Exploring the width of Feshbach resonances in ^{6}Li-^{40}K mixtures

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^{6}Li-^{40}K mixture - why?

Combines the possibilities of the ^{6}Li and ^{40}K systems with new properties of the mixture:

- Long-range mediated interactions ($1/r^2$)
- Unconventional pairing of fermions
  - unequal mass ($m_1 \neq m_2$)
  - mediated pairing (Efimov)
  - formation of long-lived heteronuclear (dipolar) molecules
- Important analogies with solid-state physics (optical lattices)
  - strongly-interacting superfluids (high-Tc and quark-gluon plasma)
  - quantum magnetism (magnetic order, Kondo problem,...)
- Precision determination of molecular potentials

We search for a *large tunable scattering length*

(we focus on Feshbach tunable resonance)

Degeneracy in Fermi gases first observed in 1999 at JILA in ^{40}K

outline

- Feshbach phenomenology
- Asymptotic Bound-state Model (ABM)
- Experimental
- Width measurement
- Comparison with new ABM-results
- Conclusion

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scattering: length scales

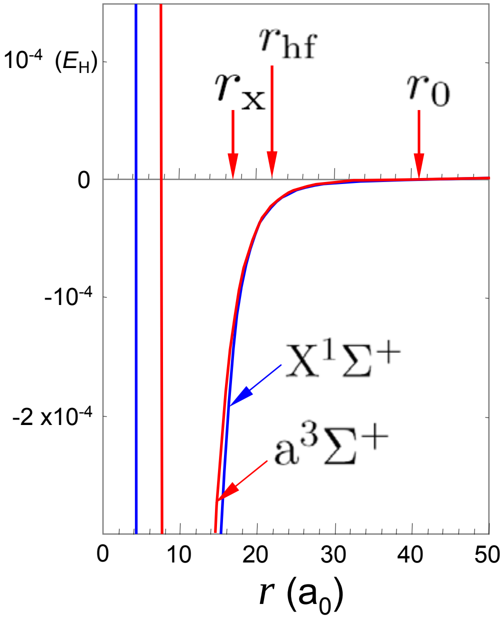
Van der Waals range: $r_0 \simeq \left(2\mu C_6/\hbar^2\right)^{1/4}$

dilute limit: $n r_0^3 \ll 1$

ultracold: $k r_0 \ll 1$

hyperfine radius: r_{hf}

exchange radius: r_{x}



phase shift:

effective range

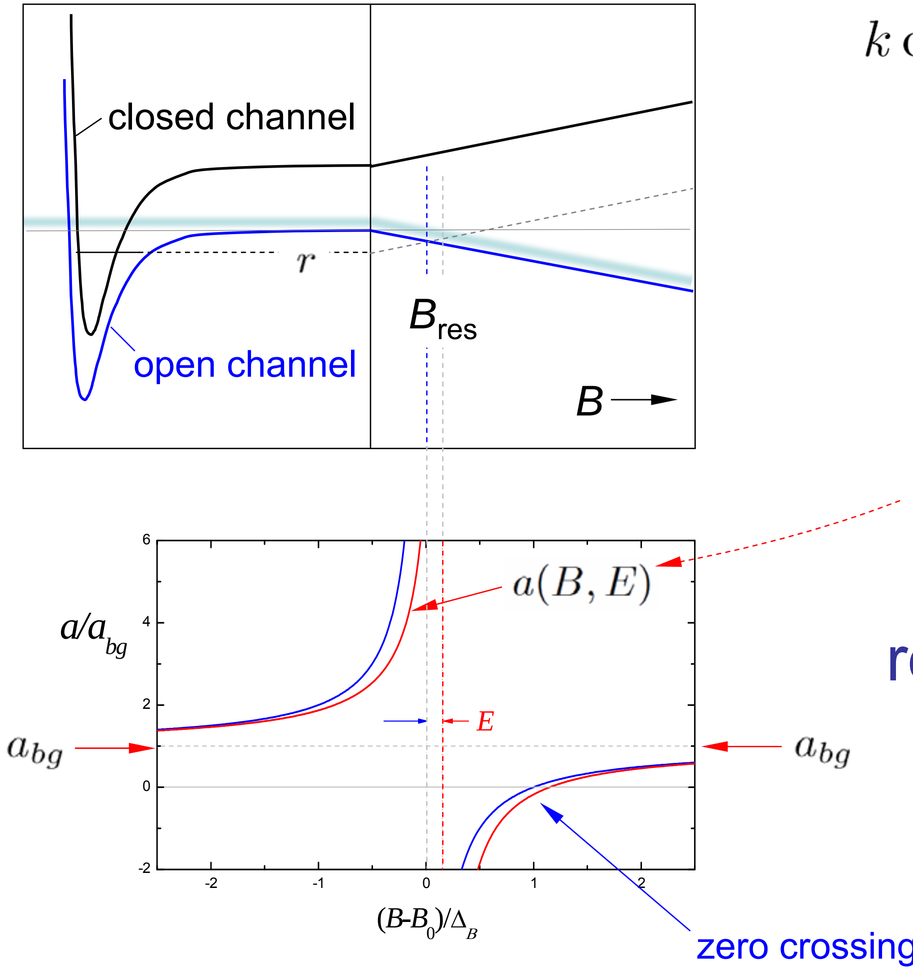
$$k \cot \eta_0 = -\frac{1}{a} + \tfrac{1}{2} k^2 r_e$$

scattering length

$$f_0 = \frac{1}{k \cot \eta_0 - ik}$$

$$\sigma = 4\pi \frac{1}{k^2 \cot \eta_0 + k^2}$$

Feshbach scattering length



$$k\cot\eta_0 = -\frac{1}{a_{bg}(B,k) - a_{res}(B,k)} + \cdots$$

open channel (background)

closed channel (resonance)

$$a(B,E) = a_{bg} + \frac{a_{bg}\mu_{\rm rel}\Delta_B}{E - \mu_{\rm rel}(B - B_0)}$$

resonance strength parameter:

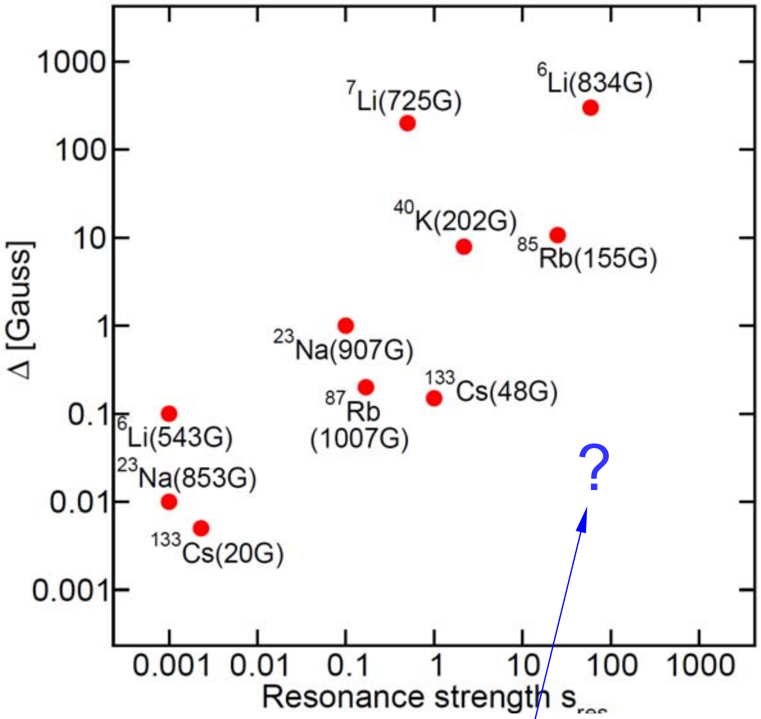
$$s_{res} = \frac{a_{bg}\mu_{\rm rel}\Delta_B}{r_0\left(\hbar^2/2\mu r_0^2\right)}$$

resonance strengths

Innsbruck measurements:[1]

$$s_{res} = \frac{\overbrace{a_{bg}\mu_{\mathrm{rel}}}\Delta_B}{r_0\left(\hbar^2/2\mu r_0^2\right)}$$

this work



^{6}Li-^{40}K

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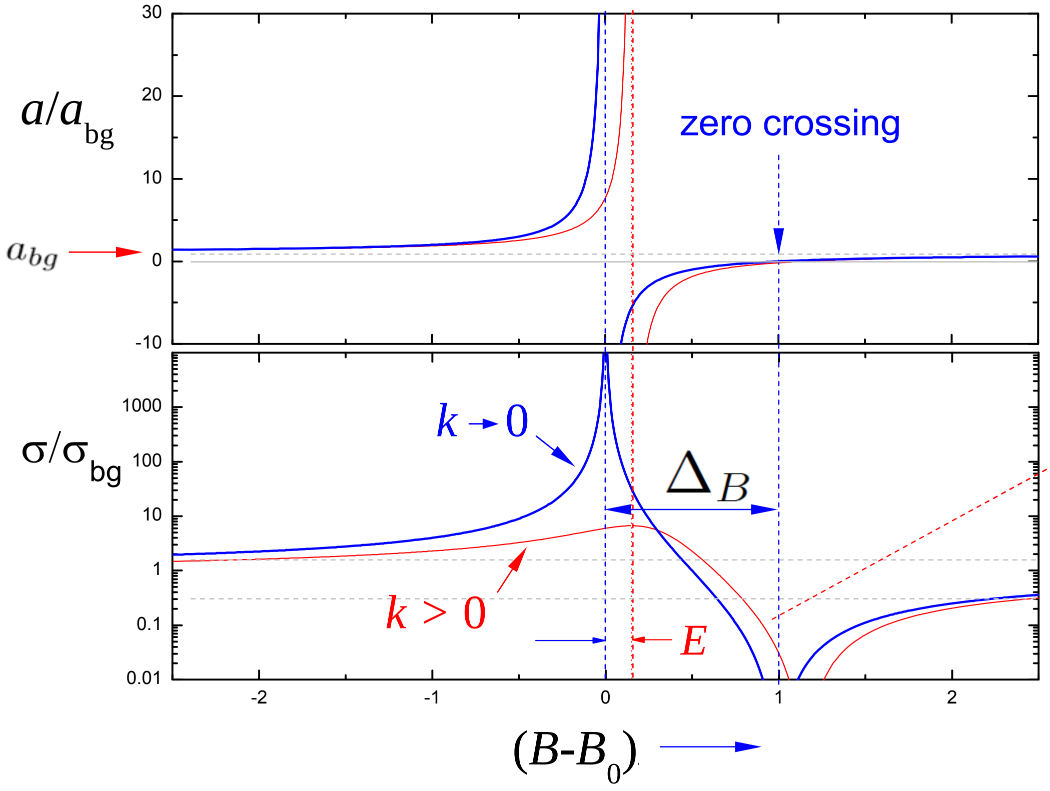
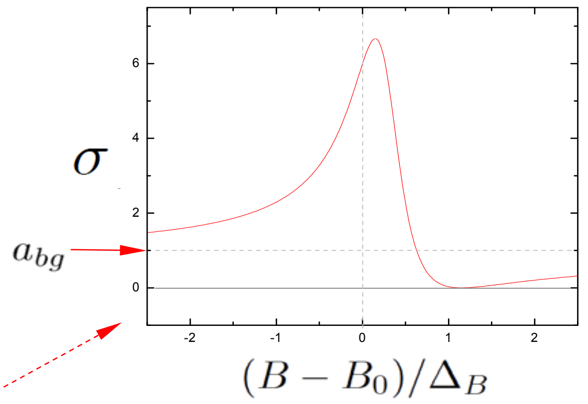
[1] E. Wille et al., Phys. Rev. Lett. 100 (2008) 053201

