Atomic Bose-Bose mixtures as quantum simulators

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Motivations

- Quantum magnetism:

  antiferromagnetic Néel state
  xy-ferromagnetic state or supercounterfluidity/paired superfluidity

- Heteronuclear dipolar bosonic molecules:

  double Mott insulator with one particle per species per site ideal starting point

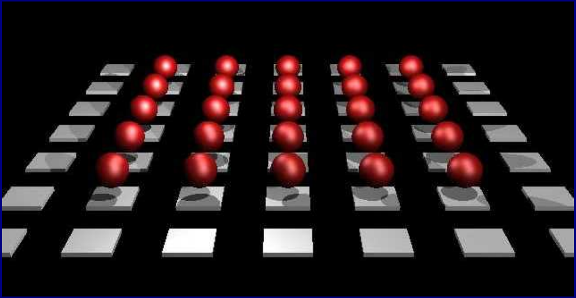
- Entropy control of species A by means of a species B

Outline

1. Quantum magnetism with BB mixtures
   - Mimicking spin systems
   - Mean-field results
   - Quantum Montecarlo results
2. Experiments with BB mixtures in Optical Lattices
   - KRb mixture in 3D optical lattice
   - Control of KRb interactions
3. Open questions
   - Detection
   - Critical temperature
   - Entropy control in harmonic trap

Quantum Magnetism

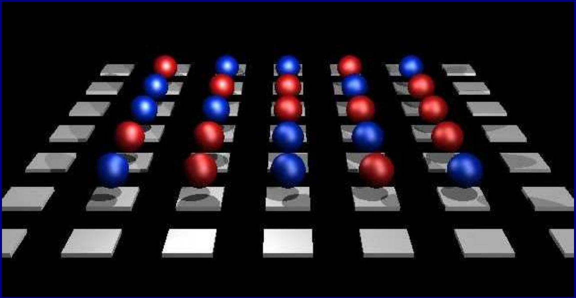
In deep optical lattices, atom localize



Quantum Magnetism

In deep optical lattices, atom localize

Add species/flavor/spin degree of freedom: at zero tunnelling, huge degeneracy as $\sim 2^{2N}$ states have same energy

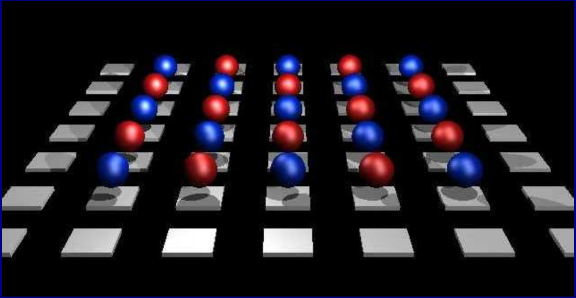


Quantum Magnetism

In deep optical lattices, atom localize

Add species/flavor/spin degree of freedom: at zero tunnelling, huge degeneracy as $\sim 2^{2N}$ states have same energy

At finite tunnelling, second order tunnelling can create ordered phases



Two species Bose-Hubbard model

- Starting point: single band approximation valid for both species (more on this later)
- Two species Bose-Hubbard model (2sBHm):

$$H = \sum_{\langle i,j \rangle} -(J_a a_i^\dagger a_j + J_b b_i^\dagger b_j + h.c.) + \sum_i U a_i^\dagger a_i b_i^\dagger b_i + (V_a/2) a_i^\dagger a_i^\dagger a_i a_i + (Vb/2) b_i^\dagger b_i^\dagger b_i b_i - \mu_a a_i^\dagger a_i - \mu_b b_i^\dagger b_i$$

- For typical experiments, $\mu_{a,b}$ are site-dependent due to the underlying harmonic confinement

2sBHm, perturbative analysis

In the regime of small tunnellings: $J_a, J_b \ll V_a, V_b$
second order perturbation theory is used [A. B. Kuklov and B. V. Svistunov, PRL 90, 100401 (2003)]

Mapping of creation/annihilation to spin operators:

$$
\begin{aligned}
S_j^z &= (a_j^\dagger a_j - b_j^\dagger b_j)/2 \\
S_j^y &= i(a_j^\dagger b_j - b_j^\dagger a_j)/2 \\
S_j^x &= (a_j^\dagger b_j + b_j^\dagger a_j)/2
\end{aligned}
$$

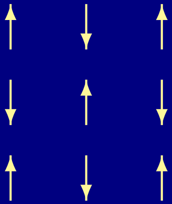
Effective XXZ hamiltonian, for a balanced mixture with filling factor equal to $S/2$ *per species*

$$H_{\mathrm{eff}} = -\sum_{\langle ij \rangle} \left[J_\perp (S_i^x S_j^x + S_i^y S_j^y) + J_z S_i^z S_j^z \right] + u \sum_i (S_i^z)^2 - h \sum_i S_i^z$$

