Fermi-Bose and Bose-Bose quantum degenerate K-Rb mixtures

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OUTLINE

Sympathetic cooling of potassium with rubidium: BEC of ^{41}K

Collisional physics for potassium-rubidium mixtures

Two species BEC (scissor mode oscillations)

Fermi-Bose (^{40}K-^{87}Rb) degenerate mixture with strong attractive interaction

Collapse of a degenerate Fermi gas

Perspectives

Degenerate mixtures of (different) alkali atoms:

- new degenerate species
- cooling of fermions
- ultracold heteronuclear molecules

Results from:

Paris, Rice (^{7}Li-^{6}Li) : different isotopes

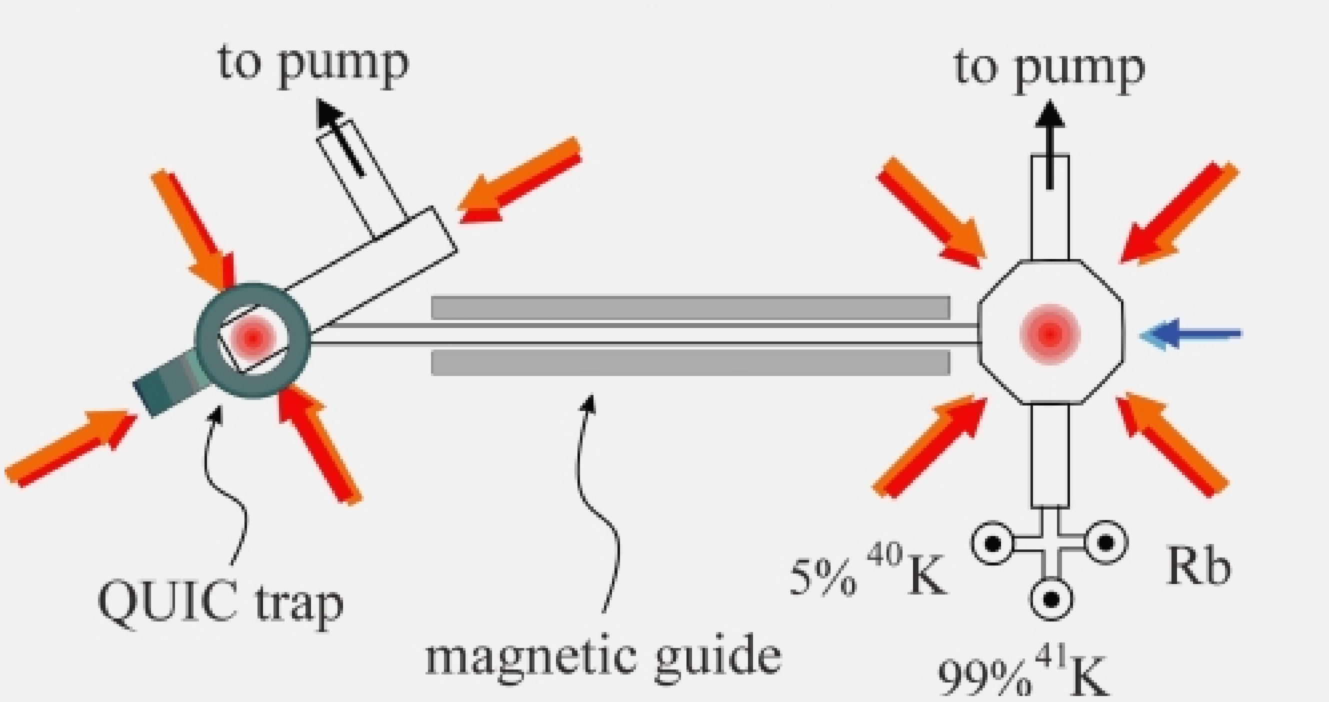
MIT (^{23}Na-^{6}Li) : different species

Firenze (^{87}Rb-^{40}K, ^{87}Rb-^{41}K)

Interactions at ultralow temperatures:

sympathetic cooling, mechanical stability, phase coexistence or separation, pairing, ...

Mixing rubidium with potassium



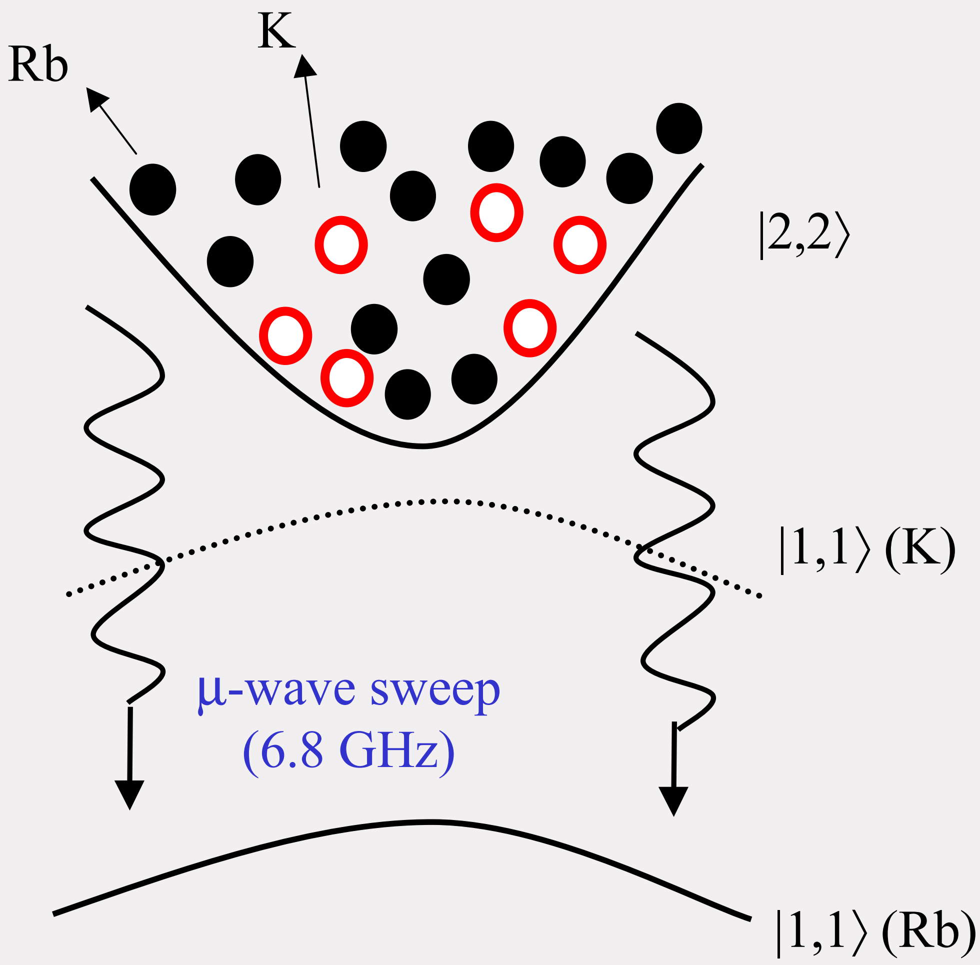
With minor changes we create boson-boson and boson-fermion mixtures.

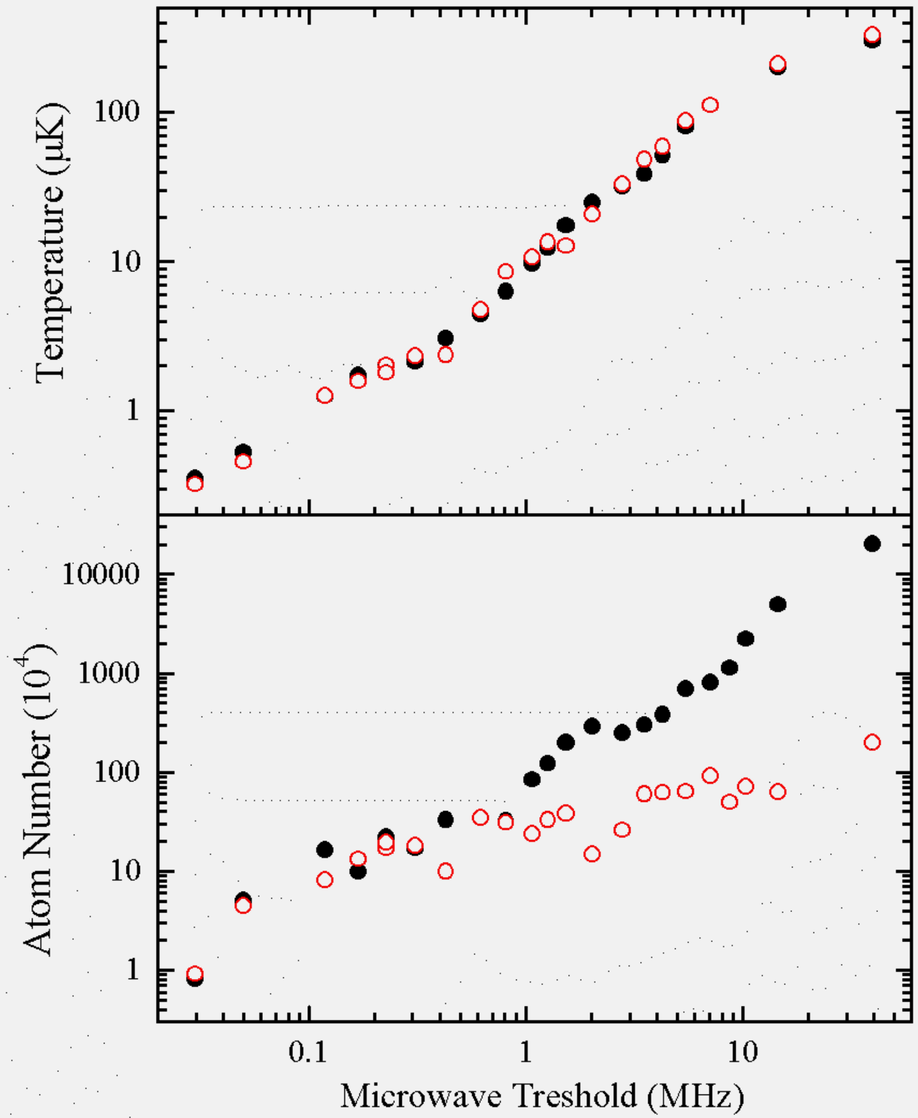
Typical abundances before magnetic trapping:

