

Nontrivial Nature and Penetration Depth of Topological Surface States in SmB_6 Thin Films

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The nontrivial feature and penetration depth of the topological surface states (TSS) in SmB_6 were studied via spin pumping. The experiments used SmB_6 thin films grown on the bulk magnetic insulator $\text{Y}_3\text{Fe}_5\text{O}_{12}$ (YIG). Upon the excitation of magnetization precession in the YIG, a spin current is generated in the SmB_6 that produces, via spin-orbit coupling, a lateral electrical voltage in the film. This spin-pumping voltage signal becomes considerably stronger as the temperature decreases from 150 to 10 K, and such an enhancement most likely originates from the spin-momentum locking of the TSS and may thereby serve as evidence for the nontrivial nature of the TSS. The voltage data also show a unique film thickness dependence that suggests a TSS depth of ~ 32 nm. The spin-pumping results are supported by transport measurements and analyses using a tight binding model.

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SmB_6 is a Kondo insulator (KI) [1–4] that undergoes a metal-to-insulator transition when the temperature (T) is reduced below 150 K [5,6]. This transition originates from hybridization between conduction electrons and localized f electrons that opens a band gap at the Fermi level [7,8]. SmB_6 has been studied extensively since 1969 when it was identified as the first KI [5]. Since 2010, it has attracted a new wave of interest thanks to the prediction of nontrivial topology in the band structures of a group of KIs including SmB_6 [9]. It is predicted that at low T some KIs could have a topologically protected metallic surface atop of an insulating bulk, manifesting a new class of materials—*topological Kondo insulators* [9–14].

The prediction invoked considerable studies, experimental [15–34] and theoretical [9–13,35,36], on the topological surface states (TSS) in SmB_6 . These studies, mostly using bulk SmB_6 , seem to provide evidence for the existence of the TSS, but also yield controversial conclusions as exemplified here. (i) The low- T metallic surface states have been observed by transport [14,19–21], angle-resolved photoemission spectroscopy (ARPES) [22–25], scanning-tunneling microscopy [26–28], neutron scattering [29], and quantum oscillation measurements [30]. The helical spin texture on the surfaces has also been observed using spin-resolved ARPES [31]. Despite those works, however, no Dirac cones have been found experimentally, leaving ample room for doubts about the nature of the observed surface states. Indeed, other ARPES studies [32] suggested that the TSS in SmB_6 could be topologically trivial states

associated with an intrinsic property of hexaborides, while the helical spin texture observed [31] might be attributed to spin-polarized Rashba-split states. (ii) Torque magnetometry studies showed quantum oscillations in SmB_6 , but the data yielded conflicting results about whether the Fermi surface is two dimensional [30] or three dimensional [33], only the former supporting the topological nature. On the other hand, magnetoresistance measurements did not find evidence of quantum oscillations [34]. (iii) Recent experiments showed that the low- T limiting resistance in SmB_6 slabs is independent of the slab thickness, as expected [14,19,20]. This independence, however, could also arise from an accidental layer on the surface [14,37], and the penetration depth (d_{TSS}) of the TSS remains unknown.

SmB_6 films with a thickness down to about d_{TSS} offer possibilities to address many of the unresolved debates. Further, SmB_6 in thin film form enables device fabrication, allowing for exploration of potential applications. In contrast to considerable previous studies using bulk SmB_6 , work on thin films has been limited, mainly on film growth and characterization [38–40]. Nevertheless, there have been reports on the superconducting proximity effect in SmB_6/Nb bilayers [41] and spin-orbit-torque switching in $\text{SmB}_6/\text{ferromagnet}$ multilayers [42].

This Letter reports the use of SmB_6 films to study the nontrivial nature and depth of the TSS in SmB_6 . The experiments used 10–300 nm thick SmB_6 films grown on $\text{Y}_3\text{Fe}_5\text{O}_{12}$ (YIG) and spin pumping [43–47] to probe the

spin-momentum locking of the TSS. A microwave is used to excite spin waves in the YIG, and the latter pumps a spin current into the SmB_6 . Via spin-orbit coupling (SOC) the spin current produces an electrical voltage across the SmB_6 film, and the analysis of this signal enables the evaluation of the SOC strength.

