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Formation of p-wave Feshbach molecules in a gas or ultracold 6Li atoms

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Formation of *p*-wave Feshbach molecules in a gas of ultracold ^{6}Li atoms

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superfluidity by fermion pairs

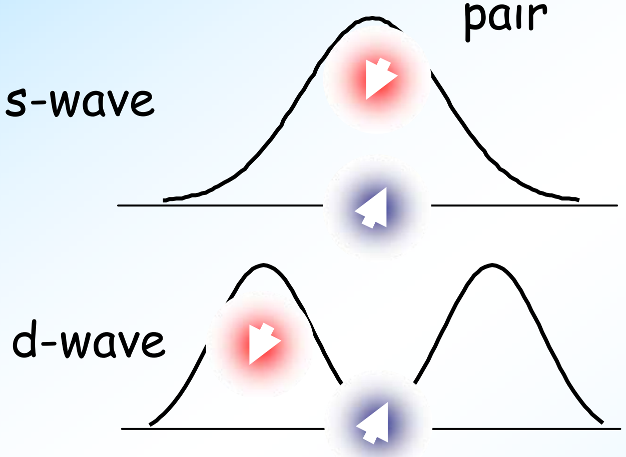
Fermionic superfluidity

Two fermions form a pair, and behave like a boson and shows superfluidity.

- superconductor : electron pairs
- superfluid ^{3}He : ^{3}He atom pairs

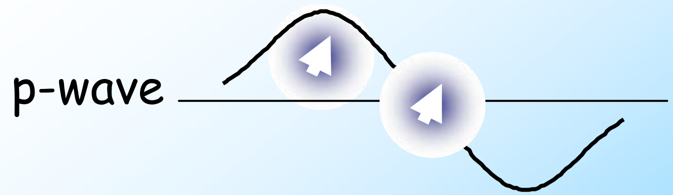
…

spin singlet — s-wave, d-wave pair



- superconductor
- High-Tc material

spin triplet — p-wave pair



- liquid ^{3}He
- superconductor (UPt_3, Sr_2RuO_4)

Spin triplet superfluidity

Phase diagram of Liquid ^{3}He

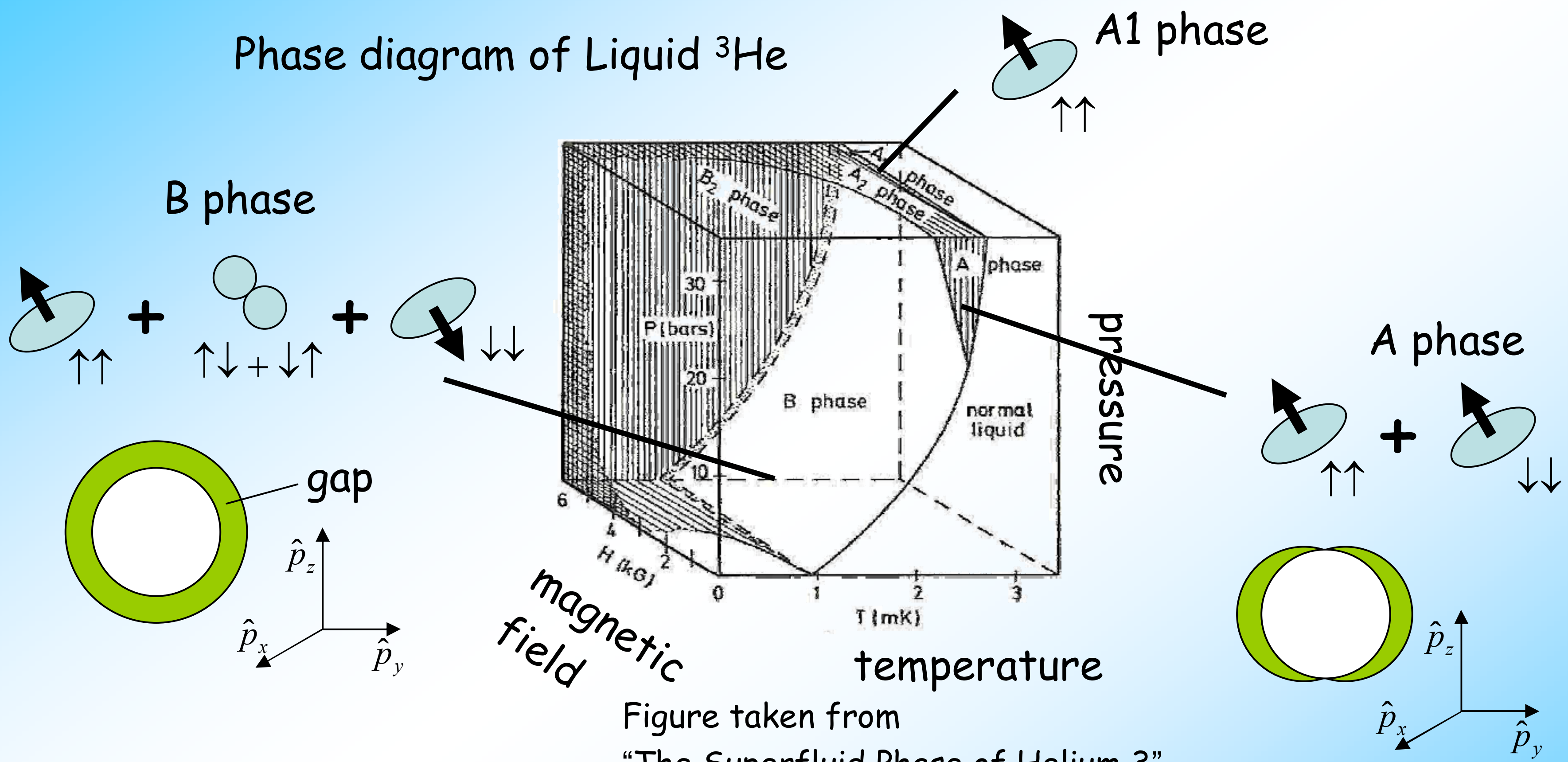


Figure taken from
"The Superfluid Phase of Helium 3"
D. Vollhardt and P. Wolfle

- multiple superfluid phases due to orbital and spin degrees of freedom
- phase transition between superfluid phases

ultracold atomic gas system

- undoubtedly the interaction is in *p*-wave channel
- tunable interaction -> phase transition between superfluid phases
- interaction is asymmetric in spin space
- interaction depend also on the projection of angular momentum

p-wave Feshbach resonance

p-wave Feshbach resonance

- narrow Feshbach resonance

  atom tunnels through the barrier

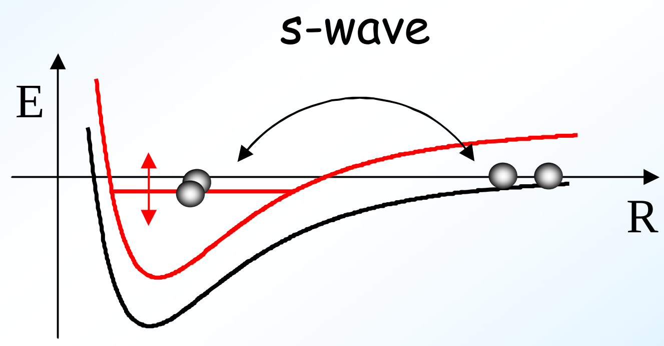
- quasi-bound state

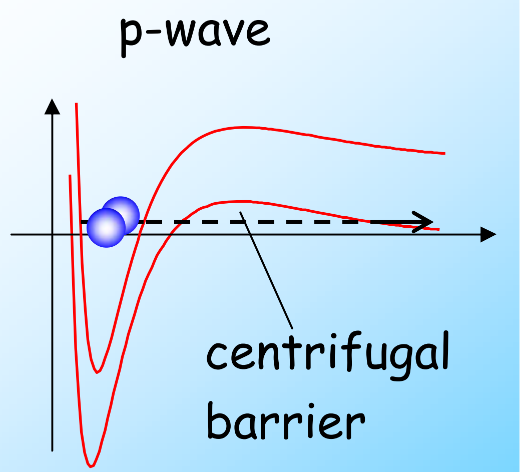
  finite lifetime at higher energy than the dissociation limit

- small size of molecules even at the resonance

  small molecule even at the resonance

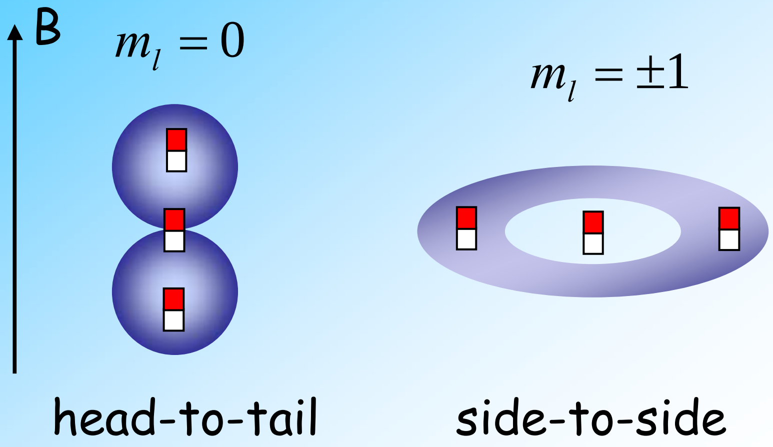
- doublet structure





doublet structure

doublet structure



magnetic dipole-dipole interaction splits the resonance of $m_l=0$ and $m_l=\pm 1$

