An Effort toward Fully Fault-tolerant Quantum Computing

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Memory space of Quantum computer has eclipsed that of current supercomputers

IBM; Q   50 qubits

Intel;   Tangle Lake 49 qubits

Google, D-Wave;   ?

What’s next ?

Fully Fault-tolerant Quantum Computing

Fully fault-tolerant universal quantum computing

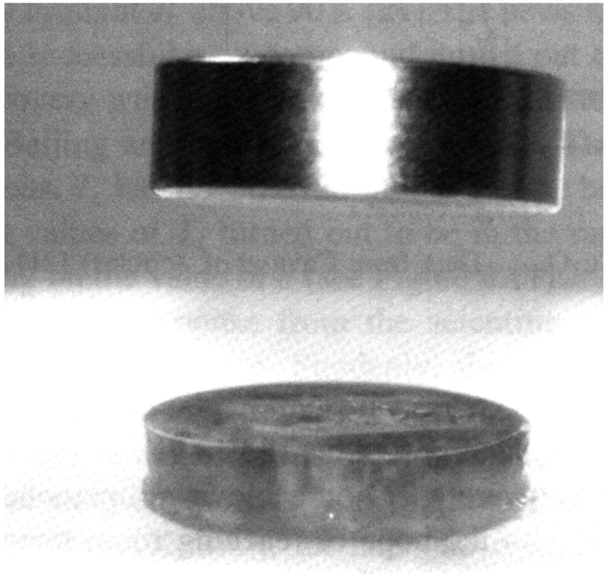
REVIEW ARTICLE OPEN

Building logical qubits in a superconducting quantum computing system

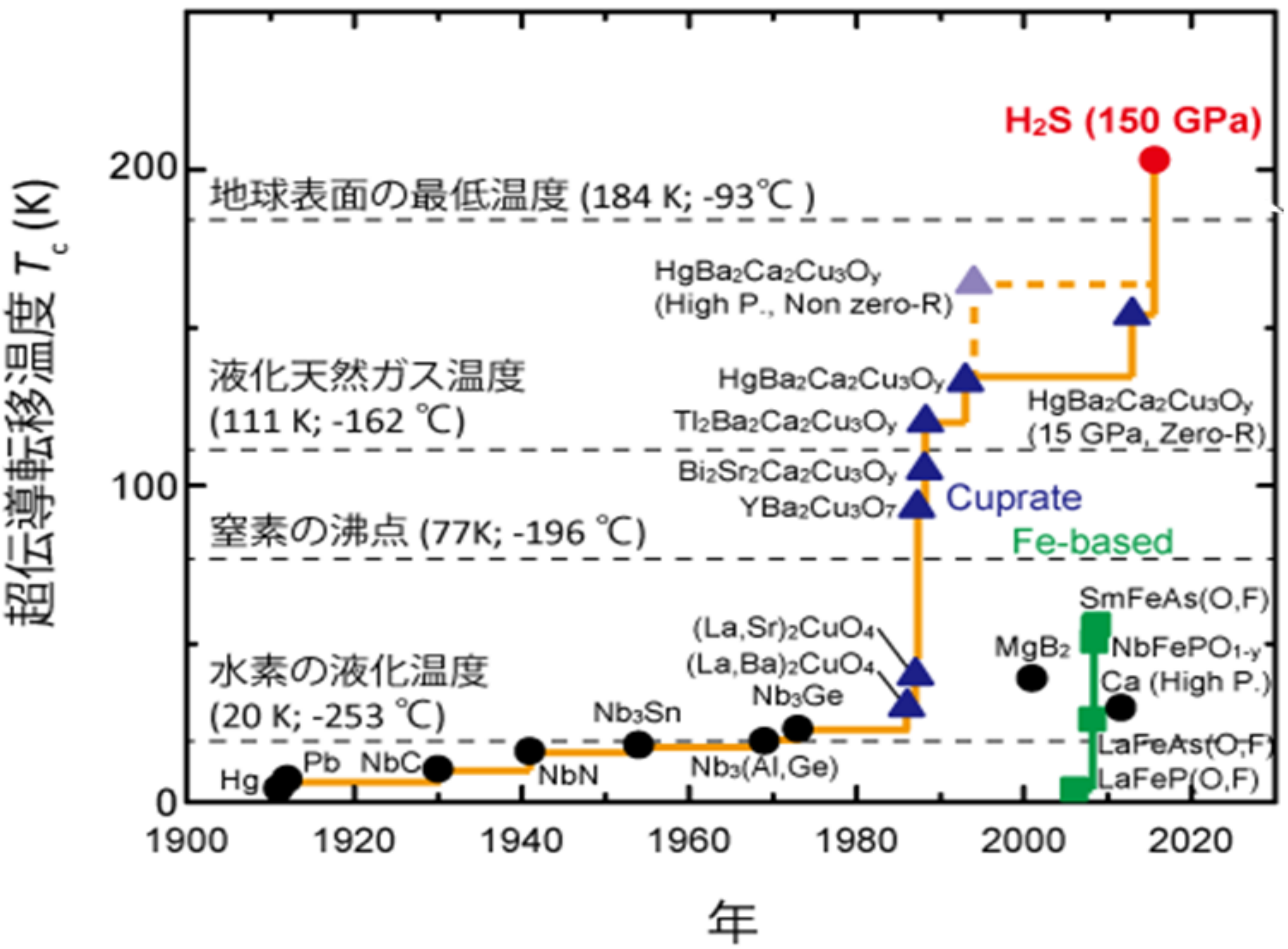
Jay M. Gambetta[1], Jerry M. Chow[1] and Matthias Steffen[1]

- a physical qubit that is well isolated from the environment and is capable of being addressed and coupled to more than one extra qubit in a controllable manner,
- a fault-tolerant architecture supporting reliable logical qubits, and
- universal gates, initialization, and measurement of logical qubits

Superconducting qubits



Cuprate superconductors



Limitations of current standard electronic state calculation methods; Molecular orbital theory, Density functional theory

The Basis of the Electron Theory of Metals, with Special Reference to the Transition Metals by N. F. Mott, 1949

The main purpose of this paper is to suggest that these two model are not, as is usually believed, different approximations to the same exact function.

