

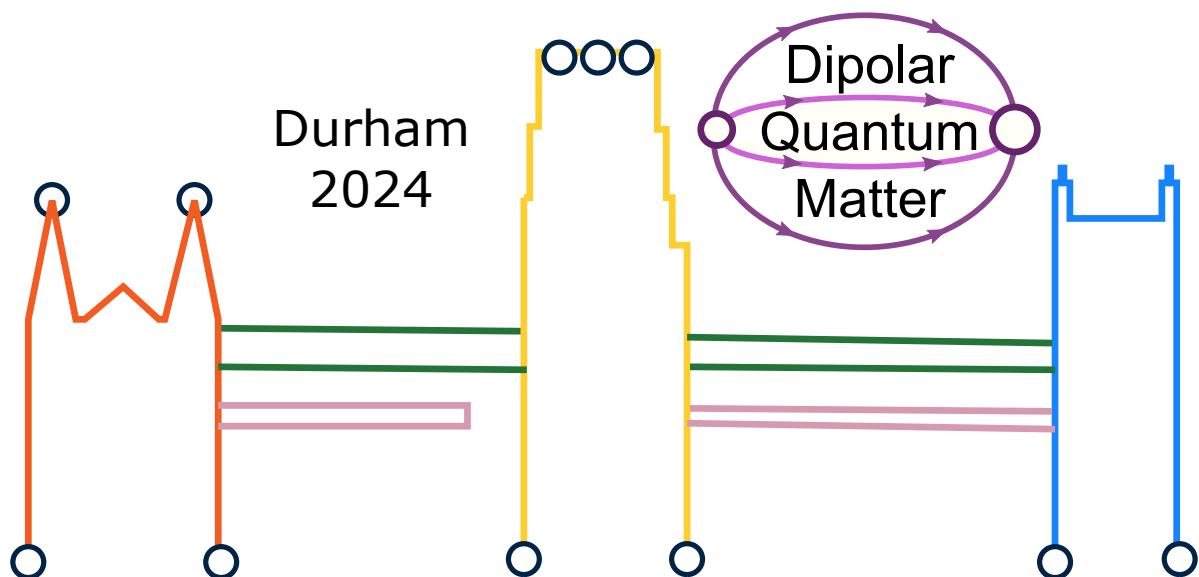
Dipolar Quantum Matter

ICAP

Satellite meeting 2024

Book of Abstracts

22nd - 24th July 2024
Durham University

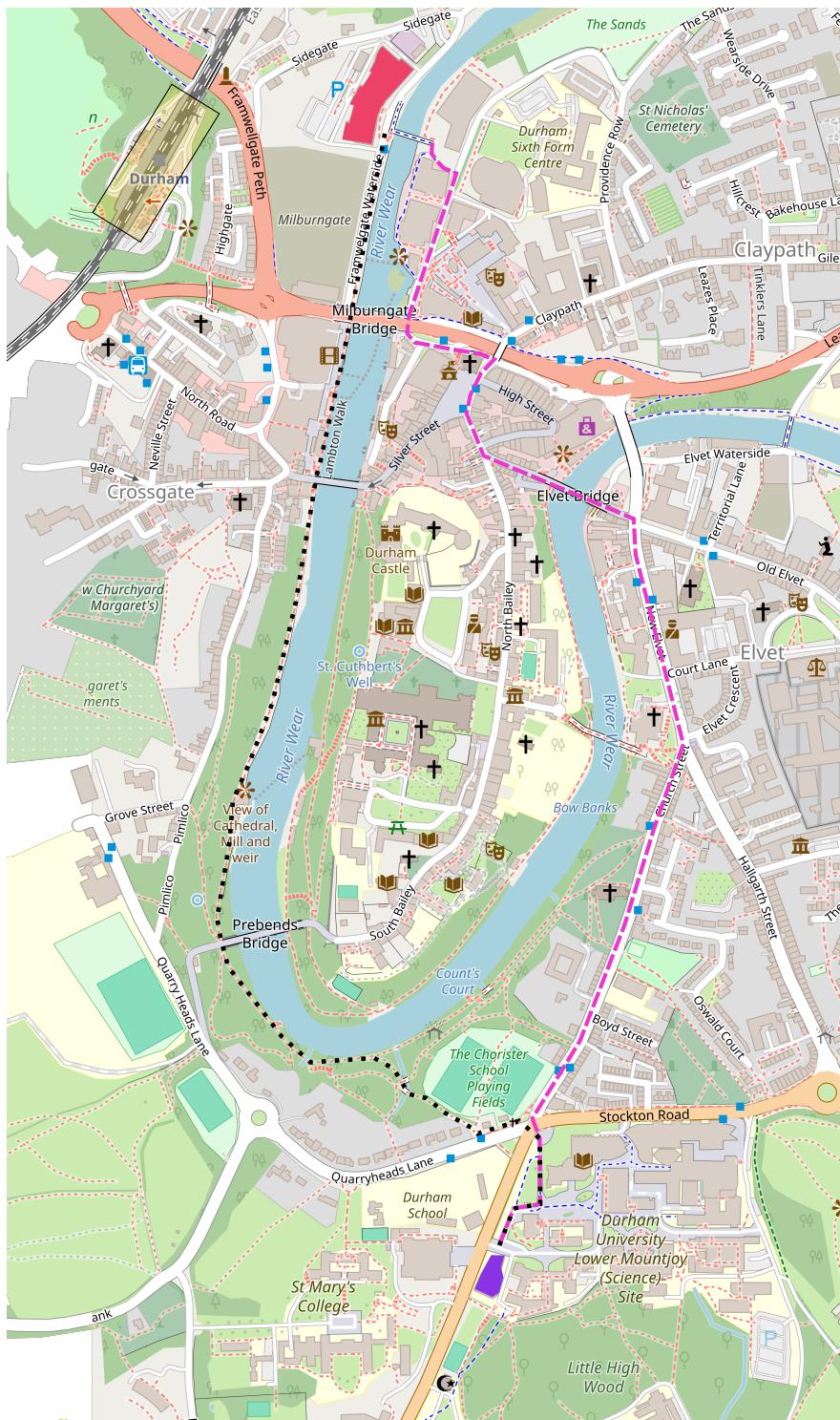


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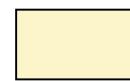
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	Monday	Tuesday	Wednesday
9:15	Arrive / Lab tours	S Evered	H Middleton-Spencer
9:40		A de Oliveira	E Casotti
10:00		A Guttridge	S Prasad
10:20		Discussion	Discussion
10:45		Coffee	Coffee
11:15		L Chomaz	I Ferrier-Barbut
11:40		T Bland	O Scarlatella
12:00		M Lecomte	A Journeaux
12:20		Discussion	Discussion
12:45	Lunch	Lunch	Lunch
13:45	B Gadway	K Hazzard	Lab tours / leave
14:20	H Manetsch	L Anderegg	
14:55	S Agarwal	M Frye	
15:15	Discussion	Discussion	
15:30	Coffee	Coffee	
16:00	A Park	Posters Durham Physics Dept.	
16:35	A Schindewolf		
16:55	J Mortlock		
17:15	K Voges		
17:35	Discussion		
17:50	End		
19:00	Dinner	Free time	

Map & Routes



Radisson Blu Conference Hotel



Train station



Ogden Centre West - Poster venue



Route 1
off road
25 mins



Route 2
on road
25 mins

Durham is a hilly city with many stairs, if you have mobility requirements please let us know and we will arrange taxis.

Durham City Taxis - 0191 367 0503

Laser Cooled Molecules for Quantum Science and Fundamental Physics

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Ultracold molecules offer a diverse array of potential applications ranging from fundamental physics to quantum simulation and computation. Motivated by potential discoveries in these areas, significant advances in controlling molecules at the single-quantum-state level have occurred over the past decade. Recently, molecules have been loaded into optical tweezer arrays allowing both high-fidelity readout and quantum control of individual molecules. In this talk, we will discuss creating and employing optical tweezer arrays of diatomic (CaF) and polyatomic (CaOH) molecules to unlock new quantum science applications. We demonstrate second scale coherence times for molecular qubits in optical tweezer traps, parametrizing the potential performance of polar-molecule-based quantum simulators or computers. Additionally, we show progress towards realizing the goal of high-fidelity molecular qubits by demonstrating dipolar interactions and entanglement between molecules. The full quantum state control afforded by this platform allows us to study quantum state specific collisions and control the dynamics of the molecular collisions. Finally, extending the tools of quantum control to polyatomic molecules leads to powerful new scientific avenues, including significant improvements to searches for physics beyond the Standard Model. We demonstrate the experimental protocols needed for such a search and leverage the structural characteristics of polyatomic molecules to extend coherence times, paving the way towards orders-of-magnitude improved experimental sensitivity to time-reversal-violating physics.

