ISSN1027-5495. Functional Materials, 32, No.3 (2025), p. 367-371
doi:http://dx.doi.org/10.15407/fm32.03.367 © 2025 — STC "Institute for Single Crystals"

Resistive investigations of pressure effect on the fluctuations paraconductivity in $Y_{0.66}Pr_{0.34}Ba_2Cu_3O_{7-\delta}$ single crystals

V.Yu. Gres, M.V. Korobkov, G.Ya. Khadzhai, R.V. Vovk

V.N. Karazin Kharkiv National University, 61022,
Svoboda Sq. 4, Kharkiv, Ukraine

Received July 30, 2025

The effect of high hydrostatic pressure on the fluctuation paraconductivity, $\Delta\sigma(T)$, of the $Y_{0.66}Pr_{0.34}Ba_2Cu_3O_{7-\delta}$ single crystals has been studied. For all applied pressures, the experimental curves $\rho(T)$ contain linear sections at temperatures $T > T^*$. At temperatures $T < T^*$, the $\rho(T)$ curves deviate downwards from their linear extrapolation, i.e., excess conductivity $\Delta\sigma(T)$ occurs in the studied samples. It is shown that the high hydrostatic pressure leads to the significant expansion of the temperature interval for the existence of excess conductivity, thereby narrowing the region of the $\rho(T)$ linear dependence in the *ab*-plane in the normal state. The fluctuation conductivity is considered within the Lorentz-Doniach model. It was found that at pressures up to 9.7 kbar the value of the transverse coherence length $\xi c(0)$ decreases from 5.47 to 5.06 Å, simultaneously with an increase in T_c. Accordingly, the 2D-3D crossover temperature shifts toward higher values. This behavior is qualitatively different from similar baric dependences of $\xi c(0)$, obtained both for pure YBaCuO samples of optimal composition and for single crystals lightly doped with praseodymium. Possible mechanisms of the influence of high pressure on the critical temperature and coherence length are discussed within framework of a model that assumes the presence of singularities in the charge carriers electron spectrum typical for lattices with strong coupling.

Keywords: fluctuation conductivity; doping; $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals; coherence length; 2D-3D crossover.

Резистивні дослідження впливу тиску на флуктуаційну парапровідність у монокристалах $Y_{0.66}Pr_{0.34}Ba_2Cu_3O_{7-\delta}$. *В.Ю. Гресь, М.В. Коробков, Г.Я. Хаджай, Р.В. Вовк*

Досліджено вплив високого гідростатичного тиску на флуктуаційну парапровідність $\Delta\sigma(T)$ монокристалів $Y_{0.66}Pr_{0.34}Ba_2Cu_3O_{7-\delta}$. Для всіх прикладених тисків експериментальні криві $\rho(T)$ містять лінійні ділянки при температурах **$T > T^*$. При температурах $T < T^*$ криві** $\rho(T)$ відхиляються вниз від своєї лінійної екстраполяції, тобто у досліджуваних зразках виникає надлишкова провідність $\Delta\sigma(T)$. Показано, що високий гідростатичний тиск приводить до значного розширення температурного інтервалу існування надлишкової провідності, тим самим звужуючи область лінійної залежності $\rho(T)$ в *ab*-площині в нормальному стані. Флуктуаційна провідність розглядається в рамках моделі Лоренца-Доніаха. Встановлено, що при тисках до 9,7 кбар значення поперечної довжини когерентності $\xi_c(0)$ зменшується з 5,47 до 5,06 Å зі збільшенням T_c та зміщується по температурі точка 2D-3D кросовера, що якісно відрізняється від аналогічних баричних залежностей $\xi_c(0)$, отриманих як для чистих зразків YBaCuO оптимального складу, так і для монокристалів, слабо легованих празеодимом. Можливі механізми впливу високого тиску на критичну температуру та довжину когерентності обговорюються в рамках моделі, що припускає наявність сингулярностей в електронному спектрі носіїв заряду, типових для ґраток із сильним зв'язком.

