Spin and particle conductance of a strongly interacting Fermi gas

Atomtronics in Benasque, May 2015

Theory :
Ch. Grenier

Experiments :
M. Lebrat S. Krinner
D. Husmann S. Haüsler
S. Nakajima J.P Brantut
T. Esslinger

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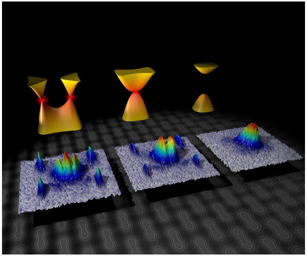
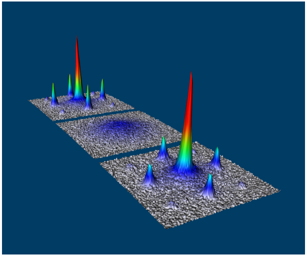
Quantum simulation with cold atoms





Cold atoms : quantum simulators
→ Phase transitions
→ Condensates
→ Lattices

- Extension to transport properties ? Mass, spin, heat ...
- Controlled study of interactions, disorder

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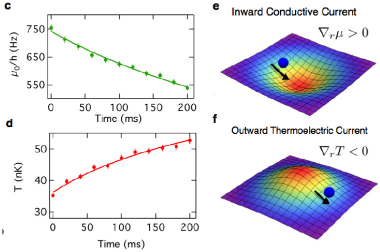
Cold atom transport : a few examples

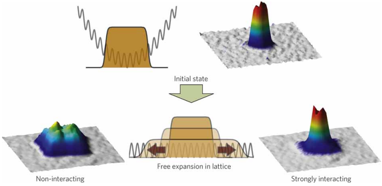
Boson thermoelectricity (Chicago, 2013)

E. Hazlett *et al.*, arxiv



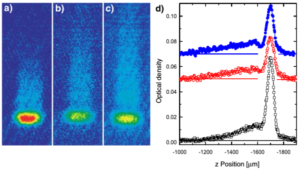
Interactions (LMU, 2012)

U. Schneider *et al.*, Nat. Phys.



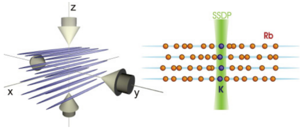
Transport with Tonks gas (Cambridge, 2009)

S. Palzer *et al.*, Phys. Rev. Lett.



Impurities (LENS, 2012)

J. Catani *et al.*Phys. Rev. A



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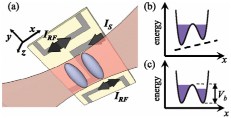
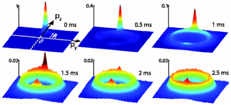
Even closer to mesoscopic physics



Josephson junction w. ultracold bosons

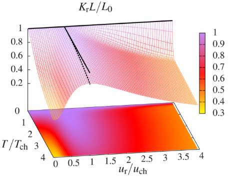
L. J. Leblanc *et al*, Phys. Rev. Lett. (2011)



Disorder - Anderson localization

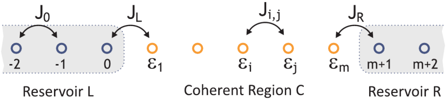
J. Billy *et al* Nature (2008), G. Roati *et al*, Nature (2008)

F. Jendrzejewski *et al*, Phys. Rev. Lett (2012)



Violation of Wiedemann-Franz law

M. Filippone *et al* (2014)



Engineered transmissions w. optical lattices

M. Bruderer, W. Belzig, Phys. Rev. A (2012)

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Motivation

Transport with cold atoms ?

- New regimes : High temperature, attractive interactions, exotic lattices
- Atomtronics : Electronics with new particles
- Address fundamental questions of transport
- Input from mesoscopic physics to cold atoms

Theory challenges :

- Interactions : controlled, but non perturbative
- Strong out of equilibrium situations
- Transport in a isolated system :Thermalization, dissipation

Some extra motivation ...