**Forming Supersolids: Towards a New Experiment with Tailored Trapping
of Ultracold Magnetic Gases & a Theoretical Investigation of the
Kibble-Zurek Mechanism**

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TBC

Quantum error correction and digital quantum simulation with reconfigurable atom arrays

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Suppressing errors is one of the central challenges for useful quantum computing, requiring quantum error correction for large-scale processing. However, the overhead in the realization of error-corrected “logical” qubits, where information is encoded across many physical qubits for redundancy, poses significant challenges to large-scale logical quantum computing. Here we will discuss recent advances in quantum information processing using dynamically reconfigurable arrays of neutral atoms, where physical qubits are encoded in long-lived hyperfine states and entangling operations are realized by coherent excitation into Rydberg states. With this platform we have realized programmable quantum processing with encoded logical qubits, combining the use of 280 physical qubits, high two-qubit gate fidelities, arbitrary connectivity, and mid-circuit readout and feedforward. Using this logical processor with various types of error-correcting codes, we demonstrate that we can improve logical two-qubit gates by increasing code size, outperform physical qubit fidelities, create logical GHZ states, and perform computationally complex scrambling circuits using 48 logical qubits and hundreds of logical gates. Finally, we demonstrate how the same architecture can be used for gate-based quantum simulations, by realizing tunable Floquet Hamiltonians through a periodic sequence of quantum gates and atom rearrangement. Together, these results chart a path toward future large-scale quantum processors and highlight unique near-term opportunities for gate-based quantum simulation.

- [1] S. Evered*, D. Bluvstein*, M. Kalinowski* et al. Nature 622, 268-272 (2023)
- [2] D. Bluvstein, S. Evered et al. Nature 626, 58-65 (2024)

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Collective light-matter interactions in atomic ensembles

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The understanding of the cooperative emission of light by an ensemble of atoms in free space has been an outstanding problem of atomic physics for decades. This driven-dissipative many-body system poses an outstanding challenge to theory and requires dedicated experiments. I will present experimental results from our group where we study the cooperative interaction of ensembles of cold atoms in free space with resonant radiation. First, by measuring the photons radiated by an atomic cloud that is resonantly driven by a laser, one can retrieve the existence of high-order correlations in the steady-state, due to light-induced resonant dipole-dipole interactions. Second, by using the tools of single-atom manipulation and readout, one can measure the effect of cooperative scattering by an ordered array, now at the single atom level to unravel the microscopic mechanisms behind collective effects.

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Synthetic dimensions in Rydberg atom arrays

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Arrays of dipolar-interacting spins - magnetic atoms, polar molecules, and Rydberg atoms - represent powerful and versatile platforms for analog quantum simulation experiments. The internal state dynamics in such dipolar arrays provide a natural setting to explore problems of equilibrium and non-equilibrium quantum magnetism. The presence of many different internal states of the atoms and molecules in such experiments enable studies of large-spin magnetism, but also holds promise for more general quantum simulation studies. Here we describe how the simple addition of multi-frequency microwave fields to Rydberg arrays enables highly controllable studies of few- and many-body dynamics along an internal-state “synthetic” dimension. We discuss several early studies in this Rydberg synthetic dimension platform, touching on interaction-driven phenomena relevant to topology, artificial gauge fields, and disorder-induced localization. Looking forward, such microwave manipulation opens up several new directions for exploring complex, driven quantum matter in dipolar arrays.

This material is based upon work supported by the National Science Foundation under grant No. 1945031 and the AFOSR MURI program under agreement number FA9550-22-1-0339. In relation to the work discussed in this talk, we acknowledge collaborations with theorists Kaden R. A. Hazzard, Tomoki Ozawa, Hannah Price, Rohit Patil, and Marcos Rigol.

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SU(N) magnetism with ultracold molecules

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The creation of Bose-Einstein condensates and degenerate Fermi gases of molecules that are shielded from destructive collisions by external electromagnetic fields opens new possibilities for quantum science. Remarkably, we find that the collisional shielding enhances the symmetry of the interactions to an SU(N) symmetry amongst the hyperfine states [1]. N can be controlled in each molecule and is as large as 32 for bosonic molecules and 36 for fermions. In contrast to lower symmetry systems, SU(N) symmetry allows large degeneracy (high spin) without becoming classical, and results in many interesting quantum phenomena. While SU(N) symmetry also occurs in alkaline-earth atoms, there it occurs only for fermions, repulsive interactions, and N at most 10. Ultracold molecules provide, in addition to larger N , both fermions and bosons, and tunable attractive and repulsive interactions.

I will describe the physical mechanism leading to the SU(N) symmetry and present results of coupled channels calculations quantifying it for dc-shielded CaF, a numerically tractable case. These show the s-wave scattering length deviates from the spin-free values by only about 3%. The experimentally-important bi-alkali molecules are treated by an effective model we derive, which predicts they enjoy an even more precise SU(N) symmetry. A range of qualitatively new possibilities in many-body physics can be studied in SU(N)-symmetric molecular systems. I will overview these and describe some of the first theoretical predictions for attractive SU(3) fermions in a lattice.

[1] B. Mukherjee, J. M. Hutson, K. R. A. Hazzard, arXiv:2404.15957

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6100 highly coherent atomic qubits

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Neutral atoms trapped in optical tweezer arrays have recently emerged as a leading quantum platform for the scalability and controllability that they offer. However, scaling to thousands of atomic qubits with long coherence times and low-loss, high-fidelity imaging has been an outstanding challenge and critical for progress in quantum computing, simulation, and metrology, in particular, towards applications with quantum error correction. In this talk, we present an experimental realization of a 12,000 site array of optical tweezers trapping over 6,100 neutral atoms while simultaneously demonstrating and surpassing state-of-the-art performance for several key metrics associated with fundamental limitations of the platform. We demonstrate a coherence time of 12.6(1) seconds, a record for hyperfine qubits in an optical tweezer array, and further show trapping lifetimes close to 23 minutes in a room-temperature apparatus, enabling state of the art imaging fidelity and survival. Such results pave the way for near-term implementation of universal quantum computing at scale, which we address further along with a discussion of readily achievable steps in this direction.

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Realising topological defects in synthetic dimensional systems

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Synthetic dimensions provide a powerful approach for simulating condensed matter physics in cold atoms and photonics, whereby a set of discrete degrees of freedom are coupled together and re-interpreted as lattice sites along an extra artificial dimension.

In this talk, we will firstly review how to create a long and controllable synthetic dimension of atomic harmonic trap states by periodically modulating the trapping potential in time. This approach was recently utilised in an experiment in Birmingham to observe Bloch oscillations along a synthetic dimension of atomic trap states. We will then discuss theoretical proposals for how to extend this type of system, first to realise a 2D quantum Hall model by combining the synthetic dimension with a real spatial dimension and an artificial magnetic field, and second to study the effect of interactions in a 2D quantum Hall model and the resulting vortex lattices.

In the second part of the talk, we will present our recent work on studying the interactions of extra-dimensional superfluid vortices. Here, will introduce the concept of vortex reconnection in a four-dimensional system, elucidating the three identifiable regimes uncovered during this investigation, before finally briefly discussing methods of experimental implementations.

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Sub-millisecond Entanglement and iSWAP Gate between Molecular Qubits

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Individual trapping of polar molecules enables precise control over their rich rotational-hyperfine structure and their long-range anisotropic electric dipole-dipole interactions. We report sub-millisecond dipolar exchange between two rotational states of NaCs molecules separated by $1.9 \mu\text{m}$. Using this dipolar exchange interaction, we create a maximally entangled Bell state with a fidelity of $0.94(3)$ in trials where both molecules are present. Lastly, by introducing a third state in a different hyperfine manifold, we implement the iSWAP gate, paving the way for universal quantum computing and quantum simulation in multilevel systems.

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Entanglement generation in weakly-driven arrays of multilevel atoms via dipolar interactions

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We investigate the driven-dissipative dynamics of 1D and 2D arrays of multilevel atoms interacting via photon-mediated dipole-dipole interactions and trapped at subwavelength scales. In contrast to two-level atoms, we show that multilevel atoms in the low excitation (weak drive) regime can become strongly entangled. The entanglement manifests as the growth of collective spin-waves in the ground state manifold, and survives even after turning off the drive. We propose to use the $\sim 2.9\mu\text{m}$ cyclic transition between ${}^3\text{P}_2 \leftrightarrow {}^3\text{D}_3$ in ${}^{88}\text{Sr}$ with 389nm trapping light as an ideal experimental platform for validating our predictions and as a novel quantum interface for the exploration of complex many-body phenomena emerging from light-matter interactions.

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How solid is a dipolar supersolid?

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The conceptual roots of supersolidity can be traced back to 1960, when Eugene Gross calculated the appearance of long-range spatial order in the ground state of a system of interacting bosons. In 2004, an abrupt change in the shear modulus of solid Helium-4 was interpreted as the first experimental evidence of a solid-to-supersolid transition. However, this proved to be a false dawn, with the shear modulus shift arising from structural changes in the classical solid instead. The eventual experimental observation materialized via a superfluid-to-supersolid phase transition in ultracold gases, with particular success in dipolar Bose Einstein condensates (BECs). To complement this robust experimental platform, we use the extended Gross-Pitaevskii equation (eGPE) to theoretically probe the distinctly solid properties of the supersolid. We shear the crystal to produce perpendicular shear waves in the supersolid — this transverse wave only propagates in solids, and can be probed across the BEC-to-supersolid transition. We find the appearance of a non-zero shear modulus at the BEC-to-supersolid transition, which increases as the superfluid fraction is reduced. Our results match closely with a semi-analytic model for the crystal deformation.

