A Study of Ultra-Cold Atoms in the Strongly Interacting Regime

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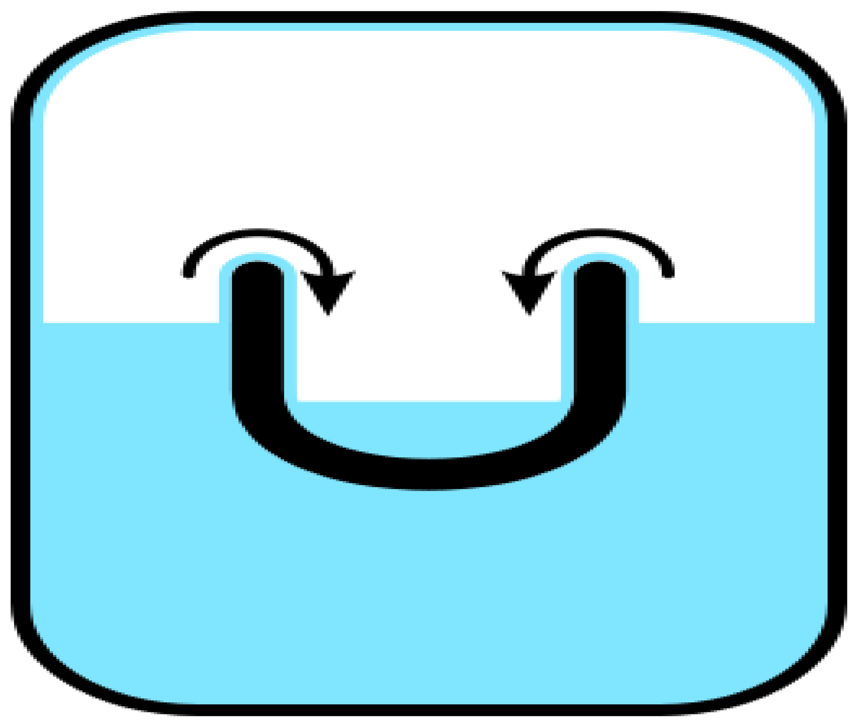
Abstract

We study properties of a superfluid state made of fermionic atoms. We present a method for finding the critical temperature at which a gas of interacting fermions goes into a superfluid state in the unitary regime at low density using the Fermi-Hubbard Model. We find agreement between the behavior of density from theoretical considerations and from the Fermi-Hubbard model.

Motivation for research

Superfluids

- Zero viscosity
- Ability to overcome friction
- Macroscopic quantum properties



The liquid Helium II creeping along a container in a superfluid.

Fermions

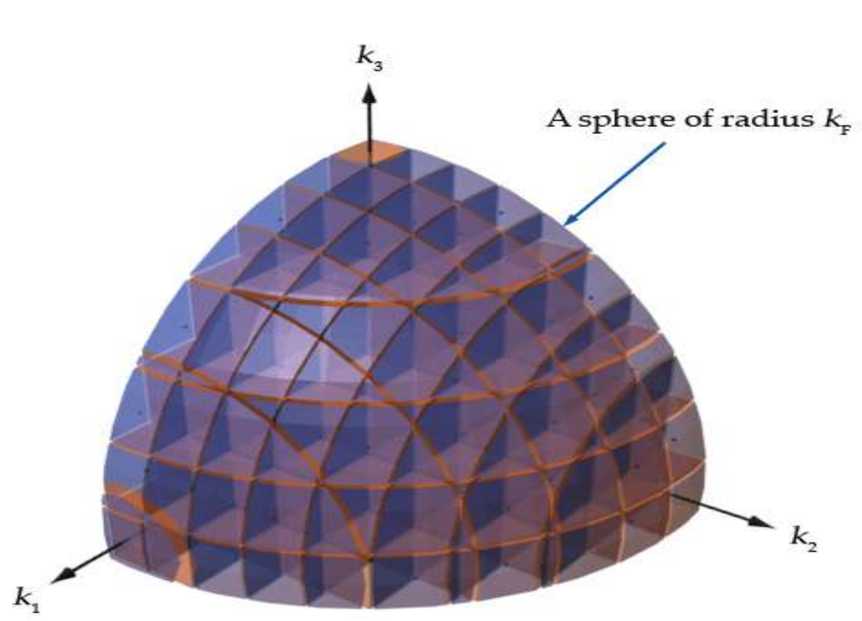
Have half integer spin

Include:

