Initialization of quantum simulators by sympathetic cooling

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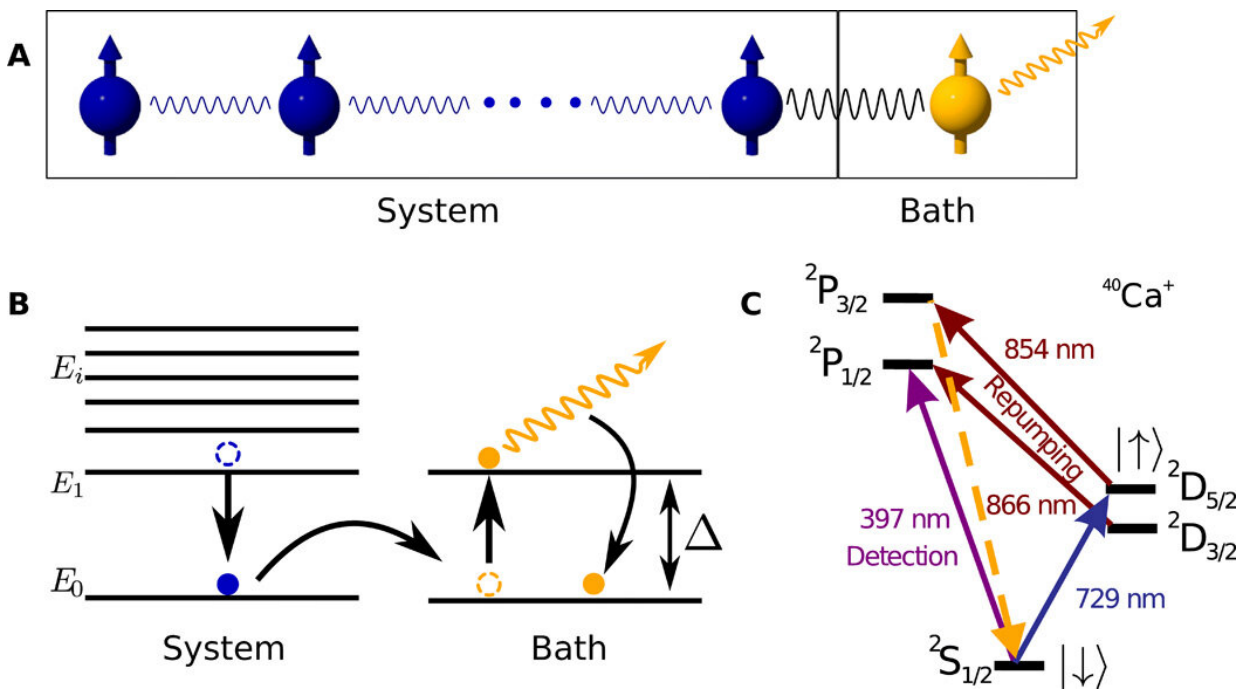


Sympathetic cooling of a quantum simulator. (A) A system of N spins performing the quantum simulation is interacting with an additional bath spin that is dissipatively driven. (B) Sketch of the energy level structure showing resonant energy transport between the system and the bath, after which the bath spin is dissipatively pumped into its ground state. (C) Level scheme for the implementation with trapped 40Ca+ ions. Credit: Science Advances, doi: 10.1126/sciadv.aaw9268

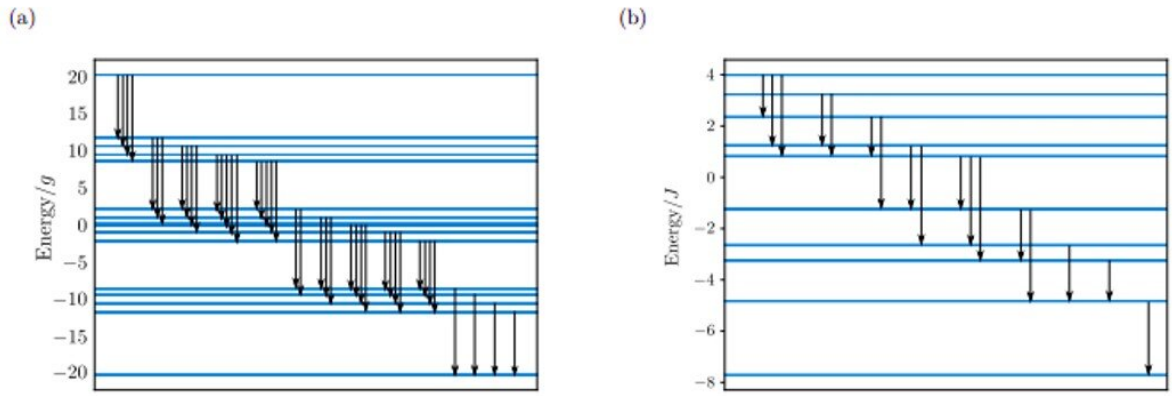
Simulating computationally complex many-body problems on a quantum

