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PHYSICAL REVIEW LETTERS (2008), 100(11)

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Anomalous In-Plane Anisotropy of the Onset of Superconductivity in (TMTSF)$_2$ClO$_4$

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(Received 2 August 2007; published 17 March 2008)

We report the magnetic-field amplitude and field-angle dependence of the superconducting onset temperature $T_c^{\text{onset}}$ of the organic superconductor (TMTSF)$_2$ClO$_4$ in magnetic fields $H$ accurately aligned to the conductive $ab'$ plane. We revealed that the rapid increase of the onset fields at low temperatures occurs both for $H \parallel b'$ and $H \parallel a$, irrespective of the carrier confinement. Moreover, in the vicinity of the Pauli-limiting field, we report a shift of a principal axis of the in-plane field-angle dependence of $T_c^{\text{onset}}$. This feature may be related to an occurrence of Fulde-Ferrell-Larkin-Ovchinnikov phases.

DOI: 10.1103/PhysRevLett.100.117002

PACS numbers: 74.70.Kn, 74.25.Dw, 74.25.Fy, 74.62.-c

Since the discovery of the organic superconductors (TMTSF)$_2$X (where TMTSF stands for tetramethyl-tetrascalene-fuvalene, $X = \text{ClO}_4, \text{PF}_6$, etc.) [1,2], their superconductivity has been widely studied. Because of the strong anisotropy in the electrical conductivity of these materials [3], they provide excellent opportunities to study the properties of quasi-one-dimensional (Q1D) superconductors. One of the most important and controversial issues on the superconductivity of (TMTSF)$_2$X is the superconducting (SC) pairing symmetry [4]. In this Letter, we provide experimental results that contain new crucial clues to understand the SC symmetry of (TMTSF)$_2$ClO$_4$.

It has been suggested that the superconductivity of (TMTSF)$_2$X is unconventional through the NMR relaxation time $\tau$ and the impurity concentration dependence of the transition temperature $T_c$ [6]. However, its SC symmetry is still controversial. One key feature of the SC symmetry is their unusually high upper critical fields $H_{c2}(T)$. Lee et al. [7] reported that $H_{c2}(T)$ of (TMTSF)$_2$PF$_6$ determined from resistivity diverges as temperature decreases and $H_{c2}(T)$ reaches up to 80 kOe at the lowest temperatures when magnetic fields $H$ are applied parallel to the $b'$ axis (perpendicular to the most conductive $a$ axis in the $ab$ plane). In this field direction, carriers are confined in the $ab$ plane due to the field-induced dimensional crossover (FIDC) [4,8,9]. The FIDC suppresses the orbital pair-breaking effect and may allow the superconductivity to survive in higher fields. Interestingly, 80 kOe for $H_{c2} \parallel b'$ far exceeds the so-called Pauli-Clogston limit $H_P$ [10], which fulfills a relation $H_P/T_c = 18.4$ kOe/K for an isotropic gap, where singlet Cooper pairs are unstable because unpaired carriers have a lower energy due to the Zeeman effect. In the case of Ref. [7], $H_P$ was estimated to be 20 kOe. Similar results have been obtained in (TMTSF)$_2$ClO$_4$ by resistivity and magnetic torque measurements [11]. One interpretation attributes this survival of superconductivity above $H_P$ to a spin-triplet state [12,13]. On the other hand, in Q1D superconductors, even singlet superconductivity can be stable far above $H_P$ by forming a spatially modulating SC state [14,15], which is called the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state [16,17]. In 2002, Lee et al. [18] reported the absence of a change in the $^{77}$Se Knight shift of (TMTSF)$_2$PF$_6$ at $T_c$ under pressure, in favor of a triplet scenario. However, recently Shinagawa et al. [19] observed a clear change of the $^{77}$Se Knight shift of (TMTSF)$_2$ClO$_4$ at $T_c$ in lower fields. This finding motivated us to re-examine the possibility of singlet pairing in (TMTSF)$_2$X.

To resolve this puzzle, we are interested in the superconductivity in $H \parallel a$ and its in-plane anisotropy. Although not much attention has been paid to the superconductivity for $H \parallel b'$ so far, data for $H_{c2}(T) \parallel a$ of (TMTSF)$_2$PF$_6$ [7] look quite interesting: it has a steep slope near $H = 0$ but saturates when it reaches $H_P$ probably due to the Pauli effect, and it slightly increases again below 0.3 K. However, for (TMTSF)$_2$ClO$_4$ $H_{c2}(T) \parallel a$ was reported only above 0.5 K [20]. The in-plane anisotropy of $H_{c2}$ of (TMTSF)$_2$ClO$_4$ was also reported but only at 1.03 K [20], where $H_{c2}(T)$ is far below $H_P$.

