

Quantum fluctuations-driven melting transitions in two-dimensional superconductors

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Quantum fluctuations are pivotal in driving quantum phase transitions, exemplified by the quantum melting of Wigner crystals into Fermi liquids in electron systems. However, their impact on superconducting systems near zero temperature, particularly in the superconductor-insulator/metal transition, remains an open question. In this study, through electric transport measurements on the two-dimensional (2D) superconductor (SnS)_{1.17}NbS₂, we demonstrate that quantum fluctuations induce vortex displacement from their mean position, leading to the quantum melting of vortex solid near zero temperature. Quantitative analysis suggests the magnetic field-induced anomalous metal originates from this quantum melting transition, with energy dissipation governed by quantum fluctuations-driven vortex displacements. Remarkably, further extending this analysis to various 2D superconductors yields the same results, and many properties of anomalous metal can be qualitatively understood within the framework of quantum melting. The connection between the quantum melting of vortex solids and dissipative anomalous metal opens a pathway toward understanding quantum phase transitions through vortex dynamics, providing insights on both fields.

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I. INTRODUCTION

Stemming from the uncertainty principle, quantum fluctuations play a critical role in the various physical phenomena, spanning from the cosmic microwave background of the Universe [1] down to spontaneous photon emission of a single atom [2]. Thereinto, quantum phase transitions (QPT) driven by quantum fluctuations have been widely studied in cold atomic gases [3], magnetic materials [4], and superconductors [5–7], resulting from a competition between two ground states. However, in 2D superconducting systems, this direct QPT scenario is disrupted by an intermediate bosonic anomalous metal state located in the quantum critical region of

the superconductor-insulator or metal transition (SIT/SMT) [7–10]. The temperature-independent residual resistance in the anomalous metallic state has been observed in various 2D superconductors [9,11–16], raising the natural question of whether quantum fluctuations can drive a finite dissipative state at zero temperature.

Energy dissipations in type-II superconductors typically arises from mobile vortices [17]. Although the dynamics of mobile vortices at finite temperature is well understood through the thermal melting of vortex solids [18–20], their zero-temperature behavior remains poorly explored due to the unresolved role of quantum fluctuations [21]. Analogous to the quantum melting of Wigner crystal in electron systems [22,23], quantum fluctuations in superconductors could similarly melt vortex solids at zero temperature. Mobile vortices are generated in this quantum melting transition, leading to a dissipative state near zero temperature with a subtle connection to the elusive anomalous metallic state [7]. Yet, experimental evidence for quantum melting of vortex solids remains scarce, and the role of quantum fluctuations in driving dissipative state remains largely uncharted.

In this study, we investigate the field-tuned SMT in the 2D superconductor, (SnS)_{1.17}NbS₂, through systematic transport measurements. Our results point to quantum melting

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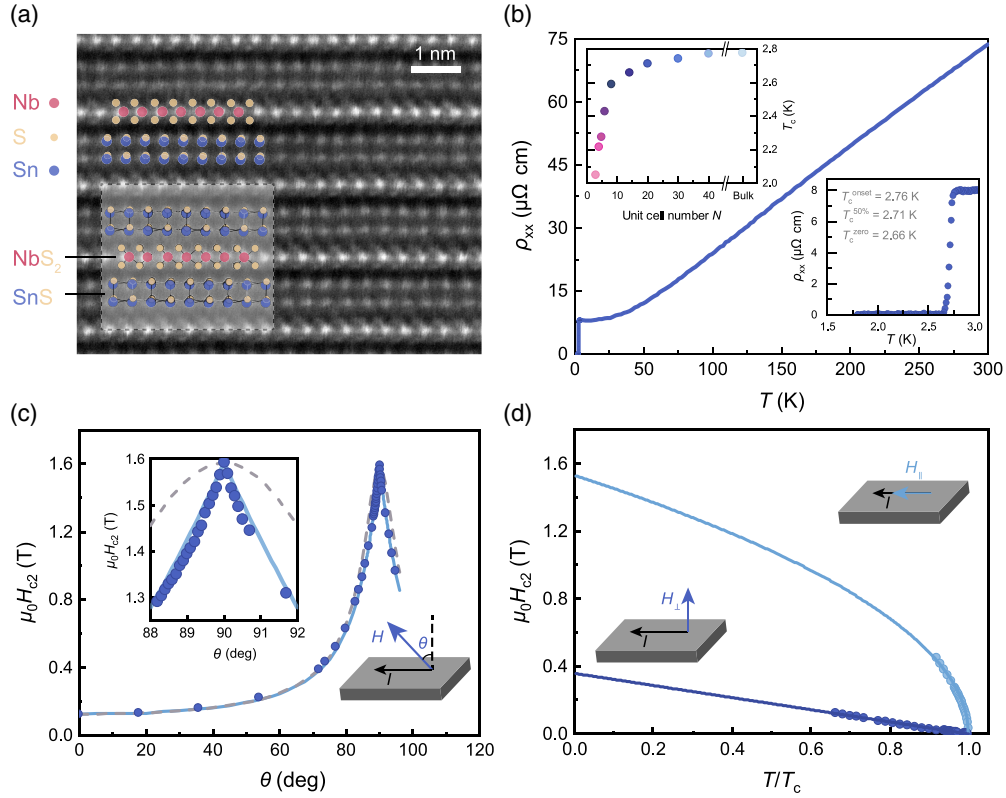


