

**Field-induced spin-exciton condensation in the  $d_{x^2-y^2}$ -wave superconductor CeCoIn<sub>5</sub>**

V. P. Michal and V. P. Mineev

*Commissariat à l'Energie Atomique, Institut Nanosciences et Cryogénie, Service de Physique Statistique, Magnétisme et Supraconductivité, F-38054 Grenoble, France*

(Received 21 June 2011; published 22 August 2011)

The implications of the spin exciton mechanism are exposed in the context of a spin density wave (SDW) instability occurring inside the superconducting phase of a layered heavy electron compound. In this model a magnetic field serves as a tuning parameter bringing the system to the point where the transverse spin correlations are enhanced due to  $d_{x^2-y^2}$ -wave superconductivity and inducing an instability to a phase with coexisting superconductivity and SDW order. The model considers electrons in a crystal with antiferromagnetic interactions and provides restrictions on the Fermi surface characteristics and on the ordering wave vector (which can be commensurate or incommensurate close to commensuration). The applications of the model are addressed to the low-temperature–high-magnetic-field phase of CeCoIn<sub>5</sub> [M. Kenzelmann *et al.*, *Science* **321**, 1652 (2008); M. Kenzelmann *et al.*, *Phys. Rev. Lett.* **104**, 127001 (2010)].

DOI: 10.1103/PhysRevB.84.052508

PACS number(s): 74.25.Dw, 74.20.Rp, 74.25.Jb, 74.70.Tx

A significant experimental finding was achieved by Kenzelmann and collaborators<sup>1</sup> while using elastic neutron scattering to probe magnetism in the superconducting phase of CeCoIn<sub>5</sub> at low temperature and under a strong magnetic field applied in the basal plane of its tetragonal crystal structure. The upper critical field in CeCoIn<sub>5</sub> is mostly determined by paramagnetic limiting [ $H_{c2}(T=0) \simeq 11.7$  T] and due to this the phase transition to the superconducting state below  $T = 0.4T_c$  ( $T_c = 2.3$  K)<sup>2</sup> is of the first order.<sup>3</sup> In Ref. 1 the authors observed a magnetic ordering with wave vector  $\mathbf{Q} = (q, q, 1/2)$  where  $q \simeq 0.45$  is an incommensurate wave vector (here we use reciprocal lattice units in which  $2\pi/a = 1$ ,  $a$  being the in-plane lattice constant), which was independent of the field magnitude. The small value of the magnetic moment on cerium sites  $m = 0.15\mu_B$  ( $\mu_B$  is the Bohr magneton) oriented along the  $c$ -tetragonal axis indicated that the ordering is of itinerant origin. It was remarkable there that an incommensurate spin density wave (SDW) was confined inside the superconducting phase, meaning that here superconductivity is an essential ingredient for SDW to develop. The existence of the magnetic order was initially detected by the technique of NMR<sup>4</sup> and its precise field dependence later determined.<sup>5</sup>

Theoretically, these coexisting orders were discussed within models that can be divided into three classes. In the first class<sup>1,6–9</sup> theories rely on coupling between SDW, superconductivity, and superconductivity with Cooper pairs having nonzero center of mass momentum [Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) phase, pair density wave (PDW), or  $\pi$ -triplet superconductivity], which stabilizes SDW and superconductivity at high field and low temperature. Evidence for the occurrence of a staggered superconducting state in CeCoIn<sub>5</sub> is however still to be revealed. A second point of view<sup>10</sup> highlighted the role played by the vortex lattice, which can increase the density of states in the nodal direction of the gap and trigger a magnetic instability. The third class<sup>11,12</sup> emphasized the importance of Pauli limiting in  $d$ -wave superconductors for stabilizing SDW order in the case where the ordering wave vector is the nesting wave vector  $Q_N$  (in the sense that it joins two points of the normal-state Fermi line where the Fermi velocities are parallel). It was found

that the low-temperature–high-field superconducting phase in CeCoIn<sub>5</sub> is a coexisting phase of FFLO and incommensurate SDW orders.<sup>11</sup> Also, the enhancement of nesting by superconductivity in the gap nodal direction was proposed.<sup>12</sup>

Another important observation was made on CeCoIn<sub>5</sub> thanks to inelastic neutron scattering (INS). Stock and collaborators<sup>13</sup> measured a spin resonance that was sharp in energy ( $\omega = 0.60 \pm 0.03$  meV) and having wave vector distribution centered on  $\mathbf{Q} = (1/2, 1/2, 1/2)$  with a width of  $\simeq 0.15$ . Thereafter Panarin and collaborators<sup>14</sup> studied the evolution of the resonance in a magnetic field applied in the  $[1, -1, 0]$  direction. They observed the same resonance with a decrease in its energy and a broadening in its line shape as the field increased. They were able to measure it up to  $\simeq 0.5H_{c2}$  where the signal was lost in the incoherent part of the spectrum.