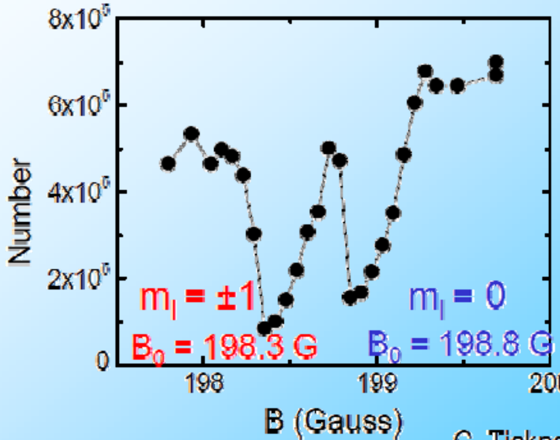
splitting of two resonances

^{40}K : 0.47 ± 0.08 G (|m=-7/2>-|m=-7/2>)

D. S. Jin et al., ICOLS 2007 proceedings.

^{6}Li : 0.0036 G (|1>-|2>)

F. Chevy *et al.*, Phys. Rev. A, **71**, 062720 (2005)



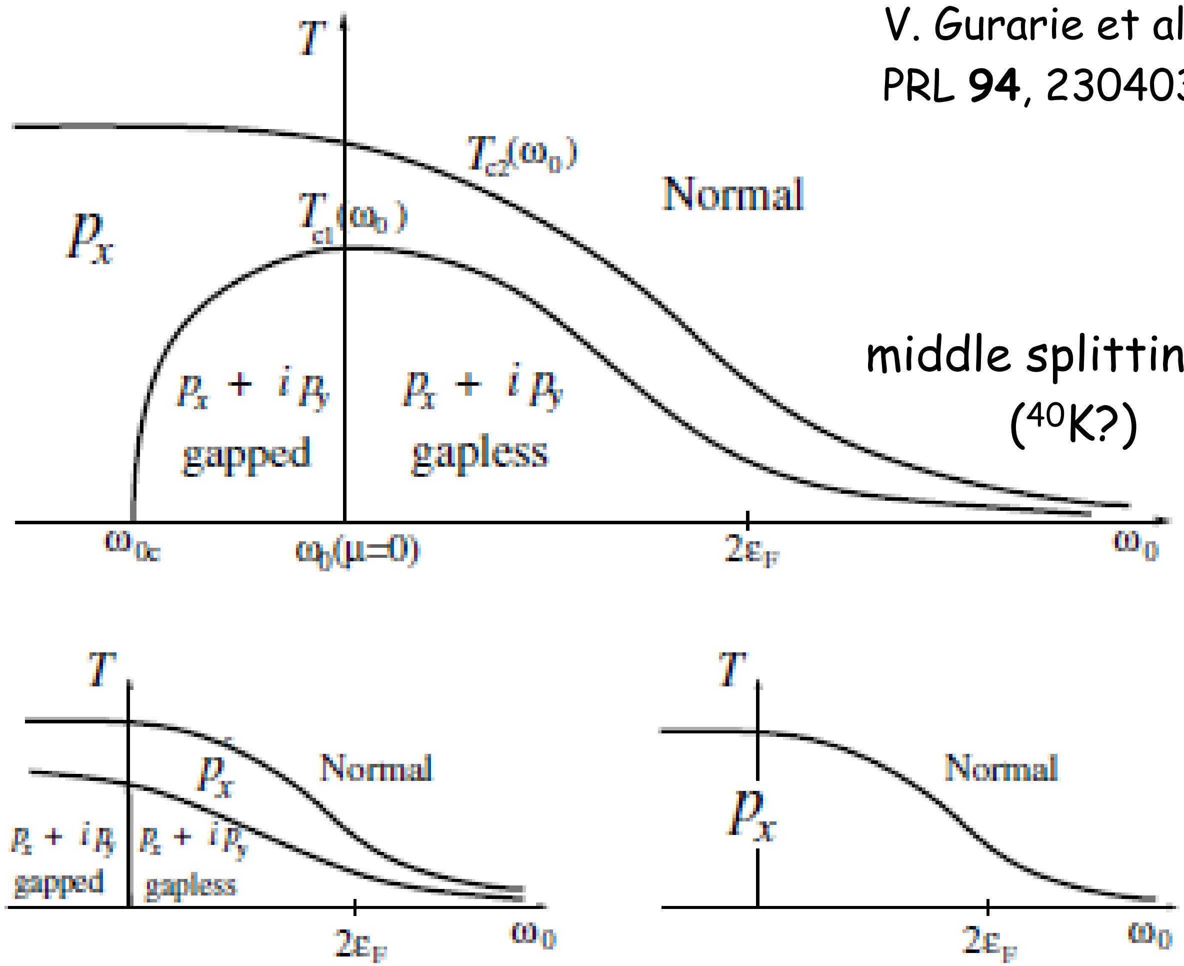
C. Ticknor,

With ^{40}K, interaction is different for $|m_l|=1$ and $m_l=0$ channel

With ^{6}Li, interaction is similar for $|m_l|=1$ and $m_l=0$ channel

phase diagram

V. Gurarie et al.
PRL **94**, 230403 (2005)



middle splitting case
(^{40}K?)

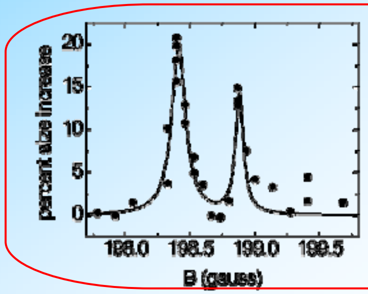
small splitting case
(^{6}Li)

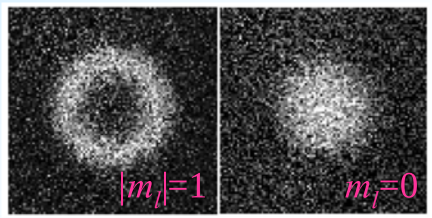
large splitting case
(^{40}K?)

Work done so far with p-wave Feshbach resonances

^{40}K

- ✓ p-wave Feshbach resonance [1]
- ✓ splitting between $m_l = 0$ and $|m_l| = 1$ resonances[2]
- ✓ p-wave molecule creation[3]
- ✓ lifetime of p-wave molecules (~ 7ms) [3]





[1] C. A. Regal et. al. PRL **90**, 053201 (2003)

[2] C. Ticknor et. al. PRA **69**, 042712 (2004)

[3] J. P. Gaebler et. al. PRL **98**, 200403 (2007)

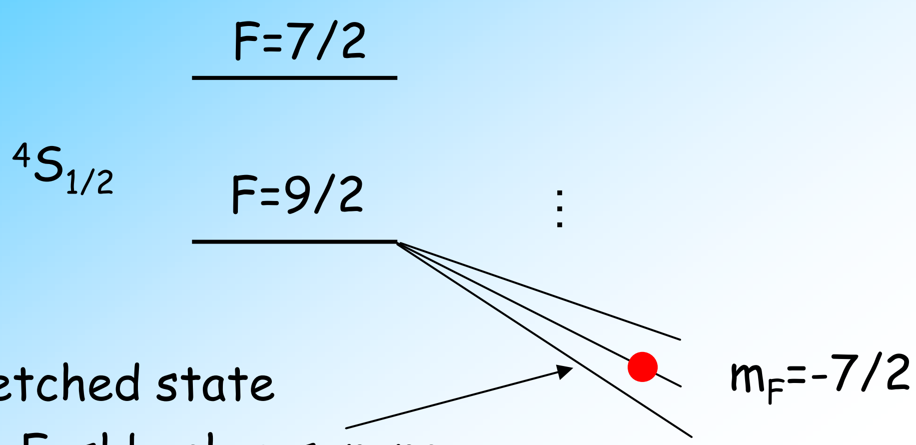
^{6}Li

- ✓ observation of p-wave Feshbach resonances[4-7]
- ✓ association and dissociation of molecules near the Feshbach resonance[4]
- ✓ determination of the magnetic moment of p-wave molecular state[7]