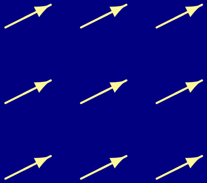
with following parameters
$u = V_a - U = V_b - U$, $J_\perp = \frac{4 J_a J_b}{U}$, $J_z = 2\frac{J_a^2 + J_b^2}{U}$, $h = z(2S+1)\frac{J_a^2 - J_b^2}{U}$

Qualitative phase diagram

Simplest case: 1/2 filling per species, i.e., total filling $= 1$



$J_z > J_\perp$ Neel state



$J_\perp > J_z$ XY ferromagnet

In the language of two species:

- Neel state $\longrightarrow$ checkerboard phase, A-B-A-B-A-B-...
- XY ferromagnet $\longrightarrow$ "supercounterfluid" [A. B. Kuklov and B. V. Svistunov, PRL 90, 100401 (2003)]
  paired order parameter $\langle a_j^\dagger b_j \rangle \neq 0$

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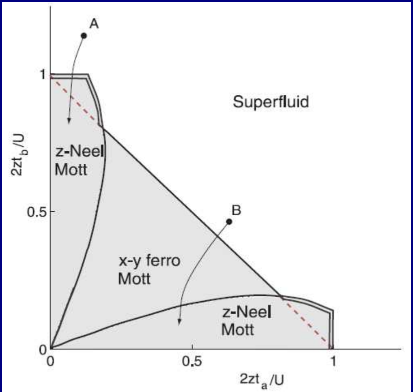
Mean-field phase diagram

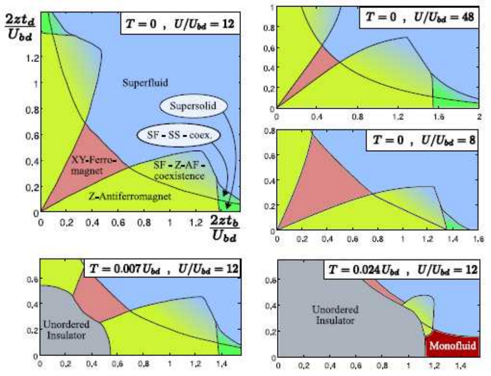
Phase diagram with mean-field approach (E. Altman *et al.*, New J. Phys. 2003)



Similar results: A. Isacsson *et al.*, PRB 2005

Mean-field phase diagram

Phase diagram with Bosonic Dynamic Mean-Field Theory (A. Hubener *et al.*, arXiv:0902.2212)

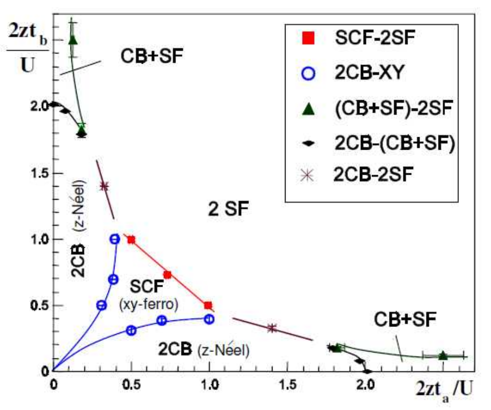


Notice: here $U = V_a = V_b$

Outline

Quantum Montecarlo phase diagram

Only recently, QMC results in 2D (S. G. Söyler *et al.*, arXiv:0811.0397)
Half-filling per species, hard-core bosons $V_{a,b} = \infty$



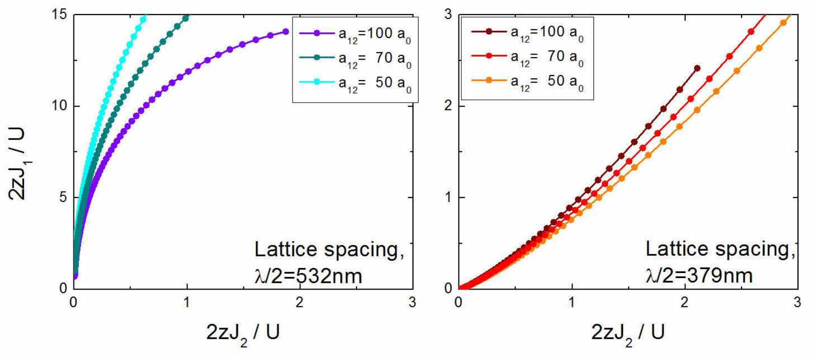
Qualitatively similar to mean-field but quantitative differences for phase boundaries

