

Experimental realization of a symmetry protected topological phase of interacting bosons with Rydberg atoms

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The concept of topological phases is a powerful framework to characterize ground states of quantum many-body systems that goes beyond the paradigm of symmetry breaking. While a few topological phases appear in condensed matter systems, a current challenge is the implementation and study of such quantum many-body ground states in artificial matter. Here, we report the experimental realization of a symmetry protected topological phase of interacting bosons in a one-dimensional lattice, and demonstrate a robust ground state degeneracy attributed to protected edge states. The setup is based on atoms trapped in an array of optical tweezers and excited into Rydberg levels, which gives rise to hard-core bosons with an effective hopping by dipolar exchange interaction.

INTRODUCTION

The paradigm of symmetry breaking has proven very successful for characterizing quantum phases. However, not all of them follow this paradigm, and some of these phases are nowadays characterized in the framework of topological phases. The most prominent example of a topological phase is the integer quantum Hall state with its remarkably robust edge states giving rise to a quantized Hall conductance [1]. For a long time, it was believed that such phases occurred only in the presence of a magnetic field, until the prediction of topological insulators [2] revealed a novel class of topological states of matter, nowadays denoted as symmetry protected topological phases (SPT). They occur in systems displaying an excitation gap in the bulk, i.e., bulk insulators, and an invariance under a global symmetry. Their defining property is that the ground state at zero-temperature cannot be transformed into a conventional insulating state upon deformations of the system that do not close the excitation gap or violate the symmetry. In particular, the edge states are robust to any perturbation commuting with the symmetry operators.

SPT phases were first predicted and observed in materials where the interaction between electrons can be effectively neglected [3, 4]. In this specific case of non-interacting fermions, SPT phases can be classified based on the action of the Hamiltonian on a single particle [5, 6]. Thus, the appearance of robust edge states is fully understood from the single-particle eigenstates. This remarkable simplification motivated experimental studies of topological phenomena at the single-particle level with artificial quantum matter realized on ultracold atoms platforms [7–13], and in classical systems of

coupled mechanical oscillators [14, 15], as well as optical [16–19] or radio-frequency circuits [20], and plasmonic systems [21, 22].

In contrast, the situation is different for bosonic SPT phases as the ground state of non-interacting bosons is a Bose-Einstein condensate. Therefore, it is well established that strong interactions between the particles are required for the appearance of topological phases. Their classification is not derived from single-particle properties, but requires the analysis of the quantum many-body ground state; a classification of bosonic interacting SPT phases based in terms of group cohomology has been achieved [23]. A notable example is the Haldane phase of the anti-ferromagnetic spin-1 chain [24], which has been experimentally observed in some solid-state materials [25, 26]. However, the realization of topological phases in artificial matter, where one has full microscopic control on the particles, would allow to gain a deeper understanding on the nature of such topological states of matter. A first step has recently been achieved by introducing interactions between bosonic particles in a system with a topological band structure [13, 27], but studies were restricted to the two-body limit, still far from the many-body regime.

Here, we report the first realization of a many-body SPT phase of interacting bosonic particles in an artificial system. Our setup is based on a staggered one-dimensional chain of Rydberg atoms, each restricted to a two-level system, resonantly coupled together by the dipolar interaction [28]. We use this to encode hard-core bosons, i.e., bosonic particles with infinite on-site interaction energy, coherently hopping along the chain. The system then realizes a bosonic version of the Su-Schrieffer-Heeger (SSH) model [29]; the latter originally described fermionic particles hopping on a dimerized lattice, giving rise to a SPT phase of non-interacting fermions. Similarly, our bosonic setup gives rise to two distinct phases of an half-filled chain: a trivial one with a single ground

