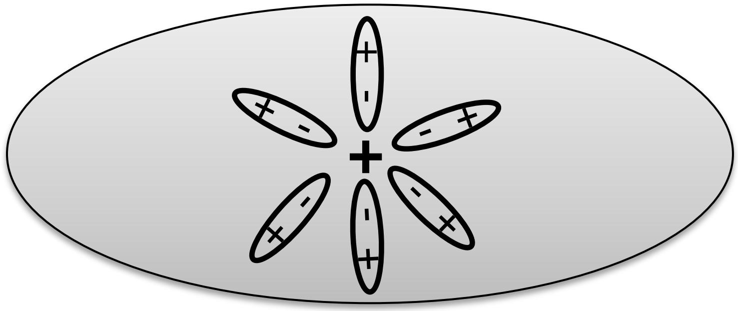
Inelastic collisions between a single ion and ultracold neutral atoms

Michael Köhl

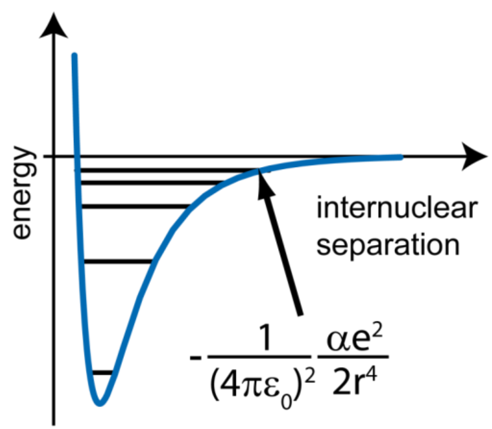
UNIVERSITY OF CAMBRIDGE

Atom-ion interactions



Local change of energy W = **-p·E = -** $\alpha/2$ **E²**

Microscopic description:



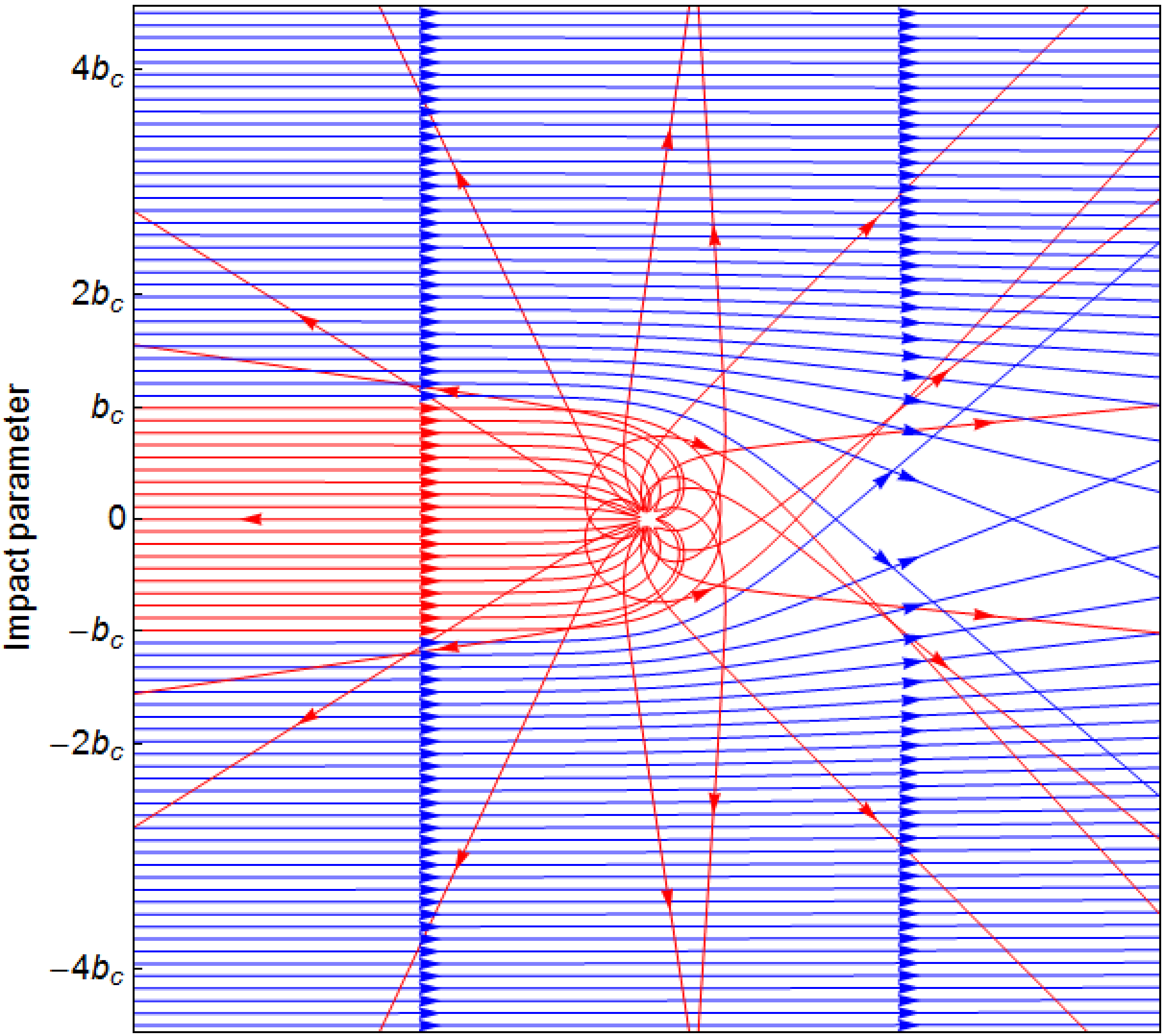
<u>Atom-ion hybrid system</u>

- Single-particle control
- Attractive long range interaction: bound states
- Cold temperatures: towards quantum limited chemistry
- Large trap depth: Long manipulation and interrogation times for reactants and reaction products

Theory: Busch, Calarco, Cote, Dalgarno, d'Ambrumenil, Gao, Giamarchi, Idziazek, Julienne, Kollath, Landau, Massey, Mott, Pethick, Zoller, ...

Experiment: MIT, UConn, Ulm, Weizmann, Tokyo, Oxford, UCLA, Basel, Aarhus, Düsseldorf ...

Cold ion-neutral collisions



Total scattering cross section

$$\sigma_{el}(E) = \pi\left(1+\frac{\pi^2}{16}\right) r^{*2}\left(\frac{\hbar^2}{\mu r^{*2} E}\right)^{1/3}$$

