Universal Spin Transport in Strongly Interacting Fermi Gases

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Spin Transport

• Net relative motion of atoms with different spin

• Damped due to collisions

Earlier experiments:
DeMarco & Jin, PRL 88, 040405 (2002)
Du et al, PRL 101, 150401 (2008)

Some theory:
Parish & Huse. PRA 80, 063605 (2009)
Bruun. NJP 13, 035005 (2011)
Unitary Fermi Gas

• Ultracold (~100nK) fermionic atoms
• Interactions tunable by an applied magnetic field (Feshbach resonance)
  – Strongest interactions at s-wave resonance (unitarity)
• Superfluid transition
• Nearly zero (quantum-scale) viscosity
Connection to Other Systems

• Spintronics
  – Magnetic data storage, information processing

• Quark-gluon plasma
  – Strongly interacting Fermions
  – Nearly zero viscosity:
    Elliptic flow in heavy ion collisions at RHIC\textsuperscript{1} and ALICE at LHC\textsuperscript{2}
Spin transport parameters

• Spin drag coefficient $\Gamma_{sd}$

$$F_{sd} = \frac{1}{2} M \Gamma_{sd} v_{rel}$$


• Spin diffusivity $D_s$

$$J_s = -D_s \frac{\partial (n_\uparrow - n_\downarrow)}{\partial z}$$

  - Parish & Huse. PRA 80, 063605 (2009)
  - Bruun. NJP 13, 035005 (2011)
Experiment

• $^6$Li trapped in a magnetic / optical dipole trap
• 50/50 mixture of two spin states
• Separate the spin states via magnetic gradient pulses
• Rapidly set the magnetic field to the Feshbach resonance
• Apply cooling or heating
• Observe the evolution
Collision of Two Fermi Gases
Measuring Spin Drag

Overdamped, use an exponential fit to get $\Gamma_{sd}$

\[ \ddot{d} + \Gamma_{sd} \dot{d} + \omega^2 d = 0 \]
Spin Drag vs Interaction Strength

- Maximum drag on resonance

\[ \frac{T}{T_F} = 0.32, 0.16 \]
Results for Spin Drag: Unitarity

- Maximum drag near $T_F$

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Measuring Spin Diffusivity

• $D_s$ from spin density gradient and equilibration time

Gradient decays at the same rate as $d$
Spin Diffusion at Unitarity

- Minimum $D_s = 6.3(3) \, \hbar/m$ for $T < 0.5 \, T_F$
- $T^{3/2}$ scaling for $T > 2 \, T_F$
  - unconstrained fit: $T^{1.4(1)}$

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Highly Polarized Gas

- Same procedure, but with a 90/10 mixture
- More Pauli blocking than in 50/50 case

Solid line: Bruun et al., PRL 100, 240406 (2008)
Spin Transport in SF

- 60/40 mixture
- Below $T_C$: superfluid core

- Still overdamped.
- Collisions at SF-Normal interface or inside the SF?
Conclusions

• Spin drag is strong at unitarity
• Measured spin drag and spin diffusivity vs temperature
• Maximum spin drag near $T_F$
• Minimum spin diffusion below $T_F$
• Stronger Pauli blocking in highly-polarized gas
• Sping drag also observed in a superfluid
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Spin Diffusion vs Interaction Strength

- Minimum diffusivity on resonance
Varying Interactions

![Graph showing varying interactions with different $k_F a$ values](image)

- $k_F a = 0$
- $k_F a = 0.08$
- $k_F a = 0.13$
• More Pauli blocking in the polaron case

Drag reduction from peak down to $0.15 \, T_F$:

- **Polaron**:
  51(6)% reduction

- **Balanced Gas**:
  26(4)% reduction
Spin Susceptibility

- Spin conductivity: \( \sigma_s = n/(m\Gamma_{sd}) \)

- Einstein relation: \( \chi_s = \sigma_s/D_s \)

- Derivation – Magnetization in a spin-dependent potential:

  \( spin-diffusion \leftrightarrow spin-conduction \)

  \[
  0 = -D_s \nabla (n_1 - n_2) + \sigma_s \nabla (\mu_1 - \mu_2)
  \]
Spin Susceptibility

Susceptibility $<\text{Compressibility}$ for $T<T_F$

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Getting the gradient
Expectations

- Known power laws at high temperature
- For $T \approx T_F$, expect $D_s \approx \hbar/m$
- For $T \ll T_F$, correlations may influence transport

See:
Riedl et al., PRA 78, 053609 (2008)
Bruun and Smith PRA 72, 043605 (2005)
Comparison

• No enhanced spin drag at low T

Riedl et al., PRA 78, 053609 (2008)

Sommer et al, Nature 472, 201 (2011)
Relation to Homogeneous Values

• Non-uniform density and average velocity
• Trap average: \[ \langle G \rangle = \frac{1}{N} \int d^3 \mathbf{r} \ G(\mathbf{r}) \ n(\mathbf{r}) \]
• Measured values:

\[ \Gamma_{sd} = \frac{\langle \tilde{\Gamma}_{sd} u_z,\text{rel} \rangle}{\langle u_z,\text{rel} \rangle} \]

\[ D_s = \tilde{D}_s(0) \frac{\langle u_z,\text{rel} \rangle}{u_{z,\text{rel}}(0)} \]

\[ \chi_s = \frac{\tilde{\Gamma}_{sd}(0) u_{z,\text{rel}}(0)}{\omega_z^2 d} \tilde{\chi}_s(0) \]
Center of Mass Difference

- Bouncing at early times
- Exponential relaxation at late times