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Superconductivity and magnetism/Supraconductivité et magnétisme

Interplay between magnetism and superconductivity in URhGe

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Abstract

The magnetization rotation transition occurs in the itinerant ferromagnet URhGe when the field about 12 Tesla is applied in direction perpendicular to spontaneous magnetization in the plane of the smallest magnetic anisotropy energy. The transition is accompanied by the maximum of resistivity in the normal state and by re-entrance of superconductivity at lower temperatures in the field interval between 8 and 13 Tesla [F. Lévy et al., Science 309 (2005) 1343].

We discuss the magnetization orientation transition and the modification of triplet pairing superconducting state coexisting with ferromagnetism up to the fields about 2 Tesla and then reappearing in the broad vicinity of the transition.

The nonsymmorphic space group crystal symmetry of ferromagnetic URhGe allows the existence of antiferromagnetic ordering of magnetic moments of pairs of uranium atoms along the a-axis. We show that the amplitude of this weak antiferromagnetic ordering increases below the phase transition into superconducting state due to Cooper pairs spontaneous magnetism. ***To cite this article: V.P. Mineev, C. R. Physique 7 (2006).***

Résumé

Interaction entre le magnétisme et la supraconductivité dans URhGe. Une transition de phase métamagnétique se produit dans le composé ferromagnétique itinérant URhGe lorsqu'un champ magnétique approximativement égal à 12 Tesla est appliqué le long de l'axe de faible anisotropie, dans le plan perpendiculaire à la direction de l'aimantation spontanée. Cette transition s'accompagne d'un maximum de la résistivité dans l'état normal et, à basse température, un état supraconducteur réentrant apparaît sous un champ magnétique compris entre 8 et 12 Tesla [F. Lévy et al., Science 309 (2005) 1343].

Nous discutons la transition de rotation de l'aimantation, ainsi que les différentes symétries de la phase supraconductrice qui coexiste avec l'état ferromagnétique jusqu'à 2 Tesla, puis réapparaît sous des champs proches de la transition metamagnétique.

Le groupe de symétrie cristalline de URhGe est non symorphique. Un ordre antiferromagnétique avec les moments magnétiques des paires des atomes d'Uranium orientés le long de la direction a est donc possible. L'amplitude du paramètre d'ordre antiferromagnétique faible augmente au dessus de la transition dans l'état supraconducteur grâce au magnétisme spontané des paires de Cooper. ***Pour citer cet article : V.P. Mineev, C. R. Physique 7 (2006).***

Keywords: Unconventional superconductivity; Ferromagnetism

Mots-clés : Supraconductivité non conventionnelle ; Ferromagnétisme

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1. Introduction

The new class of superconducting materials UGe_2 [1], URhGe [2], and UIr [3] has been revealed recently where the superconducting state coexists with an itinerant ferromagnetic ordered state. The large band splitting and the high low temperature value of upper critical field [4,5] in uranium ferromagnetic superconductors indicate that here we deal with Cooper pairing in the triplet state which earlier has been attributed, with evidence, only to superfluid phases of liquid Helium-3 [6]. The discovery has brought into the open the intriguing possibility of unconventional mechanism of pairing or magnetically mediated superconductivity which is now under intensive investigation (see for instance [7] and references therein). At the same time, essential progress was achieved in a general phenomenological description of triplet superconducting states in ferromagnetic metals [8–10].

The superconductivity of itinerant ferromagnets presents the particular example of multiband superconductivity [11,12]. Another manifestation has been recently found in a conventional two band superconductor MgB_2 [13]. The multiband effects can also be important in superconductors without inversion center—another hot point of up-to-date condensed matter physics (see [12] and references therein).

The coming to light of superconductivity in any new material gives rise to the problem of the determination of the type of the superconducting state. In particular it is always important to know:

(i) what kind of superconductivity, conventional or nonconventional, we are dealing with (this means: is the symmetry of the order parameter lower than the symmetry of the crystal in the normal state or it is not [14]?);
(ii) is it a singlet or triplet type of Cooper pairing;
(iii) are there nodes in the superconducting quasiparticle spectrum, and, if yes, what kind of the nodes are we dealing with—symmetry nodes or occasional nodes;
(iv) is the superconducting state magnetic or not—in other words, does it possess a spontaneous magnetic moment or it does not?

