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ABSTRACT

310 | STATISTICAL MECHANICS & NONLINEAR PHYSICS (SM)

Beyond Constant-Temperature Reservoirs: A Stirling Cycle with Constant Heat-Generation Rate

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ABSTRACT

Conventional heat-engine models typically assume two reservoirs at fixed temperatures, whereas radioisotope power systems provide heat at a constant generation rate rather than a constant temperature. We develop a theoretical framework for finite-time heat engines operating between constant heat-generation-rate hot sources and constant-temperature cold reservoirs, establishing a universal relation between average power and efficiency that is independent of engine cycle or working substance. As an illustrative example, we analyze a finite-time Stirling cycle with different control protocols, and find the match between our predicted efficiency and that of practical data. We also quantify the long-term performance degradation due to radioactive decay. This work introduces a new prototype for heat-engine theory and offers guidance for analyzing and designing radioisotope power systems.

ABSTRACT TOPIC

- Energy efficiency and retrofitting

KEYWORDS

Radioisotope power systems, Constant heat-generation-rate, Power-efficiency relation, Control protocols, Long-term performance degradation

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Statistics of Fluctuations in Anderson Localization

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ABSTRACT

The fluctuations of the wave density logarithm in a two-dimensional Anderson localized wave packet are shown to obey the key features of Kardar-Parisi-Zhang (KPZ) universality class. The fluctuations in localized wavepacket dynamics are found to exhibit an algebraic scaling with distance from the localization centre, characterized by an exponent of 1/3, and follow the Tracy-Widom distribution. Within a directed polymer picture of KPZ physics, one can also identify the dominant contribution of a directed path to the wave packet density and find that its transverse fluctuations are characterized by a roughness exponent 2/3. Leveraging on this connection with KPZ physics, we verify that an Anderson localized wave packet in 2D exhibits a stretched exponential correction to its well-known exponential localization. Together with extensive analysis of eigenstates in 2D Anderson problem, our results establish a unified KPZ framework for describing fluctuations and microscopic organization in 2D Anderson localization, revealing the glassy nature of localized states and providing new understanding into the universal structure of disordered quantum systems.

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KEYWORDS

Anderson localization, KPZ physics, fluctuation statistics, disordered systems.

Manipulating evanescent waves with non-Hermitian spectral singularities

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ABSTRACT

Evanescent waves, characterized by exponential decay along the propagation direction and associated with imaginary wavevector components, play a crucial role in phenomena such as subwavelength imaging and super-Planckian thermal radiation. However, research on wave scattering in non-Hermitian photonics has long focused primarily on propagating waves, and a systematic understanding of evanescent-wave manipulation in non-Hermitian systems remains lacking.

This talk focuses on the role of non-Hermitian spectral singularities in controlling evanescent waves and reveals their synergistic interplay with effective parity–time (PT) symmetry and nonlinear effects. We show that anti-PT-symmetric photonic heterostructures exhibit effective PT-symmetric scattering behavior under evanescent-wave excitation. When the poles of the generalized scattering matrix describing evanescent-wave scattering evolve onto the real-frequency axis, the system supports an evanescent-wave spectral singularity that coalesces with a zero, forming a PT-symmetric laser–absorber mode.

Based on this mode, strong amplification and coherent perfect absorption of evanescent waves can be achieved. Under realistic dispersive conditions, highly tunable near-field energy transport can also be realized. Furthermore, unidirectional spectral singularities can be engineered, enabling strong reflection from one side and vanishing reflection from the other, while maintaining finite and reciprocal transmission. In addition, through the interplay between spectral singularities and nonlinearity, pronounced nonreciprocal transmission of evanescent waves can be achieved without magnetic bias.

These results provide a new perspective on non-Hermitian control of evanescent waves and deepen the understanding of near-field wave dynamics in non-Hermitian systems.

ABSTRACT TOPIC

- Statistical Mechanics and Nonlinear Physics

KEYWORDS

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Evanescent waves, Spectral singularities, Non-Hermitian photonics

THE PHYSICAL MECHANISMS OF BRAIN FUNCTIONS

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ABSTRACT

The human brain is the most complex and mysterious system, performing various important functions of the brain. However, its microscopic mechanism remains a long-standing unsolved problem. In recent years, it has been one of the most important issues in the fields of nonlinear science and complex networks. Based on the progress of complex network science, significant results have been achieved in both brain structural networks and brain functional networks. Particularly in the microscopic mechanism of brain function, the results include chimera states, remote synchronization, remote propagation, and condensation of eigenmodes, etc. This talk will report the preliminary exploration of our group on these issues in recent years, with a focus on discussing the role of complex network science in exploring the microscopic physical mechanism of brain function.

REFERENCE

Physical mechanisms of human brain functions, *Quantitative Biology,* 2025, e70, 2025). Zonghua Liu

KEYWORDS

Brain networks, Brain functions, Chimera state, Remote synchronization, Remote propagation.