1. London-Heitler model, VB theory

2. Bloch model, molecular orbital theory

Scientific Background on the Nobel Prize in Physics 2016

TOPOLOGICAL PHASE TRANSITIONS AND TOPOLOGICAL PHASES OF MATTER

compiled by the Class for Physics of the Royal Swedish Academy of Sciences

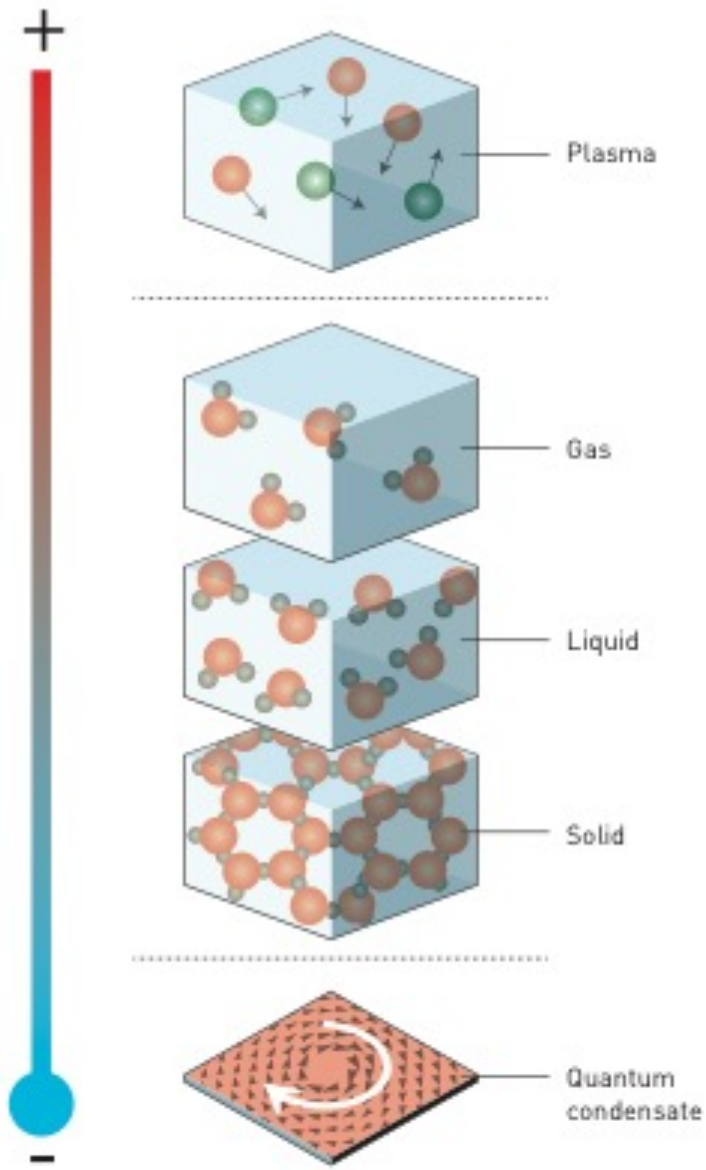


Illustration: ©Johan Jarnestad/The Royal Swedish Academy of Sciences

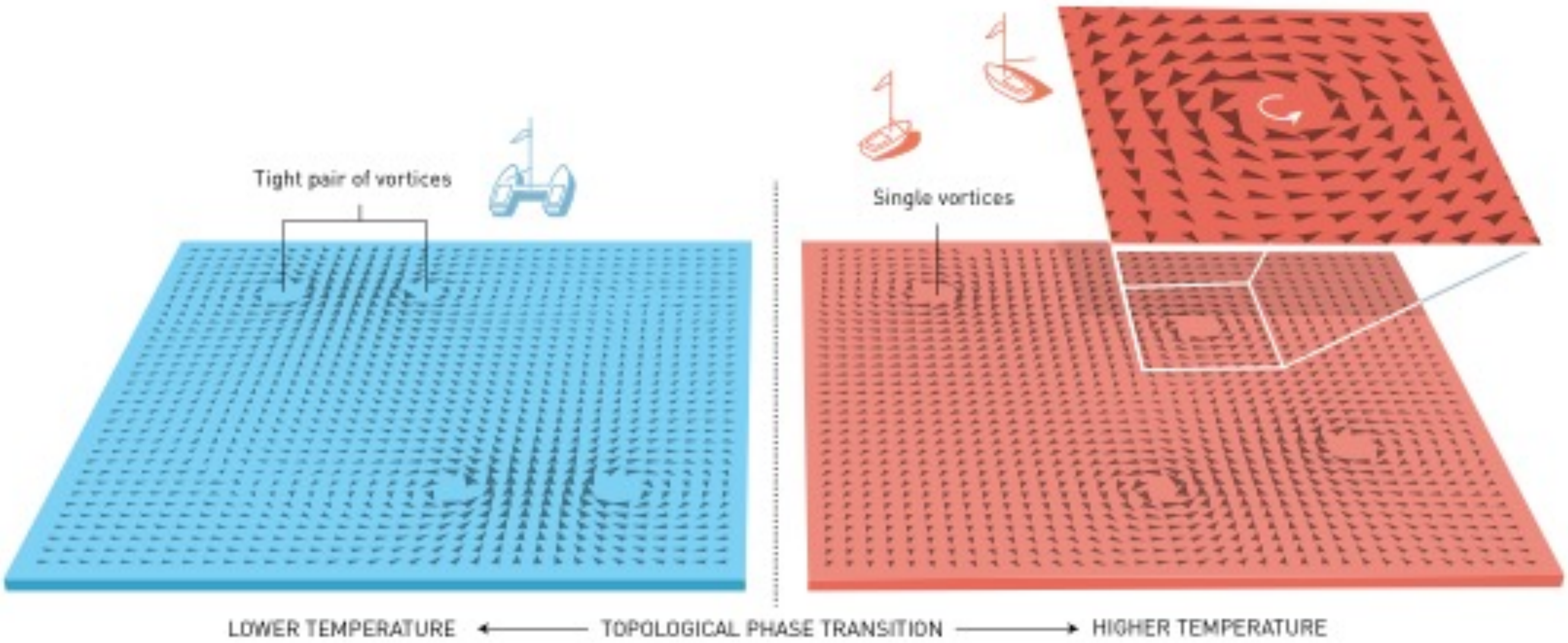
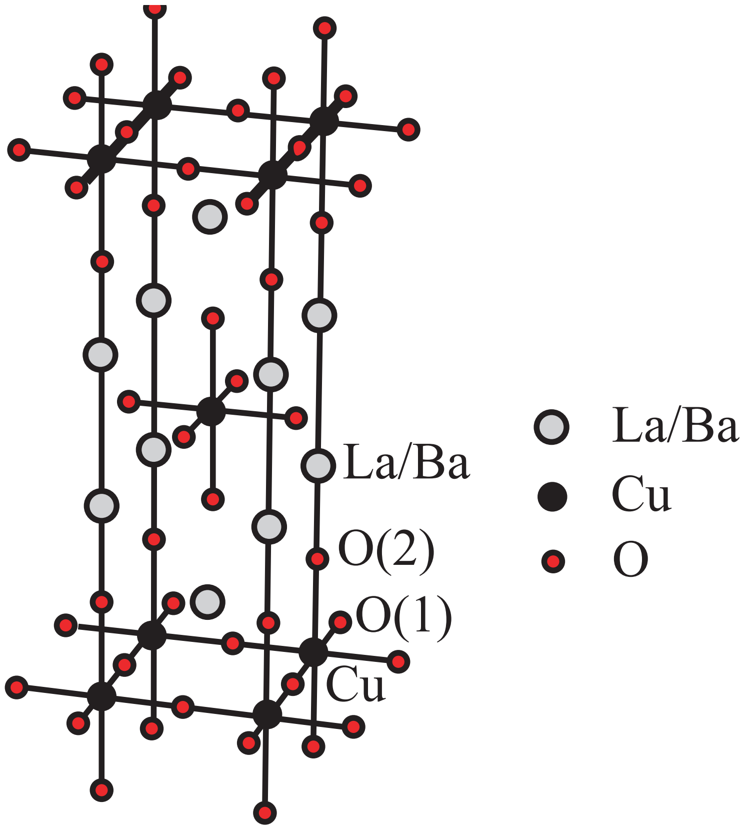
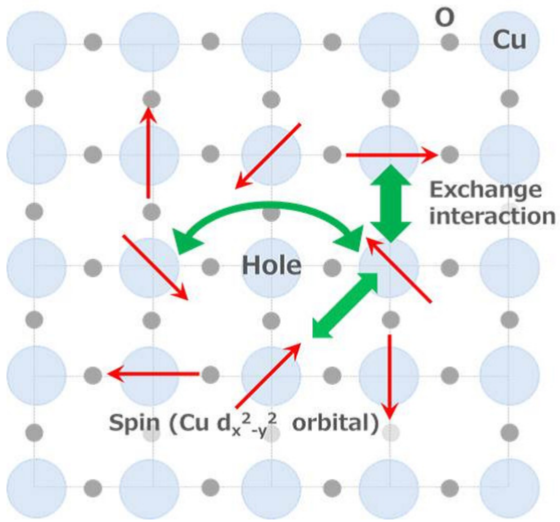