In the present article, we discuss the magnetic properties of the ferromagnetic superconductor URhGe: first, we look at the quite recently discovered [15] metamagnetic transition at the magnetic field at about 12 Tesla directed perpendicular to the spontaneous magnetization accompanied by the maximum of resistivity in the normal state and by re-entrance of superconductivity at lower temperatures in the broad vicinity of this transition between 8 and 13 Tesla. We shall follow up the modifications of the superconducting state in ferromagnetic URhGe under a magnetic field perpendicular to the spontaneous magnetization and argue that the re-entrance of the superconductivity under the magnetic field is compatible with triplet Cooper pairing in this material.

Secondly, we shall describe the interplay between the nonunitary triplet superconductivity and the weak antiferromagnetism allowed by symmetry in this ferromagnet. The effect of the stimulation of weak antiferromagnetism by the Cooper pairs' magnetic moment will be demonstrated. The latter reveals the new possibility of direct experimental determination of spontaneous magnetism in the URhGe superconducting state.

The plan of the article is as follows. In the next section we will describe the metamagnetic transition. Then, the overview of the triplet superconducting states in orthorhombic ferromagnets will be given, followed by the description of modifications acquired by superconducting state under magnetic field. In the last section we present the symmetry analysis of the interplay between the ferromagnetism, antiferromagnetism and superconductivity in URhGe.

2. Magnetic orientation transition

URhGe has the orthorhombic crystal symmetry with ferromagnetic moment directed in the direction of c crystallography axis. The experimental observations of field dependence of magnetization along different crystallographic directions [16], as well as numerical calculations of magnetic anisotropy energy [17], yield the c-axis to be the easy magnetization axis and the a-axis the hard magnetization axis. The magnetic anisotropy energy in the a–c plane is more than the four times larger than in the b–c plane meaning that URhGe is the b–c easy magnetization plane ferromagnet. Following [17] one can write the b–c plane anisotropy energy as

$$E_{\rm anis}(\theta, H) = \alpha \sin^2\theta + (\beta/4)\sin^2 2\theta - MH\sin\theta \tag{1}$$

where θ is the angle between c-axis and total magnetization in b–c plane, magnetic field H directed along b-axis. The anisotropy energy may be considered as a part of the total Landau energy of ferromagnet in magnetic field

$$F = \alpha_z(T)M_z^2 + \alpha_y M_y^2 + \beta_z M_z^4 + \beta_y M_y^4 + 2\beta_{yz} M_z^2 M_y^2 - M_y H \tag{2}$$

Here y, z are the directions of the spin axes pinned to (b, c) crystallographic directions, respectively. At the temperatures below the Curie temperature $\alpha_z(T) < 0$, and in the absence of magnetic field, the z-component of magnetization has a finite value. The magnetic field creates the magnetization along its direction but decreases the magnetization parallel to c. This process is finished at some value of the field, then the M_z drops to zero, and the M_y component equilibrium value is also abruptly changed. In other words, the field induces the first order type transition between the states with magnetization projections (M_{y0}, M_{z0}) and $(\widetilde{M}_{y0},\ 0)$. To prove this statement one must investigate the evolution of minima of the free energy depending on two projections of magnetization. This is a slightly cumbersome problem. Instead, assuming $|\mathbf{M}| = const$ we have a much easier investigation of anisotropy energy (1) depending on just one angular variable.

