an oven (TRIμP)

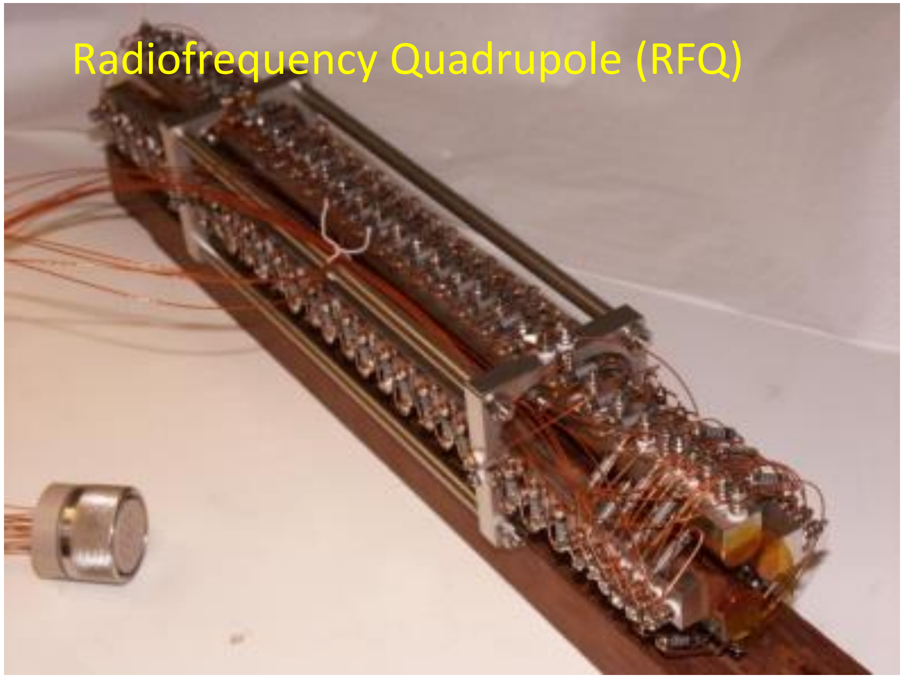
Other Isotopes

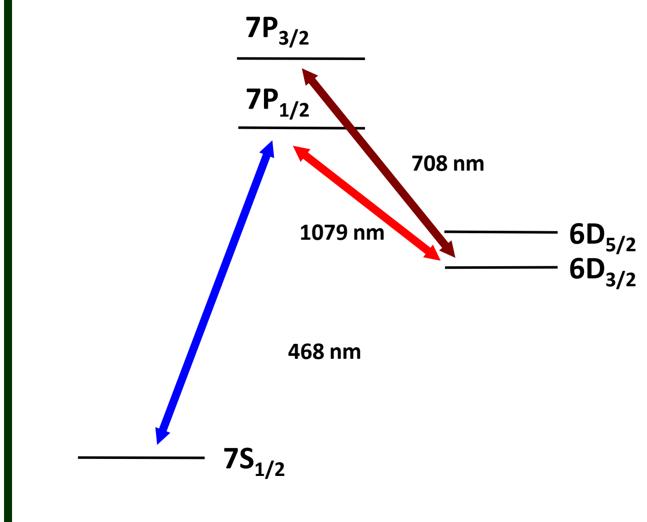
Online production at accelerator facilities
e.g.
TRIμP (flux > 10^5/s) (until 2013)
ISOLDE (flux < 10^7/s)

		Lifetime	Spin
TRIμP@KVI	209	4.6(2) s	5/2
	211	13(2) s	1/2
	212	13.0(2) s	
	213	2.74(6) m	1/2
	214	2.46(3) s	
Sources or fragmentation	221	28.2 s	5/2
	223	11.43(5) d	3/2
	224	3.6319(23) d	
	225	14.9(2) d	1/2
	226	1600 y	
	227	42.2(5) m	3/2
	229	4.0(2) m	5/2

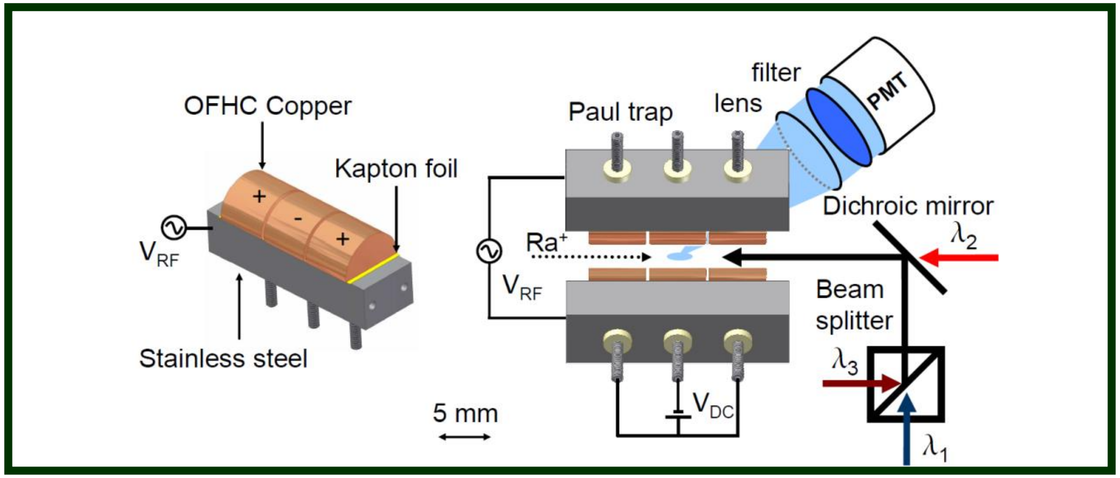
$\Delta N < 10$ (212 ↔ 224)

