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# Hall coefficient diagnostics of surface state in pressurized $\text{SmB}_6$

Yazhou Zhou<sup>1</sup>, Priscila F. S. Rosa<sup>2,3</sup>, Jing Guo<sup>1</sup>, Shu Cai<sup>1</sup>, Rong Yu<sup>4</sup>, Sheng Jiang<sup>5</sup>,  
Ke Yang<sup>5</sup>, Aiguo Li<sup>5</sup>, Qimiao Si<sup>6</sup>, Qi Wu<sup>1</sup>, Zachary Fisk<sup>2</sup>, Liling Sun†<sup>1,7,8</sup>

<sup>1</sup>*Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China*

<sup>2</sup>*Department of Physics and Astronomy, University of California, Irvine, CA92697, USA*

<sup>3</sup>*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

<sup>4</sup>*Department of Physics, Renmin University of China, Beijing 100872, China*

<sup>5</sup>*Shanghai Synchrotron Radiation Facilities, Shanghai Institute of Applied Physics, Chinese Academy of Sciences,  
Shanghai 201204, China*

<sup>6</sup>*Department of Physics & Astronomy, Rice University, Houston, Texas 77005, USA*

<sup>7</sup>*University of Chinese Academy of Sciences, Beijing 100190, China*

<sup>8</sup>*Songshan Lake Materials Laboratory, Dongguan, Guangdong 523808, China*

In this study, we report the first results of the high-pressure Hall coefficient ( $R_H$ ) measurements in the putative topological Kondo insulator  $\text{SmB}_6$  up to 37 GPa. Below 10 GPa, our data reveal that  $R_H(T)$  exhibits a prominent peak upon cooling below 20 K. Remarkably, the temperature at which surface conduction dominates coincides with the temperature of the peak in  $R_H(T)$ . The temperature dependent resistance and Hall coefficient can be well fitted by a two-channel model with contributions from the metallic surface and the thermally activated bulk states. When the bulk of  $\text{SmB}_6$  becomes metallic and magnetic at  $\sim 10$  GPa, both the  $R_H(T)$  peak and the resistance plateau disappear simultaneously. Our results indicate that the  $R_H(T)$  peak is a fingerprint to diagnose the presence of a metallic surface state in  $\text{SmB}_6$ . The high-pressure magnetic state of  $\text{SmB}_6$  is robust to 180 GPa, and no evidence of superconductivity is observed in the metallic phase.

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Samarium hexaboride ( $\text{SmB}_6$ ) is a unique compound in strongly correlated electron systems, because it is not only a prototypical Kondo insulator but also has an exotic metallic surface state. At high temperatures,  $\text{SmB}_6$  behaves as a correlated bad metal but undergoes a metal-to-insulator crossover upon cooling due to the hybridization between the localized  $f$ -electrons and the conduction electrons [1-10]. Below  $\sim 4$  K, the electrical resistivity of  $\text{SmB}_6$  displays a plateau, which has been a puzzling issue for decades [1,2]. This has been revealed recently to be attributed to an exotic metallic surface state that coexists with a bulk insulating state [6,11-18]. Thus,  $\text{SmB}_6$  could be the first example of a new class of topological insulators with strong electronic correlations [19-21]. Considerable experimental efforts have been made to confirm the topological nature of the surface states in  $\text{SmB}_6$ , and the correlation between the resistance plateau and a metallic surface state was established [6,11-18]. Unlike the non-trivially topological insulators whose metallic surface state is solely protected by its insulating bulk state [22], the exotic surface state of the strongly correlated electron Kondo insulator  $\text{SmB}_6$  stems from not only the Kondo physics, i.e., the hybridization between the localized  $f$ -electrons and the conduction electrons [17], but also the other strongly correlated interactions including the degrees of freedom of lattice and valence state [21,23-26]. Therefore, the surface state of  $\text{SmB}_6$  is protected by the insulating bulk in a more complicated way than that of topological insulators. It is expected that  $\text{SmB}_6$  should have peculiar response to electric field and magnetic field at low temperature. It is known that it exhibits a resistance plateau and oscillation at low temperature [13,27], however the connection of the  $R_H(T)$  peak with

the exotic metallic surface state and all the key factors of this strongly correlated system is still lacking, although it has been extensively investigated under pressures before the discovery of its metallic surface state [28-36].

Pressure is a clean and effective way of tuning interactions in solids with multiple degrees of freedom without introducing chemical complexity [26,37-46]. For such a strongly correlated electron system, the change of Hall coefficient with pressure and temperature can reflect the evolutions on the interactions among the lattice instability [47], the valence change of Sm ions [26] and the hybridization between  $4f$  electron and conducting electrons [17]. In this work, we are the first to perform the combined Hall and resistance measurements on the high quality  $\text{SmB}_6$  single crystals under pressure, with the attempt to identify how the metallic surface and insulating bulk states evolve with  $R_H(T)$ . We propose that the  $R_H(T)$  peak can be taken as a fingerprint to diagnose the presence of an exotic surface state in  $\text{SmB}_6$ .

