Quantum simulations for dipolar spin systems in optical lattices

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Dipole-dipole interactions

$$V_{dd} = \frac{\mu_0}{4\pi} S^2 \left( g_J \mu_B \right)^2 \left( 1 - 3 \cos^2(\theta) \right) \frac{1}{R^3}$$

Ising Exchange

$$\hat{H}_d \propto S_{1z}S_{2z} - \frac{1}{4} \left( S_{1+}S_{2-} + S_{1-}S_{2+} \right)$$

Chromium atom: a dipolar species

Quantum Magnetism in 3D lattices: preparation

- Long range Anisotropic

- Rectangular lattice of anisotropic sites

- Deep 3D lattice $\rightarrow$ strong correlations, Mott transition

- Shallow 3D lattice $\rightarrow$ superfluid state

- Competition between dipolar interactions, tunneling and tunneling assisted superexchange

In lattice with one atom per site spin dynamics is purely dipolar

dipolar atomic systems: Stuttgart (Dy), Innsbruck (Er), Stanford (Dy), Paris (Dy), Harvard (Er),…
Out of equilibrium spin dynamics

Towards (?) adiabatic production of the ground state of a transverse Hamiltonian
Out of equilibrium dynamics: Principle of the experiments

1- Excite the spins

\[ \Psi_{initial} = |-3z, -3z, \ldots, -3z, -3z\rangle \]

2- Free evolution under the effect of interactions

\[ \Psi_{(t=0)} = |-3\theta, -3\theta, \ldots, -3\theta, -3\theta\rangle \]

3- Measurement of Spin populations

Stern-Gerlach separation:
(magnetic field gradient)

Out of equilibrium dynamics characterized by the change of the populations of the Zeeman components
Spin dynamics in lattice: comparison with simulations

10000 atoms!

NO exact simulation available beyond 15 atoms: problem with border effects!

Mean field simulations

Quantum simulations (Generalized Dichotomized Truncated Wigner Approximation) developed by J. Schachenmayer

Short time exact results:

\[ \hat{H} = \sum_{i>j}^{N} V_{ij} \left[ \hat{S}_i^z \hat{S}_j^z - \frac{1}{2} \left( \hat{S}_i^x \hat{S}_j^x + \hat{S}_i^y \hat{S}_j^y \right) \right] \]

\[ p_{m_S}(t) = p_{m_S}(0) + \sin[\theta]^4 \alpha_{m_S}(\theta) t^2 V_{\text{eff}} \]

\[ V_{\text{eff}} \equiv \sqrt{\sum_{i,j \neq i}^{N} V_{ij}^2 / N} \]
Spin dynamics in lattice: comparison with simulations

Quantum simulations (GDTWA)

The quantum simulations agree well with data: a very good test for GDTWA for large atom numbers

Spin dynamics in lattice as a function of lattice depth

The Gutzwiller method aims to describe bosons in an optical lattice. Our work is the first to consider the extension of this method to describe spin-3 bosons with dipole-dipole interactions. It treats onsite terms exactly and inter-site couplings (due to tunneling and interactions) at the meanfield level.

Spin dynamics in lattice: Quantum Thermalization

1- Our data show that spin dynamics stops in about 60-80 ms in agreement with quantum simulations (solid lines) while mean field simulations show revivals at this time scale (dashed lines)

2- Asymptotic experimental populations are close to population distributions maximizing entropy at fixed magnetization

3- A more elaborated model includes the one body physics quadratic energy term

\[ E(m_s) = B Q m_s^2 \]

\[ \dot{\rho} = \exp[-\beta \hat{H}] \approx \text{Id} - \beta \hat{H} \]

\[ P_{m_s} = \frac{1}{7} \left( 1 + \beta B Q (4 - m_s^2) \right) \]

A long-range interacting many particle isolated system which internally thermalizes through entanglement build-up, and develops an effective thermal-like behavior through a mechanism which is purely quantum and conservative

Other experiments:
- Greiner: few ½ spins, superexchange processes
- B. Lev: Dy atoms, thermalization through collisions

Adiabatic production of the ground state of an Hamiltonian: principle

\[ \hat{H}_{XXZ} = \sum_{i<j}^{N} J_{i,j} \left( \Delta \hat{S}^z_i \hat{S}^z_j + (\hat{S}^x_i \hat{S}^x_j + \hat{S}^y_i \hat{S}^y_j) \right) + \mu B_z \sum_{i=1}^{N} \hat{S}^z_i + \mu B_x \sum_{i=1}^{N} \hat{S}^x_i \]

longitudinal transverse

\[ \hat{H}_{\text{tot}} = \sum_{i>j}^{N} V_{i,j} \left( \hat{S}^z_i \hat{S}^z_j - 2 \left( \hat{S}^x_i \hat{S}^x_j + \hat{S}^y_i \hat{S}^y_j \right) \right) + \hbar \delta \sum_{i=1}^{N} \hat{S}^z_i + \hbar \Omega_{RF} \sum_{i=1}^{N} \hat{S}^x_i \]

Theoretical model

Experimental realization

\[ \Omega_{RF} = \text{RF Rabi frequency} \]

\[ \hat{H}_{dd} = \text{Dipolar Hamiltonian} \]

\[ \delta = \omega_{\text{Larmor}} - \omega_{RF} \]

Ferromagnetic Ground state:
All spins aligned along Ox=RF field

Principle of the experiment:
Perform an adiabatic passage with an easy knob (RF amplitude) from a polarized state to a non trivial ground state of the dipolar Hamiltonian
Adiabatic production of the ground state of an Hamiltonian: results (preliminary!)

Theoretical prediction (Tommaso Roscilde)
mean field calculations

Magnetization
(set by $\delta$)

Order parameter

$\Omega/J_0 \quad J_0 = V_{i,i+1}$

$\Omega_{2pr}$: RF Rabi frequency

Experimental measurements

"distance" to a ferromagnetic state
thank you for your attention! We are looking for a post doc!