Simplifying long-range quantum interactions in many-body systems

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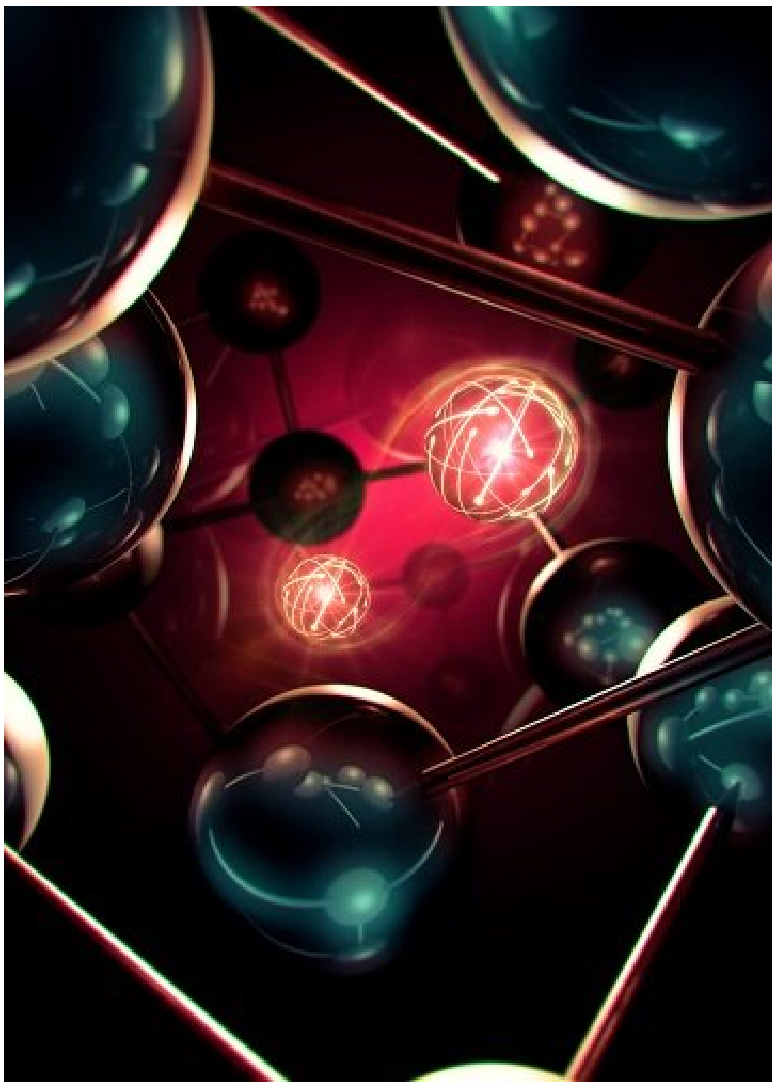

Figure 1: Modeling long-range entanglement in quantum many-body systems is made easier by assuming the area law. Credit: Tony Melov/Science Photo Library

Calculations for certain quantum systems whose parts interact over long distances will be much easier to perform thanks to the work of a RIKEN physicist and his collaborator, who have extended an assumption that holds for materials with short-range interactions.

Famously dubbed "spooky action at a distance" by Albert Einstein, entanglement is one of the most fascinating aspects of quantum physics. It is an invisible connection between quantum systems that means that one system cannot be fully described without including the states of the others—a link that cannot be understood using classical mechanics.

Entanglement plays a central role in the physics of quantum systems made up of many parts needed to understand materials at low temperatures. One of the most rigorous ways to quantify entanglement is using entanglement entropy, which characterizes the complexity of a material's lowest energy state. A state with a zero entanglement entropy is classical and exhibits no quantum properties. States with a small but non-zero entanglement entropy can be described using relatively simple quantum theory. But states with larger entanglement entropy become very difficult to model mathematically.

In many materials, entanglement occurs over a short range, existing only between nearest neighbors. These systems have been shown to have a low entanglement entropy. Known as the area law conjecture, this assumption greatly simplifies modeling.

But some materials can exhibit unusual states of matter in which the interactions between atoms can be maintained over longer distances. And so the question arises: does the area law still hold in materials with non-local quantum connections? This is the question investigated by Tomotaka Kuwahara from the RIKEN Center for Advanced Intelligence Project and Keiji Saito from Keio University.

"Several numerical and theoretical studies have indicated that the area law is violated in long-range interacting systems," explains Kuwahara. "Our result is mathematically rigorous and settles the debate over the area law conjecture in one-dimensional, long-range interacting systems."

Providing a detailed proof of an area law is extremely challenging. Kuwahara and Saito simplified the mathematics of the problem by modeling a one-dimensional chain. They looked at a chain of long-range interacting magnetic particles. They decomposed the total system into two subsystems, left and right, and simulated the boundary as a series of discrete points. In this way, the pair showed that the entanglement entropy has a maximum possible value, which is a signature of an area law.

"The next step for us is to prove the area law conjecture in systems with more than one dimension," says Kuwahara. "We exploited several new mathematical techniques in our present study, and we hope to apply them to higher dimensional cases."

More information: Tomotaka Kuwahara et al. Area law of noncritical ground states in 1D long-range interacting systems, *Nature Communications* (2020). DOI: 10.1038/s41467-020-18055-x

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