simulator has great potential to deliver insights into physical, chemical and biological systems. Physicists had previously implemented Hamiltonian dynamics but the problem of initiating quantum simulators to a suitable quantum state remains unsolved. In a new report on *Science Advances*, Meghana Raghunandan and a research team at the institute for theoretical physics, QUEST institute and the Institute for quantum optics in Germany demonstrated a new approach. While the initialization protocol developed in the work was largely independent of the physical realization of the simulation device, the team provided an example of implementing a trapped ion quantum simulator.

Quantum simulation is an emergent technology aimed at solving important open problems relative to high-temperature superconductivity, interacting quantum field theories or many-body localization. A series of experiments have already demonstrated the successful implementation of Hamiltonian dynamics within a quantum simulator—however, the approach can become challenging across quantum phase transitions. In the new strategy, Raghunandan et al. overcame this problem by building on recent advances in the use of dissipative quantum systems to engineer interesting many-body states.

Almost all many-body Hamiltonians of interest remain outside a previously investigated class and therefore require generalization of the dissipative state preparation procedure. The research team therefore presented a previously unexplored paradigm for the dissipative initialization of a quantum simulator by coupling the many-body system performing the quantum simulation to a dissipatively driven auxiliary particle. They chose the energy splitting within the auxiliary particle to become resonant with the many-body excitation gap of the system of interest; described as the difference of the ground-state energy and the energy of the first excited state. During such conditions of resonance, the energy of the quantum simulator could be transferred efficiently to the auxiliary particle for the former to be cooled sympathetically, i.e.,

particles of one type, cooled particles of another type.

