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14. ABSTRACT

Two of the most exciting recent developments in atomic physics have been the advent of quantum gas microscopy and the production of degenerate alkaline earth gases. Single-lattice-site-resolved quantum gas microscopy has allowed unprecedented insight into the behavior of controllable quantum systems. In parallel with these advances, ultracold atomic physics has expanded beyond the first column of the periodic table to alkaline earth species such as strontium and ytterbium, opening up new horizons for the investigation of exotic quantum phases, simulation of

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Report Title

Final Report: Alkaline Earth Quantum Gas Microscope for High-Resolution Imaging of Ultracold Strontium

ABSTRACT

Two of the most exciting recent developments in atomic physics have been the advent of quantum gas microscopy and the production of degenerate alkaline earth gases. Single-lattice-site-resolved quantum gas microscopy has allowed unprecedented insight into the behavior of controllable quantum systems. In parallel with these advances, ultracold atomic physics has expanded beyond the first column of the periodic table to alkaline earth species such as strontium and ytterbium, opening up new horizons for the investigation of exotic quantum phases, simulation of complex materials, and quantum sensing. This DURIP award has funded an instrument designed to combine both these breakthroughs: a quantum gas microscope for high-resolution studies of ultracold alkaline earth atoms.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

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(c) Presentations

Title: New Techniques for Cold Atom Quantum Emulation
Presenter: Zachary Geiger
Meeting: CAIQuE Meeting, Berkeley CA, January 2016

Number of Presentations: 1.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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TOTAL:

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TOTAL:

Patents Submitted

Patents Awarded

Awards

NSF CAREER Award (for PI Weld), February 2016

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

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Total Number:	

Names of Faculty Supported

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Total Number:

Names of other research staff

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Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

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Technology Transfer

Final Report: Alkaline Earth Quantum Gas Microscope for High-Resolution Imaging of Ultracold Strontium

Prepared for Dr. Paul Baker, ARO

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Foreword

Two of the most exciting recent developments in atomic physics have been the advent of quantum gas microscopy and the production of degenerate alkaline earth gases. In the few experiments where it has been realized, single-lattice-site-resolved quantum gas microscopy has allowed unprecedented insight into the behavior of controllable quantum systems. In parallel with these advances, ultracold atomic physics has expanded beyond the first column of the periodic table to alkaline earth species such as strontium and ytterbium, opening up new horizons for the investigation of exotic quantum phases, simulation of complex materials, and quantum sensing. This proposal has supported the purchase of equipment for an instrument combining both these breakthroughs: a quantum gas microscope for high-resolution studies of ultracold alkaline earth atoms. The instrument is an extension of the ultracold strontium apparatus which was the subject of our AFOSR YIP grant FA9550-12-1-0305, and significantly enhances its research capabilities, while opening up new possibilities for our investigations of nonequilibrium quantum dynamics (funded by ARO PECASE award W911NF-14-1-0154) and tunable quasiperiodic quantum systems (funded by ONR award N000141410805). The precision and control inherent in single-site resolution can enable characterization of novel quantum fluids, detection and manipulation of edge states in cold atom quasicrystals, and high-spacetime-resolution studies of dynamical quantum phenomena. Furthermore, the instrument enables new experiments not currently possible with any apparatus.

Final Report

A. Statement of the problem studied

This proposal supported the purchase of equipment used to build an alkaline earth quantum gas microscope. The instrument is attached to our existing ultracold strontium apparatus (AFOSR YIP award FA9550-12-1-0305), which was designed to allow for expandability. The overarching goal of our AFOSR-funded strontium work has been to develop novel tools and techniques for quantum simulation and quantum sensing using the unique properties of alkaline earth atoms. The scientific reach of our ARO-funded work on nonequilibrium quantum dynamics (ARO PECASE award W911NF-14-1-0154) and our ONR-funded work on tunable quasiperiodic quantum systems (ONR award N000141410805) are also significantly enhanced by the possibility of realizing the relevant phenomena in a quantum degenerate gas with single-site resolution. In all these projects, the data we can extract from our apparatus is limited by the finite optical resolution of our imaging system. This limitation, common to nearly all optical-lattice-based quantum simulation and quantum sensing experiments, requires that all data be extracted via bulk probes with a spatial resolution of at best several lattice sites. This restricts probes of small-scale correlations and imposes a requirement that any measurement be averaged over some multiple-lattice-site area of the sample. The quantum gas microscope discussed in this proposal circumvents this limitation by exploiting the special properties of strontium to enable single-lattice-site-resolved imaging. The instrument builds on existing techniques of quantum gas microscopy while also taking advantage of the unique properties of strontium to enable new techniques of control and detection. The strontium quantum gas microscope thus combines the novel abilities offered by quantum gas microscopy and ultracold alkaline earth atoms. As outlined in the sections below, the instrument extends the capabilities of our current DoD-supported research, opens up entirely new avenues of DoD-relevant research currently not accessible to any instrument, and enhances the quality of research-related education at UCSB.