1. Introduction

The question of the influence of dimensionality on the formation of the superconducting (SC) subsystem in layered SC compounds still remains open, despite the long-term efforts of experimental and theoretical groups [1,2]. As is known, HTSC compounds are characterized by the presence of a wide temperature region of excess conductivity [1-3], which near the transition temperature to the SC state ($T_c \leq T \leq 1.1T_c$) is caused by the processes of fluctuation pairing of current carriers [1,4-6]. Depending on the morphology of the defect ensemble and the degree of remoteness from T_c, these processes are well described by the theoretical models of Aslamazov-Larkin [4], Maki-Thompson [5] and Lawrence-Doniah [6], which assume the presence of one or more dimensional crossovers in the system.

The application of high pressure to samples of various types of HTSC compounds, including the large family of $RBa_2Cu_3O_{7-\delta}$ (R = Y or lanthanides), in the overwhelming majority of cases leads to a significant increase in T_c, a change in the width and shape of the superconducting transition and the overall three-dimensionalization of the system [2,7,8], which in turn has a significant impact on the formation of the mode of occurrence of superconducting fluctuations in the system. Of particular interest for research in this aspect are compounds of the $Y_xPr_{1-x}Ba_2Cu_3O_{7-\delta}$ type [9,10], which is due to several reasons at once. Firstly, partial or complete replacement of yttrium with praseodymium causes the appearance of the so-called "praseodymium anomaly" - suppression of the conductive characteristics and a decrease in the value of the critical parameters of this superconductor [10]. Secondly, in stoichiometric oxygen content $Y_xPr_{1-x}Ba_2Cu_3O_{7-\delta}$ systems, a nonequilibrium state caused by the presence of labile oxygen practically does not arise; this state can easily be caused by the application of high pressure [8,11,12], a sharp change in temperature [13,14], and also occurs as a result of aging [15,16]. And thirdly, unlike most other $RBa_2Cu_3O_{7-\delta}$ (R= Y or lanthanides) compounds, in which a positive value of the pressure derivative is observed, $dT_c/dP > 0$, in $Y_xPr_{1-x}Ba_2Cu_3O_{7-\delta}$ compounds, cases of negative values of the pressure derivative $dT_c/dP < 0$ have been recorded [10].

At the same time, there is a very small number of works devoted to the study of excess conductivity in $Y_xPr_{1-x}Ba_2Cu_3O_{7-\delta}$ systems. As a rule, studies were carried out on ceramic, textured or film samples of very different technological backgrounds with a significant content of intergranular and interboundary bonds and the corresponding specificity of the defect structure [10,17-19]. In our previous works [20-21] the effect of excess conductivity of $Y_xPr_{1-x}Ba_2Cu_3O_{7-\delta}$ single crystals with a relatively low praseodymium content $x \leq 0.23$ was investigated. In our previous work [22] we considered the effect of high pressure on excess conductivity caused by the manifestation of the pseudogap state at temperatures far from critical ($T \gg T_c$). This paper presents the results of studies of the influence of high hydrostatic pressure up to 9.7 kbar on the fluctuation paraconductivity of highly perfect $Y_xPr_{1-x}Ba_2Cu_3O_{7-\delta}$ ($x \approx 0.34$) single crystals at temperatures near critical ($T \geq T_c$). At such Pr concentrations, a change in the sign of dT_c/dP was previously recorded [10] for polycrystalline samples.

2. Experimental

$Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals were grown using the solution-melt technology [14, 22]. The initial components for growing the crystals were Y_2O_3, $BaCO_3$, CuO and Pr_5O_{11} compounds in the appropriate proportions. The growth and oxygen saturation modes of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ crystals were the same as for undoped single crystals [2, 8]. The electrical resistivity in the *ab* plane was measured using the standard four-contact technique. The contacts were created by applying silver paste to the crystal surface, followed by attaching silver conductors with a diameter of 0.05 mm and annealing the sample for three hours at a temperature of 200°C in an oxygen atmosphere. This procedure made it possible to obtain a contact resistance of less than 1 Ohm and measure resistance at transport currents in the *ab* plane up to 10 mA. Hydrostatic pressure was created in a piston-type multiplier [8]. The pressure value was determined using a manganin manometer, and the temperature was determined using a copper-constantan thermocouple installed on the outer surface of the chamber at the level of the sample.

3. Results and Discussion

The temperature dependences of the electrical resistivity $\rho(T)$ in the *ab* plane of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystal are shown in Fig. 1.