Theoretically Eremin and collaborators<sup>15</sup> have attributed the resonance to the proximity to the threshold of the particle-hole excitations continuum, which is at energy  $\omega_c = \min(|\Delta_{\mathbf{k}}| + |\Delta_{\mathbf{k}+\mathbf{q}}|)$ . Another scenario related to a magnon excitation was proposed by Chubukov and Gor'kov.<sup>16</sup>

In this Brief Report we propose to interpret the occurrence of a phase with coexisting superconductivity and SDW in CeCoIn<sub>5</sub> where the phenomena in Ref. 1 on the one hand and in Refs. 13, 14 on the other hand are closely connected: The resonance that exists at  $\omega = 0.6$  meV shifts to lower energies as a transverse magnetic field is applied and triggers a magnetic instability before superconductivity is suppressed.<sup>17</sup> We consider here a situation with electrons in a crystal having antiferromagnetic correlations as was previously discussed.<sup>13,15</sup>

We use a model of a two-dimensional system and show that it provides a consistent scenario for the presence in CeCoIn<sub>5</sub> of a SDW order that is confined inside the superconducting state without requiring the coupling with another state such as FFLO or PDW, or nesting properties of the Fermi surface. The applicability of a two-dimensional (2D) model for CeCoIn<sub>5</sub> was already discussed<sup>16</sup> because of a lack of strict two dimensionality for the compound. Here we argue that the Fermi surface in CeCoIn<sub>5</sub> has sufficient 2D character so that we can consider a model of a 2D metal from which

superconductivity develops. This assumption is corroborated by experimental observations.<sup>18,19</sup> In particular, Ref. 18 points out that the direction (1,1,0) manifests particularly strong two dimensionality.

We found that the  $c$ -axis static susceptibility increases under a field directed in the basal plane due to the proximity to the resonance and becomes larger than in the normal state. The wave vector of the SDW is not constrained by the in-plane orientation of the field (as remarked experimentally<sup>1</sup>) but by the gapped energy spectrum characteristics. The conditions for stabilization of magnetism with respect to the normal state at finite magnetic field are the following: (i) The Fermi line must contain hotspots with ordering wave vector close to (1/2, 1/2) corresponding to antiferromagnetic correlations. (ii) The two values of the gap on hotspots must be nonzero and of opposite signs. As already emphasized<sup>15</sup> for CeCoIn<sub>5</sub>, this requires the symmetry of the gap to be  $d_{x^2-y^2}$  wave. This gives an upper boundary for the value of the field that induces SDW  $\mu B_{\text{SDW}} < (\Delta_{\text{hs1}} + \Delta_{\text{hs2}})/2$ , where  $\mu = g\mu_B/2$  is the electron magnetic moment.

Superconducting and antiferromagnetic correlations can be dealt with in a random phase approximation<sup>20,21</sup> with susceptibility  $\chi(\mathbf{q}, \omega) = \chi_0(\mathbf{q}, \omega)/[1 - U_q \chi_0(\mathbf{q}, \omega)]$ , where  $\chi_0(\mathbf{q}, \omega)$  is the susceptibility that includes superconducting correlations and  $U_q$  is a momentum-dependent Hubbard-Coulomb repulsion potential (this was originally introduced for  $q$ -independent interaction). In this model the conditions for a collective excitation (called spin exciton) to occur are  $U_q \Re \chi_0(\mathbf{q}, \omega) = 1$ , and  $U_q \Im \chi_0(\mathbf{q}, \omega) \ll 1$ .

