Enhancement of the superconductivity and quantum metallic state in the thin film of superconducting Kagome metal \( \text{KV}_3\text{Sb}_5 \)

Teng Wang,1,2,3 Aobo Yu,1,2,4 Han Zhang,1,2,4 Yixin Liu,1,2,4 Wei Li,5 Wei Peng,1,2,4 Zengfeng Di,1,4 Da Jiang,1,2,4 and Gang Mu1,2,4

1State Key Laboratory of Functional Materials for Informatics, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, China
2CAS Center for Excellence in Superconducting Electronics(CENSE), Shanghai 200050, China
3School of Physical Science and Technology, ShanghaiTech University, Shanghai 201210, China
4University of Chinese Academy of Sciences, Beijing 100049, China
5State Key Laboratory of Surface Physics and Department of Physics, Fudan University, Shanghai 200433, China

Recently V-based Kagome metal attracted intense attention due to the emergence of superconductivity in the low temperature. Here we report the fabrication and physical investigations of the high quality single-crystalline thin films of the Kagome metal \( \text{KV}_3\text{Sb}_5 \). For the sample with the thickness of about 15 nm, the temperature dependent resistance reveals a Berezinskii-Kosterlitz-Thouless (BKT) type behavior, indicating the presence of two-dimensional superconductivity. Compared with the bulk sample, the onset transition temperature \( T_{\text{onset}} \) and the out-of-plane upper critical field \( H_{c2} \) are enhanced by 15% and more than 10 times respectively. Moreover, the zero-resistance state is destroyed by a magnetic field as low as 50 Oe. Meanwhile, the temperature-independent resistance is observed in a wide field region, which is the hallmark of quantum metallic state. Our results provide evidences for the existence of unconventional superconductivity in this material.

Materials with Kagome lattice manifest abundant exotic quantum phenomena including geometric spin frustration, non-trivial topological states, charge and spin density wave orders, etc.4,5 The discovery of superconductivity in the Kagome metal \( \text{AV}_3\text{Sb}_5 \) (A = K, Rb, Cs) added a new physical dimension to this novel system.6,7 Theoretically the unconventional pairing has been proposed for this material due to the proximity to the multiple van Hove singularities of the superconducting (SC) state.8 In the experimental side, the double-dome-shaped evolution of the SC transition temperature \( T_c \) with pressure has been confirmed by several groups.9,11 Concerning the gap structure, the conclusions from different techniques are still inconsistent.12,13 The observation of zero-bias conductance peak inside the vortex core indicates the possibility for the Majorana bound states.14 These experimental results initially show the signs of unconventional superconductivity. Currently more solid experimental results are necessary in order to confirm the unconventional behaviors of this material. It is an important perspective to investigate the physical performances in low dimension. Actually, in recent years, two-dimensional (2D) superconductivity has drawn great interest due to the emergence of new quantum phenomena, including Ising superconductivity,15,18 quantum metallic state,13,22,23,24 Berezinskii-Kosterlitz-Thouless (BKT) transition,22,24,25 and even the significant enhancement of \( T_c \).27,30 Thus, revealing the performance of SC properties in the low dimension is vary crucial in understanding the intrinsic properties of this material.

In this Letter, we report the mechanical exfoliation and superconducting properties of the thin film of \( \text{KV}_3\text{Sb}_5 \). Both the onset transition temperature \( T_{\text{onset}} \) and the out-of-plane upper critical field \( H_{c2} \) are enhanced significantly in the thin samples. Two-dimensional superconductivity is revealed by both the BKT-type resistance transition and the logarithmic evolution of the flux-flow activation energy. Strikingly, a transition from the superconducting to quantum metallic state is induced by a very small perpendicular magnetic field (\( \sim 50 \) Oe), while the onset transition point is only moved to about 0.5 K by the magnetic field as high as 6000 Oe. The present work reveals the unconventional behaviors in Kagome superconductors and also provides an important platform to study the dimensionality effect of this system.

The \( \text{KV}_3\text{Sb}_5 \) single crystals were grown by the self-flux method.4 Utilizing the characteristics of layered structure, the mechanical exfoliation method was adopted. The \( \text{KV}_3\text{Sb}_5 \) thin flake was exfoliated from its single crystal by scotch tape and transferred onto \( \text{SiO}_2/\text{Si} \) substrate (\( \text{SiO}_2 \)-300 nm; \( \text{Si} \)-500 \( \mu \)m)31. Typically the in-plane dimension of the fabricated samples can be as large as 200 \( \mu \)m. All the studies in this work are carried out on samples with a thickness of 15 nm. The electrical transport data were collected on the dilution refrigerator based on the electrical property measurement system (Quantum Design, PPMS) by a standard four-probe method, and the silver paste was used to prefabricate the electrodes. The external magnetic field was applied perpendicular to sample surface and the electric current. The applied electric current is 10 \( \mu \)A.