Trapped Ra^+ Spectroscopy



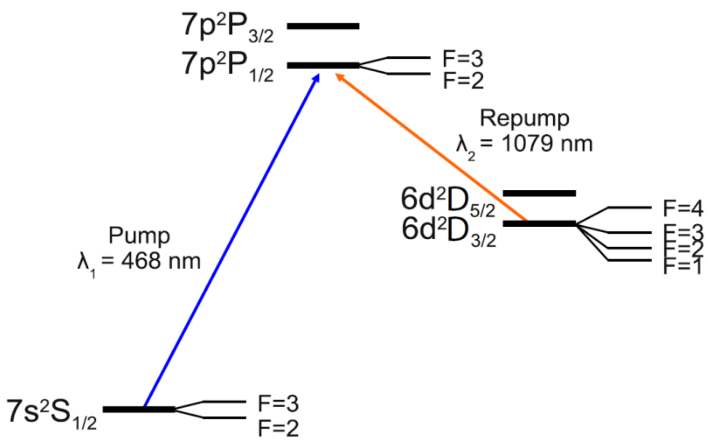


Level Scheme of Ra^+



Hyperfine Structure of 6d $^2D_{3/2}$ in Ra^+

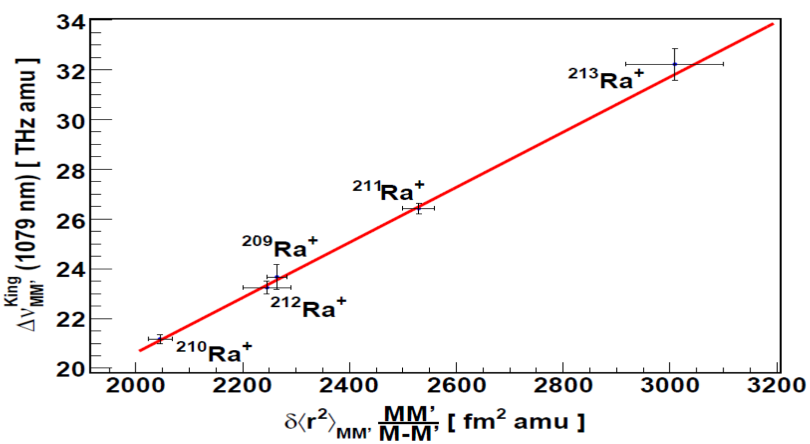
$^{211,209}Ra^+$ (I=5/2)

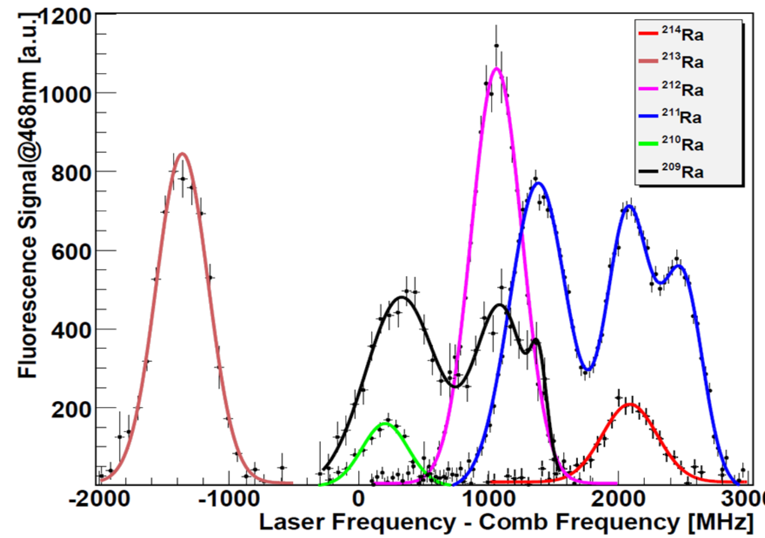


		This work	Theory
$^{211}Ra^+$	A	151(2)	155* [4], 150* [10],155* [16]
	B	103(6)	147(12)** [10]
$^{209}Ra^+$	A	148(10)	153* [4], 148* [10], 153* [16]
	B	104(38)	122(12)** [10]

~ 3,5 σ

Probe of atomic wave functions at the origin

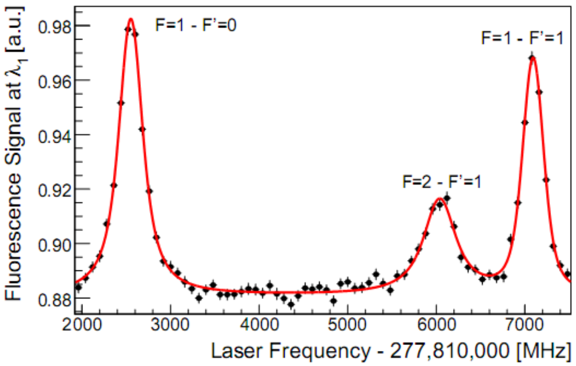




Probe of atomic theory & size and shape of the nucleus

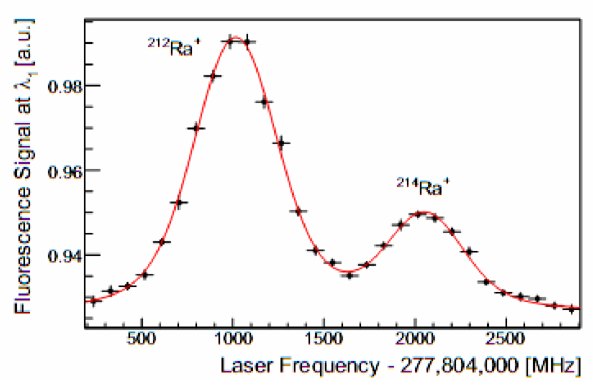
O. O Versolatao et. al., Phys. Lett. A375 (2011) 3130-3133
G. S. Giri et al. Phys. Rev. A 84, 020503(R) (2011)
[10] B.K. Sahoo *et al.* Phys. Rev. A, 76 (2007)
B.K. Sahoo *et al.* Phys. Rev. A, 79, 052512 (2009)

Summary Ra⁺ Measurements



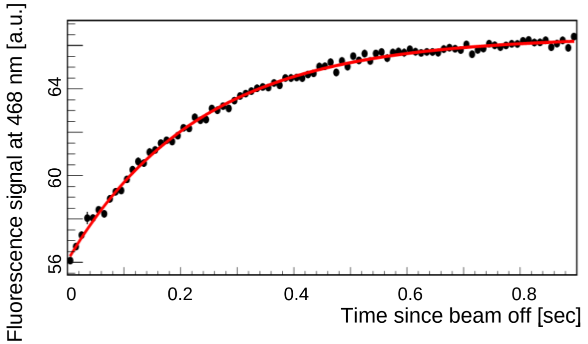
Hyperfine Structure:

Atomic wave functions at the origin



Isotope Shifts:

Atomic theory & size and shape of the nucleus



State lifetime:

Probe of S-D E2 matrix element

agreement with atomic structure calculations at % level

Atomic Properties

COMPLEMENTARY RADIUM EXPERIMENTS

Activity at CERN/ISOLDE

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Collinear resonance ionization spectroscopy of radium ions

CERN-INTC-2014-043 / INTC-P-413
30/05/2014

K.M. Lynch[1], J. Billowes[2], M.L. Bissell[1], I. Budinčević[1], T.E. Cocolios[2], T. Day Goodacre[2,3], R.P. de Groote[1], V.N. Fedosseev[3], K.T. Flanagan[2], S. Franchoo[4], R.F. Garcia Ruiz[1], H. Heylen[1], T. Kron[5], B.A. Marsh[3], G. Neyens[1], R.E. Rossel[3,5,6], S. Rothe[3], I. Strashnov[2], H.H. Stroke[7], K.D.A. Wendt[5].

[1] *KU Leuven, Instituut voor Kern- en Stralingsfysica, B-3001 Leuven, Belgium*
[2] *School of Physics and Astronomy, The University of Manchester, Manchester, M13 9PL, UK*
[3] *EN Department, CERN, CH-1211 Geneva 23, Switzerland*
[4] *Institut de Physique Nucléaire d'Orsay, F-91406 Orsay, France*
[5] *Institut für Physik, Johannes Gutenberg-Universität Mainz, D-55128 Mainz, Germany*
[6] *Hochschule RheinMain, Fachbereich Design Informatik Medien, D-65197 Wiesbaden, Germany*
[7] *Department of Physics, New York University, NY, New York 10003, USA*

Spokesperson and Local Contact: Kara M. Lynch (kara.marie.lynch@cern.ch)

muX@PSI

Radium Charge Radium

Beamtime to improve sensitivity of muonic x-ray measurements this summer

Measurement of the charge radius of radium

A. Antognini[1,2], N. Berger[3], D. vom Bruch[3], P. Indelicato[4], K. Jungmann[5], K. Kirch[1,2], A. Knecht[1], A. Papa[1], R. Pohl[6], M. Pospelov[7,8], E. Rapisarda[1], N. Severijns[9], F. Wauters[3], and L. Willmann[5]

Abstract

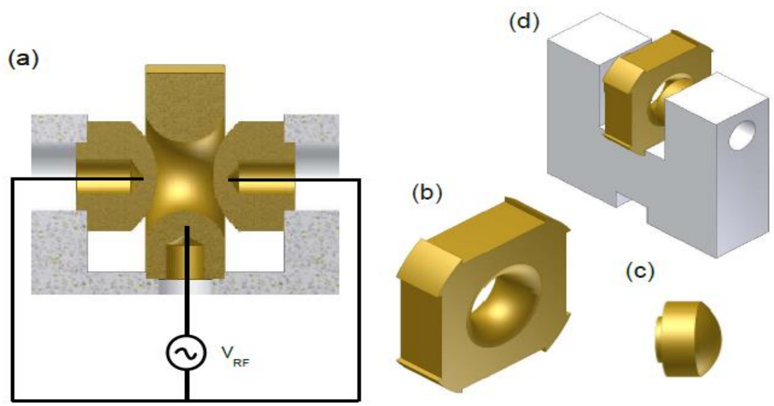
The charge radius of a nucleus is one of its defining parameters and of inherent importance for the understanding and the calculation of its interactions. In the realm of radioactive atoms only a few absolute charge radii have been measured and especially in the case of radium an upcoming experiment aiming at measuring atomic parity violation in a single Ra^+ ion will only be able to reach its full potential if the so far unmeasured radium charge radius is known to 0.2% or better.

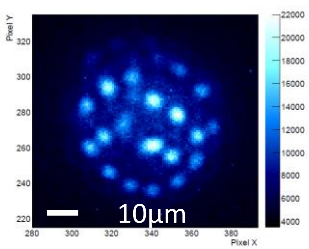
We propose to employ the slow muon beam line developed for the Lamb shift experiment in order to stop the negative muons in a radium target of several micrograms. Precise gamma spectroscopy of the emitted muonic X-rays will allow the extraction of the radium charge radius with sufficient accuracy. Additionally also the unknown charge radii of rhenium, curium, and polonium will be obtained over the course of the experimental campaign.

