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journal or publication title	The science reports of the Tohoku University. Ser. 8, Physics and astronomy
volume	20
number	1
page range	191-192
year	1999-07-30
URL	http://hdl.handle.net/10097/26028

Dynamics and Quasi-Particle Picture of One-Dimensional Quantum Systems with Long-Range Interaction

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One-dimensional (1D) quantum systems are characterized by large quantum fluctuation. The large quantum fluctuation leads to breakdown of the Fermi liquid. Consequently, there appear such features as (i) disappearance of Landau quasi-particles and (ii) the spin-charge separation. Dynamical properties reveal these features most remarkably.

Owing to existence of various quasi-1D materials (in which the interaction between electrons along one direction is strong due to special structure of the material), dynamics for lattice models describing the realistic systems has been studied theoretically. However, one has difficulty in interpreting the result because of its intricacy. For interpretation, the quasi-particle picture is very useful. Here the "quasi-particle" does not mean the Landau quasi-particle but a general elementary excitation from the ground state. Above all, quasi-particles peculiar to one dimension are spinons, holons, and so on. It is known that the long-range models, which have the interaction proportional to the inverse square of the distance, provide the free quasi-particle picture obeying fractional statistics. For these models, the number of quasi-particles contributing to dynamics is finite due to a high symmetry of the model. Then the dynamical properties can be well understood in terms of the quasi-particle picture.

The purpose of this thesis is to clarify the dynamical properties for 1D quantum systems with long-range interaction, especially for the XXZ model and the t-J model. The exact diagonalization technique is largely used. We elucidate the effects of the Ising anisotropy and the interaction range on the dynamical spin structure factors for the 1D XXZ model. We also investigate the dynamics for the t-J model in zero and nonzero magnetic field. In both models, obtained results are interpreted from the quasi-particle picture.

We begin with a discussion of the dynamical spin structure factor $S(q,\omega)$ for the XXZ chain. (q and ω denote the momentum transfer and the excitation energy, respectively.) Two types of the exchange interaction are considered: one is the nearest-neighbor (NN) type, and the other is the inverse-square (IS) one. It is known that in the isotropic case the intensity diverges at the lower edge of the continuum spectrum for both types of the exchange; particularly for the IS type, the dynamics is described by two free spinons in the pseudomomentum space. Here "pseudomomentum" means the momentum which includes the effect of interaction for the system. We focus on the characteristic change when the Ising anisotropy is increased.

In the transverse component $S^{xx}(q,\omega)$, there appears a noticeable difference between the two types of the exchange. For the NN type, the peak frequency of $S^{xx}(q,\omega)$ for each q approaches the center of the continuum spectrum. On the contrary, the peak frequency for the IS type moves to the upper edge of the continuum, and separates from the continuum for the anisotropy larger than the threshold value. This difference is understood in terms of whether the interaction between spinons in the real space is absent or repulsive in the Ising limit. In the IS type, there is a repulsion which gives rise to an anti-bound state, i.e., an isolated mode above the continuum. On the other hand, the feature of the dynamics in $S^{zz}(q,\omega)$ is scarcely different between the two types.

Next, we explain the dynamical properties for the long-range supersymmetric t-J model. For this model, the regions of nonvanishing spectral weight in the energy-momentum space ("compact support") have been obtained for $S(q,\omega)$, the dynamical charge structure factor $N(q,\omega)$ and the single-particle spectral function $A(k,\omega)$. We make an issue of these spectral weights themselves. In particular, we find a remarkable result on $S(q,\omega)$; this quantity is independent of the electron density in the small momentum region of (q,ω)-plane where only two spinons contribute [Fig. 1]. We refer to this result as the "strong spin-charge separation", in contrast with the mere difference between spin and charge velocities. We also consider the charge and spin dynamics for the model in a magnetic field. In an applied field, the strong spin-charge separation appears twofold. First, $N(q,\omega)$ is independent of the magnetization in the region where only quasi-particles with the charge degree of freedom (holons and antiholons) are excited. Second, for fixed magnetization, the longitudinal component $S^{zz}(q,\omega)$ of spin dynamics does not depend on the hole density in the region where only quasi-particles with the spin degree of freedom (spinons and antispinons) contribute. These features reflect the high symmetry of the model.

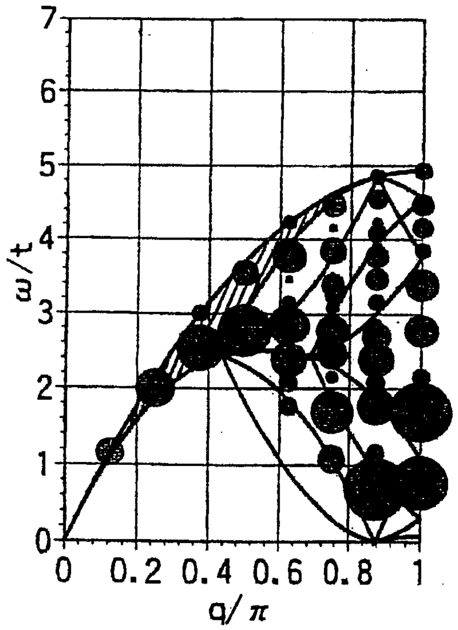

Fig. 1 $S(q,\omega)$ of the long-range supersymmetric t-J model with 16 sites and 2 holes. The unit of energy is the transfer energy t. The intensity of each pole is proportional to the *area* of the circle. The solid lines are the dispersion lines of elementary excitations for the compact support. The hatched area indicates the region where only two spinons contribute.