OPTOMECHANICS WITH ION CHAINS

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Theoretical Quantum Physics

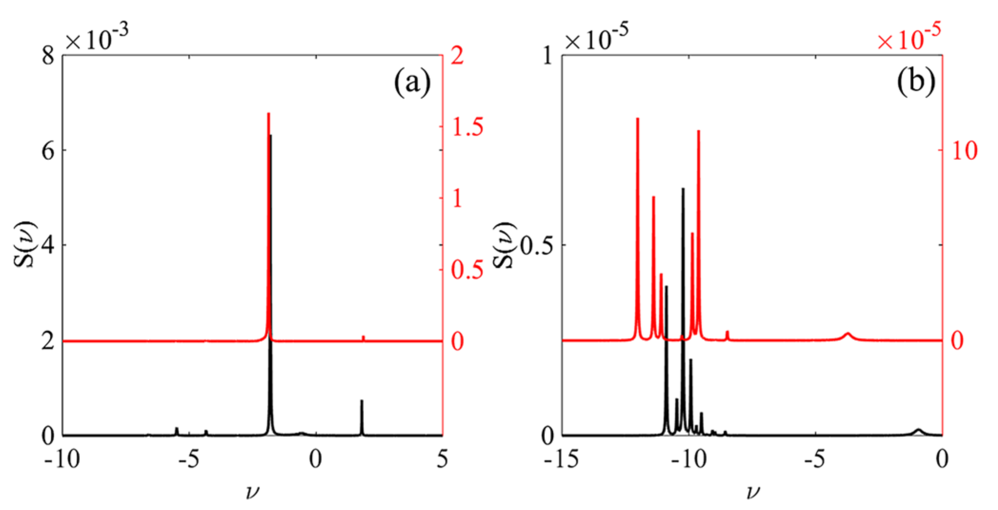
ABSTRACT

In this work we report on the optomechanical dynamics of ion chains, whose vibrations couple with the high-Q mode of an optical cavity. The dynamics results from the interplay between the long-range Coulomb repulsion and the cavity-induced interactions. The latter are due to multiple scatterings of laser photons inside the cavity and become relevant when the laser pump is sufficiently strong to overcome photon decay. We study the stationary states of ions coupled with a mode of a standing-wave cavity as a function of the cavity and laser parameters, when the typical length scales of the two self-organizing processes, Coulomb crystallization and photon-mediated interactions, are incommensurate. The dynamics are frustrated and in specific limiting cases can be cast in terms of the Frenkel-Kontorova model, which reproduces features of friction in one dimension. We numerically recover the sliding and pinned phases. For strong cavity nonlinearities, they are in general separated by bistable regions where superlubric and stick-slip dynamics coexist (Ref. 1). The cavity, moreover, acts as a thermal reservoir and can cool the chain vibrations to temperatures controlled by the cavity parameters and by the ions phase (Ref. 2).

We then focus on the regime in which the length scale are almost commensurate and investigate how the commensurate-incommensurate transition is modified by cavity backaction. We finally discuss how these features are imprinted in the radiation emitted by the cavity, which is readily measurable in state-of-the-art setups of cavity quantum electrodynamics.

CAVITY OUTPUT

Spectrum at cavity output for $C < 0$:



Taken from Ref. [1].

(a) sliding phase, (b) pinned phase.

Resonances:

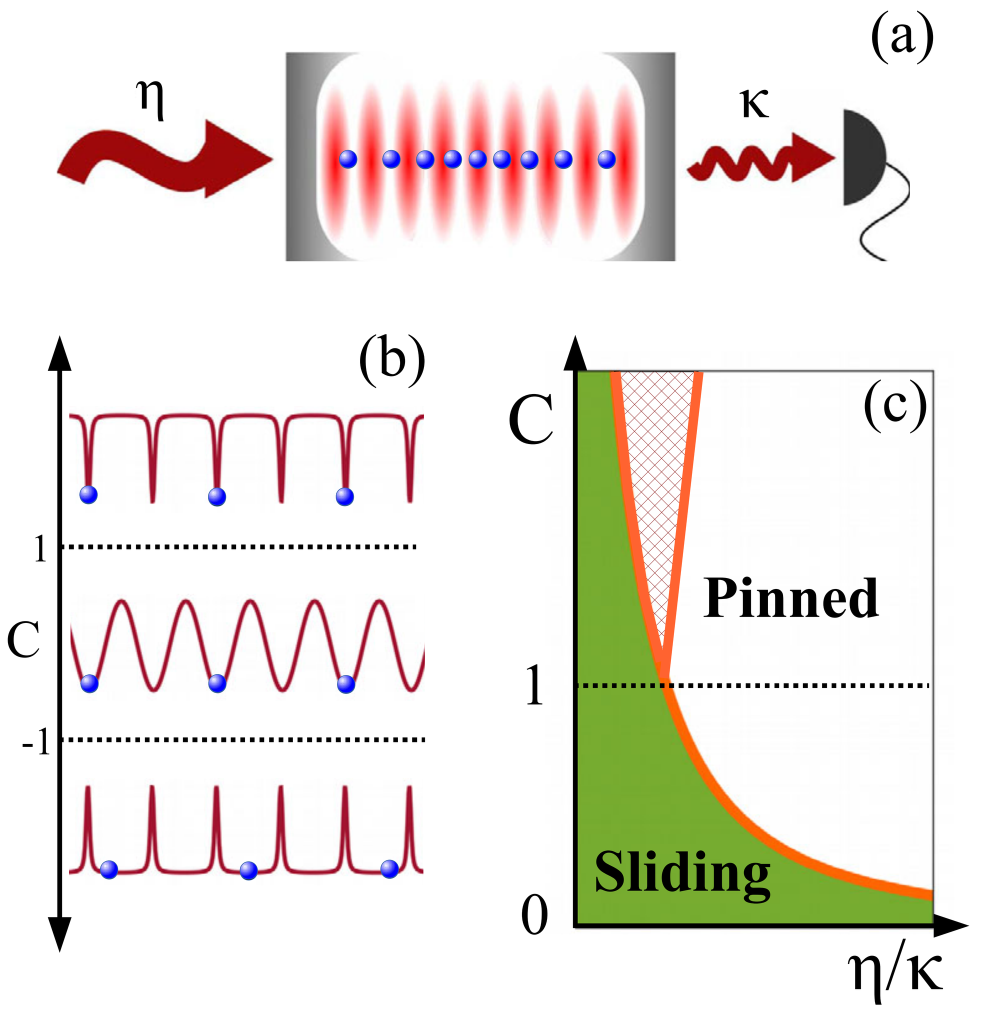
- correspond to vibrational eigenmodes,
- change as C is increased.

REFERENCES

[1] T. Fogarty, C. Cormick, H. Landa, Vladimir M. Stojanovic, E. Demler, and Giovanna Morigi; Phys. Rev. Lett. **115**, 233602 (2015)

[2] T. Fogarty, H. Landa, C. Cormick, and Giovanna Morigi; ArXiv:1604.07548 (2016)

SYSTEM MODEL



Taken from Ref. [1].

- No field: ⇒ ion distance d,
- cavity potential with $\lambda/2$ periodicity.

Mean photon number in cavity:

$$\bar{n} = |\eta|^2/[\kappa^2 + \Delta_{\rm eff}(\{x_j\})^2].$$

Nonlinear dependence on ion positions

$$\Delta_{\rm eff} = \Delta_{\rm c} - NU_0 B_N(\{x_j\}).$$

Order parameter: Bunching parameter $B_N(\{x_j\})$

$$B_N(\{x_j\}) = \sum_j \cos^2(kx_j)/N.$$

Hamiltonian of ion chain:

$$\hat{H} = \hat{V}_{\rm ion} + \hat{V}_{\rm cav},$$

with nonlinear cavity potential (periodicity $\lambda/2$)

$$V_{\rm cav} = -\frac{\hbar|\eta|^2}{\kappa}\tan^{-1}(\Delta_{\rm eff}(\{x_j\})/\kappa).$$