Here superconductivity is accounted for in the mean field BCS theory for electrons under a magnetic field that couples to the electron spin via the Zeeman energy (the effect of vortices on the spin exciton are discussed in Ref. 22 in the context of high- $T_c$  superconductors). The Gor'kov-Green's functions are written once compacted into the Nambu (particle-hole space) notation

$$\mathcal{G}_\sigma(\mathbf{k}, i\omega_n) = \frac{(i\tilde{\omega}_n + \sigma\mu B)\tau_0 + \Delta_k\tau_1 + \xi_k\tau_3}{(i\tilde{\omega}_n + \sigma\mu B - E_k)(i\tilde{\omega}_n + \sigma\mu B + E_k)}. \quad (1)$$

Here  $\tilde{\omega}_n = \omega_n + \text{sign}(\omega_n)/(2\tau)$ ,  $\omega_n = \pi T(2n + 1)$  are the Matsubara frequencies, and  $\tau$  is the electron relaxation time. We consider a gap order parameter  $\Delta_k$  that is uniform in space and its phase was set equal to zero,  $E_k = \sqrt{\xi_k^2 + \Delta_k^2}$  is the zero-field energy of excitations in the superconducting state,  $\tau_0$  is the unity matrix, and  $\tau_1$  and  $\tau_3$  the Pauli matrices. Throughout we take the spin quantization axis the same as the magnetic field direction, which is fixed to be the  $z$  direction in our spin-space frame and belongs to the basal plane of the crystal.

The normal-state electron energy spectrum in CeCoIn<sub>5</sub> was calculated<sup>23</sup> in a model involving hybridized conduction-electron bands and  $f$ -electron bands with Coulomb's interaction. Here we take the two-dimensional spectrum (see Fig. 1)

$$\xi_k = 2t[\cos(k_a) + \cos(k_b)] + 4t'\cos(k_a)\cos(k_b) + 2t''[\cos(2k_a) + \cos(2k_b)] + \varepsilon, \quad (2)$$

with  $t' = -0.5t$ ,  $t'' = 0.4t$  and  $\varepsilon = 0.6t$ . We consider a singlet  $d_{x^2-y^2}$ -wave superconducting state with gap  $\Delta_k = (\Delta_0/2)[\cos(k_a) - \cos(k_b)]$  corresponding to the irreducible representation  $B_{1g}$  of the tetragonal crystal point group. In

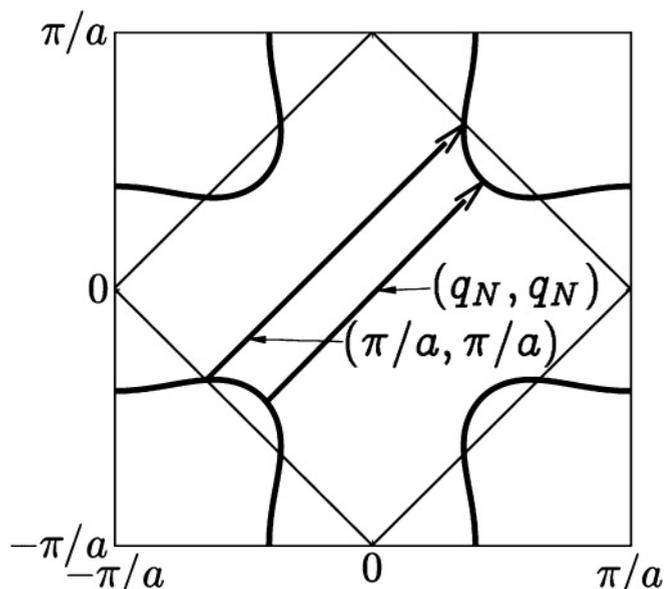


FIG. 1. Contour plot of the normal-state energy spectrum  $\xi_k = 0$  (the Fermi line) in the first Brillouin zone. The configurations of the commensurate and nesting wave vectors are drawn.

the following all energies are counted with respect to the scale given by the gap  $\Delta_0$  at zero temperature and zero field, and we set  $t/\Delta_0 = 7$ .

The free electron spin susceptibility is defined as

$$\chi_0^{ab}(\mathbf{q}, i\nu_m) = -\frac{T}{2} \sum_{k, \omega_n, \sigma, \sigma'} \text{Tr}[\sigma_{\sigma\sigma'}^a \mathcal{G}_{\sigma'}(\mathbf{k}, i\omega_n) \times \sigma_{\sigma'\sigma}^b \mathcal{G}_\sigma(\mathbf{k} + \mathbf{q}, i\omega_n + i\nu_m)],$$