- 5×10^8 ^{87}Rb atoms at 50μK + 10^7 ^{41}K atoms at 300μK
- 5×10^8 ^{87}Rb atoms at 50μK + 5×10^5 ^{40}K atoms at 50μK

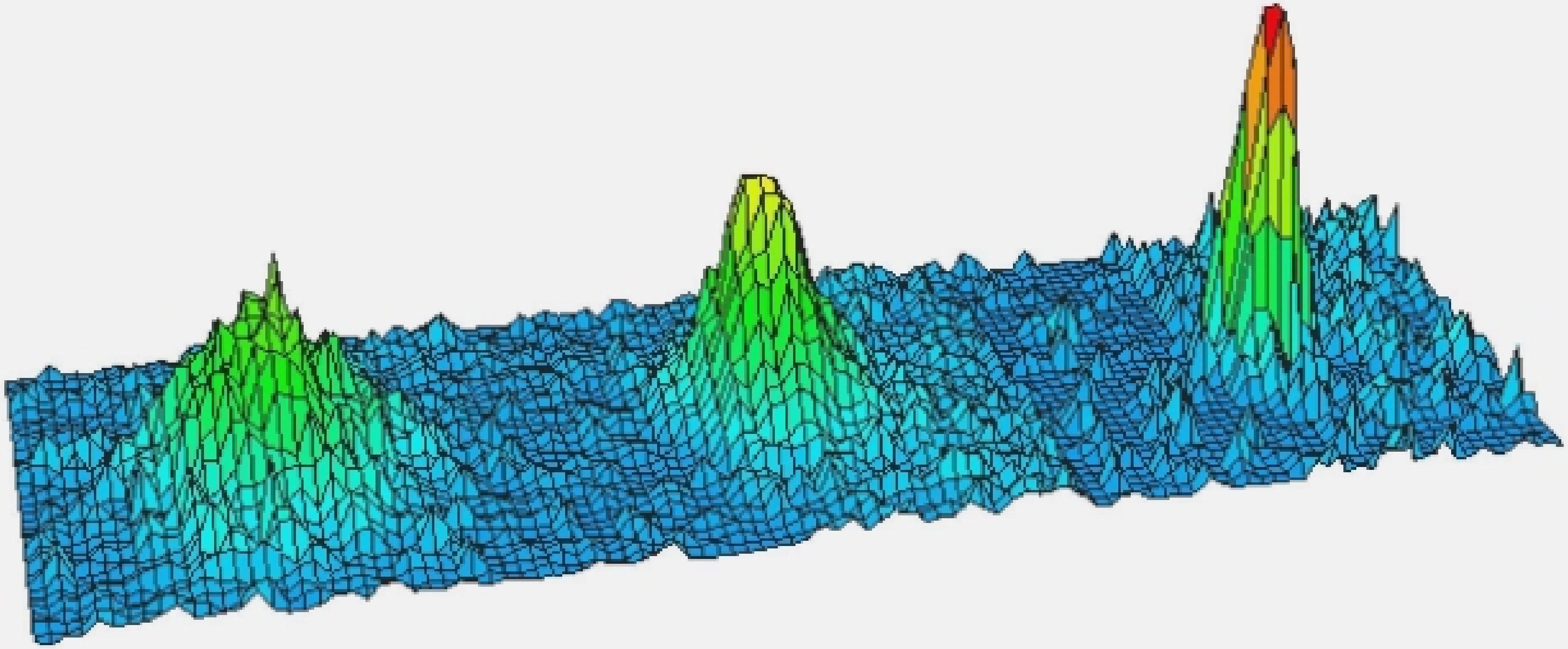
Sympathetic cooling between different species

- Simultaneous trapping of a Rb-K mixture
- Selective evaporation of Rb





^{41}K BEC



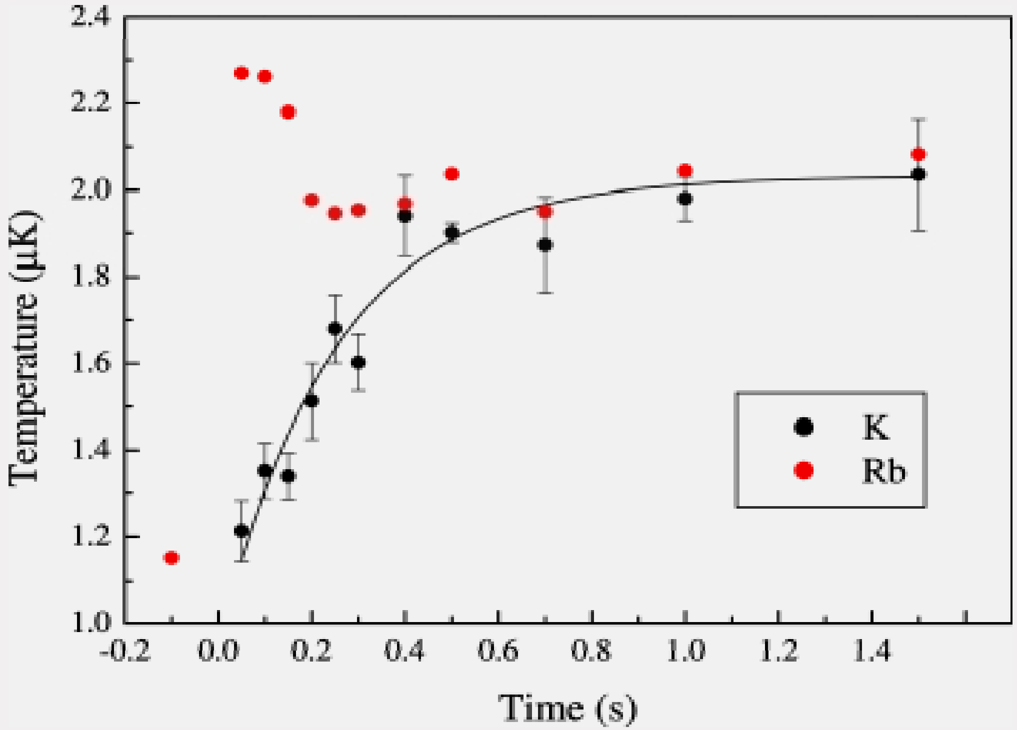
Favourable collisional properties

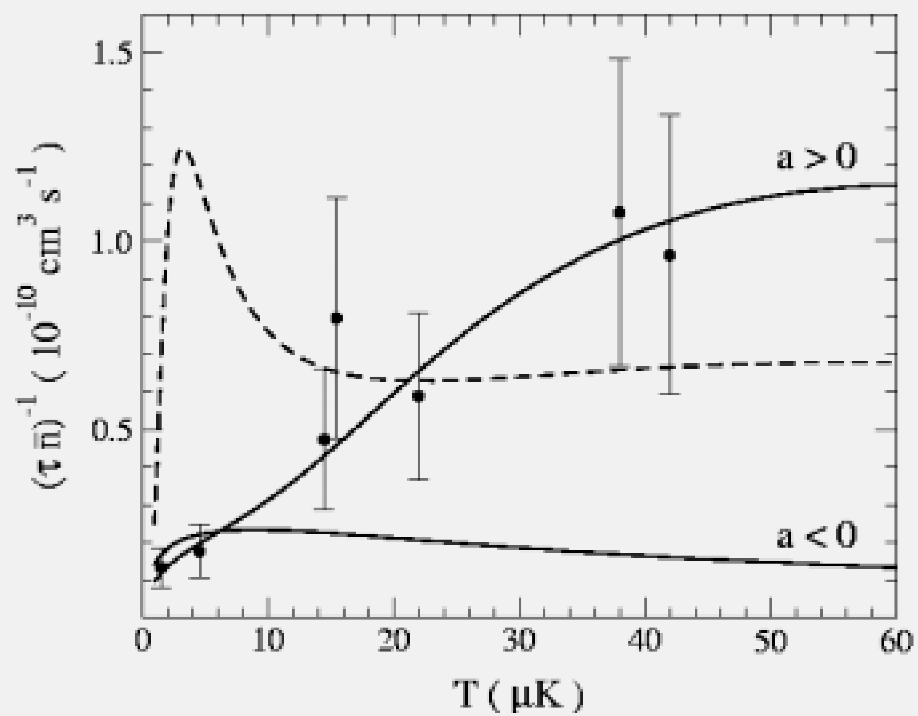
G. Modugno, G. Ferrari, G. Roati, R. J. Brecha, A. Simoni, M. Inguscio,
Science **294**, 1320 (2001)

Interspecies elastic collisions

G. Ferrari, M. Inguscio, W. Jastrebski, G. Modugno, G. Roati, A. Simoni, Phys. Rev. Lett. **89**, 053202 (2002).

- heat Rb by shaking the trap at twice the Rb frequency
- increase of K temperature
- extract collisional cross-section





