Quantum Science with Ultracold Atoms on a 50 nm Scale

We propose to use a new super-resolution method to position atoms at 50 nm scale, much shorter than the wavelength of light. This will allow us to study and harness the electric and magnetic forces between two atoms at such a short range. Electric and magnetic dipolar forces, which scale as the inverse cube of the distance between the atoms, are enhanced by a factor of 1,000 by using resolution 10 times better than the wavelength of light. For two atoms, collective light scattering via coupled electric dipoles will be studied, and magnetic interactions will lead to strong spin exchange. Pairs of atoms with strong magnetic coupling will be used as building blocks for quantum materials and to realize a purely magnetic quantum gate.

The new super-resolution method involves two laser frequencies with orthogonal circular polarizations which will allow the localization of a spin-up and spin-down atom at distances no longer limited by the wavelength of light. The atom of choice is dysprosium due to its favorable electron configuration enhancing angular momentum and magnetic interaction strength. We will explore various techniques to control the focal spots of light with 10 nm precision. This includes polarization control, dispersion control, and phase control.

A major focus of the proposed research is bilayer physics, where two thin layers of atoms are magnetically coupled. This makes connections to research with interlayer excitons and bilayer graphene. More generally, we will study physics in one layer which is modified by the second layer via proximity effects on a subwavelength scale. These studies can be extended to ladder systems of two magnetically coupled 1D chains. Attractive magnetic interactions should induce pairing between atoms in different layers (or chains). More generally, we will explore different systems and geometries for strongly correlated dipolar matter.

The impact of this work is in the areas of many-body physics, quantum simulations, and quantum computation. The research will provide new insight into quantum materials, in particular materials with strong interactions and correlations. This includes a deeper understanding of already known phenomena, but also the realization of materials which have no currently known counterpart in nature. Some of this insight may inspire the realization of new advanced materials and atomic sensing devices, which open new possibilities for civilian and military applications of interest to the DoD. Since no exact calculations are possible for many strongly interacting systems, our experiments are analog quantum simulations using a novel platform, which can be used to benchmark many-body calculations. The realization of a purely magnetic quantum gate for ground state atoms is different from quantum gates using electric interactions between excited atoms (Rydberg gates) or between polar molecules with rotational excitation.

Another impact is the training of the next generation of high performing researchers. The field of ultracold atoms attracts many of the brightest students and prepares them for leadership positions in research, education and national security.