Trajectories in phase diagram

Experimentally, 1+2 control parameters:

1. lattice wavelength (change in 1+ week)
2. strength of optical lattice → changes both J_1 and J_2, NOT independently
3. interspecies interactions, via Feshbach resonances

Example, ^{87}Rb and ^{41}K



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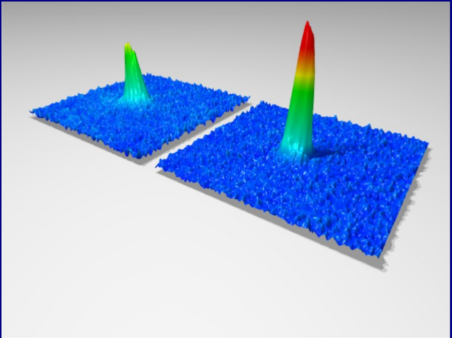
K-Rb mixture, double BEC



^{41}K ^{87}Rb

^{41}K:

$$\begin{aligned} R_x &= 60\,\mu\text{m} \\ R_y &= 144\,\mu\text{m} \\ N_K &= 27.5 \times 10^3 \end{aligned}$$

^{87}Rb:

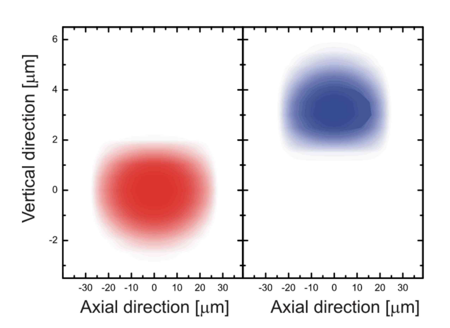
$$\begin{aligned} R_x &= 68\,\mu\text{m} \\ R_y &= 119\,\mu\text{m} \\ N_K &= 40.0 \times 10^3 \end{aligned}$$

See also G. Modugno *et al.* PRL (2002)
K. Aikawa *et al.*, NJP 11 055035 (2009)

Topology of the ground state

Same magnetic trapping potential but samples displaced by:

- gravity
- strong repulsive interatomic interactions, $a_{K-Rb} \gg a_K, a_{Rb}$



Numerical integration of 2 coupled Gross-Pitaevskii equation shows that the mixture is in phase separation

- $N_K = 20 \times 10^3, \quad a_K = 65 a_0$
- $N_{Rb} = 40 \times 10^3, \quad a_{Rb} = 98 a_0$
- $a_{K-Rb} = 163 a_0$

Starting point before raising lattice

Degenerate BB mixture in a 3D optical lattice

RAPID COMMUNICATIONS

PHYSICAL REVIEW A **77**, 011603(R) (2008)

Degenerate Bose-Bose mixture in a three-dimensional optical lattice

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(Received 19 June 2007; published 24 January 2008)

We produce a heteronuclear quantum degenerate mixture of two bosonic species, ^{87}Rb and ^{41}K, in a three-dimensional optical lattice. On raising the lattice barriers, we observe the disappearance of the inference pattern of the heavier ^{87}Rb, shifting toward shallower lattice depths in the presence of a minor fraction of ^{41}K. This effect is sizable and requires only a marginal overlap between the two species. We compare our results with similar findings reported for Fermi-Bose mixtures and discuss the interpretation scenarios proposed to date, arguing that the explanation may be linked to the increased effective mass due to the interspecies interactions.

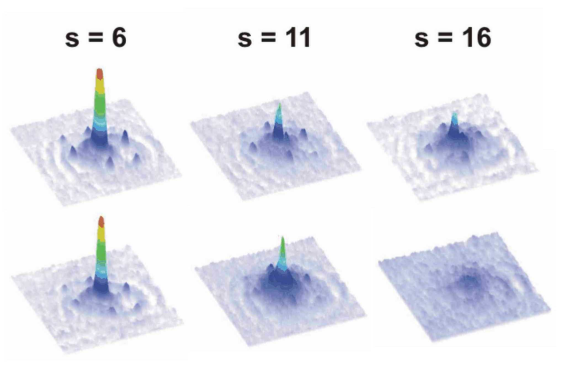
DOI: 10.1103/PhysRevA.77.011603 PACS number(s): 03.75.−b, 05.30.Jp, 73.43.Nq

Degenerate BB mixture in a 3D optical lattice

A 3D optical lattice ($\lambda/2 = 532\,\mathrm{nm}$) is imposed on the double condensate