As the applied pressure increases, the electrical resistivity of the samples decreases and the critical temperature increases, which is consis-

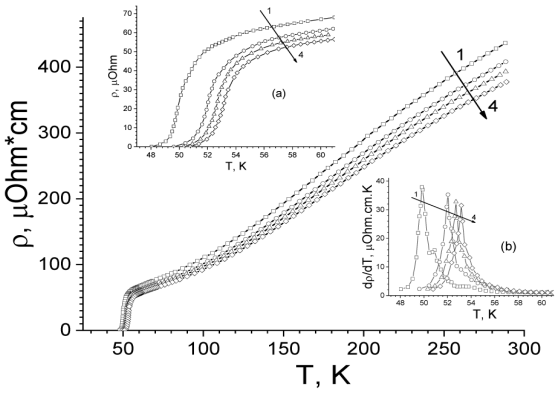

Fig. 1. Temperature dependences of electrical resistivity $\rho(T)$ in the basal plane of the $\rho(T)$ of the $Y_{0.66}Pr_{0.34}Ba_2Cu_3O_{7-\delta}$ single crystal measured at pressures of 0; 3.72; 6.53; 9.7 kbar – curves *1–4*, respectively. Insert (a): baric dependences of *Tc* (squares) and ρ(300 K) (circles) of this single crystal. Insert (b): temperature dependence of excess conductivity $\Delta\sigma(T)$ of this single crystal at atmospheric pressure.

tent with previous studies [7, 8, 10, 23]. The derivatives dTc/dP decrease almost linearly from about 6 to 1.4 K/GPa, and the value $d\ln\rho$(300 K)/dP increase almost linearly from approximately –0.174 to –0.128 $(GPa)^{-1}$ when the pressure changes from $P = 0$ to $P = 0.97$ GPa.

At the same time, it should be noted that all the $\rho(T)$ dependences have a section with a characteristic thermal activation deflection. As follows from Fig. 1, when the sample temperature decreases below T^*, the $\rho(T)$ graph deviates downwards from the linear dependence, which indicates the appearance of excess conductivity, $\Delta\sigma(T)$. The temperature dependence of the excess conductivity is usually approximated by the equation:

$$\Delta\sigma = \sigma - \sigma_0 \qquad (1)$$

where $\sigma_0 = \rho_0^{-1} = (A+BT)^{-1}$ is the normal state conductivity determined by extrapolating the linear section to the low temperature region, and $\sigma = \rho^{-1}$ is the experimental value of the conductivity at low temperatures.

It is known that the excess conductivity near T_c is probably due to the processes of fluctuation pairing of current carriers and can be described by the power-law dependence obtained in the theoretical Lorenz-Doniach model [6], which assumes the presence of a very smooth crossover from the two-dimensional to the three-dimensional regime of fluctuation conductivity when the temperature of the sample decreases:

$$\Delta\sigma = \left[\frac{e^2}{16\hbar d}\right]\varepsilon^{-1}\left\{1 + J\varepsilon^{-1}\right\}^{-1/2}, \qquad (2)$$

where $\varepsilon=(T-T^{mf}_c)/T^{mf}_c$ is the reduced temperature; T^{mf}_c is the critical temperature in the mean field approximation; $J=(2\xi_c(0)/d)^2$ is the interplane pairing constant; ξ_c is the coherence length along the *c* axis and *d* is the thickness of the two-dimensional layer. In extreme situations (either near T_c, at $\xi_c >> d$, when the interaction between fluctuating Cooper pairs is realized in the entire volume of the superconductor (3D mode), or away from T_c, at $\xi_c << d$, when the interaction is possible only in the planes of the conductive layers (2D mode)), formula (2) is transformed into the known relations for three- and two-dimensional cases from the Aslamazov-Larkin theory [4]:

$$\Delta\sigma_{2D} = \frac{e^2}{16\hbar d}\varepsilon^{-1}, \qquad (3)$$

$$\Delta\sigma_{3D} = \frac{e^2}{32\hbar\xi_c(0)}\varepsilon^{-1/2}, \qquad (4)$$

When comparing with experimental data, it is important to accurately determine the value T^{mf}_c, which significantly affects the slope of the dependencies $\Delta\sigma(\varepsilon)$. Usually, when comparing with experimental $\xi_c(0)$ data, the values of *d* and T_c in equations (2-4) are fitting parameters [24]. However, when using this method, as a rule, significant quantitative discrepancies between theory and experiment are observed. In this case, a scaling coefficient, the so-called C-factor, is used as an additional fitting parameter. It allows combining experimental data with calculated data and, thus, taking into account the possible non-uniformity of the distribution of the transport current for each specific sample. In our case, T^{mf}_c was taken as T_c, determined, as noted above, by the maximum point on the $d\rho_{ab}/dT(T)$ dependences in the region of the superconducting transition, as proposed in [7] and shown in the insert (*b*) to Fig. 1.

