The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2030-29

Conference on Research Frontiers in Ultra-Cold Atoms

4 - 8 May 2009

Ultracold heteronuclear Fermi-Fermi molecules

DIECKMANN Kai

Ludwig Maximilians Universitaet Muenchen
Department of Physics
Schellingstrasse 4, 80799 Munich
GERMANY

Ultracold Heteronuclear Fermi-Fermi Molecules

Kai Dieckmann

Ludwig-Maximilians-University of Munich
Max-Planck-Institute for Quantum Optics, Garching
Germany

Trieste, May 6th, 2009

€€€:
Max-Planck-Society
Munich Center for Advanced Photonics (MAP)
DFG Research Unit FOR 801 „Strong Correlations in Multiflavor Ultracold Quantum Gases“

Polar Molecules

Cold polar molecules:

^{133}Cs – ^{7}Li Bose-Bose mixture:

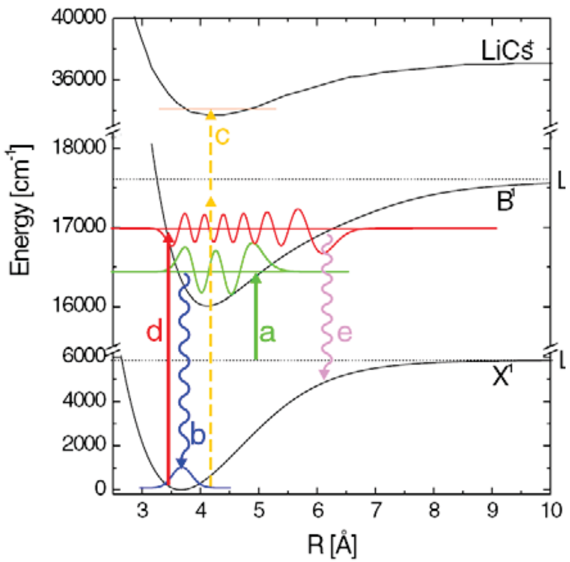
Single step of photoassociation process

J. Deiglmayr et al., PRL ***101****, 133004 (2008)*

^{87}Rb – ^{40}K Bose-Fermi mixture:

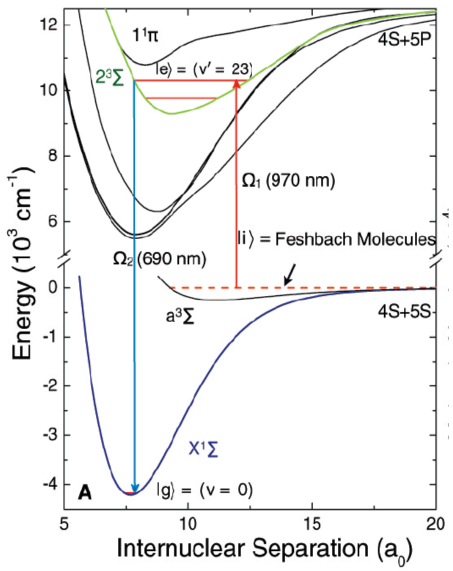
Single step of stimulated Raman transfer

K.-K. Ni et al., Science ***322****, 231 (2008)*



^{6}Li – ^{40}K Fermi-Fermi mixture:

- **Long lifetime** of Feshbach molecules facilitate STIRAP
- **High dipole moment**
  Absolute ground state LiK 3.6 Debye
  M. Aymar and O. Dulieu, J. Chem.Phys., ***122****, 204302 (2005)*
- **Bosonic** molecules



Perspective: longlived BEC of ground state molecules with anisotropic, long-range interaction

Dipole Moments of Ground State Molecules

Dipole moments of vibrational ground state: υ=0

Mixture	[Debeye]
Li-Na	0.56
Li-K	3.6
Li-Rb	4.2
Li-Cs	5.5
Na-K	2.8
Na-Rb	3.3
Na-Cs	4.6
K-Rb	0.6
K-Cs	1.9
Rb-Cs	1.2

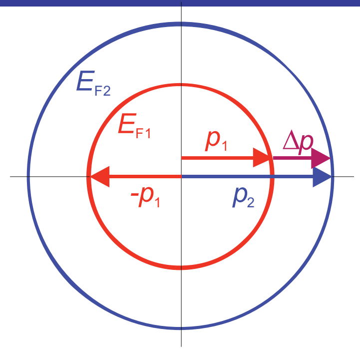
M. Aymar and O. Dulieu, J. Chem.Phys., 122, 204302 (2005)

3.6 Debeye $\triangleq$ 13kHz interaction energy for lattice spacing of 532 nm.

Strongly Interacting Mixture

Strongly interacting Fermi gases:

- Imbalanced Fermi gases
  - *Y. Shin et. al, PRL **97**, 030401 (2006)*
  - *G. B. Partridge, Science **311**, 503 (2006)*



Fulde-Ferrell-Larkin-Ovchinnikov states (FFLO) in 1D traps or 1D optical lattices

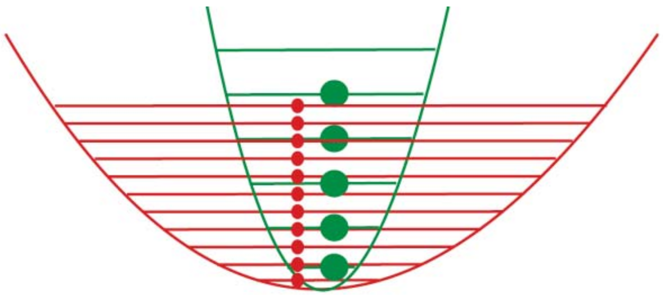
- crystalline phase, BEC-BCS crossover, resonant pairing, …

Theoretical calculations on FFLO in 1D:
A.E.Feiguin , F. Heidrich-Meisner, PRA. 220508 (2007)
*G. Orso, PRL **98**, 070402 (2008)*
*G. G. Batrouni, PRL **100**, 116405 (2008)*
*M. Tezuka et al., PRL **100**, 110403 (2008)*
*M. Rizzi et al., PRB **77**, 245105 (2008)*
*A. Lüscher et al., PRA **78**, 013637 (2008)*
*X.-J. Liu, PRA **78**, 023601 (2008)*
…

Experimental possibilities of heteronuclear system:

Independent control of optical potentials, i.e. densities

- Selective evaporative cooling, adiabatic expansion
- tuning of effective mass
- "Magic" wavelength

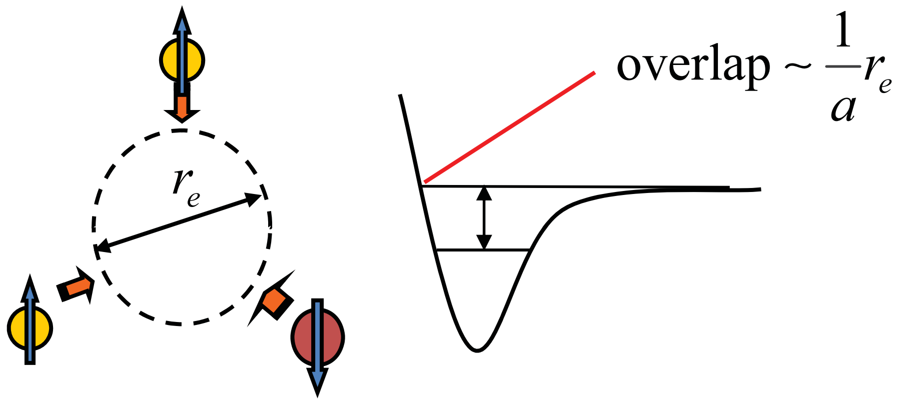


Long Lifetime of Fermions at FBR

$$^6\text{Li},\ \left|\uparrow\right\rangle + \left|\downarrow\right\rangle @\ 834\ \text{G FBR} : \tau \approx 1\ \text{s}$$

Vibrational relaxation suppressed due to Pauli exclusion principle

D.S.Petrov et al., 2003 onwards

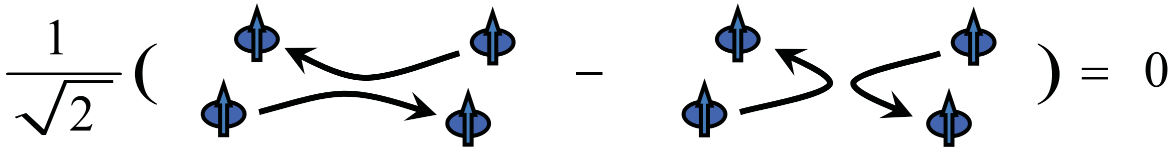


D. Petrov's talk on Thursday 11:45

Triple Degenerate Mixture

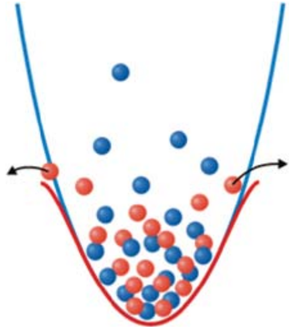
Why three species?

- **Fermions in identical states do not interact**



> Use of mixtures for sympathetic cooling

Amsterdam, Innsbruck: Li: $|1\rangle \,\&\, |2\rangle$ & K $\left|\frac{9}{2}; -\frac{9}{2}\right\rangle$



- **Fermi-Fermi-Bose mixture**

Munich:

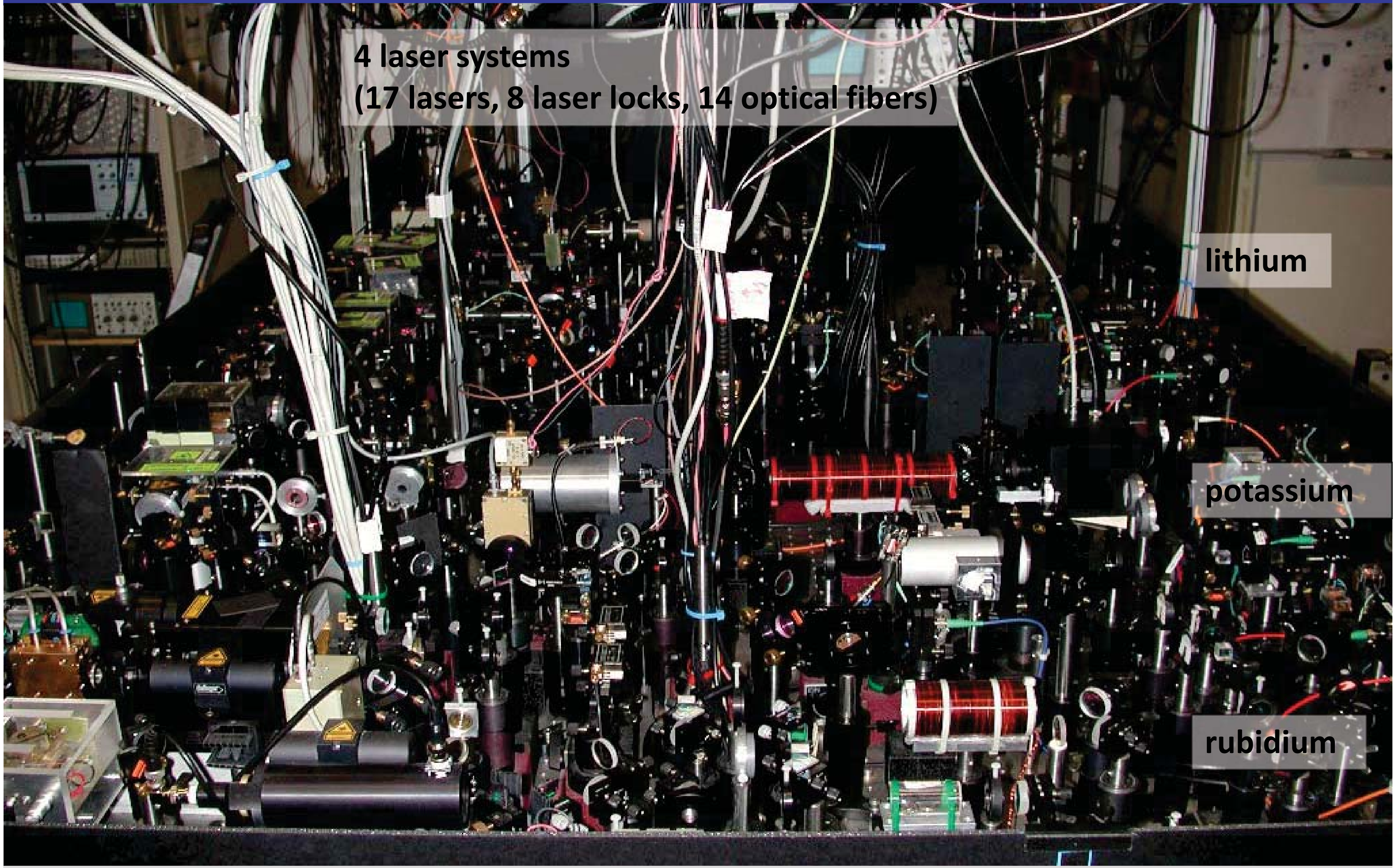
^{6}Li	^{40}K	^{87}Rb
fermion	fermion	boson

