Effects of La substitution on superconducting state of CeCoIn$_5$

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We report effects of La substitution on superconducting state of heavy fermion superconductor CeCoIn$_5$, as seen in transport and magnetization measurements. As opposed to the case of conventional superconductors, pair breaking by nonmagnetic La results in depression of $T_c$, and indicates strong gap anisotropy. Upper critical field $H_{c2}$ values decrease with increased La concentration, but the critical field anisotropy, $\gamma = H_{c2}^{\perp}/H_{c2}^{\parallel}$, does not change in the Ce$_{1-x}$La$_x$CoIn$_5$ ($x=0-0.15$). The electronic system is in the clean limit for all values of $x$.

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I. INTRODUCTION

Heavy fermion superconductors have been extending for more than two decades the affluence of physical phenomena associated with Cooper pair formation. The competition between magnetism and superconductivity for the same Fermi surface of heavily renormalized carriers resulted in observations of unconventional superconductivity and raised speculations that spin pairing might be mediated by magnetic interaction. Research in the field was associated with difficulties in sample preparation, sample to sample variation, experimental conditions and ultimately, in the number of examples where relevant physical phenomena can be observed in a clean form. The recently discovered CeMIn$_5$ family (M=Ir, Rh, Co) of heavy fermion superconductors encapsulates many aspects of important physics in this class of materials. CeRhIn$_5$ superconductors under applied pressures above 17 kbar with $T_c$ around 2 K whereas CeIrIn$_5$ and CeCoIn$_5$ are ambient pressure superconductors. CeCoIn$_5$ offers clean example of ambient pressure heavy fermion superconductivity with a remarkably high $T_c=2.3$ K. The intriguing properties of CeCoIn$_5$ led to speculation that it may exhibit d-wave superconductivity and Fulde-Ferrel-Larkin-Ovchinnikov state in high magnetic fields. In order to have more insight into the nature of CeCoIn$_5$ we perturbed its superconducting state by substituting La onto the Ce site. For the purpose of comparing influences of magnetic and nonmagnetic pair breaking on $T_c$ suppression, we also substituted 5% of Nd on Ce site. We find that the anisotropy in the upper critical field does not change in the whole concentration range and that the decrease of $T_c$ with increased La doping cannot be explained solely with pressure effects due to unit cell expansion. In addition, our results present an evidence for an anisotropic order parameter in CeCoIn$_5$.

II. EXPERIMENT

Single crystals of Ce$_{1-x}$La$_x$CoIn$_5$ were grown by the self flux method in a manner previously described. Crystals grew as thin plates with the c axis perpendicular to the plate. Removal of In from the surface was performed by etching in concentrated HCl for several hours followed by thorough rinsing in ethanol. All samples obtained with this process showed no signs of In contamination. Powder X-ray patterns showed that samples crystallized in HoCoGa$_5$ structure without any additional peaks introduced by La alloying. In addition, magnetization measurements provided a more sensitive test of possible presence of magnetically ordered second phases. Both as grown and etched samples showed no sign of antiferromagnetic transition of CeIn$_3$. Electrical contacts were made with EpoTek-H20E silver epoxy. In-plane resistivity was measured in Quantum Design MPMS and PPMS measurement systems from 0.35 to 300 K and in fields up to 90 kOe applied parallel and perpendicular to the c-axis. There is uncertainty in nominal resistivity values associated with sample geometry and uneven surfaces of etched samples. We measured several samples for each concentration in order to reduce measurement error which allowed us to estimate uncertainties in nominal values as well. The dimensions of the samples were measured by high precision optical microscope with 10\(\mu\)m resolution and average values are presented. Randomly chosen samples within each batch had no difference in their $R(T)$ curves. Magnetization measurements were performed in MPMS-7 Quantum Design magnetometer in the magnetic field of 10kG, applied parallel and perpendicular to c axis.

III. RESULTS

The results of powder X-ray diffraction measurement taken at room temperature are summarized in Table 1 and shown in Fig. 1, together with the unit cell volume of LaCoIn$_5$. As expected, La doped samples have larger unit cell volume. The volume increase in the concentration range $x = 0 - 0.175$ is consistent with expansion of the unit cell as La substitutes Ce in accordance with Vegard’s law.