Other work on Li-K (molecules):
A.C.-Voigt et al., Phys. Rev. Lett. 102 (2009) 020405
Experiments (6Li and/or 40K): JILA, LENS, Innsbruck, MIT, ENS, Rice, Duke, ETH, Hamburg, Tübingen, Münich, etc.…
Spectroscopy: E. Tiemann et al., Phys. Rev. A 79, 042716 (2009)

width from: *elastic cross section*





$$\sigma = 4\pi \frac{\left[a_{bg} - a_{res}\right]^2}{1 + k^2 \left[a_{bg} - a_{res}\right]^2}$$

on resonance ($a \to \infty$): *unitarity limited scattering* ($\sigma = \dfrac{4\pi}{k^2}$)

for $a_{bg} \neq 0$ asymmetric line shape: *Fano profile*

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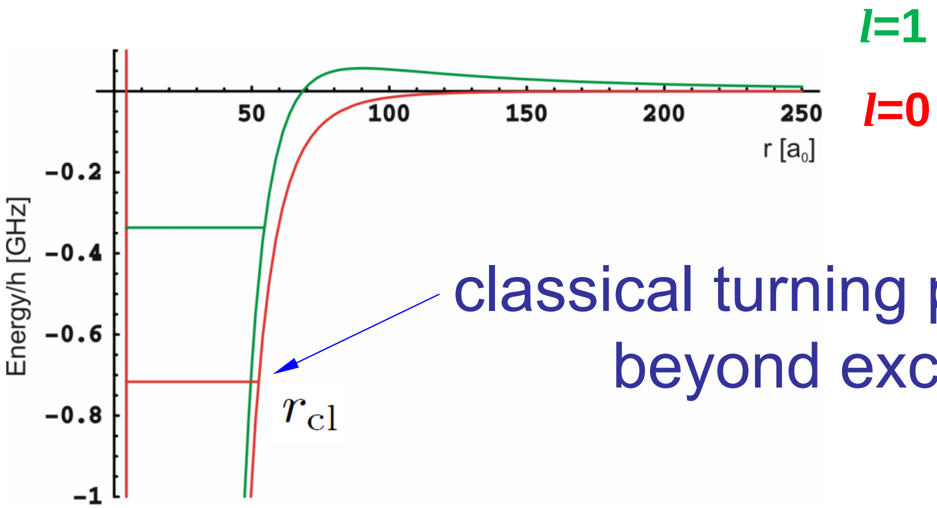
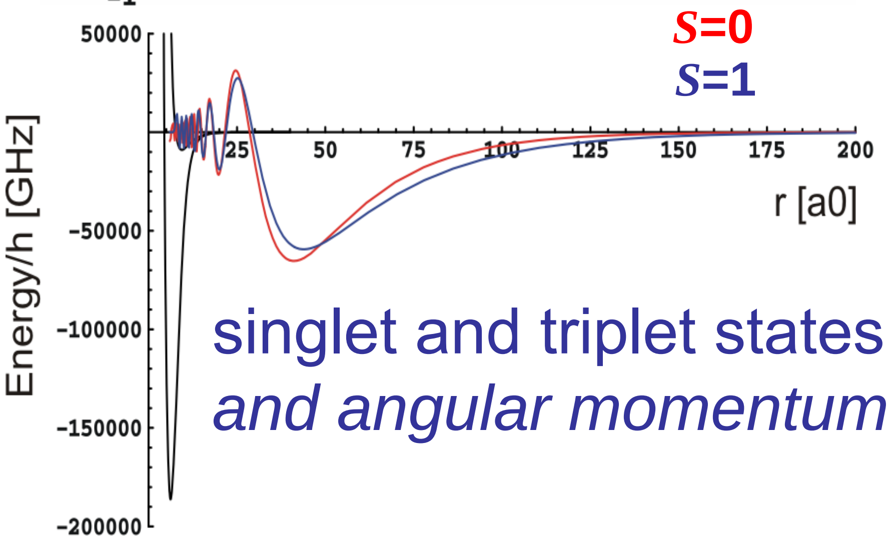
asymptotically bound states



classical turning point
beyond exchange radius ($r_{\mathrm{cl}} > r_{\mathrm{x}}$)



$$\langle R^{S=1}_{v',l} | R^{S=0}_{v,l} \rangle \simeq 1$$

singlet and triplet states *with the same binding energy and angular momentum* have large Franck-Condon overlap

ABM-analysis

Asymptotic Bound-state Model (ABM) for analysis of Feshbach resonances

$$\mathcal{H} = \mathcal{H}_{\mathrm{rel}} + \mathcal{H}_Z + \mathcal{H}_{\mathrm{hf}}^{+} + \mathcal{H}_{\mathrm{hf}}^{-}$$

conserving exchanging

$\mathbf{S} = \mathbf{s}_1 + \mathbf{s}_2$

$$\mathcal{H}_Z = \gamma_e \mathbf{S} \cdot \mathbf{B} - \gamma_1 \mathbf{i}_1 \cdot \mathbf{B} - \gamma_2 \mathbf{i}_2 \cdot \mathbf{B}$$

$$\mathcal{H}_{\mathrm{rel}} = \frac{p_r^2}{2\mu} + \frac{l\,(l+1)\,\hbar^2}{2\mu r^2} + V_s(r) + J(r)S$$

$$\mathcal{H}_{\mathrm{hf}} = \left(a_{\mathrm{hf}1}/\hbar^2\right) \mathbf{i}_1 \cdot \mathbf{s}_1 + \left(a_{\mathrm{hf}2}/\hbar^2\right) \mathbf{i}_2 \cdot \mathbf{s}_2$$

diagonalize hamiltonian for given l and M_F

ABM-diagonalization

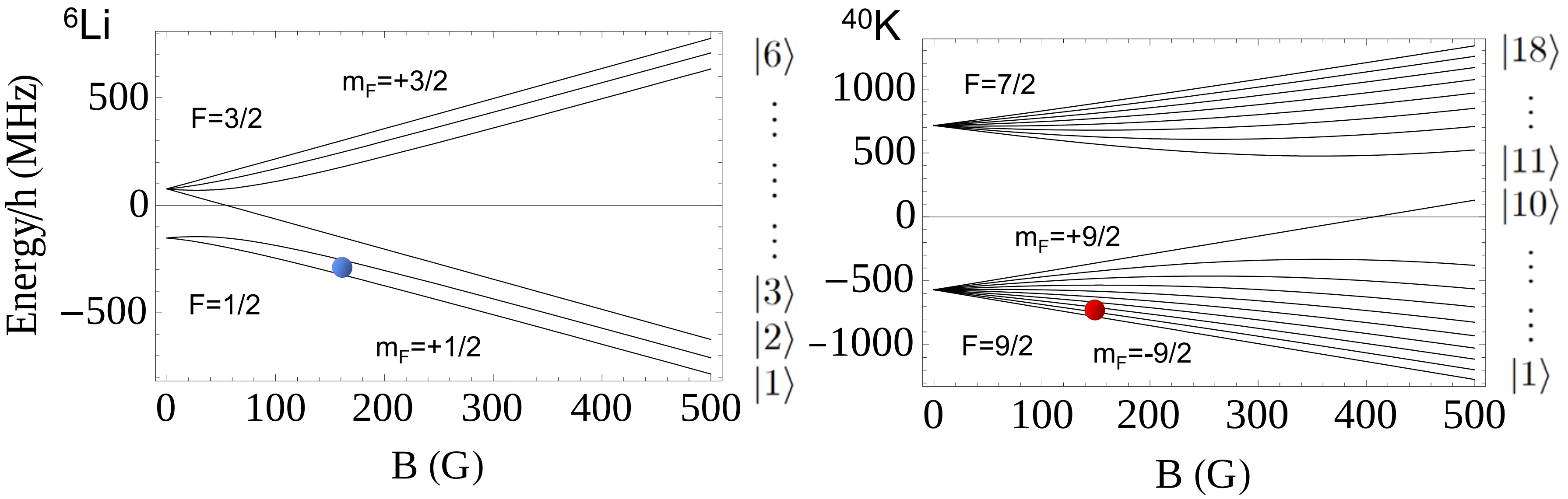
diagonalization in singlet-triplet basis

$$\left| \langle S', M'_S, m'_1, m'_2 | \langle R_l^{S'} | \mathcal{H} - E \left| R_l^S \right\rangle | S, M_S, m_1, m_2 \rangle \right| = 0.$$

$$\left| {}_{l,v'}\langle S', M'_S, m'_1, m'_2 | \mathcal{H}_Z + \underbrace{\mathcal{H}_{\rm hf}}_{\mathcal{H}^+_{\rm hf} + \underbrace{\langle R^{S'}_{v',l} | R^S_{v,l} \rangle}_{= 1} \mathcal{H}^-_{\rm hf}} + \varepsilon^S_{v,l} - E \, | S, M_S, m_1, m_2 \rangle_{l,v} \right| = 0$$

binding energies of ABM states in singlet and triplet potentials used as fitting parameters

hyperfine structures



special for mixtures with ^{40}K:

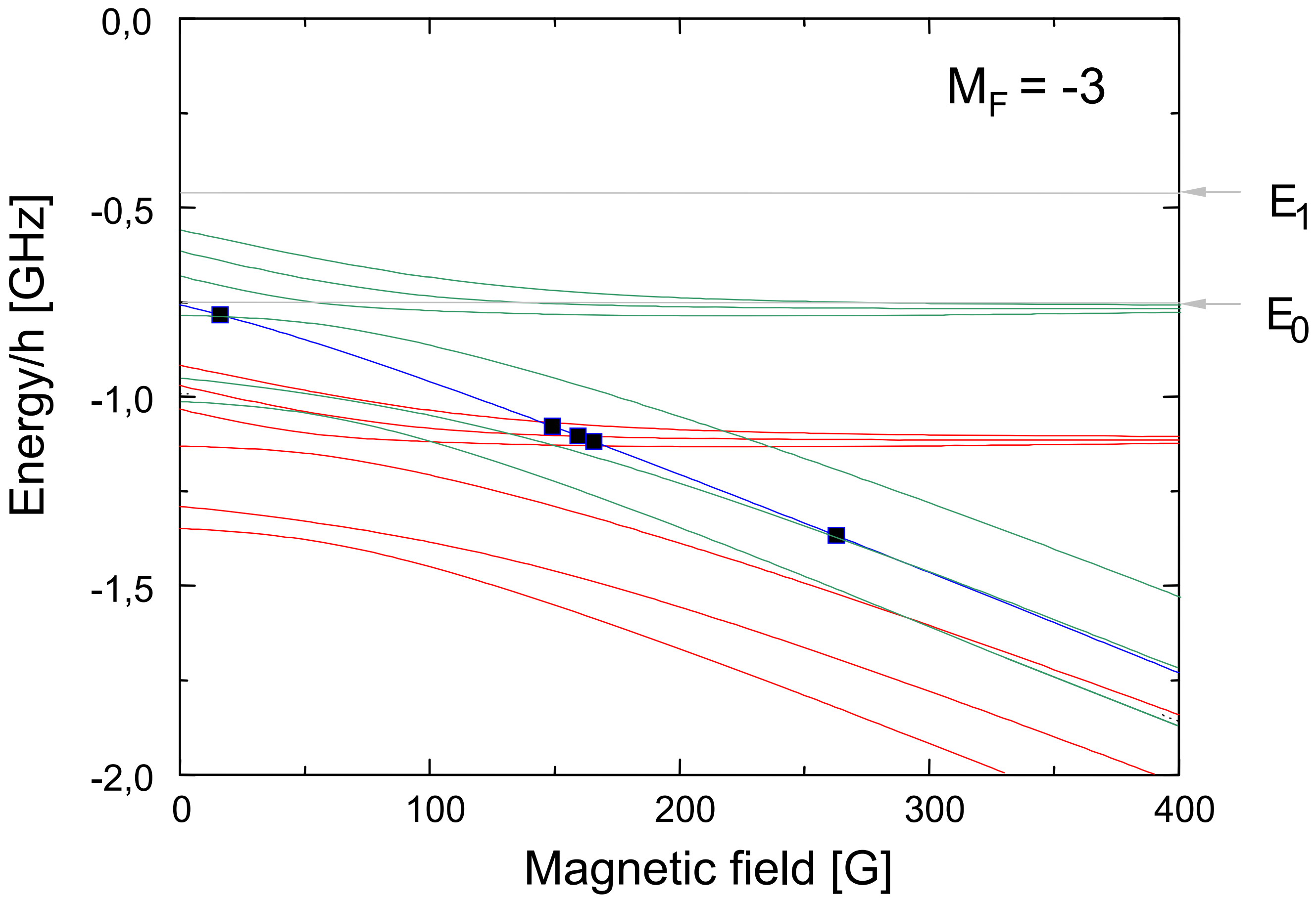
inverted hyperfine structure makes mixture *stable against spin-exchange losses* if one component is in the lowest hyperfine state

ABM analysis will be discussed for case $M_F = -3$

free atoms: ^{6}Li $|F = 1/2, m_F = +1/2>$ ^{40}K $|F = 9/2, m_F = -7/2>$

^{6}Li-^{40}K loss features in M_F = -3

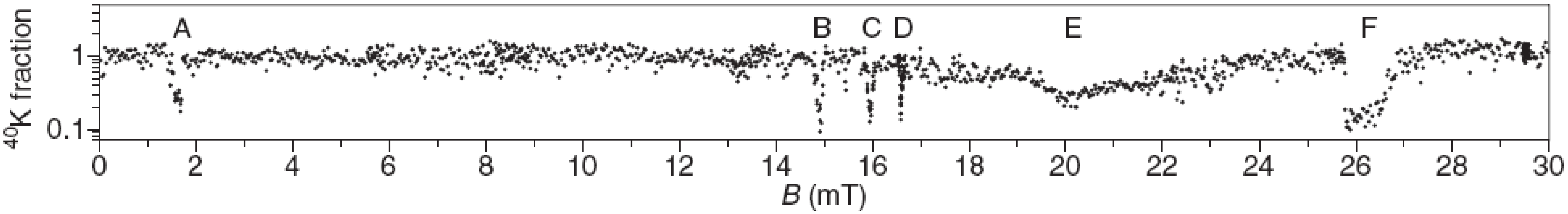
free atoms: ^{6}Li $|F = 1/2, m_F = +1/2>$ ^{40}K $|F = 9/2, m_F = -7/2>$

