Commun. Theor. Phys. (Beijing, China) **48** (2007) pp. 445–448
© International Academic Publishers Vol. 48, No. 3, September 15, 2007

Perfect Transfer of Many-Particle Quantum State via High-Dimensional Systems with Spectrum-Matched Symmetry*

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(Received September 15, 2006)

Abstract *The quantum state transmission through the medium of high-dimensional many-particle system (boson or spinless fermion) is generally studied with a symmetry analysis. We discover that, if the spectrum of a Hamiltonian matches the symmetry of a fermion or boson system in a certain fashion, a perfect quantum state transfer can be implemented without any operation on the medium with pre-engineered nearest neighbor (NN). We also study a simple but realistic near half-filled tight-binding fermion system with uniform NN hopping integral. We show that an arbitrary many-particle state near the fermi surface can be perfectly transferred to its translational counterpart.*

PACS numbers: 03.67.Hk, 05.50.+q, 32.80.Lg
Key words: high-dimensional many-particle system, perfect quantum state transfer

1 Introduction

With minimal spatial and dynamical control over the interactions between qubits, the transmission of quantum state through a solid state data bus is an experimental challenging and a theoretically necessary for implementing a scalable quantum computation based on realistic silicon devices. S. Bose first demonstrated the possibility of the use of the quantum spin system as data bus.[1] In principle, a perfect quantum state transfer (QST) can be realized by specifically engineering the coupling constants between the nearest neighbor (NN) spins in one-dimensional chain.[2] Our recent study showed that a quantum system possessing a commensurate structure of energy spectrum matched with the corresponding parity symmetry can ensure the perfect quantum state transfer also in one-dimensional case.[3] In this letter we will prove that, to realize a higher-dimensional QST, a quantum data bus needs to possess an extendable symmetry matching its spectrum.

The present investigation is motivated by our recent exploration that an isotropic antiferromagnetic spin ladder system was proposed as a novel robust data bus.[4] In such a kind of gapped system, the non-zero spin states are only virtually excited, and then the QST has a very high fidelity. It implies that the perfect quantum-state transfer is also possible in other high-dimensional many-particle systems as robust quantum data bus.

Actually, many recent researches have been devoted to QST with quantum chains with permanent couplings or "always-on" inter-spin couplings.[5−16] Using such kinds of systems as quantum data bus, the quantum information can be transferred with minimal controls only on the sending and the receiving parties, rather than in the body of data bus. However most of these mentioned works only focus on the single-particle and one-dimensional solid state systems except the pioneer work,[17] which made serious consideration of state transfer in higher excitation subspaces. In this letter a large class of three-dimensional models with modulated NN interaction is proposed to perform QST. As an application, a realistic model, that is a simple near half-filled tight-binding fermion model with uniform hopping integral, is investigated analytically. It is found that the transmission of the quantum state near the fermi surface benefits from the quantum correlation of many-particle system. In other words, for such kinds of models, the coherent transfer of a many-particle state has higher fidelity than that of single-particle state at lower temperature.

Spectrum-symmetry matching condition (SSMC). To sketch our central idea, let us first consider a system with the Hamiltonian H possessing an arbitrary symmetry described by an operator R, i.e., $[H,R]=0$. Let ϕ_n be the common eigen-function of H and R corresponding to the eigen-values ε_n and p_n respectively. It is easy to find that any state ψ at time τ can evolve into its symmetrical counterpart $R\psi$ if the eigenvalues ε_n and p_n match each other and satisfy the spectrum-symmetry matching condition (SSMC),

$$\exp(-\mathrm{i}\varepsilon_n\tau)=p_n\,. \qquad (1)$$

Actually, an arbitrary state $\psi(0)=\sum_n C_n\phi_n$ at $t=0$ can evolve into $\psi(\tau)=R\psi(0)$ at $t=\tau$. Obviously,

*The project supported by National Natural Science Foundation of China under Grant Nos. 90203018, 10474104, and 10447133, and the Knowledge Innovation Program (KIP) of the Chinese Academy of Sciences, the National Fundamental Research Program of China under Grant No. 2001CB309310

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when the transmission of the quantum state is concerned, this SSMC always refers to the spatial symmetry operator, such as the reflection symmetry, translational symmetry, etc. For the former, the SSMC appears as so-called spectrum-parity matching condition (SPMC)[3] $\varepsilon_n = N_n E_0$, $p_n = \pm\exp(\mathrm{i}\pi N_n)$, for arbitrary positive integer N_n and $\tau = \pi/E_0$.