[4] J. Zhang et al. PRA **70**, 030702(R) (2004)
[5] C. H. Schunck et al. PRA **71**, 045601 (2005)
[6] B. Deh et al. PRA **77**, 010701(R) (2008)
[7] J. Fuchs et al. PRA **77**, 053616 (2008)

p-wave Feshbach resonance of ^{40}K and ^{6}Li

^{40}K case



stretched state

= no Feshbach resonance

for $|m_F=-9/2\rangle - |m_F=-9/2\rangle$

molecules not in

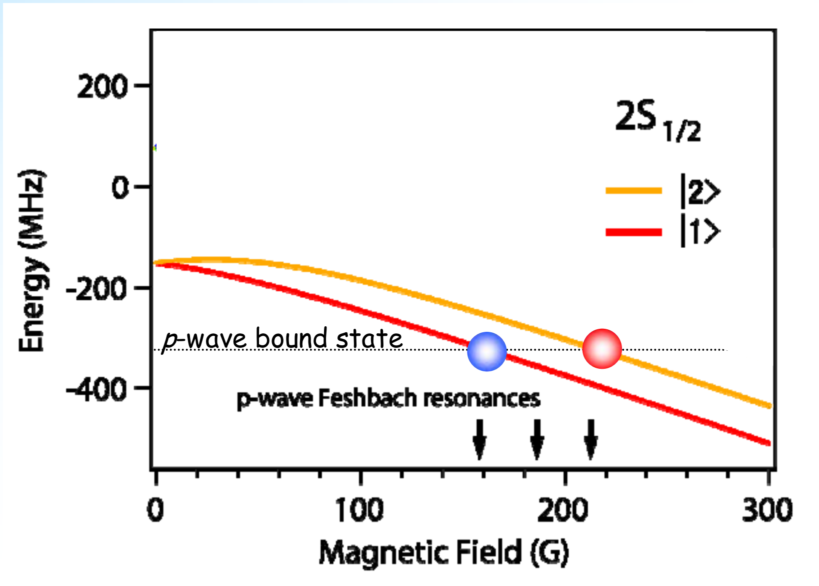
the lowest energy state

⇩

dipolar loss (due to spin-flip)

lifetime ~ 7ms

J. P. Gaebler et. al. PRL **98**, 200403 (2007)



Three p-wave Feshbach resonances of ^{6}Li

$|1\rangle-|1\rangle$: 159 G

$|1\rangle-|2\rangle$: 185 G

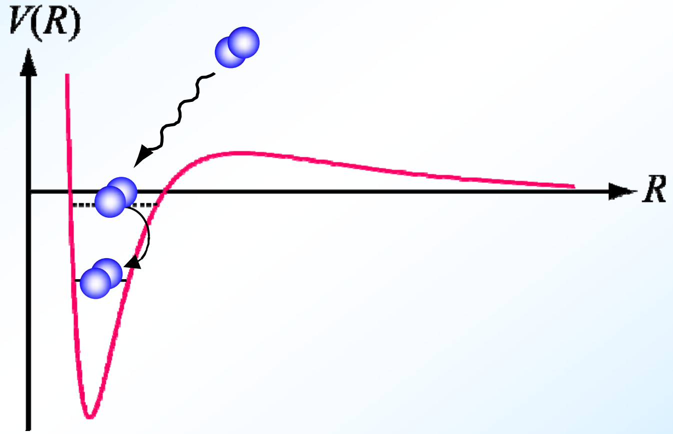
$|2\rangle-|2\rangle$: 215 G

$$\left(\begin{array}{c} \quad\quad F \quad m_F \\ |1\rangle = |1/2,\ 1/2\rangle \quad |2\rangle = |1/2,\ -1/2\rangle \end{array} \right)$$

$|1\rangle-|1\rangle$ combination has no dipolar loss.

vibrational quenching

Still, it is not clear if ^{6}Li p-wave molecules have long lifetime, since the vibrational state deexcitation could be the dominant loss channel.

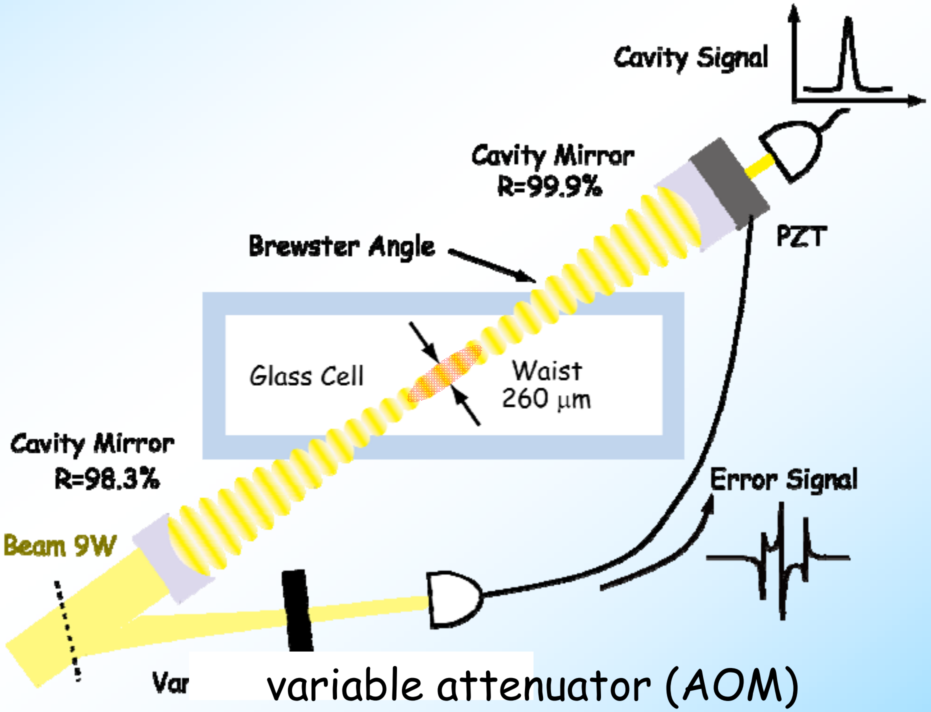


Cavity-Enhanced Optical dipole Trap

- Wavelength λ = 1064 nm
- Power I = 9 W
- Beam waist w = 260 μm
- Enhancement A = 110

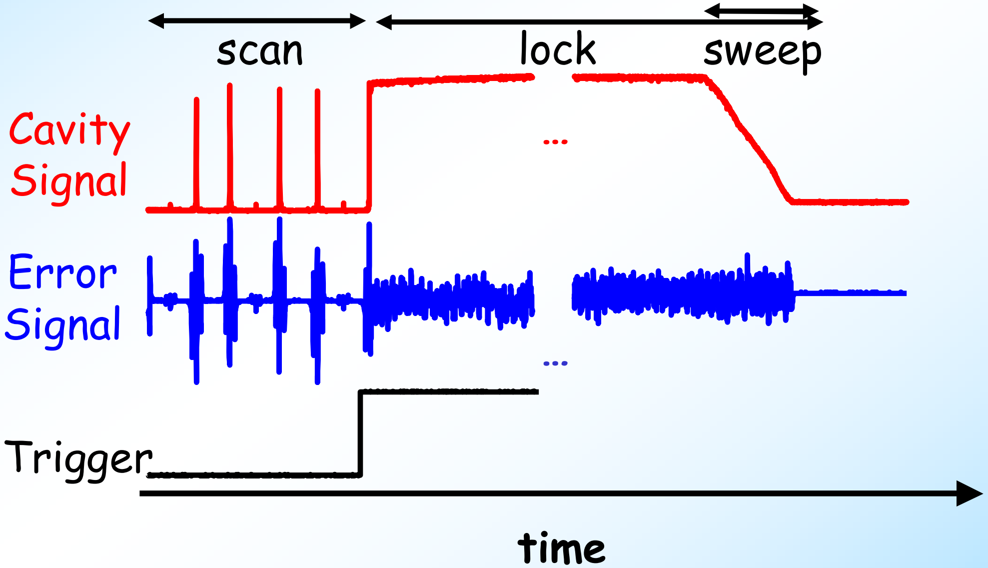
I_{cav}=9×110=990W !!