In Fig.1a we show the temperature dependence of electrical resistance measured in a  $\text{SmB}_6$  sample upon cooling under pressures up to 36.8 GPa. The resistance of the sample at 1.1 GPa displays a continuous increase upon cooling and then exhibits a plateau below 5 K, identical to the behavior at ambient pressure [17,48-54]. Further, the resistance plateau is clearly visible at pressures below 7.6 GPa, but becomes indistinguishable at 8.5 GPa. Further compression to pressures above 9.7 GPa leads to the disappearance of the resistance plateau and to a substantial drop of the magnitude of the electrical resistance at low temperature, a signature of an insulator-to-metal transition. It is worth noting that the critical pressure of the insulator-to-metal

transition found in this study is  $\sim 10$  GPa (see the experimental details in Supplementary Information [55]), in excellent agreement with the critical pressure applied to the sample using argon as pressure medium [31].

High-pressure Hall coefficient measurements were performed upon warming after the resistance measurements. As shown in Fig.1b, in the temperature range of 1.8 K - 30 K,  $R_H(T)$  is negative at all pressures, indicating that the electron carriers are dominant. Remarkably, the plot of  $R_H$  versus temperature displays a dome-like behavior in the temperature range below 10.7 GPa (Fig.1b and inset). The dome-like  $R_H(T)$  observed in the SmB<sub>6</sub> sample is attributed to the combined contribution from surface and the bulk states. For temperatures ranging from 300 K to 10 K, the temperature dependence of resistance exhibits an insulating behavior, implying that the bulk state is dominant (Fig.1a). In this case, the charge carriers decrease upon cooling and corresponding  $R_H$  increases. At the lower temperature where the resistance plateau presents,  $R_H$  shows a decrease upon cooling due to the dominance of the metallic surface state [24]. The temperature dependence of both resistance and Hall coefficient obtained under pressure can be fitted by a two-channel model consisting of a thermally activated bulk in parallel with a temperature-independent surface state [24,25]. The resistance can be described as:

$$R = (1/R_S + 1/R_B)^{-1} \quad (1)$$

where  $R_S$  and  $R_B$  represent the resistance from surface and bulk channels, respectively. Here,  $R_B = R_{B_0} e^{E_g/k_B T}$ , in which  $E_g$  is the activated energy gap,  $k_B$  is Boltzmann constant,  $R_{B_0}$  is the bulk resistance in the high-temperature limit and  $T$  is temperature.

The Hall coefficient can be expressed as:

$$R_H = \left( R_{H-S} d \rho_B^2 + R_{H-B} (d \rho_S)^2 \right) / (d \rho_S + \rho_B)^2 \quad (2)$$

where  $R_{H-S}$  and  $R_{H-B}$  are the Hall coefficient of the surface and bulk states, respectively.  $\rho_S$  and  $\rho_B$  are resistivity of the surface and bulk states,  $d$  is the thickness of the sample (the estimated  $d$  used in the fit was  $\sim 10$   $\mu\text{m}$ ).

The solid lines in Fig.1a and 1b are the fit results. At low pressures, our results are fairly described by the two-channel model. The surface state dominates the electrical conductivity when the resistance plateau appears, whereas the bulk insulating state dominates above the temperature of the resistance plateau formation. At  $\sim 10.7$  GPa,  $R_H(T)$  is featureless, indicating that the conductance of the bulk state is comparable with that of the surface state due to the pressure-induced metallization. Although our experimental results deviate from the fit at the temperatures below the  $R_H(T)$  peak (Fig.1b), this should be an intrinsic feature of the sample, because  $\text{SmB}_6$  is a temperature sensitive compound whose lattice and valence show complicated changes upon cooling. Its valence displays a decrease upon cooling and then shows an increase at lower temperature where its resistance saturates [26,47]. We propose that the deviation of the fit to our experimental results at temperatures below the peak of  $R_H(T)$  should be attributed to the combined effects of pressure and temperature. These results demonstrate that the dome-like  $R_H(T)$  can be taken as a fingerprint to distinguish the coexistence of the metallic surface in  $\text{SmB}_6$ .

Magnetic order has been found previously in pressurized  $\text{SmB}_6$  by nuclear forward scattering of synchrotron radiation measurements [56]. The magnetic

ordering temperature ( $T_M$ ) has been confirmed to lie in the 10 -12 K range at  $\sim 10$  GPa [56]. We find that the mid-point temperatures ( $T'$ ) of the resistance drop in the metallic  $\text{SmB}_6$  are close to its corresponding  $T_M$  measured by nuclear magnetic resonance measurements. If  $T'$  is taken as a characteristic temperature of  $T_M$  (Fig.2a), it is surprising to find that  $T_M$  is robust under pressures as high as 180 GPa (Fig.2b). Because  $R(T)$  curves measured in the pressure range of 10 GPa - 180 GPa exhibit similar behavior and no structure phase transition is observed under pressures to 167 GPa (Fig.3), we propose that the magnetically ordered state remains in the pressurized metallic phase throughout this pressure range.

