

Dynamical excitation control and multimode emission of an atom-photon bound state

Claudia Castillo-Moreno,^{1,*} Kazi Rafsanjani Amin,¹ Ingrid Strandberg,¹
Mikael Kervinen,^{1,†} Amr Osman,¹ and Simone Gasparinetti^{1,‡}

¹*Department of Microtechnology and Nanoscience,
Chalmers University of Technology, 412 96 Gothenburg, Sweden*
(Dated: April 9, 2024)

Atom-photon bound states arise from the coupling of quantum emitters to the band edge of dispersion-engineered waveguides. Thanks to their tunable-range interactions, they are promising building blocks for quantum simulators. Here, we study the dynamics of an atom-photon bound state emerging from coupling a frequency-tunable quantum emitter – a transmon-type superconducting circuit – to the band edge of a microwave metamaterial. Employing precise temporal control over the frequency detuning of the emitter from the band edge, we examine the transition from adiabatic to non-adiabatic behavior in the formation of the bound state and its melting into the propagating modes of the metamaterial. Moreover, we experimentally observe multi-mode emission from the bound state, triggered by a fast change of the emitter’s frequency. Our study offers insight into the dynamic preparation of atom-photon bound states and provides a method to characterize their photonic content, with implications in quantum optics and quantum simulation.

Coupling quantum emitters to photonic lattices or metamaterials strongly modifies their spontaneous emission. When the frequency of the emitter lies within a band gap of the lattice, and still close to a band edge, an atom-photon bound state is formed – a stationary excitation whose photonic component is exponentially localized around the physical location of the emitter. Because the localization length is controlled by the frequency detuning from the band edge, atom-photon bound states can mediate long-distance interactions with tunable range [1]. Following theoretical studies [1–13], atom-photon bound states have been observed in ultra-cold atoms coupled to photonic waveguides, optical lattices, and superconducting circuits [14–22] and their properties have been leveraged to simulate spin models, prepare many-body correlated states, and explore many-body quantum phase transitions [19, 23–28].

In spite of these advances, a dynamical characterization of individual atom-photon-bound states is still lacking. The (static) exponential localization of the photonic component has been characterized through their interaction with the metamaterial edges or among atom-photon bound states clouds [29–31], or by coupling a controllable emitter to each resonator site [25, 32]. In addition, time-dependent measurements have been performed on atom-photon bound states to observe non-Markovian dynamics [33], population exchanges [34], and photonic hoppings through the metamaterial [25]. These measurements involve fast “quenches” in which the photonic fraction of the atom-photon bound state, as well as its localization length, are rapidly changed by varying the frequency of the emitter. However, neither the dynamics and characteristic time scale of the change nor the

decomposition of the photonic component of the atom-photon bound state in terms of the photonic modes of the metamaterial have been investigated.

In this Letter, we study the time-dependent formation and melting of an atom-photon bound state in a superconducting circuit. We combine dispersive measurements of the atomic population with frequency-resolved measurements of the radiation emitted by the atom-photon bound state as the emitter’s frequency is rapidly changed. We observe a crossover from adiabatic to non-adiabatic dynamics due to multi-state Landau-Zener tunneling to the frequency modes at the band edge of the photonic band. We further characterize the emitted radiation when quenching the atom-photon bound state, and detect multi-mode emission from up to 9 modes of the photonic metamaterial. We find that while the general trends are well-described by an effective model, the precise dynamics and spectral content of the emission are very sensitive to disorder in the metamaterial. Our methodology is generally applicable to localized excitations of emitters coupled to photonic lattices and can facilitate the design of quantum simulators [1, 25, 26] and topological interconnects [35].

Our superconducting quantum circuit includes a metamaterial consisting of an array of 21 nearest-neighbor-coupled, lumped-element resonators. Each resonator features an array of 10 Josephson junctions as the inductor, shunted by a capacitive element, resulting in a characteristic impedance $Z_r \approx 390 \, \Omega$ [34]. Input and output ports are capacitively coupled to the first and last site of the metamaterial to facilitate direct measurements of its transmission band and collect emitted radiation from the system. Two frequency-tunable, transmon-type artificial atoms [36] are capacitively coupled to the metamaterial resonators at sites 10 and 13 from left. The two transmons are nominally identical and use asymmetric superconducting quantum interference devices (SQUIDs) as nonlinear inductors, resulting in two first-order flux insensitive points (sweet spots). We engineer the lower

* claudiac@chalmers.se

† Present address: VTT Technical Research Centre of Finland Ltd. Tietotie 3, Espoo 02150, Finland

‡ simoneg@chalmers.se

sweet spot to reside well below the photonic band of the metamaterial and the upper sweet spot inside it. Dedicated lines in the chip allow precise control of the transmon's frequency, via the flux (Z control), and population excitation, through the charge (XY control), while dispersively-coupled, frequency-multiplexed read-out resonators allow measurement of the transmon populations [37]. In the following, we use the transmon coupled to site 13 [false-colored in blue in Fig. 1(a)] as a quantum emitter, whereas the second transmon is kept at its lower sweet spot and does not participate in the presented experiments.

We characterize the metamaterial by measuring the transmission coefficient, $|S_{21}|$, across it while keeping the emitter far detuned from the transmission band. This measurement reveals a transmission band between 5.088-5.93 GHz composed of 21 modes (detected as peaks), corresponding to the (hybridized) 21 resonators [Fig. 1(b)]. A tight-binding description of the system, assuming identical resonators of frequency ω_r and nearest-neighbor coupling J , predicts a transmission band in the frequency range $[\omega_r - 2J, \omega_r + 2J]$. Using this expression and the measured extent of the band, we extract $\omega_r/2\pi \approx 5.5$ GHz, and $J/2\pi \approx 211$ MHz. However, the spacing and linewidth of the modes significantly deviate from the tight-binding prediction, a previously reported effect [34] that we ascribe to disorder in the resonators.

To characterize the interaction of the emitter with the metamaterial, we sweep its bare frequency deep inside the band by varying the flux applied through the SQUID, and measure its dressed frequency with two-tone spectroscopy [Fig. 1(c)]. Far away from the photonic band, the data points follow the usual flux dependence of asymmetric split transmons [38]. Yet, when the emitter frequency approaches the band edge, its interaction with modes in the metamaterial causes the measured frequency to deviate from the expected flux dependence: the emitter frequency is prevented from entering the transmission band, signaling the formation of an atom-photon bound state at the lower band edge [5] [Fig. 1(c)]. The effect of the coupling between the emitter and the modes in the photonic band is also evident by the observed shifts in the frequency of several modes in the band, which are interpreted as due to multimode strong-coupling in a finite-bandwidth waveguide [30] [Fig. 1(d)]. The coupling to the metamaterial using the tight-binding description is $g/2\pi \approx 80$ MHz.

The exact frequencies of the modes and their shifts due to the interaction with the emitter are very sensitive to the specific realization of the disorder in our circuit; as a result, they cannot be quantitatively reproduced by an effective model assuming identical resonators. To make contact with the spectroscopy data, and model subsequent time-domain experiments, we resort to a model in which the frequency of the modes in the band, as well as the coupling of each mode to the quantum emitter, are left as free parameters. This effective model is described