FIG. 1. Two-dimensional superconductivity in superlattice $(\text{SnS})_{1.17}\text{NbS}_2$. (a) HAADF-STEM image of the $(\text{SnS})_{1.17}\text{NbS}_2$ taken along the $[010]$ axis (scale bar, 1 nm). A simulation of the model structure is overlaid. Sn, S, and Nb atoms are depicted as blue, yellow, and red circles, respectively. (b) Sheet resistance as a function of temperature $\rho_{xx}(T)$ in $(\text{SnS})_{1.17}\text{NbS}_2$. Upper inset: Thickness dependence of the T_c in $(\text{SnS})_{1.17}\text{NbS}_2$. Lower inset: $\rho_{xx}(T)$ near the superconducting transition. (c) Angular dependence of upper critical field $\mu_0 H_{c2}(\theta)$ measured at $T = 1.8$ K, which is defined by the field when resistance reaches 90% R_N . The solid curve and dash-dotted line are the theoretical representations of the 2D Tinkham model and the 3D anisotropic Ginzburg-Landau model. (d) Temperature dependence of perpendicular upper critical field $\mu_0 H_{c2\perp}$ and parallel upper critical field $\mu_0 H_{c2\parallel}$. Solid curves are theoretical curves obtained from the 2D Ginzburg-Landau equations.

of vortex solid as a reasonable mechanism dominating the zero-temperature transport property. By identifying a linear correlation between the mobile vortex density in the anomalous metal and the vortex displacements driven by quantum fluctuations, we consider the transition toward anomalous metal is a quantum melting transition. Extending this analysis to other reported field-tuned SMTs uncovers a similar relation, implying that anomalous SMTs in diverse materials share a common origin associated with the quantum melting of vortex solid. The framework of quantum melting provides new insights into many puzzling properties of anomalous metal, enriching the understanding of the interplay between quantum fluctuations and exotic quantum phases in 2D superconductors.

II. RESULTS

A. Two-dimensional superconductivity in $(\text{SnS})_{1.17}\text{NbS}_2$

The $(\text{SnS})_{1.17}\text{NbS}_2$ single crystal is fabricated by chemical vapor transport (CVT) [24,25]. Figure 1(a) shows a cross section of the structure imaged by high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) with the model structure superimposed. The transition metal dichalcogenides (TMD) layer NbS_2 is sandwiched between

incommensurate SnS layers, which is also confirmed by the single crystal x-ray diffraction (Fig. S2 in the Supplemental Material [26]). According to the density functional theory calculations, the intercalated SnS layer induces band degeneracy which leads to the rearrangement of energy levels near the Fermi level (Fig. S3 in the Supplemental Material [26]). Thin crystalline flakes can be exfoliated from the bulk by the Scotch tape method, and electric transport measurements were conducted by measuring four-probe voltages in a Hall barlike device configuration. Figure 1(b) illustrates the temperature dependence of resistivity $\rho_{xx}(T)$ near the superconducting transition for a 50 nm thick $(\text{SnS})_{1.17}\text{NbS}_2$ flake. The mean-field transition temperature T_c was determined as the temperature when resistance reaches 50% normal state resistance (R_N). The upper inset of Fig. 1(b) shows the monotonic reduction of T_c with decreasing the unit-cell number N , which follows the expected trend in niobium containing transition metal dichalcogenides.