We summarize our results in Fig.4.  $\text{SmB}_6$  hosts a metallic surface state below 10 GPa, which is characterized by the resistance plateau and the peak in  $R_H(T)$ . This peak decreases with increasing pressure and eventually disappears at  $\sim 10$  GPa as the bulk state of the sample becomes metallic state (Fig.4a). Significantly, the thermal instability of  $R_H(T)$  indicates that the temperature-induced lattice change plays a vital role in tuning the valence state of Sm ions and the population of conducting electrons, as well as their interaction [47], which are the central issues for such a strongly correlated electron system with Kondo physics. Moreover, we noted that the criterion of the  $R_H(T)$  peak can be applied to topological insulators such as  $\text{Bi}_2\text{Te}_2\text{Se}$  and  $\text{Bi}_{1.08}\text{Sn}_{0.02}\text{Sb}_{0.9}\text{Te}_2\text{S}$  [57,58], whose  $R_H$  appears decrease dramatically in the temperature range of the surface state dominance. The behaviors of the  $R_H(T)$  peak found in the compounds of  $\text{SmB}_6$  or topological insulators with the coexistence of metallic surface state and the bulk insulating state lead us to suggest that the  $R_H(T)$

peak may be a common feature for the materials hosted the exotic surface state, no matter that the surface state stems from nontrivially topological physics or electron correlated physics. This interesting issue deserves further experimental and theoretical investigations.

We also find that the mid-point of the resistance drop,  $T'(P)$ , coincides with the magnetic transition temperature  $T_M$  detected by nuclear scattering forward measurements [56], and it is present to 180 GPa. These results suggest that a robust magnetically ordered state is stabilized, which prevents the emergence of superconductivity. The corresponding pressure dependence of the  $R_H$  obtained at 1.8 K is shown in Fig. 4b. Below  $\sim 10$  GPa,  $R_H$  decreases with increasing pressure and then stays almost constant in the metallic magnetic state up to  $\sim 37$  GPa. It is known that  $\text{SmB}_6$  is a mixed valence compound at ambient pressure with valence  $v_{\text{Sm}} \sim 2.6$ . The application of pressure drives the valence change with the tendency from non-magnetic  $\text{Sm}^{2+}$  to magnetic  $\text{Sm}^{3+}$  ions. Previous high-pressure absorption measurements [23,26,36,59] indicated that its mean valence is very close to  $3+$  at  $P > \sim 10$  GPa. The pressure-induced valence change of  $\text{Sm}^{2+}(4f^6) \rightarrow \text{Sm}^{3+}(4f^5+5d)$ , together with its stable cubic lattice structure, should be responsible for the robustness of long-ranged magnetic order [23,26,36,59].

In conclusion, the prominent feature of the temperature dependent Hall coefficient for the coexistence of surface and bulk states in a putative topological insulator  $\text{SmB}_6$  has been revealed for the first time. The intimate correlation between the low-temperature  $R_H$  and the exotic surface state suggests that  $R_H(T)$  is one of the



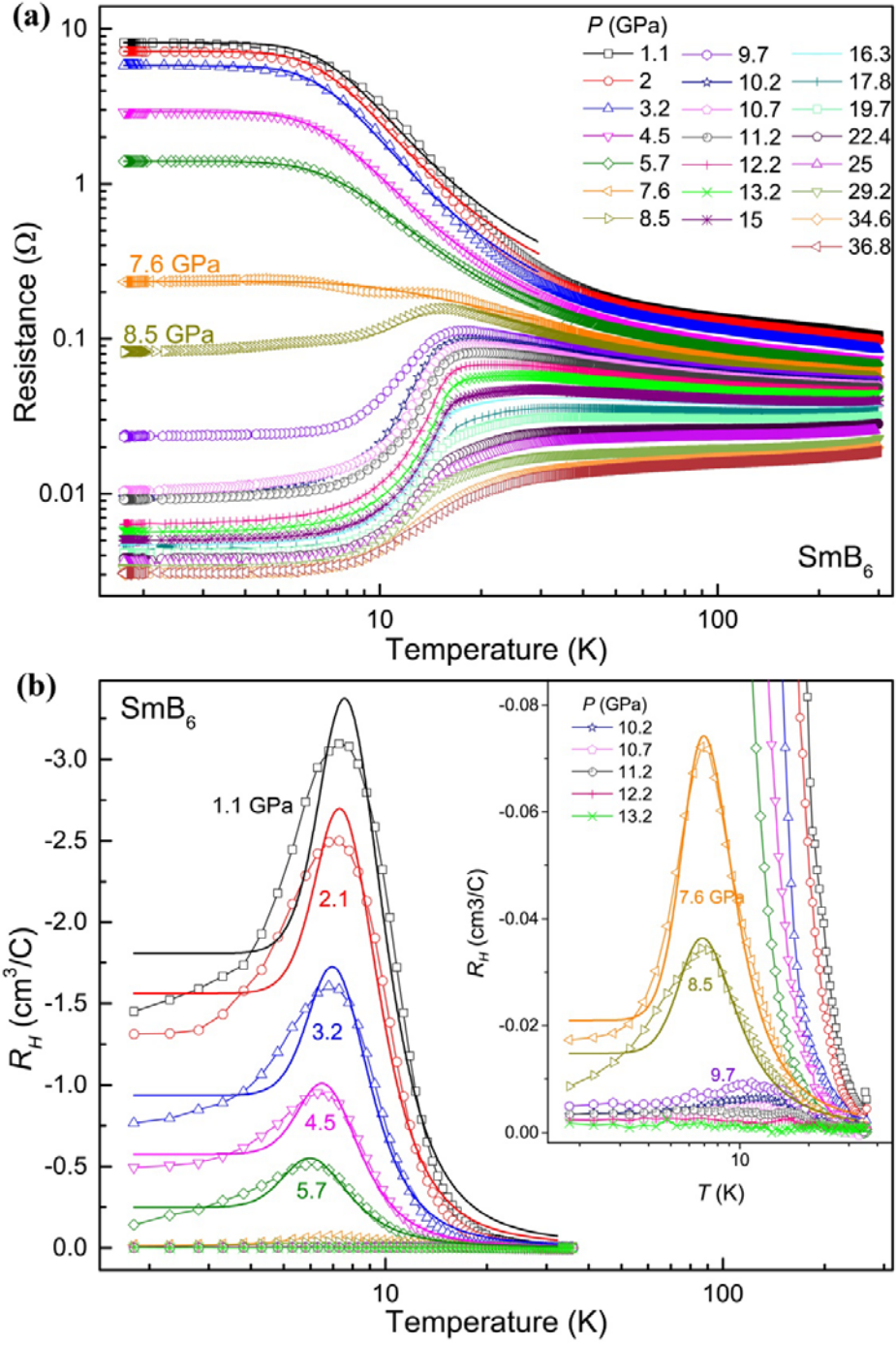
most useful diagnostic methods to identify the existence of the exotic surface state in  $\text{SmB}_6$  and in some of topological insulators such as  $\text{Bi}_2\text{Te}_2\text{Se}$  and  $\text{Bi}_{1.08}\text{Sn}_{0.02}\text{Sb}_{0.9}\text{Te}_2\text{S}$ . Furthermore, we find the extraordinary robustness of the crystal structure and metallic state in compressed  $\text{SmB}_6$  up to 180 GPa and no superconductivity is observed in the pressure range investigated.