U_{dipole} = k_Bx2 mK



cavity-enhanced ODT:

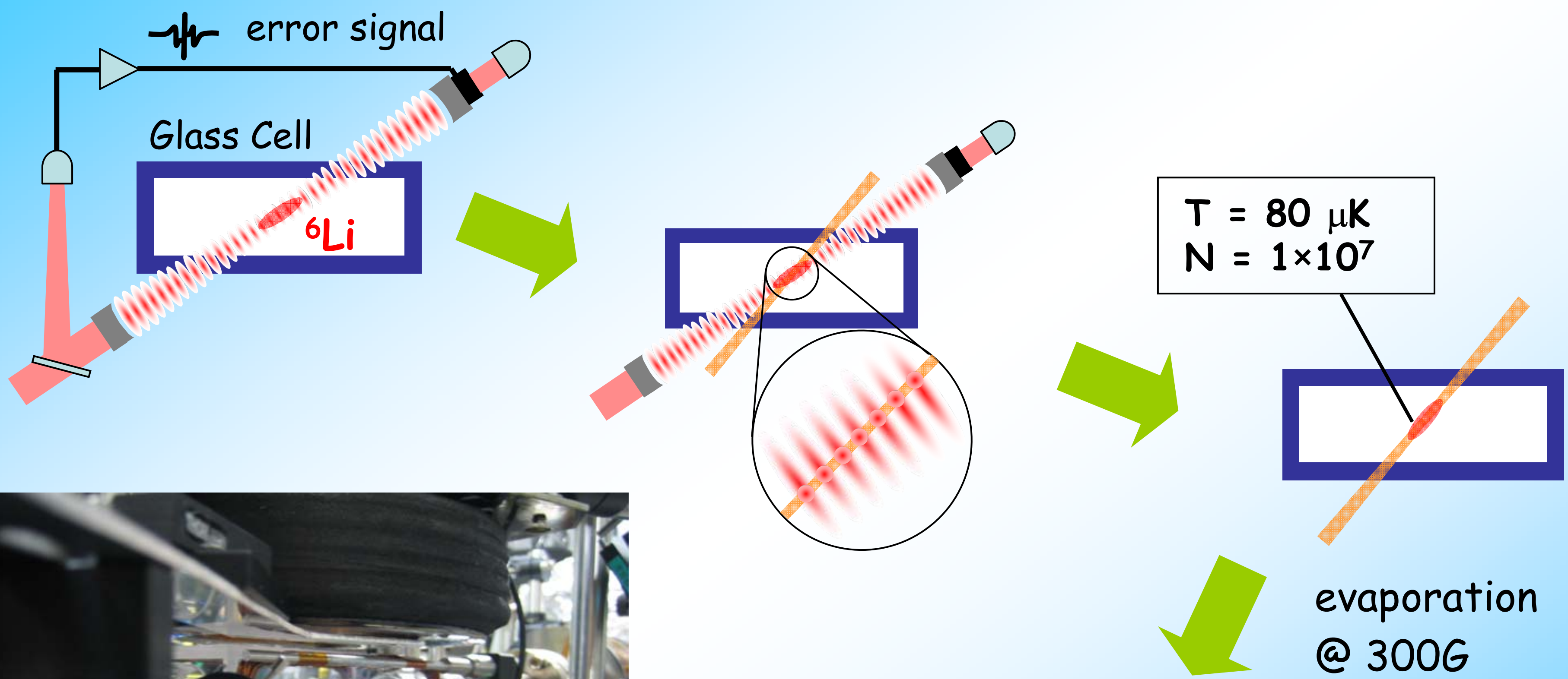
A. Mosk, S. Jochim, H. Moritz, T. Elsässer, M. Weidemüller, R. Grimm, Opt. Lett. 26, 1837 (2001).

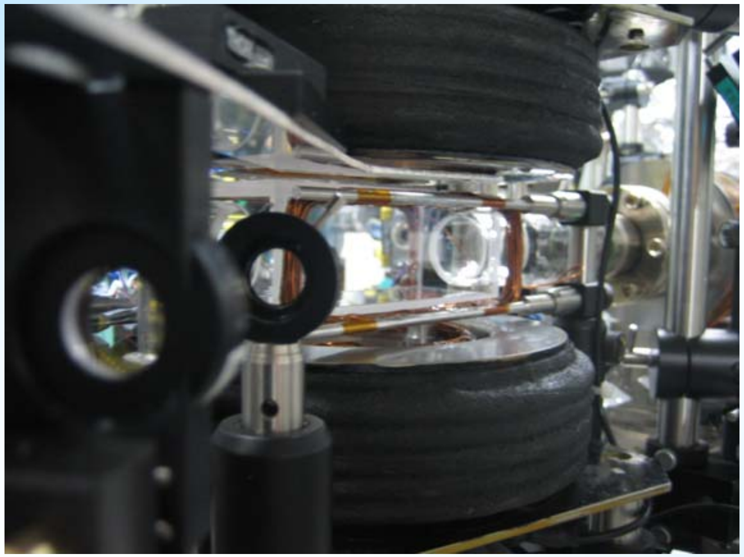


Features

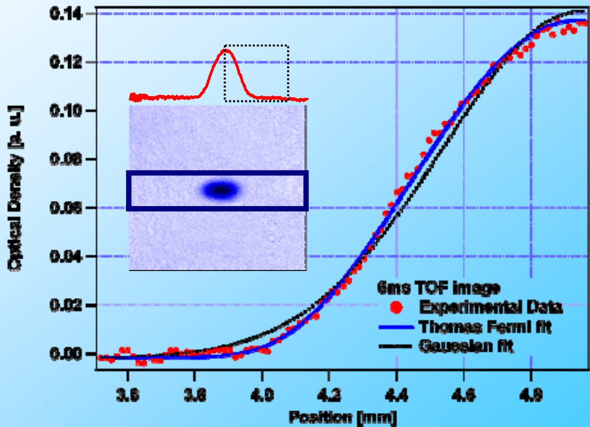
- High stability servo system
  dI/I ~ 0.03
- Auto locking system
- Controllable intensity