Magnetoresistance measurements were performed to investigate the dimensionality of the superconductivity in $(\text{SnS})_{1.17}\text{NbS}_2$ [27]. Figure 1(c) demonstrates the angular-dependent upper critical field $\mu_0 H_{c2}(\theta)$ follows the 2D Tinkham model [28], $(H_{c2}(\theta) \sin \theta / H_{c2\parallel})^2 + |H_{c2}(\theta) \cos \theta / H_{c2\perp}| = 1$, instead of anisotropic 3D Ginzburg-

Landau model $H_{c2}(\theta) = H_{c2\parallel} / [\sin^2\theta + (H_{c2\parallel}\cos\theta/H_{c2\perp})^2]^{1/2}$. Additionally, Fig. 1(d) also indicates that the temperature dependance of the $\mu_0 H_{c2\parallel}$ and $\mu_0 H_{c2\perp}$ follows the 2D Ginzburg-Landau (GL) behavior:

$$\mu_0 H_{c2\perp} = \frac{\Phi_0}{2\pi\xi_{GL}^2(0)} \left(1 - \frac{T}{T_c}\right), \quad (1)$$

$$\mu_0 H_{c2\parallel} = \frac{\Phi_0\sqrt{12}}{2\pi\xi_{GL}(0)d_{SC}} \sqrt{1 - \frac{T}{T_c}}, \quad (2)$$

where Φ_0 is the flux quantum, $\xi_{GL}(0)$ is the zero-temperature GL coherence length, and d_{SC} is the temperature-independent superconducting thickness. These features clearly confirm the 2D nature of the superconductivity in $(\text{SnS})_{1.17}\text{NbS}_2$.

B. Resistive transition toward field-induced anomalous metal

The intrinsic ground state of $(\text{SnS})_{1.17}\text{NbS}_2$ was investigated in heavily filtered dilution refrigerators. The combination of Thermocoax and resistor-capacitor filter reduces the initial noise power to $\sim 0.001\%$ (-50 dB) in the MHz range, and the applied current is 100 nA to eliminate the self-heating effect. Thus, the extrinsic origin of the resistance saturation can be excluded (Figs. S5 and S6 in the Supplemental Material [26]). As the dimensionless magnetic field, $b = B/B_{c2,T=0}$, exceeds a threshold, the superconductivity is suppressed and residual resistance appears near zero temperature. Here we define this threshold as the onset magnetic field b_{AM} of the anomalous metal, denoting the minimal dimensionless magnetic field required to induce detectable resistance at zero temperature. Figures 2(a) and 2(b) present resistance transition of $R_{\text{sheet}}(T)$ under different perpendicular fields of a thick ($N = 22\text{UC}$) and a thin ($N = 3\text{UC}$) sample, respectively. Crucially, the vanishing Hall effect measured within this phase confirms that the saturated resistance cannot originate from classical percolation, in which normal-state regions in a superconducting background generate finite resistance (Figs. S7 and S8 in the Supplemental Material [26]).

Prior to the onset of the anomalous metal, the deviation from thermally assisted flux-flow (TAFF) at low temperature has been a perplexity since its initial discovery [11,29,30]. Below we show that the exponential behavior of the TAFF is replaced by a power-law scaling at low temperature. Figures 2(a) and 2(b) illustrate that the transition towards the anomalous metal in two independent samples both follow a three-step process. At high temperature, the resistance obeys the TAFF behavior, $R(T) = R_0 e^{-U(B)/k_B T}$, where k_B is Boltzmann's constant and the $U(B)$ is the field-dependent activation energy [29,31]. Below the T_{cross} (Fig. S9 in the Supplemental Material [26]), the system deviates the TAFF and enters a regime described by the power-law scaling, $R(T) = R_{AM} + A \cdot T^s$, where R_{AM} is the residual resistance of the anomalous metal, s is the extracted exponent, and A is a numeric factor. Further cooling results in the resistance saturation, $R(T) = R_{AM}$, with the onset temperature of saturation marked by T_{AM} (Fig. S10 in the Supplemental Material [26]).

Figure 3(a) shows the magnetic dependence of T_{AM} . Figure 3(b) shows the extracted exponent s of the relation $R(T) = R_{AM} + A \cdot T^s$ under different magnetic field, with value roughly in the range of 2.7 ± 0.9 . This observed

