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Project Full Name: Ultracold Bose-Fermi Mixtures of Metastable Helium

Marie Curie Actions
IIF Final Report

The “bosefermiHe” project has launched research on ultracold metastable helium atoms on the road towards the realization of strongly interacting systems of ultra cold atoms which lend themselves to detection on a single atom basis. The project has permitted a brilliant PhD student, Guthrie Partridge, who, during his PhD work acquired extensive experience in the physics of correlated ultracold Fermionic atoms, to work in a leading european laboratory (the Laboratoire Charles Fabry de l’Institut d’Optique, in Palaiseau, France) specializing in the physics of degenerate gases of metastable helium. The combination of these two areas of expertise has led to several important publications concerning correlations in degenerate quantum gases, and although the project is now officially over, several more results are in the analysis stage.

Metastable helium atoms have the unique feature that they can be brought to quantum degeneracy and can be detected using microchannel plates and electron multipliers. This feature means that single atoms are easily detected. Micro channel plates, which have excellent intrinsic time resolution, can also be coupled with position sensitive anodes to acquire a true three dimensional imaging capability. Chris Westbrook’s group in Palaiseau has, in in the past 6 years, adapted this technology to the detection of metastable atoms and, before the arrival of Dr. Partridge, had already achieved several firsts in the competitive field of degenerate quantum gas physics, most of which involved the detection of various types of 2 particle correlations. This work has continued, and even accelerated during the tenure of Dr. Partridge.

Before discussing the scientific details of the project’s achievements, we will make a few remarks on the societal impact of the project. The study of strongly correlated systems corresponds to a large fraction of the research effort in quantum condensed matter physics. An outstanding example is the physics of copper-oxide superconductors with high transition temperatures. Twenty five years after their discovery, unsolved fundamental questions remain, and they are only a small part of a large class of materials with strong electronic correlations which display remparkable physical properties. The theoretical modeling of these systems is confronted by an daunting numerical problem – the exponential size of the computing power and memory necessary to perform a numerical calculation. The only solution may be to use physical systems to construct a quantum simulator - essentially an analog quantum computer. Strongly correlated systems may have another important application: they may provide a practical means to generate strongly entangled systems which Our research has been geared towards further understanding this class of problems using a new tool: ultra-cold atoms and our ability to make measurements on individual atoms and their correlation properties. We hope that we can contribute to mankind's knowledge of this subject - a subject which may have important technologcical ramifications in the future.

Our research proceeded in three steps, each of which resulted in a publication that appeared in 2010. In the first phase of the project, the group undertook a careful study of the atom pair production process in four wave mixing process of matter waves. Building on an experiment performed in 2007, the group modified the geometry of the experimental configuration to better reveal the anisotropies of the atom pair formation process. The most surprising result concerned an anisotropy observed in the relative momenta of the atom pairs. Instead of being distributed on a perfect sphere as is dictated by elementary phase matching considerations, the momentum of the atoms showed a periodic variation of about 5% as a function of the angle of emission. This measurement was only possible because of the extremely accurate and imaging possible with the delay line anode detector. After extensive analysis and modeling, this anisotropy was shown to be due to a complicated interplay between mean field and many body effects in the condensates giving rise to the pairs. The result was published in Physical Review Letters in April 2010. Further, less surprising effects related to the collision anisotropy were also observed. These are currently still under analysis and a further paper is planned.

Second the group, led by Partridge introduced the worlds first laser trap for metastable helium and used in to cool atoms to quantum degeneracy. The ability to optically trap atoms promises to be important for further studies of bose-fermi mixtures because of its robustness and the fact that it can trap atoms independent of their spin state. The group used this capability to make measurements of inelastic rate constants among different spin states, confirming recent theoretical calculations which showed that different combinations could have very different inelastic loss rates. This was the first measurement of spin dependent losses for metastable helium. A paper on this research was published in the Physical Review in May 2010.

Having perfected the laser trap, the group went on to study relative number squeezing, again using the four wave mixing process. The high shot to shot stability of the laser trap proved extremely valuable in this study, because in allowed us to average our measurements over 3600 repetitions with little technical noise. A straight forward analysis showed that the four wave mixing process did indeed produce relative number squeezing at the level of about 10% in the variance (-0.5 dB). The observed squeezing was limited primarily by the quantum efficiency of the detector. Indeed the measurement amounted to the best current limit on the metastable helium detection efficiency, a quantity that is in general difficult to measure directly. This result paves the way towards using correlated pairs to improve the accuracy of signals in interferometry experiments. The results were published in Physical Review Letters in November of 2010.

In addition to this published work. the group has used the laser trap and correlation techniques to acquire data on several other processes in trapped metastable helium. In one experiment in spin mixtures, atoms were given a spin dependent velocity and made to collide in the trap. The collision between two dense clouds exhibits a discontinuity at a velocity corresponding to the sound velocity: below this velocity, the clouds pass through each other, while at higher velocity, we see thermalization of the two clouds corresponding to the breakdown of superfluidity and onset of viscous flow. Furthermore, as time passes, the number of atoms decreases due to evaporative loss and inelastic two-body processes. Remarkably, below a critical atom number, we see a total back-reflection of the colliding clouds. This behavior signals the transition to a quasi-1-dimensional regime in which the transverse trapping frequency is higher than both the atomic chemical potential and the collisional energy. Further analysis is in progress. In collaboration with several theorists, we have also been examining the response of an elongated Bose condensate to a sudden change in the trapping conditions. It has been predicted that in this system, the acoustic analog of the “dynamic Casimir effect” may be observable in the form of the creation of atom pairs with equal and opposite momenta.