sympathetic cooling with large and stable ^{87}Rb reservoir

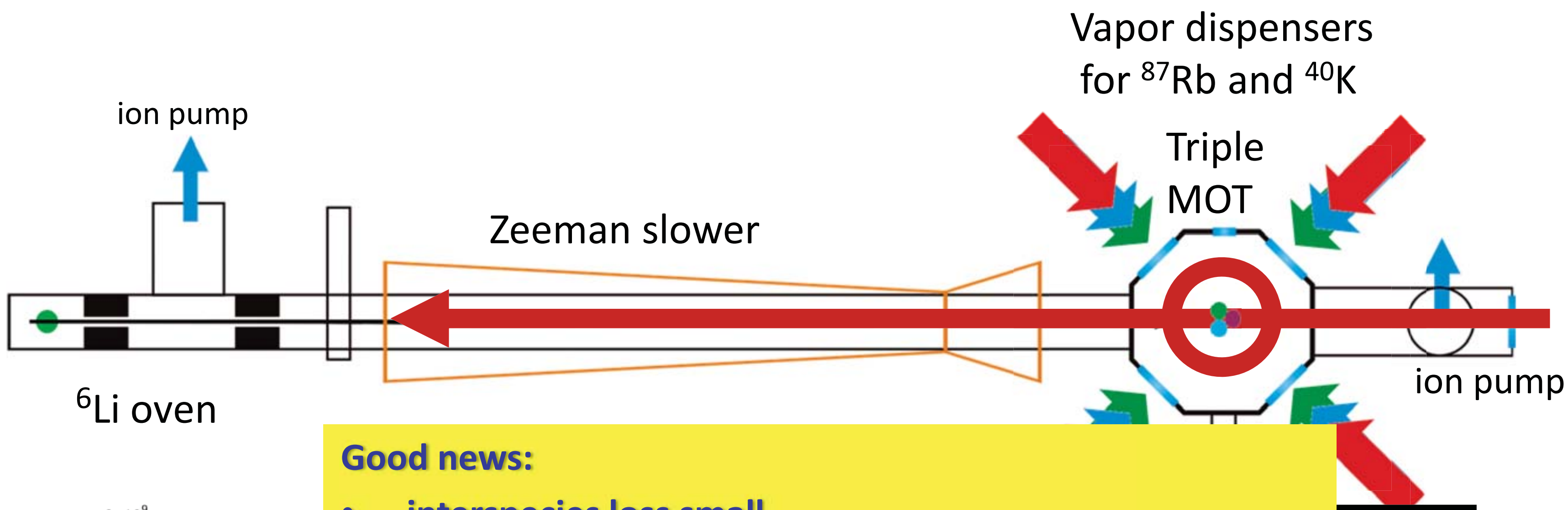
Advantages:

- No doubled Pauli blocking when cooling into quantum degeneracy
- Fermions are not evaporated: lower initial fermion atom numbers are sufficient
- Flexibility: to study Fermi-Fermi and Fermi-Bose mixtures

Laser Systems

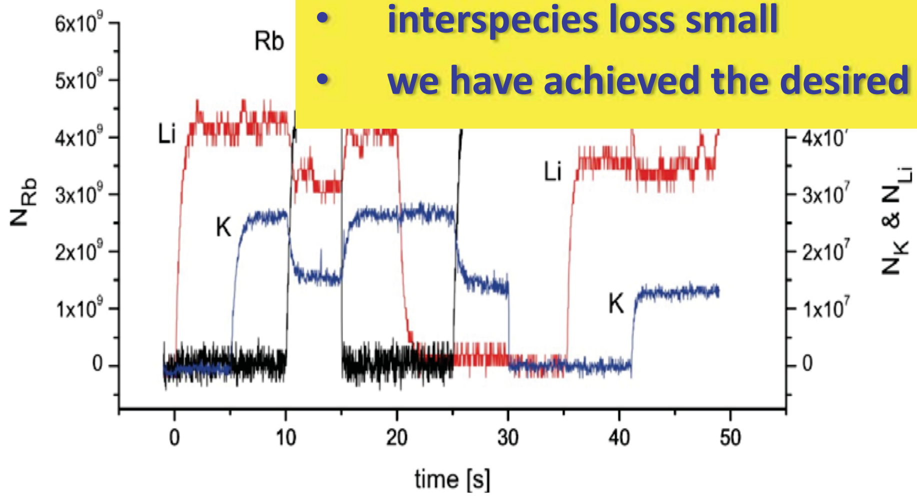


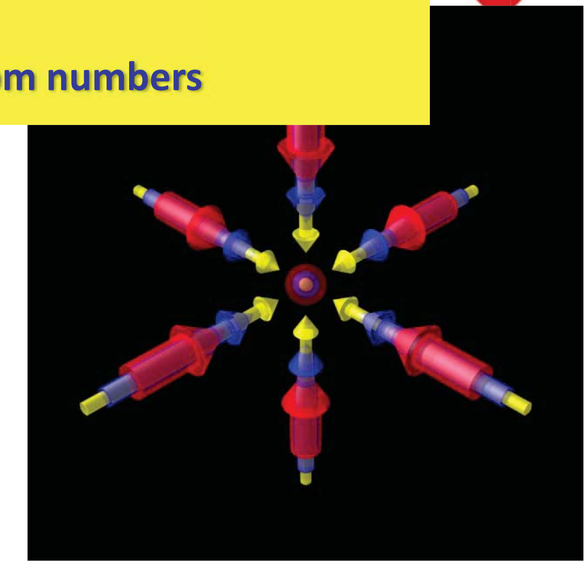
Triple MOT



Good news:

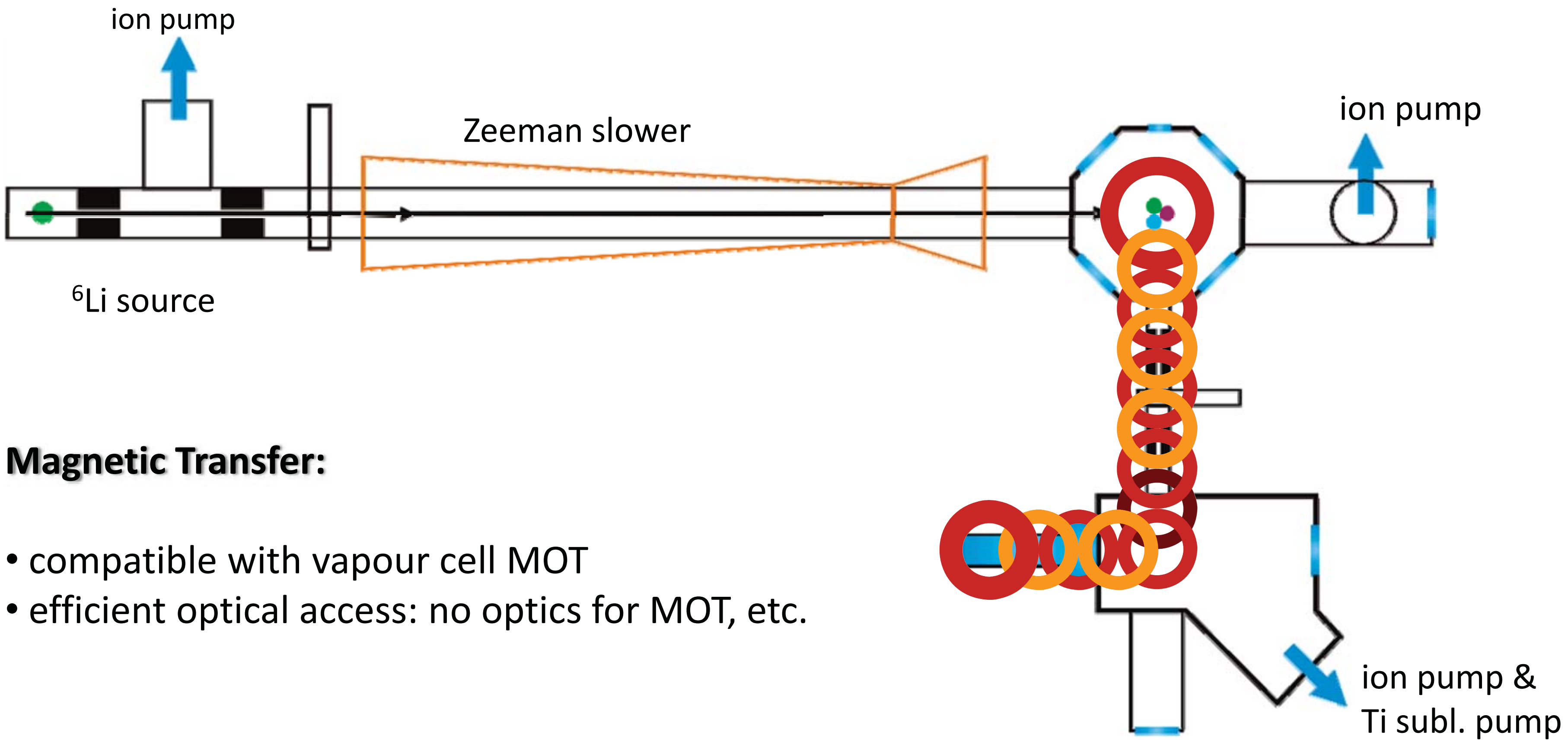
- **interspecies loss small**
- **we have achieved the desired atom numbers**





M. Taglieber, A.-C. Voigt, F. Henkel, S. Fray, T. W. Hänsch, and K. Dieckmann Phys. Rev. A 73, 011402 (R) (2006).

Concept of the Machine

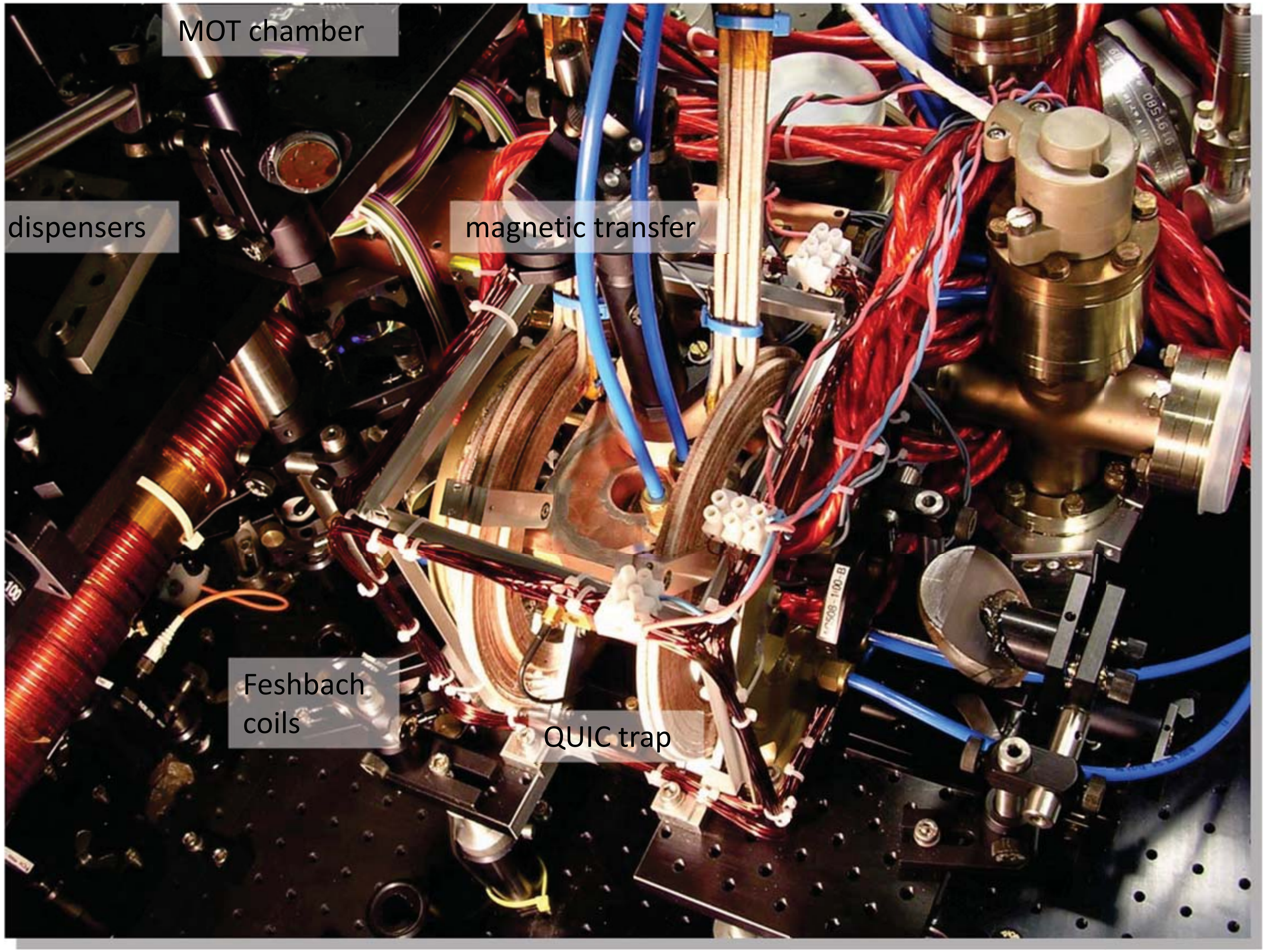


Magnetic Transfer:

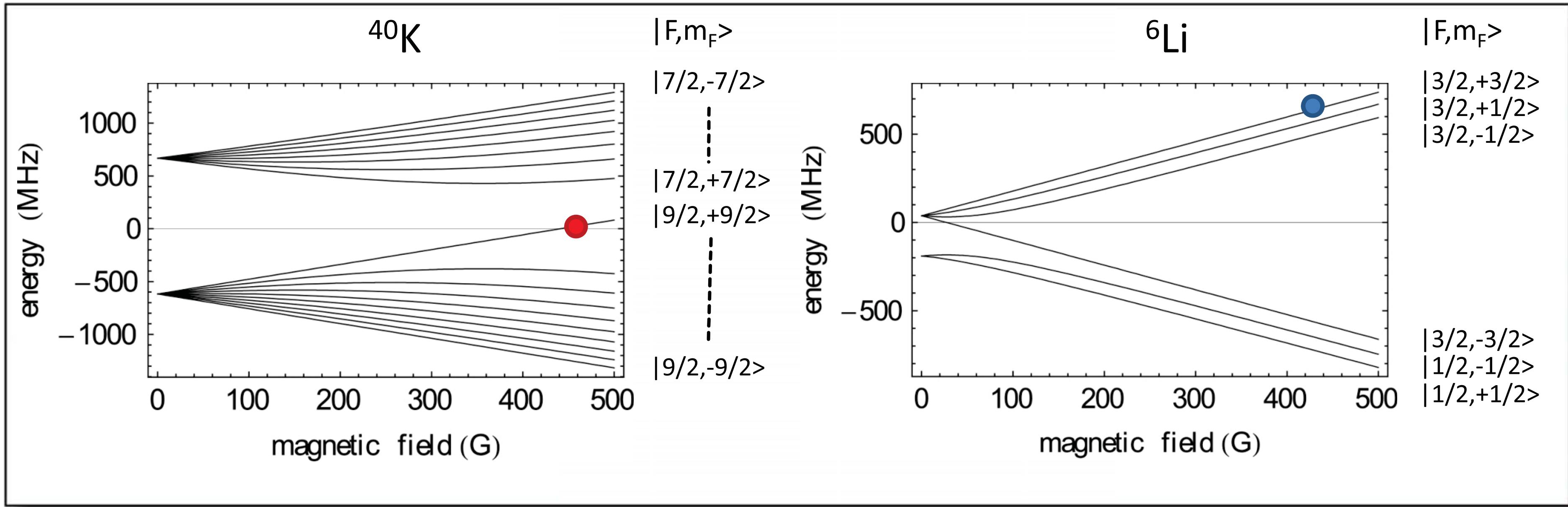
- compatible with vapour cell MOT
- efficient optical access: no optics for MOT, etc.

M. Greiner et al., PRA 63, 031401 (2001)

Science Chamber



Magnetic Trapping



Magnetically trappable states:

- ^{6}Li: $\left|3/2;3/2\right\rangle$, $\left|3/2;1/2\right\rangle$

  for B<27G additionally $\left|1/2;-1/2\right\rangle$

- ^{40}K: $\left|9/2;9/2\right\rangle$, $\left|9/2;7/2\right\rangle$, $\left|9/2;5/2\right\rangle$, $\left|9/2;3/2\right\rangle$, $\left|9/2;1/2\right\rangle$

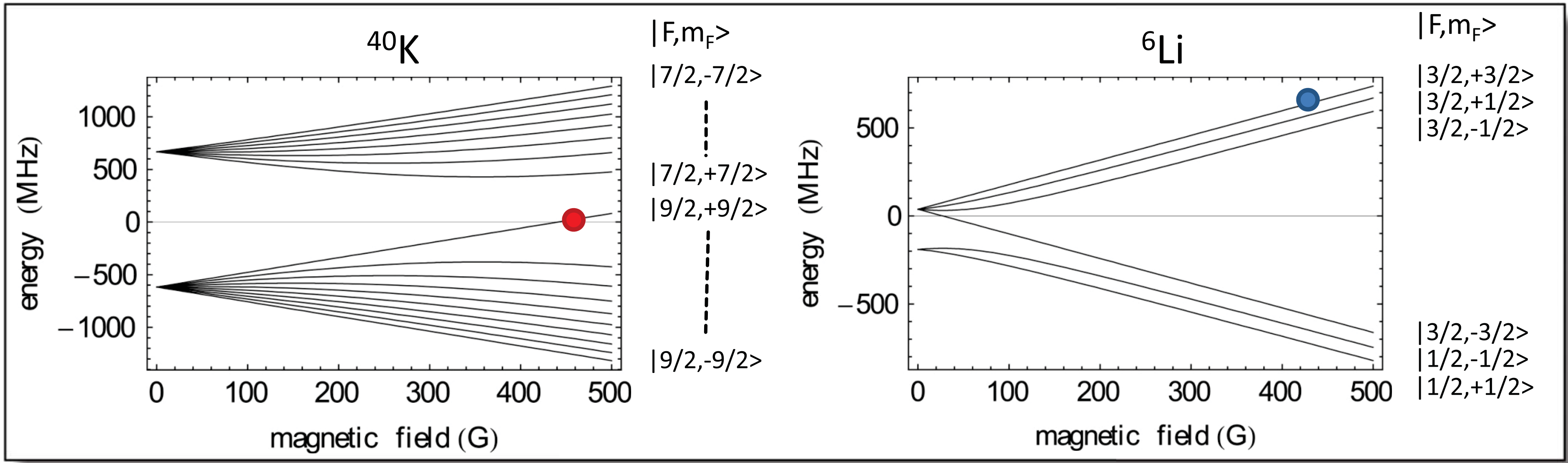
  $\left|7/2;-7/2\right\rangle$, $\left|7/2;-5/2\right\rangle$, $\left|7/2;-3/2\right\rangle$, $\left|7/2;-1/2\right\rangle$

- ^{87}Rb: $\left|1;-1\right\rangle$, $\left|2;2\right\rangle$, $\left|2;1\right\rangle$

  at high B fields additionally $\left|2;0\right\rangle$

} Not absolute ground states !

Magnetic Trapping



Stable mixtures:

Selection rule for spin exchange collisions: $\Delta F_z = \Delta\left(m_F^{\mathrm{Li}} + m_F^{\mathrm{K}} + m_F^{\mathrm{Rb}}\right) = 0$

- Stable mixture (doubly polarized states):

$$\mathrm{Li}\ \left|{}^3\!/_2;\ {}^3\!/_2\right\rangle\ \&\ \mathrm{K}\ \left|{}^9\!/_2;\ {}^9\!/_2\right\rangle\ \&\ \mathrm{Rb}\ \left|2;\ 2\right\rangle$$

- Additional stable mixture for Li-Rb experiments (maximally stretched states):

$$\mathrm{Li}\ \left|{}^1\!/_2;\ -{}^1\!/_2\right\rangle\ \&\ \mathrm{Rb}\ \left|1;\ -1\right\rangle$$

But unstable for K-Rb and in Li-K-Rb mixture (inverted HFS of ^{40}K).

- All states trappable in optical dipole trap. Interesting stable examples:

$$\mathrm{Li}\ \left|{}^1\!/_2;\ {}^1\!/_2\right\rangle\ \&\ \mathrm{K}\ \left|{}^9\!/_2;\ m_F\right\rangle \qquad \mathrm{Li}\ \left|{}^1\!/_2;\ m_F\right\rangle\ \&\ \mathrm{K}\ \left|{}^9\!/_2;\ -{}^9\!/_2\right\rangle$$

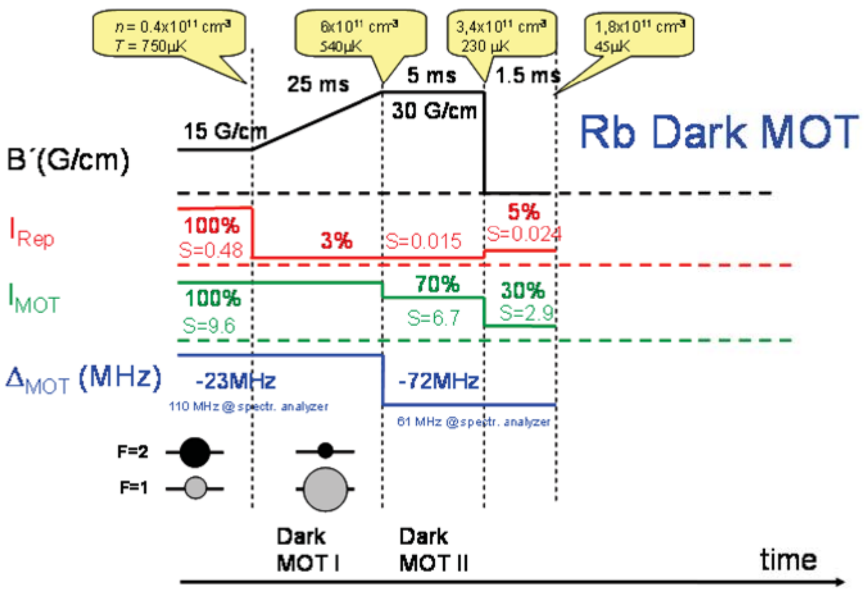
Challenges & Measures

- Li: low mass and high MOT temperature
    - Large diameter differential pumping hole
    - Special QUIC loading mechanism
    - Li: Compressed MOT, Rb: D-MOT

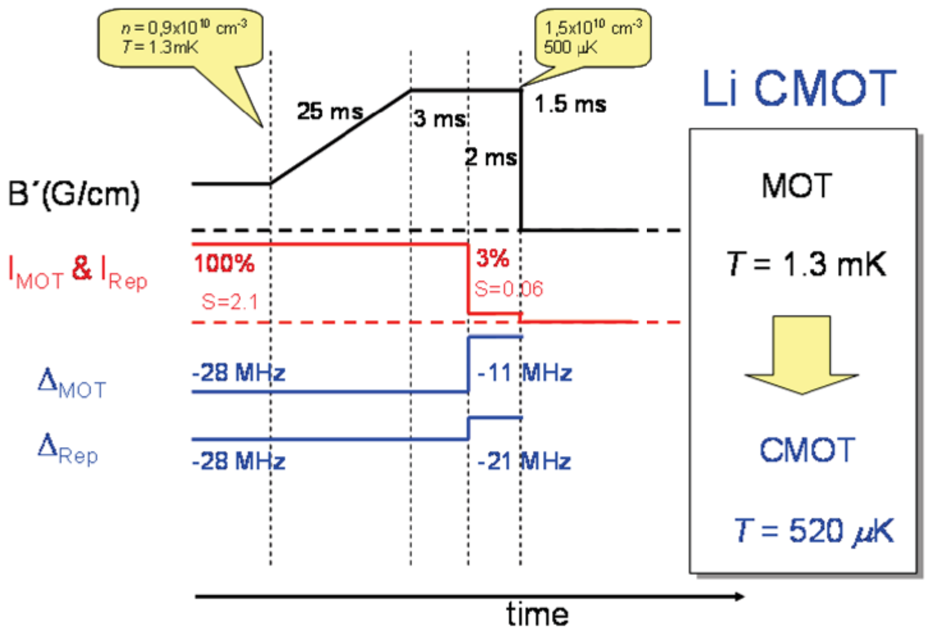
Li C-MOT & Rb D-MOT

Additional compression and cooling sequences before magnetic capture:

^{87}Rb



^{6}Li



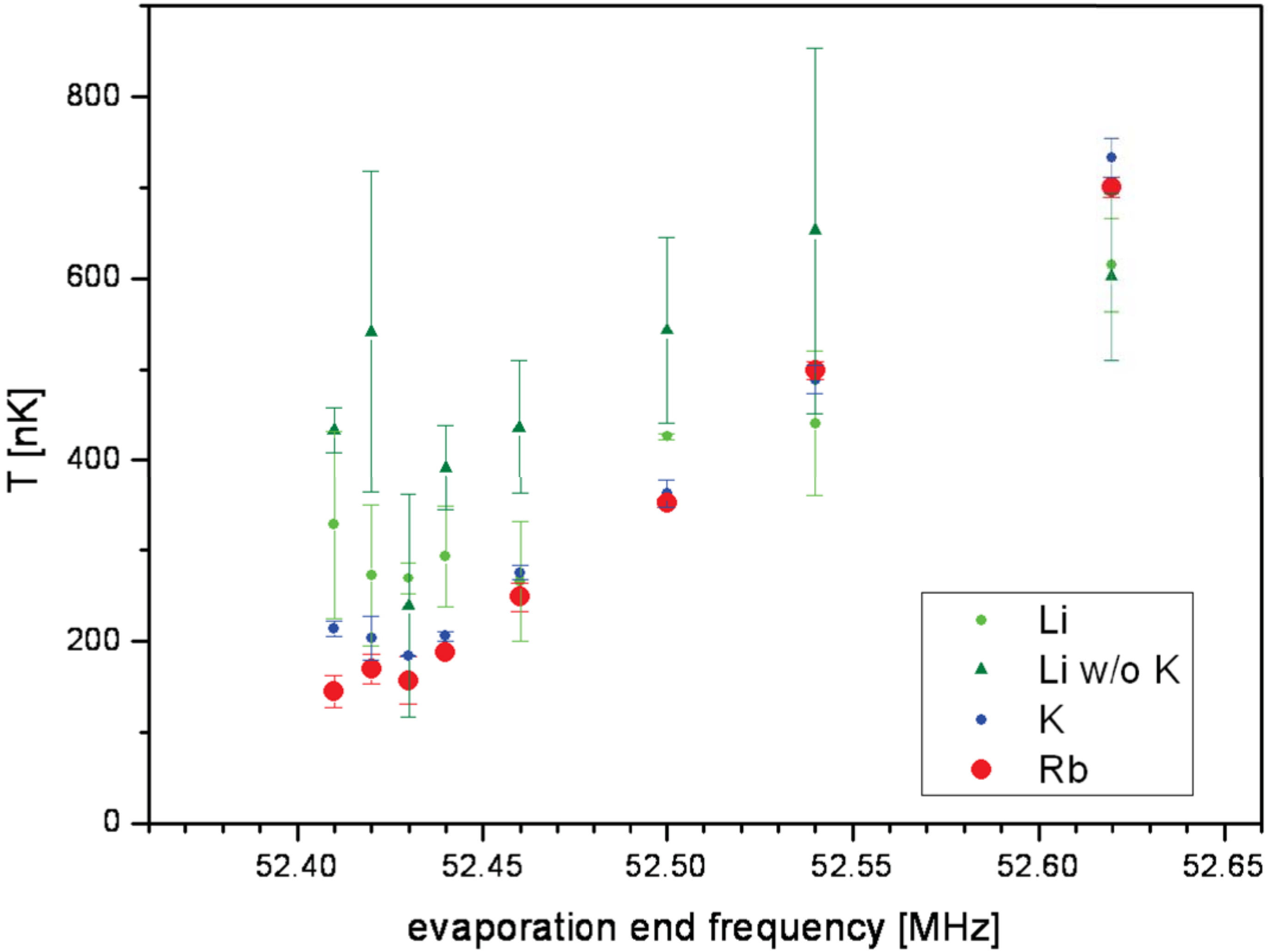
Rb: density increase: x3

Challenges & Measures

- Li: low mass and high MOT temperature
  - Large diameter differential pumping hole
  - Special QUIC loading mechanism
  - Li: Compressed MOT, Rb: D-MOT
- Small fermion atom numbers compared to Rb
  - Continuous state cleaning of Rb
- Small s-wave scattering wavelength: $\left|a_T(Li, Rb)\right| = 20^{+9}_{-6}\ a_0$

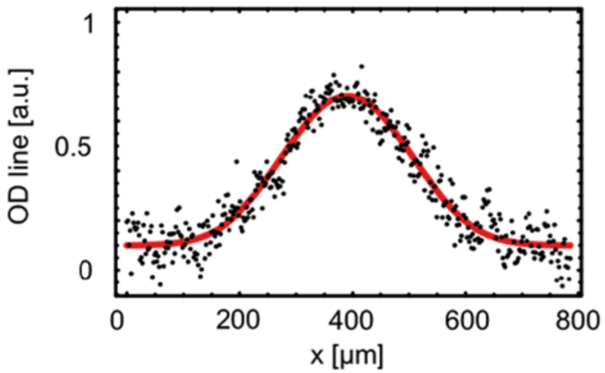
  C.Silber et al., PRL 95, 170408 (2005)
  - Rb dark MOT
  - 63 s evaporation
  - Continuous removal of high energy Li from trap
  - Catalytic cooling of Li by K

Catalytic Cooling I



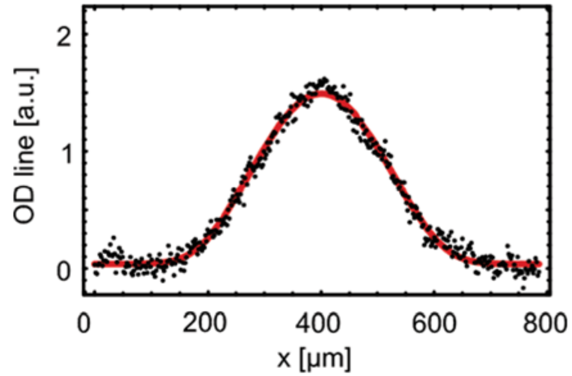
Catalytic Cooling II

no K present



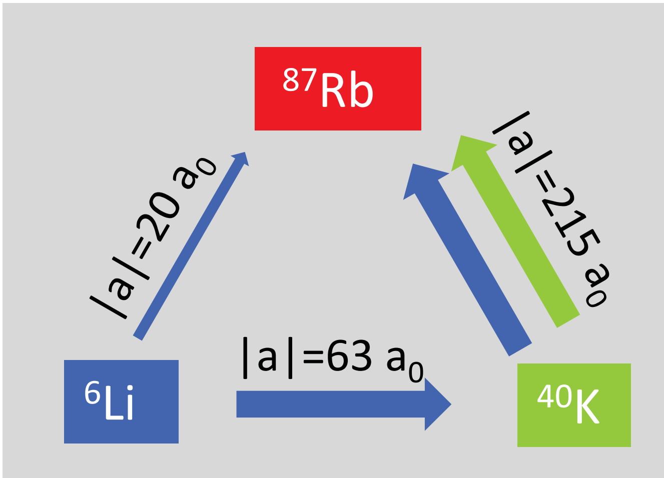
$$N = 0.8 \times 10^5$$
$$T = 450 nK = 0.4\, T_F$$

K present



$$N = 1.8 \times 10^5$$
$$T = 265\, nK = 0.2\, T_F$$

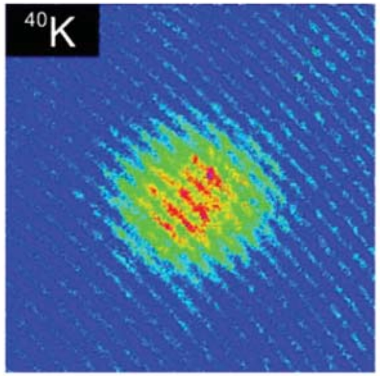
presence of K improves cooling of Li

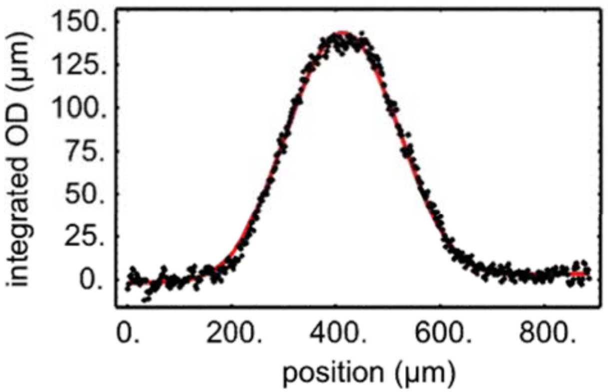


Triple Degeneracy

M.Taglieber, A.-C. Voigt, T. Aoki, T.W. Hänsch, and K. Dieckmann, PRL 100, 010401 (2008)

TOF = 15ms

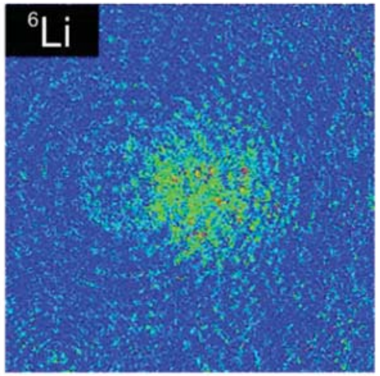


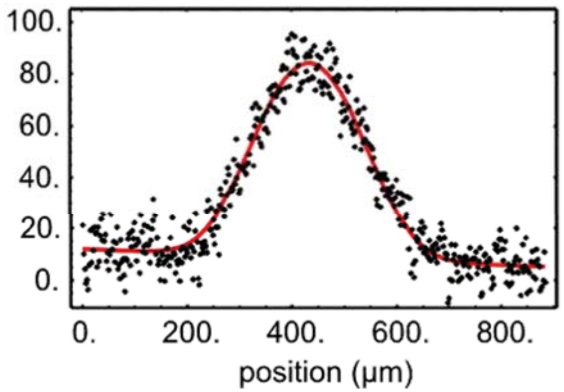


$N = 1.3 \times 10^5$

$T = 184\, nK = 0.35\, T_F$

TOF = 4ms

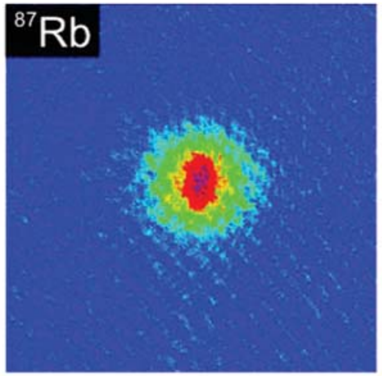


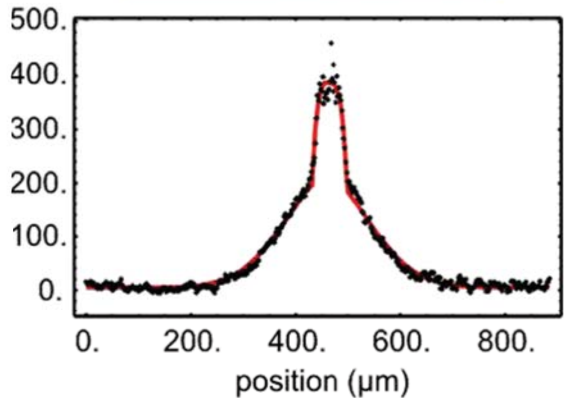


$N = 0.9 \times 10^5$

$T = 313\, nK = 0.27\, T_F$

TOF = 20ms





$N_{total} = 2.0 \times 10^5$

$T = 189\, nK = 0.9\, T_c$

➡ First quantum degenerate mixture of 3 different atomic species

^{6}Li-^{40}K Molecules

Li-K Feshbach Resonances in Innsbruck

Loss measurement in non-degenerate mixture: *E. Wille et al., PRL 100, 053201 (2008)*

i, j	M_F	Experiment B_0 (mT)	Experiment ΔB (mT)	ABM B_0 (mT)	Coupled channels B_0 (mT)	Coupled channels ΔB_s (mT)	type
2, 1	-5	21.56[a]	0.17	21.67	21.56	0.025	s
1, 1	-4	15.76	0.17	15.84	15.82	0.015	s
1, 1	-4	16.82	0.12	16.92	16.82	0.010	s
1, 1	-4	24.91	1.07	24.43	24.95	-	p
1, 2	-3	1.61	0.38	1.39	1.05	-	p
1, 2	-3	14.92	0.12	14.97	15.02	0.028	s
1, 2	-3	15.95[a]	0.17	15.95	15.96	0.045	s
1, 2	-3	16.59	0.06	16.68	16.59	0.0001	s
1, 2	-3	26.28	1.07	26.07	26.20	-	p
1, 3	-2	not observed		1.75	1.35	-	p
1, 3	-2	14.17	0.14	14.25	14.30	0.036	s
1, 3	-2	15.49	0.20	15.46	15.51	0.081	s
1, 3	-2	16.27	0.17	16.33	16.29	0.060	s
1, 3	-2	27.09	1.38	27.40	27.15	-	p