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Machine Learning Approach for Heat Conduction in Realistic Materials

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ABSTRACT

First-principles calculations have enabled significant progresses in predicting material's thermal properties without fitting parameters, offering a valuable tool for exploring novel materials. However, challenges remain in modeling complex factors that exists in realistic experiments due to the formidable computational costs. In this talk, I will discuss the advantages of using machine learning approach to study heat conduction in realistic materials and complex systems. A few examples will be demonstrated, including multi-objective prediction, high-order anharmonicity, and structural optimization.

KEYWORDS

Machine learning, heat conduction, high-order anharmonicity, thermal conductivity

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QUANTUM INFORMATION-THERMODYNAMIC COST RELATIONS BEYOND LANDAUER'S PRINCIPLE

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ABSTRACT

Landauer's principle establishes a fundamental connection between thermodynamic cost and information, serving as a cornerstone at the intersection of thermodynamics and information science. While it has proven successful in a wide range of scenarios, its reliance on assumptions about thermal baths may limit its applicability in generic open nonequilibrium quantum systems, where the environment can be non-thermal and finite-sized. Understanding the intrinsic relationship between information and thermodynamic cost in such systems calls for new theoretical tools. In this talk, we will present our recent theoretical efforts in developing such tools. Our approach builds on a thermodynamic inference strategy that relies solely on system observables, yielding information–thermodynamic cost relations that are agnostic to environmental details and thus broadly applicable. These relations lead to several novel insights, including an upper bound on the heat dissipation of information erasure that complements Landauer's principle, and a generalization of its underlying spirit to constrain higher-order fluctuation costs.

ABSTRACT TOPIC

- Smart grids and energy management systems

KEYWORDS

Nonequilibrium quantum systems, Quantum thermodynamics, Information-cost relation, Thermodynamic inference

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On the Stochastic Thermodynamics of Moving Bodies

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ABSTRACT

The principle of covariance, a cornerstone of modern physics, asserts the equivalence of all inertial frames of reference. Fluctuation theorems, as extensions of the second law of thermodynamics, establish universal connections between irreversibility and fluctuation in terms of stochastic thermodynamic quantities. However, these relations typically assume that both the thermodynamic system and the heat bath are at rest with respect to the observer, thereby failing to satisfy the principle of covariance. In this study, by introducing covariant work and heat that incorporate both energy-related and momentum-related components, we promote fluctuation theorems into covariant forms applicable to moving thermodynamic systems and moving heat baths. We illustrate this framework with two examples: the work statistics of a relativistic stochastic field and the heat statistics of a relativistic Brownian motion. Although our study is carried out in the context of special relativity, the results can be extended to the nonrelativistic limit. Our work combines the principle of covariance and fluctuation theorems into a coherent framework and may have applications in the study of thermodynamics relevant to cosmic microwave background as well as the relativistic hydrodynamics for heavy-ion collisions.

REFERENCE STYLE

Exact work distribution and Jarzynski's equality of a relativistic particle in an expanding piston, *Phys. Rev. E,* 110, 024128-024128, 2024. X. Zhang, T. Shi, H. T. Quan

Promoting Fluctuation Theorems into Covariant Forms, *Phys. Rev. Lett.* 134, 237102–237102, 2025, Ji-Hui Pei, Jin-Fu Chen, H. T. Quan,

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Exact four-vector work distribution and covariant Jarzynski's equality for a relativistic particle in an expanding piston, *arXiv: 2511.22431*, T. Shi, C. Qi, H. T. Quan,

KEYWORDS

Fluctuation Theorems, Covariance principle, Special Relativity, Stochastic Thermodynamics

Current-driven Archimedes chiral molecular motor

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Single-molecule junctions serve as an ideal platform for understanding nonequilibrium statistical and thermodynamic processes at small scales. Even at the single-molecule level, transport properties of molecules can be influenced by various degrees of freedom, such as molecular vibrons, localized plasmons, and spins, either within the molecule itself or in the surrounding environment. Studying these interactions and the accompanying energy conversion processes can enhance our understanding of fundamental small-scale thermodynamics and nonequilibrium statistics, while also expanding the functionality of single-molecule junctions in basic research. This talk will focus on the heat and work processes between electrons and atomic degrees of freedom molecules, focusing on theoretical design and experimental realization of a current-driven chiral molecular motor, akin to Archimedes screw.

Time-Optimal Qubit Reset Enabled by Structural Environment Spectrum

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ABSTRACT

A serious tension may exist between the quantum computation and erase processes, the former (latter) aims to enable more logical gates (restore the qubit with shorter time) requiring low (high) decoherence rate, which is determined by the coupling to the environment. To resolve such tension, we develop a switch-restore-switch scheme to minimize the reset time, where the qubit is switched from the low-decoherence configuration for computation to a fast-decoherence one for restoring. We implement the current scheme in the superconducting qubit with 4 representative environments. The shortest reset time is shortened from $\gtrsim$ 100 ns to 20 ns, which is as short as 0.4 times the typical two-qubit gate time. The current scheme shall provide an efficient way to reuse qubits in the current era with a limited number of qubits.