Lattice strength V_0 same for K and Rb,
$s_{\mathrm{Rb}} \equiv V_0/E^r_{\mathrm{Rb}} = 2.3 s_{\mathrm{K}} \quad E^r = h^2/2m\lambda^2$

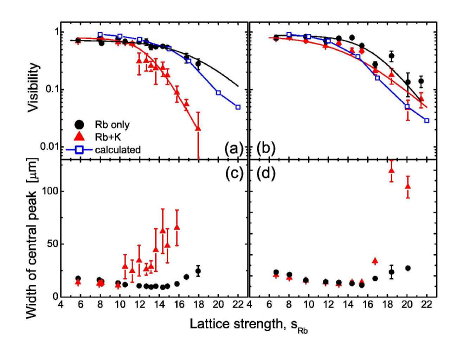
Smearing of momentum distribution $\rightarrow$ loss of Rb phase coherence (Mott insulator)

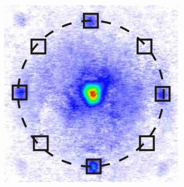


Only Rb

Rb in presence of 10% K impurities (K not shown)

Analyze visibility and width of Rb peaks



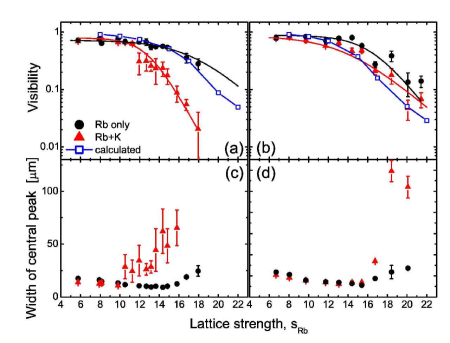


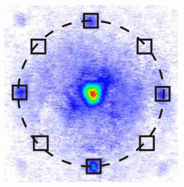
Fit the visibility
$v = (N_{\text{peaks}} - N_{\text{diag}})/(N_{\text{peaks}} + N_{\text{diag}})$
with phenomenological Fermi function:

$$v = \frac{v_0}{1 + \exp(\alpha(s - s_c))},$$

- $s_c = 12.4(3)$ with K

Analyze visibility and width of Rb peaks





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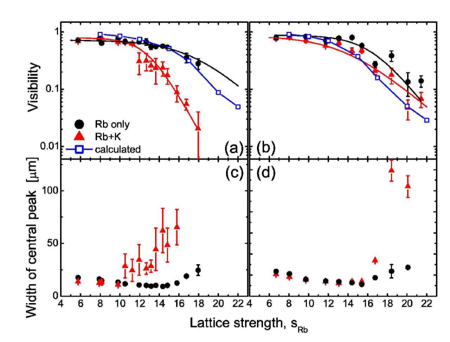
$v = (N_{\text{peaks}} - N_{\text{diag}})/(N_{\text{peaks}} + N_{\text{diag}})$
with phenomenological Fermi function:

$$v = \frac{v_0}{1 + \exp(\alpha(s - s_c))},$$

- $s_c = 12.4(3)$ with K
- $s_c = 16.8(4)$ without K

Analyze visibility and width of Rb peaks



Remarkable facts:

- Rb phase transition of Rb shifted to lower lattice depths due to the small fraction of superfluid K:
- only a marginal overlap due to phase-separation is expected
- similar results in Bose-Fermi mixtures
  (K. Günter *et al.* PRL 2006,
  S. Ospelkaus *et al.* PRL 2006,
  Th. Best *et al.* PRL 2009)

Indications of breakdown of single-band approx

Outline

Feshbach resonances

Control of $U(V_a, V_b)$ parameter of the Bose-Hubbard hamiltonian by means of control of relevant scattering length

Applied magnetic field induces degeneracy between bound state and unbound state belonging to two different scattering channels

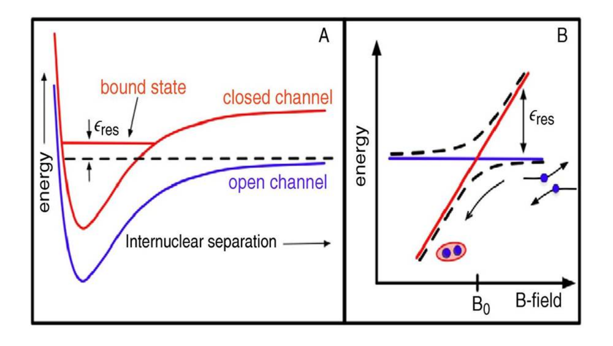
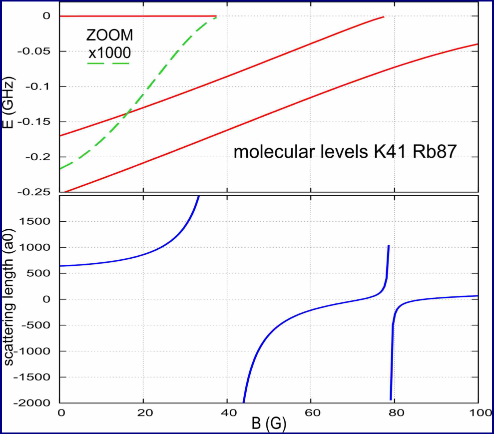


