# Schlussbericht

**zum Teilvorhaben: Superauflösende Quantengas-Mikroskopie an Ultrakalten Dysprosium Atomen**

**im Verbundprojekt: Magnetic Atom Quantum Simulator (MAQS)**
**Zuwendungsempfänger: Tilman Pfau, Universität Stuttgart, 5. Phys. Institut**

**Förderkennzeichen: 13N15231**

**Laufzeit des Vorhabens: 01.02.2020 – 31.01.2023**

## Teil I: Kurzbericht

Ziel dieses Projekts war es, einen neuen Quantensimulator basierend auf ultrakalten Dysprosium Atomen mit langreichweitiger Dipol-Dipol-Wechselwirkung zu konstruieren.
Die wesentlichen Schritte dabei sind (A) der Aufbau eines neuen Experiments zum Studium ultrakalter Dysprosium Atome in optischen Gittern mit kurzer Periodizität, (B) die Realisierung superauflösender Quantengas-Mikroskopie und (C) die Quantensimulation neuer Materiezustände, Korrelationen und Dynamiken.

Zu A) Die Planung des experimentellen Aufbaus wurde fertiggestellt. Der Vakuumaufbau, der Zeemanslower, ein Aufbau für transversales Kühlen, sowie die erforderliche Optik für die Magneto-Optische Falle (MOT) sowie die optischen Dipolfallen (ODT) wurden erfolgreich fertiggestellt. Das gleiche gilt für die erforderlichen Magnetfeldspulen sowie hochauflösende Abbildungsmethoden. Es konnte eine Fünfstrahlen-MOT mit bis zu einer Milliarde Atomen (bei etwa 20 µK) realisiert werden, was einer signifikant höheren Atomzahl - bei gleichzeitig besserem optischen Zugriff - verglichen mit früheren Aufbauten mit vergleichbaren Kühlmethoden entspricht. Die Atome konnten mit hoher Effizient in optische Dipolfallen geladen werden, wo sie in einem nächsten Schritt durch evaporatives Kühlen kondensiert werden sollen.

Zu B) Für die superauflösende Quantengas-Mikroskopie sind alle benötigten Lasersysteme bereits aufgebaut. Tests der ursprünglich eingeplanten Glaszelle sowie detaillierte Simulationen der gesamten Abbildungsprozedur sowie der benötigten Fallengeometrie für die Realisierung der physikalischen Parameter haben jedoch gezeigt, dass eine gewünschte Durchführung der Experimente mit Hilfe der Glaszelle mit erheblichen unerwarteten Problemen einhergehen würden. Daher wurde dieser Teil des Experiments neu geplant und ein Aufbau mit einer Stahlvakuumkammer sowie einem in einer Ultrahochvakuum-Umgebung verwendbaren Objektiv mit extrem hoher numerischer Apparatur entwickelt. Die Simulationen zeigen, dass superauflösende Quantengas-Mikroskopie mit diesem Aufbau möglich sein wird. Die Planung für alle neuen Komponenten ist abgeschlossen, und kritische Komponenten wie das Mikroskopobjektiv sowie die Vakuumkammer sind bestellt und werden im Laufe dieses Jahres geliefert. Daher verzögert sich die Umsetzung der unter Punkt C zusammengefassten Quantensimulationen über das eigentliche Ende des Finanzierungszeitraums. An den ursprünglich formulierten Zielen wird jedoch weiterhin festgehalten und von uns durchgeführte Rechnungen und Simulationen bestärken uns in diesen Zielen sowie dem experimentellen Ansatz der entsprechenden Umsetzung.

## Teil II: Eingehende Darstellung

### The project:

We are building a quantum gas simulator using magnetic atoms. Leveraging our extensive experience with ultracold dysprosium atomic gases and recent progress in quantum gas microscopy, we will experimentally study many-body quantum systems in a 180 nm 2D lattice formed with an ultra-violet (UV) laser. Our quantum gas microscope (QGM) will be used to perform analog quantum simulations of extended Bose- and Fermi-Hubbard physics that include strong long-range interactions. Using super-resolution techniques, we will probe many-body states with a resolution down to the individual lattice site. Imaging individual sites will allow us to study both nearest and next-nearest neighbor site correlations. Furthermore, investigations of the non-equilibrium dynamics of many-body quantum states with strong dipolar interactions present will be performed.

