

Suppression of quantum correlations in a clean-disordered atom-nanophotonic interface

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Quantum correlations are essential to the emergent behaviors of quantum systems, supporting key phenomena such as localization or delocalization of particles, quantum avalanches in many-body localized systems, and quantum information transfer. In open atom-nanophotonic systems characterized by long-range spin-exchange interactions, we examine the influence of clean system size on high-order quantum correlations among a clean-disordered atomic array with multiple atomic excitations. By initializing the system far from equilibrium, we observe a suppression of quantum correlations for localized atomic excitations in the disordered zone as the clean system size increases, showcasing the delocalization behavior in the high-order spin-exchange processes. The calculation of the entanglement entropy at the interface further substantiates this thermalizing effect. Our results manifest distinct quantum correlations enabled by long-range interactions mediated by the waveguide, enhance the theoretical comprehension of clean-disordered systems, and provide insights to nonequilibrium quantum dynamics in an atom-nanophotonic platform.

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I. INTRODUCTION

Quantum correlations are fundamental to emergent behaviors of quantum systems, influencing phenomena such as quantum criticality [1,2] and the quantum Kibble-Zurek mechanism [3–5]. In particular, quantum correlation can act as a probe of the avalanche mechanism [6], relevant to the fate of the many-body localized phase [7–14], which is associated with an accelerated transport of thermalized penetration into the localized system [15–18]. This design of an interface with two separated zones of quench dynamics has led to rich phenomena, in addition to quantum avalanches in a one-dimensional (1D) Bose-Hubbard system [6], involving the observation of Hilbert space fragmentation [19–24] that defies thermalization in a tilted two-dimensional (2D) Bose-Hubbard model [25] and the Rayleigh-Taylor instability that results in a turbulent mixture in a binary quantum fluid [26].

Recently, an interface in 1D atomic chains was proposed theoretically to separate two dissimilar arrays as an alternative platform to study excitation localization to delocalization transitions under single excitation [27], resembling the Anderson localization behavior [28]. This atom-nanophotonic platform

[29–33] forms one of the strongly coupled open quantum systems [34–38] for nonclassical states generation [39–42], revealing photon-photon [43,44] or atom-atom correlations [45], and promises scalable quantum computation using graph states [46]. With individually controlled atoms in optical tweezers, a scalable atomic array coupled to a waveguide can be envisioned to tackle the effect of thermal inclusions on the localized atomic excitations under strong disorders at long time [47–50].

The effect of thermal penetrations as quantum avalanche to many-body localization has been experimentally studied in the Bose-Hubbard model [6], which manifests a speedup in penetration depths into the localized region and decaying quantum correlations from the interface, as the clean size scales up. However, this is limited by system sizes for further studies due to the difficulty in resolving quantum dynamics from a half-filling insulator state under the exact and finite-size Bose-Hubbard simulations. Here we aim to reveal the effect of clean zone sizes on the localization behaviors and their robustness against the clean zone effect. We further provide a scalable analysis of the size effect in open atom-nanophotonic systems with a bottom-up approach of few atomic excitations, and we provide insights of localization or delocalization behaviors under all-to-all couplings as a comparison to the nearest-neighbor ones.

This paper focuses on multiexcitation dynamics far from equilibrium in a clean-disordered atom-nanophotonic system with inherent nonlocal spin-exchange couplings [51,52]. We probe the impact of variable clean system sizes on the excitation dynamics and obtain the associated quantum correlations using Kubo cumulant expansions [53]. By configuring the

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system with initial states, such as the half-Dicke state [54], as localized excitations in a disordered region, we numerically calculate the high-order quantum correlations among the clean and disordered zones at sufficiently long time. These correlations are designated for atomic excitations quenched in the clean and disordered sites or distributed in respective zones, where we find significant suppression of these long-time and long-range quantum correlations as the clean zone size increases. This suppression indicates a transition towards excitation delocalization, which is also manifest in a greater entanglement entropy at the interface. Our results elucidate the pivotal influence of the clean system size, as thermal inclusions to the excitation localization, and enhance the comprehension of the mechanism in excitation delocalization from collective photon-mediated spin-exchange interactions in open atom-nanophotonic platforms.