Illustration: ©Johan Jarnestad/The Royal Swedish Academy of Sciences



Spin-twisting itinerant motion of electrons

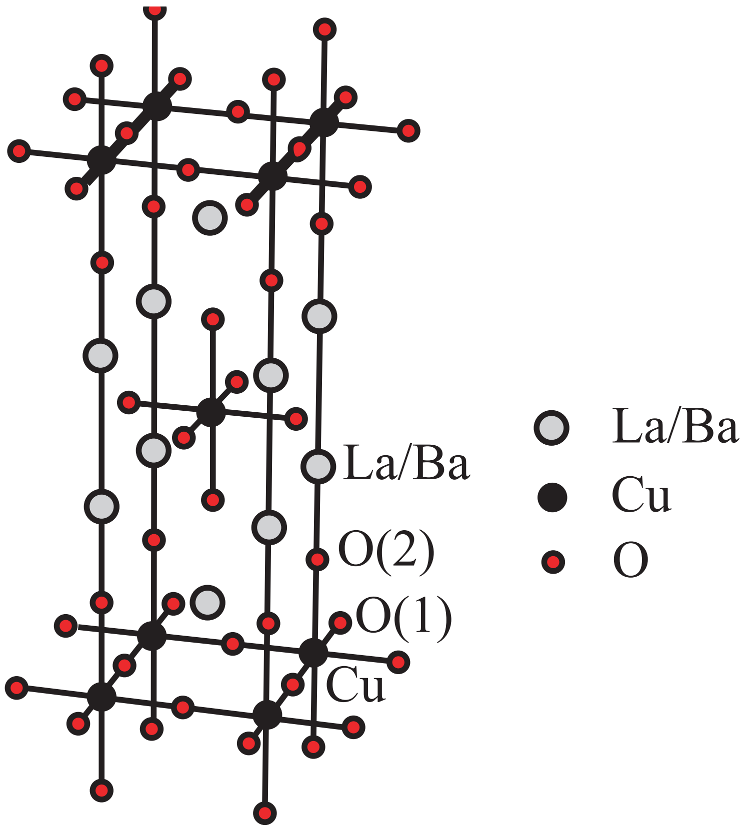


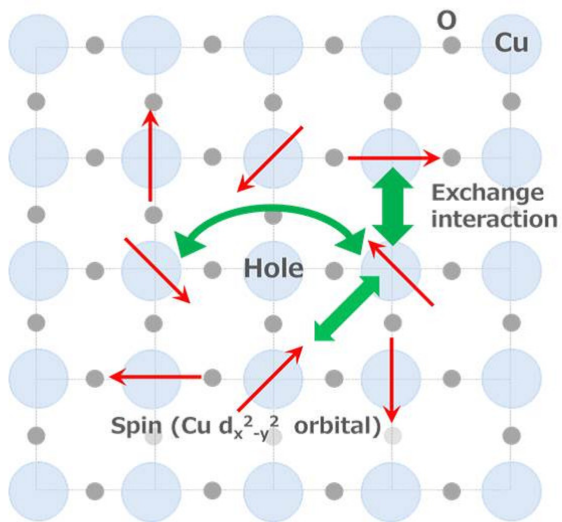
Singularities of wave functions that are not singularities of the Hamiltonian emerge.

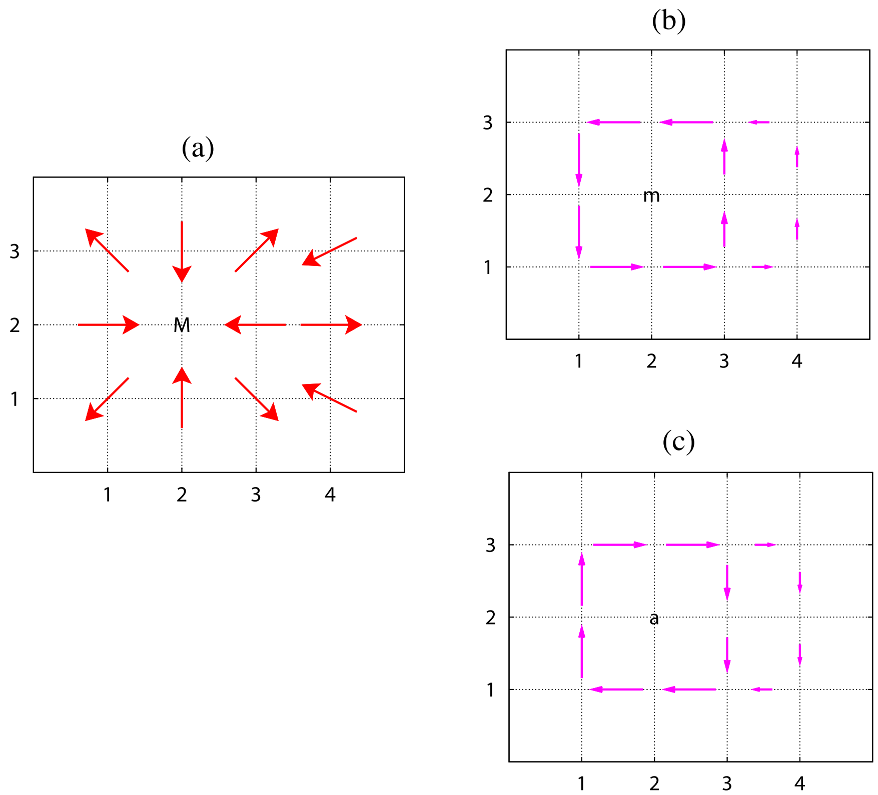
The energy minimizing wave function becomes multi-valued with respect to coordinates.

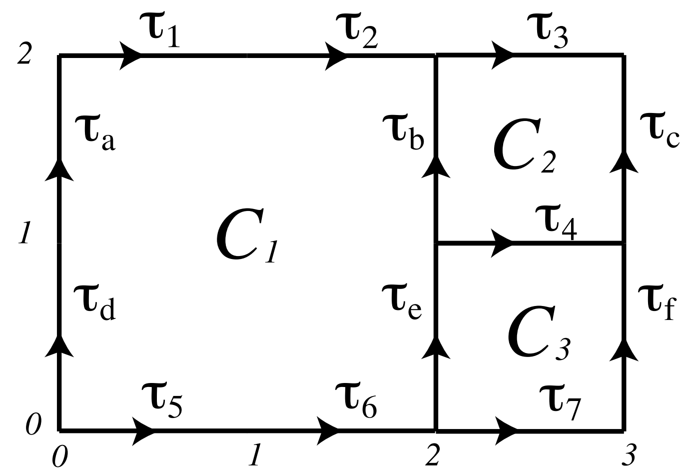
The fundamental assumption for the DFT is violated.

The energy minimizing wave function becomes multi-valued with respect to coordinates.


