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Condensed Matter Physics and Quantum Simulations with Cold Polar Molecules and Rydberg Atoms

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Polar molecules prepared in their electronic and vibrational ground state are characterized by large dipole moments associated with rotational excitations. This gives rise to large dipole-dipole interactions between molecules, which can be manipulated with external DC and AC microwave fields. The possibility to tune these strong, long-range and anisotropic interactions, combined with the trapping in reduced dimensions, raises interesting prospects for cold ensembles of polar molecules as *strongly correlated* condensed matter system, i.e. provides *analog quantum simulation* of strongly interacting systems and quantum phases. Specific examples to be discussed include the engineering of various spin and Hubbard models for polar molecules in optical lattices, e.g. the Kitaev model and three body interactions, and the tailoring effective molecular interaction potentials based on "blue-shields" with microwave fields. Furthermore, dipolar gases in 1D and 2D trapping geometries can form self-assembled lattice structures in single layer and bilayer systems. In addition, a mixture of cold atoms and polar molecules forming a self-assembled lattice gives rise to a new realization of Hubbard models with widely tunable lattice parameters and small lattice spacing, which represents a systems with both strong correlation and phonon dynamics. Extremely strong dipolar or Van der Waals interactions can also be obtained in cold atomic gases excited to Rydberg states. We will briefly discuss new ideas of developing a *digital quantum simulator* for spin models. It is based on performing a stroboscopic sequence of many particle quantum gates based on manipulating dipolar interactions between groups of Rydberg atoms in large spacing optical lattices.