The anisotropy energy at $H = 0$ has two minima: absolute at $\theta_1 = 0$ and metastable at $\theta_2 = \pi/2$, and one maximum in between them given by $\sin^2\theta_m = (\alpha+\beta)/2\beta$ that is $\theta_m \approx 60^\circ$ if we take the numerical values of coefficients $\alpha+\beta \approx 4.4$ meV and $\beta = 2.9$ meV found in [17]. The values of the anisotropy energy at both minima decrease with increasing field, but the metastable minimum $E_{\rm anis}(\pi/2, H)$ drops faster and at some field becomes lower. Still, at this point between the two minima, there is the maximum: it is easy to check by direct calculation that $\partial^2 E_{\rm anis}(\theta, H)/\partial\theta^2|_{\theta=\pi/2}$ is positive at an arbitrary magnetic field and the values of α- and β-parameters pointed out above. Hence we have the first order type transition from the state with finite M_z component of magnetization to the state there this component is absent.

The crystal symmetry is changed with magnetic field increasing. First, at zero field the magnetic symmetry group of the orthorhombic crystal with magnetization oriented along c-axis is

$$D_2(C_2^z) = (E, C_2^z, KC_2^x, KC_2^y) \tag{3}$$

where K is the time reversal operation. Then, at intermediate fields, the magnetization has both M_b and M_c components, and the crystal symmetry is decreased to monoclinic

$$C_2^x = (E, KC_2^x) \tag{4}$$

Finally, after the first order type transition, the orthorhombic symmetry is recreated but with magnetization directed along b-direction

$$D_2(C_2^y) = (E, KC_2^z, KC_2^x, C_2^y) \tag{5}$$

3. Superconducting states in the orthorhombic ferromagnet with triplet pairing

The symmetry description of all possible superconducting states in orthorhombic ferromagnets was given in [9, 11,12]. We recall briefly here the main points of this description. In an itinerant ferromagnetic metal the internal exchange field lifts the Kramers degeneracy of the electronic states. The electrons with spin 'up' fill the states in some bands and the electrons with spin 'down' occupy the states in other bands. Hence we have the specific example of a multiband metal with states in each band filled by electrons with only one spin direction. Let us discuss for simplicity the two-band ferromagnet. If there is some pairing interaction, one can discuss intraband or spin 'up' – spin 'up' (spin 'down' – spin 'down') pairing of electrons, as well as interband or spin 'up' – spin 'down' pairing. In general, the Fermi surfaces of spin up and spin down bands are situated in different places of the reciprocal space and have different shapes. That is why pairing of electrons from the different bands occurs only in the case of nesting of some pieces of the corresponding Fermi surfaces. In such the situation, similar to SDW or CDW ordering, the superconducting ordering is formed by Cooper pairs condensate with finite momentum known as the Fulde–Ferrel–Larkin–Ovchinnikov state. We shall not discuss this special possibility here. So, we neglect of pairing of electrons from different bands giving Cooper pairs with zero spin projection. Hence, the only superconducting state should be considered it is the state with triplet pairing and the order parameter given by

$$\mathbf{d}^{\Gamma}(\mathbf{R}, \mathbf{k}) = \frac{1}{2}\big[-(\hat{x} + \mathrm{i}\hat{y})\Delta_{\uparrow}(\mathbf{R}, \mathbf{k}) + (\hat{x} - \mathrm{i}\hat{y})\Delta_{\downarrow}(\mathbf{R}, \mathbf{k})\big] \tag{6}$$

Superconducting states $\mathbf{d}^{\Gamma}(\mathbf{R},\mathbf{k})$ with different critical temperatures in the ferromagnetic crystals are classified in accordance with irreducible co-representations Γ of the magnetic group M of crystal [8,9]. All the co-representations in ferromagnets with orthorhombic symmetry are one-dimensional. However, they obey multicomponent order parameters determined through the coordinate dependent pairing amplitudes: one for each band populated by electrons with spins 'up' or 'down'. For the two-band ferromagnet under discussion, they are

$$\Delta_{\uparrow}(\mathbf{R},\mathbf{k}) = -\eta_1(\mathbf{R})f_{-}(\mathbf{k}), \qquad \Delta_{\downarrow}(\mathbf{R},\mathbf{k}) = \eta_2(\mathbf{R})f_{+}(\mathbf{k}) \tag{7}$$

