Near-Carnot quantum heat engine realized through a frustrated spin-1 Heisenberg diamond chain with topological and bound-magnon phases

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We study the magnetic and thermodynamic properties of a frustrated spin-1 Heisenberg diamond chain in an external magnetic field focusing on the interplay between topologically nontrivial Haldane states and bound-magnon states. Using a combination of analytical approaches and large-scale numerical methods (DMRG, exact diagonalization, and quantum Monte Carlo), we identify a rich ground-state phase diagram comprising uniform and cluster-based Haldane phases, fragmented states, and bound-magnon crystals.

In the strongly frustrated regime, destructive quantum interference leads to the formation and crystallization of bound magnons, which give rise to flat-band physics and fractional magnetization plateaux. We demonstrate that fragmentation mechanisms stabilize cluster-based Haldane states providing a link between topology and localized excitations. Furthermore, an effective lattice-gas description captures low-temperature thermodynamics and field-driven quantum phase transitions with high accuracy.

Our results reveal clear thermodynamic fingerprints of topological and magnon-bound states and highlight frustrated quantum spin systems as versatile platforms for exploring quantum criticality, magnetocaloric effects, and emergent phenomena relevant to quantum technologies.

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