where the trace is performed in the particle-hole (Nambu) space and  $\sigma_{\sigma\sigma'}^a$  are the Pauli matrices in spin space. The susceptibility is calculated by taking account of the self-consistency equation for the order parameter, yielding slight decrease in the gap magnitude at high field. We evaluate the retarded susceptibility along the crystal  $c$  axis ( $x$  direction of the frame in spin space introduced above) under a magnetic field applied in the crystal basal plane ( $z$  direction)

$$\chi_0^{xx}(\mathbf{q}, \omega) = \frac{1}{2} \sum_{\mathbf{k}, \sigma} \left\{ -l^2(\mathbf{k}, \mathbf{q}) [f(E_k - \sigma\mu B) - f(E_{k+q} + \sigma\mu B)] \times \left[ \frac{1}{E_k - E_{k+q} - 2\sigma\mu B + \omega + i/(2\tau)} + \frac{1}{E_k - E_{k+q} - 2\sigma\mu B - \omega - i/(2\tau)} \right] + p^2(\mathbf{k}, \mathbf{q}) [1 - f(E_k - \sigma\mu B) - f(E_{k+q} - \sigma\mu B)] \times \left[ \frac{1}{E_k + E_{k+q} - 2\sigma\mu B + \omega + i/(2\tau)} + \frac{1}{E_k + E_{k+q} - 2\sigma\mu B - \omega - i/(2\tau)} \right] \right\} \quad (3)$$

Here  $\sum_{\mathbf{k}} = \int_{\text{B.Z.}} d^2k a^2 / (2\pi)^2$ , the integral being evaluated over the (first) Brillouin zone  $k_a, k_b \in [-\pi/a, \pi/a]$ . The coherence factors are

$$l^2(\mathbf{k}, \mathbf{q}) = \frac{1}{2} \left( 1 + \frac{\xi_k \xi_{k+q} + \Delta_k \Delta_{k+q}}{E_k E_{k+q}} \right), \quad (4)$$

$$p^2(\mathbf{k}, \mathbf{q}) = \frac{1}{2} \left( 1 - \frac{\xi_k \xi_{k+q} + \Delta_k \Delta_{k+q}}{E_k E_{k+q}} \right). \quad (5)$$

Under the condition of a superconducting gap having  $d_{x^2-y^2}$ -wave symmetry, the coherence factor  $p^2$  is close to unity at the points of the Fermi line where  $\Delta_k = -\Delta_{k+q}$ . The importance of the symmetry of the order parameter was emphasized<sup>20,24</sup> for the occurrence of the resonance. Throughout we considered the temperature  $T = 0.05\Delta_0$ , the  $g$  factor  $g = 2$ , and the damping parameter  $1/(2\tau) = 0.02\Delta_0$ .

The field dependence of the real static susceptibility  $\chi_0^{xx}(\omega = 0, B)$  is shown in Fig. 2 for incommensurate ordering wave vector and illustrates the condition for the magnetic instability to occur, which is  $\chi_0^{xx}(\mathbf{q}, \omega = 0) = 1/U_q$  with the additional condition for the existence of superconductivity  $B < H_p$  (the zero temperature paramagnetic critical field was computed from the superconducting free energy with the band structure introduced above and was found to be  $H_p = 0.36\Delta_0/\mu$ ). Due to  $d_{x^2-y^2}$ -wave superconductivity the free susceptibility increases with field, becomes larger than the normal-state susceptibility and reaches a maximum at the value  $B = \Delta_{\text{hs}}/\mu$ . Before this point a field can possibly trigger a SDW instability in contrast to the normal-state case where  $\chi_{0N}^{xx}(B)$  remains essentially constant. For arbitrary direction, the free spin susceptibility writes  $\chi_0^{\varphi\varphi} = \cos^2(\varphi)\chi_0^{xx} + \sin^2(\varphi)\chi_0^{zz}$ , where  $\varphi$  is the angle between the magnetic field and the  $c$  axis. The longitudinal susceptibility  $\chi_0^{zz}$  doesn't carry the field dependence in the denominator and therefore for  $\mathbf{B}||c$