La/Ba
O(2)
O(1)
Cu
La/Ba
Cu
O


O
Cu
Exchange interaction
Hole
Spin (Cu $d_{x^2-y^2}$ orbital)


(a)
M
(b)
m
(c)
a


τ_1
τ_2
τ_3
τ_a
τ_b
τ_c
C_1
C_2
C_3
τ_4
τ_d
τ_e
τ_f
τ_5
τ_6
τ_7

$$|\gamma\rangle = \sum_{i} e^{-i\frac{\chi_j}{2}}[e^{-i\frac{\xi_j}{2}} D^{\gamma}_{j\uparrow} c^{\dagger}_{j\uparrow} + e^{i\frac{\xi_j}{2}} D^{\gamma}_{j\downarrow} c^{\dagger}_{j\downarrow}]|\mathrm{vac}\rangle, \tag{12}$$

$$w_{\ell}[\xi] + w_{\ell}[\chi] = \text{even number for any loop } C_{\ell}. \tag{13}$$

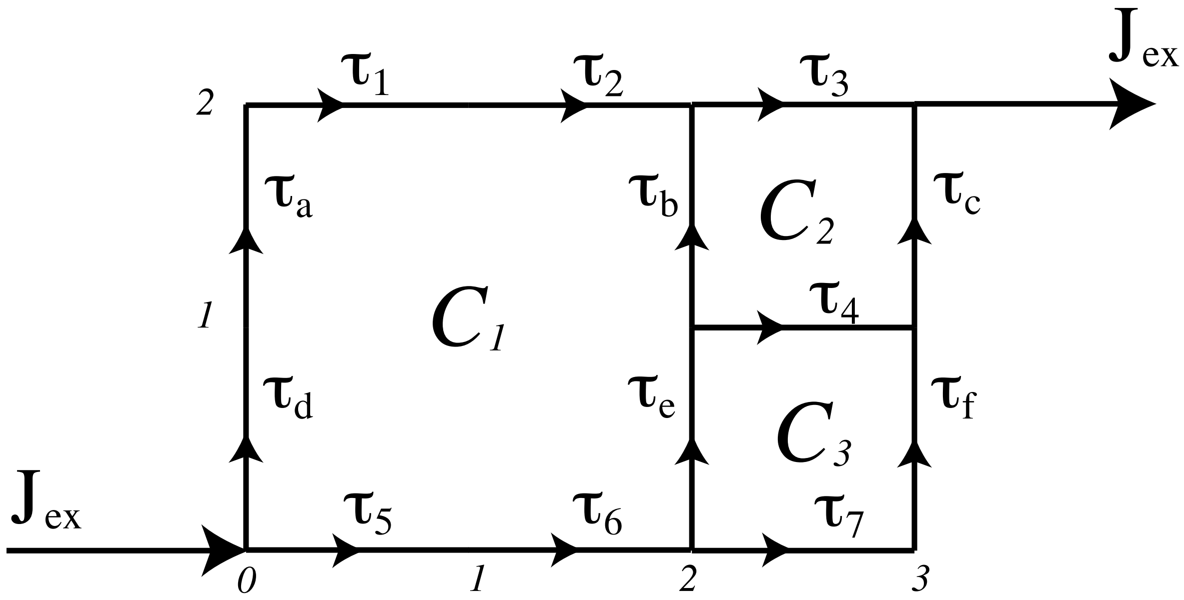
$$F[\nabla\chi] = E[\nabla\chi] + \sum_{\ell=1}^{N_{\mathrm{loop}}} \lambda_{\ell}\left(\oint_{C_{\ell}} \nabla\chi \cdot d\mathbf{r} - 2\pi\bar{w}_{\ell}\right), \tag{16}$$

where $E[\nabla\chi]$ is the energy functional given by

$$E[\nabla\chi] = \langle\Psi|H^{HF}_{\mathrm{EHFS}}|\Psi\rangle. \tag{17}$$

The term with λ_{ℓ}'s imposes the constraint,

$$\oint_{C_{\ell}} \nabla\chi \cdot d\mathbf{r} = 2\pi\bar{w}_{\ell}, \tag{18}$$



$$F[\nabla\chi] = E[\nabla\chi] + \sum_{\ell=1}^{N_{\mathrm{loop}}} \lambda_\ell \left(\oint_{C_\ell} \nabla\chi \cdot d\mathbf{r} - 2\pi\bar{w}_\ell \right),$$

J Supercond Nov Magn (2015) 28:3221–3233
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ORIGINAL PAPER

Superconducting Transition Temperature of the Hole-Doped Cuprate as the Stabilization Temperature of Supercurrent Loops Generated by Spin-Twisting Itinerant Motion of Electrons

Akira Okazaki[1] · Hikaru Wakaura[1] · Hiroyasu Koizumi[1] · Michel Abou Ghantous[2] · Masashi Tachiki[3]

