Many-Body Physics from Spin-Phonon Coupling in Rydberg Atom Arrays

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Setup

Spin-phonon coupling: Spin interaction could be affected by the oscillation of the atoms.
(Phonons are excited)

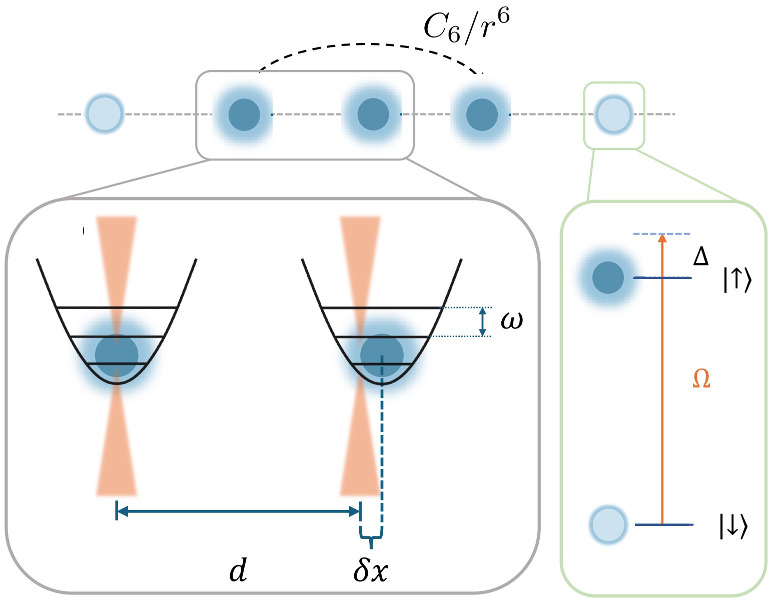


Fig. 1. Schematic of the model

The total Hamiltonian of in the optical tweezer is given by

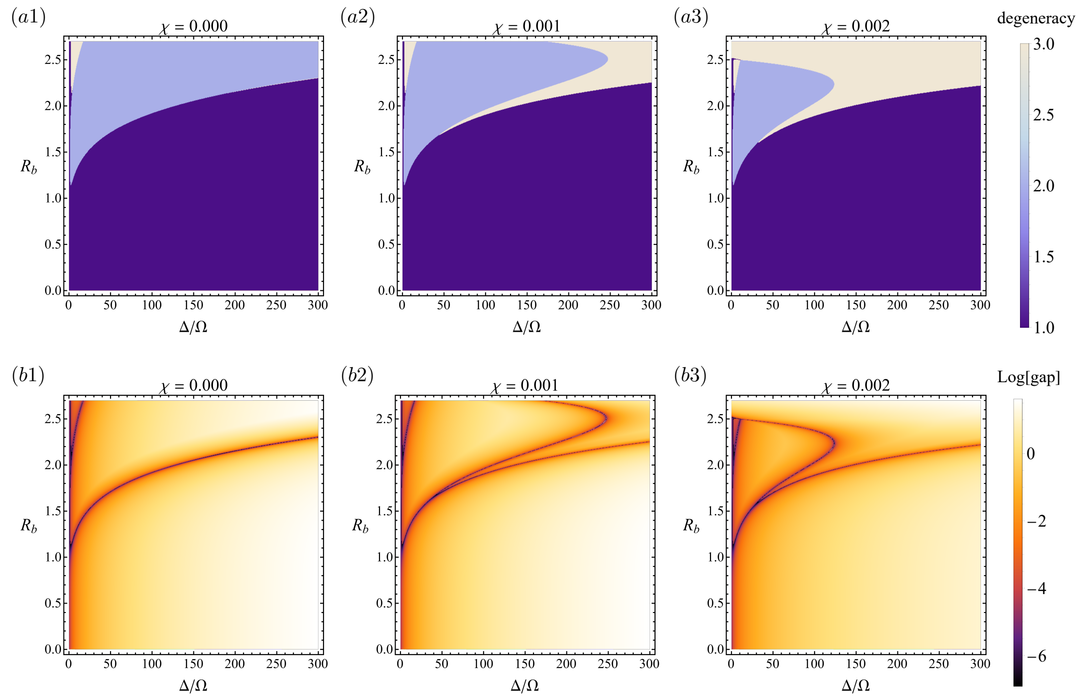
$$\hat{H} = \sum_{j=1}^{N}\left(\frac{\Omega}{2}\hat{\sigma}_j^x - \Delta\hat{n}_j + \frac{\hat{\mathbf{p}}_j^2}{2m} + \frac{1}{2}m\omega^2\delta\hat{\mathbf{r}}_j^2\right) + \sum_{i<j}\frac{C_6}{|\hat{\mathbf{r}}_i - \hat{\mathbf{r}}_j|^6}\hat{n}_i\hat{n}_j.$$