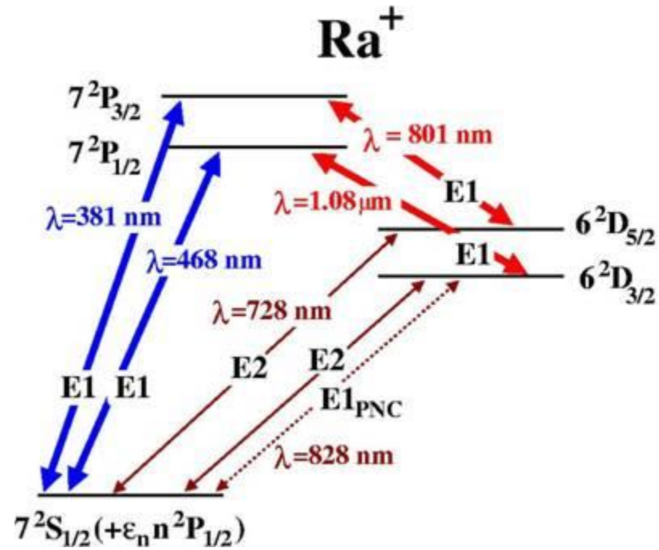
Ba^+ Atomic Parity Violation

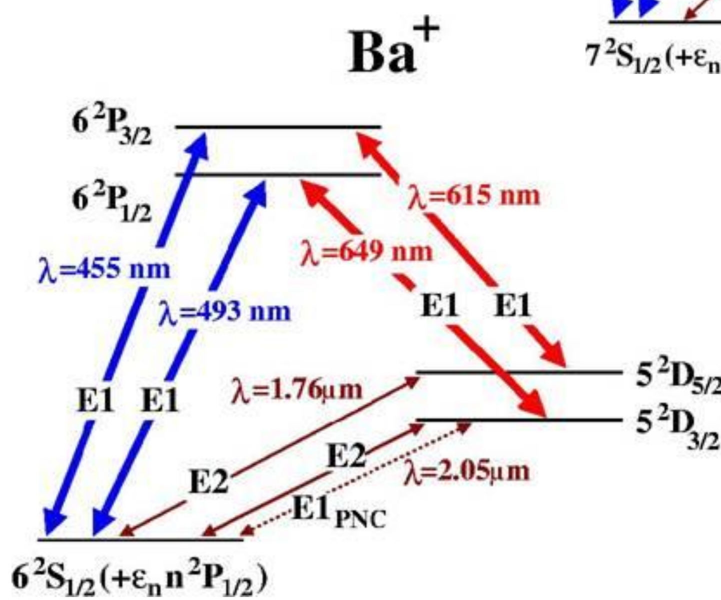
BARIUM ION

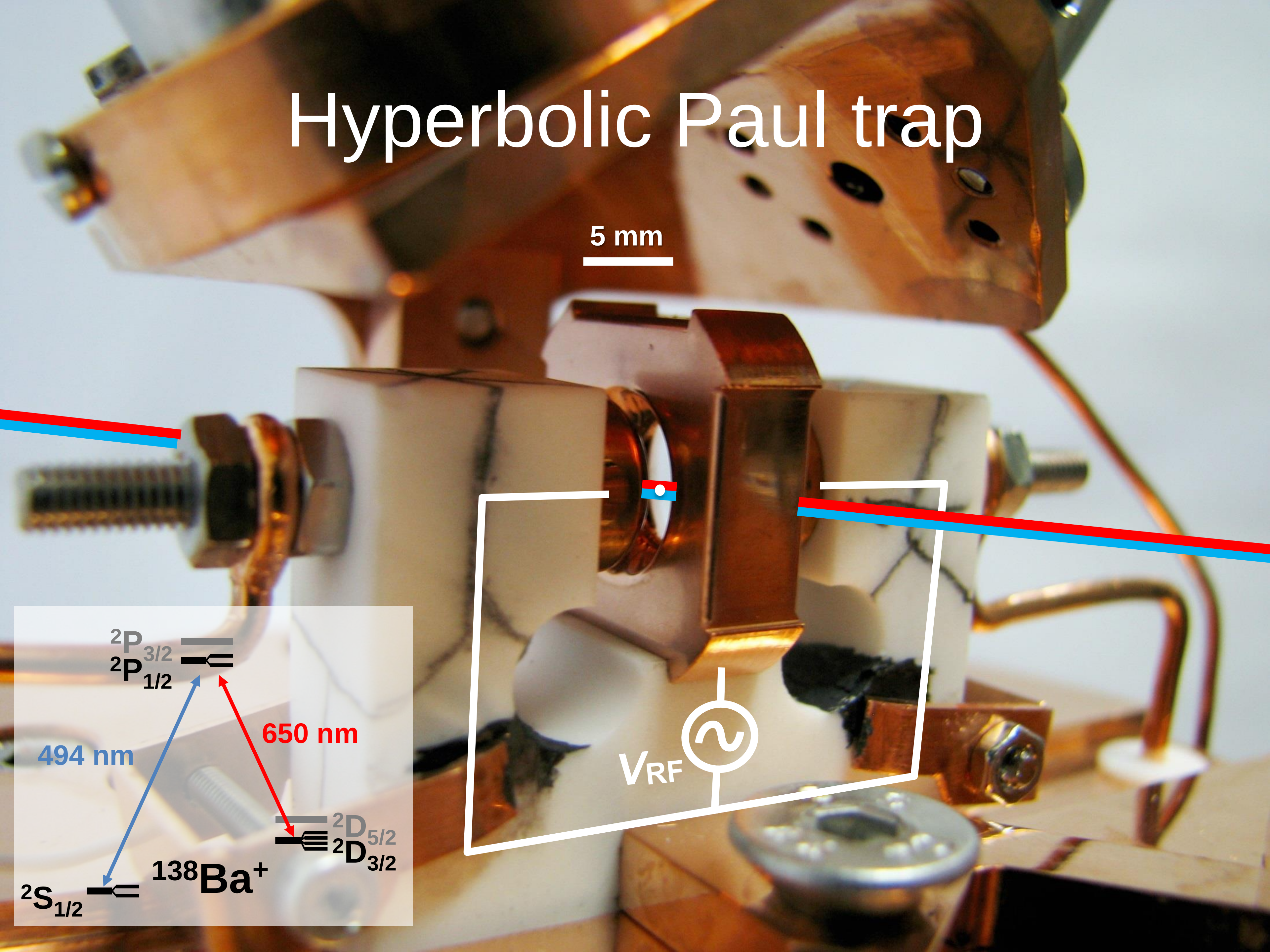
Hyperbolic Single Ion Trap

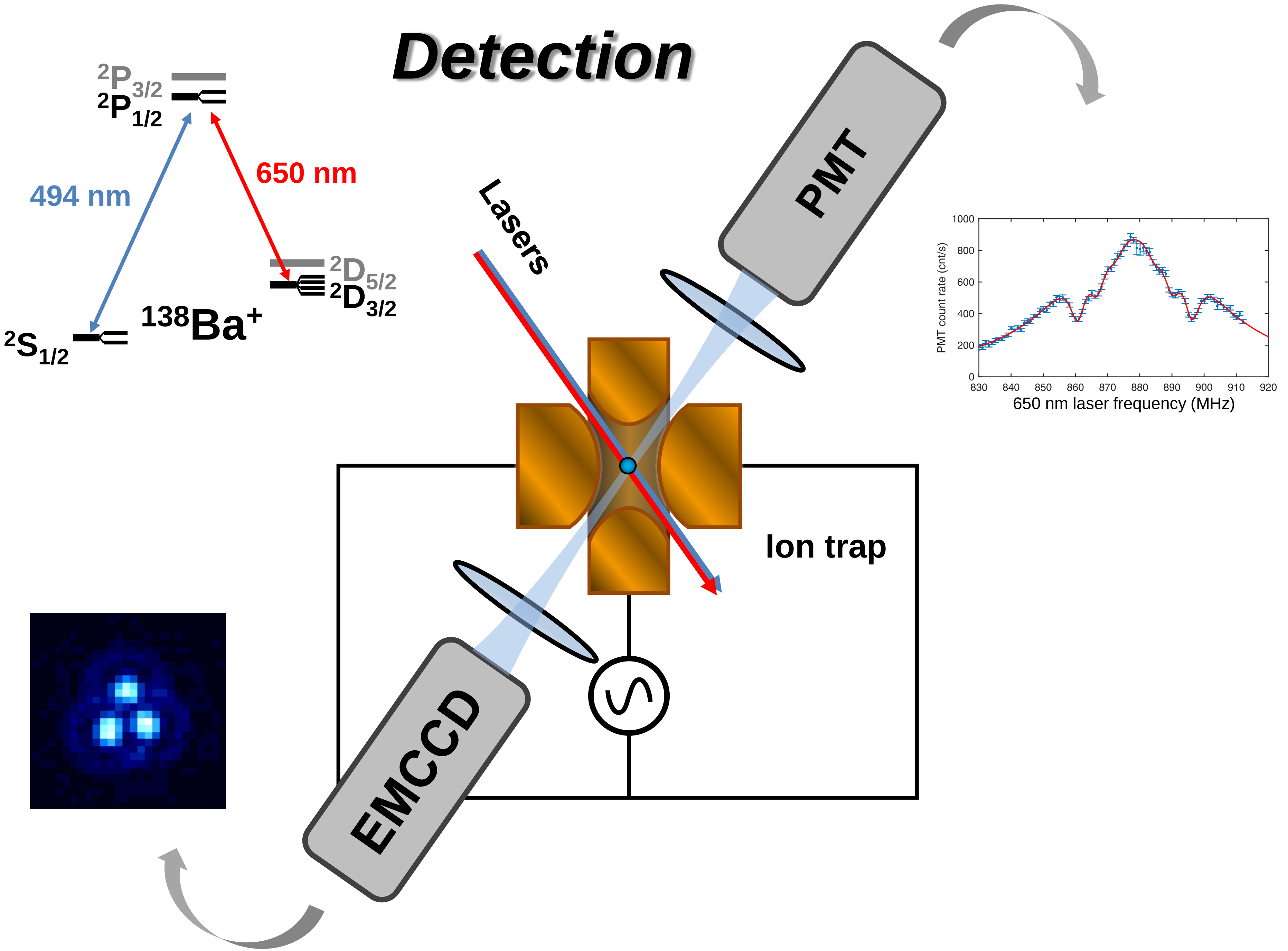









Hyperbolic Paul trap
5 mm
V RF
$^2P_{3/2}$
$^2P_{1/2}$
494 nm
650 nm
$^2D_{5/2}$
$^2D_{3/2}$
$^{138}Ba^+$
$^2S_{1/2}$



Detection
$^2P_{3/2}$
$^2P_{1/2}$
494 nm
650 nm
$^2D_{5/2}$
$^2D_{3/2}$
$^2S_{1/2}$
$^{138}Ba^+$
Lasers
PMT
1000
800
600
400
200
0
PMT count rate (cnt/s)
830 840 850 860 870 880 890 900 910 920
650 nm laser frequency (MHz)
Ion trap
EMCCD