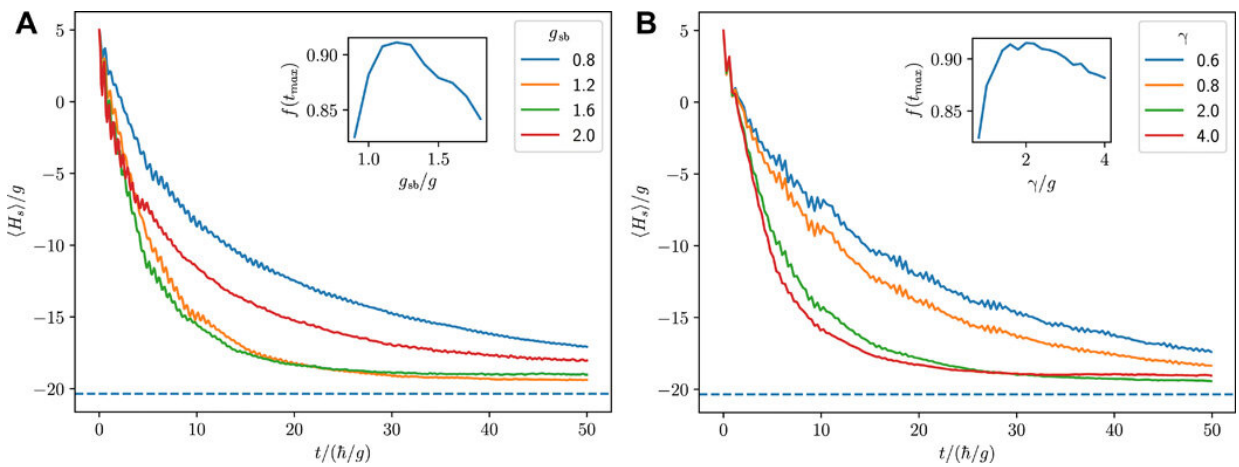


Possible paths via which an excitation can be cooled down to the ground state: Each black arrow corresponds to an energy difference $\Delta - \gamma \leq E_i - E_j \leq \Delta + \gamma$. Each cooling step leads to a reduction of the energy of the system, eventually reaching the ground state. The energy levels are shown for (a) the Ising model ($N = 5$, $J/g = 5$, $\gamma/g = 3.5$) and (b) the Heisenberg model ($N = 5$, $\gamma/J = 1.26$). Credit: Science Advances, doi: 10.1126/sciadv.aaw9268

While the value of the many-body excitation gap is usually unknown prior to simulation, Raghunandan et al. showed the gap could be determined from quantum simulation data via a spectroscopic measurement. The dissipative initialization process also simultaneously provided important information about the many-body system and they noted that cooling by a single auxiliary particle was efficient and robust against unwanted noise processes occurring in the quantum simulator.

Specifically, the research team considered different model one-dimensional (1-D) spin ½ many-body systems coupled to a single dissipatively driven auxiliary bath spin (low temperature environment

dominated by nuclear and paramagnetic spin). The setup could be generalized to bosonic or fermionic many-body systems. The experimental platform imposed modest requirements, which worked effectively for both analog and digital quantum simulators. The setup did not require control across individual particles of the quantum simulator.

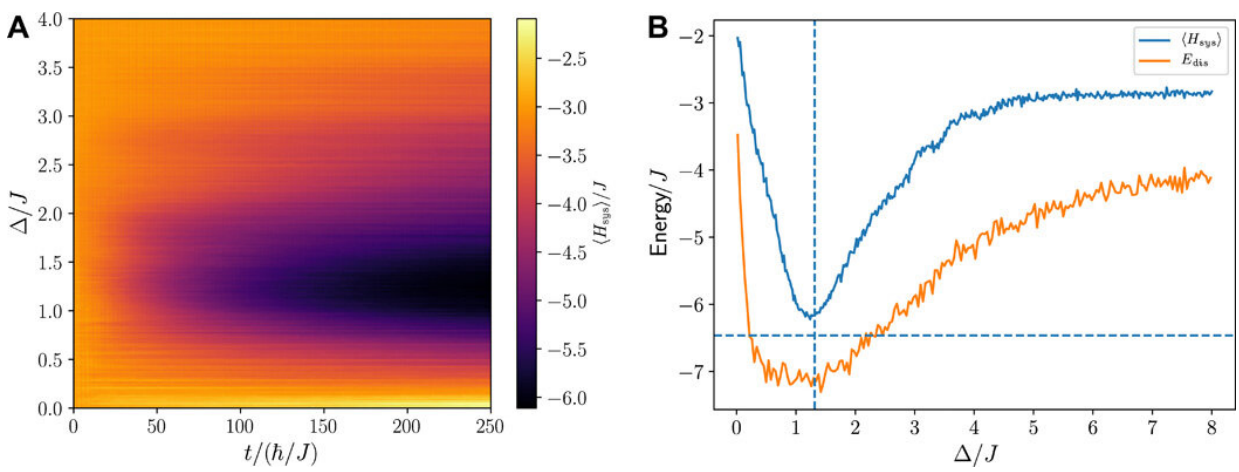


Sympathetic cooling of the transverse field Ising model in the ferromagnetic phase (J/g = 5, N = 5, fx, y, z = {1,1.1,0.9}). The speed of the cooling dynamics and the final energy of the system depend on the system-bath coupling gsb for γ/g = 1.9 (A) and the dissipation rate γ for gsb/g = 1.15 (B). The ground-state energy is indicated by the dashed line. The insets show that the ground state can be prepared with greater than 90% fidelity. Credit: Science Advances, doi: 10.1126/sciadv.aaw9268

As a first definitive model, Raghunandan et al. considered the Ising model in a transverse field to form a simple platform outside the class of frustration-free Hamiltonians. They analyzed the cooling performance of the setup by tracking the system energy using wave-function Monte Carlo simulations. The transverse Ising field is generally known to undergo a quantum phase transition from a paramagnetic phase to a

ferromagnetic phase. The team observed the energy of the system decrease rapidly and finally approach a value close to the numerically calculated ground-state energy.