Positive sign of a from the dependence on temperature of σ:

$$\sigma \approx \frac{4\pi a^2}{(1 - 1/2\, r_e a k^2)^2 + a^2 k^2}$$

^{41}K-^{87}Rb scattering length

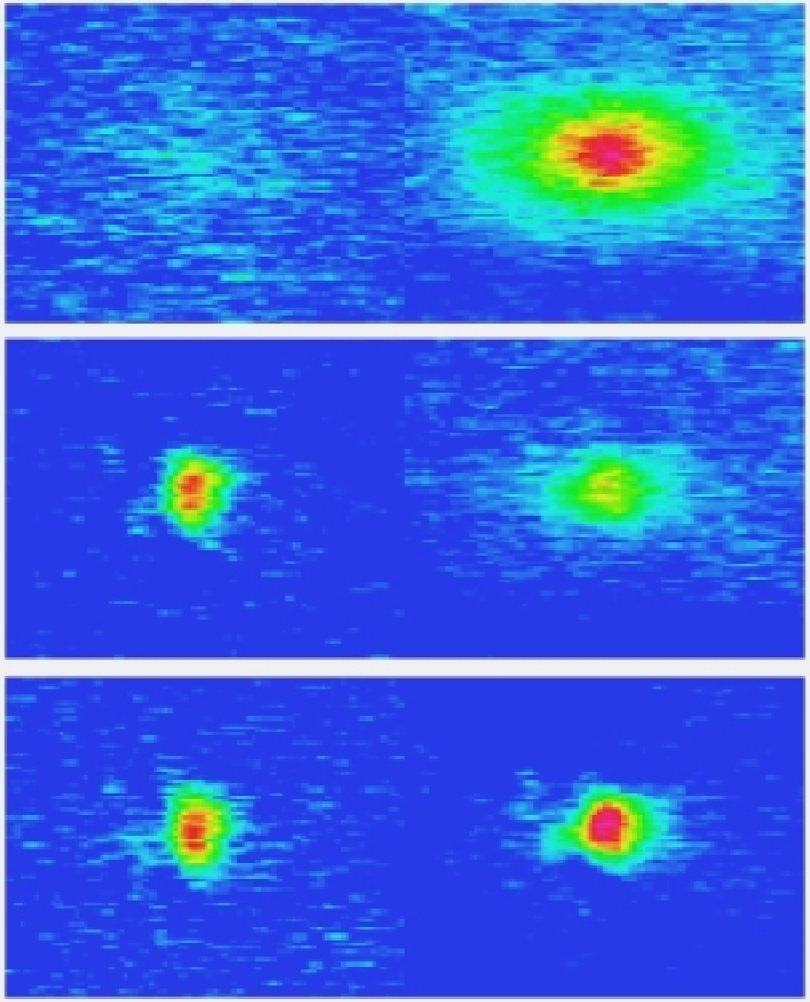
$$\mathbf{a_3 = +\,163\;(+57\;-12)\;a_3}$$

… all other combinations by mass scaling…

G. Ferrari, M. Inguscio, W. Jastrebski, G. Modugno, G. Roati, A. Simoni Phys. Rev. Lett. **89**, 053202 (2002).

A two-species BEC

^{41}K ^{87}Rb



1 μK

80 nK

<80 nK

Different critical temperatures:

$$T_c = \frac{\hbar\overline{\omega}}{k_B}(N/1.2)^{1/3} \propto M^{-1/2}$$

T_c:	120 nK K	80 nK Rb

G. Modugno, M. Modugno, F, Riboli, G, Roati, M. Inguscio, cond-mat/0205485

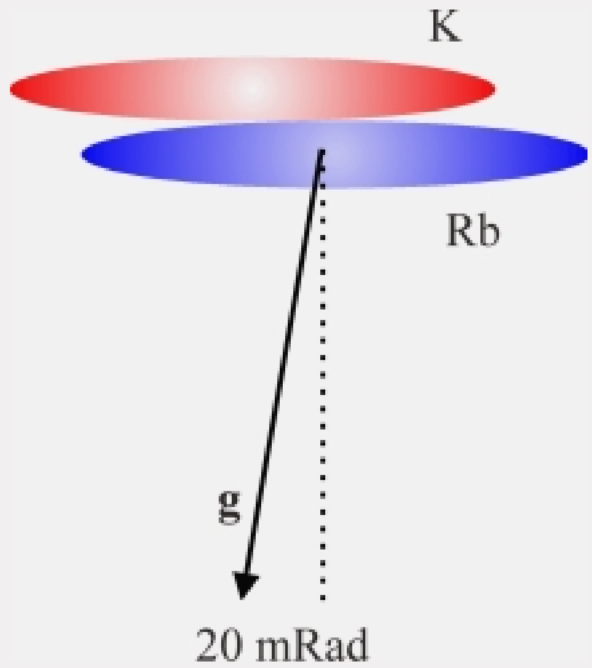
Stability and interactions

Interacting condensates:

$$g_i = \frac{4\pi \hbar^2 a_i}{m_i} \qquad g_{ij} = \frac{2\pi \hbar^2 a_{ij}}{\mu}$$

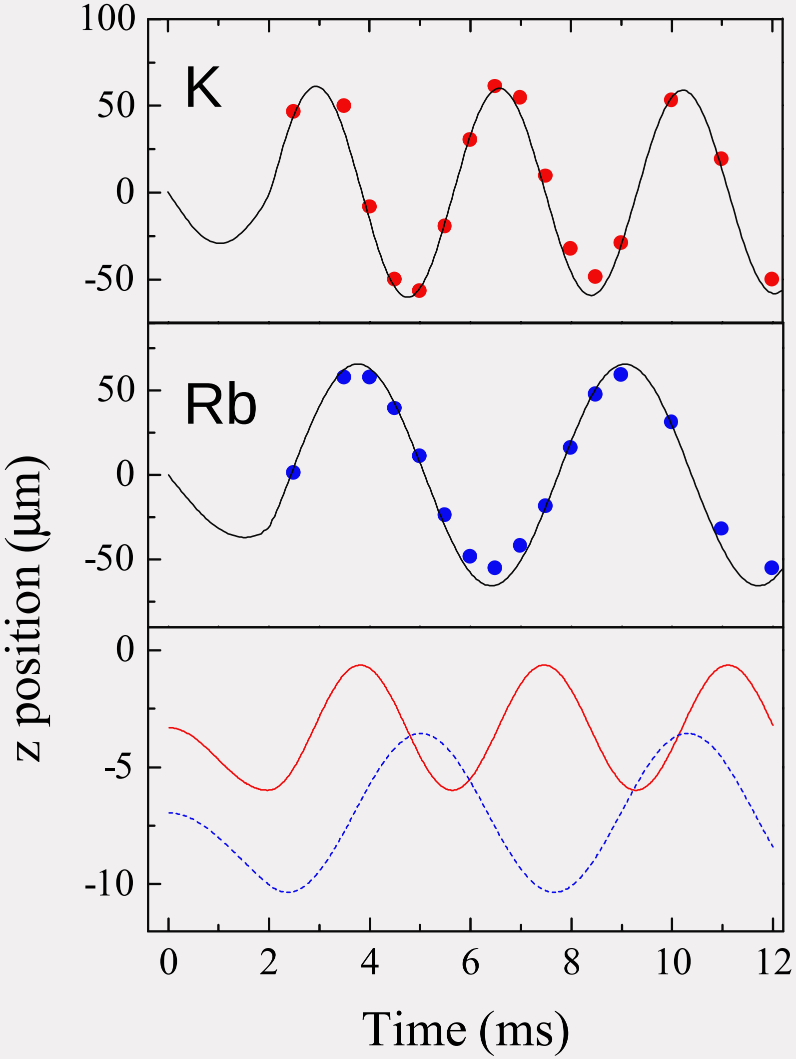
$$\Delta = \frac{g_{12}}{\sqrt{g_1 g_2}}$$

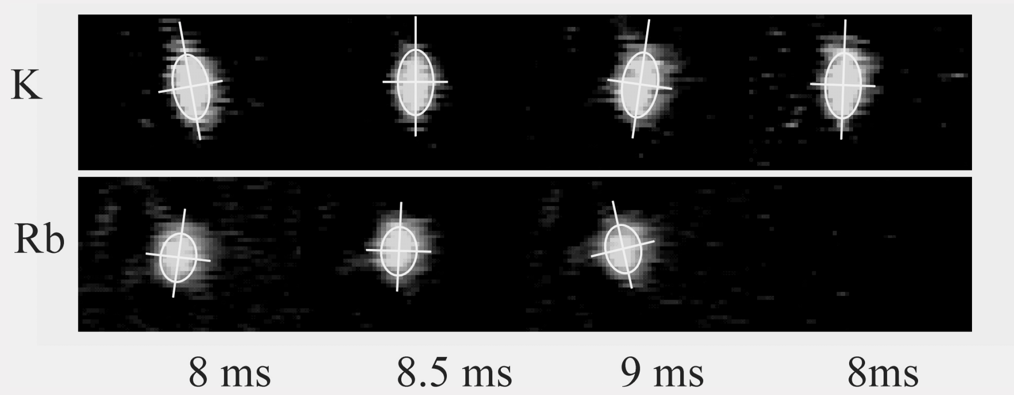
$$a_K = 60 a_0 \quad a_{Rb} = 100 a_0 \quad a_{KRb} = 160 a_0$$