On the other hand, when the translational symmetry is concerned, we have $\exp(-\mathrm{i}H\tau) = T_r$, where T_r is translational operator with the translational spacing r, i.e., $T_r a_j^\dagger T_r^{-1} = a_{j+r}^\dagger$. For instance, consider a toy model on an N-site ring,

$$H = -\sum_{j=1}^{N}\sum_{l=1}^{N-1} J_l a_j^\dagger a_{j+l} + \text{h.c.} + \mu\sum_{j=1}^{N} n_j\,, \qquad (2)$$

where

$$J_l = \frac{\pi}{N}\Big(1 - \mathrm{i}\cot\frac{\pi l}{N}\Big), \quad \mu = (N-1)\frac{\pi}{N}\,. \qquad (3)$$

In k-space, it can be diagonalized as $H = \sum_k k a_k^\dagger a_k$, which obeys SSMC with respect to translational symmetry. Thus at instant $\tau = N/2$, an arbitrary initial state $|\psi(r, t = 0)\rangle$ can evolve to $|\psi(r, t = \tau)\rangle = |\psi(r - \tau, 0)\rangle$. For $N = 4$, a 4-dimensional representation of the Hamiltonian can be explicitly obtained on basis $\{|i\rangle = a_i^\dagger|0\rangle, i = 1, 2, 3, 4\}$. A straightforward diagonalization can give four eigenvalues $\lambda = 0$, $2\pi/4$, $4\pi/4$, and $6\pi/4$ with respect to the eigen-states $a_k^\dagger|0\rangle$. Correspondingly, the four eigenvalues of $T_{r=2}$ are $1, -1, 1, -1$ respectively. Obviously, they do meet SSMC.

Nevertheless, this is a toy model with very specific coupling. An example to demonstrate such a kind of QST scheme in more practical system will be discussed at the end of this paper. Furthermore the SSMC can be applied to the high-dimensional many-body system and it should be helpful to accomplish the task of QST in practical problems.

High-dimensional scalable systems for QST. Consider a Hamiltonian $H = \sum_{i=1}^{n} H_i$ containing n commutative sub-Hamiltonian H_i. The time evolution operator can be factorized as $U(t) = \prod_{j=1}^{n} U_j(t)$ by $U_j = \exp(-\mathrm{i}H_j t)$. If each sub-evolution operator $U_j(\tau)$ is just a certain spatial symmetry operation R_j at a same instance τ, such as the reflection or translation, the time evolution should result in symmetry transformation $R = \prod_{j=1}^{n} R_j$ from the initial state localized around a spatial point to the final state localized around another point. The above arguments mean that the conditions for such high-dimensional scalable systems are of two folds: (i) The spectrum of each H_j should satisfy the SSMC; (ii) The sub-Hamiltonian H_j should commute with each other. The previous works in Refs. [2] $\sim$ [4], [9], and [10] have proposed many schemes based on quantum spin system to meet the condition (i) exactly or approximately with respect to reflection operation by the spacial modulation of the NN coupling constants.

Now we start from a simple system on a three-dimensional lattice $N_1 \times N_2 \times N_3$, which is illustrated schematically in Fig. 1.

