Observation of dc voltage on segments of an inhomogeneous superconducting loop

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In order to verify a possibility of a dc voltage predicted on segments of an inhomogeneous superconducting loop the Little-Parks oscillations are investigated on symmetrical and asymmetric Al loops. The amplitude of the voltage oscillations $\Delta V$ measured on segments of symmetrical loop increases with the measuring current $I_m$ and $\Delta V = 0$ at $I_m = 0$ in accordance with the classical Little-Parks experiment. Whereas the $\Delta V$ measured on segments of asymmetric loop has a maximum value at $I_m = 0$. The observation of the dc voltage at $I_m = 0$ means that one of the loop segments is a dc power source and others is a load. The dc power can be induced by both thermal fluctuation and a external electric noise.

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Recently thought-provoking claims were made about violation of the second law of thermodynamics in the quantum regime [1–3]. These claims were made independently by three research teams from different lands and are concerned to different branches of knowledge such as quantum thermodynamics, biomolecules, superconductivity and others. The publication of such sensation statement has attracted the attention of the scientific press [4] but most scientists still are not buying [5] the theoretical arguments presented in [1–3].

The present work is devoted to the experimental verification of a theoretical result [6] according to which a dc voltage can be observed on segments of an inhomogeneous superconducting loop at $T \approx T_c$ without any external current. The value and sign of this dc voltage depend in a periodic way on a magnetic flux $\Phi$ within the loop $V_{os}(\Phi/\Phi_0)$. The work [6] was provoked by an experimental observation [7] which is not published up to now, however. According to the opinion [8] by one of the authors of the present and [6] works the existence of the dc voltage contradicts to the second law if $V_{os}(\Phi/\Phi_0)$ is induced by the thermal fluctuations in the thermodynamic equilibrium state.

In order to verify the result [6] we used the mesoscopic Al structures, one of them is shown on Fig.1. These microstructures are prepared using an electron lithograph developed on the basis of a JEOL-840A electron scanning microscop. An electron beam of the lithograph was controlled by a PC, equipped with a software package for proximity effect correction "PROXY". The exposition was made at 25 kV and 30 pA. The resist was developed in MIBK: IPA = 1: 5, followed by the thermal deposition of a high-purity Al film 60 nm and lift-off in acetone. The substrates are Si wafers. The measurements are performed in a standard helium-4 cryostat allowing us to vary the temperature down to 1.2 K. The applied magnetic field, which is produced by a superconducting coil, never exceeded 35 Oe. The voltage variations down to 0.05 $\mu$V could be detected.

We have investigated the dependencies of the dc voltage $V$ on the magnetic flux $\Phi \approx BS$ of some round loops with a diameter $2r = 1$, 2 and 4 $\mu$m and a linewidth $w = 0.2$ and 0.4 $\mu$m at the dc measuring current $I_m$ and different temperature closed to $T_c$. Here $B$ is the magnetic induction produced by the coil; $S = \pi r^2$ is the area of the loop. The sheet resistance of the loops was equal approximately 0.5 $\Omega$/ at 4.2 K, the resistance ratio $R(300K)/R(4.2K) \approx 2$ and the midpoint of the superconducting resistive transition $T_c \approx 1.24 K$. All loops exhibited the anomalous features of the resistive dependencies on temperature and magnetic field which was observed on mesoscopic Al structures in some works [8] before. We assume that these features can be connected with big value of the Al superconducting coherence length which can exceed a structure size near $T_c$.

FIG. 1. An electron micrograph one of the aluminum loop structures, samples. $I_1$ and $V_1$ are the current and potential contacts of the symmetrical loop. $I_2$ and $V_2$ are the current and potential contacts of the asymmetric loop. $V_3$ are the additional potential contacts of the asymmetric loop.