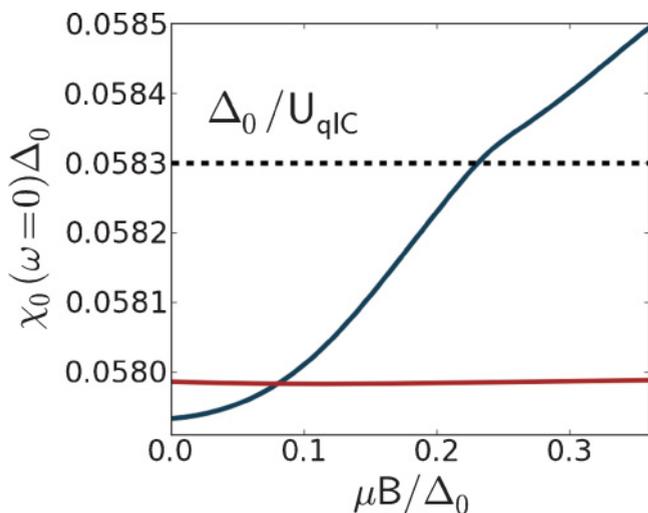


FIG. 2. (Color online) Condition for obtaining an instability from the superconductivity to coexisting superconductivity and SDW ordering at finite field in the case of incommensurate wave vector  $q_{\text{IC}} = 0.45$ . The red (gray) line represents the normal-state static susceptibility along the crystal  $c$  axis  $\chi_0^{xx} = \sum_{\mathbf{k}\sigma} [f(\xi_{\mathbf{k}} - \sigma\mu B) - f(\xi_{\mathbf{k}+q} + \sigma\mu B)] \times [\xi_{\mathbf{k}} - \xi_{\mathbf{k}+q} - 2\sigma\mu B] / [(\xi_{\mathbf{k}} - \xi_{\mathbf{k}+q} - 2\sigma\mu B)^2 + 1/(2\tau)^2]$  and the blue (dark gray) line represents the superconducting susceptibility.

no magnetic ordering along the  $c$  axis can be induced. This point is consistent with experiment<sup>25</sup> where it was found that signal of magnetic ordering disappears as the angle between the field and the crystal plane increases.

The upper part of Fig. 3 shows the evolution with field of the collective excitation as given by the random-phase approximation (RPA) dynamic susceptibility at wave vector  $\mathbf{Q} = \mathbf{Q}_{\text{IC}} = (0.45, 0.45)$ . The value of the gap at hotspots is  $\Delta_{\text{hs}} \simeq 0.25\Delta_0$ . We here discuss several points: (i) The zero field collective peak appears at energy  $\omega_{\text{res}} \simeq 0.384\Delta_0 \lesssim 2\Delta_{\text{hs}}$ . (ii) Under a transverse magnetic field a well-defined collective peak is shifted to lower energy due to Zeeman splitting of the energy of elementary excitations. The higher energy feature of  $\Im\chi^{xx}(\omega)$  is not present since the excitations are strongly damped by the continuum. This observation is consistent with experiment.<sup>14</sup> (iii) The field at which the excitation softens to zero energy is  $\mu B^* = 0.2293\Delta_0 \lesssim \Delta_{\text{hs}}$ ,