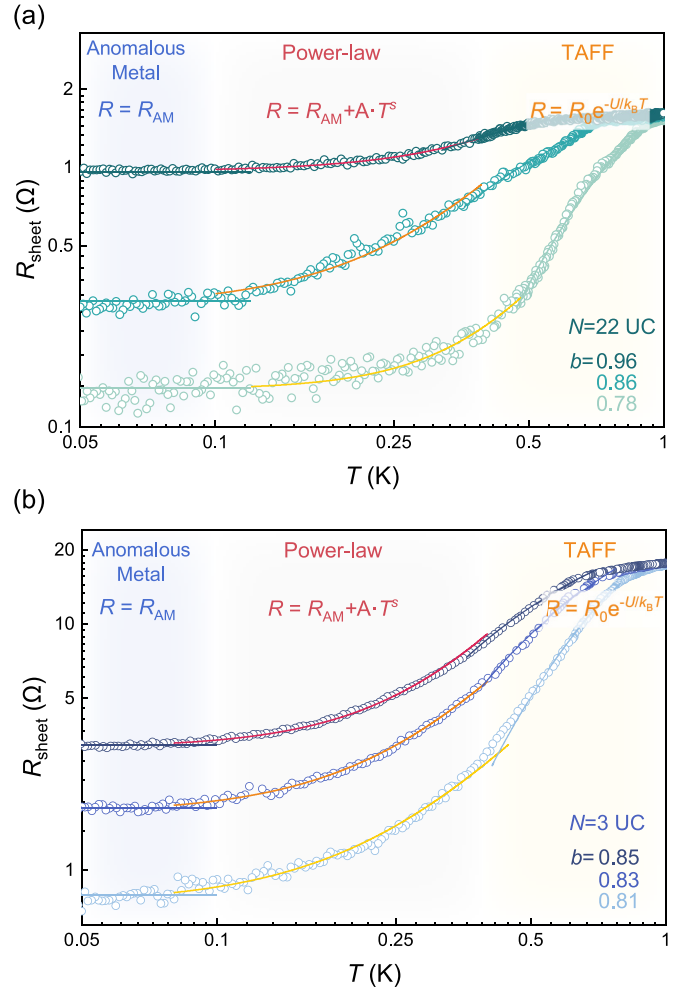


FIG. 2. Anomalous metal, power-law, and TAFF regimes in $(\text{SnS})_{1.17}\text{NbS}_2$. (a), (b) Three-step resistance transitions of the $R_{\text{sheet}}(T)$ of a thick (sample 1) and a thin (sample 2) $(\text{SnS})_{1.17}\text{NbS}_2$ flake at various perpendicular magnetic fields. In each regime, the $R_{\text{sheet}}(T)$ is well fitted by the corresponding formulas in the figures (solid lines).

power-law dependance prior to the resistance saturation is reminiscent of that in the vortex glass melting transition driven by thermal fluctuations [17,18]. In the seminal work by Fisher, Fisher, and Huse [18], they derived the so-called Fisher-Fisher-Huse scaling expression of the critical behavior during the vortex glass melting, $R(T) \propto (T - T_g)^s$, where the s is the critical exponent and T_g is the glass melting temperature. Theoretical work and numerical simulations yield the critical exponent s within the range of $2.7 \sim 8.5$ [17,32], whereas the experimentally observed s locates in the range of $0.6 \sim 8.0$ [17,33]. The extracted exponent s in our samples mostly falls in the range of $1.8 \sim 3.6$, therefore, we imply the observed power-law resistivity plausibly associated with the thermal melting of vortex glass occurring at $T_g = 0$.

C. Quantum melting of vortex solid at zero temperature

The influence of quantum fluctuations gradually overwhelms thermal fluctuations as the temperature approaches zero, but how quantum fluctuations induce the anomalous

