



Pressure-induced Lifshitz and quantum phase transitions in electron-doped cuprate superconductors

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We report observations of a pressure-induced Lifshitz transition coupled with a quantum phase transition in the electron-doped cuprate superconductor $\text{Pr}_{0.87}\text{LaCe}_{0.13}\text{CuO}_{4\pm\delta}$, by combining high-pressure electrical resistance, Hall coefficient (R_H), and synchrotron X-ray diffraction (XRD) measurements at low temperatures. Our low-temperature Hall coefficient (R_H) measurements reveal that the R_H decreases continuously and reaches zero at ~ 10 GPa (critical pressure of P_{c1}). Upon further compression beyond P_{c1} , R_H unexpectedly changes its sign from negative to positive, signaling a reconstruction of the Fermi surface from electron-dominated to hole-dominated topology. Concurrently, the superconducting transition temperature (T_c) exhibits a monotonic suppression, vanishing completely at ~ 17.6 GPa (critical pressure of P_{c2}), where the system enters a nonsuperconducting metallic state. Our low-temperature XRD measurements unequivocally demonstrate the absence of any structural phase transition across P_{c1} and P_{c2} . Therefore, the sign change in R_H at P_{c1} is associated with a Lifshitz transition, which is never found in the compressed bulk electron- or hole-doped cuprate superconductors. Moreover, the quantum phase transition observed at P_{c2} contrasts sharply with known high-pressure behavior of hole-doped cuprates, uncovering a fundamental difference on how pressure tunes the ground states of electron- vs. hole-doped systems. These findings provide crucial insights into the different pressure responses on the interplay among Fermi surface topology, electronic correlations, and superconductivity between these two kinds of cuprate superconductors.

superconductivity | high-pressure | quantum phase transition

Although four decades have passed since the discovery of high- T_c superconductivity in copper-oxide (1), a unified understanding of its underlying mechanism has yet to be achieved (2–8). It is well known that the two control parameters, chemical doping and external pressure, can effectively tune the superconductivity. To date, doping effects on both hole- and electron-doped cuprates have been extensively investigated, providing valuable insights into the complex phenomena and physics of these materials (5, 8–19). Currently, what we know is that the undoped parent compounds of these high- T_c superconductors are antiferromagnetic (AFM) Mott insulators. As electron or hole carriers are introduced through doping, the AFM state is suppressed and then the superconductivity emerges (1, 7, 8, 16, 18, 20, 21). By contrast, applying pressure to the undoped parent compound does not appear to induce a transition from the AFM to the superconducting state, as no such a case has been reported to date. Although pressure has a limited influence on the AFM state, its impact on the superconducting state of hole-doped cuprates is significant. Notable examples include the pressure-induced enhancement of T_c (22–27) and the emergence of new phenomena in hole-doped cuprates (28–30). However, high-pressure studies on superconductivity of electron-doped cuprates remain remarkably unexplored (31–34). In this study, we report systematic investigation on the superconductivity of the electron-doped cuprate superconductor $\text{Pr}_{0.87}\text{LaCe}_{0.13}\text{CuO}_{4\pm\delta}$ (PLCCO), through high-pressure and low-temperature measurements of Hall coefficient, synchrotron X-ray diffraction, and resistance.

Results

Superconductivity Under Pressure. First, we performed high-pressure resistance measurements on the superconducting PLCCO single crystals. As shown in (Fig. 1 A–D and SI Appendix), the superconducting transition temperature (T_c) of the five samples displays slight variation upon increasing pressure up to ~ 10 GPa, above which T_c begins to decrease monotonically. Zero resistance is maintained up to 15.3 GPa. However, between

Significance

Tuning the electronic ground state of high-temperature superconducting cuprates is a key issue for understanding the underlying mechanism of superconductivity. Here, we present evidence of two distinct pressure-induced electronic transitions in an electron-doped cuprate superconductor. At the first critical pressure, a Lifshitz transition takes place, characterized by a change in Fermi surface topology. At a second critical pressure, the system undergoes a quantum phase transition from a superconducting to a metallic state. This behavior contrasts with that of hole-doped cuprates and highlights the distinct pressure response of electron-doped systems. Using an effective two-band model, we show the pivotal role of Fermi surface topology in governing both the process of quantum phase transitions and the stability of superconductivity.