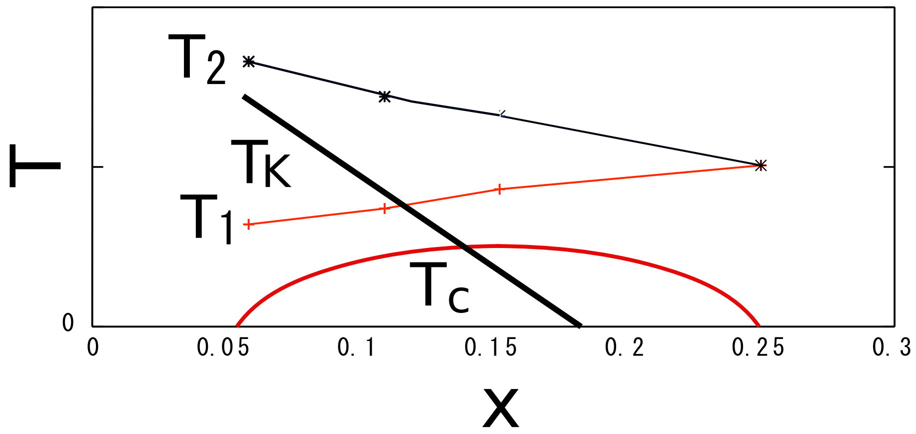
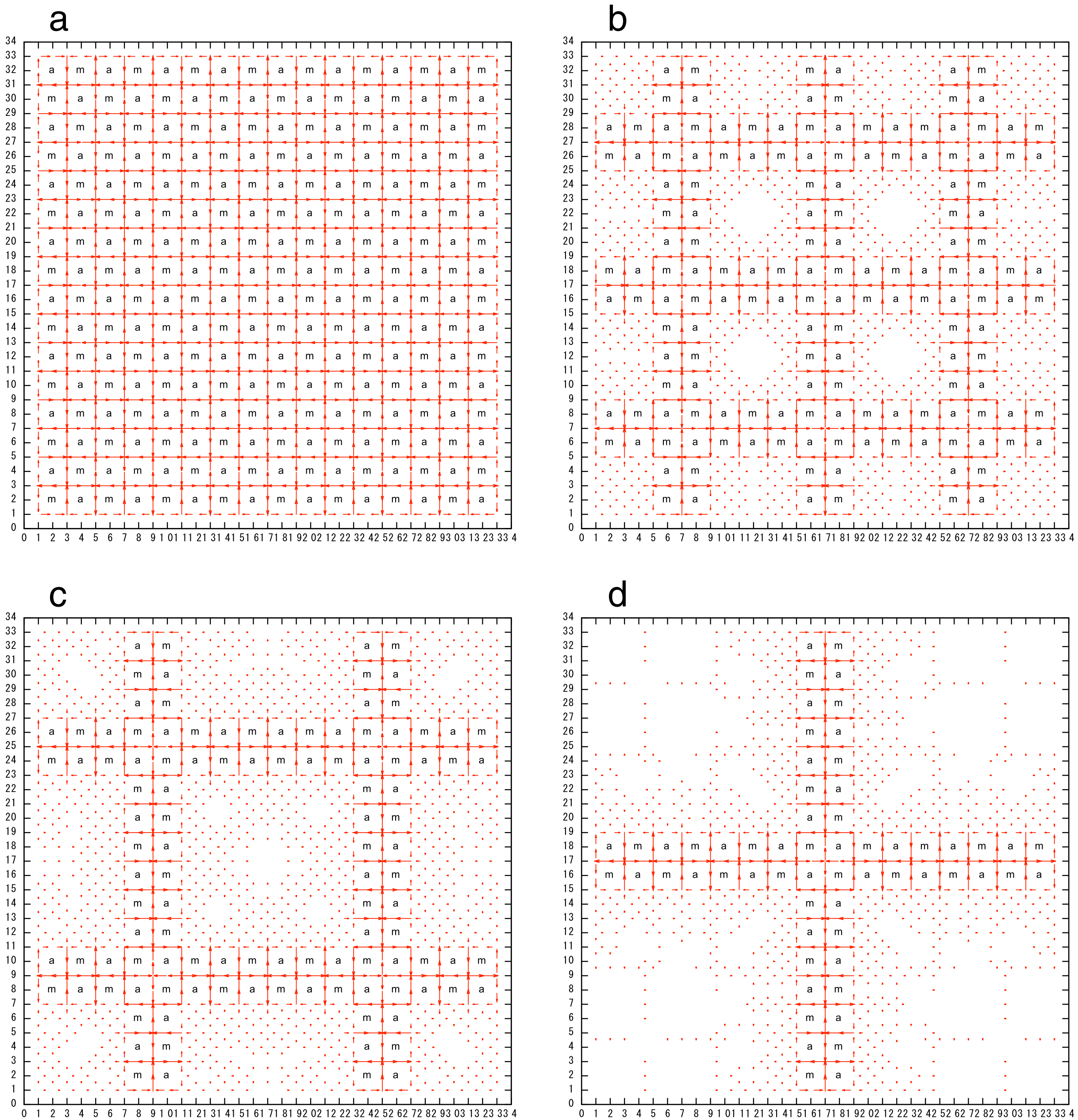
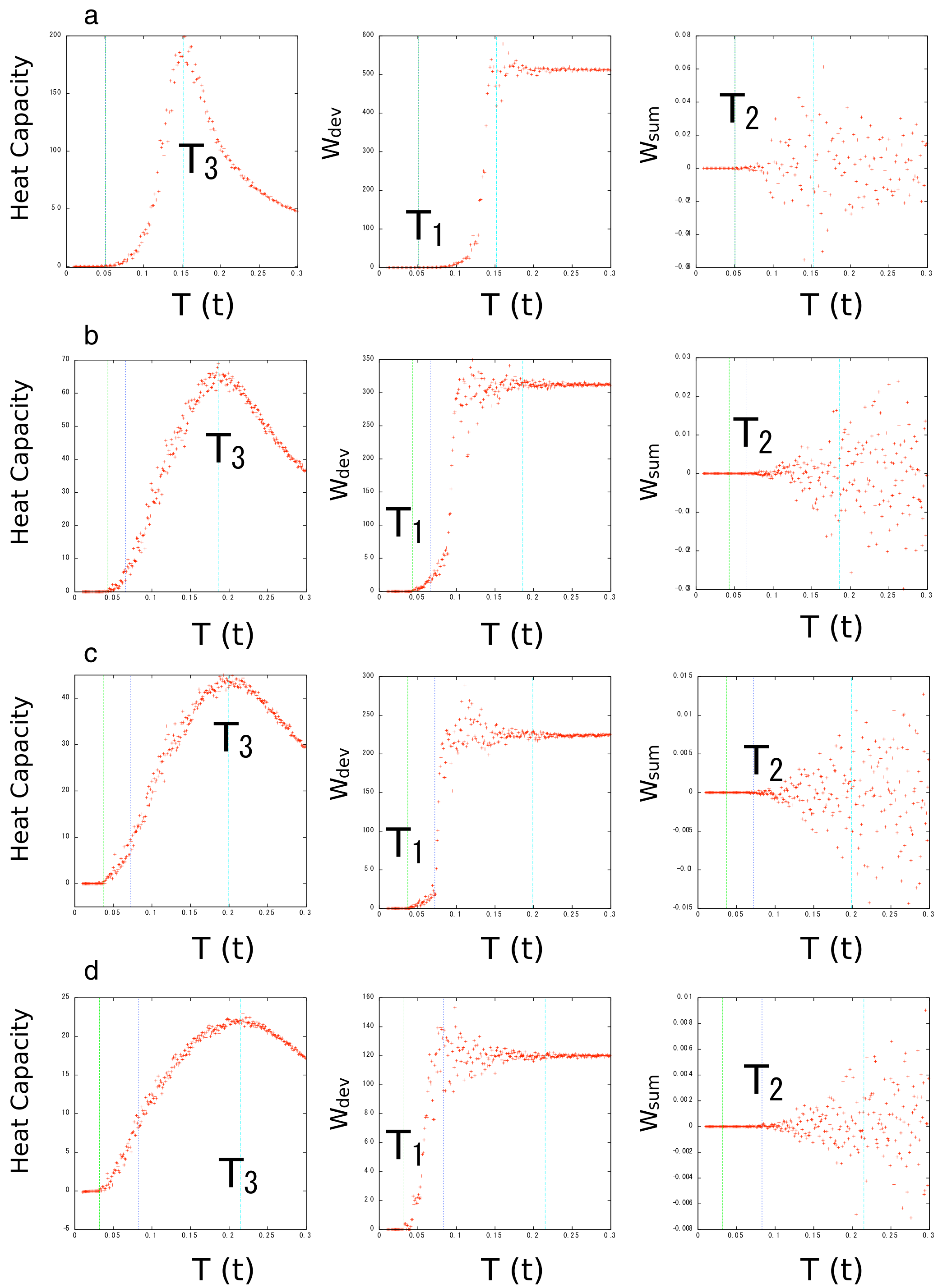


Fig. 7 Schematic plots of doping dependence of T_c and T_K. The superconducting transition temperature is reduced from T_1 to T_c due to the criticality arising from the quantum critical points at $x = x_{min}$ and $x = x_{max}$. The Kerr rotation temperature is reduced from T_2 to T_K due to criticality arising from the quantum critical point at around $x \approx 0.18$. T_K below T_c is disclosed as the peak of T_c by the application of a magnetic field that destabilizes the loop-currents and reduces T_c [25]