Questions :

I. How close cold atom systems are from mesoscopic ones ?
Differences, advantages, drawbacks ... ?

II. What do we learn by adding a cold atom flavour to mesoscopic physics ?

Outline

1. **Mesoscopic structures made of cold atoms**
2. **Quantized conductance and interactions**

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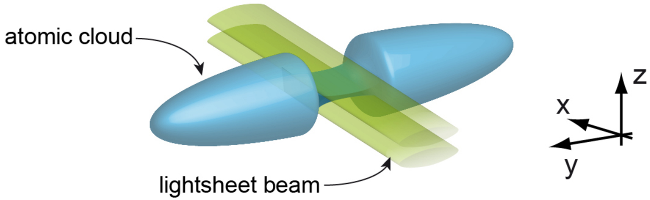
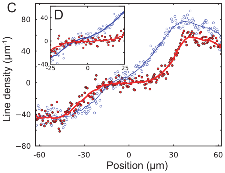
1. **Mesoscopic structures made of cold atoms**
2. Quantized conductance and interactions

The toy : a cold atom two terminal setup ...

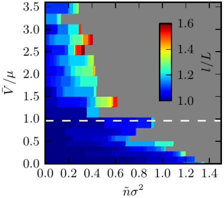


- Lithium 6 : fermions
- $T/T_F \simeq 0.1$
- $\simeq$ 100000 atoms
- Cold atom equivalent of a two terminal setup

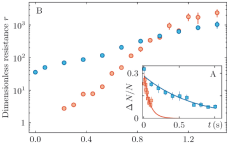
... To play which games ?



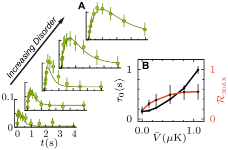
Ballistic vs. diffusive



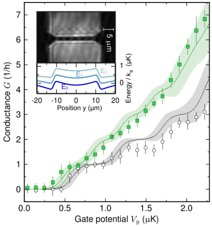
Superfluid and disorder



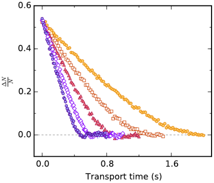
Superfluid vs. normal



Thermoelectricity



Quantized conductance



Nonlinear SF

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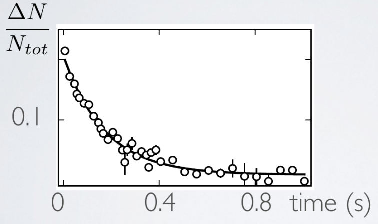
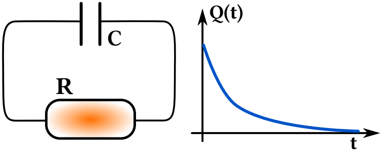
By the way

How is conductance measured ?





Discharge of a capacitor ⇒ typical timescale $\tau = RC$

i. **Linear response** :

$$I_N = \frac{d\Delta N}{dt} = -G\Delta\mu \Leftrightarrow I = G \cdot V$$

ii. **Thermodynamics** :

$$\Delta N(t) = \kappa \cdot \Delta\mu(t) \Leftrightarrow Q = C \cdot V$$

iii. **Imbalance :**

$$\Delta N(t) = \Delta N_0 \exp\left[-t/\tau\right], \tau = \kappa / G$$

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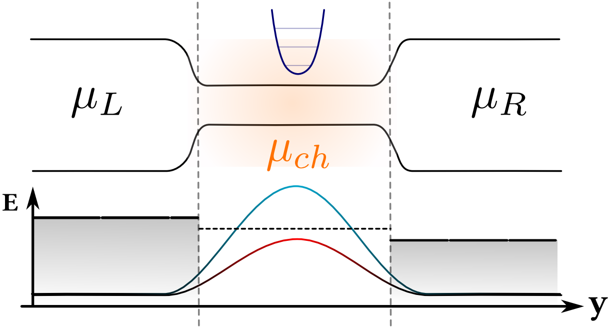
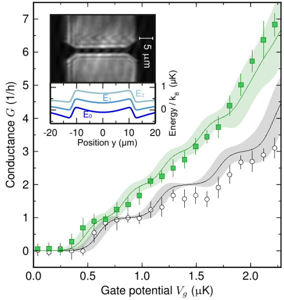
Quantized conductance

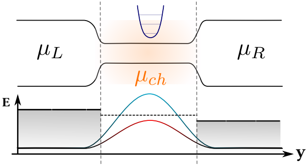




Two ways to tune transport :

- At fixed μ_{ch}, vary confinement
- At fixed confinement, vary μ_{ch} (gate potential)

Where does it come from ?