REFERENCE STYLE

Time-Optimal Qubit Reset Enabled by Structural Environment Spectrum, *[unpublished]*, 2026, Hong-Bo Huang, Hui Dong

KEYWORDS

Fast qubit reset, Structural environment spectrum, Superconducting qubit

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Chiral phonons and emergent novel effects

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ABSTRACT

Phonons were traditionally considered as linearly polarized. Recently we predicted that phonons can be chiral and have angular momentum both in magnetic and nonmagnetic systems. The nondegenerate chiral phonons are also predicted and easily tuned in graphene/hexagonal Boron Nitride heterostructures. The chiral phonons were observed in monolayer tungsten diselenide, where the phonon chirality was confirmed by the infrared circular dichroism arising from pseudoangular momentum conservation. Our further experiments showed that through the emission of a chiral phonon the momentum-dark intervalley exciton is brightened and chiral phonons can have entanglement with photons. Recently, we predicted that the chiral phonons can propagate along high-symmetry axis of 3D materials, and can show a diode effect in chiral systems, and can induce high-temperature superconductivity. We also observed a chiral-phonon-activated spin-Seebeck effect in chiral materials very recently.

KEYWORDS

Chiral phonons

The Kai Protein Biological Clock Synchronization Mechanism

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ABSTRACT

This paper systematically investigates the synchronization mechanism of the cyanobacterial Kai protein circadian clock, aiming to reveal the physical essence of the cooperative phosphorylation/dephosphorylation of KaiC proteins from the perspective of microscopic interactions. The article begins by reviewing the ubiquity and significance of synchronization phenomena in complex systems science, highlighting that "correlations" among individuals are key to understanding emergent behavior. In terms of theoretical modeling, this paper introduces the BBGKY hierarchy as a statistical physics tool, deriving the evolution equations for one-body and two-body distribution functions from the Liouville equation. Taking the "altruistic resource-sharing" model as an example, it rigorously derives the model's dynamical equations and finds that its first and second levels of the BBGKY hierarchy are decoupled. This indicates that the model fails to genuinely characterize the correlations among KaiC proteins and thus cannot reveal the physical essence of synchronization. To further explore the correlation mechanisms underlying synchronization phenomena, this paper introduces the Kuramoto model to investigate the collective synchronization behavior of coupled oscillator systems, offering a new theoretical perspective for understanding the phase synchronization among KaiC proteins. This work provides a new analytical framework for theoretical research on the synchronization mechanism of the Kai protein circadian clock and offers methodological insights for the physical modeling of emergent phenomena in complex systems.

Abstract Topic

The Synchronization Mechanism of the Kai Protein Biological Clock

REFERENCE STYLE

UnPublished

KEYWORDS

synchronization phenomenon, Kai protein circadian clock, correlation, BBGKY hierarchy, Kuramoto model

Advanced Thermal Management Materials for Electronic Packaging

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ABSTRACT

Thermal Interface materials (TIMs) are indispensable materials for heat dissipation and thermal management of modern electronics [1]. In this talk, I will report some most recent developments of the TIM by using liquid metal (LM) [2-4].

First, I will report a flexible LM@GN/ANF films are made by coating LM nano-droplets with graphene nanosheets (GN) via sonication, and then they are combined with aramid nanofibers (ANF). The LM@GN/ANF film is found to have a thermal conductivity of 5.67 W m^{-1} K^{-1} and a 24.5% reduction in Young's modulus,

Secondly, I will report a flexible composite TIM which enables magnetic field-triggered direction to change of heat flow, namely, the TIM acts effectively as a thermal switch. The material consists of liquid metal@nickel (LM@Ni) networks and diamond microparticles embedded in a polydimethylsiloxane (PDMS) matrix. The LM@Ni achieves both enhanced wettability on PDMS and magnetic responsiveness, while diamond provides the composite with high intrinsic thermal conductivity (13.92 $W \cdot m^{-1} \cdot K^{-1}$). Upon applying a magnetic field, the composite undergoes a rapid deformation, creating an “on” or “off” state with a switching ratio of 22.

Lastly, I will report how this Muti-functional TIM can be integrated into an all-solid-state elastocaloric cooling prototype.

Our work not only extends the application of TIM but also bridges compact solid-state cooling with efficient thermal management, establishing a new paradigm for TIM in smart thermal management applications [4].

REFERENCE STYLE

Paper Title, *Journal Name*, Volume Number, Page Numbers, Year of Publication, Initial1. LastName1, Initial2. LastName2, Initial3. LastName3, Initial4. LastName4.

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2. 3D Network of liquid metal-embedded graphen via surface coating for flexible thermal management, *Small* 20 (50), 240657 (2025), W. Luo, B. Wei, T. Luo, B. Li*, and G. Zhu*.
3. A Flexible thermal interface materials as the heat switch for solid state cooling, *Advanced Functional Materials*, e12421 (2025), W. Luo, X. Zhang, T. Luo, B. Li, B. Wei*, J. Zhang*, G. Zhu*.

4. Sustainable all-solid elastocaloric cooler enabled by non-reciprocal heat transfer, *Nature Sustainability* 8, 651–660 (2025), J. Zhang, M. Chen, W. Luo, B. Wei, T. Luo, X. Shen*, B. Li*， G. Zhu*.