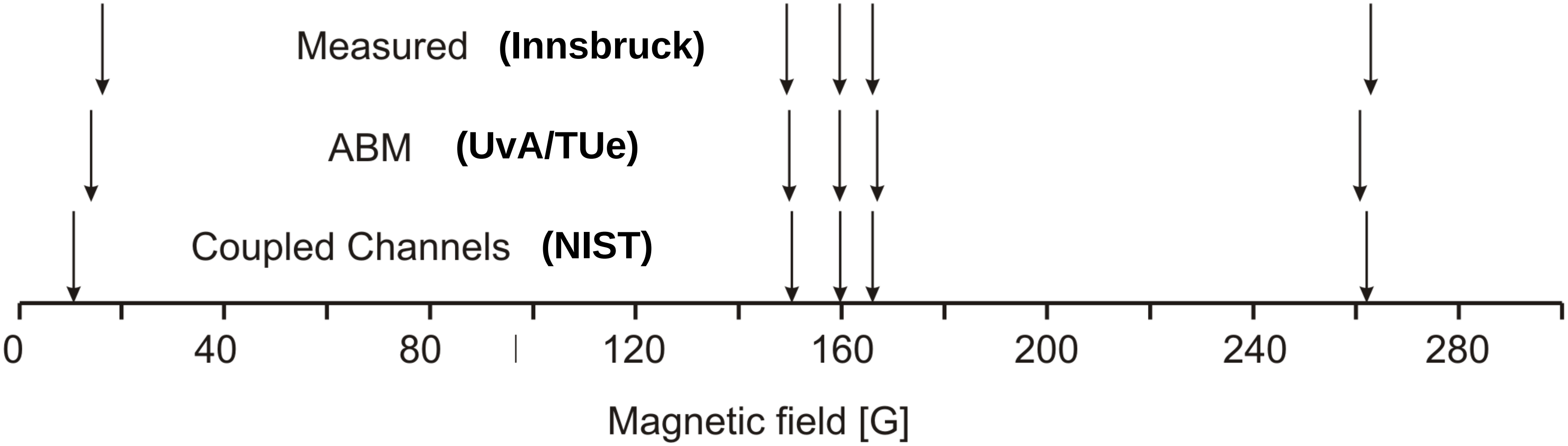


E. Wille et al., Phys. Rev. Lett. 100 (2008) 053201

Li-K loss features in $M_F=-3$

Relative 40K atom number





Measured **(Innsbruck)**

ABM **(UvA/TUe)**

Coupled Channels **(NIST)**

E. Wille et al., Phys. Rev. Lett. 100 (2008) 053201

background scattering length

from fit: binding energies of last bound states:

CC detailed
potential

singlet:	E_0/h = 716(15) MHz	$a_s = 52.1(3)\ a_0$
triplet:	E_1/h = 425(5) MHz	$a_t = 63.5(1)\ a_0$
	ABM	$r_0 = 41\ a_0$

→ **scattering length a_s and a_t non-resonant**

$ka_s << 1$ and $ka_t << 1$ → *s*-wave scattering amplitudes: $f_0 = \begin{cases} -a_s \\ -a_t \end{cases}$

degenerate internal states (DIS) approximation for scattering wavefunction[1]:

$$\psi_k(r) \underset{r\to\infty}{\sim} e^{ikz} + \left[f_t + (f_s - f_t) \sum_{IM_I} |\langle 00IM_I | h_1 h_2 \rangle|^2 \right] \frac{e^{ikr}}{r} .$$

→ background scattering length $a_s < a_{bg} < a_t$

a_{bg} non-resonant for any $|h_1h_2>$ → for *any* field

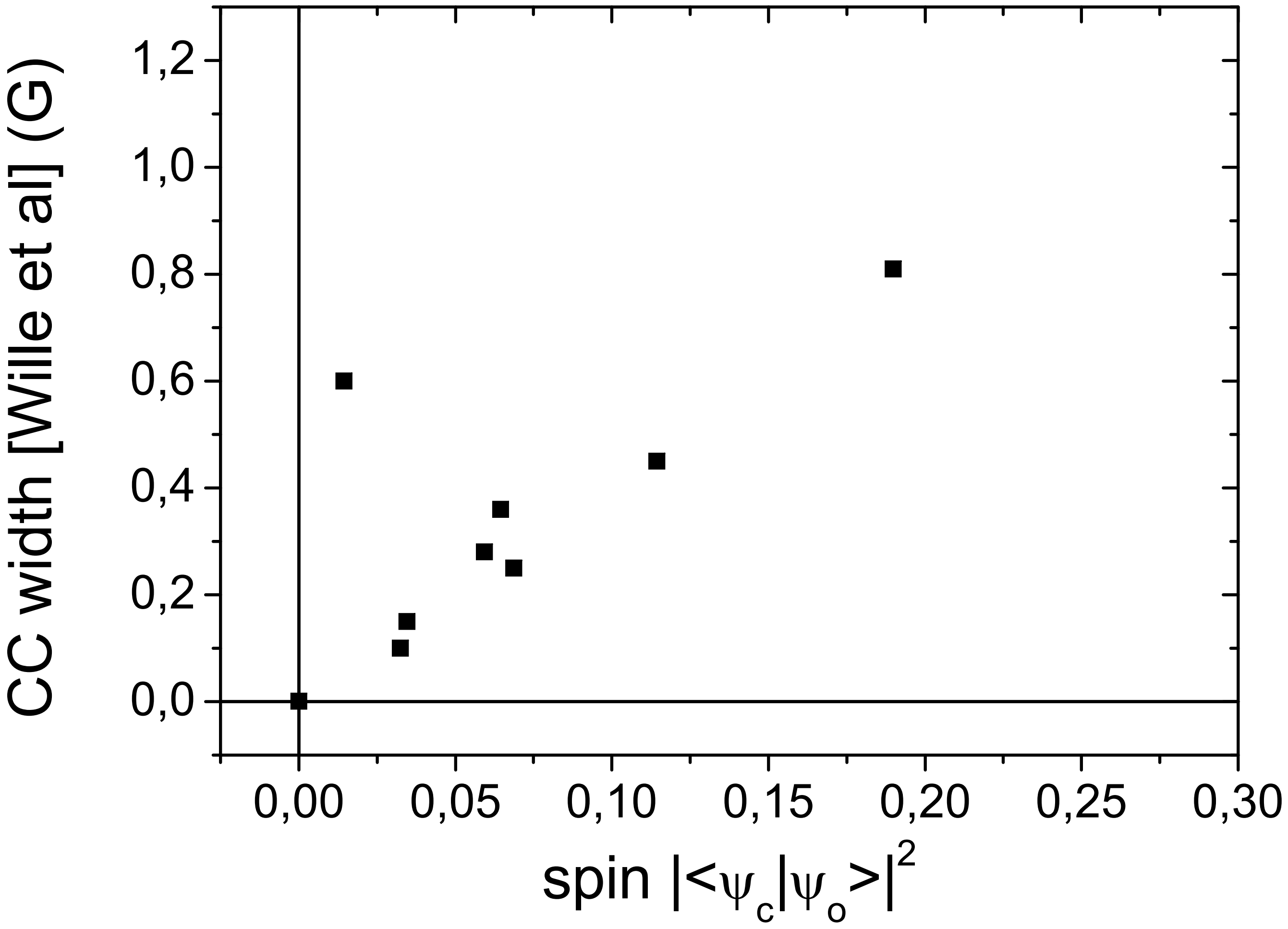
988)

Recap

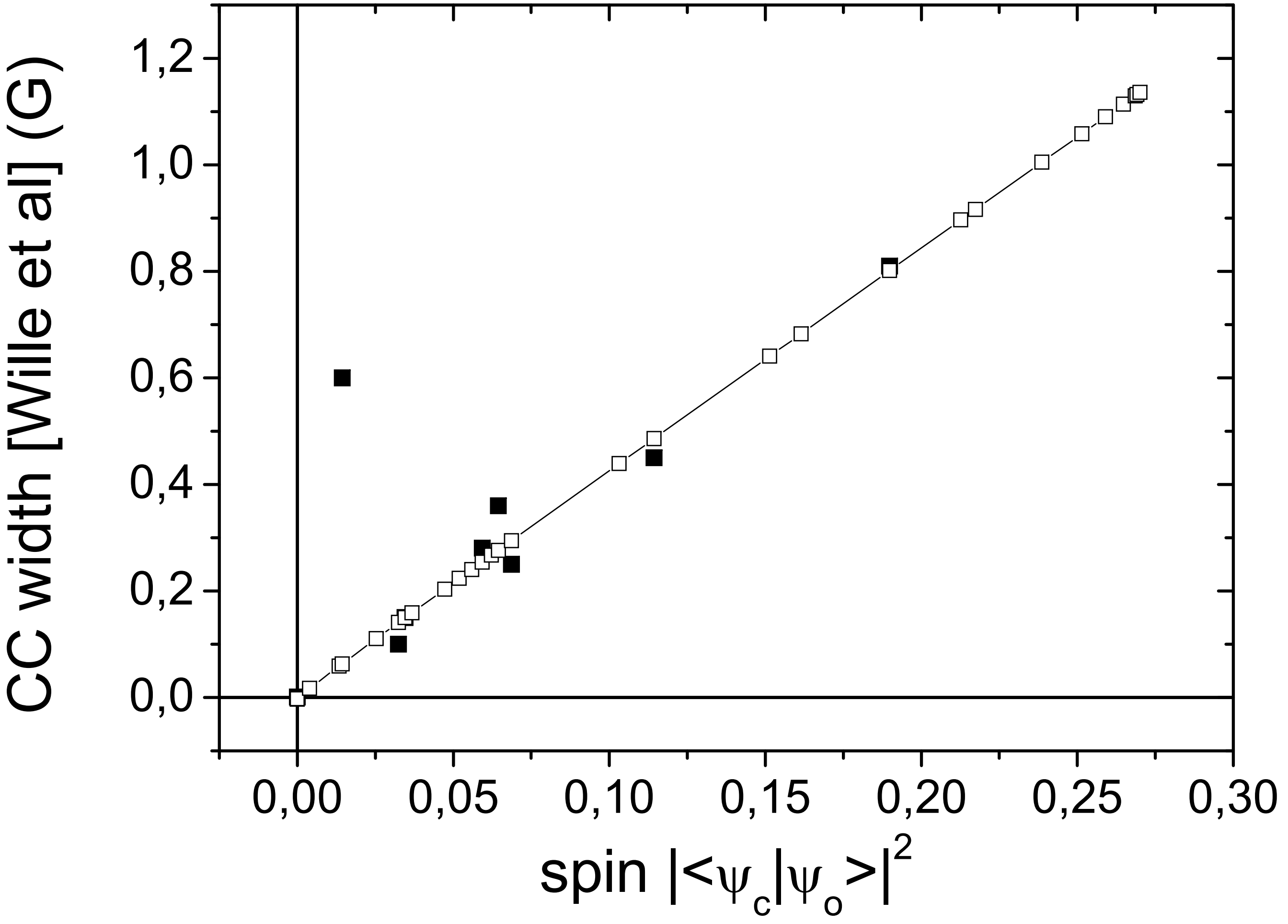
$$s_{res} = \frac{a_{bg}\mu_{\rm rel}\Delta_B}{r_0\left(\hbar^2/2\mu r_0^2\right)}$$

- a_{bg} obtained from fit to Feshbach positions
- μ_{rel} obtained from ABM model
- ΔB to be measured

Broadest resonance?



Broadest resonance?