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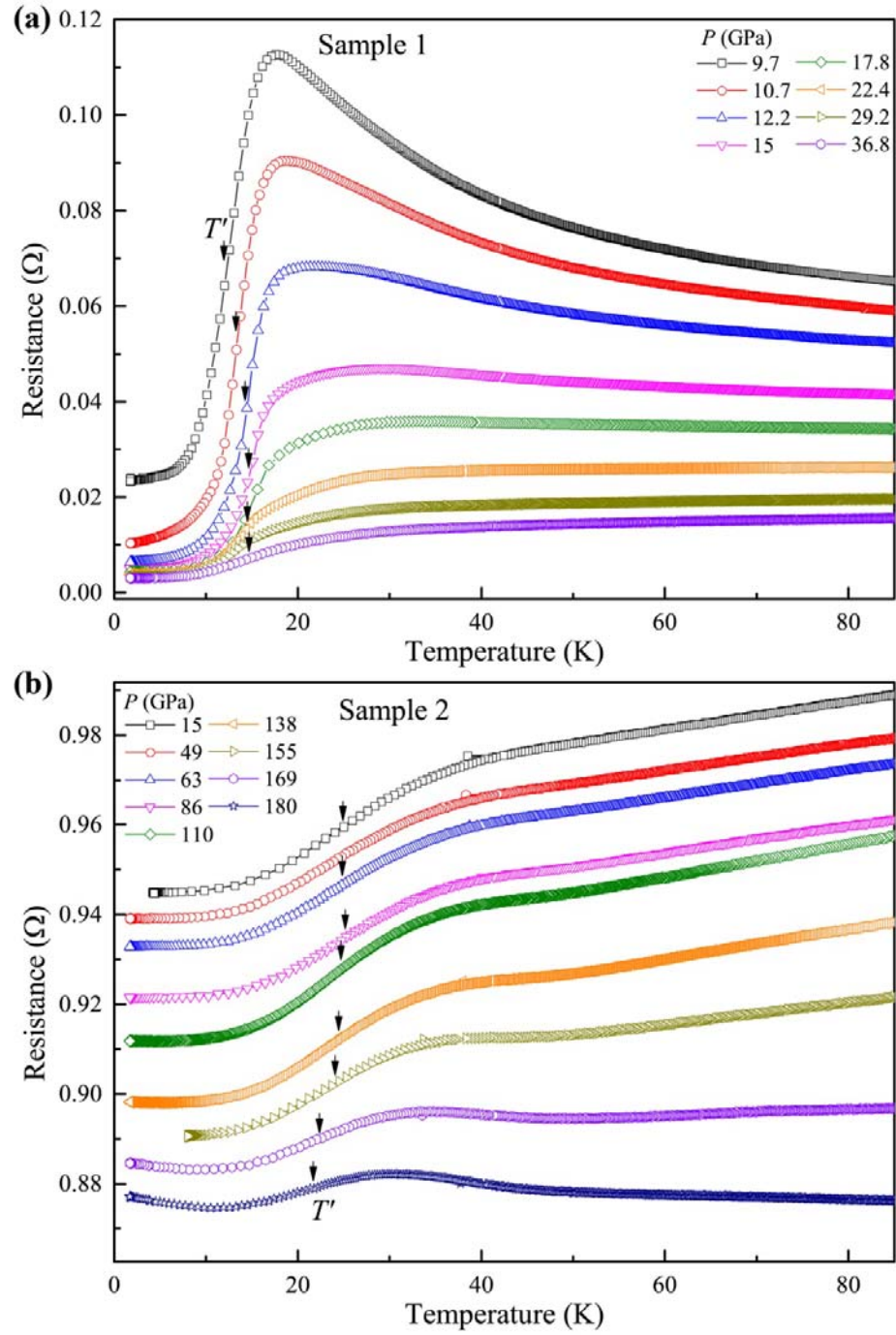
†Corresponding authors