B. Background and Key Concepts

Before detailing the functioning and design of the instrument, we outline in this section the key features of these two central experimental techniques.

Quantum Gas Microscopy: Ultracold atoms in optical lattices are ideal tools for the experimental study of many-body quantum systems [1]. Until recently, most such research has focused on the bulk properties of macroscopic highly correlated quantum gases. In recent years a new approach called “quantum gas microscopy” has been developed, which enables the detection and control of individual atoms in a lattice [2, 3]. Site-resolved optical imaging of single atoms has also been demonstrated in large-wavelength or sparsely-populated lattices [4, 5], and using an electron microscope [6]. In the case of the quantum gas microscope, however, a combination of high fidelity single atom detection and small lattice constants uniquely enable high-resolution quantum simulation and quantum sensing. These 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 macroscopic and scalable sample. The quantum gas microscope is based around a high-numerical-aperture optical system, which simultaneously serves to generate the lattice potential and to measure the population of individual lattice sites. Such devices have enabled a startling number of breakthroughs in recent years, including study of the superfluid-Mott insulator transition at the single-atom level [7], the detection of nonlocal string order in quantum gases [8], the development of algorithmic cooling [9], the detection of antiferromagnetic spin chains in the density sector [10], measurement of light-cone-like correlation spreading [11], study of the quantum dynamics of a mobile spin impurity [12], and observation of magnon bound states [13].

Alkaline Earth Atoms: An important development in the field of ultracold atoms has been the extension of techniques for achieving quantum degeneracy beyond the stable alkali metals (hydrogen, lithium, sodium, potassium, rubidium, and cesium). Bose condensates and/or degenerate Fermi gases have been prepared in ultracold samples of several non-alkali elements, such as metastable helium [14, 15], chromium [16], calcium [17], ytterbium [18], dysprosium [19], erbium [20], and strontium [21–25]. These advances have opened the door to a number of new approaches to both quantum simulation and quantum sensing. At UCSB, we have constructed a flexible apparatus capable of producing ultracold strontium in optical lattice traps. This apparatus is designed to implement proposals (e.g. [26–29]) for exotic quantum simulation with bosonic and fermionic alkaline earth atoms in static or time-varying optical lattices. Strontium, an alkaline earth metal, is uniquely well suited to these goals. It has four reasonably abundant isotopes (^{84}Sr, ^{86}Sr, ^{87}Sr, and ^{88}Sr), which enables a flexible approach to quantum simulation of both bosonic and fermionic systems and bose-fermi mixtures. The four stable isotopes exhibit widely varying background scattering lengths. Strontium's rich electronic structure, including ultranarrow singlet-to-triplet intercombination transitions and the associated optically excited metastable states, is diagrammed in Fig. 1. This rich atomic structure is at the root of proposals to simulate exotic states such as Kondo lattice models [28], realize quantum information processors [30, 31], construct optical atomic clocks [32], and realize bio-inspired sub-diffraction imaging techniques (as discussed later in this proposal). Long-wavelength transitions from the metastable states offer the possibility of straightforwardly engineering controllable long-range interactions in a quantum gas without using Rydberg atoms or molecules [33]. The high nuclear spin of ^{87}Sr enables the simulation of exotic phenomena such as magnets with $\mathrm{SU}(N)$ symmetry [26, 34], and the analogous property of ytterbium has been experimentally shown to allow Pomeranchuk cooling of cold-atom Mott insulators [35]. The singlet ground state and the zero nuclear spin of all stable bosonic isotopes are advantageous for noise-immune quantum sensing schemes.

C. Results: description of purchased instrument

Here we briefly describe the ultracold strontium source to which the QGM is attached, before going on to detail the design and function of the quantum gas microscope.

