Barium ion – how exact do we know?

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PSAS 2016: 24th May 2016

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Projects @ CIG.CQT.NUS

Cold Ion Group Overview

Precision measurement

Phys. Rev. A 90, 012509 (2014)
Phys. Rev. A 91, 040501(R) (2015)
https://arxiv.org/abs/1604.01488 (2016)

Quantum emulation

Phys. Rev. Lett. 111, 170406 (2013)
Phys. Rev. A 85, 063401 (2012)
J. Phys. B 49, 055502 (2016)

Artificial gauges (Berry Phase)

Phys. Lett. A377 228–231 (2013)
http://arxiv.org/abs/1410.5057

Solving the SF_6 structure (with MPIK)

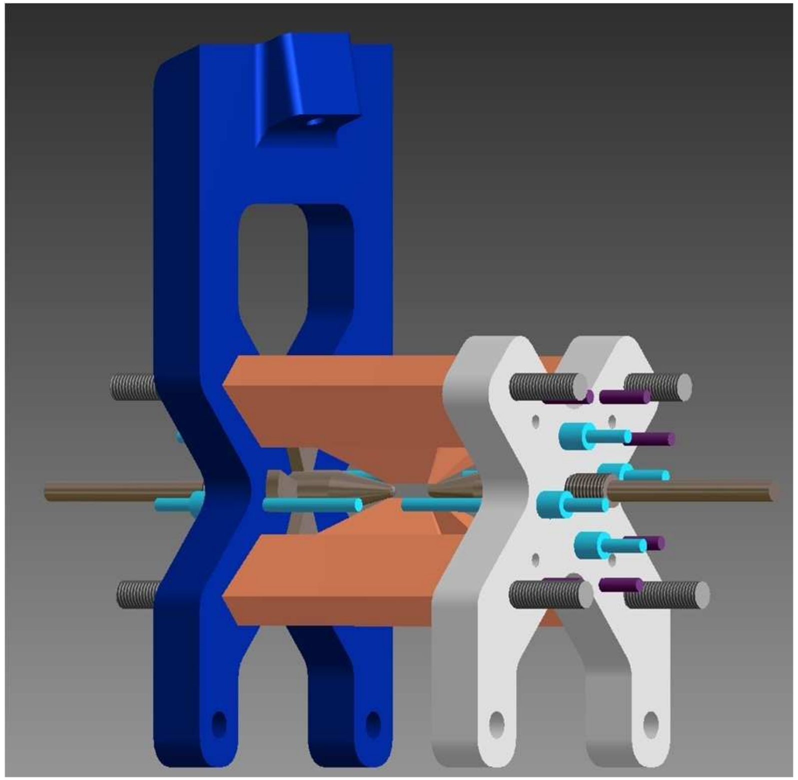
Phys. Rev. A 89, 022502 (2014)

Quantum thermodynamics

Phys. Rev. A 92, 023637 (2015)

Quantum synchronization

JOSA B, in print (2016)



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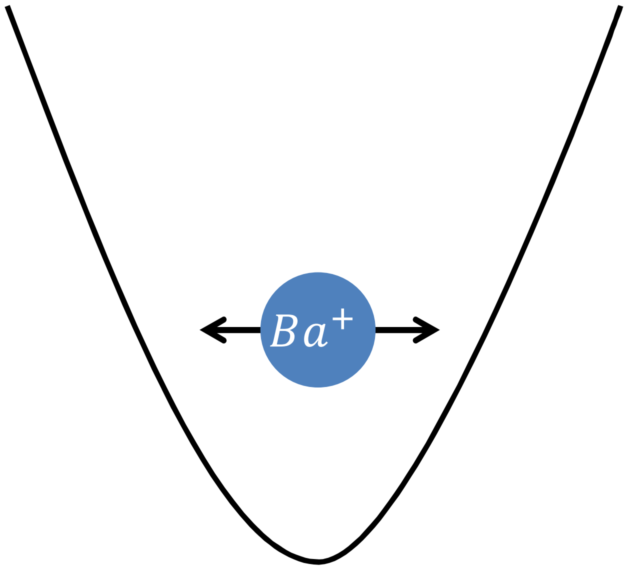
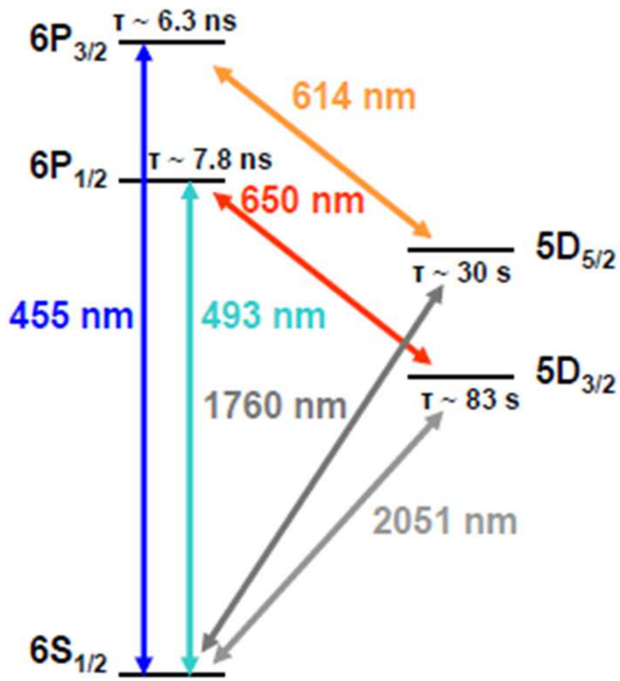
Quantized external motion



