 

*CONFERENCES AND SYMPOSIA*

PACS number: 01.10.Fv

# Scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (31 March 1999)

A scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (RAS) was held at the P L Kapitza Institute for Physical Problems, RAS on 31 March 1999.

Four papers were presented at this session:

(1) **Feĭgel'man M V** (L D Landau Institute for Theoretical Physics, RAS, Moscow) "A quantum bit based on a Josephson contact between conventional and high-temperature superconductors (theory)";

(2) **Ryazanov V V** (Institute of Solid-State Physics, RAS, Chernogolovka) "Josephson superconductor – ferromagnet – superconductor π-contact as an element of a quantum bit (experiment)";

(3) **Morozov A I, Sigov A S** (Moscow State Institute for Radio Engineering, Electronics and Automation (Technical University), Moscow) "New type of domain boundaries in multilayer magnetic structures";

(4) **Latyshev Yu I** (Institute for Radioengineering Electronics, RAS, Moscow) "Quantum interference of a moving charge density wave on columnar defects containing magnetic flux".

An abridged version of the papers is given below.

PACS numbers: 03.67.Lx, 73.23.Hk, **73.40.–c**, 85.25.Cp

## A quantum bit based on a Josephson contact between conventional and high-temperature superconductors (theory)

M V Feĭgel'man

For realization of quantum computing algorithms (see, for example, the review article [1]), one has to control as many as $n \gg 1$ generalized quantum spins 1/2 (in other words, quantum two-level systems, or quantum bits) in much the same way as the computational program of a conventional computer manages the states of classic binary cells 0,1 (see Table 1). Thus, for physical realization of quantum computations one has to create the system satisfying three contradictory to each other requirements:

(a) the system consists of a large number ($n \gg 1$) of quantum bits (or qubits for short);

(b) the system is decoupled from the environment as much as possible (to preserve quantum coherence in the course of computations), and

(c) the state of the system (that is, the wave function of each qubit) can be controlled with a high degree of precision.

*Uspekhi Fizicheskikh Nauk* **169** (8) 917 – 926 (1999)
Translated by A S Dobroslavskiĭ; edited by A Radzig

**Table 1**

| Logical devices | Classical | Quantum |
|---|---|---|
| Information elements and their physical representation | Bits: 0, 1; bistable systems | Qubits — quantum systems with two basis states $\|0\rangle$, $\|1\rangle$ |
| State of the memory | Sequence of bits 010...10 | Quantum state — basis: $\|010\ldots10\rangle$ $\|\Psi\rangle = \sum_{a_1,\ldots,a_4} C_{a_1,\ldots,a_4} \|a_1,\ldots,a_4\rangle$ |
| Elementary operations | Logical operations with 1 or 2 bits | Unitary transformations with 1 or 2 qubits |

Several fundamentally different approaches to the solution of these problems have been proposed.

**(1) Ions in a trap.** This is the first and the most well-developed idea. Experimental technique is available that allows confinement of an individual ion in a trap formed by an alternating electric field for a long time (of the order of one hour). The ion can be 'cooled' (cancelling its vibrational motion) with a laser beam. Adjusting the length and repetition frequency of laser pulses, one can prepare an arbitrary superposition of the ground and excited states. It seems, however, that it will be too difficult to manipulate a large number of ions in this way at the same time, as required for running a quantum processor.

**(2) Nuclear magnetic resonance.** In a molecule with several *different* nuclear spins, an arbitrary unitary transformation can be accomplished with a sequence of pulses of a magnetic field. This has been experimentally verified at room temperature. To prepare the initial state, however, the temperature must be brought down to less than $10^{-3}$ K. In addition to problems with cooling, there appear other complications, since spurious interactions between the molecules heighten at this temperature. Moreover, it is not clear how to act upon a given spin selectively if there are several similar spins in the molecule.