1. *Ultracold Strontium Apparatus*

A diagram of the ultracold strontium setup to which the QGM is attached is shown in Fig. 2. The strontium trap is loaded from an effusive oven which contains a multi-isotope source. An adequate pressure ratio between the oven and trapping regions is maintained by two 40 L/s ion pumps in a differential pumping configuration. A nozzle consisting of a close-packed array of stainless steel microcapillaries achieves both a high atomic flux and tight beam collimation. The bulk of this atomic beam is decelerated by a Zeeman slower with a laser detuned 750 MHz from the $(5\mathrm{s}^2)^1\mathrm{S}_0 - (5\mathrm{s}5\mathrm{p})^1\mathrm{P}_1$ transition at 461 nm. Transverse cooling light provides further beam collimation in order to maximize the atomic flux into our main chamber.

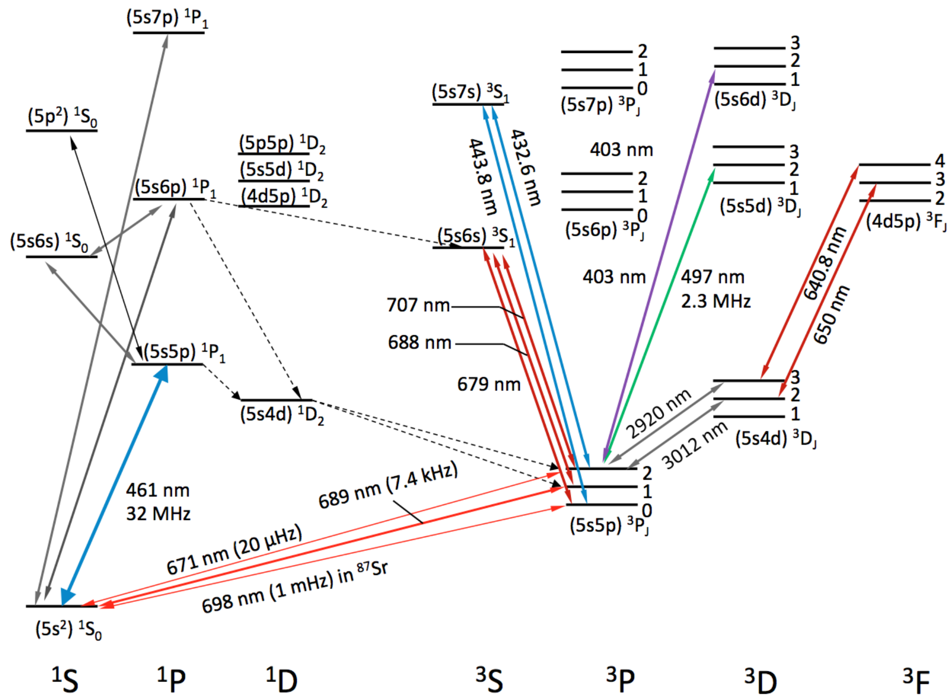

FIG. 1: Energy level diagram for strontium. Relevant wavelengths and linewidths are noted.

The slower loads a Magneto-optical Trap (MOT) operating at 461 nm. The MOT has a capture velocity of order 25 m/s and a final temperature of approximately 4 mK, which is limited by the relatively broad 32 MHz transition linewidth. Ground state atoms are nonmagnetic, and thus must be trapped optically. Since an optical trap depth of 4 mK is difficult to attain, we employ the Katori cooling scheme [36], which utilizes additional cooling on the $(5s^2)^1S_0 - (5s5p)^3P_1$ intercombination line. This triplet state (along with the $(5s5p)^3P_2$ state) is populated due to a leak in the cycling transition of the 461 nm MOT. The quadrupolar magnetic field of the MOT acts as a trap for the now magnetic triplet-state atoms. We use 403 nm light operating on the $(5s5p)^3P_2 - (5s6d)^3D_2$ transition to pump atoms from the otherwise inaccessible and long-lived $(5s5p)^3P_2$ state to the $(5s5p)^3P_1$ state. A MOT operating on the intercombination line at 689 nm performs further cooling to approximately 2.5 μK, now only limited by the narrow 7.4 kHz natural linewidth. In the next stage of cooling, the atoms are loaded into a crossed optical dipole trap (ODT), where evaporative cooling to quantum degeneracy proceeds via trap weakening. A momentum-space image of a Bose-Einstein condensate of ^{84}Sr created in this apparatus appears in Fig. 3.

