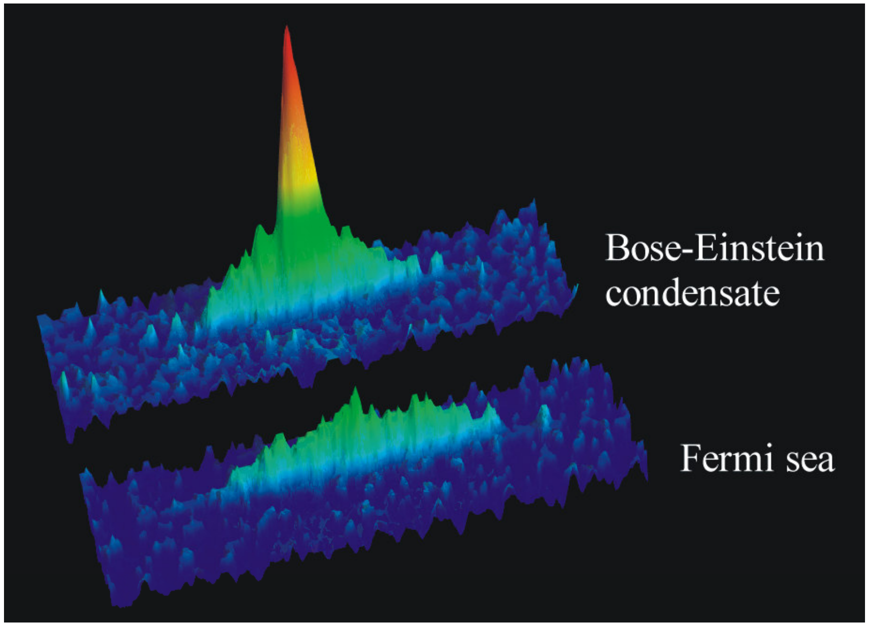
Atom-molecule mixture in a cold degenerate Fermi gas



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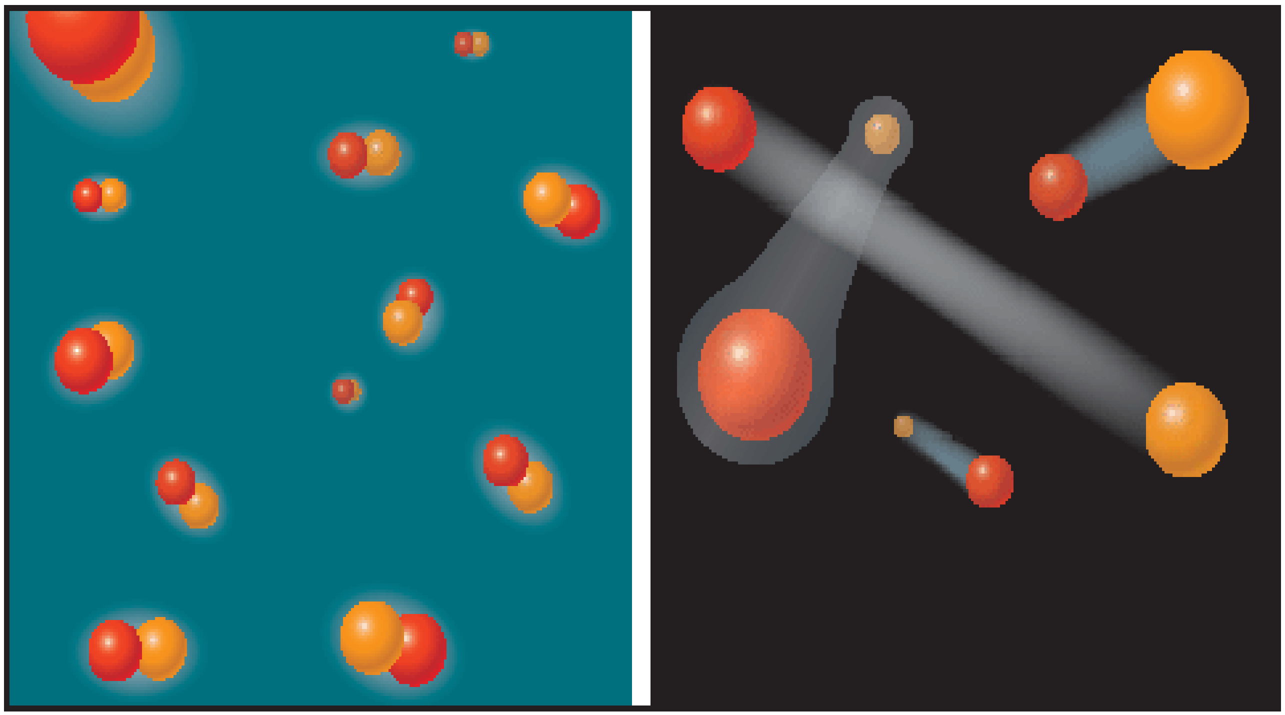
Outline of talk

- Study of Li Feshbach resonance
  - Feshbach resonances and bound states
  - Measurement resonance interaction energy
  - Theoretical explanation
- Formation ultra-cold molecules
  - Reversible process between Fermi – Bose gases
  - Long-lived molecules
- Perspectives

Molecular BEC and Fermi superfluidity

Two component Fermi gas at very low temperature
s-wave interaction, scattering length *a*

$a > 0$ $a < 0$



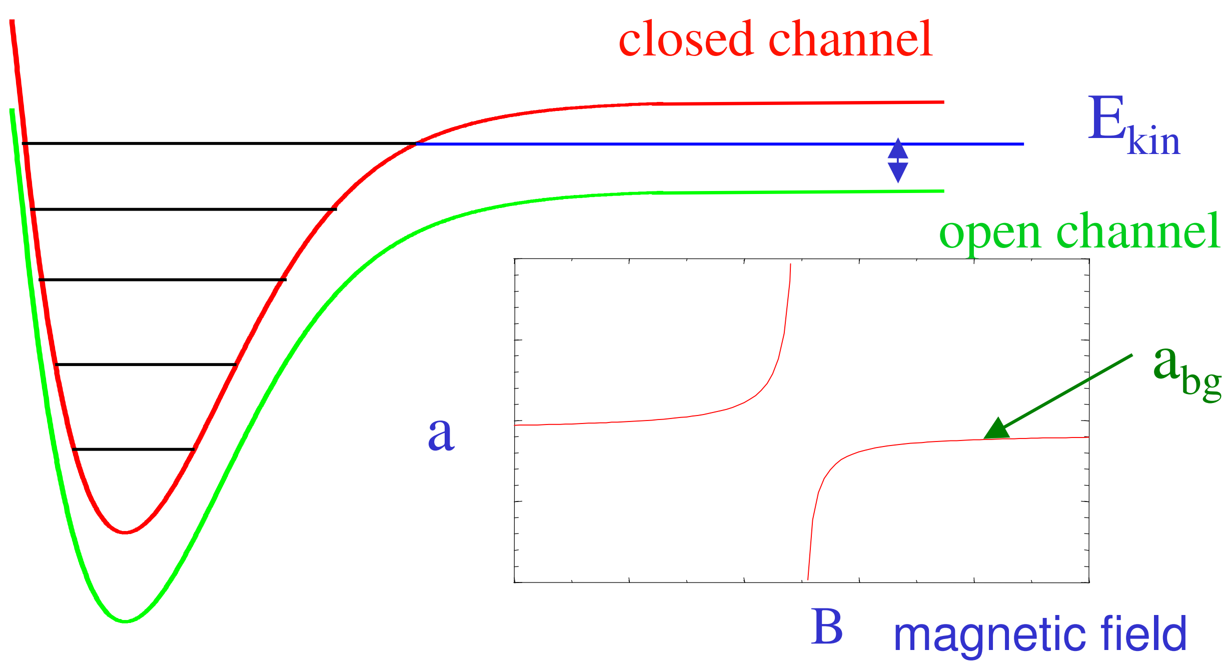
Molecular BEC ? Fermi superfluid ?