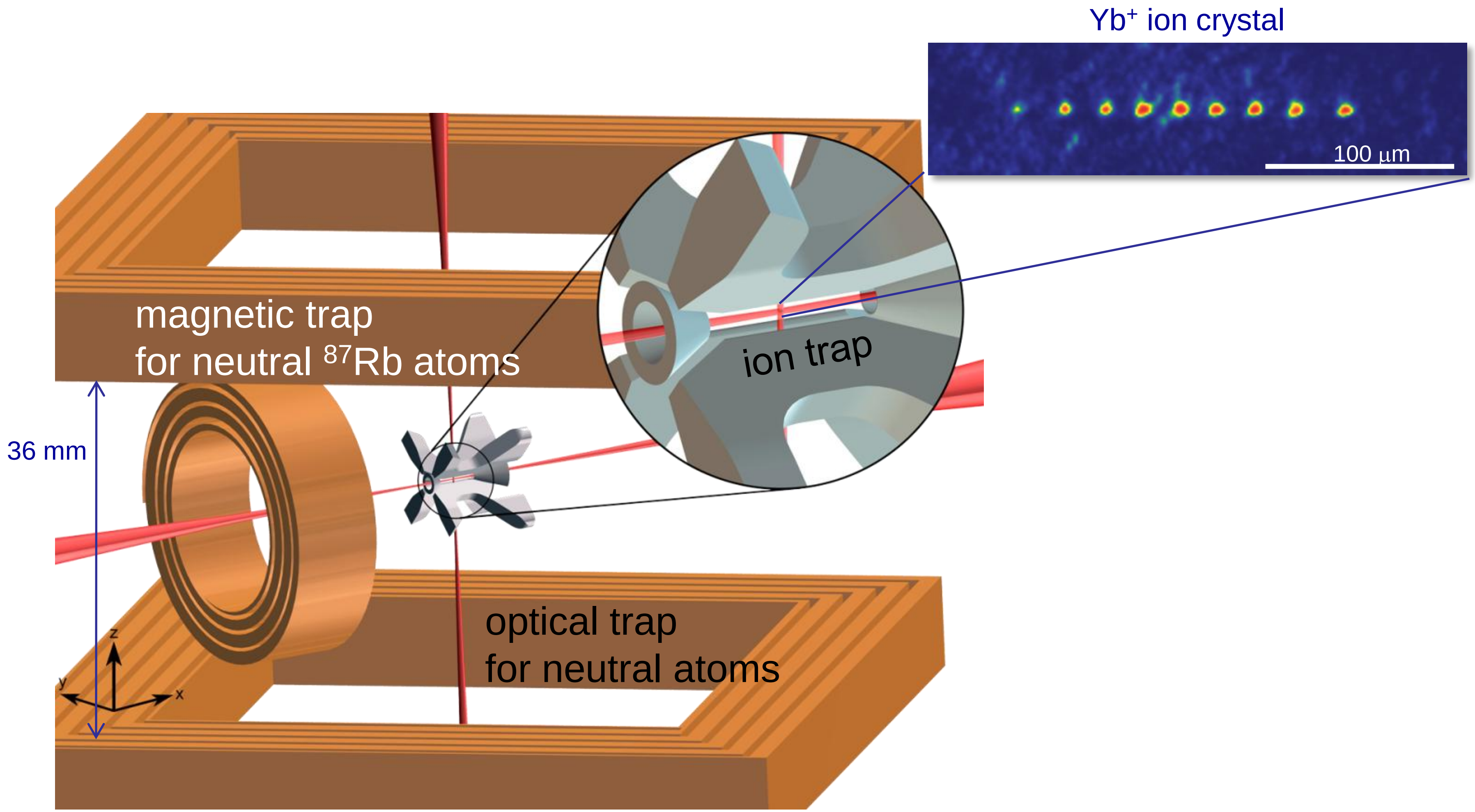
Langevin cross section

$$\sigma_{el}(E) = \pi\left(\frac{2C_4}{E}\right)^{1/2}$$

collision rate constant
is energy independent

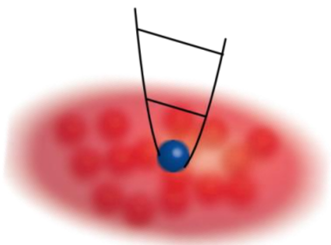
Vogt & Wannier (1954)

Hybrid apparatus



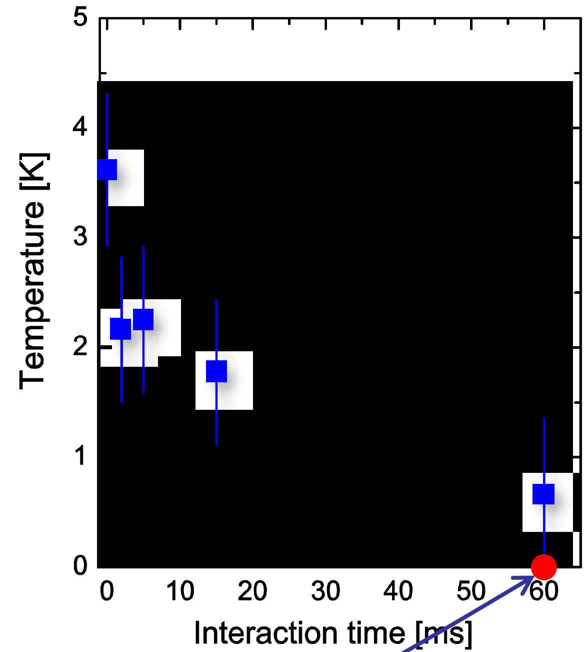
C. Zipkes, S. Palzer, C. Sias, MK, Nature 464, 388 (2010)

Elastic collisions: Sympathetic cooling



Ion trap
(level spacing ≈2 μK)

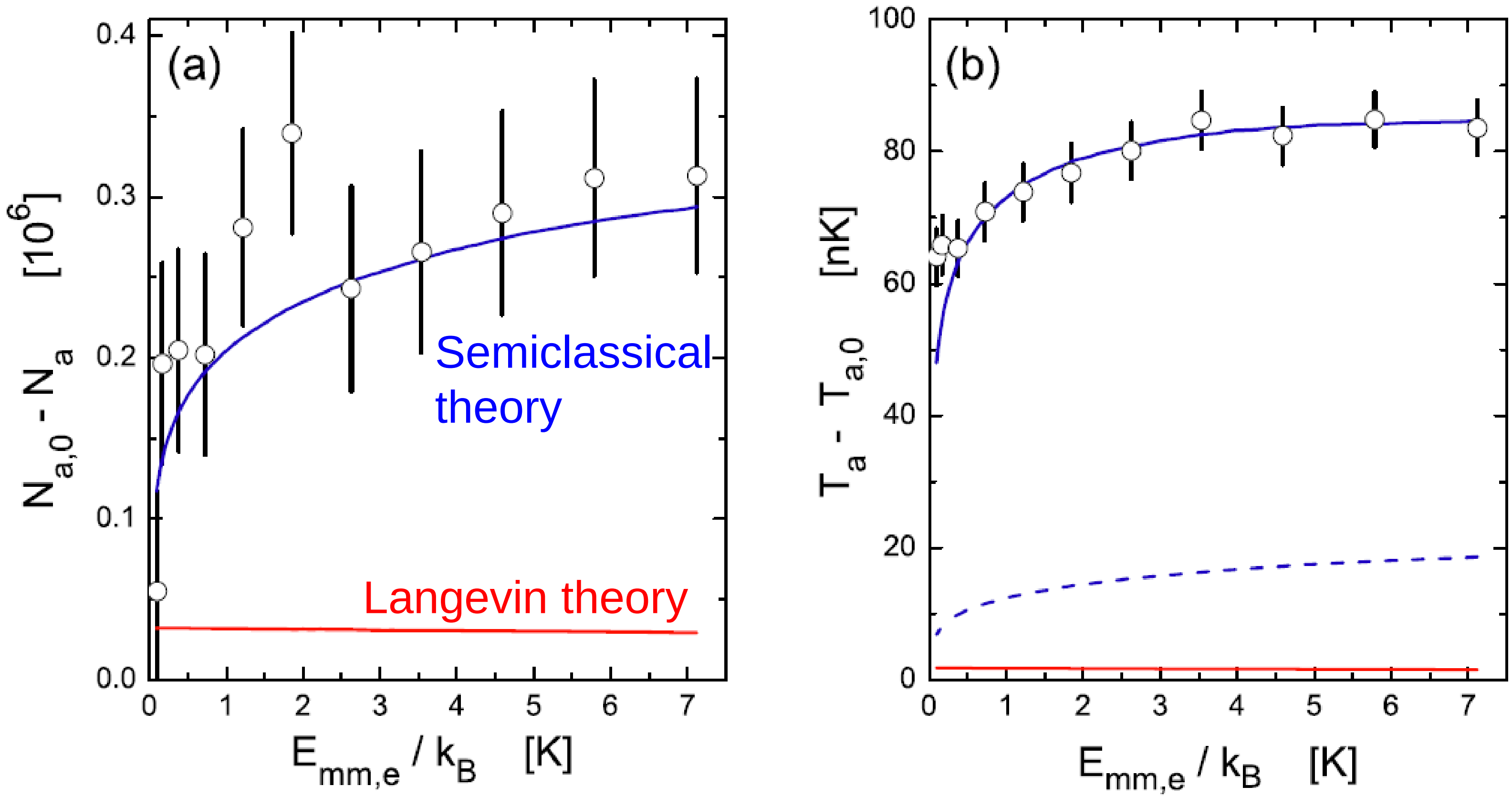
Bose-Einstein condensate
T ≈ 100 nK, trap depth ≈ 1 μK