The chamber is fabricated from 316L stainless steel and is equipped with 11 pairs of windows which are antireflection coated at the appropriate wavelengths. A "turret" design provides high conductance to the 75 L/s main chamber ion pump and titanium sublimation pump while allowing excellent 360° optical access to the atoms. A large-bore all-metal gate valve is attached to the one of the windows which is designated as the "microscopy chamber port." This is the port to which the QGM is attached.

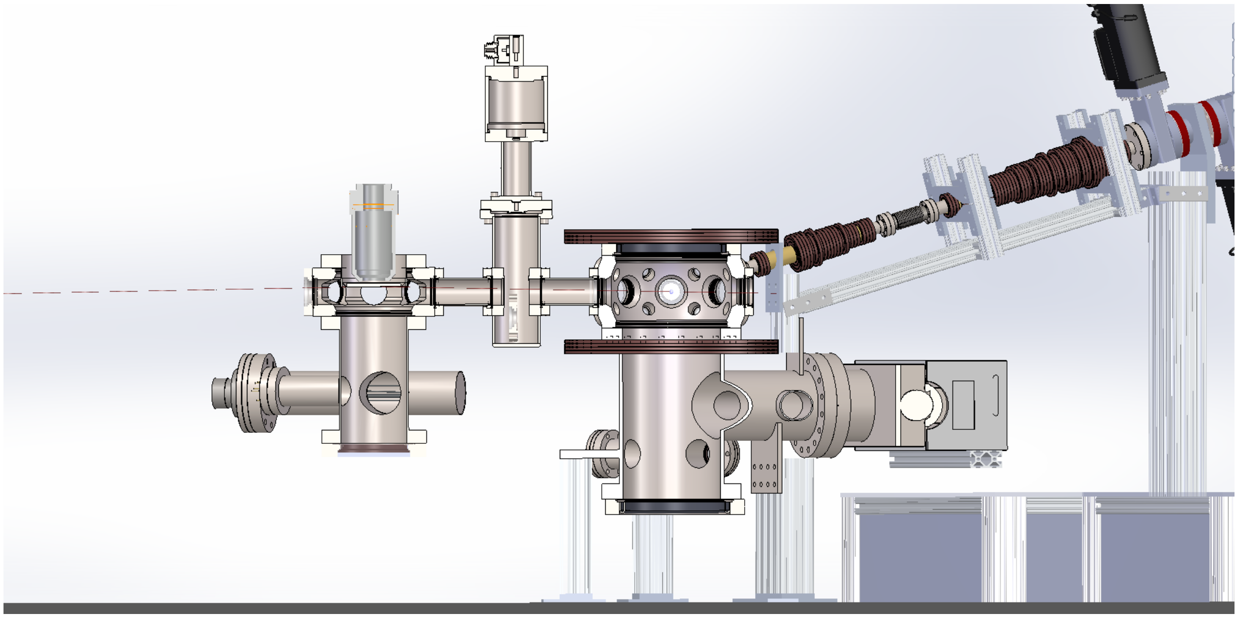

FIG. 2: Cutaway rendering of the main body of the quantum gas microscope (QGM) and the apparatus to which it is attached. The QGM is the leftmost part of the chamber, and is attached to the main strontium apparatus by the all-metal gate valve in the center. The high-resolution lens is shown immediately above the QGM. Support hardware is omitted for clarity.

2. *Components of Instrument*

The strontium quantum gas microscope consists of the following components, broadly divisible into three categories: the vacuum system, the optical trapping and lattice system, and the imaging system.

- **Vacuum System**
  - Microscopy chamber
  - Coated side windows
  - Custom pumping manifold
  - Ion pump and controller
  - Titanium sublimation pump and controller
  - Ion gauge and controller
- **Optical Trap System**
  - Trapping & lattice optical amplifier
- **Imaging System**
  - Custom objective lens
  - Camera

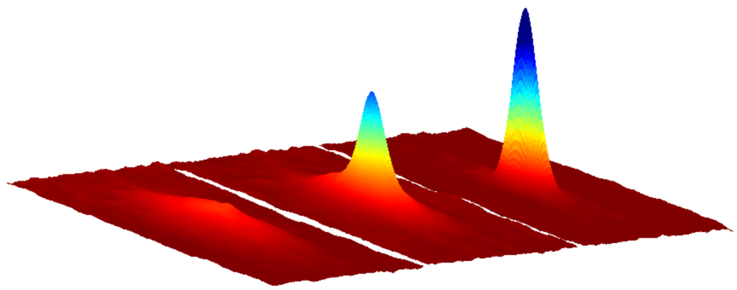

FIG. 3: Momentum-space image of ultracold ^{84}Sr in the UCSB ultracold strontium apparatus, before, during, and after Bose condensation. The sharp peak is a strontium BEC.