Importance of Line Shape

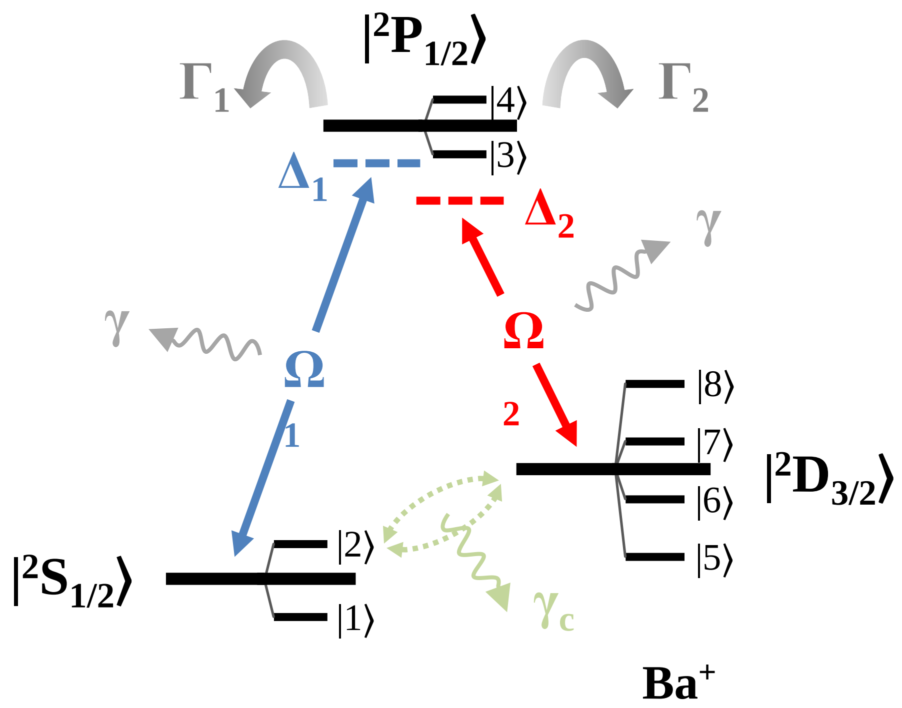
Optical Bloch equation

3 level example

$$\frac{d}{dt}\rho_{ij} = \frac{i}{\hbar}[H,\rho] + R(\rho)$$

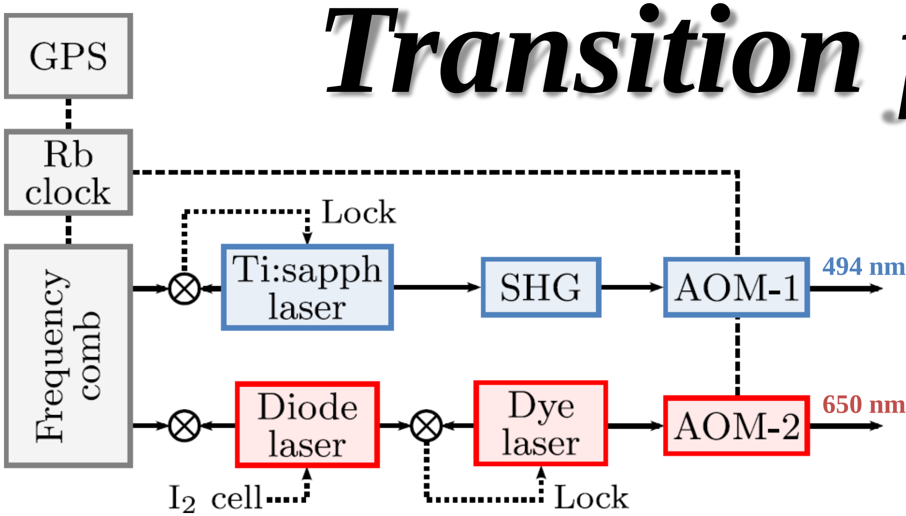
$$H = \hbar\begin{pmatrix}
\Delta_1-\omega_B & 0 & -\frac{2}{\sqrt{3}}\Omega_1 & 0 & 0 & 0 & 0 & 0\\
0 & \Delta_1+\omega_B & 0 & \frac{2}{\sqrt{3}}\Omega_1 & 0 & 0 & 0 & 0\\
-\frac{2}{\sqrt{3}}\Omega_1 & 0 & -\frac{1}{3}\omega_B & 0 & \frac{i}{\sqrt{2}}\Omega_2 & \frac{2}{\sqrt{6}}\Omega_2 & -\frac{i}{\sqrt{6}}\Omega_2 & 0\\
0 & \frac{2}{\sqrt{3}}\Omega_1 & 0 & \frac{1}{3}\omega_B & 0 & \frac{i}{\sqrt{6}}\Omega_2 & \frac{2}{\sqrt{6}}\Omega_2 & -\frac{i}{\sqrt{2}}\Omega_2\\
0 & 0 & -\frac{i}{\sqrt{2}}\Omega_2 & 0 & \Delta_2-\frac{6}{5}\omega_B & 0 & 0 & 0\\
0 & 0 & \frac{2}{\sqrt{6}}\Omega_2 & -\frac{i}{\sqrt{6}}\Omega_2 & 0 & \Delta_2-\frac{2}{5}\omega_B & 0 & 0\\
0 & 0 & \frac{i}{\sqrt{6}}\Omega_2 & \frac{2}{\sqrt{6}}\Omega_2 & 0 & 0 & \Delta_2+\frac{2}{5}\omega_B & 0\\
0 & 0 & 0 & \frac{i}{\sqrt{2}}\Omega_2 & 0 & 0 & 0 & \Delta_2+\frac{6}{5}\omega_B
\end{pmatrix}$$

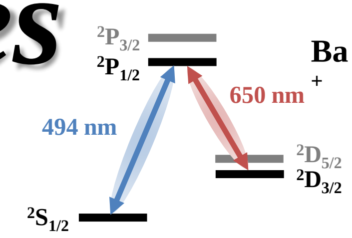
$$R(\rho) = \begin{pmatrix}
\Gamma_1(\frac{1}{3}\rho_{33}+\frac{2}{3}\rho_{44}) & -\Gamma_1\frac{1}{3}\rho_{34} & -\gamma'\rho_{13} & -\gamma'\rho_{14} & -\gamma_l\rho_{15} & -\gamma_l\rho_{16} & -\gamma_l\rho_{17} & -\gamma_l\rho_{18}\\
-\Gamma_1\frac{1}{3}\rho_{43} & \Gamma_1(\frac{2}{3}\rho_{33}+\frac{1}{3}\rho_{44}) & -\gamma'\rho_{23} & -\gamma'\rho_{24} & -\gamma_l\rho_{25} & -\gamma_l\rho_{26} & -\gamma_l\rho_{27} & -\gamma_l\rho_{28}\\
-\gamma'\rho_{31} & -\gamma'\rho_{32} & -\Gamma\rho_{33} & -\Gamma\rho_{34} & -\gamma'\rho_{35} & -\gamma'\rho_{36} & -\gamma'\rho_{37} & -\gamma'\rho_{38}\\
-\gamma'\rho_{41} & -\gamma'\rho_{42} & -\Gamma\rho_{43} & -\Gamma\rho_{44} & -\gamma'\rho_{45} & -\gamma'\rho_{46} & -\gamma'\rho_{47} & -\gamma'\rho_{48}\\
-\gamma_l\rho_{51} & -\gamma_l\rho_{52} & -\gamma'\rho_{53} & -\gamma'\rho_{54} & \Gamma_2\frac{1}{2}\rho_{33} & \Gamma_2\frac{1}{2\sqrt{3}}\rho_{34} & 0 & 0\\
-\gamma_l\rho_{61} & -\gamma_l\rho_{62} & -\gamma'\rho_{63} & -\gamma'\rho_{64} & \Gamma_2\frac{1}{2\sqrt{3}}\rho_{43} & \Gamma_2(\frac{1}{3}\rho_{33}+\frac{1}{6}\rho_{44}) & \Gamma_2\frac{1}{3}\rho_{34} & 0\\
-\gamma_l\rho_{71} & -\gamma_l\rho_{72} & -\gamma'\rho_{73} & -\gamma'\rho_{74} & 0 & \Gamma_2\frac{1}{3}\rho_{43} & \Gamma_2(\frac{1}{6}\rho_{33}+\frac{1}{3}\rho_{44}) & \Gamma_2\frac{1}{2\sqrt{3}}\rho_{34}\\
-\gamma_l\rho_{81} & -\gamma_l\rho_{82} & -\gamma'\rho_{83} & -\gamma'\rho_{84} & 0 & 0 & \Gamma_2\frac{1}{2\sqrt{3}}\rho_{43} & \Gamma_2\frac{1}{2}\rho_{44}
\end{pmatrix}$$

