RESEARCH

Currently 30 research papers have been published or accepted in refereed journals. These theoretical works are closely related to testable predictions, and some of them are carried out in association with experimental groups. My recent research is in the fields of many-body theory as applied to the strong interacting ultra-cold fermions and bosons. I have been worked on:

- Unltracold fermions in optical lattices with low dimensionality
- Collective oscillations of Bose gases
- Collective oscillations of Fermi gases at BCS-BEC crossover
- Dynamics of trapped Bose-Fermi mixtures at zero and finite temperature
- Super-fluidity of a rotating BEC
- Theory of quantum measurement

Untracold Fermions in optical lattices

The Mott metal-insulator transition is a fundamental concept in the strongly correlated many-body systems. The recent advances in ultracold aromic gases in a well-controlled manner. By now the Mott metal-insulator transition of ultracold bosonic atoms confined in optical lattices has been demonstrated by Greiner et al. [1]. The Mott metal-insulator transition with ultracold fermions, an even more traditional phenomenon in condensed matter physics, has not been realized experimentally yet. However, its realization is within reach of present-day technique.

Motivated by this possibility, my collaborator Prof. Drummond, Dr. Hui Hu and I address the problem of how to detect the emergence of fermionic Mott-insulator phases in real experiments [2]. We consider a zero temperature, one-dimensional Hubbard model with a harmonic potential, as a model of an ultra-cold spin 1/2 fermionic atomic cloud in a deep optical lattice with strong radial and weak axial confinement. Based on the exact Bethe ansatz solution of the homogeneous 1D Hubbard model, together with the local density approximation, we calculate the density profile of the cloud as functions of a characteristic filling factor and coupling constant. This leads to a generic phase diagram including a metallic phase and a Mott-insulator phase. We then investigate the collective density oscillations of the cloud in different phases using Luttinger liquid theory, which describes long wavelength hydrodynamic behaviour. We find that in the metallic phase the collective oscillation is an overall motion that goes through all sites of the cloud. This quenches gradually towards the phase transition point, with the mode frequency decreasing monotonically to zero. After entering the Mott-insulator phase, the density oscillation revives, but is restricted to the compressible wings. The corresponding frequency increases rapidly. Therefore, a sharp dip appears in all collective mode frequencies in the vicinity of the phase boundary, giving a clear signature of the Mott metal-insulator transition. A detailed experimental implementation is proposed.

1. M. Greiner et al., Nature (London) **415**, 39(2002)
2. **Xia-Ji Liu**, Peter D. Drummond and Hui Hu; *Physical Review Letters,* **94***, 136406* (2005).

Collective oscillations of a confined Bose gas

Soon after the realization of Bose-Einstein condensation in trapped atomic gases, an important development in this field has been the measurement of the frequencies and damping rates of collective excitations. These measurements are very accurate and provide a unique opportunity for quantitative tests of quantum theories of the dynamics of many-body systems. In particular, the measurements, of the lowest-energy excitations made at JILA [3] on ^{87}Rb gases at various temperatures have proved hard to understand at simple mean-field level and have therefore stimulated a number of theoretical studies to address effects beyond the mean-field approximation.

My collaborator, Dr. Hui Hu, Dr A..Minguzzi, Prof. M.P. Tosi, and I present a theory for the linear dynamics of a weakly interacting Bose gas confined inside a harmonic trap at finite temperature. The theory treats the motions of the condensate and of the noncondensate on an equal footing within a generalized random-phase approximation, which (i) extends the second-order Beliaev-Popov approach by allowing for the dynamical coupling between fluctuations in the thermal cloud, and (ii) reduces to an earlier random-phase scheme when the anomalous density fluctuations are omitted. Numerical calculations of the low-lying spectra in the case of isotropic confinement show that the present theory obeys with high accuracy the generalized Kohn theorem for the dipolar excitations and demonstrate that combined normal and anomalous fluctuations play an important role in the monopolar excitations of the condensate. Mean-field theory is instead found to yield accurate results for the quadrupolar modes of the condensate. Although the restriction to spherical confinement prevents quantitative comparisons with measured spectra, it appears that the non-mean-field effects that we examine may be relevant to explain the features exhibited by the breathing mode as function of temperature in the experiments carried out at JILA on a gas of ^{87}Rb atoms.

3. D. S. Jin et al., *Phys. Rev. Lett.* **78**, 764 (1997)
4. **Xia-Ji Liu**, Hui Hu, A. Minguzzi, and M. P. Tosi, Phys. Rev. A **69**, 043605(2004)

Collective modes in BCS-BEC crossover

Current experiments on ultracold Fermi gases are rapidly advancing towards the realization of superfluid states, and Bose-Einstein condensation of dimmers has already been achieved. A key tool for the manipulation of atomic gases is the use of a Feshbach resonance to vary the magnitude and the sign of the coupling strength. Across the resonance the *s*-wave scattering lengthe *a* goses from large positive to large negative values, thus allowing exploration of the crossover from the Bardeen-Cooper-Schrieffer (BCS) state to the Bose-Einstein condensate (BEC) of bound-fermion pairs. As Fermi gases have been demonstrated to be stable also near the reasonance, they offer a new opportunity to investigate highly correlated many-body systems.

My collaborator, Dr. Hui Hu, Dr A..Minguzzi, Prof. M.P. Tosi, and I evaluate the frequencies of collective modes and the anisotropic expansion rate of a harmonically trapped Fermi superfluid at varying coupling strengths across a Feshbach resonance driving a BCS-BEC crossover [5]. The equations of motion for the superlfuid are obtained from a microscopic mean-field expression for the compressibility and are solved within a scaling ansatz. Our results confirm non monotonic behavior in the crossover region and are in quantitative agreement with current measurements of the transverse breathing mode by Kinast *et al*.[6] and of the axial breathing mode by Bartenstein *et al*.[7].