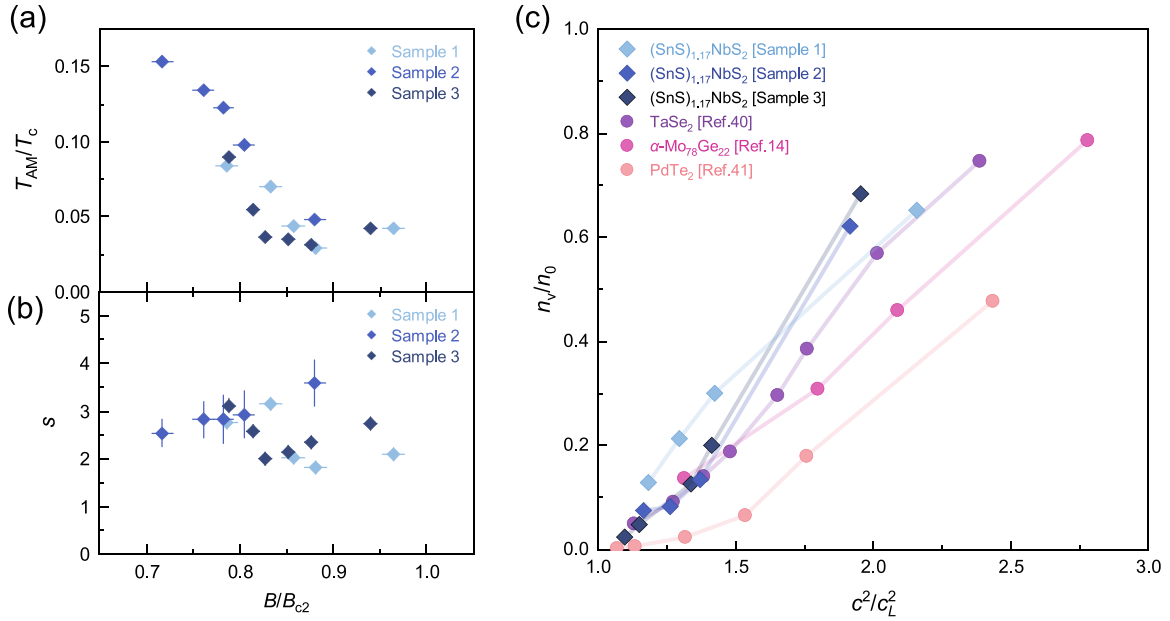


FIG. 3. Quantum melting transitions to field-induced anomalous metals. (a) Field-dependence of T_{AM} and (b) extracted component s in three independent $(\text{SnS})_{1,17}\text{NbS}_2$ samples. (c) Correlations between the n_v/n_0 and c^2/c_L^2 in different $(\text{SnS})_{1,17}\text{NbS}_2$ flakes, $\text{Mo}_{78}\text{Ge}_{22}$ films [14], $4H\alpha\text{-TaSe}_2$ flakes [40], and PdTe_2 films [41].

metal remains an open question [5–7]. Generally, the dissipation in a type-II superconductor originates from the vortex motion. Various theoretical models have proposed that mobile vortex contribute to the finite dissipation in the anomalous metal [8,34,35], which was recently supported by Nernst measurements at low temperatures [14,36]. Thus, incorporating vortex dynamics is critical to understanding the field-induced anomalous metal. However, the origin of the mobile vortices near zero temperature—the key to uncover the emergence of the field-induced anomalous metal—has been barely studied. Given that the anomalous metal is a ground state within the quantum critical region of the SMT, it is essential to evaluate how quantum fluctuations destabilize the vortex solid. For the magnetic field-tuned SMT, quantum fluctuations may melt the vortex lattice in analogy to thermal melting at finite temperatures. This process, termed quantum melting of vortex solid, has recently been linked to the field-induced anomalous metallic state [7]. In this work, we demonstrate that mobile vortices in the zero-temperature anomalous metal arise from the quantum melting of vortex solid [19–21].

To establish the occurrence of quantum melting of vortex solids, two criteria should be addressed: (i) “quantum:” the transition must occur near zero temperature, where thermal fluctuations are negligible and quantum fluctuations dominate. (ii) “melting:” the transition must satisfy the Lindemann melting criterion. Since the magnetic field-tuned SMT occurs near zero temperature, we focus on proving that the SMT is a melting transition. Below we show that the experimentally measured mobile vortex density scales linearly with the theoretically calculated vortex vibration displacements—a hallmark of melting transitions.

Thermal-melting transitions at finite temperature are well studied, where the pinned vortices are mobilized by thermal fluctuations and cause dissipation. However, the

zero-temperature property cannot be extrapolated from the finite-temperature theories due to the absence of thermal fluctuations. Instead, quantum fluctuations are considered to induce a dissipative quantum vortex liquid once the magnetic field exceeds a threshold ($b > b_{AM}$) [7,21,37]. In the seminal theoretical work of Blatter *et al.* [21], they suggest that quantum fluctuations lead pinned vortices vibrate around their mean position at zero temperature, rendering them “fuzzy” with effectively enlarged cores. These vibrations are quantified by the zero-temperature mean squared displacement $\langle u^2 \rangle$:

$$\frac{\langle u^2 \rangle}{\xi^2} = \frac{4}{\pi^2} \frac{R_s}{R_Q} f_0(b),$$

$$f_0(b) = \frac{1}{4} \int_0^1 dx \left\{ \ln \left(1 + \frac{\beta^2}{x^2} \right) + \ln \left(1 + \frac{\beta^2 x^2}{(x^2 + \alpha)^2} \right) \right\}. \quad (3)$$

Here, ξ is the superconducting coherence length, R_s is the sheet resistance, R_Q is the resistance quantum, and $f_0(b)$ is a function of dimensionless magnetic field b with parameters $\alpha = 4/b(1-0.3b)$ and $\beta = 8/[\pi b(1-b)^2(1-0.3b)]$.

