Bose-Bose mixtures in confined dimensions

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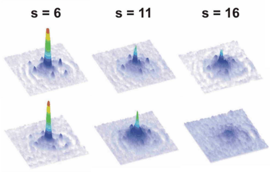
22nd International Conference on Atomic Physics
Cairns, July 29, 2010

Why Bose-Bose mixtures? (Our) motivation

▷ Bose-Bose mixtures in optical lattices map to spin hamiltonians



J. Catani et al., Phys. Rev. A (2008)

▷ few-body physics in ultracold collisions:

- Efimov resonances with heavy/light atoms [G. Barontini et al., Phys. Rev. Lett. (2009)]
- scattering in confined dimensions [G. Lamporesi et al., Phys. Rev. Lett. (2010)]

▷ entropy control (and thermometry) of species A by means of a species B

[J. Catani et al., Phys. Rev. Lett. (2009)]

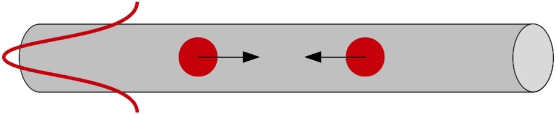
Two-body scattering in low dimensions

Scattering in a waveguide

[M. Olshanii, Phys. Rev. Lett. 81, 938 (1998)]

Quick reminder: scattering of two atoms via a pseudo-potential $U(r) = g\delta(\vec{r})(r\partial_r)$ in a tight waveguide

Strong confinement along two directions: $E \ll \omega, \quad k\,\ell \ll 1, \ell = \sqrt{\hbar/m\omega}$



- Scattering amplitude

$$f = -\frac{1}{1 + ika_{1D}}$$

- 1-dimensional scattering length

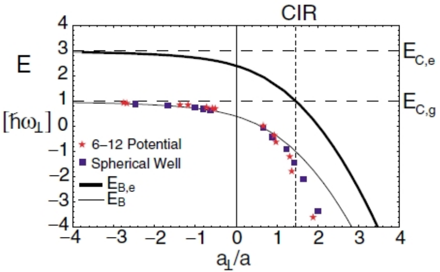
$$a_{1D} = -\frac{\ell^2}{a}(1 - C\frac{a}{\ell}), C = 1.4603/\sqrt{2}$$

- Same as 1D potential $U(z) = g_{1D}\delta(z), \quad g_{1D} = -\frac{\hbar^2}{\mu a_{1D}}$

Confinement-induced resonance (CIR): $a_{1D} \to 0$, $g_{1D} \to \infty$ for $\ell = Ca$

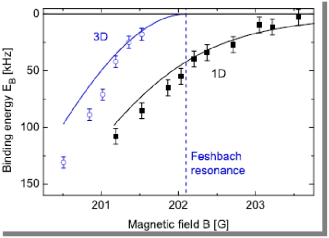
Confinement-induced resonances, interpretation

[T. Bergeman et al., Phys. Rev. Lett. 91, 163201 (2003)]



- 1D, bound state for all values of scattering length, a (vs 3D: bound state for $a > 0$)
- CIR as FR: "closed channel" = set of excited harmonic transverse levels
- only 1 CIR for all excited states
- decoupling of internal and center-of-mass motion

Confinement-induced molecules and resonances, exp

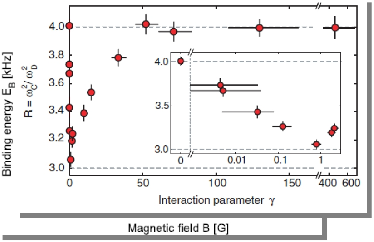


Experiments

- Confinement-induced molecules with ^{40}K atoms

  [H. Moritz et al., Phys. Rev. Lett. 94, 210401 (2005)]

Confinement-induced molecules and resonances, exp



Experiments

- Confinement-induced molecules with ^{40}K atoms

  [H. Moritz et al., Phys. Rev. Lett. 94, 210401 (2005)]