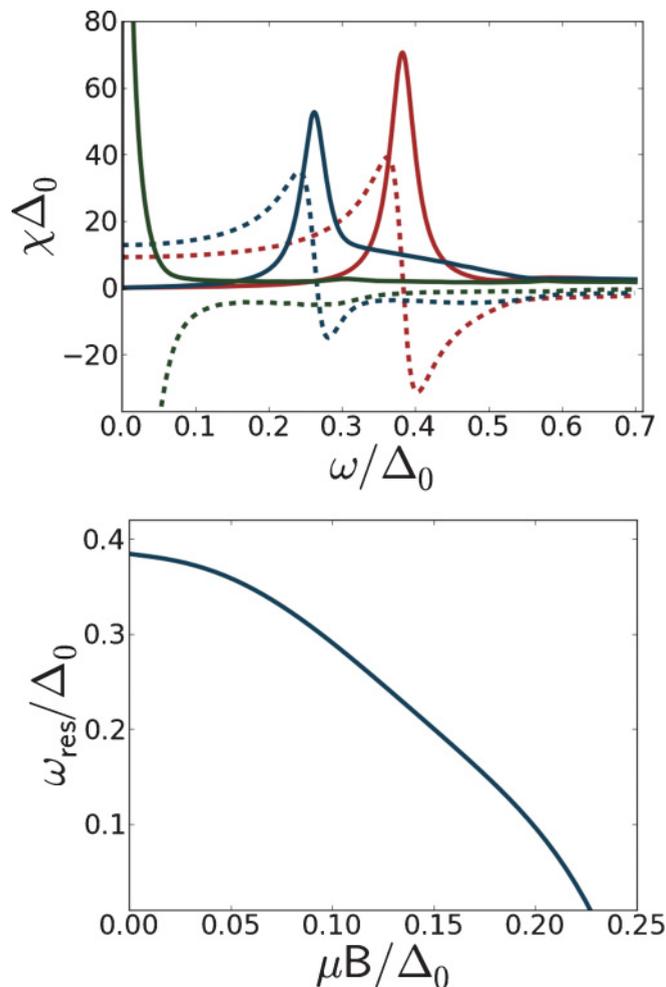


FIG. 3. (Color online) Top: real (dotted lines) and imaginary (full lines) parts of the RPA susceptibility computed at magnetic fields  $\mu B = 0$  (red, light gray),  $\mu B = \mu B^*/2 = 0.11465\Delta_0$  (blue, gray), and  $\mu B = \mu B^* = 0.2293\Delta_0$  (green, dark gray). We used the potential energy value  $U_{q_{\text{IC}}}/\Delta_0 = 1/0.0583$ . See text for discussion. Bottom: evolution of the resonance energy with a magnetic field applied parallel to the crystal plane. The value of the condensation field corresponding to vanishing resonance energy is found to be  $B^* = 0.2293\Delta_0/\mu$ .

hence showing the transition from the finite energy resonance (that corresponds to the condition  $U_q \Re \chi_0(\mathbf{q}, \omega) = 1$ ) to the ground-state instability at the spin-exciton condensation field. The evolution of the resonance energy with applied field is represented in the lower part of Fig. 3. We emphasize here the necessity for the transition from superconducting to normal state to be of the first order since a vanishingly small gap would give negligibly small effect. The physics behind the effect described here is reminiscent of the excitonic phases close to a semiconductor-semimetal transition.<sup>26</sup> Here excitons originate from  $d_{x^2-y^2}$ -wave superconductivity under a time-dependent perturbation and magnetic ordering represents the zero-energy condensation of excitons at finite wave vector under a transverse magnetic field.

CeCoIn<sub>5</sub> is a system close to antiferromagnetism. For this reason the interaction  $U_q$  is considered to be maximum at the antiferromagnetic wave vector and as a consequence the collective excitation dispersion is predicted<sup>15</sup> to be centered on the commensurate wave vector. The dispersion shows<sup>15</sup> a downward shape and an incommensurate ground state is expected. However, this situation is sensitive to the precise band structure, which is known<sup>19</sup> to be quite complicated and to consist of several bands. Experimental determination in CeCoIn<sub>5</sub> of the excitation dispersion would represent progress on this issue.

To summarize, we have presented a scenario for understanding magnetism that is tied with superconductivity in CeCoIn<sub>5</sub>.

The condensation of the preformed, induced by  $d_{x^2-y^2}$ -wave superconductivity spin exciton driven by the Zeeman splitting of the energy of elementary excitations results in a state with coexisting magnetism and superconductivity. It was found that the static RPA susceptibility along the  $c$  direction in quasi-2D-tetragonal  $d$ -wave superconductors under strong enough magnetic field applied in the basal plane is singular. The instability occurs at wave vector  $\mathbf{Q}$ , which connects points of the Fermi line with a finite gap. Because of the proximity of the compound to antiferromagnetism this can be commensurate or incommensurate close to commensuration. This presents evidence that the feedback of  $d_{x^2-y^2}$ -wave superconductivity can have drastic consequences not only on collective excitations in the system but also on the ground-state properties when an external parameter tunes the excitation energy to zero (here realized with magnetic field applied in the tetragonal crystal plane). Several questions on this transition however remain, in particular, spectroscopic probes such as electron spin resonance (free of low-energy incoherent peaks) might help in studying the transition closely.

This work was partly supported by the SINUS program of Agence Nationale de la Recherche of France. V. Michal would like to thank J. Panarin and S. Raymond for discussions on recent inelastic neutron scattering experiments and also M. Lavagna and M. Zhitomirsky for useful conversations.

