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Correlations in excited states of local Hamiltonians

Physical properties of the ground and excited states of a k-local Hamiltonian are largely determined by the k-particle reduced density matrices (k-RDMs), or simply the k-matrix for fermionic systems—they are at least enough for the calculation of the ground state and excited state energies. Moreover, for a non-degenerate ground state of a k-local Hamiltonian, even the state itself is completely determined by its k-RDMs, and therefore contains no genuine $>k$-particle correlations, as they can be inferred from k-particle correlation functions. It is natural to ask whether a similar result holds for non-degenerate excited states. In fact, for fermionic systems, it has been conjectured that any non-degenerate excited state of a 2-local Hamiltonian is simultaneously a unique ground state of another 2-local Hamiltonian, hence is uniquely determined by its 2-matrix. And a weaker version of this conjecture states that any non-degenerate excited state of a 2-local Hamiltonian is uniquely determined by its 2-matrix among all the pure n-particle states. We construct explicit counterexamples to show that both conjectures are false. It means that correlations in excited states of local Hamiltonians could be dramatically different from those in ground states. We further show that any non-degenerate excited state of a k-local Hamiltonian is a unique ground state of another $2k$-local Hamiltonian, hence is uniquely determined by its $2k$-RDMs (or $2k$-matrix).