- CIR on Cs atoms

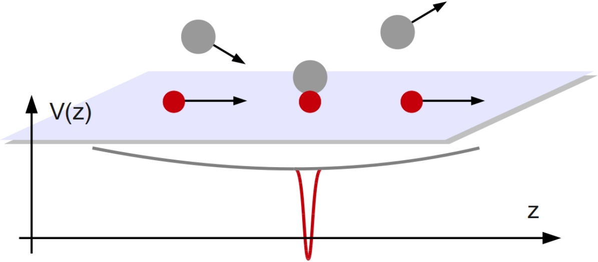
  [E. Haller, Science 325, 1124 (2009)]

Very recently,

- CIR in elliptic waveguide [E. Haller et al., Phys. Rev. Lett. 104, 153203 (2010)]
- CIR in quasi-2D with ^{6}Li atoms [P. Dyke et al., poster Mo77]

Mix-dimensional configuration

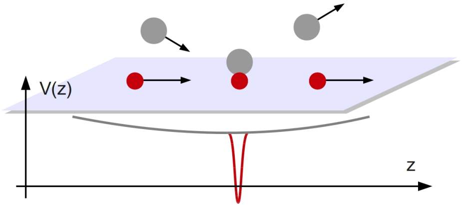
Different kind of particles can live in different dimensions



- In our experiment, two atomic species: ^{87}Rb free in 3D, ^{41}K confined in 2D

Scattering resonances in mixed dimensions

[in collaboration with Y. Nishida, MIT]



Translational symmetry in the (xy) plane, drop center-of-mass X, Y coordinates

$$\left[-\frac{\hbar^2}{2\mu}\nabla^2_{\mathbf{r}} - \frac{\hbar^2}{2m_1}\nabla^2_{z1} - \frac{\hbar^2}{2m_2}\nabla^2_{z2} + \frac{1}{2}m_1\omega^2 z_1^2 + gV\right]\psi(\mathbf{r}, z_1, z_2) = E\psi(\mathbf{r}, z_1, z_2),$$

where $\mathbf{r} = (x_1 - x_2, y_1 - y_2)$

Scattering resonances in mixed dimensions (II)

General solution

$$\psi(\mathbf{r}, z_1, z_2) = \psi_0(\mathbf{r}, z_1, z_2) + g \int_{-\infty}^{\infty} dx' \, G_E(\mathbf{r}, z_1, z_2; \mathbf{0}, z', z') \psi_{reg}(z')$$
$$V\psi(\mathbf{r}_1, \mathbf{r}_2) \equiv \psi_{reg}(\mathbf{r})|_{\mathbf{r}=\mathbf{r}_1=\mathbf{r}_2} = \psi_{reg}(z)$$

At large distance $r, |z_1 - z_2| \to \infty$:

$$\psi(\mathbf{r}, z_1, z_2) = \phi_0(z_1) \left[\frac{1}{a_{eff}} - \frac{1}{\sqrt{\frac{m_2}{\mu} z_2^2 + r^2}} \right], \qquad (1)$$

which defines the effective scattering length a_{eff}
At short distance $R = \sqrt{r^2 + (z_1 - z_2)^2} \to 0$

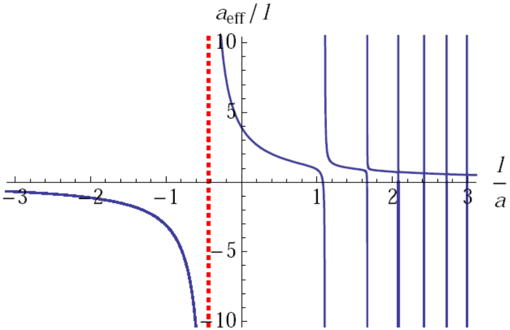
$$\psi(\mathbf{r}, z_1, z_2) = \left[\frac{1}{a} - \frac{1}{R} \right] \psi_{reg}(z)|_{z=z_1=z_2},$$

Secular equation ties a_{eff} with a:

$$\frac{1}{a} b_i - \tilde{M}_{ij} b_j = \left[\frac{1}{a_{eff}} \sqrt{\frac{m_2}{\mu}} \delta_{0i}\delta_{0j} + M_{ij} \right] b_j$$

Scattering length in mixed dimensions (III)

Result: $a_{eff} \to \infty$ for multiple values of a/ℓ depending only on the mass ratio m_1/m_2 (*)



[courtesy of Y. Nishida]

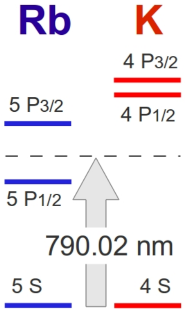
Analysis very close to previous work of P.Massignan and Y.Castin, Phys. Rev. A 74, 013616 (2006)

(∗) only approx with effective range corrections ...