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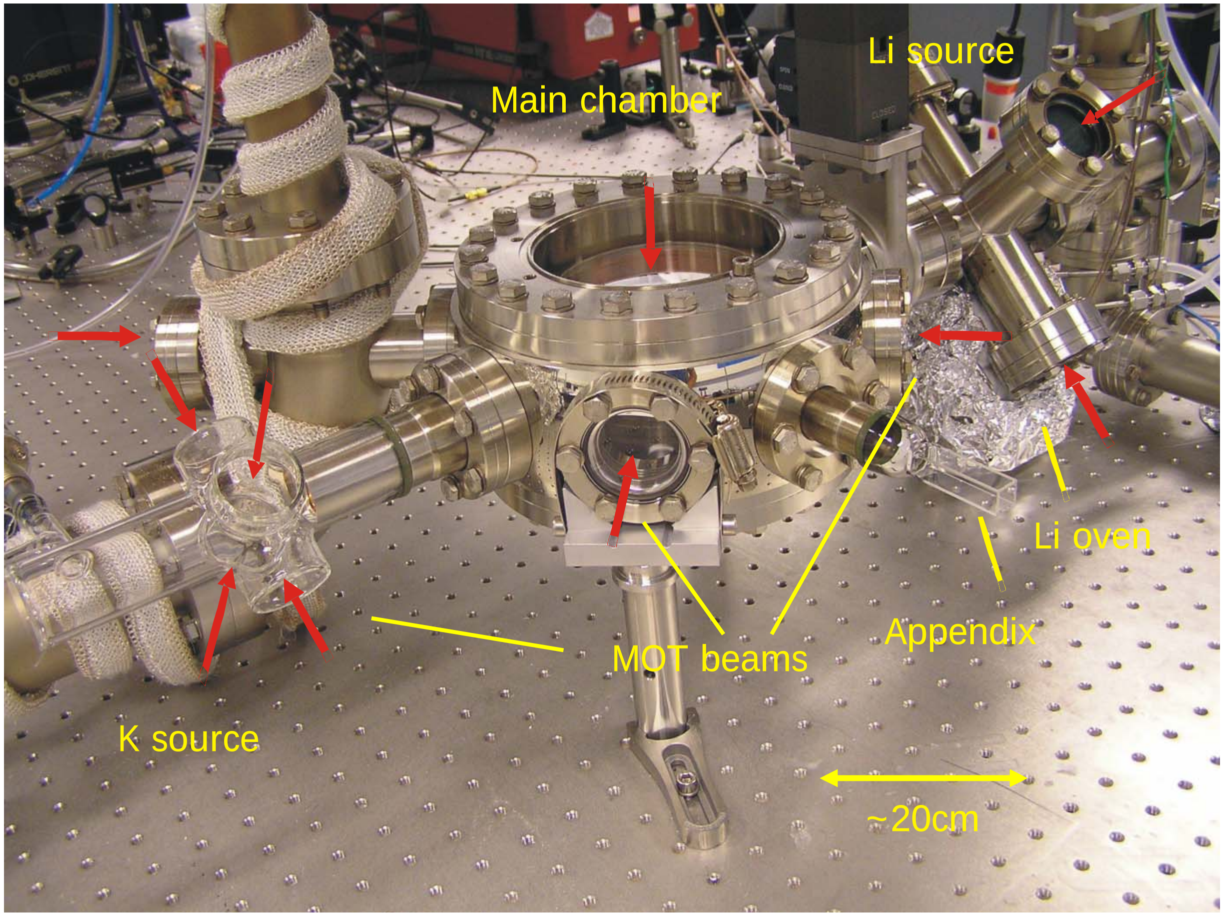
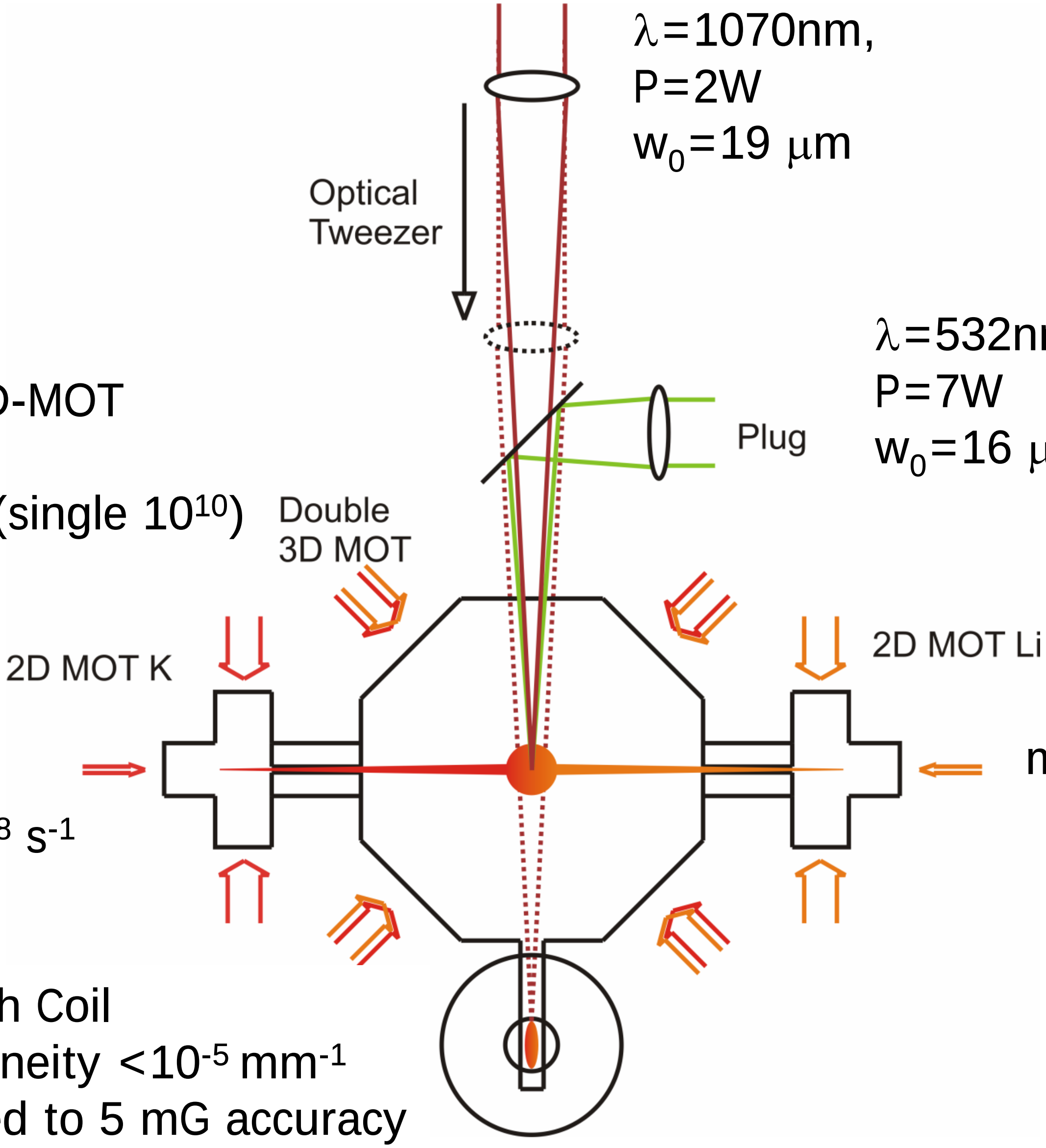
Experiment


Li source
Main chamber
Li oven
Appendix
MOT beams
K source
~20cm

Experiment



λ=1070nm,
P=2W
w_0=19 μm

λ=532nm,
P=7W
w_0=16 μm

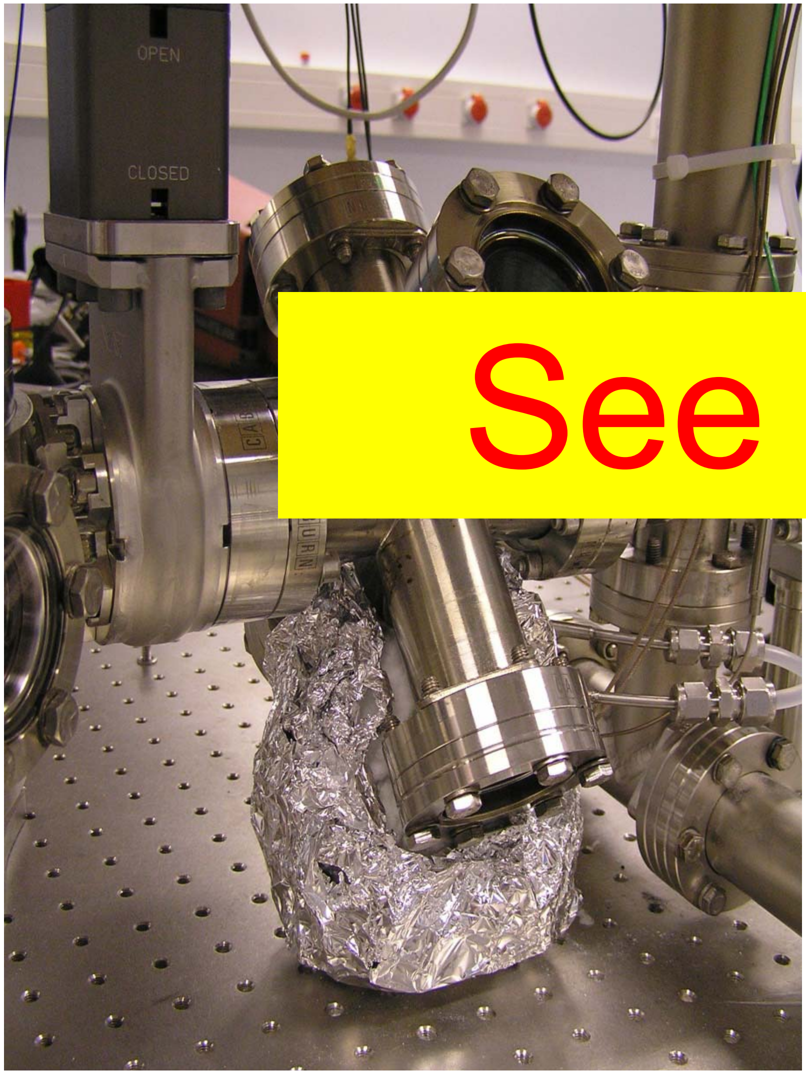
Double 3D-MOT
K: 2×10^9
Li: 3×10^9 (single 10^{10})