Fig. 2 shows the magnetic susceptibility for Ce$_{0.95}$Nd$_{0.05}$CoIn$_5$, Ce$_{0.85}$La$_{0.15}$CoIn$_5$, and CeCoIn$_5$, respectively.
taken in the applied field of 10kOe. In the whole temperature range above $T_c$, the substitution of magnetic Ce$^{3+}$ by nonmagnetic La$^{3+}$ reduces susceptibility values in La doped sample when compared with undoped CeCoIn$_5$. Comparison of high temperature moments through Curie-Weiss analysis of the polycrystalline susceptibility average at high temperatures shows that approximately 14% Ce ions were substituted with La. No quantitative difference from undoped CeCoIn$_5$ was detected in high temperature susceptibility of 5% Nd doped sample. Low temperature magnetic susceptibility of Ce$_{0.85}$La$_{0.15}$CoIn$_5$ does not reveal any difference in Curie tail from pure material, thus ruling out Kondo-hole interpretation of La dilution (Fig. 2 inset). We also see broadening of the plateau-like feature in $\chi_c$ in Ce$_{0.85}$La$_{0.15}$CoIn$_5$ ascribed to thermal depopulation of Ce 4f levels. On the other hand, Nd impurities contribute to pronounced Curie tail at low temperatures. Subtraction of magnetic susceptibility of CeCoIn$_5$ from Ce$_{0.95}$Nd$_{0.05}$CoIn$_5$ in the normal state below 10K is consistent with approximately 8% of Nd$^{3+}$ paramagnetic moment, result close to nominal stoechiometric value and within rough approximation of our analysis.

Temperature dependent electrical resistivities normalized to their value at 300 K for Ce$_{1-x}$La$_x$CoIn$_5$ and Ce$_{0.95}$Nd$_{0.05}$CoIn$_5$ are presented in Fig. 3a. There are several key features to notice. Resistivities of all samples are weakly temperature dependant at high temperatures, and they pass through a maximum as temperature is decreased. This behavior is traditionally interpreted as a crossover from incoherent Kondo scattering to coherent Bloch states of heavy electrons in the Kondo lattice. In the case of CeCoIn$_5$ this drop, at least partially, could be attributed to depopulation of crystalline electric field levels. We observe decrease of $T_{max}$ for higher La concentrations (Fig. 3a inset). At low temperatures, there is a clear suppression of $T_c$ as more Ce ions are replaced by La (Fig. 3 inset). The increase of the normal state residual resistivity $\rho_0$ is probably due to disorder which contributes to increased conduction electron scattering. On the other hand, the resistive transition width sharpens with La alloying. It is interesting to note that Ce$_{1-x}$La$_x$CoIn$_5$ is not in the well defined Fermi liquid regime above $T_c$: the $\rho(T)$ curves above $T_c$ do not show signs of $T^2$ dependence, as it has been reported for CeCu$_2$Si$_2$. Depression of $T_c$ in CeCoIn$_5$ seems to scale with $\rho_0$ values for both magnetic and non-magnetic dopants, as seen by comparison of the $\rho(T)$ data of Ce$_{0.95}$Nd$_{0.05}$CoIn$_5$ and Ce$_{0.95}$La$_{0.02}$CoIn$_5$.

Fig. 4 shows the anisotropic upper critical field for Ce$_{1-x}$La$_x$CoIn$_5$, normalized to transition temperature in zero field for each value of $x$ (values for $x=0$ were taken from previous report). The $H_{c2}$ data were determined as a midpoint between onset and zero in resistivity from $\rho(T)$ curves at constant field and $\rho(H)$ curves at constant temperature. Adding La impurities results in depression of $H_{c2}$, however, anisotropy $\gamma = H_{c2}^a/H_{c2}^\perp$ remains at the same value of $\gamma \approx 2$ (inset in Fig. 4). Uncertainty in our estimate of $\gamma$ decreases for higher field data, away from H=0 transition ($T/T_c \approx 1$).

Assuming that Fermi surface properties of doped material do not change substantially in the dilute La limit it is reasonable to assume inverse proportionality between $\rho$ and $l$, and therefore values of $l_0$ could be estimated from $\rho_0$ for the whole doping series ($l_0 = \frac{l}{\rho_0}$) using the the value of constant A from reported $l_0$ and $\rho_0$ values for pure material. We obtain $l_0 \approx 540 A$ for CeCoIn$_5$ without La impurities. Fig. 5 shows the ratio of the mean free path $l_0$ to in-plane superconducting coherence length $\xi (\xi^2(T) = \Phi_0 / 2\pi H_{c2}(T))$ for Ce$_{1-x}$La$_x$CoIn$_5$ obtained at $T=T_c/2$. In the whole doping range electronic system is in the clean limit which could explain nearly constant value of $\gamma = H_{c2}^a/H_{c2}^\perp$.