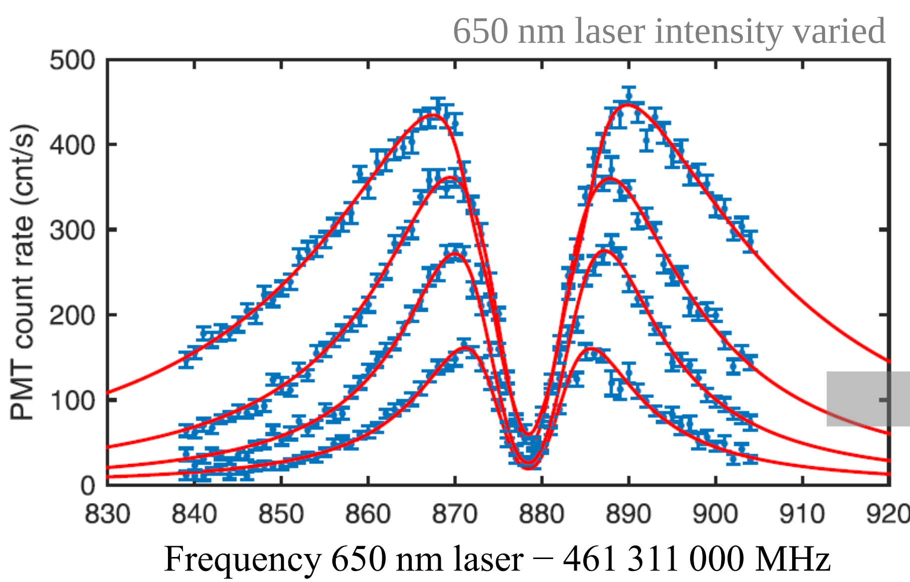


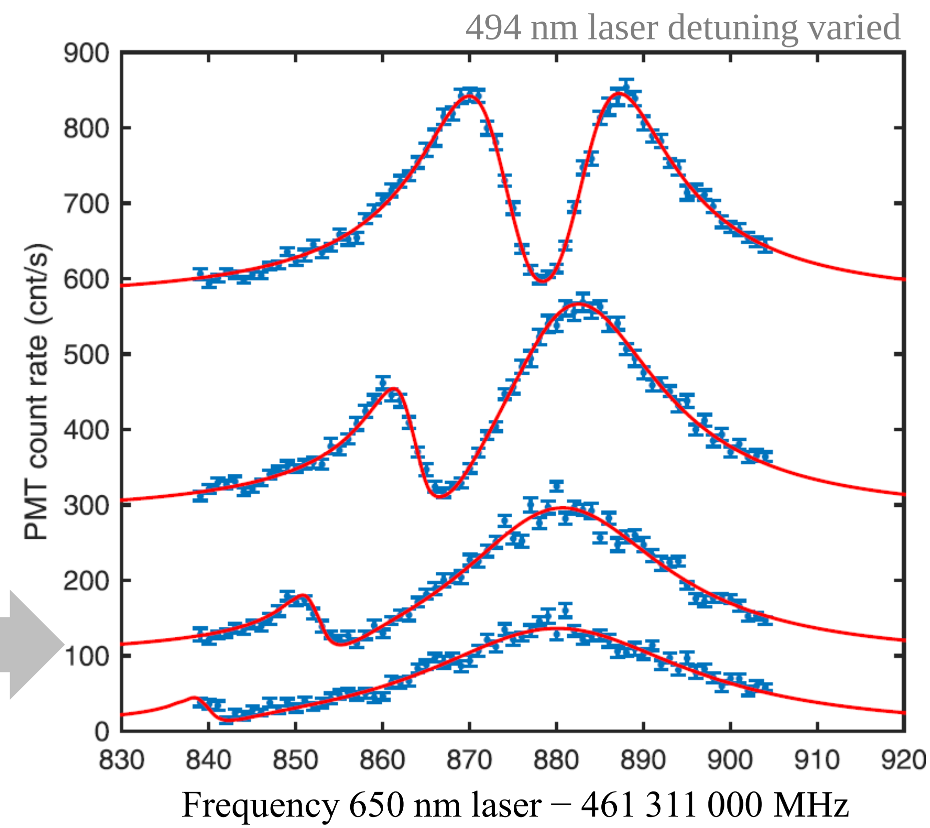
Ω_1, Ω_2	Rabi frequencies (laser power)	$\Gamma = \Gamma_1 + \Gamma_2$	relaxation rate
		$\gamma = \Gamma/2$	decoherence rate
Δ_1, Δ_2	laser detunings	γ_c	laser linewidth

Transition frequencies





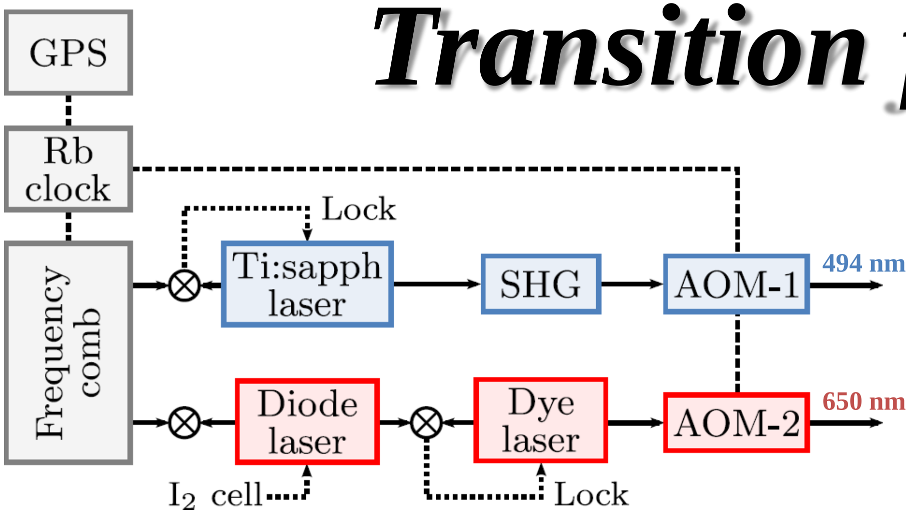


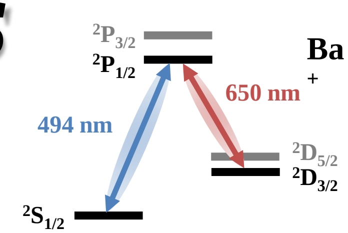


- Fitted with optical Bloch equation model
- Extract transition frequencies with 100 kHz accuracy

Dijck et al., Phys. Rev. A **91**, 060501(R) (2015)

