Observation of microscopic confinement dynamics by a tunable topological θ-angle

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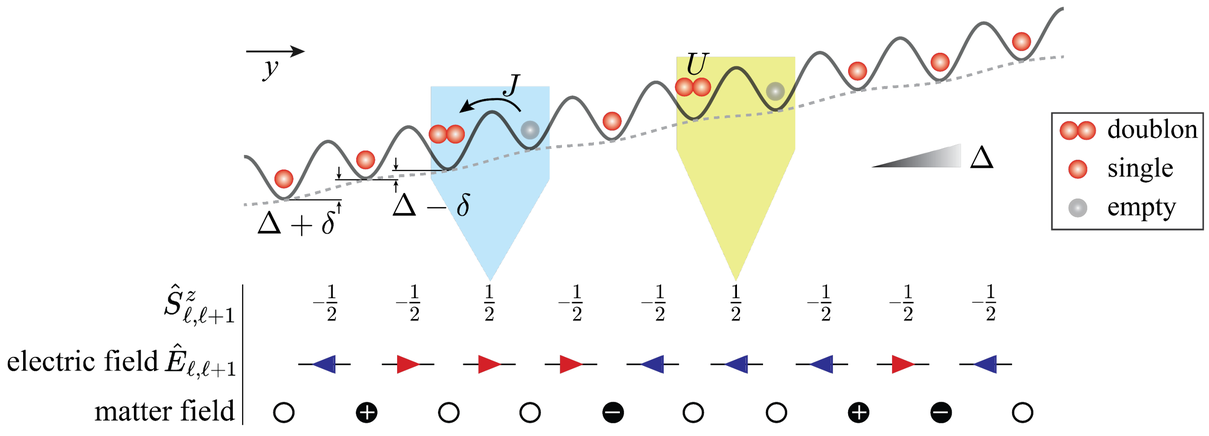
Introduction

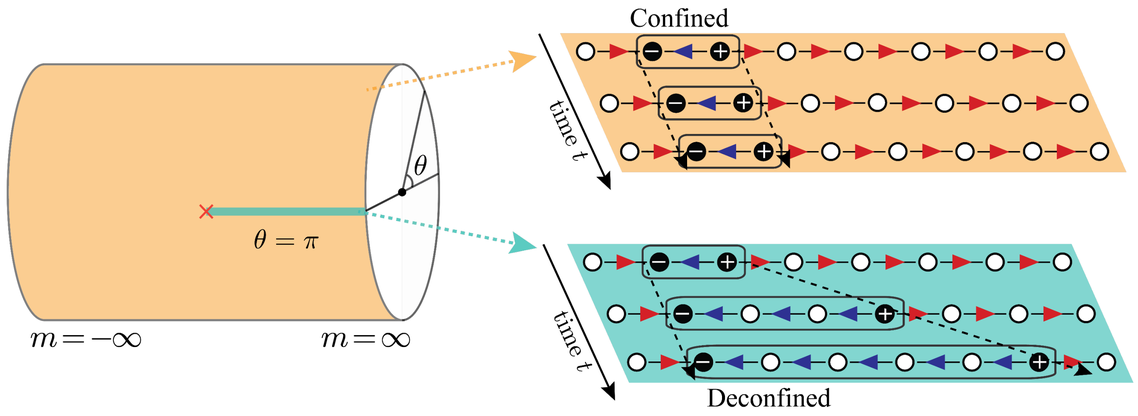
The topological θ-angle is crucial in understanding diverse phenomena in gauge theories which can induce a transition between confined and deconfined phases in 1 + 1D quantum electrodynamics. We present the experimental realization of a tunable topological θ-angle in a Bose-Hubbard gauge-theory quantum simulator, achieved through a tilted superlattice potential that induces an effective background electric field. We demonstrate the rich physics due to this angle by directly observing the confinement-deconfinement transition of (1 + 1)D quantum electrodynamics.

