Prolonging the lifetime of collective Rydberg excitations with use of spatial AC Stark shift

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Collective Rydberg excitations provide a promising platform for quantum information processing, simulation, and precision electrometry, but they are strongly limited by rapid thermal dephasing. At typical temperatures of $\sim 100\,\mu\mathrm{K}$, coherence times remain below $1\,\mu\mathrm{s}$. The existing lifetime-extension techniques are largely restricted to ground-state memories.

Here we demonstrate an alternate method utilizing spatial AC-Stark phase modulation that suppresses motional dephasing by effectively freezing atomic coherence. The scheme uses two off-resonant laser beams to imprint a spatial phase pattern, resulting in a more than tenfold increase in spin-wave lifetime. Numerical simulations incorporating finite pulse duration, residual misalignment, and atomic motion are in good agreement with the experimental results.

We observe a lifetime of $\tau_{\mathrm{mod}} = 27(1)\,\mu\mathrm{s}$, approaching the intrinsic Rydberg state limit. The modulation efficiency reaches $\eta_{\mathrm{acS}} = 71\%$, limited primarily by intensity fluctuations. This extension enables significantly longer interaction times, opening new possibilities for long-lived collective qubits, quantum simulation, light-matter interfaces, and ultra-sensitive electrometry. Further improvements, including stronger modulation, state-selective schemes, and cryogenic operation, could enhance efficiency and suppress residual decoherence.

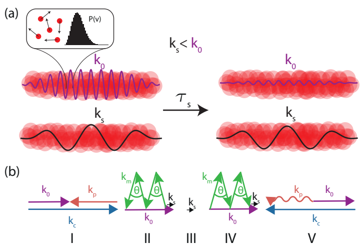

FIG. 1. (a) Thermal blurring of spin-waves; larger wavevectors dephase faster. (b) Geometry of the lifetime-extension protocol.

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