Collective Oscillations of an Imbalanced Fermi Gas: Axial Compression Modes and Polaron Effective Mass

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We investigate the low-lying compression modes of a unitary Fermi gas with imbalanced spin populations. For low polarization, the strong coupling between the two spin components leads to a hydrodynamic behavior of the cloud. For large population imbalance we observe a decoupling of the oscillations of the two spin components, giving access to the effective mass of the Fermi polaron, a quasi-particle composed of an impurity dressed by particle-hole pair excitations in a surrounding Fermi sea. We find $m^*/m = 1.17(10)$, in agreement with the most recent theoretical predictions.

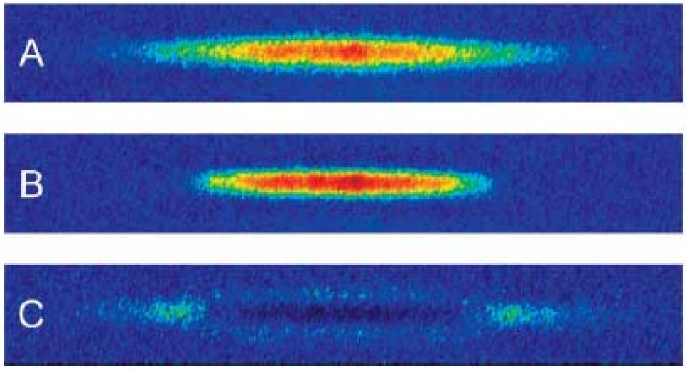
Group meeting by Jason McKeever
July 28, 2009

Background: Ultracold Fermions with Imbalanced Spin Populations

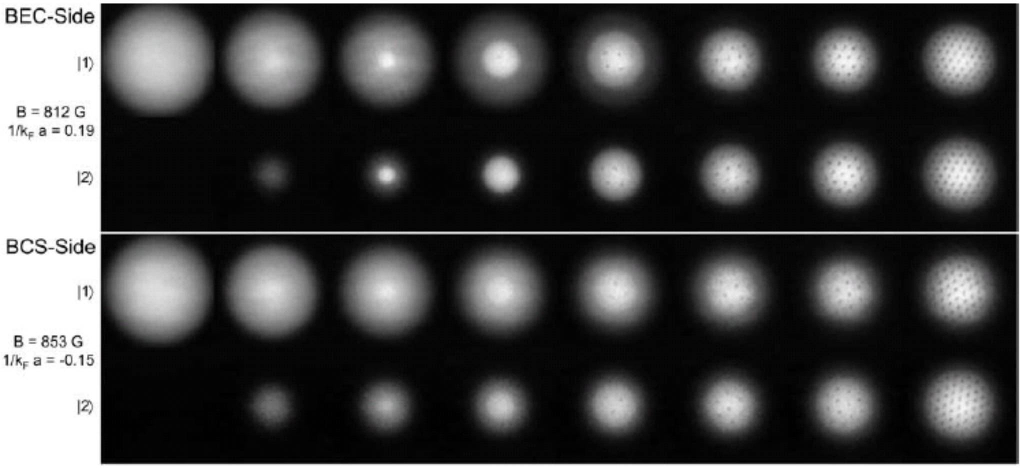
Subject first treated in 1962 by Clogston and Chandrasekhar, who were considering the effect of polarizing superconductors with a magnetic field. There is a critical field (and polarization) above which superconductivity should disappear. However, the Meissner effect will kick in and quench superconductivity at lower fields in these systems.

Experimental work began on ultracold fermionic atoms around 2006, at Rice and MIT. Phase separation (shell structure) was clearly observed, although the details were debated vigorously (what is critical polarization? How many phases?)
Discrepancy attributed to relatively high aspect ratio and low atom number at Rice.

