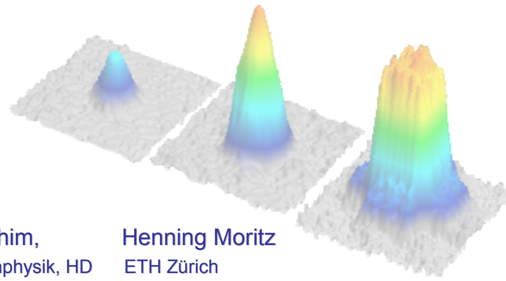
Creating new states of matter: Experiments with ultra-cold Fermi gases



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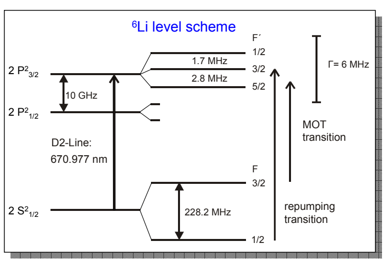
Outline

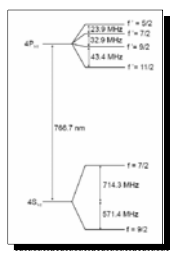
- ***Cooling (difficulties) with Fermions***
- ***Scattering***
- ***Concept of Feshbach resonances***
- ***Ultracold molecules***
- ***Making a BEC of molecules***

Fermionic Alkalis

Only ^{6}Li and ^{40}K stable fermions

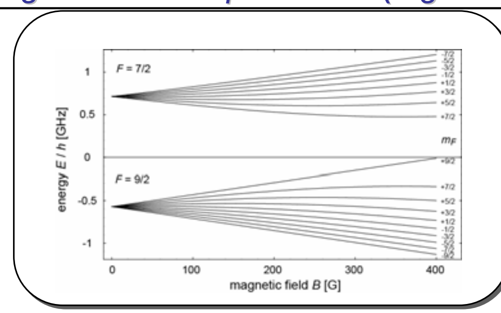


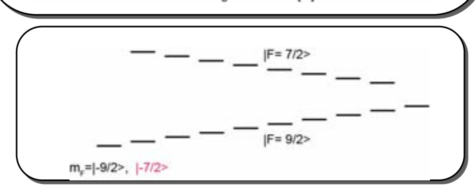
^{6}Li, rel. isotope abundancy in Li=7%
I=1, melting point ~180°C



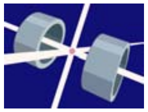
^{40}K, abundancy=0.01%
I=4, melting point ~60°C

Magnetic field dependence (e.g. ^{40}K)



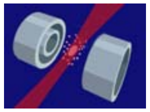


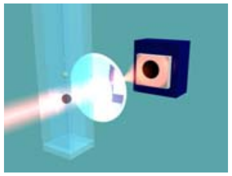
Cooling Methods



Laser cooling
~0.1 mK
~ 10^9 atoms

Evaporative cooling
in magnetic trap or dipole trap
T< 100 nK< T_F, 10^6 atoms





Absorption imaging

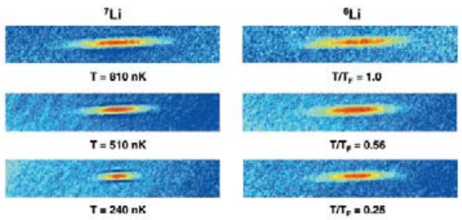
Ideal Fermi Gas in an harmonic trap

$$
\begin{aligned}
f(\varepsilon) &= \frac{1}{\exp(\frac{\varepsilon-\mu}{kT}) - 1} \\
D(\varepsilon) &= \frac{\varepsilon^2}{2(\hbar\bar{\omega})^3} \quad \text{3D harmonic oscillator} \\
N &= \int_0^\infty D(\varepsilon) f(\varepsilon) \\
\Rightarrow E_F &= k_B T_F = \hbar\omega(6N)^{1/3} \quad \sim 0.1 - 1\mu K
\end{aligned}
$$

$$k_F = \sqrt{2mE_F} = (6\pi^2\, n_0)^{1/3}$$
$$n_0^{-1/3} \approx 0.3 - 1\mu m$$

$$
\begin{aligned}
R_F &= a_{ho}(48N)^{1/6} \\
&\approx 10 - 100\mu m
\end{aligned}
$$