**(3) Mesoscopic electron systems** (semiconducting quantum wells, systems of small superconducting granules with Josephson contacts, a two-dimensional electron gas in the regime of the quantum Hall effect). These systems as distinct from atoms or molecules contain a large number ($10^6 - 10^{12}$) of electrons. Nevertheless, their properties are qualitatively different from those of macroscopic bodies. The common feature of such systems of submicrometer size, as related to the construction of a quantum computer, is the possibility of their natural scaling (as opposed to the atomic systems, where it is the problem of scaling that seems to be very difficult to solve). For mesoscopic systems, in turn, it is very difficult to preserve quantum coherence. The fact is that because the number of internal electronic degrees of freedom available in each qubit of submicrometer size is very large, at least one such degree of freedom, as a rule, is very likely to get excited, which will immediately destroy the quantum state of the qubit. The solution to this problem is sought in several directions. For example, it was proposed to use spins of electrons in quantum wells as the basis for quantum bits, and to control their interactions with the aid of external electric fields [2]. Another option suggested by A Kitaev [3] consists in using *anyons* in two-dimensional electron systems for doing quantum computations. In such a case, the coherence will be preserved for a period of time that is exponentially large with respect to the ratio of the size of such elementary system to the atomic scale. The simplest example of such anyons is realized in the states of the fractional Hall effect. For quantum computers, however, more complex 'non-Abelian' anyons are required, and their physical realizations are not yet clear. By this means, even though the anyon direction may appear to be optimal, so far it has been very little studied.

Today, the most realistic direction leading to the creation of qubits seems to be associated with *mesoscopic superconductors* — Josephson junctions and SNS junctions of submicrometer size. On the one hand, such systems admit natural scaling (for example, experiments on quantum superconductor – insulator phase transitions in networks of Josephson contacts are carried out with systems comprising more than $10^4$ contacts with almost identical properties [4, 5]). On the other hand, the presence of a gap in the energy spectrum of a superconductor highly reduces (at low enough temperatures $T \ll \Delta$) the probability of excitation of quasiparticles. Because of this, the quantum coherence may be preserved for the time $t_{\mathrm{coh}}$ much longer than the time $t_0$ of elementary operation (according to current estimates, quantum computations can be realized if $t_{\mathrm{coh}}/t_0 \geqslant 10^3 - 10^4$).

There are two basic approaches to the construction of qubits based on Josephson contacts. One relies on using for the quantum variable (analogous to the spin 1/2) the charge on the central island of superconducting one-electron transistor [6], on which the electric potential $V_g$ is maintained at a value near $V_g^0$. In this case the states differing by $2e$ (i.e. by one Cooper pair) have the same electrostatic energy. We shall call this object the charge qubit. The transitions accompanied by the change of the number of Cooper pairs by one occur owing to the weak Josephson interaction between the islands: $E_{\mathrm{J}} \ll E_{\mathrm{C}} = e^2/C$ (because of this, the Josephson interaction is only important when $V_g \approx V_g^0$). The first experiment that demonstrated long-time quantum coherence in such a device was performed recently [7]. It appears that charge qubits can be realized, but they all have a common drawback: since the charge of a qubit is different in the two basis states, in a quantum processor there will be the unavoidable Coulomb interaction between the qubits in different states that only slowly decreases with the distance (as well as a qubit interaction with the environment). Because of this, the realization of large quantum processors on this principle seems problematic.

Another, in some sense dual approach to the construction of superconducting qubits is based on the idea of describing the quantum state of the island in terms of the *phase* of the superconducting order parameter relevant to the island, and such will be referred to as phase qubits. As a matter of fact, there is no fundamental difference between these two types of qubits, since in quantum-mechanical description the charge and the phase of a superconducting island are canonically conjugate quantities (much like the coordinate and momentum of a Schrödinger particle). In practice, however (continuing this analogy), there exist a big distinction between the Schrödinger wave packet close to a plane wave and a heavy particle almost localized in space. In the phase qubit, the two basis states 1, 2 differ in the value of phase $\phi$, and the Josephson energy of the system $U(\phi)$ has two almost degenerate minima at $\phi = \phi_{1,2}$, separated by a potential barrier. The transitions between these states occurs by way of quantum tunneling under the barrier, and the 'kinetic' energy is represented by the energy of Coulomb interaction. If the capacitance of the island is large enough ($e^2/C \ll E_{\mathrm{J}}$), the amplitude of phase tunneling (and hence the splitting of symmetric and antisymmetric energy levels) is exponentially small compared with the scale of the potential barrier $|U(\phi_{1,2}) - U(\phi_{\max})|$. Most of the time the phase qubit passes with the phase close to $\phi_1$ or $\phi_2$, and the charge $Q$ only appears at the time of tunneling (since $Q = C_{\mathrm{eff}} V = C_{\mathrm{eff}}\,(\hbar/2e)(\mathrm{d}\phi/\mathrm{d}t)$), which to a large extent resolves the problem of 'parasitic' Coulomb interaction between the qubits. There is no direct interaction (through the nonconducting medium) between the phases of the order parameters of different islands (qubits), and so it is the purely phase qubit that appears to be the most promising building block of large quantum processors.

