Experimental optical quantum simulation of a spin ring under a magnetic field

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The link between entanglement and critical phenomena such as quantum phase transitions is an open problem that has been studied theoretically for several years. One simple but nonetheless very rich example to try and understand this link is the case of a circular chain of spins submitted to a transverse magnetic field (see e.g. [1] and [2]). Here we report on the experimental characterisation of the ground state of such a system, by means of a photonic quantum simulation set-up.

The system considered here is a ring of $N = 3$ spins that is described by the following isotropic 1D-Ising hamiltonian: $\mathcal{H} = J\left(-\sum_{n=1}^{N}\sigma_n^x \otimes \sigma_{n+1}^x + \beta\sum_{n=1}^{N}\sigma_n^z\right)$, where σ_n^i, $i = x, z$ are the well-known Pauli matrices acting on the n^{th} spin, J represents the coupling between the individual spins and $\beta = B/J$ denotes the relative strength of a transverse magnetic field B applied to the ring. For $\beta \leq 0$, the ground state of the three-spin ring is given by: $|g(\beta)\rangle = \frac{1}{\sqrt{a_0^2+3}}[a_0|000\rangle + |011\rangle + |101\rangle + |110\rangle]$, with $a_0 = -1 - 2\beta + 2\sqrt{1+\beta+\beta^2}$.
It has been shown theoretically [2] that $|g(\beta)\rangle$ is a Greenberger-Horne-Zeilinger (GHZ) state for $\beta = 0$: $|g(0)\rangle = [|+++\rangle + |---\rangle]/2$ (with $|+\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$ and $|-\rangle = (|0\rangle - |1\rangle)/\sqrt{2}$), therefore exibiting maximal genuine three-partite entanglement [3]. When increasing $|\beta|$, however, this three-partite entanglement diminishes rapidly untill $|\beta| \simeq 1$, which is a critical point, and is then completely lost for $|\beta| \to \infty$. In contrast, the two-partite entanglement between two spins in the ring is non-existent both for $\beta = 0$ and $|\beta| \to \infty$ but reaches a non-zero value around the critical point $|\beta| = 1$.

We experimentally simulated the ground state $|g(\beta)\rangle$ using a three-qubit hyperentangled two-photon state in a doubly displaced Sagnac interferometer, allowing us to introduce a variable attenuation on $|000\rangle$ with respect to $|011\rangle + |101\rangle + |110\rangle$ in order to mimic the effect of β. For different values of $\beta \in [-2\,;0]$, we measured both the three-partite and the two-partite entanglement in the state, by means of 2-qubit and 3-qubit entanglement witnesses [4] and the 3-qubit Svetlichny inequality [5].

Our experimental results, in very good agreement with the theoretical predictions, lead us to two major conclusions: firstly that there is indeed a strong link between the presence of the critical point and the evolution of the ground state entanglement in its vicinity; and more generally that quantum photonics does have a huge potential for simulating other, less easily-controllable, quantum systems [6] and is therefore a good candidate for future quantum simulators.

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