[llsun@iphy.ac.cn](mailto:llsun@iphy.ac.cn)

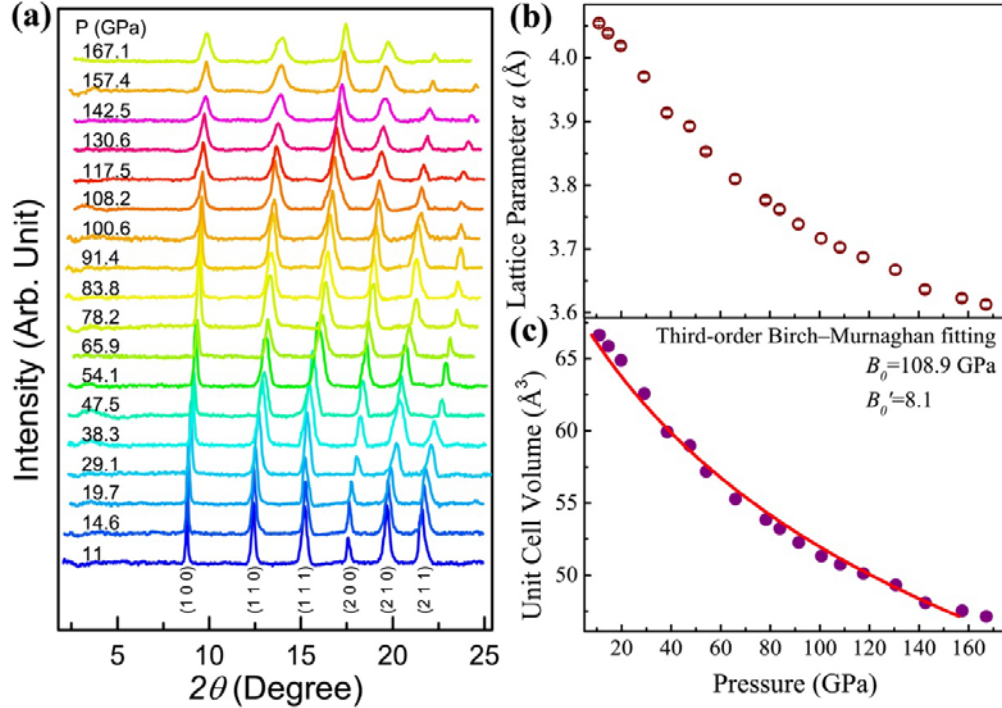


**Figure 1** Transport properties in pressurized  $\text{SmB}_6$ . (a) Temperature dependence of resistance from 1.7 K to 300 K at different pressures in log-log scale. Solid line is fitting by a two-channel model. (b) Hall coefficient ( $R_H$ ) as a function of temperature

measured at different pressures. The inset is the large view of  $R_H(T)$  obtained at higher pressure. Solid lines are fitting result.