A comparison of the effects of La substitution on $T_c$
FIG. 3: (a) Electrical resistivity $\rho$ normalized to its value at 300 K vs. temperature for Ce$_{1-x}$La$_x$CoIn$_5$ for $x = 0, 0.1$ and $0.175$. $T_{\text{max}}$ is shifted to lower temperatures with increased La substitution (inset) (b) Low temperature resistivity shows depression of $T_c$ and increase in $\rho_0$.

FIG. 4: Anisotropy in the upper critical field $H_{c2}$ for Ce$_{1-x}$La$_x$CoIn$_5$ ($x = 0-0.15$). Inset shows value of $\gamma = H_{c2}^\parallel/H_{c2}^\perp$ vs. $T_c/T_c(H=0)$ for various La concentrations: $x=0.02$ (circles), $x=0.05$ (up triangles), $x=0.075$ (down triangles), $x=0.15$ (diamonds).

FIG. 5: Ratio of mean free path ($l$) to coherence length ($\xi$) for Ce$_{1-x}$La$_x$CoIn$_5$. Electronic system is in the clean limit already at $T=T_c/2$ for La concentrations $x = 0-0.15$

FIG. 6: Comparison of La doping on $T_c$ of CeCoIn$_5$ (this work) and CeCu$_{2.2}$Si$_2$ (ref. 18). Inset shows increase in $\rho_0$ of Ce$_{1-x}$La$_x$CoIn$_5$ caused by La substitution.

in CeCoIn$_5$ and CeCu$_{2.2}$Si$_2$ is shown on Fig. 6. Doping results in depression of $T_c$ in both cases but CeCoIn$_5$ is more robust to pair breaking arising from La impurities. The initial rate of $T_c$ suppression is smaller than the rate seen in CeCu$_{2.2}$Si$_2$: [(0.056T$_c$)/(1% of La substitution) in CeCoIn$_5$ vs (0.085T$_c$)/(1% of La substitution in CeCu$_{2.2}$Si$_2$)]. La doping in CeCoIn$_5$ is associated with only modest increase in nominal residual resistivity values $\rho_0$, shown in Fig. 6 inset. The $\rho_0$ values for $x = 0$ ($\sim 5\mu\Omega\text{cm}$) in our experiment are in between values reported previously in literature (3.1$\mu\Omega\text{cm}$ [4] and $\sim 7\mu\Omega\text{cm}$ [5]).
IV. DISCUSSION AND CONCLUSIONS

The slope of $H_c^2$ vs $T$ curve at $T_c$ can be used to estimate zero temperature orbital critical field $H_{c2c}(0)$ using the weak - coupling formula for conventional superconductors in Werthamer-Helfand-Hohenberg model (WHH): $H_{c2c}(0) \approx 0.7(H')^2 T_c$.

Table 1 shows estimates of $H'_{c2}$ near $T_c$ for doped samples, together with previously reported value for $x = 0$ for both crystalline directions. All investigated samples have high initial slopes, as expected in the case of heavy fermion superconductors. Values of $H_{c2c}(0)$ decrease with introduction of La impurities (Table 1). The paramagnetic limiting field $H_p(0) = \Delta_0/\mu_B \sqrt{\gamma}$ (where $\Delta_0$ is energy gap at $T=0$ and $\mu_B$ is Bohr magneton) for pure CeCoIn$_5$ ($T_c=2.3$K) is well below the orbital critical field $H_{c2c}(0)$ for either s-wave $(\Delta_0 = 2.52k_B T_c)$ or d-wave pairing state $(\Delta_0 = 2.14k_B T_c)$ and our results indicate that this unusual situation is valid for investigated La doping range. We note that experimental values of upper critical field for Ce$_{1-x}$La$_x$CoIn$_5$ ($x=0.15$) are most likely below the values obtained by applying WHH model (Table 1), probably due to polarization of magnetic sublattice due to enhanced internal field along both crystalline axes.