Quantized internal atomic states

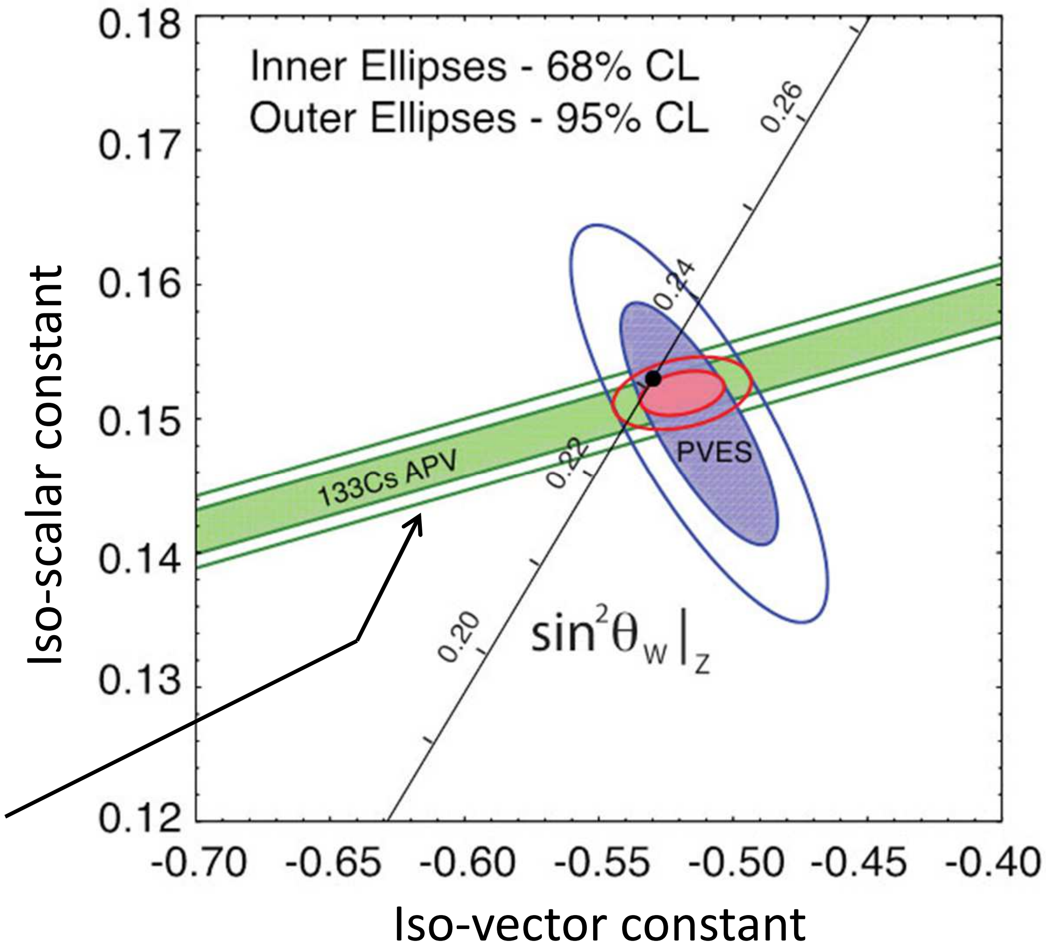


$^{138}Ba^+$ Energy diagram

Atomic parity violation with Ba^+

Precision measurement

Why to measure atomic parity violation?



The gold standard with 0.3% precision

C. S. Wood et al., Science 275, 1759 (1997)

Importance of atomic structure

competing proposals using trapped ion

Disadvantage of Cs atomic beam experiments

- Atomic beam measurement : limited observation time
- Nuclear Anapole moment (NAM) relies on atomic structure calculations

Alternative approach: trapped Ba^+ ion (N. Fortson, Phys. Rev. Lett. 70, 2383 (1993))

- Single trapped ion: long observation time
- Lower possible systematics
- Unambiguous NAM measurement possible

Require both theory and experiment to be known below 1% precision

Alternative approach: entangled trapped Ba^+ ion
(P. Mandal and M. Mukherjee Phys. Rev. A 82, 050101(R) (2010))

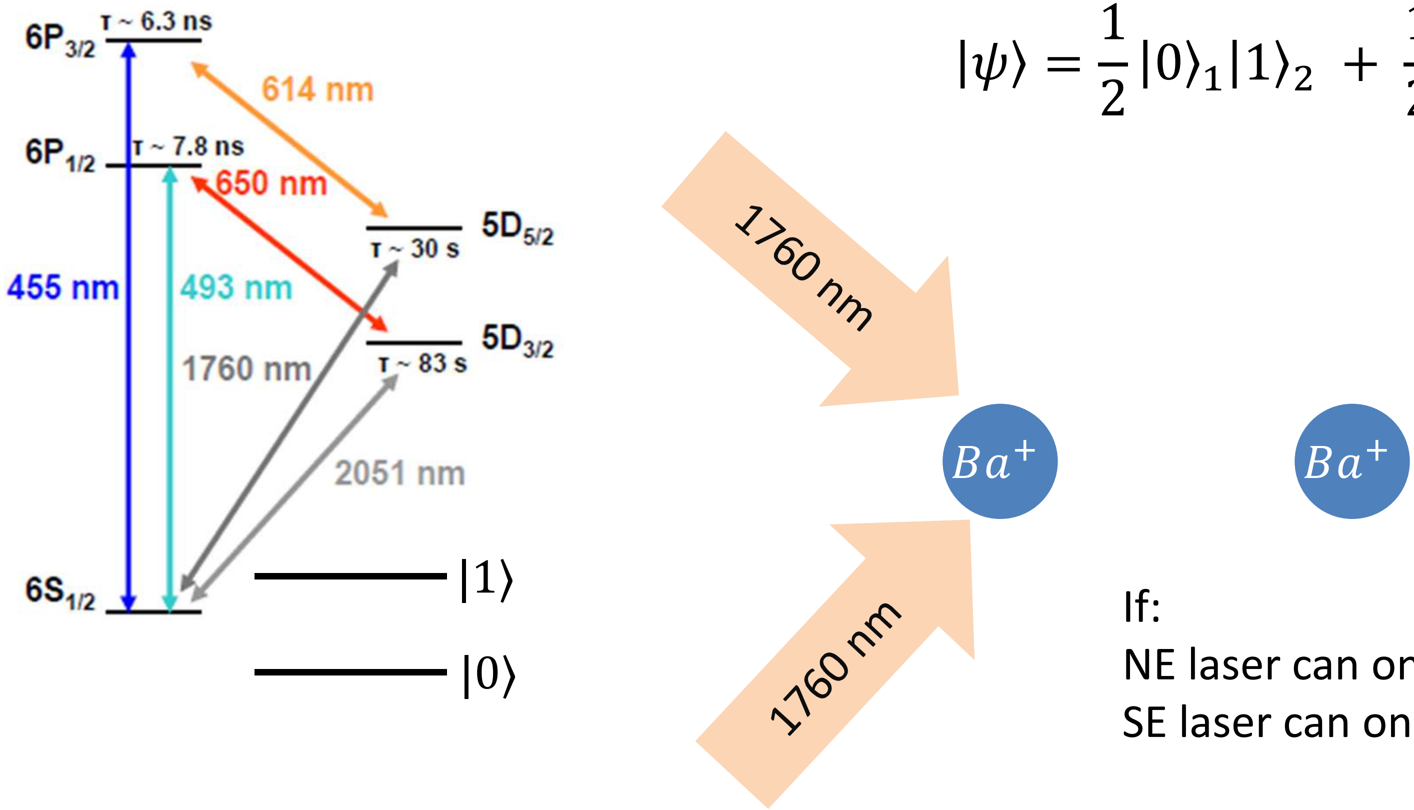
- Entangled ion pair in decoherence free sub-space: negligible systematics
- S/N is twice that of Fortson's proposal
- Unambiguous NAM measurement possible

(B. K. Sahoo, P. Mandal and M. Mukherjee Phys. Rev. A 83, 030502(R) (2011))

Requirement for APV measurement

Quantum metrology

Can quantum technology help measure atomic parity violation experiment?



$$|\psi\rangle = \frac{1}{2}|0\rangle_1|1\rangle_2 + \frac{1}{2}e^{\frac{i\Delta E t}{\hbar}}|1\rangle_1|0\rangle_2$$

If:

NE laser can only drive dipole

SE laser can only drive quadrupole

Then, $\Delta E = E_{PNC}$

P. Mandal and M. Mukherjee Phys. Rev. A 82, 050101(R) (2010)

Requirement for APV measurement

Needs to measure dipole matrices as well

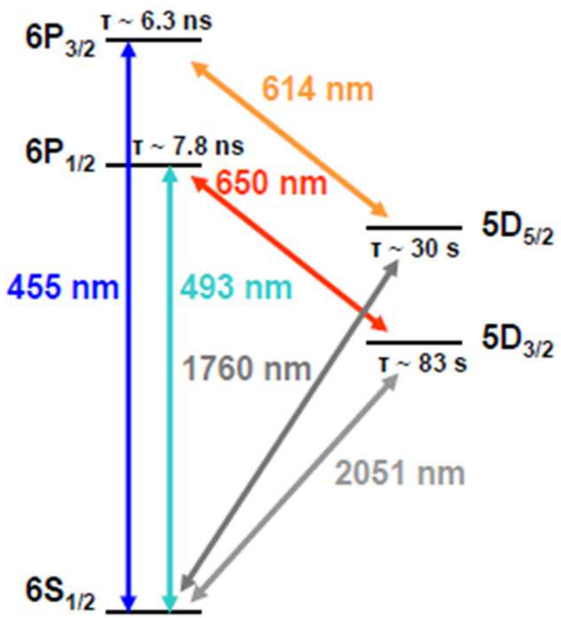
$$\varepsilon_{m'm}^{PNC} = \sum_n \frac{< D_{3/2}, m' | er | nP_{1/2}, m >< nP_{1/2}, m | H^{PNC} | 6S_{1/2}, m >}{W_{6S_{1/2}} - W_{nP_{1/2}}} + h.c$$