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The authors declare no competing interest.

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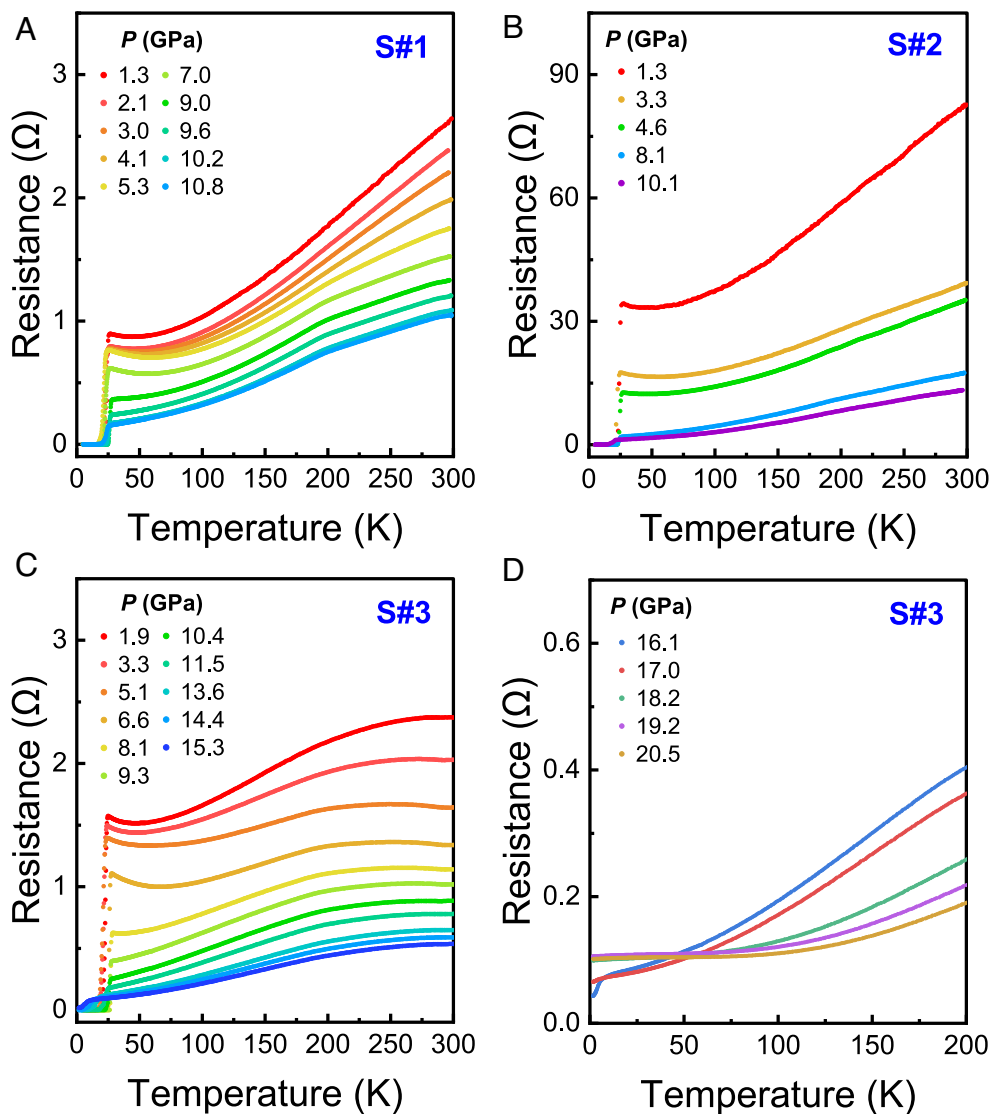


Fig. 1. Transport properties of the $\text{Pr}_{0.87}\text{LaCe}_{0.13}\text{CuO}_{4+\delta}$ single crystals at different pressures. Temperature dependence of in-plane resistance in the pressure range of (A) 1.3 to 10.8 GPa for sample 1 (S#1); (B) 1.3 to 10.1 GPa for sample 2 (S#2); (C) 1.9 to 15.3 GPa for sample 3 (S#3); (D) 16.1 to 20.5 GPa for sample 3 (S#3).