II. THEORETICAL MODEL

The system under consideration is a 1D atomic array consisting of N atoms and M excitations, divided into two separate regions: a clean zone and a disordered zone, as illustrated in Fig. 1(a). We assign the interface position at the $m = 0$ site, separating two zones, and the dimensionless interparticle distances in the clean and disordered regions are represented by ξ_1 and ξ_2 , respectively. We consider two-level quantum emitters (the ground state $|g\rangle$ and the excited state $|e\rangle$ as a spin-1/2 system) coupled to a nanophotonic waveguide [33], where photon-mediated spin-exchange interactions emerge among every pairwise atoms [41,55] due to the guided modes. The system dynamics can be described by a density matrix ρ in Lindblad forms ($\hbar = 1$), with in general left (L) and right (R) propagating decay modes [30,41], as

$$\frac{d\rho}{dt} = -i[H_L + H_R, \rho] + \mathcal{L}_L[\rho] + \mathcal{L}_R[\rho]. \quad (1)$$

The coherent and dissipative terms can be expressed respectively as

$$H_{L(R)} = -i \frac{\gamma_{L(R)}}{2} \sum_{\mu < (>) \nu} \sum_{v=1}^N (e^{ik_s|r_\mu - r_\nu|} \sigma_\mu^\dagger \sigma_\nu - \text{H.c.}) \quad (2)$$

and

$$\begin{aligned} \mathcal{L}_{L(R)}[\rho] = & -\frac{\gamma_{L(R)}}{2} \sum_{\mu, \nu} e^{\mp i k_s(r_\mu - r_\nu)} \\ & \times (\sigma_\mu^\dagger \sigma_\nu \rho + \rho \sigma_\mu^\dagger \sigma_\nu - 2\sigma_\nu \rho \sigma_\mu^\dagger), \end{aligned} \quad (3)$$

where we can define a dimensionless and equal interparticle distance as $\xi = k_s|r_\mu - r_\nu|$ with spacings $\xi_{1,2}$ for different zones. The dipole operators are $\sigma_\mu^\dagger \equiv |e\rangle_\mu \langle g|$ with $\sigma_\mu = (\sigma_\mu^\dagger)^\dagger$, and $\gamma_L \neq \gamma_R$ represent the nonreciprocal coupling strengths. The directionality factor can be defined as $D \equiv (\gamma_R - \gamma_L)/\gamma$ [29], which quantifies the preference of directional spin-exchange interactions under 1D reservoirs [39], with a total decay rate $\gamma = \gamma_R + \gamma_L \equiv 2|dq(\omega)/d\omega|_{\omega=\omega_{eg}} g_{k_s}^2 L$, where $|dq(\omega)/d\omega|$ indicates an inverse of group velocity with a resonant wave vector $q(\omega)$, the atom-waveguide coupling strength is g_{k_s} , and the quantization length is L . The factor