Rice

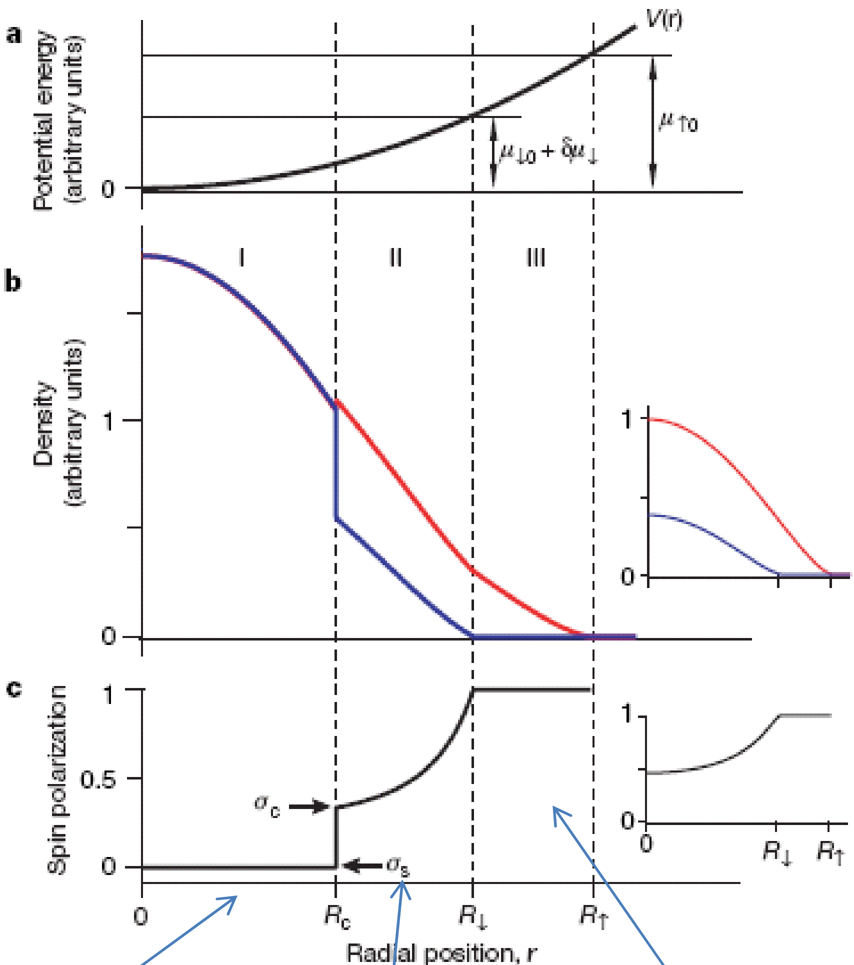


MIT



Background: Ultracold Fermions with Imbalanced Spin Populations

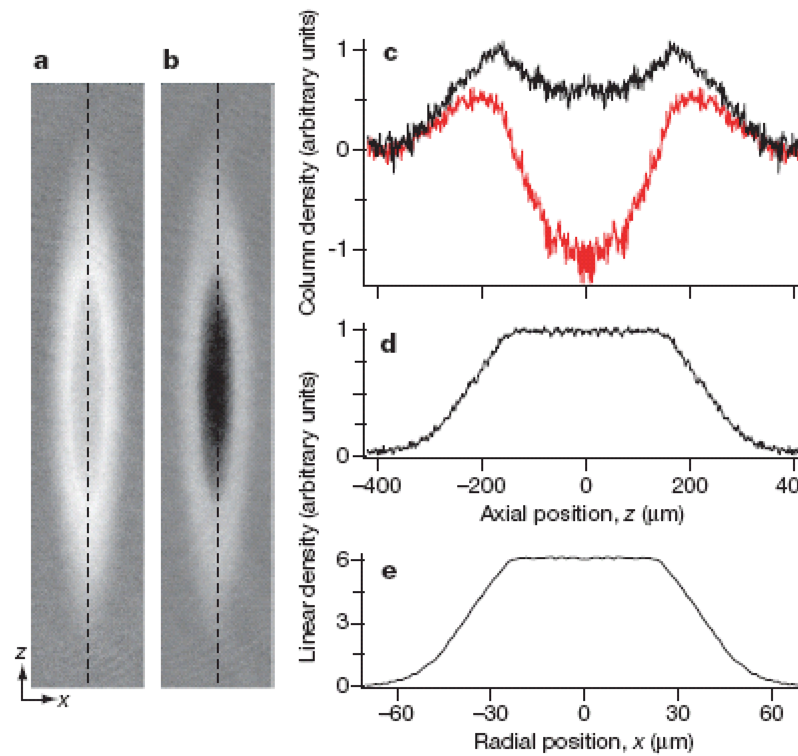
MIT, 2008



Superfluid (fully paired)

Partially polarized normal gas

Fully polarized normal gas



In situ phase-contrast imaging. Panels (d) and (e), twice integrated density, exhibit characteristic flat top where 3D density difference vanishes.

Background: Fermi Polarons

MIT 2009, group meeting by Dylan, April 2009

Fermi polarons: dressed spin-down impurities in a spin-up Fermi sea of ultracold atoms.