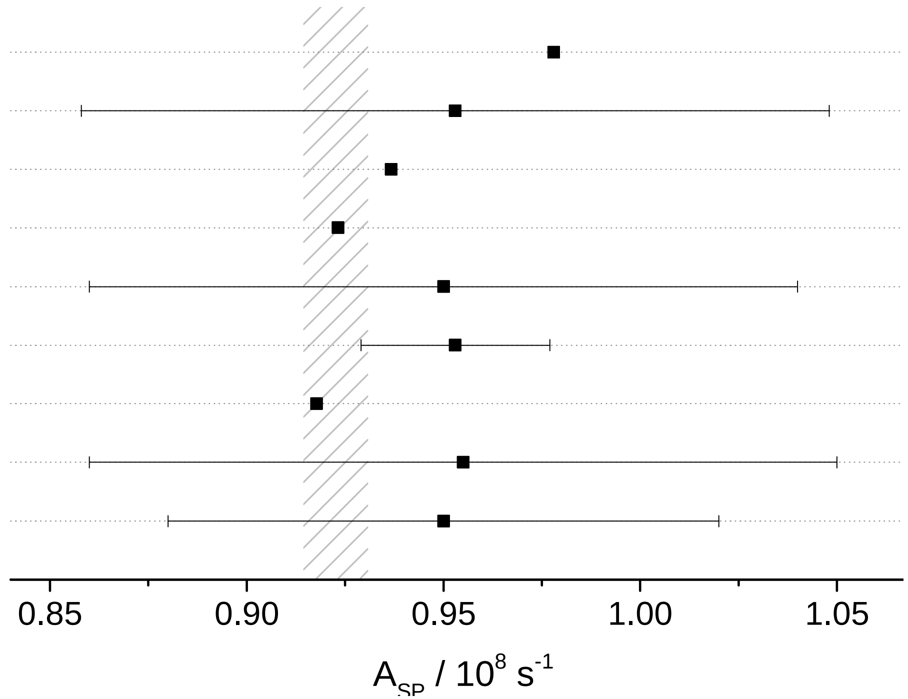
$$H_{\bar{n}n}^{PNC} \cong i1.8 \times 10^{-17} Z^2 Q_W K_r \frac{(W_n W_{\bar{n}})^{3/4} (a_0)^{1/2}}{(Z_{ion} + 1)e}$$

To know Q_W to below 1% the dipole matrix D-P and S-P needs to be know to better than 1%

Requirement for APV measurement

Needs to measure dipole matrices as well



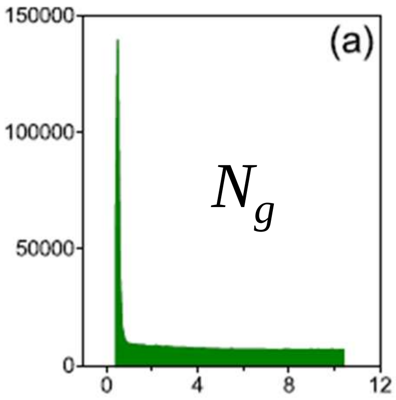


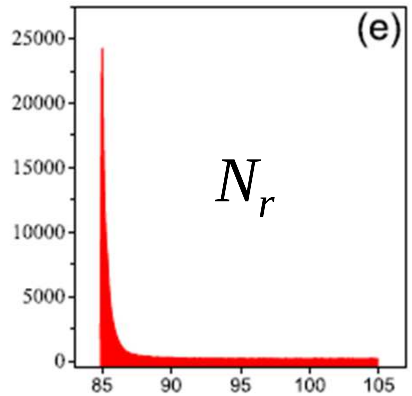
S-$P_{1/2}$ transition probabilities

To know Q_W to below 1% the dipole matrix D-P and S-P needs to be know to better than 1%

