Frontiers of Ultracold Atoms and Molecules in KITP

# Thermodynamics in a Unitary Fermi Gas

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## Unitary Fermi gas

**Many body problems in strong interaction ???**

**Fermion mixture $^6$Li | ½, ±½ >, Feshbach Resonance, B=834G, $1/k_Fa=0$**

**Local density approximation** $\mu(r)=\mu(0)-V(r)$

**Thermodynamics in cold atoms**

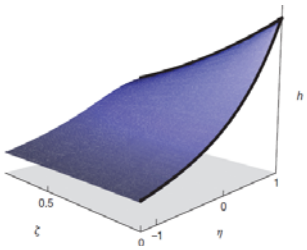
$$P(\mu_1,\mu_2,T)=P_1(\mu_1,T)h(\eta=\frac{\mu_2}{\mu_1},\varsigma=\exp(\frac{-\mu_1}{k_BT}))$$

**Idea gas**

$P_1(\mu_1,T)$

**Universal function**

$h(\eta,\varsigma)$




$h(\eta,\varsigma)$ **is a benchmark to understand the complex many-body system**

## Experimental procedure

- **Sympathetic cooling with $^7$Li and $^6$Li in Ioffe magnetic trap in | 3/2, 3/2>**
- **Optical loading in single beam (100w, 35um)**

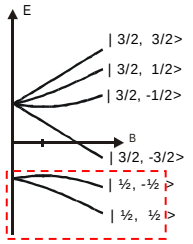
**Axial curvature, B**

- **Adiabatic spin state transfer in high magnetic field using RF**
- **Evaporation in mixture | ½, ±½ > in Feshbach resonance**
- **$10^5$ atoms in the lowest temperature ($T\leqslant 0.03T_F$)**

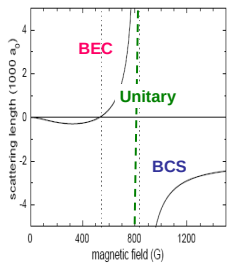
$\nu_{ax}$**=20 Hz,** $\nu_{rad}$**=450 Hz**

- **High field imagine B=834G**

**$^6$Li Level Structure**




**BEC-BCS Crossover**




## Equation of state for balanced Fermi gas

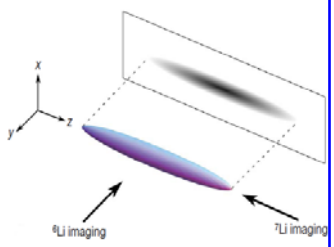
**Previous work:** equation of state on quantities averaged on the trap

**Our work:** direct measurement of homogeneous gas

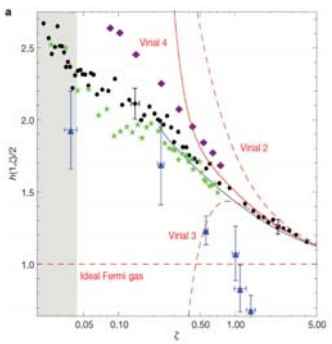
$$P(\mu_{1z},\mu_{2z},T)=\frac{m\omega_r^2}{2\pi}(n_1(z)+n_2(z))$$

$$n_i(z)=\int n_i(x,y,z)dxdy$$

**Weakly interacting $^7$Li used as thermometry**




**Comparison with theory**




**High temperature virial expansion**

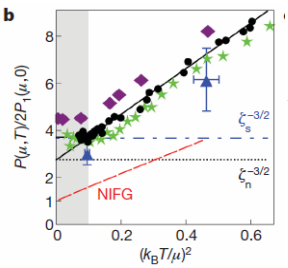
$$\frac{h(1,\varsigma)}{2}=\frac{\sum_{k=1}^{\infty}((-1)^{k+1}k^{-5/2}+b_k)\varsigma^{-k}}{\sum_{k=1}^{\infty}(-1)^{k+1}k^{-5/2}\varsigma^{-k}}$$

| $b_3$ | $b_4$ |
|---|---|
| -0.35(2) | 0.96(5) |

**Superfluid/normal phase transition**

| $(k_BT/u)_c$ | $(u/E_F)_c$ | $(T/T_F)_c$ |
|---|---|---|
| -0.32(3) | 0.49(2) | 0.157(15) |

**Normal phase: a new Fermi fluid**



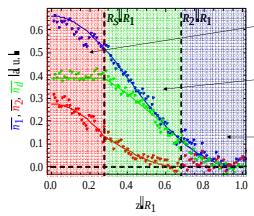

**State of equation for Fermi liquid**

$$P(\mu,T)=2P_1(\mu,0)(\xi_n^{-3/2}+\frac{5\pi^2}{8}\xi_n^{-1/2}\frac{m^*}{m}(\frac{k_BT}{\mu})^2)$$

| $\xi_n$ | $m^*/m$ |
|---|---|
| 0.51(2) | 1.13(3) |

## Equation of state for imbalanced Fermi gas

**Phase separation**




**Superfluid core**

**Partially polarized normal state**

**Polarized outer shell**

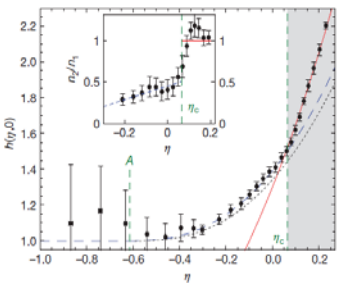
**Superfluid phase**

$$h(\eta,0)=(1+\eta)^{5/2}/(2\xi_s)^{3/2}$$

**Normal state: idea polaron gas**

$$h(\eta,0)=1+(\frac{m_p^*}{m})^{3/2}(\eta-A)^{5/2}$$

**Equation of state**

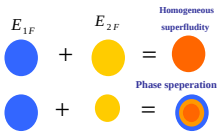



| $m_p^*/m$ | $\eta_c$ | $(n_2/n_1)_c$ |
|---|---|---|
| 1.20(2) | 0.065(20) | 0.5(1) |

## Future work in WIPM

**Symmetry destroyed Fermi gas:**

**Heteronuclear degenerate Fermi gas $^6$Li and $^{40}$K**




Heteronuclear | Imbalanced population

$$E_F=k_BT_F=\frac{\hbar^2}{2m}(6\pi^2\tilde{n})^{2/3}$$

- **Thermodynamics and hydrodyamics**
- **Many-body problems**
- **Lower dimensional interaction**
- **Bosonic Molecule creation**