Target Model

- Experimental implementation



- Phase diagram



- Hamiltonian

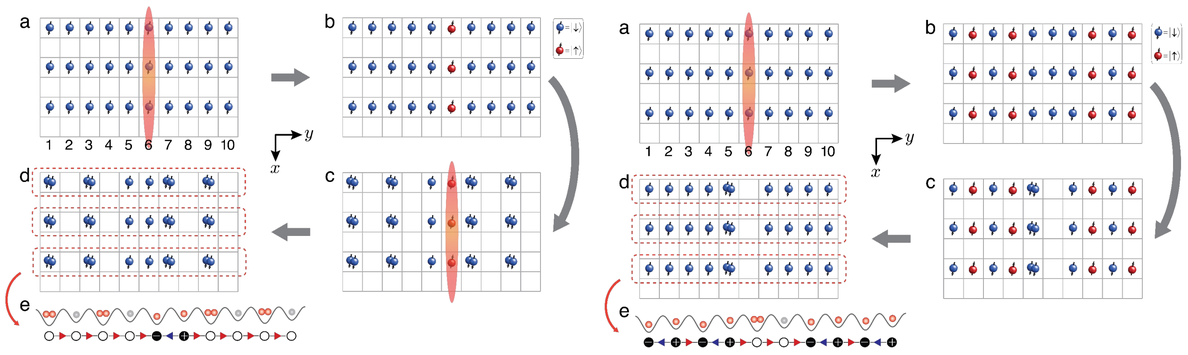
$$\hat{H}_{\mathrm{QLM}} = -\kappa \sum_{\ell=1}^{L-1} \left(\hat{\psi}_\ell \hat{S}^+_{\ell,\ell+1} \hat{\psi}_{\ell+1} + \mathrm{H.c.} \right) + m \sum_{\ell=1}^{L} \hat{\psi}^\dagger_\ell \hat{\psi}_\ell + \boldsymbol{\chi(\theta)} \sum_{\boldsymbol{\ell=1}}^{\boldsymbol{L-1}} (-1)^{\ell+1} \hat{\boldsymbol{S}}^{\boldsymbol{z}}_{\boldsymbol{\ell},\boldsymbol{\ell+1}}$$

$$\hat{H}_{\mathrm{PXP}} = \sum_{\ell} \left[-\kappa \hat{P}_{\ell-1,\ell} \hat{S}^x_{\ell,\ell+1} \hat{P}_{\ell+1,\ell+2} - 2m \hat{S}^z_{\ell,\ell+1} \right]$$

$$\hat{H}_{\mathrm{BHM}} = -J \sum_{\ell=1}^{L-1} \left(\hat{b}^\dagger_\ell \hat{b}_{\ell+1} + \mathrm{H.c.} \right) + \sum_{\ell=1}^{L} \left[\frac{U}{2} \hat{n}_\ell (\hat{n}_\ell - 1) + \ell \Delta \hat{n}_\ell \right] + \sum_{\boldsymbol{\ell=1}}^{\boldsymbol{L}} (-1)^{\boldsymbol{\ell}} \frac{\boldsymbol{\delta}}{\boldsymbol{2}} \hat{\boldsymbol{n}}_{\boldsymbol{\ell}}$$

Initial state preparation

- Positive mass region
- Negative mass region

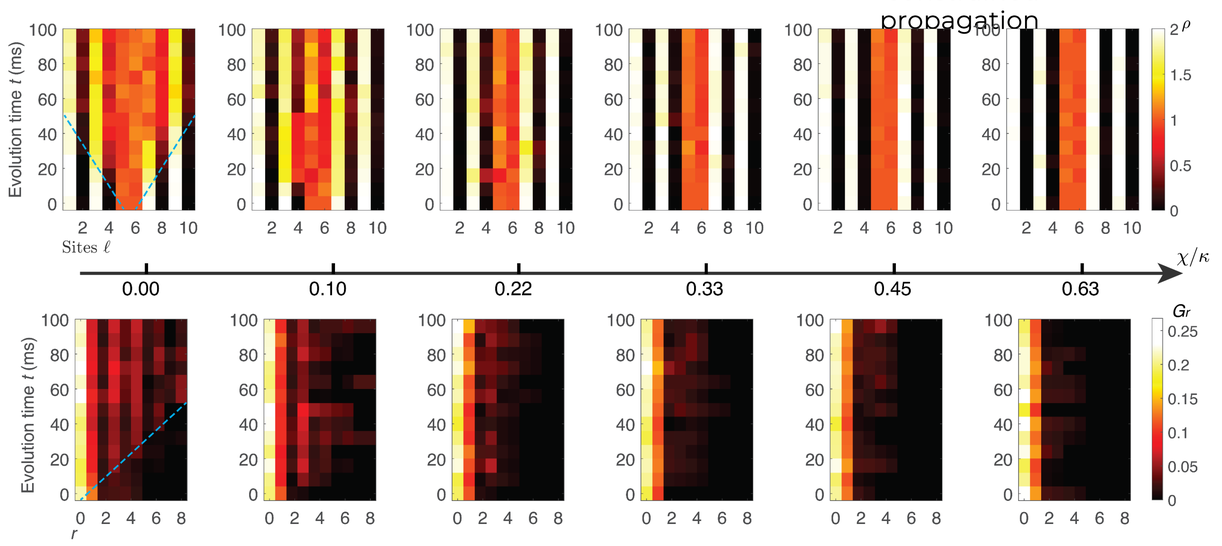


Confinement through tuning topological θ-angle

- Evolution of densities and two-point correlations

two-point charge correlation

$$G_r(t) = \sum_{\ell} \left\langle \left[\hat{Q}_\ell(t) - \bar{Q}^{\mathrm{gs}}_\ell \right] \left[\hat{Q}_{\ell+r}(t) - \bar{Q}^{\mathrm{gs}}_{\ell+r} \right] \right\rangle$$