According to the Lindemann criterion [19–21], a vortex solid undergoes melting transition when the ratio between the vortex vibration displacements $\langle u^2 \rangle^{1/2}$ and vortex lattice constant a_0 , $c = \langle u^2 \rangle^{1/2}/a_0$, exceeds the Lindemann number c_L . To compare results across different devices and materials, the dimensionless parameter c^2/c_L^2 is used to quantify the quantum melting transition, rather than the material details-dependent $\langle u^2 \rangle^{1/2}$. Therefore, the extent of the melting transition can be theoretically described as follows:

$$\frac{c^2}{c_L^2} = \frac{b}{b_{AM}} \frac{f_0(b)}{f_0(b)|_{b=b_{AM}}}. \quad (4)$$

The normalized vortex displacement c^2/c_L^2 quantifies the extent to which the quantum fluctuations melt the vortex solid, with $c^2/c_L^2 = 1$ marking the threshold for quantum melting. As the quantum melting transition proceed, c^2/c_L^2 increases, and an increasing fraction of pinned vortices become mobile.

To establish that the field-induced transition to the anomalous metal is a quantum melting transition, the above-mentioned vortex displacement should scale with the experimentally measured mobile vortex density. Mobile vortices naturally lead dissipation [38], and the corresponding resistance $R_v = \hbar^2 \pi^2 \mu n_v / e^2$, where $\hbar$ is the reduced Planck constant, e is the electronic charge, and μ is the vortex mobility. For the dirty-limit superconductor $(\text{SnS})_{1.17}\text{NbS}_2$, the vortex mobility follows the Bardeen-Stephen relation, $\mu = 2e^2 \xi_{\text{GL}}^2 R_N / \hbar^2 \pi$ [39], enabling experimental extraction of $n_v(B)$ from the magnetoresistance of anomalous metal, $n_v(B) = R_{\text{AM}}(B) B_{c2, T=0} / \Phi_0 R_N$. While the total vortex density $n_0 = B / \Phi_0$ increase linearly with magnetic field, the mobile vortex density n_v may increase trivially with B . Thus, analyzing the proportion of mobile vortex in the anomalous metal is critical to determine whether the mobile vortices originate from proceeding melting transition. The dimensionless parameter, the proportion of mobile vortex n_v/n_0 , can be read as

$$\frac{n_v}{n_0} = \frac{R_{\text{AM}}(b)}{R_N} \frac{1}{b} \quad (5)$$

with n_0 denoting the vortex density ($n_0 = a_0^{-2} = B / \Phi_0$ and a_0 is the lattice constant of the Abrikosov vortex lattice).

For demonstrating that the magnetic field-tuned SMT is a quantum melting transition, the experimentally measured proportion of mobile vortex n_v/n_0 must correlate with the theoretically calculated vortex vibration displacements c^2/c_L^2 . Figure 3(c) shows the correlation between the n_v/n_0 and c^2/c_L^2 in $(\text{SnS})_{1.17}\text{NbS}_2$ samples. The mobile vortex proportion n_v/n_0 increases linearly with normalized vortex displacements c^2/c_L^2 in three independent samples. This linear correlation suggests quantum fluctuations-induced vortex displacements render pinned vortices mobile. Given that the superconductor-anomalous metal transition in $(\text{SnS})_{1.17}\text{NbS}_2$ can be characterized by Lindemann melting criterion, we propose the anomalous metal may originate from the quantum melting of vortex solid.

Moreover, the abovementioned analysis can also be conducted in other different systems, such as amorphous films ($\text{Mo}_{78}\text{Ge}_{22}$ [14]) and crystalline materials ($4\text{H}\alpha\text{-TaSe}_2$ [40], PdTe_2 [41]). Surprisingly, as shown in Fig. 3(c), even with orders of magnitude variations in R_N and B_{c2} , all systems exhibit a similar linear relation between n_v/n_0 and c^2/c_L^2 . This ubiquitous linear correlation among various 2D superconductors suggests that the quantum melting of the vortex solid is likely a reasonable mechanism to quantitatively explain the field-induced anomalous metal in 2D superconductors.

