論文の内容の要旨

Replica manipulation of the ground state in one-dimensional quantum spin systems

（１次元量子スピン系における基底状態のレプリカ操作）

熊野　裕太

In the last decade it has become evident that information-theoretic quantities, which quantify a quantum entanglement encoded in a quantum state, are extremely useful to analyze a state of mane-body systems. Celebrated examples are the entanglement entropy and the Shannon entropy, which extract universal information of the underlying field theory of the system. Furthermore, a significant concept, the entanglement spectrum, has been proposed recently. It contains more complete information than the entanglement entropy. They have achieved a considerable success in characterizing exotic quantum phases that are beyond conventional descriptions.

Inspired by these developments, we propose a new state, which we name a Rényified state, as follows: For a given quantum state $|\Psi\rangle = \sum_i \psi_i |i\rangle$ and the basis states $|i\rangle$, the Rényified state is defined by raising the wave-function coefficients ψ_i to the power of n (and normalized). The Shannon entropy can be obtained from the Rényified state. Moreover, the latter contains more information than the former.

We study the Rényified state starting from a Tomonaga-Luttinger liquids (TLL), which is an important universality class of one-dimensional quantum systems. A TLL is characterized by a TLL parameter K, and described by the free boson field theory with a central charge $c = 1$ in the conformal field theory (CFT) context. We will show, using analytical argument and numerical calculations, that the Rényified state is also a TLL described by a modified TLL parameter $\tilde{K} = K/n$, when $n < 4K$.. The TLL description breaks down at $n = 4K$, which is related to a phase transition in the Rényi-Shannon entropy. Beyond the transition, $n > 4K$, we show that the Rényified state is no longer a TLL since the longitudinal correlations decay exponentially while the transverse ones remain algebraic. This exceptional behavior is unlikely to be realized in the ground state of a Hamiltonian with only short-range interactions. This indicates that the Rényified state beyond the transition belongs to a new class of exotic quantum phase. We explain an origin of the exotic behavior by using a replica approach and the construction of a particular conformal invariant boundary state of a two-component massless free boson. A few exact solutions of the Rényified state for a free fermion lattice model support our field theoretical analyses. The relationship between the Rényified state and the Rényi-Shannon entropy is also elucidated in boundary CFT formalism.