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Intrinsically frustrated superconducting array of superconductor-ferromagnet-superconductor π junctions

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We report a direct observation of the transition of the superconductor-ferromagnet-superconductor (SFS) junctions to the π state. This manifests itself in the half-period shift of the external magnetic field dependence of the transport critical current in the triangular SFS arrays. The shift is associated with the appearance of spontaneous supercurrents in the array at zero external field, with the ground state degenerated with respect to the two possible current flow directions. In conventional Josephson arrays this state can be observed only by imposing a frustrating external field equal to a half-integer number of magnetic flux quanta per array cell.

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In recent years considerable attention has been given to the realization of "π -contacts," i.e., weakly coupled junctions formed in superconducting structures which demonstrate a π shift of macroscopic phase differences in the ground states. Among such structures one should mention bicrystals[1] and "*s-d*" contacts[2] based on high-temperature superconductors with assumed "nontrivial" (*d*-wave) symmetry of the order parameter, mesoscopic superconductor–normal metal–superconductor (SNS) junctions controlled by current along the N layer,[3] and finally, recently observed superconductor-ferromagnet-superconductor (SFS) π junctions.[4,5] In the experiments[4,5] the phase π shift manifested itself in reentrant superconducting behavior of the critical supercurrent temperature dependence, $I_c(T)$, of the Nb-Cu/Ni-Nb Josephson SFS junctions. In this work we present direct evidence of the phase π shift which shows itself as a half-period shift of the external magnetic-field dependence of the transport critical current through a triangular SFS junction array. This shift is associated with the appearance of spontaneous supercurrents in the investigated π junction array at zero external field. Two possible (opposite) directions of the supercurrent flow signify the existence of a double-degenerate ground state of the array. In conventional Josephson arrays a double-degenerate state can be observed only by imposing a frustrating external field equal to a half-integer number of magnetic quanta per cell.[6] Self-frustrated superconducting networks with π junctions are intended to be used for the realization of the superconducting quantum bit (qubit).[7,8] Originally, the suggested superconducting "phase" qubits[9,10] were based on magnetic-frustrated superconducting networks. In this case it is necessary to apply half a quantum of the magnetic flux, $\Phi_0/2$, to create a degenerated two-level coherent quantum system. In order not to spoil quantum coherence for a sufficiently long time the use of an external source of frustrating field is unfavorable, since this field should be controlled with precision better than 10^{-6}.[8] The application of an intrinsically frustrated array with a π junction provides an effective way to overcome the above problem; qubits using such a junction are supposed to have much longer coherence time. Another possible application of π junctions is related to the development of superconducting digital "complementary" electronics where a π junction can be used as a superconducting phase inverter.[11] The complementary Josephson logic is analogous to the common complementary metal-oxide-semiconductor (CMOS) logic family and its basic element is the combination of conventional dc and π superconducting quantum interference devices (SQUID's). The π SQUID contains a π junction which shifts the magnetic field dependence of the SQUID critical current by a half-period.

The π state in a SFS junction arises due to an oscillating (sign -reversal) behavior of the superconducting order parameter induced in the ferromagnet close to the SF interface.[12,13,5] It was shown in Ref. 5 that in the case of weak exchange energy $E_{\mathrm{ex}} \sim k_B T$, when the thermal and exchange energy make comparable contributions to the pair decay process, the general expression for the complex coherence length in the dirty ferromagnet is

$$\xi_F = \left(\frac{\hbar D}{2(\pi k_B T + i E_{\mathrm{ex}})} \right)^{1/2}, \tag{1}$$

where D is the electron diffusion coefficient in the ferromagnet and k_B is the Boltzmann constant. The imaginary part of ξ_F,

$$\xi_{F2} = \sqrt{\frac{\hbar D}{[(\pi k_B T)^2 + E_{\mathrm{ex}}^2]^{1/2} - \pi k_B T}}, \tag{2}$$