Image taken from J.Williams *et al*, NJP 6, 123 (2004)

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

At a Feshbach resonances, both 2-body elastic and 3-body inelastic collisions are enhanced

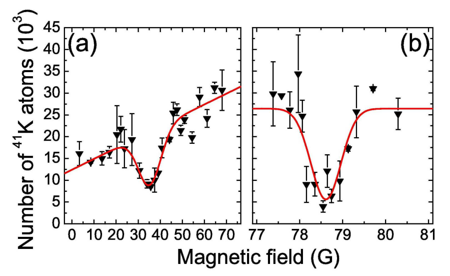


^{41}K-^{Rb}Rb mixture, theoretical predictions by A. Simoni, University of Rennes

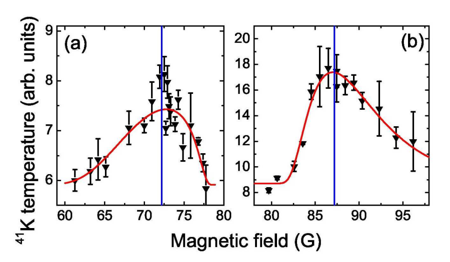
Collisional model, i.e., interatomic potential, built from existing data on isotopic mixture ^{40}K^{87}Rb

Ferlaino *et al.*, PRA 73, 040702 (2006)
Klempt *et al.*, PRA 76, 020701 (2007)

Experimental observation of Feshbach resonances



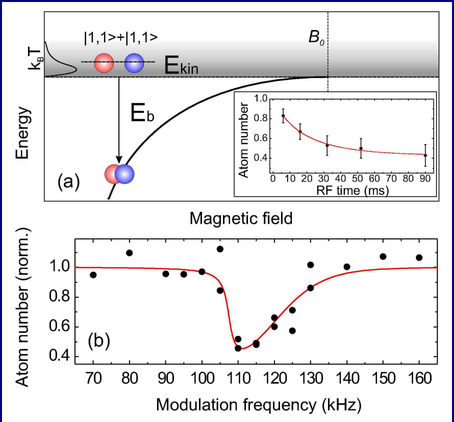
Atomic losses versus magnetic field: two interspecies resonances, broad one around 39 G, narrow one around 78 G



Thermalization efficiency proportional to elastic cross section: localize two zero-crossings, i.e., magnetic field where $a_{12} = 0$
Thalhammer *et al.*, PRL 2008

Experimental observation of Feshbach resonances

More precise method: molecular spectroscopy, drive free-to-bound transitions by oscillating magnetic field (Thompson *et al.* PRL 2005)

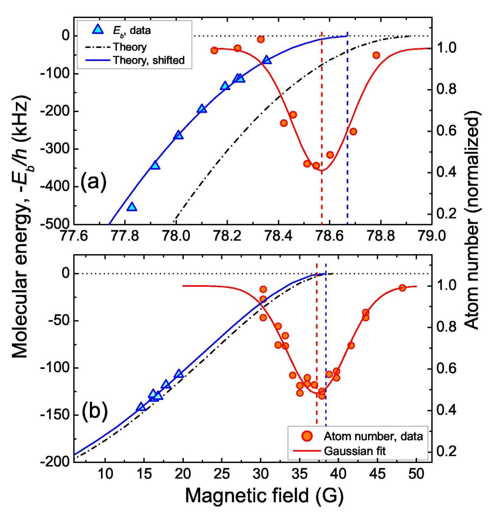


Measure loss of atoms converted in molecules

Lifetime < 5 ms, due to collisions with atoms

(Weber *et al.* PRA 2008)