In the present study, we revealed the rapid increase of the onset fields not only for $H \parallel b'$, where the electronic state becomes essentially 2D due to the FIDC, but also for $H \parallel a$, where the electronic state remains anisotropic 3D. We also observed new features of the in-plane anisotropy developing above 20 kOe, which provide a crucial step to understand the origins of the enhancement of $H_{c2}$, in terms of FFLO states.

We used single crystals of (TMTSF)$_2$ClO$_4$ grown by an electrowaxcrystallization technique, with dimensions of approximately $2.0 \times 0.2 \times 0.1 \text{ mm}^3$. We report here the results of the sample with the highest $T_c$ among up to 10 samples. We note that we obtained similar results in another sample. The resistance along the $c^*$ axis $R_{c^*}$ was measured using an ac four-probe method (the $c^*$ axis is perpendicular to the $ab'$ plane and is the least conductive direction) in a dilution refrigerator down to 80 mK. Temperature was measured using a RuO$_2$ resistance thermometer with magnetoresistance correction. Around 24 K, the anion ordering temperature of (TMTSF)$_2$ClO$_4$, a cool-
ing rate as slow as 2 mK/ min, was chosen to ensure that the whole sample is in the “relaxed state.” Magnetic fields are applied using the “Vector Magnet” system [21], with which we can control the field direction without mechanical heatings. The directions of the orthogonal crystalline axes (the a, b’, and c* axes) of the sample were determined from the anisotropy of Hc2 at 0.1 K. The accuracy of field alignment with respect to the ab’ plane and of the a axis within the ab’ plane are both better than 0.1°. We also determined the directions of the triclinic crystalline axes (the b and c axes) from angular magnetoresistance oscillations. The details of these procedures will be presented elsewhere. Hereafter, we denote the azimuthal angle within the ab’ plane as φ which is measured from the a axis. We defined φ so that the b axis lies in the quadrant 0° < φ < 90° as indicated in Fig. 1(a).

We first present Rc(T) in zero field in Fig. 1(a). Although Rc of this sample started to drop at as high as 1.45 K and reached zero at 1.30 K, Rc increases again below 0.8 K. This increase, which is almost independent of magnetic fields, is probably attributed to small cracks in the sample. The data of Rc(T) for H || b’ at 50 kOe are presented in Fig. 1(b). We observed a decrease of Rc below 0.2 K, consistent with a previous report [22]. In order to confirm that such a decrease is due to a superconducting contribution, we measured Rc(T) after adding a small out-of-plane component Hc = 0.5–1.0 kOe to the magnetic field. If this decrease is due to the superconductivity, Hc should suppress the superconductivity and eliminate the decrease of Rc(T). As plotted in Fig. 1(b), the decrease was indeed eliminated by adding Hc. Therefore, it was confirmed that the decrease of Rc(T) is a contribution of the superconductivity. Then we evaluated the conductance difference Δσ = Rc−1(Tc, Hc = 0) − Rc−1(Hc > 0) and defined the onset temperature Tonset as the temperature at which Δσ(T) exhibits a sharp increase, as marked by the small arrow in Fig. 1(b). This definition characterizes the very onset of superconductivity. We note that this anomaly in Δσ(T) is not due to the normal state magnetoresistance, because it is unlikely that an abrupt change in Δσ(T) occurs at a certain temperature. The definition has the advantage that Tonset is not affected by the extrinsic small increase of Rc because it is cancelled in the subtraction. For H || c*, Tonset(H) was determined similarly from the conductance difference Δσ(H) ≡ Rc−1(Hc = H) − Rc−1(Hc = H + ΔH).

The phase diagrams for H || a, H || b’, and H || c* are presented in Fig. 2. In the vicinity of H = 0, linear temperature dependences of the curves were observed for all field directions. Within a GL theory for a clean type-II superconductor, with a tight-binding model, the slope dHc2(T)/dT at Tc(H = 0) is related to the transfer integral t of each direction [23]. By taking into account the kz dependence and the nodes of the gap over the Fermi surface (FS), we obtain tua = 1200 K, tpb = 310 K, and tccc = 7.0 K from the initial slopes indicated by the broken lines in Fig. 2. These values agree favorably with realistic band parameters [3]. From these analyses, it is clear that Hc2(T) is governed by the orbital limitation at low fields in all three directions.