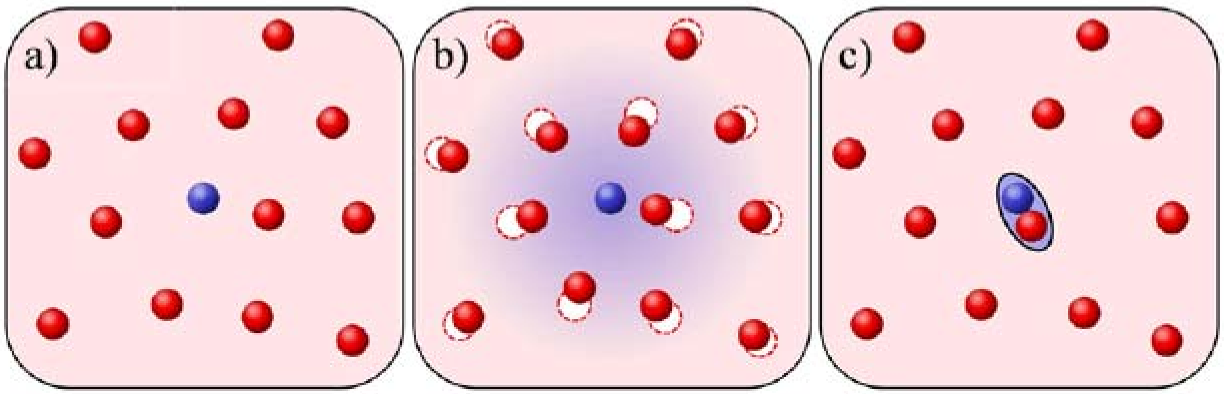
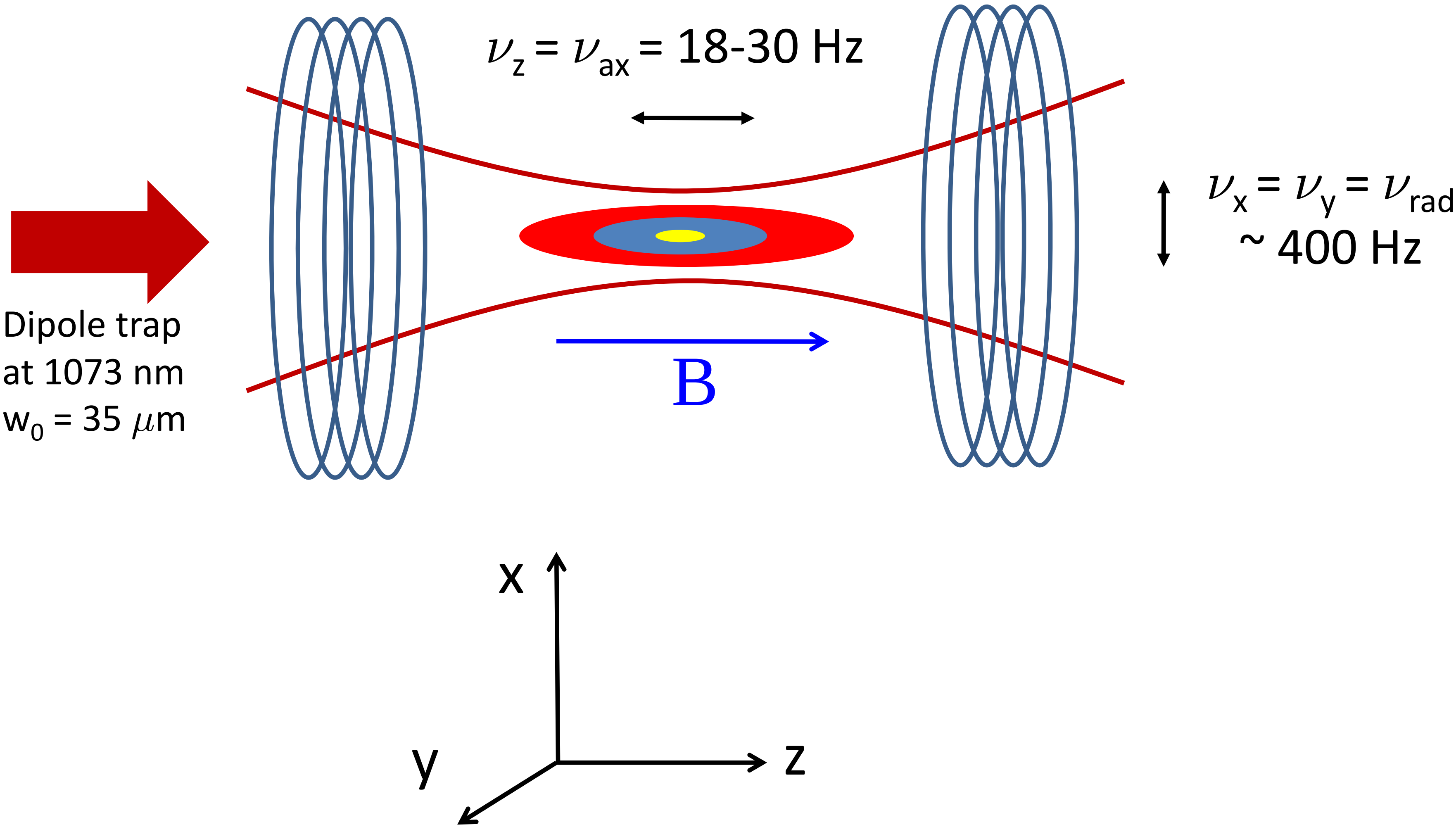


FIG. 1 (color online). From polarons to molecules. (a) For weak attraction, an impurity (blue) experiences the mean field of the medium (red). (b) For stronger attraction, the impurity surrounds itself with a localized cloud of environment atoms, forming a polaron. (c) For strong attraction, molecules of size a form despite Pauli blocking of momenta $\hbar k < \hbar k_F \ll \hbar/a$ by the environment.

Experimental Setup

8×10^4 ^{6}Li atoms at T<~ 0.09 T_F

Coils provide both Feshbach field and axial confinement



Theoretical model, based on Landau theory of the Fermi liquid

G. Baym: “*Although strongly interacting many-particle systems are very difficult to describe in general, Landau saw, with great insight, that at low temperature an exact simplicity arises, enabling one to describe the properties of extended systems in terms of a dilute collection of elementary excitations … or ‘quasiparticles’…*”

Low energy spectrum of the polaron, in the local density approximation (LDA)

$$E_2(\boldsymbol{r},\boldsymbol{p}) = AE_{F1}(\boldsymbol{r}) + V(\boldsymbol{r}) + \frac{p^2}{2m^*} + \ldots$$

Dimensionless factor characterizing the attraction of the impurity by the majority atoms

Local Fermi energy of the majority species

External potential

Kinetic energy term, with m* the effective mass of polaron

Theoretical model, based on Landau theory of the Fermi liquid

$$E_2(\boldsymbol{r},\boldsymbol{p}) = AE_{F1}(\boldsymbol{r}) + V(\boldsymbol{r}) + \frac{p^2}{2m^*} + \ldots$$

- At unitarity (a $\rightarrow\infty$) A = -0.61, according to recent theory and MIT experiment.
- Predictions for m* range from 1.06 to 1.20 m. Measurement made in this paper.