KEYWORDS
Thermal Interface materials, thermal management, liquid metal, Muti-functional TIM

MECHANISM OF SYMMETRY RESTORATION IN TURBULENT RAYLEIGH-BÉNARD CONVECTION

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ABSTRACT

Symmetry breaking is a ubiquitous phenomenon occurring in nature and is a cornerstone in modern physics. An example of spontaneous symmetry breaking in fluid turbulence is the existence of a single-roll large-scale flow structure in turbulent thermal convection, rather than an axisymmetric one expected from the symmetry of the system. However, it was recently discovered that the axisymmetric flow structure can be restored when a minute amount of polymer additives is introduced [1]. Although this symmetry restoration is accompanied by an anisotropic suppression of velocity fluctuations, it remains unclear whether such anisotropy is the cause or a consequence of the symmetry restoration. To resolve this question, we perform a series of numerical simulations of Rayleigh–Bénard convection incorporating both isotropic and anisotropic large-scale friction. Counterintuitively, isotropic friction preferentially damps horizontal motions and can restore a symmetric flow state, which cannot be found in an anisotropic friction case. These comparative simulations demonstrate that anisotropic suppression is a consequence rather than the cause of symmetry restoration. Additional simulations further show that the restoration cannot be attributed to flow laminarization either. We notice that flow symmetry restoration in turbulent thermal convection requires an orienting mechanism, for which buoyancy serves as a natural candidate. By comparing polymer-laden experimental data with numerical simulations employing large-scale friction, we find a common signature of buoyancy predominance in both systems, manifested by an enhanced and nearly time-symmetric velocity–temperature correlation. As buoyancy becomes predominant, the velocity field is slaved to buoyancy, leading to a buoyancy-aligned flow structure. We conclude that this buoyancy-dominated regime provides a necessary mechanism for restoring flow symmetry in turbulent thermal convection [2].

We gratefully acknowledge support of this work by the National Natural Science Foundation of China through Grants: 12232010, 12594530010, 12595302.

[1] Restoration of axisymmetric flow structure in turbulent thermal convection by polymer additives, Phys. Rev. Lett. 134, 084001 (2025). F. Xu, X.-S. Liu, X.-M. Li, and K.-Q. Xia,

[2] G.-Y. Ding, F. Xu, and K.-Q. Xia (to be submitted).

KEYWORDS
Spontaneous symmetry breaking, symmetry restoration, turbulent flows

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From Monte Carlo to nonequilibrium Green's functions

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ABSTRACT

I like to summarize and highlight 40 years of my research experience, from the well-known work on cluster algorithms (the Swendsen-Wang algorithm) to the nonequilibrium Green's functions (NEGF) for mesoscopic transport. Finally, I briefly outline the photon transport in nonequilibrium or Floquet-driven states.

Universal laws of thermalization in lattice systems

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ABSTRACT
Over the past decade, significant progress has been made regarding the Fermi–Pasta–Ulam–Tsingou problem: whether weakly nonlinear lattices thermalize and how. Current understanding is as follows. (a) Classical lattices fall into two universal classes. In the first, the Hamiltonian has extended normal modes. For sufficiently large systems, the thermalization time scales as $T_{\mathrm{eq}} \sim g^{-2}$, where g measures nonlinearity. Thus, in the thermodynamic limit, thermalization is inevitable. Examples include common one-, two-, and three-dimensional lattices. In the second class, all normal modes are localized. Here, although $T_{\mathrm{eq}} \sim g^{-\gamma}$, the exponent γ diverges as $g \to 0$; thus, arbitrarily weak nonlinearity cannot induce thermalization, making such systems theoretical thermal insulators. (b) For the first class, disorder does not hinder thermalization. By breaking translational symmetry, disorder relaxes wave-vector resonance constraints and increases quasi-resonant processes, thereby accelerating thermalization. (c) In systems of the second class, when both on-site potentials and disorder are present, all normal modes become localized in large systems, suppressing thermalization. The perturbative framework underlying these conclusions is also outlined, emphasizing the thermalization criterion based on resonance network connectivity, an approach originating from weak wave turbulence theory.

REFERENCE STYLE
The Fermi-Pasta-Ulam-Tsingou problem after 70 years: Universal laws of thermalization in lattice systems, DOI: 10.48550/arXiv.2603.23347，Weicheng Fu , Zhen Wang , Wei Lin , Dahai He , Yong Zhang, Hong Zhao

KEYWORDS
Fermi-Pasta-Ulam-Tsingou problem, thermalization

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Finite-Time Thermodynamics Perspective into Nuclear Power Plant Heat Cycle

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ABSTRACT

Nuclear power plants are representative heat-to-work conversion systems, and improving their thermodynamic performance is essential for cost-effective low-carbon energy supply. Classical thermodynamics provides an upper bound on efficiency, but offers limited guidance when power output is the primary concern under realistic finite-rate heat transfer. In this work, nuclear power plant heat cycles are revisited from the perspective of finite-time thermodynamics. First, the structural evolution and efficiency characteristics of nuclear power plants across four generations are reviewed, showing that gross efficiency generally increases with Carnot efficiency and is strongly associated with higher coolant outlet temperature. A finite-time model is then developed for the Brayton cycle without phase transition and for the Rankine cycle with liquid-vapor phase transition. For the Brayton cycle, the analysis recovers the Curzon-Ahlborn efficiency at maximum power. For the Rankine cycle, the model explicitly incorporates phase transition and reveals an intrinsic trade-off between output power and efficiency. Numerical calculations based on representative nuclear-power-plant conditions further show that the mass flow rate, high-temperature pressure, and phase-change properties of the working fluid substantially affect the attainable power-efficiency domain, with identifiable optimal operating conditions for maximum power. These results provide physical insight and a practical framework for optimizing nuclear power plants and other Rankine-type energy-conversion systems.