15.3 and 16.1 GPa, the samples lose zero-resistance (Fig. 1 C and D), indicating the suppression of the superconducting state. Upon further compression, the superconducting state is completely suppressed and replaced by a metallic state. This continuous evolution from a superconducting (SC) to a metallic (M) ground states provides strong evidence for a quantum phase transition (QPT).

Previous work by Butch et al. (35) established that such a quantum phase transition can be tuned by doping in the $\text{La}_{2-x}\text{Ce}_x\text{CuO}_4$ system, where the low-temperature normal-state resistivity evolves from a T -linear behavior in the superconducting doping regime to a T^2 dependence in the nonsuperconducting regime. However, our high-pressure results reveal a markedly different temperature dependence of the normal-state resistivity (Fig. 1 and SI Appendix), suggesting that the effects of pressure and doping are not the same. This discrepancy warrants further investigation to elucidate the underlying physics.

Hall Resistance Under High Pressure and Low Temperature. Next, we conducted high-pressure Hall resistance (R_{xy}) measurements, a powerful technique for probing Fermi surface properties

in a metal (36), by sweeping the magnetic field (B) from 0 to 5 T perpendicular to the ab plane of single-crystal sample 3 (S#3) and sample 4 (S#4) at 40 K. Unexpectedly, a sign change in $R_{xy}(B)$ from negative to positive was observed between 9.3 and 10.4 GPa for S#3 (Fig. 2A) and above 9.9 GPa for S#4 (Fig. 2B). Based on the results from the experiments conducted over the two runs, we estimate the critical pressure (P_{c1}) associated with this sign change to be around 10 GPa. It is found that, although electron carriers dominate conduction below 10 GPa, the contribution of hole carriers is significantly enhanced upon increasing pressure.

High-Pressure and Low-Temperature Structure Information. To investigate whether the pressure-induced change in the dominant carrier type and the suppression of superconductivity in PLCCO are associated with any pressure-induced structural phase transition, we perform the high-pressure and low-temperature synchrotron X-ray diffraction (XRD) measurements on the PLCCO sample (Fig. 3), which has not been performed before. The XRD patterns were collected at 40 K, the same as the temperature used for the Hall resistance measurements. In these experiments, the sample was cooled from 300 K down to 40 K, then the XRD patterns were

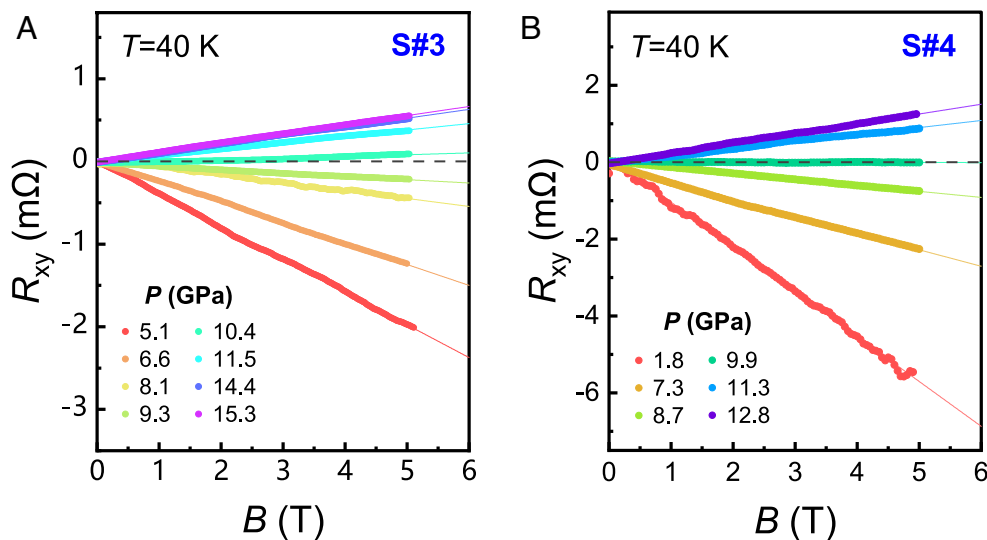


Fig. 2. Hall resistance (R_{xy}) as a function of magnetic field (B) at 40 K for the $\text{Pr}_{0.87}\text{LaCe}_{0.13}\text{CuO}_{4\pm\delta}$ superconductors. (A) R_{xy} vs. B for sample 3 in the pressure range of 5.1 to 15.3 GPa. (B) R_{xy} vs. B for sample 4 in the pressure ranges of 1.8 to 12.8 GPa. A crossover from an electron- to hole- dominant carrier behavior is observed in both samples.