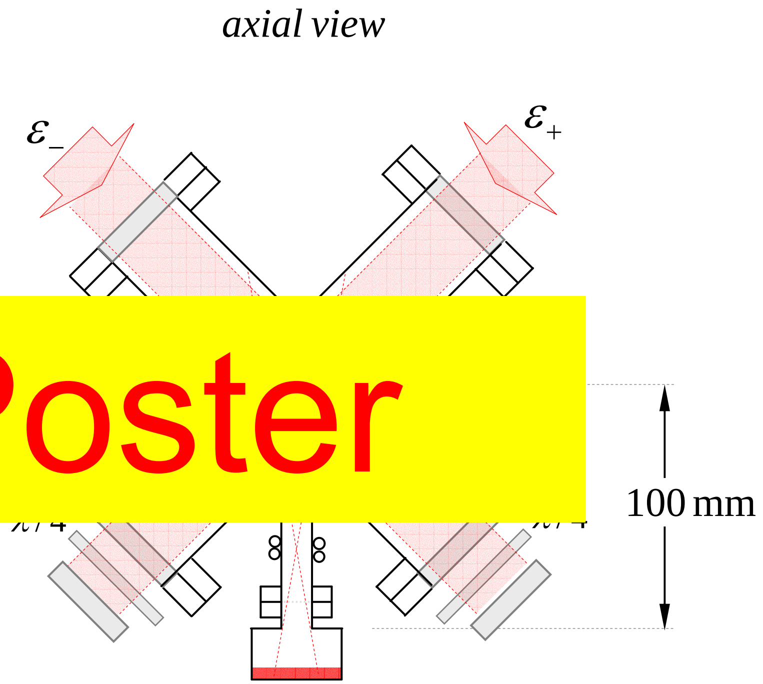
max flux=10^9 s^{-1}

max flux=3×10^8 s^{-1}

Feshbach Coil
Homogeneity <10^{-5} mm^{-1}
calibrated to 5 mG accuracy

Lithium 2D-MOT configuration

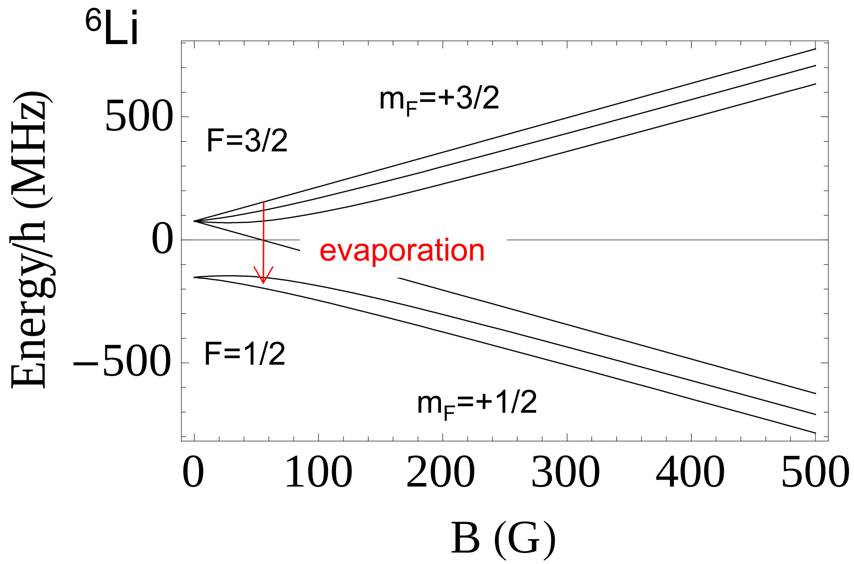


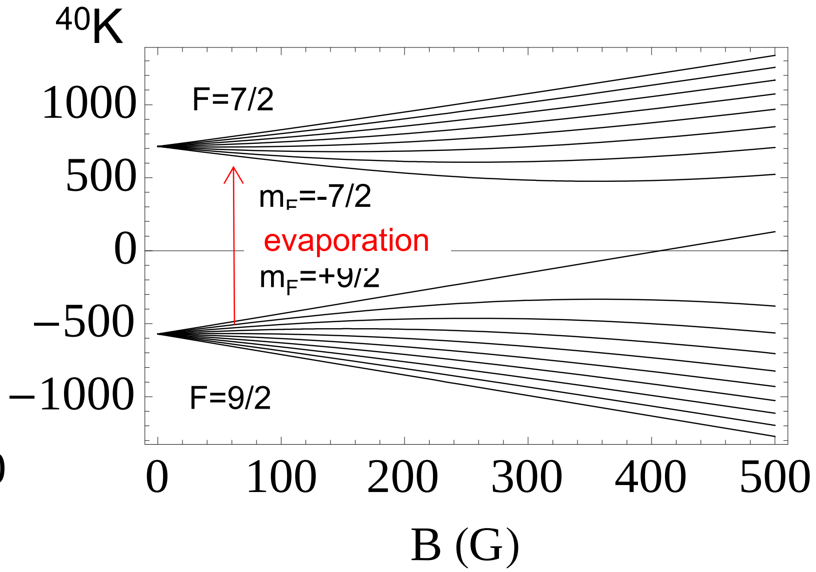


See Poster

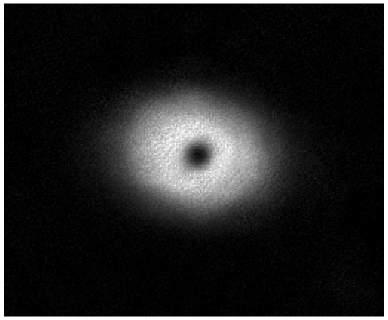
- 2D-quadrupole magnetic field generated by two permanent magnets
- Maximum 3D-MOT loading rate of 10^9 s^{-1}
- Maximum captured atom number 10^{10}
- Preprint: arXiv:0905.1063v1

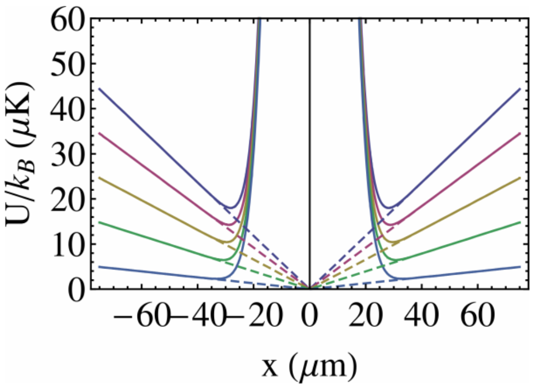
Evaporative cooling/Plug trap

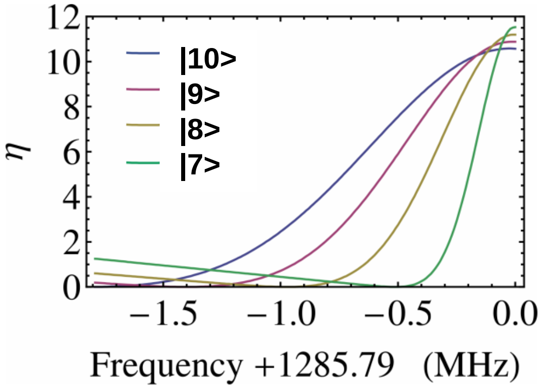




Plug beam imposes an effective B_0. P=7W, w_0=16 μm
Therefore we can clean the K spin mixture by MW evaporation 'inside' the plug.



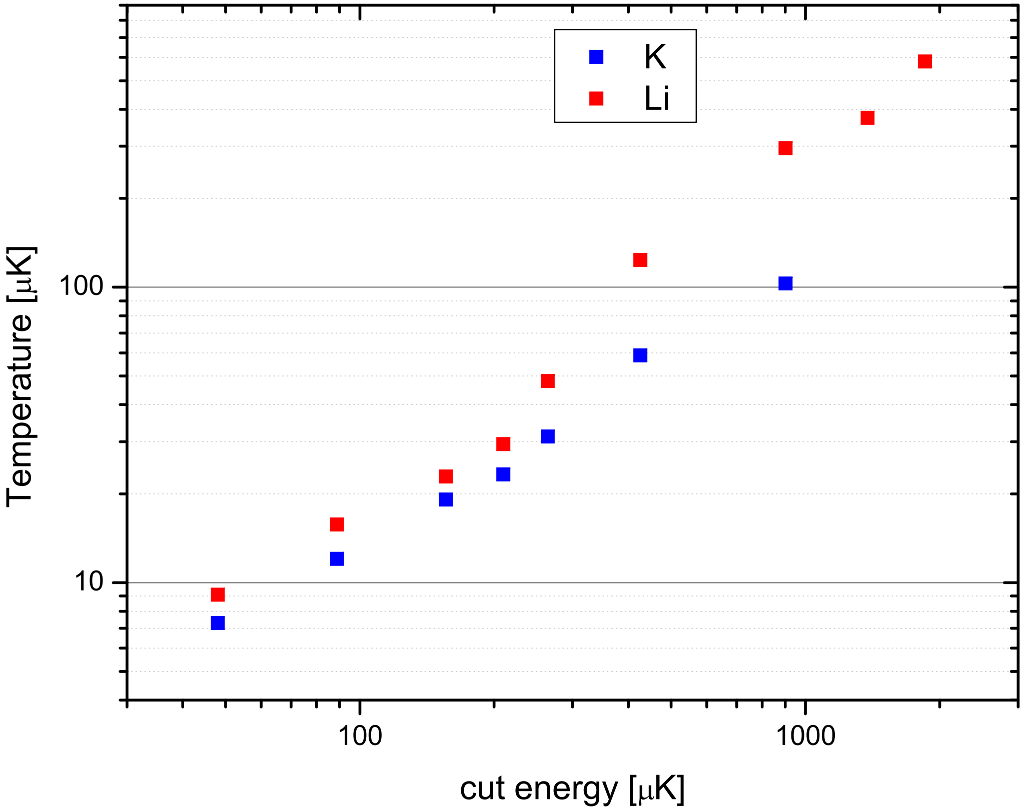




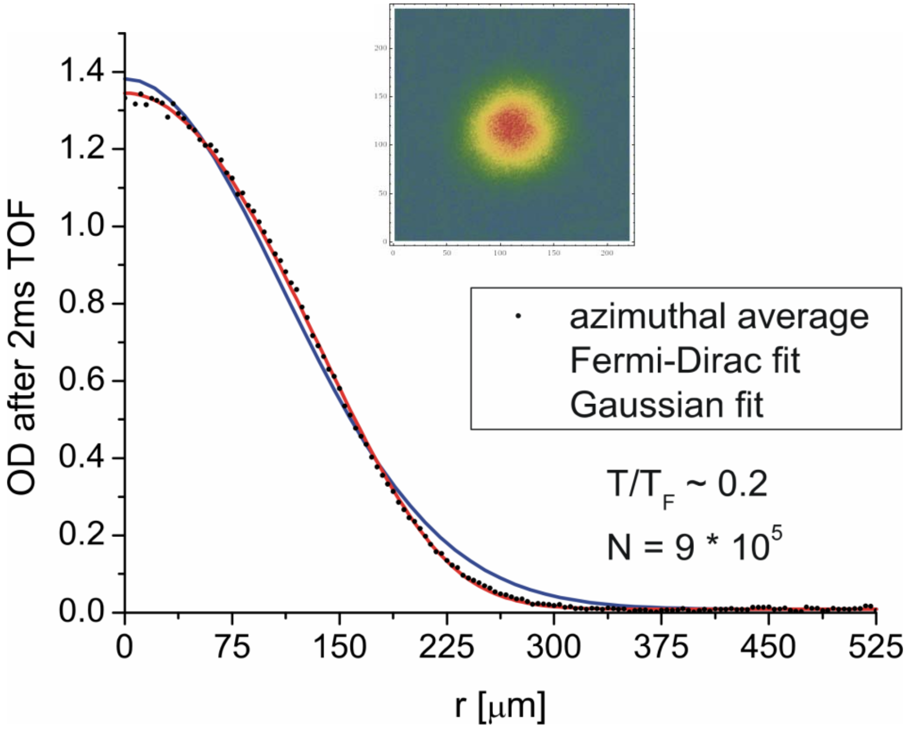
MT sympathetic cooling

Sypathetically cool Li by spin mixture of K instead of both stretched
Li: |3/2,+3/2>   K: |9/2,+9/2> & |9/2,+7/2> & |9/2,+5/2>

•$\sigma_{KK} \sim 8\ \sigma_{KLi}$ $a_{T,K}=170\ a_0$, $a_{TK\text{-}Li}=64\ a_0$
•$T_K \ll T_{Li}$ lighter & no sub doppler cooling for Li
•Need more collisions to rethermalise due to mass difference