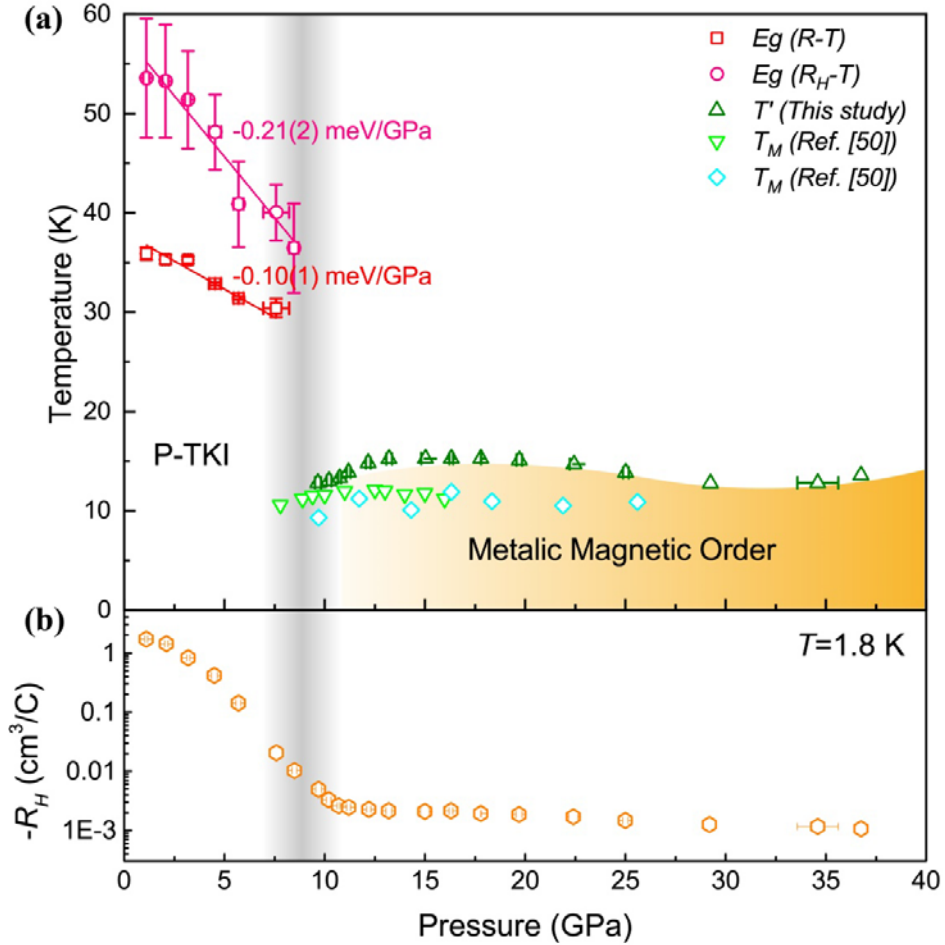


**Figure 2 High pressure behavior of metallic SmB<sub>6</sub>.** (a) Resistance versus temperature in the pressure range of 9.7 GPa ~ 36.8 GPa for the sample 1. (b) Temperature dependence of resistance under pressure up to 180 GPa for the sample 2.  $T'$  represents maximum of  $dR/dT$  curves indicating the resistance drop in the metallic phase. The sample 1 and the sample 2 were cut from the same batch, which were loaded into the different two high pressure cells for high pressure (~37 GPa) and very high pressure measurements (~180 GPa).



**Figure 3 High pressure structure information of SmB<sub>6</sub>.** (a) X-ray diffraction patterns of SmB<sub>6</sub> collected at different pressures. (b) and (c) Pressure dependences of lattice parameter and volume. Error bars in Fig. 3 (b) are in the brown circles. The volume versus pressure data are fit to the third-order Birch–Murnaghan equation of state [54], as displayed by the solid line in Fig.3c. The  $B_0$  is the isothermal bulk

modulus at ambient pressure,  $B_0'$  is the pressure derivative of  $B_0$  evaluated at zero pressure.



**Figure 4 Pressure-temperature phase diagram and Hall coefficient at 1.8 K. (a)**

Plots of pressure versus characteristic temperatures. P-TKI stands for putative topological Kondo insulator. Pink circle and red square are the activated gap  $E_g$  obtained from temperature-dependent  $R-T$  curves and Hall coefficient respectively and is converted to temperature by equation of (1) and (2). Olive triangle is characteristic temperatures  $T'$  obtained from our  $R-T$  curves. Green inverted triangle and cyan rhombus is magnetic ordering temperature taken from Ref. [50] (b) Plot of

Hall coefficient ( $R_H$ ) versus pressure obtained at 1.8 K. Gray interval indicates the pressure region of insulator-to-metal transition.

## References

- [1] J. W. Allen, B. Batlogg, and P. Wachter, *Physical Review B* **20**, 4807 (1979).
- [2] J. W. Allen, R. M. Martin, B. Batlogg, and P. Wachter, *Journal of Applied Physics* **49**, 2078 (1978).
- [3] K. Flachbart, K. Gloos, E. Konovalova, Y. Paderno, M. Reiffers, P. Samuely, and P. Švec, *Physical Review B* **64**, 085104 (2001).
- [4] E. Frantzeskakis, N. de Jong, B. Zwartsenberg, Y. K. Huang, Y. Pan, X. Zhang, J. X. Zhang, F. X. Zhang, L. H. Bao, O. Tegus, A. Varykhalov, A. de Visser, and M. S. Golden, *Physical Review X* **3**, 041024 (2013).
- [5] B. Gorshunov, N. Sluchanko, A. Volkov, M. Dressel, G. Knebel, A. Loidl, and S. Kunii, *Physical Review B* **59**, 1808 (1999).
- [6] M. Neupane, N. Alidoust, S. Y. Xu, T. Kondo, Y. Ishida, D. J. Kim, C. Liu, I. Belopolski, Y. J. Jo, T. R. Chang, H. T. Jeng, T. Durakiewicz, L. Balicas, H. Lin, A. Bansil, S. Shin, Z. Fisk, and M. Z. Hasan, *Nature Communications* **4**, 2991 (2013).
- [7] S. Rößler, T.-H. Jang, D.-J. Kim, L. H. Tjeng, Z. Fisk, F. Steglich, and S. Wirth, *Proceedings of the National Academy of Sciences* **111**, 4798 (2014).
- [8] W. Ruan, C. Ye, M. Guo, F. Chen, X. Chen, G.-M. Zhang, and Y. Wang, *Physical Review Letters* **112**, 136401 (2014).