Quasi-particle "moves" in an effective potential formed by first two terms.

And since $$E_{F1}(\boldsymbol{r}) = E_{F1}(\boldsymbol{0}) - V(\boldsymbol{r})$$ (LDA)

We can write $$\frac{\omega^*}{\omega} = \sqrt{\frac{1-A}{m^*/m}}.$$

Assuming V is a harmonic trap with frequency ω.

Integrated in situ density profiles

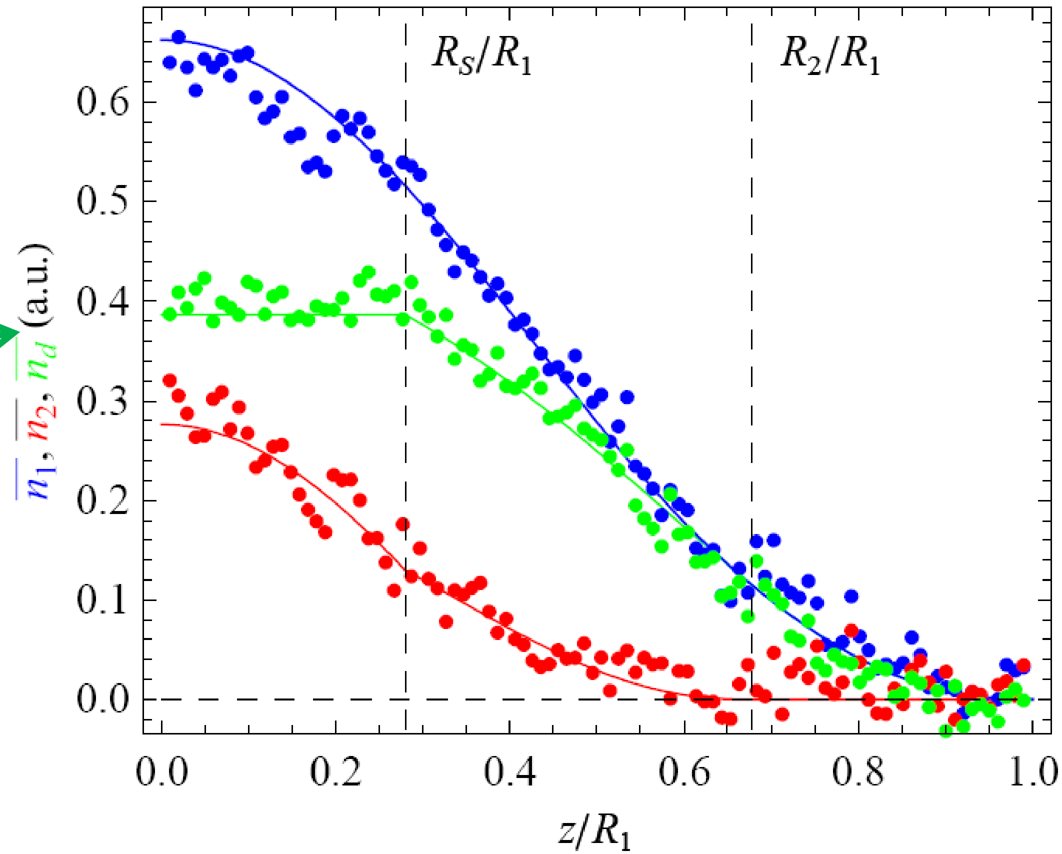
$$\bar{n}(z) = \int \mathrm{d}x\mathrm{d}y \; n(x, y, z)$$

B = 834 G (on Feshbach resonance)

