Field-induced transition from chiral spin-triplet to mixed-parity Fulde-Ferrell-Larkin-Ovchinnikov superconductivity

Alfonso Romano, Mario Cuoco, Canio Noce, Paola Gentile, and Gaetano Annunziata
CNR-SPIN, I-84084 Fisciano (Salerno), Italy
and Dipartimento di Fisica "E. R. Caianiello," Università di Salerno, I-84084 Fisciano (Salerno), Italy
(Received 6 December 2009; revised manuscript received 1 February 2010; published 22 February 2010)

We analyze the response to a magnetic field of a two-dimensional spin-triplet superconductor with chiral order parameter when triplet pairing is closely competing with the singlet one. The study is performed via numerical solution of the Bogoliubov-de Gennes equations, assuming that the translational symmetry is broken in one direction by the presence of an interface beyond which superconducting pairing is not effective. We show that as the intensity of the magnetic field is increased above a threshold value, the system undergoes a transition to a spatially inhomogeneous state of the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) type where chirality disappears and a singlet-triplet mixing takes place along the direction perpendicular to the interface. Subdominant singlet components are found to accompany the triplet dominant ones in both phases. They develop close to the interface at low fields, then turning continuously into oscillating long-range ones as the field is increased. A similar behavior is found for the magnetization. It nucleates at the interface in the chiral phase, then acquiring in the FFLO phase an oscillatory behavior reaching its maximum amplitude at the sites where the dominant triplet component has a node. At these sites, the local spin-resolved density of states exhibits strong resonances, associated with the formation of Andreev bound states, which tend to broaden and decay in intensity as increasingly high magnetic fields are considered.

DOI: 10.1103/PhysRevB.81.064513 PACS number(s): 74.20.Rp, 74.25.Dw, 74.70.Pq, 71.10.Li

I. INTRODUCTION

In spatially homogeneous superconductors the application of an external magnetic field is known to be detrimental to the stability of the superconducting phase. In most of the cases, orbital pair-breaking effects lead to the emergence of the Abrikosov vortex state, eventually making the system become fully normal as the upper critical field H_{c2} is exceeded. However, under very specific conditions a breaking-up of the translational invariance may allow the superconducting order to remain stable even in the presence of a polarizing field.[1] The most celebrated example of an inhomogeneous state where SU(2) and U(1) symmetries are simultaneously broken, can probably be considered the so-called Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state.[2] In this state Cooper pairs acquire a finite center-of-mass momentum and, as a consequence, the superconducting order parameter (OP) and the magnetization both exhibit a modulation in space.

Little evidence, however, has so far been reported of the occurrence of the FFLO state in real systems. This is mostly due to the fact that the coupling of a magnetic field to the electron spin via Zeeman effect is required to break Cooper pairs more efficiently than orbital coupling does, a situation which is typically not encountered in most of the known type-II superconductors. Nonetheless, besides the case of systems such as $ErRh_4B_4$,[3] where aligned magnetic impurities generate a very strong internal exchange field, a spin paramagnetic effect dominating over the orbital one can in principle take place in quasi-two-dimensional (2D) layered systems where an external magnetic field is applied parallel to the planes. In this case orbital effects can be small or even negligible due to the weakness of the interlayer coupling and thus the Zeeman effect is expected to dominate. A further element hindering the formation of the FFLO state is that it is not robust against the presence of impurities and thus its occurrence requires very clean samples. Presently, these rather stringent conditions are likely to be satisfied in very few superconducting systems, essentially belonging to two classes of systems, the heavy-fermion compounds[4] and the organic superconductors.[5] Within the former, evidence of the FFLO state has been found in several measurements performed on the compound $CeCoIn_5$ (Ref. 6) while in the latter a clearcut signature has been provided by specific-heat measurements on κ-$(BEDT\text{-}TTF)_2Cu(NCS)_2$ (Ref. 7) [though it is also conjectured that the FFLO state is realized in the quasi-one-dimensional (1D) Bechgaard salts $(TMTSF)_2X$ with $X = PF_6$ (Ref. 8) and ClO_4 (Ref. 9)].

A further peculiar feature of the FFLO state is that it tends to be stabilized by the mixing of even and odd parity pairings. Evidence for this behavior has been given by Shimahara[10] for a quasi-two-dimensional system where singlet pairing interactions coexist with relatively weak triplet ones. Moreover, an enhancement of the stability of the FFLO state due to the singlet-triplet mixing has also been demonstrated in recent studies on spin-fluctuation-mediated superconductivity performed within the Hubbard model on a square lattice[11] as well as on two-leg ladders becoming superconducting away from half-filling.[12]

The interest in superconductors with parity mixing has rapidly increased in the last years also because of the discovery of superconductivity in several noncentrosymmetric heavy-fermion compounds. Its first observation in $CePt_3Si$ (Ref. 13) at ambient pressure, and in $CeRhSi_3$ (Ref. 14) and $CeIrSi_3$ (Ref. 15) under pressure, has stimulated many experimental[16–20] and theoretical[21] studies motivated by the fact that this class of systems gives a unique opportunity of probing the effect of parity violation, which is otherwise hard to achieve by imposing specific external conditions to standard centrosymmetric compounds. When crystal structure lacks an inversion center, the corresponding asymmetry in the electric potential gives rise to an antisymmetric Rashba-type spin-orbit coupling which prevents the classification of Cooper-pair states according to parity. As a consequence, the superconducting phase is characterized by order parameters of mixed parity, consisting of an admixture of spin-singlet and spin-triplet pairing components.[22,23] The mixed spin structure of the order parameter in superconducting noncentrosymmetric systems also leads to very specific features in the behavior close to interfaces, essentially because the presence of a strong spin-orbit interaction makes the interface scattering become spin active.[24]