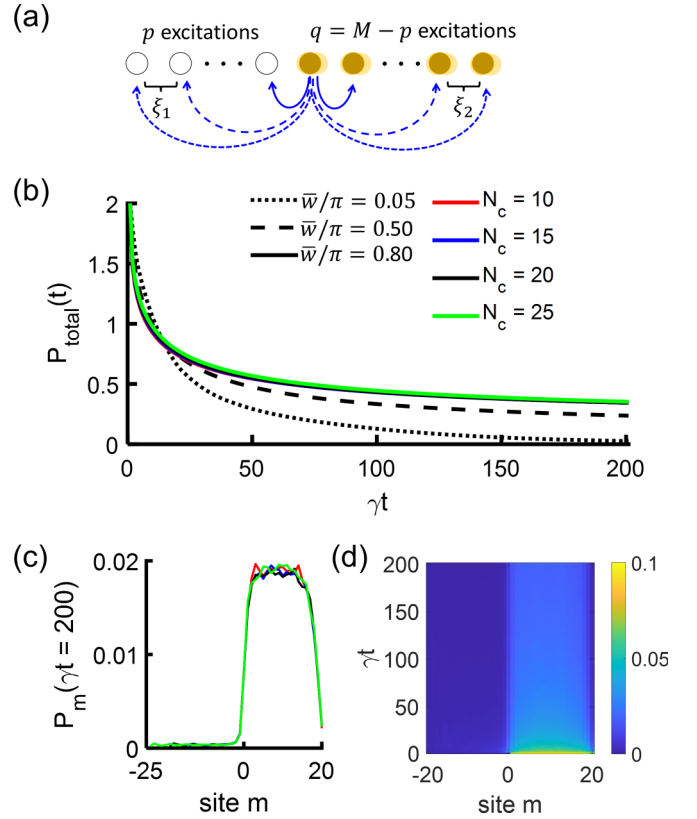


FIG. 1. (a) Schematic of an atomic array featuring a clean-disordered interface, with nonreciprocal couplings (γ_L and γ_R). For M excitations, we initialize p excitations in the clean zone and q excitations in the disorder zone, with dimensionless interatomic spacings $\xi_{1,2} = k_s d_{1,2}$, respectively, at a resonant wave vector k_s on the waveguide with distances $d_{1,2}$. All-to-all couplings are delineated by lines with arrows from the perspective of the atom in the middle. Here $p = 0$ as an example with q excitations shared among all sites in the disordered zone. (b) Time evolution of the total population $P_{\text{tot}}(t)$ for different clean zone sizes $N_c = 10, 15, 20, 25$ in solid lines under a disorder strength $\bar{w}/\pi = 0.8$ and for different disorder strengths $\bar{w}/\pi = 0.05, 0.5, 0.8$ (dotted, dashed, and solid black) at $N_c = 20$. (c) Cross-sectional population distribution at $\gamma t = 200$ for varying clean zone sizes and (d) population evolution across each site for $N_c = 20$ under a disorder strength $\bar{w}/\pi = 0.8$. All plots consider a disorder zone size of $N_d = 20$. All systems in (b), (c), and (d) are initialized with symmetric Dicke state with $M = 2$ excitations in the disordered zone ($p = 0, q = 2$) at $\xi_1 = \xi_2 = \pi/4$ and $D = 0$.

$D = \pm 1$ and 0 presents the chiral coupling scheme [56–58] and the reciprocal coupling regime, respectively.

The theoretical model under consideration is well formulated and can be applied in many waveguide QED systems involving atoms, quantum dots, or superconducting qubits [33]. This all-to-all coupled model has predicted nonlocal entanglement generations [41] and correlated photon transport [43], and showcased superradiance [52] and directional spontaneous emissions [29]. Recently, we proposed dissimilar atomic arrays with two different interparticle distances forming an interface to investigate intriguing quantum dynamics of excitation trapping [59] and interaction-induced depletion phenomena [60], providing insights to quantum information

storage and processing, respectively. Here moreover, we use a clean-disordered atom-nanophotonic interface to study delocalization mechanism from the clean zone size effect, which promises a scalable analysis from a bottom-up approach with few atomic excitations.

For initial states far from equilibrium, we designate the numbers of p and $q = M - p$ quenched atomic excitations in the clean and the disordered zones, respectively, among a total of M excitations. The disorders can be established in atomic position fluctuations, leading to the onsite phase disorders denoted by $W_\mu \in [-\bar{w}, \bar{w}]$ on top of r_μ in Eqs. (2) and (3), with $\bar{w}/\pi = [0, 1]$. Taking $|\phi_s\rangle = \sigma_j^\dagger \sigma_{k>j}^\dagger \cdots \sigma_l^\dagger \sigma_{m>l}^\dagger |0\rangle$ as the labeled s th bare state basis for M excitations in general [61], the corresponding probability amplitudes $a_s(t)$ in the state function $|\Psi(t)\rangle \equiv \sum_s a_s(t) |\phi_s\rangle$ [$\rho = |\Psi(t)\rangle\langle\Psi(t)|$] can be directly solved from

$$\dot{a}_s(t) = \sum_{s'=1}^{C_M^N} V_{s,s'} a_{s'}(t), \quad (4)$$

where C denotes the binomial coefficient and $V_{s,s'}$ represents the interaction matrix between every bare states, encoding photon-mediated dipole-dipole interactions and waveguide-mediated couplings [42,45]. We solve Eq. (4) numerically, and the results are averaged over 2000 disorder realizations, which ensures a statistical convergence [62].