Sample polarization P = $(N_1-N_2)/(N_1+N_2)$ = 0.54

Colour Legend:
Majority atoms
Minority atoms
Difference

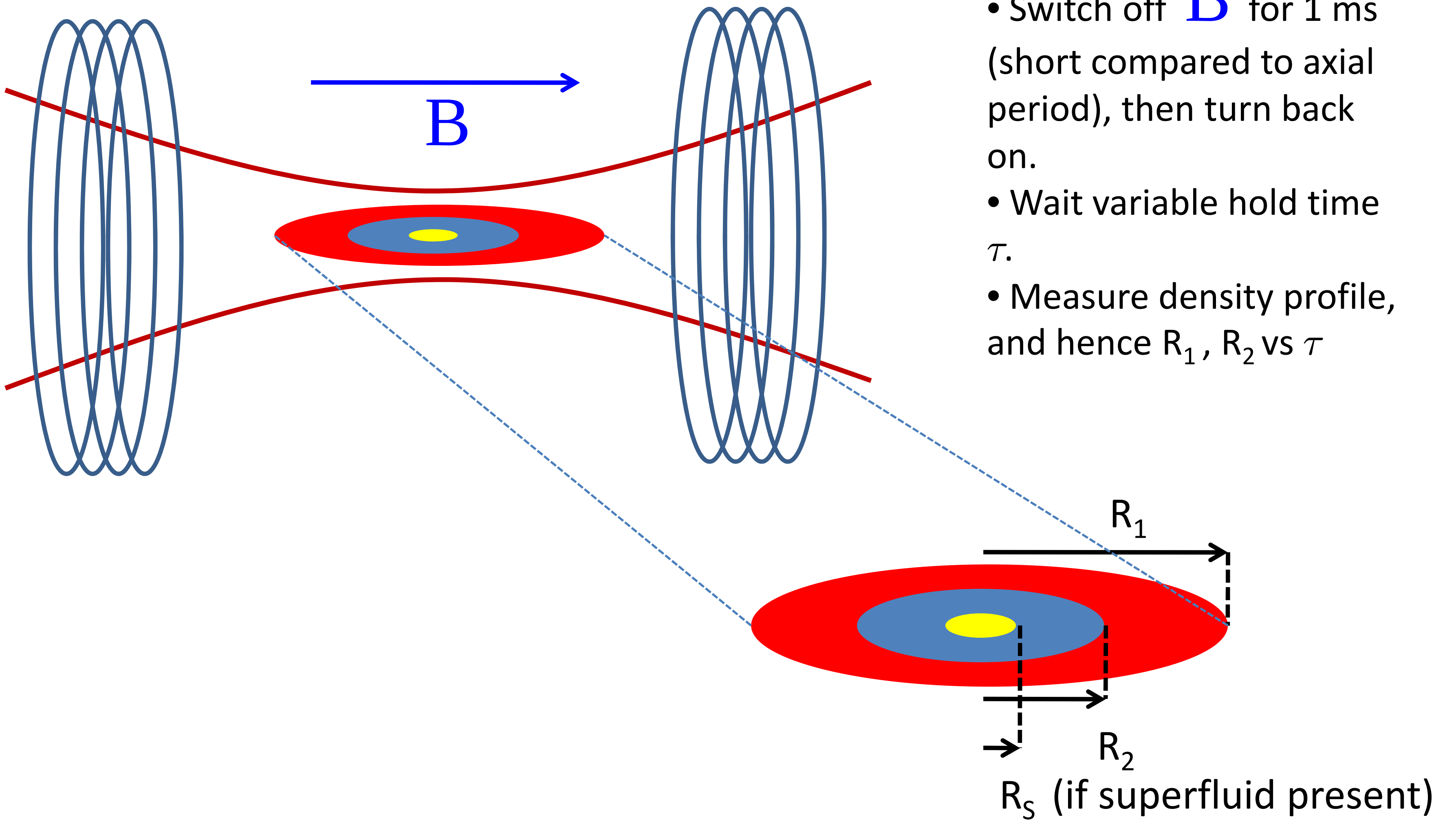
Flat-top signals equal 3D densities in fully paired, superfluid core.



Superfluid disappears for P>0.76(3).
Consistent with MIT, inconsistent with Rice.

Solid lines are predictions of Monte-Carlo theories, with the only fit parameters being the number of atoms in each spin state.

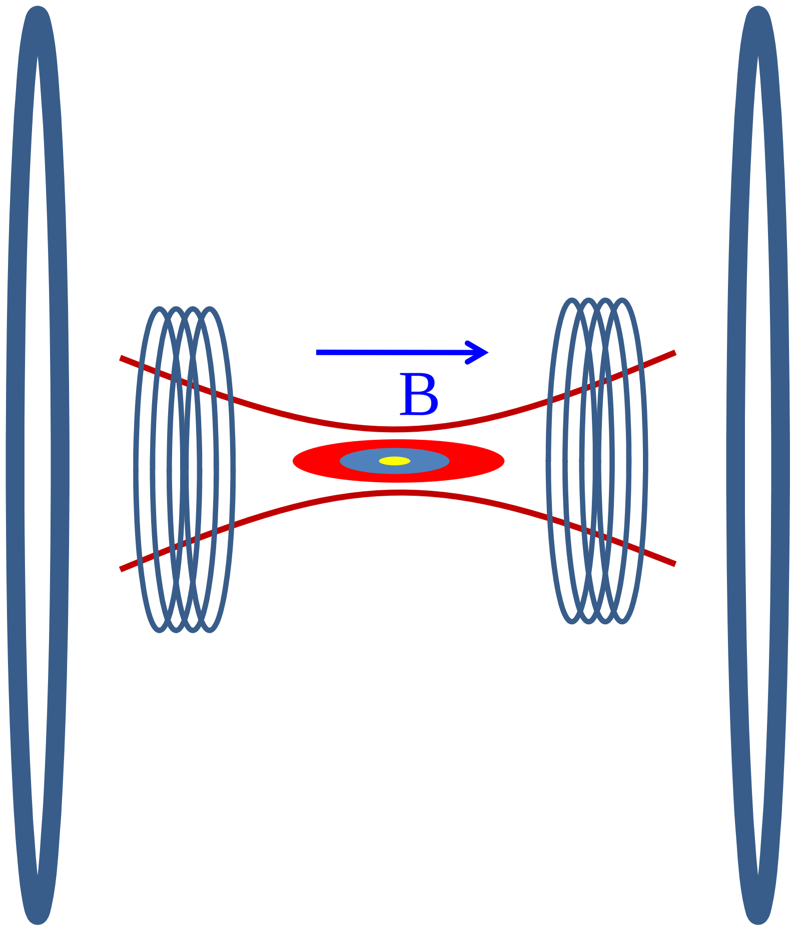
Collective mode excitation: procedure basics