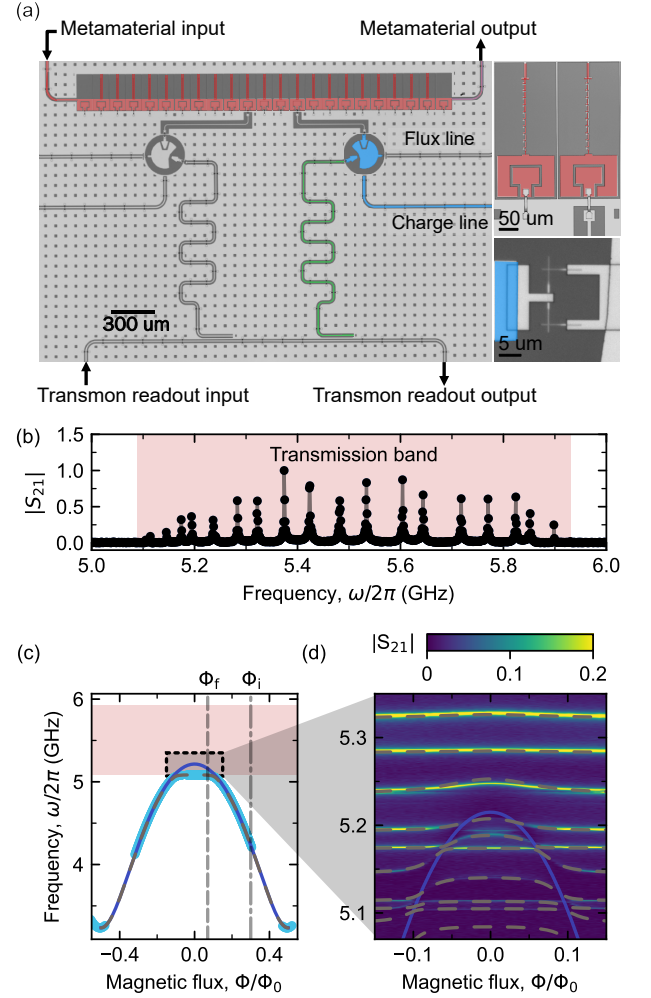


FIG. 1: Quantum emitter coupled to a metamaterial. (a) False-color micrograph of the device, including external connections. Salmon: lumped-element resonator array forming the metamaterial. Blue: transmon circuit acting as a quantum emitter. Green: readout resonator. Enlarged insets show (top) an individual resonator, including an array of Josephson junctions as the inductor, and (bottom) the two Josephson junctions of the transmon. (b) Transmission across the metamaterial, $|S_{21}|$ vs frequency. The 21 peaks forming the transmission band are shaded in salmon. (c) Emitter frequency vs magnetic flux. Blue dots: atom-photon bound state frequency, measured by two-tone spectroscopy. (Blue, solid line) bare emitter frequency and (Gray, dashed) atom-photon bound state frequency from the effective model. Vertical gridlines mark the working points chosen for this study. (d) $|S_{21}|$ vs flux and frequency, showing the response to the 9 lowest-frequency modes of the metamaterial to a change in the bare emitter frequency (in dark blue). Dashed lines: eigenmodes from the model.

by the Hamiltonian

$$H = \sum_{n=1}^N \tilde{\omega}_n a_n^\dagger a_n + \omega_q(\Phi) \frac{\sigma_z}{2} + \sum_{n=1}^N g_n (a_n \sigma_+ + a_n^\dagger \sigma_-), \quad (1)$$

in which $\tilde{\omega}_n$ are the dressed frequencies of the photonic modes, a_n ($a_n^\dagger$) are their corresponding photon annihilation (creation) operators, $\omega_q(\Phi)$ is the flux-dependent emitter frequency, and g_n are the static couplings between the emitter and each photonic mode. We truncate the Hamiltonian to the single-excitation subspace as our measurements are limited to this subspace (Supplementary Information). In addition, we consider only the first $N = 9$ modes from the lower band edge, since we do not observe any appreciable frequency shift in the others as the bare frequency of the emitter is tuned in and out of the photonic band [Fig. 1(d)]. Such a model quantitatively reproduces the spectroscopy data when we use mode frequencies extracted from measurements with the emitter far detuned and best-fitted coupling strengths g_n with values ranging from 3 to 25 MHz.

We study the formation and melting of an atom-photon bound state by manipulating the magnetic flux Φ in time, which, in turn, changes the emitter frequency. We primarily explore transitions between two points: an 'emitter-like point', denoted by the flux value Φ_i , in which the emitter is far from the band edge and responds as a two-level system, and a 'photon-like point', Φ_f , in which the emitter is highly hybridized with the photonic band. In the latter case, the emitter forms an atom-photon bound state whose photonic wavefunction is exponentially localized around the coupling site [39] [Fig. 1(c)].

We study the dynamics of the bound state's formation and melting by transitioning between the emitter-like and photon-like points at different speeds [Fig. 2(a)]. Starting at Φ_i , we excite the emitter with a π -pulse. Then, we apply a flux pulse between Φ_i and Φ_f . This pulse has a trapezoidal envelope characterized by a rise time τ_r ranging from 10 to 200 ns, a hold time τ_{hold} between 0 and 400 ns, and a fall time τ_f from 10 to 200 ns. After returning to Φ_i , we measure the remaining population in the emitter. To single out changes in the recovered population ($P_{|1\rangle}$), which shows an exponential decay with a time constant $T_1 = 4.4 \mu\text{s}$, we normalize the measurements to a reference obtained in the absence of the flux pulse.

We measure the population retained by the emitter as a function of the time spent in Φ_f for varying rise and fall times [Fig. 2(b)]. As the rise/fall time of the pulse is decreased, the relative retained population decreases on average and exhibits oscillations. An increasing number of frequencies contribute to these oscillations, as confirmed by a fast-Fourier transform (FFT) of the population record [Fig. 2(c)]. For $\tau_r = \tau_f = 200$ ns, the emitter's population is largely restored and no apparent oscillation is observed. For $\tau_r = \tau_f = 50$ ns, the average retained population decreases, and reproducible oscillations appear, as evident from FFT. For even shorter $\tau_r = \tau_f = 10$ ns, the

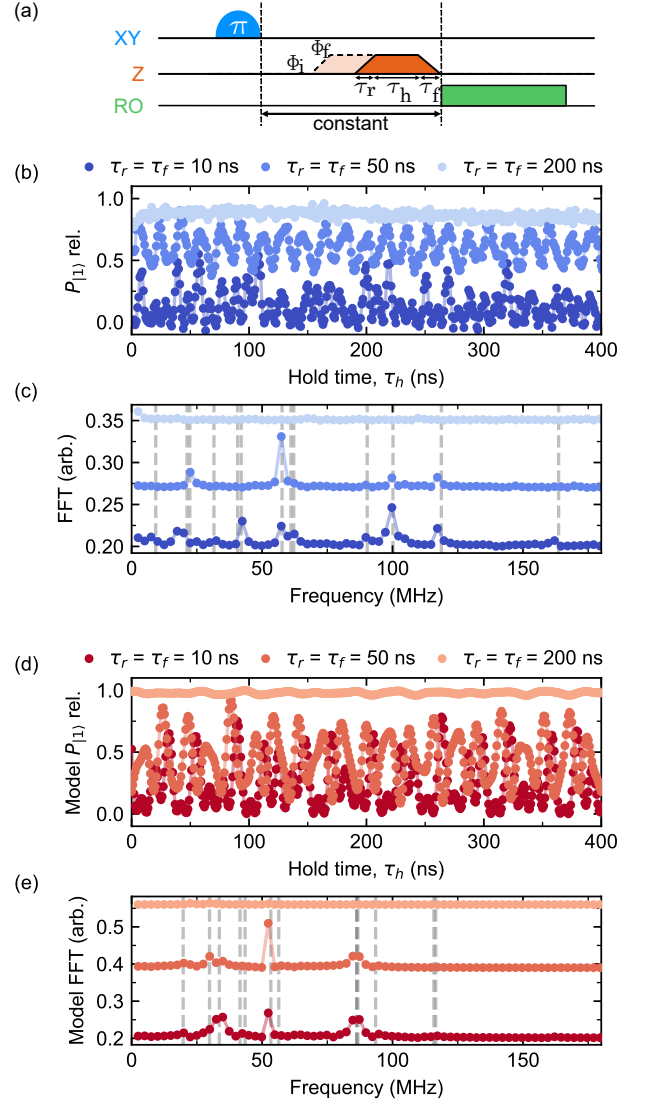


FIG. 2: Atom-photon bound state formation and melting at different speeds. (a) Pulse sequence of the measurement. (b) Measurement of the relative transmon population depending on hold time for $\tau_r = \tau_f = 10, 50, 200$ ns in a color gradient from dark to light. (c) FFT of the relative transmon population measurement. The data have been shifted vertically for clarity. Dashed lines correspond to the frequency differences between the modes at the final flux point. (d,e) Simulation results for parameter values resembling the experimental conditions in (b,c).

overall population decreases further, and more frequency components appear in the oscillatory population dynamics.

To understand the trends in the data, we solve the time-dependent Schrödinger equation using the Hamiltonian in Eq. 1, and coupling parameters g_n extracted from the measurement in Fig. 1; we include the time-dependent frequency of the emitter according to the applied flux pulse and flux-to-frequency transfer function. Our model qualitatively reproduces the observed behav-

ior in both the population and the FFT analyses, with decreasing population and increasing oscillations with increasing formation and melting speeds [Fig. 2(d),(e)].

