BCS-BEC Crossover

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Outline

• Bose-Einstein Condensation (BEC)

• Bardeen Cooper Schrieffer Theory of Superconductivity (BCS)

• BCS-BEC Crossover

• Realization Of Crossover
Bose-Einstein Condensation
Introduction

- In 1924, Satyendra Bose discovered a way to distribute a collection of indistinguishable particles.

\[ N = \sum_j \frac{1}{e^{\beta (\epsilon_j - \mu)} - 1} \]

- Together with Einstein, they formed the basis for Boson statistics
Bose-Einstein Condensation

• Main achievements of the theory was the idea of Bose-Einstein Condensation

• As temperature decreases, so does the chemical potential until it reaches zero
Bose-Einstein Condensation

- This leads to a macroscopic occupation of the lowest energy state
BCS Theory
Introduction

• In 1957, Bardeen, Cooper, and Schrieffer proposed the BCS Theory of superconductivity.

• The model described an attractive interaction between electrons.

\[ \mathcal{H} = \sum_k \epsilon(k) \left( c_{k,\uparrow}^\dagger c_{k,\uparrow} + c_{-k,\downarrow}^\dagger c_{-k,\downarrow} \right) - g \sum_{k,k'} c_{k,\uparrow}^\dagger c_{-k,\downarrow}^\dagger c_{-k',\downarrow} c_{k',\uparrow} \]
We can understand this attraction through polarization of the lattice
BCS Theory

- If we consider s-wave pairing between electrons, opposite spin and momenta are paired.

- The pair behaves like a boson and at low temperature it can condense and behave collectively.
BCS-BEC Crossover
BCS-BEC Crossover

- What happens if we tune the interaction strength between atoms?

- Is there a smooth crossover between BEC and BCS?
BCS-BEC Crossover

• BEC wave function

$$|\Psi_{BEC}\rangle = N \exp \left( \sum_k \phi_k c_k^\dagger c^\dagger_{-k} \right) |0\rangle$$

• BCS wave function

$$|\Psi_{BCS}\rangle = \prod_k (u_k + v_k c_k^\dagger c^\dagger_{-k}) |0\rangle$$

• Wave functions are actually the same!
BCS-BEC Crossover

• The BEC and BCS regimes are described by the same wavefunction that evolves smoothly.

• This is a crossover not a transition.

• Based on a mean-field theory so does it hold in experiment?
Realization Of Crossover
Realization Of Crossover

• Interactions between atoms can be tuned using a Feshbach resonance

• The interaction strength is characterized by the s-wave scattering length

Realization of Crossover

• The field dependent scattering length is given by

\[ a(B) = a_{BG} \left( 1 - \frac{\Delta B}{B - B_0} \right) \]

Ferlaino, Grimm, APS Physics 3,9 - 2010
Realization of Crossover

- Tuning this interaction leads to three regimes:
  - BEC \( a > 0 \)
  - Unitary \( a \to \infty \)
  - BCS \( a < 0 \)

- Interesting behavior in the crossover/unitary regime – interactions are the strongest
Realization of Crossover

Observation of Pair Condensation in the Quasi-2D BEC-BCS Crossover
– MG Ries, et al. 2015
Realization of Crossover
Summary

• There is a similarity between BCS and BEC physics that can be described by a smooth crossover

• This can be realized experimentally using ultra cold atomic gases whose interactions are tuned through a Feshbach resonance

• The Unitary Fermi Gas regime where the scattering length diverges allows for the study of strongly interacting systems
References

• Feshbach Resonances in Ultracold Gases – C. Chin, et al., 2009

• BCS-BEC Crossover and the Unitary Fermi Gas – M. Randeria, E. Taylor, 2014

• Statistical Mechanics – Pathria, Beale, 2011

• Theory of Superconductivity – Bardeen Cooper Schreiffer, 1957