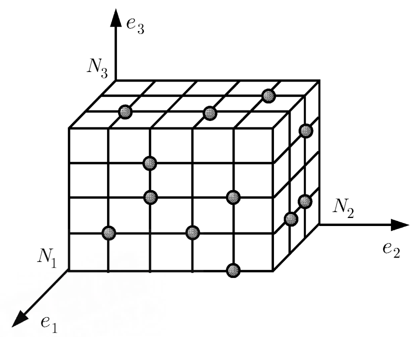

Fig. 1 A three-dimensional many-particle system on a $N_1 \times N_2 \times N_3$ lattice. It shows that the fermion or boson system with pre-engineered NN hopping constant can perform perfect many-particle state transfer.

$$H = \sum_{i=1}^{3} H_i = \sum_{i=1}^{3}\sum_{\boldsymbol{r},\sigma} J_{\boldsymbol{r},i} c_{\boldsymbol{r},\sigma}^\dagger c_{\boldsymbol{r}+\boldsymbol{e}_i,\boldsymbol{\sigma}} + \text{h.c.}\,, \qquad (4)$$

where $c_{\boldsymbol{r},\sigma}^\dagger$ is the fermion or boson creation operator at the position $\boldsymbol{r} = n_1\boldsymbol{e}_1 + n_2\boldsymbol{e}_2 + n_3\boldsymbol{e}_3$ ($n_i = 1, 2, \ldots, N_i$; $i = 1, 2, 3$) with spin $\sigma = \pm 1$, $\boldsymbol{e}_i$ is the unit vector for N_i. The NN hopping constants are restricted to be nonzero. Obviously, the sub-Hamiltonian H_i describes the particle hopping process along the direction $\boldsymbol{e}_i$. In general cases, the commutation relations between the sub-Hamiltonians are $[H_i, H_j] \neq 0$.

In the following, we will seek the special formation system with NN couplings to satisfy $[H_i, H_j] = 0$. Notice that for a cubic or square lattice, this commutation relation can always be rewritten as the form

$$[H_i, H_j] = \sum_l [P_l, Q_l]\,, \qquad (5)$$

where

$$P_l = \sum_{\boldsymbol{\sigma}} (l_{12} c_{l1,\sigma}^\dagger c_{l2,\sigma} + l_{34} c_{l3,\sigma}^\dagger c_{l4,\sigma} + \text{h.c.})\,,$$

$$Q_l = \sum_{\boldsymbol{\sigma}} (l_{13} c_{l1,\sigma}^\dagger c_{l3,\sigma} + l_{24} c_{l2,\sigma}^\dagger c_{l4,\sigma} + \text{h.c.})\,, \qquad (6)$$

denote the sub-Hamiltonian of a 2×2 plaquette labelled by l (see Fig. 2) and l_{12}, l_{34}, l_{13}, and l_{24} are the corresponding NN hopping constants. Straightforward calculation shows that if $l_{12} = l_{34}$ and $l_{13} = l_{24}$ one must have $[P_l, Q_l] = 0$ for any l. Therefore, we have reached the conclusion that $[H_i, H_j] = 0$ must hold, if all the hopping constants $J_{\boldsymbol{r},k}$ $(i, j, k = 1, 2, 3)$ are engineered as $J_{\boldsymbol{r}',k} = J_{\boldsymbol{r}'',k} = \cdots = J_{\boldsymbol{r}''',k}$, for the sites $\boldsymbol{r}', \boldsymbol{r}'', \ldots, \boldsymbol{r}'''$ on the same layer, i.e., $\boldsymbol{r}'\cdot\boldsymbol{e}_k = \boldsymbol{r}''\cdot\boldsymbol{e}_k = \cdots = \boldsymbol{r}'''\cdot\boldsymbol{e}_k$. This condition means that all the hopping constants between two layers (xy, yz, or zx) are identical. A simple example is the case that all the hopping constants along the same direction are identical. Obviously, the three sub-Hamiltonians commutate with each other. But we know that the spectrum of such a model does not satisfy the SSMC.