In both the measurement and the model, the frequencies of the oscillations correspond to frequency differences between the dressed modes of the system [Fig. 2(c),(e)]. This correspondence suggests that for fast rise/fall times, the emitter's excitation is distributed over several dressed modes. Such distribution is understood by considering multi-mode Landau-Zener tunneling transitions [40–42], with beatings in the emitter population in time due to quantum interference effects. By contrast, for long rise/fall times, the large population recovery and the lack of oscillations indicate that the population of the emitter is adiabatically transferred to the lowest-energy eigenmode, i.e., the atom-photon bound state. The speed threshold for adiabatic transfer is generally sensitive to the mode frequencies and their coupling strength. However, a coarse estimate can be obtained from the single-mode Landau-Zener formula for a diabatic transition, $P_{LZ} = \exp(-2\pi\Gamma)$, with $\Gamma = g^2\Delta t/\Delta E$, by taking ΔE as the difference between the emitter's energy at the initial and final point, Δt as the rise time of the pulse, and g as a typical coupling between the emitter and the metamaterial modes. For our parameters, we predict that the average adiabatic limit is reached for a rise time between 200 and 300 ns, consistent with our observations.

However, there are two quantitative differences between the model and the data. A complete recovery of the population is predicted by simulations for $\tau_r = \tau_f = 200$ ns (adiabatic regime), while the recovery is only partial in the data. In addition, the frequencies and intensities of FFT peaks do not exactly match [Fig. 2(d),(e)]. We attribute the incomplete recovery to the presence of a coherent two-level system coupled to the emitter, with a resonant frequency between $\omega_q(\Phi_i)$ and $\omega_q(\Phi_f)$, which we detect by two-level-system spectroscopy [43–46] (Supplementary Information). As for the differences in the oscillatory patterns, they may be due to an incorrect estimate of the model parameters from the spectroscopy data, or to the non-ideal transfer function of the flux line used to apply the pulses [47], which we do not compensate for.

The demonstrated dynamic control opens the possibility of directly accessing the photonic component of the bound state, by releasing it into the metamaterial following a fast change in the emitter frequency. To do so, we first adiabatically prepare the bound state in a coherent superposition by exciting the emitter with a $\pi/2$ pulse and then slowly ramping the flux between Φ_i and Φ_f . Then, we quickly ramp the flux back to Φ_i . At the same time, we record the coherent component, $\langle \hat{a}_{out} \rangle$, of the outgoing field from the output port of the metamaterial, for a total duration of 20 μs [Fig. 3(a)]. In the diabatic limit, that is, for a fast change of the emitter frequency, we expect populations to be trapped in the instantaneous eigenstates preceding the quench. As a result, the photonic population stays photonic as the bound state is dis-

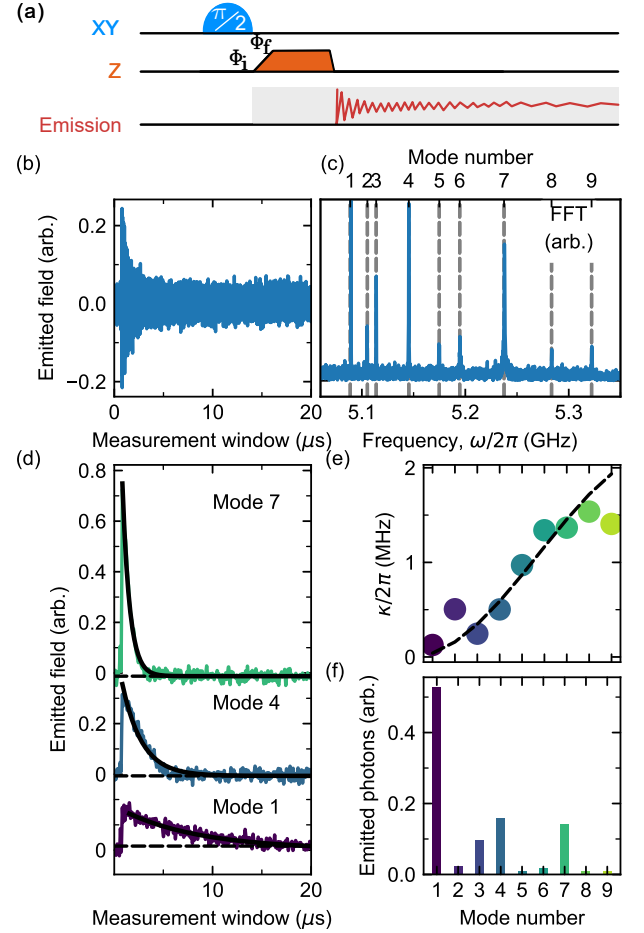


FIG. 3: Multimode emission. (a) Pulse sequence (see text for details). (b) Time trace of the emitted field. (c) FFT of the emitted field. Vertical gridlines denote the frequencies of the metamaterial modes, extracted from the spectroscopy in Fig. 1(d). (d) Demodulated time traces for selected modes and corresponding exponential fits (black lines). (e) Decay rates of the emission vs mode index, extracted from fits as in (d) (filled circles). Dashed line: decay rates of the modes as predicted by the tight-binding model. (f) Emitted photon number vs mode index, extracted as explained in the main text.

solved, and is converted into propagating photonic modes in the metamaterial.

The time trace [Fig. 3(b)] is digitally recorded with a 1-GHz-wide acquisition band centered at 5 GHz. Its FFT reveals a total of 9 prominent peaks [Fig. 3(c)]. Notably, the frequencies of the peaks show a one-to-one correspondence with the frequencies of the 9 lowest-frequency modes of the photonic band, as measured in Fig. 1. We extract the temporal envelope of the radiation emitted into each mode by demodulating the time trace at the each of the peak frequencies [selected traces are shown in Fig. 3(d)]. The emission from each mode decays exponentially with a distinct decay rate [Fig. 3(e)]. As a general trend, the decay rates are slower near the band edge and become faster towards the center of the band. When

we compare the measured decay rates to those predicted from the tight-binding model [solid line in Fig. 3(e)], we find a good agreement.

We quantify the total emitted photons at each mode by integrating $\langle \hat{a}_n \rangle$ and squaring the result [Fig. 3(f)]. This last measurement is interpreted as a decomposition of the photonic part of the atom-photon bound state into the propagating photonic modes it consisted of, also providing a quantitative estimate of the relative population strengths. Because the multimode emission stems from a single excitation in the atom-photon bound state, we expect these modes to be entangled. However, we leave a detailed study of the mode correlations to further studies.

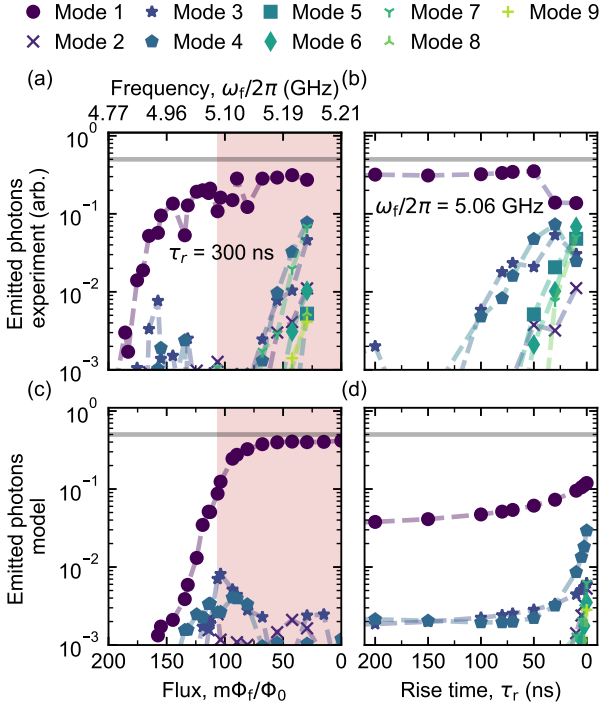


FIG. 4: Mode components of the emission depending on control parameters. (a) Mode components of the emission as a function of the photon-like points, Φ_f , for an adiabatic rise time $\tau_r = 300$ ns. In salmon: Transmission band. The data are normalized so that the total emission deep into the transmission band is equal to 0.5 photons (horizontal gray line). (b) Emission mode components for the same photon-like point vs rise time (the x axis is inverted). (c,d) Numerical simulations corresponding to (a,b).