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Observation of vortices in a dipolar supersolid

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Supersolids are exotic states of matter that spontaneously break two symmetries: gauge invariance through the phase-locking of the wavefunction, and translational symmetry owing to the emergence of a crystalline structure. First predicted in solid helium, they have recently been observed in ultracold atoms, with particular success coming from dipolar atoms [1, 2, 3, 4]. The crystalline structure is naturally observable as a modulation of the integrated in situ density profile. Phase coherence has instead been probed by studying the self-interference pattern of an expanding supersolid [1, 2, 3] and the emergence of Goldstone modes [5]. What had not yet been observed are quantized vortices, a hallmark of superfluidity. Here, we report on the theoretical study and experimental observation of vortices in a dipolar supersolid of Dysprosium [6]. When rotated, the supersolid phase shows a mixture of rigid-body and irrotational behavior, highlighting a fundamental difference between modulated and unmodulated superfluids. Our observations open the way to study the peculiar properties of vortices in supersolids: the reduced angular momentum, the influence of the crystal structure on the vortex dynamics and further applications to the study of other systems with multiple spontaneously broken symmetries, such as neutron stars [7].

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Demonstration of weighted graph optimization on a Rydberg atom array using local light-shifts

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Abstract

Neutral atoms have emerged as a powerful and scalable platform for quantum computing, offering the ability to generate large numbers of identical and high quality qubits in reconfigurable arrays. By coupling atoms to highly excited Rydberg states with strong, long-range dipole-dipole interactions this system can natively implement graph problems [1] including finding the maximum independent set (MIS) on a unit disk graph [2], providing a route to performing analogue optimisation of real problems however with large systems required to reach a regime competitive against current classical optimisation protocols. To extend this approach to explore optimisation of a wider class of problems including weighted graphs and quadratic unconstrained binary optimisation (QuBO), it is necessary to introduce locally addressed light-shifts to enable weighting of nodes during the optimisation process, enabling problems to be encoded with at worst a quadratic resource overheads [3].

In this talk we present work to develop a large-scale system for quantum computing and annealing, and show preliminary results highlighting our ability to implement small-scale demonstrations of weighted graph optimisation using programmable local light-shifts across an atom array [4]. We introduce a hybrid annealing process combining global addressing with ramped light shifts, and outline prospects for scaling this approach to larger graph problems as a potential pathway to quantum utility.

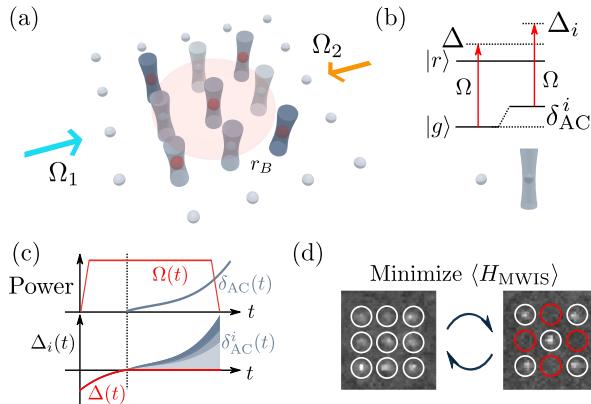


Fig. 1: Weighted graph optimisation with local light-shifts. (a) The target graph problem is embedded onto a neutral atom array as a Maximum Weighted Independent Set (MWIS) on a Unit Disk Graph (UDG), using global Rydberg excitation lasers ($\Omega_{1,2}$) and an additional set of tweezer beams for implementing local light-shifts with a programmable shift on each qubit site. The Rydberg blockade mechanism prevents two atoms within distance r_B being simultaneously excited. (b) Atoms without light-shift experience an effective two-photon Rabi frequency Ω and global detuning Δ . The light-shift tweezers induce AC shift $\delta_{AC}^i = w_i \delta_{AC}$ on atom i to implement a local detuning $\Delta_i = \Delta + \delta_{AC}^i$ with relative weight w_i . (c) Annealing protocol using a two-stage process with the global Rydberg laser ramped from an initial negative Δ to resonance, then positive detunings defined by controlling power in light-shift tweezers to scale δ_{AC} resulting in local detunings with fixed relative ratios defined by weightings w_i . (d) Ground-state solutions obtained via closed-loop optimisation of the annealing profile to minimise the expectation value of the classical MWIS cost function.

This work is supported by the EPSRC Prosperity Partnership with M Squared Lasers, Grant No. EP/T005386/1.

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Ultracold CaF+Yb collisions: bound states, electric-field resonances, and prospects for triatomic molecule formation

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There has been much recent progress in cooling molecules to ultracold temperatures, particularly laser cooling molecules like CaF. There is now interest in controlling collisions of such molecules with ultracold atoms, and using these to form triatomic molecules. Such molecules may have uses in precision spectroscopy, such as searches for beyond-standard-model physics or time variation of fundamental constants. Sensitivity in such experiments can be enhanced by level structures in polyatomic molecules, and also by heavy elements such as Yb.

We have calculated the interaction potential of the CaF–Yb complex. It is highly anisotropic, with its global minimum bound by 8000 cm^{-1} in a bent CaF–Yb configuration (Fig. 1a). In scattering, the anisotropy provides a strong coupling between rotational states of CaF, but is not likely to drive strong magnetic Feshbach resonances. Instead we focus on effects of electric fields, where resonant states can be coupled directly by the interaction anisotropy. We have calculated scattering lengths as a function of electric field up to 20 kV/cm and find a rich spectrum of Feshbach resonances (Fig. 1b), which we locate and characterise numerically. The resonances are fairly sparse and narrow below 5 kV/cm but increase dramatically up to 10 kV/cm and beyond. The widest have widths of several kV/cm but there are also many narrower.

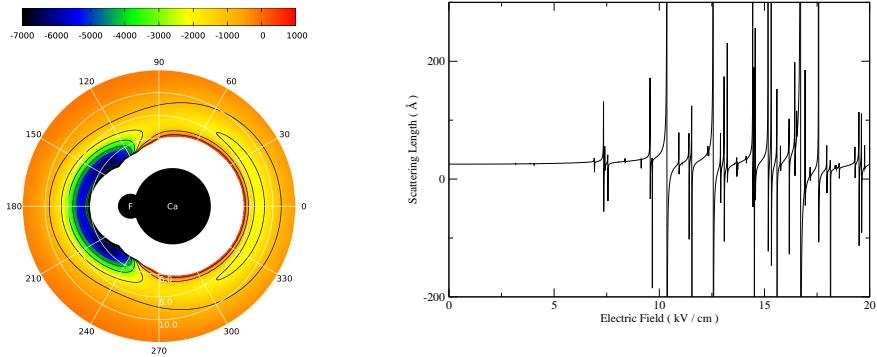


Fig. 1: Left: CaF+Yb interaction potential. Right: Scattering lengths as a function of electric field, showing many Feshbach resonances.

This method is completely general and does not rely on any internal spin structure or state, so is applicable to any combination of heteronuclear molecule and atom. These results pave the way for a new generation of experiments towards control of atom+molecule mixtures and novel electro-association into triatomic complexes.

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A programmable hybrid system of ultracold molecules and Rydberg atoms

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Ultracold dipolar systems, like atoms excited to Rydberg states and polar molecules, hold great potential for quantum simulation and computation. Rydberg atoms offer strong, long-range interactions, facilitating the engineering of quantum entanglement and multi-qubit gates through the Rydberg blockade mechanism. Similarly, polar molecules exhibit long-range interactions but also possess numerous long-lived internal states. These states can be effectively coupled using microwave fields and can exhibit long coherence times for robust storage of quantum information [1]. Programmable arrays of optical tweezers have enabled flexible trapping of both these systems, creating the possibility of a hybrid system that combines the advantages of both platforms.

In this presentation, I will present our hybrid system consisting of ultracold RbCs molecules in their rovibrational ground state and Rb atoms trapped in species-specific optical tweezers. I will demonstrate how Rydberg blockade due to the charge-dipole interaction with a RbCs molecule [2] facilitates the detection of individual molecules. Furthermore, I will describe the toolbox of techniques we have developed for the control and readout of individually trapped polar molecules in optical tweezers [3]. Finally, I will highlight some recent results on the production of heteronuclear Rydberg molecules in separate optical tweezers and the observation of resonant dipole-dipole interactions between a Rydberg atom and a polar molecule. These results lay the foundation for future explorations of quantum computation and precision measurements utilising this hybrid platform.