collected under pressure starting at 1.4 GPa. As shown in Fig. 3A, the sample crystallizes in the tetragonal T' phase with space group $I4/mmm$ for pressures ranging from 1.4 GPa to 20.7 GPa, which encompasses the critical pressure for the sign change in R_{xy} (B). Given that the diffraction peaks of the T' phase remain clearly visible and show systematic shifts to higher 2θ values over the pressure range investigated, we propose that the sample remains in the T' phase up to 20.7 GPa (Fig. 3B). We then extracted the lattice parameters a and c at each pressure point and plotted them in Fig. 3C, revealing a continuous reduction with increasing pressure. These results confirm the absence of any pressure-induced structural phase transition within the studied pressure range. Thus,

all changes observed in the high-pressure transport measurements are most likely of electronic origin.

It is worth noting that our room-temperature high-pressure XRD measurements reveal a different behavior from that observed at low temperature. Specifically, a partial transition from the T' phase to the T phase starts at ~ 9.3 GPa (SI Appendix). Upon further compression, the T' phase and T phase coexist up to 41.4 GPa. The same phenomenon was also reported previously (34, 37). These observations suggest that the low-temperature T' phase becomes metastable beyond the critical pressure (P_c) as the temperature increases (SI Appendix). At low temperatures, the system lacks sufficient thermal energy to overcome the energy barrier,

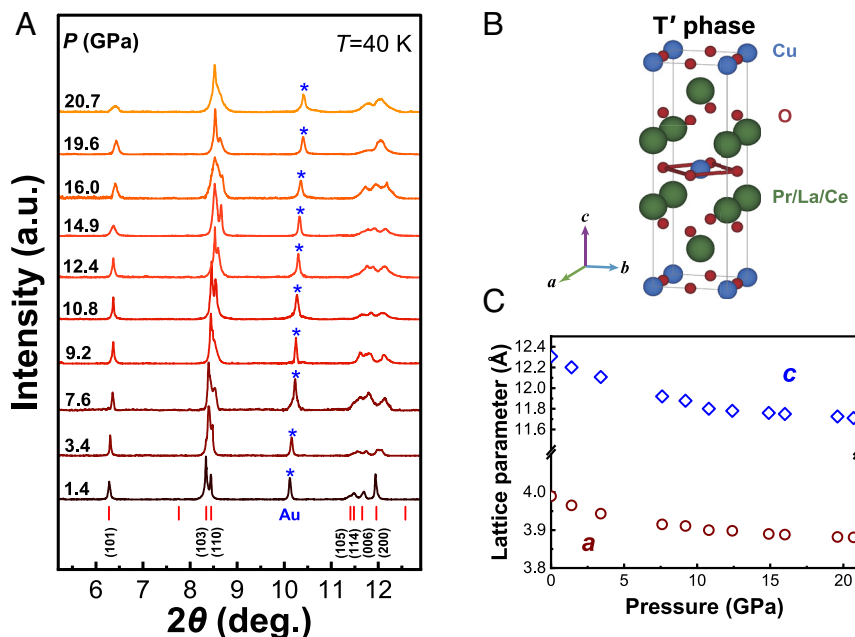


Fig. 3. High-pressure structural information of $\text{Pr}_{0.87}\text{LaCe}_{0.13}\text{CuO}_{4\pm\delta}$ superconductors obtained at 40 K. (A) X-ray diffraction patterns collected in the pressure range of 1.4 to 20.7 GPa. Peaks corresponding to the sample are indexed with Miller indices at the bottom. Given that gold (Au) was placed in the sample chamber to serve as an internal pressure calibrant, its diffraction peak (as indicated by the blue star) was observed. (B) Crystal structure of the tetragonal T' phase, showing the positions of Cu (blue), O (red), and rare earth elements Pr/La/Ce (green) atoms in the tetragonal $I4/mmm$ structure. (C) Pressure dependence of lattice parameters a and c for PLCCO in the T' phase, displaying continuous compression of the lattice parameters with increasing pressure up to 20.7 GPa. The ambient-pressure data in Fig. 3C is extrapolated from our high-pressure and low-temperature measurements.

