Cooling across a superfluid-normal interface in spin-imbalanced fermions - An analogue of a dilution fridge ?

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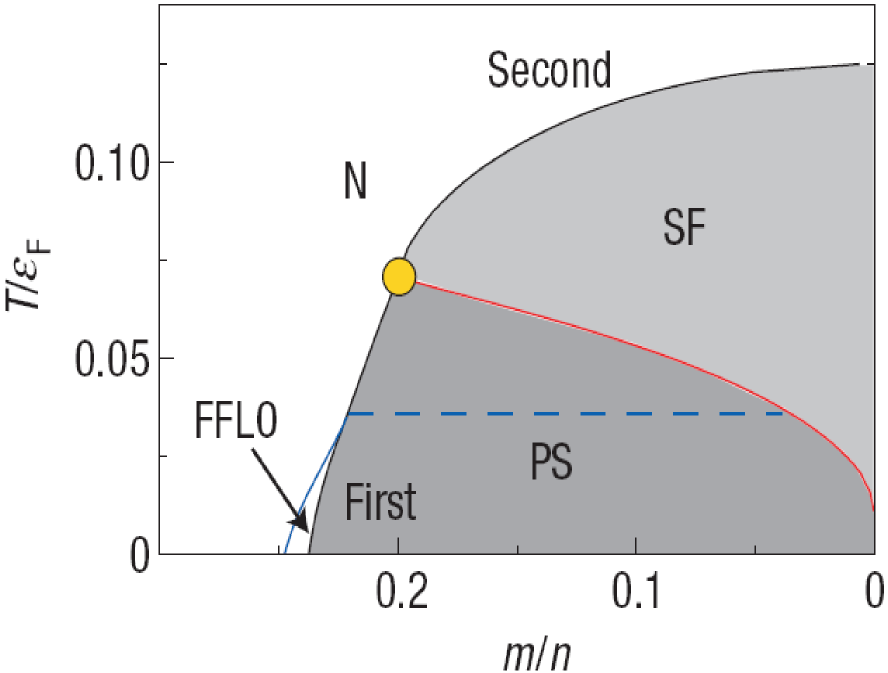
Spin-imbalanced fermions close to unitarity

- The phase diagram of spin-imbalanced fermionic atoms interacting via a feshbach resonance shares interesting features with He_3-He_4 mixture.

- At higher temperatures there is a line of second order transitions between a paired superfluid and normal leading to a tri-critical point.

- Below the tri-critical point the transition turns first order and the system phase separates between partially polarized normal and an unpolarized superfluid.



$$n/2 \equiv (n_\uparrow + n_\downarrow)/2$$
$$m \equiv n_\uparrow - n_\downarrow$$

Mean-field phase diagram at $1/k_F a = -1$

Parish et. al., Nature Physics 3, 124 - 128 (2007)

Only qualitatively correct (except perhaps FFLO) but quantitatively inaccurate.

Experiments with spin-imbalanced fermions (MIT)

Zwierlein et. al., Nature (London) 442, 54 (2006)