According to [6] the dc voltage can observed in a inhomogeneous loop and should not observed in a homogeneous one. In order to investigate the influence of the
heterogeneity of loop segments we made both symmetrical and asymmetric loops in each investigated structure (see Fig.1). Because of the additional potential contacts the higher and lower segments of the lower loop (on Fig.1) can have a different resistance at \( T \simeq T_c \), when the magnetic flux \( \Phi \) contained within a loop is not divisible by the flux quantum \( \Phi_0 = \pi \hbar c / e \), i.e. \( \Phi \neq n \Phi_0 \), whereas the one of the higher loop should have the same resistance if any accidental heterogeneity is absent.

The voltage oscillations measured on the \( V_1 \) contacts Fig.2 and on the \( V_2 \) contacts Fig.3 confirm qualitative difference between the symmetrical and asymmetric loops. In the first case the amplitude \( \Delta V \) of the voltage oscillations increases with the measuring current \( I_m \) and the oscillations are not observed at \( I_m = 0 \). Whereas in the second case the greatest oscillations are observed at \( I_m = 0 \) and the \( \Delta V \) value does not increase with the \( I_m \), Fig.3. Not only the voltage value but also the sign of the voltage are changed with the magnetic field at \( I_m = 0 \), Figs.3,4.

In the present work we consider only the region \( \Phi / \Phi_0 < 7 \) where the dependencies \( V \simeq R_m(\Phi / \Phi_0, T / T_c(I_m))I_m \) Fig.2 corresponds to the classical Little-Parks (LP) experiment \([11]\). The anomalous behaviour, the downfall observed before the disappearance of the oscillation Fig.2, will be considered later. In contrast to the classical LP experiment no resistance but voltage oscillations are observed on the asymmetric loop: \( V \simeq V_{os}(\Phi / \Phi_0) + R_{nos}I_m \) Fig.3. The resistance \( R_{nos} \) depends faintly on \( I_m \) and on the magnetic field at low \( I_m \) Fig.3. At a high \( I_m \) value the negative magnetoresistance \( R_{nos} \) is observed Fig.3. Such anomaly was observed also on other our loops and in other works \([11]\).

According to the universally recognized explanation \([11]\) the LP resistance oscillations are observed \([11]\) because of the fluxoid quantization \([10,12]\). The resistance increase at \( \Phi \neq n \Phi_0 \) is interpreted as a consequence of the \( T_c \) decrease at a non-zero velocity of superconducting pairs \( v_s \neq 0 \): \( \Delta R = -(dR(T-T_c)/dT)\Delta T_c \sim (dR/dT)v_s^2 \) \([11]\). Because of the quantization

\[
\int_I dlv_s = \frac{\hbar}{m}(n - \frac{\Phi}{\Phi_0})
\]

the \( v_s \) circulation can not be equal zero at \( \Phi = BS + LI_s \simeq BS \neq n \Phi_0 \) \([11]\). At zero measuring current the \( v_s \) value is proportional to the superconducting screening current \( v_s \propto I_{sc} = 2en_1s^s = 2e \cdot n_{s^{-1}}^{-1} > 1 \) \((\pi \hbar / ml)(n - \Phi / \Phi_0), < n_{s^{-1}}^{-1} > = \bar{l}^{-1} \int dl n_{s^{-1}}^{-1} \) is used because the superconducting current \( I_s = js \propto 2en_1s^s \) should be constant along the loop in the stationary state. At \( I_m \neq 0 \) and \( < n_{s^{-1}}^{-1} > \neq 0 \) in one of the loop segments \( |v_s| \propto |I_m|/2 + I_{sc} \) and in the other one \( |v_s| \propto |I_m|/2 - I_{sc} \).

![FIG. 2](image1.png)

FIG. 2. The voltage oscillations measured on the \( V_1 \) contacts of the symmetrical loop with \( 2r = 4 \mu m \) and \( w = 0.2 \mu m \) at different \( I_m \) values between the \( I_1 \) contacts: 1 - \( I_m = 0.000 \mu A \); 2 - \( I_m = 1.83 \mu A \); 3 - \( I_m = 2.10 \mu A \); 4 - \( I_m = 2.66 \mu A \); 5 - \( I_m = 3.01 \mu A \). \( T = 1.231K \) is corresponded to the bottom of the resistive transition.