Experiment setup



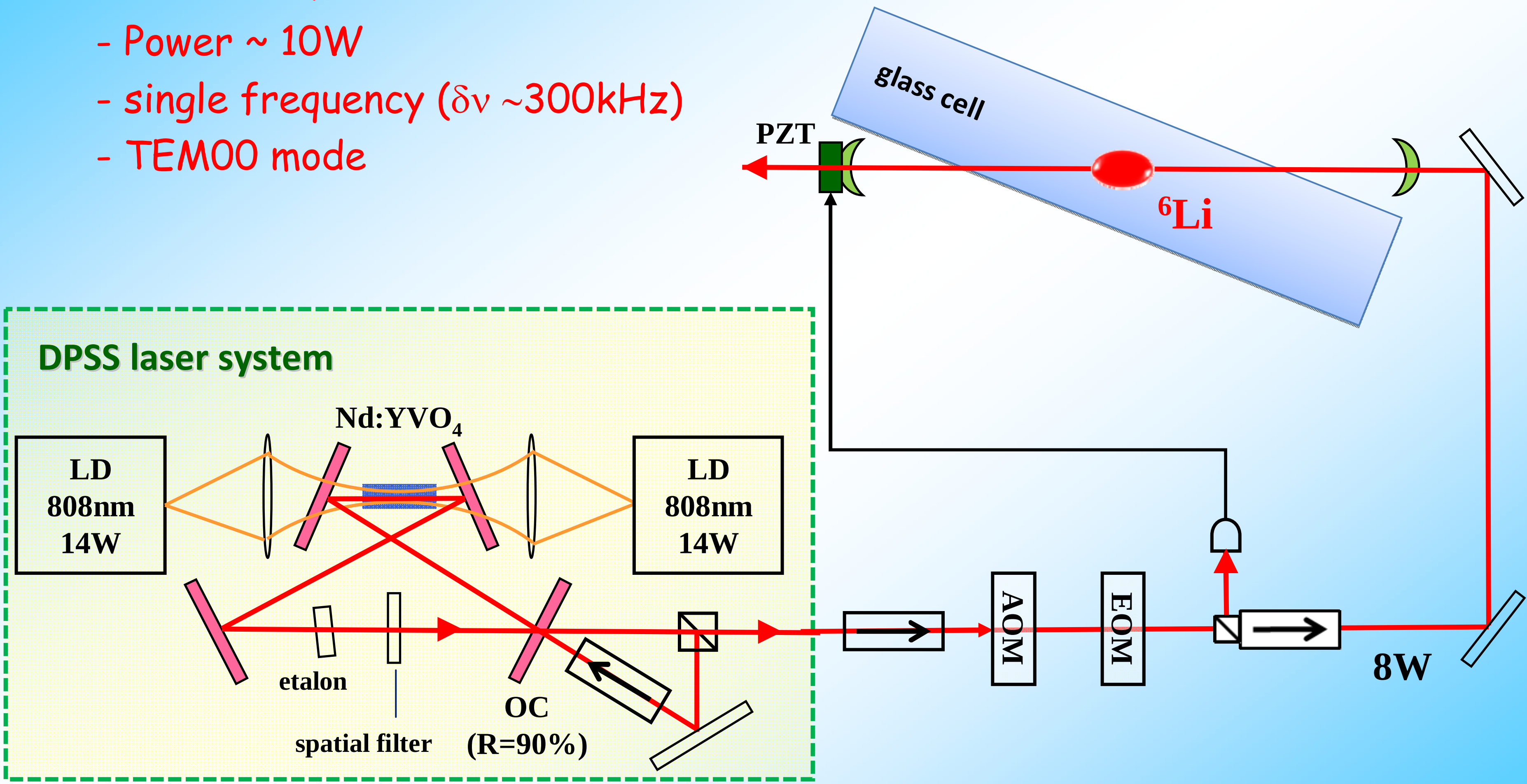


T/T_F = 0.1
N = 1×10^6

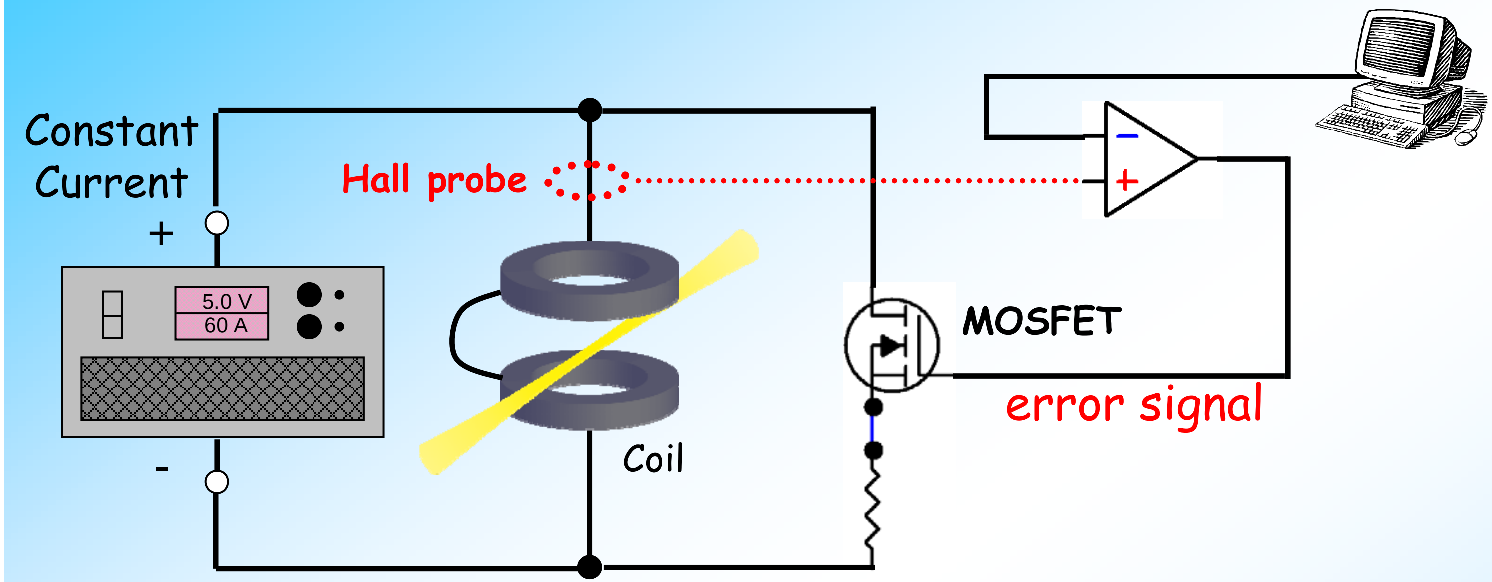


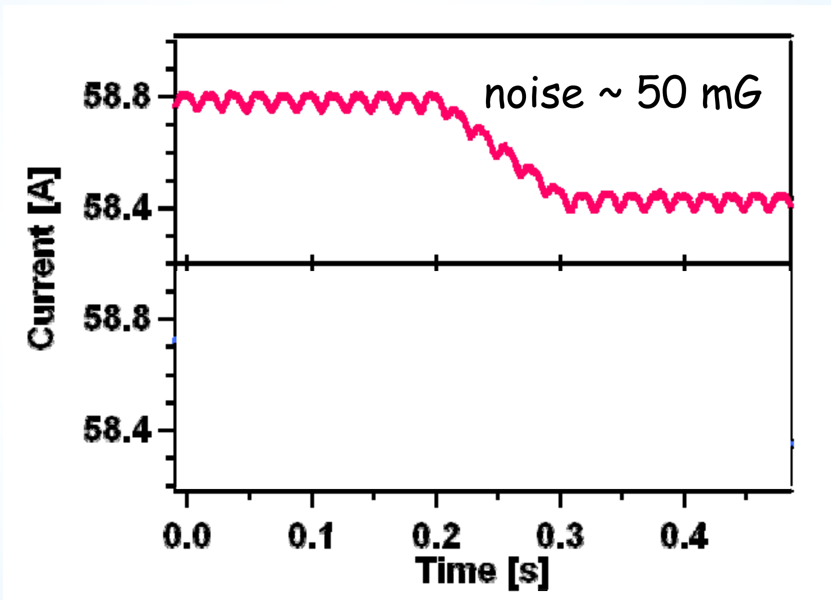
Diode Pump Solid State (DPSS) laser system

- λ = 1064nm
- Power ~ 10W
- single frequency ($\delta\nu$ ~300kHz)
- TEM00 mode



current stabilization

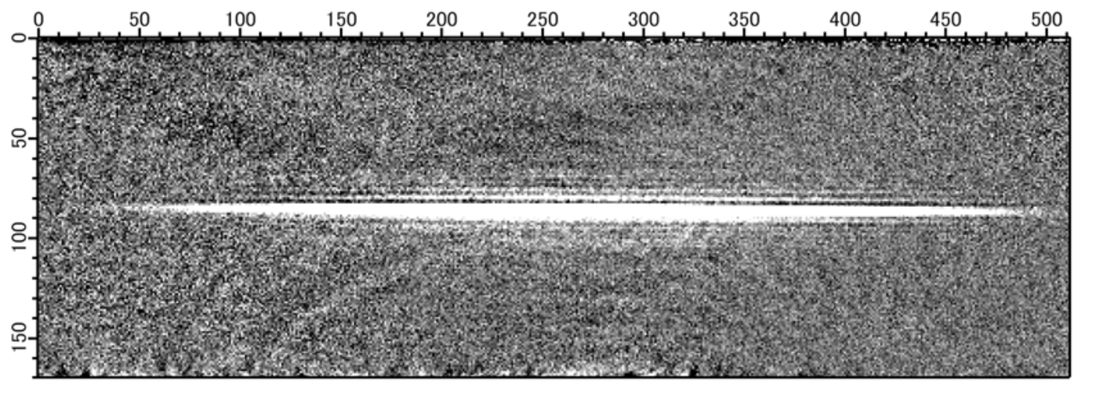




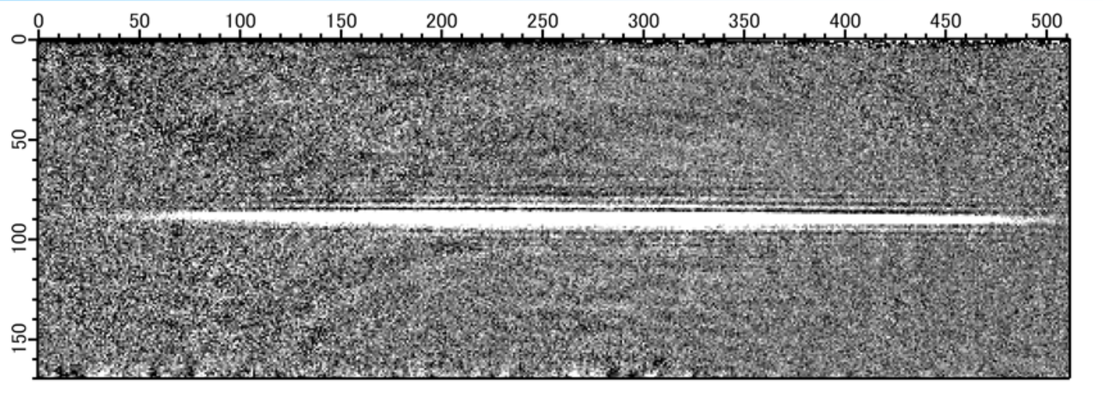
without the current stabilization

with the current stabilization

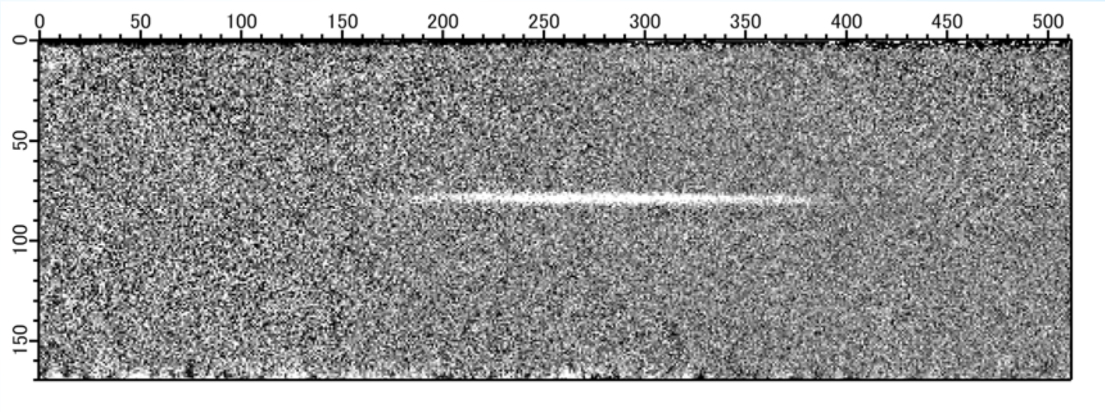
The very first signal of *p*-wave Feshbach molecules