REFERENCE STYLE

Manuscript under review at PRX Energy.

KEYWORDS

nuclear power plants, finite-time thermodynamics, Rankine cycle, power-efficiency trade-off

Novel Phonon Thermal Transport in Quantum Two-Dimensional Materials

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ABSTRACT

The study of heat conduction in micro-nano materials has both practical application value and theoretical research value. With gradual shrinking of the size of current microelectronic devices, excessive heat will be locally generated and concentrated, which affects the performance and life of the devices. Thermal management at the nanoscale is therefore particularly significant. For both 1D and 2D materials, there exist theoretical calculations and experiments to verify the existence of anomalous heat conduction, and the physical mechanism is worthy of further study. This talk will present recent advances in phonon-mediated thermal conduction in 2D materials, with an emphasis on how nanostructuring, dimensionality, and defect engineering influence phonon transport. Special attention will be given to interfacial thermal transport between the 2D materials and various substrates, a bottleneck in nanoscale heat dissipation. Moreover, the presentation will explore thermal management strategies in 2D FETs, highlighting how optimized heat dissipation pathways can significantly enhance device stability and performance.

REFERENCE STYLE

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KEYWORDS
Phonon transport, 2D, heat dissipations, low dimensional materials

ROLE OF EXCITATIONS IN SUPERCOOLED LIQUIDS

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ABSTRACT

One of the central open problems in condensed matter physics is to understand why glasses relax so slowly and eventually become rigid without developing crystalline order. A widely held idea is that relaxation is controlled by localized excitations, but identifying these excitations and determining how they contribute to dynamics has remained a major challenge.

Here we introduce an algorithm that extracts the elementary excitations of glasses over an unprecedented energy range, allowing us to directly characterize their density, geometry, and spatial organization. This makes it possible to address a key missing piece in the field: how these excitations, and the interactions between them, shape structural relaxation. We find that both the excitations themselves and their mutual interactions are strongly predictive of where and how relaxation occurs. Most strikingly, the geometry of the excitations reveals evidence for a dynamical transition, suggesting that this transition plays an important role in relaxation even deep in the low-temperature regime.

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KEYWORDS

Glass, Excitation, Landscape

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Time-optimal Qubit Reset via Environmental Spectral Structure

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ABSTRACT

Fast qubit reset is essential for qubit reuse in the noisy intermediate-scale quantum computing era, yet it conflicts with the weak decoherence required for high-fidelity computation. We solve the time-optimal reset problem for a frequency-tunable qubit coupled to a structural environment under realistic spectral and control constraints. The optimal strategy consists of a switch–restore–switch sequence, where the qubit is moved from a low-decoherence computational configuration to a high-decoherence restoring configuration and then returned for reuse. For superconducting qubits in four representative environments, this strategy reduces the reset time from typically $\gtrsim 100$ ns to 20 ns, about 40% of a typical two-qubit gate time, while achieving a reset precision of 10^{-5}. Our results identify environmental spectral structure as a practical resource for rapid, high-fidelity qubit reset and provide a design principle for qubit reuse on qubit-limited processors.

REFERENCE STYLE

Time-optimal Qubit Reset via Environmental Spectral Structure, *[In Submission]*, 2026, Hong-Bo Huang, Hui Dong.

KEYWORDS

Qubit reset, Mid-circuit reset, Time-optimal control, Superconducting qubit, Spectral engineering,

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Granular gas thermodynamics

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ABSTRACT

Granular gas is a physical system formed by random collisions of macroscopically nearly identical particles driven by a vibrating plate. Due to the randomness of collisions, granular gas exhibits stochastic motion similar to that of microscopic molecules. Therefore, on one hand, granular gas can serve as a thermal bath with certain thermodynamic properties such as a temperature and pressure, driving the random motion of asymmetric Brownian motors and enabling the exploration of stochastic thermodynamic principles, including entropy increase laws and fluctuation theorems. On the other hand, as a natural model system of hard-sphere matter, granular gas itself can be regarded as a small thermodynamic system of hard-spheres. Thus, after carefully addressing various non-ideal factors in experiments, granular gas becomes a natural platform for exploring the thermodynamic laws of small systems.