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body ground state corresponding to an half-filled chain. For non-interacting fermions, the properties of the SSH chain follows from the Fermi sea picture based on the single-particle eigenstates: in the trivial configuration one obtains a single insulating ground state, while, in the topological configuration, (i) an excitation gap appears in the bulk, and (ii) the ground state is four-fold degenerate as the two zero-energy edge modes can be either empty or occupied. For interacting bosons, the description of the many-body ground state is much more challenging. In the special case with only nearest neighbor hoppings J and J' , the bosonic many-body ground states for hard-core bosons can be derived via a Jordan-Wigner transformation from the fermionic ones, and inherits the properties of a bulk excitations gap and a four-fold ground state degeneracy in the topological configuration [33]. Based on the general classification of bosonic SPT phases [23], these properties are robust by adding longer-range hoppings as well as additional interactions between the bosons as long as the bulk gap remains finite and the protecting symmetry is respected. Here, the protecting symmetries are the particle number conservation and the anti-unitary operator

$$\mathcal{S}_B = \prod_{i=1}^N [b_i + b_i^\dagger] K, \quad (2)$$

where $b_i + b_i^\dagger$ is a particle-hole transformation and K denotes the complex conjugation. In contrast to the chiral symmetry (protecting the single-particle properties and the fermionic SPT phase), next nearest neighbor hoppings $J'' = J_{i,i+2}$ are symmetry allowed, i.e., $[H, \mathcal{S}_B] = 0$ even when including J'' . We will demonstrate this fundamental difference by engineering a perturbation which shifts the edge modes away from zero-energy at the single particle level, but preserves the ground state degeneracy in the bosonic many-body system.

EXPERIMENTAL REALIZATION WITH RYDBERG ATOMS

Our realization of the bosonic SSH model is performed on an artificial structure with $N = 14$ sites of individually trapped ^{87}Rb atoms [34–36] (Fig. 1C-D). The motion of the atoms is frozen during our experiment, occurring in a few microseconds. Coupling between the atoms is achieved, despite the large inter-atomic distance ($\sim 10\text{ }\mu\text{m}$), by considering Rydberg states for which the dipole-dipole coupling is enhanced to a few MHz [28, 37].

We first prepare each atom in a Rydberg s-level, $|60S_{1/2}, m_J = 1/2\rangle$, using a two-photon stimulated Raman adiabatic passage (STIRAP) with an efficiency of 95% [33]. From there, the atom can be coherently transferred to a Rydberg p-level, $|60P_{1/2}, m_J = -1/2\rangle$, using a microwave field tuned to the transition between the two Rydberg levels ($E_0/h \sim 16.7\text{ GHz}$). The detuning from the transition is $\Delta_{\mu\text{w}}$, and the Rabi frequency is

$\Omega_{\mu\text{w}}/(2\pi) \sim 0.1 - 20\text{ MHz}$. We denote the state with all Rydberg atoms in the s-level as the ‘vacuum’ $|0\rangle$ of the many-body system, while a Rydberg atom at site i excited in a p-level is described as a bosonic particle $b_i^\dagger|0\rangle$. Since each Rydberg atom can only be excited once to the p-level, we obtain naturally the hard-core constraint. The resonant dipolar interaction occurring between the s- and p-levels of two Rydberg atoms at site i and j gives rise to hopping of these particles [28], as illustrated in Fig. 1B. We use this to engineer the hopping matrix J_{ij} . At the end of the experiment, we de-excite atoms in the Rydberg s-level to the electronic ground state and detect them by fluorescence imaging, while an atom in the Rydberg p-level is lost from the structure. The detection errors are at the few percent level [33]. For each experimental run, we thus obtain the occupancy of each site, which is then averaged by repeating the experiment every $\sim 0.3\text{ s}$.