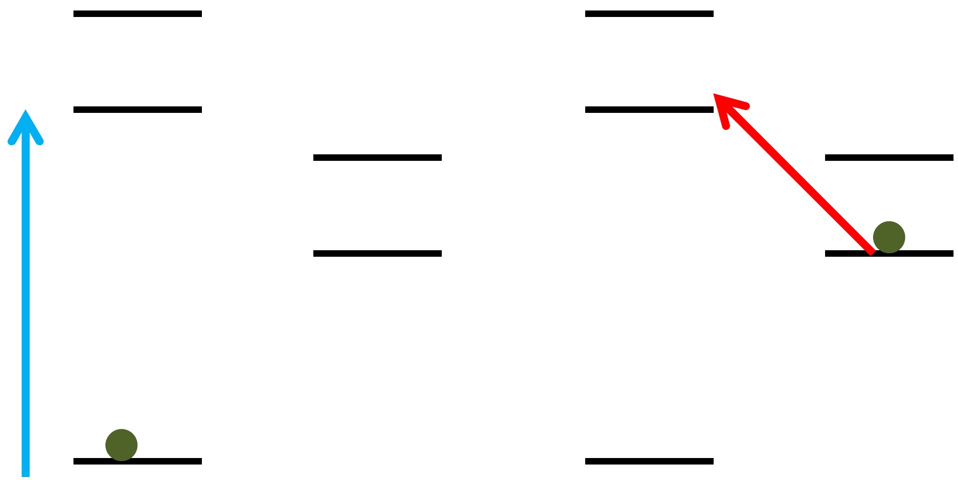
Projects @ CIG.CQT.NUS

Simplified Quantum system





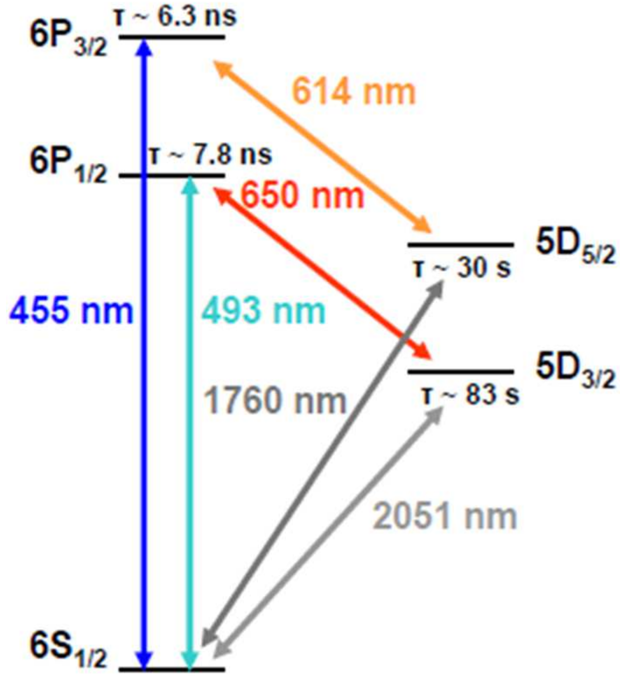
$$r = \frac{N_g}{N_g + N_r}$$



Step 1

Step 2

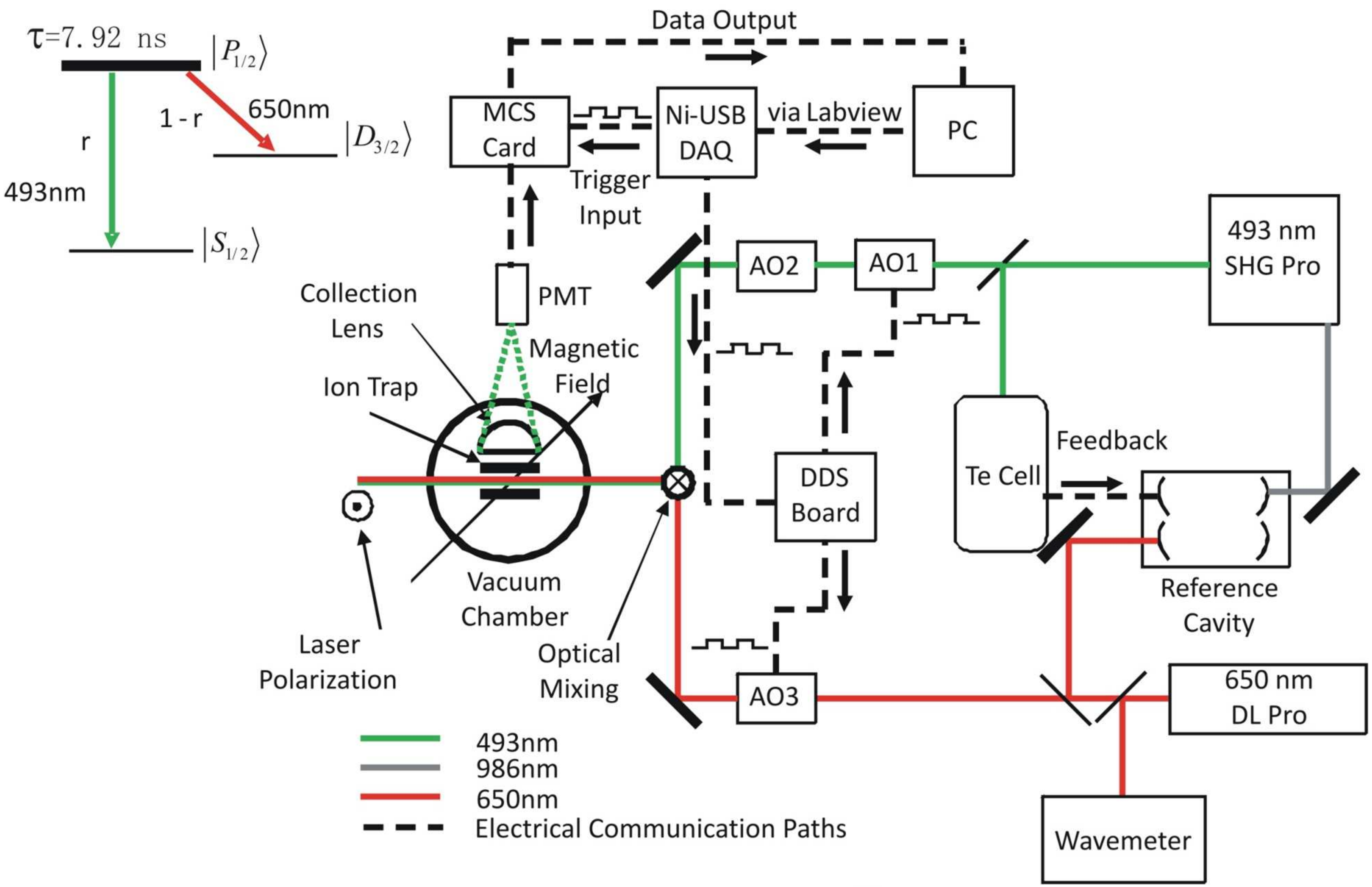
M. Ramm et *al*. Phys.Rev.Lett. 111. 023004 (2013)