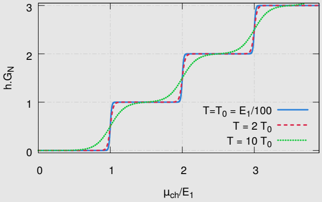


- velocity : $v_n(\varepsilon) = \dfrac{\hbar k_n}{m} = \sqrt{\dfrac{2(\varepsilon - \varepsilon_n)}{m}}$
- d.o.s. : $g_n(\varepsilon) = \dfrac{1}{2\pi}\dfrac{dk_n}{d\varepsilon} = \dfrac{1}{2\pi\hbar v_n(\varepsilon)}$
- current : $I = \sum \int_{\varepsilon_F}^{\varepsilon_F + \Delta\mu} d\varepsilon\, v_n(\varepsilon) g_n(\varepsilon) T_n(\varepsilon)$

Quantized conductance

$$G_N = \frac{1}{h}\sum_n f(E_n - \mu_{ch})$$

- **Requires :** - Elastic scattering
  - Good mode matching
- **OK for :** - Ballistic systems
  - Fermi liquids



What for spin ? What happens when interactions are switched on ?

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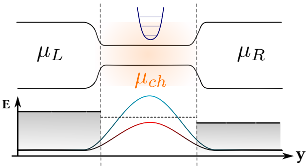
Where does it come from ?



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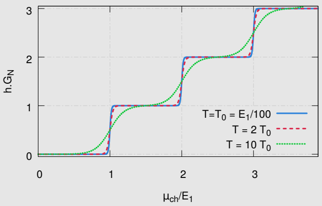

What for spin ? What happens when interactions are switched on ?

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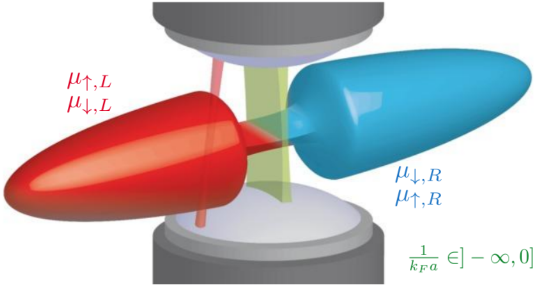
Outline

Interacting spin and particle transport



- Attractive interactions : BCS side of the resonance
- Particle and spin transport
- **Particle :** Deviation from quantization ?
- **Spin :** Spin drag ? Spin gap ?

At low interaction strength ...

→ The two species are independent :

$$I_\uparrow = -G_\uparrow \Delta\mu_\uparrow$$
$$I_\downarrow = -G_\downarrow \Delta\mu_\downarrow$$

Equivalent picture : Particle/spin :

$$I_N = -G_N \Delta\mu$$
$$I_S = -G_S \Delta b$$

$\mu = \frac{\mu_\uparrow + \mu_\downarrow}{2}$ and $b = \frac{\mu_\uparrow - \mu_\downarrow}{2}$

At low interaction strength, particle and spin have the same conductance...
What when *a* increases ?

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Spin drag physics

In the up/down picture :

$$\begin{aligned} I_\uparrow &= -G_\uparrow \Delta\mu_\uparrow - \Gamma \Delta\mu_\downarrow \\ I_\downarrow &= -\Gamma \Delta\mu_\uparrow - G_\downarrow \Delta\mu_\downarrow \end{aligned}$$

$\Gamma / G_\uparrow$ = fraction of carried down spin
For particle and spin conductance :

$$I_N = -G_N \Delta\mu \quad \text{with} \quad G_N = G_\uparrow + G_\downarrow + 2\Gamma$$
$$I_S = -G_S \Delta b \quad \text{with} \quad G_S = G_\uparrow + G_\downarrow - 2\Gamma$$

In a single channel, with the Hamiltonian :

$$\mathscr{H} = \sum_{k\sigma} \varepsilon_{k,\sigma} c^\dagger_{k,\sigma} c_{k,\sigma} + \frac{U}{2} \sum_{k,k',q,\sigma} c^\dagger_{k+q,\sigma} c^\dagger_{k'-q,-\sigma} c_{k',-\sigma} c_{k,\sigma} \, .$$

→ Simple estimate of spin drag (eqn. of motion + 2nd order RPA) :

$$\Gamma \simeq \frac{4\gamma^2}{9h} \left[\frac{T}{T_F} + \frac{3}{2} \left(\frac{T}{T_F} \right)^2 \right] Ln, \gamma \equiv int.parameter$$