In order to implement the sub-lattice symmetry, we use the angular dependence of the dipolar coupling $J_{ij} = d^2(3\cos^2\theta_{ij} - 1)/R_{ij}^3$ with d the transition dipole moment between the two Rydberg levels. The hopping depends on the separation R_{ij} , as well as the angle θ_{ij} with respect to the quantization axis defined by the magnetic field $B_z \simeq 50\text{ G}$. In Fig. 1A, we show the measured angular dependence, vanishing at the ‘magic angle’ $\theta_m = \arccos(1/\sqrt{3}) \approx 54.7^\circ$, which allows us to suppress the hopping along this direction. By arranging the atoms in two sub-chains aligned along the magic angle, we thus satisfy the sub-lattice symmetry. The measured nearest neighbor couplings are $J/h = 2.42(2)\text{ MHz}$ and $J'/h = -0.92(2)\text{ MHz}$, in full agreement with numerical determination of the pair potential [38]. The dipolar interaction also gives rise to longer range hopping on the order of $\sim 0.2\text{ MHz}$ to third neighbors, which do not qualitatively change the properties of our system but are fully taken into account for quantitative comparison between theory and experiment.

SINGLE-PARTICLE SPECTRUM

As a benchmark of our system, we first study the properties of a single particle in the chain. The single-particle spectrum is probed by microwave spectroscopy (Fig. 2A). Initializing the vacuum state $|0\rangle$ with all Rydberg atoms in the s-level, a weak microwave probe with a Rabi frequency $\Omega_{\mu\text{w}}/(2\pi) = 0.2\text{ MHz}$ applied for a time $t = 0.75\text{ }\mu\text{s}$ can lead to the coherent creation of a particle only if an eigenstate energy matches the microwave detuning $\Delta_{\mu\text{w}}$ and if this state is coupled to $|0\rangle$ by the microwave field. We show in Fig. 2B the site-resolved probability to find a particle on a given site for the two different chain configurations. In both cases, we observe a clear signal for $\hbar\Delta_{\mu\text{w}} < |J'| - |J|$ from lower band modes delocalized along the chain. States in the upper band are not observed as the microwave coupling from $|0\rangle$ to these states is very small. Only in the topological