### Progress:

We have completed the construction of the vacuum chamber and have installed our MOT as well as Feshbach and compensation coils around the MOT chamber where a Dysprosium BEC will be created. The measured values of the pressure in the chamber are at UHV level (~$10^{-11}$ mbar) and we have successfully created a large and cold Dysprosium five-beam MOT in our main chamber. An important metric is the number of atoms contained in the MOT, as this directly influences the number of atoms that can be evaporated into a BEC. The BEC will then be transported to our glass science cell for the loading of atoms into our UV lattice for quantum gas microscopy. By extensive optimization, we have achieved a MOT with approximately one billion atoms at a temperature of around 20 µK. This a significant increase in atom number when compared to previous atom numbers in a MOT created with comparable setups (*Maier et. al. Optics Letters 2014*) at similar temperatures. We have designed and built a setup for trapping and evaporatively cooling the atoms in a highly tunable and flexible crossed beam ODT geometry. The position of the ODT arms can be modulated with the help of an acusto-optical deflector, which allows us to realize a wide range of different potential landscapes when utilizing time-averaged potentials. We can transfer a significant fraction of the atoms into the ODT. The next step is to cool the atoms into quantum degeneracy. We have designed and characterized a setup for the optical transport of the cold atoms from the MOT chamber to the separate ‘science’ chamber where the quantum gas microscope will be implemented.

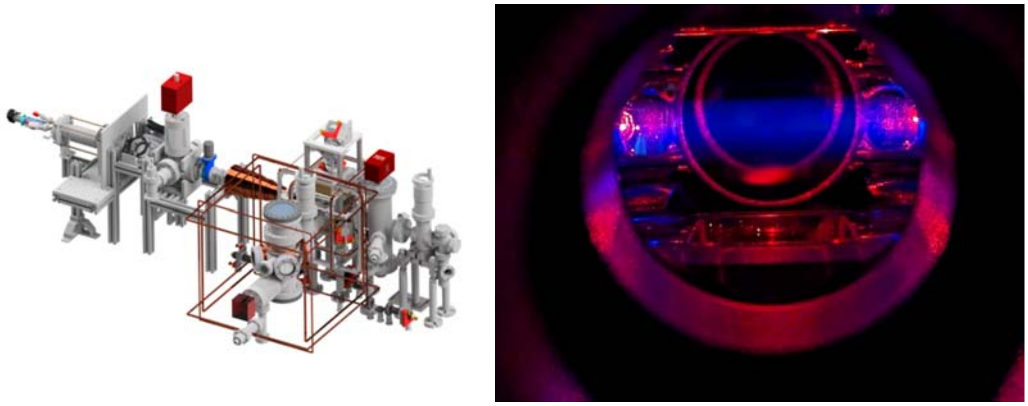

*Figure 1. (a) Drawing of the experimental apparatus. All vacuum components except the science cell are attached and all magnetic field coils (except from those associated with the science cell) are in place. The surrounding laser setup (not shown) is built up. (b) Photograph of the MOT chamber through one of the viewports. Atoms fluorescing in the Zeeman slower beam on the blue 421 nm transition as well as atoms fluorescing in the MOT on the orange 626 nm transition can be seen.*

### Design and Construction of the Quantum Gas Microscope

Conceptual considerations prior to construction and design of optics for the quantum gas microscope have been performed. We have performed extensive calculations in relation to the parameters of the UV lattice during the loading of atoms, performing analog quantum simulation (Bose/Fermi-Hubbard physics), and imaging of the atoms in the lattice. One particularly crucial step that requires careful consideration for the successful implementation of the quantum gas microscope is the technique of resolving Dysprosium atoms, which are only 180 nm apart, with fluorescence imaging. We will image the atoms without any optical cooling during imaging, either in free space or in a weak trapping potential. To ensure that this is feasible using the strong $\Gamma = 2\pi \times 32$ MHz transition at 421 nm for imaging, we have performed simulations of the diffusive behavior of neighboring Dy atoms that are 180 nm apart. For a realistic imaging time of 5µs we can expect to scatter more than 300 photons per atom of which we will collect around 45 photons using an extremely high NA objective (NA~0.9). Reliable high-fidelity single atom detection using a comparable number of collected photons has previously been demonstrated using an EMCCD camera. We plan to extend these methods to also include super resolution of individual lattice sites. To this end, we have also extended these simulation to incorporate the full imaging procedure. This includes the light scattering on the atoms, the collection of light through the objective and other optical components involved as well as the response from the EMCCD camera. This gives us a very faithful simulation of expected quantum gas microscope images, which in turn allowed us to quantify the expected imaging performance as well as develop suitable analysis methods.
The results from the simulations were the following:

- With the available laser wavelengths and powers, it is indeed possible to create trap geometries which allow us to reach the strongly correlated regime, where all relevant energy scales (tunneling, on-site interactions, nearest-neighbor interactions, and temperature) are on the same order and large enough (>~ 200 Hz) using a special geometry of optical dipole traps.
- Realizing these optimized geometries is not possible with the original design of the science cell consisting of a glass cell, a solid immersion lens and a high numerical aperture (NA) objective. They are however possible to be realized

with an adapted setup consisting of a steel science chamber combined with a special very high NA in-vacuum objective.

- With the expected parameters of the new chamber and objective design, also taking into account tolerances specified by the manufacturers of the components, a reliable single atom and single site detection scheme will be possible.

The new design of the science cell consists of a steel chamber and an in-vacuum objective with a NA of 0.9 and a diffraction-limited performance at our imaging wavelength of 421 nm. This configuration has the key advantage that we can create all the optical traps in the center of the vacuum chamber while maintaining a very high NA. Therefore, the trap geometry becomes significantly simpler and higher trap frequencies are reached, which is crucial for realizing the strongly correlated regime. Also, as we will work in a regime where the energy scales related to in particular the tunneling are small compared to the total potential depth of the ODT (ratio about $10^{-4}$), we are very sensitive to stray light and polarization-dependent light shifts. These are minimized by avoiding the necessity of reflections under large angles at the top plate of the glass cell as originally planned in the first design. We additionally took further measures to minimize detrimental stray light. These include the design of the chamber itself, special coating layouts on all optical surfaces and designing the objective with a small hole going through it on the optical axis. While this hole has only a small influence on the imaging point-spread-function and the light collection efficiency, it allows for small-NA on-axis optical access for off-resonant dipole traps without passing through many additional optical components. This re-design of the science chamber and objective constitute an essential improvement over the original design and was thus undertaken despite the time delay associated with it. All the critical components of the new setup, such as the objective and the vacuum chamber are already ordered and are expected to be delivered this year.

Based on the full simulation of the imaging process, taking into account the redesign detailed above, we confirm that a reliable super-resolution single atom and single site imaging performance is indeed possible. We furthermore confirm that both a stochastic shelving approach on the 1001 nm line, where a fraction of the atoms is transferred - at random - into a long-lived excited state before imaging as well as a deterministic approach making use of a superlattice structure to shift every other atom into resonance with the 1001 nm transition, is feasible. We implemented, tested and compared different image analysis methods based on thresholding, a maximum Likelihood analysis as well as a machine learning based analysis using an unsupervised autoencoder network.

