Universal Fermi gases in *mixed* dimensions

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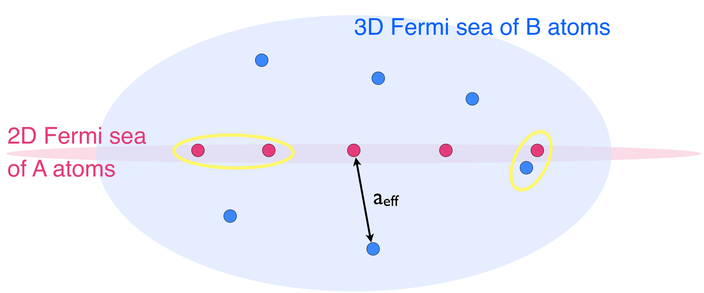
Introduction

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 : $a_{\rm eff} \to -0$

- 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

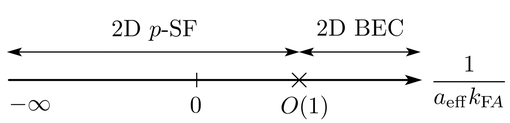
$$V_{\rm ind}(r) = \frac{a_{\rm eff}^2}{m_{AB}} \frac{2k_{FB} r\cos(2k_{FB}r) - \sin(2k_{FB}r)}{4\pi r^4} + O(a_{\rm eff}^3)$$

- ***P-wave pairing occurs between A atoms in 2D***

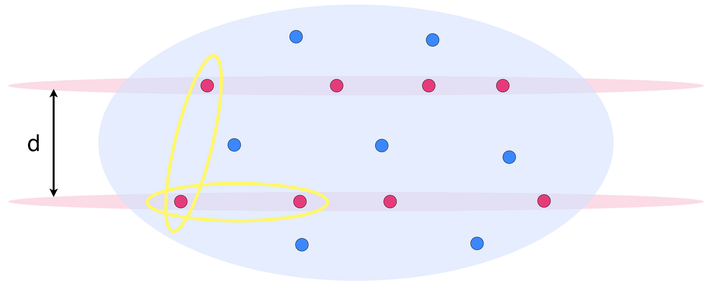
$$\frac{\Delta(\boldsymbol{p})}{\varepsilon_{FA}} \propto (\hat{p}_x \pm i\hat{p}_y)\, e^{-\#/(a_{\rm eff}k_{FB})^2}$$

2. strong coupling region : $a_{\rm eff} \to +0$

- A atoms capture B atoms to form tightly bound molecules (dimers)
- ***2D BEC of AB dimers occurs*** as long as $a_{\rm eff} k_{FA} \lesssim O(1)$ (dimer size should be smaller than the mean interparticle distance)



More phases in a bilayer geometry



1. weak coupling region : $a_{\rm eff} \to -0$

- Induced interaction $V_{\rm ind}(r)$ 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 : $a_{\rm eff} \to +0$

- Dimer BEC in each layer as long as $a_{\rm eff} k_{FA} \lesssim O(1)$ & $a_{\rm eff} \lesssim d$
- ***Two layered BECs are coupled*** via the induced interaction $V_{\rm ind}(r)$

3. unitarity region : $|a_{\rm eff}| \to \infty$

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

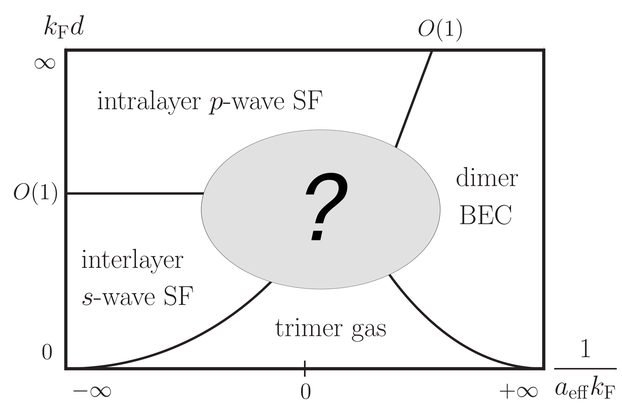


Fig.1: critical layer separation

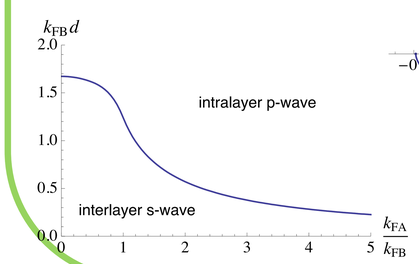
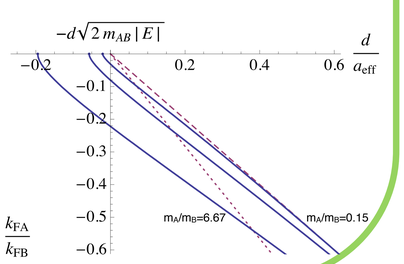


Fig.2: 3-body binding energy



Efimov effect in 1D-3D mixture

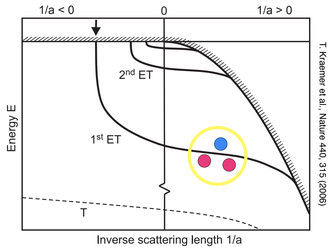
The Efimov effect (formation of 3-body bound states near the 2-body resonance) has NOT been observed in Fermi-Fermi mixtures because a large mass ratio m_A/m_B>13.6 is needed to overcome the centrifugal barrier. ***Our mixed dimensional system helps to realize the Efimov effect using a mixture of ^{40}K and ^{6}Li!***

- ***Critical mass ratio decreases well below m_K/m_{Li}=6.67***

m_A/m_B>13.6 in 3D

→ 6.35 in 2D-3D

→ 2.06 in 1D-3D

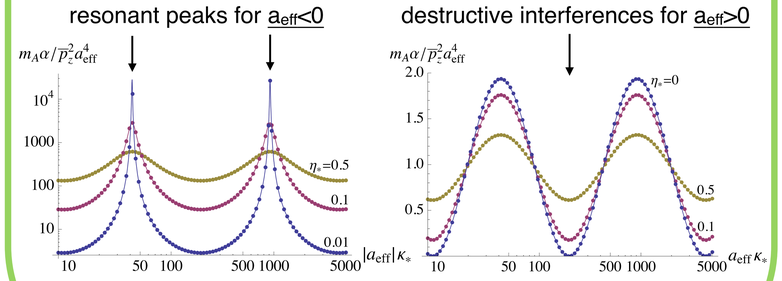


- 3-body recombination results in atom losses:

$$\dot{n}_A \approx -2\alpha n_A^2 n_B \qquad (A+A+B \Rightarrow A+AB)$$

Its rate constant α has the characteristic log-periodic behaviors due to the Efimov effect with a scaling factor 22.0

resonant peaks for $a_{\rm eff}$<0 — destructive interferences for $a_{\rm eff}$>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, multiwire geometries, Bose-Bose mixtures, and Bose-Fermi mixtures, and may open up new research directions.

References

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P-wave superfluidity: Y.N., Ann. Phys. 324, 897 (2009)
Bilayer Fermi gas: Y.N., PRA 82, 011605(R) (2010)
Efimov effect: Y.N. & S.Tan, PRA 79, 060701(R) (2009)