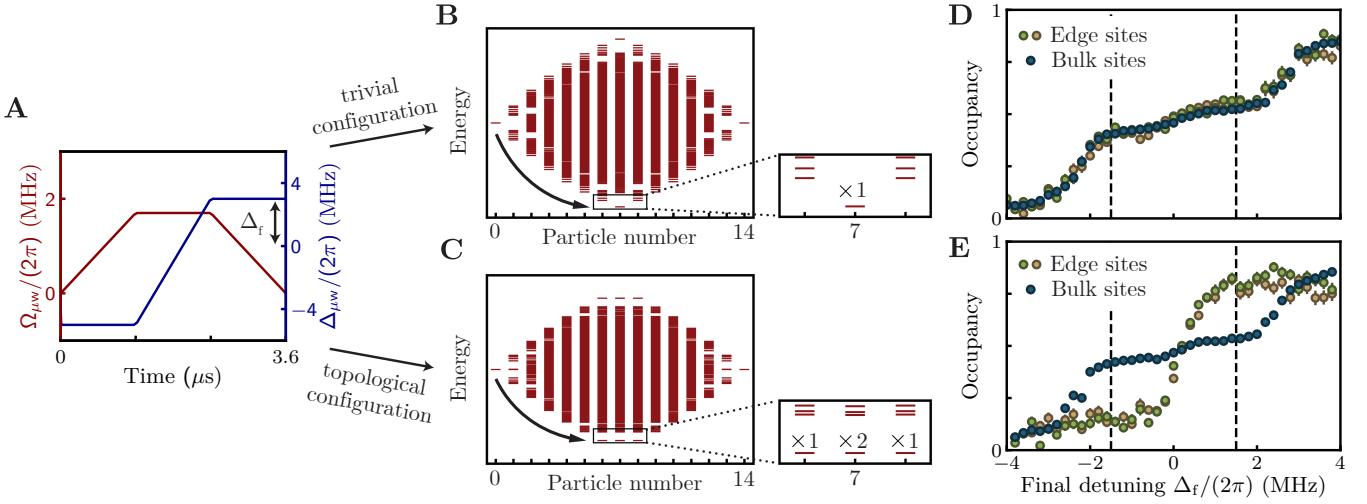


Figure 3. Preparing the many-body phase at half-filling. (A) Microwave sweep with time-varying Rabi frequency $\Omega_{\mu w}$ and detuning $\Delta_{\mu w}$; the latter ends at Δ_f . (B,C) Energy spectrum of the many-body system in the trivial (top) and the topological (bottom) configuration for different particle numbers. The trivial chain exhibits a single gapped ground state with 7 particles, while the topological configuration exhibits a four-fold degeneracy involving 6, 7 (two-fold degenerate), and 8 particles. Starting from the empty chain, the microwave adiabatic sweep loads hard-core bosons in the lattice and prepares the lowest energy states. (D,E) We measure the occupancy of bulk (blue) and edge sites (green and brown) as a function of the final detuning Δ_f . For a sweep ending in the single-particle gap (dashed lines), the bulk of the chain is half-filled. Bosons are loaded in the edge sites of the topological configuration when $\Delta_f > 0$. The error bars represent the standard errors of the mean (s.e.m.).

a theoretical analysis simulating the full time-evolution, we expect that our ramping procedure ending at a final detuning $|\hbar\Delta_f| < |J| - |J'|$ prepares the ground state with high fidelity [33].

We present in Fig. 3D-E the dependence of the local density of particles on Δ_f : the bulk sites occupancy (blue curves) exhibits a characteristic plateau at half-filling within the single particle gap. Especially, the fluctuations of the number of particles in the bulk are strongly reduced with a probability of 48 % to find exactly 6 particles on the 12 bulk sites (mainly decreased from 100 % by detection errors [33]). While the local bulk properties are independent of the topology of the setup, the situation is drastically different for the edge occupancy: in the trivial configuration, the edge sites behave as the bulk sites, whereas for the topological chain the boundaries remain depleted for $\Delta_f < 0$ and exhibit a sharp transition to full occupancy for $\Delta_f > 0$. This behavior is consistent with the expected ground state degeneracy.

We gain more insight about the many-body state by analyzing the correlations between particles, that we can measure as our detection scheme provides the full site-resolved particle distribution. In the strongly dimerized regime $|J| \gg |J'|$, we expect the $\sim N/2$ particles in the bulk to be highly correlated as they can minimize their energy by each delocalizing on a dimer (two sites connected by a strong link J). The picture remains valid even in our regime where $|J| \simeq 2.6|J'|$. We measure a large and negative density-density correlation $C^z(2i, 2i + 1) = \langle Z_{2i}Z_{2i+1} \rangle \simeq -0.67(1)$ with

$Z_i = 1 - 2b_i^\dagger b_i$, corresponding to a suppressed probability to find two particles on the same dimer. We also access the off-diagonal correlations, $C^x(i, j) = \langle X_i X_j \rangle$ with $X_i = b_i + b_i^\dagger$ measuring the coherence between two sites i and j , by applying a strong microwave pulse before the detection which rotates the local measurement basis around the Bloch sphere. We obtain $C^x(2i, 2i+1) \simeq +0.48(2)$ indicating that a particle is coherently and symmetrically delocalized on two sites forming a dimer. Furthermore, our detection scheme allows us to determine string order parameters, which have emerged as an indicator of topological states [40, 41]:

$$C_{\text{string}}^z = - \left\langle Z_2 e^{i \frac{\pi}{2} \sum_{k=3}^{N-2} Z_k} Z_{N-1} \right\rangle \quad (3)$$

and in analogy for C_{string}^x . Indeed, we measure a finite string order in the topological phase with $C_{\text{string}}^z = 0.11(2)$ and $C_{\text{string}}^x = 0.05(2)$, while in the trivial phase they are consistent with zero, e.g., $C_{\text{string}}^z = -0.02(3)$. All measured correlators are in good agreement with simulations [33].