Sympathetic Cooling

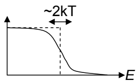


Bosons *Fermions*

BEC has no entropy, only thermal atoms
⟹ heat capacity vanishes for T→0

$$N_{th}, C_{BEC} \sim \left(\frac{T}{T_C}\right)^3$$

For Fermions

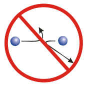


$$C_{Fermi} \sim \frac{T}{T_F}$$

A. G. Truscott, K. E. Strecker, W. I. McAlexander,G. B. Partridge, R. G. Hulet, Science 291, 2570 (2001);

The difficulty in cooling fermions

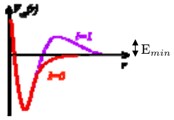
Collisions are required for cooling, but at low T spin polarised fermions stop colliding



Two particle wavefunction: $\Psi_{1,2} = \chi_{\text{spin}} \cdot \psi_{\text{space}}$

Partial wave expansion: $\psi_{\text{space}} = \psi_{\text{s-wave}} + \psi_{\text{p-wave}}$

symmetric ***anti-symmetric***

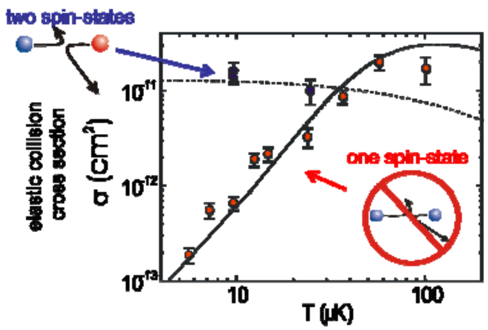


Only s-wave collisions energetically possible
⇒ χ_{spin} antisymmetric ⇒ spin mixture

$$
\begin{aligned}
mv \cdot r_{eff} &= \hbar \\
\Rightarrow E_{min} &= 1/2mv^2 = \frac{\hbar^2}{mr_{eff}^2} \\
&\approx 10 - 100\mu K
\end{aligned}
$$

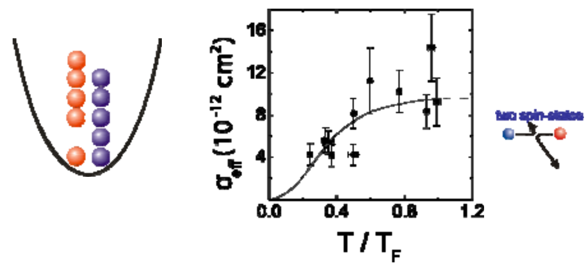
$$
\begin{aligned}
\psi(r) &\sim e^{ikr} + f(k,\theta)\frac{e^{ikr}}{r} \\
\sigma &= \int_\Omega |f(k,\theta)|^2 d\Omega \\
\sigma_l &\propto k^{2l}; \quad \sigma_s = 4\pi a^2
\end{aligned}
$$

Collision cross-sections



B. DeMarco *et al.*, PRL 82, 4208 (1999)

Pauli Blocking of Collisions



Collisions die out at low T
Cooling difficult! Limit T~ 20% T_F

B. deMarco, S. Papp, D. S. Jin, PRL 86, 5409 (2001);

Condition for Superfluidity

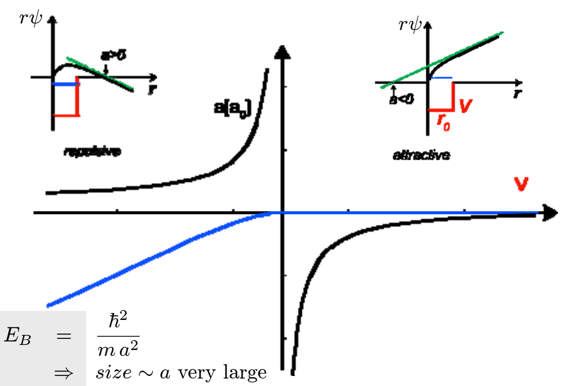
$$T_{BCS} \approx 0.2\, T_F \exp\left(-\frac{\pi}{2k_F|a|}\right)$$