These components are assembled and interfaced with the existing ultracold strontium source to create a quantum gas microscope. In the QGM, the relevant Hamiltonian corresponding to the problem under study is then applied to the sample; for example, the experimenter might vary nuclear spin populations, impurity concentrations of metastable states, effective long range interactions, quasiperiodic potentials, or time-dependent forces. After a wait time which depends on the phenomena under study, the lattice depth is greatly increased in order to pin the density distribution. In the main imaging configuration, spontaneously emitted photons from the two main ground-state transitions are collected by a custom-built high-resolution objective lens (optimized for use at both 461 nm and 689 nm) and imaged onto a camera for analysis. Computer-based image processing is then applied to extract centroids of individual lattice sites, infer lattice phase, and measure the population on each site. The imaging procedure (the heart of any quantum gas microscope) is discussed in more detail below. Ultra-high vacuum in the microscopy chamber is critical for long imaging times; this vacuum is measured by the ion gauge and maintained by an ion pump and a titanium sublimation pump attached to a custom pumping manifold which enables high-conductance pumping without sacrificing optical access. The vacuum system of the quantum gas microscope is shown in Fig. 2. The quantum gas microscope is connected to the main chamber via an all-metal large-aperture gate valve, which is already attached to the existing strontium apparatus. This enables us to separately bake the quantum gas microscope without compromising the vacuum in the rest of the machine. Viewports evenly spaced around the chamber allow us to address the atoms with different wavelengths of light (note that due to a minor design change these windows are somewhat larger and less numerous than those in our original DURIP proposal). The window configuration provides excellent optical access by allowing a 71 mm microscope objective less than a half-inch from the atom trapping site. The 75 liter/second ion pump in conjunction with the titanium sublimation pump allows us to achieve pressures on the order of 1×10^{-11} Torr, monitored by an ion gauge.

3. High-Resolution Imaging

The heart of a quantum gas microscope is the imaging procedure, and the core functionality of the instrument depends upon the optical and atomic processes which enable single-site resolution. The three most important technical challenges for a quantum gas microscope are achieving sufficiently good spatial resolution, collecting enough scattered photons to detect the presence or absence of a single atom, and avoiding heating processes which move the atoms during the imag-

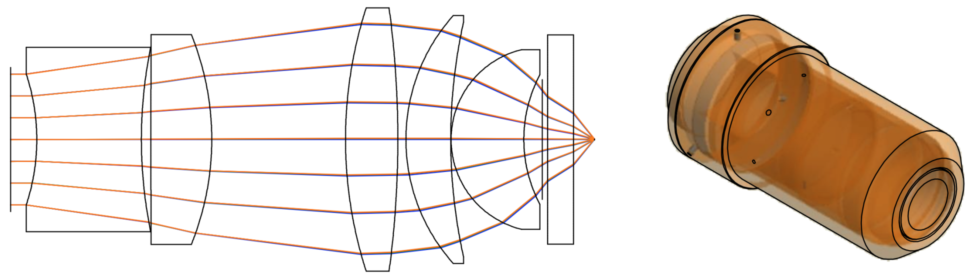

FIG. 4: Ray-tracing diagram and schematic view of high-resolution lens developed in conjunction with UCSD and Special Optics for use in this instrument. The numerical aperture is 0.8 at 461 nm and 0.77 at 689, and the total working distance is 9 mm (including 5 mm of glass). The lens performance was tested on an air force target at UCSD in collaboration with the group of Julio Barreiro.

ing process. The UCSB QGM addresses these three challenges using a combination of established quantum gas microscopy techniques and new methods enabled by the rich electronic structure of strontium.

The first challenge, maximizing spatial resolving power, is the domain of classical optics. Achieving the best possible resolution depends on careful design of multi-element objective lenses, correction for aberration including that caused by the unavoidable presence of a vacuum window, and careful alignment and testing. This process, straightforward for low-numerical-aperture optics, becomes increasingly difficult at the high numerical apertures typical for a quantum gas microscope (NA 0.8 with solid immersion in Ref. [2] and NA 0.68 without solid immersion in Ref. [3].) The custom objective lens we have designed and constructed for this proposal has a numerical aperture of 0.8 at 461 nm and 0.77 at 689 nm and is corrected for spherical aberration due to the vacuum window. To enable the future study of three-dimensional samples and to avoid problems associated with trapping atoms very near a surface, we do not use a solid immersion configuration.