Fermions, Neutrons, Protons, Baryons, Muons, Tauons

Obey Fermi-Dirac Statistics

Cannot occupy the same state due to the Paul-Exclusion Principle

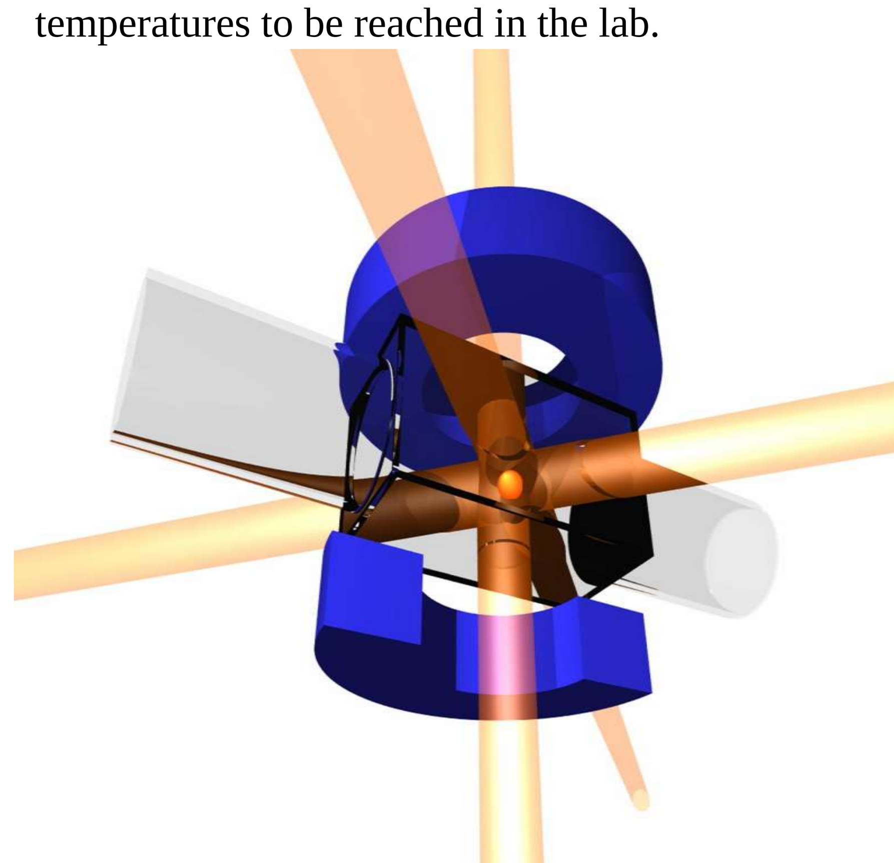


Bosons

- Photons, W and Z bosons, gluons
- Do not obey the Pauli-Exclusion Principle

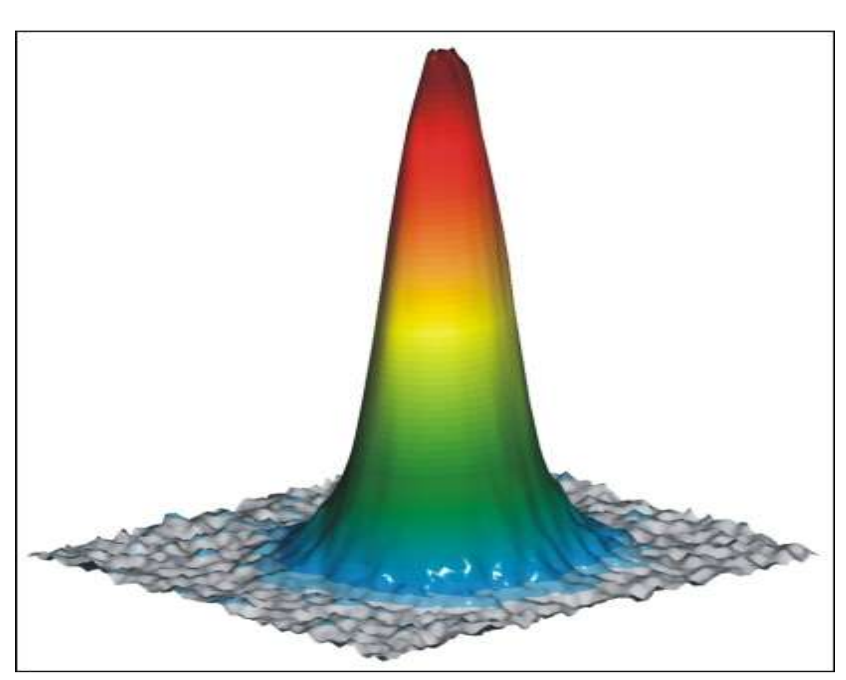
Einstein's Prediction

- Bosons are not bound by the Pauli-Exclusion principle and can occupy the same state.
- Einstein predicted that at extremely low temperatures, a portion of a group of bosons would condense, exhibiting the same quantum properties.
- Until recently, this prediction went untested. Recently technology has allowed necessary low temperatures to be reached in the lab.



Experimental set-up at William and Mary College designed to achieve ultra-cold temperatures.

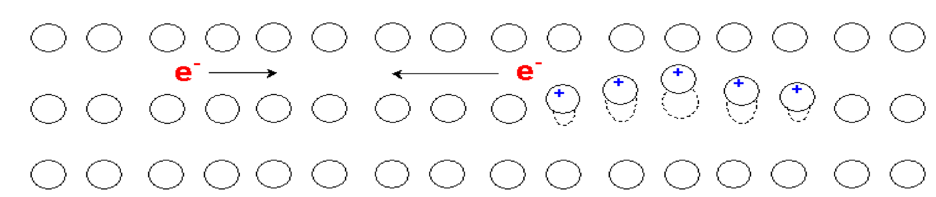
These condensates, referred to as Bose-Einstein Condensates, are an example of a superfluid.



Visual representation of a Bose-Einstein Condensate from a recently performed experiment.

Further Motivation for Research

- Fermions can couple or pair with each other to form bosons. Systems of these couple fermions have conditions at which they will go into a superfluid state commonly characterized by a critical temperature. It is this critical temperature that experimentalist need to know to further explore the fascinating properties of superfluids. This pairing of Fermions is shown below. The example below shows paired Fermions in a superconductor, a