III. EXCITATION TRANSPORT

In order to study the excitation localization phenomenon, not all interparticle distances ξ lead to disorder-induced localization. When $\xi = \pi$ or 2π , the atomic excitation dynamics involves populated subradiant and decoherence-free sectors [63], leading to disorder-induced decays in the excitations instead. Therefore, we focus on small $\xi < \pi/2$ near the superradiant sectors, in a parameter regime for disorder-induced localization under strong disorders [62]. In Figs. 1(b)–1(d), we demonstrate the clean zone size effect on the excitation population dynamics in the disordered zone at long time. We first focus on an initialized half-Dicke state $|\Psi(t=0)\rangle = \sqrt{2}/\sqrt{N_d(N_d-1)} \sum_{i=1}^{N_d-1} \sum_{j=i+1}^{N_d} \sigma_i^\dagger \sigma_j^\dagger |0\rangle$, where two atomic excitations are equally distributed in the disordered zone. This configuration avoids positional biases of excitations relative to the interface or chain boundaries, and, at the time of initialization, the total spin excitations should be conserved, that is $\sum_{m=1}^N P_m(0) = M$, where $P_m \equiv \langle\Psi|\sigma_m^\dagger \sigma_m|\Psi\rangle$. In Fig. 1(b), we find that the total populations are largely unaffected by the clean system sizes and remain in the disordered zones when deep in the localization regime. This shows negligible effect of spin-exchange interactions on the excitation transport from the disordered to the clean zones [27,48], which is further evidenced in the overlapped site-resolved populations at long time under variable clean zone sizes, as shown in Fig. 1(c). Moreover, Fig. 1(d) reveals that an absence of population exchanges is established immediately upon initialization, showing the robustness of disorder-induced excitation localization.

This long-time decaying localization of multiple atomic excitations can turn to a faster timescale by a finite D , where a larger D directs spin excitations preferentially toward one

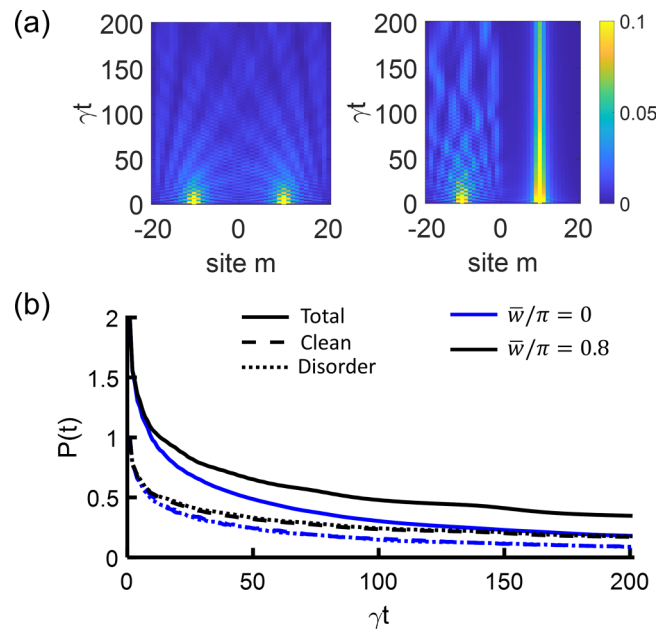


FIG. 2. Time evolution of the total excitation populations in an initialization with two atomic excitations with $p = q = 1$. (a) Two-dimensional plots of the population dynamics for $\bar{w} = 0$ (left panel) and $\bar{w} = 0.8\pi$ (right panel), illustrating the effects of disorders on population distributions over time. (b) Comparison of the total population (solid lines), populations in the clean (dashed lines) and disordered zones (dotted lines) for $\bar{w} = 0$ (blue) and $\bar{w} = 0.8\pi$ (black). The $N_{c,d} = 20$ and the other parameters are the same as in Fig. 1.

side of the system [30,41]. This asymmetry accelerates the spin transport toward the boundaries, leading to increased excitation losses. In the following investigations, we focus on the reciprocal coupling regime of $D = 0$ by avoiding the influence from asymmetric coupling losses. Additionally, the presence of unavoidable nonguided modes γ_{ng} of the system can further lead to a limited time window ($1/\gamma_{ng}$) for observation of the long-time behaviors [62]. Therefore, a strong coupling regime $\beta = \gamma/(\gamma + \gamma_{ng}) \approx 1$ is required for disorder-induced localization phenomenon and other novel collective radiations [30] or applications like photon routing using atom-nanophotonic interfaces [33].