Fig. 2 shows the temperature dependences $\Delta\sigma(T)$ in $\ln\Delta\sigma(ln\varepsilon)$ coordinates. It is evident that near T_c these dependences are satisfactorily approximated by straight lines with a slope angle of $\alpha_1 \approx -0.5$, corresponding to the exponent –1/2 in equation (4), which indicates the three-dimensional nature of fluctuation superconductivity in this temperature range. With further increase in temperature, $\Delta\sigma$ decreases faster ($\alpha_2 \approx -1$), which, may indicate a change in the dimensionality of fluctuation conductivity. As follows from (3) and (4), at the 2D-3D crossover point:

$$\varepsilon_0 = 4\left[\xi_c(0)/d\right]^2. \qquad (5)$$

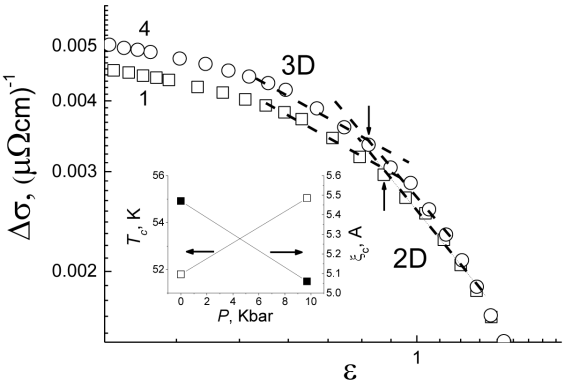

Fig. 2. Temperature dependencies $\Delta\sigma(T)$ in $\log\Delta\sigma$–$\log\varepsilon$ coordinates at different pressures. The numbering corresponds to Fig. 1. The insert shows the baric dependencies $T_c(P)$ and $\xi_c(P)$. The dots on the inset correspond to the curves on the main panel.

In this case, having determined the value of ε_0 and using the literature data on the dependence of T_c and the interplanar distance on δ [25, 26], it is possible to calculate the values $\xi_c(0)$. As can be seen from the insert to Fig. 2, the value $\xi_c(0)$, calculated according to (5), decreases from 5,47 to 5,06 Å as T_c increases, which is qualitatively different from similar baric dependences $\xi_c(0)$ obtained both for pure YBaCuO samples of optimal composition [27] and for single crystals lightly doped with praseodymium [23].

As established in [27,28], the value of $\xi_c(0)$ obtained for optimally oxygen-doped crystals changes slightly with pressure. At the same time, for single crystals lightly doped with praseodymium [23], the value of $\xi_c(0)$ increases by approximately 15% with increasing the applied pressure from 0 to 17 kbar. In our case, there is a clear correlation between the baric dependencies $\xi_c(P)$ and $T_c(P)$ when high pressure is applied (see insert to Fig. 2). Both values change almost symmetrically – as $T_c(P)$ increases, the value of $\xi_c(P)$ decreases and vice versa, which may indicate the same nature of the change in these characteristics. The change in T_c under pressure can be caused by a change in the electron-phonon interaction constant and the concentration of current carriers. The latter, in turn, implies a change in the density of states at the Fermi level $N(E_F)$: an increase in pressure leads to an increase in $N(E_F)$, and a decrease – leads to a decrease in $N(E_F)$.