Temperature dependence of resistance of the thin \( \text{KV}_3\text{Sb}_5 \) sample is shown in Fig. 1. The thickness of this sample is estimated to be 15 nm from the comparison of the resistance of the thin and bulk samples. A SC transi-
The BKT transition temperature is determined to be
of KV
3
bulk sample [6] is also shown for comparison (right axis). Th e
described by the equation [32, 33],
binding of vortex-antivortex pairs. As shown by the red
on this picture, the zero-resistance state is driven by the
KosterlitzThouless (BKT) transition [22, 26, 32]. Based
materials, which were explained in terms of the Berezinskii-
vealing a tail-like feature in a wide temperature range.

R
exp[−(1)
(2)
where
k_B
is the Boltzmann constant and
U
is the ther-
ally activated energy of the flux flow. Th us
U(H)
 can be obtained from the slope of this linear part in the
Arrhenius plot. The acquired
U(H)
at various mag-
netic fields from 50 to 6000 Oe are summarized in Fig.
3(b). It is found that
U
is proportional to −lnH (see the
dashed line in Fig. 3(b)). Theoretically it was pointed
out that [36, 37], the activation energy is determined by
the free energy barriers to create a single free dislocation
when the vortex translational correlation length is small
ough. In this case, the logarithmic relationship can be
pected. Th us our observations here strongly imply the
2D liquid state for the vortices.

With the increase of
1/T,
the resistance becomes con-
stant, which is independent of temperature. Similar
omena have been reported in other 2D SC systems and
are considered as a hallmark of the quantum metallic
state [13, 22]. Such a metallic state in the vicinity of SC
region could not be understood in the classic framework.
Different theories have been proposed to interpret this
dissipation in the low temperatures. Typically the differ-
ent models can be distinguished by the magnetic field de-
pendent behaviors of the saturated resistance at low tem-
peratures. By considering the temperature-independent

FIG. 1: (color online) Temperature dependence of resistance of KV
Sb
thin film at zero magnetic field. Th e data of the
bulk sample [6] is also shown for comparison (right axis). Th e red
line is the fitting curve representing the BKT transition (see text).
Shown in the lower right inset is the same data using a semilog scale.

below out-of-plane magnetic field. As shown in Fig. 2(a),
the
R−T
curves show the systematically evolution with
the increase of field. Th ese data provide three impor-
tant messages that need to be emphasized in particular.
Firstly, as shown in Fig. 2(b), the magnetic field as high
as 6000 Oe suppresses the onset transition temperature
(T
onset
(determined using the criterion 99% R_n)
from 1.5
K to 0.5 K, which indicates a rather high upper critical
field above 6000 Oe. Th is value is more than 10 times
higher than that of the bulk samples [6]. Secondly, the
zero-resistance state is destroyed by the magnetic field as
low as 50 Oe, suggesting a very narrow flux solid state
(if it exists). Thirdly, the temperature-independent resis-
tance is observed in a very wide field range from 50
to 6000 Oe, which is a hallmark of the quantum metal-
state [19, 22]. Th ese striking features unambiguously
demonstrate the dimensional effect of this system.

In order to further understand the unconventional tempera-
ture-independent behavior of the
R−T
curves, we plot
the Arrhenius plots (ln
R
vs 1/T) under several
typical fields in Fig. 3(a). Ln
R
shows a transforma-
tion from the linear evolution to the 1/T-independent ten-
dency with the increase of 1/T, which are represented by
the dashed and dotted lines respectively. Th e intersec-
tions of the dashed and dotted lines are used to
determine the transition temperature between the two behaviors.

The linear relation is the consequence of the thermal ac-
tivated flux flow (TAFF) behavior, where the resistance
R
obeys the relationship [34, 35]

R = R_0 \exp\left(-\frac{U}{k_BT}\right),
(2)
which demonstrates the occurrence of BKT transition.

Th e BKT transition temperature is determined to be
T_{BKT} = 0.08 K. Th e BKT-type behavior suggests pre-
liminarily that 2D superconductivity is achieved at zero
magnetic field in our sample. Considering the fact that
the upper critical field is only several hundred osters in
the bulk sample [6], the coherence length should be rel-
atively large. Th us, it’s rather reasonable that a film
with the thickness of 15 nm can meet the requirement of
two-dimensional limit.

We next focus on the electrical transport behaviors un-
quantum metallic state should follow \[ R \propto \exp\left[ A \left( \frac{H}{H_{c2}} - 1 \right) \right]. \] (3)

On the other hand, a Bose metallic (BM) phase, where the interacting Cooper pairs form a gapless non-superfluid liquid, was also proposed \[20, 39\]. Based on this model, the unbinding of quantum dislocation-antidislocation pairs due to strong gauge field fluctuations will give rise to

\[ R \propto \left( H - H_{c0} \right)^{2\nu_0}, \] (4)

where \( H_{c0} \) is the critical field for SC-BM transition. With a careful analysis, we found that Eq. (3) deviates seriously from the experimental results in a wide field range (see the red dashed line in Fig. 3(c)). The exponent \( \nu \) is determined to be 0.34. The value of critical field \( H_{c0} \) (47 Oe) is quite reasonable, because the metallic state can be induced by the lowest field in our experiment, 50 Oe. The above analysis shows that the present system is more consistent with the theoretical model based on Bose metal.