More exotic forms of mixed singlet-triplet superconductivity can be obtained when pairing-time correlations lead to an even-frequency component in one of the spin-symmetry channels and an oddlike frequency dependence in the other. The interest in this direction has been triggered by the observation of long-range proximity effect in junctions made of a spin-singlet superconductor interfaced with a half-metallic ferromagnet.[25,26] A similar attention has also been devoted to other hybrid systems where due to interfaces, spin-active sources of scattering, or inhomogeneous profiles of the magnetization, a mixing of singlet and triplet pairing with a nontrivial time dependence may be generated.[27–30]

Within the paired states having mixed parity, it often happens that a dominant spin-singlet component is accompanied by a closely competing spin-triplet one. The possibility of turning such scenario toward a dominant spin-triplet component is provided by the recent discovery of several systems exhibiting a spin-triplet superconducting phase. Indeed, apart from the well-known case of superfluid ^{3}He, where the condensate is made of atomic pairs, a general consensus, mainly originating from Knight-shift measurements, exists in favor of triplet superconductivity in the ferromagnetic compound $ZrZn_2$,[31] in the organic system $(TMTSF)_2PF_6$,[32] and in several heavy-fermion compounds which can be nonmagnetic [UPt_3 (Refs. 33 and 35)], antiferromagnetic [UNi_2Al_3 (Refs. 34 and 35)], or ferromagnetic [UGe_2 (Ref. 36) and URhGe (Ref. 37)]. A further fundamental example of spin-triplet superconductor with a chiral order parameter is the layered perovskitic system Sr_2RuO_4,[38] which for its specific properties has probably offered in the last years the best opportunity to study the relevant features of spin-triplet pairing. It is also worth mentioning that a peculiar modification of the superconducting behavior of this compound has been detected in two types of eutectic solidifications which contain it, i.e., Sr_2RuO_4/Ru and $Sr_3Ru_2O_7/Sr_2RuO_4$. In the case of Sr_2RuO_4/Ru, where the critical temperature is enhanced from $T_c=1.5$ K of pure Sr_2RuO_4 to $T_c=3$ K,[39] lamellar microdomains of metallic ruthenium are embedded in the perovskitic oxide in such a way that a nonchiral spin-triplet component may occur at the interface or a spin-singlet pairing from the metallic ruthenium is mixed with the spin-triplet one of Sr_2RuO_4.[40] On the other hand, for $Sr_3Ru_2O_7/Sr_2RuO_4$ an anomalous proximity effect as well as multiple superconducting transitions have recently been observed.[41,42] The behavior of both kinds of eutectic system underlines the subtle competition between spin-triplet pairing and translational and orbital symmetry breaking.

The rich phenomenology of the classes of systems mentioned above is intimately related to the complex evolution of the superconducting state when extra symmetries other than the U(1) gauge invariance are spontaneously or explicitly broken. Indeed, time-reversal symmetry breaking can lead to inhomogeneous superconducting states (i.e., FFLO), and the removal of the crystal-inversion symmetry or the presence of interfaces are accompanied by different types of mixed parity pairing. Recently, some aspects of this issue have theoretically been investigated[43] for the case of a low-dimensional singlet superconductor with spin-fluctuation-mediated pairing coexisting with charge fluctuations, showing that as the magnetic field is gradually increased, consecutive transitions occur from singlet pairing to mixed parity FFLO and further to $S_z=1$ triplet pairing. In close connection to this scenario, we try in this paper to give an answer to the following questions. Which is the response to a magnetic field of a system where (i) an interface breaks translational invariance and (ii) chiral spin-triplet pairing dominates at zero field but in close competition with the spin-singlet one? If a state with FFLO-like features emerges at suitably high fields, what is its nature? To this purpose, we consider a two-dimensional system where translational symmetry breaking is explicitly introduced by the presence of an interface perpendicular to one of the two spatial directions. Hence, the system consists of a chiral superconductor with a nearest-neighbor pairing potential effective both in the singlet and the triplet channels, and a paramagnetic metal where no electron pairing is assumed to take place. With this choice, the physical system representing the best candidates for the application of our approach is the previously mentioned ruthenate compound Sr_2RuO_4, together with its derived eutectic phases. Indeed, for such system the experimental and theoretical knowledge collected so far seems to confirm the presence of a zero-field superconducting state with triplet pairing and time-reversal symmetry breaking. Hence, the model analyzed here may mimic a Sr_2RuO_4/normal-metal bilayer junction as well as a system where planar Sr_2RuO_4 areas are interfaced with metallic domains of Ru or $Sr_3Ru_2O_7$. Chiral superconducting regions adjacent to normal metallic ones are also present in the mixed state of Sr_2RuO_4, where the vortex cores play the role of normal domains.

