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Identifying Topological Quantum Spin Liquid in Physical Realistic Models

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Quantum spin liquids (QSLs) are elusive magnets without magnetism, resisting symmetry breaking even at zero temperature due to strong quantum fluctuations and geometric frustration. The simplest QSLs known theoretically are characterized by topological order, i.e., topological quantum spin liquid, and support fractionalized excitations. However, there is no practical way to directly determine the topological nature of states, such as QSLs. We propose a practical and extremely simple approach, i.e., cylinder construction, to numerically calculate the topological entanglement entropy (TEE), and thereby identify topological order of the state [H. C. Jiang, Z. Wang, and L. Balents, arXiv:1205.4289]. We have successfully applied this approach to a variety of lattice models and S=1/2 Kagome Heisenberg model. By extracting an accurate TEE, we identify a quantum spin liquid with topological order for the first time in physically realistic SU(2)-invariant lattice model. We emphasize that the TEE provides positive, "smoking gun" evidence for a topological quantum spin liquid, and excludes any topologically trivial states, including the valence bound solid state. Besides the Kagome Heisenberg model, based on large-scale accurate density-matrix renormalization group studies of numerous long cylinders with circumferences up to 14 lattice spacings, our results [H. C. Jiang, H. Yao, and L. Balents, Physical Review B 86, 024424(2012)], through a combination of the absence of magnetic or VBS order, nonzero spin singlet and triplet gaps, as well as a finite TEE extremely close to ln(2), provide compelling evidence that the two-dimensional ground state of the square J_1-J_2 Heisenberg model is a topological quantum spin liquid.