a
b
c
d

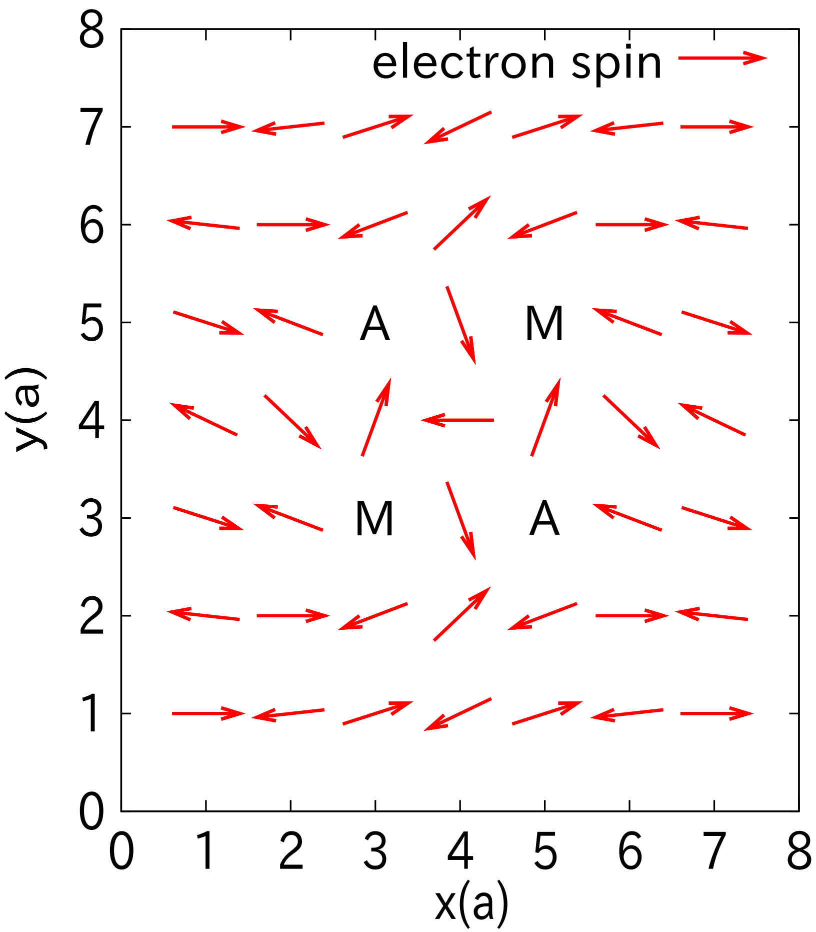


a
b
c
d
Heat Capacity
Wdev
Wsum
T (t)
T1
T2
T3

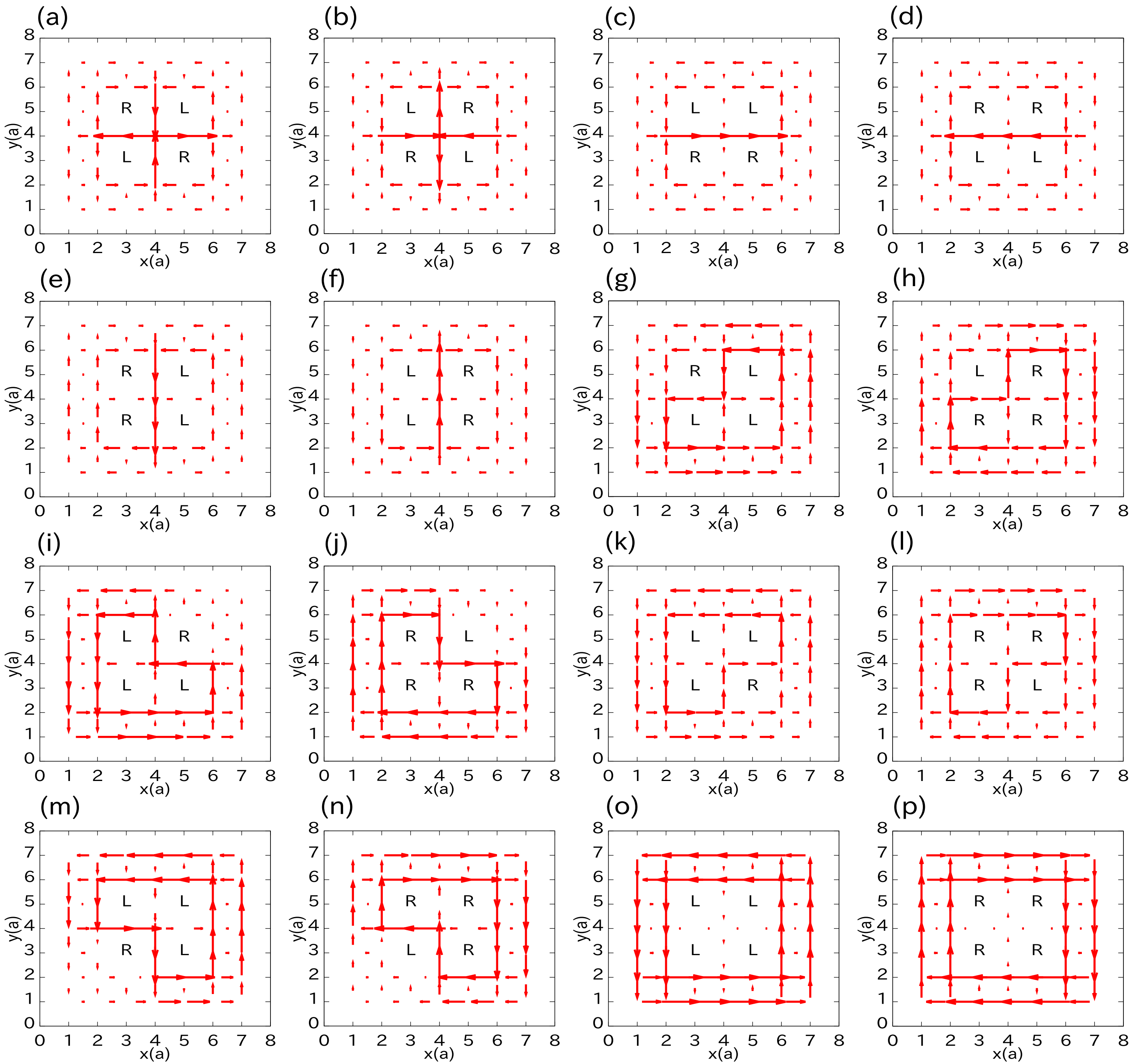
PAPER • OPEN ACCESS

External current as a coupler between the spin-vortex-induced loop current qubits