Estimate based on energy-dependence of cross section:
T ≤ 20 mK

C. Zipkes, S. Palzer, C. Sias, MK, Nature 464, 388 (2010)
see also S. Schmid et al., PRL 105, 133202 (2010)

Elastic collisions: Effect on neutral atoms



C. Zipkes et al., New J. Phys. 13, 053020 (2011)
C. Zipkes et al., PRL 105, 133201 (2010)

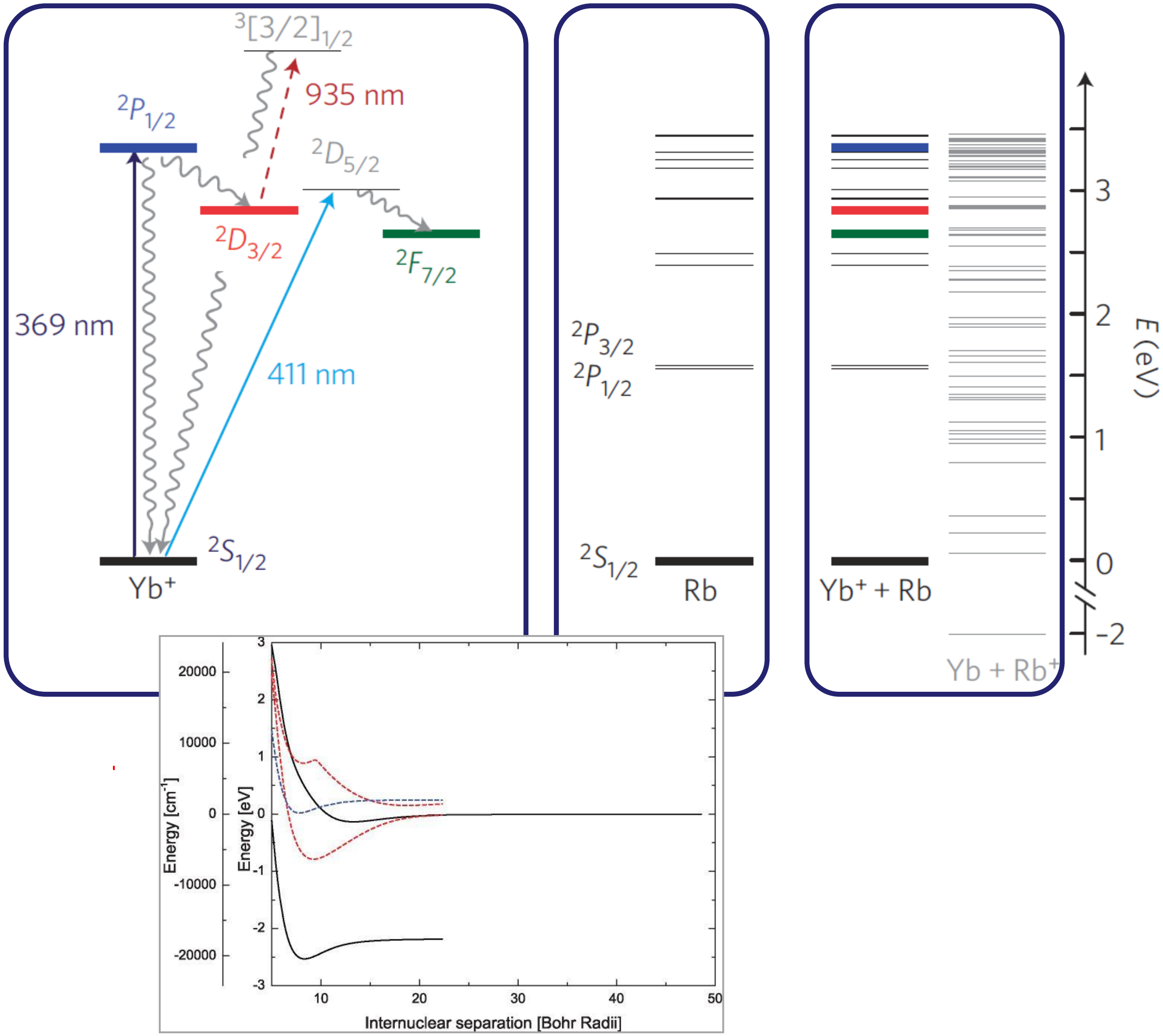
Overview

1. Charge exchange reactions in the ground state

2. Inelastic collisions of excited electronic states

3. Inelastic collisions of spin states

Level scheme

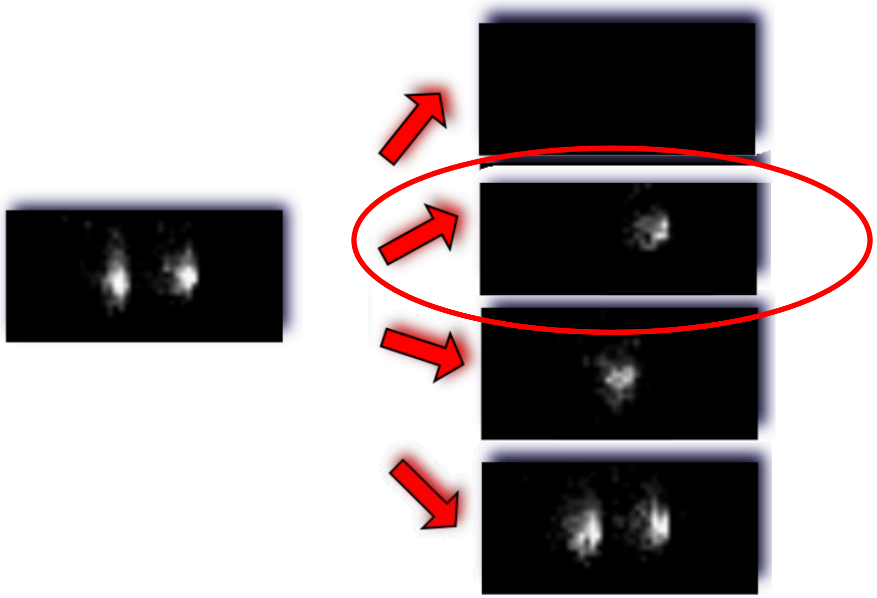


Energy scales:

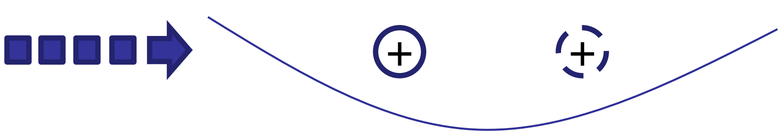
- electronic excitation: 3eV
- trap depth: 300 meV
- ....
- hyperfine interaction Rb: 30μeV
- collision energies: 3μeV

Single ion chemistry

Before Interaction | After Interaction

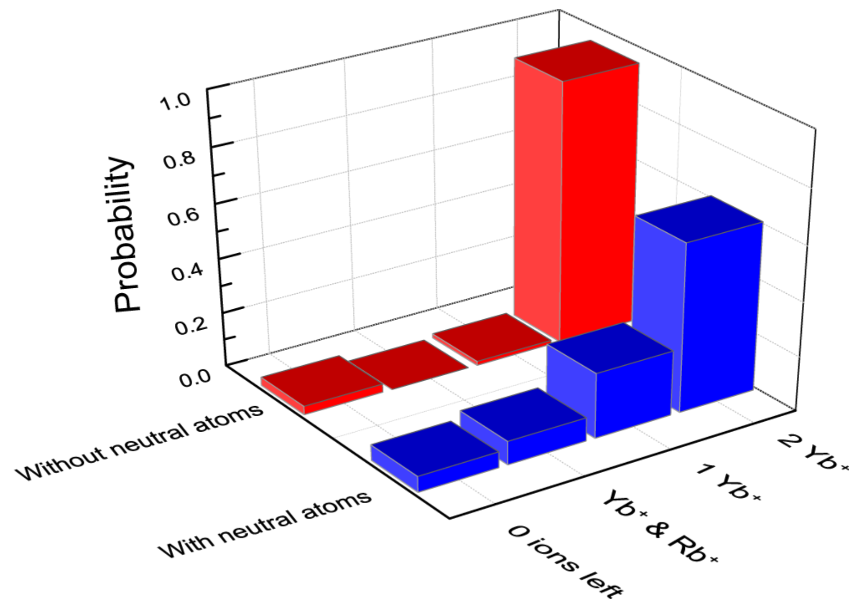


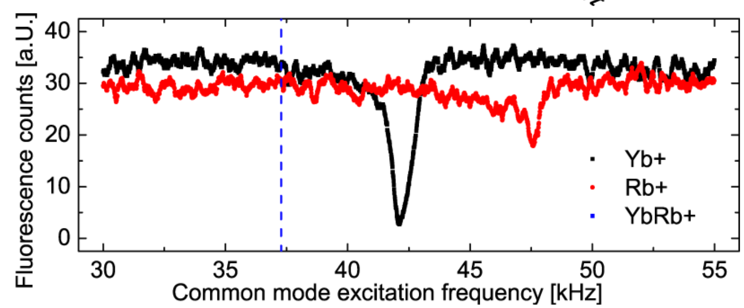
Mass spectroscopy



Similar technique: Aarhus, Dusseldorf, Oxford, ...

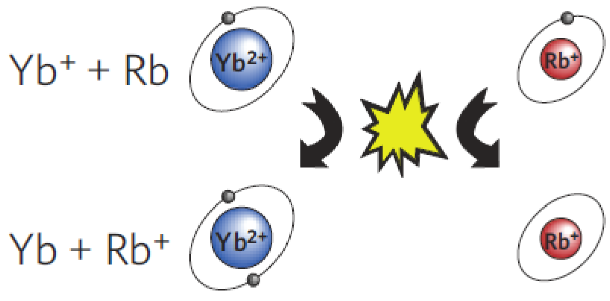
After 8 seconds interaction time
(~ 1500 measurements)