Feshbach resonance

See Science news focus, August 8th, 2003

Principles of Feshbach resonance

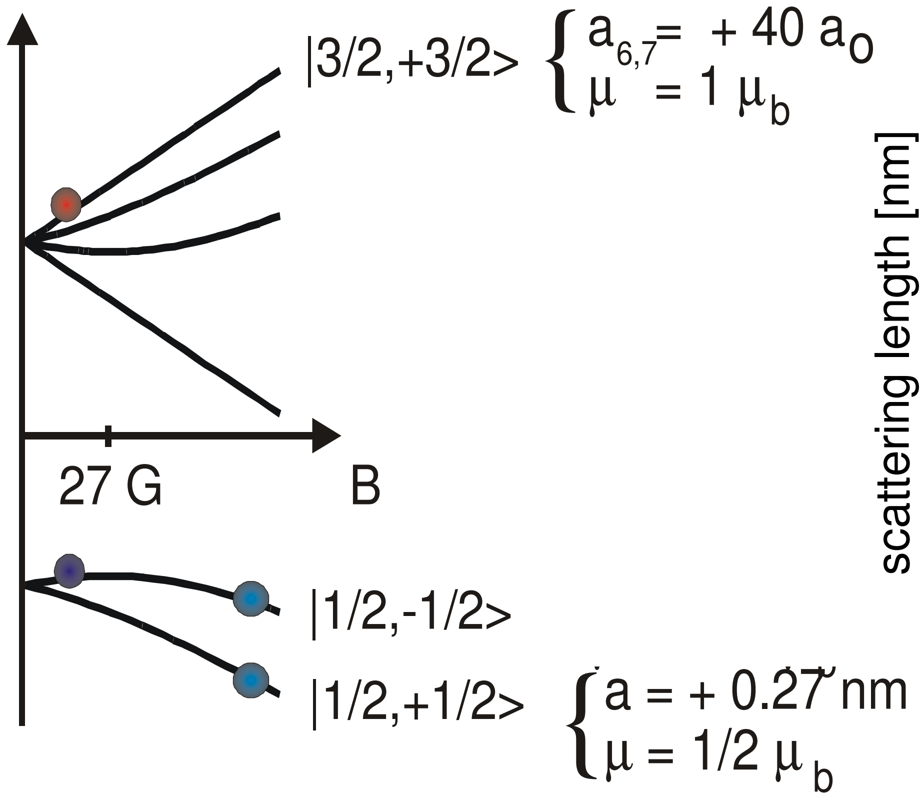
Coupling between open and closed channels:

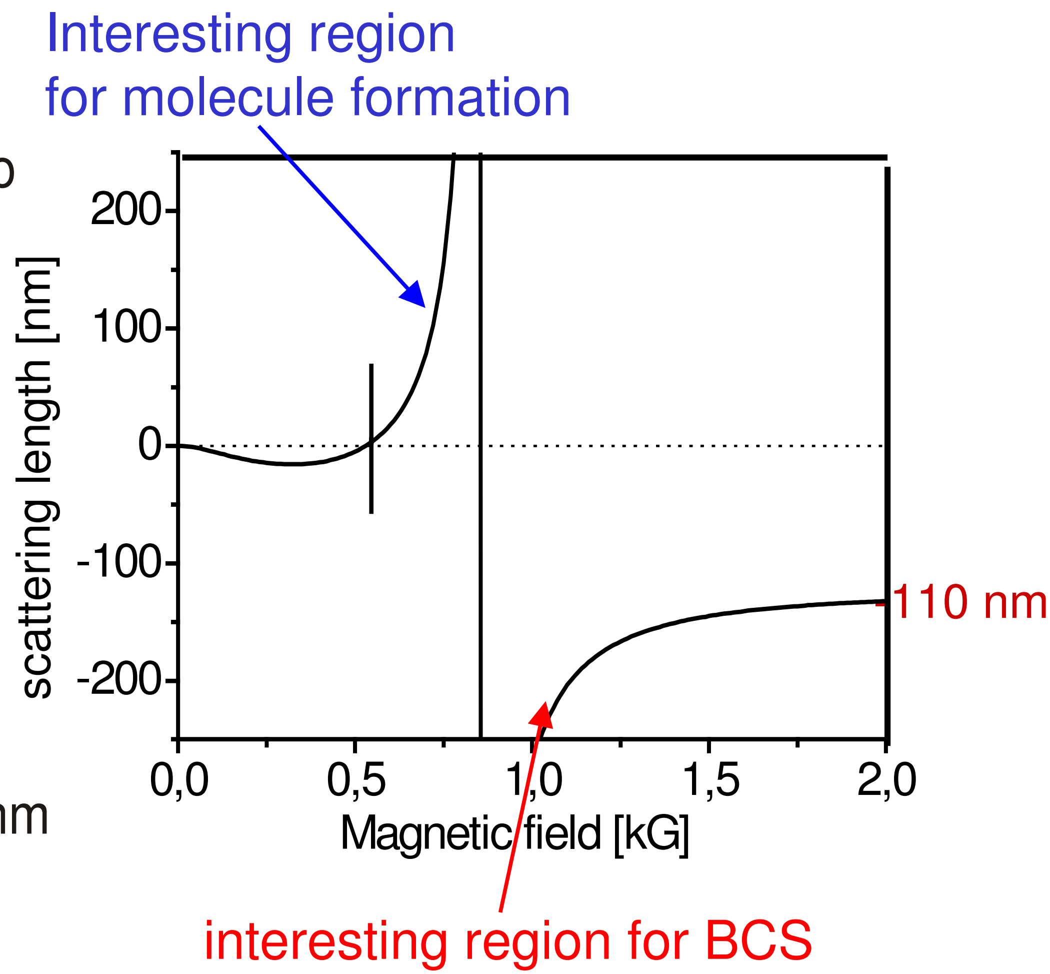


- Modifies the scattering length
- Scattering becomes strongly energy-dependent
- Mixture of atoms and molecules possible

➡ Explosion of both theoretical and experimental work in last years

^{6}Li Feshbach resonance





^{6}Lithium

Resonance superfluidity?

[Holland et al, PRL **87**, 120406 (2001)]

Fermi systems with strong interactions

Several recent interesting experiments:

- Inverse expansion ⇒ Superfluidity or hydrodynamic?

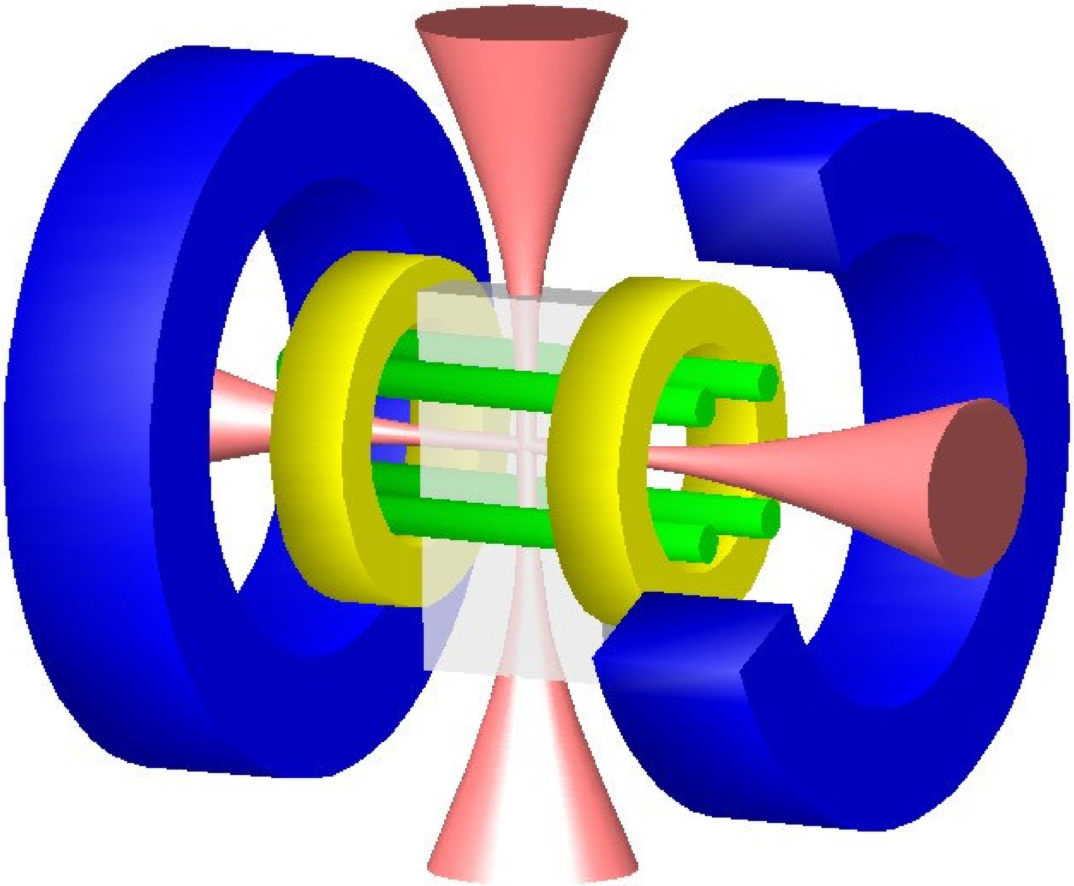
  [O'Hara et al., Science **298**, 2179 (2002)]
- Measurement interaction energy