$^{138}Ba^{+}$ Energy diagram

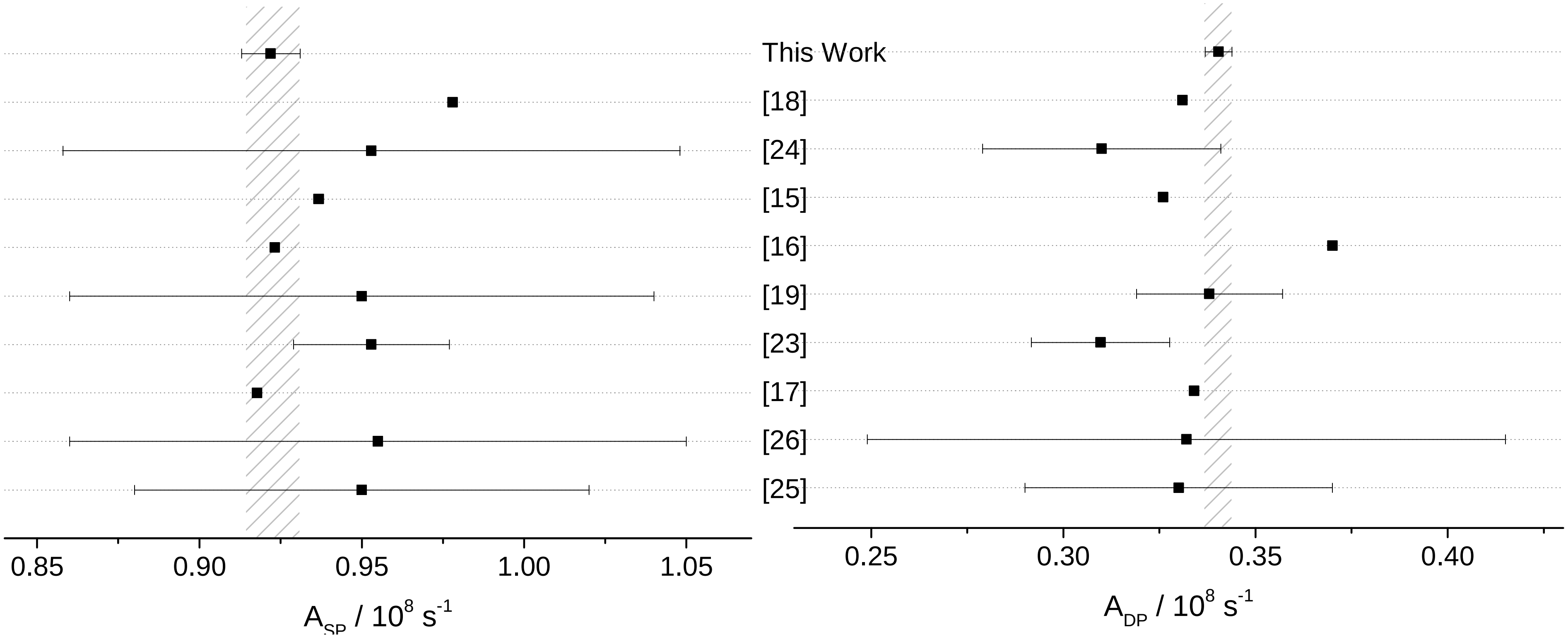
Experimental setup

Protocol of Measurement



Experimental results

Measurement results and comparison with theory for S-$P_{1/2}$



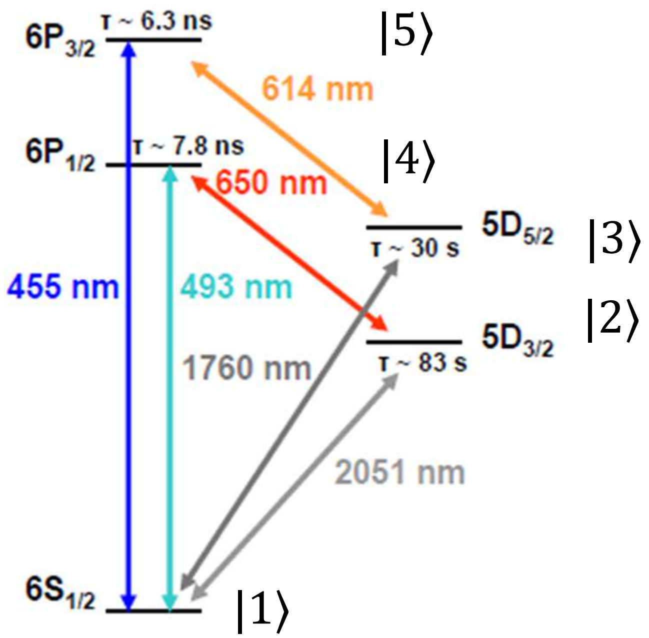
[18] Rev. Lett.**96**, 163003 (2006)

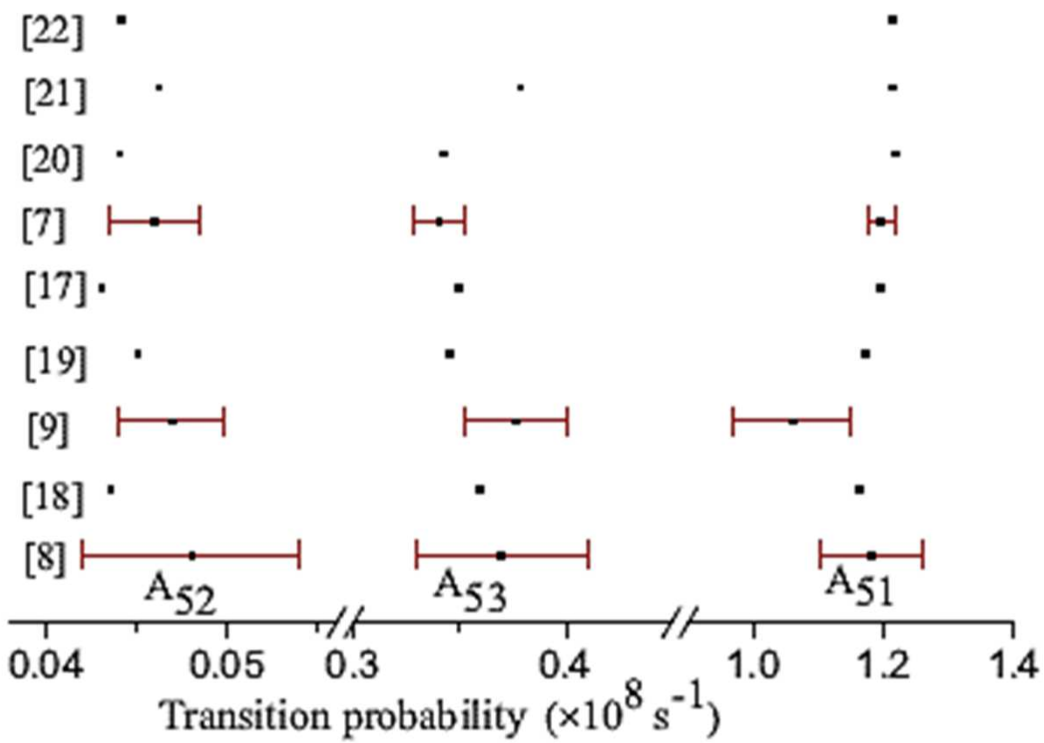
[17] Phys. Rev. A**44**, 1531 (1991).

References are according to Phys. Rev. A 91, 040501(R) (2015)

Experimental results

What about the S-$P_{3/2}$





Cannot use same technique for $P_{3/2}$ as used for $P_{1/2}$ decay as Hanle effect is significant

References as in https://arxiv.org/abs/1604.01488 (2016)

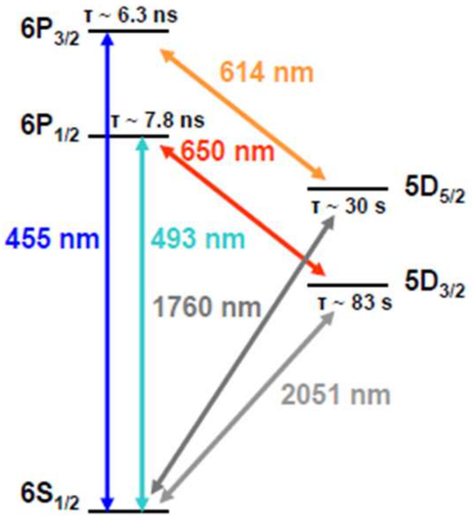
Centre for Quantum Technologies

Experimental results

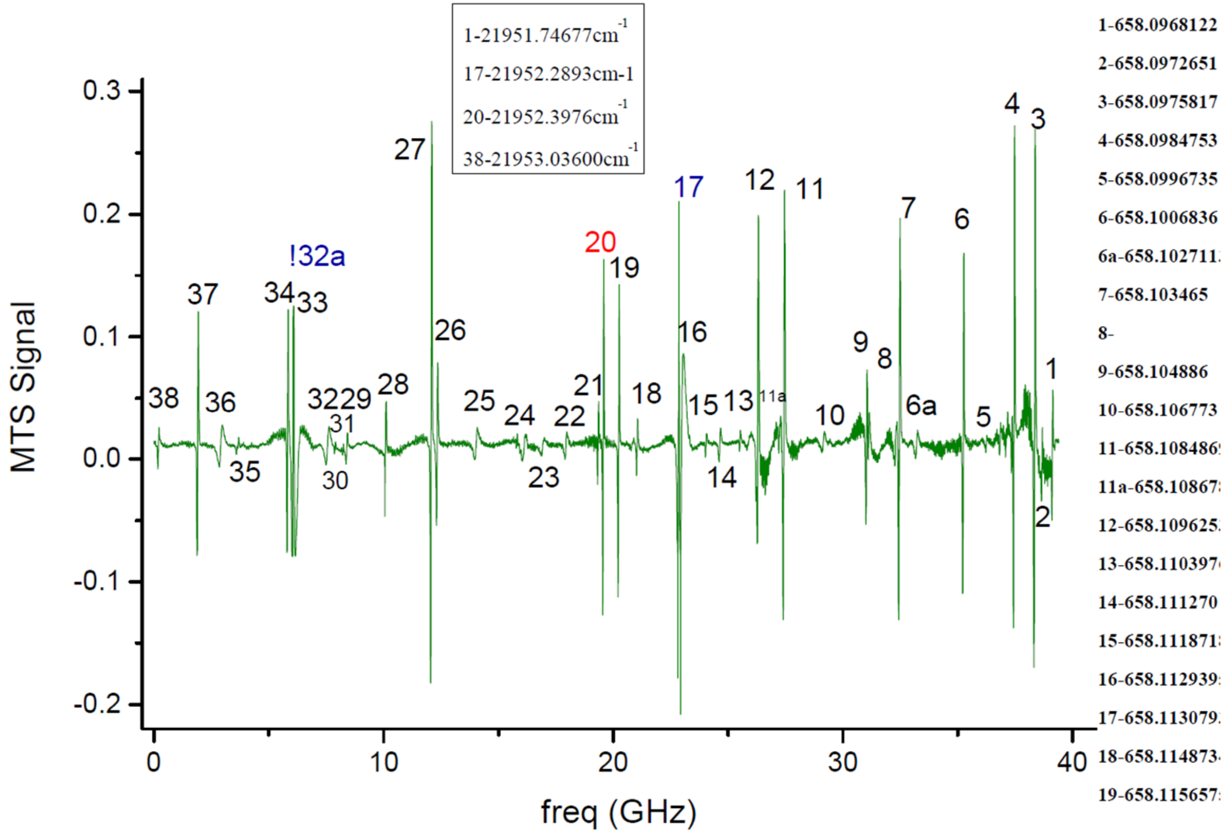
Laser at 455 nm and absolute lock to Te2

