From quantum spins to classical dimers: approaching a Kasteleyn transition in a frustrated Heisenberg model

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We demonstrate how classical critical phenomena governed by local constraints can emerge from a fully SU(2)-symmetric quantum system. Specifically, we study the spin-1/2 Heisenberg antiferromagnet on a diamond-decorated honeycomb lattice and identify a regime where the low-energy sector is described by an effective statistical model of dimers with a tunable density of defects.

In the dimer–tetramer phase, the ground-state manifold maps onto close-packed dimer coverings of the honeycomb lattice, establishing a direct bridge between frustrated quantum magnetism and classical dimer statistics. Upon introducing a weak spatial anisotropy, this manifold is lifted and gives rise to an effective anisotropic dimer model with rare monomer defects. The resulting thermodynamics exhibits a pronounced low-temperature anomaly associated with the proximity to the Kasteleyn transition, characterized by the proliferation of extended string excitations.

Although the presence of monomers forbids a true thermodynamic singularity, their density is exponentially suppressed at low temperatures, enabling an arbitrarily sharp crossover that asymptotically approaches the inverse square-root singularity of the pure dimer problem. Large-scale numerical simulations of both the microscopic quantum model and its effective classical description reveal quantitative agreement and confirm that the observed behavior is governed by emergent dimer constraints rather than conventional symmetry breaking.

Our results establish a concrete realization of Kasteleyn-type criticality in a quantum Heisenberg magnet and highlight a general mechanism by which constrained statistical physics can arise from quantum many-body systems.

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