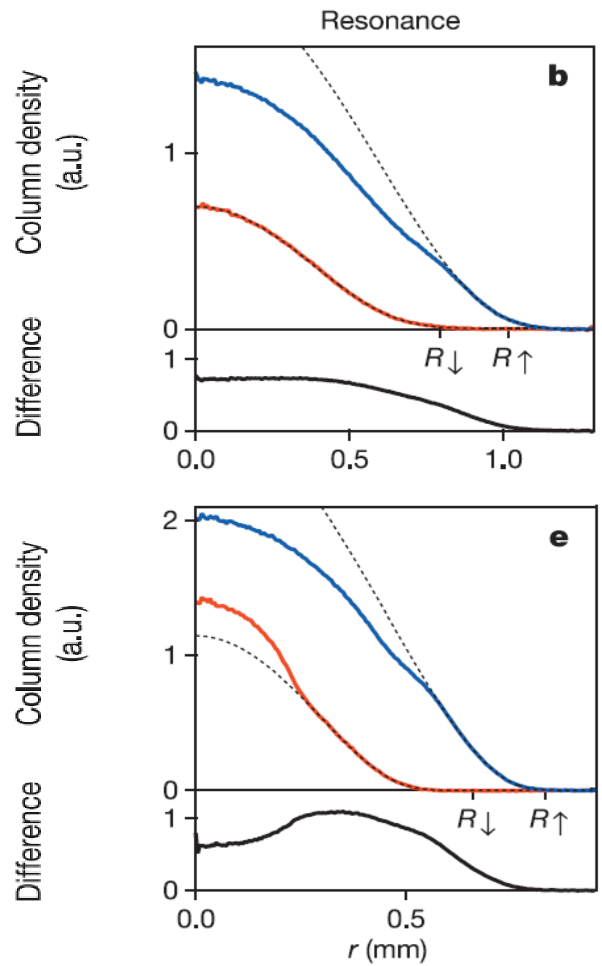
- The polarized superfluid is unstable at high polarization. What is critical polarization at equilibrium ?

  Polarization δ is defined to be

$$\delta = (N_\uparrow - N_\downarrow)/(N_\uparrow + N_\downarrow))$$

- The critical polarization observed in the MIT group $\delta_c \approx 0.7$ (consistent with QMC predictions assuming Local Density approximation(LDA))

- Trap aspect ratio ≈ 5



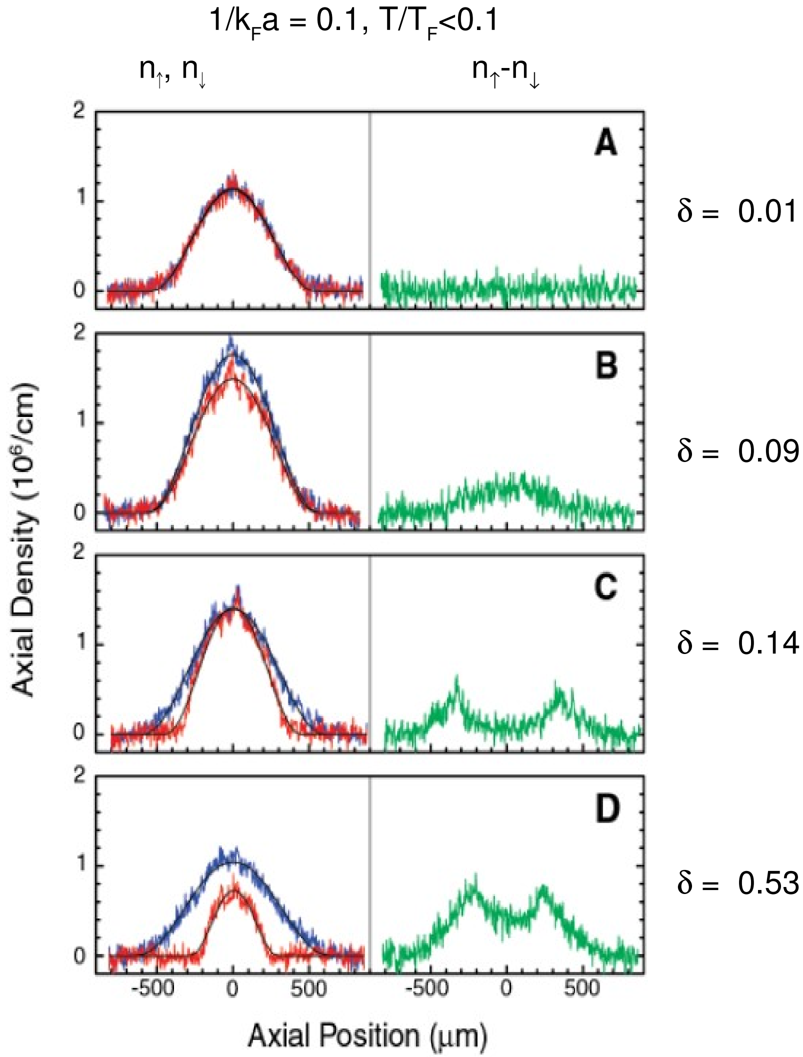
Normal state
$\delta = 0.63$
T/T_F=0.15

Superfluid state
$\delta = 0.60$
T/T_F=0.06

Experiments with spin-imbalanced fermions (Rice)