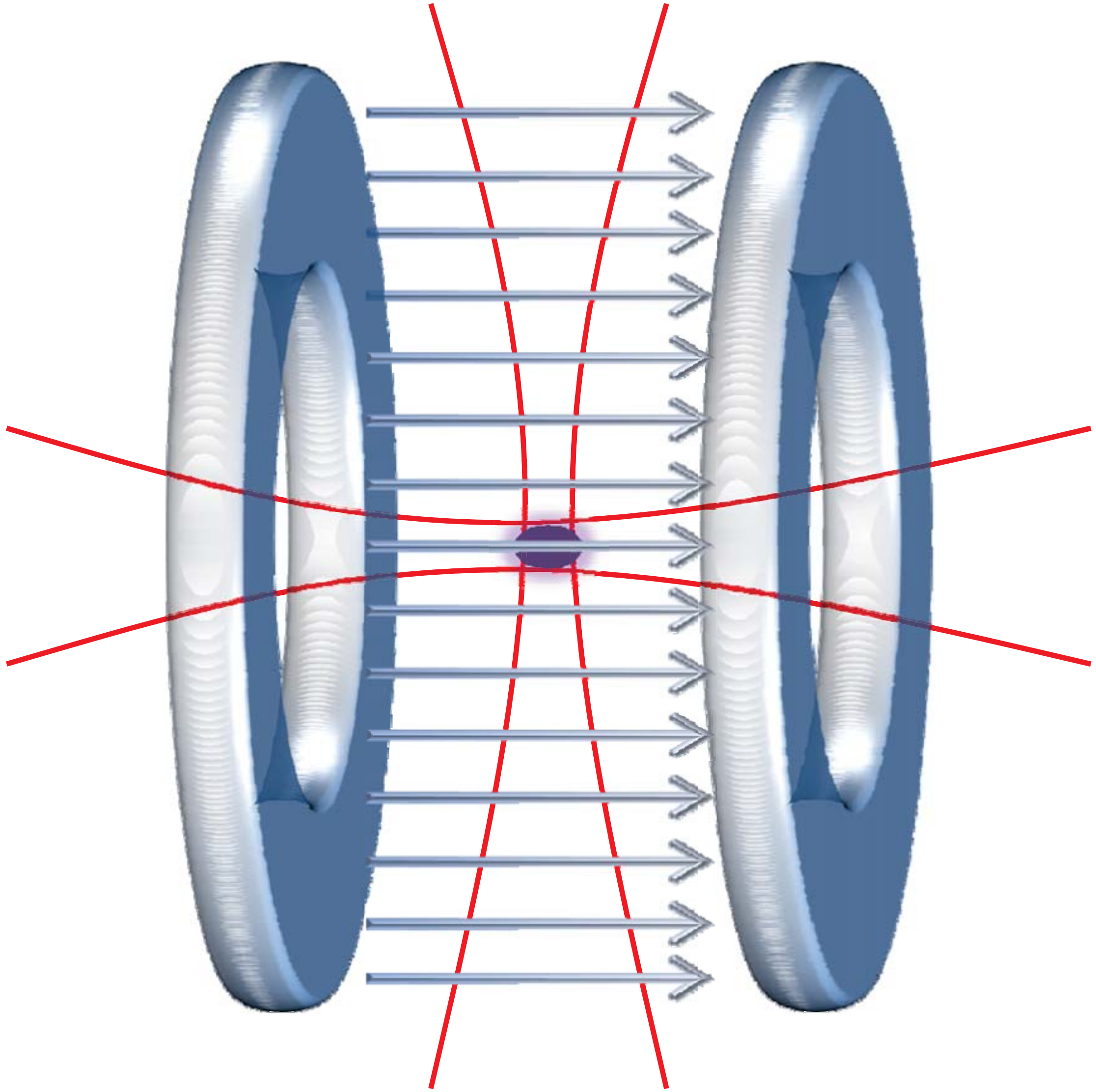
Molecules in Munich

Tiemann:
Not predicted in
Revised theory

Molecules Munich

s-wave resonances expected to be narrow , close channel dominated

Optical Trap and Magn. Coils



Crossed optical dipole trap:

- 1064 nm
- waists: 50 μm, 55 μm
- Trap frequencies:
  Li: 725 Hz
  K: 1245 Hz

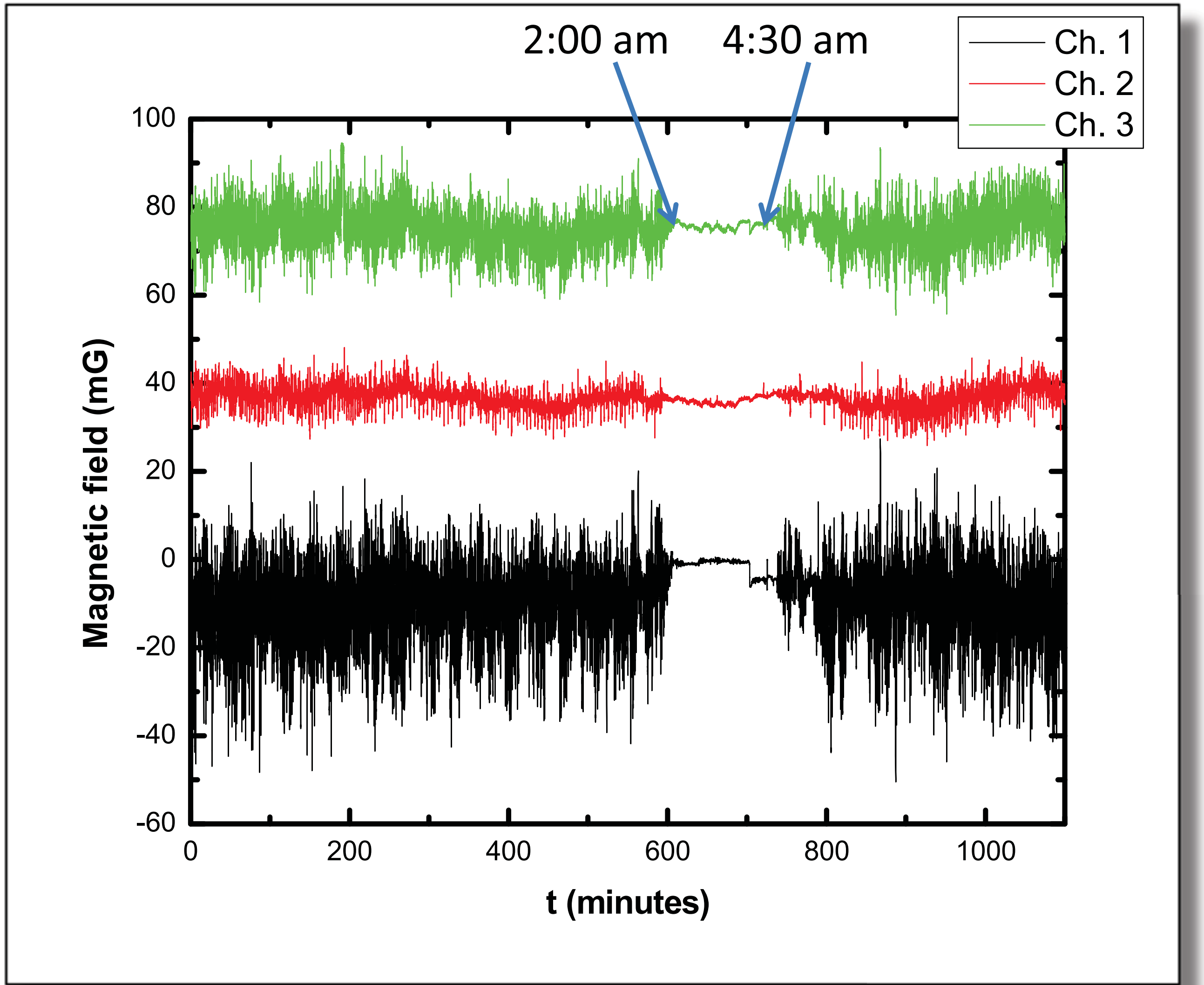
Feshbach coils:

- almost Helmholtz configuration
- hollow, water-cooled wire

Parameters (for I=500A):
B = 930 G
B'' = 7 G/cm^2
P = 6.6 kW

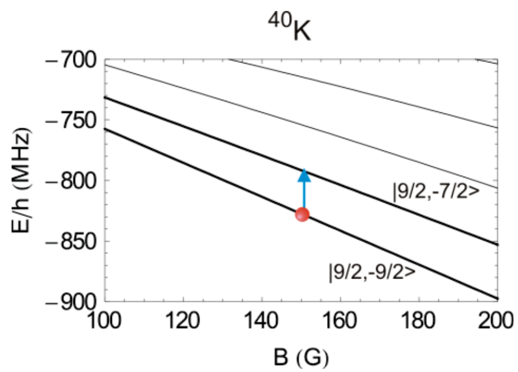
Maximum B-field inhomogeniety at FBR : < ±5 mG