NUS National University of Singapore

$^{138}Ba^{+}$ Energy diagram



Te2 lines to lock both 493 nm and 455 nm

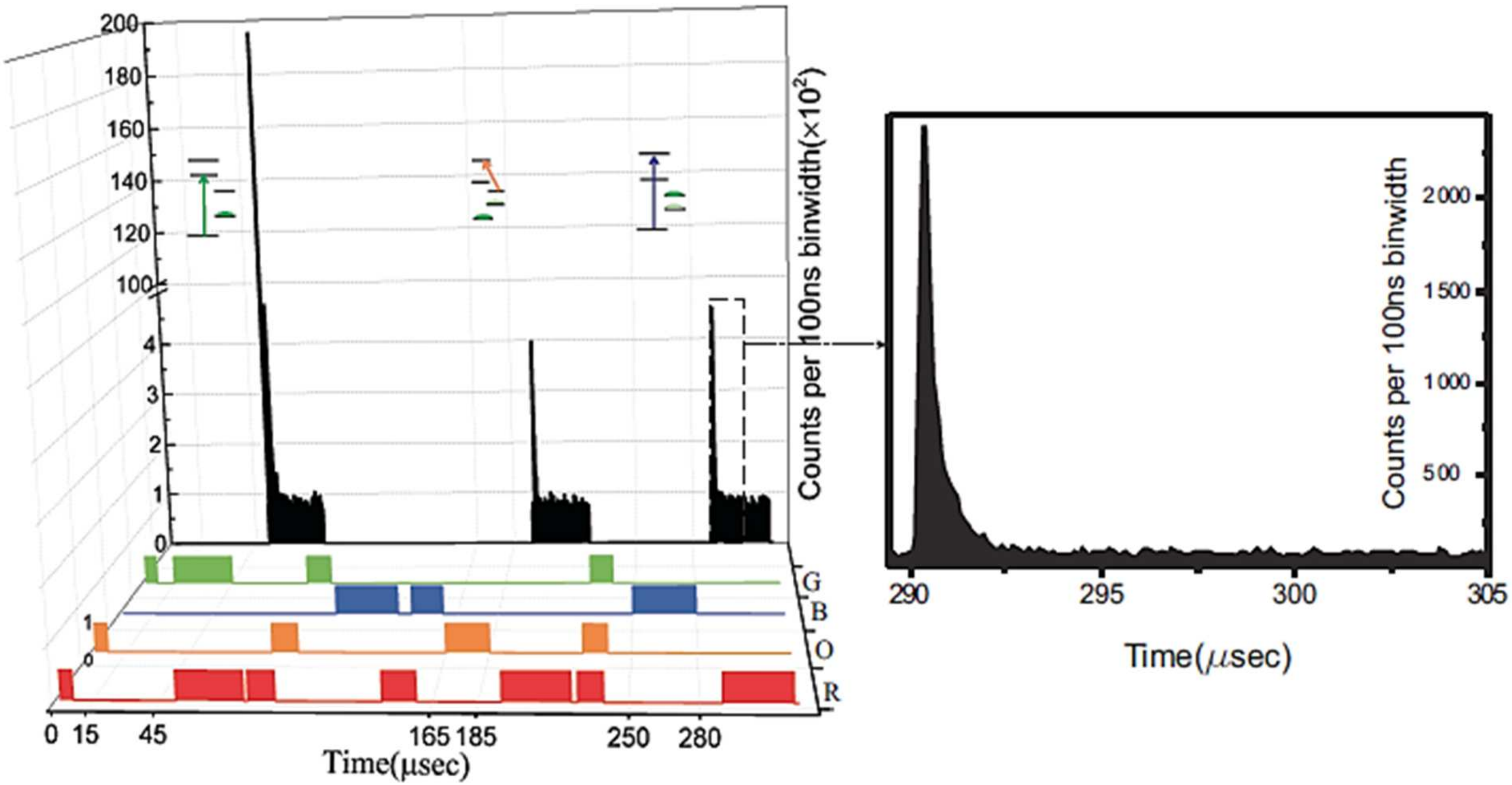


Over 40 new reference lines near 455 nm

T. Dutta, D. De Munshi, M. Mukherjee JOSA B 33, 1177-1181 (2016)

Experimental results

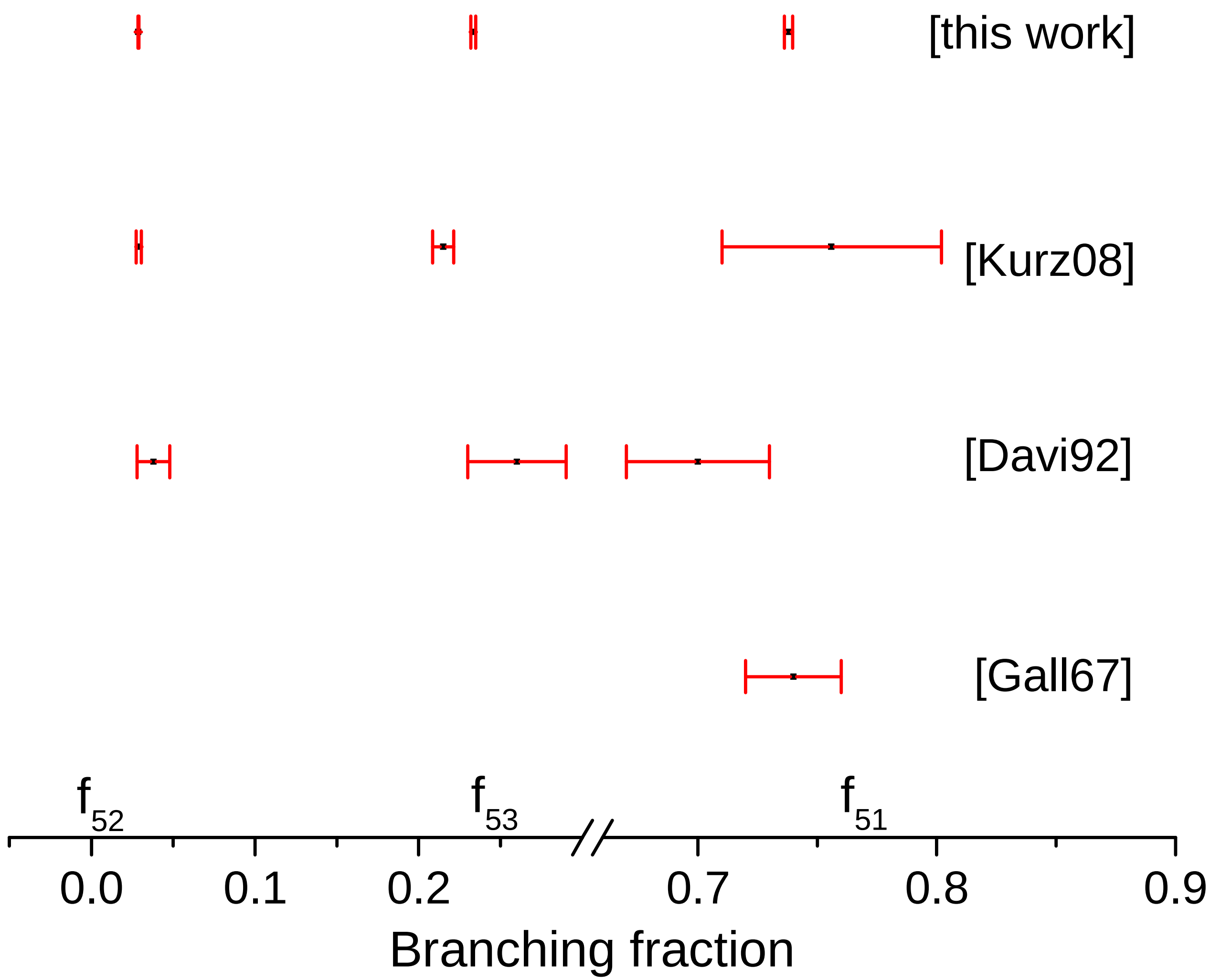
Measurement protocol for $P_{3/2}$ decay channels