defines the order parameter oscillation wavelength $2\pi\xi_{F2}$ that decreases with decrease of temperature. This allows observation of the SFS junction transition to the π state as temperature decreases down to $T = T_\pi$, when the ferromagnetic interlayer thickness, d_F, becomes close to the half-wave of the oscillations, $\pi\xi_{F2}$. It was demonstrated in Ref. 5 that the transition from the ordinary 0-phase state to the π state in a single SFS junction leads to a zero-crossing temperature dependence of the critical current or, more truly, to a sharp cusp in the $I_c(T)$ dependence with vanishing of I_c amplitude at $T = T_\pi$ (due to an obvious fact that only the absolute value of a critical current can be observed in a single junction). Measurements reported in Ref. 5 were carried out for Nb-Cu/Ni-Nb Josephson sandwiches with ferromagnetic layers fabricated from Cu/Ni alloy with concentrations from 52 at. % Ni (with T_{Curie} about 20–30 K) to 57 at. % Ni (where T_{Curie} was above 100 K).

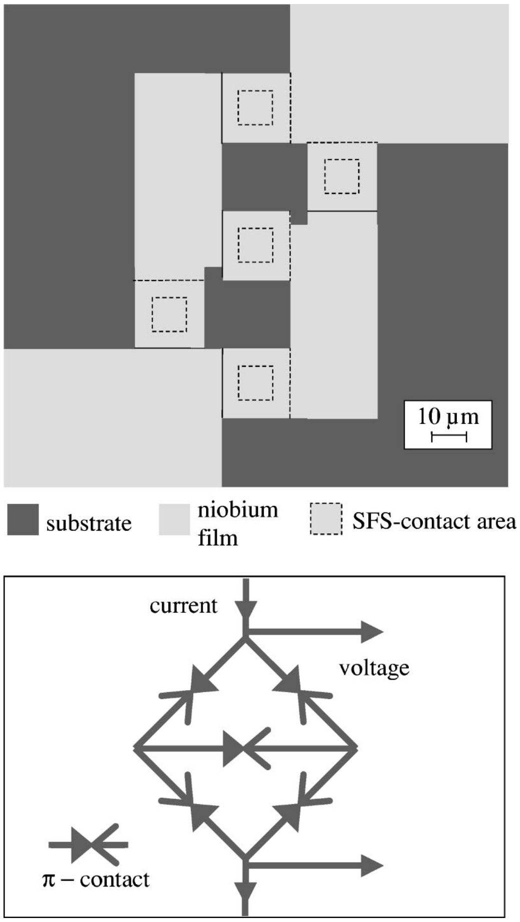

FIG. 1. Real (upper) and schematic (lower) picture of the network of five SFS sandwiches Nb-$\mathrm{Cu}_{0.46}\mathrm{Ni}_{0.54}$-Nb ($d_F = 19\,\mathrm{nm}$), which was used in the phase-sensitive experiment.

Several experimental phase-sensitive methods of direct detection of the π state transition were suggested.[14,2] The signature of the π state would be the appearance of a spontaneous magnetic flux equal to half of the flux quantum, $\Phi_0/2$, in a high-inductance superconducting loop containing a π contact. The Josephson π junction was first predicted in Ref. 14 and it was shown there that the state with a spontaneous flux could be realized in such a one-contact interferometer only if $2\pi L I_c \geqslant \Phi_0$, where L is the loop inductance and I_c is the contact critical current. For our purposes it is more convenient to use weakly inductive interferometers with $2\pi L I_c \ll \Phi_0$. In such a case the signature of the transition to the π state would be the shift of the external flux Φ dependence of the transport critical current $I_m(\Phi)$ for a two-contact interferometer made of Josephson 0 and π contacts of nearly equal critical currents. However, in our case it was found to be very difficult to fabricate 0 and π junctions with close Josephson critical currents. Therefore we actually used a slightly more complicated intrinsically frustrated structure consisting of five identical SFS junctions arranged into two loops (shown in Fig. 1). Still, before starting the presentation of our real data, we offer discussion of the phenomenon which would be seen in a "0-π interferometer," since it presents the most logically transparent route to the understanding of our results.