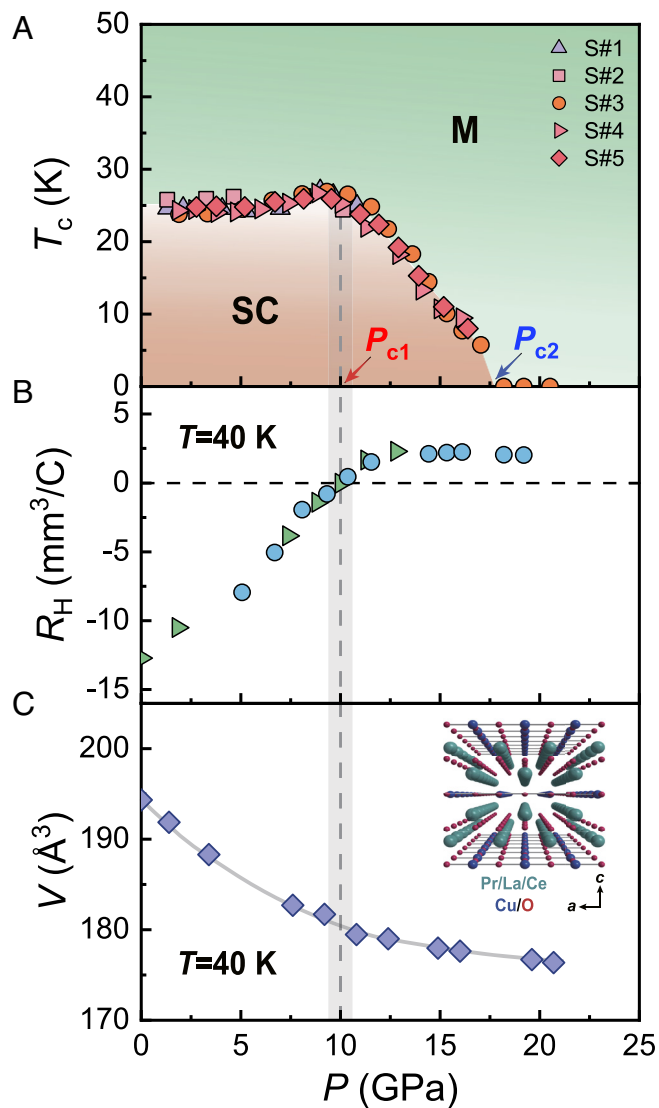


Fig. 4. Pressure dependence of superconducting transition temperature (T_c), Hall coefficient (R_H), and unit cell volume (V) for $\text{Pr}_{0.87}\text{LaCe}_{0.13}\text{CuO}_{4.86}$ superconductors. (A) T_c as a function of pressure for five PLCCO samples (S#1 to S#5). Below P_{c1} (~ 10 GPa), T_c exhibits a small variation with increasing pressure. Above P_{c1} , a clear suppression of superconductivity is observed, with T_c decreasing monotonically from $\sim 25 \pm 1.5$ K at 10 GPa down to 10 K at 15.3 GPa. At P_{c2} (~ 17.6 GPa), T_c disappears completely and a metallic state sets in. (B) Pressure dependence of Hall coefficients (R_H) obtained at 40 K, showing a sign change from a large negative value (~ -12.7 mm^3/C , estimated by an extrapolation of the data from S#4) at ambient pressure to a positive value above P_{c1} , and then shows a steady state between P_{c1} and P_{c2} . (C) Unit cell volume (V) as function of pressure at 40 K, showing continuous compression, from ~ 195.9 $\text{\AA}^3$ at ambient pressure to ~ 176.4 $\text{\AA}^3$ at 20.7 GPa, without structural phase transitions. The *Inset* of Fig. 4C illustrates the schematic crystal structure of PLCCO in the T' phase. The vertical dashed line marks the critical pressures (P_{c1}) where a Lifshitz transition takes place. The ambient-pressure data in Fig. 4B and C are extrapolated from our high-pressure and low-temperature measurements.

thereby becoming trapped in the metastable T' phase. However, as the temperature rises to room temperature, thermal fluctuations considerably affect its stability, driving the transformation toward the T phase (SI Appendix).