To further investigate the population dynamics, we examine the case of $p = 1$ and $q = 1$, where the initial state is prepared with one excitation quenched at position $m = -10$ in the clean zone and the other at $m = 10$ in the disorder zone, as shown in Fig. 2. In the disorder-free case in the left panel of Fig. 2(a), the excitations spread evenly across all sites over time due to the reciprocal coupling, resulting in interference fringes from equal counterpropagating spin excitation transport. In contrast, under a strong disorder in the disordered zone (right panel), the excitation localization emerges, while the excitation in the clean zone spreads freely within its region and does not penetrate the other side. Interestingly, despite the different behaviors of excitation evolution in the clean and disordered zones, the spin-exchange interactions between two zones induce a back-action effect. This effect ensures that the respective total populations in the clean and disordered

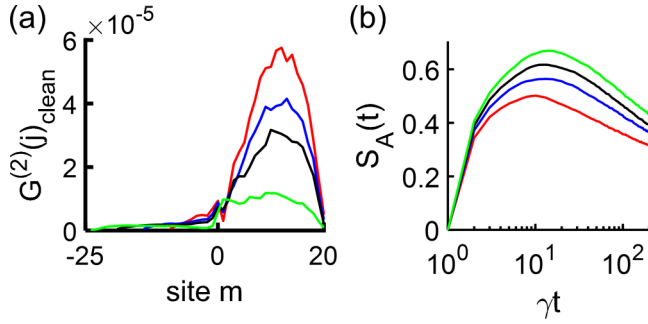


FIG. 3. Mean second-order correlations $G^{(2)}(j)_{\text{clean}}$ and entanglement entropy $S_A(t)$ for an initialization with $M = 2$ excitations, $p = 0$, and $D = 0$. (a) Suppression of $G^{(2)}(j)_{\text{clean}}$ as N_c increases at $\gamma t = 200$. (b) Entanglement entropy $S_A(t)$ with varying clean zone sizes, with a logarithmic scale in time. The line colors for different N_c are the same as in Fig. 1.

zones almost overlap over time, regardless of the presence or absence of disorders, as illustrated in Fig. 2(b). This back action arises because the clean and disordered zones exchange excitation populations at all ranges, influencing each other and creating balanced dynamics [62]. Specifically, the localized excitation in the disorder zone, affected by the delocalized excitation in the clean zone, exhibits a reduced population compared to a standalone disordered array. Conversely, the excitation in the clean zone, which would typically experience a rapid population decay, retains its population for longer time due to the coupling with the localized excitation in the disordered zone and manifests an effective slowing down in decay compared to the disorder-free case.

IV. QUANTUM CORRELATIONS

Furthermore, high-order quantum correlations can provide insights and probe the clean-disordered system under multiple excitations. For finite atomic excitations in the clean zone, a larger clean system size promotes entanglement as time evolves and induces intriguing many-body dynamics, which complicates the clean zone size effect on the excitation localization in the disordered zone. Therefore, we focus on empty sites in the clean zone as thermal baths to the disordered zone.

Using $M = 2$, $N_d = 20$, and $p = 0$ with a half-Dicke state as the initial excitation, we focus on the strong disorder regime to study the impact of clean system sizes on quantum correlations. The nonclassical correlation between two sites in terms of Kubo cumulant expansions [53] can be defined as

$$G^{(2)}(i, j) = \langle n_i n_j \rangle - \langle n_i \rangle \langle n_j \rangle, \quad (5)$$

where $n_j \equiv \sigma_j^\dagger \sigma_j$. Specifically, we can compute the mean correlation of the clean zone as [6]

$$G^{(2)}(j)_{\text{clean}} = \overline{G^{(2)}(i, j)}|_{i \in \text{clean}}, \quad (6)$$

which isolates the effect of the clean system on the whole chain. As shown in Fig. 3(a), the mean correlations in the clean zone are extremely low, which reflects limited spin excitations spreading into the clean zone from the disordered zone. By contrast, the mean correlation in the disorder zone is consistently higher than in the clean zone, emphasizing

the role of disorders in enhancing localization-induced correlations [62]. This observation aligns with the pronounced excitation localization in the disorder zone in Fig. 1(c).

