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論 文 要 旨

THESIS SUMMARY

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要旨（英文 800 語程度）
Thesis Summary（approx.800 English Words ）

Understanding quantum many-body systems with interactions is an important problem common to various fields of physics, such as atomic physics, condensed matter physics, nuclear physics, and particle physics. Among others, ultracold atoms have provided ideal grounds to study strongly interacting systems and to explore exotic quantum states because of their high controllability. We can widely control the strengths of the interactions from weak to strong as well as the geometry of the systems. In order to deepen our understanding of quantum many-body systems with interactions, we in this thesis investigate two types of one-dimensional (1D) systems realizable with ultracold atoms; bosons and spinless fermions near two-body resonances and bosons near a three-body resonance.

One-dimensional systems near two-body resonances have been intensively studied because, in the homogeneous cases, they are exactly solvable systems. The energy spectra and thermodynamic quantities exactly obtained by the Bethe ansatz have greatly contributed to deepening our comprehension of many-body systems in 1D. On the other hand, the exact computations of correlation functions, which encode information about excitations of the systems, are in general much more complicated even in the integrable systems.

Motivated by this background, we derive a series of exact relations for correlation functions in bosons and fermions near two-body resonances. These relations called universal relations originate from the universal properties of the resonant systems: Their properties depend on the interactions only through the scattering lengths characterizing the low-energy scattering. The universal relations are strong constraints on the systems because the relations hold for any particle number, scattering length, temperature, and with or without a trapping potential. The relations include the asymptotic behaviors of correlation functions in high-energy regime as well as the energy relations, in which the energies are expressed in term of the momentum distributions. The universal relations involve two- and three-body contacts, which are the integrals of local pair and triad correlations, respectively.

Firstly we derive, in both bosons and fermions, universal relations for static correlation functions such as static structure factors and momentum distributions within the first-quantized formalisms. The power laws of the static correlation functions for large momentum and the energy relations are obtained. The coefficients in these power-law behaviors are proportional to the two-body contact. We clarify that the three-body contact makes no contribution to the bosonic energy relation, but it plays a crucial role in the fermionic one.

Secondly, we derive universal relations for dynamic correlation functions for bosons. Using the operator product expansion (OPE) in the field theoretical formalism, we obtain the large-energy-momentum behaviors of the dynamic structure factor, the dynamic current correlation, and the single-particle spectral density as well as the quasiparticle energy and the scattering rate in high-energy regime. While the behaviors of the dynamic structure factor and the current correlation are proportional to the two-body contact, that of the single-particle spectral density is proportional to the number density. Because of the interrelation between 1D bosons and fermions near two-body resonances, the results of the dynamic structure factor and the current correlation for bosons also hold for the fermions.

Thirdly, the quantum field theory for fermions near a two-body resonance is studied to derive universal relations for the single-particle spectral density. Unlike for bosons, the regularization is necessary for the field theory for fermions. Performing a renormalization group analysis, we find that not only two-body but also three-body couplings are renormalized and clarify that the renormalization of the three-body coupling is associated with the appearance of the three-body contact in the fermionic energy relation. Applying OPE to the constructed field theory, we investigate the large-energy-momentum behavior of the single-particle spectral density. As a result, the behavior is found to be proportional to the number density.

The high controllability of ultracold atoms allows us to extinguish their two-body interaction, leading to the realization of unique systems governed by the three-body interaction, which is otherwise hidden behind the two-body interaction. In such systems, novel bound states, which are not stabilized by two-body interactions, are expected to appear. From this perspective, 1D bosons with a resonant three-body interaction are investigated in this thesis. We reveal that they form few-body bound states as well as a many-body droplet stabilized by the quantum mechanical effect. Their binding energies relative to that of three bosons are all universal and the ground-state energy of the dilute droplet is found to grow exponentially as $E_N/E_3 \to \exp(8N^2/3\pi)$ with increasing particle number $N \gg 1$. This exponential growth of E_N results from the asymptotic freedom associated with the three-body interaction in 1D.

While our studies of the resonantly interacting systems in 1D are motivated by highly tunable ultracold atoms, the properties of the systems are universal in the sense that they are independent of microscopic details of the interaction potentials. Accordingly, our result can be applied not only to ultracold atomic gases in elongated traps but also other 1D quantum systems in which microscopic length scales associated with interactions are much smaller than other length scales such as the scattering lengths, thermal de Broglie wavelengths, and mean interparticle distances.