It has recently been reported that $T_c$ in CeCoIn$_5$ increases under applied pressure. Negative chemical pressure should cause some decrease in $T_c$. In the lack of better approximation, we take bulk modulus of CeCoIn$_5$ to be the same as the one for CeIn$_5$ (650kbar) and we calculate approximate chemical pressure ($P_{\text{chemical}}$) for each La concentration using $\frac{\Delta \rho}{\rho} \approx 650$ kbar. The results are shown in Table 1. Depression of $T_c$ occurs at a rate $\frac{dT_c}{dP} \approx 0.43$ K/kbar - a slope that is an order of magnitude larger than reported increase of $T_c$ under hydrostatic pressure. An order of magnitude difference from pure pressure effect on $T_c$ is likely to exceed error in estimation of bulk modulus, and therefore points to the conclusion that the pair breaking mechanisms which enter through disorder due to La alloying and increased scattering of Cooper pairs are dominant in CeCoIn$_5$. In contrast to conventional superconductors where magnetic impurities have small effect on $T_c$, Cooper pairs formed in CeCoIn$_5$ are rather sensitive to La doping: 2% of La depresses $T_c$ to the same value as ~5% of Nd.

The $T_c$ suppression induced by the nonmagnetic La substitution in Ce$_{1-x}$La$_x$CoIn$_5$ is reminiscent of the pair breaking effect by magnetic impurities. Although various factors may suppress $T_c$ (an anisotropic scattering, for example) we focus here on the scenario of CeCoIn$_5$ having an anisotropic gap $\Delta(x\vec{k})$ on the Fermi surface. This scenario is quite likely given the unconventional nature in many heavy-fermion materials.

It is known [2] that if $\Delta$ depends on the position at the Fermi surface, the critical temperature is suppressed by nonmagnetic scattering according to:

$$ln \frac{T_{c_\alpha}}{T_c} = \alpha \left[ \psi \left( \frac{1 + \mu}{2} \right) - \psi \left( \frac{1}{2} \right) \right], \mu = \frac{\hbar}{2\pi T_c}$$

Here $T_{c_\alpha}$ is the critical temperature of the material in the absence of all scattering, $\tau$ is the scattering time by nonmagnetic impurities, and $\alpha = 1 - \langle \Delta \rangle^2 / \langle \Delta^2 \rangle$ characterizes the gap anisotropy, $\langle \Delta \rangle$ stands for averaging over Fermi surface, and $\psi$ is the digamma function. For a weak gap anisotropy, this result is due to Hohenberg, see also later publications. It can be shown that in fact Eq. (1) holds for an arbitrary gap anisotropy. For isotropic $\Delta$, $\alpha = 0$, and we come to Anderson’s theorem: $T_c=T_{c_\alpha}$. For pure d-wave order parameter, $\langle \Delta \rangle = 0$, and Eq. (1) describes the d-pair breaking by nonmagnetic scattering (which differs from the Abrikosov-Gor’kov result only by the factor of 2 in the definition of the parameter $\mu_m = \hbar/\pi T_c \tau_m$).

To analyze the $T_c(x)$ data shown in Fig. 6, one has to relate $x$ to the scattering time $\tau$, a nontrivial connection. We avoid this difficulty by assuming that the residual resistivity $\rho_0$ is proportional to $1/\tau$. Further, we exclude parameter $T_{c_\alpha}$ from Eq. (1) by writing it for two values of $x$ and subtracting the results:

$$ln \frac{T_{c_1}}{T_{c_2}} = \alpha \left[ \psi \left( \frac{1 + \mu_1}{2} \right) - \psi \left( \frac{1 + \mu_2}{2} \right) \right], \mu_{1,2} = \beta \frac{T_{1,2}}{T_{1,2}} \frac{\rho_1}{\rho_2}$$

$$\frac{T_{c_1}}{T_{c_2}} = \alpha \left[ \psi \left( \frac{1 + \mu_1}{2} \right) - \psi \left( \frac{1 + \mu_2}{2} \right) \right], \mu_{1,2} = \beta \frac{T_{1,2}}{T_{1,2}} \frac{\rho_1}{\rho_2}$$

where $T_{1,2} = T_c(x_{1,2})$ and $\beta$ is a constant to be determined. Writing this equation for two different pairs $x_{1,2}$ one can determine the unknown $\alpha$ and $\beta$. This procedure yields values scattered around $\alpha = 0.5$ and $\beta = 0.2K/\mu$cm.