We further explore the spectrally resolved emission from the atom-photon bound state by varying the conditions for its preparation, while keeping a short fall time $\tau_f = 10$ ns. In the adiabatic regime ($\tau_r = 300$ ns) at different final emitter frequencies, parametrized by Φ_f , we expect the emission to mirror the decomposition of the photonic component of the atom-photon-bound state into the metamaterial modes. Far away from the band, the emission is weak and mostly from the mode at the

lower edge of the band. Deeper inside the band, the total emission saturates (as the atom-photon bound state becomes mostly photonic), and other modes contribute to the emission. The participation of other modes in the emission is affected by the realization of the disorder in the array, and its dependence on the emitter frequency can be non-monotonic, as seen in Fig. 4(a).

We investigate the dependence of the emission on the rise time of the flux pulse, for a 'photon-like' point close to the band edge, at $\omega_f/2\pi = 5.06$ GHz [Fig. 4(b)]. Here, the emitted radiation shows a clear transition from single-mode to multi-mode as the rise time is decreased. Furthermore, with shorter rise times, modes nearer to the band center contribute more significantly to the emission. We interpret this emission as due to nonadiabatic preparation of the atom-photon bound state, leading to direct excitation of propagating modes.

The trends observed in these measurements are partly reproduced by our model [Fig. 4(c),(d)]. The model correctly captures the dominant emission from the lowest-frequency mode in the regime of adiabatic formation [Fig. 4(c)], and the increased participation of higher-frequency modes at shorter rise times [Fig. 4(d)]. However, there are quantitative differences, which we ascribe to a combination of factors. First, for fast pulses, pulse distortions due to the transfer function of the flux line will affect the speed at which the modes are crossed, and therefore the probabilities of having multi-mode Landau-Zener transitions. As mentioned before, the extraction of the model parameters from the spectroscopy data may not be entirely precise. In addition, including more modes in the model may be needed to explain the data closer to the center of the band. Lastly, disorder in the array may cause the propagating modes to have non-symmetric spatial distributions and uneven couplings to the input and output ports of the metamaterial, which would affect the relative strength of their detected emission.

In conclusion, our study integrates measurements of emitter population and frequency-resolved radiation detection to elucidate the dynamic interaction between a quantum emitter and a metamaterial. The finite coupling of the emitter to the modes of the metamaterial results in a speed threshold at which the state is adiabatically transferred from the bare emitter to the atom-photon bound state. Understanding this threshold is important to use atom-photon bound states in quantum simulators, especially given that bound states have smaller anharmonicities than the bare emitters they originate from [31, 34], so adiabatic preparation of their state may offer advantages compared to direct pulsed excitation. In addition, we have directly observed the melting of an atom-photon bound state following a fast change in the emitter frequency, by detecting the radiation emitted from it. By resolving the frequency components of the emitted radiation, we gain direct access to the spectral decomposition of the atom-photon bound state into its photonic components. This method can be applied,

for example, to study the composition of atom-photon bound states hosted by more exotic photonic lattices, of multiple bound states coupled to the same lattice, or of multi-photon bound states beyond the single-excitation subspace, thus providing a way – complementary to static spectroscopy studies – to characterize light-matter interactions in these systems.

We are grateful to Aamir Ali and Axel Eriksson for technical support, to Linus Andersson for fabricating the sample package, to Anita Fadavi Roudsari for her contributions to the nanofabrication recipes, to Alejandro

Gonzalez-Tudela and Francesco Ciccarello for their input on the manuscript, and to Ariadna Soro and Anton Frisk Kockum for initial discussions. The Schrödinger equation was solved using QuTiP [48]. The device in this work was fabricated in Myfab, Chalmers, a micro and nanofabrication laboratory. This work received support from the Swedish Research Council; and the Knut and Alice Wallenberg Foundation through the Wallenberg Center for Quantum Technology (WACQT). SG acknowledges financial support from the European Research Council via Grant No. 101041744 ESQuAT.

-
- [1] J. S. Douglas, H. Habibian, C.-L. Hung, A. V. Gorshkov, H. J. Kimble, and D. E. Chang, Quantum many-body models with cold atoms coupled to photonic crystals, *Nat Photon* **9**, 326 (2015).
 - [2] A. González-Tudela, C.-L. Hung, D. E. Chang, J. I. Cirac, and H. J. Kimble, Subwavelength vacuum lattices and atom-atom interactions in two-dimensional photonic crystals, *Nature Photonics* **9**, 320 (2015).
 - [3] A. Biella, L. Mazza, I. Carusotto, D. Rossini, and R. Fazio, Photon transport in a dissipative chain of nonlinear cavities, *Phys. Rev. A* **91**, 053815 (2015).
 - [4] L. Lu, J. D. Joannopoulos, and M. Soljacic, Topological states in photonic systems, *Nat Phys* **12**, 626 (2016).
 - [5] G. Calajó, F. Ciccarello, D. Chang, and P. Rabl, Atom-field dressed states in slow-light waveguide QED, *Phys. Rev. A* **93**, 033833 (2016).
 - [6] V. M. Martinez Alvarez and M. D. Coutinho-Filho, Edge states in trimer lattices, *Phys. Rev. A* **99**, 013833 (2019).
 - [7] R. Belyansky, S. Whitsitt, R. Lundgren, Y. Wang, A. Vrajitoarea, A. A. Houck, and A. V. Gorshkov, Frustration-induced anomalous transport and strong photon decay in waveguide QED, *Physical Review Research* **3**, L032058 (2021).
 - [8] G. Fedorov, S. Remizov, D. Shapiro, W. Pogosov, E. Egorova, I. Tsitsilin, M. Andronik, A. Dobronosova, I. Rodionov, O. Astafiev, and A. Ustinov, Photon Transport in a Bose-Hubbard Chain of Superconducting Artificial Atoms, *Physical Review Letters* **126**, 180503 (2021).
 - [9] F. Ciccarello, Resonant atom-field interaction in large-size coupled-cavity arrays, *Physical Review A* **83**, 043802 (2011).
 - [10] A. S. Sheremet, M. I. Petrov, I. V. Iorsh, A. V. Poshakinskiy, and A. N. Poddubny, Waveguide quantum electrodynamics: Collective radiance and photon-photon correlations, *Reviews of Modern Physics* **95**, 015002 (2023).
 - [11] D. Fernández-Fernández and A. González-Tudela, Tunable Directional Emission and Collective Dissipation with Quantum Metasurfaces, *Physical Review Letters* **128**, 113601 (2022).
 - [12] J. Roman-Roche, E. Sanchez-Burillo, and D. Zueco, Bound states in ultrastrong waveguide QED, *arXiv:2001.07643* (2020).
 - [13] G. Calajó, Y.-L. L. Fang, H. U. Baranger, and F. Ciccarello, Exciting a Bound State in the Continuum through Multiphoton Scattering Plus Delayed Quantum Feedback, *Phys. Rev. Lett.* **122**, 073601 (2019).
 - [14] C.-L. Hung, A. González-Tudela, J. I. Cirac, and H. J. Kimble, Quantum spin dynamics with pairwise-tunable, long-range interactions, *Proceedings of the National Academy of Sciences* **113**, E4946 (2016), eprint: <http://www.pnas.org/content/113/34/E4946.full.pdf>.
 - [15] D. Chang, J. Douglas, A. González-Tudela, C.-L. Hung, and H. Kimble, *Colloquium* : Quantum matter built from nanoscopic lattices of atoms and photons, *Reviews of Modern Physics* **90**, 031002 (2018).
 - [16] C. D. Bruzewicz, J. Chiaverini, R. McConnell, and J. M. Sage, Trapped-ion quantum computing: Progress and challenges, *Applied Physics Reviews* **6**, 021314 (2019).
 - [17] A. McDonald, T. Pereg-Barnea, and A. Clerk, Phase-Dependent Chiral Transport and Effective Non-Hermitian Dynamics in a Bosonic Kitaev-Majorana Chain, *Physical Review X* **8**, 041031 (2018).
 - [18] T. Manovitz, Y. Shapira, N. Akerman, A. Stern, and R. Ozeri, Quantum Simulations with Complex Geometries and Synthetic Gauge Fields in a Trapped Ion Chain, *PRX Quantum* **1**, 020303 (2020).
 - [19] M. K. Joshi, A. Elben, B. Vermersch, T. Brydges, C. Maier, P. Zoller, R. Blatt, and C. F. Roos, Quantum Information Scrambling in a Trapped-Ion Quantum Simulator with Tunable Range Interactions, *Physical Review Letters* **124**, 240505 (2020).
 - [20] I. Carusotto, A. A. Houck, A. J. Kollár, P. Roushan, D. I. Schuster, and J. Simon, Photonic materials in circuit quantum electrodynamics, *Nature Physics* **16**, 268 (2020).
 - [21] J. D. Brehm, A. N. Poddubny, A. Stehli, T. Wolz, H. Rotzinger, and A. V. Ustinov, Waveguide bandgap engineering with an array of superconducting qubits, *npj Quantum Materials* **6**, 1 (2021).
 - [22] M. Mirhosseini, E. Kim, V. S. Ferreira, M. Kalaei, A. Sipahigil, A. J. Keller, and O. Painter, Superconducting metamaterials for waveguide quantum electrodynamics, *Nat. Comm.* **9**, 3706 (2018).
 - [23] A. Morvan, T. I. Andersen, X. Mi, C. Neill, A. Petukhov, K. Kechedzhi, D. A. Abanin, A. Michailidis, R. Acharya, F. Arute, K. Arya, A. Asfaw, J. Atalaya, J. C. Bardin, J. Basso, A. Bengtsson, G. Bortoli, A. Bourassa, J. Bo-vaird, L. Brill, M. Broughton, B. B. Buckley, D. A. Buell, T. Burger, B. Burkett, N. Bushnell, Z. Chen, B. Chiaro, R. Collins, P. Conner, W. Courtney, A. L. Crook, B. Curtin, D. M. Debroy, A. Del Toro Barba, S. Demura, A. Dunsworth, D. Eppens, C. Erickson, L. Faoro, E. Farhi, R. Fatemi, L. Flores Burgos, E. Forati, A. G. Fowler, B. Foxen, W. Jiang, C. Gidney, D. Gilboa,