p-wave molecules created



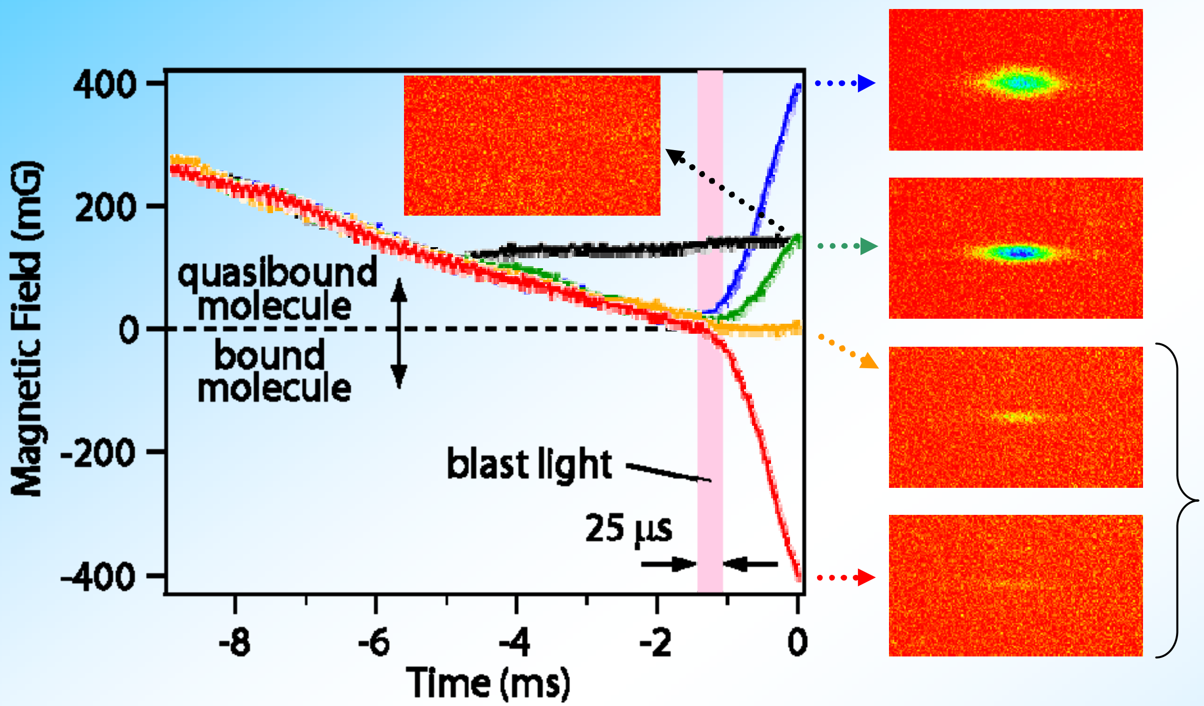
no p-wave molecules



p-wave molecules created and unpaired atoms were blown away

Creation and dissociation of *p*-wave Feshbach Molecules

creation of |1>-|1> molecules



higher dissociation energy

finite Franck-Condon factor between the molecular state and atomic state

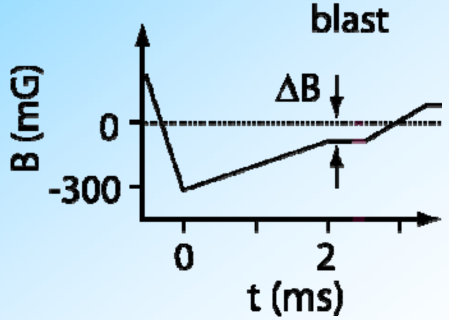
1. go to 215 G (*p*-wave Feshbach resonance of |2>) and remove |2> state atoms
2. ramp down the field close to the 159 G resonance
3. blow away the unpaired atoms (with the "blast light")

<u>imaging of |1>-|1> molecules</u>

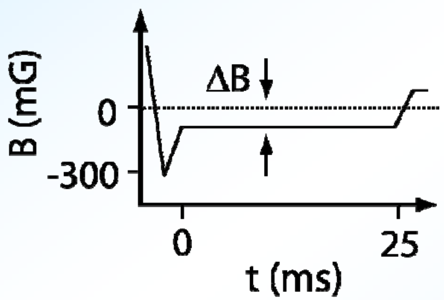
4. ramp up the field to let the molecules dissociate

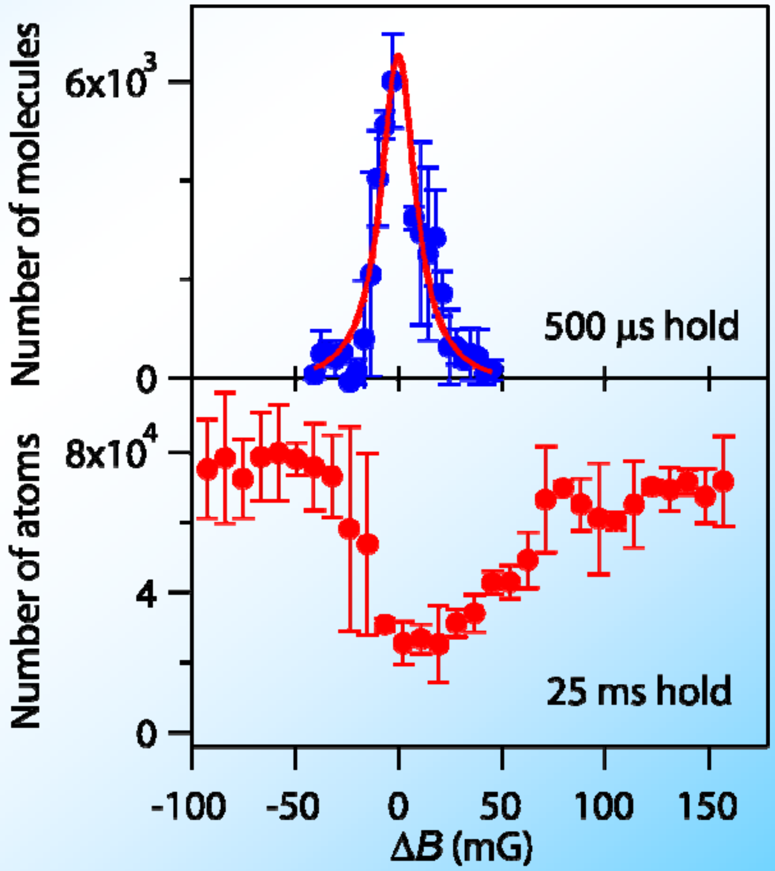
molecular creation efficiency and atomic loss

Creation of molecules



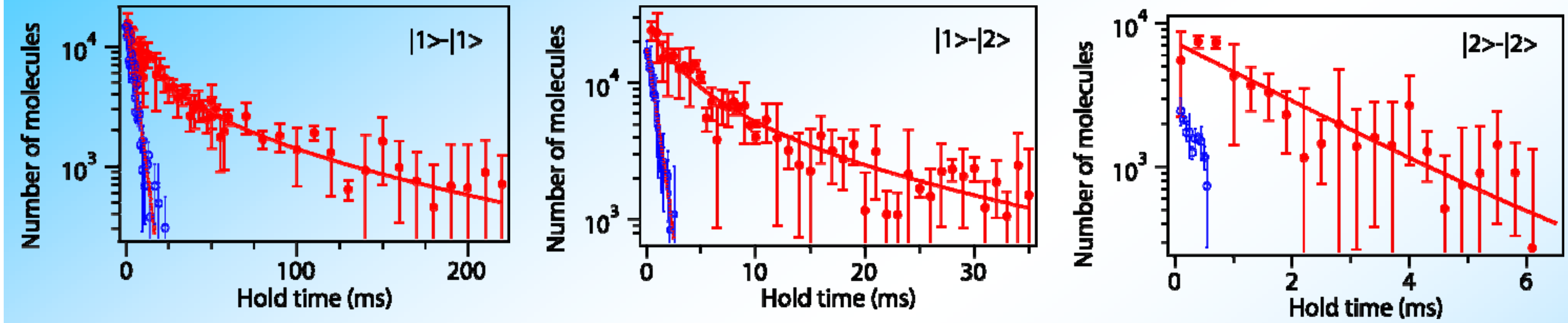
Loss of atoms





molecular decay due to inelastic collisions

● : only molecules in a trap
○ : molecules with atoms



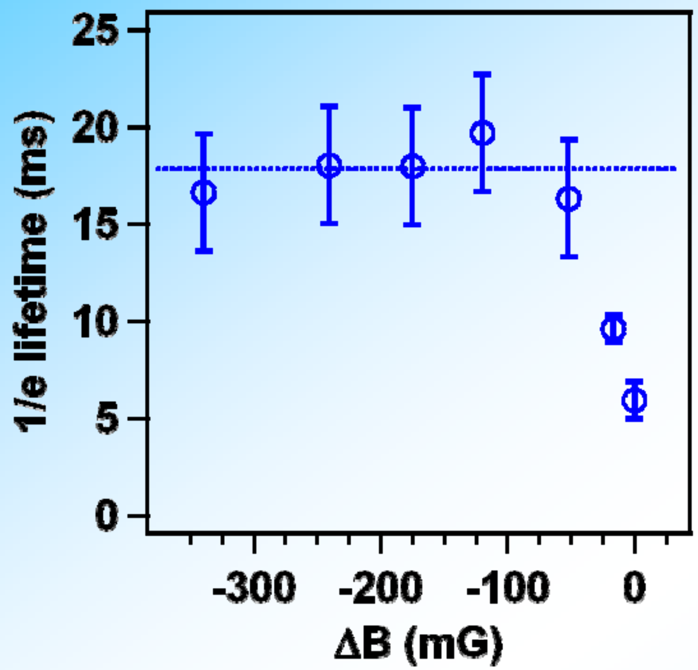
$$\frac{\dot{n}_d}{n_d} = \underbrace{-\alpha}_{a} \underbrace{- K_{ad} n_a}_{b} \underbrace{- K_{dd} n_d}_{c}$$

a: dipolar-relaxation
b: atom-dimer inelastic loss
c: dimer-dimer inelastic loss

$n_a(n_d)$: density of atoms (molecules)