The coordinate dependent complex order parameter amplitudes $\eta_1(\mathbf{R})$ and $\eta_2(\mathbf{R})$ are not completely independent:

$$\eta_1(\mathbf{R}) = \big|\eta_1(\mathbf{R})\big|e^{i\varphi(\mathbf{R})}, \qquad \eta_2(\mathbf{R}) = \pm\big|\eta_2(\mathbf{R})\big|e^{i\varphi(\mathbf{R})} \tag{8}$$

Being different by their modulus they have the same phase with an accuracy $\pm\pi$. The latter property is due to the consistency of transformation of both parts of the order parameter under the time reversal.

The general forms of odd functions of momentum directions of pairing particles on the Fermi surface $f_{\pm}(\mathbf{k}) = f_x(\mathbf{k}) \pm i f_y(\mathbf{k})$ for the different superconducting states in ferromagnets can be found following the procedure introduced in [9]. We shall not repeat it here but just write the order parameter corresponding to 'conventional' superconductivity in an orthorhombic ferromagnet with magnetic moment oriented along $\hat{c}$-direction. The symmetry group of such a crystal is given by Eq. (3). The 'conventional' superconducting state obeys the same symmetry (3) as the normal state and only the gauge symmetry is broken. The general form of the order parameter $\mathbf{d}(\mathbf{R},\mathbf{k})$ given by Eqs. (6) and (7), compatible with symmetry (3) being obtained by the following choice of the functions $f_{\pm}(\mathbf{k})$:

$$f_{\pm}(\mathbf{k}) = k_x(u_1 \mp u_4) + ik_y(u_2 \pm u_3) \tag{9}$$

where $u_1, \ldots$ are real functions of k_x^2, k_y^2, k_z^2. From the expression for the order parameter one can conclude that the only *symmetry dictated nodes in quasiparticle spectrum* of conventional superconducting states in orthorhombic ferromagnets are the nodes lying on the northern and southern poles of the Fermi surface $k_x = k_y = 0$. Along with superconducting state given by Eq. (9) there is another equivalent superconducting state transforming as $i\mathbf{d}^*(\mathbf{R},\mathbf{k})$. One can prove [9] that these two states coexist in the same ferromagnetic crystal but in domains with the opposite direction of magnetization.

All the superconducting states in the orthorhombic ferromagnets and in particular the conventional superconducting state are non-unitary and obey the *Cooper pair spin momentum*

$$\mathbf{S} = i\langle \mathbf{d}^* \times \mathbf{d}\rangle = \frac{\hat{z}}{2}\big\langle |\Delta_{\uparrow}|^2 - |\Delta_{\downarrow}|^2\big\rangle \tag{10}$$

and *Cooper pair angular momentum*

$$\mathbf{L} = i\left\langle \mathbf{d}_{\alpha}^*\left(\mathbf{k}\times\frac{\partial}{\partial\mathbf{k}}\right)\mathbf{d}_{\alpha}\right\rangle = \frac{i}{2}\left\langle \Delta_{\uparrow}^*\left(\mathbf{k}\times\frac{\partial}{\partial\mathbf{k}}\right)\Delta_{\uparrow} + \Delta_{\downarrow}^*\left(\mathbf{k}\times\frac{\partial}{\partial\mathbf{k}}\right)\Delta_{\downarrow}\right\rangle \tag{11}$$

where the angular brackets denote the averaging over $\mathbf{k}$ directions. As the consequence, the magnetic moment of ferromagnet changes at the transition to the ferromagnetic superconducting state [12]. We shall denote this change as $\mathbf{M}_s$.