How-to? Species-selective dipole potential

Suitable choice of laser wavelength → optical dipole potential selective on atomic species
[L. J. LeBlanc and J. H. Thywissen, Phys. Rev. A 75, 053612 (2007)]

For our particular mixture, i.e. ^{87}Rb–^{41}K, $\lambda = 790.02\,$nm.



For Rb, D1 and D2 light-shifts cancel out

Tight confinement realized by 1D optical lattice
$V_0 = sE_r$
Array of 2D traps:

$$\ell = \lambda/(2\pi s^{1/4})$$

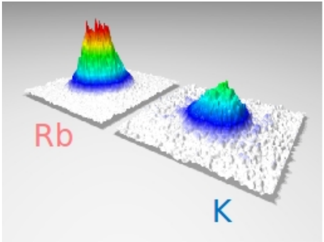
(e.g. $\ell = 1200 a_0$ for $s = 15$)

Entropy transfer

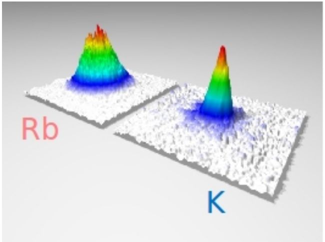
Interspecies entropy transfer

Idea: compress only K

- $\omega(K)$, $T_c(K)$ increase
- $T \sim$ const (thanks to Rb)
- $T/Tc(K)$ decreases $\rightarrow$ K entropy lower



before



after compression

Similar to reversible BEC with "dimple" potential

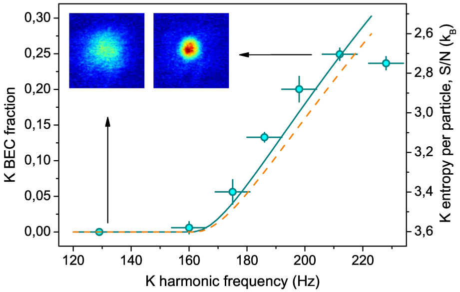
[D. M. Stamper-Kurn et al., Phys. Rev. Lett. 81, 2194 (1998)]

BEC transition

Textbook thermodynamics, ideal gases in harmonic trap $\omega \rightarrow$ K BEC fraction

Total entropy conservation

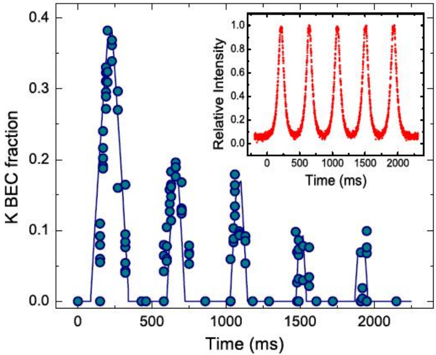
- Above T_c: $S/(Nk_B) = 4g_4(z)/g_3(z) - \log(z)$
  with $N = g_3(z)(T/\omega)^3$, $g_n(z) = \sum_{k>0} z^k/k^n$
- Below T_c: $S/(Nk_B) = 4[g_4(1)/g_3(1)](1 - f_c)$
  BEC fraction $f_c = 1 - t^3 - \eta[g_2(1)/g_3(1)]t^2(1 - t^3)^{2/5}$, $\quad t = T/T_c$, $\quad \eta = \mu/k_B T$



[J. Catani *et al.*, Phys. Rev. Lett. 103, 140401 (2009)]

Reversibility of BEC phase transition

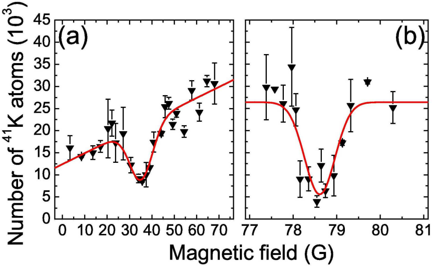
Compression/decompression cycles: $\omega_K/(2\pi) = 128 \leftrightarrow 216\,\text{Hz}$
Up to 5 cycles of BEC



