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Entanglement Scaling Laws and Eigenstate Thermalization in Many-Particle Systems

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While entanglement entropy of ground states usually follows the area law, violations do exist, and it is important to understand their origin. In 1D they are found to be associated with quantum criticality. Until recently the only established examples of such violation in higher dimensions are free fermion ground states with Fermi surfaces, where it is found that the area law is enhanced by a logarithmic factor. In Ref. [1], we use multi-dimensional bosonization to provide a simple derivation of this result, and show that the logarithimic factor has a 1D origin. More importantly the bosonization technique allows us to take into account the Fermi liquid interactions, and obtain the leading scaling behavior of the entanglement entropy of Fermi liquids. The central result of our work is that Fermi liquid interactions do not alter the leading scaling behavior of the entanglement entropy, and the logarithmic enhancement of area law is a robust property of the Fermi liquid phase. In sharp contrast to the fermioic systems with Fermi surfaces, quantum critical (or gapless) bosonic systems do not violate the area law above 1D (except for the case discussed below). The fundamental difference lies in the fact that gapless excitations live near a single point (usually origin of momentum space) in such bosonic systems, while they live around an (extended) Fermi surface in Fermi liquids. In Ref. [2], we studied entanglement properties of some specific examples of the so called Bose metal states, in which bosons neither condense (and become a superfluid) nor localize (and insulate) at T=0. The system supports gapless excitations around "Bose surfaces," instead of isolated points in momentum space. We showed that similar to free Fermi gas and Fermi liquids, these states violate the entanglement area law in a logarithmic fashion. Compared to ground states, much less is known concretely about entanglement in (highly) excited states. Going back to free fermion systems, in Ref. [3] we show that there exists a duality relation between ground and excited states, and the area law obeyed by ground state turns into a volume law for excited states, something widely expected but hard to prove. Most importantly, we find in appropriate limits the reduced density matrix of a subsystem takes the form of thermal density matrix, providing an explicit example of the eigenstate thermalization hypothesis. Our work [3] explicitly demonstrates how statistical physics emerges from entanglement in a single eigenstate.

[1] Entanglement Entropy of Fermi Liquids via Multi-dimensional Bosonization, Wenxin Ding, Alexander Seidel, Kun Yang, Phys. Rev. X 2, 011012 (2012).
[2] Violation of Entanglement-Area Law in Bosonic Systems with Bose Surfaces: Possible Application to Bose Metals, Hsin-Hua Lai, Kun Yang, N. E. Bonesteel, Phys. Rev. Lett. 111, 210402 (2013).
[3] Entanglement entropy scaling laws and eigenstate thermalization in free fermion systems, Hsin-Hua Lai, Kun Yang, arXiv:1409.1224.