Within such scenario, we investigate several issues related to how superconducting and magnetic properties are affected by the interplay of the orbital, spin, and spatial symmetry breaking. Choosing an electron density such that in zero field a triplet superconducting component of the chiral type dominates over the singlet ones, we follow the evolution of the system as a constant exchange field, which can equivalently be seen as an internal or an external one, is gradually turned on. In particular, we find that as the field is increased beyond a temperature-dependent crossover value, the system evolves continuously from the chiral phase into an FFLO-like one characterized by the coexistence of odd and even-parity pairing oscillating components of comparable amplitudes (the triplet one remaining dominant). Moreover, similarly to what happens for the singlet subdominant components, the magnetization in the chiral phase is found to be nonvanishing only in proximity of the interface. Then, as the field is increased, it gradually acquires an oscillatory behavior extending all over the sample with an amplitude which is maximal in correspondence of the nodes of the triplet-dominant order parameter. At these sites, the local spin-resolved density of states exhibits strong resonances, associated with the formation of Andreev bound states,[44,45] which tend to broaden and decay in intensity as higher magnetic fields are considered.

The paper is organized as follows. In Sec. II we introduce the model used to describe the inhomogeneous system investigated here, specifying that it is solved in the clean limit within a standard Bogoliubov-de Gennes approach. In Sec. III we analyze the evolution of the superconducting phase from the chiral to the FFLO state as the temperature and the magnetic field are varied. Section IV is devoted to the conclusions.

II. MODEL AND FORMALISM

We consider a two-dimensional superconductor separated from a normal metal by a perfectly transparent interface. Denoting by x (y) the direction perpendicular (parallel) to the interface, we assume that the system is uniform along the y axis so that inversion and translational symmetries are broken only in the x direction. The system is described in terms of a microscopic tight-binding model on a square lattice that we treat within the Hartree-Fock approximation. It is assumed that metallic ferromagnetism can develop via a standard Stoner-type mechanism associated with the presence of a uniform exchange field, causing a rigid shift in the relative positions of the majority and minority spin bands. We will develop our analysis choosing an electron density such that in the absence of the field the superconducting order parameter is characterized by a triplet pairing symmetry of the chiral p_x+ip_y type.

The total Hamiltonian of the system is defined on a two-dimensional finite-size square lattice of size $2L\times 2L$ (for unit lattice constant), where each site is denoted by a vector $\mathbf{i}\equiv(i_x,i_y)$, i_x and i_y being integers ranging from $-L$ to $+L$. In standard second quantization notation it has the form

$$H=-t\sum_{\langle\mathbf{i},\mathbf{j}\rangle,\sigma}(c^{\dagger}_{\mathbf{i}\sigma}c_{\mathbf{j}\sigma}+\text{H.c.})-\mu\sum_{\mathbf{i},\sigma}n_{\mathbf{i}\sigma} - \sum_{\substack{\langle\mathbf{i},\mathbf{j}\rangle\\ i_x,j_x>0}}V(n_{\mathbf{i}\uparrow}n_{\mathbf{j}\downarrow}+n_{\mathbf{i}\downarrow}n_{\mathbf{j}\uparrow})-h\sum_{\substack{\mathbf{i}\\ i_x>0}}(n_{\mathbf{i}\uparrow}-n_{\mathbf{i}\downarrow}),$$

where $\langle\mathbf{i},\mathbf{j}\rangle$ denote nearest-neighbor sites and μ is the chemical potential. The presence of an interface in the system separating a superconducting region from a paramagnetic one is simulated via a nearest-neighbor attraction $-V(V>0)$ assumed to be nonvanishing only for $i_x>0$. It is effective in the singlet as well as in the triplet channel, as it happens, for instance, when the pairing interaction is mediated by antiferromagnetic fluctuations.[46] Finally, the magnetic field h, which can be equivalently seen either as an external or an intrinsic one, is for simplicity assumed to be nonvanishing only in the superconductor side.

The model defined by the above Hamiltonian is solved here by applying to H a standard Hartree-Fock decoupling and then solving numerically the corresponding Bogoliubov-de Gennes equations by means of the self-consistent iterative procedure described in detail in Ref. 47. The numerical simulation has been performed adopting open (periodic) boundary conditions in the x (y) direction, for a system size corresponding to $L=60$. We have also verified that larger values of L leave our results qualitatively unchanged.

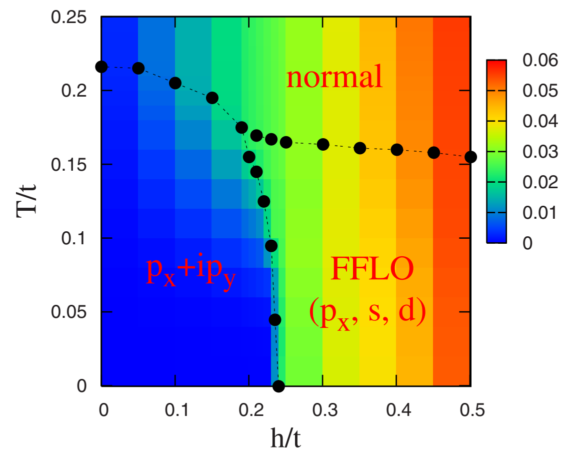

FIG. 1. (Color online) h-T phase diagram at low and intermediate field values. Up to $T/t\simeq0.16$, the increase in h leads to a transition from a chiral p-wave state to an FFLO one with oscillating triplet and singlet components, accompanied by analogous oscillations of the spin polarization. At $T=0$ the transition to the normal phase takes place for $h/t\simeq2$ (the corresponding region of the phase diagram is not shown). The different colors denote the maximum value of the magnetization in the superconducting and in the normal region.