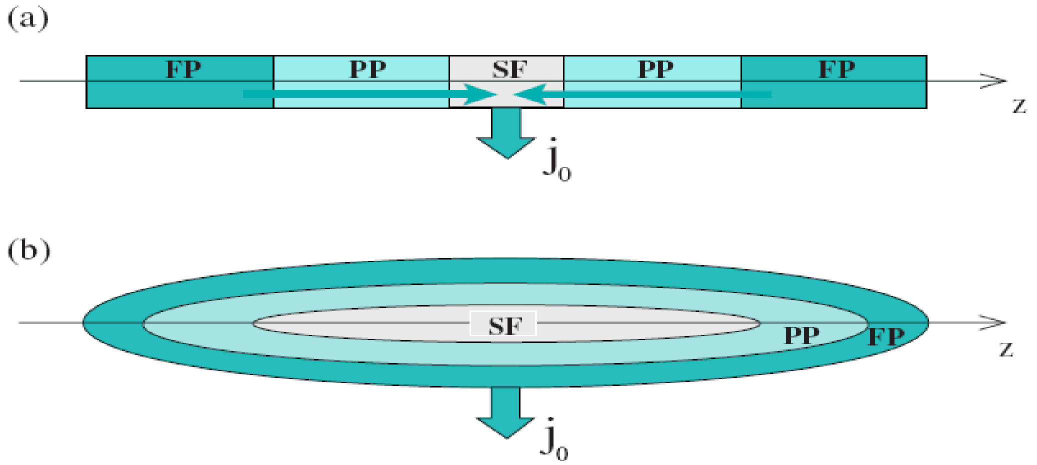
Partridge et. al., Science 311, 503 (2006)

- The critical polarization observed in the Rice group $\delta_c \approx 0.9$ (apparent violation of Clogston limit)
- Trap aspect ratio ≈ 30
- The spin densities violate LDA
- Both experiments report temperatures which are low enough for δ_c to be close to the T=0 value.



Non-equilibrium scenario in quasi 1D

Meera Parish and David Huse
Phys. Rev. A 80, 063605 (2009)



Quasi 1D

3D

- For a highly elongated trap, evaporation occurs from the SF phase predominantly removing ↑ atoms at low T.

- This generates a chemical potential gradient producing a spin current along the axial direction.

- But the spin-gap of the SF blocks spin current across the SF-N interface thus effectively depolarizing the SF.

Metastable phase

Y. A. Liao, et. al., arXiv:1105.6369

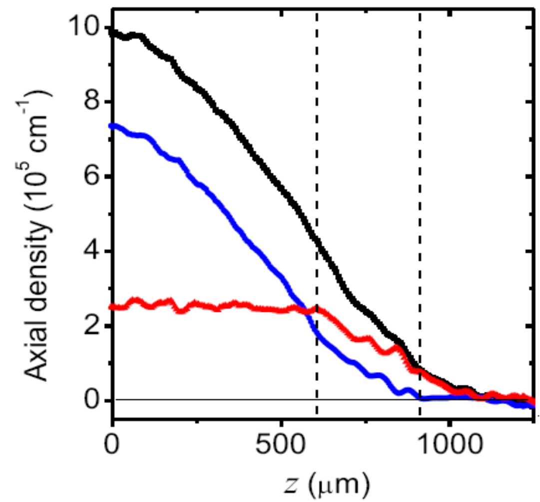
- Ramping the trap depth exponentially from U=160μK to 2.2μK over 3.4s.