We now demonstrate the degeneracy of the many-body ground state in the topological phase and the bulk excitation gap. We first prepare the many-body ground state with the bulk at half-filling but empty edge states by an adiabatic sweep ending at $\Delta_f/(2\pi) = -1$ MHz. We then apply a weak microwave probe at various detunings $\Delta_{\mu w}$ (see Fig. 4A) and observe when particles are created or annihilated in order to probe the excitation spectrum of the many-body ground state. Figure 4B-C shows the three expected and measured transitions: (i) a particle

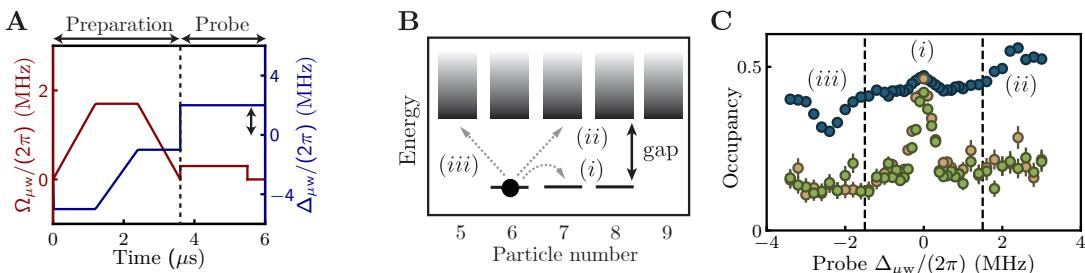


Figure 4. Probing the SPT phase degeneracy and bulk excitation gap. (A) A microwave sweep ending at $\Delta_f/(2\pi) = -1$ MHz first prepares the many-body ground state with 6 particles, and we then apply for $2\ \mu s$ a microwave probe with a Rabi frequency $\Omega_{\mu w}/(2\pi) = 0.3$ MHz and a variable detuning $\Delta_{\mu w}$. (B) Zoom on the bottom of the energy spectrum of a chain in the topological configuration. Starting from the ground state with 6 particles (solid disk), we can (i) reach one of the other degenerate ground states by adding a particle at the edge for zero energy cost. In addition, we can probe the bulk excitation gap by (ii) adding a particle to, or (iii) removing a particle from, the bulk. (C) Measured occupancy of bulk (blue) and edge sites (green and brown) showing the three expected transitions. Error bars are s.e.m.

is added at zero energy at the edge, and we reach another of the four degenerate ground states, (ii) particles are added to the bulk, which requires at least the bulk gap in energy, while (iii) particles are removed from the bulk, which appears as a dip at negative detuning.

PROBING THE PROTECTING SYMMETRY

We finally probe the robustness of the four-fold ground state degeneracy to small perturbations, which respect the protecting symmetry S_B . To do so, we distort the chain on one side by moving the rightmost site out of the sub-lattice B , see Fig. 5A. As the edge site and its second neighbor are not at the ‘magic angle’ anymore, this creates a coupling $J''/h \simeq 0.26$ MHz between them. This perturbation breaks the chiral symmetry protecting the fermionic SSH model, and correspondingly leads to a splitting of the single-particle edge modes. However, such a perturbation commutes with the symmetry S_B and therefore should not break the many-body ground state degeneracy. To check these expectations, we first repeat the spectroscopic measurement in the single-particle regime (applying the microwave probe on an empty chain, as shown in Fig. 2A), and observe a splitting of the edge modes, see Fig. 5B. In contrast, the spectroscopic measurement for the bosonic many-body ground state (applying the probe after the adiabatic preparation reaching half-filling of the bulk, as done in Fig. 4) indeed reveals a degenerate ground state, see Fig. 5C. In [33], we checked that when we prepare the ground state with a half-filled bulk, i.e., when Δ_f lies in the region $|\hbar\Delta_f| < |J| - |J'|$, the spectroscopic measurement reveals a symmetry protected ground state degeneracy.