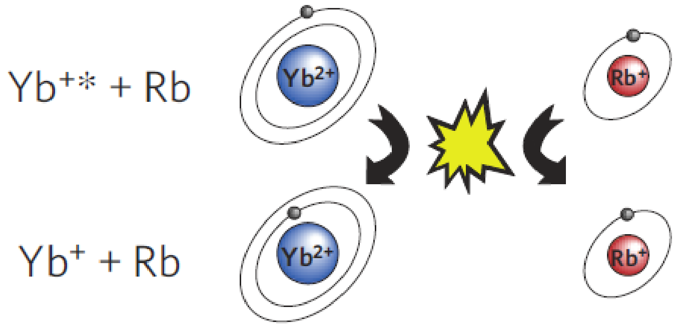


C. Zipkes et al., PRL 105, 133201 (2010)

Inelastic electronic processes

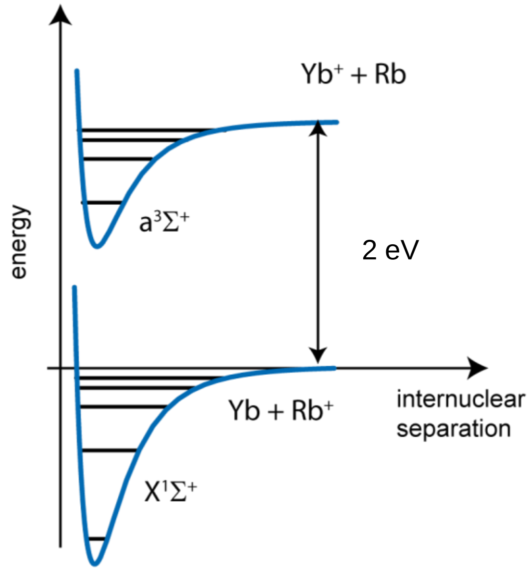


Charge exchange reaction



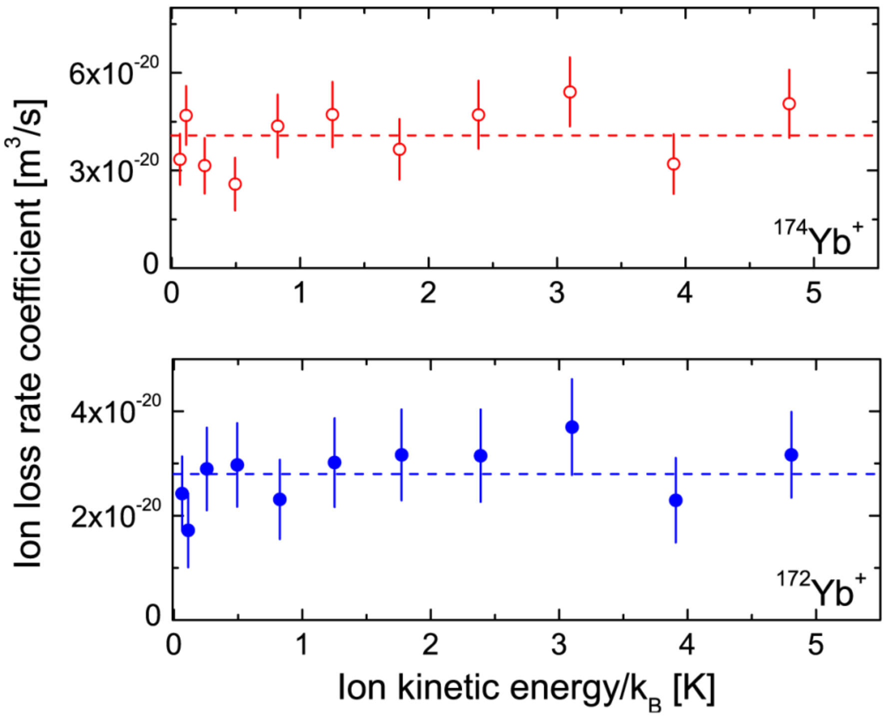
Collisional quenching

Charge exchange in the ground state



small charge-exchange rate:
$\sim 10^{-5}\,\gamma_L$

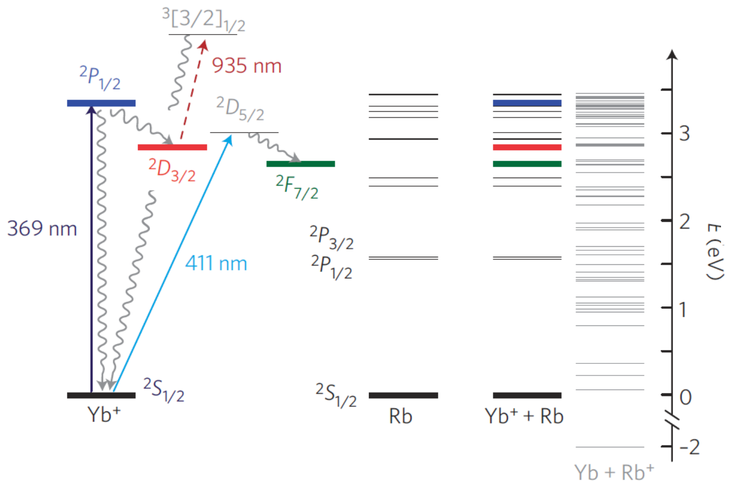
(each data point: ~ 150 measurements)



Energy independent rate constant

C. Zipkes, S. Palzer, L. Ratschbacher, C. Sias, MK, PRL 105, 133201 (2010)
for equal elements of ions and neutral: Grier et al., PRL (2009)

How reactive are the different internal states?



$$\gamma_\ell = 2\pi\sqrt{C_4/\mu}\, n_a \left(p_S\,\epsilon_S + p_P\,\epsilon_P + p_D\,\epsilon_D + p_{D[3/2]}\,\epsilon_{D[3/2]}\right)$$

Langevin collision rate

State occupation

“reactivity”

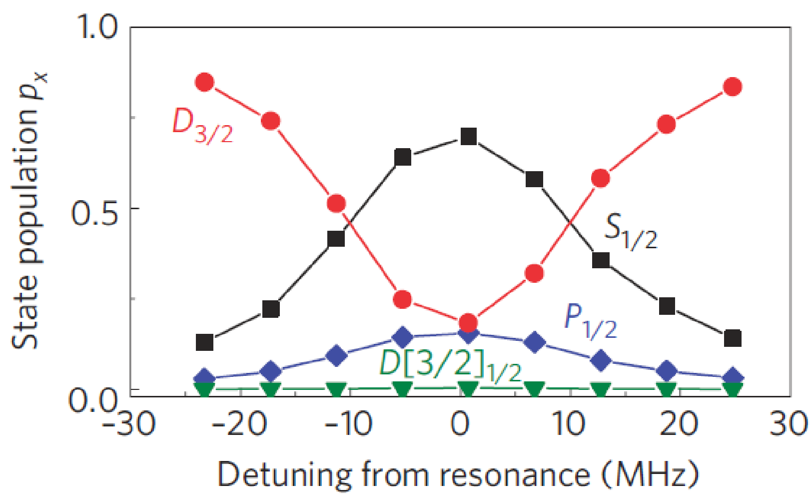
Table 1 | Measured proportionality constant ϵ and branching ratios.

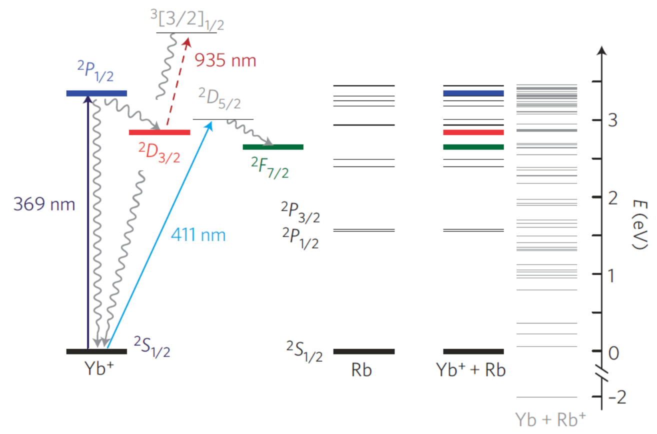
	$^2S_{1/2}$	$^2D_{3/2}$	$^2F_{7/2}$	$^2P_{1/2}$
ϵ	$10^{-5\pm0.3}$	1.0 ± 0.2	0.018 ± 0.004	0.1 ± 0.2
Charged particle lost	65%	87%	84%	
Rb^+ identified	35%	12%	15%	
Dark Yb^+ identified		$<1\%$		
Hot ion (unidentified)			1%	
Number of events	283	754	225	