Certainly, below the phase transition of a ferromagnet to the superconducting state its magnetic moment is screened by the London supercurrents flowing around the surface of the specimen [14]. In the case of UGe_2 and URhGe this screening is, however, incomplete, just because the size of ferromagnetic domains [18] and the London penetration depth [2] have the same order of magnitude $\sim 10^{-4}$ cm. It is known [19,14] that even in the absence of the external field, the Abrikosov vortices penetrate into the bulk ferromagnet if the spontaneous ferromagnetic moment exceeds the lower critical field $M_0 > H_{c1}$. In presence of domain structure this criteria is modified [20] as follows: $M_0 > H_{c1}(\lambda/w)^{2/3}$; here λ is the London penetration depth and w is the domain wall thickness. To operate with measurable values one can rewrite this inequality as

$$M_0 > \left(\frac{\xi_0}{w\kappa^2}\right)^{2/3} H_{c2} \tag{12}$$

Here $H_{c2} \approx 2T$ is the upper critical field, $\xi_0 \approx 2\times 10^{-6}$ cm is the coherence length, $\kappa = 50$–100 is the Ginzburg–Landau parameter. The value of spontaneous magnetization $4\pi M_0$ in URhGe is [5] of the order of 500 G. Taking the domain wall width as $w = 10^{-7}$–10^{-6} cm we see that just the opposite inequality takes place. Hence, in the absence of the external field, the domain structure in URhGe is vortex free.

4. Field induced superconductivity

As we already mentioned, the magnetization orientation transition is accompanied at low temperatures [15] (below 0.4 K) by the reappearance of superconductivity. The phenomenon of magnetic field induced superconductivity has been known more than two decades. First it was discovered in pseudoternary molybdenum halcogenides $Eu_xSn_{1-x}Mo_6S_8$ [21]. The orbital critical field in this material is likely to be sufficiently high due to large impurity scattering. Hence, the critical field value is mostly controlled by a paramagnetic limiting mechanism. Moreover, the formation of an antiferromagnetic state below 1 K ($T_c = 4$ K) completely suppresses superconductivity. However, in fields above 4 Tesla, the superconducting state reappears. The common belief is that it is due to the Jaccarino–Peter effect [22] consisting of compensation of the external applied field by the internal exchange field of magnetic ions with magnetic moments oriented by high external field. A similar phenomenon has been observed in the two-dimensional organic superconductor $\lambda - (BETS)_2\,FeCl_4$ [23,24]. The very high orbital field value is maintained here by the field orientation parallel to conducting layers. Again due to the Jaccarino–Peter mechanism, the high field re-entrance of superconductivity occurs.

A quite different situation happens in URhGe. First of all, even in the low field region, the superconducting state exists up to about 2 Tesla [5]. That is about 4 times larger than the paramagnetic limiting field. This means that we are dealing with triplet superconductivity and the critical field entirely determined by the orbital mechanism. Here we always tell about the field orientation parallel to the b-axis that is perpendicular equilibrium direction of magnetization. Then, after suppression, superconductivity reappears at a field about 8 Tesla and persists until about 13 Tesla [15].

The analysis made in the paper [5] shows that among the superconducting states (6)–(9) the best fit for the upper critical field temperature behavior gives a one-band superconducting state with the order parameter

$$\mathbf{d}(\mathbf{R}, \mathbf{k}) = (\hat{x} + \mathrm{i}\hat{y})k_x\eta(\mathbf{R}) \tag{13}$$

As was described above, under the field influence the magnetization rotates in the b–c plane from the c-direction until it suddenly proves to be oriented parallel to the b-axis at the field value ≈ 12 Tesla. We already pointed out that during the process of magnetization rotation, the crystal symmetry is changed from (3) to (5). The order parameter form (13) is compatible with all these symmetry transformations if we choose the $\hat{y}$-axis lying in the plane perpendicular to the total magnetization direction, such that $\hat{x} \times \hat{y} = \mathbf{M}/M$. It is worth noting that, similarly, one can consider a multiband superconducting state.

Hence, the order parameter shape is stable with respect to the magnetization rotation. This is an important observation, but it does not explain the re-entrance of superconductivity in the high field region. Leaving this problem for future investigation we only note here that if the first order type transition is very weak, in other words, if it is close to the second order, then in the vicinity of it one can expect the appearance of well developed magnetic fluctuations, possibly stimulating of electron pairing.

