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QUANTUM GAS MICROSCOPE DEVELOPMENT

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Abstract: Quantum gas microscopes allow high-resolution imaging of ultracold atoms in an optical lattice. These recently-developed instruments bridge the "top-down" and "bottom-up" approaches to quantum simulation by allowing detection and control of the microscopic degrees of freedom in a many-body quantum system. Single-lattice-site-resolved quantum gas microscopy has allowed unprecedented insight into the behavior of controllable quantum systems in recent years. In this project, the undergraduate will develop and test technological subsystems for the quantum gas microscope being built in the Weld lab. The particular focus of the project will be on techniques of moving and addressing alkaline earth atoms. Weld group graduate student Peter Dotti will mentor the student in tasks such as the design, construction, and testing of a system of tunable-focus lenses for transferring atoms into the microscope, and the development of a near-UV laser system for depletion-enhanced sub-diffraction microscopy.

At its creation in 2009 [1], the quantum gas microscope (QGM) was shown to enable both macroscopic and microscopic control and observation in quantum gas systems [2, 3]. A QGM is essentially two subsystems: (1) a confinement system and (2) a high resolution imaging apparatus. The confinement system holds the atoms in the 2D imaging plane. A rough analogy to a classical microscope is that the confinement system is the "microscope slide" (combined with illumination usually) and the imagining system is the magnifying optics. The QGM images an ultracold 2D atomic cloud subject to a potential landscape produced by carefully projecting light onto the confined atoms. In particular, this projection can create a lattice potential and thereby simulate particles in a 2D lattice. Quantum gas microscopy enables a continuum of experimental designs from "top-down" experiments, in which the collective atoms are prepared in a macrostate (e.g. a thermodynamic ensemble of given parameters) to "bottom-up" experiments, in which many individually confined atoms are prepared and manipulated.

The Weld Lab is equipped with a machine for evaporating, trapping, and cooling strontium gas into a Bose-Einstein condensate (BEC). We have proposed implementing the QGM in a new chamber of the machine (dubbed the "Science Chamber") that branches off from the main chamber. We plan to cool the atoms into a BEC in the main chamber and then transport them to the science chamber using infrared laser light and tunable focus lenses. The strontium atoms are attracted to the point of maximal intensity of the infrared beam, i.e. the beam focus. Such a beam is known as an optical dipole trap (ODT) and is broadly used in AMO physics. This trap has already been successfully used in the final strontium cooling and trapping stage. Moving the focus of the beam could be a means of moving the atoms in the ODT. Building upon Jacob Hines' Summer 2015 Worster Fellowship work and subsequent thesis on temperature calibrated focus-tunable lenses [4], we would like to implement this design in an atom transfer system.

One specific technique that we would like to apply to quantum gas microscopy is Stochastic Optical Reconstruction Microscopy (STORM), adopted from biology. This is a sub-diffraction imaging technique in which only a few random atoms are illuminated at a time. In doing this, the position of each atom can be precisely determined by mathematically fitting the center of each diffraction pattern from the imaging light. Specifically, we will populate the strontium atoms in a metastable state ($^3P_2$) using a 397nm UV laser. Then we stimulate the emission of a small subset of atoms with 403 nm light. In doing this, the atoms will randomly emit at a low, random rate, enabling STORM.

Under the mentorship of Peter Dotti and Professor Weld along with support from the other Weld Lab graduate students, an undergraduate would learn various details of the design and operation of a QGM. In particular, the undergraduate would design and construct the detailed implementation of the above discussed atom transfer system. Specific challenges of the project are determining the optimal geometry of the lens setup based on the limitations of the focal length tunability and with the necessity of minimizing the heating and loss of the atoms during transfer. In work on the STORM illumination system, the undergrad will construct the new 397nm laser and the various collimating and directing optics involved. At the same time they will learn about atomic structure and the STORM technique more generally.

We believe that the development of subsystems for a quantum gas microscope will be invaluable to an undergraduate interested in AMO research. In carrying out the proposed project, the undergraduate will learn broadly applicable optical system design and construction. Additionally, they will gain a familiarity of the principles of optical dipole traps, while learning about atomic structure and the way that structure is utilized in trapping and imaging systems. The project will be an excellent opportunity for a motivted undergraduate to develop crucial experimental skills and deepen their understanding of quantum mechanics in a hands-on setting.

References

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