III. RESULTS

We start by selecting a set of parameters ($\mu=-1.8$ and $V=2.5$, all the energies being expressed in units of the hopping amplitude t) such that the ground state has in zero field a p-wave character with broken parity and broken time-reversal symmetry (p_x+ip_y). Previous studies on the extended Hubbard model[48] have shown that a $d_{x^2-y^2}$-wave superconducting state is stabilized near half-filling ($\mu\sim0$) while an extended s wave appears at high (and low) densities for $|\mu|$ falling in a range going approximately from $2.5t$ to $4t$. In the region between d- and s-wave states, the triplet chiral phase develops.

The type of pairing state which is established in the superconductor as the field h and the temperature T are varied can be deduced from the phase diagram shown in Fig. 1. As already stated above, the chosen electron density (approximately equal to $\langle n_i\rangle=0.4$) is such that for $h=0$ the pairing symmetry is the chiral p_x+ip_y one. As the magnetic field is turned on at suitably low temperatures, a transition occurs for a moderate threshold value of h to a spatially inhomogeneous state where chirality gets lost and a mixing of singlet and triplet oscillating components, accompanied by similar oscillations of the spin polarization, takes place in the direction perpendicular to the interface. The corresponding region

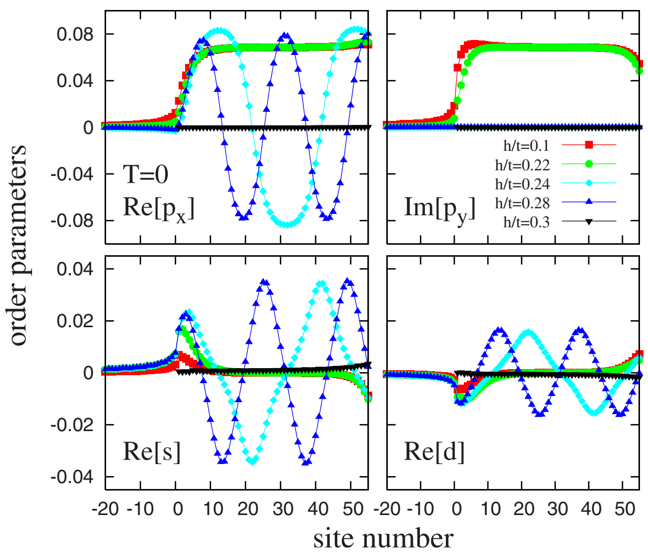

FIG. 2. (Color online) Spatial variation in the superconducting OPs at $T=0$ for different values of the field h across the transition from the chiral to the FFLO phase (sites are numbered in units of the lattice constant). The upper and the lower panels show the nonvanishing triplet and singlet amplitudes, respectively. The separation between the superconducting and the normal region is set at the site zero.

of the phase diagram, which can be associated with an FFLO state, extends up to relatively high values of the field before the transition to the normal state takes place (at zero temperature this happens for $h/t \simeq 2$). To get an estimate of the zero-temperature critical field h_c at which the transition to the FFLO state occurs, one can observe that the ratio between h_c and the zero-field critical temperature T_{c0} is about 1.11. This implies that for T_{c0} of the order of 1 K, a field approximately equal to 1.6 T is needed to observe the transition at zero temperature.

The profiles of the order parameters at $T=0$ for values of h in the region of the crossover from the chiral to the FFLO state are shown in Fig. 2. At low values of h, the superconductor exhibits a bulk OP with triplet p_x+ip_y symmetry, accompanied by induced much smaller singlet components developing only in proximity of the interface. Above a relatively moderate value of h (at $T=0$ equal approximately to 0.23), no contribution survives along the y direction in the triplet channel, so that chirality disappears and the dominant phase becomes of pure p_x type. The nonvanishing superconducting components now all acquire an oscillating behavior, typical of the FFLO state, and all are specified to within a common phase factor. Indeed, the breakdown of the translational invariance in the direction perpendicular to the interface helps to stabilize a solution with a modulation of the amplitude of the order parameter (LO-type solution) rather than a modulation of the phase (FF-type solution) as a consequence of the suppression of the order parameter near the interface. Moreover, we underline that the solution exhibits a single mode q vector for the oscillating functional behavior of the order parameter. Such feature is not trivial because the Fermi surface along the x direction does not have any special nesting conditions to deduce a single-mode modulation. Nevertheless, the breaking of the translational symmetry introduces an energy indetermination around the Fermi level that cooperates to set a single-mode oscillating profile as the best compromise for the coexistence of superconductivity and spin polarization in the inhomogeneous phase.

Across the transition, a continuous field evolution characterizes the behavior of the singlet subdominant components, which, besides getting larger in amplitude, are no more confined at the interface, but rather develop throughout the superconductor, with the same kind of oscillating behavior which characterizes the dominant p_x component. In particular, the frequency of the oscillations increases with increasing h and is the same for all the order parameters, with a phase opposition such that nodes of the triplet component correspond to minima and maxima of the singlet ones, and vice-versa. We notice that when, as in our case, the attractive potential is effective both in the singlet and the triplet channels, the mixing of even and odd parity states is a typical feature stabilizing the FFLO state. This is, in particular, pointed out in Ref. 10, where it is shown that when in a singlet superconductor a triplet interaction, even much smaller than the singlet one, is effective, the corresponding FFLO state is much more stable compared to the case where only singlet pairing is present. A strong parity mixing also characterizes the FFLO phase induced by the application of a magnetic field to a singlet superconductor where spin-fluctuation-mediated pairing coexists with charge fluctuations.[43] This behavior has been conjectured to take place in the quasi-1D organic compounds $(TMTSF)_2X$ ($X=PF_6$ or ClO_4).