Procedure:

- Switch off B for 1 ms (short compared to axial period), then turn back on.
- Wait variable hold time τ.
- Measure density profile, and hence R_1, R_2 vs τ

Collective mode excitation: procedure discussion



Coil sets oppose each other, so switching off ***only the small coils*** leads to an ***increase*** in field magnitude.

- Effect of B-switch-off is two-fold:
  1. Interactions are strongly quenched (B $\rightarrow$ 1050 G, $k_F a$~-1). This is the desired effect: want to provide an impulse to the inner core (region where both spin states are present and interacting). Should excite *compression* mode.
  2. Axial frequency is strongly reduced. Unfortunately this affects non-interacting majority as well. However this should be a small effect due to the short duration of the impulse. Further studies of this issue are planned.

Collective mode excitation: Experimental results

• For each value of polarization P, measure R_1 vs time [inset (a), P=0.85(2)]

• Fit this to exponentially damped sinusoid, of frequency ω_1 and damping rate γ_1

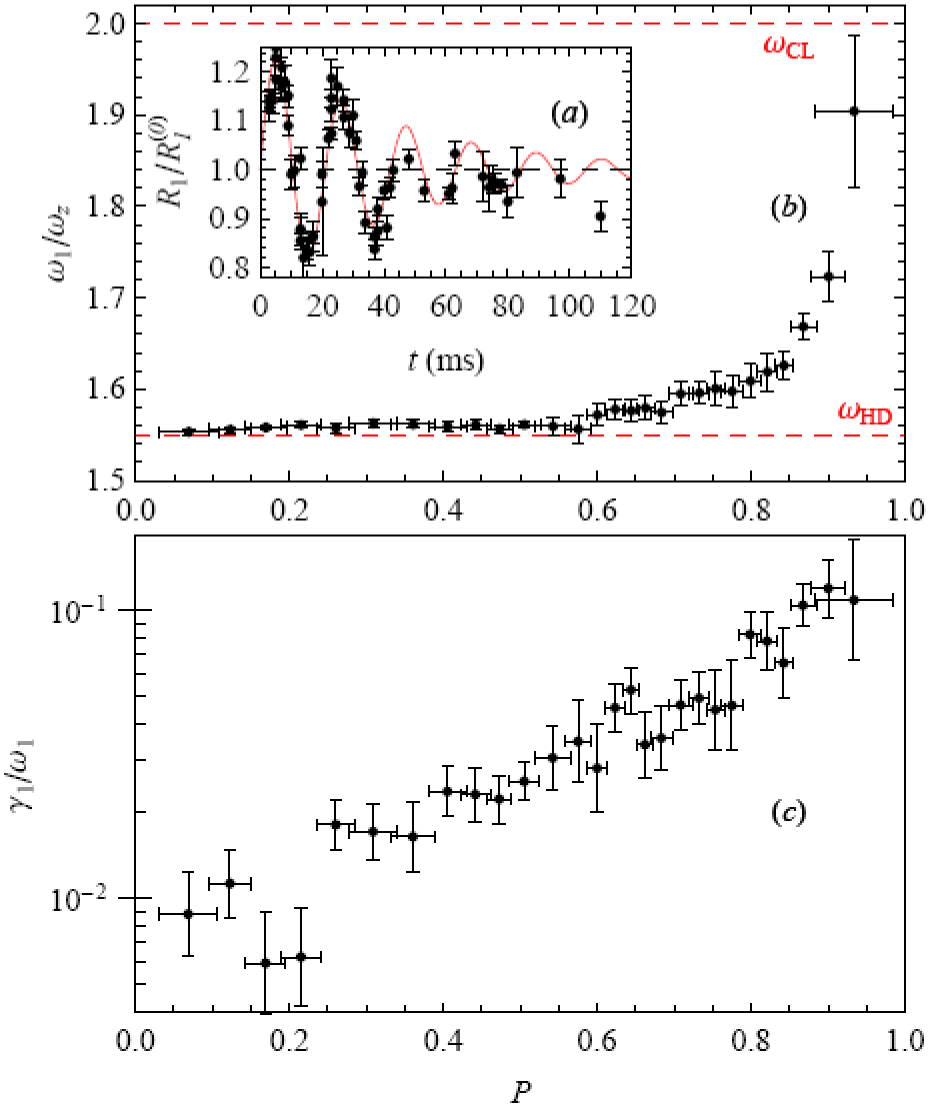
• Variations of ω_1 and γ_1 vs P are displayed in (b) and (c).

• Red dashed lines are the hydrodynamic (ω_{HD}) and collisionless (ω_{CL}) limits.

Interesting features:

• Frequency vs P is very flat for low P.