References

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Spin-dependent scattering lengths and Feshbach resonances: towards dipolar spinor condensates

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Strongly dipolar spinor Bose gases are fascinating platforms but yet marginally explored. In this work we provide a clear route to the manipulation of a binary dipolar spin mixture of Dy¹⁶². We demonstrate the preparation of spin-polarized degenerate gases of dysprosium in the three lowest energy Zeeman sub-levels thanks to a light-induced quadratic Zeeman effect. From the expansion of these spin-polarized BECs, we deduce the scattering lengths describing the contact interaction between particles in these states, which is a crucial step towards the preparation and manipulation of dipolar spinor condensates. Moreover, the study of the dipolar relaxation rate allows us to identify a magnetic field sweet-spot, where the dipolar relaxation is reduced by a tenfold factor. Finally, we identify spin-dependent Feshbach resonances close to the magnetic field sweet-spot, which are crucial for the study of different regimes of miscibility in binary mixtures.

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Loss features in ultracold ^{162}Dy gases : pairwise versus three-body processes

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Dipolar gases like erbium and dysprosium have a dense spectrum of resonant loss features associated with their strong anisotropic interaction potential. These resonances display various behaviours with density and temperature, implying diverse microscopic properties. Here, we quantitatively investigate the low-field ($B < 6$ G) loss features in ultracold thermal samples of ^{162}Dy , revealing two- and three-body dominated loss processes. We investigate their temperature dependence and detect a feature compatible with a d-wave Fano-Feshbach resonance, which has not been observed before. We also analyse the expansion of the dipolar Bose-Einstein condensate as a function of the magnetic field and interpret the changes in size close to the resonances with a variation in the scattering length.

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Single molecule imaging and high fidelity state transfer in RbCs

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Realising the potential of ultracold molecules in quantum simulation will require the development of enhanced manipulation and high fidelity detection of the quantum state of individual molecules. This talk will cover our work towards a quantum gas microscope for RbCs molecules in a lattice. This new experiment will allow us to study microscopic correlations in the wide variety of many body systems which can be realised with dipolar molecules. I will also discuss our work towards enhancing the detection efficiency of associated molecules via highly efficient STIRAP. Using a simple and versatile optical feed forward technique we remove high frequency phase noise from our laser system to realise a STIRAP efficiency of 98.7(1)% , comparable to the detection efficiency realised in atomic quantum gas microscopes.

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Three-dimensional dipolar superfluid vortex dynamics

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As a signature of superfluidity in quantum systems, quantum vortices are of considerable theoretical and experimental interest in the study of Bose-Einstein condensates. In dipolar Bose-Einstein condensates (dBECs), the static and dynamic properties of vortices are influenced by the anisotropic and long-ranged nature of the dipole-dipole interaction (DDI). Furthermore, the recent experimental discoveries of vortices in both the superfluid [1] and supersolid [2] phases of a dBEC have opened up a new platform for exploring the interplay between vorticity and atomic interactions in superfluids.

Motivated by these experimental results, we have studied the structure of single vortices and the equilibrium behaviour of pairs of straight vortex lines in a background uniform three-dimensional dBEC. For a straight vortex line, we find that the effective DDI potential induced by the vortex core is axially anisotropic when the dipole moments have a nonzero projection orthogonal to the vortex line. This results in a corresponding elongation of the vortex core along this projection as well as an anisotropic superfluid phase and enhanced compressibility in the vicinity of the vortex core. Consequently, the trajectories of like-signed vortex pairs are described by a family of elliptical and oval-like curves rather than the familiar circular orbits. Similarly for opposite-signed vortex pairs their translation speeds along the binormal axis are found to be DDI-dependent [3].

Based on the insights gleaned from this idealised system, we have also studied a non-equilibrium scenario involving pairs of antiparallel vortex lines where the Crow instability of mutually out-of-phase Kelvin waves drives the vortices towards reconnections and a subsequent cascade into vortex loops. Assuming identical initial conditions, we find that the time evolution of the Kelvin wave distribution on each vortex depends strongly on the polarisation angle and strength of the dipole moments. This is shown to be related to the curvature of the vortex lines being either suppressed or enhanced by the presence of the DDI, depending on the polarisation axis. This results in a dipolar dependence of the specific modes on each vortex that contribute most strongly to the Crow instability, thereby mediating the size of the vortex loops that form after the unstable modes have induced vortex-vortex reconnections [4].

Together, these results open the door to a greater understanding of vortex ensembles in dBECs and we expect that these findings will shed greater light on phenomena such as the dynamics of vortex lattices, vortex reconnection scaling and quantum turbulence in these systems.

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Fate of the Mollow triplet in strongly-coupled atomic arrays and beyond

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Subwavelength arrays of quantum emitters have emerged as an interesting platform displaying prominent and controllable collective effects. In this talk I will discuss such arrays of two-level atoms under coherent driving, realizing an open quantum many-body problem in a strongly non-linear regime. I will show that the spectrum of scattered light at strong drive intensities, characterized by the famous Mollow triplet for a single atom, develops a characteristic broadened lineshape with some universal features, independent of the specific geometry and only determined by local ordering and dipolar interactions [1]. This emission spectrum characterizes atomic arrays and distinguishes them from disordered ensembles and non-interacting emitters. Our predictions are based on a novel dynamical mean-field theory (DMFT) approach to the problem, paving the way for further studies of these systems. I will then discuss the steady-state phase diagram and show that this is dramatically modified if beyond mean-field fluctuations are taken into account [2]. Finally, I will discuss how the existence of non-radiative modes in these platforms can lead to strongly non-linear behaviour even at low drive intensities.

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The prospects of studying field-linked states with alkali-silver molecules

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Field-linked states offer the possibility to weakly bind dipolar molecules [1] and tune their contact interaction interaction [2], while simultaneously suppressing inelastic short-range collisions in strong microwave fields. They also became relevant for the condensation of the first BEC of dipolar molecules [3]. Experiments could so far access the first two field-linked resonances and, while it was possible to form field-linked molecules coherently, their one-body lifetime could not be pushed beyond 10 ms. Both, the number of accessible resonances and the intrinsic lifetime of the field-linked states scales with the coupling of the dipole moment to the external field. To maximize both quantities I propose to study field-linked states with alkali-silver molecules that offer electric dipole moments that are unprecedently large compared to existing ultracold molecules [4]. These molecules will provide access to high-partial-wave scattering resonances in microwave fields and even offer a variety of field-linked resonances in static electric fields [5]. To study controlled collisions between the molecules I propose to use an optical tweezer platform. This would also provide an ideal testbed for the investigation of field-linked states composed of three or more dipolar molecules [6] and the transition of field-linked molecules to tightly bound metal-cluster states.

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Developing a Hybrid Tweezer Array of Rydberg Atoms and Polar Molecules

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Hybrid tweezer arrays of atoms and molecules are a new and innovative tool for quantum science and technology. Tweezer arrays allow for flexible and dynamical trap scenarios. With their rich level structures and long rotational state coherence times, molecules are ideal for storing quantum information and make excellent qubits. Their interactions can be enhanced enormously by using Rydberg atoms to mediate long-range dipole-dipole interactions. This platform presents an interesting approach to quantum simulation [1] and computing [2,3].

Here, I present our efforts to build such a hybrid tweezer array using ultracold Rb atoms and CaF molecules. I discuss the advantages and challenges of multispecies hybrid systems and present our schemes for preparing ultracold Rb atoms and CaF molecules. I further show our recent progress in atom cooling, trap loading, imaging and trap characterisation. Cooling and loading of optical traps can be performed using the Rb D1 transition, where we can reach temperatures in free-space molasses in the low μK regime. Finally, I present our ideas for loading both species into separate tweezer arrays using a dual-color tweezer approach.

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Supersolidity and persistent currents in Bose-Einstein condensates with reversed dipolar interactions

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Dipolar Bose-Einstein condensates, particularly those of highly magnetic dysprosium atoms, are intriguing systems that exhibit novel features compared to regular superfluids. When the dipoles are aligned with a rapidly rotating magnetic field, it may give rise to a tunable interatomic potential where the overall sign of the interaction can be reversed. We have recently shown that in this setup, a harmonically trapped condensate can exist as a supersolid in the form of disk-shaped droplets connected by a dilute background. We have drawn a zero-temperature phase diagram for such a system within an experimentally interesting range of parameters. Furthermore, we have investigated the excitation spectrum across the phase transition and observed degeneracy-breaking in the two lowest-lying modes. Additionally, when a repulsive potential is added in the middle of the harmonic trap, the droplets take the form of rings, which can host persistent currents generated by stirring the gas with a barrier. We found that an asymmetrical barrier can induce superfluid and rigid body motion in the system at the same time. These results could lead to new applications in atomic interferometry and atomtronics.

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Making molecules by mergoassociation

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An enormous number of experiments exploring quantum simulation, quantum computation, and different tests of fundamental physics use ultracold molecules. The molecules used in these experiments are now, almost exclusively, produced via magnetoassociation or direct laser cooling. The former requires magnetically tuneable zero-energy Feshbach resonances to exist in collisions between the molecules' constituent atoms. The latter requires a molecule to have diagonal Frank-Condon factors. Researchers are therefore limited in the number of molecular systems available to them. Mergoassociation is a new way to produce ultracold molecules. The mergoassociation of two ultracold atoms to form a weakly bound molecule can occur when two optical traps, each containing a single atom, are merged. We have developed the theory of mergoassociation for pairs of nonidentical nonspherical traps and have illuminated the effects of trap length and aspect ratio on the mergoassociation process.