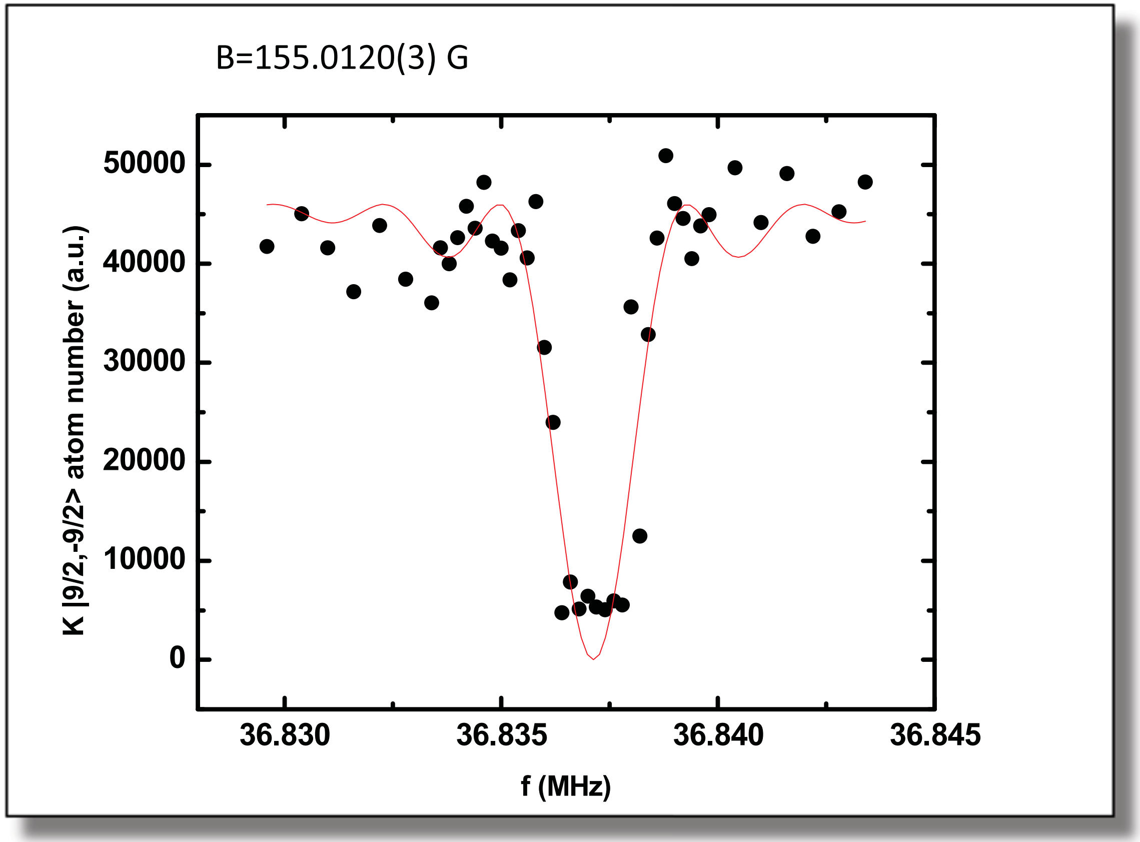
Ambient Magnetic Field



Magnetic Field Calibration

K |9/2,9/2> → |9/2,7/2> rf transition, field sensitivity 180.3 kHz/G





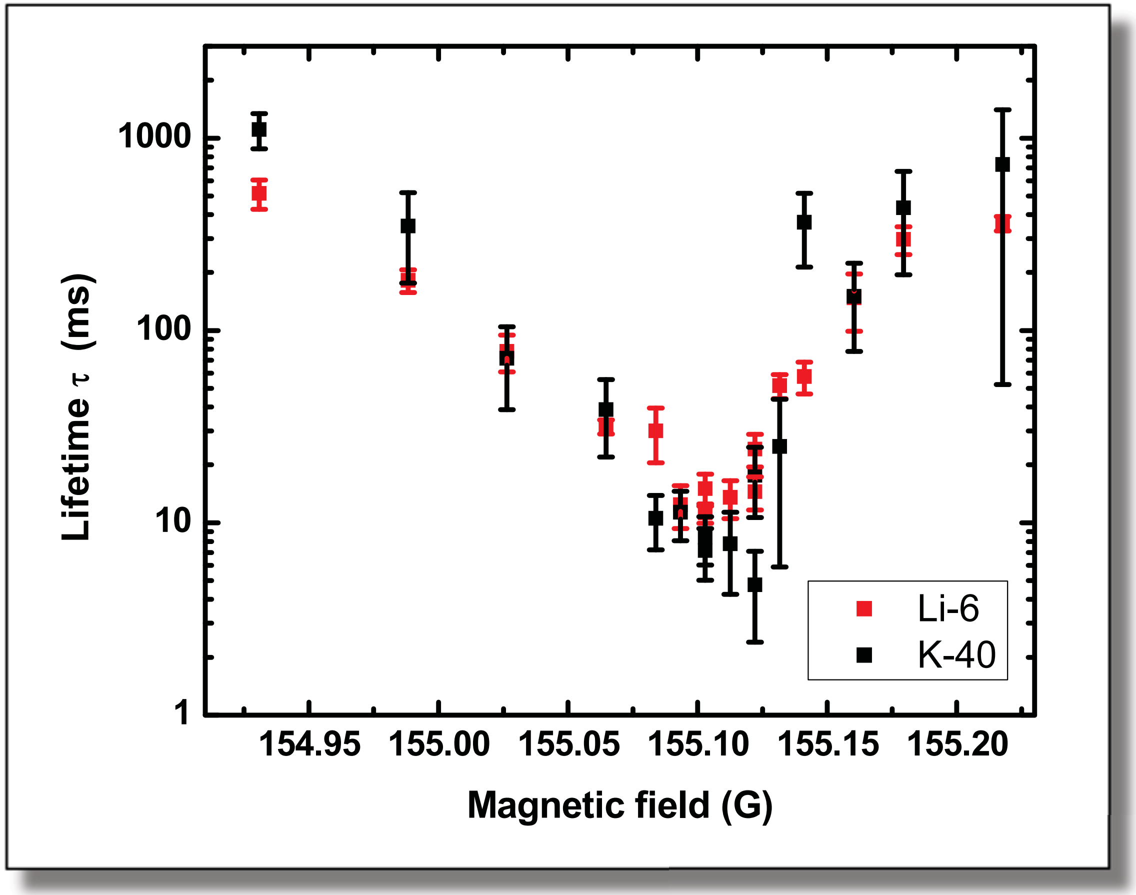
Long term stability: **<7mG**, (compare calibrations after six weeks)

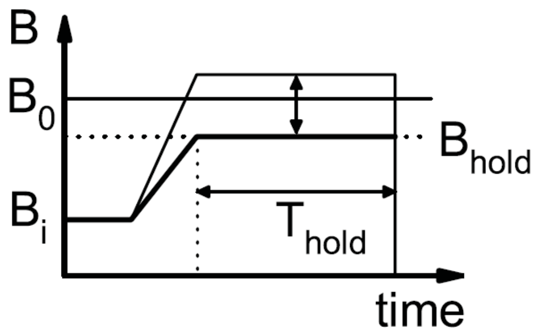
Mapping the Resonance via Lifetime

Typical initial conditions:

^{6}Li: |1/2,+1/2> $n_{Li} \approx 2 \cdot 10^{13} cm^{-3}$ $T / T_F^{Li} = 0.6$

^{40}K: |9/2,-5/2> $n_K \approx 1 \cdot 10^{14} cm^{-3}$ $T / T_F^{Li} = 0.4$

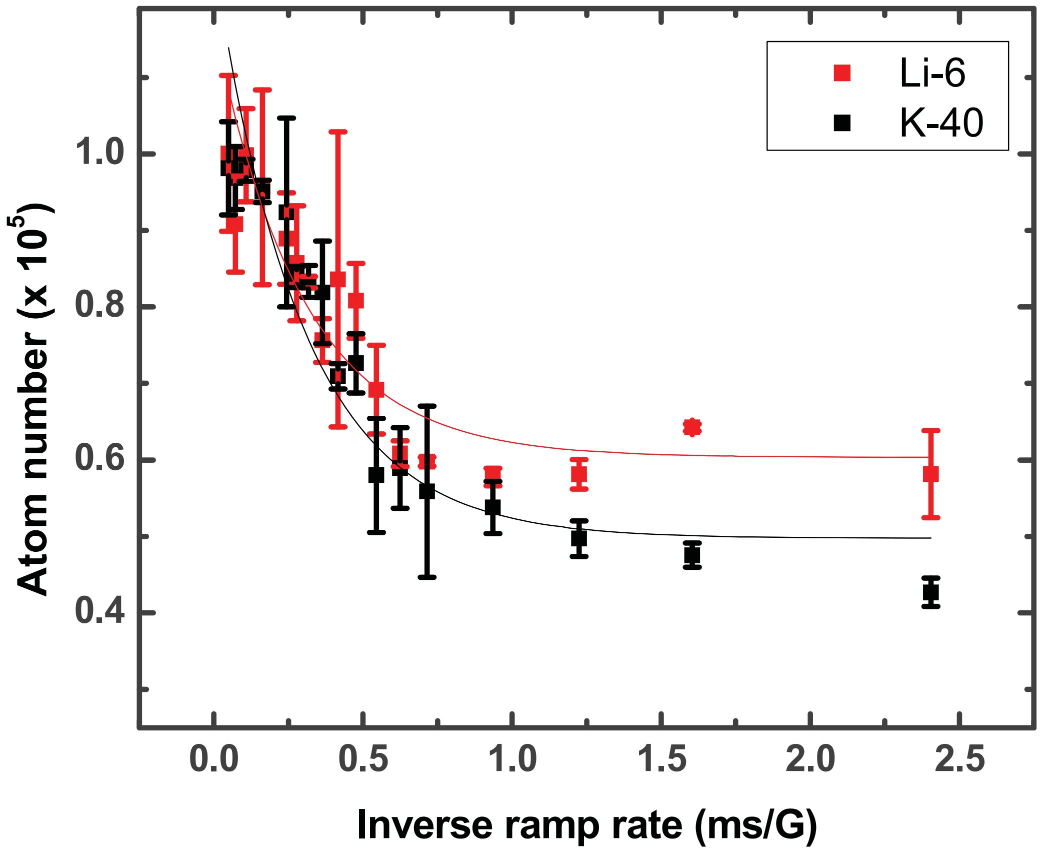


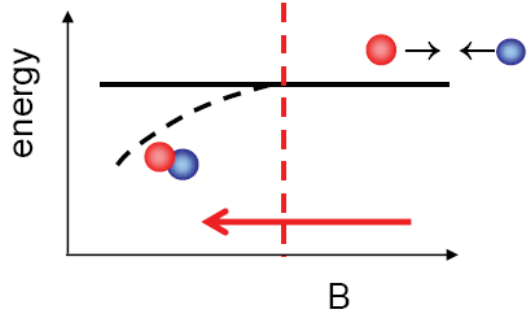


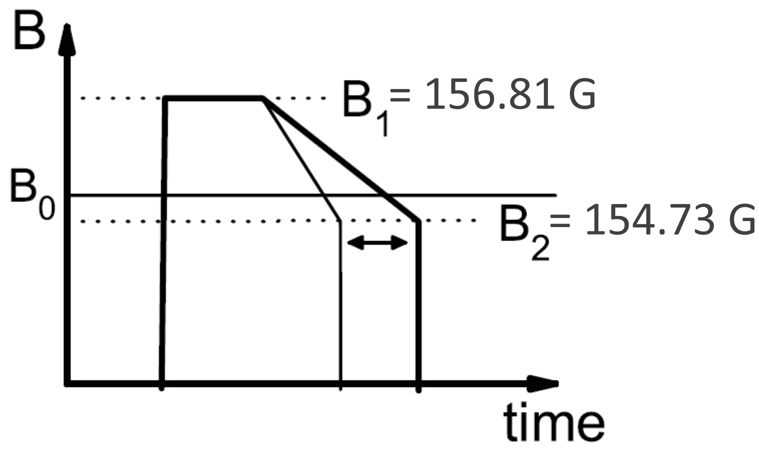
$B_0 = 155.10(5)$ G

$\Delta B_{3dB} = 50$ mG (Innsbruck: 2 G)

Feshbach Association Ramp Speed



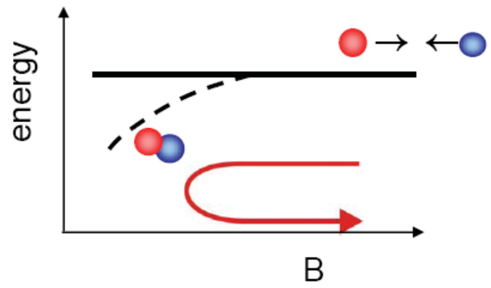


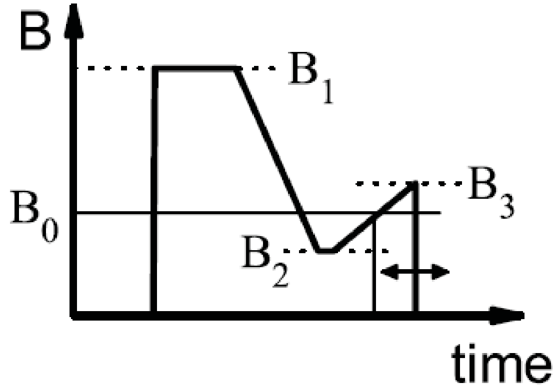


- Conversion efficiency up to 50%, up to 4×10^4 molecules
- 1/e inverse ramp speed 0.3 ms/G
- use in experiment 1ms/G

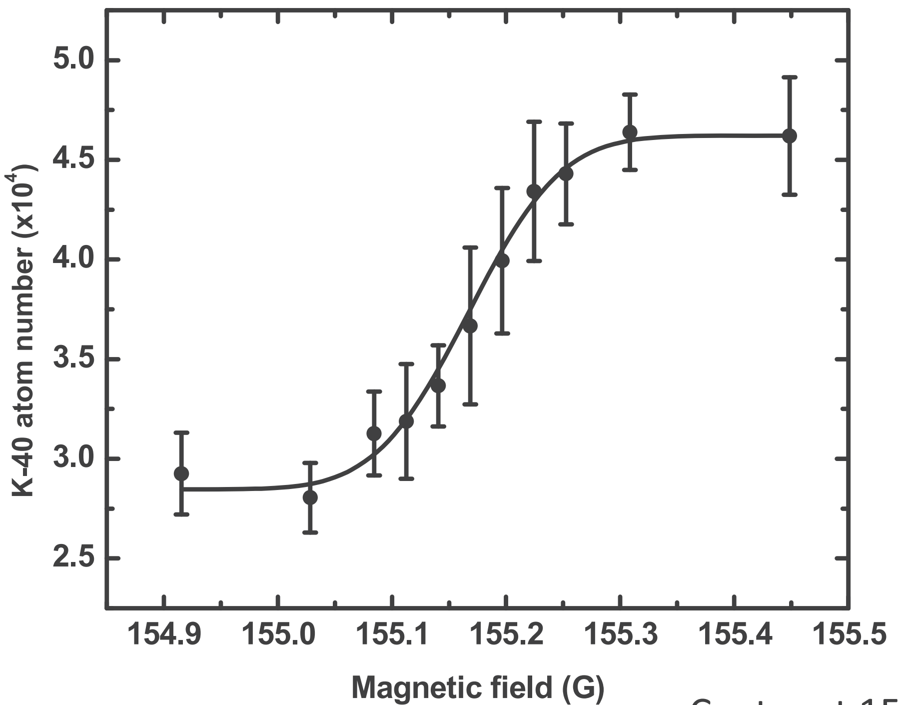
Feshbach Association / Dissociation

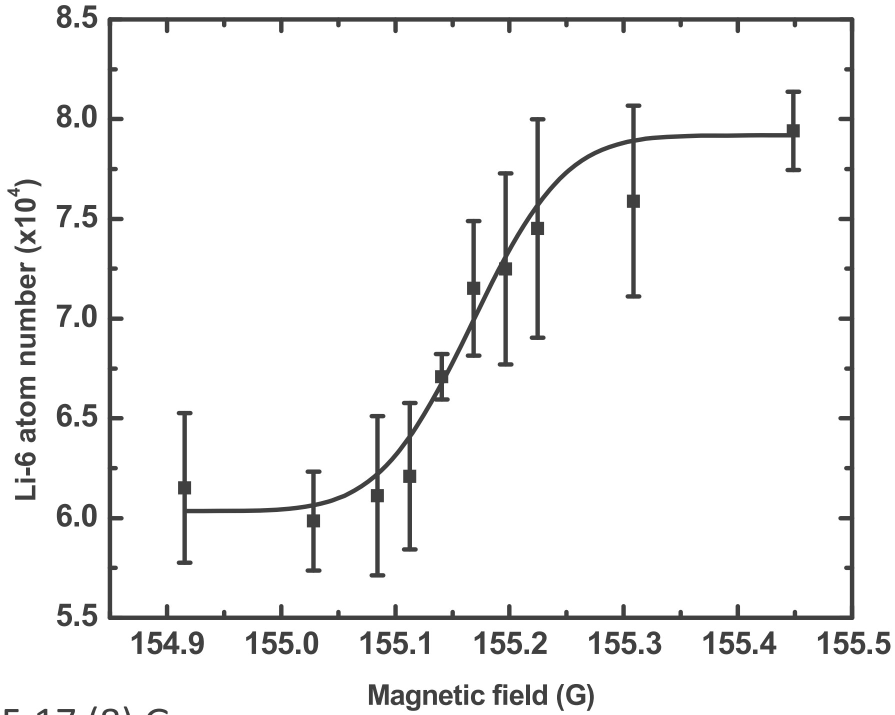
Reversed sweep:





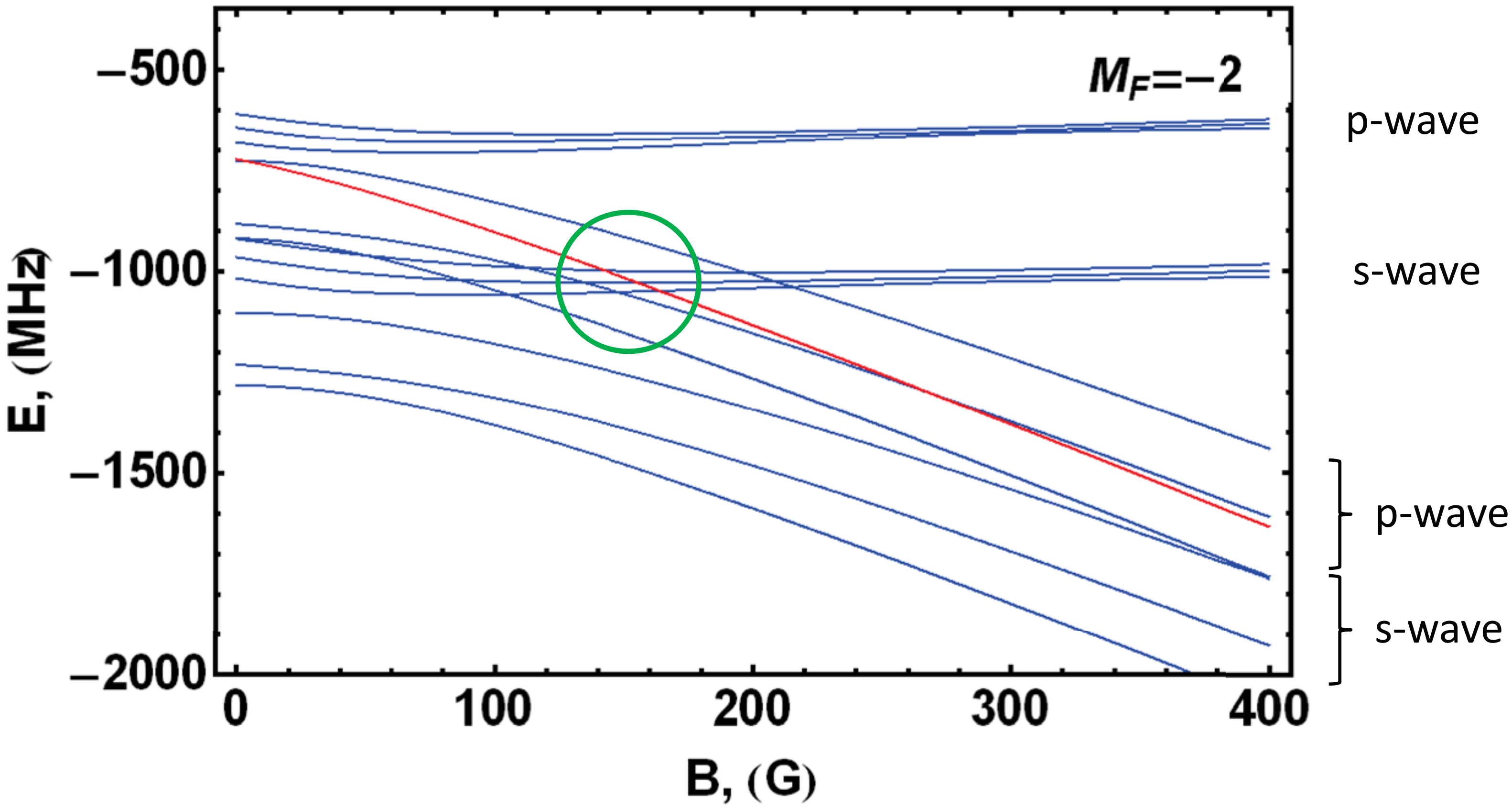
B_2 = 154.73 G
B_1 = 156.81 G





Center at 155.17 (8) G

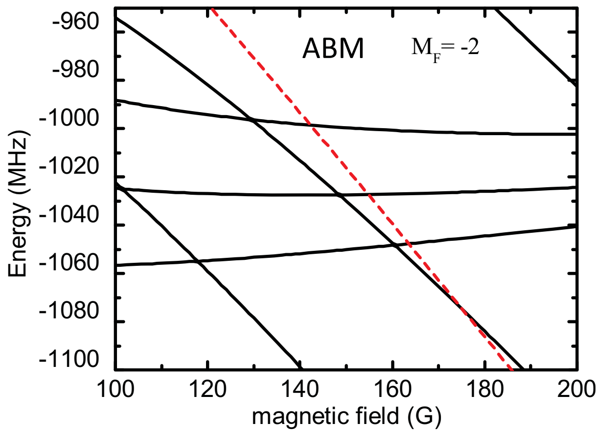
ABM Model M= -2



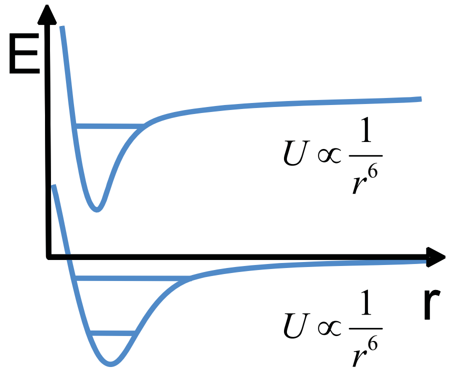
- Magnetic moment of molecular state near zero

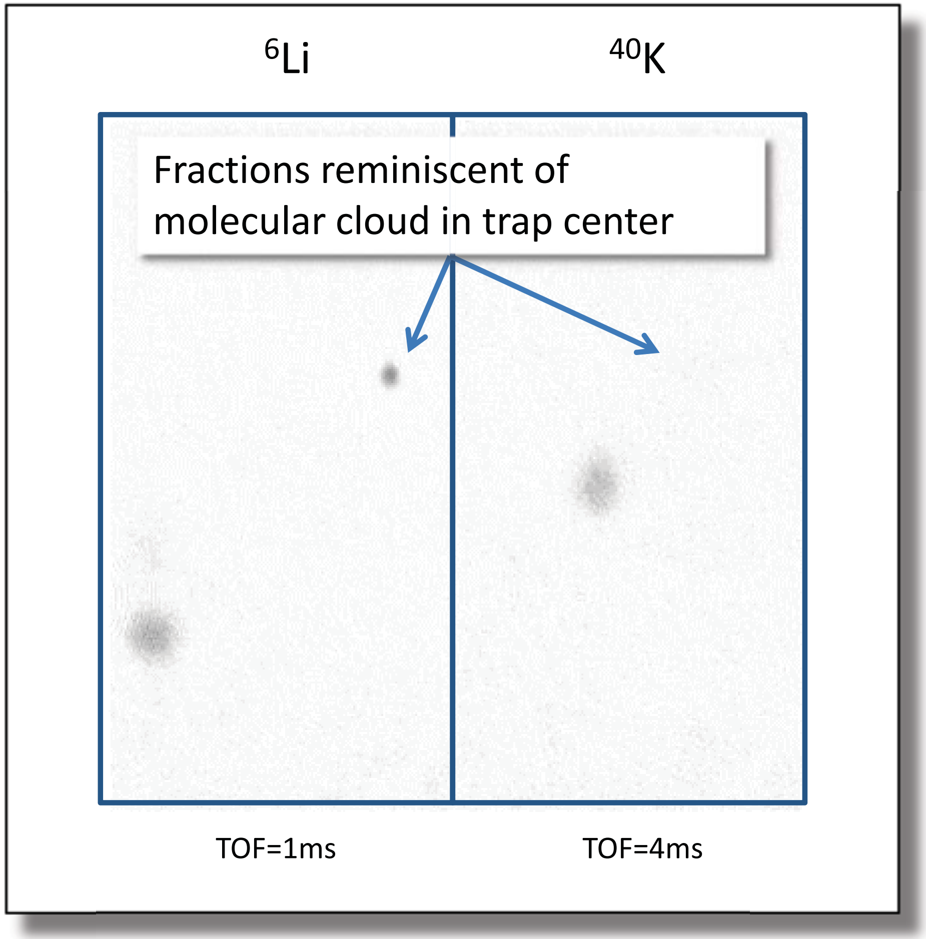
Direct Imaging of Heteronuclear Molecules

- Stern-Gerlach pulse:
  ~ 570µs at 157 G/cm



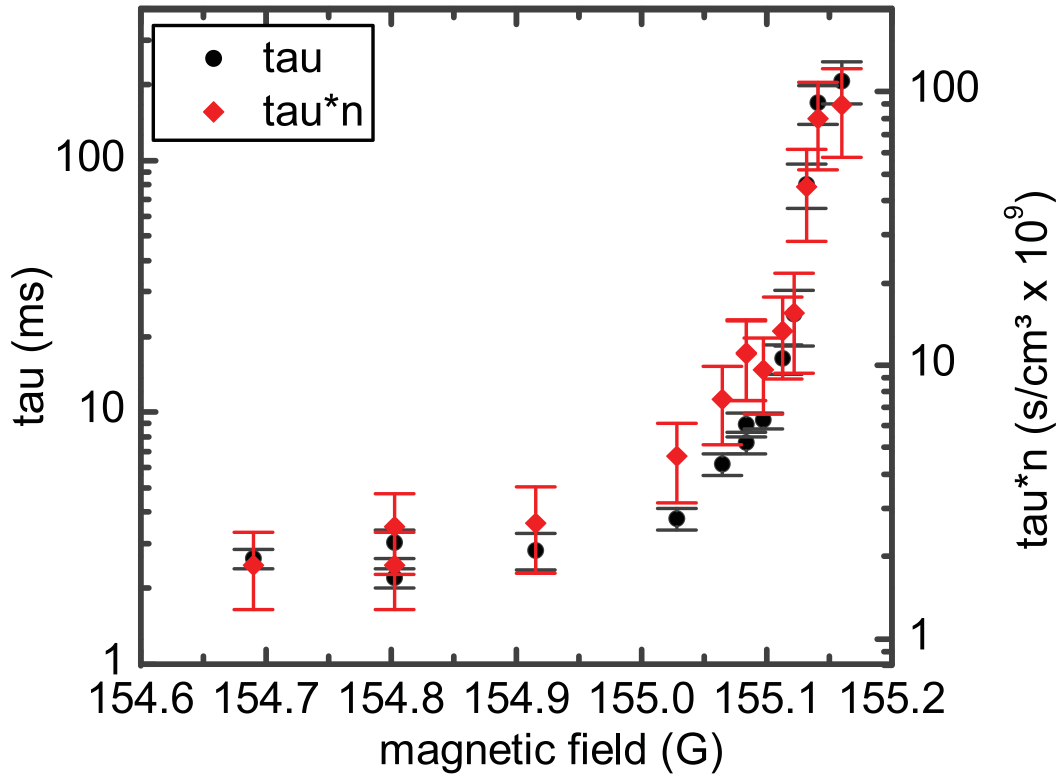
- Simultaneous high field imaging of atoms and molecules