The phase diagram of Fig. 1 also shows that in a narrow range of values of h around $h/t=0.2$ the transition from the chiral to the FFLO state can also be induced by a temperature variation. This is illustrated in Fig. 3, where the increase in T first leads to a crossover from a bulk p_x+ip_y phase to an FFLO one with real oscillating triplet and singlet components, and then makes the system become normal.

The oscillation of the order parameters in the FFLO phase is accompanied by a related oscillating behavior of the magnetization $m_i=n_{i\uparrow}-n_{i\downarrow}$. As for the subdominant superconducting components, this behavior nucleates from the interface as the polarizing field is raised across the crossover value, as shown in the upper panel of Fig. 4. The oscillations take place around a fixed nonvanishing value with an amplitude gradually decreasing as h is increased. We see that the frequency of m_i is twice as large as the frequency of the order parameters with maxima occurring in correspondence of the nodes of the dominant p_x component and minima developing at the sites where the latter takes maxima or minima. This result was expected since for triplet pairing we have excluded from the very beginning the possibility of equal spin pairing so that a large absolute value of the ($S_z=0$) p_x component requires the minimization of the difference between up- and down-spin electrons and a consequent minimum value of the magnetization. Conversely, the largest values of m_i are reached at the sites corresponding to nodes of the dominant p_x component.

The oscillating behavior of both the superconducting components and the magnetization allows one to see the system as made of one-dimensional stripes developing parallel

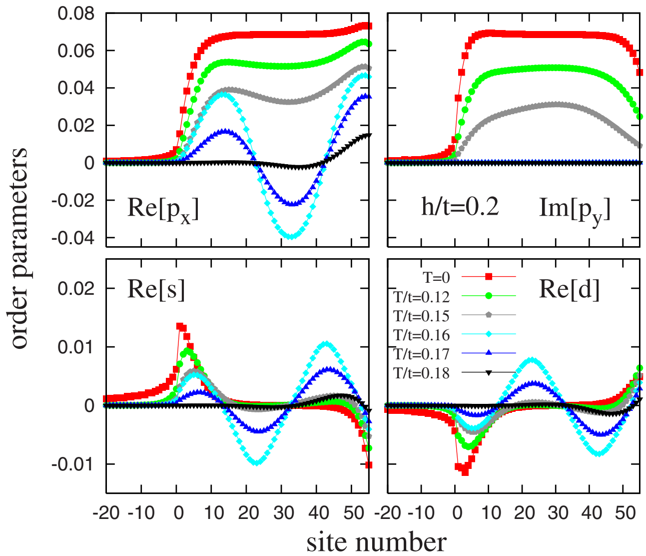

FIG. 3. (Color online) Spatial variation for $h/t=0.2$ of the nonvanishing superconducting components for different values of the temperature T across the transition from the chiral to the FFLO phase and then to the normal phase (sites are numbered in units of the lattice constant). The upper and the lower panels show the nonvanishing triplet and singlet amplitudes, respectively. The separation between the superconducting and the normal region is set at the site zero.

to the interface between two consecutive nodes of a given OP. In this picture, the node sites play the role of domain walls where due to the change in sign of the OP, Andreev

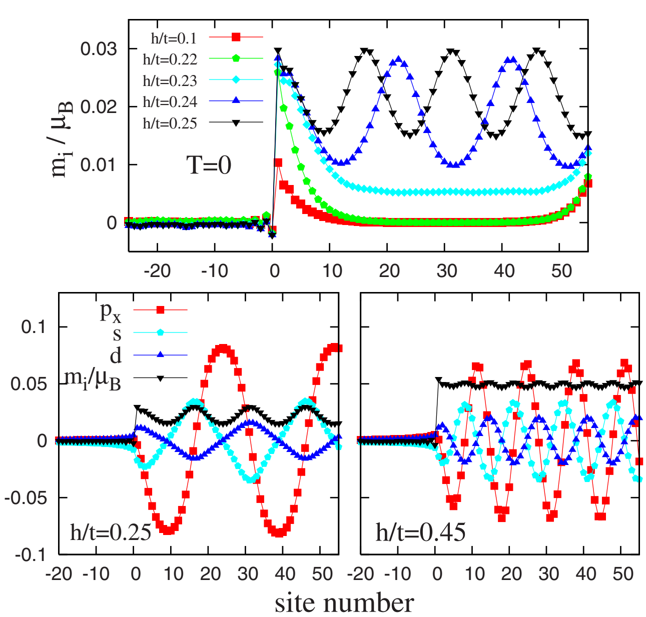

FIG. 4. (Color online) Upper panel: spatial variation in the magnetization at $T=0$ (μ_B is the Bohr magneton), for different values of the field h across the transition from the chiral to the FFLO phase (sites are numbered in units of the lattice constant). Lower panels: spatial variation at $T=0$ of the magnetization and of the nonvanishing superconducting components for $h/t=0.25$ (left) and $h/t=0.45$ (right). The separation between the superconducting and the normal region is set at the site zero.