- M. Giustina, A. Grajales Dau, J. A. Gross, S. Habegger, M. C. Hamilton, M. P. Harrigan, S. D. Harrington, M. Hoffmann, S. Hong, T. Huang, A. Huff, W. J. Huggins, S. V. Isakov, J. Iveland, E. Jeffrey, Z. Jiang, C. Jones, P. Juhas, D. Kafri, T. Khatyar, M. Khezri, M. Kieferová, S. Kim, A. Y. Kitaev, P. V. Klimov, A. R. Klots, A. N. Korotkov, F. Kostritsa, J. M. Kreikebaum, D. Landhuis, P. Laptev, K.-M. Lau, L. Laws, J. Lee, K. W. Lee, B. J. Lester, A. T. Lill, W. Liu, A. Lochar, F. Malone, O. Martin, J. R. McClean, M. McEwen, B. Meurer Costa, K. C. Miao, M. Mohseni, S. Montazeri, E. Mount, W. Mruczkiewicz, O. Naaman, M. Neeley, A. Nersisyan, M. Newman, A. Nguyen, M. Nguyen, M. Y. Niu, T. E. O'Brien, R. Olenewa, A. Opremcak, R. Potter, C. Quintana, N. C. Rubin, N. Saei, D. Sank, K. Sankaragomathi, K. J. Satzinger, H. F. Schurkus, C. Schuster, M. J. Shearn, A. Shorter, V. Shvarts, J. Skrzynny, W. C. Smith, D. Strain, G. Sterling, Y. Su, M. Szalay, A. Torres, G. Vidal, B. Villalonga, C. Vollgraft-Heidweiller, T. White, C. Xing, Z. Yao, P. Yeh, J. Yoo, A. Zalcman, Y. Zhang, N. Zhu, H. Neven, D. Bacon, J. Hilton, E. Lucero, R. Babbush, S. Boixo, A. Megrant, J. Kelly, Y. Chen, V. Smelyanskiy, I. Aleiner, L. B. Ioffe, and P. Roushan, Formation of robust bound states of interacting microwave photons, *Nature* **612**, 240 (2022).
- [24] M. Bello, G. Platero, and A. González-Tudela, Spin Many-Body Phases in Standard- and Topological-Waveguide QED Simulators, *PRX Quantum* **3**, 010336 (2022).
- [25] X. Zhang, E. Kim, D. K. Mark, S. Choi, and O. Painter, A scalable superconducting quantum simulator with long-range connectivity based on a photonic bandgap metamaterial, *Science* **379**, 278 (2023), arXiv:2206.12803 [quant-ph].
- [26] C. Tabares, A. Muñoz de las Heras, L. Tagliacozzo, D. Porras, and A. González-Tudela, Variational Quantum Simulators Based on Waveguide QED, *Physical Review Letters* **131**, 073602 (2023).
- [27] T. McBroom-Carroll, A. Schlabe, X. Xu, J. Ku, B. Cole, S. Indrajeet, M. D. LaHaye, M. H. Ansari, and B. L. T. Plourde, Entangling interactions between artificial atoms mediated by a multimode left-handed superconducting ring resonator (2023), arXiv:2307.15695 [cond-mat, physics:quant-ph].
- [28] V. S. Ferreira, G. Kim, A. Butler, H. Pichler, and O. Painter, Deterministic generation of multidimensional photonic cluster states with a single quantum emitter, *Nature Physics*, 1 (2024).
- [29] V. D. Vaidya, Y. Guo, R. M. Kroeze, K. E. Ballantine, A. J. Kollár, J. Keeling, and B. L. Lev, Tunable-Range, Photon-Mediated Atomic Interactions in Multimode Cavity QED, *Physical Review X* **8**, 011002 (2018).
- [30] Y. Liu and A. A. Houck, Quantum electrodynamics near a photonic bandgap, *Nature Physics* **13**, 48 (2016).
- [31] N. M. Sundareshan, R. Lundgren, G. Zhu, A. V. Gorshkov, and A. A. Houck, Interacting Qubit-Photon Bound States with Superconducting Circuits, *Phys. Rev. X* **9**, 011021 (2019).
- [32] E. Kim, X. Zhang, V. S. Ferreira, J. Banker, J. K. Iverson, A. Sipahigil, M. Bello, A. González-Tudela, M. Mirhosseini, and O. Painter, Quantum Electrodynamics in a Topological Waveguide, *Physical Review X* **11**, 011015 (2021).
- [33] V. S. Ferreira, J. Banker, A. Sipahigil, M. H. Matheny, A. J. Keller, E. Kim, M. Mirhosseini, and O. Painter, Collapse and Revival of an Artificial Atom Coupled to a Structured Photonic Reservoir, *Physical Review X* **11**, 041043 (2021).
- [34] M. Scigliuzzo, G. Calajò, F. Ciccarello, D. Perez Lozano, A. Bengtsson, P. Scarlino, A. Wallraff, D. Chang, P. Delsing, and S. Gasparinetti, Controlling Atom-Photon Bound States in an Array of Josephson-Junction Resonators, *Physical Review X* **12**, 031036 (2022).
- [35] C. Vega, D. Porras, and A. González-Tudela, Topological multimode waveguide QED, *Physical Review Research* **5**, 023031 (2023).
- [36] J. Koch, T. M. Yu, J. Gambetta, A. A. Houck, D. I. Schuster, J. Majer, A. Blais, M. H. Devoret, S. M. Girvin, and R. J. Schoelkopf, Charge-insensitive qubit design derived from the Cooper pair box, *Phys. Rev. A* **76**, 042319 (2007).
- [37] A. Blais, A. L. Grimsmon, S. Girvin, and A. Wallraff, Circuit quantum electrodynamics, *Reviews of Modern Physics* **93**, 025005 (2021).
- [38] M. Hutchings, J. Hertzberg, Y. Liu, N. Bronn, G. Keefe, M. Brink, J. M. Chow, and B. Plourde, Tunable Superconducting Qubits with Flux-Independent Coherence, *Physical Review Applied* **8**, 044003 (2017).
- [39] F. Lombardo, F. Ciccarello, and G. M. Palma, Photon localization versus population trapping in a coupled-cavity array, *Physical Review A* **89**, 053826 (2014).
- [40] A. V. Shytov, Landau-Zener transitions in a multilevel system: An exact result, *Physical Review A* **70**, 052708 (2004).
- [41] K. Saito, M. Wubs, S. Kohler, Y. Kayanuma, and P. Hänggi, Dissipative Landau-Zener transitions of a qubit: Bath-specific and universal behavior, *Physical Review B* **75**, 214308 (2007).
- [42] A. Stehli, J. D. Brehm, T. Wolz, A. Schneider, H. Rotzinger, M. Weides, and A. V. Ustinov, Quantum emulation of the transient dynamics in the multistate Landau-Zener model, *npj Quantum Information* **9**, 1 (2023).
- [43] P. Klimov, J. Kelly, Z. Chen, M. Neeley, A. Megrant, B. Burkett, R. Barends, K. Arya, B. Chiaro, Y. Chen, A. Dunsworth, A. Fowler, B. Foxen, C. Gidney, M. Giustina, R. Graff, T. Huang, E. Jeffrey, E. Lucero, J. Mutus, O. Naaman, C. Neill, C. Quintana, P. Roushan, D. Sank, A. Vainsencher, J. Wenner, T. White, S. Boixo, R. Babbush, V. Smelyanskiy, H. Neven, and J. Martinis, Fluctuations of Energy-Relaxation Times in Superconducting Qubits, *Physical Review Letters* **121**, 090502 (2018), publisher: American Physical Society.
- [44] J. J. Burnett, A. Bengtsson, M. Scigliuzzo, D. Niepce, M. Kudra, P. Delsing, and J. Bylander, Decoherence benchmarking of superconducting qubits, *npj Quantum Information* **5**, 1 (2019).
- [45] J. Lisenfeld, A. Bilmes, A. Megrant, R. Barends, J. Kelly, P. Klimov, G. Weiss, J. M. Martinis, and A. V. Ustinov, Electric field spectroscopy of material defects in transmon qubits, *npj Quantum Information* **5**, 1 (2019).
- [46] A. Bilmes, A. Megrant, P. Klimov, G. Weiss, J. M. Martinis, A. V. Ustinov, and J. Lisenfeld, Resolving the positions of defects in superconducting quantum bits, *Scientific Reports* **10**, 3090 (2020).
- [47] M. A. Rol, L. Ciorciaro, F. K. Malinowski, B. M. Tarasinski, R. E. Sagastizabal, C. C. Bultink, Y. Salathe,