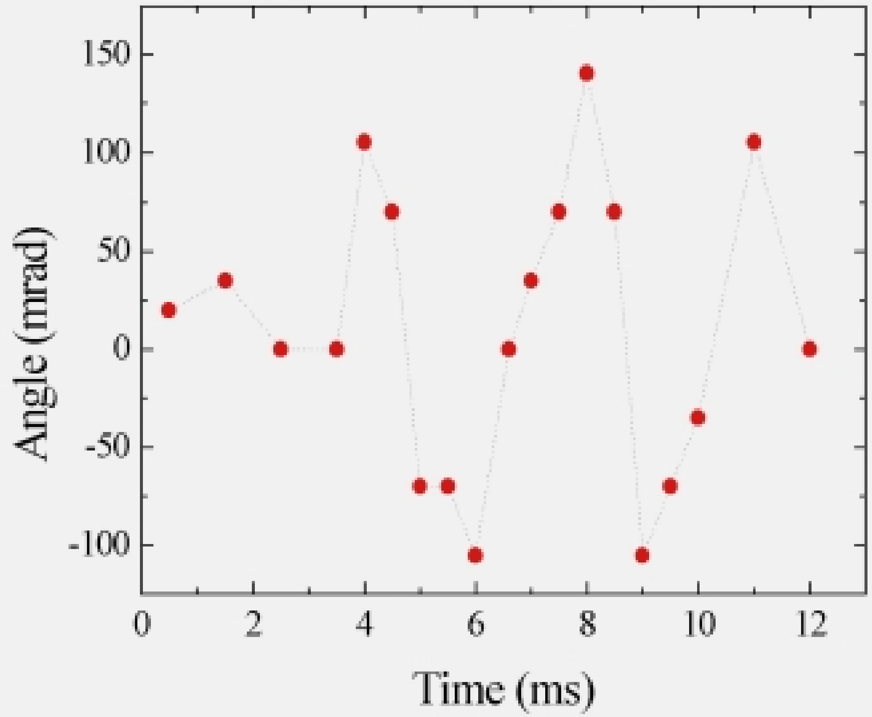


$\Delta = 3$ phase separation

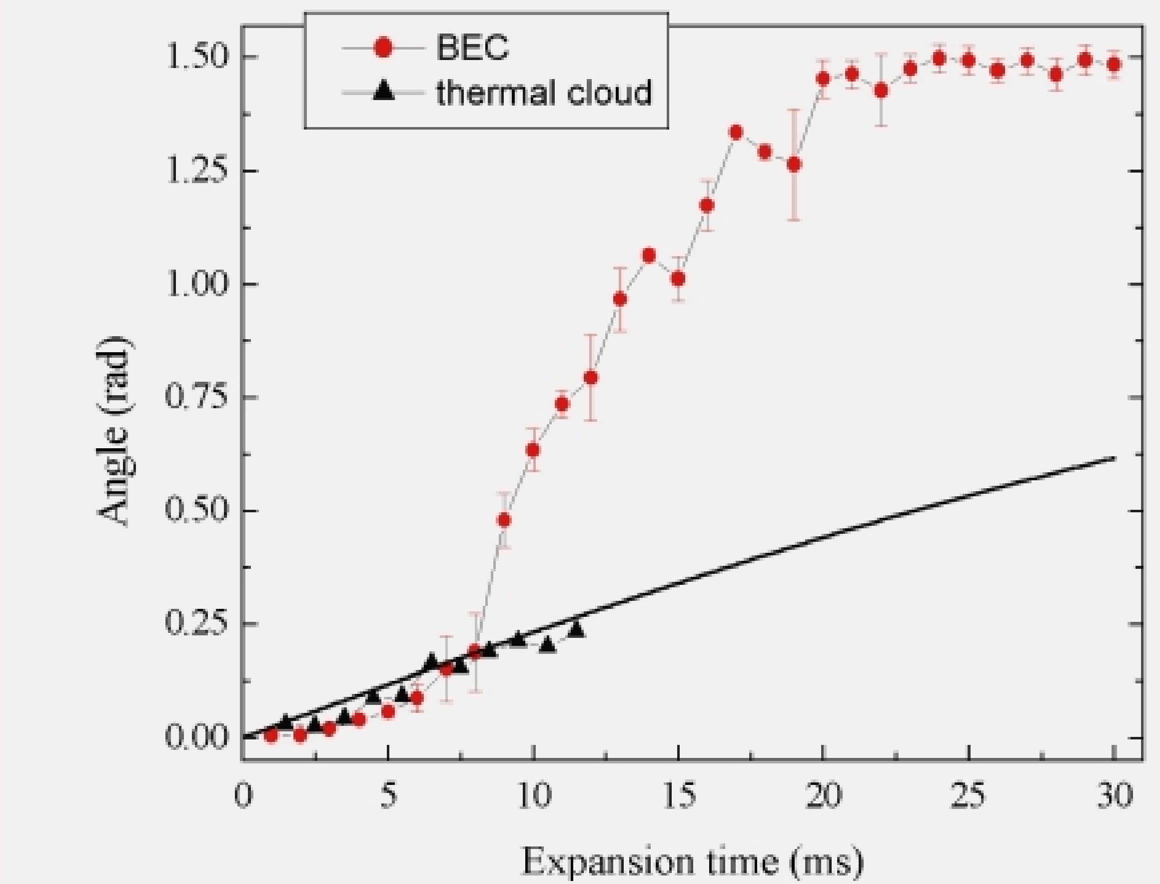
Collision-induced scissors mode







Expansion after release



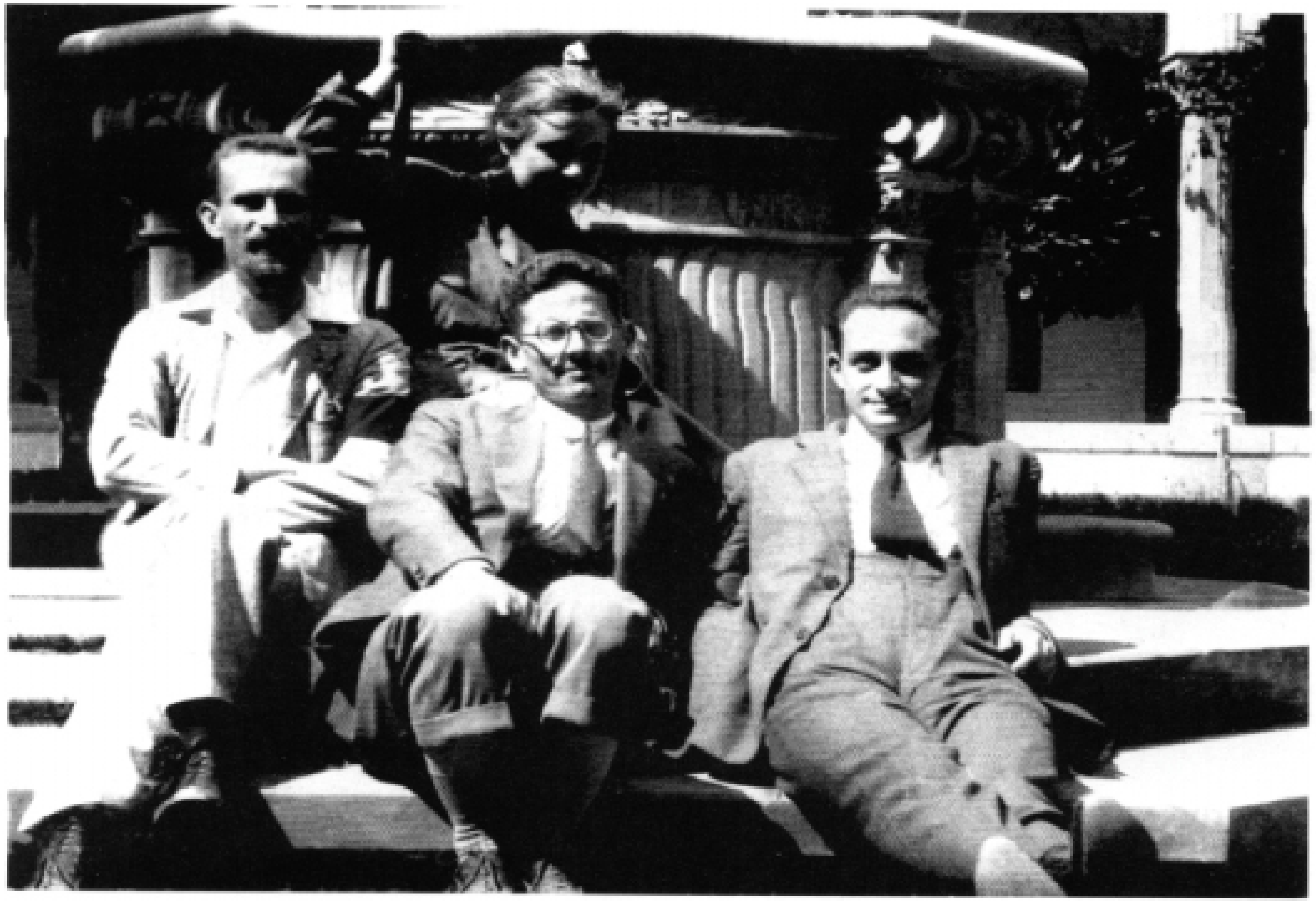
Quenched moment of inertia

$$\Theta = \frac{< z^2 - x^2 >^2}{< z^2 + x^2 >^2} \Theta_{\text{rig}}$$

$$\Theta_{\text{rig}} = Nm < z^2 + x^2 >$$

M. Modugno, G. Modugno, G. Roati, C. Fort, M. Inguscio, cond-mat/0205015.

Fermi(ons) in Firenze



Ad Arcetri nel 1925: Franco Rasetti, Fermi e Nello Carrara con Rita Brunetti als Funktionen der Zeit gegeben. Dabei ist

$$H = \frac{h}{2\pi^2 \nu m} \tag{I5}$$

gesetzt worden; α_1, α_2 und α_3 bedeuten Phasenkonstanten, welche, mit gleicher Wahrscheinlichkeit, jedes beliebege Wertesystem annehmen können. Hieraus, und aus den Gl. (I4), folgt, dass $|x| \leq \sqrt{Hs_1}$, $|y| \leq \sqrt{Hs_2}$, $|z| \leq \sqrt{Hs_3}$ und dass die Wahrscheinlichkeit, dass x, y, z zwischen den Grenzen x und $x+dx$, y und $y+dy$, z und $z+dz$ liegen, folgenden Ausdruck hat:

$$\frac{dx\,dy\,dz}{\pi^3\sqrt{(Hs_1-x^2)(Hs_2-y^2)(Hs_3-z^2)}}$$

Wenn wir nicht die einzelnen Werte von s_1, s_2, s_3 sondern nur ihre Summe kennen, so ist unsere Wahrscheinlichkeit durch

$$\frac{1}{Q_s}\,\frac{dx\,dy\,dz}{\pi^3}\sum\frac{1}{\sqrt{(Hs_1-x^2)(Hs_2-y^2)(Hs_3-z^2)}} \tag{I6}$$

ausgedrückt; die Summe ist auf alle ganszählige Lösungen der Gl. (3) zu erstrecken, die den Ungleichugen

$$Hs_1 \geq x^2;\quad Hs_2 \geq y^2;\quad Hs_3 \geq z^2$$

genügen. Wenn wir die Wahrscheinlichkeit (I6) mit der Anzahl N_s der "s" Moleküle multiplizieren, so bekommen wir die Zahl der "s" Moleküle, die im Volumenelement dx dy dz enthalten sind. Unter Berücksichtigung von (II) finden wir also, dass die Dichte der "s" Moleküle am Ort x, y, z durch

$$n_s = \frac{\alpha e^{-\beta s}}{1+\alpha e^{-\beta s}}\,\frac{1}{\pi^3}\sum\frac{1}{\sqrt{(Hs_1-x^2)(Hs_2-y^2)(Hs_3-z^2)}}$$

gegeben ist. Für hinreichend grosses s kann man vorige Summe durch ein zweifaches Integral ersetzen; nach Ausführung der Integrationen finden wir

$$n_s = \frac{2}{\pi^2 H^2}\,\frac{\alpha e^{-\beta s}}{1+\alpha e^{-\beta s}}\sqrt{Hs - r^2}$$

Mit Benutzung von (I3) und (I5) finden wir jetzt, dass die Dichte der Moleküle mit kinetischer Energie zwischen L und $L+dL$ am Ort x, y, z folgenden Ausdruck hat:

$$n(L)\,dL = n_s\,ds = \frac{2\pi(2m)^{3/2}}{h^3}\sqrt{L}\,dL\,\frac{\alpha e^{-\frac{2\pi^2\nu m\beta r^2}{h}}\,e^{-\frac{\beta L}{h\nu}}}{1+\alpha e^{-\frac{2\pi^2\nu m\beta r^2}{h}}\,e^{-\frac{\beta L}{h\nu}}} \tag{I7}$$

Zeitschrift für Physik 1926

EFFECT OF AN ALTERNATING MAGNETIC FIELD ON THE POLARISATION OF THE RESONANCE RADIATION OF MERCURY VAPOUR

E. FERMI and F. RASETTI

«Nature» (London), *115*, 764 (1925).

Recently, A. Ellett («Nature», December 27, 1924, p. 931) and W. Hanle («Zs. f. Phys.», *30*, 93, 1924) observed the depolarising effect of a weak magnetic field on resonance radiation. When the intensity of the field was sufficiently small they found, not only partial depolarisation, but also a rotation of the plane of polarisation. This is accounted for, on the classical point of view, by the superposed effect of the Larmor rotation and of the damped vibrations of the oscillator.

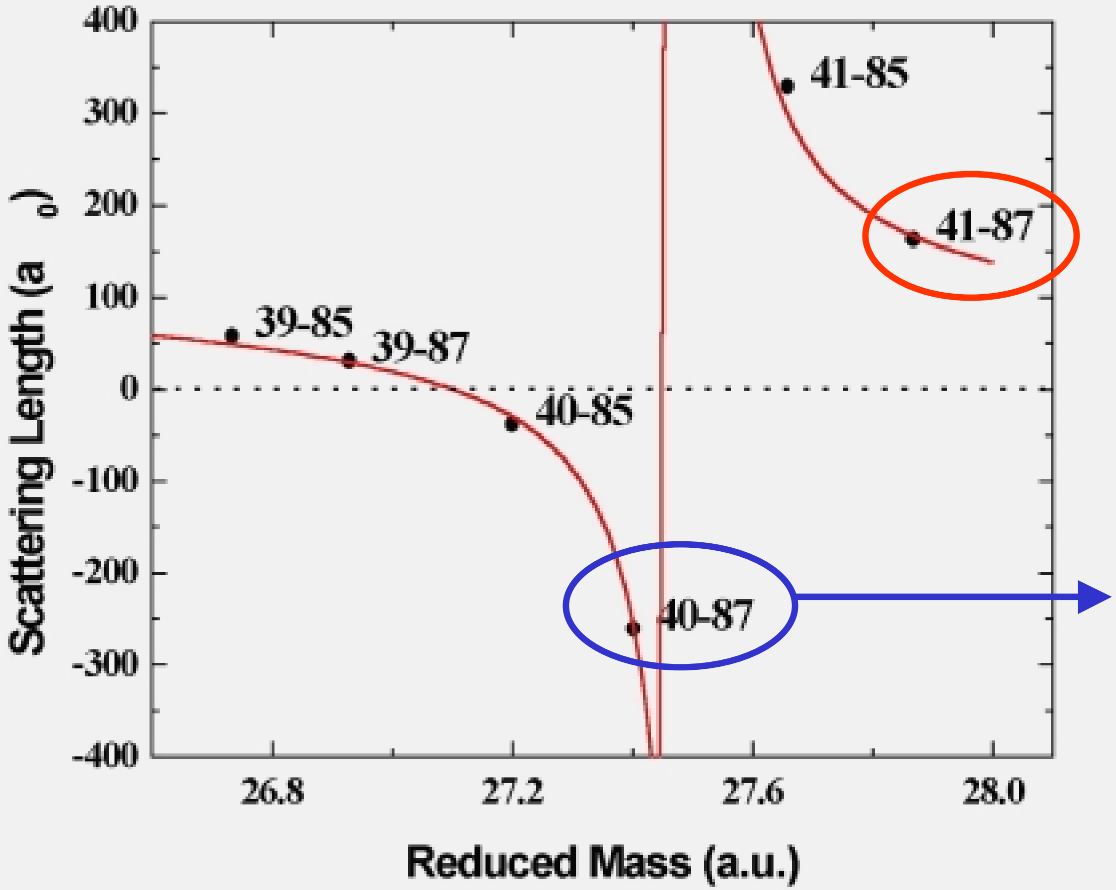
The same classical views suggest that the depolarising action of a high frequency alternating magnetic field of constant amplitude will vanish with increasing frequency. The effect should be well observable with fields of 2 or 3 gauss, and frequencies between 10^6 and 10^7.

We have performed the experiment, and have detected the presence of the expected phenomenon. A strong increase of the polarisation was actually observed in passing from a frequency of $1 \cdot 5 \times 10^6$ to one of 5×10^6, though the amplitude of the field remained constant.

We are carrying out further experiments in order to determine the quantitative features of the effect.

Istituto Fisico dell'Università, Firenze, Italy, April 3.

K-Rb triplet scattering lenghts

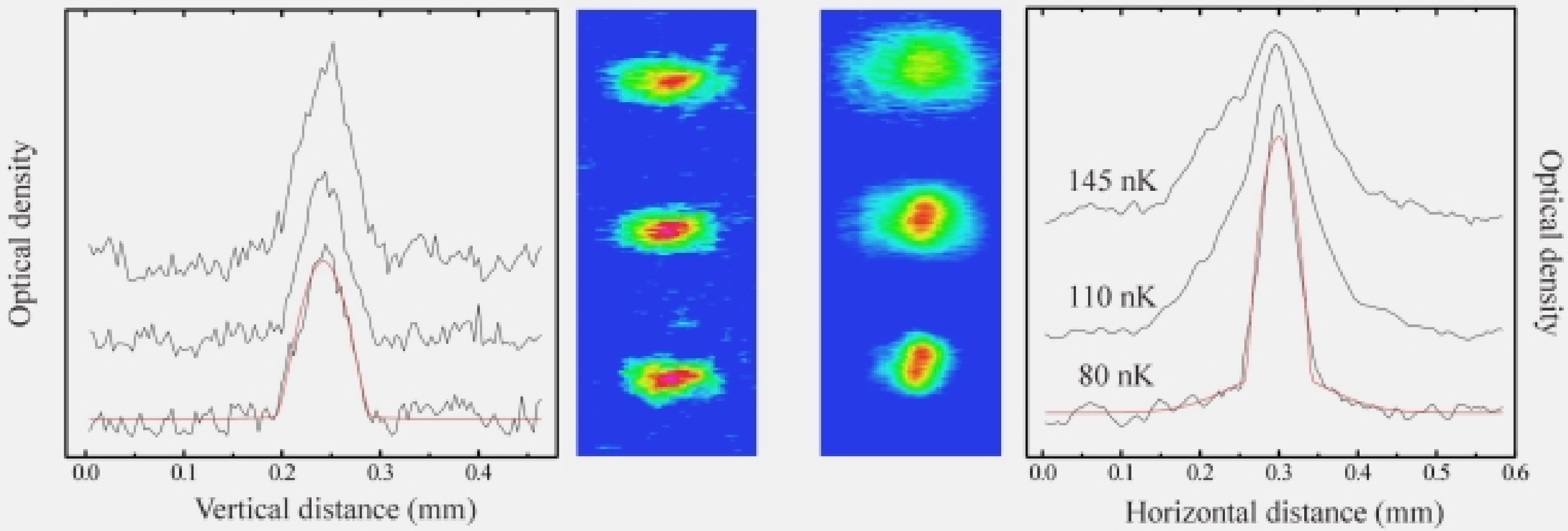


-261^{+170}_{-159}

inferred from
^{41}K-^{87}Rb

large attractive interaction for ^{40}K and ^{87}Rb
sympathetic cooling to a Fermi-Bose gas is possible