![FIG. 3](image2.png)

FIG. 3. The voltage oscillation measured on the \( V_2 \) contacts of the asymmetric loop with \( 2r = 4 \mu m \) and \( w = 0.4 \mu m \) at different value of the measuring current between the \( I_2 \) contacts: 1 - \( I_m = 0.000 \mu A \); 2 - \( I_m = 0.29 \mu A \); 3 - \( I_m = 0.65 \mu A \); 4 - \( I_m = 0.93 \mu A \); 5 - \( I_m = 1.29 \mu A \); 6 - \( I_m = 1.79 \mu A \); 7 - \( I_m = 2.06 \mu A \); 8 - \( I_m = 2.82 \mu A \); 9 - \( I_m = 3.34 \mu A \); 10 - \( I_m = 3.85 \mu A \). \( T = 1.231K \) is corresponded to the bottom of the resistive transition.

Because \( I_{sc} = 0, R_{hs} \neq 0 \) or/and \( R_{ls} \neq 0 \) at \( < n_{s^{-1}}^{-1} > = 0 \) when any loop segment in the normal state, i.e. the density of superconducting pairs \( n_s = 0 \), and \( R_{hs} = 0, R_{ls} = 0 \) at \( < n_{s^{-1}}^{-1} > \neq 0 \) when the whole loop is in the superconducting state, i.e. \( n_s \neq 0 \) along the whole loop, the LP oscillations are observed only near \( T_c \) where the switching between the states with \( < n_{s^{-1}}^{-1} > \neq 0 \) and \( < n_{s^{-1}}^{-1} > = 0 \) take place and the \( I_{sc}, R_{hs}, R_{ls} \) values change in time. Here \( R_{hs} \) and \( R_{ls} \) are the resistance of the higher and lower segments in
According to (1) the voltage measured at the LP experiment are the average in time values: \( V = \overline{V(t)} = t^{-1}_{\text{long}} \int_{t_{\text{long}}} dt V(t) \); \( R_m \approx (1/R_{hs} + 1/R_{ls})^{-1} = \sum P(R_{hs}, R_{ls})/(1/R_{hs} + 1/R_{ls})^{-1} \). Where \( P(R_{hs}, R_{ls}) \) is the probability of the states with non-zero \( R_{hs} \) and \( R_{ls} \) values.

According to [11] not only the average \( \overline{I}_{sc} = l_{\text{long}} \int_{t_{\text{long}}} dt I_{sc}^{2} \) but also \( s_{sc} = \overline{I}_{sc} = t_{\text{long}} \int_{t_{\text{long}}} dt I_{sc} \approx s_{2n > n_{s} > 1}^{(1)} \pi h/m \) is not equal zero at \( \Phi \neq n \Phi_{0} \) and \( \Phi \neq (n + 0.5) \Phi_{0} \). The theoretical dependence \( \Delta T_{c} \propto - (n - \Phi/\Phi_{0})^{2} \min \), where \( n \) is centered to minimum possible value \( v_{s}^{(n)} \approx (n - \Phi/\Phi_{0})^{2} \) describes well enough the experimental data (see for example Fig.4 in [8]). Therefore \( (n - \Phi/\Phi_{0}) \approx (n - \Phi/\Phi_{0})_{\text{min}} \) when \( \Phi \) is not close to \( n \Phi_{0} \). \( T_{sc} = 0 \) at \( \Phi = (n + 0.5) \Phi_{0} \) because the permitted states with opposite \( v_{s} \) direction have the same \( v_{s} \) value. Thus, the LP experiment is evidence of the persistent screening current \( I_{p,c} = \overline{I}_{sc} \) along the loop at a constant magnetic flux, \( \Phi \neq n \Phi_{0} \) and \( \Phi \neq (n + 0.5) \Phi_{0} \) and \( R_{t} \neq 0 \).

