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Quantum Information Processing in the Wall of Microtubule*

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Abstract: Microtubule (MT) is described as an anisotropic two-dimensional pseudo-spin model on a triangular lattice, in which there are three different "spin-spin" interactions. The mobile electron in each lattice site is described based on the pseudo-spin model. Then, the processing of quantum information in the MT wall is presented by virtue of the scheme of driving quantum computer in sequence of laser pulse developed by Lloyd.

Key words: microtubule; quantum; pseudo-spin; processing

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1 Introduction

Recently, quantum computers in which the elements that carry bits of information are atoms have attracted the attention of many scientists[1－10]. Usually, we assume that minimal system for carrying a bit of information is an atom with two states, which can be populated either in the ground state $|0\rangle$, or in the excited state $|1\rangle$. Accordingly, information can then be represented by a set of atoms, some of which are in the ground state $|0\rangle$ and others in the excited state $|1\rangle$.

In 1994, Lloyd[11] suggested a scheme of driving a quantum computer with a sequence of laser pulses, involving an array of weakly coupled atoms (nearest-neighbor interaction). Ref. [11] considers a one-dimensional array of three types of two-level atoms (heteropolymer) ABC ABC ABC …, in which each atom possesses along-lived excited state and the resonant frequencies ω_A, ω_B, and ω_C. The light pulses transfer the atom from $|0\rangle$ to $|1\rangle$, or vice versa. Based on the properties of the edge atoms, whose frequencies are different from the frequencies of all other atoms, different sequences of resonant pulses permit one to load information, to process it, and to read-out the information. In Fig. 1, use sequences of the type $\omega_{01}^{A}\,\omega_{11}^{A}\,\omega_{10}^{B}\,\omega_{11}^{B}\,\omega_{01}^{A}\,\omega_{11}^{A}$ to move information along the one-dimensional array of two types of two-level atoms (AB AB AB…), where ω_{ij}^{A} means that the left neighbor of atoms A is in the state $|i\rangle$, and the right neighbor of atoms A is in the state $|j\rangle$. The pulse with frequency ω_{01}^{A} acts only on the atoms A_{01}, i. e. transfers atoms A from $|0\rangle$ to $|1\rangle$, or from $|1\rangle$ to $|0\rangle$.

	AB	A*B	AB*	A*B*
ω_{01}^{A}	AB	A*B	A*B*	AB*
ω_{10}^{A}	AB	A*B*	A*B	AB*
ω_{01}^{A}	AB	AB*	A*B	A*B*

Fig. 1 Change of the initial states under the influence of the sequence $\omega_{01}^{A}\,\omega_{11}^{A}\,\omega_{10}^{B}\,\omega_{11}^{B}\,\omega_{01}^{A}\,\omega_{11}^{A}$.
(Asterisk means that an atom is in the excited state).

For a biological system, MTs are important for components and function units in cytoskele-

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tons, as well as cellular organization and information processing, so the problem of information processing of MTs has attracted additional attention. From X-ray crystallography[12], MTs are hollow cylindrical polymers of the protein tubulin and are 25 nm in outer diameter and 14 nm in inner diameter. The cylinder walls of microtubules are comprised of 13 longitudinal protofilaments in which each is a series of tubulin subunit proteins. Each tubulin subunit is an 8 nm × 4 nm × 5 nm heterodimer which consists of two slightly different monomers known as alpha and beta tubulin (α- and β-tubulin). Each tubulin is a dipole (beta plus, alpha minus) and has a net mobile electronegative charge, which is localized predominantly towards the α-monomer. Certainly, this net negative is an unbound mobile electron too, which can be localized either more toward the α-monomer or more toward the β-monomer. Thus the tubulin dimmer protein has only two basic states $|\alpha\rangle$ and $|\beta\rangle$, i. e. the information can be transferred when the states change from $|\alpha\rangle$ to $|\beta\rangle$ or from $|\beta\rangle$ to $|\alpha\rangle$.

Some models for the MT dynamics have been presented[13, 14—18]. For the tubulin dimmer dipoles in one protofilament of a MT, some authors[16] have taken the well-known double-well potential model which is very successful in many fields[19, 20]. However, according to the quantum character of mobile electrons and a matter worth noting: quantum tunneling effects penetrating the barrier, each double-well may be represented by one pseudo-spin[21]. In this paper, the system is described as the two-dimensional pseudo-spin model and processing of quantum information in the MT wall is presented by virtue of the scheme of driving quantum computer in sequence of laser pulse developed by Lloyd.

2 Two-dimensional Pseudo-spin Systems

The tubulin dimer subunits within the cylinder wall are arranged in a hexagonal lattice which is slightly twisted; resulting in different neighbor relationships among each subunit and its six nearest neighbors[22]. Basic premise[13] physically views the entire MT as a regular array of coupled local dipole states which interact with their immediate neighbors. Considering the quantum characters of mobile electrons and the spin wave theory developed in the solid state physics[23] and ferroelectrics, each double-well may be represented by one pseudo-spin. The two possible orientations of the pseudo-spin, up and down (i. e. $|\alpha\rangle$ and $|\beta\rangle$), correspond to the two possible localized positions of the mobile electron, the site of α-well and the site of β-well.