Rb BEC in a K Fermi sea



N_F=10^4 T_F=250nK T_{min}=80nK=0.3T_F N_B=2 10^4 T_C=110nK

bosons in T-F approx.:

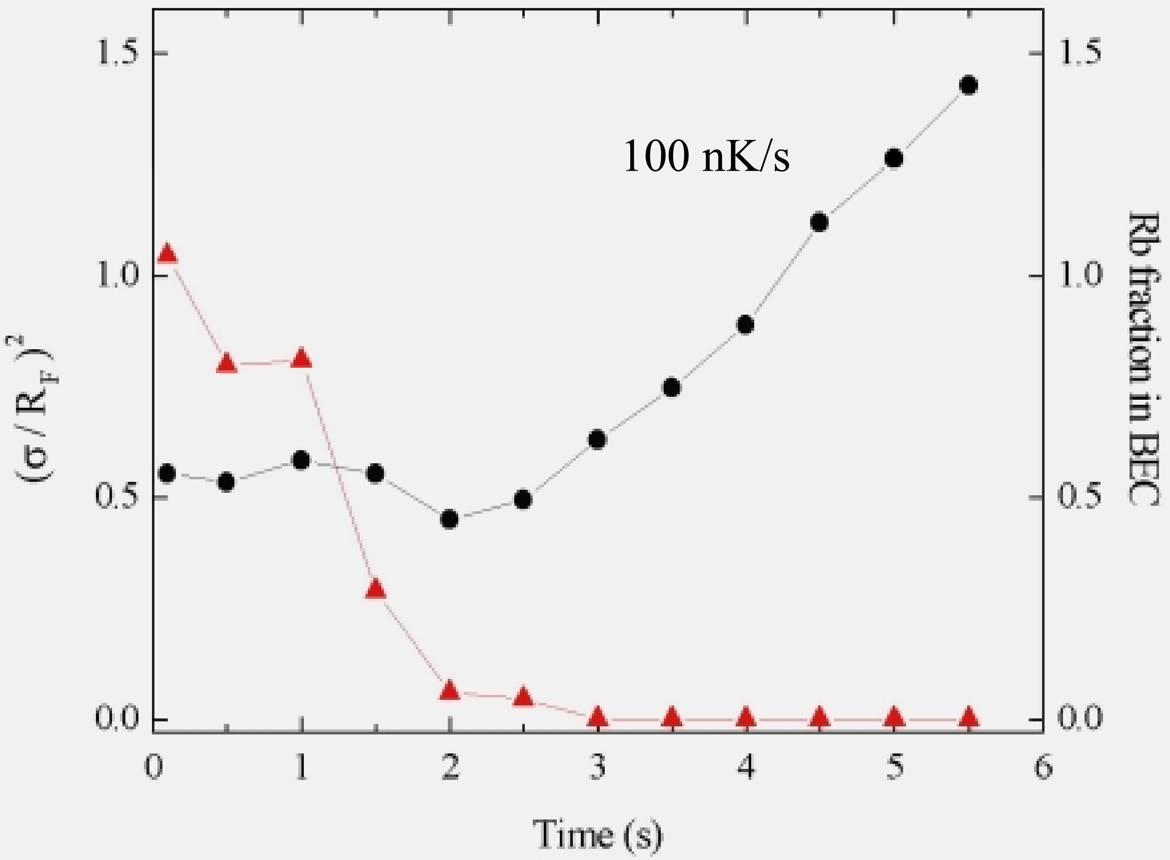
$$n(r) = n_0(1-(r/R_B)^2)$$

non-interacting fermions:

$$n(r) = n_0(1-(r/R_F)^2)^{3/2}$$

G. Roati, F. Riboli, G. Modugno, M. Inguscio Phys.Rev.Lett. in press (cond-mat/0205015)

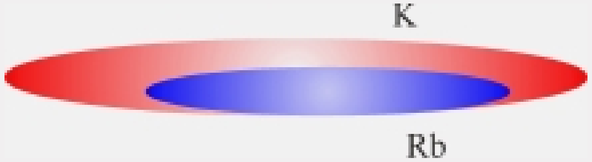
Thermal contact in a Fermi-Bose gas



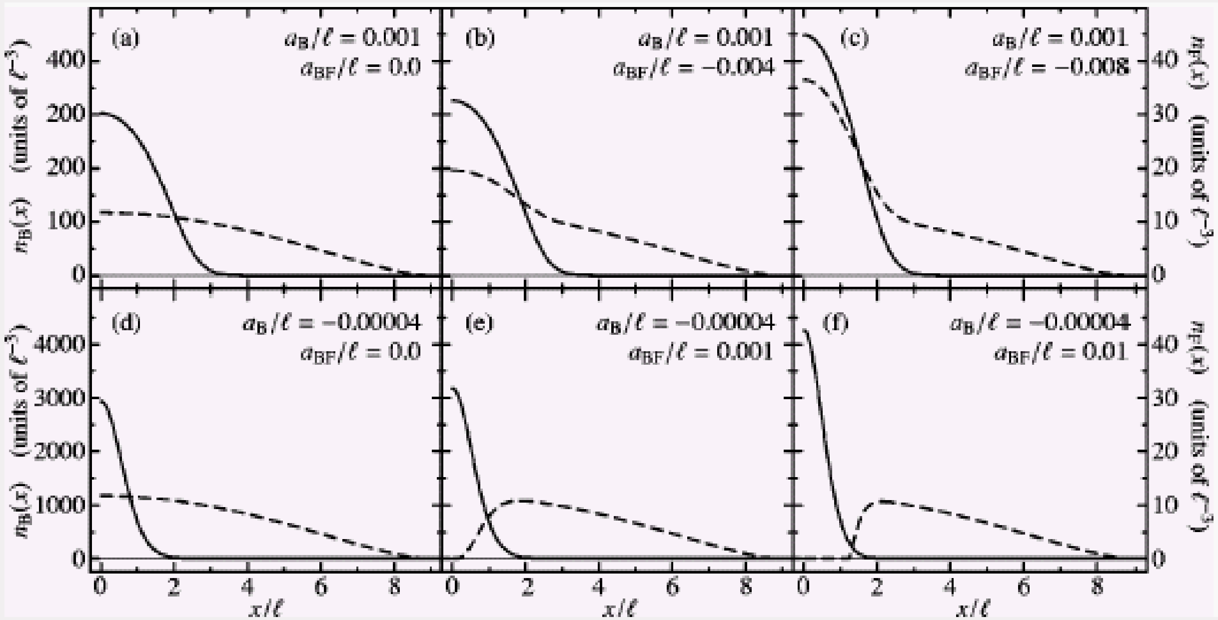
- produce the degenerate mixture
- leave a RF shield on Rb
- wait for trap heating to remove Rb