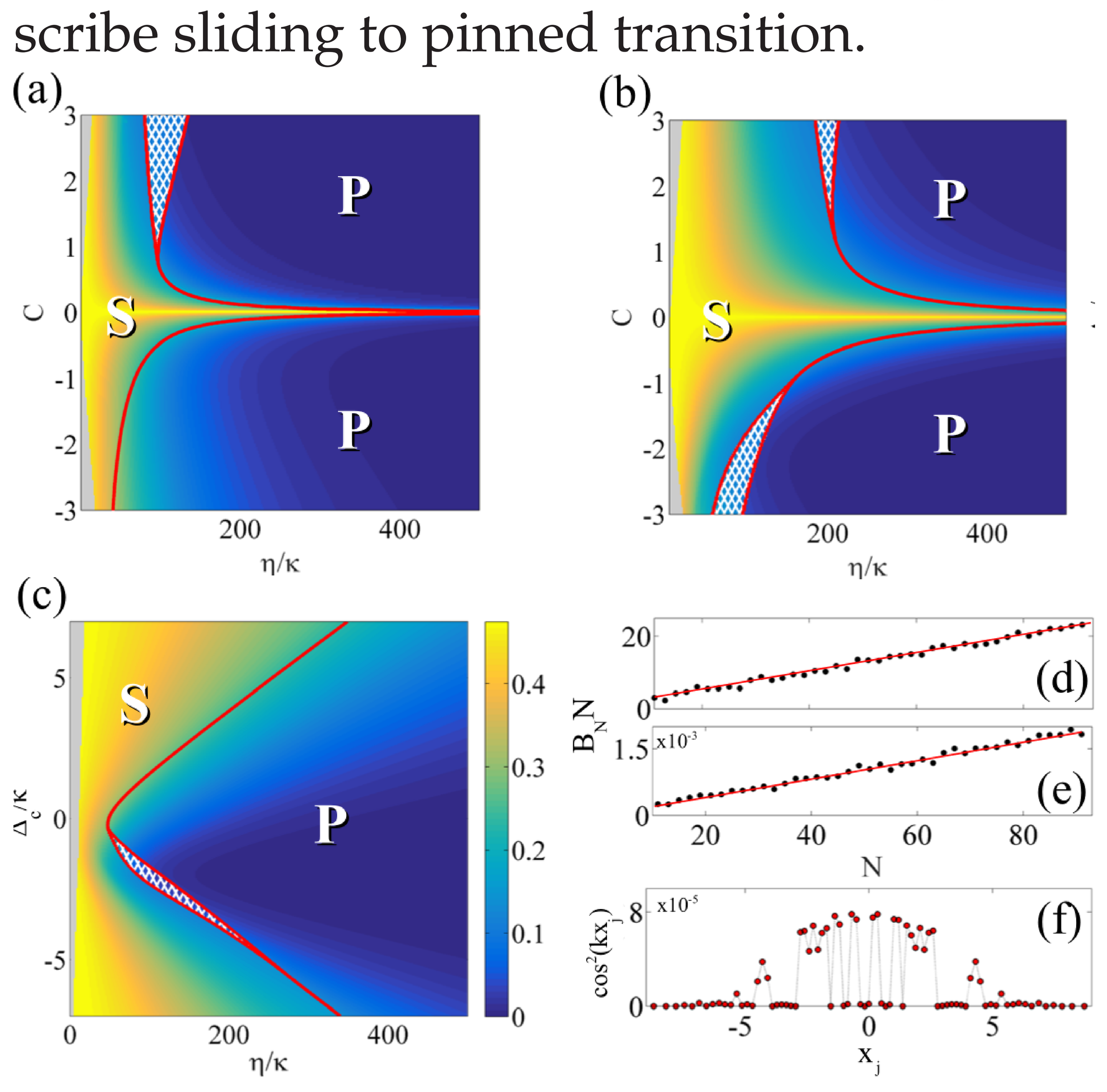
⇒ Cavity mediated long range interaction + competing length scales.

PINNING TRANSITION

Sliding to pinned transition as a symmetry breaking transition

- symmetric chain, uneven number of ions,
- central ion at potential maximum.

⇒ Shift of central ion and phonon gap describe sliding to pinned transition.



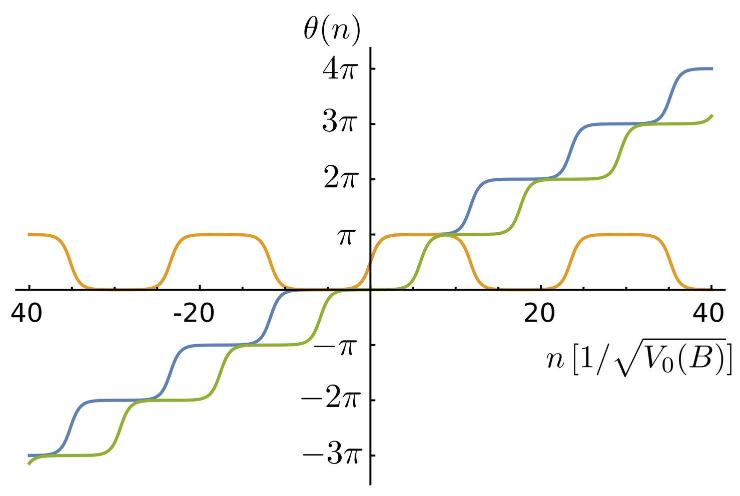
Taken from Ref. [1].