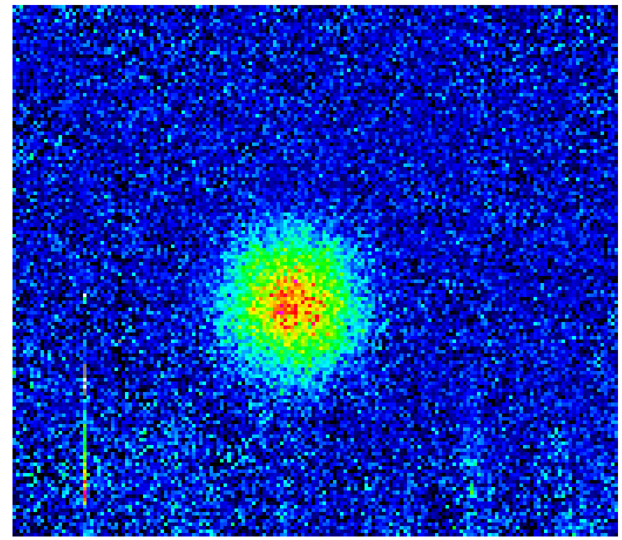
  [Gehm et al, cond-mat/0212499], [Bourdel et al, Phys. Rev. Lett. **91**, 020407 (2003).], [Regal and Jin, Phys. Rev. Lett. **90**, 230404.]
- Interaction strengths measured via frequency shifts

  [Gupta et al, Science Express (2003)]
- Evidence for molecules out of fermions

  [J. Cubizolles et al., cond-mat/0308018], [S. Jochim et al, cond-mat/0308095], [Regal et al, cond-mat/0308606], [Strecker et al., Phys. Rev. Lett. **91**, 080406 (2003)]]

Strongly interacting ^{6}Li gas in optical trap





$T_F \;=\; 5\ \mu K$

$T/T_F = 0.22$

$N_{total} = 1\ 10^5$

$E_{interaction} = -0.35\ E_{kin,}$

$k_F\ |a| > 1$

$na^3 > 1$

Duke, ENS, MIT

Two YAG beams
with 2.5 W and waist of 38 μm

Measurement of interaction energy

Energy of trapped gas:

$E_{total} = E_{trap} + E_{kin} + E_{int}$

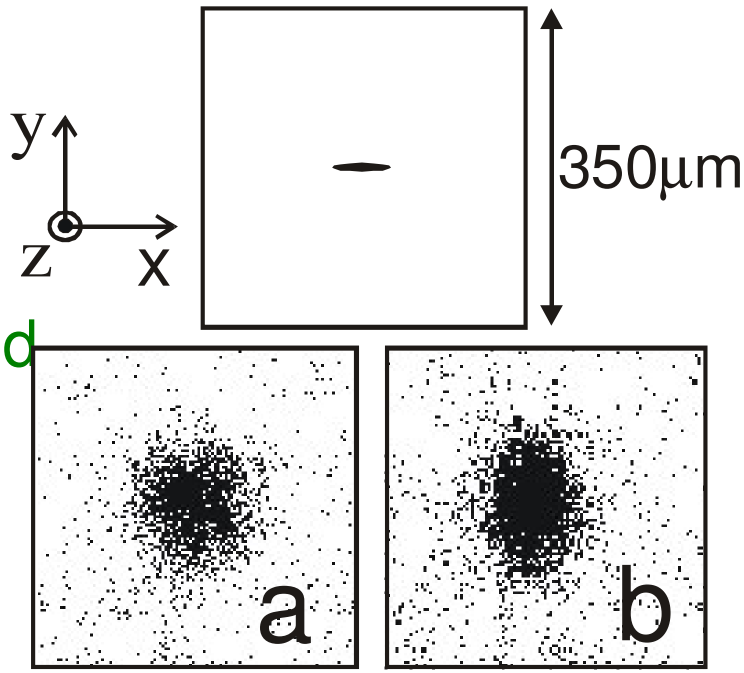
Time of flight images:

- (a) Expansion without field

  $E_{total} = E_{kin}$

- (b) Expansion with field

  $E_{total} = E_{kin} + E_{int}$



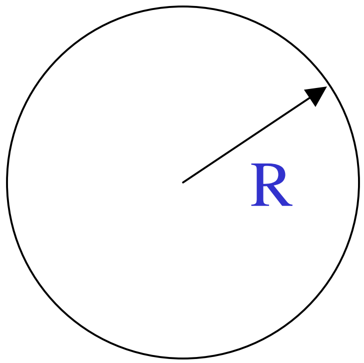
$T/T_F = 0.6$, $N = 7\ 10^4$ atoms

Expansion is governed by collisional hydrodynamics

Study of mean field energy

What is the correct expression for the self-interaction around resonance?

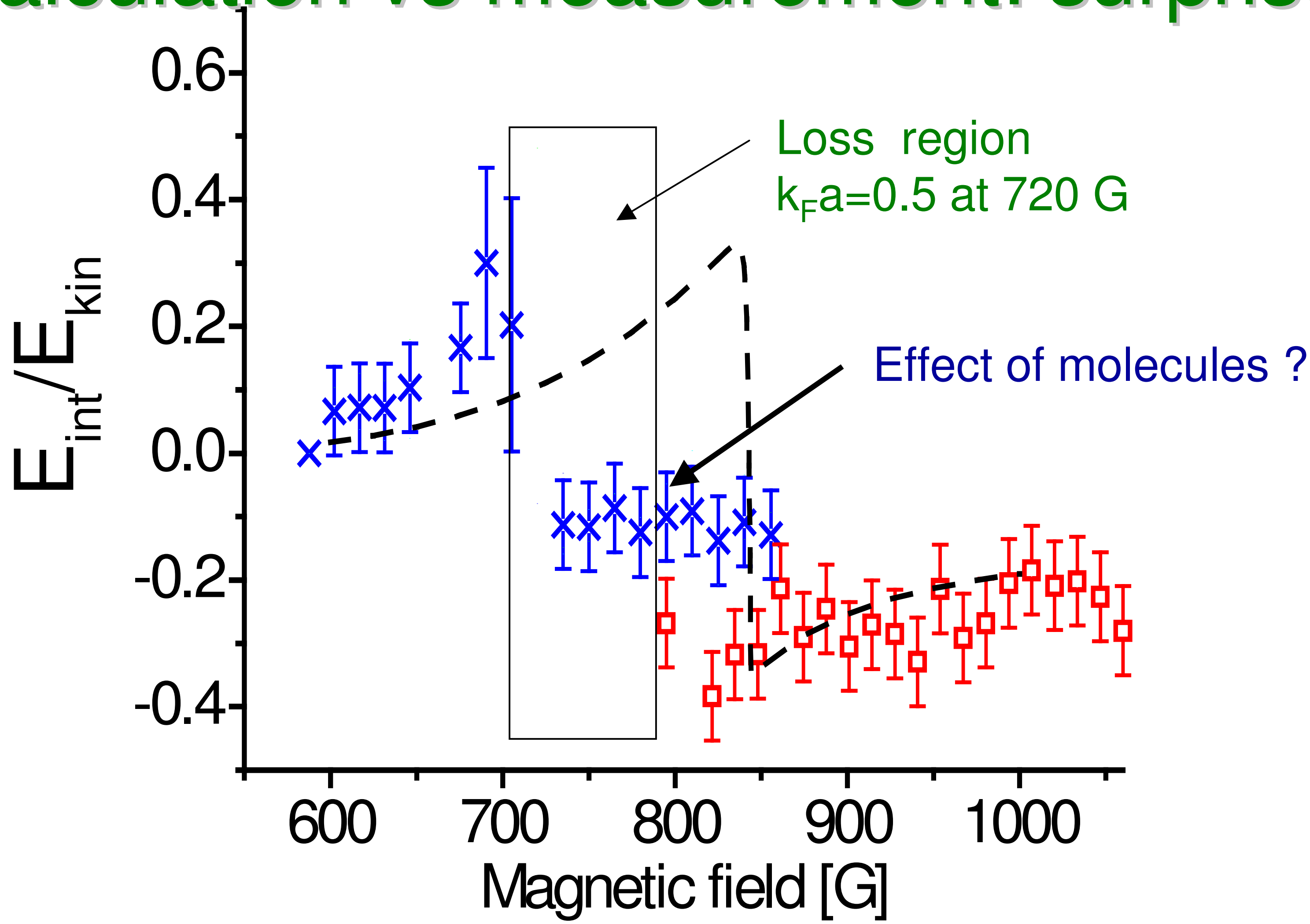
- Regular $U = \frac{4\pi\hbar^2}{m} a$ fails, diverges
- Energy-dependent T-matrix $U = \frac{4\pi\hbar^2}{m} T^{\mathrm{Re}}(k)$
  - From higher-order kinetic theory
  - However, problems arise See [Mahan, Many-particle physics]
- Scattering phase shift!
  - Colliding particles in spherical box [Fumi, Philos. Mag. 46, 1007 (1995).]