K starts to heat up only when Rb is completely removed

Attractive interaction



$R_F \approx 2R_B$
good geometrical overlap

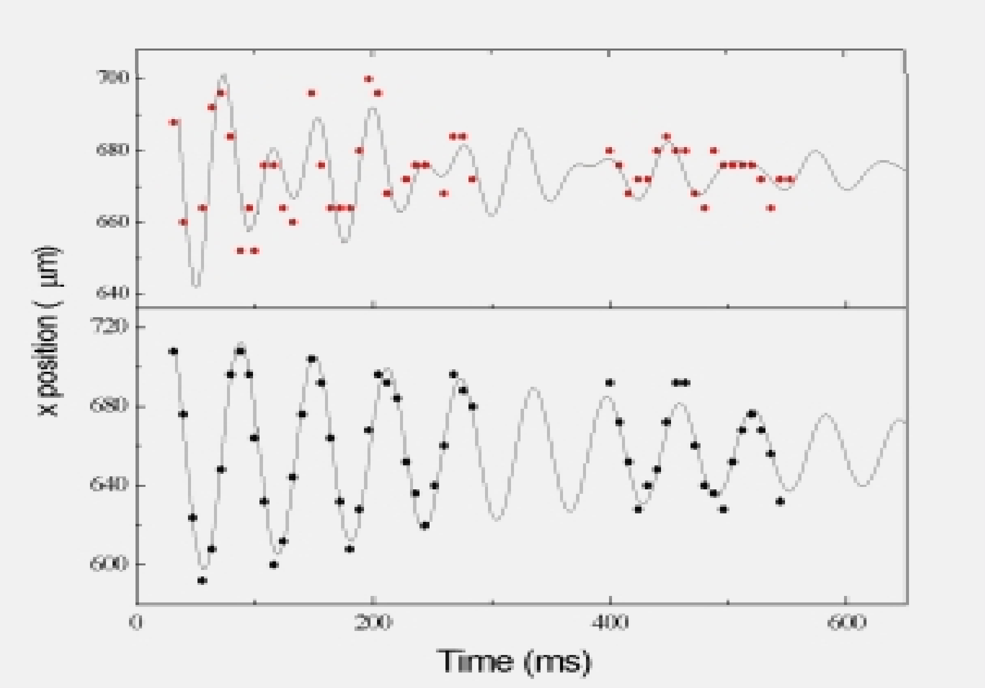


attractive interaction: better overlap

R. Roth and H. Feldmeier, PRA **65**, 021603(R) (2002)

Dipole oscillations

^{41}K

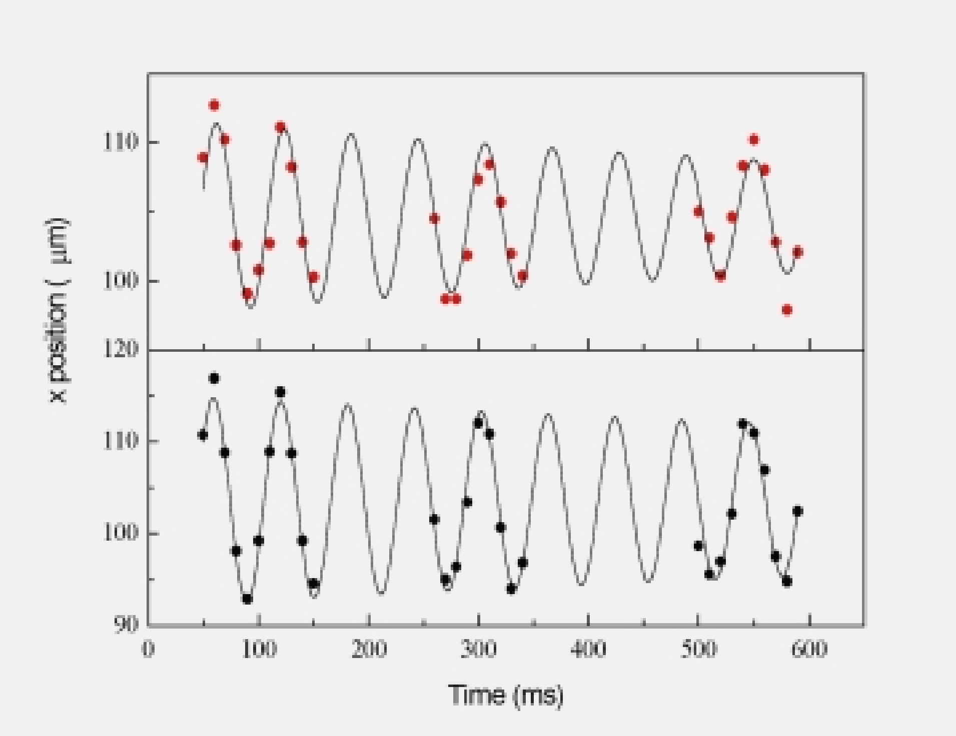


^{87}Rb

a_{KRb}=160 a_0

Collisionless regime

^{40}K



^{87}Rb

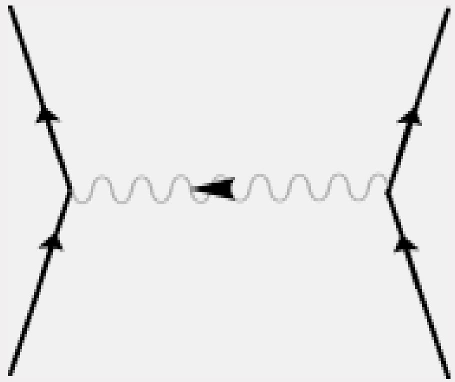
a_{KRb}< - 300 a_0

Hydrodynamic regime

-21.7 (+4.8 -4.3) nm

Tailoring the Fermi-Fermi interaction

Feshbach resonances: magnetic field.
Fermi-Bose mixture: bosonic field:



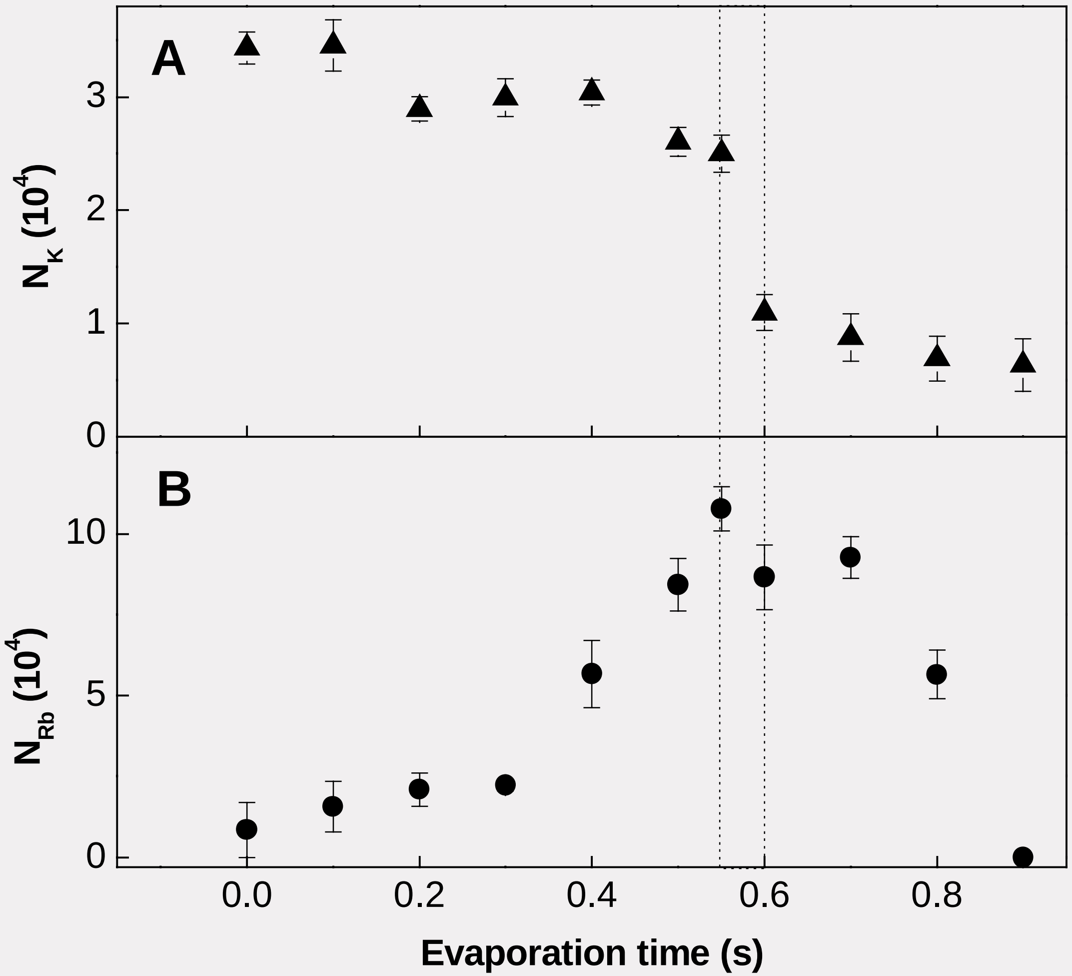
An attractive Fermi-Fermi interaction can be induced by a large interaction with bosons (like in superconductivity).

In our system we have the proper magnitude of interaction (also the sign ensures no phase-separation)

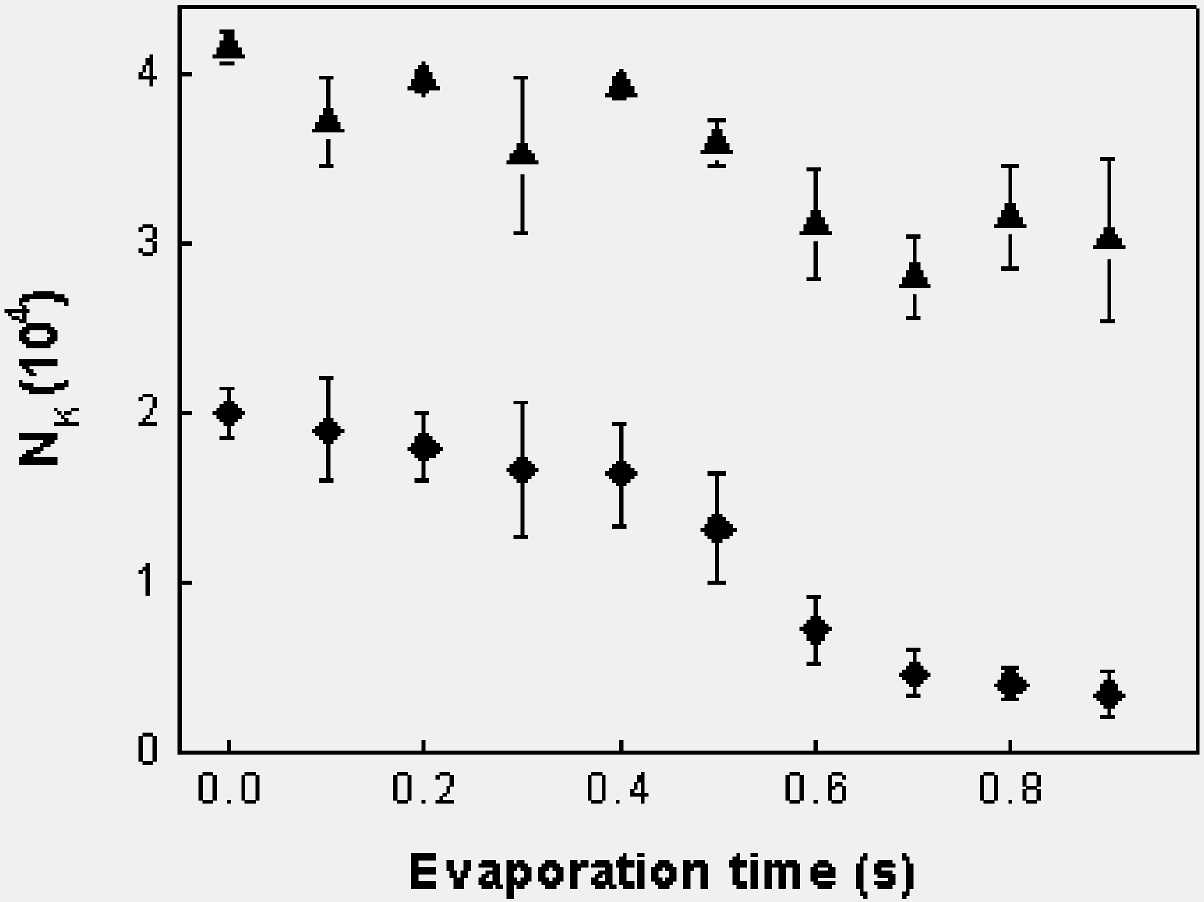
$U_{induced}$ (attractive) > $U_{repulsive}$ (Fermi pressure) => mechanical instability

Bijlsma et al., Phys. Rev. A **61**, 053601 (2000); Viverit et al., Phys. Rev. A **61**, 053605 (2000).