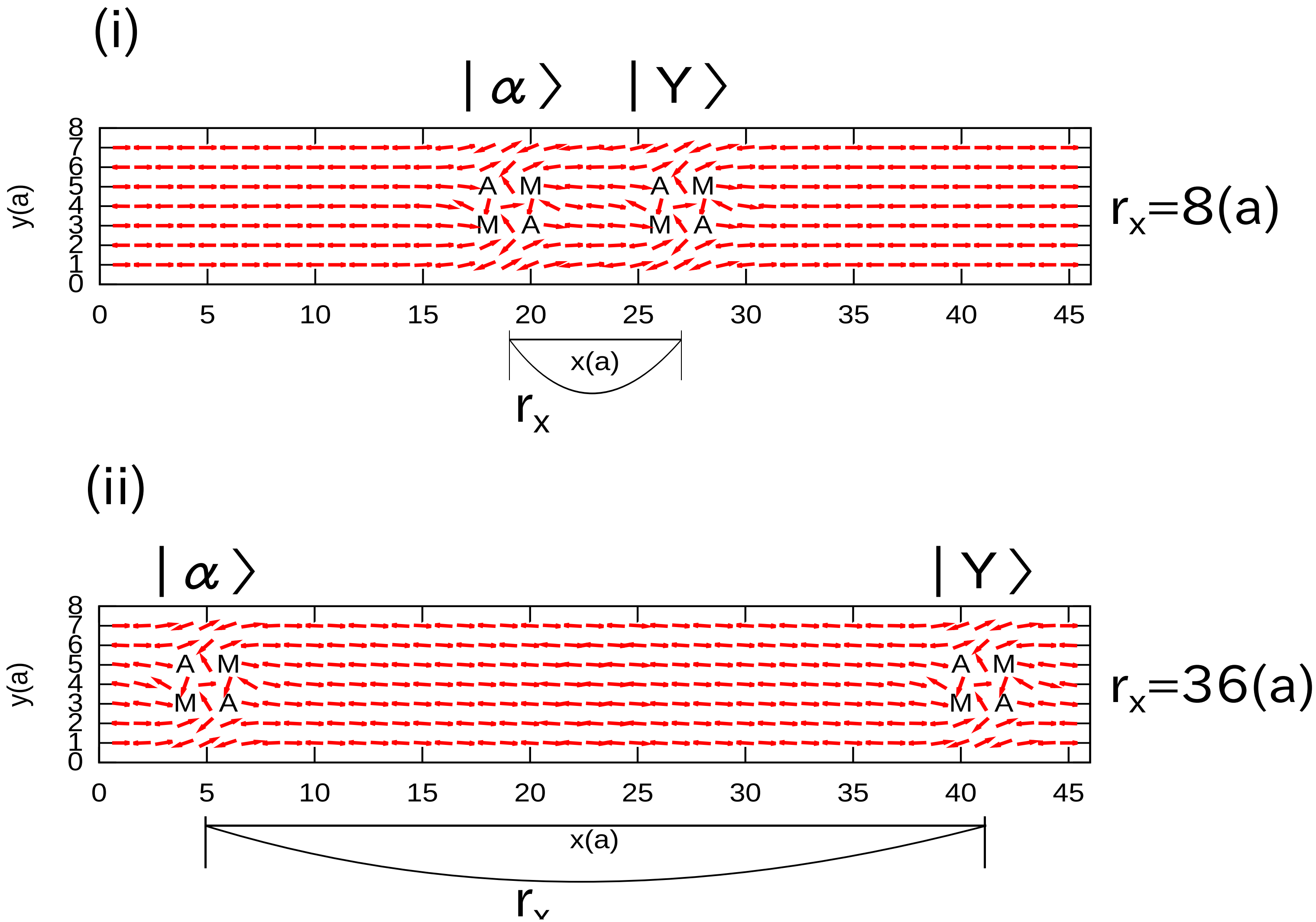
To cite this article: Hikaru Wakaura and Hiroyasu Koizumi 2017 *J. Phys. Commun.* **1** 055013



electron spin
A
M
M
A
x(a)
y(a)
0
1
2
3
4
5
6
7
8



(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
(m)
(n)
(o)
(p)
x(a)
y(a)
R
L



(i)
|α⟩
|Y⟩
A M A M
M A M A
y(a)
x(a)
r_x
r_x=8(a)
(ii)
|α⟩
|Y⟩
A M A M
M A M A
y(a)
x(a)
r_x
r_x=36(a)

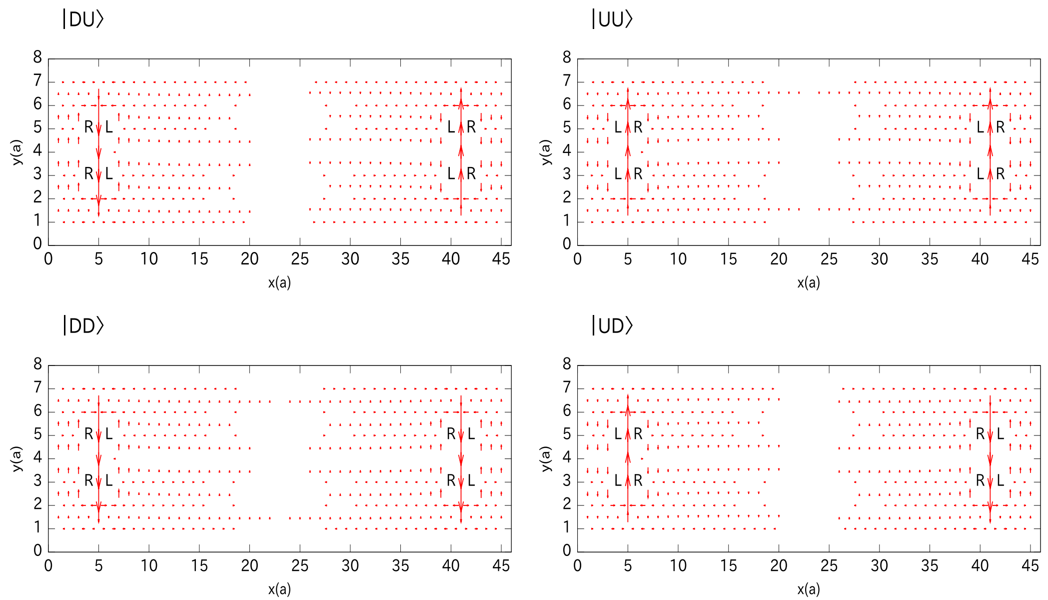


Figure 8. The current distribution of four states of the two DCQ qubit system. One lattice distance corresponds to the current of the magnitude 1/3 in the units of $2et/\hbar$. The four states are indicated as |DU⟩, |UU⟩, |DD⟩ and |UD⟩, respectively. The centers of the two DCQs are $(x, y) = (5, 4)$ and $(41, 4)$.

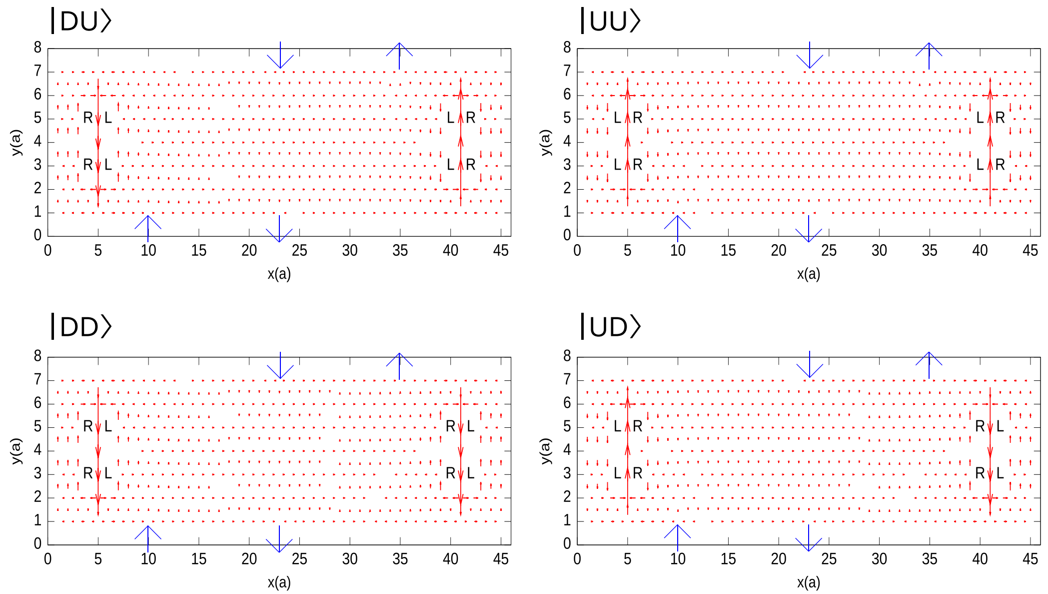


Figure 9. The current distribution of four states of 2-qubit system of DCQ with feeding currents J_{ex}. The external currents enter the system at $(x, y) = (10, 1)$ and $(23, 7)$, and exit at $(x, y) = (23, 1)$ and $(35, 7)$. The magnitude of the external currents is $0.049(2et/\hbar)$ for each source and drain. The blue arrow indicates the source or drain of the external currents.

(i) All qubits can be differentiated in a controlled manner by modifying the environment of them. The controlled modification may be achieved by applying a magnetic field, applying an electric field, or feeding external currents.

