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Quantum simulation of the central spin model with a Rydberg atom and polar molecules in optical tweezers

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Central spin models, where a single spinful particle interacts with a spin environment, find wide application in quantum information technology and can be used to describe, e.g., the decoherence of a qubit over time. We propose a method of realizing an ultracold quantum simulator of a central spin model with XX (spin-exchanging) interactions. The proposed system consists of a single Rydberg atom ("central spin") and surrounding polar molecules ("bath spins"), coupled to each other via dipole-dipole interactions. By mapping internal particle states to spin states, spin-exchanging interactions can be simulated. As an example system geometry, we consider a ring-shaped arrangement of bath spins, and show how it allows to exact precise control over the interaction strengths. We numerically analyze two example dynamical scenarios which can be simulated in this setup: a decay of central spin polarization, which can represent qubit decoherence in a disordered environment, and a transfer of an "input" spin state to a specific "output" spin, which can represent the transmission of a single bit across a quantum network. We demonstrate that this setup allows to realize a central spin model with highly tunable parameters and geometry, for applications in quantum science and technology.

[1] J. Dobrzyniecki, M. Tomza, arXiv:2302.14774 (2023)

Primary authors: Dr DOBRZYNIECKI, Jacek (University of Warsaw); TOMZA, Michal (University of Warsaw)

Presenter: TOMZA, Michal (University of Warsaw)

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