In two-dimensional pseudo-spin system[21], the effective interaction terms between two neighboring lattice sites are (in Fig. 2)

$$H_{i,j} = -\sum J_{ij} S_i^z S_j^z \,, \tag{1}$$

here exchange constants J_{ij} take the values J_1, J_2, J_3 depending on the choice of dipole pairs, with

$$J_{ij} = -4\nu_{++--}(i,j) \tag{2}$$

$$\nu_{\lambda\nu\gamma\delta} \cong \iint w_\lambda^*(x-i) w_\nu(x-i) \frac{e^2}{\varepsilon |x-x'|} \cdot w_\gamma^*(x'-j) w_\delta(x'-j) \mathrm{d}x \mathrm{d}x' \,, \tag{3}$$

here $\nu_{\lambda\nu\gamma\delta}(i,j)$ represent the coupling between the two tubulin dimers at the site i and site j, which depend on the distance between the two sites, and also the quantum states λ, ν, γ and δ. $w_\lambda(x-i)$ and $w_\lambda^*(x-i)$ represent the Wannier function and its conjugate, respectively.

In Fig. 2, using the formula (2) and taking two harmonic potentials to simulate the double-well potential mentioned above, we may approximately present the numerical results for the constants J_1, J_2, J_3 and the corresponding angles. For example, $J_1 = 0.1976(1/\varepsilon)$ eV, $\theta_1 = 0°$, here the ε is the dielectric constant of the medium.

From the above model, we can know it is a triangular as repeated cell in crystal lattice (in the wall of the MT), in which there are three different "spin-spin" interactions. Because of three different

$J(J_1, J_2, J_3)$, we can describe the repeated cell as three types of two-pseudo-spin (i. e. the spin of up ↑ and the spin of down ↓) atoms (dimers). Hence, the entire MT wall can be mapped the chain of three types of two-pseudo-spin atoms shown in Fig. 3, where it is three longitudinal protofilament in MT. For two dipolar lattices, the triangular with shadow is the correct array and we can describe these dimers such as 1 2 3, 1 2 3, 1 2 3 ···; i. e. the chain of three types of two-pseudo-spin dimers.

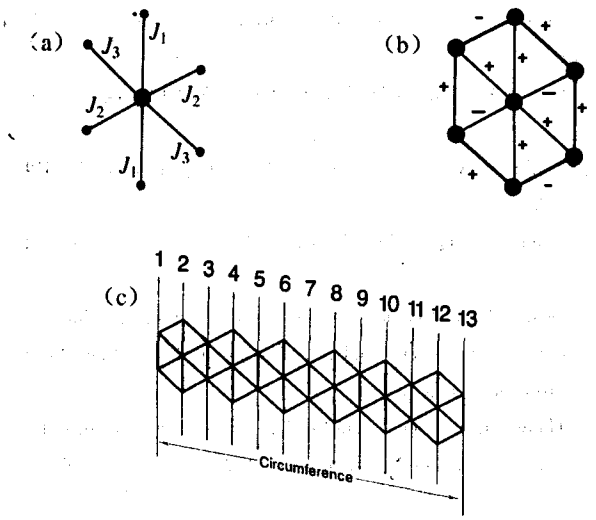

Fig. 2 (a) Exchange constants; (b) their signs within a unit hexagonal cell; (c) A band of hexagons spanning the circumference of a microtubule.

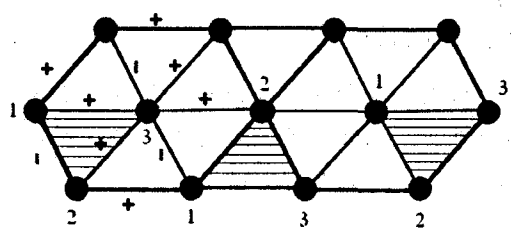

Fig. 3 Three types of two-pseudo-spin atoms.

3 Quantum Information Processing

In this paper, we can apply Lloyd's schemes for loading and processing of information in the wall of MTs. Then, the three types of two-pseudo-spin atom system (ABC··· ABC··· ABC···) described by the Hamiltonian:

$$H = -\frac{1}{2}\sum_i \omega_i \sigma_i^z + J_{i,i+1}\sigma_i^z \sigma_{i+1}^z ,$$
$$i = \mathrm{A}, \mathrm{B}, \mathrm{C} \qquad (4)$$

here σ_i^z is the Pauli operator, J is the effective constant of interaction which can be positive or negative, and ω is the resonant frequency for the effective spin when the interaction is absent. Take B atoms as example, if some state of B atoms in the system is in the ground state or the spin of the down ↓ :

$$E_{\mathrm{B}0} = \langle AB_0C \mid H \mid AB_0C \rangle ,$$
$$\mid A\rangle = \mid A_0\rangle \text{or} \mid A_1\rangle = \mid 0\rangle \text{or} \mid 1\rangle , \qquad (5)$$