- N. Haandbaek, J. Sedivy, and L. DiCarlo, Time-domain characterization and correction of on-chip distortion of control pulses in a quantum processor, *Appl. Phys. Lett.* **10.1063/1.5133894** (2020).
- [48] J. R. Johansson, P. D. Nation, and F. Nori, QuTiP 2: A Python framework for the dynamics of open quantum systems, *Computer Physics Communications* **184**, 1234 (2013).
- [49] M. C. Collodo, J. Herrmann, N. Lacroix, C. K. Andersen, A. Remm, S. Lazar, J.-C. Besse, T. Walter, A. Wallraff, and C. Eichler, Implementation of Conditional Phase Gates Based on Tunable $\$ZZ\$$ Interactions, *Physical Review Letters* **125**, 240502 (2020).
- [50] G. L. C. Roberts, *Quantum Fluids in a Bose-Hubbard Circuit*, Ph.D. thesis.
- [51] M. Wubs, K. Saito, S. Kohler, P. Hänggi, and Y. Kayanuma, Gauging a Quantum Heat Bath with Dissipative Landau-Zener Transitions, *Physical Review Letters* **97**, 200404 (2006).
- [52] S. Krinner, N. Lacroix, A. Remm, A. Di Paolo, E. Genois, C. Leroux, C. Hellings, S. Lazar, F. Swiadek, J. Herrmann, G. J. Norris, C. K. Andersen, M. Müller, A. Blais, C. Eichler, and A. Wallraff, Realizing repeated quantum error correction in a distance-three surface code, *Nature* **605**, 669 (2022).
- [53] X. Gu, A. F. Kockum, A. Miranowicz, Y.-X. Liu, and F. Nori, Microwave photonics with superconducting quantum circuits, *Physics Reports Microwave photonics with superconducting quantum circuits*, **718-719**, 1 (2017).
- [54] Y. Sun, J. Ding, X. Xia, X. Wang, J. Xu, S. Song, D. Lan, J. Zhao, and Y. Yu, Fabrication of airbridges with gradient exposure, *Applied Physics Letters* **121**, 074001 (2022).
- [55] P. Krantz, M. Kjaergaard, F. Yan, T. P. Orlando, S. Gustavsson, and W. D. Oliver, A quantum engineer's guide to superconducting qubits, *Applied Physics Reviews* **6**, 021318 (2019).
- [56] M. Scigliuzzo, A. Bengtsson, J.-C. Besse, A. Wallraff, P. Delsing, and S. Gasparinetti, Primary Thermometry of Propagating Microwaves in the Quantum Regime, *Physical Review X* **10**, 041054 (2020).
- [57] S. Chakram, K. He, A. V. Dixit, A. E. Oriani, R. K. Naik, N. Leung, H. Kwon, W.-L. Ma, L. Jiang, and D. I. Schuster, Multimode photon blockade, *Nature Physics* **18**, 879 (2022).
- [58] Z. Chen, A. Megrant, J. Kelly, R. Barends, J. Bochmann, Y. Chen, B. Chiaro, A. Dunsworth, E. Jeffrey, J. Y. Mutus, P. J. J. O'Malley, C. Neill, P. Roushan, D. Sank, A. Vainsencher, J. Wenner, T. C. White, A. N. Cleland, and J. M. Martinis, Fabrication and characterization of aluminum airbridges for superconducting microwave circuits, *Applied Physics Letters* **104**, 052602 (2014).
- [59] R. H. Dicke, Coherence in Spontaneous Radiation Processes, *Physical Review* **93**, 99 (1954).
- [60] A. H. Kiilerich and K. Mølmer, Input-Output Theory with Quantum Pulses, *Physical Review Letters* **123**, 123604 (2019).

SUPPLEMENTARY INFORMATION

APPENDIX A. EXPERIMENTAL SETUP

In Fig. S1, we show the full wiring diagram for our experiment. The device under test is installed inside a dilution refrigerator that reaches a temperature below 9 mK. It is shielded from electromagnetic interference with rf-tight copper shields, and from static magnetic fields with two Cryoperm shields and a superconducting shield. We attenuate incoming signals to minimize thermal photon generation, and the output lines include multiple amplification stages, including a low-temperature High Electron Mobility Transistor (HEMT) and two (three) room-temperature amplifiers for the readout resonator (metamaterial). To mitigate noise external to our frequency range and avoid aliasing, we incorporate additional filters and DC blocks.

Microwave signals are sent and recorded with a microwave transceiver (Presto from Intermodulation Products AB) capable of direct digital synthesis in the band of interest. A Keysight PXI chassis is used to send both flux DC signals and flux DC pulses, through a Source Measure Unit (SMU) and an Arbitrary Wave Generator (AWG), respectively. We use the SMU DC signal in the flux line of the unused emitter to detune its frequency from the rest of the elements.