As we have already noted in [20], the relatively weak influence of pressure on the values of T_c and ξ_c for optimally doped samples can be explained within the framework of a model that assumes the presence of a Van Hove singularity in the spectrum of charge carriers [29,30], characteristic of lattices with strong coupling. As is known, for crystals with $T_c \approx 90$K, the Fermi level lies in the valley between two peaks of the density of states, while the density of states at the Fermi level $N(E_F)$ depends significantly on the ratio $(a\text{-}b)/a$ [29,30]. Increasing the ratio $(a\text{-}b)/a$ leads to an increase in the distance between the peaks of the density of states and, accordingly, to a decrease in $N(E_F)$ and T_c. A decrease in the ratio $(a\text{-}b)/a$ leads to a convergence of the peaks of the density of states, which leads to an increase in $N(E_F)$ and T_c. This pattern of change in T_c was observed when studying the effect of uniaxial compression along ***a*** and ***b*** axes on the critical temperature of single crystals with $T_c \approx 90$K [31]: when applying a load along the ***a***-axis, the critical temperature increased, and when applying a load along the ***b***-axis, it decreased. When exposed to hydrostatic pressure, the ratio $(a\text{-}b)/a$ changes insignificantly, since it is determined only by the difference in the compression moduli along the ***a***- and ***b***-axes. Therefore, the change in critical temperature under the action of hydrostatic pressure is relatively small.

For crystals with reduced $T_c < 70$K the Fermi level can be shifted from the middle of the band (including due to doping with substitution elements [32]) and is located far from the peak of the density of states. Therefore, if the critical temperature is primarily determined by the density of electron states, then the shift of the Fermi level towards the peak of the density of states under the action of hydrostatic pressure can lead to a more significant increase in the absolute value dT_c/dP and $\xi_c(0)$. However, verification of the validity of this assumption requires additional studies of the effect of all-round compression on the critical temperature of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ compounds, including in a wider range of praseodymium concentrations. It should be taken into account that a certain role here can be played by specific mechanisms of quasiparticle scattering [33-35], caused by the presence of kinematic and structural anisotropy in the system.

4. Conclusions

The results of the study allow us to draw the following main conclusions. Firstly, the application of external pressure to $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ ($x \approx 0.34$) single crystals causes a significant expansion of the interval of the linear dependence $\Delta^*_{ab}(T)$ and a narrowing of the temperature region of the pseudogap regime. The pressure-induced evolution of the fluctuation conductivity

in lightly Pr-doped $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals is likely determined by two processes: the general "three-dimensionalization" of the system, due to the evolution of the ξ_c and d ratio and the shift of the Fermi level with respect to the features in the density of states caused by Pr doping. Until now, in contrast to YBCO samples without impurities and with a low Pr content, the application of high pressure leads to a substantial increase in the pressure derivatives dT_c/dP and $d\xi_c/dP$.