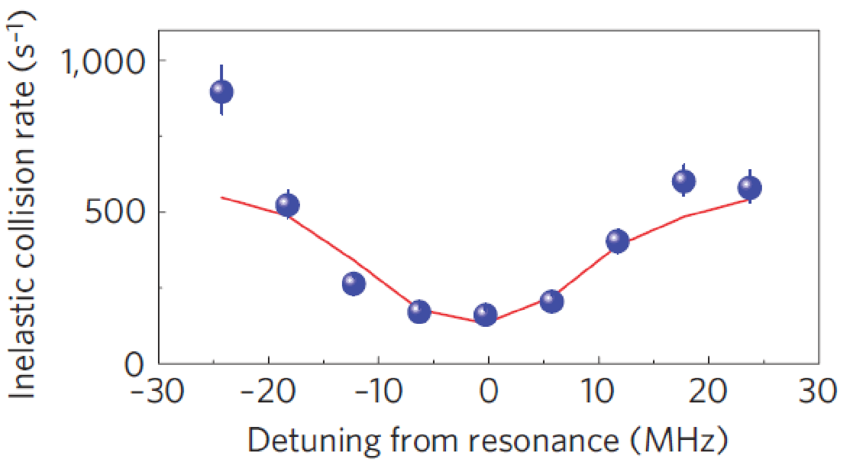
Rb |F=2, m_F=2>

L. Ratschbacher et al., Nature Phys. 8, 649 (2012)

Reaction control



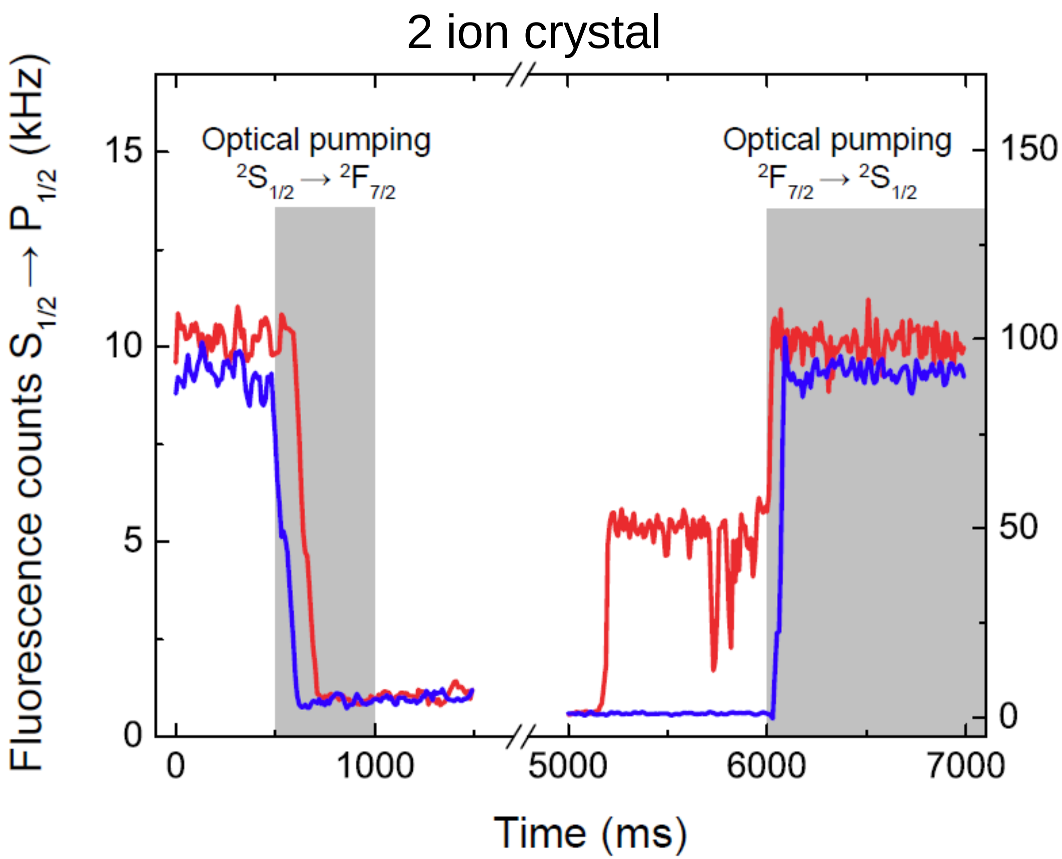


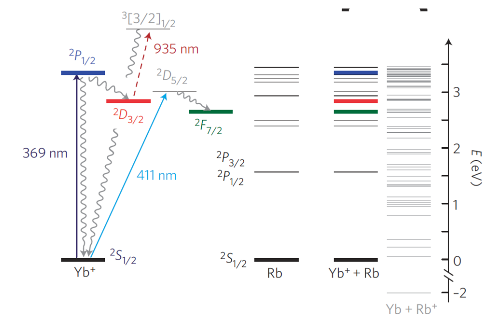


Inelastic collisions are dominated by the $D_{3/2}$ state!

L. Ratschbacher et al., Nature Phys. 8, 649 (2012)

Collisional quenching $F_{7/2} \to S_{1/2}$

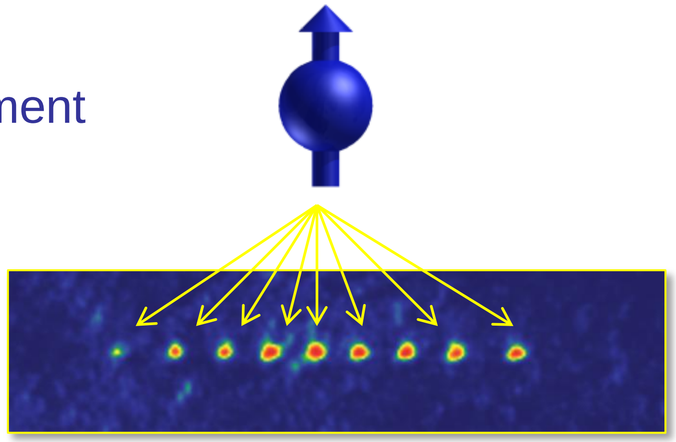




L. Ratschbacher et al., Nature Phys. 8, 649 (2012)

Spin dynamics and decoherence

Idealized quantum system:
single spin-1/2 in perfect isolation from environment



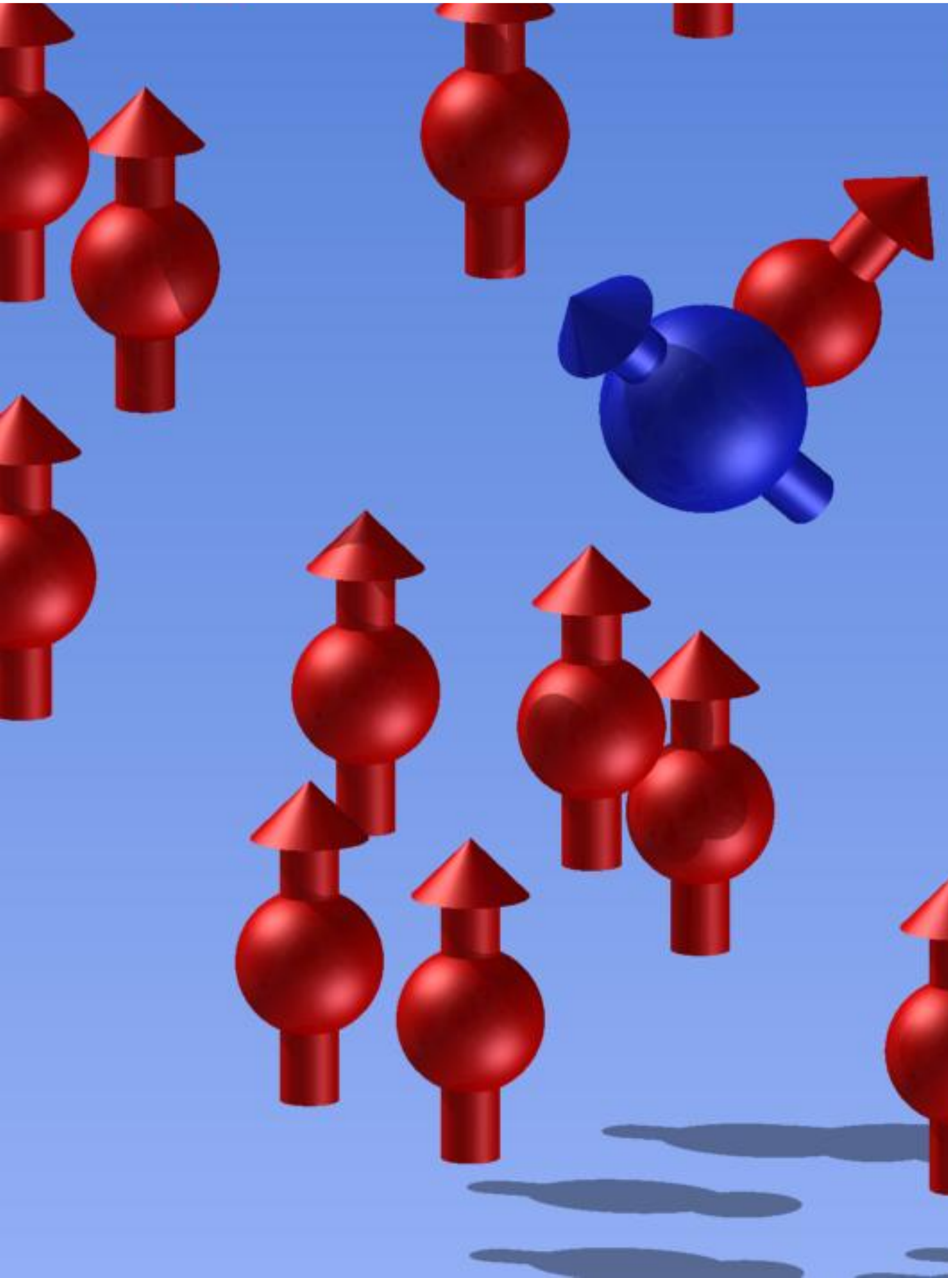
With many of them:

- Quantum computing
- Quantum simulation

Problem: not many particles yet and not for long ...

=> understand the effects of decoherence in an environment

Spin dynamics in a polarized environment



Spin-1/2 coupled to environment

=> Decoherence

Controlled experiments are necessary

[So far: mostly spontaneous emission]

<u>Specific atom-ion questions:</u>

Spin-spin coupling/spin exchange ?

Spin relaxation ?

Decoherence ?

Models for coupling spin-1/2 to environments

Harmonic oscillator bath

Spin-1/2 coupling to a set of harmonic oscillator modes (phonons, photons)
=>Continuous spectrum
“Spin-boson problem”

$$H = -\frac{\Omega}{2}\sigma_x + \sum_q \omega(q) b_q^+ b_q + \frac{\sigma_z}{2}\sum_q \lambda_q \left(b_q + b_q^+\right)$$

Caldeira, Legett, Feynman, Vernon, ...

Spin bath

Spin-1/2 coupling to a set of localized spins (semiconductors, nuclear spins)
=> discrete spectrum

$$H(\vec{S};\{\hat{\vec{\sigma}}\}) = H_0(\vec{S}) + \frac{1}{S}\sum_{k=1}^{N} \omega_k \vec{S}\cdot\hat{\vec{\sigma}}_k + H_{\text{env}}(\{\hat{\vec{\sigma}}\});$$

Prokofev, Stamp, ...