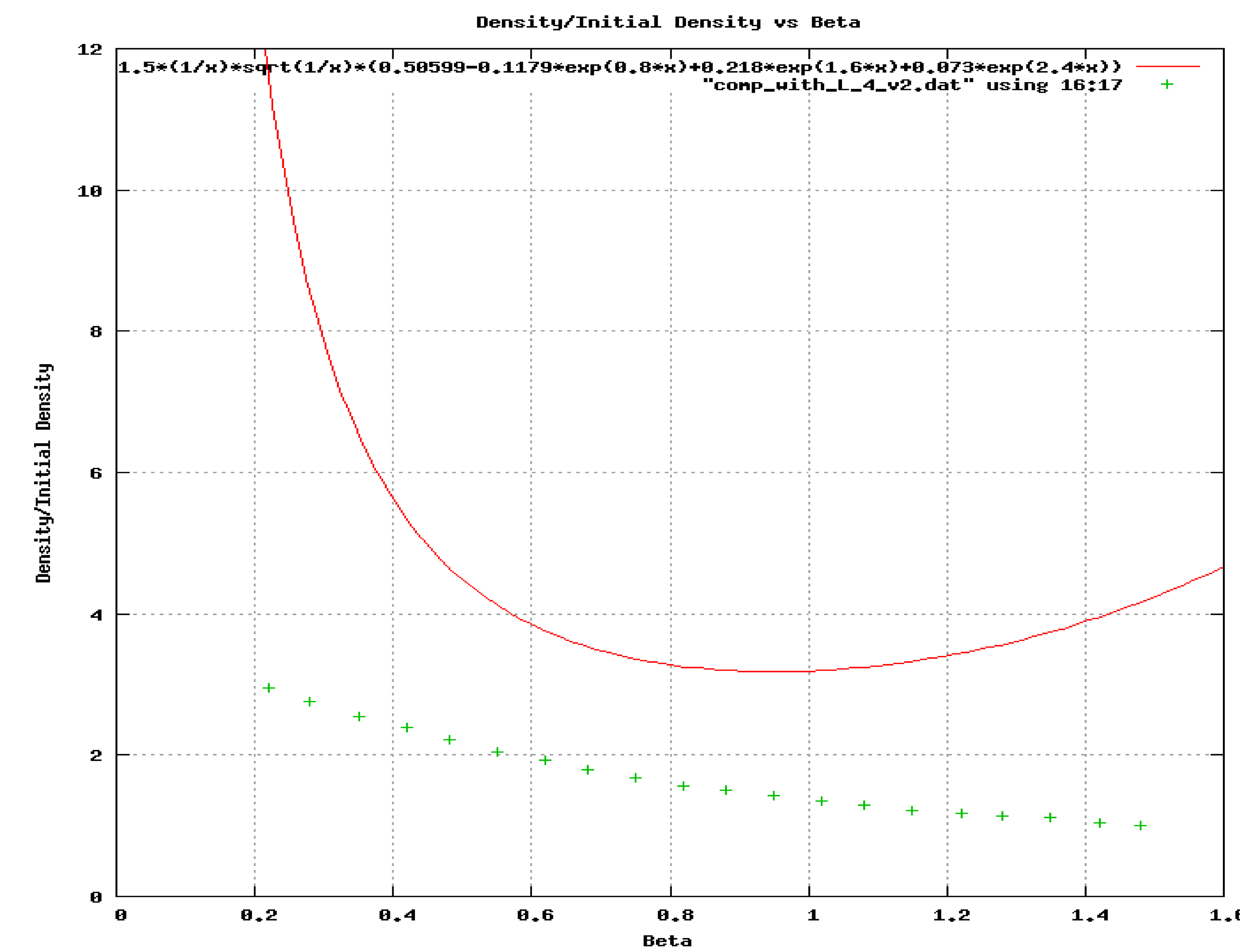


BEC versus BCS

- A system of fermions allowed to couple can be in one of two regimes, the BCS (Bardeen, Cooper, and Schrieffer) or the BEC regimes. In the BCS regime, the interactions between the Fermions are not great enough for a BEC to form. But at high interactions, the fermions form bosons and can form a BEC. It is not surprising to know then, that at in the BEC regime, the temperature at which the system goes into a superfluid state is the same as the BEC temperature.
- Research has been done in both the BEC and BCS regimes. There is excellent agreement between theoretical groups in both of these regions in regards to the value of the critical temperature. It is the region between these regimes that disagreement exist.

Method of Research

- The research utilized the Fermi-Hubbard Model to represent a system of interacting fermions. Several parameters can be determined before each run of the program including temperature, chemical potential, dimensions of the system, and the interaction between fermions.
- Our model of fermions placed the fermions at the points of a 3-D lattice. To find the critical temperature, the research made use of important contributions by Binder. He proved that Green's Function is independent of lattice size. Thus, Green's Function can be plotted for different lattice sizes, and the temperature at which the graphs cross is the critical temperature.
- Because of the computing power used, only small systems could be modeled (12*12*12). Experimentalist need to know what the critical temperature is for low density. If a system is very dense, it goes into a liquid state and is contaminated by the surrounding environment.