$$\begin{aligned} a < 0 \quad & \Rightarrow \text{attractive interaction} \\ k_F \quad & \propto n^{1/3} \sim 1/\text{mean distance} \\ k \cdot |a| \quad & < 1 \Rightarrow T_{BCS} \ll T_F \end{aligned}$$

Still a long way to go:

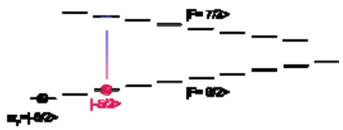
Interaction strength ~ a an important parameter:
- ***increases T_C***
- ***makes cooling more efficient***

Scattering length and bound states



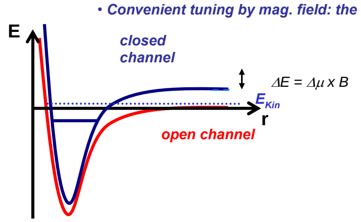
$$\begin{aligned} E_B &= \frac{\hbar^2}{m\,a^2} \\ &\Rightarrow size \sim a \text{ very large} \end{aligned}$$

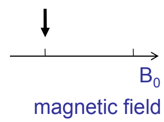
Feshbach resonance



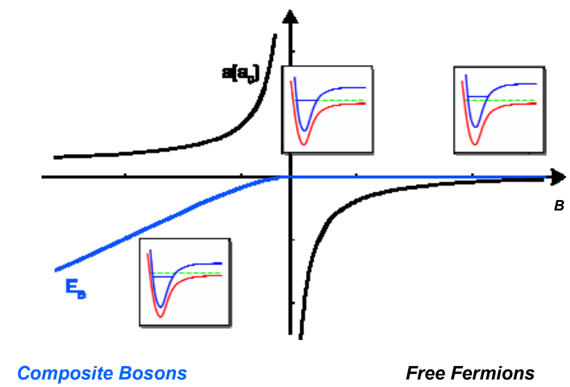
Interaction between spins of atoms at close distance may couple states m_{tot} conserved

- *Tune bound state of a "closed channel" into degeneracy with the continuum*
- *Convenient tuning by mag. field: the two states have different mag. moment*





Scattering length and bound states



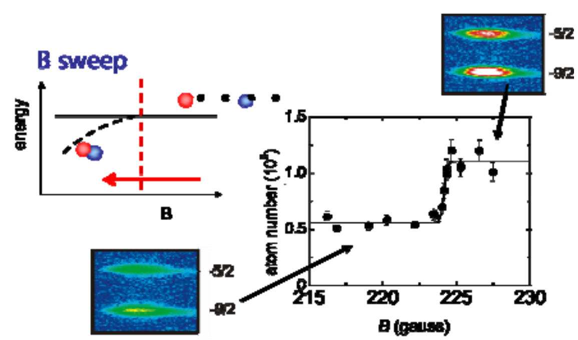
How to see the molecules?

Molecules have different optical transition frequency

Why: *If on constituent is excited, its dipole couples resonantly polarises the other ⇒ Potential between two dipoles ~R^{-3}, R molecule size*

$$\text{Shift} \approx \hbar\Gamma \left(\frac{\lambda}{2\pi R}\right)^3$$

How to see the molecules?



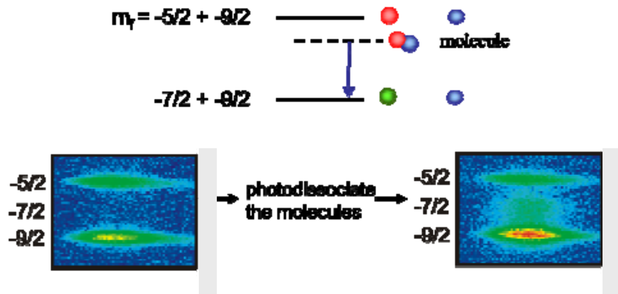
C. A. Regal *et al.*, Nature 424, 47 (2003).

