Creating entanglement in an ensemble of 40 atoms using quantum feedback and quantum Zeno dynamics in a fiber cavity

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Multiparticle entanglement enables quantum simulations, quantum computing and quantum-enhanced metrology. Yet, there are few methods to produce and measure such entanglement while maintaining single-qubit resolution as the number of qubits is scaled up. Using atom chips and fiber-optical cavities, we have developed two methods to create symmetric entangled states and perform their tomography in ensembles of several tens of atoms.

The first one is based on non-destructive collective measurement and conditional evolution [1]. Applying this method we create entangled states with mean atom numbers up to 41. In order to fully characterize the produced state, we have developed a tomography technique which measures the Husimi-Q distribution of the total spin. We are able to demonstrate that the created entangled states are a good approximation of the W state

$$|W\rangle = 1/\sqrt{N}(|10\ldots0\rangle + |010\ldots0\rangle + \ldots + |00\ldots1\rangle). \quad (1)$$

Additionally we have devised a criteria for entanglement in the vicinity of the W state based on the sole comparison of the populations of $|W\rangle$ and of the classical state $|0\rangle = |0\ldots0\rangle$. By means of this criterion we could prove that our sample contains at least 13 entangled atoms.

The second method used is based on Quantum Zeno Dynamics (QZD), which has been theoretically studied for more than a decade [2] and experimentally implemented for single-particle dynamics very recently [3, 4]. QZD combines a unitary evolution U with a measurement that projects into a multidimensional subspace of the Hilbert space, applied simultaneously. The measurement effectively restricts the coherent evolution to that subspace. This results in quantum states that would be inaccessible to U alone, and which are potentially interesting for quantum engineering. We experimentally demonstrate the use of QZD, with our high-finesse optical cavity, to deterministically generate different multi-particle entangled states in an ensemble of 36 qubit atoms in less than 5 μs [5]. Our cavity measurement distinguishes the state $|0\rangle$, for which the cavity transmits, from the subspace Z of all other states, for which it reflects. If the state starts in Z and the cavity measurement is performed continuously, transition to the $|0\rangle$ state is inhibited. When the state is forced along a trajectory that would pass through $|0\rangle$, it "flows around" the subspace forbidden by the measurement. We can observe this behaviour by performing quantum state tomography at different times. Stopping the evolution when the state completely encircles $|0\rangle$ yields a multiparticle entangled state close to the W state. We compare it to the separable state that is observed without the simultaneous measurement, and quantify its depth of entanglement by means of the aforementioned criterion. Additionally, driving the state on a trajectory that only tangentially touches the forbidden subspace, we produce entangled "compressed" states. In this case we demonstrate the entanglement generation by computing the corresponding Fisher information, which exceeds the classical limit. We also measure the properties of the entangled state as a function of the strength of the measurement.

Our results show that QZD can be used as a versatile tool for fast and deterministic entanglement generation. Both our methods are independent of atom number and should allow generalization to other entangled states and other physical implementations including circuit quantum electrodynamics.

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