III. DISCUSSION

In Fig. 4(a), we construct a comprehensive B - T phase diagram to illustrate the quantum melting transition toward

anomalous metal. Phase boundaries are defined as follows: The onset of the vortex solid corresponds to the point where resistance drops below 5% R_N [blue pentagons in Fig. 4(a)]. The plausible-thermal melting onset temperature T_{cross} [orange diamonds in Fig. 4(a)] is identified when the measured resistance deviates by 5% from the TAFF prediction, $R_s(T)/R_{\text{TAFF}}(T) > 1.05$. The vortex liquid regime spans the region where resistivity follows TAFF behavior, extending from $T_c(B)$ to $T_{\text{cross}}(B)$.

Starting with the superconducting vortex solid at zero temperature [blue region in Fig. 4(a)], the anomalous metal [purple region in Fig. 4(a)] can be approached via increasing magnetic field at zero temperature [blue arrow in Fig. 4(a)]. Around zero temperature, the pinned vortex vibrates due to the quantum fluctuations [21]. As the vortex vibration displacement $\langle u^2 \rangle^{1/2}$ exceeds a critical value $c_L a_0$, a proportion of vortex becomes mobile and the anomalous metal emerges [Fig. 4(b)]. Further increasing magnetic field leads more pinned vortex melting into mobile vortex [Fig. 4(c)]. In addition, when increasing the temperature, thermal fluctuation starts depinning vortex. As the anomalous metal is “heated up” at a fixed magnetic field [red arrow in Fig. 4(a)], the system undergoes a plausible thermal melting transition with a power-law resistivity. Further increasing temperature leads to the appearance of the conventional vortex liquid state where the TAFF behavior is recovered. Therefore, the deviation of TAFF at low temperature, known as the characteristic of the field-induced anomalous metal [11,29,30], can be understood by the occurrence of melting transitions of vortex solid.

Besides, other properties of the field-induced anomalous metal can be understood based on the abovementioned scenario. Since the quantum fluctuation strength is irrelevant to the temperature and thermal fluctuations is negligible near zero temperature [17,21], the mobile vortex proportion remains unchanged with decreasing temperature, and thus the resistance of anomalous metal is temperature independent [7]. Moreover, due to rare occurrence probability of the quantum melting when magnetic field slightly exceeds b_{AM} , the mobile vortex density can be arbitrarily low, giving rise to a resistance of anomalous metal much lower than the R_N [7]. As the magnetic field increases, more pinned vortices are dislodged by quantum fluctuations [Fig. 4(c)], leading to the giant positive magnetoresistance. Furthermore, pinned vortices are softened by quantum fluctuations-induced vortex displacements, and thus the anomalous metal is extremely sensitive to external perturbations [40,42]. For instance, softened pinned vortex can be easily dislodged by excess Lorentz force [17,43], leading to a current-dependent resistance in the anomalous metal [17,40,43].

Next, we discuss the peculiarity of the quantum melting. Figure 4(b) illustrates this melting transition with the notion of Lindemann criterion. Compared to the thermal melting, the quantum melting is associated with the quantum fluctuations-induced time-dependent vortex motion [21]. In thermal melting, a vortex is dislodged once thermal fluctuations overcomes the pinning potential [17,18,44], hence this process is irrelevant to time. However, in the quantum melting