Control of interspecies interactions via magnetic field



Measured binding energies +

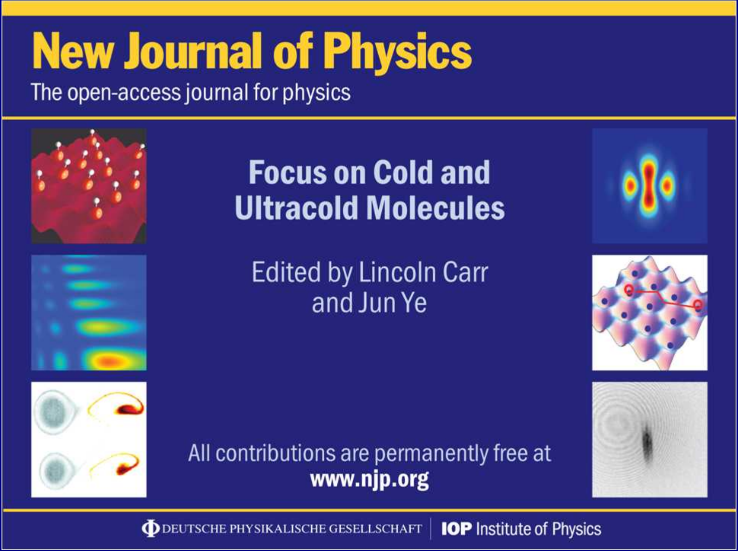
higher angular momentum Feshbach resonances +

collisional model →

accurate knowledge of scattering length, hence U parameter of Bose-Hubbard hamiltonian

Weber *et al.* PRA 78, 061601(R) (2008)
Thalhammer *et al.*, NJP 11, 055044 (2009)

Control of interspecies interactions via magnetic field



Toward experimental exploration of Bose-Bose phase diagram

Combine
degenerate mixture in optical lattice +
control of interspecies interactions
to explore the phase diagram.

Still remain a few issues
III: What are the main challenges for simulating quantum systems and using ultracold atoms and molecules for quantum information processing? What new simulation techniques on classical computers can be brought to bear on these challenges?

IV: What is the best way to perform a quantum computation in ultracold atoms and molecules with the appropriate fidelity? How does one then interrogate such a quantum simulation or "read out" the answer from such a quantum computer?

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Detection of spin order

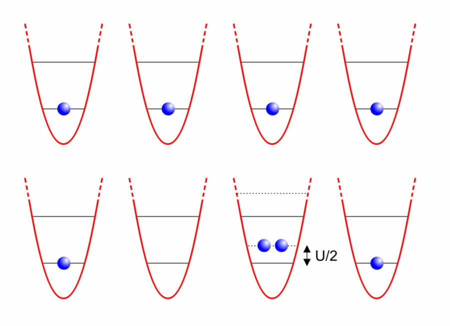
Borrowing techniques from single-species experiments, for checker-board phase:

- spectrum of particle-hole excitations
- noise correlations

Particle-hole excitation

Deep in Mott insulator

- $n = 1$, lowest excitation costs energy U

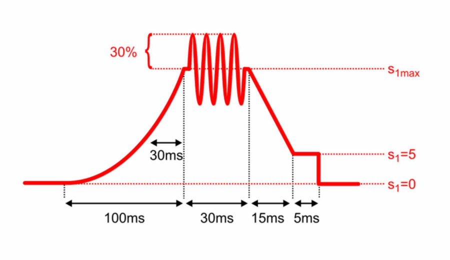


Particle-hole excitation

Deep in Mott insulator

- $n = 1$, lowest excitation costs energy U
- Recipe:
  modulate the lattice strength at ω
  go back to SF, measure the momentum distribution $n(k)$

  Excitations $\longrightarrow$ broadened $n(k)$



Particle-hole excitation

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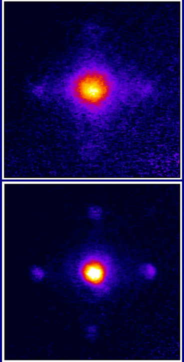
- Recipe:

  modulate the lattice strength at ω
  go back to SF, measure the momentum distribution $n(k)$

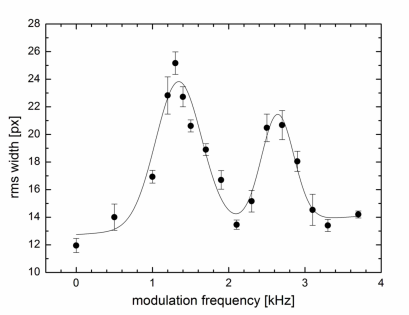
  Excitations $\longrightarrow$ broadened $n(k)$
- Quantify by width of peak at $k = 0$
  with and without modulation
  T. Stöferle *et al.*, PRL 92, 130403 (2004)



Mott insulator, excitation spectrum

Width of $n(k = 0)$ peak vs. modulation frequency ω

Excitation occurs when ω match energy cost of excitation, $V_a(V_b)$ for single-species Mott insulator