- [9] N. E. Sluchanko, V. V. Glushkov, B. P. Gorshunov, S. V. Demishev, M. V. Kondrin, A. A. Pronin, A. A. Volkov, A. K. Savchenko, G. Grüner, Y. Bruynseraede, V. V. Moshchalkov, and S. Kunii, *Physical Review B* **61**, 9906 (2000).
- [10] N. Xu, X. Shi, P. K. Biswas, C. E. Matt, R. S. Dhaka, Y. Huang, N. C. Plumb, M. Radović, J. H. Dil, E. Pomjakushina, K. Conder, A. Amato, Z. Salman, D. M. Paul, J. Mesot, H. Ding, and M. Shi, *Physical Review B* **88**, 121102 (2013).
- [11] E. Frantzeskakis, N. de Jong, B. Zwartsenberg, Y. K. Huang, Y. Pan, X. Zhang, J. X. Zhang, F. X. Zhang, L. H. Bao, O. Tegus, A. Varykhalov, A. de Visser, and M. S. Golden, *Physical Review X* **3**, 041024 (2013).
- [12] J. Jiang, S. Li, T. Zhang, Z. Sun, F. Chen, Z. R. Ye, M. Xu, Q. Q. Ge, S. Y. Tan, X. H. Niu, M. Xia, B. P. Xie, Y. F. Li, X. H. Chen, H. H. Wen, and D. L. Feng, *Nature Communications* **4**, 3010 (2013).
- [13] G. Li, Z. Xiang, F. Yu, T. Asaba, B. Lawson, P. Cai, C. Tinsman, A. Berkley, S. Wolgast, Y. S. Eo, D.-J. Kim, C. Kurdak, J. W. Allen, K. Sun, X. H. Chen, Y. Y. Wang, Z. Fisk, and L. Li, *Science* **346**, 1208 (2014).
- [14] W. K. Park, L. Sun, A. Noddings, D.-J. Kim, Z. Fisk, and L. H. Greene, *Proceedings of the National Academy of Sciences* **113**, 6599 (2016).
- [15] S. Rößler, T.-H. Jang, D.-J. Kim, L. H. Tjeng, Z. Fisk, F. Steglich, and S. Wirth, *Proceedings of the National Academy of Sciences* **111**, 4798 (2014).
- [16] N. Xu, X. Shi, P. K. Biswas, C. E. Matt, R. S. Dhaka, Y. Huang, N. C. Plumb, M. Radović, J. H. Dil, E. Pomjakushina, K. Conder, A. Amato, Z. Salman, D. M. Paul, J. Mesot, H. Ding, and M. Shi, *Physical Review B* **88**, 121102 (2013).

- [17]X. Zhang, N. P. Butch, P. Syers, S. Ziemak, R. L. Greene, and J. Paglione,  
Physical Review X **3**, 011011 (2013).
- [18]Z. H. Zhu, A. Nicolaou, G. Levy, N. P. Butch, P. Syers, X. F. Wang, J. Paglione,  
G. A. Sawatzky, I. S. Elfimov, and A. Damascelli, Physical Review Letters **111**,  
216402 (2013).
- [19]V. Alexandrov, M. Dzero, and P. Coleman, Physical Review Letters **111**, 226403  
(2013).
- [20]M. Dzero, K. Sun, P. Coleman, and V. Galitski, Physical Review B **85**, 045130  
(2012).
- [21]M. Dzero, K. Sun, V. Galitski, and P. Coleman, Physical Review Letters **104**,  
106408 (2010).
- [22]M. Z. Hasan and C. L. Kane, Reviews of Modern Physics **82**, 3045 (2010).
- [23]N. P. Butch, J. Paglione, P. Chow, Y. Xiao, C. A. Marianetti, C. H. Booth, and J.  
R. Jeffries, Physical Review Letters **116**, 156401 (2016).
- [24]D. J. Kim, S. Thomas, T. Grant, J. Botimer, Z. Fisk, and J. Xia, Scientific Reports  
**3**, 3150 (2013).
- [25]P. Syers, D. Kim, M. S. Fuhrer, and J. Paglione, Physical Review Letters **114**,  
096601 (2015).
- [26]Q. Wu and L. Sun, Reports on Progress in Physics **80**, 112501 (2017).
- [27]B. S. Tan, Y.-T. Hsu, B. Zeng, M. C. Hatnean, N. Harrison, Z. Zhu, M. Hartstein,  
M. Kiourlappou, A. Srivastava, M. D. Johannes, T. P. Murphy, J.-H. Park, L. Balicas,  
G. G. Lonzarich, G. Balakrishnan, and S. E. Sebastian, Science **349**, 287 (2015).



- [28]J. Beille, M. B. Maple, J. Wittig, Z. Fisk, and L. E. DeLong, Physical Review B **28**, 7397 (1983).
- [29]J. C. Cooley, M. C. Aronson, Z. Fisk, and P. C. Canfield, Physica B: Condensed Matter **199-200**, 486 (1994).
- [30]J. C. Cooley, M. C. Aronson, Z. Fisk, and P. C. Canfield, Physical Review Letters **74**, 1629 (1995).
- [31]J. Derr, G. Knebel, D. Braithwaite, B. Salce, J. Flouquet, K. Flachbart, S. Gabáni, and N. Shitsevalova, Physical Review B **77**, 193107 (2008).
- [32]J. Derr, G. Knebel, G. Lapertot, B. Salce, M. A. Méasson, and J. Flouquet, Journal of Physics: Condensed Matter **18**, 2089 (2006).
- [33]S. Gabáni, E. Bauer, S. Berger, K. Flachbart, Y. Paderno, C. Paul, V. Pavlík, and N. Shitsevalova, Physical Review B **67**, 172406 (2003).
- [34]K. Nishiyama, T. Mito, G. Pristáš, Y. Hara, T. Koyama, K. Ueda, T. Kohara, Y. Akahama, S. Gabáni, M. Reiffers, K. Flachbart, H. Fukazawa, Y. Kohori, N. Takeshita, and N. Shitsevalova, Journal of the Physical Society of Japan **82**, 123707 (2013).
- [35]P. Parisiades, M. Bremholm, and M. Mezouar, EPL (Europhysics Letters) **110**, 66002 (2015).
- [36]Y. Zhou, Q. Wu, P. F. S. Rosa, R. Yu, J. Guo, W. Yi, S. Zhang, Z. Wang, H. Wang, S. Cai, K. Yang, A. Li, Z. Jiang, S. Zhang, X. Wei, Y. Huang, P. Sun, Y.-f. Yang, Z. Fisk, Q. Si, Z. Zhao, and L. Sun, Science Bulletin **62**, 1439 (2017).

