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

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Abstract

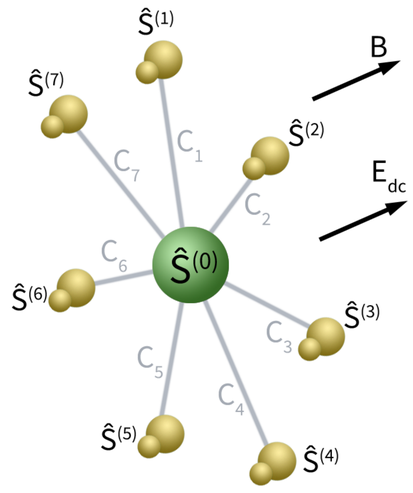
Central spin models, where a single spinful particle interacts with a spin environment, find wide application in quantum information technology and can describe e.g. the decoherence of a qubit in a disordered environment. We propose a method of realizing an ultracold quantum simulator for such a model. The proposed system consists of a single Rydberg atom ("central spin") and polar molecules ("environment spins"), coupled via dipole-dipole interactions. By mapping internal particle states to spin states, spin-exchanging interactions can be simulated. The model can be precisely controlled by directly manipulating the placement of environment spins. As an example, we consider a ring-shaped arrangement of environment spins, and show how the system's time evolution is affected by the tilt angle of the ring.

The proposed setup

The setup: Ultracold system of a Rydberg atom and N polar molecules, arranged into the desired geometry by optical tweezers. Uniform external magnetic/electric fields (B/E_{dc}) define the direction of the quantization axis

Largest length scale: ~1 μm (Tweezer spacing)

Longest time scale: ~10^{-4} s (Rydberg state lifetime)



Spin-1/2 particle simulation:

Molecules = “environmental 1/2-spins” $S^{(1)}$, $S^{(2)}$... $S^{(N)}$

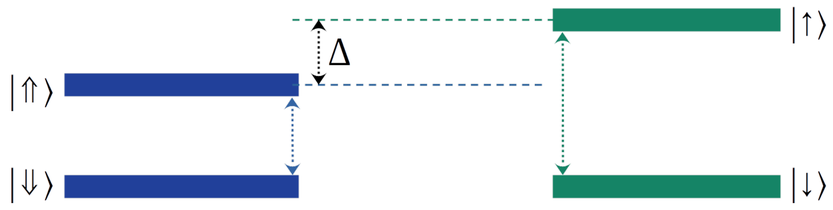
Atom = “central 1/2-spin” $S^{(0)}$

Electric dipole-dipole interactions = “spin” interactions

1/2 pseudospin states

Atom states

Molecule states



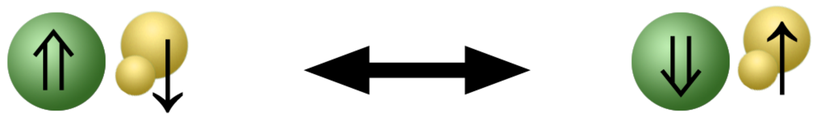
Two internal Rydberg states act as pseudospin states ⇑,⇓

⇑,⇓ can be coupled by electric dipole interaction

Two molecular rotational states act as pseudospin states ↑,↓

↑,↓ can be coupled by electric dipole interaction

The magnetic/electric field is used to tune the atomic transition ⇑ ↔ ⇓ into resonance with the molecular transition ↓ ↔ ↑ so as to minimize the mismatch Δ, allowing resonant "central/environment spin exchange" via dipolar interaction



Deriving the effective spin Hamiltonian

Atom-molecule system Hamiltonian:

$$\hat{H} = \hat{h}_{\mathrm{atom}} + \sum_{k=1}^{N} \hat{h}_{\mathrm{mol}}^{(k)} + \hat{V}_{\mathrm{atom-mol}} + \hat{V}_{\mathrm{mol-mol}}$$

