Photonic Quantum Simulation of Frustrated Spin Systems

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Over the few years the degree of control over photonic single- and two-qubit operations has improved substantially, which recently enables the simulation of a Heisenberg-interacting spin-1/2 tetramer.

The precise single-particle addressability [1] and tunable measurement-induced interactions allow entangled photonic systems for the simulation of four spin-1/2 particles interacting via any Heisenberg-type Hamiltonian. Recently we realized an analog quantum simulation of arbitrary Heisenberg-type interactions among four spin-1/2 particles [2]. This spin-1/2 tetramer is the two-dimensional archetype system and its ground state belongs to the class of so-called valence-bond states. These states are of interest because it was conjectured that a transition from an localized valence-bond configuration to the superposition of different valence-bond states might explain high-temperature superconductivity in cuprates. Here we model our spin tetramer with nearest-neighbor interactions of the strength \( J_1 \) and \( J_2 \) by the Hamiltonian

\[
H = J_1 \vec{S}_1 \cdot \vec{S}_3 + J_1 \vec{S}_2 \cdot \vec{S}_4 + J_2 \vec{S}_1 \cdot \vec{S}_2 + J_2 \vec{S}_3 \cdot \vec{S}_4,
\]

where \( \vec{S}_i \) is the Pauli spin operator for spin \( i \). All the properties of the system depend only on the coupling ratio \( \kappa = J_2/J_1 \). In our quantum simulation, we use the polarization states of four photons to simulate the spin of this tetramer, where the singlet state is analogous to the anti-ferromagnetic coupling of two spin-1/2 particles. The initial ground state, \( |\Phi_\text{g}\rangle \), is prepared by generating the photon-pairs 1 & 2 and 3 & 4 in two singlet states. Then the analog quantum simulation is performed utilizing the measurement-induced interaction, consisting of quantum interference and the detection of a four-photon coincidence after superimposing photons 1 & 3 on a tunable directional coupler (TDC). We map the parameter \( \kappa \) to the splitting ratio of the tunable directional coupler: reflection rate \( R \)/ transmission rate \( T \) = \( \kappa + \sqrt{\kappa^2 - \kappa + 1} \). The particular advantages of the precise single-particle addressability and a tunable measurement-induced interaction allow us to obtain not only various valence-bond states, but also fundamental insights into entanglement dynamics among individual particles. The figure shows a schematic drawing of the experimental setup and the various valence-bond states created via changing the effective coupling among the spins.

![Schematic drawing of the experimental setup](image_url)

**FIG. 1:** A schematic drawing of the experimental setup (A). Two parametric down-conversion crystals (PDC) are pumped to emit two pairs of photons that are superimposed at a tunable directional coupler (TDC). Dependent of the TDC’s splitting ratio various spin-configurations can be simulated (B,C).