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Including thermodynamics

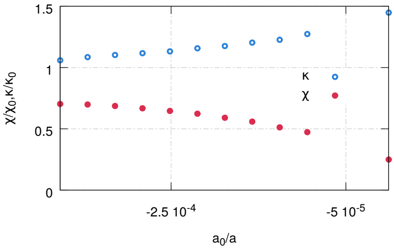
Uncoupled spin and particle transport :

$$I_N = \frac{d\Delta N}{dt} = -G_N \Delta\mu$$
$$I_S = \frac{d\Delta M}{dt} = -G_S \Delta b$$

On the thermodynamics side :

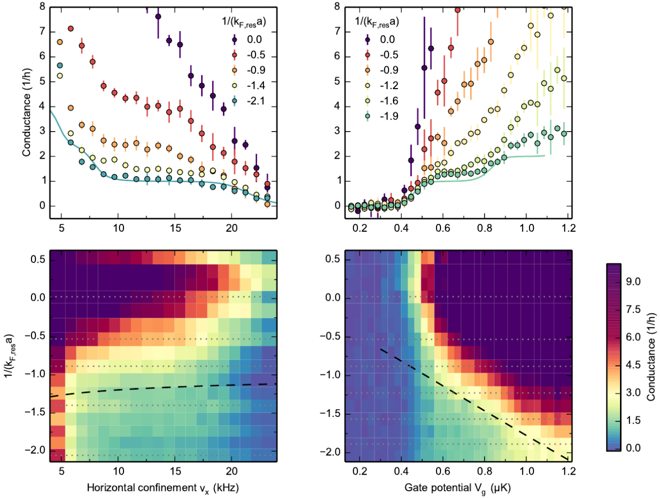
$$\Delta N = \kappa \Delta\mu$$
$$\Delta M = \chi \Delta b$$

compressibility,susceptibility : ENS data on polarized gas (+ trap averaging) :



N. Navon *et al*, Science (2010)

Results - Particle conductance



Results - Particle conductance

Normal phase :

- Quantized conductance (≃ Particle number conservation in the Hamiltonian)
- Modified width of the plateaux, and transition slopes ≡ mean-field physics

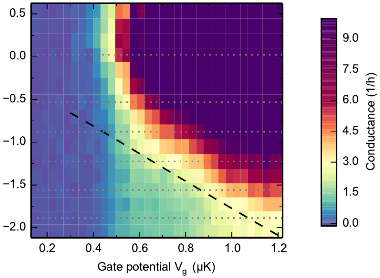
Fluctuation regime :

- Still quantized
- Renormalized height

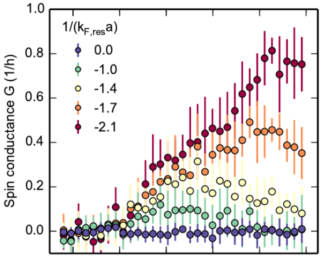
→ Entrance to the superfluid phase

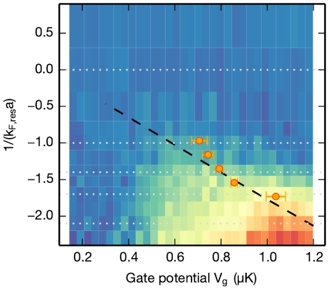
Superfluid transport :

- No quantization anymore
- Enhanced particle transport



Results - Spin conductance





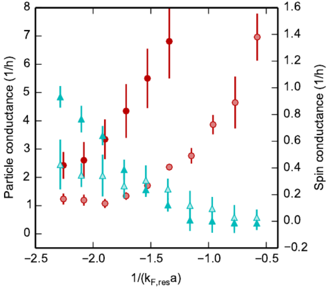
G_S vs. V_g :

- Strong suppression at large gate
- Small increase at small V_g
- Competition between channel opening and increasing gap

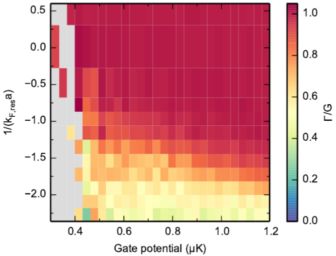
G_S vs. $1/k_F a$:

- Spin transport already suppressed for weak interactions
- No spin transport at all for unitary
- Max. $\simeq$ matches modified BCS expression