In CB phase, excitation peak expected to occur at U instead of $V_a(V_b)$

Noise correlations

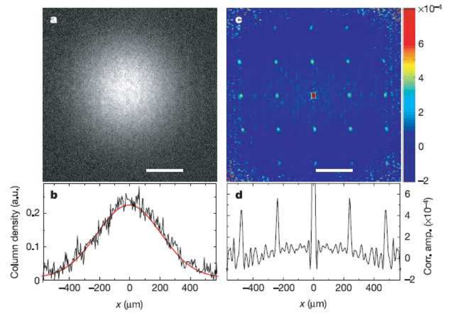


Image taken from S. Fölling *et al.*, Nature 2005

Mott insulator: no phase coherence but density-density correlation function displays peaks at momenta $2nk = 2n\pi/d$, $d = \lambda/2$

Proposed by E. Altman *et al.*, PRA 70, 013603 (2004)

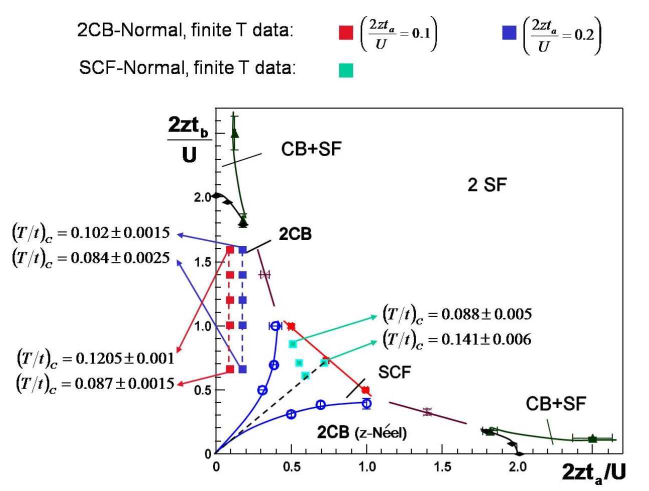
Observed: S. Fölling *et al.*, Nature 434, 481 (2005)
M. Greiner *et al.*, PRL 94, 110401 (2005)

In CB atoms of one species in every second site $\rightarrow$ expect half-periodicity at $k = \pi/d$

Outline

How cold? Critical temperature

Preliminary (unpublished) QMC results, courtesy of B. Capogrosso-Sansone



Critical temperature for KRb mixture

Line in checker-board (AFM) phase:

$$2zJ_a/U = .2 \rightarrow s_{\mathrm{Rb}} \simeq 48(a = \mathrm{Rb}, b = \mathrm{K})$$

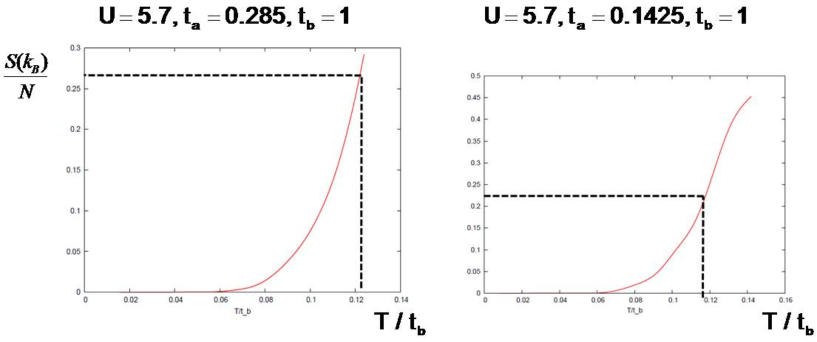
Therefore

s_{Rb}	$J_{\mathrm{a,Rb}}$	$J_{\mathrm{b,K}}$	T_c
48	0.076 Hz	10 Hz	1 Hz
			48 pK (!)

Extremely low temperatures

How cold? Entropy per particle

Temperature in deep optical lattices difficult to predict and to measure
Focus on entropy
Preliminary (unpublished) QMC results, courtesy of B. Capogrosso-Sansone



Required entropy per particle $\sim 0.2k_B$

In harmonic trap, $S/N = 0.2k_B \rightarrow$ condensate fraction ~ 0.95

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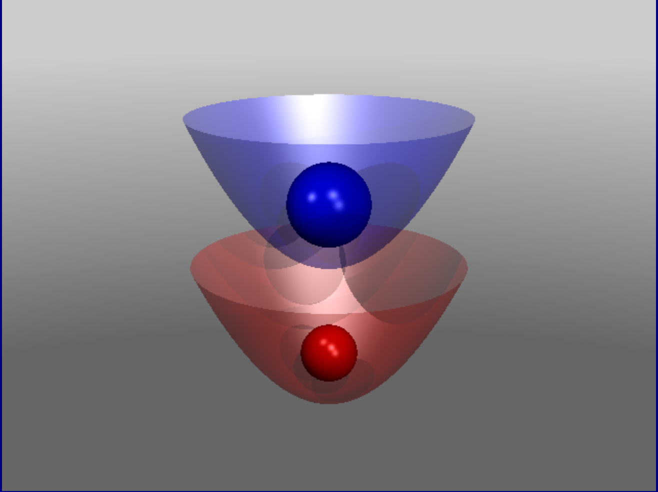
Independent manipulation of each species

