Research Proposal for a
Master of Science Thesis

תכנית מחקר לעבודת גמר
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גז פרמי מנוון קוונטית במעבר ה- BEC-BCS
Quantum degenerated Fermi gas across the BEC-BCS crossover

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Introduction

In the last century it has been known, and reasonably well understood, that superconductors and superfluids exist firmly within one of the two limits. Either the celebrated Bardeen-Cooper-Schrieffer (BCS) theory of pairing [1] in Fermi systems described them, or they could be understood in terms of the Bose Einstein condensation (BEC) of bosons, with repulsive interactions.

There has been great excitement, however, about recent experimental and theoretical progress in elucidating the BCS to BEC crossover for ultracold Fermi gases [2]. For the first time, the ultracold Fermi gases exhibited behavior that, with the turn of a knob, could be made to span the entire range from BCS to BEC. While such a crossover had been theoretically predicted, its actual realization in the laboratory was a major advance [3, 4], and led to intense investigation of the properties of the very strongly interacting, unitary regime that lies right in the middle of the crossover. Furthermore, the unitary Fermi gas has remarkable universal properties, arising from scale invariance, and connects with a diversity of fields such as nuclear physics and string theory.

Research Objective

Our purpose is to achieve quantum degenerated Fermi gas with ultracold atoms, and to investigate the BCS-BEC crossover. We intend to perform several experiments to provide a deeper physical understanding of the BEC-BCS crossover; they may also probe unknown dynamics across it.

Detailed description of the proposed research

We have taken steps to achieve quantum degenerated Fermi gas with ultracold atoms: designing a dual chamber apparatus, building and adjusting lasers for cooling and trapping two species atoms(Rb^{87} - boson and K^{40} - fermion) with magneto-optical trapping (MOT), compressing the MOT ,and using optical molasses (polarization gradient cooling) to cool the atoms further. Finally we simulated the magnetic trap and the magnetic transport from the MOT chamber to a second chamber in higher vacuum ("science chamber").Using a series of 12 pairs of coils,3 cm spaced in an L shape with a total length of 42.3 cm we intend to transport the atoms to the science chamber in 4.6secby magnetic conveyor [5] and then reduce the temperature by evaporative cooling in a magnetic trap to achieve quantum degeneracy.

This should be done as follows, after capturing the atoms in the MOT and using optical molasses to cool them, we load the atoms to a magnetic quadropole trap, which is formed by two opposed, separated, coaxial current loops (same coils that are used for the MOT but with higher currents) that create an approximated potential $V = \mu b' \sqrt{x^2 + y^2 + 4z^2}$ close to the center of the trap ($\vec{r} = 0$).

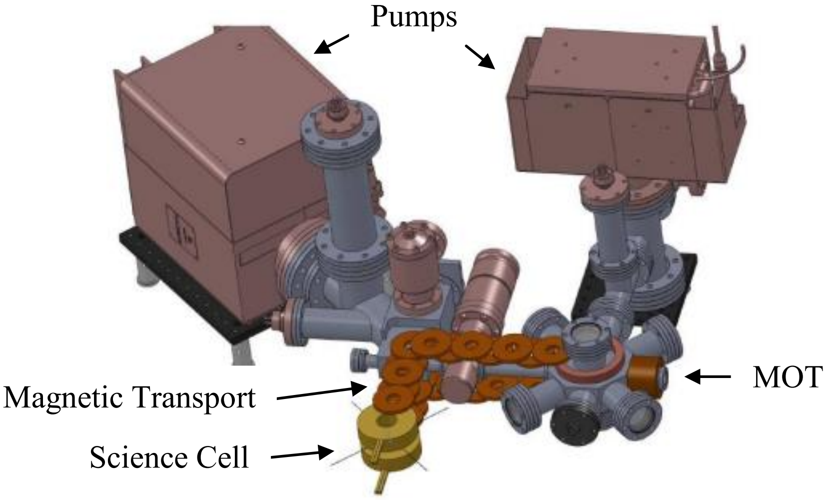

Figure 1 – Schematic sketch of our apparatus

The magnetic potential is moved by adiabatically changing the currents in 3 adjacent coil pairs thus changing the potential minimum and the atom cloud position. At the end of the transition, the atoms will be placed in a final magnetic quadruple trap in the science cell for evaporative cooling.A well-known limitation of the quadropole trap is that the magnetic field goes to zero at its center,therefore atoms moving through the center will experience Majorana spin flip [6,7], which may result in the atom being lost from the trap.When the atoms get colder the probability for a spin flip increases as they are closer to the center. To solve this problem we will use a blue-detuned laser beam tightly focused on the magnetic field zero [8, 9], which creates a repulsive dipole force that prevents atoms from reaching the central region. We plan to use a 10W of 532nm wavelength laser (Verdi-V10) focused to a 30µm waist at the center of the trap to produce a dipole potential at the order of 100µK that will allow us to evaporative cool the atoms to a less than$1\mu K$ temperature. The last step is to load the atoms to a dipole trap produced by a 42W 1064nm laser for more evaporative cooling to achieve quantum degenerated Fermi gas with K^{40}.

Many experiments can be done with quantum degenerated Fermi gas. We intend to use rapid ramps across the BEC-BCS transition or drive the system with a sinusoidal modulation to measure the gap in fermionic excitations Δ_{gap} as proposed by [10], where Δ_{gap} equals to the order parameter $|\Delta|$ in the BCS regime and to $\sqrt{(\mu^2 + \Delta^2)}$ in the BEC regime (μ is the chemical potential). That is done by changing the magnetic field in the dipole trap which controls $1/\mathrm{k_f a}$ of the K^{40} atoms close to a Feshbach Resonance [11, 12] where a is the s-wave scattering length and $\mathrm{k_f}$ is Fermi momentum. Linearly changing $1/\mathrm{k_f a}$ results in weakly damped oscillations in $|\Delta|$ with a frequency $2\frac{\Delta_{\mathrm{gap}}}{\hbar}$ [13]. These oscillations originate from the threshold for the creation of fermionic excitations by pair breaking, following a time dependent perturbation. In the BCS regime the oscillation amplitude decays as $t^{-1/2}$, whereas in the BEC regime it decays as $t^{-3/2}$ [14]. These oscillations are also known as the "Higgs mode" [15-17] due to a formal analogy between the gap phenomenon in superfluid Fermi liquids and mass creation by the Higgs mechanism in the theory of elementary particles. Although some investigation into the response of a superfluid Fermi gas to a modulation of the scattering length have been conducted [18, 19], the Higgs mode has never actually been observed in Fermi gases. Analogous phenomena, however, have been observed in superconductors [20, 21] and for bosons near the Mott-insulator transition [22].

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