and the others of B atoms occupies the excited state or the spin of the up ↑. Certainly, all other spins are unchanged, and then the difference E between the energies of these two states (two spins) is

$$\Delta E_{\mathrm{B}} = E_{\mathrm{B}1} - E_{\mathrm{B}0} . \qquad (6)$$

So, we find the following four eigenfrequencies of the Hamiltonian which correspond to four energy levels speit by energy level of B atoms:

$$\omega^{\mathrm{B}} = \begin{cases} \omega_{00}^{\mathrm{B}} \to \omega_{\mathrm{B}} + J_{\mathrm{AB}} + J_{\mathrm{BC}} \\ \omega_{01}^{\mathrm{B}} \to \omega_{\mathrm{B}} + J_{\mathrm{AB}} - J_{\mathrm{BC}} \\ \omega_{10}^{\mathrm{B}} \to \omega_{\mathrm{B}} - J_{\mathrm{AB}} + J_{\mathrm{BC}} \\ \omega_{11}^{\mathrm{B}} \to \omega_{\mathrm{B}} - J_{\mathrm{AB}} - J_{\mathrm{BC}} , \end{cases}$$
$$\hbar\omega_{\mathrm{B}} = \Delta E_{\mathrm{B}} \quad \omega_{\mathrm{A}} = \omega_{\mathrm{B}} = \omega_{\mathrm{C}} = \omega_0 . \qquad (7)$$

Similarly, the four frequencies of A atoms and C atoms can be given. The system is assumed to have only nearest-neighbor interaction, which shifts the energy levels of each atom as a function of the states of its neighbors. This means that each energy level splits into four levels as computed results above.

4 Conclusion

In this paper, two-dimensional pseudo-spin model is presented, which is intended to describe the physical dynamics of unbound mobile electrons in the wall of cytoskeletal microtubule. Due to the inherent symmetry structures and the electric prop-

erties in the MT and the double-well potential, we treat it as a pseudo-spin system, and it is a triangular as repeated cell in crystal lattice, where there are three different "spin-spin" interactions. In conclusion, we can describe the repeated cell as three types of two-pseudo-spin atoms, i. e. the entire MT wall can be mapped the chain of three types of two-pseudo-spin atoms such as 1 2 3, 1 2 3, 1 2 3 …, and then we can apply Lloyd's schemes for loading and processing of information.

References:

[1] Feynman R P. Found Physics, 1986, **16**: 507.

[2] Toffoli T. Math Syst Theory, 1981, **14**: 13.

[3] Benioff P. J Stat Phys, 1980, **22**: 563.

[4] Deutsch D. Proc R Soc, 1985, **A400**: 97.

[5] Feynman R P. Opt News, 1985, **11**: 11.

[6] Zurek W H. Phys Rev Lett, 1984, **53**: 391.

[7] Peres A. Phys Rev, 1985, **A32**: 3 266.

[8] Margolus N. Ann NY Acad Sci, 1986, **480**: 487.

[9] Landauer R. IBM J Res Dev, 1961, **5**: 183.

[10] Bennett C H. IBM J Res Dev, 1979, **6**: 525.

[11] Lloyd S. Science, 1993, **261**: 1 569.

[12] Amos L A S. Biol Quantum Chem, 1982, **2**: 641.

[13] Tuszynski J A, Hameroff S H Sataric, Trpisova M V. J Theo Bio, 1995, **174**: 371.

[14] Mavromatos N E, Nanopoulos D V. Int J Mod Phys, 1998, **B12**: 517.

[15] Mavromatos N E, Mershin A, Nanopoulos D V. Int J Mod Phys, 2002, **B16**: 3 623.

[16] Sataric M V, Tuszy_nski J A, Zakula R B. Phys Rev, 1993, **E48**: 589.

[17] Jibu M, Hagan S, Hamero S R, *et al*. Biosystems, 1994, **32**: 195.

[18] Chen Y, Qiu X. J Acta Phys Sin, 2003, **52**: 1 554 (in Chinese).

[19] Sataric M, Koruga D, Zakula R B. J Mol Electr, 1990, **6**: 63.

[20] Collins M A, Blumen A, Currie J F. J Phys Rev, 1979, **B19**: 3 630.

[21] Chen Ying, Qiu Xijun, Li Ruxin. Chin Phys Soc, 2005, **14**: 427.

[22] Dustin P. 1984 General Physiology of Tubulins and Microtubules. (In) Microtubules (ed. Dustin P.) New York: Springer-Verlag, 94 – 126.

[23] Haken H. 1976 Quantum Field Theory of Solids-An Introduction. New York: North-Holland, 142.

微管壁上量子信息的传递

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摘 要：微管管壁上的原丝纤维可以描述成各项异性的二维赝自旋模型，其最小重复单元是三角形状的。在这个模型中存在三种不同的"自旋-自旋"相互作用。而每一维上的自由电子可以看作是赝自旋模型。那么，微管壁上的量子信息传递就可以用 Lylod 提出的激光控制量子计算的模型来解释.

关 键 词：微管；量子；赝自旋；传递