5. Weak antiferromagnetism in superconducting URhGe

The interesting observation has been made in the paper [25] and discussed in more details in [17]. The uranium atoms in the orthorhombic unit cell of URhGe form two 'pairs' (1,2) and (3,4) called U_I and U_{II}. These pairs of atoms can be translated on to each other by means of nonprimitive translations; that means the URhGe crystal lattice is related to a nonsymmorphic space group. It is easy to check that under the group (3) transformations accompanying by nonprimitive translations, the magnetic moments of uranium atoms behave as follows

$$\begin{aligned}
&C_2^z : U_I(M_x, M_y, M_z) \to U_{II}(-M_x, -M_y, M_z)\\
&KC_2^x : U_I(M_x, M_y, M_z) \to U_{II}(-M_x, M_y, M_z)\\
&KC_2^y : U_I(M_x, M_y, M_z) \to U_I(M_x, -M_y, M_z)\\
&KC_2^y : U_{II}(M_x, M_y, M_z) \to U_{II}(M_x, -M_y, M_z)
\end{aligned} \tag{14}$$

The symmetry (3) is possible when $M_y = 0$ but the magnetization of pair (1,2) is transformed to the magnetization of pair (3,4) as $(M_x, 0, M_z) \to (-M_x, 0, M_z)$. Hence along with the ferromagnetic moment M_z along c-axis, there is the possibility of antiferromagnetic ordering of the M_x component of U pairs (1,2) and (3,4) along the a-axis producing noncollinear magnetic ordering in the a–c plane without a further decrease of magnetic symmetry. This

type of ordering was reported in the paper [25] as a result of neutron powder diffraction experiments. The authors have found the magnetic moments of U atoms 0.26 μ_B canted in the a–c plane with an angle of $\approx \pm 30^\circ$. More recent measurements on the polycrystals [2] do not reproduce the data of [28]. The reported value of AFM component in a–c plane has a magnitude smaller than 0.06 μ_B, but the FM ordered component of 0.37 μ_B is aligned along the c-axis. These data are in good agreement with LSDA calculations [17] yielding the AFM component of 0.03 μ_B and FM component 0.293 μ_B. To be complete one must mention the recent single-crystal experiments [26] that report no AFM component, but suggest the collinear ordering of magnetization confined in b–c plane. This type of magnetization direction being away from high symmetry axis means the decrease of orthorhombic symmetry to monoclinic symmetry due to appearance of ferromagnetism. This is, in principle, possible but demands from our point-of-view, further experimental confirmation.

So, in URhGe we have FM ordering along the c-axis and a tiny AFM ordering along the a-axis of the oppositely directed magnetic moments of U_I and U_{II} pairs of uranium atoms. The Landau free energy expansion has the following form

$$F = \alpha_z(T)M_z^2 + \beta_z M_z^4 + \alpha_L L_x^2 + \gamma M_z L_x \tag{15}$$

where $L_x = M_x(U_I) - M_x(U_{II})$ is staggered AF magnetization.

Here, below the Curie temperature $\alpha_z(T) < 0$, the ferromagnetic moment has nonzero equilibrium value $M_{z0}^2 \approx -\alpha_z/2\beta_z$. At the same time the unlike positive value of α_L, the finite AF magnetization appears

$$L_x \approx -\frac{\gamma M_{z0}}{2\alpha_L} \tag{16}$$

induced by ferromagnetism. The smallness of L_z is determined by the interaction coefficient γ. The situation reminds us of the well known phenomenon of weak ferromagnetism [27] allowed by symmetry in antiferromagnetic crystals and induced by the small relativistic Dzyaloshinskii–Moriya interaction. Here we have just the opposite situation: the antiferromagnetic moment allowed by symmetry in a ferromagnetically ordered crystal is induced by a small relativistic interaction. One can call this phenomena by *weak antiferromagnetism*.