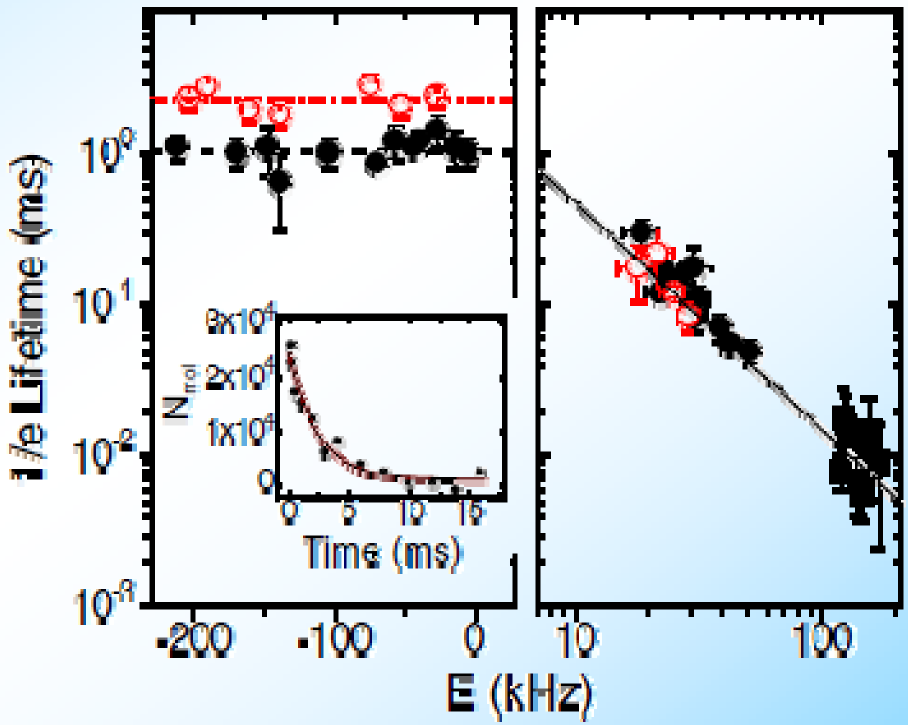
	α (s^{-1})	K_{ad} (cm^3s^{-1})	K_{dd} (cm^3s^{-1})
|1> - |1>	-	2.4(+0.5/-0.3) ×10^{-11}	2.8(0.3) ×10^{-10}
|1> - |2>	2.6(1.5) ×10^2	6.8(+1.5/-1.1) ×10^{-11}	8.1(1.8) ×10^{-10}
|2> - |2>	4.8(0.6) ×10^2	-	-

detuning dependence of molecular lifetime



^6Li

Y. Inada et. al.
PRL **101**, 100401 (2008)



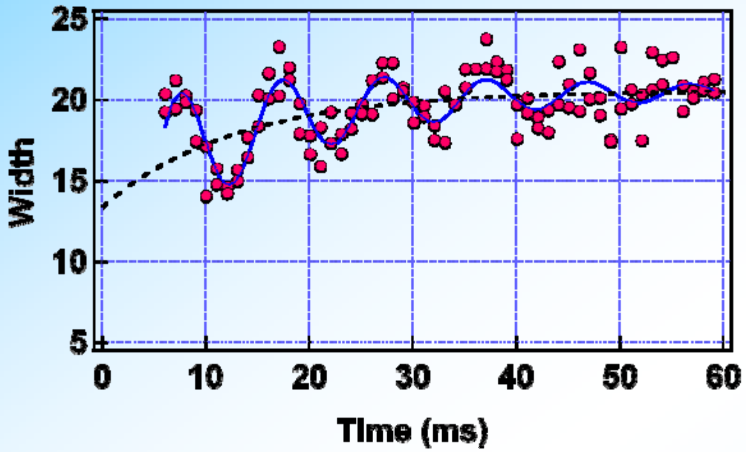
^{40}K

J. P. Gaebler et. al.
PRL **98**, 200403 (2007)

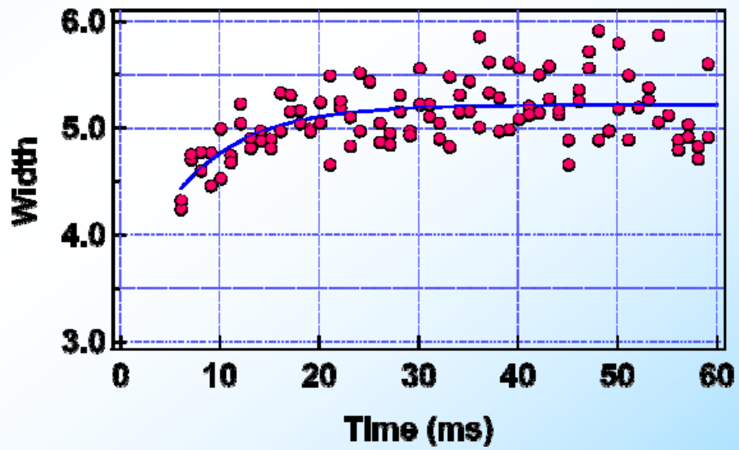
thermalization due to elastic collisions

heating due to inelastic loss is reflected to the cloud size -> thermalization

axial size



radial size



thermalization time is estimate to be 20 ms

toward p-wave superfluid

phase space density ~ 1 x 10^{-2}

thermalization time ~ molecular lifetime

$(20\text{ms})^{-1}$ $(20\text{ms})^{-1}$

This ratio has to be ~ 10^2 for an efficient evaporative cooling.

W. Ketterle and N. J. van Druten,
Adv. At. Mol. Opt. Phys. **37**, 181 (1996).

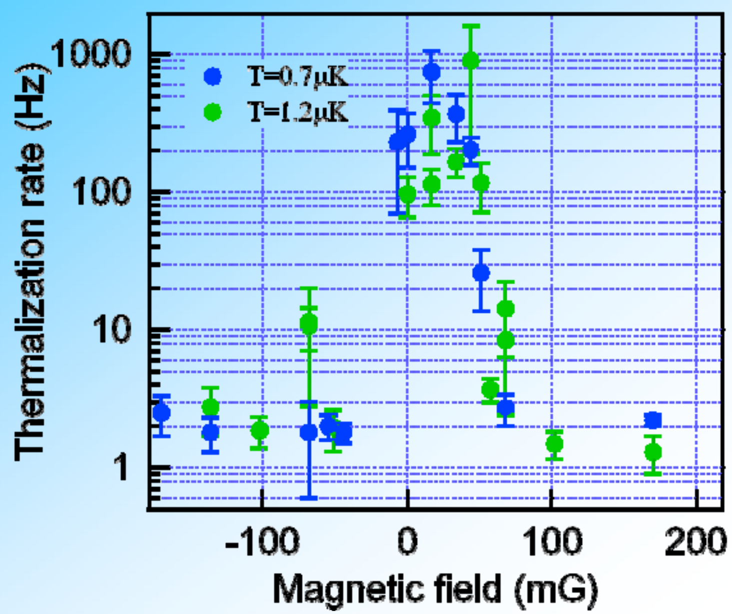
Next move

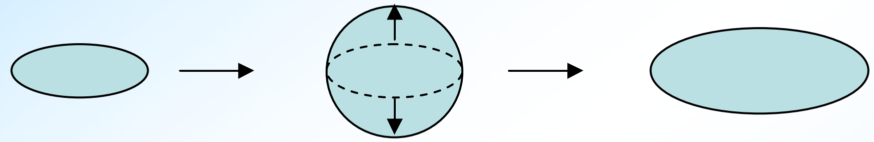
- collisional properties of atoms near p-wave Feshbach resonance

$$f_1(k) = \frac{k^2}{-\frac{1}{V(B)} + ck^2 - ik^3}$$

- creation of p-wave molecules in 3D optical lattices
- cool the atoms in the BCS side of the resonance and do "projection"