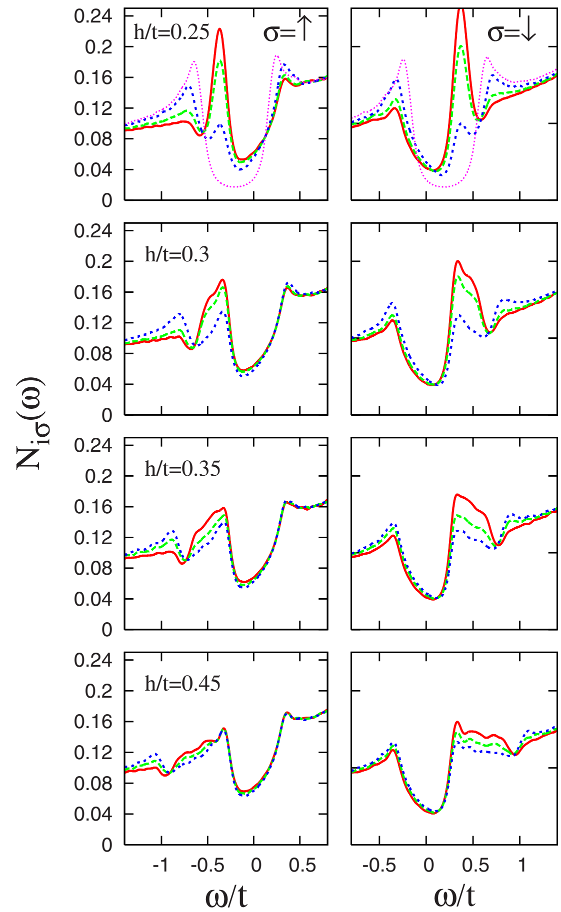

FIG. 5. (Color online) Local DOS at $T=0$ for up-spin (left panels) and down-spin electrons (right panels), for several values of the field h. Solid (red), dashed (green), and short-dashed (blue) curves denote the local DOS calculated at sites where the p_x order parameter takes zero, intermediate, and maximum amplitude, respectively. The (pink) dotted curves in the two upper panels correspond to the local DOSs evaluated in the chiral p_x+ip_y phase, at $h/t=0.2$, in the bulk of the material.

bound states are expected to form,[49,50] giving rise to corresponding peaks in the local density of states (DOS). A similar behavior is also found when the change in sign of the OP is caused by the presence of defects in the pairing potential associated, for instance, to the presence of impurities.[51] This kind of analysis has recently received a renewed attention since scanning tunneling microscopy now allows the experimental determination of the local DOS with high resolution in the energy as well as in the real-space domain.

The behavior of the spin-resolved local DOSs $N_{i\sigma}(\omega)$ ($\sigma=\uparrow,\downarrow$) within the FFLO phase is shown in Fig. 5 for several values of the magnetic field. They are evaluated in the superconducting region at three distinct sites where the oscillation amplitude of the dominant triplet component takes zero, intermediate, and maximum value, respectively. As already pointed out above, nodes of the dominant p_x component correspond to maxima or minima of the singlet ones and vice-versa. For $h/t=0.25$, i.e., for a relatively low field value within the FFLO phase, we see that a strong Andreev bound state develops at the sites where the dominant p_x component has a node. Due to the presence of the magnetic field, the corresponding peaks in the up- and down-spin local DOSs are symmetrically shifted with respect to the Fermi energy. As one moves away from the node site, the bound state tends to decay, though an evident remnant is found also at the site corresponding to the maximum of the oscillation. On the other hand, the increase in the magnetic field leads to a reduction in the oscillation period which makes the parallel domains between two consecutive nodes narrower and narrower. As a consequence, the resonance at the nodes tends to broaden and decrease in height until little difference in the local DOSs is seen as one moves from site to site. In the slightly different context of translationally invariant superconductors with no parity mixing, Andreev bound states with a similar behavior have also been found in a study of the FFLO phase in 2D *d*-wave bulk superconductors, where only 1D order-parameter modulations are considered.[44] Moreover, for the same kind of system it has recently been shown[45] that when 1D and 2D modulations are both allowed to develop, the increase in the field leads first to a transition from the uniform *d*-wave state to a 1D FFLO state, and then from the latter to a 2D FFLO one. In the intermediate-field 1D modulation regime, the behavior of the local DOSs is again very similar to the one described above for the system analyzed here.

IV. CONCLUSIONS

We have studied the response of a spin-triplet superconductor with chiral order parameter to a spin-polarizing field for the case of a model system where an explicit breaking of the translation and the inversion symmetries is introduced by the presence of an interface separating the superconductor from a paramagnetic metal. We have shown that as a consequence of the combined effect of the orbital, spin, and spatial symmetry breaking, the superconductor exhibits a h-T phase diagram with several distinctive features. They can be summarized as follows: (i) a change from chiral to oscillating nonchiral of the character of the dominant triplet superconducting order parameter, taking place at the occurrence of a field-induced crossover to an FFLO phase, (ii) an inhomogeneous mixing of singlet and triplet components, confined to the interface in the low-field chiral regime and extending to the whole sample in form of oscillating patterns in the FFLO phase; (iii) a nucleation from the interface of the magnetization, which acquires amplitude modulations around a nonzero value as the intensity of the applied field is raised across the crossover boundary, and (iv) the formation in the FFLO phase of Andreev bound states at the sites where the dominant triplet component exhibits nodes, giving rise to strong resonances in the corresponding local spin-resolved densities of states.