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Excitations of a binary dipolar supersolid

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We theoretically investigate supersolid phases in two-component dipolar Bose-Einstein condensates, which we expect to be experimentally realizable in the near future. We predict a rich excitation spectrum in a linear crystal regime, where the ground state consists of two partially immiscible components with alternating, interlocking domains. We identify three Goldstone branches, each with first-sound, second-sound or spin-sound character. In analogy with a diatomic crystal, the resulting lattice has a two-domain primitive basis and we find that the crystal (first-sound-like) branch is split into optical and acoustic phonons. We also find a spin-Higgs branch that is associated with the supersolid modulation amplitude. Further information can be found in our preprint: arXiv:2312.03390.

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Towards doubly dipolar CsYb molecules.

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Ultracold mixtures of alkali metals such as Cs and closed-shell atoms such as Yb provide an opportunity for the formation of heteronuclear molecules which exhibit both magnetic and electric dipole moments, as well as a platform for the study of dual-species ultracold gases. However, so far, producing such molecules using magnetoassociation has proven to be challenging due to the narrow width of the interspecies feshbach resonances [1][2].

As well as having a permanent electric dipole moment, heteronuclear $^2\Sigma$ molecules such as CsYb have a magnetic dipole moment. Combined with long-range electric dipole-dipole interactions, this makes CsYb a promising platform for quantum simulations of lattice spin models [4]. Furthermore, Yb has 2 bosonic and 5 fermionic isotopes, opening the possibility for both fermionic and bosonic molecules to be produced as well as covering a wide range of interspecies scattering lengths with Cs. This will also provide a wider range of Feshbach resonances with which to potentially create molecules, of which broader resonances are anticipated to be generated by exciting Yb to a metastable state prior to magnetoassociation [4][5].

We have produced a quantum degenerate mixture of Cs and Yb [6] and studied its dynamics with attractive interspecies interactions [7]. We have also made observations of magnetic Feshbach resonances between Cs and ^{173}Yb which is a crucial step in the production of ground state CsYb molecules [8].

In preparation for the production of molecules and quantum degenerate mixtures we are currently implementing optical transport from a steel chamber to a glass cell with improved optical access, high-field magnetic coils and high-resolution imaging.

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Hyperfine-resolved spectroscopy of the $X^1\Sigma^+ - b^3\Pi_0$ transitions in ultracold $^{87}\text{Rb}^{133}\text{Cs}$ molecules

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Long rotational coherence times of ultracold polar molecules are required for many proposed applications, including quantum computation and quantum simulation [1]. In our previous work [2, 3], we have demonstrated a rotationally magic trap for ultracold $^{87}\text{Rb}^{133}\text{Cs}$ molecules at a detuning of 185 GHz from the transition at 1146.1 nm from the rovibrational ground state of the $X^1\Sigma^+$ potential to the lowest vibrational level of the $b^3\Pi_0$ potential. We have observed second-scale rotational coherence and detected the dipolar interactions in a dilute gas of molecules through the loss of contrast in a Ramsey sequence. Here, we report hyperfine-resolved spectroscopy of the relevant transitions needed to develop an improved model of the magic conditions. We resolve rotational and hyperfine structures associated with the three lowest vibrational levels of the $b^3\Pi_0$ potential. From the spectroscopy, we extract the anharmonicity parameter of $^{87}\text{Rb}^{133}\text{Cs}$ molecules in the $b^3\Pi_0$ state. Linear Zeeman shifts of the hyperfine states are measured across magnetic fields ranging from 181.5 G to 210.4 G, from which the associated magnetic moments are derived. We determine the transition dipole moments to the lowest two vibrational levels by directly driving the Rabi oscillations. The results indicate partial transition linewidths of 4.7(1) kHz and 2.7(1) kHz, respectively. We also measure excited state lifetimes of 12.3(1) μs and 7.20(4) μs , corresponding to natural linewidths of 13.0(9) kHz and 22.1(8) kHz. As an outlook, we report ongoing work to load the molecules into a magic wavelength optical lattice.

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Transverse Field Zeeman Slower for ^7Li from Permanent Magnetic Dipoles

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In the field of ultracold atoms Zeeman slowers are commonly used for slowing down atomic beams. The conventional method typically involves electromagnets with high current which require water cooling and introduce further complications to the system. Here we present our design of a Zeeman slower made from an array of individual magnetic dipoles in a cylindrical Halbach configuration. This alternative method creates a stable and robust uniform transverse field while allowing high tunability of the spatial dependence of that field along the symmetry axis. Due to some details of lithium energy spectrum, a zero-crossing transverse field configuration poses unique challenges to its characterization. We present experimental result of its performance, together with theoretical description of interesting features found in this device.

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Bialkali and Beyond: Experiments with ultracold RbCs molecules and a future Ag-Cs mixture

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Ultracold polar molecules uniquely combine a rich structure of long-lived internal states with access to controllable long-range anisotropic dipole-dipole interactions. One class of molecules currently available in experiments are bialkali molecules that are produced at ultracold temperatures by association from a pre-cooled mixture of atoms. In Durham, we routinely produce ultracold gases of RbCs molecules and have recently developed a rotationally-magic trap that supports second-scale coherence times [1]. In this poster, we report on new directions for our experiments with RbCs, including plans to directly detect the molecules using either absorption imaging [2] or dispersive imaging [3]. Both imaging schemes probe transitions between the $X^1\Sigma^+ \rightarrow A^1\Sigma^+ + b^3\Pi_0$ potentials with 935nm light. We also present plans for a new project underway in Durham to produce an ultracold mixture of Ag and Cs atoms with the aim of creating ultracold polar molecules with dipole moments in the $^1\Sigma$ ground state of around 10 Debye [4].

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Modelling Isentropic Quantum Engine Cycles in an Atomic Superfluid

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Recently there has been a surge of activity in relation to quantum thermodynamics in coherent atomic superfluids. In addition to the usual quantum Otto cycle, experimental work has recently addressed isentropic cycles, through a combination of potential- and interaction-energy exchange cycles. Our investigation is motivated by the experiment of Simmons et al. (PRR 5, L042009 (2023)), in which they study a high purity trapped quantum gas of ^7Li atoms subjected to an Otto cycle. This cycle pumps energy between the magnetic and optical fields by alternately varying the scattering length and trapping frequency. Here we present our preliminary results on isentropic quantum engine efficiency and power within an atomic condensate based on mean-field calculations: in particular, we focus on the inter-dependence of the behaviour of such parameters on the underlying collective excitations induced by non-adiabatic processes in the various engine strokes – an important question to achieving maximal performance within a minimal evolution timescale. Our preliminary findings are discussed in the context of the broader literature and provide a first step towards a fully self-consistent analysis in a closed partially-condensed system, based on more advanced finite-temperature techniques.

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Entanglement of assembled molecules in magic-wavelength optical tweezers.

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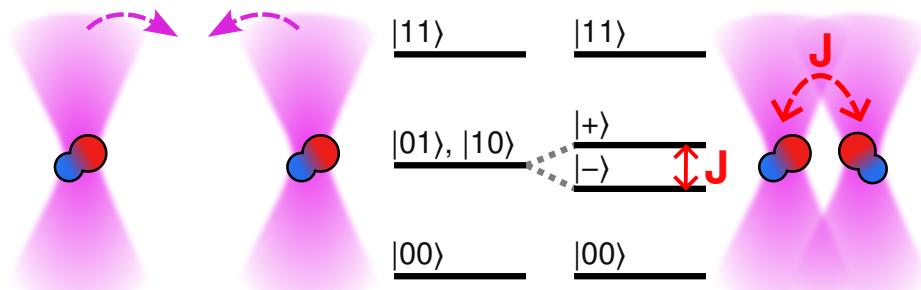


Fig. 1: (left) Two molecules in magic-wavelength optical tweezer traps, separated by a significant distance. (right) When the molecules come together, dipole-dipole interactions cause an interaction shift, large enough to be resolved spectroscopically.

The rich internal structure and tuneable interactions of ultracold molecules make them a versatile platform for quantum science [1]. Preparing molecules in a superposition of rotational states engineers dipole-dipole interactions that can be controlled using microwave fields [2], [3]. These properties make rotational states well suited to engineer qubits. Here, we report our recent experimental advances where we assemble individually trapped $^{87}\text{Rb}^{133}\text{Cs}$ molecules [4], [5] and entangle them via the dipole-dipole interaction in magic-wavelength optical tweezers.

We focus on relative populations of rovibrational ground state $|0\rangle$ and the first rotationally excited state $|1\rangle$. We engineer a readout scheme based on post-selection that directly measures the ratio of the populations of these two states within the molecule, removing errors associated with loss and leakage [6].