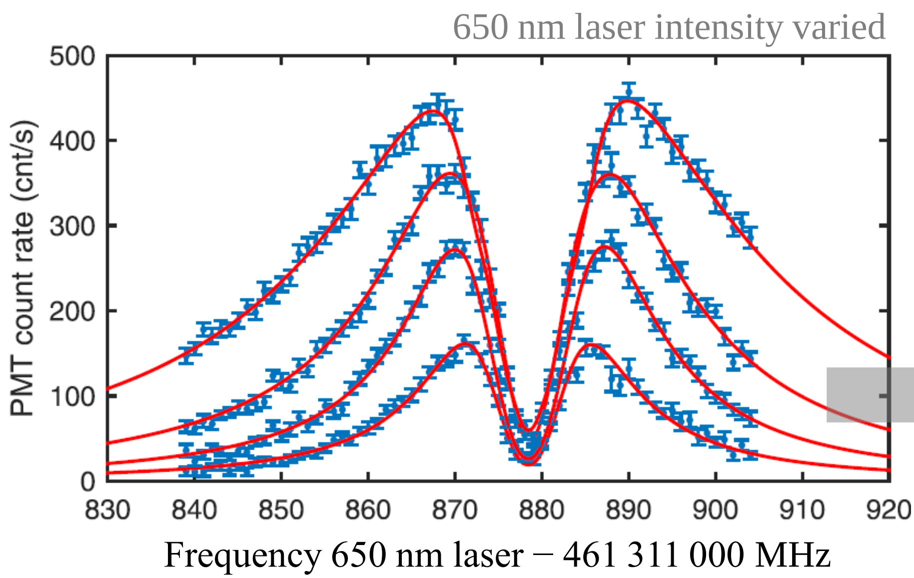
Transition frequencies

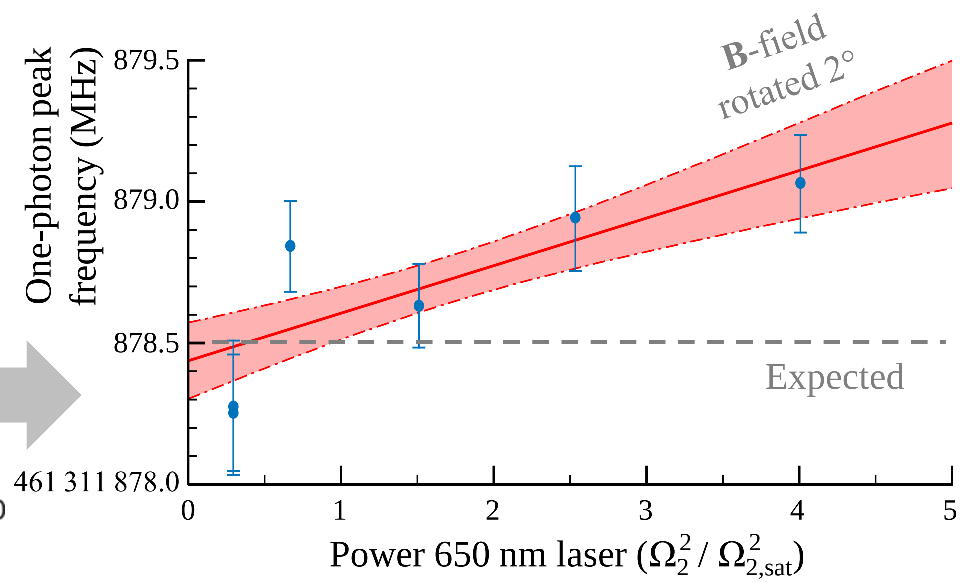




Light shift?

- Correction in transition frequencies for Ω_2 dependent shift consistent with 2° rotation of **B**-field





- Fitted with optical Bloch equation model
- Extract transition frequencies with 100 kHz accuracy

Dijck et al., Phys. Rev. A **91**, 060501(R) (2015)

Atomic Parity Violation

SUMMARY

Accuracy of Single Ion Experiment

$$\frac{\mathcal{E}^{\mathrm{PNC}}}{\delta\mathcal{E}^{\mathrm{PNC}}} \cong \frac{\mathcal{E}^{\mathrm{PNC}} E_0}{\hbar} f \sqrt{N\tau t}$$

E_0 = Light electric field amplitude, τ = Coherence time
N = Number of ions = 1, t = Time of observation

	Coherence Time	Projected Accuracy	Measurement Time
Ba^+	80 sec	0.2%	1.1 day
Ra^+	0.6 sec	0.2%	1.4 day

If coherence time can be fully exploited

Ratio measurement

Insensitivity of Ratio of measurements of $E1_{APV}$ for isotopes to atomic structure. V. A. Dzuba, V. V. Flambaum, and I. B. Khriplovich, Z. Phys. D, **1**, 243 (1985)

$$E1_{APV}(N) = k(N)\ Q_W(N) \quad \longrightarrow$$

$$\frac{E1_{APV}(N)}{E1'_{APV}(N')} = \frac{k(N)\ Q_W(N)}{k(N')\ Q'_W(N')} \cong \frac{Q_W(N)}{Q'_W(N')}$$

Best case scenario:

For radium a wide range of isotopes is available

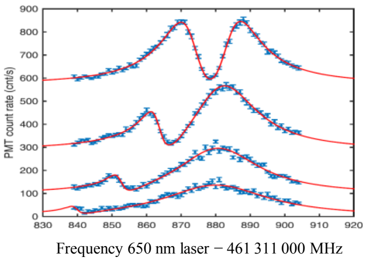
$$\Delta N = N' - N > 10$$

Laser Cooling of Ra ions for Atomic Parity Violation

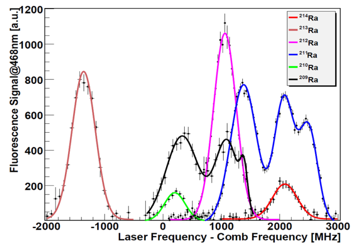
$$E1_{APV} = k \cdot Q_W$$

Atomic Parity Violation:

Ba^+
- Developing experimental setup
- Atomic properties determination
- Light shifts and Line shapes



Ra^+
- Atomic Properties from online produced radium
- Trapping and laser spectroscopy done at TRIμP
- Activity on Ra^+ colinear spectroscopy (ISOLDE)
- Muonic Radium experiments for charge radius



ISOLDE

- Ion trapping permits access to many transitions
- Laser cooling for precision
- Availability of a large range of Ra isotopes
- Lab with experience of precision lasers experiments
- Building up of a collaboration