$$\sin(kR+\delta)=0 \Rightarrow k=\frac{n\pi-\delta}{R}$$

$$U = -\frac{4\pi\hbar^2}{m}\frac{\delta(k)}{k}$$

Calculation vs measurement: surprises



Resonance found at 810(20) Gauss in good agreement with theory

Interaction energy is negative on resonance, as predicted by Heiselberg

Change of sign of E_{int} is shifted from resonance

Strongly interacting Fermi gas: k_F |a| > 1

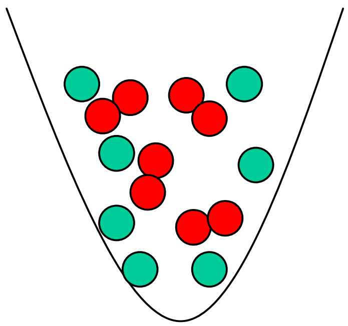
Molecules in the system?

Shift of resonance? B_{peak} = 855 +- 53 Gauss ➡ unlikely!

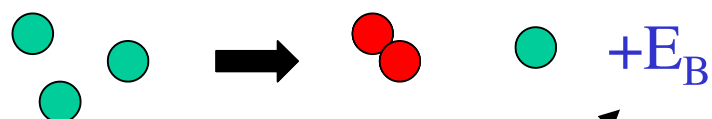
Three-body recombination [D. Petrov, PRA **67**, 010703 (2003)]

- Molecules form efficiently in highest weakly bound state
- Transition to lower states suppressed

Molecules can be trapped!



Binding energy released



$$E_B = \frac{\hbar^2}{ma^2}$$

$E_B < E_{trap}$ ➡ Particles stay in trap

$E_B > E_{trap}$ ➡ Trap loss

Thermodynamics atom-molecule system

Chemical equilibrium:

$$2\mu = -\varepsilon_b + \tilde{\mu}_m$$

Number conservation:

$$N = N_a + 2N_m$$

Two-particle momentum dependent coupling:

$$g_{kk'} = -\frac{4\pi\hbar^2}{m}\frac{\delta(|\vec{k}-\vec{k}'|/2)}{|\vec{k}-\vec{k}'|/2}$$

Molecular interactions interactions: can be included for $k_F a < 1$

Atom-molecule scattering length: $a_{am}=1.2\,a$, $g_{am}=0.9g$

molecule-molecule scattering length: $a_{mm}=0.6a$, $g_{mm}=0.3g$

[D.S. Petrov, C. Salomon, and G.V. Shlyapnikov, cond-mat/030910.]

Energy atomic component:

$$E_a = \sum_{\vec{k}} \frac{\hbar^2 k^2}{m}\nu_k + \sum_{\vec{k}\vec{k}'} \frac{g_{kk'}}{V}\nu_k \nu_{k'}$$

Atom number:

$$N_a = 2\sum_{\vec{k}} \nu_k$$

Entropy atomic component:

$$S_a = -2\sum_{\vec{k}} [\nu_k \ln \nu_k + (1-\nu_k)\ln(1-\nu_k)]$$

Thermodynamics (2)

$$S_a = -2\sum_{\vec{k}} [\nu_k \ln \nu_k + (1-\nu_k)\ln(1-\nu_k)]$$

Atomic grand potential: $\Omega_a = E_a - TS_a - \mu N_a$ ➡ $N_a = -(\partial\Omega_a/\partial\mu)_{T,V}$

⬇

Atomic occupation number: $\nu_k = [\exp\{(\varepsilon_k - \mu)/T\} + 1]^{-1}$

with $\varepsilon_k = \hbar^2 k^2/2m + U_k, \quad U_k = \sum_{\vec{k}'} g_{kk'} \nu_{k'}/V$

Combine with molecular number

$$N_m = \sum_{\vec{k}} \nu_k^m = \sum_{\vec{k}} [\exp\{(\varepsilon_k^m - \tilde{\mu}_m)/T\} - 1]^{-1} \quad \text{with} \quad \varepsilon_k = \hbar^2 k^2/m$$

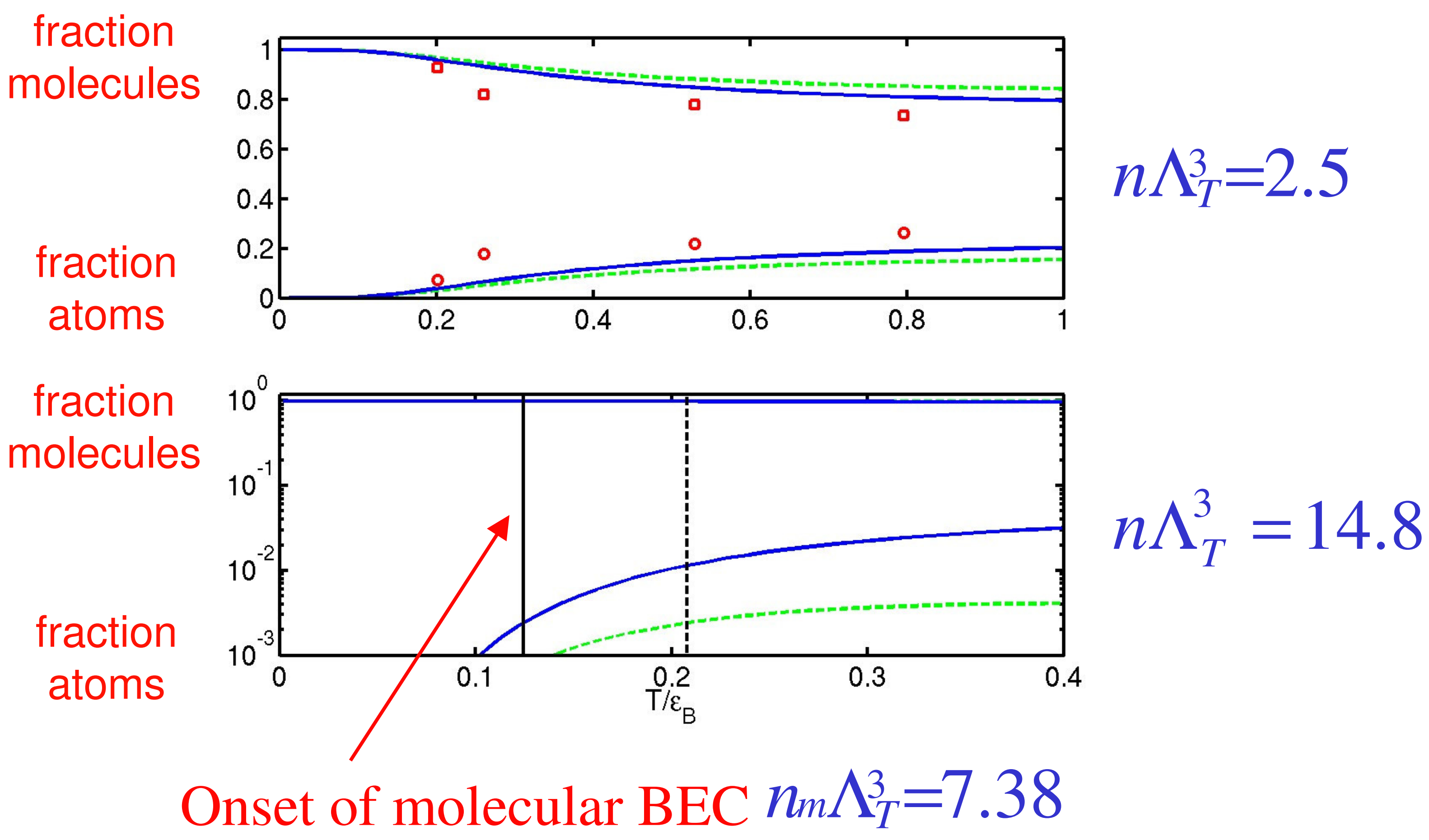
Iteration until mean field is self-consistent

➡ From this obtain all types of thermodynamic quantities!