In practice, reversibility limit is heating/atom loss of Rb

Interspecies Feshbach resonances

Interspecies ^{41}K-^{87}Rb Feshbach resonances



Inelastic atomic collisions, 2 interspecies FR:

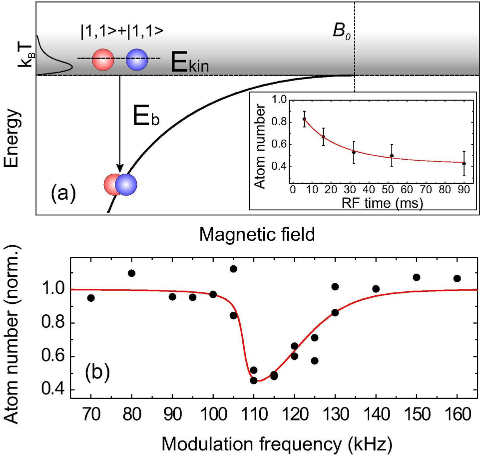
broad, $B_0 \simeq 39$G

narrow, $B_0 \simeq 79$G

G. Thalhammer *et al.*, Phys. Rev. Lett. 100, 210402 (2008)

RF association of Feshbach molecules

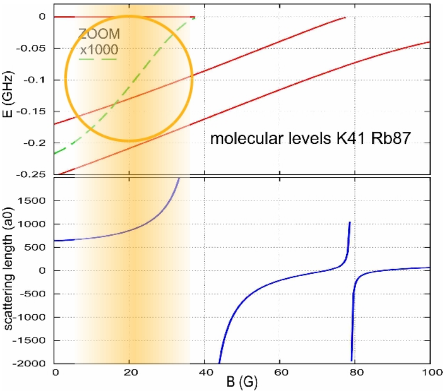
Precise method to locate FR → molecular spectroscopy, i.e. drive free-to-bound transitions by oscillating magnetic field [S. T. Thompson *et al.* Phys. Rev. Lett.95 190404 (2005)]



Measure loss of atoms converted in molecules

[C. Weber *et al.* Phys. Rev. A 78 061601(R) (2008)]

Control of interspecies interactions



Feshbach spectroscopy +

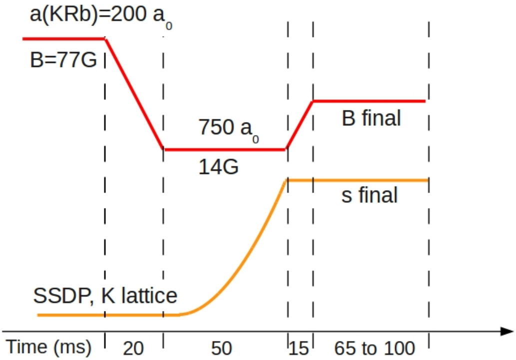
collisional model, A. Simoni, University of Rennes

→ knowledge of ^{41}K-^{87}Rb scattering length

Mix-dimensional scattering

Experiment

- Mixture in (1,1)+(1,1) hf states, sympathetic cooling in optical trap to 300 nK
- Set B below both FR, raise SSDP lattice to selectively confine K in 2D
- Set B to final value, hold for fixed time, record remaining atom number
  Assumption: enhancement of inelastic collisions, i.e. atom number minima, for $a_{\text{eff}} \to \infty$



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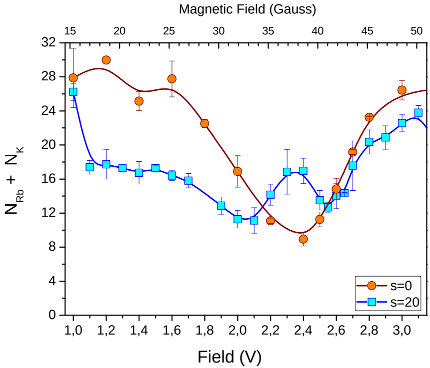