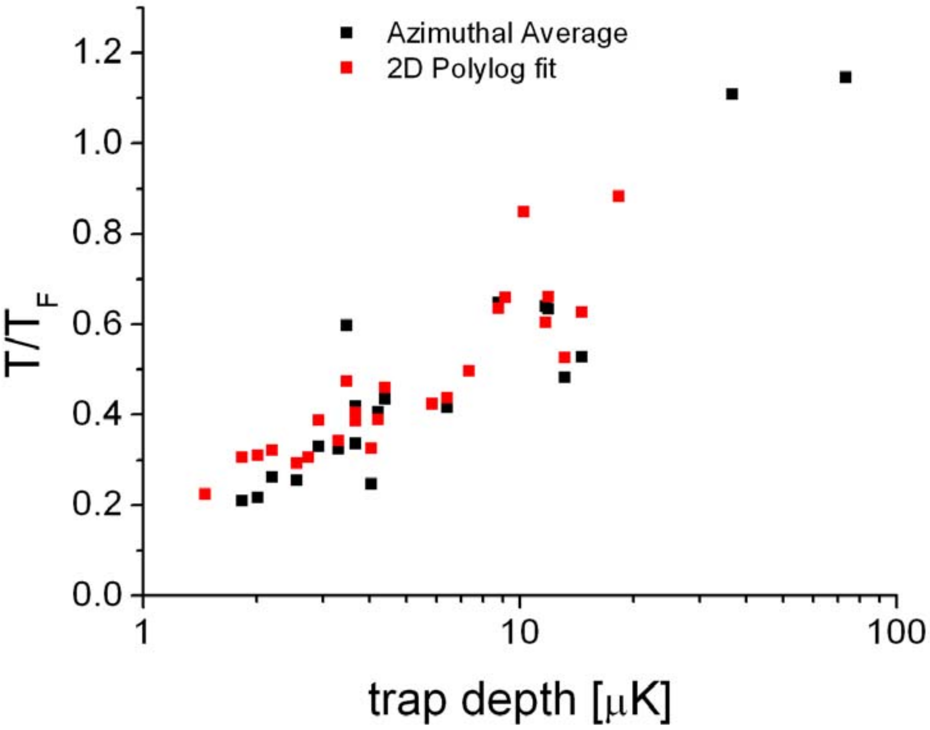


3-fold degenerate ^{40}K



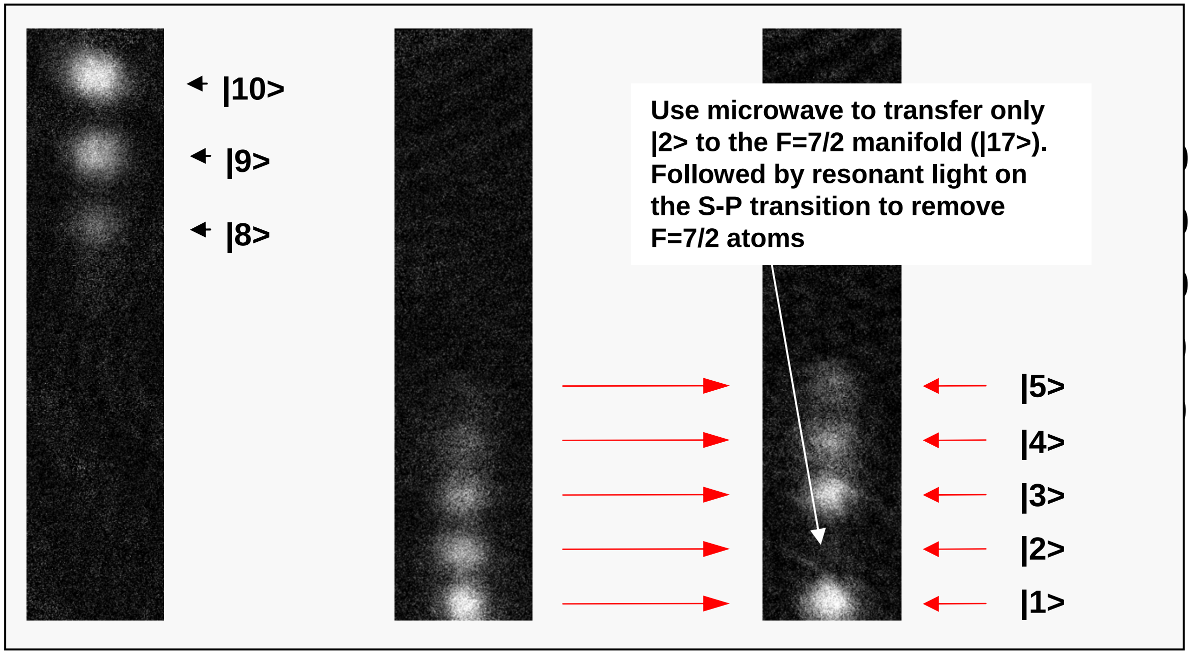
$T/T_F \sim 0.2$

$N = 9 * 10^5$

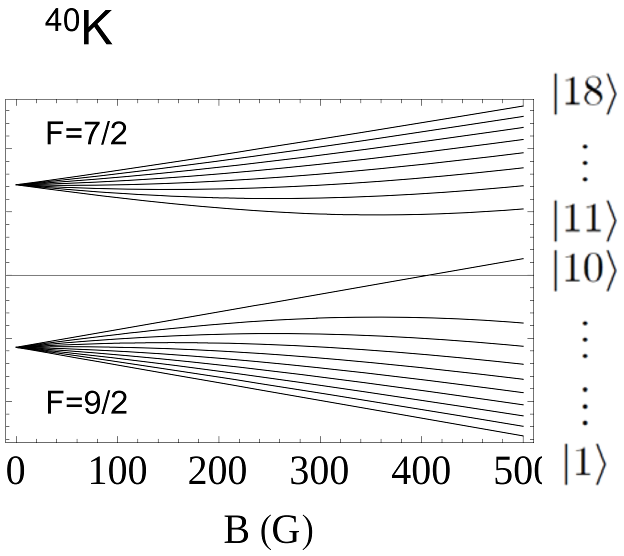


state cleaning at low field

hfs-state cleaning of ^{40}K mixture:

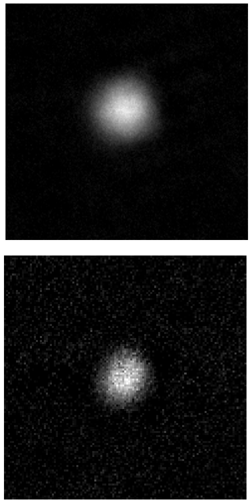


Use microwave to transfer only |2> to the F=7/2 manifold (|17>). Followed by resonant light on the S-P transition to remove F=7/2 atoms



^{6}Li transferred from |3/2,+3/2> to |1/2,+1/2> by an adiabatic passage around 10G
Remaining F=3/2 atoms removed by resonant light

Ultracold mixture in Optical Trap

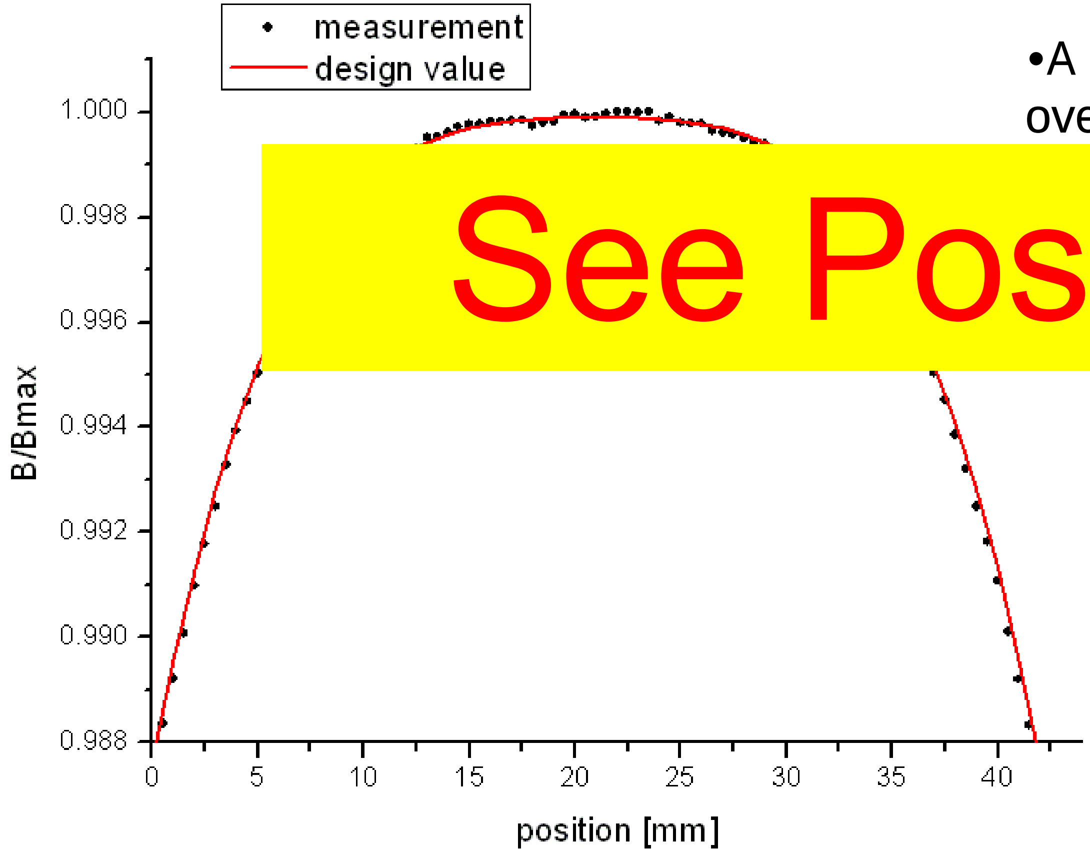


~10^5 of each for 'unclean' sample

Clean and state prepared low density sample:
2×10^4 ^{40}K in |F=9/2,mF=+9/2>
4×10^3 ^{6}Li in |F=1/2,mF=+1/2>

Homogeneous Feshbach field

- 126 windings each, anti-symmetrically wound to cancel winding errors
- A homogeneity of 10^{-5} extends over a range of 2x2x2 mm^3
- stable &



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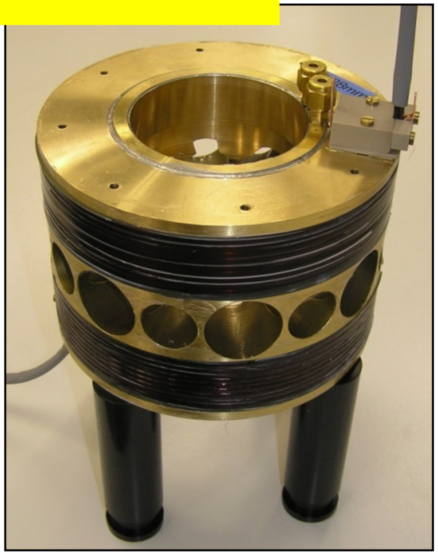

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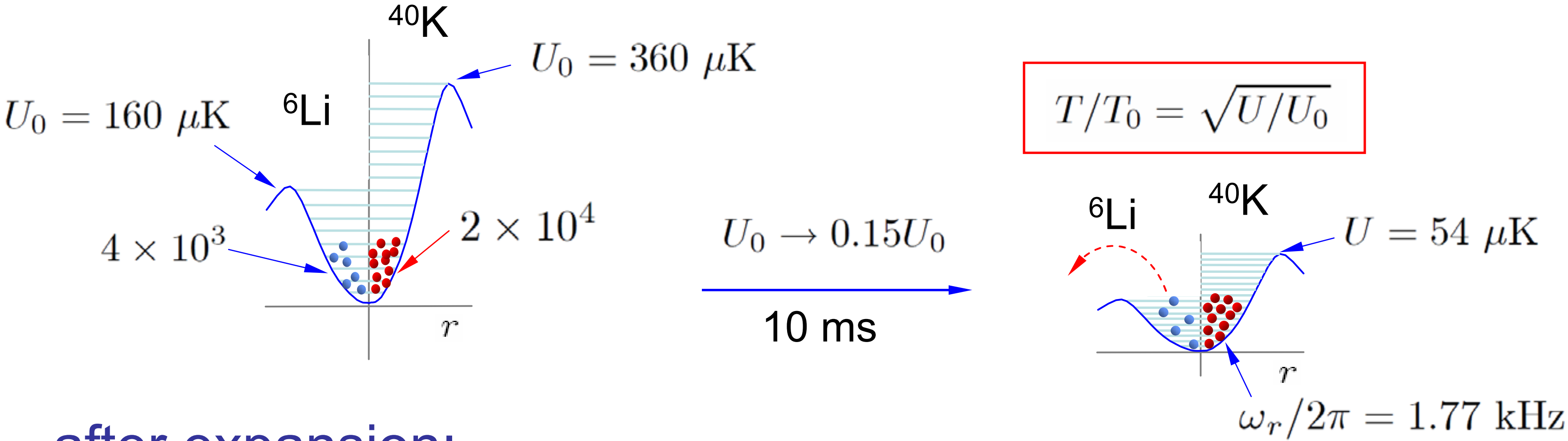
expanding the cloud to low density

adiabatic expansion gaussian trap induces evaporation:



$$\boxed{T/T_0 = \sqrt{U/U_0}}$$

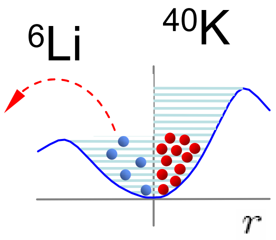
after expansion:

$$\left.\begin{array}{l} ^6\text{Li: } 4000 \text{ atoms, } n_0 = 4 \times 10^9 \text{ cm}^{-3}\ (\eta_{\mathrm{Li}} \simeq 2.7) \\ ^{40}\text{K: } 20000 \text{ atoms, } n_0 = 8 \times 10^{10} \text{ cm}^{-3}\ (\eta_{\mathrm{K}} \simeq 6.2) \end{array}\right\} T = 9\ \mu\text{K}$$

Li-K collisions induce Li evaporation
no three-body losses

$$\eta = U / k_B T$$

evaporative losses



^{40}K losses:

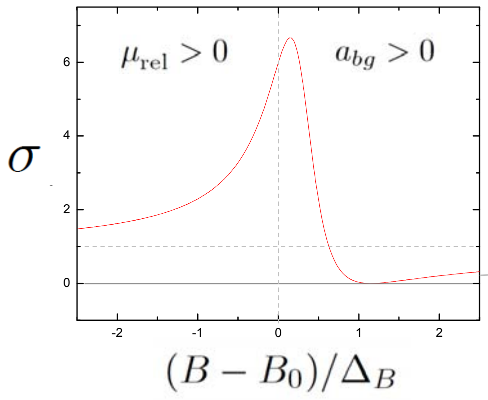
background gas dominated

lifetime τ_{vac} = 25 s

^{6}Li evaporation induced by ^{40}K

$$\tau_{ev}^{-1} \simeq n_{\mathrm{K}} \langle \sigma v_{rel} \rangle e^{-\eta_{\mathrm{Li}}}$$