CIC TRANSITION

Ground state of almost commensurate ion chain with backaction

⇒ Continuum limit, replace ion position by continuous phase $\theta(n)$

$$\frac{1}{2}\theta'^2 - V_0(B(\epsilon))\Big[\sin^2(\theta) + \epsilon\Big] = 0$$



Kink chain and cavity field characterized by parameter ϵ:

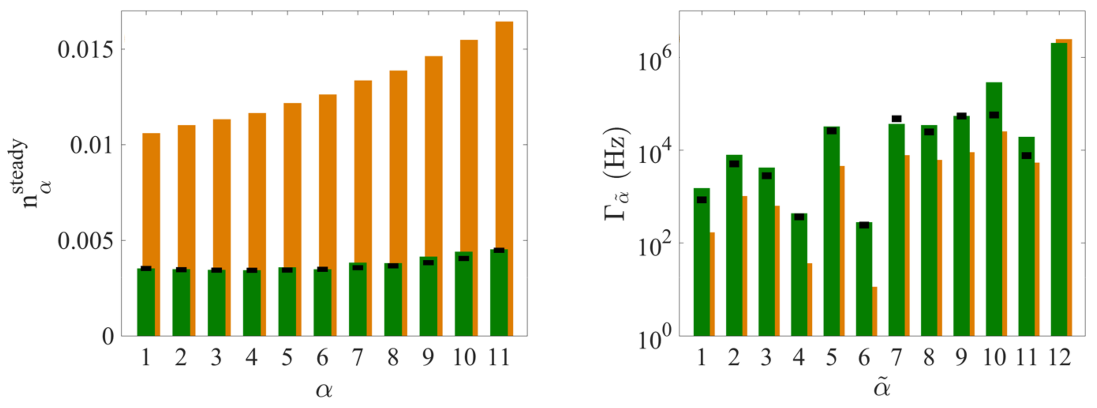
$$B(\tilde{\epsilon}) = 1 + \epsilon\Big(1 - E(-\epsilon^{-1})/K(-\epsilon^{-1})\Big).$$

Mismatch δ ⇒ determines ground state

- $\delta < \delta_c$ ⇒ commensurate state,
- $\delta > \delta_c$ ⇒ kink chain.

CAVITY COOLING

Analysis of cavity cooling for $\Delta_c = -8.5\kappa$:

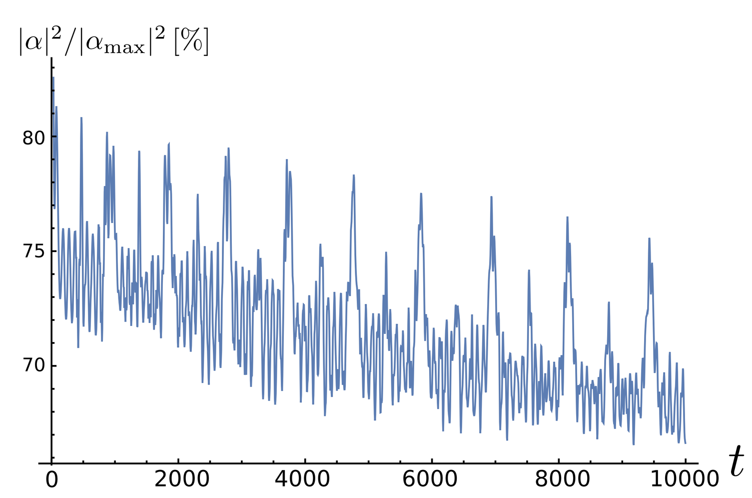


Taken from Ref. [2].

Collective cooling of all phononic modes, originating from interplay between coherent photon scattering and cavity losses.

OUTLOOK

Cavity output of two colliding kinks:



The next steps:

- determine kink dynamics,
- search for quantum phase transitions.