J. J. Zirbel et al., PRL, 100, 143201 (2008).

Lifetimes



- study strongly interacting regime (width ≈ 40 mG)
- creation of diploar molecules

- Suppression of losses close to resonance observed

- Proposed decay mechanisms:
  - Spontaneous molecular spin relaxation

*T. Köhler et al., PRL **94**, 020402 (2005)*
*J.L. Roberts et al., PRL **85**, 728 (2000)*

  - Vibrational relaxation

*D. Petrov et al., J. Phys. B: At. Mol. Opt. Phys. **38** 645 (2005)*

- Size of closed channel?

$$g_0 \approx E_F \approx k_B \cdot 1\,\mu K$$

Comparison of Heteronuclear Molecules

	Bose + Fermi	Bose + Bose		Fermi + Fermi
species	$^{40}K + ^{87}Rb$	$^{85}Rb + ^{87}Rb$	$^{41}K + ^{87}Rb$	$^{6}Li + ^{40}K$
lifetime	100 ms	< 1 ms	60 µs	>100 ms
# of molecules	15000	25000	12000	40000
Density (cm^{-3})	1×10^{12}	1×10^{14}	5×10^{11}	5×10^{12}
Dipole moment (Debye)	0.6	-	0.6	3.6

J.J. Zirbel et al., PRL 100, 143201 (2008)

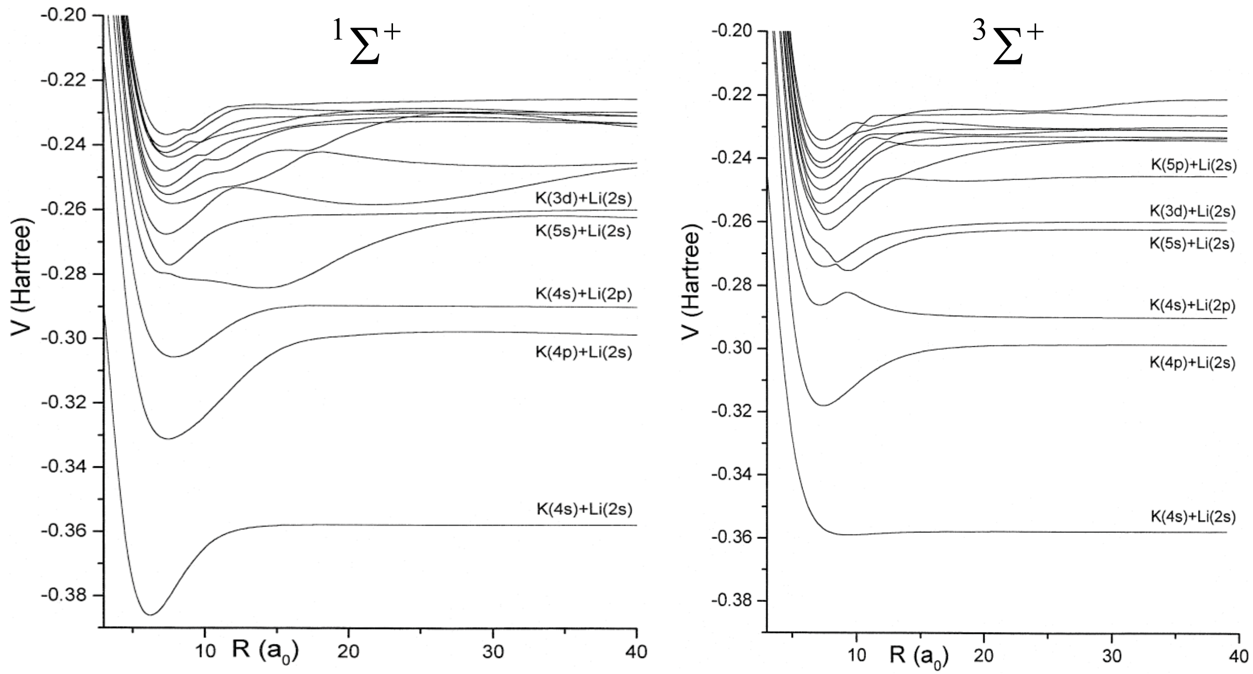
S.B. Papp and C.E. Wieman, PRL 97, 180404 (2006)

C. Weber et al., arXiv:0808.4077v1 (29 Aug 2008)

LiK Excited Molecular Potentials

Excited state potentials from spectroscopic data available:

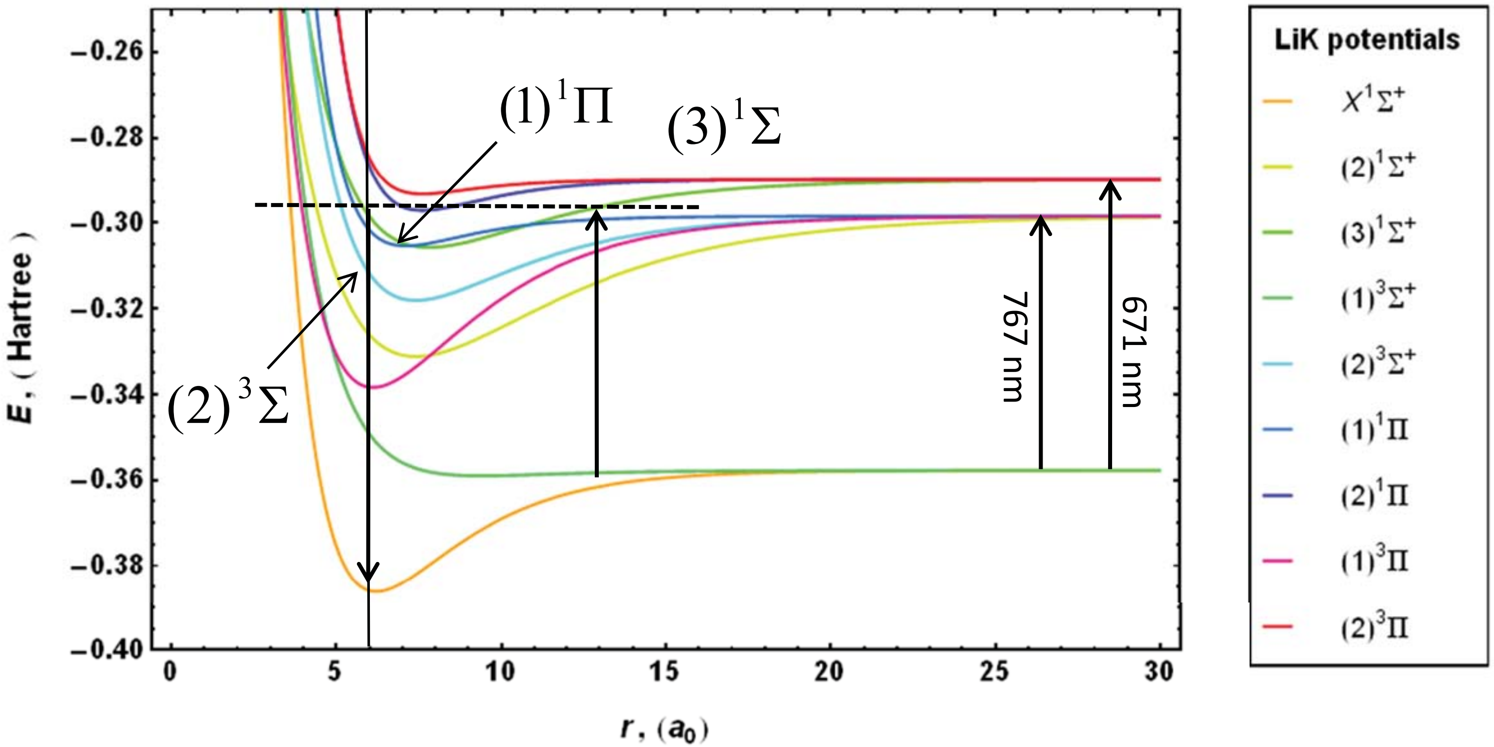
S. Russeau, et al., J. Chem. Phys., ***247****, 193, (1999)*



Also available: $^1\Pi^+,\ ^3\Pi^+,\ ^1\Delta^+,\ ^3\Delta^+$

Transfer to Ground State

Morse potentials without perturbation:



- KRb: mixing of $(2)^3\Sigma$ and $(1)^1\Pi$ states
- LiK: mixed singlet triplet character of initial state
- Repulsive C_6 for potentials connecting to Li asymptote

Summary & Outlook

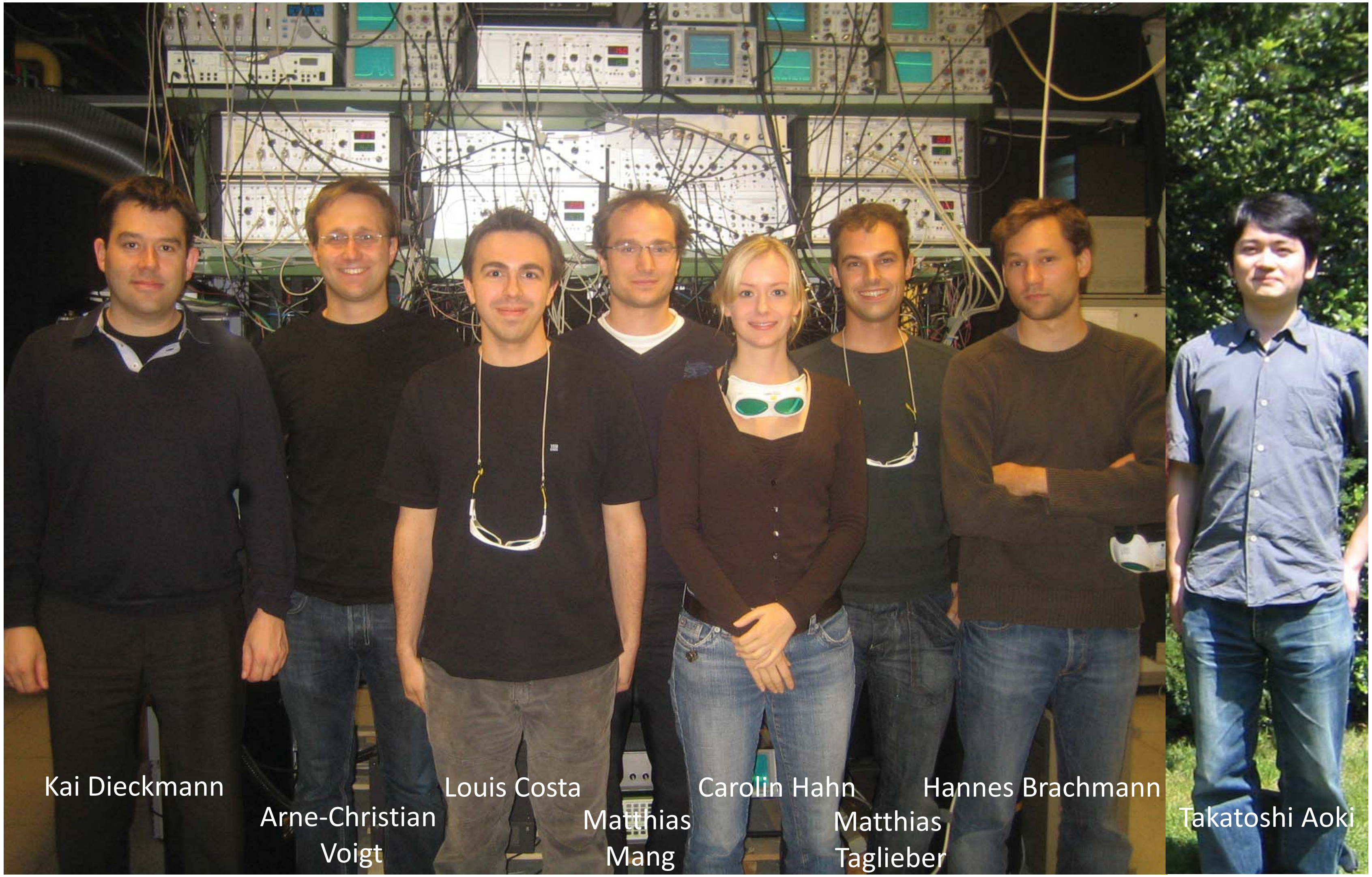
Summary:

- Triple degenerate mixture, catalytic cooling
- Feshbach resonances of degenerate Fermi-Fermi mixture
- LiK Molecules
- Pauli suppression close to resonance observed

Outlook:

- Measure scattering length to locate resonance
- Heteronuclear molecules
  - BEC of heteronuclear molecules
  - Dipolar ground state molecules
- Fermi-Fermi mixture in the strongly interacting regime
  - Narrow resonance – closed channel dominated
  - Long lifetime on resonance

The Team 2008



Thank you…