$$n_{\mathrm{K}}(t) = n_{\mathrm{K}}(0) e^{-t/\tau_{vac}}$$

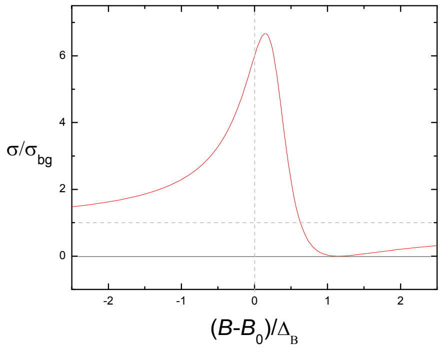


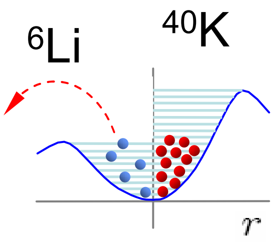
no ^{6}Li evaporation without ^{40}K

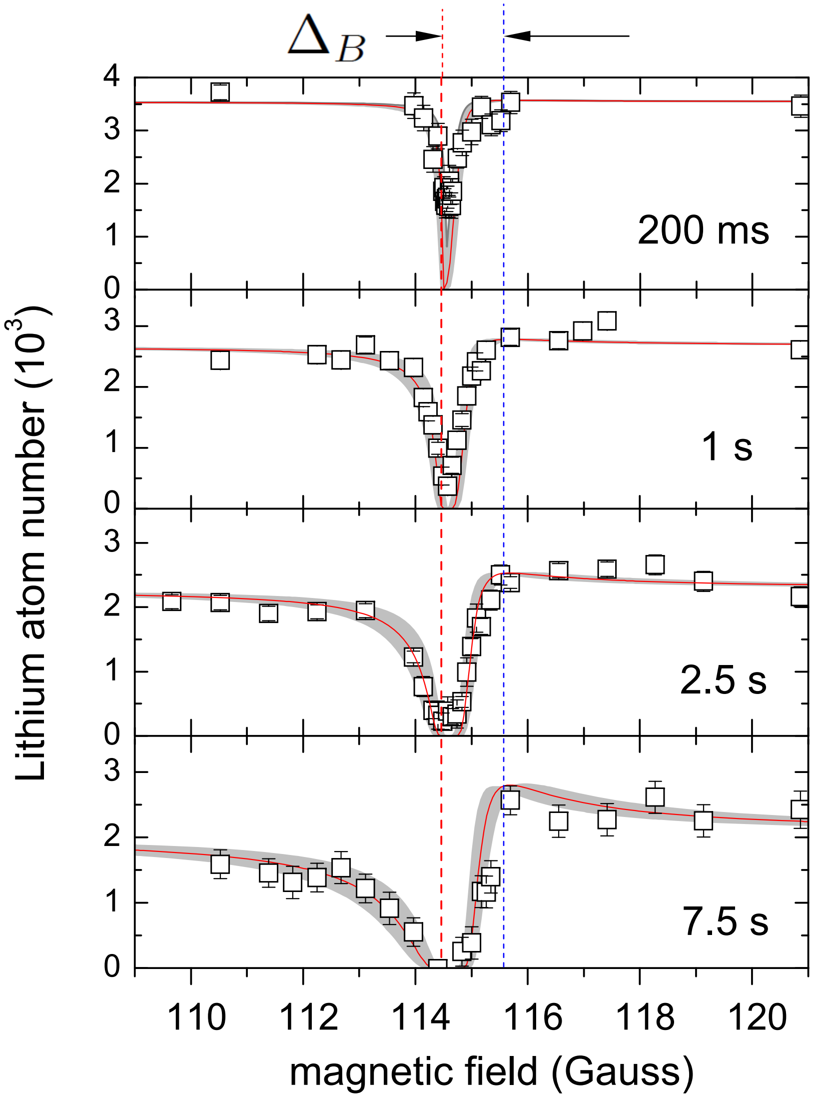
^{6}Li atoms left after holding time *t* :

$$\boxed{N_{\mathrm{Li}} = N_0 \exp(-t/\tau_{ev}) \exp(-t/\tau_{vac})}$$

precision width measurement







Li left after holding time →

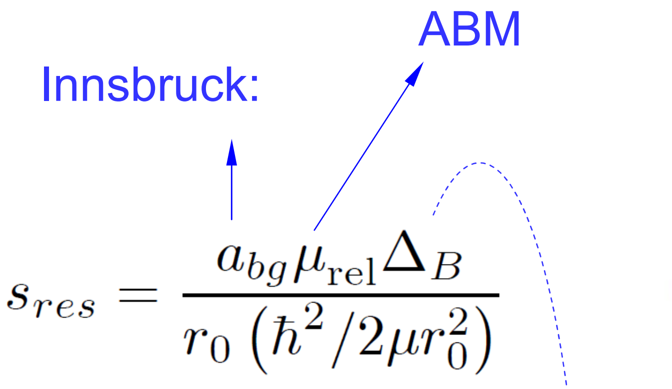
$^{6}\mathrm{Li}\ |1/2, +1/2\rangle \quad ^{40}\mathrm{K}\ |9/2, +9/2\rangle$

position: B_0 = 114.45(5) G

width: ΔB = 1.0(3) G

(*preliminary results*)

resonance strengths



Innsbruck:

ABM

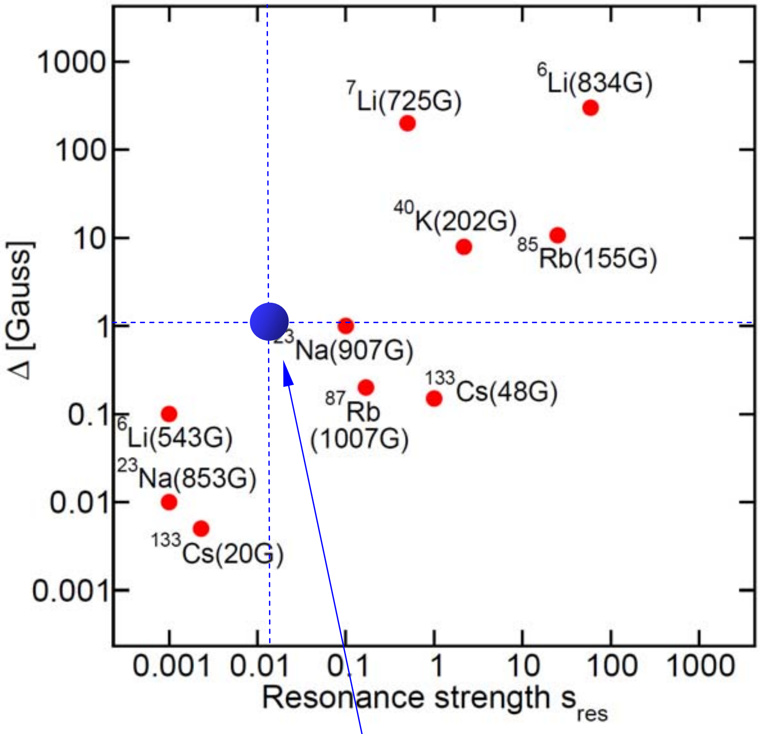
this work

$$s_{res} = \frac{a_{bg}\mu_{\rm rel}\Delta_B}{r_0\left(\hbar^2/2\mu r_0^2\right)}$$

position: B_0 = 114.45(5) G

width: ΔB = 1.0(3) G

strength: s_{res} = 0.013



^{6}Li-^{40}K (114G)

Universal behavior only for $E_F \ll 1\ \mu K$

Is this accuracy sufficient to demonstrate the limitations of Born-Oppenheimer approximation?

E. Tiemann et al., Phys. Rev. A 79, 042716 (2009)

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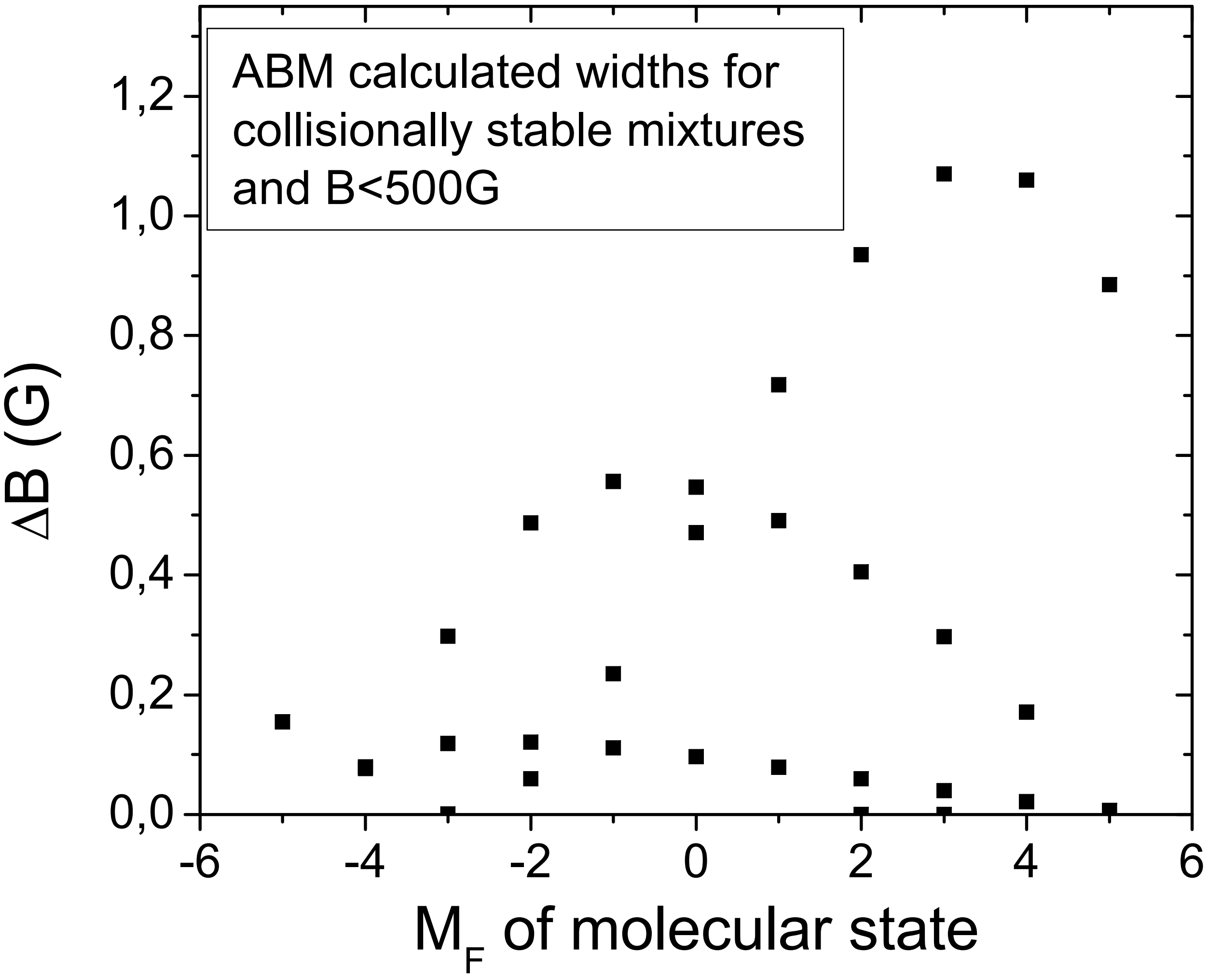
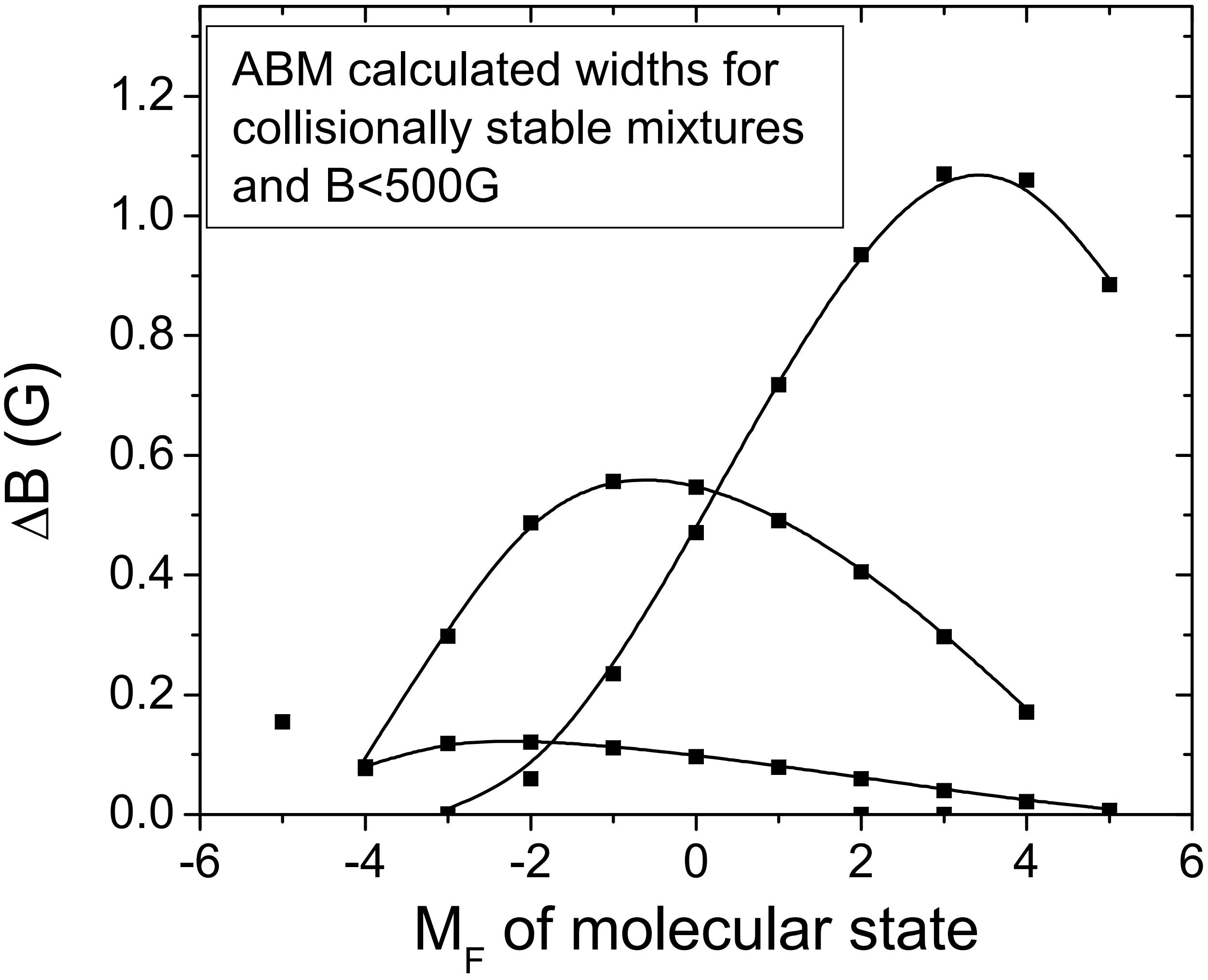
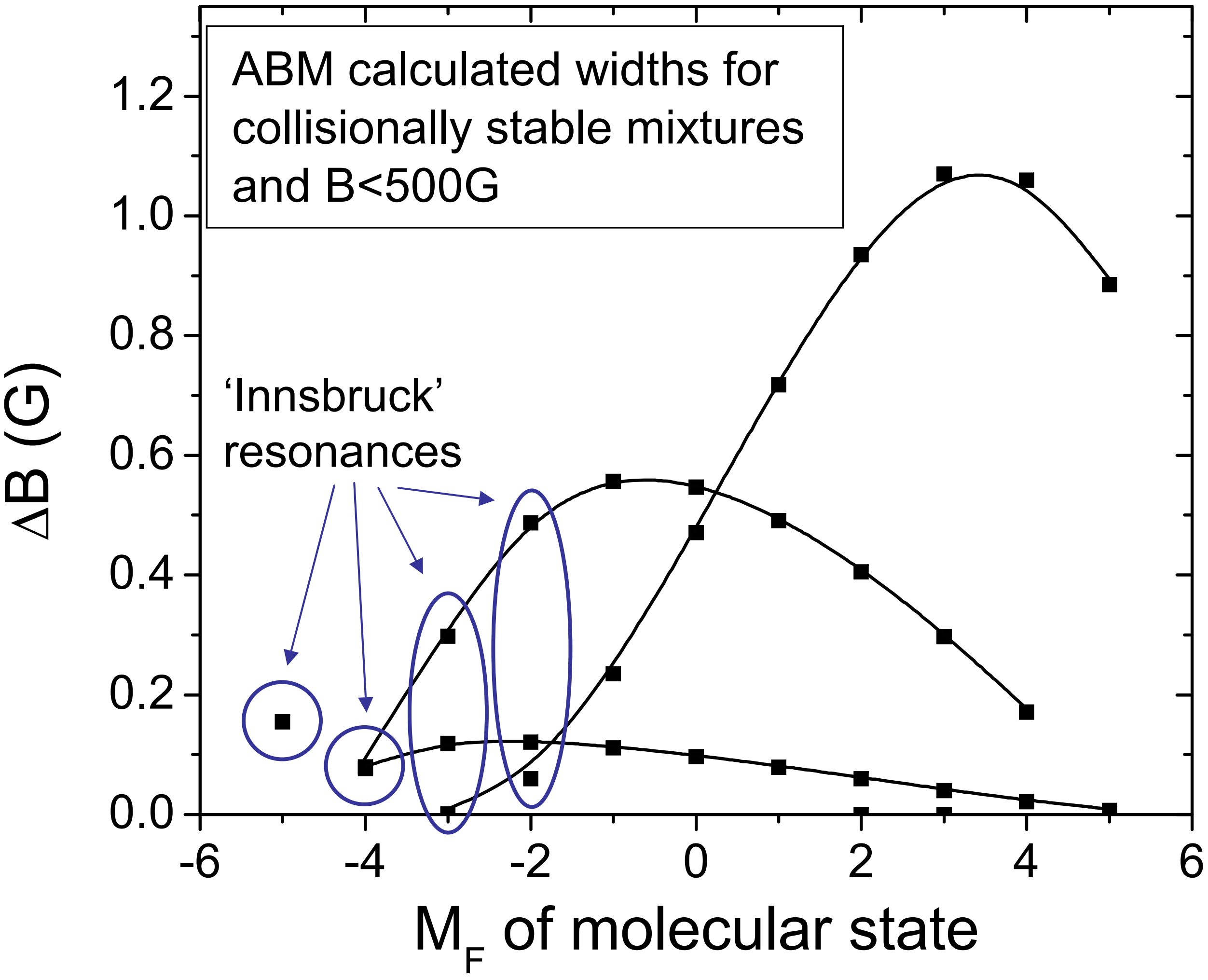
Feshbach widths in LiK mixture



