

Multidimensional entanglement and EPR-steering with atomic quantum memory

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Entanglement is not only a central concept of the quantum theory, but also an essential resource in a variety of quantum-enhanced protocols, such as secure key distribution. Particularly interesting is the broad concept of high-dimensional (HD) entangled states, for which the dimension of Hilbert space required to describe the observed correlations reaches thousands. These states offer an unprecedented informational capacity that can be readily utilized in quantum key distribution (QKD). On the other hand, their generation and characterization requires a tremendous effort as the number of settings of a hypothetical projective measurement grows exponentially with state dimension. This highlights the need for other characterization techniques, e.g. based on compressive sensing or witnesses.

For bipartite HD entangled states the uncertainty relations have proven to be a viable way of detecting entanglement. In particular, the entropic steering inequalities are able to detect EPR-steering [1] – a special case of entanglement related to the famous Einstein-Podolsky-Rosen (EPR) paradox. The generated state is EPR-steerable if the entropic witness [2, 3]

$$\Sigma_h = h(x^B | x^A) + h(k_x^B | k_x^A) \quad (1)$$

is lower than $\log(\pi e)$, where $h(x^B | x^A)$ and $h(k_x^B | k_x^A)$ are conditional Shannon entropies for measurement in two conjugate, e.g. position and momentum bases. Another commonly used witness is the product of variances [4]

$$\Pi_{\Delta^2} = \langle \Delta^2(x^B | x^A) \rangle \times \langle \Delta^2(k_x^B | k_x^A) \rangle, \quad (2)$$

which certifies EPR-steering if $\Pi_{\Delta^2} < 1/4$. This witness is well-suited to Gaussian states as any EPR-steerable Gaussian state is properly characterized by the variance-based witness. Although, for a broad range of EPR-steerable states Σ_h confirms the EPR-steering while Π_{Δ^2} might not [2].

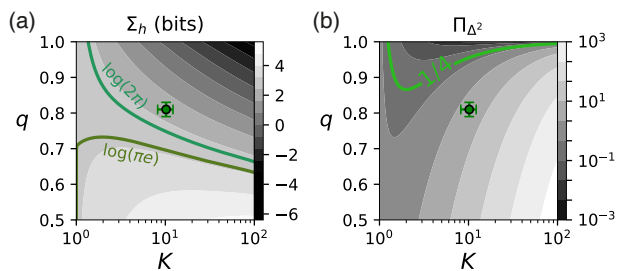


Figure 1: Entropic (a) and variance-based (b) witnesses as a function of Schmidt number K and correlated coincidence fraction q . Contour bounds correspond to EPR-steering $[\log(\pi e)]$ for Σ_h and $1/4$ for Π_{Δ^2} and the demonstration of EOF > 0 $[\log(2\pi)]$. The dot demonstrates our experimental result – only the entropic witness certifies EPR-steering.

Here we experimentally demonstrate [5] generation and characterization of an HD entangled and EPR-steerable state of a single photon and a collective atomic excitation stored in a cold rubidium ensemble quantum memory, retrievable on demand as another single photon. The HD character relies on a wide space of angular emission modes [6] and the conjugate position-space of the atomic ensemble. The HD EPR-steering is demonstrated for the first time using a single-photon resolving camera without accidentals subtraction, which offers parallel access to all coincidences and is thus necessary to truly utilize the high informational capacity of the generated state. Furthermore, we show that for the emerging domain of HD entanglement the entropic witness vastly outperforms the variance-based witness. We highlighted and solved the difficulties in entropy estimation, achieving characterization of the HD entangled state with highly undersampled data. Finally, we estimate the entanglement of formation (EOF) [7] of the generated state.

The integration of the quantum memory presented here with a practical QKD scheme provides an instantaneous advantage as Bob could perform measurements after Alice announces her basis thus effectively doubling the key rate generation. A quantum memory also opens new avenues to fundamental studies of one-particle uncertainty principles [8].

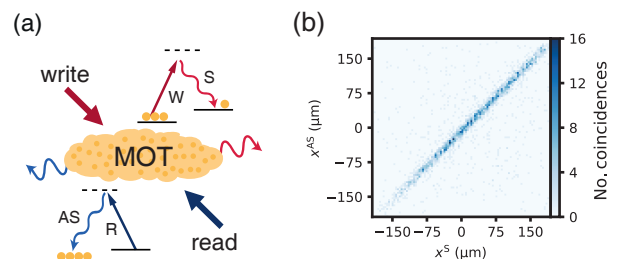


Figure 2: (a) Experimental setup: strong write (W) laser produces Stokes (S) photon as a result of Raman scattering in cold ^{87}Rb ensemble (MOT). After storage anti-Stokes (AS) photon is scattered during readout (R). (b) Example of measured coincidences for position basis in the x -dimension.

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