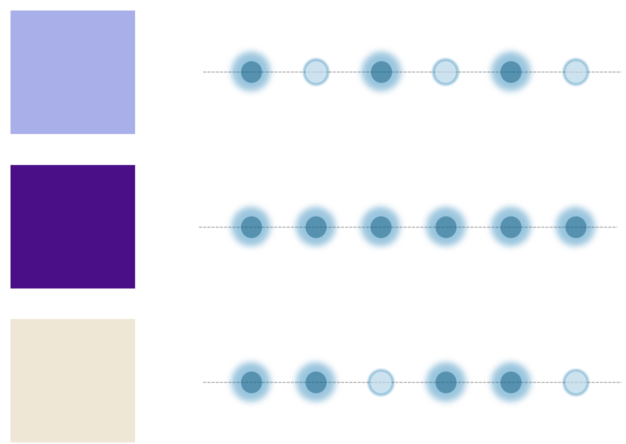
After some approximations, the effective Hamiltonian turns to be

$$\hat{H} = \sum_{j=1}^{N}\left(\frac{\Omega}{2}\hat{\sigma}_j^x - \Delta\hat{n}_j\right) + \sum_{i<j}\frac{\Omega R_b^6}{(j-i)^6}\hat{n}_i\hat{n}_j - \sum_{j=1}^{N}\chi\Omega R_b^{12}\hat{n}_j(\hat{n}_{j-1} - \hat{n}_{j+1})^2.$$

Here χ represents the strength of the spin-phonon coupling.

Equilibrium Phases





The effective Hamiltonian tells us a new $\mathbb{Z}_3$ phase emerges when the coupling grows.

Fig. 2. Equilibrium phase represented by degeneracy and energy gap at different χ

Non-equilibrium Dynamics

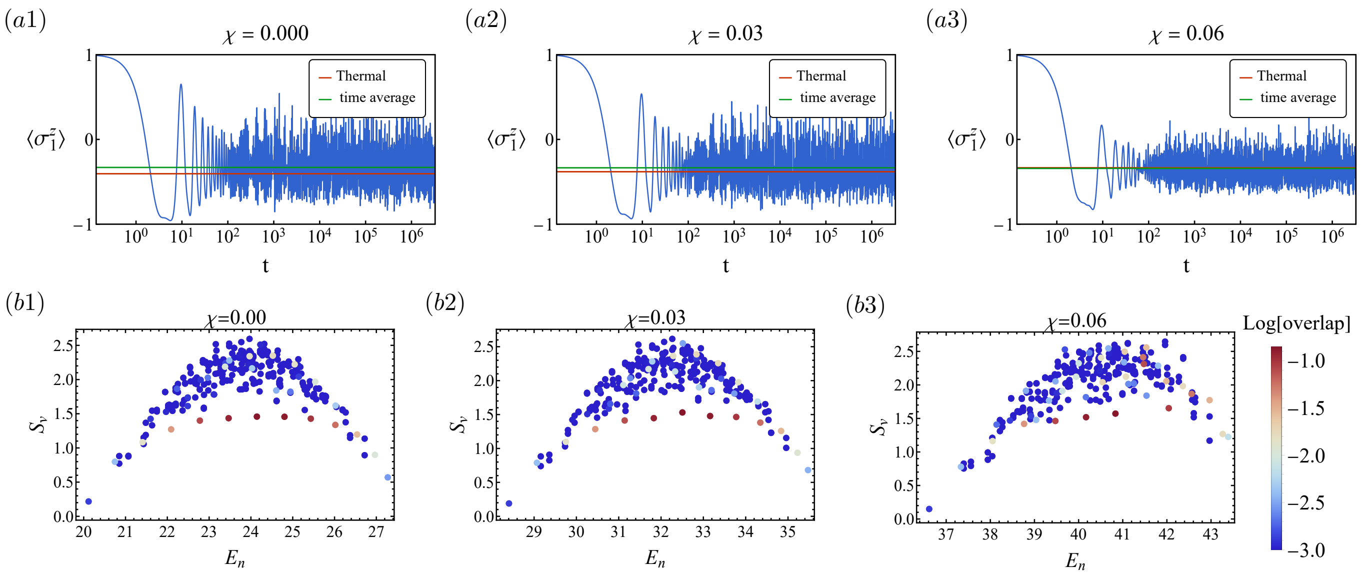


Fig. 3. Phonons suppress the violation of quantum thermalization

$$\bar{\sigma}_i^z = \lim_{T\to\infty}\lim_{t_0\to\infty}\frac{1}{T}\int_{t_0}^{t_0+T}\langle\Psi(t)|\hat{\sigma}_i^z|\Psi(t)\rangle dt$$

$$\sigma_{\text{th}}^z = \text{Tr}(\rho_{\text{th}}\hat{\sigma}_i^z)$$

Thermal and time average lines collapse at χ = 0.06

$$S_v = -\text{Tr}_v(\rho_v \ln \rho_v)$$

$$\rho_v = \text{Tr}_{\bar{v}}|E_n\rangle\langle E_n|$$

The $\mathbb{Z}_2$ state begins to have greater overlap with eigenstates that possess higher entanglement.

Reference

Zhang S, Chen L, Zhang P. Physical Review A, 2025, 112(6): 063316.

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