- Consistent with predictions based on LDA.

- Ramping the trap depth exponentially from U=160μK to 0.74μK over 1s (more aggressive evaporation).

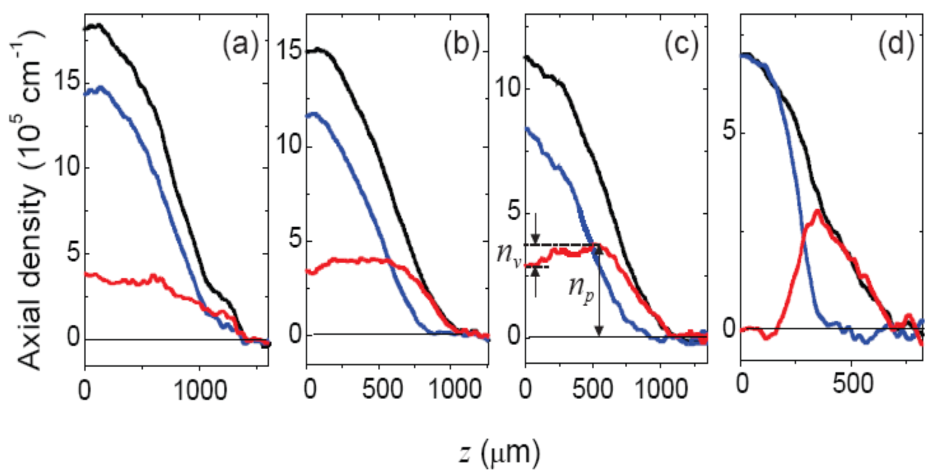
- A dip in the central density difference violating LDA.

t=3.4 s; T/T_F=0.09



$n_\uparrow$ – black
$n_\downarrow$ – blue
$n_\uparrow - n_\downarrow$ – red

t=600ms 700ms 740ms 1s

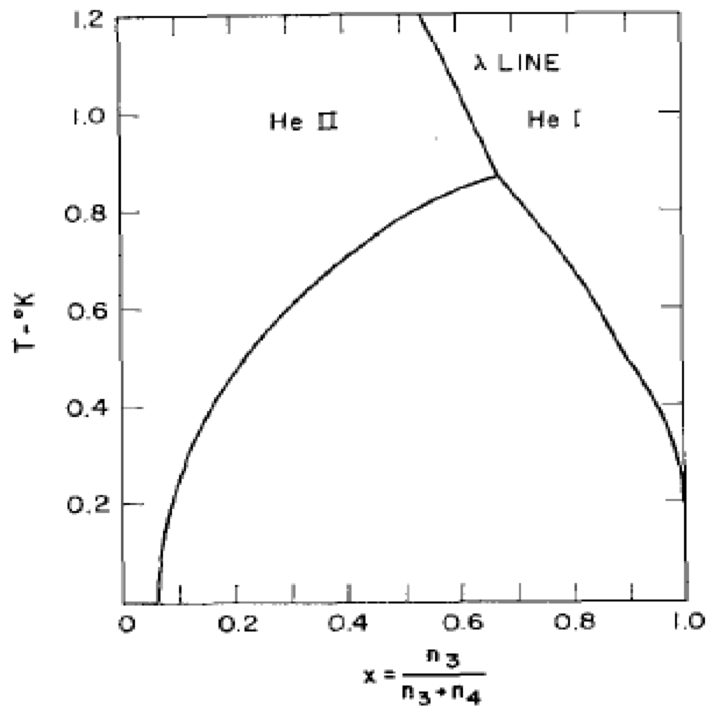


He_3 – He_4 mixture phase diagram

- At high temperatures, there is the λ-transition between superfluid and normal phase of He_4. Critical temperature is suppressed by the presence of fermionic He_3.