The above experiment illustrates that, in contrast to a non-interacting SPT phase, the robustness of the bosonic many-body ground state at half-filling cannot be understood at the single-particle level. To gain an intuition for the differences between the SPT phase of non-interacting fermions and of hard-core bosons, we use the following

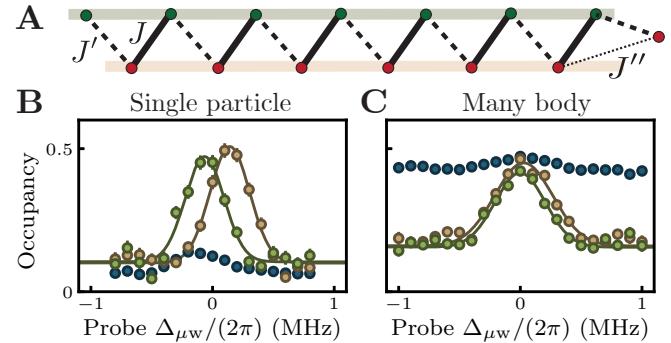


Figure 5. Perturbation and robustness of the bosonic topological phase. (A) The rightmost site is shifted upwards to give a finite hopping amplitude J'' to the second neighbor. (B,C) Probability to find a particle in the left (green) and right (brown) edge sites when scanning the detuning $\Delta_{\mu w}$ of the microwave probe. The experiment is performed either on (B) an initially empty chain to observe the energy difference between the two single-particle edge modes caused by the perturbation J'' or (C) on the many-body ground state with a half-filled bulk (6 particles in a 14-site chain) to observe the protection of the ground state degeneracy. Solid lines are Gaussian fits from which we extract an energy difference of 0.21(1) MHz in (B) and 0.03(2) MHz in (C).

simple picture. Considering only the three rightmost sites (the edge and a dimer), and taking the perturbative limit ($J \gg J', J''$), we first obtain the energy of having no particle on the edge site and one delocalized on the dimer: $-J - (J' + J'')^2 / (2J)$ (the second term is an energy correction due to virtual hopping of the particle from the bulk to the edge). On the contrary, when there is one particle on the dimer and one on the edge, we obtain $-J - (J' \pm J'')^2 / (2J)$ with an energy correction now depending on the particle quantum statistics (+ sign for bosons, - for fermions, due to commutation rules). More details can be found in S3.3 of [33]. This simplified model captures why the fermionic degeneracy is broken

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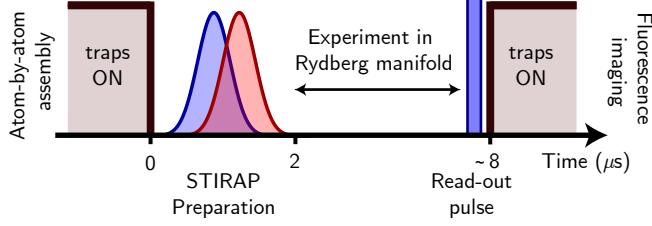


Figure S1. Typical experimental sequence. After assembling atom-by-atom a chain of ground state atoms, we transfer them to the Rydberg $60S_{1/2}$ level with a two-photon STIRAP pulse lasting $2\mu\text{s}$. We then perform an experiment in the Rydberg manifold (e.g., microwave spectroscopy, sweep...), which is ended by a $0.3\mu\text{s}$ read-out pulse depumping atoms in the $60S_{1/2}$ state back to the electronic ground states. These atoms are recaptured by the tweezers and detected in the fluorescence image, while atoms in the $60P_{1/2}$ state are lost.

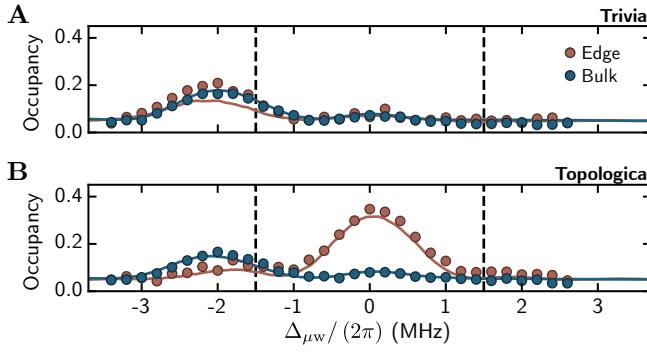


Figure S2. Comparison of the measured single-particle spectra (disks), taken from Fig. 2B of the main text, with theory (lines). The spectra show the probability to find a particle on the left or right site of the SSH chain, as well as the site-averaged probability to find a particle in the bulk as a function of the microwave detuning $\Delta_{\mu\text{w}}$. The dashed lines symbolize the band gap. The measured and calculated spectra match for the trivial configuration (A) as well as for the topological configuration (B). Error bars (s.e.m) are smaller than the symbol size.

are taken into account by a Monte Carlo sampling of the numerical results.