atomic elastic collisions near resonances





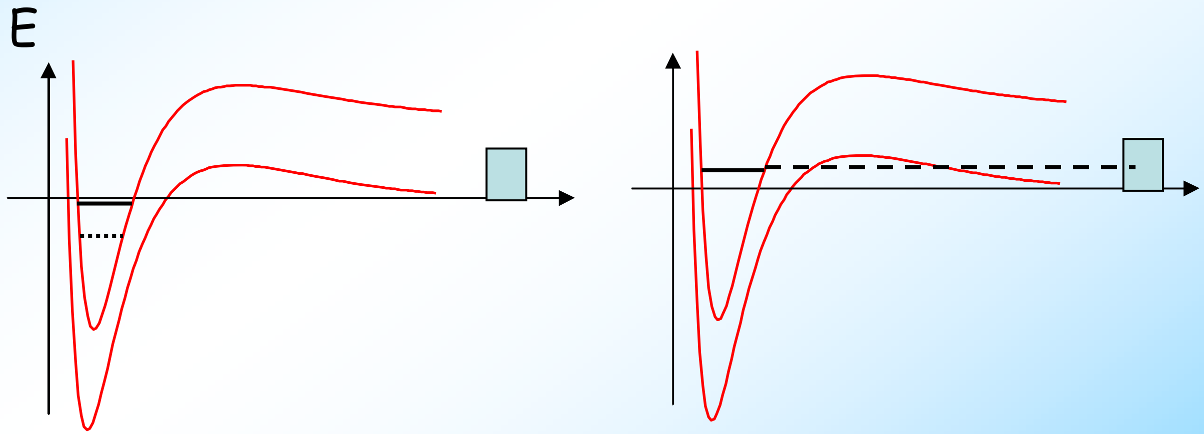
excitation in one direction

cross-dimensional thermalization

^{6}Li

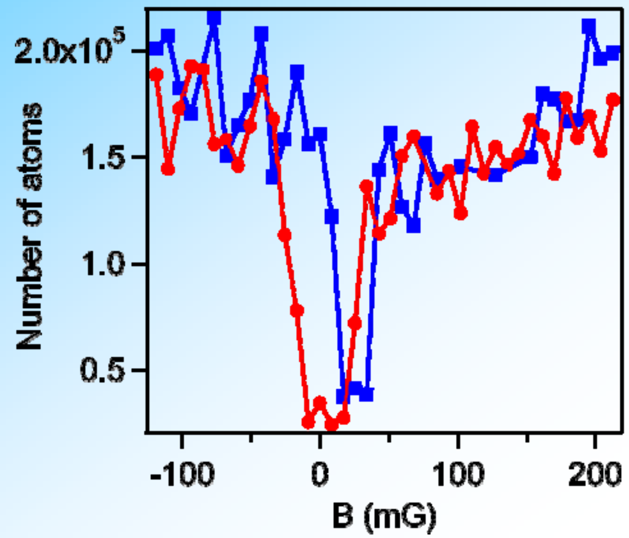
$$f_{l=1}(k) = \frac{k^2}{-\frac{1}{V(B)} + ck^2 - ik^3}$$

$$V(B) = V_{bg}\left(1 - \frac{\Delta B}{B - B_{res}}\right)$$



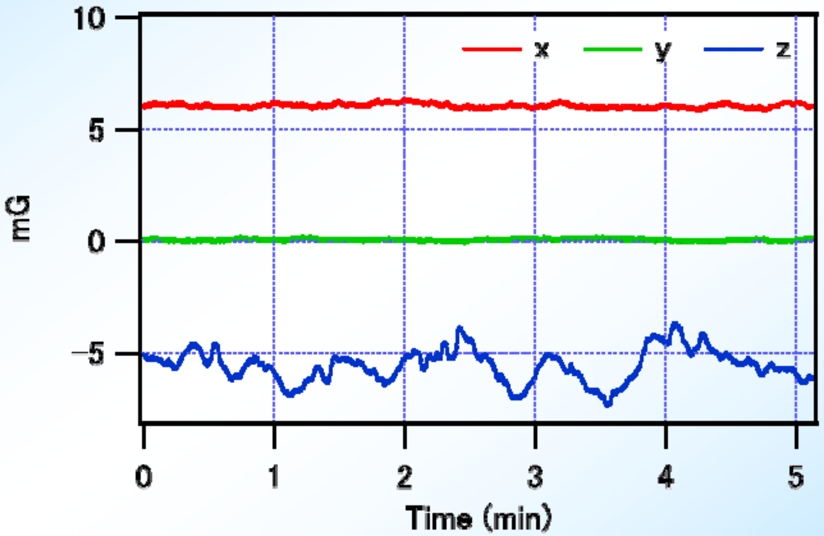
Magnetic field fluctuation

Loss of atoms near the p-wave Feshbach resonance

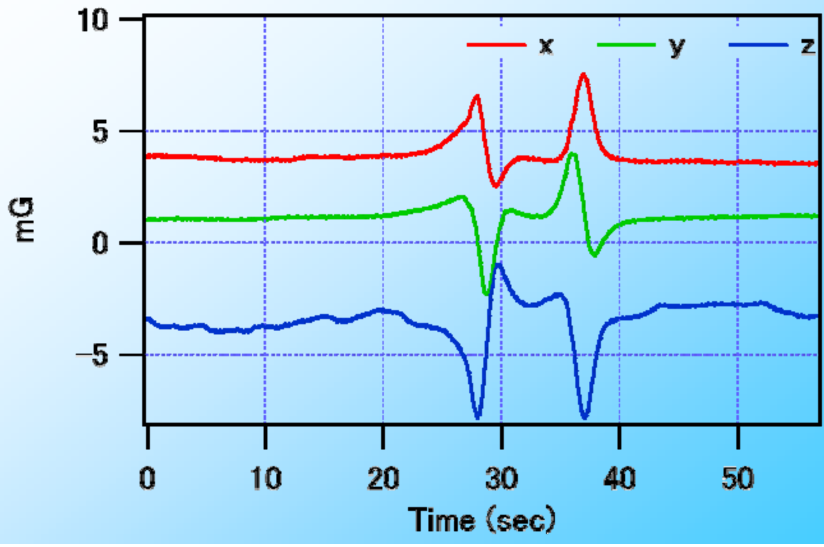


Even with the same experimental condition, resonance position fluctuates (~30mG)...

- stray magnetic field fluctuation
- magnetization of the table, optics parts ...

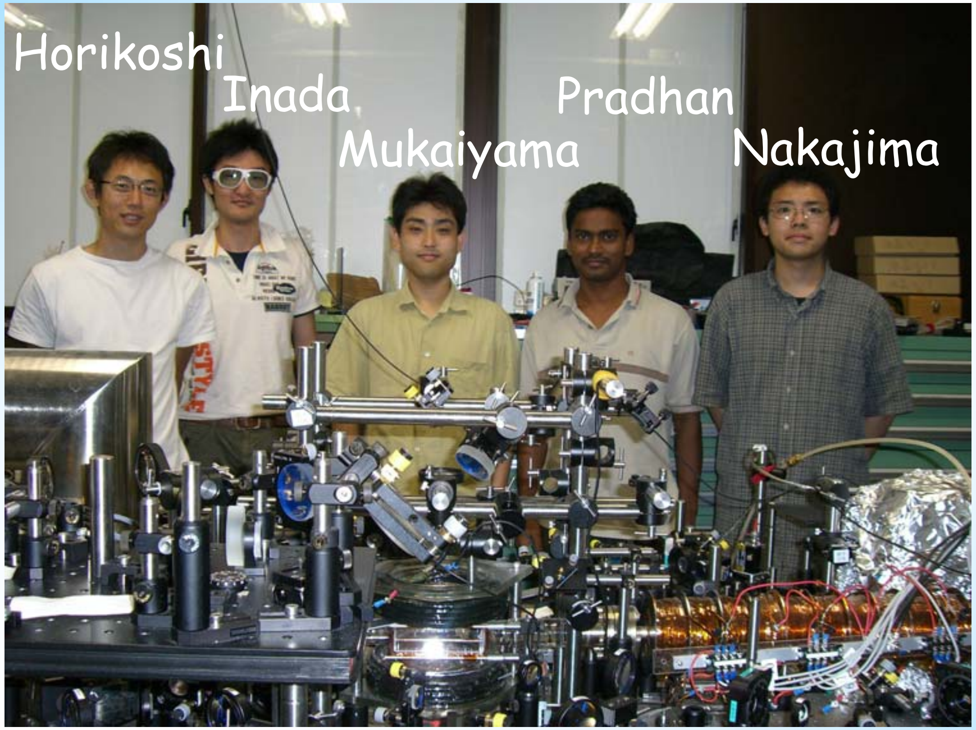


When a car passes nearby ...



summary

- formation of p-wave Feshbach molecules of ^{6}Li atoms in the lowest atomic state
- collisional properties of p-wave Feshbach molecules



The team (ERATO)

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S. Pradhan	postdoc
S. Nakajima	grad student
T. M	Group leader

Prof. M. Ueda (project leader)
Prof. M. Kuwata-Gonokami

Former members
Y. Inada
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