The cooling performance depended on the choice of the system-bath coupling (g_{sb}) and the dissipation rate (γ). If the system-bath coupling was too small, the cooling dynamics were very slow, if it was too large, then the system and the bath spin became strongly entangled to reduce the cooling performance. As a result, the two parameters had to be optimized leading to a minimum in energy within the available time. The cooling protocol was not limited to a specific model—to substantiate this, the team next turned to the especially challenging case of a critical Heisenberg chain, i.e. the archetype of quantum integrable one dimensional models.

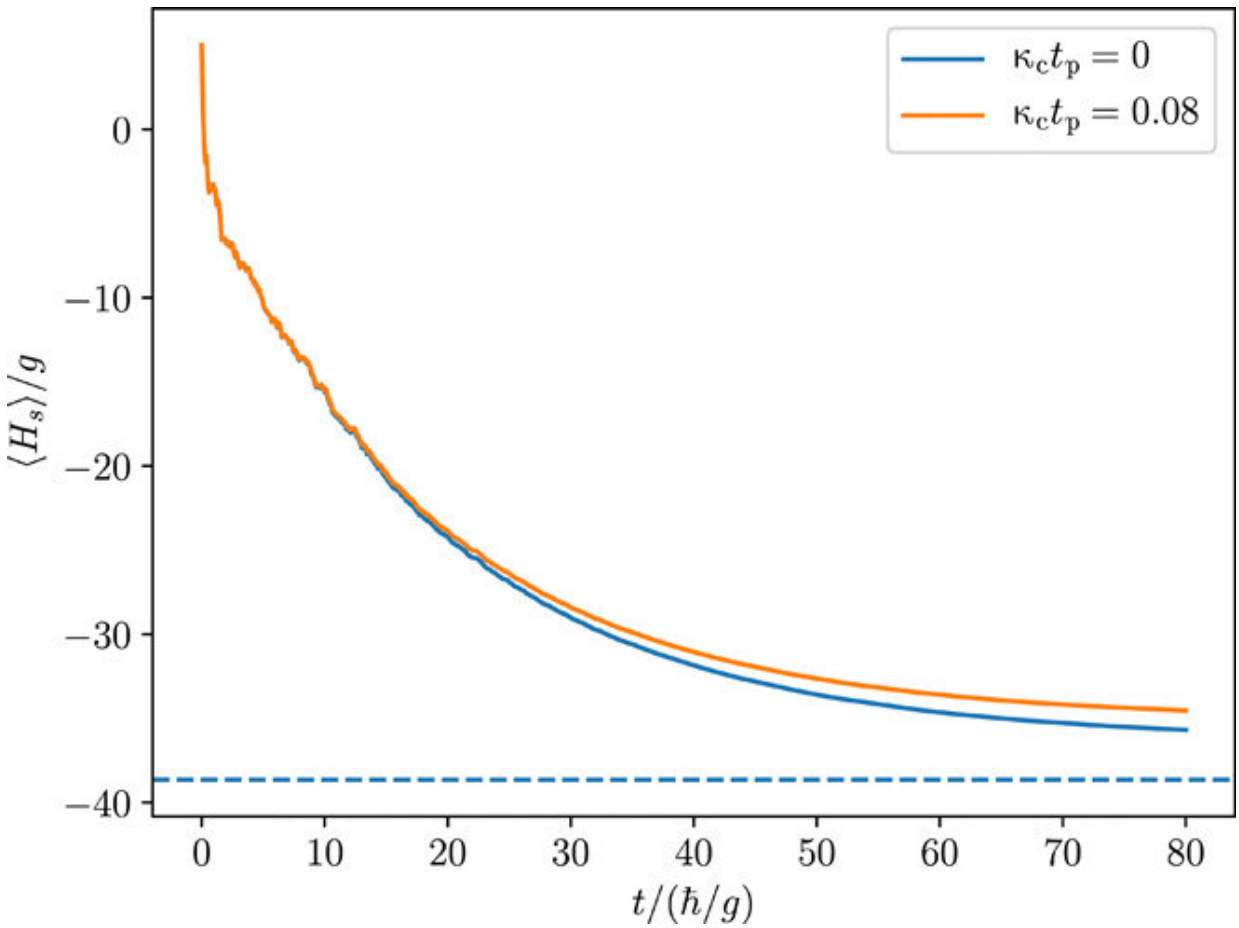


Sympathetic cooling of the antiferromagnetic Heisenberg model (N = 4, gsb/J = 0.2, γ/J = 0.6, fx,y,z = {0.4,2.3,0.3}). (A) The efficiency of the cooling procedure depends on the choice of the bath spin splitting Δ. (B) The optimal cooling leading to the lowest system energy ⟨Hsys⟩ corresponds to setting Δ to the many-body gap ΔE (vertical dashed line). The same minimum is observed when measuring the energy Edis that is being dissipated during the cooling process. The ground-state energy is indicated by the horizontal dashed line.

Credit: Science Advances, doi: 10.1126/sciadv.aaw9268

The team investigated the antiferromagnetic Heisenberg chain as a second paradigmatic (definitive) quantum many-body model. The model, however, represented a challenge for the cooling protocol. The ground state at the critical point was also highly entangled – allowing them to test the capability of the protocol to prepare entangled quantum many-body states. The team recorded the cooling performance relative to the system energy. Much like the transverse field Ising model, the system energy rapidly decreased and reached a final value close to the ground state energy (E_0), where the final state was also highly entangled.

Since it is difficult to experimentally measure the system energy on many quantum simulation architectures without performing tomography on all operators in the system, the team measured the bath spin and energy dissipated during cooling dynamics instead. They then investigated the efficiency of the cooling protocol to understand how its properties behaved with increasing system size. A protocol is typically efficient when the resources required to grow polynomially with the system size. Raghunandan et al. used a numerical simulation for standard nonlinear optimization and based on the scaling behavior, they showed that since the number of particles became a scarce resource in a quantum simulator, the required minimal overhead for initialization allowed the use of almost all particles for the actual quantum simulation.