References

1. T.A. Friedman, J.P. Rice, J. Giapintzakis, and D.M. Ginzberg, *Phys. Rev.* ***B*** **39**, 4258 (1989),
2. R.V. Vovk, A.L Solovyov, Low Temp. Phys. **44**, 81 (2018)
3. R.V. Vovk, M. A. Obolenskii, A. A. Zavgorodniy, I. L. Goulatis, A. Chroneos, E.V. Biletskiy, J. Alloys Compd. **485,** 121 (2009)
4. L.G. Aslamazov and A.I. Larkin, Phys. Lett. 26A, 238 (1968)
5. J.B. Bieri, K. Maki and R.S. Thompson, *Phys. Rev. B* 44, 4709 (1991)
6. W.E. Lawrence and S. Doniach, Proceedings of the Twelfth International Conference on Low Temperature Physics, edited by E.Kanda, Academic Press of Japan, Kyoto, p.361 (1971).
7. L. Mendonca Ferreira, P. Pureur, H.A. Borges, and P. Lejay, *Phys. Rev. B 69*, 212505 (2004)
8. D.D. Balla, A.V. Bondarenko, R.V. Vovk, M.A. Obolenskii, A.A. Prodan, *Low Temp. Phys.* 23, 777 (1997)
9. A.I. Chroneos, I.L. Goulatis and R.V. Vovk, Acta Chim. Slov. **54**, 179 (2007)
10. M. Akhavan, Physica B **321**, 265 (2002)
11. H.A. Borges and M.A. Continentino, Solid State Commun. **80**, 197 (1991)
12. R. V. Vovk, Z. F. Nazyrov, M. A. Obolenskii, I. L. Goulatis, A. Chroneos, and V.M. Pinto Simoes, Philos. Mag. **91**, 2291 (2011)
13. M.A.Obolenskii, A.V.Bondarenko, R.V.Vovk, A.A.Prodan., Low Temp. Phys. 23(11), 882 (1997).
14. A. L. Solovjov, E. V. Petrenko, L. V. Omelchenko, R.V. Vovk, I. L. Goulatis and A. Chroneos, *Sci Rep* 9: 9274 (2019)
15. B. Martinez, F. Sandiumenge, S. Pinol, N. Vilalta, J. Fontcuberta, X. Obradors, Applied Physics Letters 66 (6), 772 – 774 (1995)
16. R.V. Vovk, N.R. Vovk, G.Ya. Khadzhai, Oleksandr V. Dobrovolskiy, Z.F. Nazyrov // J Mater Sci : Mater Electron (2014) 25: 5226-5230
17. W.H. Li et al., PRB 60, 4212(1999)
18. H.B. Radousky, J. Mater. Res. **7**, 1917-1955 (1992)
19. F. A. Boyko, G. V. Bukin, V. A. Voloshin, and A. A. Gusev, Low Temp. Phys. 28, 95 (2002).
20. R.V. Vovk, N.R. Vovk, G.Ya. Khadzhai, Oleksandr V. Dobrovolskiy, Z.F. Nazyrov, Current Applied Physics 14, 1779-1782 (2014)
21. Chroneos, A., Khadzhai, G.Y., Goulatis, I.L., A. V. Mazepulin, Korobkov, M.V., Vovk, R.V., Journal of Materials Science: Materials in Electronics 33(13), 9875–9884 (2022)
22. G.Ya. Khadzhai, I. Goulatis, A. Chroneos, V.M.P. Simoes and R.V. Vovk, Funct. Mater., 32, 2, 190 (2025)
23. A.L. Solovjov, L.V. Omelchenko, E.V. Petrenko, R.V. Vovk, V.V Khotkevych, and A. Chroneos, *Sci Rep* **9,** 20424 (2019)
24. A.L. Solovjov, L.V. Omelchenko, R.V. Vovk, O.V. Dobrovolskiy, S.N. Kamchatnaya, D.M. Sergeyev, Curr. Appl Phys. **16**, 931 (2016)
25. G. D. Chryssikos, E. I. Kamitsos, J. A. Kapoutsis, A. P. Patsis, V. Psycharis, A. Koufoudakis, C. Mitros, G. Kallias, E. Gamari-Seale and D. Niarchos, *Physica C* **254,** 44 (1995)
26. R.V. Vovk, M.A. Obolenskii, Z.F. Nazyrov, I.L. Goulatis, A. Chroneos, and V.M. Pinto Simoes, J. Mater Sci.: Mater. Electron. 23, 1255 (2012).
27. R.V.Vovk, M.A.Obolenskii, A.A.Zavgorodniy, A.V.Bondarenko, I.L.Goulatis, A.V.Samoilov, A.I.Chroneos, J. Alloys and Compounds 453, 69-74 (2008).
28. R.V. Vovk, N.R. Vovk, G.Ya. Khadzhai, I.L. Goulatis, A. Chroneos, *Physica B 422,* 33-35 (2013).
29. V.M. Gvozdicov, *Physica C,* 235-240, 2127 (1994).
30. A.Perali and G.Varelogiannis, *Phys. Rev. B 61*, 3672 (2000).
31. U.Welp, M.Grimsditch, S.Flesher, W.Nessler, J.Downey, G.W.Crabtree, and J.Guimpel, Phys. Rev. Lett. 69, 2130 (1992)
32. U. Schwingensclogl, C. Schuster, Appl. Phys. Lett.100, 253111 (2012).
33. A.V.Bondarenko, A.A.Prodan, M.A.Obolenskii, R.V.Vovk, T.R.Arouri., Low Temperature Physics **27**, N5, 339 (2001).
34. A.V.Bondarenko, V.A.Shklovskij, R.V.Vovk, M.A.Obolenskii, and A.A.Prodan, Low Temp. Phys., 23(12), 962 (1997).
35. R. V. Vovk, C. D. H. Williams, and A. F. G. Wyatt, Phys. Rev. Lett. 91, 235302 (2003).
36. R. V. Vovk, C. D. H. Williams, and A. F. G. Wyatt, Phys. Rev. B 68, 134508 (2003).
37. D.H.S. Smith et al., *Phys. Rev. B 72(5)*, 054506 (2005).