To engineer a magic-trapping wavelength, we follow the scheme described in Ref. [7]. By tuning the polarisabilities of the molecule parallel and perpendicular to the internuclear axis, the polarisability becomes isotropic and the rotational superposition becomes insensitive to variations in the trapping intensity.

A recent experiment in a bulk gas of RbCs has demonstrated second-scale coherence between non-interacting rotational states following the same scheme [8]. They were able to resolve the presence of dipole-dipole interactions in this system by noting the significantly increased decoherence from the inhomogeneous dipole-dipole interactions.

The positional control afforded by using optical tweezers allows two individual molecules to be held at a well-defined distance. When holding the molecules at micron-scale distances, we realise hertz-scale dipole-dipole interactions. This represents a characteristic interaction time ~ 100 ms. Due to the second-scale coherence of the tweezers, we can probe exchanges of rotational quanta between the molecules, and form entangled states of two molecules.

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Zeeman-Sisyphus deceleration of CaF molecules

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The complex internal structure of ultracold molecules offers exciting possibilities for quantum technology, cold chemistry and fundamental physics. However, this complexity comes with additional challenges for reaching low temperatures. As a step in producing molecules in the ultracold regime, direct laser slowing has proved to be a hugely successful technique, decelerating fast molecular beams to below the capture velocity of a magneto-optical trap (≈ 20 m/s). This process requires $\approx 10^4$ photons to be scattered however, so is impractical for the vast majority of molecular species, particularly those with unfavourable branching ratios, long wavelength transitions or large masses.

Zeeman-Sisyphus deceleration [1] presents a novel way to address these concerns, reducing the number of photon scatters required by at least two orders of magnitude compared to laser slowing. Molecules travel through a spatially varying magnetic field and are optically pumped between high and low field seeking substates to ensure they are continually climbing a potential hill. This technique has previously been demonstrated for polyatomic molecules [2, 3], using two cryogenically cooled superconducting magnets.

Here, we present our current progress in building upon this work. We produce CaF molecules using a cryogenic buffer gas source [4] and use a series of permanent magnets which can be extended to many hundreds of deceleration stages.

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Decoupled sound and amplitude modes in trapped dipolar supersolids

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I will present our recent theoretical results on elementary excitations of dipolar quantum gases across the superfluid to supersolid phase transition in toroidal traps [1]. The periodic boundary conditions introduced by the confinement lead to first sound, second sound and Higgs modes, which remain decoupled from each other in a broad range of the interaction strength (see Fig. 1). I will present how these modes emerge from their respective superfluid modes when crossing the phase transition and I will explain how the sound modes can be understood as in- and out-of-phase oscillations of crystal and superfluid components.

The toroidal geometry employed in this study offers the unique opportunity to establish a direct correspondence between excitations of trapped and infinitely extended supersolids. At the same time, this geometry allows us to devise schemes to excite the individual modes selectively.

In addition to the theoretical results, I will also present our ongoing experimental efforts towards preparing large atom number Dysprosium BECs and supersolids in various potential geometries.

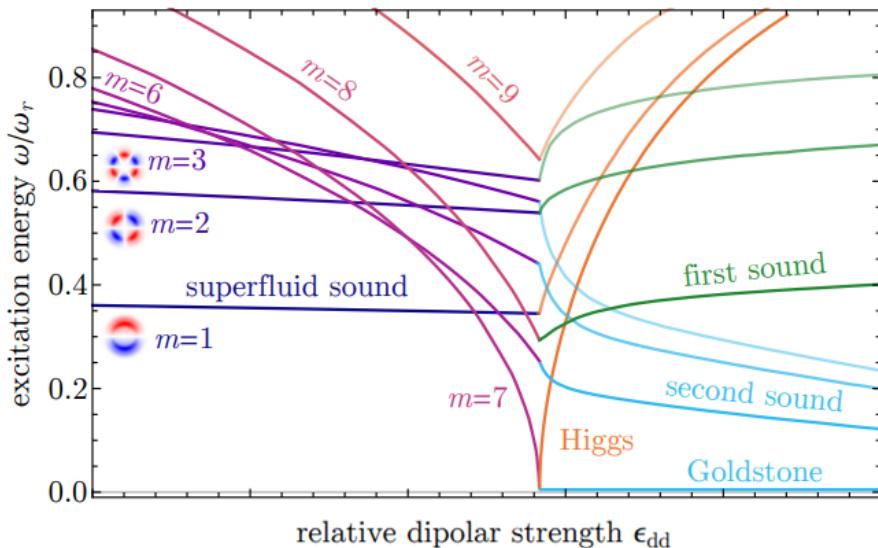


Figure 1: Numerically calculated excitation spectrum of a dipolar quantum gas in a toroidal trap. $N = 5000$ atoms are assumed and the torus trap has a radius of $\rho = 1 \mu\text{m}$ with $\omega_{ax} = 2\pi \cdot 1.7 \text{kHz}$ axial trap frequency and $\omega_{rad} = 2\pi \cdot 1.0 \text{kHz}$ radial trap frequency. The lowest 10 modes, calculated using the Bogoliubov-de-Gennes formalism are shown. Due to the periodic boundary conditions, the only allowed wavevectors are multiples of $q = \frac{1}{\rho}$. On the superfluid side, the lowest possible excitation therefore is the (first) sound mode at $q = \frac{1}{\rho}$. When approaching the supersolid phase transition the roton modes soften. At the phase transition, they split up into the ungapped Goldstone and gapped Higgs mode both at zero quasi-momentum (with the quasi momentum restricted to the first Brillouin zone set by the roton momentum). Due to the two broken symmetries, two sound branches (first and second sound) emerge as well. Crucially, in the torus geometry unlike the cigar-shaped trap, both Goldstone and Higgs mode have zero energy at the phase transition. Adapted from [1].

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Measuring the dipolar interaction shift of the BEC critical temperature

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Interactions in many-body bosonic systems induce a shift of the critical temperature for Bose-Einstein condensation compared to the ideal gas result. The effect in ultracold gases with purely contact interactions has been thoroughly studied, both theoretically and experimentally [1]. This work presents our measurements of the ‘mean-field’ critical temperature shift due to magnetic dipole-dipole interactions in a harmonically trapped, ultracold erbium gas. Analysing the transition temperature dependence on the orientation of the dipoles in a highly prolate trap, we isolate the contribution of the anisotropic dipolar interactions and demonstrate the agreement with predictions [2]. We also investigate the role of dipolar interactions in the non-saturation of the thermal gas past the transition [3], and outline a Thomas-Fermi approximation based model to explain the observations. These findings pave the way for studies of beyond-mean-field contributions to the shift of the BEC critical point in dipolar gases, as well as extending the studies into the strongly dipolar regime and the thermal gas to droplet and thermal gas to supersolid phase transitions.

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Improved STIRAP efficiency using feedforward suppression of optical phase noise

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Many experimental platforms for quantum science depend on control via optical fields. In these systems laser phase noise often limits the fidelity of control achievable, one example being the efficiency of state transfer in ultracold molecules. This challenge is exasperated in stabilized laser systems where high-frequency phase noise is an unavoidable consequence of feedback. In this work, we apply feedforward noise cancellation to reduce high-frequency phase noise in lasers used for STIRAP state transfer of RbCs molecules and demonstrate significant enhancement of the transfer efficiency. By performing over 100 state transfers on single molecules we measure a transfer efficiency of 98.7(1)%. We model our experimental noise and predict that with feedforward active our state transfer efficiency is only limited by available laser intensity. The remarkably straightforward approach used can be readily applied in many other platforms where quantum control fidelity is limited by laser phase noise.

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Applications of shielded ultracold molecules: From ultracold complexes to quantum magnetism

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Trapped samples of ultracold polar molecules offer opportunities to study important physical phenomena that range from quantum simulation to quantum magnetism. To produce a stable ultracold gas in an optical trap, it is necessary to shield pairs of molecules from close collisions that otherwise cause trap loss. Shielding can be achieved by various methods, most notably with static electric [1] and microwave fields [2]. We show that using static electric fields we can gain substantial control over the scattering length a , which is crucial for the stability or collapse of molecular Bose-Einstein condensates [3]. Furthermore, we show how we can tune the electric field to change a and create tetramer molecular bound states among various molecules. This opens up the door to study ultracold complex molecules.

In a recent proposal, we show that shielded ultracold molecules can also exhibit many-body properties associated with SU(N) magnetism, where N is the number of available spin states [4]. Until now, SU(N) symmetry has been predicted and realized with nuclear spin states of alkaline-earth-like atoms (Sr and Yb), which allow N up to 10 [5]. However, they have important limitations: they are all fermionic and have repulsive interactions, i.e., their a is positive. Shielded molecules, on the other hand, can be either bosonic or fermionic, with much greater tunability of a . We show that experimentally accessible alkali dimers might exhibit SU(N) with N as large as 36 [4]. All these features open up exciting possibilities for studying novel aspects of quantum magnetism.

