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

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Abstract

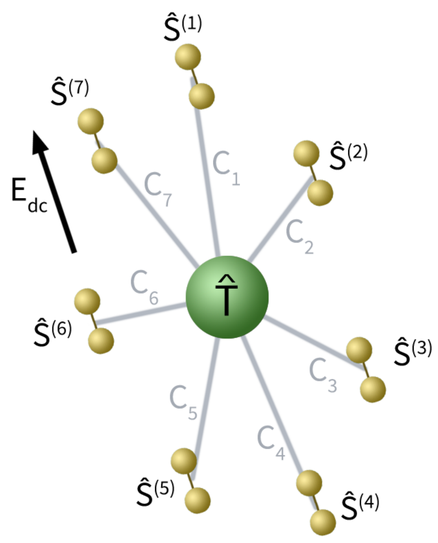
Central spin models, where a single spinful particle interacts with a spin environment, find wide application in quantum information technology and can be used to model e.g. the decoherence of a qubit in a disordered environment. We propose a method of realizing an ultracold quantum simulator for the central spin 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. Precise control over the model can be exerted 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

An uniform external field E_{dc} defines the direction of permanent dipole moments

Largest length scale: ~1 μm (Tweezer spacing)
Longest time scale: ~10^{-5} s (Rydberg state lifetime)



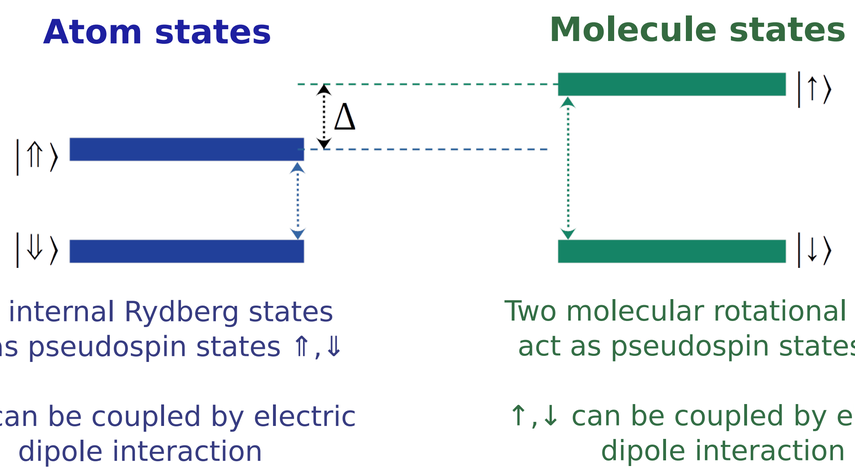
Spin-1/2 particle simulation:

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

Atom = “central 1/2-spin” **T**

Electric dipole-dipole interactions = “spin” interactions

1/2 pseudospin 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

Electric field E_{dC} 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:

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

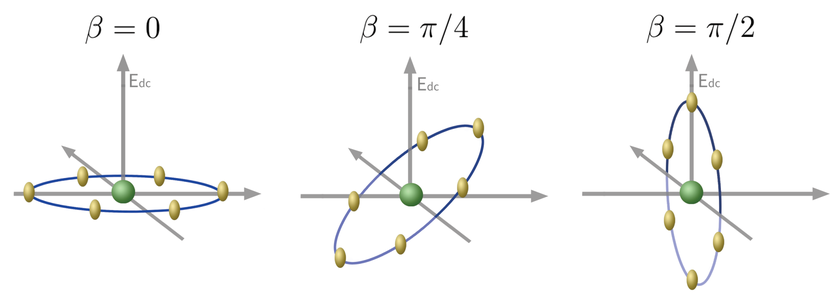
- project all Hamiltonian terms on the ⇑,⇓ / ↑,↓ state basis
- only consider energy-conserving interaction processes
- discard terms with small magnitude < [Rydberg lifetime]$^{-1}$

$$\hat{H}_{\mathrm{eff}} = \Delta \hat{T}_z + \sum_{j=1}^{N} C_j \left[\hat{T}_+ \hat{S}_-^{(j)} + \hat{T}_- \hat{S}_+^{(j)} \right]$$

XX central spin model / "Spin star"

Ring layout of environment spins

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



Tilt angle: Simply by changing the direction of E_{dc}, the ring can be effectively "tilted" with respect to the direction of the particles' dipole moments.

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

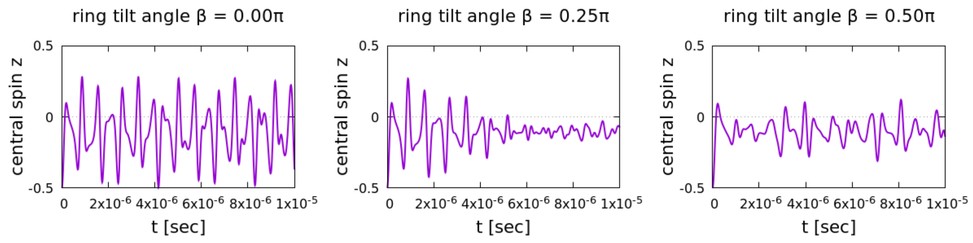
At β > 0, anisotropy of dipolar interactions makes C_j different for various molecules j = 1...N.

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

Example dynamics

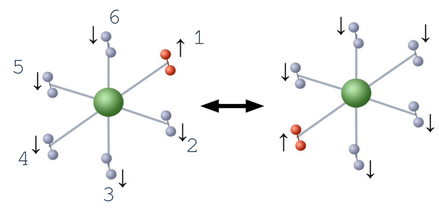
Depending on the initial state and the ring tilt angle β, different dynamical processes can be realized.

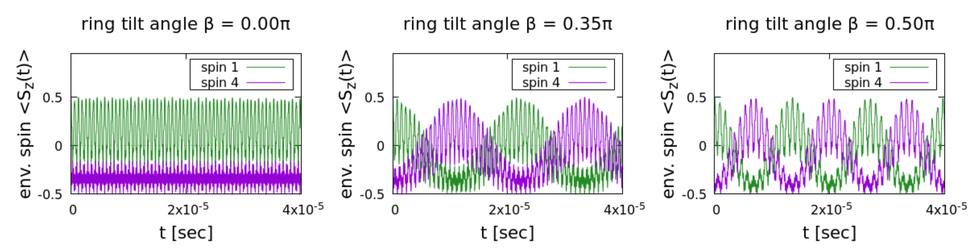
- **Central spin decay:** For an initial state with small bath polarization $|\Downarrow\rangle\otimes|\uparrow\uparrow\uparrow\uparrow\downarrow\downarrow\downarrow\downarrow\rangle$, central spin T_Z decays to zero with time; the effectiveness of this decay depends on β. *(Analogue of qubit decoherence in various environments.)*



- **Quantum state transfer:**

Initial state: $|\Uparrow\rangle\otimes|\uparrow\downarrow\downarrow\downarrow\downarrow\downarrow\rangle$.
During the time evolution, environment spin 1 (initially ↑) exchanges its state with the oppositely-placed spin 4.
(Analogue of state transfer in quantum networks.)





Summary

- We propose an ultra-cold atom/molecule quantum simulator for a central spin model.
- 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.