Fraction atoms-molecules and BEC

Fraction atoms/molecules calculated as function of two universal parameters: T/ε_k and $n\Lambda_T^3$, with $\Lambda_T=(2\pi\hbar^2/mT)^{1/2}$

Comparison with ENS experiment [J. Cubizolles et al, cond-mat/0308018]

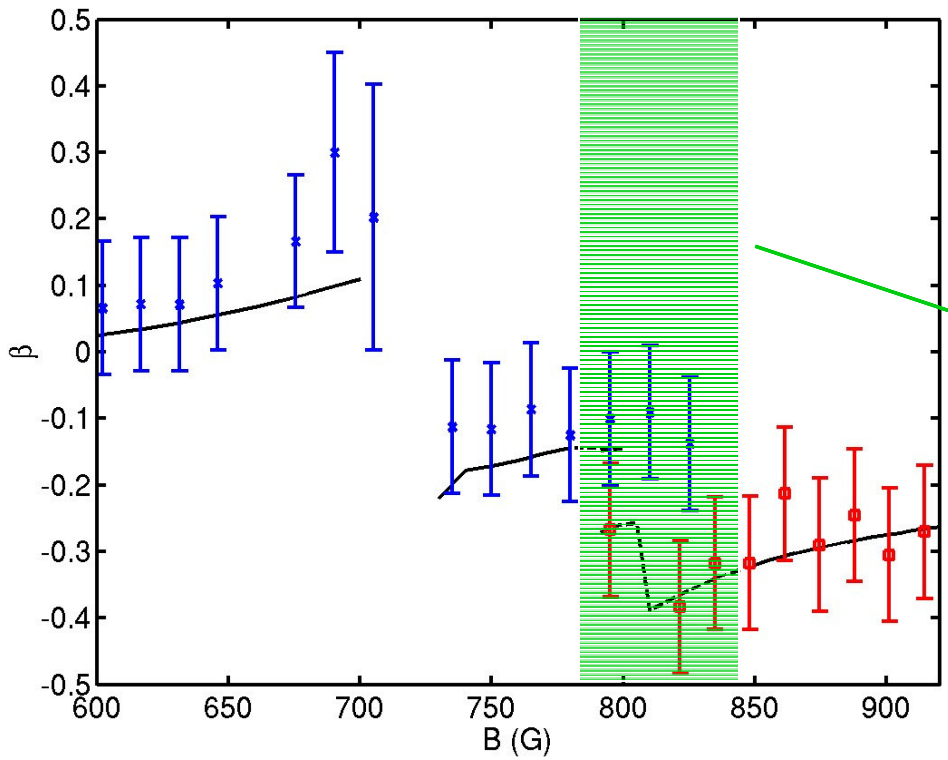


Compare with experimental shift

Interaction shift given by fractional difference of sound velocities: $\beta = \frac{v_{int}^2 - v_0^2}{v_0^2}$

$v_{int}^2 = (\partial P / \partial \rho)_s$ ➡ Sound velocity of atom-molecule mixture

v_0^2 ➡ Sudden switch-off interactions: free expansion with initial distribution and molecular relative momentum distribution



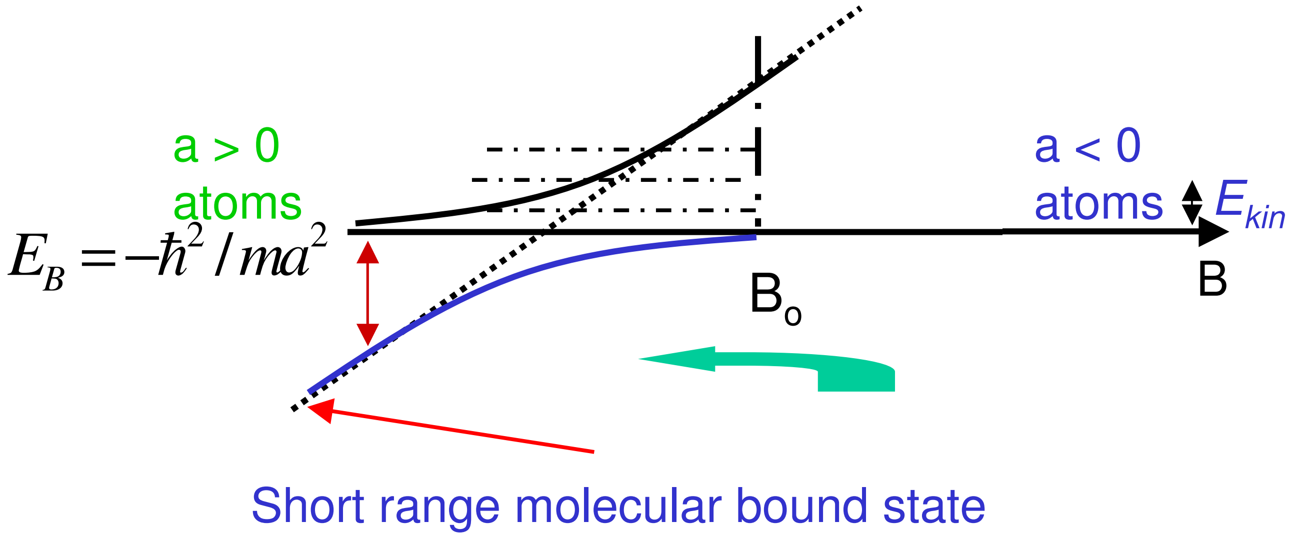
Reference: [Kokkelmans, Shlyapnikov, Salomon, cond-mat/0308384]

$n\,(a/2)^3 > 1$

Similar results energy shift for classical (Boltzmann) regime:
[Mueller and Ho, cond-mat/0306291]
[Chin and Grimm, 0309078]

Molecule formation: time dependent process

Proposed for bosons in 2000-2001:
Timmermans et al.,Verhaar et al., Julienne, Burnett et al.



Energetically favorable
to form weakly
bound molecules

If slow enough, adiabatic and reversible process: entropy is conserved

Recent experiments

With bosons:

^{85} Rb, JILA, Donley et al, 2002: coherent oscillations between a BEC and molecules
Explanation: Kokkelmans and Holland, PRL 89, 180401 (2002)

^{133}Cs, Innsbruck, Herbig et al, 2003: direct imaging of the molecules which separate from BEC via Stern and Gerlach expt

^{133}Cs, Stanford, Chin et al., 2003: spectroscopic detection of molecules

^{87}Rb, MPQ, Dürr et al., 2003: 1D trapping of molecules

But lifetime limitations: observed losses. Work at low density

With fermions:

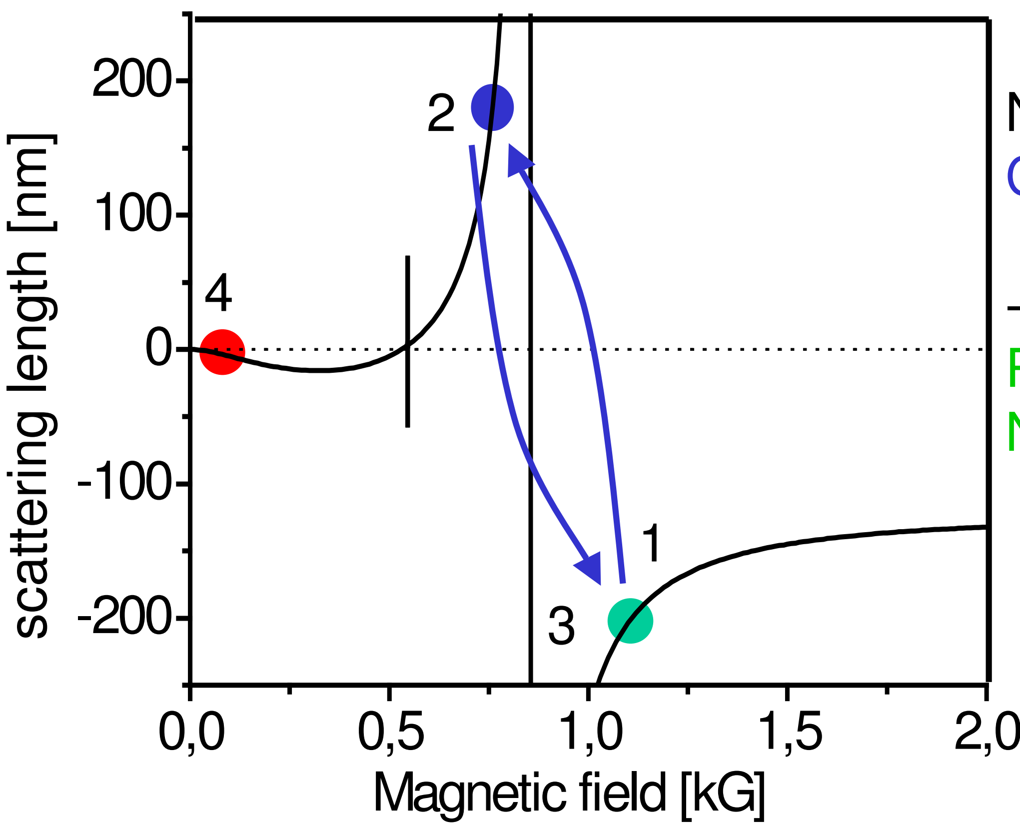
^{40}K, JILA, Regal et al., 2003: direct imaging via RF dissociation and Stern and Gerlach separation, measurement of binding energy and lifetime

^{6}Li, ENS, 2003, Cubizolles et al., 2003: observation of long lifetime (0.5 s); conversion efficiency 85%, $T/T_{BEC} \sim 2$

^{6}Li, Rice, Strecker et al., 2003: long lifetime

^{6}Li, Innsbruck, Selim et al., 2003: pure trapped molecular cloud, long lifetime

Time-dependent experiment at ENS: reversible formation of ultracold Li_2 molecules



N_1= 8 10^4 atoms initially @ (1)

Change magnetic field in 50 ms towards (2), where a is >0 and large

- Count atom number N_2 @ (2)

Return to 1 in 50 ms and count $N_{round\text{-}trip}=N_3$

-Detection @ (4)

Abruptly switch-off B field in 20 μs @ B=0, a=0

Only free atoms are detected:

Two components:

atoms and broken molecules

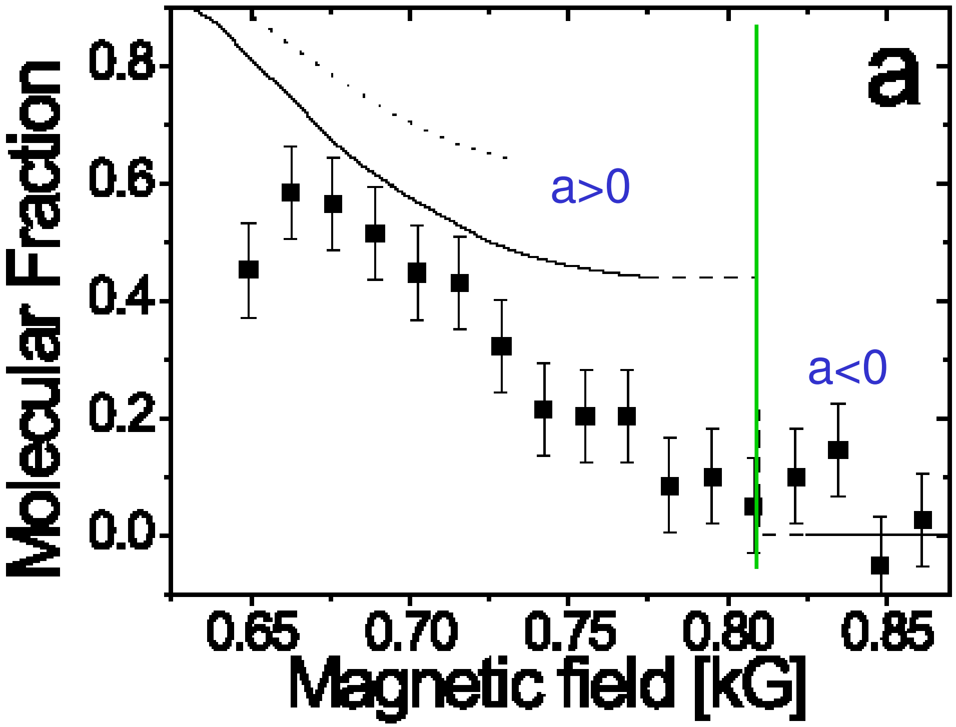
Importance of dB/dt

Binding energy of molecule

$$E_B = \hbar^2 / ma^2$$

How many molecules ?

Fraction of atoms in a molecule:
$(N_3-N_2)/N_3$



Compare

$$E_B \; and \; \hbar/\tau_{switch-off}$$

Transition zone

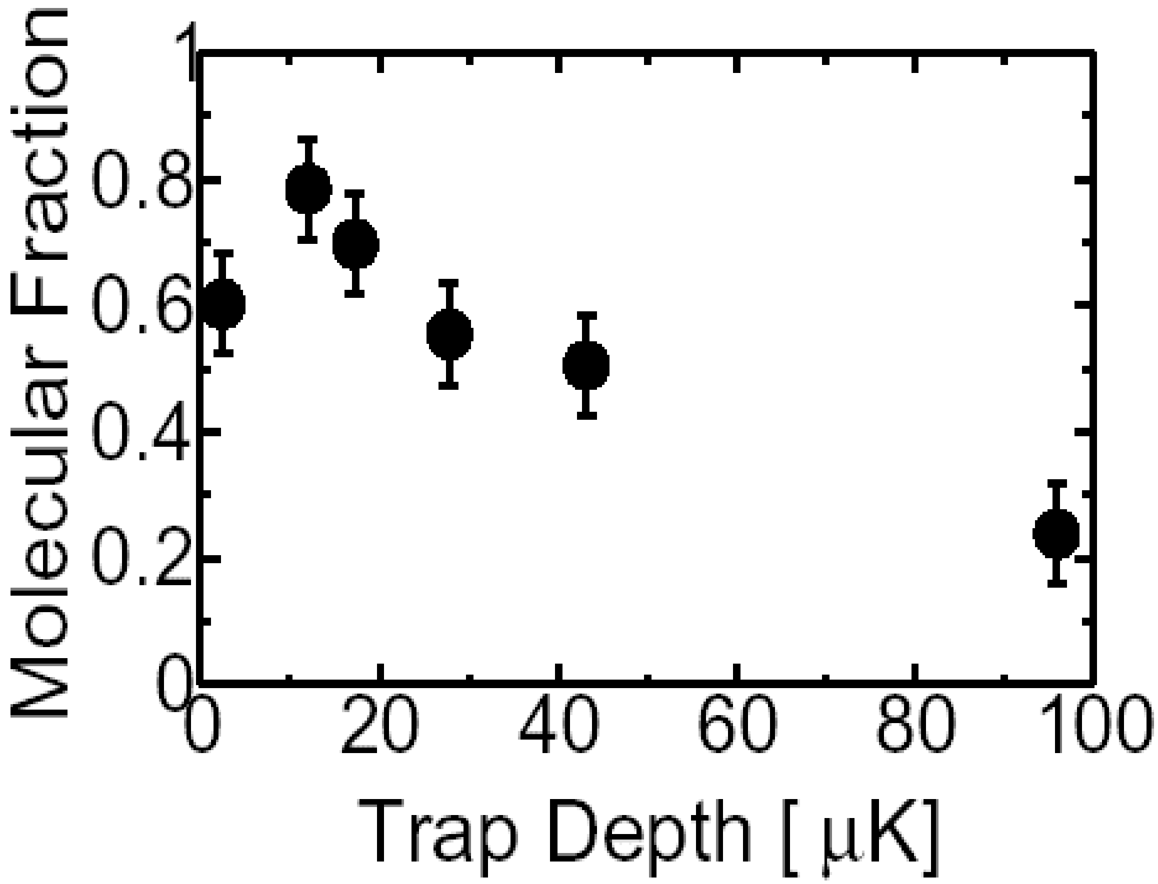
Below 750 G, molecules adiabatically follow the change of B field and are not detected