https://arxiv.org/abs/1604.01488 (2016)

Experimental results

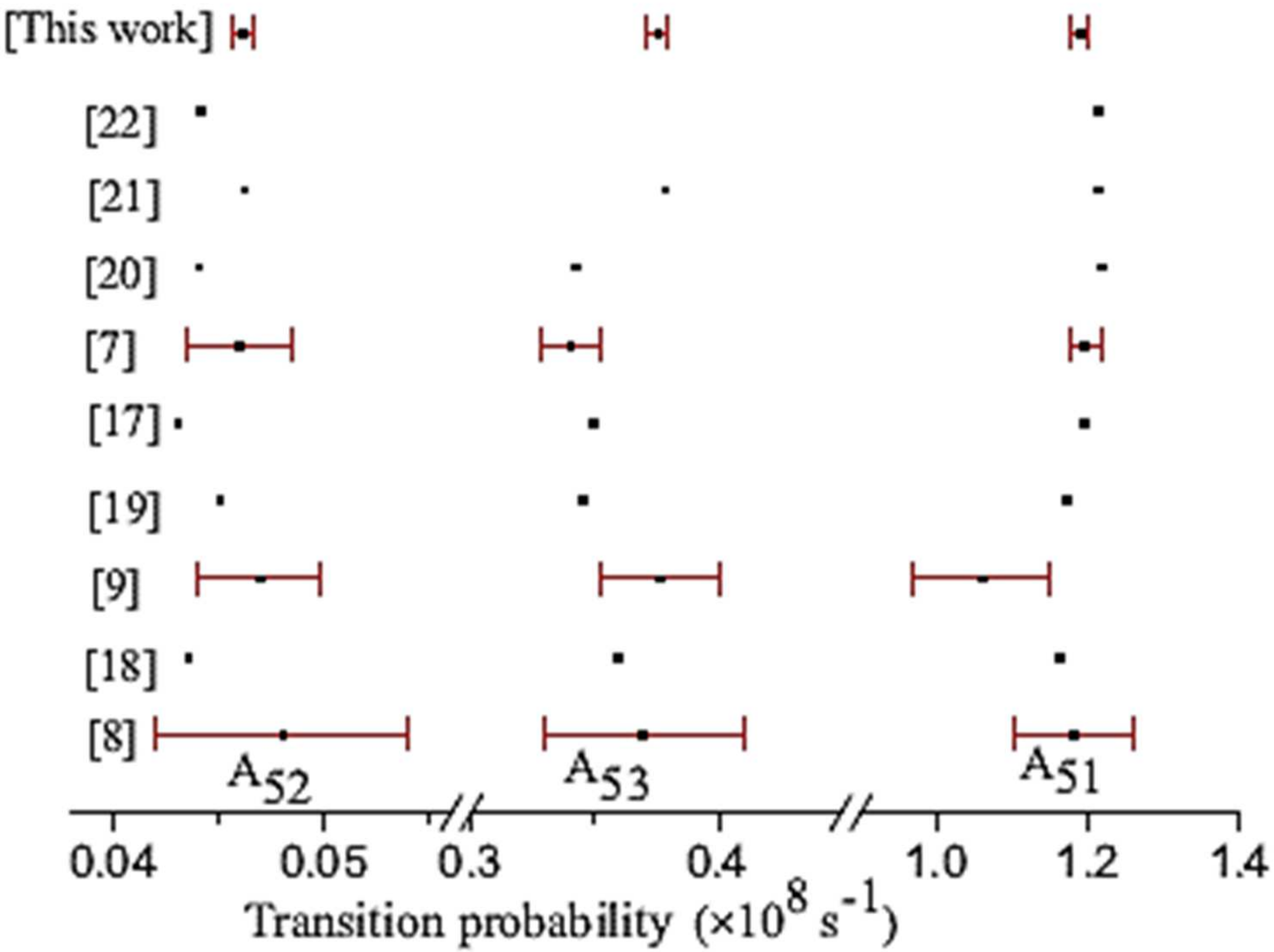
Measurement results and Comparison with theory



https://arxiv.org/abs/1604.01488 (2016)

Experimental results

Measurement results and Comparison with theory



https://arxiv.org/abs/1604.01488 (2016)

Experimental results

Measurement results and Comparison with theory

Error budget for the transition probabilities

Parameters	Shift	Rel. Uncertainties
Detector dead time	$10^{-4} – 10^{-5}$	$< 10^{-5} – 10^{-7}$
Finite measurement time		$< 10^{-8}$
Polarization of detected photons		$< 10^{-8}$
Life-time of upper state		10^{-2}
Statistical		10^{-4}