• Nothing dramatic happens at the Clogston limit P ~ 0.76, i.e. disappearance of superfluid doesn't seem to have a big effect.



Collective mode excitation: Analysis Model to explain flat region in frequency vs P data

$$H = \sum_i p_i^2/2m + U(\boldsymbol{r}_1, \boldsymbol{r}_2, \ldots)$$

← Includes potential and interactions

Subscript index denotes the ith particle.

Operator associated with compression along z: $F = \sum_i z_i^2$

Through a sum-rule approach based on Vichi & Stringari, PRA 1999, we can write

$$\omega_1^2 \simeq -2\langle z^2\rangle \Big/ \frac{\partial\langle z^2\rangle}{\partial\omega_z^2}\ .$$

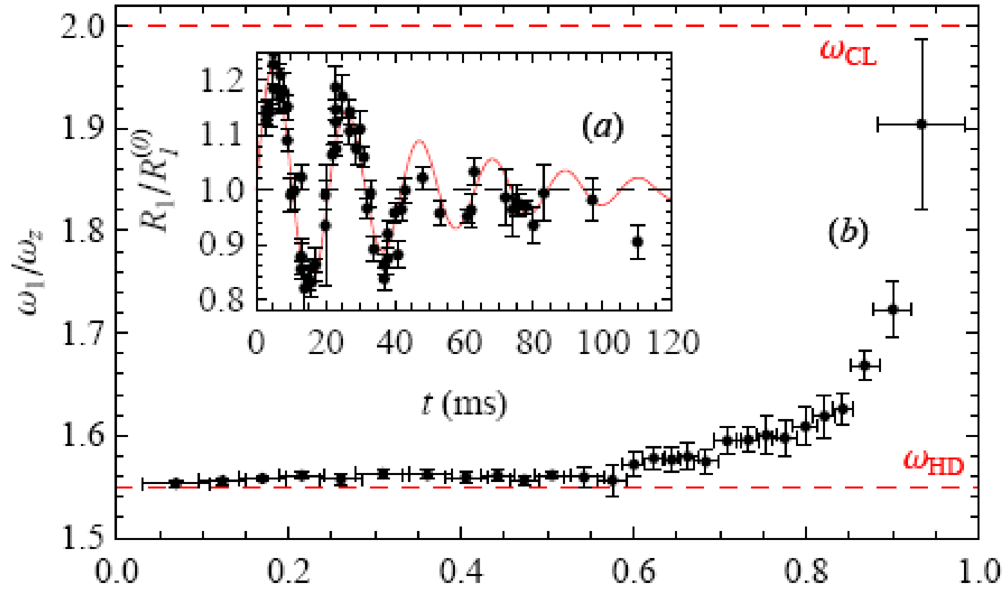
Unitarity + LDA implies $\langle z^2\rangle = R_{\mathrm{TF}}^2 f(P)$ ← Some universal function of P

$\rightarrow$ P dependence vanishes.
Explains flat behaviour.

Collective mode excitation: other measurements

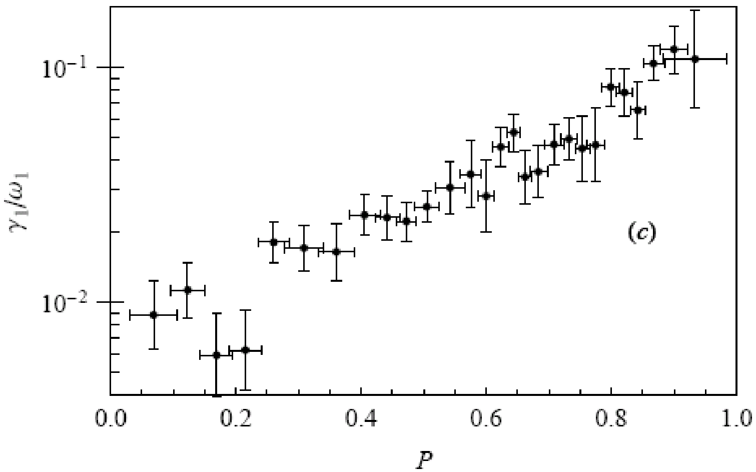
- Varying the trap aspect ratio (tried 8.2, 9.0 and 14.5) did not change these results.

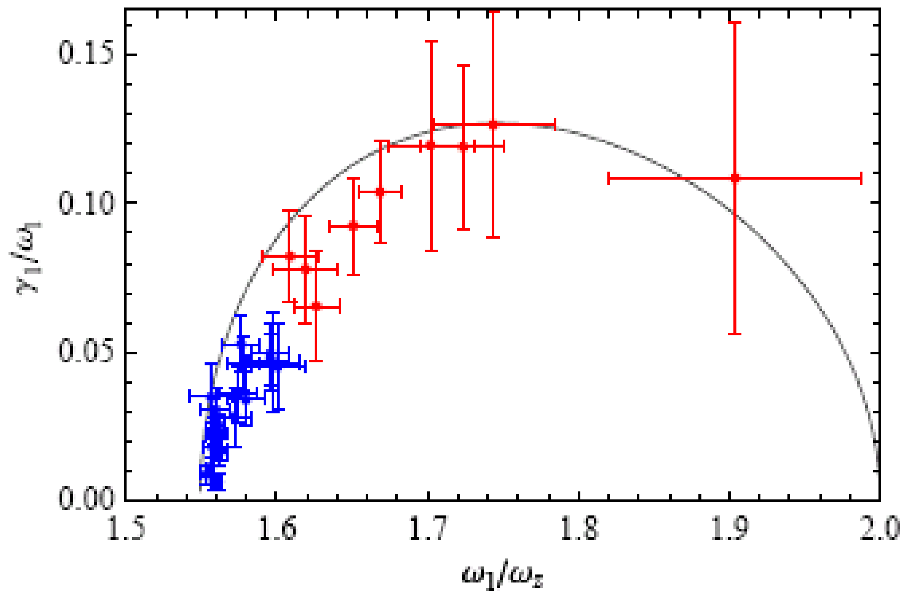
- By contrast, the effect of temperature is more pronounced.:
  At 0.12(1) T_F, ω_1(P) remains equal to ω_{HD} at all attainable polarizations (up to 0.95).