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KEYWORDS

Granular gas, hard sphere system, small system, thermodynamics

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Finite-time thermodynamics: Integrating dynamics into thermodynamics

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ABSTRACT

The central objective of finite-time thermodynamics is to optimize the efficiency of energy conversion and utilization in processes carried out within finite durations. Classical thermodynamics usually assumes quasi-static processes that proceed infinitely slowly; however, in practical engineering systems and natural processes, rapid changes often occur over limited timescales, rendering the quasi-static assumption inapplicable. This report reviews the development of finite-time thermodynamics and then focuses on three representative topics: the power-efficiency trade-off in finite-time thermodynamic cycles, geometric optimization schemes for minimizing energy dissipation under finite-time control, and related experimental progress in the field.

KEYWORDS

finite-time thermodynamics, energy efficiency, power optimization, geometric control, experimental progress

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Fermion Sign Problem and Lee-Yang Phase Transition Theory

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ABSTRACT

To simulate indistinguishable particles, recent studies of path-integral molecular dynamics formulated their partition function Z as a recurrence relation involving a variable ξ , with $\xi = 1(-1)$ for bosons (fermions) [1-3]. Inspired by Lee-Yang phase transition theory, we extend ξ into the complex plane and reformulate Z as a polynomial in ξ [4]. By analyzing the distribution of the partition function zeros, we gain insights into the analytical properties of indistinguishable particles, particularly regarding the fermion sign problem (FSP). We found that at 0 K, the partition function zeros for N particles are located at $\xi = -1, -1/2, -1/3, ..., -1/(N-1)$. This distribution disrupts the analytic continuation of thermodynamic quantities, expressed as functions of ξ and typically performed along $\xi = 1 \rightarrow -1$, whenever the paths intersect these zeros. Moreover, we highlight the zero at $\xi = -1$, which induces an extra term in the free energy of the fermionic systems compared to ones at other $\xi = e^{i\theta}$ values. If a path connects this zero to a bosonic system with identical potential energies, it brings a transition resembling a phase transition. These findings provide a fresh perspective on the successes and challenges of emerging FSP studies based on analytic continuation techniques.

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KEYWORDS

Fermion Sign Problem, Lee-Yang Zeros, Phase Transition, Monte-Carlo

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Mesoscopic Fluctuations in Entanglement Dynamics

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ABSTRACT

Understanding fluctuation phenomena plays a dominant role in the development of many-body physics. The time evolution of entanglement is essential to a broad range of subjects in many-body physics, ranging from exotic quantum matter to quantum thermalization. Stemming from various dynamical processes of information, fluctuations in entanglement evolution differ conceptually from out-of-equilibrium fluctuations of traditional physical quantities. Their studies remain elusive. Here we uncover an emergent random structure in the evolution of the many-body wavefunction in two classes of integrable—either interacting or noninteracting—lattice models. It gives rise to out-of-equilibrium entanglement fluctuations which fall into the paradigm of mesoscopic fluctuations of wave interference origin. Specifically, the entanglement entropy variance obeys a universal scaling law in each class, and the full distribution displays a sub-Gaussian upper and a sub-Gamma lower tail. These statistics are independent of both the system's microscopic details and the choice of entanglement probes, and broaden the class of mesoscopic universalities. They have practical implications for controlling entanglement in mesoscopic devices.

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KEYWORDS

Quantum simulations, nonequilibrium quantum systems, entanglement dynamics, mesoscopic physics, quantum thermalization

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Deep Learning of Electronic Structure: Challenges and Opportunities

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ABSTRACT
First-principles electronic structure calculations have profoundly advanced research in physics, chemistry and materials science, yet their further development remains constrained by the accuracy – efficiency dilemma. In this talk, I will present recent breakthroughs in deep-learning methodologies aimed at overcoming this bottleneck, with an emphasis on deep-learning density functional theory for efficient and intelligent materials simulations. These advances extend the reach of first-principles calculations to unprecedented scales and complexity, enhancing the impact of quantum mechanics in scientific discovery.

Energy Transport in Superionic Crystals

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ABSTRACT

Compared with conventional solids such as crystalline silicon, the molecular structure of superionic crystals is special. The anions form a rigid sublattice while cations are highly disordered and superionic with liquid-like mobilities, which makes the transport property of superionic crystals nontrivial and forms a judicious platform to study unique energy exchange mechanism between the rigid sublattice and an ion-conducting subsystem. For example, researchers found that more than 87% of Li^+ ion diffusion in the superionic $Li_{3.042}Ge_{0.042}P_{0.958}O_4$ originates from less than 10% of the vibrations between 8 and 20 THz. For another example, our recent preliminary results indicate that thermal conductivity resulting from the diffusion of liquid-like cations in superionic Li_2S can contribute around ~30% of the total thermal conductivity, suggesting that thermal transport channels resulting from lattice vibrations and the diffusion of liquid-like cations should be considered. These unusual transport properties, which are strongly related to interactions between ions and vibrations in superionic crystals, however, have rarely been investigated. This is mainly because the conventional theory fails to treat systems with significant movement of ions. In this talk, I will introduce our developed methodology to quantify the detailed transport process in superionic crystals, and unveil the understanding mechanisms for the abnormal transport phenomena observed in superionic crystals.

REFERENCE STYLE

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Fast Ionic Transport Governed by Collective Vibrational Dynamics, *Physical Review Letters*, 136, 126302, 2026, Y. Xu, X. Xiang, Z. Li, Y. Lu, Y. Zhou.