- At low temperatures, the system phase separates into a He_3 rich phase ("liquid") and a dilute solution of He_3 in He_4 superfluid ("vapour").

- Even at T=0 there is a finite concentration of He_3 in He_4 due to the degeneracy of the He_3 fermions and interaction effects.

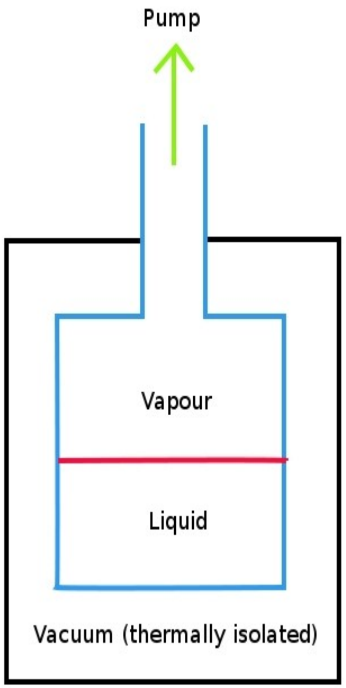


Basic working-principle of a dilution fridge

- For the He_3-He_4 mixture, the "***vapour***" phase corresponds to the dilute solution of He_3 in superfluid He_4 which is effectively at T=0.

- The "***liquid***" phase corresponds to the concentrated He_3 with very little He_4.

- Evaporating the He_3 atoms from the "***liquid***" phase results in cooling the "***liquid***" and the ***interface*** separating the 2 phases.

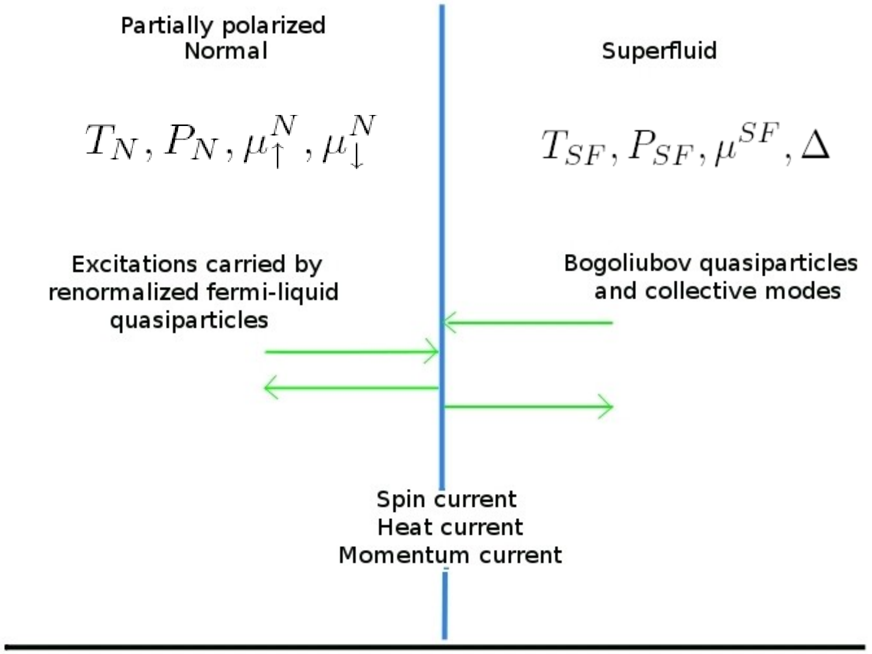


Transport across SF-N interface

- Under conditions when the system is driven (via evaporative cooling) a steady state can be established where

$$\mu_\uparrow^N + \mu_\downarrow^N \neq 2\mu_{SF}$$

due the blockage of spin transport across the interface.



- Another consequence of such a mechanism, would inhibit the transmission of heat thus resulting in a gradient in temperature as well.

$$T_N \neq T_{SF}$$