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Ultracold ${}^6\text{Li}{}^{40}\text{K}$ Molecules through Direct Association from Fermi-Fermi Mixtures in 3D Magic Optical Lattices

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Ultracold molecules confined in optical lattices offer a versatile platform for precision measurements, quantum simulations, and quantum computing. Notably, ${}^6\text{Li}{}^{40}\text{K}$ molecules in deeply-bound ro-vibronic states exhibit a significant electric dipole moment, rendering them ideal candidates for exploring dipole-dipole interactions. We propose a direct association of ultracold ${}^6\text{Li}{}^{40}\text{K}$ molecules from Fermi-Fermi mixtures of ${}^6\text{Li}$ and ${}^{40}\text{K}$ atom in 3D magic optical lattices, aimed at enhancing Feshbach association efficiency and extending molecular lifetime and coherence time.

The study employs self-consistent mean field theory to predict the density distributions of mass-imbalanced interacting Fermi clouds within 3D optical lattices. Unlike Bose-Fermi mixtures, spin-polarized Fermi-Fermi mixtures exhibit favorable density matching properties. By excluding Bosons, the mixture can be loaded into 3D lattices with at most one particle occupancy per site for each species. Through tuning of the Feshbach field towards the attractive interaction regime, enhanced interspecies overlap is achieved. The presence of heavier and denser ${}^{40}\text{K}$ atoms induces a mean field effect that compresses ${}^6\text{Li}$ cloud, thereby promoting dual-species doublon occupancy.

Additionally, frequency-dependent polarizability calculations for the ground and first rotational excited states of ${}^6\text{Li}{}^{40}\text{K}$ are conducted using CFOUR. It indicates favorable features in the polarizability spectra, particularly in the vicinity of a broad and far-detuned magic wavelength where the differential light shift remains negligible across the trap. Building upon these predictions, a 3D magic lattice configuration is designed, comprising retro-reflected beams at 1064 nm and a magic wavelength (~ 953 nm), with appropriate polarization alignment relative to the Feshbach field.

Experimentally, We first show the details of the calibration on 3D lattices with Rb atoms via superfluidity to Mott insulator transitions, Kapitza-Dirac scattering, and Brillouin zones. Subsequently, we delve into an ongoing investigation concerning the behavior of a mixture comprising ${}^{40}\text{K}$ and ${}^6\text{Li}$ atoms within these lattices. This experiment holds promise for uncovering novel quantum many-body effects and exploring emergent phases of matter.

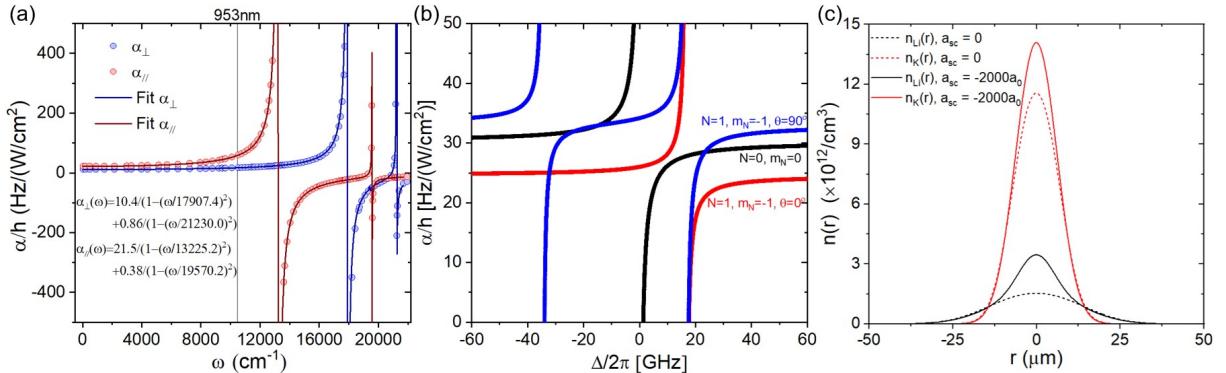


Figure 1: (a) Frequency-dependent background polarizabilities of the ground state ${}^6\text{Li}{}^{40}\text{K}$ molecules. (b) Tune-out magic condition for vibrational ground states $|N = 0, m_N = 0\rangle$ and $|N = 1, m_N = -1\rangle$. (c) Density distribution of the ${}^6\text{Li}$ and ${}^{40}\text{K}$ in the 3D optical lattices.

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Single molecule resolved imaging of RbCs molecules in an optical lattice

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The ability to resolve single atoms, and few body correlations has been transformative in quantum simulators based on ultracold atoms in optical lattices [1]. Applying these techniques to ultracold molecules will allow a wider variety of models to be studied with microscopic resolution, thanks to their rich internal structure and the long-range dipolar interactions between molecules [2]. Here we present our progress towards realising a new RbCs molecule experiment capable of realising single-site-resolved imaging of RbCs in a single layer of an optical lattice. The apparatus is designed with optical access for single site resolved imaging of both species. Utilising fast optical transport [3] and a novel scheme for dual species evaporative cooling we have significantly reduced the time needed to prepare a cloud of ultracold RbCs molecules. We have also demonstrated single-atom resolved imaging, and are now working to combine these advances to study interacting RbCs molecules with single-particle resolution.

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Towards laser cooling of AlF molecules in the deep ultraviolet

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Aluminium monofluoride (AlF) has great potential as a molecule for laser cooling. It is stable, deeply bound and can be created in large quantities as an intense molecular beam. The laser cooling scheme for AlF is very simple, requiring one cooling laser and one vibrational repump. As the cooling transition is in the deep ultraviolet (DUV), the momentum transferred by each photon is relatively large, which allows fast and efficient cooling. In this talk, we present our setup for generating light in the DUV for laser cooling using Vertical-External-Cavity Surface-Emitting Lasers (VECSELs) and highly stable enhancement cavities for second harmonic generation. The setup is tested by cooling Cd atoms in a magneto-optical trap on the $^1\text{P}_1 \leftarrow ^1\text{S}_0$ transition near 229nm, which is close to the main cooling transition of AlF (227.5nm). Finally, our progress towards laser cooling of AlF will be presented.

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Magnetic solitons in binary dipolar BECs

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Magnetic solitons can occur in two-component (binary) Bose-Einstein condensates (BECs). They exist in the miscible phase, close to the immiscibility transition, and are associated with a density trough (peak) in component 1 (component 2), with the two components having localized phase gradients in opposing directions. We theoretically investigate the interactions between magnetic solitons in binary BECs with and without dipolar interactions, finding intriguing bound states associated with inter-soliton potential maxima, since the effective masses are negative. In addition to developing a simple model to describe these bound states, we analytically solve an appropriate set of Bogoliubov-de Gennes equations to gain a deeper understanding of the relationship to the roton-maxon excitations, offering insights into the complex dynamics of magnetic solitons in binary dipolar BECs.

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A Hybrid Quantum System of Ultracold Polar Molecules and Rydberg Atoms

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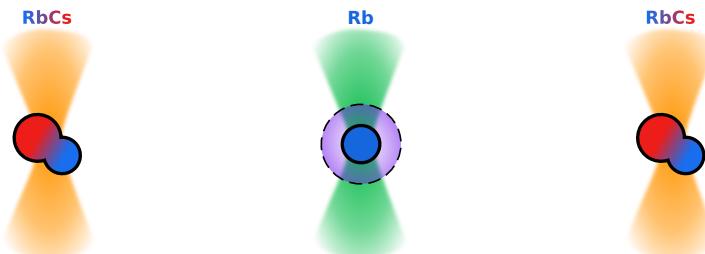


Fig. 1: A hybrid quantum system of ultracold RbCs molecules and Rb Rydberg atoms. Each particle is trapped in species-specific optical tweezers. The particles interact at long range via the charge-dipole and dipole-dipole interactions.

We envision a hybrid quantum system comprised of individually trapped polar molecules interfaced with Rydberg atoms. The rich internal structure of polar molecules enables the encoding of quantum information in their long-lived rotational states, whilst the strong long-ranged interactions between a polar molecule and Rydberg atom allows for fast multi-qubit quantum gates [1], [2]. Here, we report our recent experimental progress towards this goal where we assemble individually trapped $^{87}\text{Rb}^{133}\text{Cs}$ molecules and interface them with ^{87}Rb Rydberg atoms.

We produce single RbCs molecules in optical tweezers which allows for single-site control and imaging. Individual Rb and Cs atoms are first trapped and cooled in separate tweezers. The tweezers are then merged to prepare Rb-Cs atom pairs. Weakly bound molecules are formed by associating these atom pairs [3] and are subsequently transferred to the rovibrational ground state using two-photon stimulated Raman adiabatic passage (STIRAP). Alongside the molecules, excess Rb atoms are prepared in the motional ground state and excited to Rydberg states with a two-photon excitation scheme.

We have observed the blockade of the excitation of a Rb atom to the Rydberg state $|52s\rangle$ due to its charge-dipole interaction with a ground state RbCs molecule [4]. The atom and molecule are held in species-specific tweezers which allows them to be brought to a separation of 310(40) nm without significant collisional loss. The effect of the polar molecule is to perturb the Rydberg state energy to be off resonance with the two-photon excitation. This blockades the Rydberg excitation. The observed excitation dynamics are in good agreement with simulations using calculated interaction potentials.