Pressure-Temperature Phase Diagram. We summarize our experimental results for PLCCO in the pressure-temperature phase diagram (Fig. 4A), which is established from our resistance measurements on different samples (S#1 to S#5, the data for S#5 is provided in SI Appendix), along with the results from

high-pressure Hall coefficient and XRD measurements at 40 K (Fig. 4). The diagram reveals that T_c displays a small variation below P_{c1} (~ 10 GPa), while the value of R_H exhibits a continuous decrease from a large negative value (~ -12.7 mm^3/C) at ambient pressure to zero at P_{c1} (Fig. 4B). At $R_H = 0$, the electron and hole carrier concentrations are balanced. Upon further compression, R_H changes its sign from negative to positive. Since no crystal structure phase transition occurs at low temperature within the pressure range investigated (Fig. 4C), the high-pressure behavior observed in PLCCO is attributed to the pressure-induced reconstruction of the Fermi surface (FS). Such a Fermi surface reconstruction is commonly known as a Lifshitz transition (38, 39). The doping-induced Lifshitz transition has been observed in both bulk and film forms of hole-doped cuprates (40–42), and a similar doping-driven transition has also been reported in electron-doped cuprate films (43–45). However, no investigation of such a pressure-induced transition has yet been carried out. Observation of a pressure-induced Lifshitz transition in the bulk electron- and hole-doped cuprate superconductors. Analysis of our high-pressure and low-temperature XRD measurements find that the lattice parameter c of the sample is compressed by approximately 0.6 $\text{\AA}$ at P_{c1} , which is nearly six times larger than that of the lattice parameter a (~ 0.1 $\text{\AA}$) at the same pressure. These results suggest that the Lifshitz transition observed here may be associated with the pressure-induced anisotropic lattice reductions.

Above P_{c1} , T_c decreases monotonically with increasing pressure and eventually vanishes at P_{c2} [taking the average of two adjacent points gives $P_{c2} = (17.0 \text{ GPa} + 18.2 \text{ GPa})/2 = 17.6$ GPa], beyond which the system enters a nonsuperconducting metallic ground state. This behavior is consistent with a superconducting (SC)-to-metallic (M) quantum phase transition (QPT). In the pressure range between P_{c1} and P_{c2} , the Hall coefficient (R_H) remains positive and displays pressure-independent behavior (Fig. 4B). The observation that R_H saturates while T_c continues to decline suggests that the progressive suppression of superconductivity above P_{c1} is not driven by further changes in carrier type or Fermi surface topology. Conversely, once the Lifshitz transition is complete and hole-type carriers dominate the system, further compression primarily diminishes the effective pairing interaction, resulting in a steady suppression of superconductivity. The phase diagram indicates that the Lifshitz transition at P_{c1} and the SC-M QPT at P_{c2} represent two pressure-driven electronic transitions in PLCCO.

Theoretical Calculations and Discussion. To better understand the correlation between superconducting transition temperature (T_c) and Hall coefficient (R_H) across the critical pressures in PLCCO, we employed an effective two-band model based on upper (UHB) and lower (LHB) Hubbard bands to calculate the evolution of band structure with pressure, incorporating the pressure-dependent parameters of the superconducting pairing strength (J) in the LHB and the band splitting (R) between the LHB and UHB (SI Appendix). In this model, the superconducting order parameter is introduced only in the hole-pocket sector of the LHB, whereas the electron pocket does not participate directly in pairing. The FS reconstruction associated with R compresses the hole-like Fermi-surface sector and thereby suppresses the superconducting gap. Given that pressure intrinsically enhances the orbital hopping integral t , we model J/t and R/t as continuously decreasing with pressure, while R/t vanishes at P_{c1} , signaling a Lifshitz transition accompanied by FS reconstruction. The calculated zero-temperature superconducting gap Δ (in units of $|t_1|$) is shown in Fig. 5, with insets displaying the corresponding FS below and above P_{c1} . Below P_{c1} , electron- and hole-pockets coexist on the FS, where the essence of electron doping intrinsically enlarges the