Motivation: E. A. Donley et al., *Nature* 417, 529 (2002)

RF Photodissociation

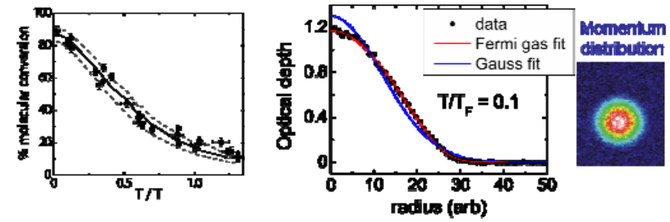
rf photodissociation

Apply rf near the atomic $m_f=-5/2$ to $m_f=-7/2$ transition



C. A. Regal *et al.*, Nature 424, 47 (2003).

Molecule Fraction and Temperature



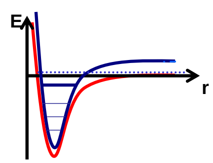
$$
\begin{aligned}
OD(x,y) &= OD_0 \cdot Li_2(-\zeta\, e^{-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}})/Li_2(-\zeta) \\
\zeta &= \exp(-T/T_F) \qquad Li_n(x) = \sum_{k=1}^{\infty} x^k/k^n
\end{aligned}
$$

E. Hodby et al. PRL 94, 120402 (2005);

From Jin Group, JILA, Boulder

Stability of molecules

Fermionic molecules are surprisingly stable
Bosonic not



Pauli Blocking prevents the atoms from coming close

$$\text{Decay rate} \sim \left(\frac{\text{Size of Potential}}{\text{Molecule size}}\right)^3 \sim a^{-3}$$

Short summary

- ***The bad news:***
  - *Sympathetic colling difficult,* — *because heat capacity of BEC vanishes*
  - *Direct cooling of Fermions:* — *Only s-wave collisions at low T*
    Become Pauli blocked at low T

End of 2001

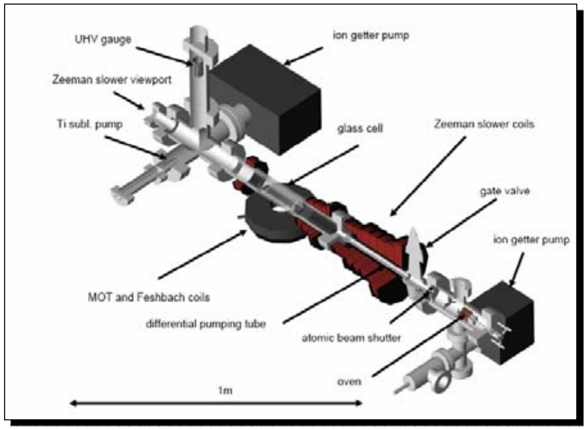
- ***The good news***
  - T_c *and rethermalisation depends on a*
  - *a tunable via Feshbach resonance*
  - *Two fermions transform into one composite Boson across resonance*
  - *molecules long lived*

Spring of 2003

Two Solutions

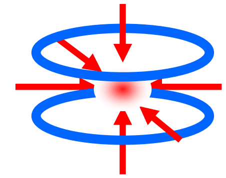
Cool very hard with Fermions — *Cooling on the Bosonic side*