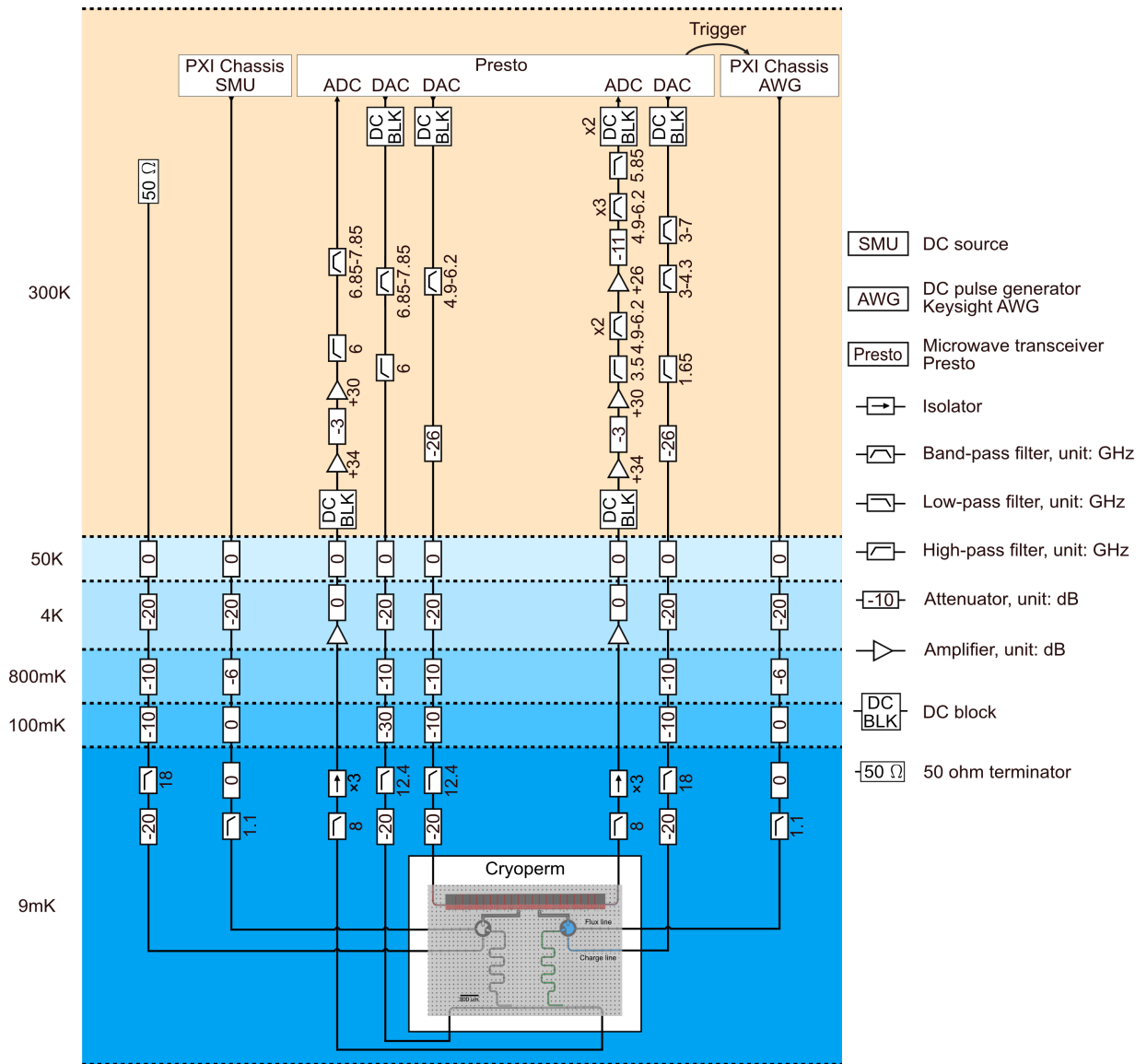


FIG. S1: **Fridge connections.** Cooling-down stages color color-coded depending on the temperature.

APPENDIX B. MODELS AND SYSTEM PARAMETERS

B.1. Ideal tight-binding model

Assuming identical resonators, our metamaterial formed from nearest-neighbor-coupled resonators can be modeled using the standard tight-binding model Hamiltonian, which reads

$$H = \sum_{n=1}^N \omega_r a_n^\dagger a_n + \sum_{n=1}^{N-1} J \left(a_n^\dagger a_{n+1} + a_{n+1}^\dagger a_n \right) + J_{nn} \sum_{n=1}^{N-2} \left(a_{n+2}^\dagger a_n + H.c. \right) + \omega_q(\Phi) \frac{\sigma_z}{2} + g \left(a_{13} \sigma_+ + a_{13}^\dagger \sigma_- \right), \quad (\text{S1})$$

Here, ω_r is the bare resonator frequency, J is the nearest-neighbor coupling between resonators, a_n ($a_n^\dagger$) is the photon annihilation (creation) operator of the n -th resonator, $\omega_q(\Phi)$ is the flux-dependent transmon frequency, β is the transmon's anharmonicity, b and $b^\dagger$ its annihilation and creation operators, and g the coupling between the transmon and the 13th site of the array.

B.2. Effective model

Our effective model comes as an alternative to the tight-binding model to study the dynamics of our atom-photon bound state formation and melting. This model aims at addressing the disorder in the system, which produces variations in our metamaterial frequencies, instead of assuming the same frequency for all the resonators. The Hamiltonian is given in Eq. 1.

B.3. Model parameters

Table SI lists the parameters extracted from the measurements using both models. The parameters ω_r and J are obtained from comparing the tight-binding model to the resonant frequencies in our metamaterial. We extract J from the bandwidth of the transmission band, $4(J/2\pi) = 842$ MHz, and ω_r corresponds to the center frequency. We obtain κ_r from the linewidth of the center resonator in the transmission band in Fig.1(b). $Z_r = \frac{1}{\omega_r C_r}$, in which C_r is obtained from the simulated capacitance matrix of the element. The value of the coupling between the atom-photon bound state and array site 13, g , is obtained fitting the experimental result of the atom-photon bound state spectroscopy [Fig.1(c)] to the frequency of the flux-dependent dressed state atom-photon bound state mode from the tight-binding Hamiltonian.

The individual couplings of the atom-photon bound state and the array modes, g_n , require a more complex fitting with an optimizer that obtains the flux-dependent eigenstates from the Hamiltonian of the effective model and fits with the spectroscopy of the atom-photon bound state [Fig.1(c)] and measured flux-dependent metamaterial in Fig.1(d).

APPENDIX C. TWO-LEVEL-SYSTEM SPECTROSCOPY

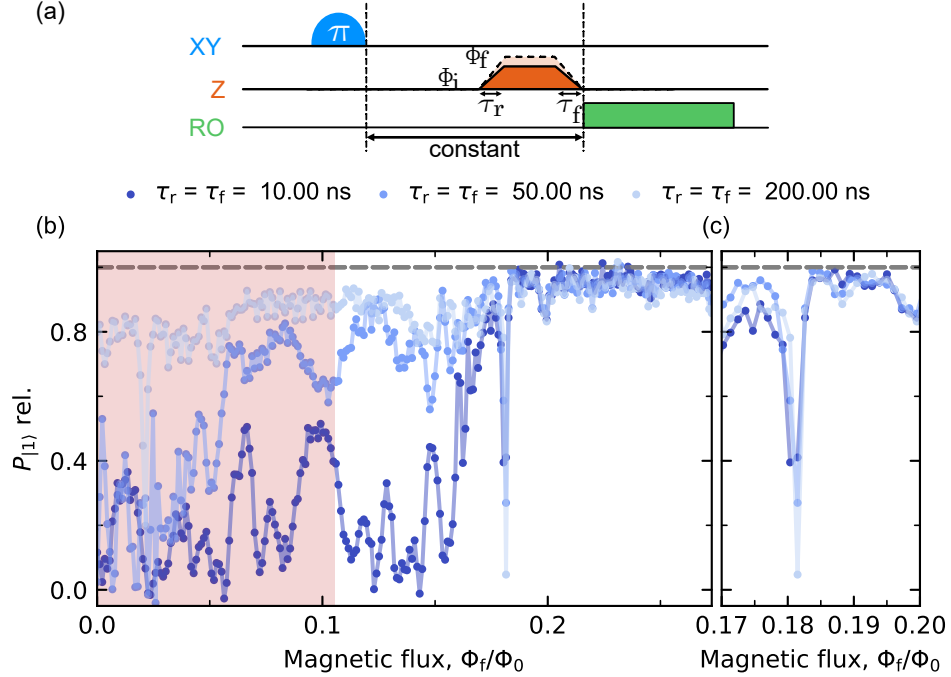
Two-level systems (TLS) are inherent to superconducting qubits. They couple to the emitter and affect its coherence, cause frequency fluctuations, and induce relaxation; decrementing the performance [43–46]. Therefore, to run reliable measurements, they need to be characterized and, if possible, avoided.

In our case, we characterize the TLS landscape of our system by measuring the total recovered population in the excited state when the transmon frequency is changed through its Z control (flux line), left interacting with the TLS for a timescale of 100 ns, and brought back, reproducing the measurement in Fig. 2. As in the previous case, we excite the emitter with a π pulse and change its frequency with an applied trapezoidal flux pulse with different flux amplitudes Φ_f . We measure the total recovered population in the excited state at the initial frequency (Φ_i or ω_i) for the three cases, previously studied in the main text, $\tau_r = \tau_f = 10, 50, 200$ ns [Fig. S2]. Because the transmon coherence time, T_1 , is reduced when coupled to a TLS, the recovered population will be reduced when a TLS is present. This measurement is similar to those conducted in [45, 46].