Cooling performance of an Ising-like chain of 5 + 1 ions of tp = 80ℏ/g = 24s. The blue line shows the dynamics in the decoherence-free case resulting in a fidelity of f = 0.92, while the orange line indicates the dynamics under a collective decoherence mechanism with rate κc = 3.3Hz, resulting in f = 0.89. The dashed line indicates the ground-state energy of the system. Credit: Science Advances, doi: 10.1126/sciadv.aaw9268

The only source of decoherence in the work stemmed from dissipative flips of the bath spin, although quantum simulation architectures can also contain unwanted decoherence processes in the system performing the simulation. As a result, it was crucial to determine the consequences of additional decoherence on the performance of the cooling protocol—the

findings were generic and applicable to other many-body models. The team credited the improved robustness against decoherence to the dissipative state preparation protocol that could self-correct decoherence events.

The team then experimentally realized the proposed initialization protocol in a trapped ion system with state-of-the-art technology. They implemented the setup with $^{40}Ca^{+}$ ions similar to a previous study. They encoded the spin stats in the optical qubit and manipulated energy splitting coherently with radial laser beams—where the rightmost ion served as the bath spin and its laser-induced coupling to the neighboring ion implemented system-bath coupling. They employed both system and system-bath Hamiltonians as H_{sys} and H_{sb} in the setup and the dominant decoherence mechanism in the platform arose from global magnetic field fluctuations.

In this way, Meghana Raghunandan and colleagues demonstrated how adding a dissipatively driven auxiliary particle could sympathetically cool a quantum simulator into low-energy states. The approach is efficient even when using only a single bath spin to exhibit strong robustness against unwanted decoherence occurring in the quantum stimulator. Raghunandan et al. intend to further investigate the scaling behavior by optimally varying the coupling constants of the bath in time.

More information: Meghana Raghunandan et al. Initialization of quantum simulators by sympathetic cooling, *Science Advances* (2020). DOI: 10.1126/sciadv.aaw9268

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