It is enough obvious from the analogy with a conventional loop that the potential difference \( V_{sc} = \overline{V} = \overline{\sum_{l}} \sum_{l} \overline{V} \) of an inhomogeneous loop at \( j_{sc} \) if the average resistivity along the segment \( \overline{\sum_{l}} \sum_{l} j_{sc} \) differs from the one along the loop \( \overline{\sum_{l}} \sum_{l} j_{sc} \). Because the \( T_{sc}(\Phi/\Phi_{0}) \) oscillations take place both in the symmetrical and asymmetrical loops the absence of the voltage oscillations at \( I_{m} = 0 \) on the contacts \( V_{2} \), Fig.2 and the observation on \( V_{3} \), Figs.3,4 mean that \( R_{hs} = R_{ls} \) in the first case and \( R_{hs} \neq R_{ls} \) in the second case. The later can be is because the critical temperature of the higher and lower segments are different: if \( T_{ch}(\Phi) \neq T_{cl}(\Phi) \) then \( R_{hs}(T - T_{ch}) \neq R_{ls}(T - T_{cl}) \) at \( T \approx T_{ch}, T_{cl} \).

Consequently, the voltage oscillations at \( I_{m} = 0 \) Fig.3,4 can be caused by the superconducting screening current, as well as the LP oscillations Fig.2. The comparison of the experimental data for symmetrical and asymmetrical loops confirms this supposition. Our investigations have shown that the voltage oscillations as well as the LP oscillations were observed only in the temperatures corresponded to the resistive transition. Both oscillations have the same period. The magnetic field regions, where they are observed, are also closed.

The oscillations on Fig.2 are observed in more wide magnetic field region than on Figs.3,4 because the width of the wire defining the loop in the first case \( w = 0.2 \mu m \) is smaller than in the second case \( w = 0.4 \mu m \). In any real case only some oscillations are observed because a high magnetic field breaks down the superconductivity, i.e \( I_{sc} \), in the wire defining the loop and the contact grounds. According to (1) \( v_{s} = (\pi h/m)Br/2 \) along the loop and \( v_{s} = (\pi h/jm)Bw/2 \) along the boundaries of the wire at \( n = 0 \). Therefore a limited number of oscillations \( 2r/w \) are observed. The wide contact grounds, with the width \( \approx 2 \mu m \) (see Fig.1), have also an influence on the oscillation number.

According to the analogy with a conventional loop the voltage measured between the \( V_{2} \) contacts \( V_{sc} = 0.5(R_{hs} - R_{ls})I_{sc} \) and consequently the voltage oscillations with the amplitude \( \Delta V \approx 1 \mu V \) observed on Fig.4 can be induced by \( I_{sc} \) oscillations with \( \Delta I_{sc} \geq 0.4 \mu A \) because \( R_{hs}, R_{ls} \leq R_{in}/2 = 5 \Omega \). The screening current \( |I_{sc}| \) inducing the \( R_m \) oscillations Fig.2 can be evaluate from the experimental data if the \( dR_{m}/d|I_{sc}| \) value is known. Although \( |I_{m}/2 + I_{sc}| > |I_{m}/2| \) in one of the segments and \( |I_{m}/2 - I_{sc}| < |I_{m}/2| \) in the other one at \( |I_{m}/2| > |I_{sc}| \) \( dR_{m}/d|I_{sc}| > 0 \) and the LP oscillations are observed at both small and large \( I_{m} \) (see Fig.2 and 3) because \( I_{sc} \), as well \( I_{m} \), decreases the probability of superconducting state \( n_{s}^{-1} \rightarrow -1 \neq 0 \) and consequently increases the \( P(R_{hs} \neq 0, R_{ls} \neq 0) \). If one assumes that the \( dR_{m}/d|I_{m}| \) and \( dR_{m}/d|I_{sc}| \) are closed in order of value then according to the data presented on Fig.2 \( |I_{sc}| \approx 0.4 \mu A \) at \( \Phi = (n + 0.5) \Phi_{0} \).