Interpretation of T dependence: in order to see collisionless behaviour, need Pauli blocking, which is suppressed at higher temperatures.

Collective mode excitation: Analysis of damping





Legend:
P > 0.8
P < 0.8

Black curve is based on a general argument about relaxation processes in fluid dynamics (Landau & Lifshitz, Course of Theoretical Physics Vol 6 : Fluid Mechanics).

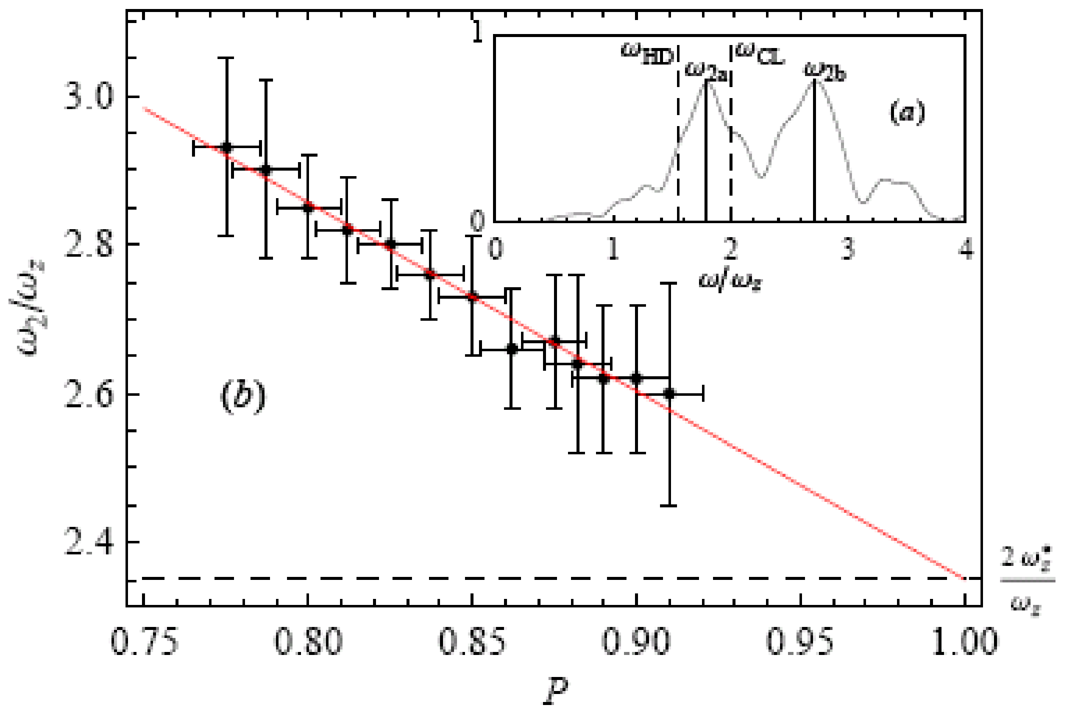
$$\omega^2 = \omega_{\rm CL}^2 + \frac{\omega_{\rm HD}^2 - \omega_{\rm CL}^2}{1 + i\omega\tau}$$

τ is an effective relaxation rate.

Collective mode excitation: Behaviour of mixed/interacting core

Now look at the dynamics of R_2, the inner core.

For large polarizations P > 0.75, two frequency components are visible in a Fourier transform of $R_2(t)$. [inset (a), P=0.90(2)]
(for lower P, only one component is seen, "indicating a strong coupling between [the two spin species].")



Higher frequency peak ω_{2b} is interpreted as axial breathing of the minority atoms, out of phase with the majority cloud. Linear extrapolation (red line) gives ω_{2b}=2.35(10) ω_z

Interpreting this breathing mode as twice the polaron oscillation frequency, we can infer

m*/m=1.17(10) First dynamic measurement of the polaron effective mass.

Conclusions

- First dynamical studies of imbalanced Fermi gas
- Compression mode is hydrodynamic for both species for large range of polarizations
- Minority species "decouples" for large polarization, and this is interpreted as the Fermi polaron breathing mode
- Polaron mass measured, although not precisely enough to distinguish between various disagreeing theories
- In future work, polaron-molecule transition will be studied by variation of scattering length. Also interested in the role of interactions, and damping phenomena.