Results - Comparison spin-particle transport



- **Low interactions :** same effect of V_g on G_S and G_N
- **Strong interactions :** $G_N \nearrow\nearrow \quad G_S \searrow\searrow$: superfluidity, spin gap



No net polarization : $G_\uparrow = G_\downarrow \equiv G$

$$G_{N,S} = 2G - 2\Gamma \quad : \quad \Gamma/G = \frac{G_N - G_S}{G_N + G_S}$$

Γ/G : fraction of $-\sigma$ carried by σ

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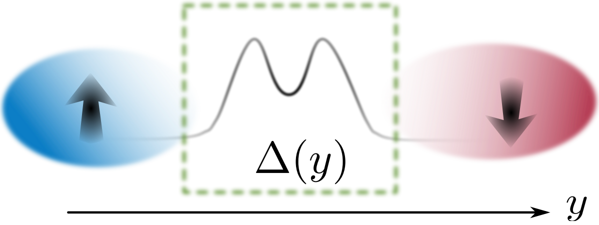
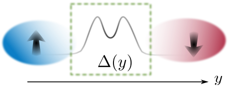
Results - Spin : interpretation-1



1. Space dependent gap
2. Only Bogoliubov QP can transport spin : spin transport ≡ excitations
3. Polarization → QP generation in reservoirs

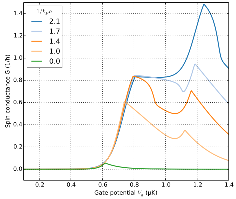
Results - Spin : interpretation-2

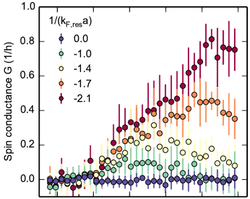
- Spin transport ≡ scattering on a space dependent potential
- Landauer-like transport with Bogoliubov QP



Transmission :

$$\mathscr{T}(\varepsilon, V_g) = \left| \exp\left[-\frac{\sqrt{2m}}{\hbar} \int dy \sqrt{(\Delta(y) - \varepsilon)} \right] \right|^2 \quad , \quad \Delta(y) \propto E_F(y) \exp\left[\frac{\pi}{2k_F(y)a} \right]$$





$$G_S = \frac{1}{h} \sum_n \int_{\Delta_{res}}^{+\infty} d\varepsilon \frac{\mathscr{T}(\varepsilon, V_g)\vartheta(\varepsilon - (E_n - V_g))}{4\cosh^2\left[\frac{\varepsilon - b}{2k_B T}\right]}$$

Gorkov, L. P., and T. K. Melik-Barkhudarov Sov. Phys. JETP (1961)

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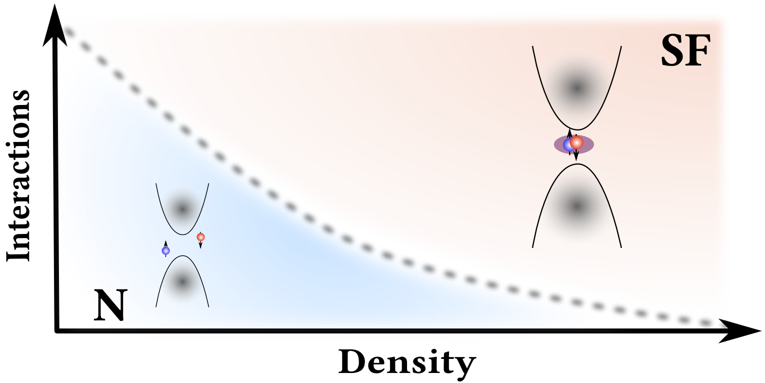
Summary



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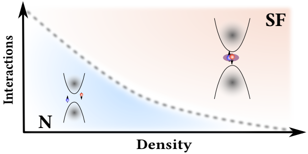
Summary-Conclusion

In a nutshell :

- Effects of interactions on quantized conductance
- Investigation of spin drag/spin gap physics
- Qualitative features captured by mean field physics
- Spin and particle transport are complementary



What's next ?

- For mesoscopic lovers : attractive equivalent of the 0.7 anomaly
- Investigation of polarization/interaction competition ?
- Continue exploring transport along the BEC-BCS crossover : thermal transport ?

The players

From left to right :

- T. Esslinger
- J.-P. Brantut
- Ch. Grenier
- S. Krinner
- M. Lebrat
- D. Husmann
- S. Nakajima
- S. Haüsler

Thanks for your attention !