Stability of superradiant state and fundamental soliton under exciton-phonon interactions in open quantum systems: application to quasi-2D hybrid perovskites

B. D. Fainberg[a*], A.A. Gladkij[b], N.A. Veretenov[b], N.N. Rosanov[b], B.A. Malomed[c,d], V. Al. Osipov[e]

[a] *Faculty of Sciences, Physics Department, Holon Institute of Technology, Holon, Israel;*

[b]*Ioffe Physical-Technical Institute, St. Petersburg, Russia;* [c]*School of Electrical Engineering, Tel Aviv University, Tel Aviv, Israel*

[d]*Instituto de Alta Investigacion, Universidad de Tarapaca, Arica, Chile*;

[e]*Institute for Advanced Study in Mathematics, Harbin Institute of Technology, Harbin, China*

Abstract— **The use of macroscopic coherent states is crucial in modern quantum technologies. In light of recent experiments demonstrating high-temperature superfluorescence in hybrid perovskite thin films, in this work we investigate the stability of the superradiant state concerning exciton-phonon interactions. We focuse on a quasi-2D Wannier excitons interacting with longitudinal optical phonons. We derive nonlinear equations in the coordinate space that govern the complex-valued polarization. The resulting equations take the form of a 2D nonlocal nonlinear Schrodinger equation. We perform a linear stability analysis of the superradiant state. Our findings indicate that, when the exciton interacts with phonons, the superradiant state is modulationally stable, provided that the square of its amplitude does not exceed a critical intensity defined by the exciton-phonon interaction. We also solve the 2D nonlocal nonlinear Schrodinger equation in the polar coordinates and obtain its fundamental soliton solution, which is stable.**

Keywords—Open quantum systems; 2D solitons; superfluorescence; perovskites

INTRODUCTION

The use of room-temperature macroscopic quantum coherence is one of the most exciting frontiers in modern physics and materials science, because it opens the door to applying quantum effects in realistic, everyday conditions without the need for cryogenics. The discovery of high-temperature super-fluorescence (SF) in hybrid perovskites [1], arising from the macroscopic quantum coherence, naturally prompted questions about its underlying mechanisms, which were addressed in Ref. [2]. In this work, we investigate the stability of the superradiant state against exciton–phonon interactions in the systems under consideration [3]. Our analysis based on the multiconfiguration Hartree approach to exciton-phonon interaction [2,4] leads to nonlinear equations in coordinate space governing the complex-valued polarization. The resulting equations take the form of a 2D nonlocal nonlinear Schrödinger (NLS) equation, a well-established framework in soliton theory. In this context, it is noteworthy that a recent experimental study [5] invoked the soliton concept to account for high-temperature SF in perovskites, providing experimental support for the theoretical considerations developed here.

MAIN RESULTS

We perform a linear stability analysis of plane-wave solutions - including the superradiant state as a special case - of the derived equations, enabling us to identify stability criteria. Our results show that when excitons interact with LO phonons, a plane-wave solution is modulationally stable, provided that its intensity remains below a critical threshold determined by the exciton–LO phonon coupling parameters. These analytical predictions are fully supported by numerical simulations. We also numerically solve the 2D nonlocal NLS equation in polar coordinates and obtain its fundamental soliton solution, which is stable [3] (Fig. 1). The amplitude of the fundamental soliton exceeds that of both a stable plane wave and the corresponding superradiant state. Entering the soliton regime therefore enhances the amplitude of a stable exciton state that drives the development of superradiance.

REFERENCES

[1] M. Biliroglu, et. al, ”Room-temperature superfluorescence in hybrid perovskites and its origins,” Nature Photonics, **16**, 324-329, 2022.

[2] B.D. Fainberg, and V.Al. Osipov, ”Theory of high-temperature super-fluorescence in hybrid perovskite thin films,” J. Chem. Phys., **161**, 114705, 2024.

[3] A.A. Gladkij, N.A. Veretenov, N.N. Rosanov, B.A. Malomed, V.Al. Osipov, B. Fainberg, ”Stability of the Quantum Coherent Superradiant States in Relation to Exciton-Phonon Interactions and the Fundamental Soliton in Hybrid Perovskites,” arXiv:2511.03600, 21 pages, 2025; Phys. Rev. B, in press.

[4] V.A. Osipov, B. Fainberg, “Hartree method for molecular polaritons”, Phys. Rev. B, **105**, 075404, 2023.

[5] M. Biliroglu, et. al, “Unconventional solitonic high-temperature super-fluorescence from perovskites,” Nature, **642**, 71-78, 2025.

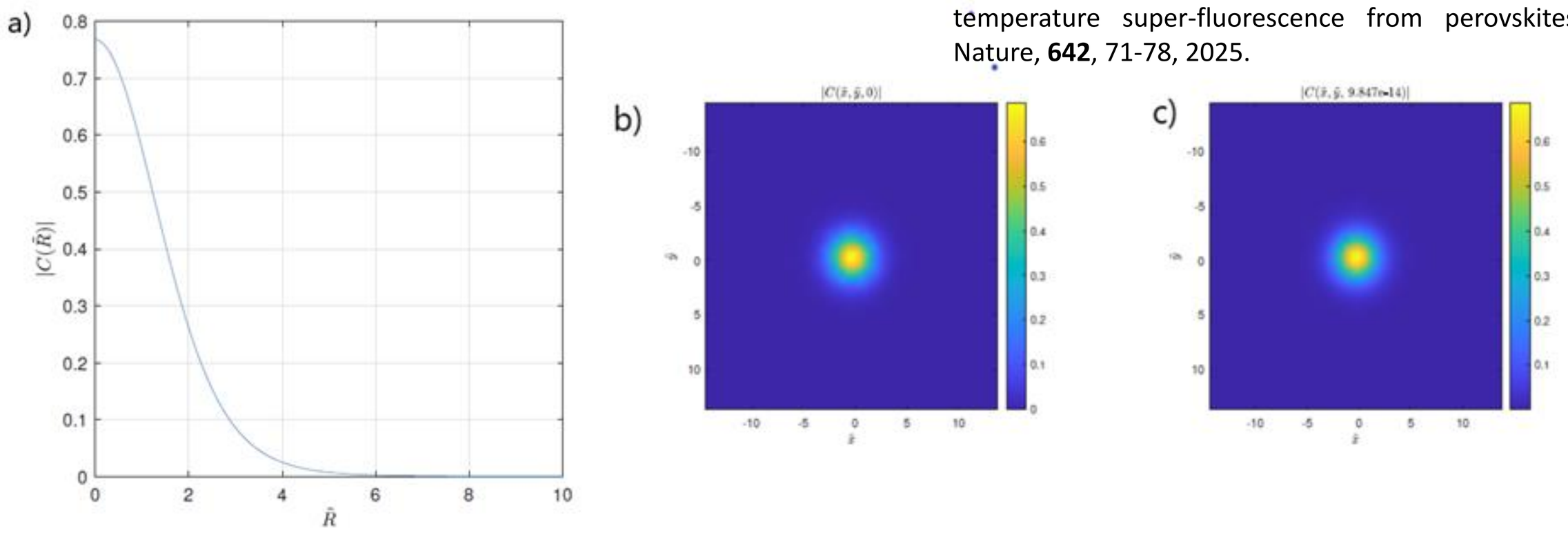

Fig. 1. Fundamental soliton profile (a), and its amplitude at the initial time moment t=0 (b) and t=73.9 fs (c).