In higher fields, the behavior of these curves is qualitatively different. The curve for H || b’ keeps a linear T dependence up to 35 kOe and exhibits a rapid upturn in higher fields. This behavior is consistent with the “initial
cooled” curve in Ref. [11]. For $H \parallel a$, the curve apparently shows limiting behavior; this is consistent with the Pauli-limiting behavior with the estimated value of $H_p = 26.7$ kOe. Interestingly, a small kink of $\Delta \sigma(T)$ exists up to 50 kOe also for $H \parallel a$, as shown in Fig. 1(c). Consequently, the onset curve diverges for $H \parallel a$ at low temperatures, too. This is, to our knowledge, the first report of the low-temperature high-field phase diagram of (TMTSF)$_2$ClO$_4$ for $H \parallel a$. We note that we obtained similar phase diagrams for another sample. It is interesting that all three onset curves in Fig. 2 look similar to those for (TMTSF)$_2$PF$_6$ [7].

Next, we focus on how $T_c^{\text{onset}}$ changes when magnetic fields are rotated in the $ab'$ plane. The data are displayed in Fig. 3 using polar plots of $T_c^{\text{onset}}(\phi)$, where the direction of each point seen from the origin corresponds to the field direction and the distance from the origin corresponds to $T_c^{\text{onset}}$. At low fields, $T_c^{\text{onset}}(\phi)$ exhibits a sharp cusp at $\phi = 0^\circ (H \parallel a)$ and a broad minimum around $\phi = \pm 90^\circ (H \parallel b')$. These low-field results are consistent with $H_{c2}(\phi)$ reported by Murata et al. [20], although the sharp peak at $\phi = 0^\circ$ cannot be explained in an anisotropic 3D GL theory [24]. The chainlike crystal structure may play an important role in generating the sharp peak.

As the field increases above 20 kOe, dips of $T_c^{\text{onset}}(\phi)$ emerge at $|\phi| = \phi_{\text{dip}} = 17 \pm 1^\circ$. We note that $R_c(T)$ in the normal state exhibits nonmetallic $T$ dependence for $|\phi| > \phi_{3D-2D} = 19 \pm 1^\circ$ above 20 kOe, signaling the onset of the FIDC [8,9]. Because $\phi_{\text{dip}} \approx \phi_{3D-2D}$, we infer that these dips are related to the FIDC. When the dimensionality of the electronic system is lowered, superconductivity in in-plane magnetic fields becomes more stable because the orbital pair-breaking effect is suppressed. Thus $T_c^{\text{onset}}(\phi)$ should be enhanced for $|\phi| > \phi_{3D-2D}$, resulting in a minimum of $T_c^{\text{onset}}(\phi)$ around $\phi_{3D-2D}$.

The most important anomaly is that in magnetic fields above 30 kOe, the $b'$ axis is no longer a symmetry axis of $T_c^{\text{onset}}(\phi)$ and a new principal axis $X$ appears around $\phi = 70^\circ$ as indicated by the solid red lines in Fig. 3. Moreover, behavior of $T_c^{\text{onset}}(\phi)$ around $X$, a principal axis at high fields, and $b'$, a principal axis at low fields, is qualitatively different: at high fields $T_c^{\text{onset}}(\phi)$ is enhanced around $X$, while at low fields $T_c^{\text{onset}}(\phi)$ exhibits a broad minimum around the $b'$ axis. In addition, this $X$ axis tends to rotate toward the $b'$ axis as the field increases. At 47.5 kOe the deviation of $X$ from the $b'$ axis is reduced to about $10^\circ$. We checked that this change of symmetry is not due to a misalignment of the magnetic fields. In Fig. 4, we plotted the relative difference between $T_c^{\text{onset}}(+45^\circ)$ and $T_c^{\text{onset}}(-45^\circ)$ against the field strength. This quantity represents the asymmetry with respect to the $b'$ axis; thus, the appearance of $X$ results in finite values. Evidently, the asymmetry, i.e., $X$, is absent in lower fields and then starts to develop around $H_p$. Therefore, the appearance of $X$ cannot be attributed to conventional origins like an anisotropy of the Fermi velocity, because variation of $T_c^{\text{onset}}(\phi)$ from such origins should develop from $H = 0$.