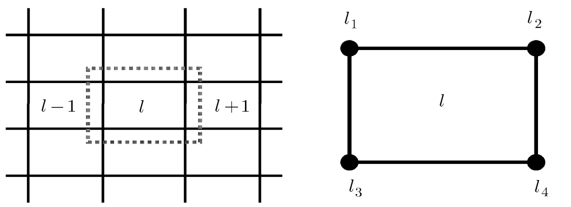

Fig. 2 The schematic illustration for the geometry of the Hamiltonian and its sub-block P_l, Q_l on a 2×2 plaquette labelled by l.

2 Pre-engineered Models

Many people have explored the free evolution of a single-magnon state via the spin networks to accomplish QST. It has been found that the homogeneous Heisenberg and XY spin chain without external field is not a good medium to transfer a single-magnon state.[3,10] For a perfect QST we usually need a pre-engineered spin chain with inhomogeneous inter-spin couplings.[2] Now we consider a pre-engineered model with the Hamiltonian,

$$H = \sum_{i=1}^{3}\sum_{\boldsymbol{r},\boldsymbol{\sigma}} J_{\boldsymbol{r},i}^{[m_i]} c_{\boldsymbol{r},\sigma}^{\dagger} c_{\boldsymbol{r}+\boldsymbol{e}_i,\boldsymbol{\sigma}} + \text{h.c.}\,, \tag{7}$$

where the hopping constants are defined as

$$J_{\boldsymbol{r},i}^{[m_i]} = \sqrt{m_i[1-(-1)^{n_i}]+n_i} \times \sqrt{m_i[1-(-1)^{n_i}]+N_i-n_i}\,, \tag{8}$$

where m_i are arbitrary positive integer numbers. Notice that for fixed m_i and N_i, the coupling constants only depend on n_i, the label of the layer. Then the pre-engineered distribution of the hopping constants $J_{\boldsymbol{r},i}^{[m_i]}$ ensures that the sub-Hamiltonians commute with each other, i.e. $[H_i, H_j] = 0$.

To see the dynamic process with such pre-engineered lattice fermion and boson systems, we start from the single-particle case by considering one particle state

$$|\phi_{\boldsymbol{k},\sigma}\rangle = \sum_{\boldsymbol{r}} f_{\boldsymbol{k},\boldsymbol{r}} |\boldsymbol{r},\sigma\rangle \equiv \sum_{\boldsymbol{r}} f_{\boldsymbol{k},\boldsymbol{r}} c_{\boldsymbol{r},\sigma}^{\dagger}|0\rangle\,, \tag{9}$$

where $|0\rangle$ is the vacuum state and $\boldsymbol{k} = \sum_{i=1}^{3} k_i \boldsymbol{e}_i$ ($k_i = 1, 2, \ldots, N_i$) can be regarded as the pseudo-momentum, which label the energy levels. Since $[H_i, H_j] = 0$, the single-particle wave function can be written formally as

$$f_{\boldsymbol{k},\boldsymbol{r}} = \varphi(k_1, n_1)\varphi(k_2, n_2)\varphi(k_3, n_3)\,. \tag{10}$$

From the previous work,[3] the eigenfunctions of the sub-Hamiltonian H_i with the corresponding eigenvalues $\varepsilon(k_i) = -N_i + 2(k_i - m_i) - 1$ for $k_i = 1, \ldots, N_i/2$; and $\varepsilon(k_i) = -N_i + 2(k_i + m_i) - 1$ for $k_i = N_i/2 + 1, \ldots, N_i$, can be constructed by the recurrence equations similar to that in Ref. [3].

The above analysis shows that $|\phi_{\boldsymbol{k},\sigma}\rangle$ is the eigen-state of the total Hamiltonian H with the single-particle spectrum $E(\boldsymbol{k}) = \sum_{i=1}^{3}\varepsilon(k_i)$. It shows that non-negative integer m_i determines the energy gap between positive and negative energies. For $m_i = 0$, it goes back to the case in Ref. [2]. This gap always keeps odd times of the minimal level spacing, which plays a crucial role in the following discussion.

