Cold atoms in a spin

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Stoner instability

\[ \hat{H} = \sum_{k\sigma} \epsilon_k c_{k\sigma}^\dagger c_{k\sigma} + g \sum_{k,k',q} c_{k\uparrow}^\dagger c_{k'\downarrow}^\dagger c_{k'\uparrow} c_{k\downarrow} + g N_{\uparrow} N_{\downarrow} \]

\[ E = \sum_{k,\sigma} \epsilon_k n_\sigma(\epsilon_k) + g N_{\uparrow} N_{\downarrow} \]

Not magnetized

Partially magnetized
Magnetism with cold atoms

• A gas of atoms simulates electrons in a solid

\[ |F = 1/2, m_F = 1/2 \rangle \quad \text{Up spin electron} \]

\[ |F = 1/2, m_F = -1/2 \rangle \quad \text{Down spin electron} \]

• Magnetic field controls interaction strength
• Contact interaction
• Clean system
Experimental evidence for ferromagnetism

Jo et al, Science 325, 1521 (2009)
Further experimental signatures

\[ E_K \propto n^{5/3} \]

\[ \Gamma \propto (k_F a)^6 n_\uparrow n_\downarrow (n_\uparrow + n_\downarrow) \]
Two vs three-body loss

Three-body mechanism

Two-body mechanism

$$E_{\text{bind}}$$

$$\frac{E_{\text{bind}}}{2}$$
Pairing loss rate

\[ \Delta_{q=0} / \varepsilon_F \]

\[ k_F a \]

\[ \text{Atom Loss Rate [1/s]} \]

\[ \text{Interaction Parameter } k^\text{p}a \]

\[ \text{Magnetic Field [G]} \]
Pairing losses: kinetic energy

![Graph showing KE rate vs. k_Fa and Magnetic Field vs. Kinetic Energy](image-url)
Mass imbalance ferromagnetism

\[ \hat{H} = \sum_k \frac{k^2}{2m^\uparrow} c_{k\uparrow}^\dagger c_{k\uparrow} + \sum_k \frac{k^2}{2m^\downarrow} c_{k\downarrow}^\dagger c_{k\downarrow} + g \sum_{kk',q} c_{k\uparrow}^\dagger c_{k'\uparrow}^\dagger + q_{\downarrow} c_{k\downarrow}^\dagger + q_{\downarrow} c_{k'\downarrow} + c_{k\uparrow} \]

- Magnetic moment formed along quantization axis

\[ ^{40}\text{K atom, } m = 40m_0 \quad \rightarrow \quad \text{Up spin electron} \]

\[ ^{6}\text{Li atom, } m = 6m_0 \quad \rightarrow \quad \text{Down spin electron} \]

Keyserlingk & Conduit, PRA 83, 053625 (2011)
Reduced three-body losses

\[
m_{\uparrow}/m_{\downarrow} = 1
\]

\[
m_{\uparrow}/m_{\downarrow} = \frac{20}{3}
\]
Reduced two-body losses

\[ \frac{m_{\uparrow}}{m_{\downarrow}} = 1 \]

\[ \frac{m_{\uparrow}}{m_{\downarrow}} = \frac{20}{3} \]

- Repulsive
- Non-interacting
Trapped behavior

- At high interaction strength light atoms forced to outside
Unique signatures of ferromagnetism

\[
\frac{m_\uparrow}{m_\downarrow} = 1 \\
\frac{m_\uparrow}{m_\downarrow} = \frac{3}{2}
\]

Maximum in cloud size

Gradient discontinuity

Cloud size vs. \( k_F a \)
Conclusions

- Equilibrium theory provides a reasonable qualitative description of the transition
- Competing many-body instabilities provide alternative explanation
- Suppress losses and give stronger signatures of ferromagnetism by studying mass imbalance
- Answer long-standing questions about solid state ferromagnetism and motivate new research arenas
Solid state ferromagnetism

Second order in Fe & Ni

First order in ZrZn$_2$

Magnetism mysteries

Mean-field theory

GJC & Simons, PRL 103, 200403 (2009)
Pairing loss rate

Pekker et al, PRL 106, 050402 (2011)