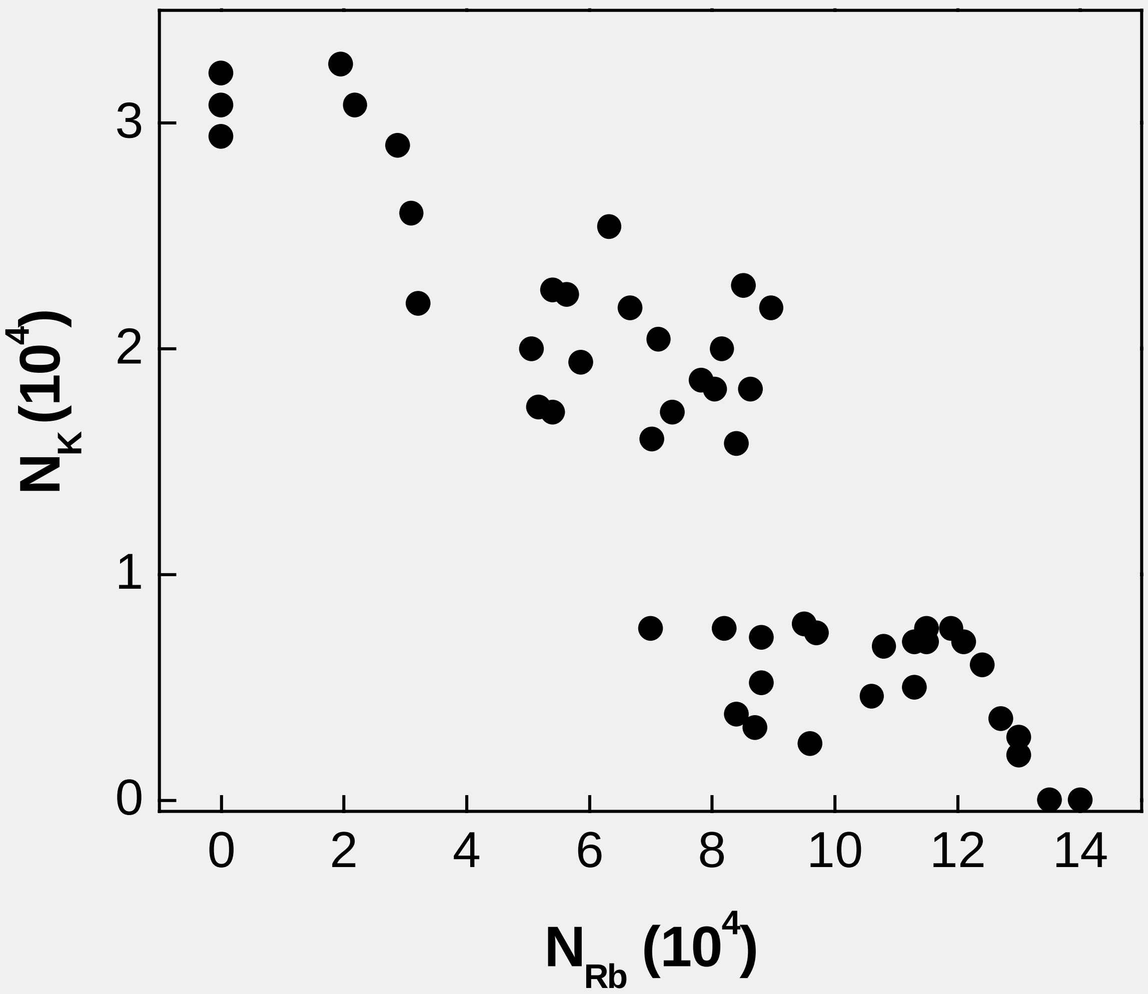
Collapse of a degenerate Fermi gas



Lifetime of fermions below critical numbers of ^{40}K (diamonds) or ^{87}Rb (triangles)

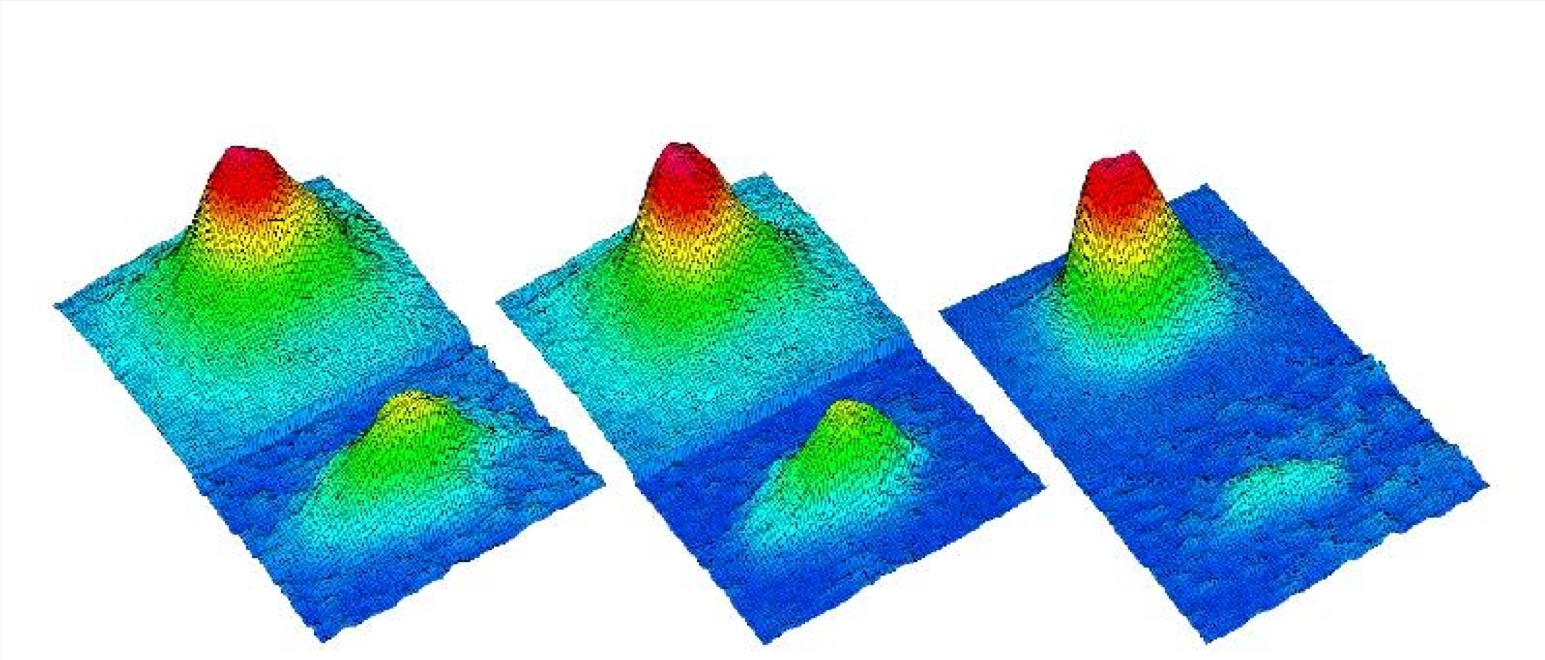


Fermions versus bosons



Two non-overlapping regions for N_K (before/after the collapse)
Gap of data between $2 x 10^4$ and $0.5 x 10^4$, with a threshold for N_{Rb} at $N_{th}=9 x 10^4$

Collapse of a degenerate Fermi gas



G.Modugno, G.Roati, F.Riboli, F.Ferlaino, R.J.Brecha, M.Inguscio
Science, published online 29 August 2002

The observation of a "collapse" of identical fermions suggests that the mixture could be suitable for the investigation of BCS.

Indeed, the optimal conditions for pairing are expected at the onset of the instability and the transition temperature is:

$$T_C \approx 0.3\ T_F\, e^{-\frac{1}{\lambda}} \qquad \lambda \approx N(0)\frac{g_{KRb}^2}{g_{Rb}}$$

stability condition: $\lambda < 1$

Viverit, cond-mat/0112354; Viverit & Giorgini, cond-mat/0207260.

Perspectives

Two-species optical lattices

Transport properties

Collective dynamics for mixed species

Polar fermionic and bosonic molecules

BCS

(quantum) degenerate-people in Firenze since 1997

Saverio Bartalini (microtraps)
Luigi Cacciapuoti (Hannover)
Francesco Cataliotti (Rb, microtraps)
Leonardo Fallani (Rb)
Francesca Ferlaino (Rb, Rb+K)
Gabriele Ferrari (Firenze, strontium)
Chiara Fort (Rb)
Pasquale Maddaloni (Rb)
Francesco Minardi (Yale)
Giovanni Modugno (Rb+K)
Nicola Poli (Firenze, strontium)
Marco Prevedelli (Bologna)
Francesco Riboli (Rb+K)
Leonardo Ricci (Trento)
Giacomo Roati (Rb+K)
Guglielmo Tino (Firenze, atom optics)

Theory:

Michele Modugno (BEC)
Andrea Simoni (ultracold collisions)
Maurizio Artoni (quantum optics)

Guests:

E. Cornell, J. Ensher,
P. Hannaford, W. Jastrzebski,
R. Corbalan, V. Ahufinger,
R. J. Brecha, S. Burger, I.Herrera