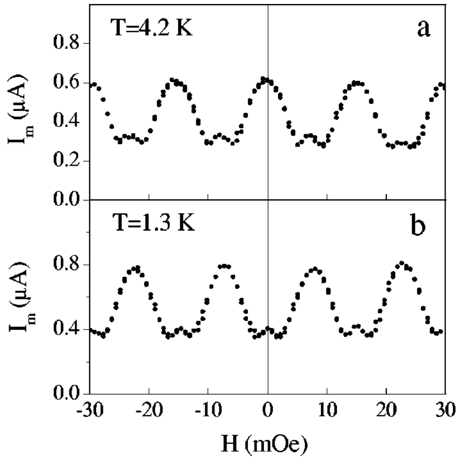

FIG. 2. Magnetic field dependences of the critical transport current for the structure depicted in Fig. 1 at temperature above (a) and below (b) T_π.

The total phase shift along the loop of the 0-π interferometer should be a multiple of 2π. Therefore, additional (to an intrinsic π shift provided by the π junction) phase shifts appear across both junctions, resulting in the circulating supercurrent (of two possible directions). In the case of the symmetric interferometer these phase shifts are both equal to $\pi/2$ (or $-\pi/2$), and the value of the circulating current is equal to the critical value I_c. Thus the critical transport current I_m through the interferometer (0-π SQUID) is equal to zero in the absence of any external magnetic flux and reaches the maximum $I_m = 2I_c$ when the external magnetic flux Φ is equal to $\Phi_0/2$. In the latter case the magnetic flux induces the additional phase shift of $2\pi(\Phi/\Phi_0) = \pi$ which compensates for the spontaneous π shift over the π junction. Thus the $I_m(\Phi)$ dependence for the 0-π interferometer is shifted by a half-period compared to the usual SQUID. Below we show that qualitatively the same behavior appears in the five-junction SFS array as a whole.

Shown in Fig. 1 is the two-cell array that is believed the most simple structure to study the intrinsically frustrated π-junction networks. Details of the SFS junction fabrication are presented in Ref. 5. All five Nb-$\mathrm{Cu}_{0.46}\mathrm{Ni}_{0.54}$-Nb junctions in the array had areas $10 \times 10\,\mu\mathrm{m}^2$, normal resistances $3 \times 10^{-4}\,\Omega$, and junction critical currents $I_c = 0.3\,\mu\mathrm{A}$ at $T = 4.2\,\mathrm{K}$. The $\mathrm{Cu}_{0.46}\mathrm{Ni}_{0.54}$ alloy with T_{Curie} about 100 K was used as a F interlayer in the SFS contacts. Because of low values of array resistance and its critical current, I_m, the current-voltage and $I_m(H)$ characteristics (H is magnetic field applied normally to the array) were measured by a SQUID picovoltmeter with a sensitivity of $10^{-12}\,\mathrm{V}$ in the temperature range of 1.2 K to 4.2 K. The SFS junctions with the F-layer thickness of $d_F = 19\,\mathrm{nm}$ demonstrate transition to the π state at $T_\pi = 2.2\,\mathrm{K}$. Above this temperature (0 state) the $I_m(H)$ pattern for the investigated array is the same as the one predicted in Refs. 15 and 16 for a two-cell interferometer [see Fig. 2(a)]. Periodical maximal peaks are observed at external fields corresponding to an integer number of the flux quanta per cell, i.e., integer frustration parameters $f = \Phi/\Phi_0$. Also small peaks can be seen at half-integer values of the frustration parameter f. These secondary peaks result from the phase interference over the outer loop of the net structure, which is twice the unit cell, so half-integer f leads to an integer number of flux quanta inside the outer loop. At temperatures below T_π (in the π state) the $I_m(H)$ pattern was found to be shifted by exactly half a period [Fig. 2(b)].

