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# Joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences and the Joint Physical Society of the Russian Federation (21 April 2004)

A joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) and the Joint Physical Society of the Russian Federation was held on 21 April 2004 at the P N Lebedev Physics Institute, RAS. The following reports were presented at the session:

(1) **Pashkin Yu A** (P N Lebedev Physics Institute, RAS, Moscow and The Institute of Physical and Chemical Research (RIKEN), Wako, Japan), **Astafiev O V** (The Institute of Physical and Chemical Research (RIKEN), Wako, Japan), **Yamamoto T, Nakamura Y, Tsai J S** (The Institute of Physical and Chemical Research (RIKEN), Wako, Japan, NEC Fundamental and Environmental Research Laboratories, Tsukuba, Japan, CREST, Japan Science and Technology Agency (JST), Kawaguchi, Japan) "Josephson solid-state qubits";

(2) **Zharkov G F** (P N Lebedev Physics Institute, RAS, Moscow) "Superconducting states and magnetic hysteresis in finite superconductors";

(3) **Elesin V F** (Moscow Engineering Physics Institute, Moscow), **Kapaev V V, Kopaev Yu V** (P N Lebedev Physics Institute, RAS, Moscow) "Coexistence of ferromagnetism and nonuniform superconductivity";

(4) **Barash Yu S, Bobkova I V** (Institute of Solid State Physics, RAS, Chernogolovka), **Kopp T** (University of Augsburg, Bavaria, Germany) "Theory of magnetic contacts between clean superconductors";

(5) **Maksimov E G** (P N Lebedev Physics Institute, RAS, Moscow) "High-temperature superconductivity today".

An abridge version of the papers is given below.

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## Josephson solid-state qubits

Yu A Pashkin, O V Astafiev,
T Yamamoto, Y Nakamura, J S Tsai

Recently, from a purely mathematical discipline, quantum computation turned into a rapidly growing experimental field. It has been proven that many computational problems that seemed to be insolvable with classical computers within a realistic time scale can be solved much faster by means of quantum algorithms [1]. Thus, the problem has been shifted from computer science and mathematics to technology. It is now a challenge for experimentalists to find a proper physical system that can be used as a quantum bit (qubit) — a building block for the future quantum computer. Although it is still not clear yet whether a quantum computer will ever be built, it is definitely worth undertaking this research, not only because of the interesting physics involved, but also because this research may eventually result in the creation of new types of measurement devices and sensors based on new principles.

Ideally, a qubit is a quantum two-level system with a long decoherence time. Solid-state qubits are of particular interest because of their potential scalability — that is, if a single qubit is built, more complex quantum-mechanical circuits containing many qubits can be made. Moreover, solid-state qubits can be, in principle, embedded into a control and/or readout circuit forming a single quantum processing chip. However, because solid-state qubits are stronger coupled to an electromagnetic environment, maintaining coherence in them is harder compared to microscopic qubits (nuclei, ions, etc.).

Experiments on qubits include three major steps: initial state preparation, state manipulation, and readout. Depending on the particular qubit, these steps may differ. Experimental facility must be designed in such a way that, on the one hand, the qubit should be well isolated from its environment to remain coherent for sufficiently long time. On the other hand, one should have access to the qubit in order to measure its state after manipulations.

Among solid-state qubits, those based on the Josephson effect have proven to be the most promising [2, 3]. After the first successful demonstration of controlled manipulation in the Josephson qubit utilizing the charge degree of freedom [4], a few other experiments have been performed on phase [5, 6], flux [7], charge [8], and combined charge/flux [9] Josephson qubits. Moreover, the coherent behavior of two-coupled-qubit circuits have been exhibited recently [10, 11]. Clear evidence for the interaction of electrostatically coupled qubits has been obtained. Based on two coupled charge qubits, the conditional gate operation, a prototype of quantum logic C – NOT gate, has also been demonstrated [12]. The next important step consists in implementing the controllable coupling of qubits [13, 14].

Now, efforts by many researchers are aimed at improving the quality of individual qubits and understanding decoherence mechanisms in Josephson-junction qubits. This was done, for example, by implementing new readout circuits with high efficiency and low back-action [15, 16]. Combining a trap and a single-electron transistor, we could perform single-shot readouts from the charge qubit, i.e., we could measure the qubit state after each manipulation event [15]. This circuit has also enabled us to investigate

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relaxation dynamics of the charge qubit [17]. From these measurements we concluded that charge noise coming from two-level fluctuators plays a crucial role in qubit energy relaxation.