- [37] A. P. Drozdov, M. I. Eremets, I. A. Troyan, V. Ksenofontov, and S. I. Shylin, *Nature* **525**, 73 (2015).
- [38] M. I. Eremets, V. V. Struzhkin, H.-k. Mao, and R. J. Hemley, *Science* **293**, 272 (2001).
- [39] S. Medvedev, T. M. McQueen, I. A. Troyan, T. Palasyuk, M. I. Eremets, R. J. Cava, S. Naghavi, F. Casper, V. Ksenofontov, G. Wortmann, and C. Felser, *Nature Materials* **8**, 630 (2009).
- [40] K. Shimizu, T. Kimura, S. Furomoto, K. Takeda, K. Kontani, Y. Onuki, and K. Amaya, *Nature* **412**, 316 (2001).
- [41] V. V. Struzhkin, R. J. Hemley, H.-k. Mao, and Y. A. Timofeev, *Nature* **390**, 382 (1997).
- [42] L. Sun, X.-J. Chen, J. Guo, P. Gao, Q.-Z. Huang, H. Wang, M. Fang, X. Chen, G. Chen, Q. Wu, C. Zhang, D. Gu, X. Dong, L. Wang, K. Yang, A. Li, X. Dai, H.-k. Mao, and Z. Zhao, *Nature* **483**, 67 (2012).
- [43] L. Sun and Q. Wu, *Reports on Progress in Physics* **79**, 084503 (2016).
- [44] H. Takahashi, K. Igawa, K. Arii, Y. Kamihara, M. Hirano, and H. Hosono, *Nature* **453**, 376 (2008).
- [45] T. Yamauchi, Y. Hirata, Y. Ueda, and K. Ohgushi, *Physical Review Letters* **115**, 246402 (2015).
- [46] H. Q. Yuan, F. M. Grosche, M. Deppe, C. Geibel, G. Sparn, and F. Steglich, *Science* **302**, 2104 (2003).

- [47] M. Mizumaki, S. Tsutsui, and F. Iga, *Journal of Physics: Conference Series* **176**, 012034 (2009).
- [48] J. W. Allen, B. Batlogg, and P. Wachter, *Physical Review B* **20**, 4807 (1979).
- [49] J. Beille, M. B. Maple, J. Wittig, Z. Fisk, and L. E. DeLong, *Physical Review B* **28**, 7397 (1983).
- [50] T. Caldwell, A. P. Reyes, W. G. Moulton, P. L. Kuhns, M. J. R. Hoch, P. Schlottmann, and Z. Fisk, *Physical Review B* **75**, 075106 (2007).
- [51] A. Menth, E. Buehler, and T. H. Geballe, *Physical Review Letters* **22**, 295 (1969).
- [52] J. C. Nickerson, R. M. White, K. N. Lee, R. Bachmann, T. H. Geballe, and G. W. Hull, *Physical Review B* **3**, 2030 (1971).
- [53] W. A. Phelan, S. M. Koohpayeh, P. Cottingham, J. W. Freeland, J. C. Leiner, C. L. Broholm, and T. M. McQueen, *Physical Review X* **4**, 031012 (2014).
- [54] N. E. Sluchanko, V. V. Glushkov, B. P. Gorshunov, S. V. Demishev, M. V. Kondrin, A. A. Pronin, A. A. Volkov, A. K. Savchenko, G. Grüner, Y. Bruynseraede, V. V. Moshchalkov, and S. Kunii, *Physical Review B* **61**, 9906 (2000).
- [55] See Supplemental Material at [xxx](#).
- [56] A. Barla, J. Derr, J. P. Sanchez, B. Salce, G. Lapertot, B. P. Doyle, R. Rüffer, R. Lengsdorf, M. M. Abd-Elmeguid, and J. Flouquet, *Physical Review Letters* **94**, 166401 (2005).

- [57]S. K. Kushwaha, I. Pletikosić, T. Liang, A. Gyenis, S. H. Lapidus, Y. Tian, H. Zhao, K. S. Burch, J. Lin, W. Wang, H. Ji, A. V. Fedorov, A. Yazdani, N. P. Ong, T. Valla, and R. J. Cava, *Nature Communications* **7**, 11456 (2016).
- [58]Z. Ren, A. A. Taskin, S. Sasaki, K. Segawa, and Y. Ando, *Physical Review B* **82**, 241306 (2010).
- [59]N. Emi, T. Mito, N. Kawamura, M. Mizumaki, N. Ishimatsu, G. Pristáš, T. Kagayama, K. Shimizu, Y. Osanai, and F. Iga, *Physica B: Condensed Matter* **536**, 197 (2018).