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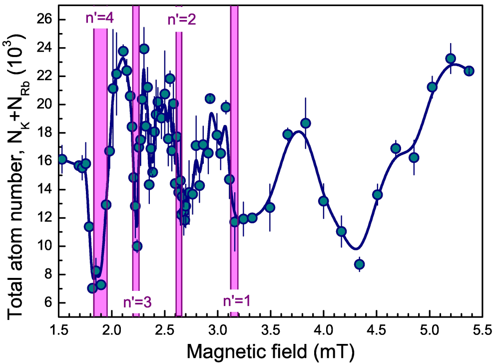
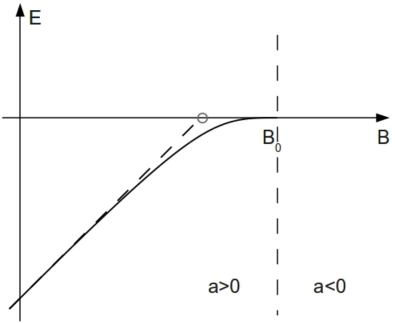


Simple physical picture

Position of resonances obtained by a simple argument



Degeneracy:
$E(\text{threshold}) = E$ of bound state

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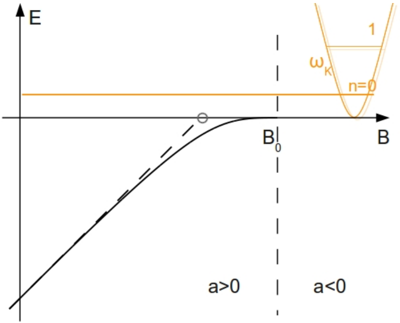

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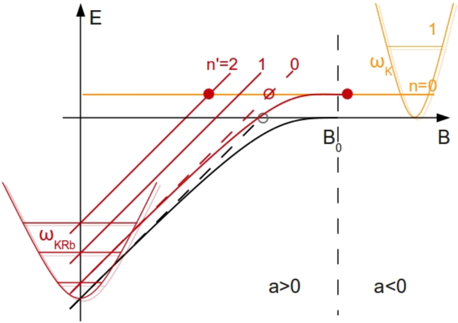


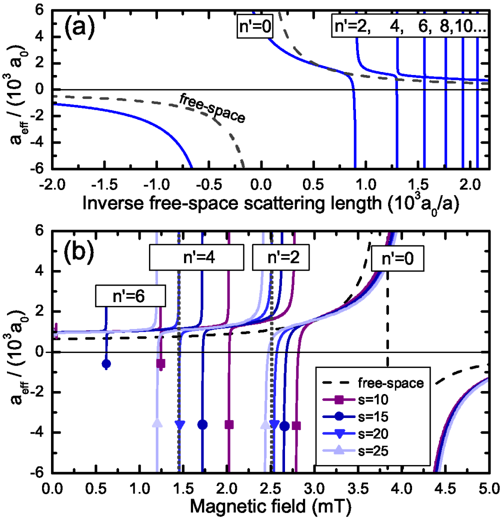
Degeneracy:
E(threshold) $=$ E of bound state from excited confined states

$$(1/2)\omega_K = (n' + 1/2)\omega_{KRb} - E_{\rm binding}/\hbar$$

where $\omega_{KRb} = \omega_K\sqrt{m_K/(m_K + m_{Rb})}$
$p_{Rb}^2/(2m_{Rb})$ neglected

- very good agreement with above results of scattering theory
- multiple resonances because internal and center-of-mass motion are coupled
- by parity conservation, only states with even-n' couple to $n = 0$ (for $p_{Rb} = 0$)

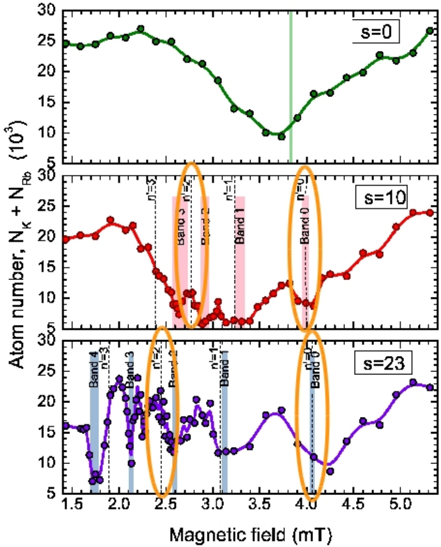
Predictions for our specific FR



To change a_{KRb}, change magnetic field

To change ω_K, ω_{KRb}, change s, strength of SSDP lattice

Experimental data



Predictions do not match the data

- positions are offset
- peaks at odd-n'