The tiny value of weak antiferromagnetic ordering in URhGe has not been revealed experimentally [2]. It was pointed out that the AF component is smaller than 0.06 μ_B. It does not contradict to the theoretically calculated value [17] yielding antiferromagnetic component ≈ 0.03 μ_B. The measurements of such a small magnetic moments are within the limits of experimental resolution. We note that much smaller values of staggered magnetization have been successfully measured in heavy fermionic materials URu_2Si_2 [28] and UPt_3 [29]. The experiments [2] have been performed on polycrystalline specimens at temperatures above ≈ 2 K, that is, inside of the ferromagnetic region (the Curie temperature is $T_C = 9.5$ K), but well above the superconductivity appearance (the critical temperature of superconducting transition is $T_s \approx 0.3$ K). As we pointed out, the superconductivity in URhGe obeys its own ferromagnetic moment [30] directed parallel to the magnetic moment of ferromagnetic normal state. It causes the additional stimulation of the amplitude of staggered antiferromagnetic moment

$$L_x \approx -\frac{\gamma M_{z0} + \gamma_s M_s}{2\alpha_L} \tag{17}$$

Hence, below the transition to the superconducting state one can expect the increase of staggered antiferromagnetic magnetization. The experimental evidence of this type behavior can serve to give the direct verification of our understanding of specific superconductivity in ferromagnetic URhGe as nonunitary superconductivity of Cooper pairs with triplet pairing.

6. Conclusion

In conclusion, we have demonstrated an appearance of an abrupt change of magnetization orientation in ferromagnetic URhGe under a magnetic field perpendicular to spontaneous magnetization direction. Then the form of the superconducting order parameter compatible with all intermediate magnetic crystal symmetries has been found.

It was shown that particular nonsymmorphic symmetry of ferromagnetic URhGe allows for the existence of antiferromagnetic ordering of pairs of uranium atoms along the a-axis. The amplitude of this weak antiferromagnetic order must increase below the phase transition into a superconducting state. The experimental verification of this is the direct test for the detection of the ferromagnetic moment of Cooper pairs.

References

[1] S.S. Saxena, P. Agarval, K. Ahilan, F.M. Grosche, R.K.W. Hasselwimmer, M.J. Steiner, E. Pugh, I.R. Walker, S.R. Julian, P. Monthoux, G.G. Lonzarich, A. Huxley, I. Sheikin, D. Braithwaite, J. Flouquet, Superconductivity on the border of itinerant-electron ferromagnetism, Nature 406 (2000) 587.

[2] D. Aoki, A. Huxley, E. Ressouche, D. Braithwaite, J. Flouquet, J.-P. Brison, E. Lhotel, C. Paulsen, Coexistence of superconductivity and ferromagnetism in URhGe, Nature 413 (2001) 613.

[3] T. Akazawa, H. Hidaka, T. Fujiwara, T.C. Kobayashi, E. Yamamoto, Y. Haga, R. Settai, Y. Onuki, Pressure-induced superconductivity in ferromagnetic UIr without inversion symmetry, J. Phys.: Condens. Matter 16 (2004) L29.

[4] A. Huxley, I. Sheikin, E. Ressouche, N. Kernavanois, D. Braithwaite, R. Calemczuk, J. Flouquet, UGe_2: A ferromagnetic spin-triplet superconductor, Phys. Rev. B 63 (2001) 144519.

[5] F. Hardi, A.D. Huxley, P-wave superconductivity in the ferromagnetic superconductor URhGe, Phys. Rev. Lett. 94 (2005) 247006.

[6] A. Leggett, A theoretical description of the new phases of liquid ^{3}He, Rev. Mod. Phys. 47 (1975) 331.

[7] T.R. Kirkpatrick, D. Belitz, Coexistence of ferromagnetism and superconductivity, Phys. Rev. B 67 (2003) 024515.

[8] K.V. Samokhin, M.B. Walker, Symmetry of the order parameter in superconducting $ZrZn_2$, Phys. Rev. B 66 (2002) 024512.

[9] V.P. Mineev, Superconducting states in ferromagnetic metals, Phys. Rev. B 66 (2002) 134504.