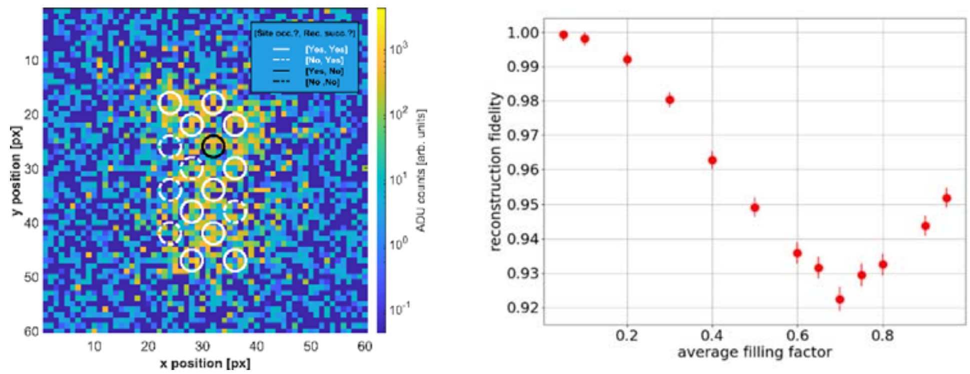


*Figure 1. (a) Performance of the image reconstruction scheme. Shown is a simulated image of a small 4 by 8 lattice system (average filling of 75%) assuming deterministic shelving of every second atom. Circles indicate the lattice positions, where solid lines indicate occupied and dash-dotted lines unoccupied sites. A maximum likelihood reconstruction scheme is used to reconstruct the lattice occupation. White circles indicate correctly reconstructed sites (above 98% of all lattice sites), while the black circle indicates an incorrectly reconstructed occupation. (b) Expected performance of a stochastic shelving scheme. Shown is the single particle reconstruction fidelity as a function of the average filling factor. With a stochastic shelving, we effectively reduce the average filling factor. Depending on the initial state, a stochastic shelving of every second atom (on average) will significantly improve the reconstruction fidelity.*

**Next steps**

With the successful creation of a cold Dy MOT with very high atom numbers, as well as the successful loading of the ODTs, we will now continue to evaporatively cool the atoms into degeneracy. We expect to achieve a significantly larger BEC compared to the previous generation of the experiment. The science cell will be attached onto the setup (without loss of vacuum) and the optical transport of atoms into the glass cell will be realized. In the meantime, the construction of the QGM will continue along with the optical setup for the UV lattice. Furthermore, additional theoretical studies on the extended Bose- and Fermi-Hubbard model for the given experimental parameters are ongoing.
During the course of this project, there were also significant experimental efforts towards studying extended Bose-Hubbard models in other groups in the field - both within and outside of this consortium (eg Su et al.: arXiv:2306.00888, Sohmen et al.: arXiv:2306.05404, Anich et al.: arXiv:2304.12844, Lagoin et al.: Nature 609, 485489 (2022)). In particular, there were first results showing solid order induced by (next-) nearest neighbor interactions (Su et al., Lagoin et al.) in the hard-core boson limit. While these results underline the growing interest in extended Hubbard models within the community, they do not strongly influence the goals and prospects of our project. This is because this project is focused at studying systems where all of the model-parameters (tunneling, on-site interactions and nearest neighbor interactions) are of similar order, while each parameter is still large enough, such that the experimental preparation is feasible.

Publications:


- L. Chomaz, I. Ferrier-Barbut, F. Ferlaino, B. Laburthe-Tolra, B. L. Lev and T. Pfau. Dipolar physics: a review of experiments with magnetic quantum gases. Rep. Prog. Phys. **86**, 026401 (2023)

- J. Fraxanet, D. González-Cuadra, T. Pfau, M. Lewenstein, T. Langen, and L. Barbiero. Topological Quantum Critical Points in the Extended Bose-Hubbard Model. Phys. Rev. Lett. **128**, 043402 (2022)
- J. Hertkorn, J.-N. Schmidt, M. Guo, F. Böttcher, K. S. H. Ng, S. D., Graham, P. Uerlings, H. P. Büchler, T. Langen, M. Zwierlein, and T. Pfau. Supersolidity in Two-Dimensional Trapped Dipolar Droplet Arrays. Phys. Rev. Lett. **127**, 155301 (2021)
- J. Hertkorn, J.-N. Schmidt, M. Guo, F. Böttcher, K. S. H. Ng, S. D., Graham, P. Uerlings, T. Langen, M. Zwierlein, and T. Pfau. Pattern formation in quantum ferrofluids: From supersolids to superglasses. Phys. Rev. Research **3**, 033125 (2021)
- J.-N. Schmidt, J. Hertkorn, M.Guo, F. Böttcher, M. Schmidt, K.S.H. Ng, S. D, Graham, T. Langen, M. Zwierlein, and T. Pfau. Roton Excitations in an Oblate Dipolar Quantum Gas. Phys. Rev. Lett. **126**,193002 (2021)
- J. Hertkorn, J.-N. Schmidt, F. Böttcher, M.Guo, M. Schmidt, K.S.H. Ng, S.D, Graham, H. P. Büchler, T. Langen, M. Zwierlein, and T. Pfau. Density Fluctuations across the Superfluid-Supersolid Phase Transition in a Dipolar Quantum Gas. Phys. Rev. X **11**, 011037 (2021)