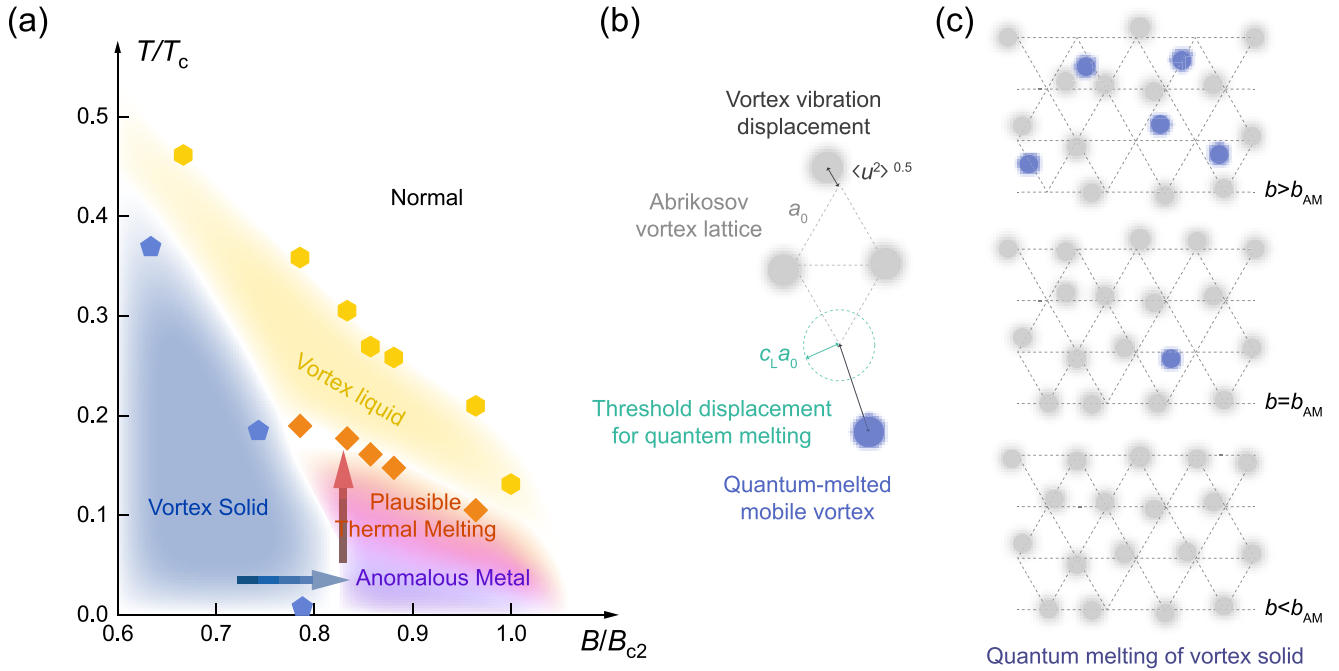


FIG. 4. Phase diagrams and schematics of quantum melting transitions of vortex solid. (a) The B - T phase diagram of the $(\text{SnS})_{1.17}\text{NbS}_2$ sample 1. Yellow hexagons divide the TAFF from the normal state. Blue pentagons denote the onset of superconducting vortex solid states. Orange diamonds divide the TAFF with an exponential resistivity and a plausible thermal-melting regime with a power-law resistivity mark the crossover from TAFF into the thermal melting transition. The purple region denotes the anomalous metallic state, in which the resistance is temperature independent. Blue arrows demonstrate the quantum melting transition, respectively. (b) The schematic of the quantum melting as described by the Lindemann criterion. Gray circles denote the pinned vortex. Blue circles denote the quantum melted mobile vortex. Black arrows denote the vortex vibration displacement $\langle u^2 \rangle^{1/2}$. Green arrow indicates the threshold displacement $c_L a_0$ for the occurrence of quantum melting. (c) The schematic of the occurrence of quantum melting of vortex solids with increasing magnetic field, where b_{AM} is the onset magnetic field of the anomalous metal.

process, the quantum fluctuations-induced vortex displacement is correlated in time domain, and a vortex can be mobile or pinned at different time [21]. This quantum fluctuations-induced motion of vortex leads to the occurrence of phase fluctuations both in spatial and temporal domain. Moreover, the inhomogeneity of the system can lead to inhomogeneous distribution of quantum fluctuation strength and the spatial variation of the quantum melting probability. Specifically, for $(\text{SnS})_{1.17}\text{NbS}_2$, the inhomogeneity might result from the crystallographic disorder due to the misfit between the SnS and adjacent NbS_2 layer. However, considering different materials shares a similar linear correlation shown in Fig. 3(c), a more general interpretation is needed to account for the origin of inhomogeneity in the QPT, such as the emergent granularity [45,46].

In conclusion, we have presented experimental evidence of the field-induced anomalous metal in a two-dimensional superconductor, $(\text{SnS})_{1.17}\text{NbS}_2$. The transition between the superconductor and anomalous metal can be interpreted as the quantum melting of vortex solid at zero temperature. This scenario offers a general understanding for the field-induced anomalous metal in various superconducting systems, which establishes an unprecedented link between quantum phase transition and vortex dynamics that could influence the way of thinking in both fields.

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J.X., H.L., and P.L. conceived the study and supervised the project. D.Q. and P.L. fabricated the samples. D.Q., Y.T., and H.W. performed the experimental measurements in dilution refrigerators. D.Q., P.L., D.Z., and C.Z. performed the angular magnetoresistance measurements. Y.W., G.R., P.L., Y.Z., X.J., and X.Z. conducted crystal growth and characterization. D.Z. and Y.Z. performed the density functional theory calculations. D.Q., H.L., P.L., Y.C., and J.X. analyzed the data. D.Q., H.L., J.X., and Y.L. wrote the manuscript with comments from J.Q. and Z.C.

The authors declare no competing interests.

DATA AVAILABILITY

All data that support the findings of this study are available in the article and the Supplemental Material. The source data have been deposited in figshare at [47].

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