The second challenge is maximizing the number of collected photons. Once the numerical aperture is specified, this depends only on the scattering rate, total imaging time, and quantum efficiency of the imaging system. Typical imaging times in existing rubidium quantum gas microscopes are on the order of one second, limited mainly by background gas collisions. Our instrument is capable of this exposure time, though below we discuss an alternative "bio-inspired" imaging modality using numerous shorter exposures. The quantum efficiency of the camera we have purchased is slightly better than 50% at the relevant wavelengths.

The third challenge is avoiding the substantial heating which would normally be associated with scattering thousands of photons from a single neutral atom. This is elegantly achieved in rubidium microscopes by performing fluorescence imaging of scattered laser cooling light, thus simultaneously imaging and cooling the sample with near-detuned light. The ability to perform sub-Doppler cooling on the transition used for imaging is thus of critical importance for quantum gas microscopy. This presents a particular challenge for strontium and other alkaline earths, since the singlet ground state lacks the substructure necessary to enable laser cooling below the Doppler limit. The electronic structure of strontium suggests several possible solutions to this challenge. First, the $(5s^2)^1S_0 - (5s5p)^3P_1$ intercombination transition does allow the attainment of very low temperatures ($\simeq$ 350 nK [38]) by simple Doppler cooling alone, due to its small natural linewidth of 7.4 KHz. However, this low attainable temperature is directly associated with a low scattering rate. Rubidium quantum gas microscopes typically operate at a total scattering rate of order 100 KHz using light detuned by several linewidths from a 6 MHz wide transition [2, 3]. Thus, while quantum gas microscopy on the intercombination line is in principle possible, the required exposure times may exceed the lifetime due to background gas collisions. Our main imaging modality thus uses the intercombination light for cooling and the main allowed transition at 461nm for imaging (though other combinations are also allowed by our flexible experimental design).

Our strontium quantum gas microscope is capable of operating in the same way as rubidium quantum gas microscopes, albeit at a substantially shorter wavelength. However, unlike rubidium or other alkali atoms, strontium has a rich electronic structure which enables various improvements on standard quantum gas microscopy. One example of such an improvement is the use of strontium's ultranarrow intercombination transitions to enable sharp tomographic imaging and addressing of "slices" of ultracold gases [39]. Another method of next-generation quantum gas microscopy enabled by the use of alkaline earth atoms is the adaptation of subdiffraction imaging techniques from the field of biology. Inspired by the need for imaging of subcellular biological structures much smaller than a wavelength of light, biological and optical researchers have developed numerous techniques of super-resolution optical imaging. While a number of such techniques have been demonstrated, two are of particular interest for alkaline earth quantum gas microscopy: Stochastic Optical Reconstruction Microscopy (STORM) and Single-molecule High-Resolution Imaging with Photobleaching (SHRImP). STORM (also sometimes called PALM or fPALM) algorithmically reconstructs the location of fluorophores randomly cycled between bright and dark states over a series of imaging cycles [40, 41]. The technique is widespread and successful: the original papers have been cited thousands of times, and commercial STORM-based microscopes are available. The related technique of SHRImP relies on the photobleaching effect of certain dyes to determine their location [42]. In both cases the super-resolution is achieved by switching only an optically resolvable subset of emitters at any given step and using the resulting difference image to reconstruct the centroid of each single emitter. An example of the enhanced resolution of the STORM technique appears in Fig. 5. Both techniques are capable of beating the diffraction limit by more than a factor of 10, and both techniques rely on the ability to optically switch (or "bleach") fluorophores into dark states where they do not scatter light. Crucially, the electronic structure of strontium also allows for efficient optically controlled transitions to and from dark states during fluorescence imaging. This is what enables our instrument to apply bio-inspired imaging techniques to quantum gas microscopy.