Hence, we find $\alpha = \langle \Delta \rangle^2 / \langle \Delta^2 \rangle \approx 0.5$ which implies a strongly anisotropic gap. Knowing the value of $\beta$ we can estimate the scattering time using measured resistivities: for $x = 0$ we obtain $\tau = \hbar/2\pi k_B \beta \rho \approx 10^{-12}$s. With the electronic specific heat coefficient $\gamma = 290mJ/moleK^2$ we roughly estimate the Fermi velocity $v_F = \frac{2e\rho_0}{\sqrt{\gamma}} \approx 2 \times 10^6$cm/s. This would correspond to the mean-free path $l \approx 260\AA$, a value smaller than expected but within factor of two of our determination of mean free path which is reasonable given the assumptions of average Fermi velocity and isotropic scattering.

In summary, diamagnetic pair breaking effect in CeCoIn$_5$ is consistent with picture of strongly anisotropic order parameter. Anisotropy in the upper critical field $\gamma = H_{c2}/H_{c2}'$ does not change for $x = (0-0.15)$ in Ce$_{1-x}$La$_x$CoIn$_5$, indicating electronic system in the clean limit.

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TABLE I: Properties of Ce$_{1-x}$La$_x$CoIn$_5$ doping series: $T_c$, lattice parameters, unit cell volumes, $H_{c2}$ $(T)$, calculated $H_{c2o}(0)$ from WHH model and approximate chemical pressure $P_{chemical}$ due to La alloying. Final row: properties of Ce$_{0.95}$Nd$_{0.05}$CoIn$_5$.

| $x$  | $T_c$(K) | $a$(Å)±(0.007Å) | $c$(Å)±(0.007Å) | $V$(Å$^3$) | $-\frac{dH_{c2}}{dT}$(kOe/K) | $H_{c2o}(0)$(kOe) | $P_{chemical}$(kbar) |
|------|----------|-----------------|-----------------|----------|--------------------------|----------------|------------------|
| 0    | 2.3      | 4.613           | 7.542           | 160.49±0.4 | 240(a),110±6(c)           | 370(a), 170(c) | 0               |
| 0.02 | 2.0      | 4.613           | 7.551           | 160.65±0.53| 170±23(a),86±3(c)         | 235(a), 119(c) | 0.6             |
| 0.05 | 1.68     | 4.614           | 7.551           | 160.76±0.2 | 190±19(a),95±7(c)         | 214(a), 107(c) | 1.1             |
| 0.075| 1.31     | 4.615           | 7.551           | 160.86±0.23| 207±27(a),98±2(c)         | 188(a), 89(c)  | 1.5             |
| 0.1  | 1.22     | 4.615           | 7.557           | 160.97±0.35| 2                     | 2              | 3.1             |
| 0.125| 0.86     | 4.623           | 7.546           | 161.27±0.1 | 3.1                     |                |                 |
| 0.15 | 0.78     | 4.619           | 7.563           | 161.35±0.4 | 236±27(a),103±2(c)        | 127(a), 55(c)  | 3.5             |
| 0.175| -        | 4.619           | 7.567           | 161.48±0.1 | 3                   |                | 3.5             |
| 1.0  | -        | 4.638           | 7.612           | 163.74±0.1 | 3                   |                |                 |
| 0.05(Nd)| 2.0     | 4.601           | 7.546           | 160.37±0.3 | 3                   |                | 3.1             |