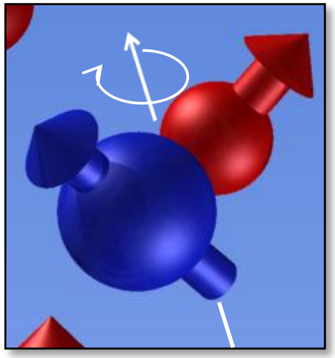
Spin-spin interaction

Spin exchange

- Conserves total spin

$^{x}Yb^{+}\downarrow + ^{87}Rb\uparrow \rightarrow ^{x}Yb^{+}\uparrow + ^{87}Rb\downarrow$

$^{x}Yb^{+}\uparrow + ^{87}Rb\downarrow \rightarrow ^{x}Yb^{+}\downarrow + ^{87}Rb\uparrow$



- Spin stretched state cannot flip

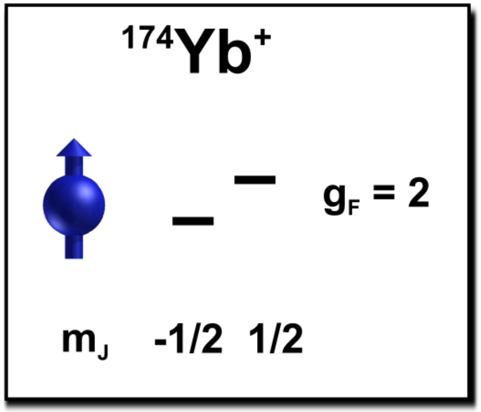
Spin relaxation

- Spin-orbit coupling breaks symmetry underlying spin conservation
- Relaxation of spin-stretched states

In a wide range of atomic systems (cold gases, optical pumping of ^{3}He, ...):

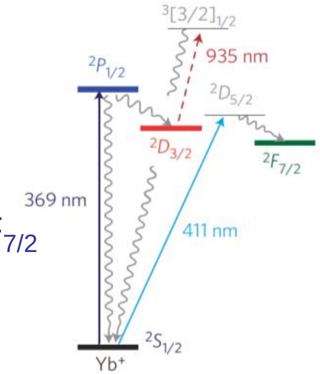
$$\gamma_{elastic} \approx \gamma_{SE} >> \gamma_{SR}$$

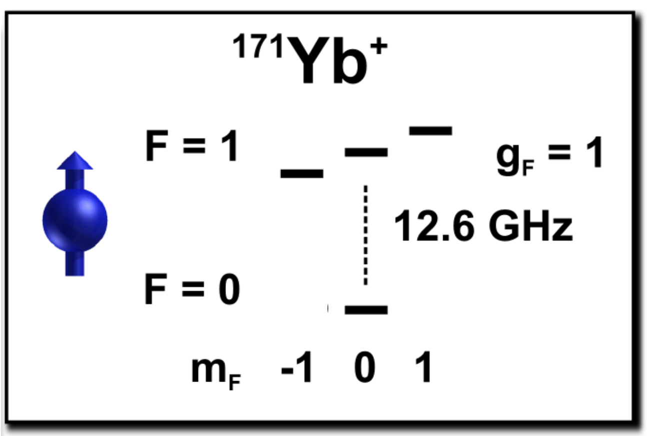
Spin qubits in Yb^+ ($S_{1/2}$ ground state)



Zeeman qubit: isolated spin-1/2 system

Detection via shelving in $F_{7/2}$

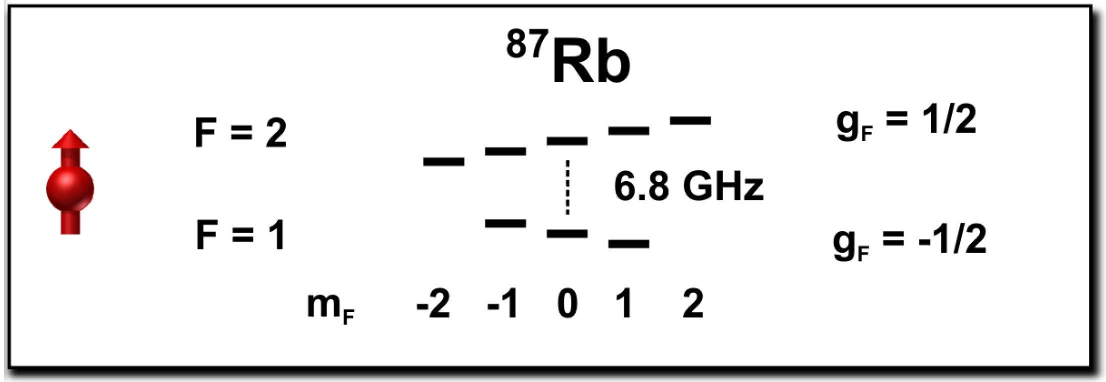




Hyperfine qubit:

- $|F=0,m_F=0\rangle \rightarrow |1,0\rangle$
  first-order magnetic insensitive hyperfine transition
- long coherence times
- however: actually a four-level system

Spin-polarized environment



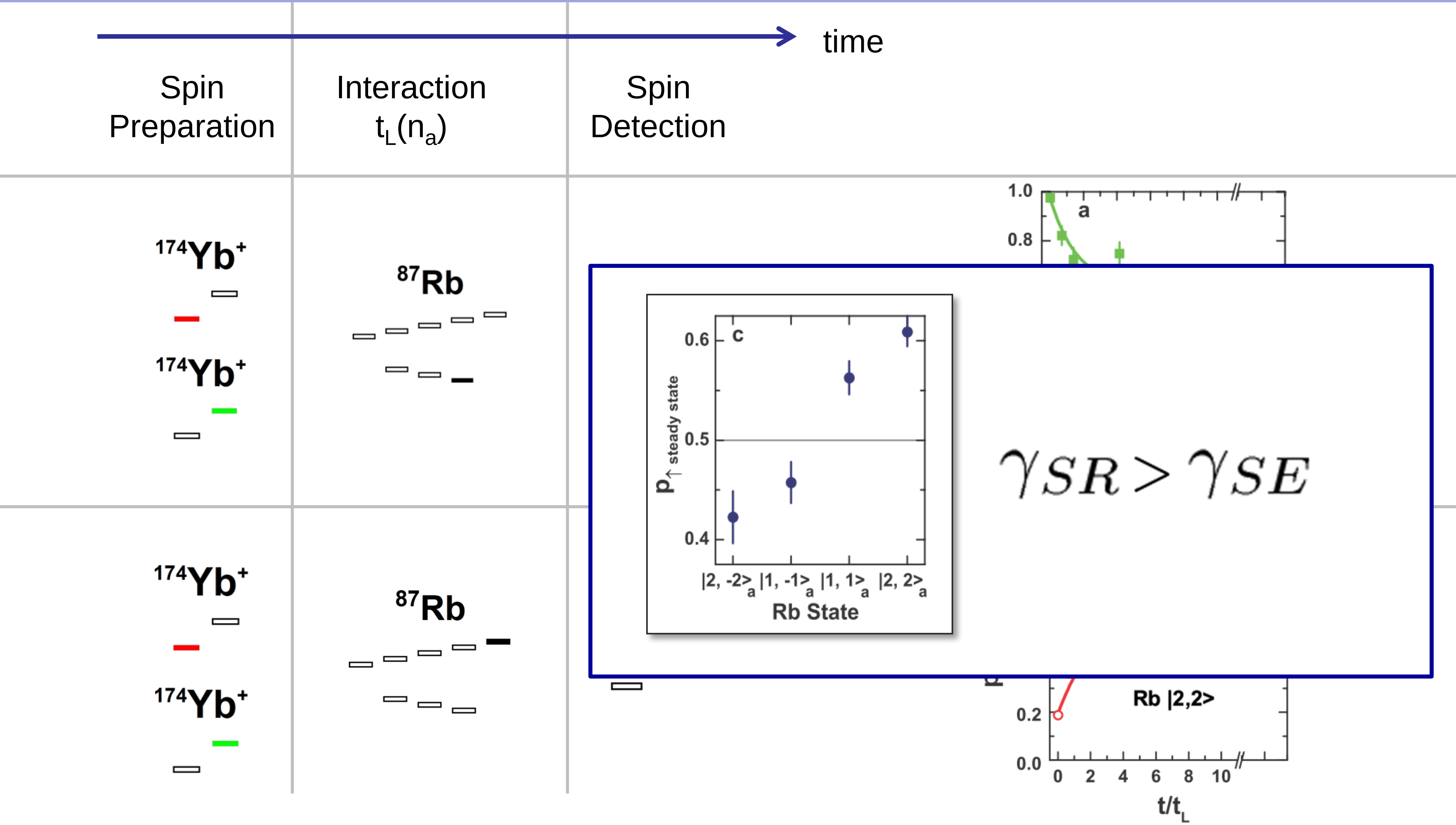
Magnetic Trap

- lower trap frequencies
- easier overlap
- better control over atomic density
- less depletion of the cloud