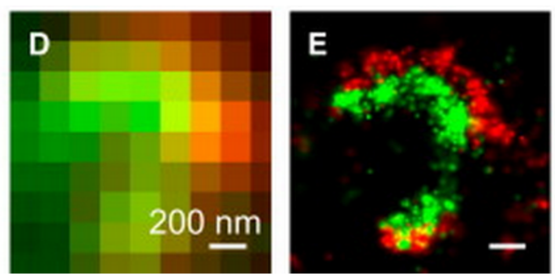

FIG. 5: Subdiffraction imaging using the STORM technique. **Left:** Conventional fluorescence image of the distribution of two proteins (labeled red and green) in a section of a mouse brain. **Right:** STORM image of the same area, showing enhanced resolution. Figure is adapted from Ref. [41].

The specific operation of STORM-enabled quantum gas microscopy (STORM-QGM) is as follows. During the imaging process described above, controlled application of an optical pumping laser can be used to populate or deplete atoms from the $(5s5p)^3P_2$ state. As shown in Fig. 1, the pumping laser can be at a variety of wavelengths, for several of which we have already developed light sources as part of our AFOSR-funded strontium work. This technique essentially treats strontium as a photoswitchable dye like those used for subdiffraction biological imaging. If enough photons can be collected over a sufficiently large number of images, the resulting data set in principle allows the reconstruction of the position of single atoms to a precision well below that achievable with even the best high-NA objective lens. Extension to 3D imaging (a possible area of future research with the strontium quantum gas microscope) has been demonstrated in a biological context [43].

It is important to note that the analogy between atoms and biological fluorophores has its limits. In particular, atoms have a finite lifetime in our trap, due to a combination of background gas collisions and spontaneous scattering. In this sense atoms are more “fragile” than the much larger fluorophores used to image biological samples, and a STORM-QGM measurement cannot collect as many photons as in a typical biological image like the right-hand panel of Fig. 5. However, our resolution requirements are actually much less stringent than those typical for subcellular biological imaging: for a standard retroreflected lattice made with a 1064nm laser, resolution of 200 nm (the scale bar in Fig. 5) is easily enough to distinguish the occupation of adjacent sites. For comparison, 600 nm FWHM resolution is typical for existing quantum gas microscopes. The main application of STORM-QGM techniques in the context of this proposal will likely be to reduce the complexity and ease the tolerances of the optical imaging system, rather than to seek higher intrinsic resolution.

4. Interface With Existing Instrumentation

Fig. 2 shows the interface between the quantum gas microscope and the ultracold strontium source. As stated in our original AFOSR YIP proposal, the strontium machine was designed with the goal of enabling the inclusion of single-site resolution in the future. This has greatly eased integration of the new instrument into our existing setup. The main point of attachment of the quantum gas microscope is the gate valve port visible in Fig. 2. The gate valve enables separate baking of the microscopy chamber and the main chamber, for experimental simplicity and optimal vacuum performance. The optical table used for the strontium experiment is 5 feet by 10 feet, allowing ample space for installation of the quantum gas microscope and associated hardware. Control of experiments in the quantum gas microscope chamber can be performed using the same hardware and software as the control of experiments in the main chamber.

5. Enhancement of Current Research-Related Education

The alkaline earth quantum gas microscope is assembled, tested, and operated by graduate students and postdocs at UCSB (chiefly graduate students Ruwan Senaratne, Shankari Rajagopal, and Zach Geiger, and postdoc Toshi Shimasaki). The unique research capabilities of this instrument are thus directly and significantly enhancing research-related education of scientists in training at the University of California by providing young scientists the opportunity to work with the cutting-edge technology of quantum gas microscopy. In addition, a number of undergraduate students have already contributed significantly to the construction of the existing UCSB ultracold strontium apparatus, building components such as external cavity diode lasers, resonant frequency doublers, RF amplifiers, electro-optic modulators, and control electronics. The greatly enhanced scientific range of experiments enabled by the addition of the alkaline earth quantum gas microscope will open opportunities for further undergraduate projects and training of the next generation of researchers. Finally, the ability of the quantum gas microscope to “make the quantum visible” may play a role in inspiring future cold atom physicists, as the remarkable images obtainable from scanning tunneling microscopes have done in the field of condensed matter.

D. Summary

This DURIP award has supported the purchase of hardware comprising a quantum gas microscope for alkaline earth atoms. This instrument combines the unique capabilities of both quantum gas microscopy and ultracold alkaline earth gases. It substantially extends the scientific range of our existing DoD-funded work. Additionally, the alkaline earth quantum gas microscope gives rise to a broad array of entirely new experimental possibilities in research areas of interest to DoD. Finally, the instrument enhances and multiplies opportunities for research-related education of undergraduates, graduate students, and postdocs in ultracold atomic physics at UCSB.

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