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# Superconducting states and magnetic hysteresis in finite superconductors

G F Zharkov

The macroscopic Ginzburg – Landau (GL) theory of superconductivity [1], evolved in 1950, is an example of the triumph of physical intuition. The theory has been successfully used to characterize the behavior of superconductors in a magnetic field and to predict many effects later verified in experiments. The key issue of the theory was the assumption that the physical state of a superconductor is described by a complex-valued function called the order parameter:

$$\Psi(\mathbf{x}) = \psi(\mathbf{x}) \exp\left[\mathrm{i}\Theta(\mathbf{x})\right],$$

where $\psi$ is the modulus, $\Theta$ is the phase of the order parameter, and $\mathbf{x}$ is the spatial variable. The uniqueness condition imposed on $\Psi(\mathbf{x})$ implies that at any point in the superconductor the phase is determined only within the factor $2\pi m$, where $m = 0, \pm 1, \pm 2, \ldots$, with $\psi(\mathbf{x})$ at this point possibly having a singularity: $\psi(\mathbf{x}) \sim x^{|m|}$ as $x \to 0$. Later on, it was found that this singularity is associated with the presence of vortices [2] (Abrikosov, 1957) in type II superconductors, for which the value of the material parameter of the theory is $\varkappa > \varkappa_0 = 1/\sqrt{2} = 0.707$.

The division of superconductors into two groups (with $\varkappa < \varkappa_0$, and with $\varkappa > \varkappa_0$) was suggested in the original GL paper, where it was established that the free energy of the interface between the superconducting (s-) and normal (n-) states of a metal in a magnetic field (in what is known as the intermediate state) vanishes at $\varkappa = \varkappa_0$ [1], which suggests that the n-state in type I superconductors ($\varkappa < \varkappa_0$) is unstable with respect to the formation of the s-phase and leads (as the strength $H$ of the external field diminishes) to a first-order (abrupt) phase transition from the supercooled (in the magnetic field) superconducting state to the normal state. The same researchers found that type I superconductors in a weak magnetic field exhibit what is known as the Meissner effect (the complete expulsion of a magnetic field from a superconducting material), while as the field strength grows a first-order phase transition from the superheated s-state to the normal n-state occurs. However, following Abrikosov's reasoning [2], we can also say that for $\varkappa > \varkappa_0$ the magnetic field begins to penetrate to the interior of a type II superconductor in the form of vortices (forming what is known as a mixed state), and, as the field strength grows, the normal cores of the vortices completely overlap and the superconductor passes to its normal state via a second-order phase transition (in the field $H_{c2} = \phi_0/(2\pi\xi^2)$, where $\phi_0 = hc/2e$ is the magnetic flux quantum, and $\xi$ is the superconductor's coherence length [2]). Thus, Abrikosov [2] described the vortex mechanism by which an external magnetic field penetrates to the interior of a type II superconductor.

It must be noted at this point that the above picture of the magnetic field penetration into a superconductor was obtained in Refs [1, 2] on the basis of thermodynamic approach for uniform superconductors of infinite dimensions and without accounting for possible edge effects. Below we shall show that in finite superconductors (cylinders or plates placed in a magnetic field in a vacuum) there is another, edge, mechanism of the penetration of a magnetic field within superconductors. With this mechanism, the vortices may not even form, but the order parameter $\psi(x)$ near the superconductor's edges is strongly suppressed and a growing magnetic field begins to penetrate the superconductor almost freely near the edges. As the field strength increases still further, such an (edge) e-state is completely suppressed as the field reaches the value $H_{c2}$. The e-states can exist only in type II superconductors with $\varkappa > \varkappa_c = 0.93$ and of fairly small lateral dimensions (a cylinder of radius $R$ or a plate of thickness $2D$), which are placed in a longitudinal magnetic field $H$. Note that as $R$ or $D$ grows, the edge e-layer, obviously, becomes unstable and splits into individual vortices which gradually fill the interior of a massive type II superconductor (in accordance with the mechanism described in Refs [2 – 5]), and the superconductor changes into the n-state.

We shall also show below that as the strong external magnetic field gets weaker, in finite superconductors with the values of $\varkappa$ falling in the interval $\varkappa_0 < \varkappa < \varkappa_c$, the supercooled normal $\bar{\mathrm{n}}$-state first transforms gradually into a specific p-state (precursor state), and then, it abruptly transforms into a fully superconducting Meissner (M) state in a field $H_r$ (the subscript 'r' stands for restoration). In superconductors with $\varkappa < \varkappa_0$, no intermediate p-state forms, and, as the field weakens, the superconductor instantaneously transforms from the $\bar{\mathrm{n}}$-state to the M-state jumpwise. Thus, finite superconductors can be nominally divided into three groups: those with $\varkappa < \varkappa_0$, with $\varkappa_0 < \varkappa < \varkappa_c$, and those with $\varkappa > \varkappa_c$.

The various edge effects have been described in detail in Refs [6 – 17]; below we only touch on the essential points of the research. For the sake of simplicity, we examine the case of cylindrical geometry, where there are no vortices in the superconductor, i.e., $m = 0$. The self-consistent solutions of the system of nonlinear GL equations for the order parameter $\psi(\mathbf{x})$ and the dimensionless magnetic-field potential $a(\mathbf{x})$ can be found by applying the iteration technique [6]. (Note that the results do not depend on the method of calculation.)