- 
- <sup>1</sup>M. Kenzelmann *et al.*, *Science* **321**, 1652 (2008); *Phys. Rev. Lett.* **104**, 127001 (2010).
- <sup>2</sup>C. Petrovic *et al.*, *J. Phys. Condens. Matter* **13**, L337 (2001).
- <sup>3</sup>A. Bianchi, R. Movshovich, N. Oeschler, P. Gegenwart, F. Steglich, J. D. Thompson, P. G. Pagliuso, and J. L. Sarrao, *Phys. Rev. Lett.* **89**, 137002 (2002).
- <sup>4</sup>B.-L. Young, R. R. Urbano, N. J. Curro, J. D. Thompson, J. L. Sarrao, A. B. Vorontsov, and M. J. Graf, *Phys. Rev. Lett.* **98**, 036402 (2007).
- <sup>5</sup>G. Koutroulakis, M. D. Stewart Jr., V. F. Mitrović, M. Horvatić, C. Berthier, G. Lapertot, and J. Flouquet, *Phys. Rev. Lett.* **104**, 087001 (2010).
- <sup>6</sup>D. F. Agterberg, M. Sigrist, and H. Tsunetsugu, *Phys. Rev. Lett.* **102**, 207004 (2009); D. F. Agterberg: JPSJ Online-News and Comments (November 10, 2009).
- <sup>7</sup>Y. Yanase and M. Sigrist, *J. Phys. Soc. Jpn.* **78**, 114715 (2009).
- <sup>8</sup>K. Miyake, *J. Phys. Soc. Jpn.* **77**, 123706 (2008).
- <sup>9</sup>A. Aperis, G. Varelogiannis, and P. B. Littlewood, *Phys. Rev. Lett.* **104**, 216403 (2010).
- <sup>10</sup>K. M. Suzuki, M. Ichioka, and K. Machida, *Phys. Rev. B* **83**, 140503(R) (2011).
- <sup>11</sup>R. Ikeda, Y. Hatakeyama, and K. Aoyama, *Phys. Rev. B* **82**, 060510(R) (2010); Y. Hatakeyama and R. Ikeda, *ibid.* **83**, 224518 (2011).
- <sup>12</sup>Y. Kato, C. D. Batista, and I. Vekhter, e-print arXiv:1104.0391 (unpublished).
- <sup>13</sup>C. Stock, C. Broholm, J. Hudis, H. J. Kang, and C. Petrovic, *Phys. Rev. Lett.* **100**, 087001 (2008).
- <sup>14</sup>J. Panarin *et al.*, *J. Phys. Soc. Jpn.* **78**, 113706 (2009).
- <sup>15</sup>I. Eremin, G. Zwirnagl, P. Thalmeier, and P. Fulde, *Phys. Rev. Lett.* **101**, 187001 (2008); P. Thalmeier, I. Eremin, A. Akbari, and P. Fulde, *J. Supercond. Nov. Magn.* **23**, 729 (2010).
- <sup>16</sup>A. V. Chubukov and L. P. Gor'kov, *Phys. Rev. Lett.* **101**, 147004 (2008).
- <sup>17</sup>A SDW transition induced by spin-exciton condensation in high- $T_c$  superconductors was described in J.-P. Ismer, Ilya Eremin, Enrico Rossi, and Dirk K. Morr, *Phys. Rev. Lett.* **99**, 047005 (2007) under the assumption of a temperature-dependent antiferromagnetic interaction.
- <sup>18</sup>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).
- <sup>19</sup>R. Settai *et al.*, *J. Phys. Condens. Matter* **13**, L627 (2001).
- <sup>20</sup>M. Lavagna and G. Stemann, *Phys. Rev. B* **49**, 4235 (1994).
- <sup>21</sup>N. Bulut and D. J. Scalapino, *Phys. Rev. B* **53**, 5149 (1996).
- <sup>22</sup>M. Eschrig, M. R. Norman, and B. Janko, *Phys. Rev. B* **64**, 134509 (2001).
- <sup>23</sup>K. Tanaka, H. Ikeda, Y. Nisikawa, and K. Yamada, *J. Phys. Soc. Jpn.* **75**, 024713 (2006).
- <sup>24</sup>Hung Fai Fong, B. Keimer, P. W. Anderson, D. Reznik, F. Doğan, and I. A. Aksay, *Phys. Rev. Lett.* **75**, 316 (1995).
- <sup>25</sup>E. Blackburn, P. Das, M. R. Eskildsen, E. M. Forgan, M. Laver, C. Niedermayer, C. Petrovic, and J. S. White, *Phys. Rev. Lett.* **105**, 187001 (2010).
- <sup>26</sup>B. I. Halperin and T. M. Rice, *Rev. Mod. Phys.* **40**, 755 (1968).