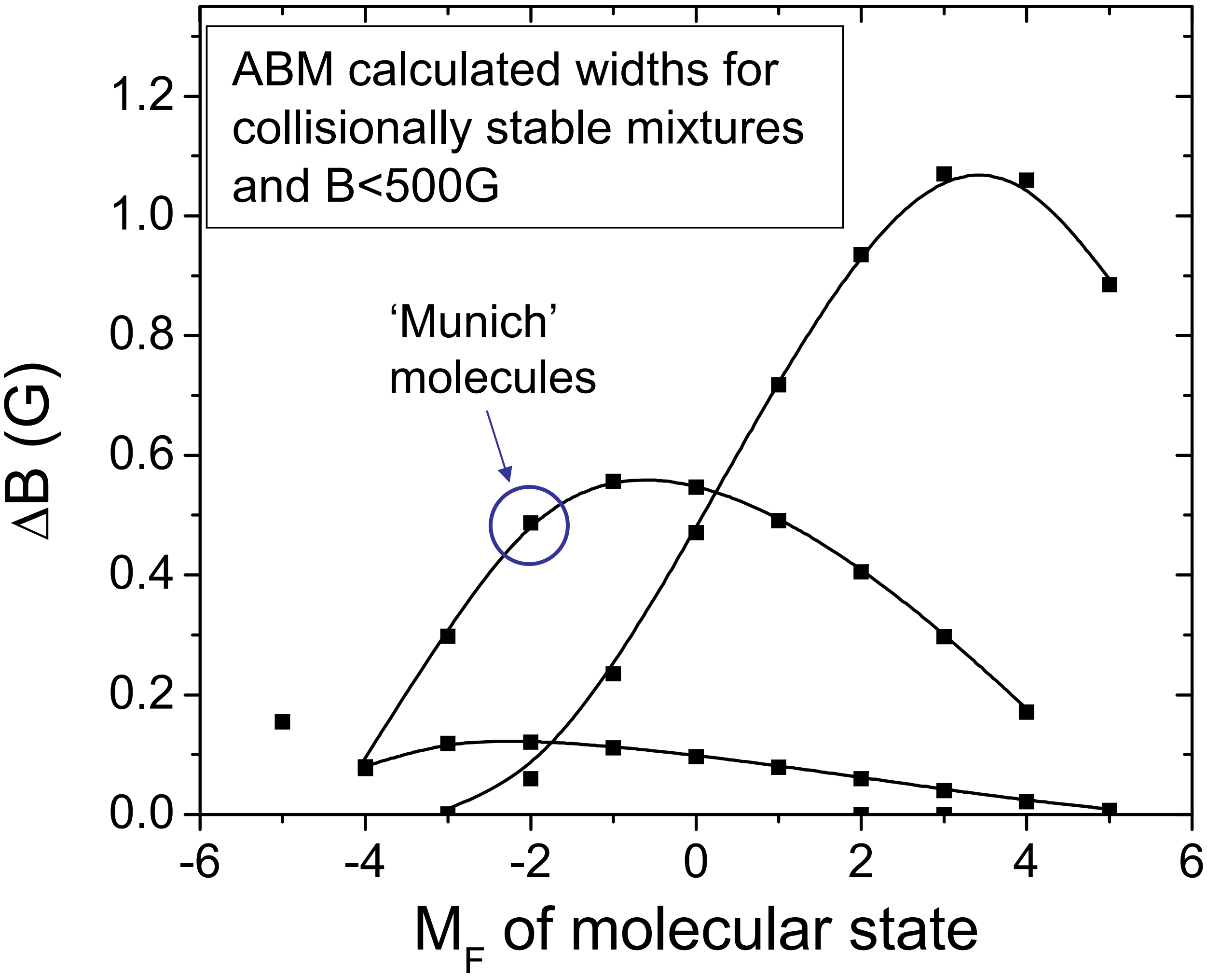
Feshbach widths in LiK mixture



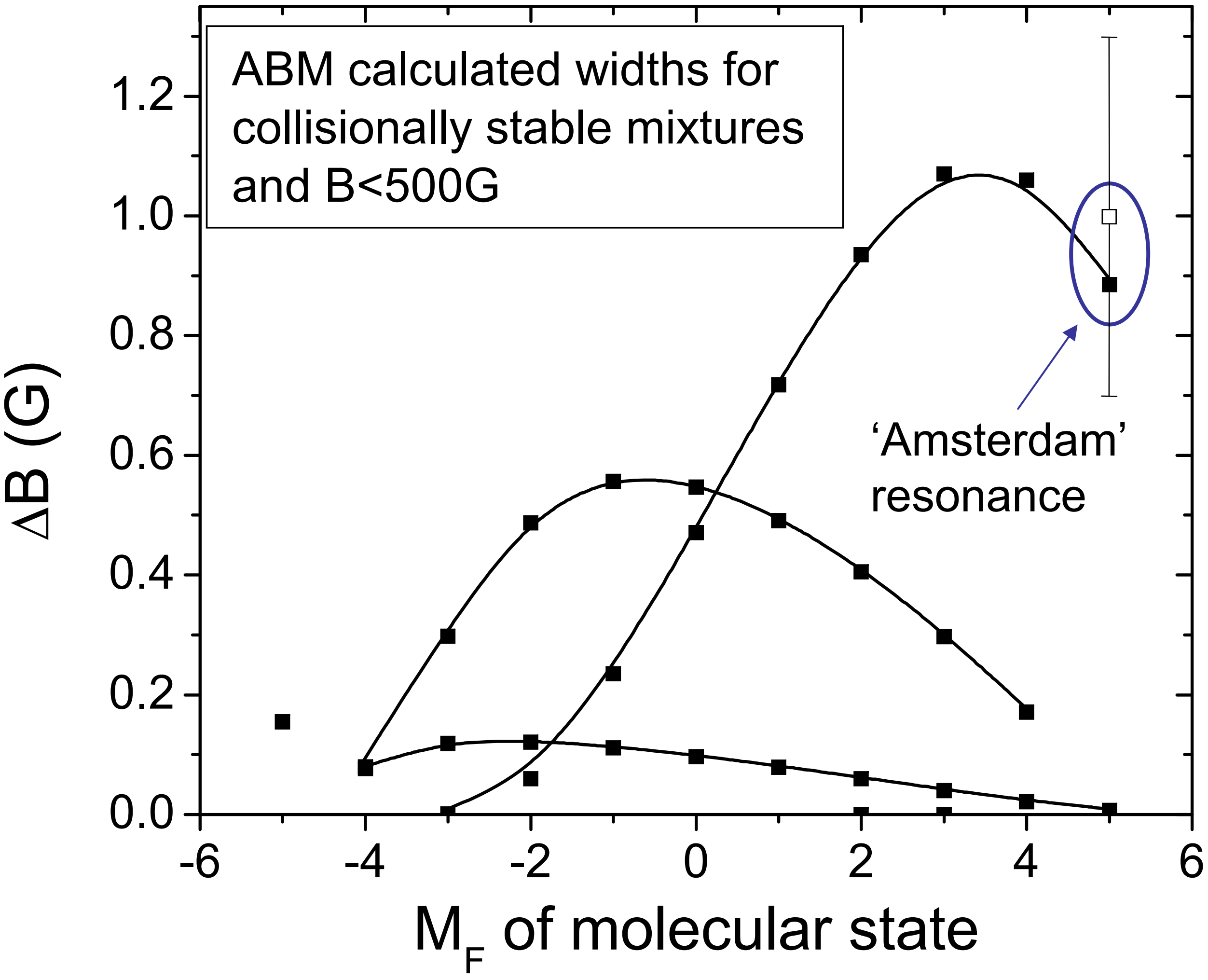
Feshbach widths in LiK mixture



Feshbach widths in LiK mixture



Feshbach widths in LiK mixture



conclusions

- First direct determination of the width of a Feshbach resonance in ^{6}Li-^{40}K mixture
- Position determined 114.45 G with an accuracy of 50 mG limitations of BO-approximation visible?
- Strength parameter s_{res} = 0.013 for width of Δ_B = 1.0(3) G
- Unlikely to find much larger values of s_{res} at any resonance
- Universal behavior only for $E << 1\ \mu$K
- Observation of superfluidity will be challenging
- Mediated interactions can be observed
- (be aware of other mechanisms to manipulate interactions)

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