Upon neglect of the additional minor peaks at half-integer frustrations the behavior of this five-loop π-junction interferometer resembles that of the 0-π interferometer described above. At $f=0$ and other integer values of f there is a current close to the junctions critical current, I_c, flowing in the outer double loop of the array. The current induces the extra phase shift $2\times\pi/2$ in each cell and compensates for the odd number of π shifts in them. Because the array is initially in the spontaneous fully frustrated state, the maximal array transport supercurrent, I_m, is close to zero at $H=0$. The external magnetic flux equal to half-integer quanta per cell produces the necessary phase shift of π in each cell in the absence of any circular currents in the structure, therefore I_m reaches maxima at half-integer frustration parameters. Due to the contribution of the outer double-cell contour of the net structure, $I_m(H=0)$ is not zero in the π state but is determined by the amplitude of the small peak, as seen in Fig. 2(b). The $I_m(T)$ dependence at $H=0$, shown in Fig. 3(a), mimics the $I_c(T)$ dependence for single junctions and demonstrates a sharp cusp at the temperature T_π of the transition into the π state. However one should keep in mind that the left and right (below and above T_π) branches of the $I_m(H=0,T)$ dependence are intrinsically asymmetric: while the high-temperature branch corresponds to the temperature dependence of the doubled junction critical current, the low-temperature branch corresponds to the dependence on temperature of the small peak amplitude only. Figure 3(b) shows the maximal peaks positions before and after the 0-π transition and demonstrates the sharpness of this transition.

To check possible residual magnetic inductance effects at low-temperatures we fabricated also a reference two-cell array of the same geometry but with the Nb-$Cu_{0.46}Ni_{0.54}$-Nb SFS junctions which did not exhibit a transition to the π state in the full experiment temperature ''window'' (from 1.2 to 4.2 K) due to a smaller ferromagnetic interlayer thickness of 18 nm. After a proper careful cooldown (described in Ref. 5) we observed the maximum value of I_m at zero applied magnetic field for all temperatures of the experiment, i.e., the $I_m(H)$ pattern did not shift with temperature change. This proves that the shift observed for the SFS junction array with $d_F=19$ nm was not associated with residual magnetic inductance changes.

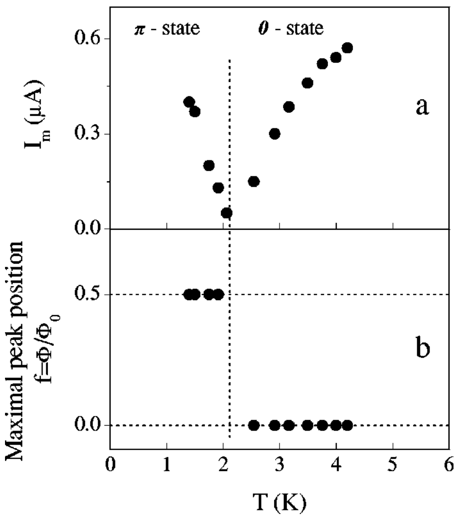

FIG. 3. (a) Temperature dependence of the critical transport current for the structure depicted in Fig. 1 in the absence of applied magnetic field; (b) temperature dependence (jump) of the position of the maximal peak on the curves $I_m(H)$, corresponding to the two limiting temperatures depicted in Fig. 2.

In conclusion, we have proved that at temperatures below the temperature of the transition to the π state, T_π, the self-frustrated state of the triangular array of the SFS junctions is observed at zero external magnetic field. This state is similar to that for a conventional array frustrated by imposing an external half-integer magnetic flux per unit cell. The proposed triangular array based on Josephson SFS junctions is a unique object to study fundamental properties of the systems described by the fully frustrated *XY* spin model with antiferromagnetic interaction.[17]

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