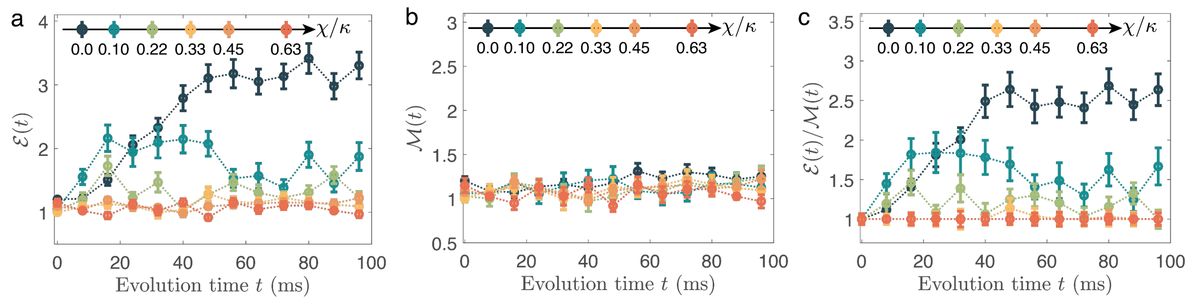
Microscopic dynamics of the particle–antiparticle pair

the length of the electric string between the particle and antiparticle

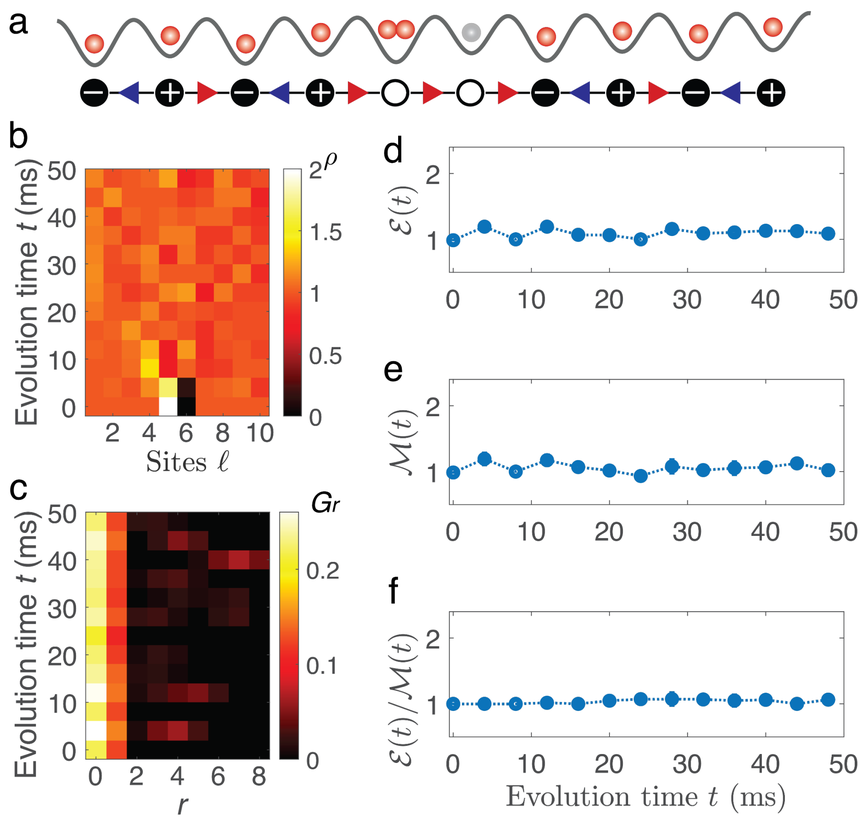
$$\mathcal{E}(t) = \sum_{\ell=1}^{L-1} \left\langle \left[\hat{E}_{\ell,\ell+1}(t) - \bar{E}^{\mathrm{gs}}_{\ell,\ell+1} \right]^2 \right\rangle$$

the number of particle–antiparticle pair

$$\mathcal{M}(t) = \frac{1}{2} \sum_{\ell=1}^{L} \left\langle \left[\hat{Q}_\ell(t) - \bar{Q}^{\mathrm{gs}}_\ell \right]^2 \right\rangle$$



Confinement in the negative mass region



Conclusion

We have directly observed the confinement–deconfinement transition in a U(1) quantum-link gauge theory via monitoring the microscopic dynamics of particle–antiparticle pairs with tunable topological θ-angle.

References

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Y. Cheng, S. Liu, W. Zheng, P. Zhang, H. Zhai, PRX Quantum 3, 040317 (2022).

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