- To be able to model systems of low density, there would only be one fermion in the entire system! It is necessary then to extrapolate what happens at low densities.



Results of the Research

- We tested the program finding several properties of the gas. One example was the density of the gas. This was plotted versus the inverse of temperature and the results are seen above. The red line represents the theoretical result and the green crosses represent the results of the program.
- It is important to note that there was a major difference between the theoretical result and the data obtained from the program. The fermions were allowed to react in the program, but the theoretical result was for non-interacting fermions. Even with this major difference, there is still some agreement in the two curves.
- It is also important to note that the theoretical prediction was for high temperature (low beta).

Future Procedures and Considerations

- FIND THE CRITICAL TEMPERATURE!
- And once we have this at one density, find over many densities to extrapolate for low densities.

Literature Cited:

D.P. Landau and Kurt Binder, A Guide to Monte Carlo Simulations in Statistical Physics. New York: Cambridge University Press (2000).

Photo Credits:

- http://en.wikipedia.org/wiki/File:Helium-II-creep.svg
- http://www.ugrad.physics.mcgill.ca/wiki/index.php/PHYS-558
- http://saaubi.people.wm.edu/ResearchGroup/Research/UltraCold_Research/Apparatus_UltraCold/Apparatus_UltraCold.html
- http://images.iop.org/objects/physicsweb/news/11/2/2/BEC-BCS2.jpg

Acknowledgments

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