For completeness, we point out that in our approach even-parity spin-triplet or odd-parity spin singlet components which are odd in frequency are also expected to occur. Preliminar calculations specifically related to this issue indicate that such features are intrinsically generated by the structure of the order parameters and of the excited states in the superconducting phase, and are a direct consequence of the presence of a finite amplitude of the equal-time singlet and triplet pair correlators.

Finally, we would like to underline that the analysis presented here may be of interest and guide also in the investigation of the proximity effect in exotic hybrid systems. Indeed, while the focus of this paper is on the evolution of the superconducting state in the presence of an applied spin-polarizing field under specific spatial boundary conditions, its outcome may represent a starting point for further studies on spin and charge transport across unconventional hybrid structures, similar to those performed for inhomogeneous superconductors in proximity of normal or ferromagnetic systems.[52,53]

ACKNOWLEDGMENT

We kindly acknowledge valuable discussions with Jacob Linder.

[1] D. F. Agterberg and H. Tsunetsugu, Nat. Phys. **4**, 639 (2008).
[2] P. Fulde and R. A. Ferrell, Phys. Rev. **135**, A550 (1964); A. I. Larkin and Yu. N. Ovchinnikov, Zh. Eksp. Teor. Fiz. **47**, 1136 (1964) [Sov. Phys. JETP **20**, 762 (1965)].
[3] For a review, see L. N. Bulaevskii, A. I. Buzdin, M. L. Kulić, and S. V. Panjukov, Adv. Phys. **34**, 175 (1985).
[4] For a review, see Y. Matsuda and H. Shimahara, J. Phys. Soc. Jpn. **76**, 051005 (2007).
[5] For a review, see W. Zhang and C. A. R. Sà de Melo, Adv. Phys. **56**, 545 (2007).
[6] H. A. Radovan, N. A. Fortune, T. P. Murphy, S. T. Hannahs, E. C. Palm, S. W. Tozer, and D. Hall, Nature (London) **425**, 51 (2003); H. Won, K. Maki, S. Haas, N. Oeschler, F. Weickert, and P. Gegenwart, Phys. Rev. B **69**, 180504(R) (2004).
[7] R. Lortz, Y. Wang, A. Demuer, P. H. M. Böttger, B. Bergk, G. Zwicknagl, Y. Nakazawa, and J. Wosnitza, Phys. Rev. Lett. **99**, 187002 (2007).
[8] I. J. Lee, M. J. Naughton, G. M. Danner, and P. M. Chaikin, Phys. Rev. Lett. **78**, 3555 (1997)
[9] J. I. Oh and M. J. Naughton, Phys. Rev. Lett. **92**, 067001 (2004).
[10] H. Shimahara, Phys. Rev. B **62**, 3524 (2000).
[11] Y. Yanase, J. Phys. Soc. Jpn. **77**, 063705 (2008); T. Yokoyama, S. Onari, and Y. Tanaka, *ibid.* **77**, 064711 (2008).
[12] G. Roux, S. R. White, S. Capponi, and D. Poilblanc, Phys. Rev. Lett. **97**, 087207 (2006).
[13] E. Bauer, G. Hilscher, H. Michor, Ch. Paul, E. W. Scheidt, A. Gribanov, Yu. Seropegin, H. Noël, M. Sigrist, and P. Rogl, Phys. Rev. Lett. **92**, 027003 (2004).
[14] N. Kimura, K. Ito, K. Saitoh, Y. Umeda, H. Aoki, and T. Terashima, Phys. Rev. Lett. **95**, 247004 (2005).
[15] I. Sugitani, Y. Okuda, H. Shishido, T. Yamada, A. Thamizhavel, E. Yamamoto, T. D. Matsuda, Y. Haga, T. Takeuchi, R. Settai,

and Y. Onuki, J. Phys. Soc. Jpn. **75**, 043703 (2006).

[16] T. Klimczuk, Q. Xu, E. Morosan, J. D. Thompson, H. W. Zandbergen, and R. J. Cava, Phys. Rev. B **74**, 220502(R) (2006).

[17] H. Q. Yuan, D. F. Agterberg, N. Hayashi, P. Badica, D. Vandervelde, K. Togano, M. Sigrist, and M. B. Salamon, Phys. Rev. Lett. **97**, 017006 (2006).

[18] I. Bonalde, W. B. Brämer-Escamilla, and E. Bauer, Phys. Rev. Lett. **94**, 207002 (2005).

[19] K. Izawa, Y. Kasahara, Y. Matsuda, K. Behnia, T. Yasuda, R. Settai, and Y. Onuki, Phys. Rev. Lett. **94**, 197002 (2005).

[20] M. Yogi, Y. Kitaoka, S. Hashimoto, T. Yasuda, R. Settai, T. D. Matsuda, Y. Haga, Y. Onuki, P. Rogl, and E. Bauer, Phys. Rev. Lett. **93**, 027003 (2004).

[21] P. A. Frigeri, D. F. Agterberg, A. Koga, and M. Sigrist, Phys. Rev. Lett. **92**, 097001 (2004); K. V. Samokhin, E. S. Zijlstra, and S. K. Bose, Phys. Rev. B **69**, 094514 (2004); I. A. Sergienko and S. H. Curnoe, *ibid.* **70**, 214510 (2004); J. Linder and A. Sudbø, *ibid.* **76**, 054511 (2007).

[22] L. P. Gor'kov and E. I. Rashba, Phys. Rev. Lett. **87**, 037004 (2001).