Defining the diagonal reflection operator $\hat{R} = \hat{R}_1\hat{R}_2\hat{R}_3$, where $\hat{R}_i$ is the reflection operator with respect to the coordinate about $\boldsymbol{e}_i$, i.e.,

$$\begin{aligned} \hat{R}_1|\boldsymbol{r},\sigma\rangle &= |\tilde{n}_1\boldsymbol{e}_1 + n_2\boldsymbol{e}_2 + n_3\boldsymbol{e}_3,\sigma\rangle\,, \\ \hat{R}_2|\boldsymbol{r},\sigma\rangle &= |n_1\boldsymbol{e}_1 + \tilde{n}_2\boldsymbol{e}_2 + n_3\boldsymbol{e}_3,\sigma\rangle\,, \\ \hat{R}_3|\boldsymbol{r},\sigma\rangle &= |n_1\boldsymbol{e}_1 + n_2\boldsymbol{e}_2 + \tilde{n}_3\boldsymbol{e}_3,\sigma\rangle\,, \end{aligned} \tag{11}$$

where $\tilde{n}_i = N_i + 1 - n_i$ is the reflection-$\hat{R}_i$ counterpart of the coordinate n_i. According to the discussion in Ref. [3], we have $\hat{R}|\phi_{\boldsymbol{k},\sigma}\rangle = (-1)^{k_1+k_2+k_3}|\phi_{\boldsymbol{k},\sigma}\rangle$. It shows that any minimal change of $k_1 + k_2 + k_3$ must induce the change of the parity and eigenvalue $E(\boldsymbol{k})$ of the state by the minimal value 2, simultaneously. Thus it satisfies the SPMC, which guarantees the perfect state transmission diagonally.

Now we define many-particle state

$$|\psi_l\rangle = \prod_{\boldsymbol{k}_i,\sigma_i} c_{\boldsymbol{k}_i,\sigma_i}^{\dagger}|0\rangle$$

by the collective operators

$$c_{\boldsymbol{k},\sigma}^{\dagger} = (1/\sqrt{\Omega})\sum_{\boldsymbol{r}} f_{\boldsymbol{k},\boldsymbol{r}} c_{\boldsymbol{r},\sigma}^{\dagger}|0\rangle\,,$$

where Ω is the normalization factor. Obviously, we can have $\hat{R}|\psi_l\rangle = (-1)^p|\psi_l\rangle$, where $p = \sum_i \boldsymbol{k}_i\cdot(\boldsymbol{e}_1+\boldsymbol{e}_2+\boldsymbol{e}_3)$. Likewise, a straightforward calculation shows that the state $|\psi_l\rangle$ also meets the SPMC. Then any state $|\Phi\rangle = \sum_l A_l|\psi_l\rangle$ at $t = 0$ evolves to its reflection counterpart $\hat{R}|\Phi\rangle$ at time $t = \tau = \pi/2$. The above analysis is available for both the fermion and boson systems with any dimension, but for XY model, this conclusion is true only in single-particle subspace for n-dimensional systems ($n > 1$).

Near perfect transfer in a real many-body system. Now we consider how to realize such QST with SSMC in a real fermion system rather than a pre-engineered system. It is an important task to seek the practical systems to meet the SSMC approximately. Most of the previous works focus on single-excitation (-particle) cases. But the investigation for the QST based on antiferromagnetic spin ladder[4] as a robust data bus shows that many-excitation systems are also good candidate for the task. On the other hand, the above analysis indicates that the practical medium could be a many-particle system. To demonstrate this, a simple example is discussed as following.