$a \rightarrow 0 \quad and \quad \hbar^2/ma^2$ increases

Adiabaticity: $\frac{1}{E_B}\frac{dE_B}{dt} << \frac{E_B}{\hbar}$

At peak : 3 10^4 cold bosonic molecules

Efficiency of molecule formation influence of trap depth

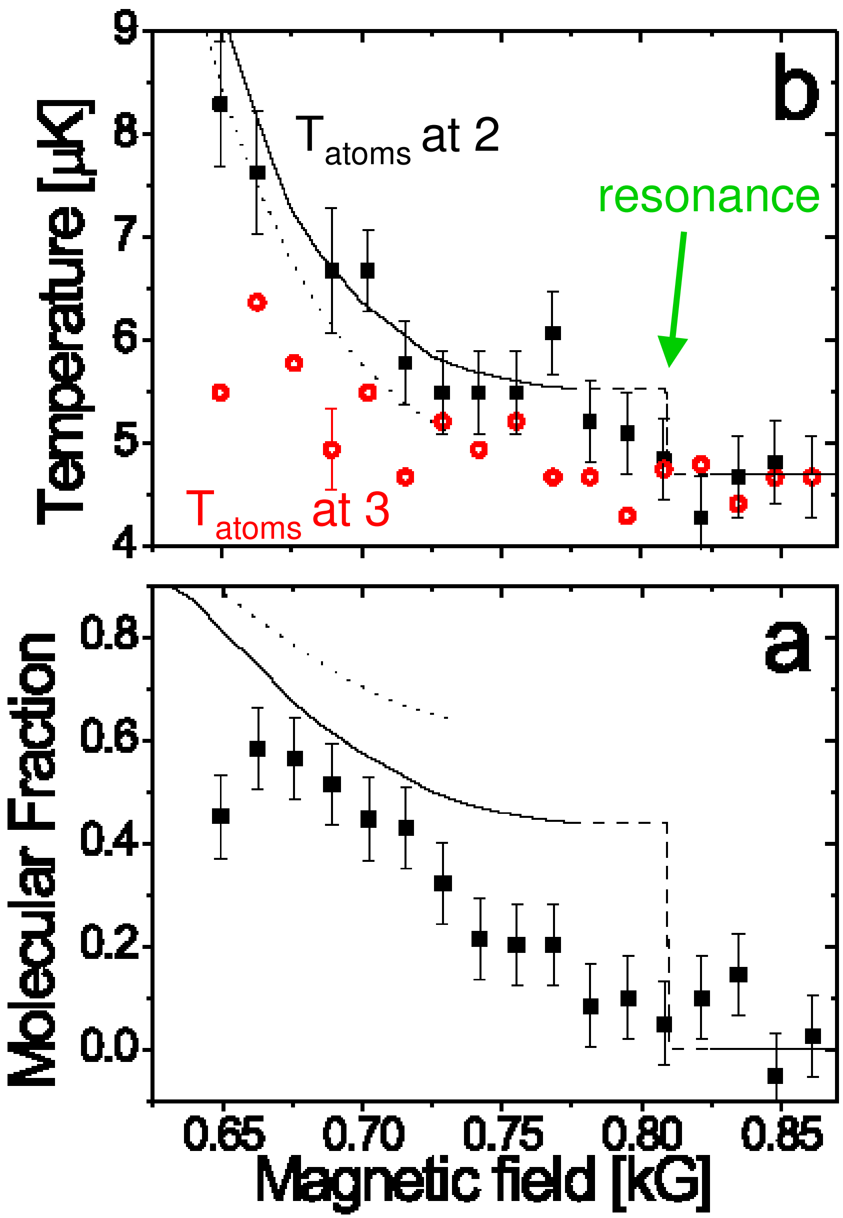


At peak : 3 10^4 cold bosonic molecules
Critical temperature for molecules: T_C= 3.5 µK
Factor 2 to gain for BEC of molecules

Most efficient when:
T/T_F is small and
T/E_B is small.
The colder the better !

At B= 689 G
a = 78 nm
E_B= 12 µK
At peak:
U_{trap}/k_B= 10 µK
$\omega=2\pi$ 1.4 kHz
T_F= 5 µK
T= 6.7 µK
$n_{0m}\sim 4\ 10^{13}$ molec/cm^3

Temperature of atom-molecule mixture



Atoms → Molecules : heating

The molecule binding energy is transferred to external motion

Molecules → atoms : cooling

Reverse process

Very little heating after 100 ms round-trip reversible process:

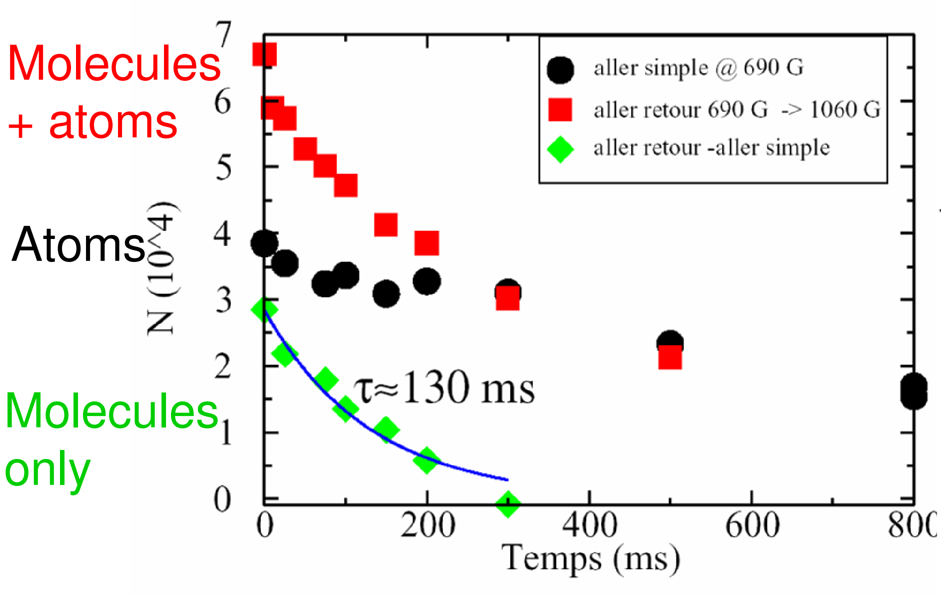
entropy is nearly conserved

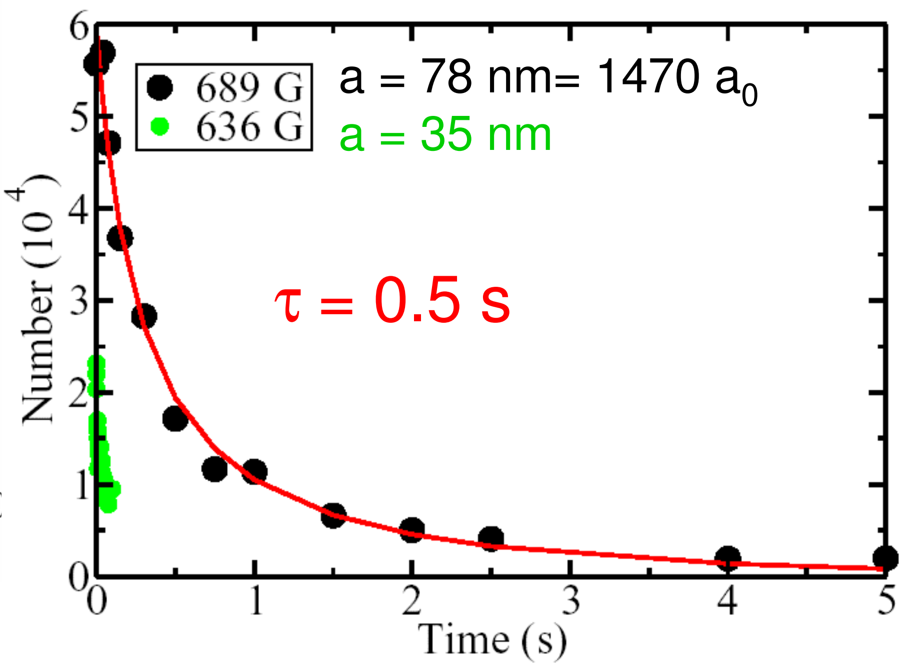
Critical temperature for molecules:

T_C= 3.5 μK

Factor 2 to gain for BEC of molecules

Lifetime of trapped molecules





Trapped molecules survive very long !