[23] N. Hayashi, K. Wakabayashi, P. A. Frigeri, and M. Sigrist, Phys. Rev. B **73**, 092508 (2006).

[24] A. B. Vorontsov, I. Vekhter, and M. Eschrig, Phys. Rev. Lett. **101**, 127003 (2008).

[25] R. S. Keizer, S. T. B. Goennenwein, T. M. Klapwijk, G. Miao, G. Xiao, and A. Gupta, Nature (London) **439**, 825 (2006).

[26] I. Sosnin, H. Cho, V. T. Petrashov, and A. F. Volkov, Phys. Rev. Lett. **96**, 157002 (2006).

[27] F. S. Bergeret, A. F. Volkov, and K. B. Efetov, Phys. Rev. Lett. **86**, 4096 (2001).

[28] A. F. Volkov, F. S. Bergeret, and K. B. Efetov, Phys. Rev. Lett. **90**, 117006 (2003).

[29] J. Linder, T. Yokoyama, and A. Sudbø, Phys. Rev. B **79**, 054523 (2009).

[30] Y. Tanaka and A. A. Golubov, Phys. Rev. Lett. **98**, 037003 (2007).

[31] C. Pfleiderer, M. Uhlarz, S. M. Hayden, R. Vollmer, H. v. Löhneysen, N. R. Bernhoeft, and G. G. Lonzarich, Nature (London) **412**, 58 (2001).

[32] I. J. Lee, S. E. Brown, W. G. Clark, M. J. Strouse, M. J. Naughton, W. Kang, and P. M. Chaikin, Phys. Rev. Lett. **88**, 017004 (2001).

[33] H. Tou, Y. Kitaoka, K. Ishida, K. Asayama, N. Kimura, Y. Onuki, E. Yamamoto, Y. Haga, and K. Maezawa, Phys. Rev. Lett. **80**, 3129 (1998).

[34] K. Ishida, D. Ozaki, T. Kamatsuka, H. Tou, M. Kyogaku, Y. Kitaoka, N. Tateiwa, N. K. Sato, N. Aso, C. Geibel, and F. Steglich, Phys. Rev. Lett. **89**, 037002 (2002).

[35] H. Tou, K. Ishida, and Y. Kitaoka, J. Phys. Soc. Jpn. **74**, 1245 (2005).

[36] S. S. Saxena, P. Agarwal, K. Ahilan, F. M. Grosche, R. K. W. Haselwimmer, M. J. Steiner, E. Pugh, I. R. Walker, S. R. Julian, P. Monthoux, G. G. Lonzarich, A. Huxley, I. Sheikin, D. Braithwaite, and J. Flouquet, Nature (London) **406**, 587 (2000).

[37] D. Aoki, A. Huxley, E. Ressouche, D. Braithwaite, J. Flouquet, J.-P. Brison, E. Lhotel, and C. Paulsen, Nature (London) **413**, 613 (2001).

[38] Y. Maeno, H. Hashimoto, K. Yoshida, S. Nishizaki, T. Fujita, J. G. Bednorz, and F. Lichtenberg, Nature (London) **372**, 532 (1994); A. P. Mackenzie and Y. Maeno, Rev. Mod. Phys. **75**, 657 (2003).

[39] Y. Maeno, T. Ando, Y. Mori, E. Ohmichi, S. Ikeda, S. NishiZaki, and S. Nakatsuji, Phys. Rev. Lett. **81**, 3765 (1998).

[40] Z. Q. Mao, K. D. Nelson, R. Jin, Y. Liu, and Y. Maeno, Phys. Rev. Lett. **87**, 037003 (2001).

[41] R. Fittipaldi, A. Vecchione, R. Ciancio, S. Pace, M. Cuoco, D. Stornaiuolo, D. Born, F. Tafuri, E. Olsson, S. Kittaka, H. Yaguchi, and Y. Maeno, EPL **83**, 27007 (2008).

[42] S. Kittaka, S. Fusanobori, S. Yonezawa, H. Yaguchi, Y. Maeno, R. Fittipaldi, and A. Vecchione, Phys. Rev. B **77**, 214511 (2008).

[43] H. Aizawa, K. Kuroki, T. Yokoyama, and Y. Tanaka, Phys. Rev. Lett. **102**, 016403 (2009).

[44] A. B. Vorontsov, J. A. Sauls, and M. J. Graf, Phys. Rev. B **72**, 184501 (2005).

[45] T. Zhou and C. S. Ting, Phys. Rev. B **80**, 224515 (2009).

[46] H. Shimahara, J. Phys. Soc. Jpn. **69**, 1966 (2000).

[47] M. Cuoco, A. Romano, C. Noce, and P. Gentile, Phys. Rev. B **78**, 054503 (2008).

[48] K. Kuboki, J. Phys. Soc. Jpn. **70**, 2698 (2001).

[49] C.-R. Hu, Phys. Rev. Lett. **72**, 1526 (1994).

[50] Q. Wang, H.-Y. Chen, C.-R. Hu, and C. S. Ting, Phys. Rev. Lett. **96**, 117006 (2006).

[51] B. M. Andersen, A. Melikyan, T. S. Nunner, and P. J. Hirschfeld, Phys. Rev. Lett. **96**, 097004 (2006).

[52] T. Yokoyama and Y. Tanaka, Phys. Rev. B **75**, 132503 (2007).

[53] Q. Cui, C.-R. Hu, J. Y. T. Wei, and K. Yang, Phys. Rev. B **73**, 214514 (2006).