Several theoretical schemes have been proposed for realization of superconducting phase qubits [8 – 10]. The technologically simplest of these consists of three or four superconducting islands connected into a ring by Josephson contacts (with the critical current $I_{\mathrm{c}}$), where the magnetic flux $\Phi \approx \Phi_0/2$ is initiated inside the ring (here $\Phi_0 = \pi\hbar c/e$ is the magnetic flux quantum). The inductance of the ring is assumed to be very small ($LI_{\mathrm{c}} \ll \Phi_0$), so that the resulting analog of a SQUID does not capture magnetic field. In such a system, the Josephson energy as a function of phases $\phi_j$ on the islands (for definiteness, we are considering a four-contact SQUID) takes the form

$$U\{\phi_j\} = -E_{\mathrm{J}}\Big[\cos(\phi_1 - \phi_2) + \cos(\phi_2 - \phi_3) + \cos(\phi_3 - \phi_4) + \cos\left(\phi_4 - \phi_1 + \frac{2\pi\Phi}{\Phi_0}\right)\Big]. \qquad (1)$$

Further on we assume that the phase of the first island is fixed: $\phi_1 \equiv 0$. At $\Phi = \Phi_0/2$, the two minima of energy (1) occur at $\phi_j = \pm j\pi/4$ and correspond to two opposing directions of superconducting current in the ring. In particular, the magnitudes of the phase $\phi_3$ in these two states differ by $\pi$. A slight deviation of the magnetic flux in the ring from $\Phi_0/2$ makes this two-level system asymmetrical — that is, in terms of the 'effective field' $\mathbf{h}$ acting on the artificial spin 1/2 we get $h_z = \Phi/\Phi_0 - 1/2$. The magnitude of the amplitude of tunneling between the two classical minima, i.e. the component of the 'field' $h_x \propto \sqrt{E_{\mathrm{J}} E_C}\exp(-a\sqrt{E_{\mathrm{J}}/E_C})$ (here $a$ is a multiplier of the order of one) can be varied by changing the effective capacitance $C_{\mathrm{eff}}$. It seems plausible that such a system (Fig. 1) will be the first version of a phase qubit realized in the laboratory [8]. Unfortunately, it has the same principal limitation as the charge qubit: apart from having different phases $\phi_j$, the two basis states differ also in the direction of current $I$ along the ring, but currents, like charges, interact at large distances. This adverse effect is weakened when the inductance of the ring is made smaller (which is why we require that $LI_{\mathrm{c}} \ll \Phi_0$), but it cannot be completely neutralized in the case of ordinary Josephson junctions.

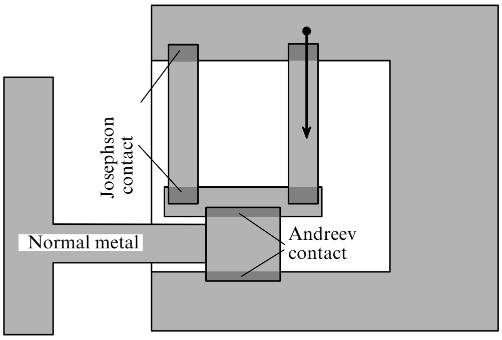


**Figure 1.** Four-contact SQUID with an Andreev probe for measuring the coherence time.

This is possible, however, if we take advantage of the unusual properties of contacts with high-temperature superconductors (HTSC) [10]. It has been firmly established [11] that superconducting pairing in the main families of HTSCs (YBaCuO, BiSrCuO) possesses an unusual symmetry: the wave function of a Cooper pair $\Psi(\mathbf{p}) = \langle c_{\mathbf{p}} c_{-\mathbf{p}} \rangle$, where $c$ is the operator of creation of an electron, strongly depends on the orientation of the unit vector on Fermi surface $\mathbf{n} = \mathbf{p}/p$ with respect to the axes of a crystal lattice: $\Psi(\mathbf{n}) \propto (n_x^2 - n_y^2)$. In other words, the sign of the pair wave function is different for various directions of $\mathbf{n}$. The left-hand part of Fig. 2 shows the scheme of the phase-sensitive experiment conducted by D Wollman et al. [11]: the different signs of wave functions of pairs escaping the HTSC crystal in directions (010) and (100) give rise to a spontaneous magnetic flux penetrating the π-circuit. As described in Ref. [10], the $d$-wave symmetry of superconducting state in HTSC can be used for creating a Josephson SDS′ contact, whose energy depends on the phase difference as $E_{\mathrm{SDS}}(\phi) = -E_2 \cos 2\phi$. In other words, such a contact has two equivalent minima of Josephson energy over the standard period of phase variation $\phi \in (0, 2\pi)$. Connecting to the SDS′ contact the ordinary Josephson contact (as shown in the right-hand part of Fig. 2) with a low critical current, we can introduce an asymmetry between the states (that so far had been degenerate with respect to energy) with the phase difference $\phi = 0, \pi$. The fundamental advantage of such a qubit is that there is no current in the SQUID contour in either of the basis states $\phi = 0$, $\phi = \pi$ (which only differ in the phase), and so the problem of spurious interactions is removed.