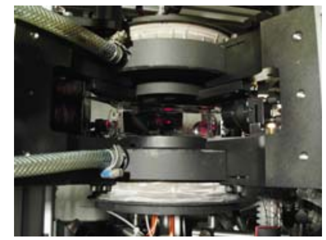
A machine to produce cold Fermions



Experimental procedure

- Magnetooptical Trap

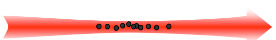




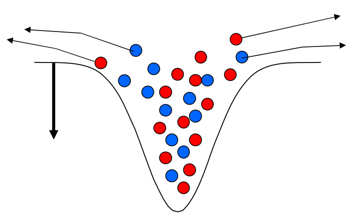
Optical dipole traps

Dipole potential:

$$U_{dip} = -\frac{1}{2}\langle p \cdot E \rangle$$

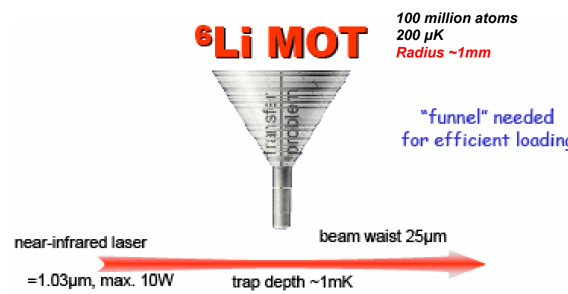


focused beam trap



cooling performed by evaporation:
simply lower the trap power!

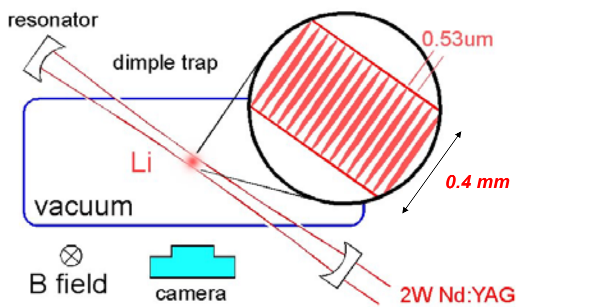
Different sizes



Funnel

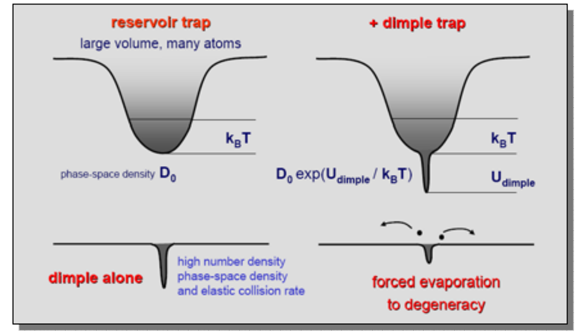
Use resonant enhancement in an optical resonantor:

→ ~130-fold enhancement
→ Deep and large volume trap

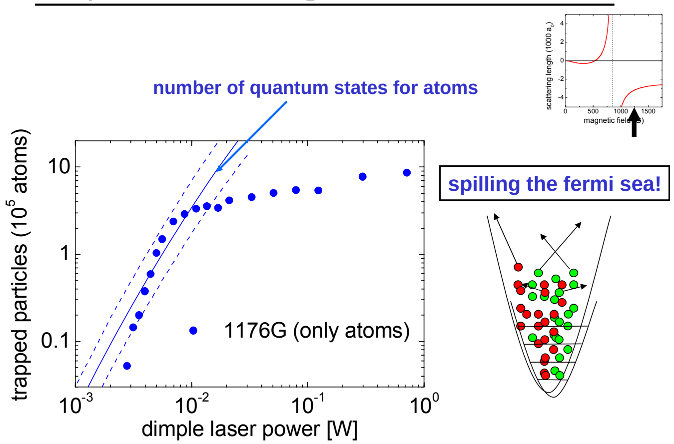


Mosk *et al.*, Opt. Lett 26, 1837-1839 (2001)