We now discuss the origin of the new principal axis $X$, indicating the field direction in which $T_c^{\text{onset}}(\phi)$ is enhanced. Its appearance should be related to the Pauli pair-breaking effect, because $X$ appears at nearly $H_p$. In the case of singlet pairing, the appearance of $X$ is attributable to the formation of an FFLO state [16,17], in which the Cooper pairs have a finite wave vector $q_{\text{FFLO}}$. In a Q1D superconductor, the stability of this state is greatly enhanced by the nesting properties of its FS [25] and that $q_{\text{FFLO}}$ essentially matches the nesting vector between the spin-up and the spin-down FSs, which should be nearly parallel to the $a$ axis and should be independent of the field direction.

For $H \parallel b'$, it has been discussed using orthorhombic band structures that an FFLO state with $q_{\text{FFLO}} \parallel a$ becomes stable with a help of the FIDC [14,15]. Although we are not
We infer that a similar FFLO state might be stable near \( T_{0.0133} \). An FFLO state in a Q1D system in fields parallel to the \( H_c \) is evident from the steep slope of \( H_{c0} \) near \( T_{0.0133} \). The absence of the FIDC, the orbital-limiting field is much larger than \( H_p \) near \( T_{0.0133} \) at low temperatures, which is evident from the steep slope of \( H_{c0}(T) \) at \( H = 0 \) in Fig. 2. An FFLO state in a Q1D system in fields parallel to the most conductive axis has been proposed in a study of doped two-leg ladder cuprates using a \( t-J \) model [26]. We infer that a similar FFLO state might be stable near \( H \parallel a \), although a theory adapted to (TMTSF)_2ClO_4, a coupled chain system, needs to be developed. The recent NMR study, which reported that the density of states at the Fermi level recovers to the normal state value in the SC phase above 20 kOe for both \( H \parallel a \) and \( H \parallel b' \) [19], would support these FFLO scenarios.

On the other hand, if (TMTSF)_2ClO_4 is a triplet superconductor, polarized Cooper pair spins may cause an anisotropy of \( T_{c0}^{\text{onset}}(\phi) \). Assuming that the spins of the Cooper pairs are fixed to one direction, superconductivity is not affected by a Pauli effect when the field is exactly parallel to the spins, while it is suppressed for the other field directions. In this case, however, it seems difficult to explain the rotation of \( X \).

In summary, we have studied the in-plane anisotropy of \( T_{c0}^{\text{onset}} \) of (TMTSF)_2ClO_4. We observed that \( T_{c0}^{\text{onset}} \) remains finite up to 50 kOe for \( H \parallel a \), as well as for \( H \parallel b' \). We suggest that the field-induced dimensional crossover plays an important role for the enhancement of \( T_{c0}^{\text{onset}} \) when the field is tilted more than 17° from the \( a \) axis. In addition, one of the principal axes for superconductivity, which points along \( b' \) at low fields, shifts away from this direction around 30 kOe but evolves back toward the \( b' \) axis at higher fields. The survival of superconductivity far above \( H_p \) and the unusual in-plane anisotropy observed in the high-field regime suggest the stabilization of modulated superconducting phases when high fields are aligned to the \( ab' \) plane, in favor of a spin-singlet scenario. We speculate that two kinds of FFLO states are realized in this compound: the one predicted by Dupuis et al. [15] near \( H \parallel b' \) and the one related to the prediction by Roux et al. [26] for \( H \parallel a \), separated by the dips of \( T_{c0}^{\text{onset}}(\phi) \) around \( \phi \sim \pm 17^\circ \). We believe that theoretical studies taking into account the triclinic band structure are desirable to understand our results and reveal the SC symmetry of (TMTSF)_2X.

We acknowledge Y. Machida, N. Joo, and M. Kriener for their support and R. Ikeda, D. Poilblanc, G. Montambaux, and N. Dupuis for useful discussions. This work has been supported by a Grant in Aid for the 21st Century COE “Center for Diversity and Universality in Physics” from the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan. It has also been supported by Grants in Aids for Scientific Research from MEXT and from the Japan Society for the Promotion of Science (JSPS). S. Y. is financially supported by the JSPS.