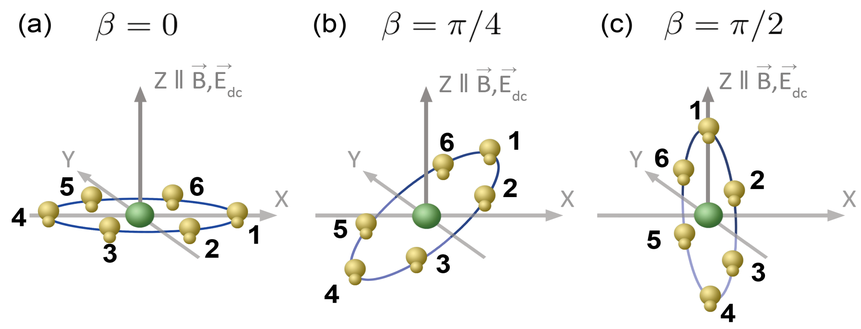
- project all Hamiltonian terms on the ⇑,⇓ / ↑,↓ state basis
- only consider energy-conserving interaction processes
- discard terms with small magnitude < [Rydberg lifetime]$^{-1}$

$$\hat{H}_{\mathrm{eff}} = c_T \hat{S}_z^{(0)} + c_S \sum_{k=1}^{N} \hat{S}_z^{(k)} + \sum_{k=1}^{N} \left[C_k \hat{S}_+^{(0)} \hat{S}_-^{(k)} + \mathrm{H.c.} \right]$$

XX central spin model / "Spin star"

Ring layout of environment spins

We consider environment spins arranged on a ring, with the central spin in the middle.



Tilt angle: Simply by changing the direction of external fields, the ring can be effectively "tilted" with respect to the quantization axis.

At β = 0, all atom-molecule coupling strengths C_k are equal.

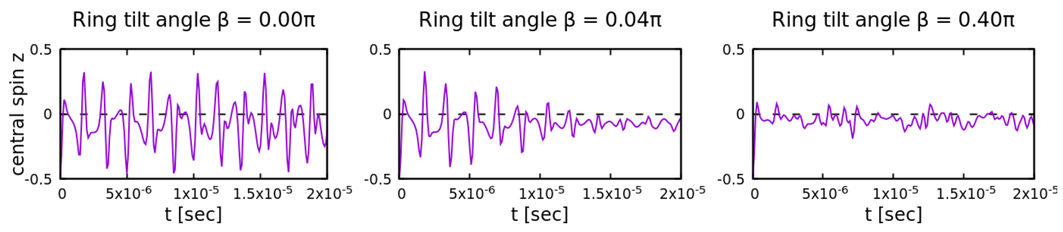
At β > 0, couplings C_k vary among different molecules k = 1...N, because of the anisotropy of dipolar interactions.

Thus, the non-uniformity of interactions can be tuned.

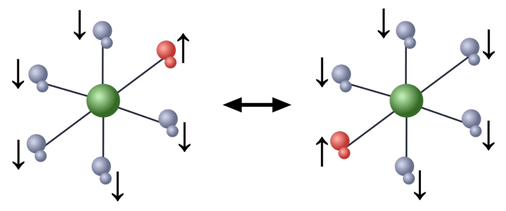
Example dynamics

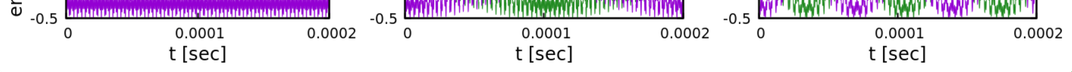
Depending on the initial state and the ring tilt angle β, different scenarios can be simulated.

- **Central spin decay.** Initial state: central spin polarized, minimal environment polarization: |⇓⟩⊗|↑↑↑↑↑↓↓↓↓↓↓⟩. As the system evolves, the central spin $S^{(0)}_Z$ decays to zero; the time scale of this decay depends on β. *(Analogous to a qubit undergoing decoherence in a disordered environment.)*



- **State transfer.** Initial state: |⇑⟩⊗|↑↓↓↓↓↓⟩. During the time evolution, environment spin 1 (initially ↑) exchanges its state with the oppositely-placed spin 4. *(Analogous to quantum state transfer in quantum networks.)*





Summary

- We propose a quantum simulator for a central spin model, built of ultracold atoms and molecules.
- If environment spins are arranged into a ring shape, the non-uniformity of central-environment couplings can be easily tuned.
- This setup can simulate various experimentally significant phenomena.

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