Optical Trap

- all states trappable
- choice of magnetic field

Zeeman qubit: Longitudinal coherence (T_1)



$$\gamma_{SR} > \gamma_{SE}$$

L. Ratschbacher, C. Sias, L. Carcagni, J. Silver, C. Zipkes, M. Köhl, arXiv:1301.5452 (2013)

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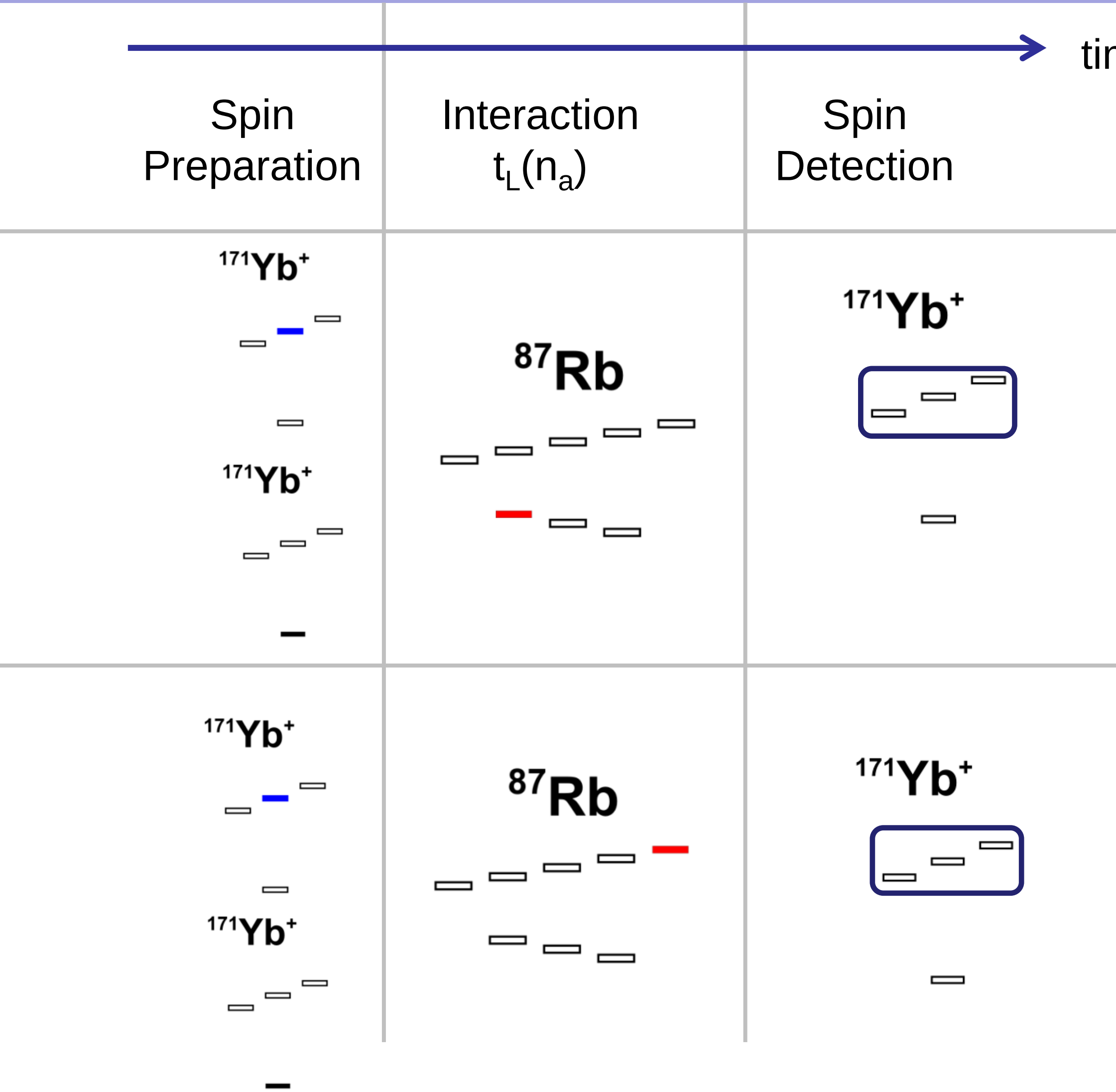
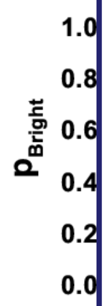
Hyperfine qubit: Longitudinal coherence (T_1)





Heat intake from hyperfine change

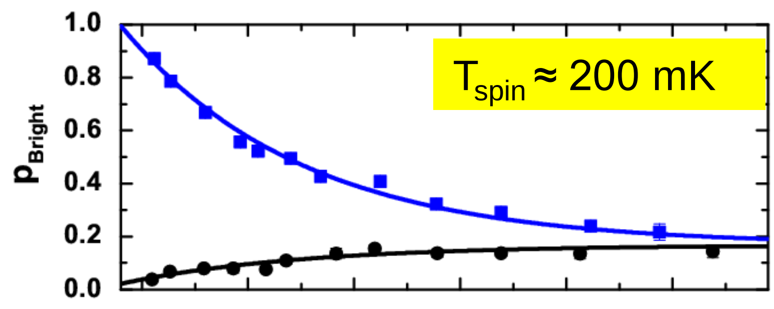
$$\delta E_{heat} = \epsilon E_a^{HFS} \frac{m_a}{m_a + m_i}$$

Cooling from elastic collisions

$$\delta E_{cool} = -\frac{2 m_a m_i}{(m_a + m_i)^2} E_{kin}$$

In equilibrium:

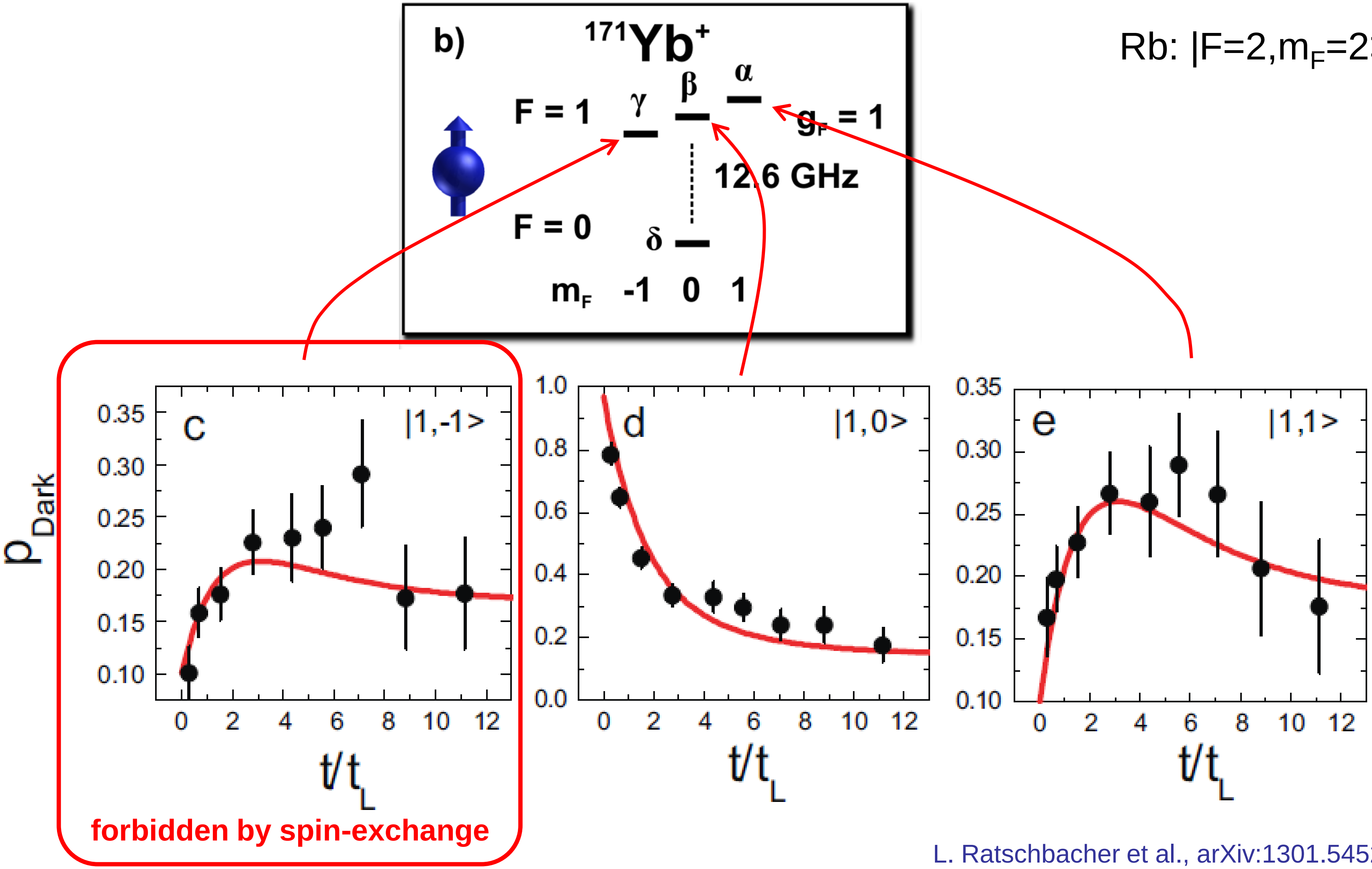
$T_{kin} \approx 240$ mK



L. Ratschbacher, C. Sias, L. Carcagni, J. Silver, C. Zipkes, M. Köhl, arXiv:1301.5452 (2013)

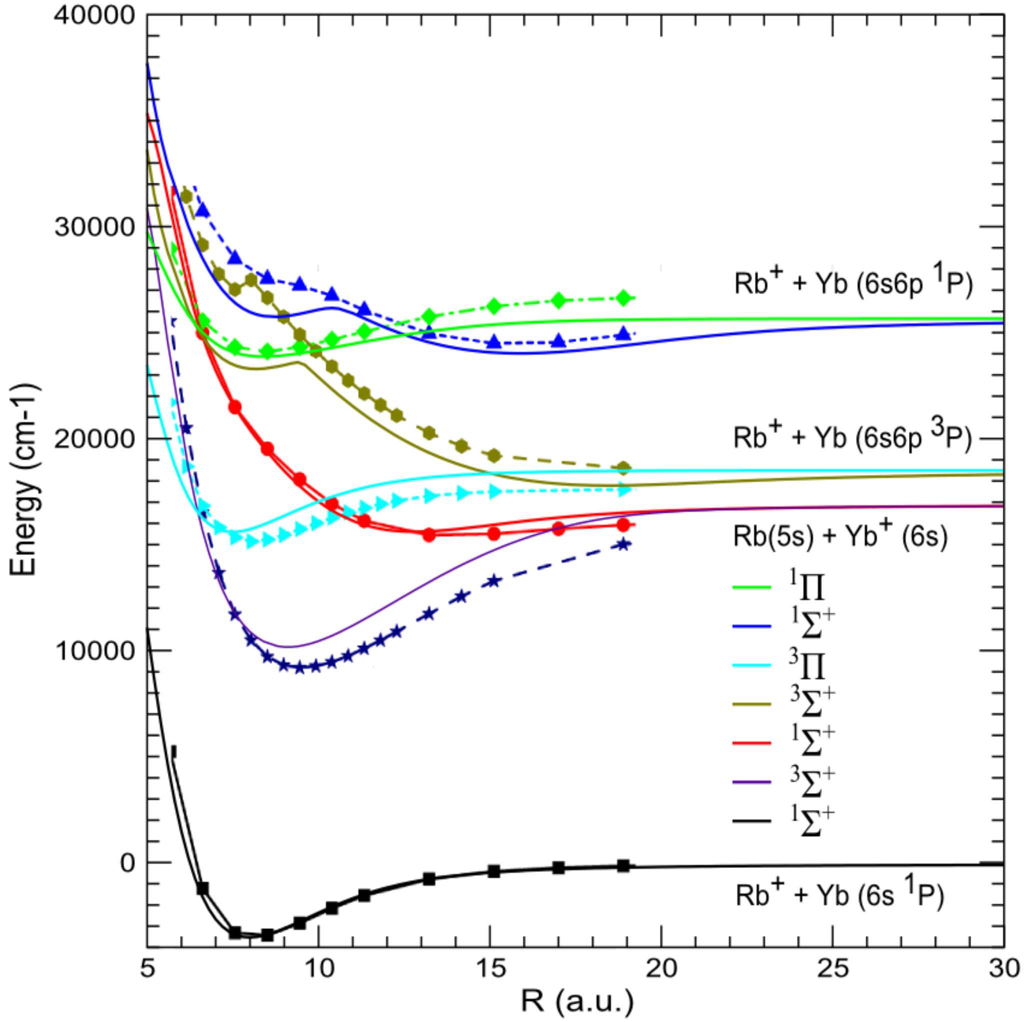
Spin redistribution

Rb: $|F=2,m_F=2>$



L. Ratschbacher et al., arXiv:1301.5452 (2013)

Zero energy electronic level crossing ?



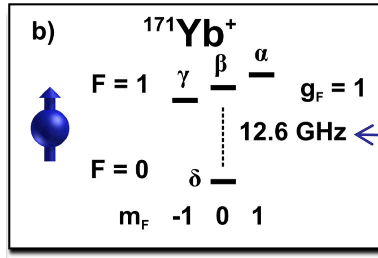
Possibly zero energy crossing in the Yb^{+} + Rb system.

(Theoretical potential energy curves not accurate enough yet for a definitive statement ...)

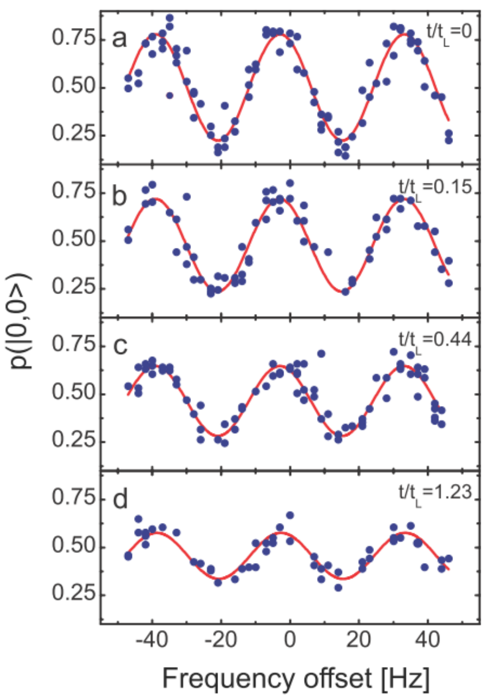
Private communication by O. Dulieu; A. A. Buchachenko & A. K. Belyaev

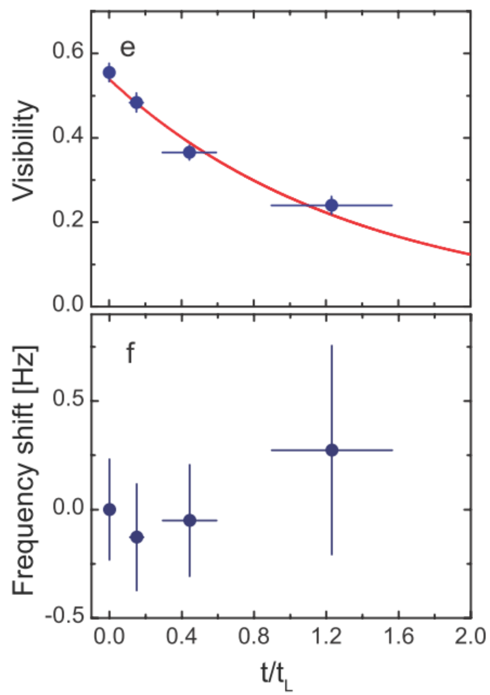
Hyperfine qubit: Transverse coherence (T_2)

Ramsey interferometry in presence of |2,2> atoms



microwave clock transition





- Decay of the coherence on the timescale expected from T_1
- Ability to measure frequency shifts limited by fast decay of coherence

L. Ratschbacher, C. Sias, L. Carcagni, J. Silver, C. Zipkes, M. Köhl, arXiv:1301.5452 (2013)

Summary

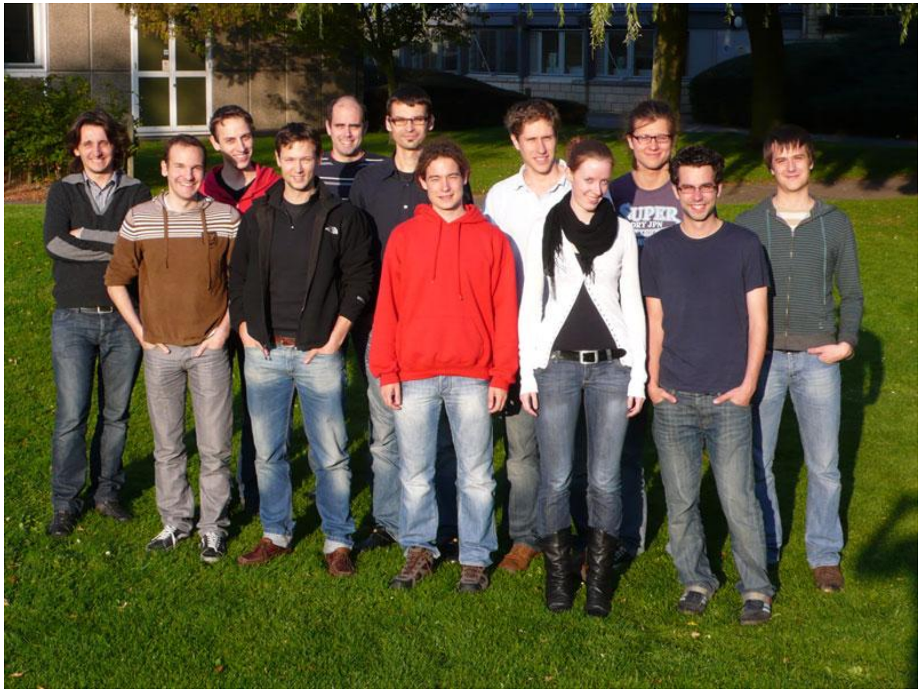
Elastic collisions, sympathetic cooling

Charge exchange in ground and excited states

Control of reactions with laser light at the single particle level

Spin-spin interaction and spin-orbit coupling

Thanks!



Ion & BEC — C. Zipkes, L. Ratschbacher, C. Sias, J. Silver, L. Carcagni

Fermi gases — E. Vogt, M. Koschorreck, D. Pertot, L. Miller, E. Cocchi, J. Bohn

Trapped ion QIP — H.-M. Meyer, M. Steiner, T. Ballance

Jakob Reichel (ENS Paris), Christian Deutsch (ENS Paris)

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