S1.2. Single-particle spectra

We first reproduce numerically the microwave spectroscopy experiment starting from an empty chain, probing the single-particle spectrum of a trivial and topological chain. For the simulation, the Hamiltonian consists of the bosonic SSH model [see Eq. (1) of the main text] and the interaction with the microwave probe with Rabi frequency $\Omega_{\mu\text{w}}/2\pi = 0.2\text{ MHz}$, which we treat in the rotating wave approximation. We use a Krylov subspace method to compute the time evolution of the system. After an evolution time of $0.75\mu\text{s}$, we calculate the

probability to find a particle on a given lattice site, see Fig. S2. The simulation, without any adjustable parameters, reproduces very well the experimental data shown in Fig. 2B of the main text, including the positions and widths (due to microwave power broadening) of the spectroscopic features.

S1.3. Hybridization of edge modes

As discussed in the main text, the energy of the symmetric and antisymmetric edge modes differs by the hybridization energy E_{hyb} . Here, we give details on Fig. 2F of the main text, which illustrates the scaling of the hybridization energy with the system size, and compare Fig. 2E of the main text with theory.

We obtain the hybridization energy by diagonalizing the coupling matrix J_{ij} for different chain lengths up to $N = 100$ sites, see Fig. S3A. After initially decreasing exponentially, E_{hyb} scales algebraically with the chain length, as the direct coupling $J_{1,N} \propto 1/N^4$ between the edges dominates over the higher-order coupling via nearest neighbor interactions $J_{i,i+1}$. The $1/N^4$ scaling is a combination of the $1/R^3$ -dependence of the dipolar interaction and the pair of edge sites getting closer to the ‘magic angle’. Note that the transition to the algebraic regime happens for significantly longer chains than studied experimentally.

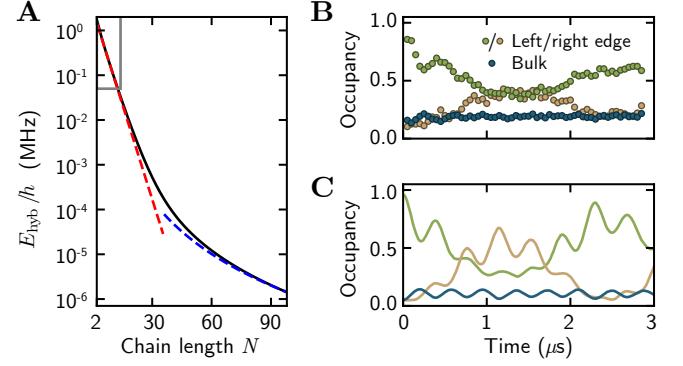


Figure S3. (A) Theoretical scaling of the hybridization energy E_{hyb} . The red curve is an exponential fit for short chain lengths. For longer chains, the hybridization energy scales algebraically as $1/N^4$ (blue curve). The region surrounded by gray lines corresponds to the range of chain lengths shown in Fig. 2F of the main text. (B) Measured and (C) simulated time evolution of the probability to find a particle on the left or right edge or in the bulk after creating a localized particle on the left edge of a topological chain of 6 sites.

As discussed in the main text, the hybridization energy is determined experimentally by measuring the frequency of the particle transfer between the two edges. For this, a localized particle is created on the left edge using a combination of an addressing beam and microwave sweeps (see Ref. [6], p.155), with an efficiency of $\sim 94\%$. We then observe the dynamics of this particle. Figure S3B,C