In a mixture, independently manipulation of two gases makes it possible to control the entropy of gas A through entropy-transfer to gas B



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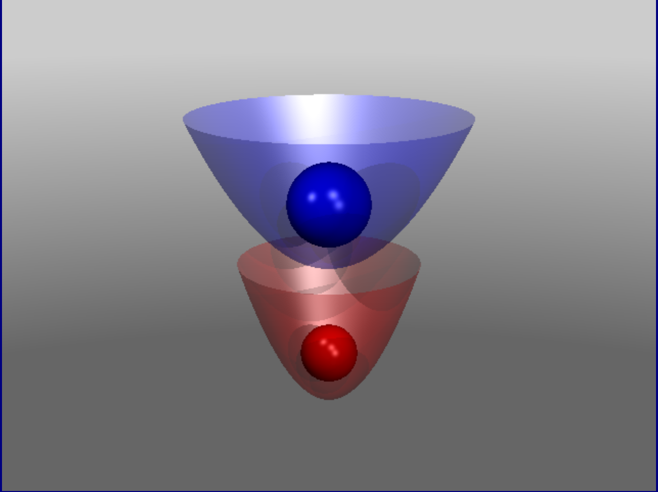

Interspecies entropy transfer

Idea: compress only gas A (for us, K) in presence of larger number of gas B (Rb)
Critical temperature of K increases ($T_c \sim \omega$) BUT T remains constant
Therefore, entropy goes from K to Rb

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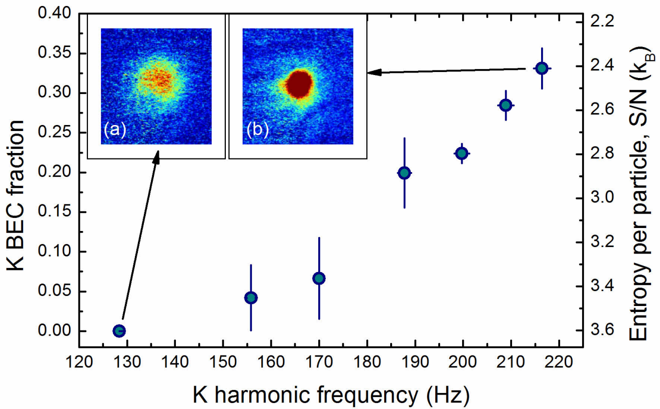
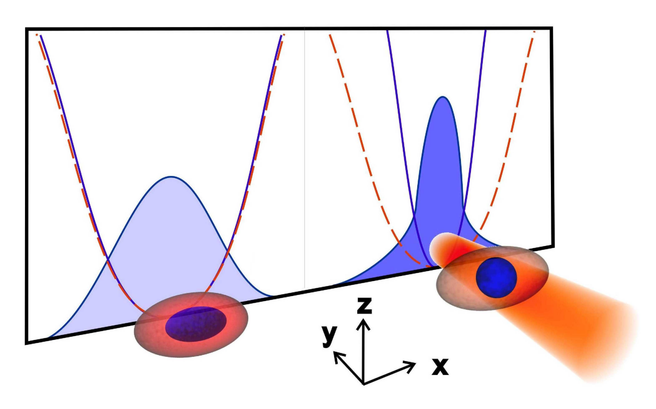


Tool: species-selective dipole potential

Selective compression of one single species by means of optical potential

Optical potential naturally distinguishes between two atomic species, in our case we tune wavelength to a “special” value so that $V_{\mathrm{Rb}} \ll V_{\mathrm{K}}$



Conclusions

- Bose-Bose mixture can simulate a specific spin hamiltonian with nearest-neighbors interactions, H_{XXZ}
- Experimental handles on hamiltonian parameters established for KRb mixture
- Still open issues:

  how to detect phases?
  can we reach the necessary low temperature/entropies?

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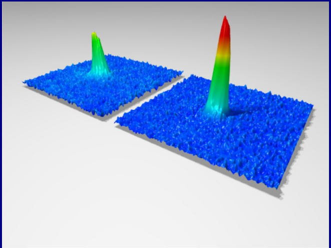
The end



Thank you