Notably, the mean correlations become suppressed as the clean system size increases, even when the population distributions are kept intact under strong disorders. This feature suggests that the clean zone influences the localized excitations in the high-order processes of thermalization via all-to-all spin-exchange interactions. The facilitated delocalization behavior in quantum correlations can also be compared to a Bose-Hubbard model with nearest-neighbor couplings and local on-site interactions, where thermal inclusions of extra baths penetrate through the interface and thermalize the insulator region with larger penetration depths [6]. By contrast, the excitation delocalization here manifests in an overall suppression of quantum correlations with no sign of characteristic length scales of correlations near the interface, due to its initialized distinction between occupied and unoccupied atomic excitations present in the disordered and clean zones, respectively.

Next, we calculate the entanglement entropy $S_A(t)$ as a complementary measure to quantum correlations to further investigate the delocalization behaviors driven by the clean system size. The entanglement entropy is defined as $S_A(t) \equiv -\text{Tr}[\rho_A(t) \ln \rho_A]$, a genuine measure for quantum entanglement in pure state analysis, where $\rho_A(t) \equiv \text{Tr}_B[\rho(t)]$ represents the reduced density matrix among the system partitions A and B with a cut at the interface. As shown in Fig. 3(b), we observe an initial rise in the entanglement entropy across all clean system sizes N_c before the effect of disorders kicks in [27]. However, after $t \sim 2\gamma^{-1}$, deviations of S_A emerge with the entropy growing to its peak value and subsequently decaying due to the excitation dissipation. Notably, as the clean system size increases, the entropy for larger systems consistently remains higher than for smaller ones, while the peak values of S_A are delayed as N_c increases, showing the timescale for information flow among two zones. This observation implies that larger clean zones allow greater access to distribute spin excitations and to build up quantum correlations as time evolves, enhancing delocalization effect.

Both the second-order quantum correlations $G^{(2)}(j)_{\text{clean}}$ and the entanglement entropy at the interface shown in Fig. 3 indicate enhanced thermalization of atomic excitations as N_c increases. The former characterizes the strength of coincidences of finding the particles within the disordered zone, while the latter identifies the correlations among two separate zones. The suppressed $G^{(2)}(j)_{\text{clean}}$ manifests the weakening of localized excitation in the disordered zone, while the increased entropy signifies a trend to thermal equilibrium, supporting the findings of restrained quantum correlations. We note that our results underscore the collective impact of the clean zone on the disordered zone via long-range spin-exchange interactions, and highlight the essential role of clean system size in engaging and influencing the overall quantum dynamics, beyond the solely local effects of entropy per particle [62] seen in systems with short-range interactions [6].

Finally, we extend the analysis to multipoint correlations by calculating the third-order correlation function $G^{(3)}(i, j, k)$, using again the Kubo cumulant expansions [6,53] to quantify nonclassical higher-order quantum correlations. The

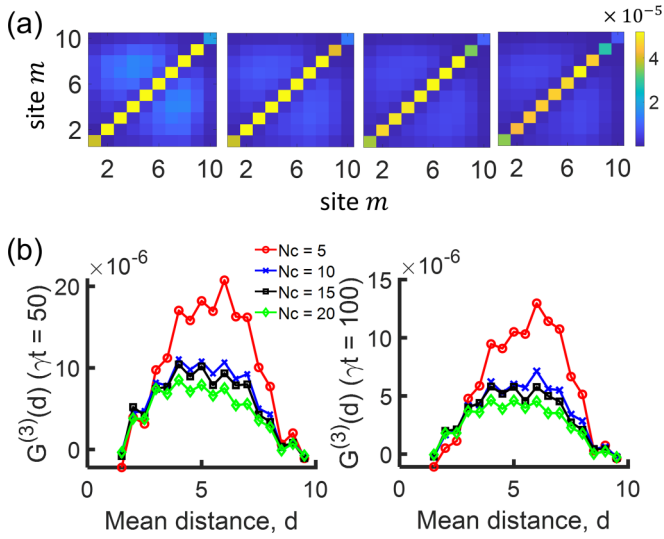


FIG. 4. Third-order correlation $G^{(3)}_{(i,j)}$ for an initialization with $M = 3$ excitations and $p = 0$, among pairs of disordered sites i and j , and one clean site k (averaged over all clean sites k), in a system with $D = 0$, $N_d = 10$, and the disorder strength $\bar{w}/\pi = 0.8$. (a) A 2D heatmap of the average correlation between disordered sites for different clean zone sizes $N_c = 5, 10, 15, 20$ (from left to right) at $\gamma t = 100$. (b) Correlation suppression with increasing clean zone sizes for $N_c = 5, 10, 15, 20$ (red, blue, black, and green), averaged over the mean distance from the interface $d = (i + j)/2$, at $\gamma t = 50$ (left panel) and $\gamma t = 100$ (right panel).