(ii) The qubit operation can be achieved by irradiating an electromagnetic field with the frequency that corresponds to the energy difference between the two qubit states.

(iii) Our previous calculation indicates that the gate-operation time is in the nanosecond order when an electromagnetic field with electric field intensity 10^5 V m^{-1} is used [6].

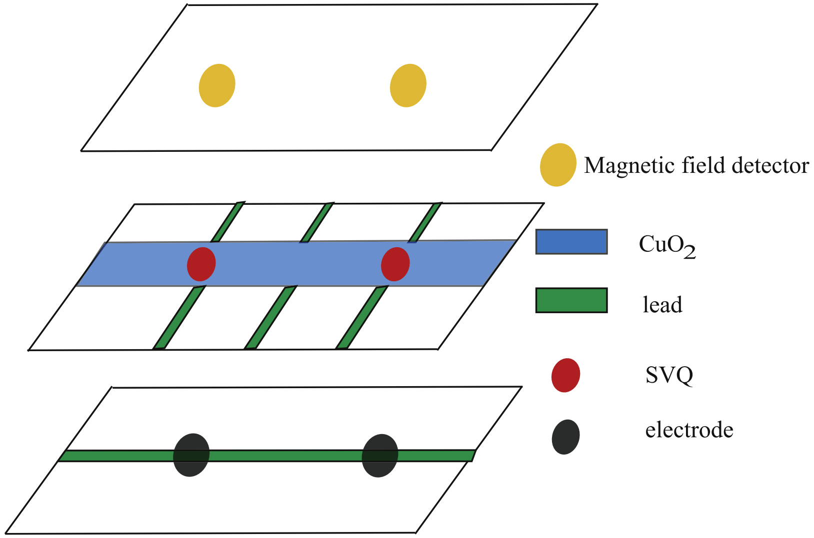
(iv) Coupling between qubits can be turned-on and off in a controlled manner as will be demonstrated in this work. The coupling is turned-off by placing qubits at a distance; the separation distance may be shortened by using barrier atoms (substituted atoms for Cu's) between the qubits. The coupling is turned-on by feeding external currents in the region between the two target qubits.

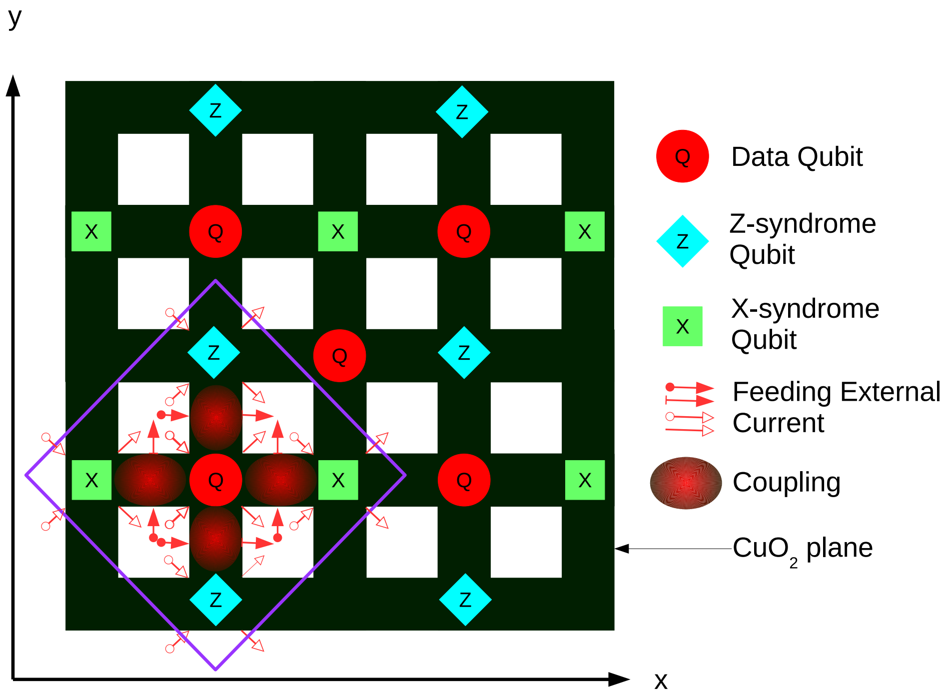
(v) The size of each qubit is about 10 nm^2. The size of the qubit-coupler using the external current feeding is also in the nanometer scale.

(vi) The stabilization temperature for the SVILCs corresponds to the superconducting transition temperature T_c for the cuprates [9] which is above the liquid nitrogen temperature. Thus, the qubit operation at temperatures above the liquid nitrogen temperature might be possible.

(vii) Readout process will be performed by measuring the magnetic field produced by SVILCs after turning-off the applied magnetic field and external feeding currents. It is also possible to use the response currents to the external feeding currents [14].

(viii) The SVILC is protected by the topological winding number, thus, it is expected to be robust against external perturbations. Besides, it does not require the Cooper pair formation, thus, it is free from the relaxation caused by unpaired electrons that is believed to be the major cause of limiting coherent time for the superconducting qubits using the Josephson junctions [15–19].


Magnetic field detector
CuO2
lead
SVQ
electrode


y
x
Z
X
Q
Data Qubit
Z-syndrome Qubit
X-syndrome Qubit
Feeding External Current
Coupling
CuO2 plane

Flux Rule

$$\text{emf} = -\frac{d\Phi}{dt}$$

``We know of no other place in physics where such a simple and accurate general principle requires for its real understanding an analysis in terms of two different phenomena. Usually such a beautiful generalization is found to stem from a single deep underlying principle. Nevertheless, in this case there does not appear to be any such profound implication. We have to understand the ``rule'' as the combined effects of two quite separate phenomena'' (excerpt from ``The Feynman Lectures on Physics, Vol. II'', 17-1, Addison-Wesley Publishing Company, Reading, Massachusetts, 1964).

$$\nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t} \qquad \mathbf{F} = q\, \boldsymbol{v} \times \mathbf{B}$$

$$\mathbf{B}^{\rm em} = \nabla \times \mathbf{A}^{\rm em}; \quad \mathbf{E}^{\rm em} = -\frac{\partial \mathbf{A}^{\rm em}}{\partial t} - \nabla \varphi^{\rm em} \tag{1}$$

$$\mathbf{p} = \frac{\hbar}{i}\nabla \rightarrow \frac{\hbar}{i}\nabla - q\mathbf{A}^{\rm em}; \quad i\hbar\frac{\partial}{\partial t} \rightarrow i\hbar\frac{\partial}{\partial t} - q\varphi^{\rm em} \tag{2}$$

$$\mathbf{A}^{\rm em} \rightarrow \mathbf{A}^{\rm em} - \frac{\hbar}{2q}\nabla\phi; \quad \varphi^{\rm em} \rightarrow \varphi^{\rm em} + \frac{\hbar}{2q}\partial_t\phi$$

$$\psi(\mathbf{x}, t) \rightarrow e^{-\frac{i}{2}\phi}\psi(\mathbf{x}, t)$$

Inseparable relation between electromagnetic field and charged particles.

The duality that a U (1) phase factor on a wave function describes a whole system motion and also plays the role of a U(1) gauge potential..

- Hiroyasu Koizumi " Flux Rule, U(1) instanton, and superconductivity", J. Supercond. Nov. Magn. 30, 3345–3349 (2017)

Conclusions

SVILC (spin-vortex-induced loop current) qubits may be promising for realizing fully fault-tolerant quantum computing.