Dimple Potential

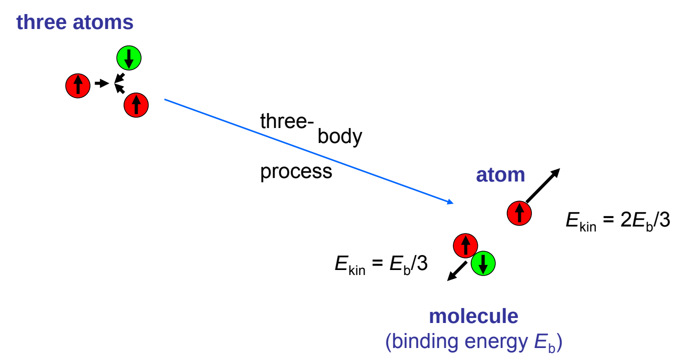


Evaporative cooling results



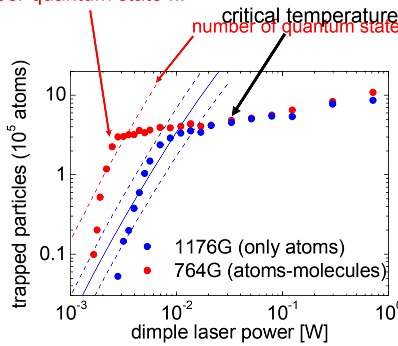
Three body recombination

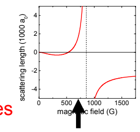
…create molecules by collisions!



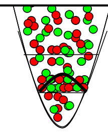
Evaporative cooling results

…now @ field where a weakly bound molecular state exists!





- quantum degeneracy !
- very long lifetime (~40s)
  → thermalization

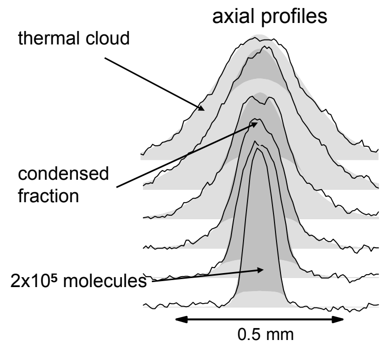


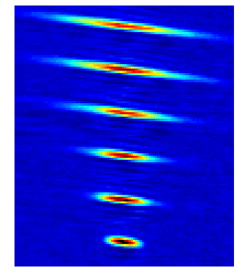
S. Jochim *et al.*, Science **302**, 2101 (2003)

⇨ These molecules must form a BEC!

Bose-Einstein condensation

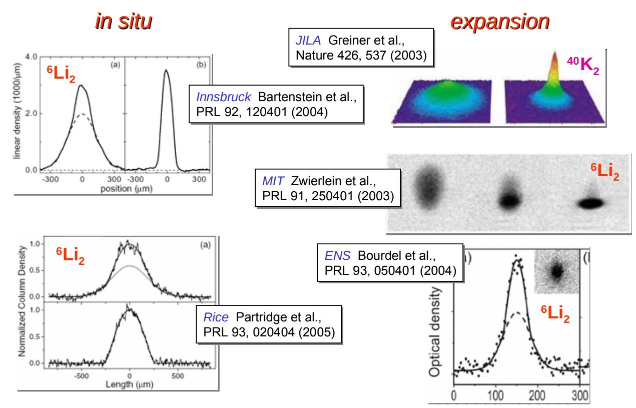
In-situ images of the molecules





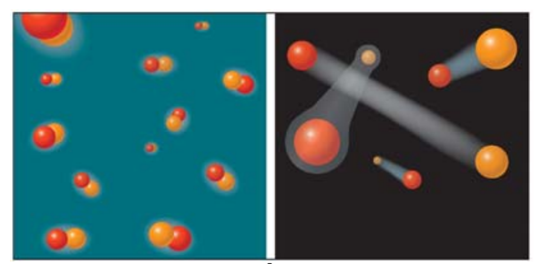
- molecular BEC was simultaneously achieved at JILA, Boulder

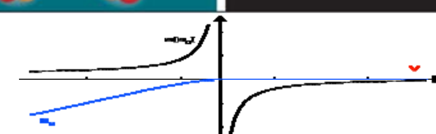
Molecular BEC gallery



BEC – BCS crossover

molecules **strong coupling** | *crossover* | ***Cooper pairs*** **weak coupling**





drawing from Cho, Science **301**, 750 (2003)