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Magnetic "three states of matter" in two and three dimensions: a quantum Monte Carlo study of the extended toric codes

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The possibility of quantum spin liquids, characterized by nontrivial entanglement properties or a topological nonlocal order parameter, has long been debated both theoretically and experimentally. Since candidate systems (e.g., frustrated quantum magnets or $5d$ transition metal oxides) may host other competing phases including conventional magnetic ordered phases, it is natural to ask what types of global phase diagrams can be anticipated depending on coupling constants, temperature, dimensionality, etc. In this talk, by considering an extension of the Kitaev toric code Hamiltonians by Ising interactions on 2D (square) and 3D (cubic) lattices, I will present thermodynamic phase diagrams featuring magnetic "three states of matter," namely, quantum spin liquid, paramagnetic, and magnetically ordered phases (analogous to liquid, gas, and solid, respectively, in conventional matter) obtained by unbiased quantum Monte Carlo simulations [YK, Y. Kato, J. Nasu, and Y. Motome, PRB 92, 100403(R) (2015)]. We find that the ordered phase borders on the spin liquid around the exactly solvable point by a discontinuous transition line in 3D, while it grows continuously from the quantum critical point in 2D. In both cases, peculiar *proximity effects* to the nearby spin liquid phases are observed at high temperature even when the ground state is magnetically ordered. Such proximity effects include flux-shrinking and a tricritical behavior in 3D and a "fractionalization" of the order parameter field at the quantum critical point in 2D, both of which can be detected by measuring critical exponents. (*) Work done in collaboration with Yasuyuki Kato, Joji Nasu, and Yukitoshi Motome