For the three cases, a visible reduction in the retrieved population happens at approximately $0.2 \phi_0$ and $0.18 \phi_0$, which we identify as two TLSs. For the TLS at $195 m\phi_0$, all the population is recovered back after crossing it. However, in the case of the TLS at $180 m\phi_0$, we obtain an average reduction of 10 %. We attribute to this TLS the loss in the recovered population when the atom-photon bound state is adiabatically created and disintegrated in the main text [Fig. 2]. In addition, we can observe the effect of the atom-photon bound state formation and the coupling

TABLE SI: Model parameters and experimentally determined values.

Parameter	Symbol	Value
Qubit and resonator		
Emitter frequency	$\omega_q/2\pi$	3.23-5.23 GHz
Relaxation time at sweet spot	T_1	8.45 μ s
Coherence time at sweet spot	T_2	6 μ s
Anharmonicity	$\beta/2\pi$	-249.8 MHz
Readout resonator frequency	$\omega_{\text{res}}/2\pi$	7.462 GHz
Readout resonator decay	$\kappa_{\text{res}}/2\pi$	178 kHz
Tight-binding model		
Metamaterial center frequency	$\omega_r/2\pi$	5.5075 GHz
Nearest-neighbor coupling	$J/2\pi$	211.25 MHz
Next-nearest-neighbor coupling	$J_{nn}/2\pi$	1.34 MHz
Resonator decay	$\kappa_r/2\pi$	6.44 MHz
Resonator impedance	Z_r	387.23 Ω
Emitter-resonator coupling	$g/2\pi$	72.85 MHz
Effective model		
Metamaterial frequencies	$\tilde{\omega}_n/2\pi$	{5.088, 5.105, 5.114, 5.145, 5.174, 5.194, 5.236, 5.283, 5.322} GHz
Emitter-resonator couplings	$g_n/2\pi$	{20.67, 5.01, 9.33, 19.01, 3.06, 11.393, 25.434, 10.99, 20.16} MHz

**FIG. S2: TLS spectroscopy showing the loss of population depending on τ_r and τ_f .** (a) Pulse sequence: A π -pulse to the XY line, a trapezoidal-shaped flux pulse to the Z line with different amplitudes or Φ_f , and a pulse to the readout line at a constant time from the π -pulse to normalize decoherence in between the measurements. (b) Recovered population for three different rise and fall times. In shaded salmon the position of the metamaterial transmission band. (c) Inset of the two-level fluctuator position and effect in the recovered population.

to the metamaterial modes already at 0.16 ϕ_0 for the diabatic cases (especially for $\tau_r = \tau_f = 10$ ns), in which the population decreases and increases, product of the LZ multilevel tunneling. However, this decrease becomes smaller for $\tau_r = \tau_f = 50$ ns and almost disappears for $\tau_r = \tau_f = 200$ ns, features of a transition to an adiabatic formation and melting, as already explained in the main text.

APPENDIX D. MODEL FITS TO THE METAMATERIAL SPECTROSCOPY DATA

We compare fits of our two models to the metamaterial spectroscopy data obtained as a function of the applied magnetic flux [Fig. S3(a,b)]. Disorder affects the distribution of the modes, which cannot be captured by the ideal tight-binding model, even when the emitter is far detuned [Fig. S3(a)]. By contrast, at the price of a large number of free parameters, the effective model reproduces the data more accurately [Fig. S3(b)].

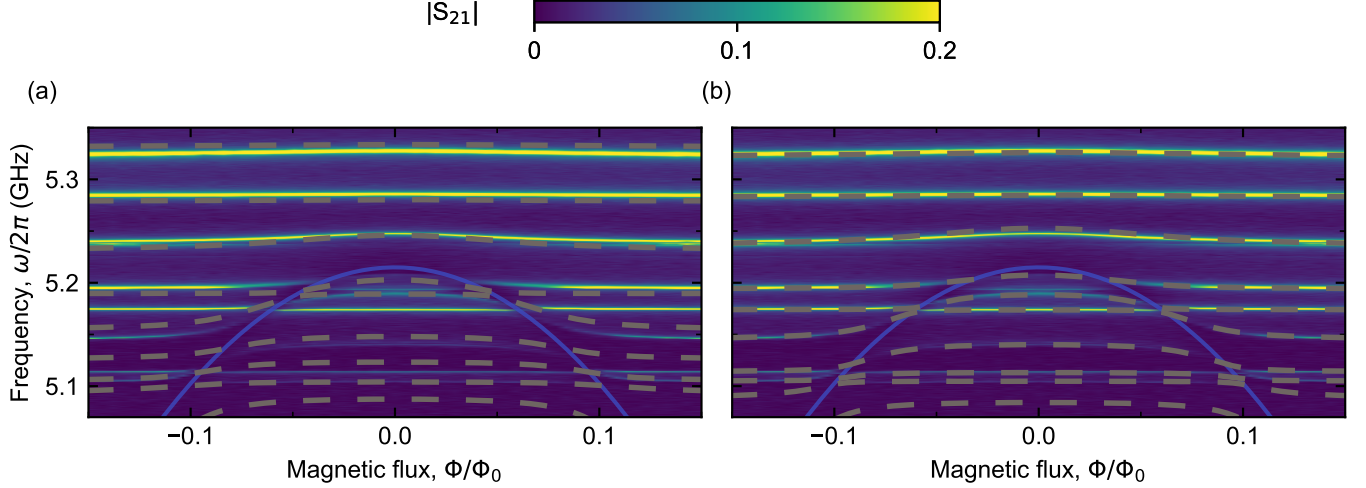


FIG. S3: Model fits to the spectroscopy data: (a) Tight-binding model. (b) Effective model.

APPENDIX E. EXPONENTIAL DECAY OF THE EMITTED FIELD

The demodulated signal for each mode in the emitted field (see Fig. 3) exhibits an exponential decay behavior with a lifetime, τ , which correlates with the predicted mode linewidths provided by the tight-binding model (see Fig. S4). Therefore, these fits reveal a consistent trend: higher mode numbers correspond to smaller lifetimes (or larger linewidths), with the modes near the center expected to have minimal decay. We attribute variances from this trend in the modes with a smaller emission to a smaller signal-to-noise ratio.

However, for the fifth mode, the emitted signal displays not only exponential decay but also concurrent behavior. Although we leave the characterization of this effect to further studies, we hypothesize that these concurrences may arise from a less-coupled mode to the ports, which causes revivals in its population triggered by the reflection of the signal at the ports.

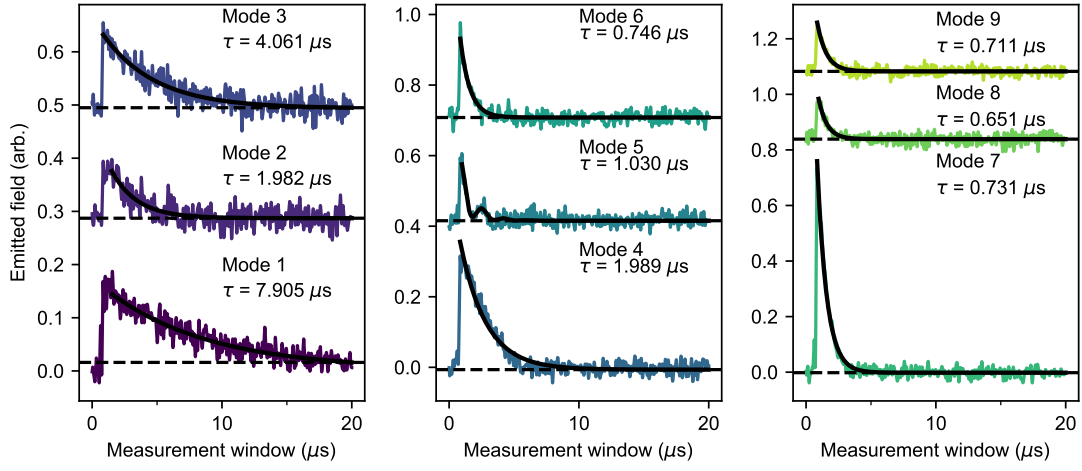


FIG. S4: Demodulated signal decays with their corresponding decay constant. The signals have been shifted for comparison. The dashed lines represent the baseline of the emission once all population has been emitted, while the colored points depict the resulting demodulated emission from the different modes (Time step size is 1 ns in the measurement). The fitting is indicated in black, with τ representing the decay constant.