![FIG. 4. Oscillation of the voltage measured on the V2 contacts (upper curve) and on the V3 contacts (lower curve) of the asymmetrical loop with 2r = 4 \mu m and w = 0.4 \mu m. I_m = 0. T = 1.231K corresponding to the bottom of the resistive transition.](image-url)
the voltage oscillations Fig.4 can be explain by an accidental temperature difference \( V_{os} = S_{th} \Delta T \) only if the thermopower \( S_{th} \) is oscillated and its sign is switched together with the \( \overline{T}_{sc} \). The thermopower oscillations are observed in some Andreev interferometer \([13]\) but its value is very small in order to explain the voltage oscillations observed in our work.

Because the voltage and LP oscillations are observed in the same region it is naturally to explain the observation of the dc power as a direct consequence of the contradiction of the LP experiment with the Ohm’s law \( R_{l} I_{sc} = \int_{s} dE = -(1/c)\Phi/dt \) and other fundamental laws \([14]\).

The existence of \( \Delta T_{sc} \neq 0 \) at \( R_{l} \neq 0 \) and \( d\Phi/dt = 0 \) is explained \([4]\) by the change of the momentum circulation of superconducting pairs from \( \int_{s} d\mu = \int_{0}^{\Phi} dl(2mv_{s} + (2e/c)A) = (2e/c)\Phi \) at \( n = n_{s}^{-1} > 1 \) to \( \int_{0}^{\Phi} dl(n2\pi \hbar) \approx n_{s}^{-1} \neq 0 \) at the closing of superconducting state, when its connectivity changes.

These momentum changes because of the quantization of \( 2n\pi \hbar / (2e/c) = 2n\pi \hbar (n - \Phi/\Phi_{0}) \) takes the place of the Faraday’s voltage \( -(1/c)d\Phi/dt \). The force maintaining the persistent current, as well as the Faraday’s electric field \( -(1/c)d\Phi/dt \), should be uniform along the loop because the momentum change on the unit volume \( \Delta \Phi \propto j_{s} \) \([4]\). This warrants the analogy with a conventional loop used above.

At a enough low frequency, when the switching takes place between the stationary states

\[
V_{os} = \frac{1}{l} \frac{\pi \hbar}{e} (n - \Phi/\Phi_{0}) \omega \tag{2}
\]

on a \( l_{s} \) segment. \( \omega = N_{sw}/t_{long} \) is the average frequency of a switching between the superconducting state with different connectivity; \( N_{sw} \) is the number of switching for \( t_{long} \). The amplitude of the oscillations \( \Delta V_{os} \leq 0.25(\pi \hbar/e)\omega \) at \( l_{s} = 1/2 \). \( \pi \hbar/e = 2.07 \mu V/\text{GHz} \) is equal to the ratio of the voltage and the frequency in the Josephson effect \([4]\). Consequently, according to (2) the oscillations Fig.4 with \( \Delta V \approx 1 \mu V \) can be observed if \( \omega \geq 2 \text{ GHz} \).

The \( \Delta V_{os} \) increases more slowly with the frequency than (2) if \( \omega > 1/\tau_{rel} \). Where \( \tau_{rel} \) is any relaxation time in stationary states, which can be equal the relaxation time of superconducting fluctuations \( \tau_{f} \) or the decay time of the screening current \( \tau_{R} \). \( 1/\tau_{R} \approx 2 \text{ GHz} \) in order of value because \( \tau_{f} = \pi \hbar / 8k_{B}(T - T_{c}) \) in the linear approximation region above \( T_{c} \) \([4]\) and the width of the critical region of our loops \( \Delta T_{c, l} \approx 0.02K \). \( 1/\tau_{R} \approx (2e^{2}/m)n_{s}\rho_{n} \approx e\mu_{n}/\mu_{v} \approx 10 \text{ GHz} \) in order of value. Here the value \( \mu_{v} = \mu_{s}/m \approx 30 \text{ m/s} \) for \( n - \Phi/\Phi_{0} = 0.5 \) and the \( \rho_{n} \) value of Al were used. Consequently, the voltage oscillations observed in our work Fig.3,4 can be induced by a switching between the superconducting state with different connectivity.