The simplest version of a phase qubit — a four-contact SQUID in a magnetic field — has yet another disadvantage: one has to maintain a magnetic flux equal to $\Phi_0/2$ at its

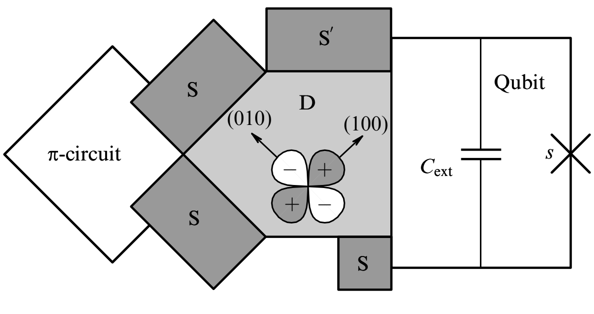


**Figure 2.** SQUIDs of conventional and high-temperature superconductors.

'working point' with an aid of the external current, which by itself is a source of noise. In place of the magnetic flux, however, one can use a Josephson π-contact inserted in the SQUID contour. One possible realization of such a contact was described above (see the left-hand part of Fig. 2). Another and more technologically accepted way was proposed in Ref. [12], where a Josephson SFS contact with a critical current was realized for the first time.

## References

1. Ekert A, Josza R *Rev. Mod. Phys.* **68** 733 (1996)
2. Loss D, Di Vincenzo D P *Phys. Rev. A* **57** 120 (1998)
3. Kitaev A Yu "Fault-tolerant quantum computation by anyons" http://xxx.lanl.gov, quant-ph/9707021 (1997)
4. Van der Zant H et al. *Phys. Rev. B* **54** 10081 (1996)
5. Delsing P *et al. Phys. Rev. B* **50** 3959 (1994)
6. Makhlin Yu, Schoen G, Shnirman A *Nature* (London) **398** 305 (1999)
7. Nakamura Y, Pashkin Yu, Tsai J S *Nature* (London) **398** 786 (1999)
8. Mooij H et al. *Science* **235** 1036 (1999)
9. Ivanov D A, Feĭgel'man M V *Zh. Eksp. Teor. Fiz.* **114** 640 (1998) [*JETP* **87** 349 (1998)]
10. Ioffe L B *et al. Nature* (London) **398** 679 (1999)
11. Wollman D A et al. *Phys. Rev. Lett.* **71** 2134 (1993); Kirtley J R et al. *Nature* (London) **373** 225 (1995)
12. Ryazanov V V *Usp. Fiz. Nauk* **169** 920 (1999) [*Phys. Usp.* **42** 825 (1999)]

PACS numbers: 03.67.Lx, 73.23.Hk, **73.40.–c**, 85.25.Cp

# Josephson superconductor – ferromagnet – superconductor π-contact as an element of a quantum bit (experiment)

V V Ryazanov

## 1. Introduction

The authors of Refs [1, 2] proposed several realizations of a quantum bit on the base of superconducting structures including the Josephson '0'- and π-junctions — that is, ordinary superconducting contacts with a weak link, and the contacts exhibiting a spontaneous π-shift of macroscopic phase difference of superconducting wave functions (order parameter) on the electrodes of the Josephson junction. A brief account of theoretical and experimental studies on structures exhibiting spontaneous phase shift is given in Section 2 of this presentation. The main part of this report deals with the results of investigations participated in by the author and concerned with SFS (superconductor – ferromagnet – superconductor) junctions that appear to be most promising for the construction of perspective quantum-logic elements.

## 2. Josephson structures exhibiting spontaneous π-shift of a phase difference

Recent works on π-contacts have been mostly concerned with the study of the nontrivial order parameter in high-temperature superconductors (HTSC). In the case of assumed $d$-wave symmetry ($d_{x^2-y^2}$), the sign of the order parameter depends on the direction in the basal plane of the HTSC crystal and must change upon passing from one crystal face to the normally arranged another (which