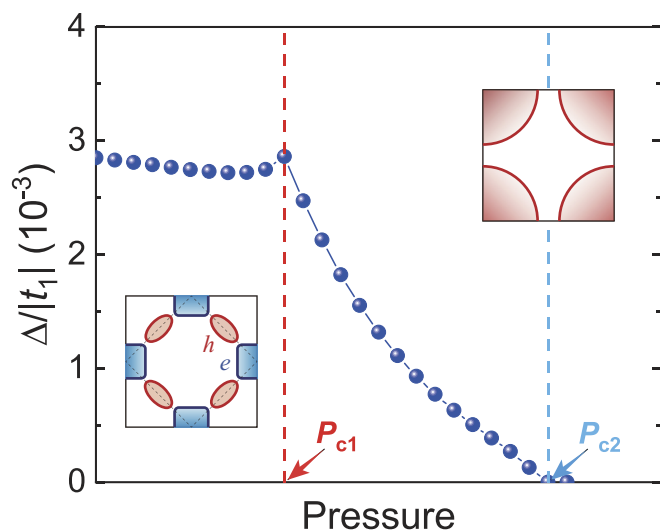


Fig. 5. Results of theoretical calculations. The variation of zero-temperature superconducting gap Δ (in units of $|t_1|$) across a Lifshitz transition at P_{c1} and quantum phase transition at P_{c2} . The insets display the corresponding electron- (blue) and hole- (red) type pockets on FS below and above P_{c1} .

electron pocket, leading to a negative R_H . As pressure reduces R , the compression of the hole-like Fermi-surface sector is relieved, which tends to enhance superconductivity on the hole pocket. At the same time, the reduction of the pairing strength J suppresses superconductivity. The competition between these two effects naturally stabilizes T_c below P_{c1} . Beyond P_{c1} , the distinct electron- and hole- pockets fully merge into a single hole-dominated FS, resulting in a saturated positive R_H . Once this Lifshitz transition is completed, further pressure produces little additional change in Fermi-surface topology, whereas the continued reduction of J continuously suppresses superconductivity until it vanishes entirely at P_{c2} . These trends are in excellent agreement with our experimental observations.

Although pressure drives superconductivity toward a QPT in both electron- and hole-doped cuprates, their nonsuperconducting ground states and QPT natures are markedly different. Hole-doped systems become insulating-like under pressure (29), while PLCCO in this study transitions to a metallic state. Additionally, the pressure-induced Lifshitz transition observed in electron-doped cuprates is absent in hole-doped ones (29). These differences extend to their fragility and decoherence: hole doping yields an insulating ground state with a resistance upturn at low temperatures, whereas electron doping results in a metallic state with saturated resistance. Together, these observations suggest that a full understanding of high- T_c superconductivity requires considering not just pairing interactions, but also how superconductivity is destroyed and what follows. They also reveal that pressure

does not simply act as a generic bandwidth-control parameter in cuprates. Its effect depends strongly on the initial electronic structure, carrier type, and lattice environment of the CuO_2 planes.

In conclusion, this work presents the observation of a pressure-induced Lifshitz transition and superconducting-to-metallic quantum phase transition in the bulk electron-doped cuprate superconductor PLCCO through high-pressure and low-temperature Hall and XRD measurements, along with high-pressure resistance measurements. Our results reveal a sign change in R_H at P_{c1} (~ 10 GPa), a clear signature of a Fermi surface reconstruction from electron- to hole-dominated topology, alongside only a slight variation in T_c . Low-temperature XRD measurements confirm the absence of any structural phase transition across P_{c1} , firmly establishing the purely electronic origin of this Lifshitz transition. Above P_{c1} , T_c decreases and vanishes at P_{c2} (~ 17.6 GPa), leading to a quantum phase transition from a superconducting state to a metallic state. Our findings demonstrate the pivotal role of Fermi surface topology in governing both the process of quantum phase transitions and the stability of superconductivity. Furthermore, they impose essential constraints for developing a unified theoretical description of the superconductivity in both the hole- and electron-doped cuprate families.

Data, Materials, and Software Availability. The data supporting the conclusions of this study are included in the article and its [Supplementary Information](#). All primary data (high pressure transport properties, Hall resistance as a function of magnetic field at 40 K, high-pressure structural information obtained at 40 K, pressure dependence of superconducting transition temperature, Hall coefficient, and unit cell volume for the investigated samples, and theoretical calculation data) will be deposited in Figshare and made publicly available at <https://doi.org/10.6084/m9.figshare.33876445> (46). All other data are included in the manuscript and/or [SI Appendix](#).

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