Universal Fermi gases in mixed dimensions

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Introduction
Ultracold atom experiments have studied a wide variety of physics by changing the dimensionality of space from 3D to 2D and to 1D by confining atoms with strong optical lattices. However, people in ultracold atoms have not paid much attention to systems in mixed dimensions*, where different types of particles live in different spatial dimensions. (*One such example is a “brane world” model of the Universe.)

Question: What happens in a two-species Fermi gas when one species is confined in 2D or 1D and interacts with the other species in 3D by a tunable short-range interaction? Such a system is a new type of imbalanced Fermi gas and leads to very rich physics!

P-wave superfluidity in 2D-3D mixture

1. weak coupling region : $a_{\text{eff}} \rightarrow 0$
   - A-B pairing does NOT take place because of the “mismatch” of two Fermi surfaces
   - Instead, B atoms mediate an effective interaction between A atoms
     $$V_{\text{ind}}(r) = \frac{a_{\text{eff}}^2}{m_{\text{AB}}} \frac{2k_F^4 \cos(2k_Fr) - \sin(2k_Fr)}{4\pi r^4} + O(a_{\text{eff}}^3)$$
   - P-wave pairing occurs between A atoms in 2D
     $$\Delta(p) \propto (p_x + i p_y) e^{-\gamma/(a_{\text{eff}}k_F)}$$

2. strong coupling region : $a_{\text{eff}} \rightarrow +0$
   - A atoms capture B atoms to form tightly bound molecules (dimers)
   - 2D BEC of AB dimers occurs as long as $a_{\text{eff}} k_F A \lesssim O(1)$ (dimer size should be smaller than the mean interparticle distance)

More phases in a bilayer geometry

1. weak coupling region : $a_{\text{eff}} \rightarrow 0$
   - Induced interaction $V_{\text{ind}}(r)$ leads to 2 possibilities [Fig.1]:
     - P-wave pairing of A atoms in same layers for large $d$
     - S-wave pairing of A atoms in different layers for small $d$

2. strong coupling region : $a_{\text{eff}} \rightarrow +0$
   - Dimer BEC in each layer as long as $a_{\text{eff}} k_F A \lesssim O(1)$ & $a_{\text{eff}} \lesssim d$
   - Two layered BECs are coupled via the induced interaction $V_{\text{ind}}(r)$

3. unitarity region : $|a_{\text{eff}}| \rightarrow \infty$
   - Two A atoms in different layers and one B atom form a 3-body bound state (trimer) when $|a_{\text{eff}}| \geq d$ [Fig.2]
   - AAB trimer Fermi gas is realized as long as $k_F A \lesssim O(1)$ (trimer size should be smaller than the mean interparticle distance)

Efimov effect in 1D-3D mixture

The Efimov effect (formation of 3-body bound states near the 2-body resonance) has NOT been observed in Fermi-Fermi mixtures because a large mass ratio $m_A/m_B=13.6$ is needed to overcome the centrifugal barrier. Our mixed dimensional system helps to realize the Efimov effect using a mixture of $^{40}\text{K}$ and $^4\text{He}$

- Critical mass ratio decreases well below $m_A/m_B=6.67$
  - $6.35$ in 2D-3D
  - $2.06$ in 1D-3D
- 3-body recombination results in atom losses:
  $$\tilde{n}_A \approx -2\alpha [n_A] B \quad (\tilde{n}_A A + B \rightarrow \tilde{A} + AB)$$
  Its rate constant $\alpha$ has the characteristic log-periodic behaviors due to the Efimov effect with a scaling factor $22.0$
  - Resonant peaks for $a_{\text{eff}}<0$
  - Destructive interferences for $a_{\text{eff}}>0$

- If observed, this is the very first evidence of the Efimov effect in fermions!

Conclusion
A two-species Fermi gas in mixed dimensions shows very rich physics from p-wave superfluidity to Efimov effect. In particular, the existence of background B atoms induces correlations between A atoms even if they are confined in separated layers and leads to various quantum phases. Our scheme can be widely extended to multilayer geometries, multwire geometries, Bose-Bose mixtures, and Bose-Fermi mixtures, and may open up new research directions.

References
Efimov effect: Y.N. & S.Tan, PRA 79, 060701(R) (2009)