[10] I.A. Fomin, Gap nodes in the superconducting phase of the itinerant ferromagnet UGe_2, Sov. Phys. JETP 95 (2002) 940.

[11] V.P. Mineev, T. Champel, Theory of superconductivity in ferromagnetic superconductors with triplet pairing, Phys. Rev. B 69 (2004) 144521.

[12] V.P. Mineev, Superconductivity in ferromagnetic metals and in compounds without inversion centre, Internat. J. Mod. Phys. B 18 (2004) 2963.

[13] Special issue of MgB_2, Physica (Amsterdam) 385C (2003) 1–305.

[14] V.P. Mineev, K.V. Samokhin, Introduction to Unconventional Superconductivity, Gordon and Breach, New York, 1999.

[15] F. Levy, F. Hardi, I. Sheikin, B. Grenier, A.D. Huxley, Field induced superconductivity in the ferromagnetic superconductor URhGe, Science 309 (2005) 1343.

[16] A.D. Huxley, private communication.

[17] A.B. Shick, Electronic and magnetic structure of URhGe, Phys. Rev. B 65 (2002) 180509(R).

[18] S. Sakarya, N.H. van Dijk, E. Brück, Determination of the magnetic domain size in the ferromagnetic superconductor UGe_2 by three dimensional neutron depolarization, Phys. Rev. B 71 (2005) 174417.

[19] G.E. Volovik, L.P. Gor'kov, Superconducting classes in heavy fermions systems, Zh. Eksp. Teor. Fiz. 88 (1985) 1412, Sov. Phys. JETP 61 (1985) 843.

[20] M. Fauré, A.I. Buzdin, Domain structure in a superconducting ferromagnet, Phys. Rev. Lett. 94 (2005) 187202.

[21] H.W. Meul, C. Rossel, M. Decroux, O. Fisher, G. Remenyi, A. Briggs, Observation of magnetic-induced superconductivity, Phys. Rev. Lett. 53 (1984) 497.

[22] V. Jaccarino, M. Peter, Ultra-high-field superconductivity, Phys. Rev. Lett. 9 (1962) 290.

[23] S. Uji, H. Shinagawa, T. Terashima, T. Yakabe, Y. Terai, M. Tokumoto, A. Kobayashi, H. Tanaka, H. Kobayashi, Magnetic-field-induced superconductivity in a two-dimensional organic conductor, Nature 410 (2001) 908.

[24] L. Balicas, J.S. Brooks, K. Storr, S. Uji, M. Tokumoto, H. Tanaka, H. Kobayashi, A. Kobayashi, V. Barzykin, L.P. Gor'kov, Superconductivity in an organic insulator at very high magnetic fields, Phys. Rev. Lett. 87 (2001) 067002.

[25] V.H. Tran, R. Troc, G. Andre, Magnetic ordering in URhSi and URhGe, J. Mag. Mag. Mat. 186 (1998) 81.

[26] K. Prokes, T. Tahara, Y. Echizen, T. Takabatake, T. Fujita, I.H. Hagmusa, J.C.P. Kkaasse, E. Brueck, F.R. de Boer, M. Divis, V. Sechovsky, Electronic properties a URhGe single crystal, Physica B 311 (2002) 220.

[27] I.E. Dzyaloshinskii, Thermodynamic theory of weak ferromagnetism of antiferromagnets, J. Phys. Chem. Solids 4 (1958) 241.

[28] C. Broholm, H. Lin, P.T. Matthews, T.E. Mason, W.J.L. Buyers, M.F. Collins, A.A. Menovsky, J.A. Mydosh, J.K. Kjems, Magnetic excitations in the heavy-fermion superconductor URu_2Si_2, Phys. Rev. B 43 (1991) 12809 and references therein.

[29] N.H. van Dijk, P. Rodiere, B. Fak, A. Huxley, J. Flouquet, Weak antiferromagnetic order and superconductivity in UPt_3 studied by neutron scattering, Physica B 319 (2002) 220 and references therein.

[30] The magnetic moment in domains of URhGe is screened incompletely (see the discussion at the end of Section 3).