Invited talk

Dipolar interactions between ultracold RbCs molecules in magic-wavelength traps and optical tweezers

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Ultracold polar molecules are an exciting platform for quantum science and technology. The combination of rich internal structure of vibration and rotation, controllable long-range dipolar interactions and strong coupling to applied electric and microwave fields has inspired many applications. These include quantum simulation of strongly interacting many-body systems, the study of quantum magnetism, quantum metrology and molecular clocks, quantum computation, precision tests of fundamental physics and the exploration of ultracold chemistry. Many of these applications require full quantum control of both the internal and motional degrees of freedom of the molecule at the single particle level, combined with traps that support long coherence times for rotational-state superpositions.
Using ultracold RbCs molecules assembled from ultracold atoms, we demonstrate all these requirements. We present a novel magic-wavelength trap that supports second-scale rotational coherences in a gas of molecules and gives access to controllable dipole-dipole interactions[1]. We also report the efficient assembly of individual molecules in optical tweezers[2]. Using mid-sequence detection of molecule formation errors, we demonstrate rearrangement to produce small defect-free arrays. By transferring the molecules into magic-wavelength tweezers, we demonstrate long-lived rotational coherences. In the magic-wavelength tweezers we can resolve Hertz-scale dipolar interactions between pairs of molecules. We then use the dipolar interaction to engineer entanglement, both using a spin-exchange protocol and by direct microwave excitation[3]. Correcting for leakage errors, we measure an entanglement fidelity of 0.976 ± 0.015.
Finally, as an outlook, we demonstrate a new hybrid platform that combines single ultracold molecules with single Rydberg atoms[4], opening up the prospect of non-destructive readout of the molecular state and fast entangling gates.

[1] P.D. Gregory *et al.*, *Nature Physics* **20**, 415–421 (2024).
[2] D.K. Ruttley *et al.*, *PRX Quantum* **5**, 020333 (2024).
[3] D.L. Ruttley, T.R. Hepworth, A. Guttridge and S.L. Cornish, *Nature* **637**, 827–832 (2025).
[4] A. Guttridge, D.K. Ruttley *et al.*, *Phys. Rev. Lett.* **131**, 013401 (2023).