Consider a simple spinless-fermion model of $H = -J\sum_i^N(c_i^{\dagger}c_{i+1} + \text{h.c.})$ on an N-site ring with uniform NN hopping constant. In k-space, this Hamiltonian can be diagonalized as $H = -2J\sum_k^N \cos k c_k^{\dagger}c_k$. Such a fermion system only in single-particle state is not suitable for implementing QST due to the nonlinear dispersion at lower spectrum. However, the spectrum in the region around $k = \pm\pi/2$ has the approximate linear dispersion relation, i.e., $\varepsilon(k) = -2J\cos k \sim -2J|k| + \pi J$. Then, we can separate the summation of k into two regions: linear L and nonlinear NL, which is illustrated in Fig. 3 and we rewrite Hamiltonian as

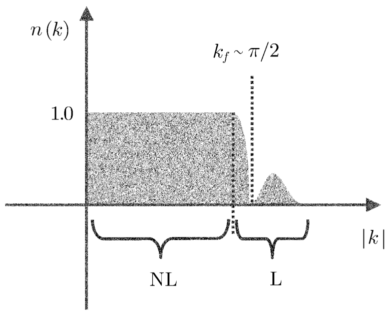

Fig. 3 The distribution of particle number in k-space for the states near the fermi surface. The character of such kinds of states allows us to separate the range of k into linear (L) and nonlinear (NL) regions.

$$H \approx -2J \sum_{|k|\in \mathrm{L}} |k| n_k - 2J \sum_{|k|\in \mathrm{NL}} n_k \cos k \,. \tag{12}$$

It is obvious that a system in the near half-filled case should be the proper medium for QST at lower temperatures. In this case, only the fermions near the fermi surface are excited and then any many-particle state can be expanded in terms of the eigen-states of the form

$$|\phi_n\rangle = \prod_{k\in \mathrm{L}} c_k^\dagger \prod_{k'\in \mathrm{NL}} c_{k'}^\dagger |0\rangle \,, \tag{13}$$

with eigen-values $-2J(\sum_{k\in \mathrm{L}} |k| + \varepsilon_0)$, where ε_0 is a constant and n labels the configuration of the fermions in the linear region. Therefore, near the fermi surface, arbitrary state will evolve according to the effective Hamiltonian $H_{\mathrm{eff}} = -2J\sum_{|k|\in \mathrm{L}} |k| n_k + \varpi_0$, where ϖ_0 is a constant which is independent of the distribution of particle number for $k \in \mathrm{L}$. On the other hand, for an N-site ring, the translational operator $\hat{T}_a$ defined by $\hat{T}_a C_j^\dagger|0\rangle = C_{a+j}^\dagger|0\rangle$ satisfies

$$\hat{T}_a|\phi_n(0)\rangle = \mathrm{e}^{\mathrm{i}\theta}|\phi_n(\tau)\rangle \,, \tag{14}$$

where θ is independent of the distribution of $k \in L$ and $\tau = a/2J$. Then any state $|\psi(0)\rangle$ localized near the fermi surface, i.e., which can be expanded by the basis vector $|\phi_n\rangle$ can evolve into its translational counterpart $|\psi(\tau)\rangle = \exp(-\mathrm{i}\theta)\hat{T}_a|\psi\rangle$ at instance $\tau = a/2J$. For two-dimensional model, one cannot find a suitable particle concentration to get an effective linear dispersion near the fermi surface. Thus the discussion for the ring system can not be extended to higher dimensional systems.

3 Summary

In summary, we have extended the SPEC to the high-dimensional many-body system with other symmetries besides the parity one. A class of three-dimensional models with modulated NN interaction is proposed to perform perfect-state transfer in bulk many-body system. This Hamiltonian can be written as a sum of commuting terms, which is not easy to be satisfied for the models with modulated (but not uniform) NN interactions. The investigation provides a way to construct such kinds of Hamiltonians in order to meet SSMC. Furthermore, a realistic near half-filled tight-binding fermion model with uniform hopping integral is investigated. It is found that, for the many-particle state near the fermi surface, the eigenvalues and wavefunctions satisfy the SSMC approximately. Then the transfer of a many-particle state has higher fidelity than that of single-particle state of the same model, i.e., the many-particle correlation can enhance the fidelity of the transmission for the corresponding quantum state.

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刊名： 理论物理通讯（英文版） ISTIC SCI
英文刊名： COMMUNICATIONS IN THEORETICAL PHYSICS
年，卷(期)： 2007，48(9)

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相似文献(1条)

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