5. Hui Hu, A. Minguzzi, **Xia-Ji Liu,** and M.P.Tosi, *Phys. Rev. Lett.* **93** 190403(2004)
6. Kinast *et al*. *Phys. Rev. Lett*. **92**, 150402(2004)
7. Bartenstein *et al. Phys. Rev. Lett.* **92**, 203201(2004)

Dynamics and thermodynamics of trapped Bose-Fermi mixtures

In 2003 I focused on the dynamics and thermodynamics of a trapped Bose-Fermi mixture, in collaboration with Dr. Hui Hu and Dr. Michele Modugno at LENS.

Based on a simple scaling assumption, we have investigated the lowest collective modes [8] and the expansion [9] of a trapped Bose-Fermi mixture at zero temperature. We had explained the experimental result of the behavior of bosons during expansion [10] and predicted the behavior of fermions at the same expansion. This work had stimulated a later experiment at LENS group, and our prediction had been quantitatively confirmed [11].

We have considered the thermodynamics of Bose-Fermi mixtures trapped in an isotropic trap by extending the Hartree-Fock-Bogoliubov-Popov theory of Bose gases [12]. Under the conditions appropriate to the experiments at LENS, we predict a sizable enhancement of the condensate fraction and of the transition temperature of BEC due to the strong Bose-Fermi attraction. Using the same theory, the stability of the mixtures at the finite temperature has been studied [13]. This gives a better understanding of the relevant experiment at LENS.

Most recently, a second-order Beliaev-Popov theory has been developed for Bose-Fermi mixtures at finite temperature, and dynamics of mixtures has been investigated in detail [14]. A signature of the phase separation of the mixture at positive interaction has been predicted.

8. **Xia-Ji Liu** and Hui Hu, *Phys. Rev. A* **67**, 023613 (2003).
9. Hui Hu, **Xia-Ji Liu**, and Michele Modugno, *Phys. Rev. A* **67**, 063614 (2003).
10. G. Roati, F. Riboli, G.Modugno, and M.Inguscio, Phys. Rev. Lett. **89**, 150403(2002)
11. F. Ferlaino, et al, Phys. Rev. Lett. **92**, 140405(2004).
12. Hui Hu and **Xia-Ji Liu**, *Phys. Rev. A* **68**, 023608 (2003).
13. **Xia-Ji Liu**, Michele Modugno and Hui Hu, Phys. Rev. A **68**, 053605 (2003)
14. **Xia-Ji Liu** and Hui Hu, Phys. Rev. A **68**, 033613 (2003).

Super-fluidity in Bose-Einstein condensate

Super-fluidity of BECs is a direct consequence of their coherent nature. It is manifested in the appearance of vortices and scissors modes, as well as in a critical velocity for the onset of dissipative processes. As a concrete example, my collaborator, Dr. Hui Hu and I have considered the formation and properties of vortices in atomic Bose-Einstein condensates [15].

We have computed numerically the ground state for harmonically trapped *N*-Boson systems with a weak repulsive contact interaction, and studied its structure as the angular momentum *L* increases up to *3N*. We show that the ground state is generally a fragmented condensate due to the angular momentum conservation. In response to an (arbitrarily weak) asymmetric perturbation of the trap, however, a fragmented condensate can be easily turned into a single condensate state. We identified this intrinsic spontaneous symmetry breaking by using conditional probability distributions calculated for the ground state. Our results show the same successive transitions between vortex states with different symmetries, as the prediction of the mean field theory.

This work has been published in *Physical Review Letters*. After that, we noticed that the previous work on super-fluidity mainly consider two extreme cases: the weak interaction limit and the strong Thomas-Fermi limit. We then continued a further study of the ground-state property of the same system with medium interaction strength. Our results show that effective interaction, density distribution and condition-probability distribution are strongly affected by the interaction strength. [16]

15. **Xia-Ji Liu**, Hui Hu, Lee Chang, Weiping Zhang, Shi-Qun Li and Yu-Zhu Wang, *Phys. Rev. Lett.* **87**, 030404 (2001).
16. **Xia-Ji Liu**, Hui Hu, Lee Chang, and Shi-Qun Li, *Phys. Rev. A* **64,** 035601 (2001).

Dynamical model for quantum measurement

My earlier interest is attached to quantum measurement. Under the instruction of Professor Chang-Pu Sun, I had studied on the dynamical approach of wave-function collapse in quantum measurement [17,18].

The postulate of wave-function collapse in quantum measurement was introduced by von Neumann outside the basic laws of quantum mechanics. Because this postulate introduces an irreducible source of sudden change of the state vector resulting from the act of measurement, it is not satisfactory to understand the quantum measurement process. However, quantum mechanics is believed to be a quite universal theory that should be valid for the whole world of physics. Naturally, one expects that it can be used to describe wave-function collapse. For the above reasons, our paper investigated quantum measurement dynamical model based on the Hepp-Coleman's model and its generalizations. However, it has to be pointed out that the correlation between the state of the measured system and that of the detector has not been emphasized well in the original Hepp-Coleman's model and its generalizations. Our investigation emphasized both the wave-function collapse and the correlation collapse. In fact, the correlation between the states of the measured system and the detector is crucial for a realistic process of measurement, which uses a scheme utilizing the macroscopic counting number of the measuring instrument-detector to show the microscopic state of the measured system.

17. **Xia-Ji Liu** and Chang-Pu Sun, *Phys. Lett. A* **198**, 371 (1995).
18. Chang-Pu Sun, Xue-Xi Yi and **Xia-Ji Liu**, Fortschr. Phys. 43, 585 (1995).