1 Z. Fisk, J.L. Sarrao, J.L. Smith and J.D. Thompson Proc. Natl. Acad.Sci. USA 92, 6663 (1995)
2 G. Bruls, D. Weber, B. Wolf, P. Thalmeir, B. Luthi, A. de Visser, A. Menovsky, Phys. Rev. Lett. 65, 2294 (1990)
3 B.S. Shivaram, J.J. Gannon, D. G. Hinks, Phys. Rev. Lett. 63, 1723 (1989)
4 K. Miyake, S. Schmitt-Rink and C. M. Varma, Phys. Rev B 34, 6554 (1986)
5 H. Hegger, C. Petrovic, E. G. Moshopolou, M. F. Hundley, J. L. Sarrao, Z. Fisk and J. D. Thompson, Phys. Rev. Lett. 84, 4986 (2000)
6 C. Petrovic, R. Movshovich, M. Jaime, P. G. Pagliuso, M. F. Hundley, J. L. Sarrao, Z. Fisk and J. D. Thompson, Europhys. Lett. 53, 354 (2001)
7 C. Petrovic, P. G. Pagliuso, M. F. Hundley, R. Movshovich, J. L. Sarrao, J. D. Thompson, Z. Fisk and P. Monthoux, J. Phys. Condens. Matter 13, L337 (2001)
8 Y. Kohori, Y. Yamato, Y. Iwamoto, T. Kohara, E. D. Bauer, M. B. Maple, J. L. Sarrao, Phys. Rev. B 64, 134526 (2001)
9 N. J. Curro, B. Simovic, P. C. Hammel, P. G. Pagliuso, J. L. Sarrao, J. D. Thompson and G. B. Martins, Phys. Rev. B 64, 180514 (2001)
10 K. Izawa, H. Yamaguchi, Y. Matsuda, H. Shishido, R. Settai and Y. Onuki, Phys. Rev. Lett. 87, 057002 (2001)
11 T. P. Murphy, Donovan Hall, E. C. Palm, S. W. Tozer, C. Petrovic, Z. Fisk, R. G. Goodrich, P. G. Pagliuso, J. L. Sarrao, and J. D. Thompson, Phys. Rev. B 65, 100514(R) (2002)
12 J. M. Lawrence, T. Graf, M. F. Hundley, D. Mandrus, J. D. Thompson, A. Lacerda, M. S. Torikachvili, J. L. Sarrao and Z. Fisk, Phys. Rev B 53, 12559 (1996)
13 I. Sheikin, D. Braithwaite, J-P. Brison, W. Assmus and J. Floquet, J. Low Temp. Phys. 118, 113 (2000)
14 T. Muramatsu, N. Tateiwa, T. Kobayashi, K. Shimizu, K. Amaya, D. Aoki, H. Shishido, Y. Haga and Y. Onuki, J. Phys. Soc. Jpn. 70, 3362 (2001)
15 C.S. Jee, B. Andraka, J.S. Kim and G.R. Stewart, Phys. Rev B 43, 2656 (1991)
16 R. Movshovich, M. Jaime, J. D. Thompson, C. Petrovic, Z. Fisk, P. Pagliuso and J. L. Sarrao, Phys. Rev. Lett. 86, 5152 (2001)
17 U. Ahlheim, M. Winkelmann, P. van Aken, C. D. Bredl, F. Steglich and G.R. Stewart, J. Magn. Magn. Matter 76&77, 520 (1988)
18 M. Nicklais, R. Borth, E. Lengyel, P. G. Pagliuso, J. L. Sarrao, V. A. Sidorov, G. Sparrn, F. Steglich and J. D. Thompson, J. Phys. Condens. Matter 13, L905 (2001)
19 N. R. Werthamer, E. Helfand and P. C. Hohenberg, Phys. Rev 147, 295 (1966)
20 S. Ikeda, H. Shishido, M. Nakashima, R. Settai, D. Aoki, Y. Haga, H. Harima, Y. Aoki, T. Namiki, H. Sato and Y. Onuki, J. Phys. Soc. Jpn. 70, 2248 (2001)
21 T. P. Orlando, E. J. McNiff, S. Foner and M. R. Beasley, Phys. Rev B 19, 4545 (1979)
22 U. Rauchschwalbe, W. Lieke, C. D. Bredl, F. Steglich, J. Aarts, K. M. Martini and A. C. Mota, Phys. Rev. Lett 49, 1448 (1982)
23 A. M. Clogston, Phys. Rev. Lett. 9, 261 (1962)
24 M. J. Graf, S-K, Yip, J.A. Sauls and D. Rainer, Phys. Rev. B 53, 15147 (1996)
25 G. Oomi, T. Kagayama and J. Sakurai, J. Mater. Process. Technol. 85, 220 (1999)
26 A. A. Abrikosov and L. P. Gorkov, Soviet Physics JETP 12, 1243 (1961)
27 J. Schmalian, private communication
28 P. Hohenberg, Zh. Exp. Theor. Phys. 4, 1208 (1963)
29 D. Markowitz and L. P. Kadanoff, Phys. Rev. 131, 563 (1963)
30 A. I. Posazhennikova and M. B. Sadovski, JETP Lett. 63, 347 (1963)
31 V. G. Kogan, unpublished