Harmonic oscillator levels are not correct → lattice band structure

- At $T = 300$ nK, $\sqrt{k_B T / m_K} \simeq 0.6\hbar k$ → thermal filling of 1st BZ
- quasi-momenta $q \neq 0$ not parity-eigenstates → odd-n' peaks allowed

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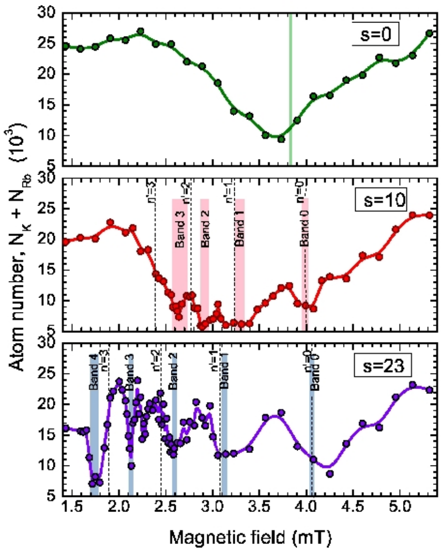

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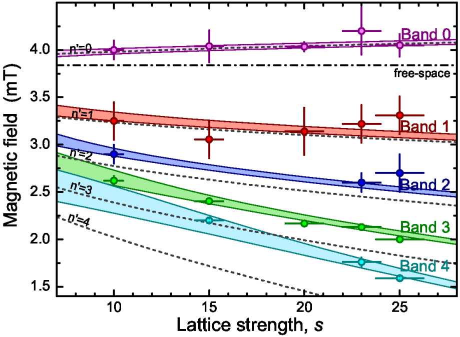
Experiment/theory comparison

Energy degeneracy re-calculated:

$$p^2/(2m_{Rb}) + \epsilon_K(0, q; V_{\rm lat}^K) = \epsilon_{KRb}(n', q + p; V_{\rm lat}^K) - E_b$$



- $\epsilon_i(n, q; V_{\rm lat}^K)$, energy of the Bloch wave of particle $i = K,\ KRb$
- (n, q) quasimomentum/band index
- $V_{\rm lat}^K$ lattice potential
- p initial Rb momentum
- E_b, binding energy

Neglect resonance shift due to channel coupling, for all $n' > 0$

Summary

- ▷ species-selective potential engineers a mix-dimensional configuration
- ▷ entropy transfer and reversible BEC
- ▷ mix-dimensional scattering resonances are observed, their position is accounted for by simple energy argument
- ▷ lattice band structure needed
- ▷ mix-dimensional configuration a route to Efimov physics?
  Identical particles: $2.3 < D < 3.8 \Rightarrow D = 3$
  2 fermions: $m_1/m_2 > 13.6$ in 3D, $m_1/m_2 > 6.35$ in 2D-3D, $m_1/m_2 > 2.06$ in 1D-3D

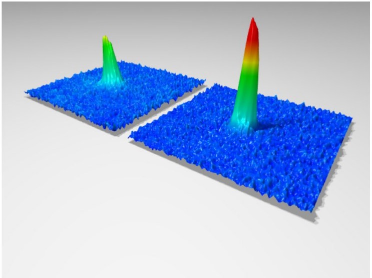
Acknowledgements

BEC3 Group at LENS, Firenze

Staff:	M. Inguscio, FM
Postdocs:	J. Catani, G. Lamporesi,
	G. Thalhammer (now in Innsbruck)
PhD students:	G. Barontini, C. Weber (now in Bonn)
Undergraduate students:	F. Rabatti

Positions available for PhD students

The end



Thank you

http://quantumgases.lens.unifi.it