We engineer stronger interactions by carefully choosing molecular and atomic states that can resonantly exchange energy. The resultant interaction is dipole-dipole. We prepare the atom in the Rydberg state $|83d\rangle$ and the molecule in the rotational state $|N = 3\rangle$. With this choice of states, we observe blockade of the Rydberg transition when the atom and molecule are separated by a distance of 2 μm .

Our results open up the prospect of a hybrid platform where quantum information is transferred between individually trapped molecules using Rydberg atoms. We present an outlook to future work including our plans to use this hybrid system to photoassociate giant polyatomic Rydberg molecules [5], [6].

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Effects of curved geometry and finite temperature in dipolar Bose Einstein Condensates

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Dipolar Bose gases showcase a wide variety of physical phenomena, remarkably the formation of supersolids and ultra cold, self-bound droplets. This phenomenology stems from the unique combination of traits (long range character and anisotropy) of the dipole-dipole interaction (DDI). Because of its anisotropy, it is interesting to study the interplay of the DDI and a geometrically non-trivial confinement, like the shell-shaped traps that can be engineered under microgravity conditions in the NASA Cold Atom Laboratory. We explore the ground state configurations of a dipolar BEC immersed in a bubble trap, and show how the frustration induced by the confinement yields ring-shape arrangements of dipolar solids and supersolids [1].

In much the same way, the combination of anisotropy and long range character makes dipolar systems specially susceptible to the effect of thermal fluctuations, even at temperatures considerably lower than the BEC critical temperature, as recently demonstrated by experimental and theoretical works [2, 3], which uncovered the emergence of supersolidity by heating. We explore the thermal effects induced on a dipolar BEC confined in a tubular geometry, and show that temperature can alter the order of the superfluid-to-supersolid phase transition present at zero temperature [4].

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Hyperfine-resolved spectroscopy of the $X^1\Sigma^+ - b^3\Pi_0$ transitions in ultracold $^{87}\text{Rb}^{133}\text{Cs}$ molecules

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Long rotational coherence times of ultracold polar molecules are required for many proposed applications, including quantum computation and quantum simulation [?]. In our previous work [? ?], we have demonstrated a rotationally magic trap for ultracold $^{87}\text{Rb}^{133}\text{Cs}$ molecules at a detuning of 185 GHz from the transition at 1146.1 nm from the rovibrational ground state of the $X^1\Sigma^+$ potential to the lowest vibrational level of the $b^3\Pi_0$ potential. We have observed second-scale rotational coherence and detected the dipolar interactions in a dilute gas of molecules through the loss of contrast in a Ramsey sequence. Here, we report hyperfine-resolved spectroscopy of the relevant transitions needed to develop an improved model of the magic conditions. We resolve rotational and hyperfine structures associated with the three lowest vibrational levels of the $b^3\Pi_0$ potential. From the spectroscopy, we extract the anharmonicity parameter of $^{87}\text{Rb}^{133}\text{Cs}$ molecules in the $b^3\Pi_0$ state. Linear Zeeman shifts of the hyperfine states are measured across magnetic fields ranging from 181.5 G to 210.4 G, from which the associated magnetic moments are derived. We determine the transition dipole moments to the lowest two vibrational levels by directly driving the Rabi oscillations. The results indicate partial transition linewidths of 4.7(1) kHz and 2.7(1) kHz, respectively. We also measure excited state lifetimes of 12.3(1) μs and 7.20(4) μs , corresponding to natural linewidths of 13.0(9) kHz and 22.1(8) kHz. As an outlook, we report ongoing work to load the molecules into a magic wavelength optical lattice.

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Progress towards long-range interactions study using lattice trapped ultracold Sr atoms

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Our research explores fundamental physics using ultracold strontium (Sr) atoms. In particular, we aim to study long-range dipole-dipole interactions by observing the collective properties of scattered light from lattice-trapped Sr atoms. We've successfully completed the first-stage cooling (Blue MOT), and measured the 3P_2 magnetic trap lifetime. We're currently implementing the second-stage cooling, aiming for Bose-Einstein Condensation (BEC). Achieving these milestones relies heavily on the innovative tools we have developed. Our innovations include a suite of systems based on Red Pitaya STEMlab, utilizing Python and C programming. This includes a laser frequency stabilization system that employs a scanning transfer cavity—a cost-effective method for stabilizing a slave laser to a master using a Fabry-Perot cavity. The master laser operates at 698 nm with a 200 Hz linewidth, while the slave operates at 679 nm. Additionally, our control system, enhanced with Redpitaya, expands our capabilities by adding digital and analog channels. This setup supports data acquisition from devices like photomultiplier tubes and photodiodes, enabling real-time, data-driven optimization. Moreover, we developed a frequency modulation system that controls and modulates the 689 nm laser, aiding the transition from a Broadband Red MOT to a Single Frequency Red MOT for more efficient second-stage cooling.

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Towards light scattering experiments in dense dipolar gases

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This poster reports on the progress made in generating dense samples of ultracold dysprosium atoms. We plan to optically transport atoms into a home-built science cell with high optical access. The creation and imaging of dense atomic samples inside the science cell is achieved using high NA custom objectives, designed and assembled in-house. We present the performance characterization and discuss the development of these objectives in our experimental system. Further, an outlook is given on future measurements exploring collective and cooperative effects in the generated sample.

A high NA custom objective, designed and assembled in-house, will then be used to create dense atomic samples inside this cell. We evaluate the performance and discuss the installation of the custom objective in our experimental system. Further, an outlook is given on future measurements exploring collective and cooperative effects in the generated sample.

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Direct Cooling of Dipolar Molecules Towards Bose-Einstein Condensation

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Bose-Einstein condensates (BECs) have been and continue to be extensively studied in atoms, with molecules being a logical next step. Molecules can have large, tunable electric dipole moments so a molecular BEC forms a strongly dipolar quantum fluid and can be used to study many-body physics and for quantum simulations. However, the production of such molecular BECs, either through association of ultracold atoms or direct cooling of the molecules, is very challenging.

In our experiment we produce, cool down, and trap CaF molecules in several steps. The molecules are generated in a cryogenic buffer gas source such that they form a cold molecular beam, then decelerated to rest using frequency-chirped slowing, are finally trapped in a magneto-optical trap (MOT). To reach the lower temperatures and higher densities necessary for the phase transition to a BEC, the molecules need to be cooled further in an optical molasses and compressed using either magnetic compression or the blue-detuned MOT method [1,2]. Afterwards, the molecules will be loaded into a crossed-dipole trap for evaporative cooling until they form a BEC. Two-body losses can be controlled and suppressed by applying an electric field, which will also improve the elastic scattering rate.

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Optical Tweezer Array of Ultracold CaF Molecular Qubits for Quantum Computation and Simulations

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Ultracold polar molecules trapped in tweezer arrays are promising candidate qubits for quantum information processing and quantum simulations. The long-lived molecular rotational states form robust qubits, the long-range dipolar interaction between molecules provides quantum entanglement, and the tweezer platform provides single-site addressability. In this work, we first show dipolar spin-exchange interactions between single calcium monofluoride (CaF) molecules trapped in tweezers. This allowed us to encode an effective spin-½ system into the rotational states of the molecules and use it to generate a Bell state through an iSWAP operation, achieving a measurement error-corrected Bell state fidelity of 0.89(6). To reduce the decoherence caused by thermal motion of the molecules in the tweezer, we then successfully applied Raman sideband cooling technique to CaF molecules in the optical tweezer array, cooling the molecules to near their motional ground state, with a 3-D motional ground state probability of 54(18)%. Furthermore, we report enhancement of molecular density through the implementation of a “conveyor-belt” MOT, as well as improvement on coherence time and prospects towards using ultracold molecules for robust quantum computation and simulation applications.

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Towards Realization of a Quantum Degenerate Gas of Laser-Cooled SrF Molecules

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Ultracold quantum gases of dipolar molecules have recently emerged as a promising platform for quantum simulation, quantum chemistry, and probes of physics beyond the Standard Model. Tremendous progress has been made in direct laser cooling and trapping of dipolar molecules, putting the prospect of reaching quantum degeneracy in laser-cooled molecules within reach. We recently demonstrated optical trapping of a bulk gas of SrF molecules in the $N = 1$ state (where N denotes rotational quantum number) at sufficient density to observe inelastic collisional loss from the trap. We measured a two-body loss rate coefficient $\beta \approx 2.7 \times 10^{-10} \text{ cm}^3 \text{ s}^{-1}$, commensurate with the universal loss rate. Following up on this work, we describe our current efforts towards preparation of SrF molecules in the absolute rovibrational ground state ($N = 0$) for single quantum state collision measurements. We also discuss upgrades to our apparatus designed to help increase the phase-space density of our bulk gas, including reduced source slowing length and a fully integrated rubidium magneto-optical trap for sympathetic cooling. Finally, we describe our plan for implementing microwave shielding in order to suppress inelastic collisional loss and enhance the elastic collision rate, which is ideal for evaporative cooling to quantum degeneracy.

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