Based on the above observations, we can draw the field-temperature phase diagram of the thin KV\(_3\)Sb\(_5\), which is shown in Fig. 4. A true zero-resistance state is not observed under the lowest field of our experiment, 50 Oe. Thus we didn’t indicate the SC region in this diagram. From the magnetoresistance data in Fig. 3(c), we found that the critical field for the SC-BM transition is 47 Oe at 0.1 K. This means indirectly that there may exist a very narrow SC region under low fields. Another remarkable
The boundary between the quantum metallic and TAFF states is determined from the $R-T$ data using the criterion of 99% $R_n$. The boundary between the quantum metallic and TAFF states is determined by the black arrows shown in Fig. 3(a). The red arrow indicates the value of upper critical field for the bulk sample. The temperature-independent behavior of the resistance onset SC transition temperature, 2D-featured thermal activation energy, and the BKT-type resistance transition are more than 10 times as compared with the bulk sample. The upper critical field exceeds that of the bulk sample (see the red arrow in Fig. 4) by more than 10 times. The origin of the such unconventional observations, especially the possible correlation to the exotic electronic structure, is a very important topic for the theoretical realm in the future.

In summary, we successfully obtained the thin samples of the Kagome metal KV$_3$Sb$_5$ with the thickness down to 15 nm by using a mechanical exfoliation method. The dimensionality effect was observed in terms of the higher onset SC transition temperature, 2D-featured thermal activated energy, and the BKT-type resistance transition. Moreover, the upper critical field is enhanced by more than 10 times as compared with the bulk sample. The temperature-independent behavior of the resistance can be described by the model based on Bose metallic state. Our results provide a very unique and suitable platform to investigate the dimensionality effect in unconventional Kagome superconductors.

**Acknowledgements**

This work is supported by the National Natural Science Foundation of China (Nos. 11204338 and 51925208) and the Youth Innovation Promotion Association of the Chinese Academy of Sciences (No. 2015187).
[21] D. Ephron, A. Yazdani, A. Kapitulnik, and M. R. Beasley, Phys. Rev. Lett. 76, 1529 (1996).
[22] Y. Saito, Y. Kasahara, J. Ye, Y. Iwasa, and T. Nojima, Science 350, 409 (2015).
[23] Y. Qin, C. L. Vicente, and J. Yoon, Phys. Rev. B 73, 100505 (2006).
[24] V. L. Berezinskii, Sov. Phys. JETP 32, 493 (1971).
[25] J. M. Kosterlitz and D. J. Thouless, J. Phys. C 6, 1181 (1973).
[26] N. Reyren, S. Thiel, A. D. Caviglia, L. F. Kourkoutis, G. Hammerl, C. Richter, C. W. Schneider, T. Kopp, A.-S. Rüetschi, D. Jaccard, et al., Science 317, 1196 (2007).
[27] A. Gozar, G. Logvenov, L. F. Kourkoutis, A. T. Bollinger, L. A. Giannuzzi, D. A. Muller, and I. Bozovic, Nature 455, 782 (2008).
[28] Q.-Y. Wang, Z. Li, W.-H. Zhang, Z.-C. Zhang, J.-S. Zhang, W. Li, H. Ding, Y.-B. Ou, P. Deng, K. Chang, et al., Chin. Phys. Lett. 29, 037402 (2012).
[29] J. Pan, C. Guo, C. Song, X. Lai, H. Li, W. Zhao, H. Zhang, G. Mu, K. Bu, T. Lin, et al., J. Am. Chem. Soc. 139, 4623 (2017).
[30] Y. Yang, S. Fang, V. Fatemi, J. Ruhman, E. Navarro-Moratalla, K. Watanabe, T. Taniguchi, E. Kaxiras, and P. Jarillo-Herrero, Phys. Rev B 98, 035203 (2018).
[31] D. Jiang, T. Hu, L. You, Q. Li, A. Li, H. Wang, G. Mu, Z. Chen, H. Zhang, G. Yu, et al., Nat. Commun. 5, 5708 (2014).
[32] C. Xu, L. Wang, Z. Liu, L. Chen, J. Guo, N. Kang, X.-L. Ma, H.-M. Cheng, and W. Ren, Nat. Mater. 14, 1135 (2015).
[33] B. I. Halperin and D. R. Nelson, J. Low Temp. Phys. 36, 599 (1979).
[34] V. M. Vinokur, M. V. Feigel’man, V. B. Geshkenbein, and A. I. Larkin, Phys. Rev. Lett. 65, 259 (1990).
[35] H. Zhang, Y. Fang, T. Wang, Y. Liu, J. Chu, Z. Li, D. Jiang, G. Mu, Z. Di, and F. Huang, Phys. Rev. B 103, L180503 (2021).
[36] M. Feigel’man, V. Geshkenbein, and A. Larkin, Physica C: Superconductivity 167, 177 (1990).
[37] W. R. White, A. Kapitulnik, and M. R. Beasley, Phys. Rev. Lett. 70, 670 (1993).
[38] E. Shimshoni, A. Auerbach, and A. Kapitulnik, Phys. Rev. Lett. 80, 3352 (1998).
[39] D. Das and S. Doniach, Phys. Rev. B 64, 134511 (2001).