third-order quantum correlation is defined as

$$G^{(3)}(i, j, k) = \langle n_i n_j n_k \rangle - \langle n_i \rangle \langle n_j n_k \rangle - \langle n_j \rangle \langle n_k n_i \rangle - \langle n_k \rangle \langle n_i n_j \rangle + 2 \langle n_i \rangle \langle n_j \rangle \langle n_k \rangle. \quad (7)$$

To analyze the influence of the clean zone, we calculate the mean third-order correlations involving two disordered sites, i and j , and one clean site, k , averaged over the clean zone, given by

$$G^{(3)}(i, j)_{\text{clean}} = \overline{G^{(3)}(i, j, k)}_{k \in \text{clean}}. \quad (8)$$

In Fig. 4, we focus on the clean system size effect on correlations among two disordered sites from an initialized half-Dicke state with three atomic excitations equally shared in the disordered zone. From the left to the right panels in Fig. 4(a), corresponding to increasing clean system sizes, the mean third-order correlations between two sites in the disordered zone are clearly suppressed, along the diagonal or on the off-diagonal parts. This trend aligns with the findings with the second-order quantum correlations and the entanglement entropy, reinforcing the delocalization effect induced by larger clean system sizes. To further analyze this reduced correlation in the disordered zone, we examine the mean correlation as a function of the mean distance, $d = (i + j)/2$, between these two sites [6]. In Fig. 4(b), a plateau of high correlations emerge around $d = 5$, corresponding to a balanced distance for two sites equally distributed in the disordered zone of $N_d = 10$. Additionally, the third-order correlation exhibits a unique spatial dependence. For two sites near the interface and at the chain boundaries, the correlations become vanishing. This behavior again contrasts with short-range interacting

systems, where the mean third-order correlation is strongest near the interface [6]. This distinction provides valuable insights into the fundamental differences between systems with nearest-neighbor hopping and long-range spin-exchange couplings, highlighting the unique collective dynamics in atom-waveguide interfaces. As a final remark, we do not observe a speedup in decaying quantum correlations as N_c increases or at longer evolution time. The former can be further clarified in regimes beyond the few atomic excitations but suffers from an exponentially growing dynamical spaces, while the latter is inevitable in generic open quantum systems.

V. EXPERIMENTAL FEASIBILITY

Our results are readily simulated and implemented in photonic crystal waveguides coupled with an atomic array [33,64,65] under the strong coupling regime $\beta \sim 1$. These scalable and trapped atoms can be manipulated by optical lattices [66] or optical tweezers [37,38], and the initialized states considered in this work can be created from controlled side excitations [29]. In particular for the Dicke state preparations, they can be initialized by few photon excitations, where the atoms can be uniformly interacted with light, and the so-called timed Dicke state can be created on absorption [67]. The clean-disordered interface can also be manipulated by partially applying position fluctuations on the disordered zone, which can be enabled by using speckled patterns of light potential or creating quasiperiodic optical lattices. For measuring quantum correlations, individual atomic excitation population readout and conditional density-density correlation measurements [5] can be conducted in a single-site resolved fashion. We envision that the experimental implementation is promising in the state-of-the-art and advancing platforms.

VI. CONCLUSIONS

We have provided comprehensive and extensive investigations of the role of clean system sizes in the multiexcitation localization in atom-nanophotonic systems using high-order quantum correlations and entanglement entropy. We uncover a suppression of quantum correlations for localized atomic excitations in the disordered zone as the clean system size increases, facilitating delocalization behaviors in the high-order spin-exchange processes even when the excitation populations are sustained by the strong disorders. Our results showcase unique quantum correlations, contrasting the behaviors in systems with short-range interactions, and offer new insights into the interplay between thermal inclusions and the disorder-induced localization. This work not only advances the theoretical understanding of a clean-disordered interface [59,60,68], but also paves the way for designing scalable quantum simulations [69] that leverage tunable long-range interactions [70] and structured environments.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available because they are owned by a third party and the terms of use prevent public distribution. The data are available from the authors upon reasonable request.

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