This switching can be induced by both the thermal fluctuations and an external electric noise. A high-frequency noise with \( I_{noise} \geq j_{sc} = (c^{2}sk_{B}T/2\pi\lambda^{2}\xi)^{1/2} \) increases the probability \( P_{sw} \) of the switching in the normal state. \( P_{sw} \approx \exp(-sl_{sw}/k_{B}T) \) at \( l_{s} \geq \xi \), where \( l_{sw} = (2\pi/c)^{2}\lambda^{2}\xi^{2} \) is the energy density of the transition in the normal state \([4]\). \( \xi \) is the superconducting coherence length; \( \lambda \) is the London penetration depth. For the loops used in our work \( (c^{2}sk_{B}T/2\pi\lambda^{2}\xi)^{1/2} \approx (\Delta T_{c,l}/T_{c})^{1/4} \cdot 10^{-5} A \approx 0.5 \mu A \). We can not guarantee that \( I_{noise} \ll 0.5 \mu A \). Moreover we observed an influence of an external electric noise on the \( V_{os} \) value. Therefore we can not state that the voltage oscillations observed in our work at \( I_{m} = 0 \) are induced in the equilibrium state although the power \( W = V_{os}I_{sc} \approx 2 \cdot 10^{-7} \text{ Wt} \) does not exceed the limit value \( k_{B}T/h \approx 10^{-12} \) \([4]\) which can be induced by the thermal fluctuations.

In conclusion, we have observed voltage oscillations measured on segments of an inhomogeneous loop at zero external direct current in the same region where the Little-Parks oscillations are observed. This voltage can be induced by both thermal fluctuation and an external electric noise.

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\[1\] A.E.Allahverdyan and Th.M.Nieuwenhuizen, Phys.Rev.Lett. 85, 1799 (2000); cond-mat/0011389
\[2\] V.Capek and J.Bok, Czech. J. of Phys. 49, 1645 (1999); Physica A 290, 374 (2001); V.Capek, cond-mat /0012056
\[3\] A.V.Nikulov, physics/9912022; Abstracts of XXII International Conference on Low Temperature Physics, Helsinki, Finland, p.498 (1999); in Supermaterials, Eds. R.Cloots et al. Kluwer Academic Publishers, 2000, p.183
\[4\] P.F.Schewe and B.Stein, on http://www.aip.org/enews/physnews2000/split/pnu491-I.htm
\[5\] P. Weiss, Science News 158, 234 (2000).
\[6\] A.V. Nikulov and I.N. Zhilyaev, J. Low Temp.Phys. 112, 227-236 (1998).
\[7\] I.N. Zhilyaev, private communication (unpublished).
\[8\] H.Vlueberghs et al., Phys. Rev. Lett. 69,1268 (1992).
\[9\] P.Santhanam, C.P.Umbach, and C.C.Chi, Phys. Rev. B 40, 11392 (1989); P.Santhanam et al. Phys. Rev. Lett. 66, 2254 (1991).
\[10\] W.A.Little and R.D.Parks, Phys. Rev. Lett. 9, 9 (1962).
\[11\] M.Tinkham, Introduction to Superconductivity. McGraw-Hill Book Company (1975).
\[12\] M.Tinkham, Phys. Rev. 129, 2413 (1963).
\[13\] J.Eom, C.J. Chien, and V.Chandrasekhar, Phys. Rev. Lett. 81, 437 (1998).
\[14\] A.V. Nikulov, Phys.Rev.B, July 2001; physics/0104073
\[15\] A.Barone and G.Paterno, Physics and Application of the Josephson Effect. A Wiley-Interscience Publication, John Wiley and Sons, New York, 1982