Mostly molecule-molecule decay

as Initial atom number is 15%

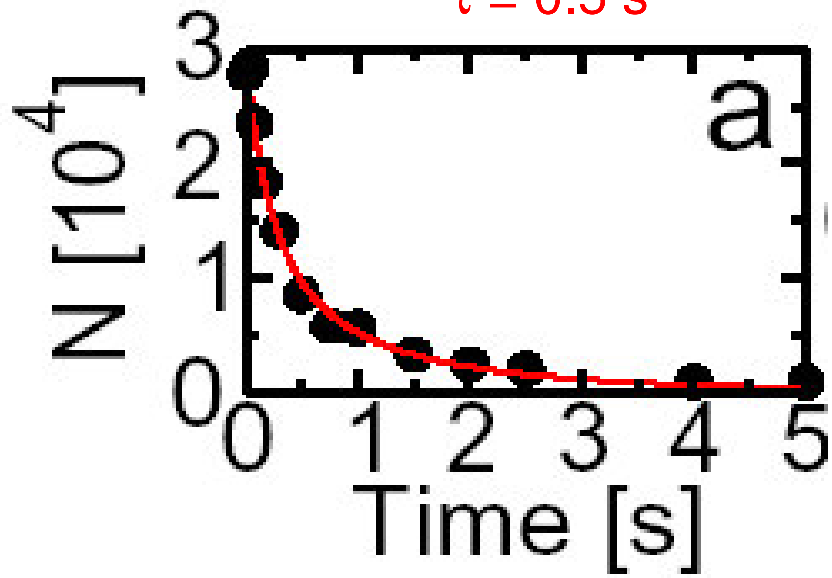
$$\frac{dN_m}{dt} = -\alpha N_m - \frac{\beta n_0}{\sqrt{8}} N_m$$

Very different from the case of dimers of bosons

Nonlinear decay of molecules:
well fitted by two-body inelastic process
Temperature remains nearly constant

Strong dependence molecular decay upon *a*

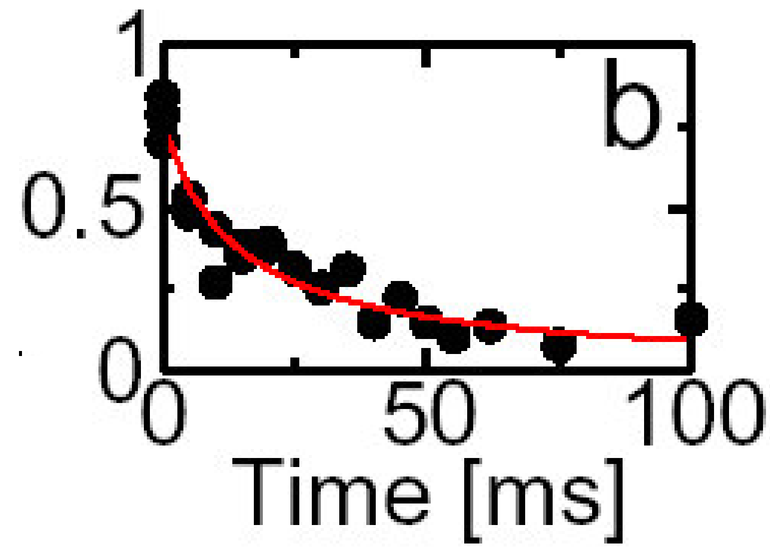
τ = 0.5 s



a = 78 nm

Loss Rate: $\beta \sim 2.4\ 10^{-13}\ cm^3/s$

τ = 20 ms



a = 35 nm

The larger is a, the longer the lifetime

Role of Fermi statistics

$G \sim 1/a^s$ with s = 2.55 for dimer-dimer collisions

3.33 for dimer-atom coll. [Petrov, Salomon, Shlyapnikov]

Towards molecular BEC

At $B = 689$ G, $a = 78$ nm
$N_{molecule} = 1.8\ 10^4$
Peak density: $n_{0m} \sim 4\ 10^{13}$ mol/cm^3

Binding energy: $E_B = 12\ \mu K$, $T_F = 11\ \mu K$
$U_{trap}/k_B = 60\ \mu K$
$\omega^3 = (2\pi)^3$ 2.2 kHz x 4.6 kHz x 5.1 kHz

For large a: $a_{dimer\text{-}dimer} = a_{dd} = 0.6\ a_{at}$ [Petrov, Salomon, Shlyapnikov]
$N_{0m} a_{dd}^3 = 5\text{x}\ 10^{-3} << 1$ dilute regime for molecules
Tc is only sligthly modified by dimer-dimer interactions
$T_c = 3.5\ \mu K$
$T_{mol} = 6.7\ \mu K$
Only a factor 2 to gain for BEC of molecules

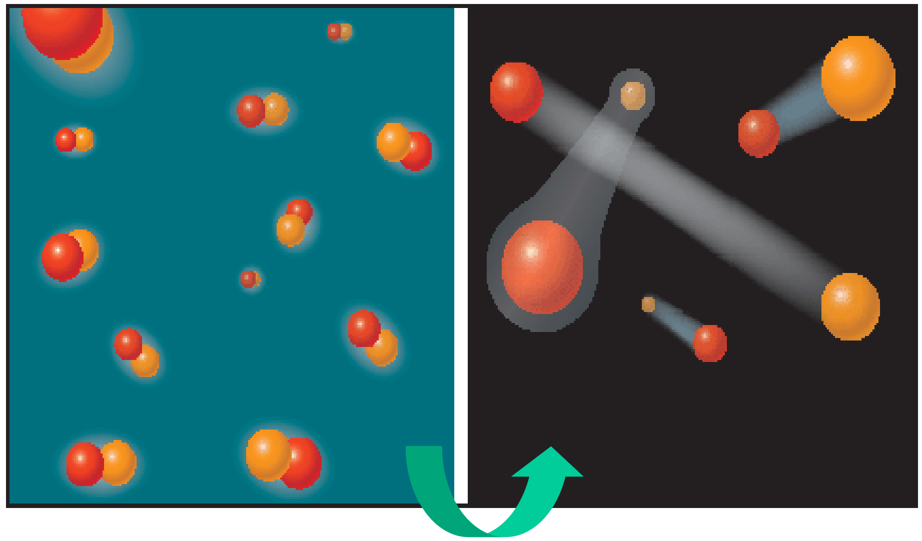
Elastic collision time: $1/n_{mol} 8\pi a_{dd}^2 v_{mol} \sim 3\ \mu s << 0.5$ s molecule lifetime
Evaporative cooling of molecules should be very efficient

➡ Molecular BEC has now been observed
at JILA and Innsbruck!! [Greiner et al, cond-mat/0311172]

Creation of Fermi superfluid

Produce BEC of molecules with $T/T_{BEC} << 1$
Cross the Feshbach resonance again adiabatically towards $a < 0$

$a > 0$



$a < 0$

Produces a deeply degenerate Fermi gas with $T=0.01\ T_F$ or lower !
[L. Carr et al,, cond-mat/0308306]
Unambiguous detection of superfluid required !!

Study crossover Condensate of molecules/ superfluid Fermi gas
(Randeria, Nozières, Ohashi et al., Milstein et al.)
Mott transition for fermions in an optical lattice (Hoffstetter et al., 2002)
Strongly correlated fermions domain is very vast !

Conclusions/perspectives

- Strong interactions with Feshbach resonances lead to interesting physics with atoms and molecules
- Molecules play crucial role in understanding of interaction energy in resonance Fermi systems
- We can convert more than 80% of atoms into molecules
- Lifetime molecules strongly dependent on a, can be of order 1 second
- Prospects for molecular BEC are good (has recently been realized)
- Realizing BCS via BEC of molecules
- Study of crossover BEC-BCS