KEYWORDS

Superionic crystals, ion transport, energy carriers

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Topside thermal mapping of phonon nonaquarium in-operando nanodevices by electronic Doppler broadening

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ABSTRACT

Localized hotspots and steep temperature gradients in nanoelectronics degrade performance and impede further device miniaturization. Imaging these nanoscale temperature fields in operando is essential for fundamentally understanding thermal transport and interfacial nonequilibrium in nanodevices and developing more effective thermal dissipation designs. Scanning transmission electron microscopy based thermometry methods, despite their high spatial resolution, cannot be used for regular devices as they require an ultrathin sample for electron transmission. Here we propose a generic topside nanoscale thermometry compatible with devices on regular thick substrates utilizing elastic energy spectroscopy of reflection electrons, termed Reflection Electron Elastic Energy Thermometry (REEET), which directly measures the mean kinetic energy of thermally vibrating atoms in materials. Local temperature is

measured by directly probing the mean kinetic energy of thermally vibrating atoms via the electronic Doppler broadening effect. The measurement principle is experimentally validated on diverse material types including graphite, Si_3N_4, and W, all showing good agreement with first-principles predictions. Using this technique, we visualized the phononic/lattice temperature field of several in operando carbon-based nanodevices, exhibiting a high spatial resolution of 14 nm. Furthermore, we experimentally reveal nonequilibrium thermal transport and anisotropic mode coupling across interfaces in Joule-heated nanodevices where Fourier's law breaks down, highlighting operando thermal imaging as essential for overcoming the heat dissipation bottlenecks in nanoelectronics. These results demonstrate that the present method, with its inherent topside imaging advantage and sample flexibility, could become a transformative tool for future nanoelectronics research and development.

KEYWORDS
Nonequilibrium phonon transport, electron-phonon coupling, nanoscale thermal transport, electron microscopy, nanoscale thermometry

Experimental Quantum Thermodynamics using Nuclear Magnetic Resonance

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ABSTRACT

Classical thermodynamics studies macroscopic systems. In small-particle systems far from the thermodynamic limit, many concepts and issues in classical thermodynamics need to be redefined and explored due to the influence of quantum effects, gradually forming the emerging field of quantum thermodynamics. With the development of quantum information technology, many quantum systems can now be precisely controlled, providing an ideal platform for experimental research in quantum thermodynamics. In particular, as a highly controllable room-temperature spin ensemble system, nuclear magnetic resonance (NMR) offers unique advantages in the study of quantum thermodynamics. In this talk, I will first briefly review the basic principles of NMR and spin control techniques. Then, by utilizing two different quantum resources, namely indefinite causal order and three-body interactions, we can construct quantum versions of working substances and implement refrigeration cycles. Finally, I will present experimental results demonstrating a "quantum refrigerator with indefinite causal order" and a "self-contained quantum refrigerator" using NMR spin ensembles.

KEYWORDS

Quantum information, Quantum thermodynamics, Nuclear magnetic resonance

Operational Metric for Quantum Chaos and the Corresponding Spatiotemporal Entanglement Structure

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ABSTRACT

Chaotic systems are highly sensitive to a small perturbation, and are ubiquitous throughout biological sciences, physical sciences and even social sciences. Taking this as the underlying principle, we construct an operational notion for quantum chaos. Namely, we demand that the future state of a many-body, isolated quantum system is sensitive to past multitime operations on a small subpart of that system. By `sensitive', we mean that the resultant states from two different perturbations cannot easily be transformed into each other. That is, the pertinent quantity is the complexity of the effect of the perturbation within the final state. From this intuitive metric, which we call the Butterfly Flutter Fidelity, we use the language of multitime quantum processes to identify a series of operational conditions on chaos, in particular the scaling of the spatiotemporal entanglement. Our criteria already contain the routine notions, as well as the well-known diagnostics for quantum chaos. This includes the Peres-Loschmidt Echo, Dynamical Entropy, Tripartite Mutual Information, and Local-Operator Entanglement. We hence present a unified framework for these existing diagnostics within a single structure. We also go on to quantify how several mechanisms lead to quantum chaos, such as evolution generated from random circuits. Our work paves the way to systematically study many-body dynamical phenomena like Many-Body Localization, measurement-induced phase transitions, and Floquet dynamics.

REFERENCE STYLE

Operational Metric for Quantum Chaos and the Corresponding Spatiotemporal Entanglement Structure, *PRX Quantum* 5, 010314 (2024), N. Dowling, K. Modi.

KEYWORDS

Quantum chaos, process tensor, local operator entanglement, volume entanglement

Comparative study of classical and quantum thermal transport at low temperatures in billiard systems

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ABSTRACT

We explore how quantum mechanics affects low-temperature heat transport in billiard systems at low temperatures. In the classical setting, by considering a simple paradigmatic model, our results reveal the emergence of negative differential thermal resistance: paradoxically, increasing the temperature bias by lowering the cold bath temperature reduces the steady-state heat current. In sharp contrast, the quantum version of the model, described by a Lindblad master equation, shows no such effect—heat current rises monotonically with bias. This marked divergence highlights the fundamental role of quantum effects in low-temperature thermal transport and underscores the need to reconsider classical predictions when designing and optimizing nanoscale thermal devices.