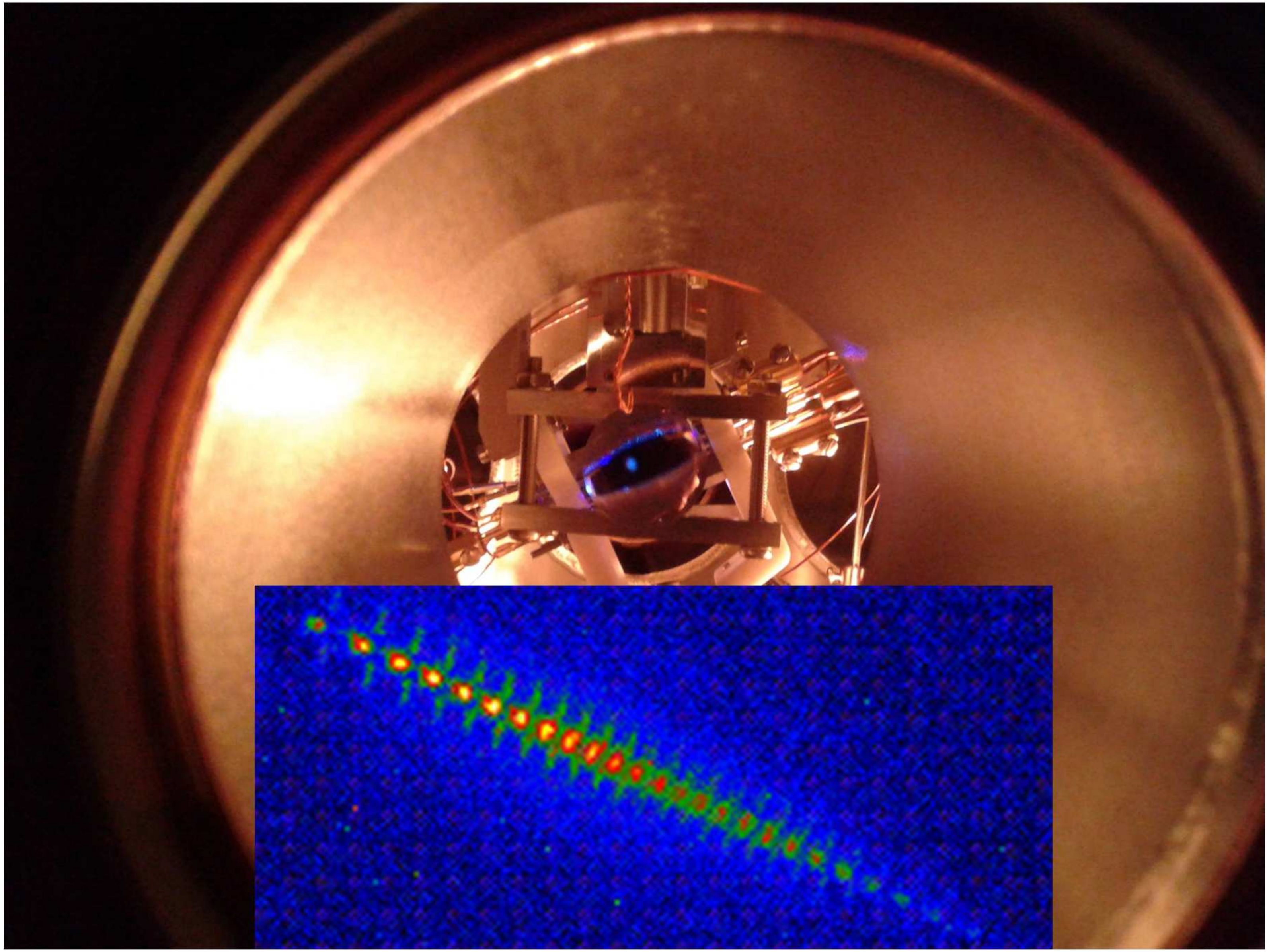
https://arxiv.org/abs/1604.01488 (2016)

Conclusion

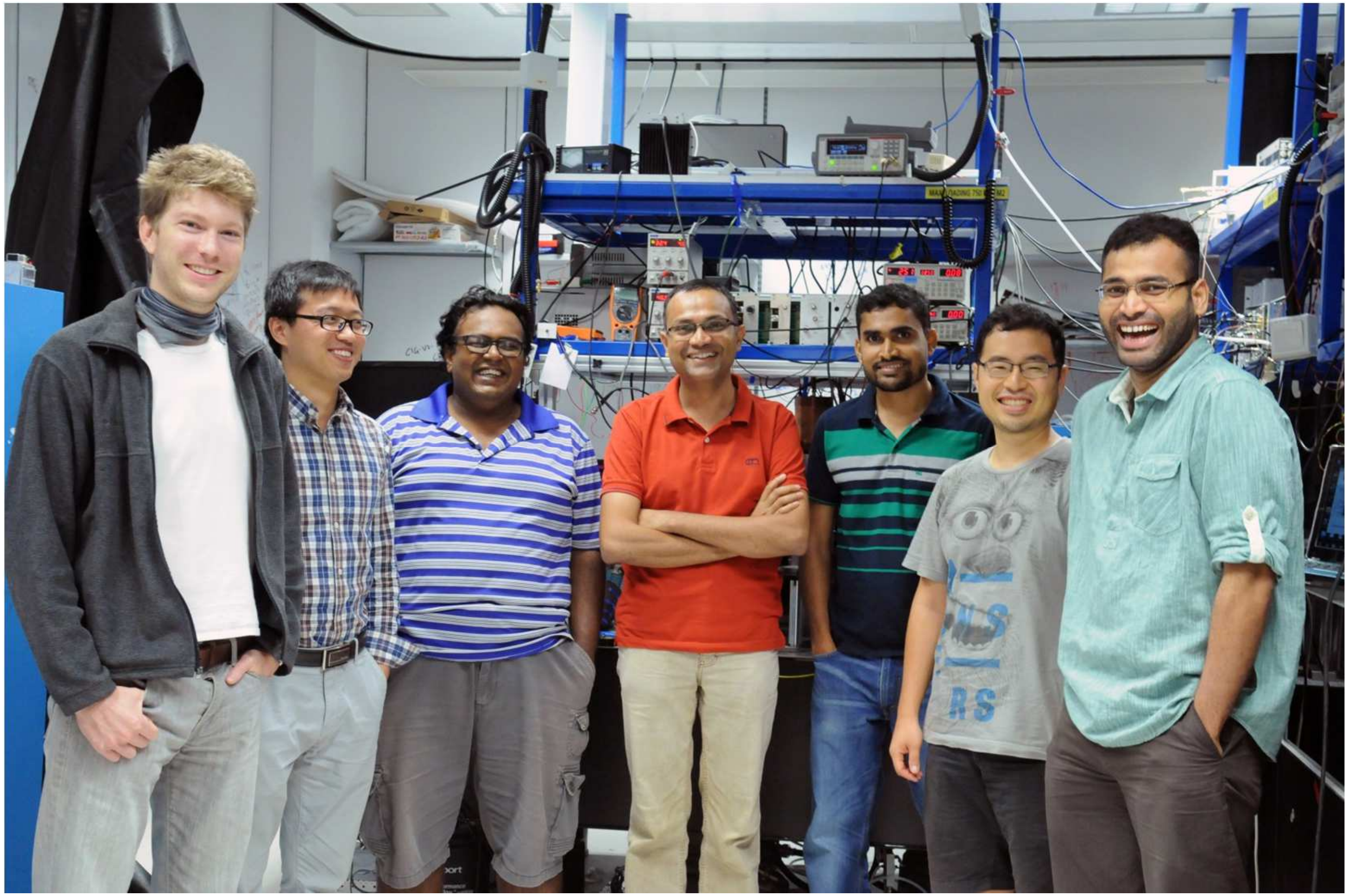
1. **Measurements of transition probabilities below 1% for benching marking of atomic structure calculation of singly charged barium ion**
2. **New protocol for branching fraction measurements with J > ½ with no known systematic effect**
3. **Life-time measurements with lower uncertainty is underway**
4. **Next step will be light shift measurements**

https://arxiv.org/abs/1604.01488 (2016)

Cold Ion Group member: Ba^+



Cold Ion Group member



https://sites.google.com/site/coldiongroup/

Group and Collaborations

Cold Ion group @ CQT

Present members:
Manas Mukherjee
Debashis De Munshi (PhD student)
Tarun Dutta (PhD student)
Swarup Das (PhD student)

Noah Van Horne (RA)
Dahyun Yum (RF)
Peiliang Liu (RF)

Former members:
Tyler Hughes (RA)
Kunal Sastry (Intern)
Guo Chu (Intern)
Dr. Riadh Rebhi (Post Doc.)

IACS, Kolkata India:
Professor K. sengupta (since 2009)
Professor A. Paul (since 2013)

MPIK, Heidelberg, Germany:
Professor K. Blaum (since 2009)

SUTD, Singapore:
Professor D. Poletti (since 2014)

NUS (Qthermo):
Professor G.Jianbin (since 2014)

CQT (Qsync):
Professor V. Vedral
Professor L. C. Kwek
Professor W. Gao (NTU)

Thank you for your attention

https://sites.google.com/site/coldiongroup/