REFERENCE STYLE

Quantum versus Classical Thermal Transport at Low Temperatures, *Physical Review Letters*, 136, 066305, 2026, Z. Zou, J. Gong, J. Wang, G. Casati, G. Benenti.

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KEYWORDS
Classical thermal transport, Quantum thermal transport, Billiard model, Low temperatures

Configuration distance and double percolation of glassy dissipations

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ABSTRACT

The origin of α and β relaxations in glass-forming liquids remains a fundamental challenge. Here we report a unified picture emerging from extensive molecular dynamics simulations. First, a double-percolation scenario is established: the α process corresponds to percolation of immobile particles, whereas the β relaxation—when well separated—originates from percolation of mobile particles. The ratio of the two percolation temperatures determines whether the β process appears as a distinct peak, a shoulder, or merely a wing. In two dimensions, where simultaneous percolation of both species is impossible, no separate β relaxation exists. Second, a global order parameter, the inherent structure minimal displacement (IS Dmin), is introduced to quantify configurational variability via pattern matching. Across seven model glass formers, the mechanical damping factor (phase angle δ) follows a universal power law with IS Dmin>, reflecting the local curvature of the potential energy landscape. Together, these findings demonstrate that percolation of dynamically distinct regions and landscape-based configurational overlap provide complementary frameworks linking atomic-scale heterogeneity to macroscopic relaxation. This unified perspective offers predictive routes for understanding and designing the mechanical properties of amorphous materials.

KEYWORDS

Glass transition, supercooled liquids, soft matter

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The FPUT Problem at 70: Do Finite Lattice Systems Ever Thermalize?

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ABSTRACT [*major heading style: Bold 12 pt, UPPERCASE*]
How energy spreads in complex materials is a fundamental question connecting physics, chemistry, and materials science. For decades, theoretical descriptions of energy transfer in nonlinear condensed matter systems have been built on multi-wave exact resonance conditions. However, the actual dynamical role of exact resonances has remained unclear.
Here, we provide direct evidence that exact resonances are *not* the dominant mechanism of energy transport in classical lattices. First, we show that symmetry-induced structures in the kinetic equations cause energy equalization within decoupled mode subsets, dynamically invalidating exact resonance conditions. Second, we demonstrate that exact and quasi-resonances exhibit opposite behaviors with respect to system size: the connectivity of exact resonances decreases monotonically, while that of quasi-resonances increases.
These findings reveal that energy redistribution and eventual thermalization are dominated by quasi-resonances—fleeting interactions enabled by nonlinear frequency broadening. This work establishes a clear distinction between the roles of exact and quasi-resonances in classical lattice dynamics, reshapes our understanding of heat and energy transport in solids, and may inform future strategies for controlling energy transfer in technologies ranging from thermal management to quantum materials. It also implies that thermalization in finite lattice systems requires a threshold in the nonlinear perturbation strength—suggesting that the original FPUT model may never truly thermalize.

KEYWORDS
Quasi-resonances, Thermalization threshold, FPUT problem

Nonlinear optical thermodynamics from a van der Waals-type mean-field theory

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ABSTRACT

Optical thermodynamics offers a distinctive framework for understanding complex phenomena in multimode systems, yet standard ideal-gas-like formulation neglects the effect of nonlinear interaction on thermodynamic quantities, significantly restricting its range of validity. Here, we overcome this limitation by developing a mean-field thermodynamic theory that incorporates the nonlinear renormalization of the mode spectrum. The resulting nonlinear equation of state, analogous to that of the van der Waals for gases, enables the prediction of power-dependent mode localization and the description of optical cooling and heating in photonic Joule-Thomson expansion. Our work establishes a unified thermodynamic perspective on the nonlinear control and transport of optical waves.

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KEYWORDS

Optical thermodynamic, Mean field, Modulation instability, Joule-Thomson expansion

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Discrete Simulation of Nonlinear Schrödinger Dynamics in a Two Coupled Fiber Loop Temporal Photonic Lattice

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ABSTRACT

The nonlinear Schrödinger equation can describe rich wave phenomena such as soliton formation, modulational instability, and nonlinear localized states. Here we investigate a two coupled fiber loop temporal photonic lattice as a discrete platform for simulating novel nonlinear Schrödinger type propagation, where the effective spatial and evolution dimensions are constructed through time multiplexing and the nonlinear response is introduced through intensity gradient-dependent phase modulation. Theoretical simulations show that, under suitable nonlinear strength and initial conditions, a Gaussian beam can form a stable localized cusp soliton structure and approximately maintain its spatial distribution during propagation. For a flat-top initial beam, the considered topological nonlinearity can preserve the sharp edges of the beam and stabilize localized structures near the boundaries. Our results indicate that the two coupled fiber loop platform can serve as an experimentally realizable system for studying novel discrete nonlinear Schrödinger dynamics, soliton formation, and nonlinear boundary localized states.

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KEYWORDS

Nonlinear Schrödinger equation, Temporal photonic lattice, Soliton formation, Nonlinear localized states，

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