The data show that in samples with SmB_6 film thickness $d \leq 50$ nm, the spin-pumping voltage decreases monotonically when T decreases from 300 to 10 K, similar to the responses in heavy metal (HM)/YIG [48,49]. When $d \geq 80$ nm, however, the signal is surprisingly enhanced when T is decreased over 10–150 K. This enhancement likely reflects the low- T enhancement of the SOC due to spin-momentum locking, demonstrating the nontrivial topological feature of the SmB_6 . At room temperature (RT), the d dependence of the signal shows a behavior very similar to that in HM/YIG [47,50] and indicates a spin diffusion length of $\lambda_{\text{sd}} = 38.7 \pm 1.8$ nm [47,51]. The d dependence at low T is different and suggests $d_{\text{TSS}} \approx 32$ nm. The TSS are further examined by transport measurements and tight binding model-based analyses [36].

The experimental approach is depicted in Figs. 1(a) and 1(b). The sample consists of a SmB_6 film grown by sputtering on a 0.5-mm-thick YIG slab with length $a = 4$ mm and width $b = 2$ mm. The stoichiometry of the SmB_6 was confirmed by x-ray photoelectron spectroscopy [42,52,53]. The YIG is magnetized by a field (H) along the y axis. The magnetic moments in the YIG are driven to precess by placing a microstrip line on the sample and feeding it with a microwave. Via spin pumping [43–47,50], the precessing moments produce a spin current in the SmB_6 . This spin current is then converted into a charge current along the x axis via SOC, through the inverse Edelstein effect [46,54,55] or the inverse spin Hall effect [43–45] depending on whether the TSS are present, resulting in a voltage signal V .

Figure 1(c) presents voltage signals measured for $H > 0$ on a SmB_6 (120 nm)/YIG sample ($d = 120$ nm). Strong signals present in some regions, and they are associated with standing spin-wave modes in the YIG. As the microwave magnetic field produced by the microstrip is spatially nonuniform, it excites spin waves in the YIG [56]. Those spin waves are quantized due to dimension confinement, with wave number vectors [57]

$$\mathbf{k} = \frac{m\pi}{a} \hat{\mathbf{x}} + \frac{n\pi}{b} \hat{\mathbf{y}}, \quad (1)$$

where m and n are mode indexes associated with the waves in the length and width directions, respectively. The analysis of those modes requires the development of a spin-wave dispersion relation for the YIG slab. As an approximation, the dispersion relation for thin films [57,58] has been used to analyze the data. Four distinct modes have been identified, and the strongest signal appears over 0.2–0.7 kOe and corresponds to the (1,0) mode [59].

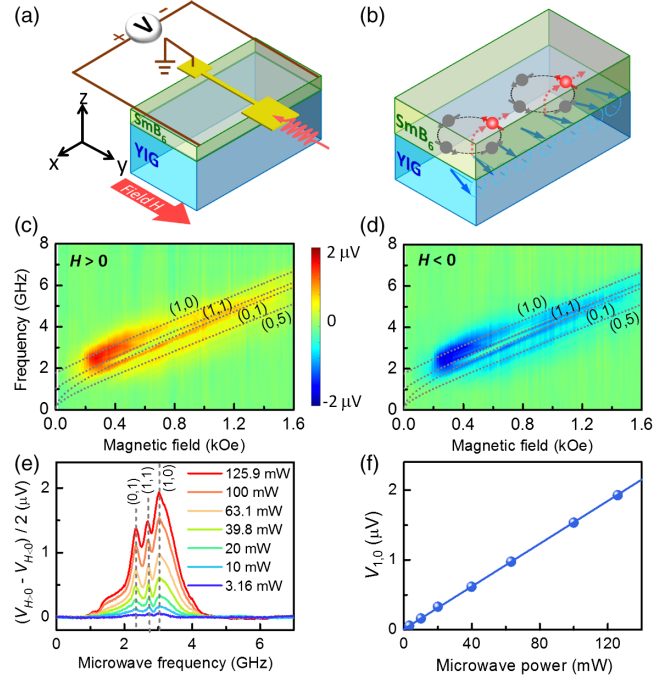


FIG. 1. Spin-pumping experiments. (a)–(b) Experiment approach. (c)–(d) Spin-pumping signals measured using opposite fields (H) and an input microwave power $P_{\text{in}} = 100$ mW. The curves show calculated spin-wave frequencies. (e) Signals measured at different P_{in} , where $V_{H>0}$ ($V_{H<0}$) is the signal measured at $H = 400$ Oe ($H = -400$ Oe). The vertical dashed lines indicate the calculated frequencies of three modes. (f) Amplitude of the (1,0) peak in (e) vs P_{in} .

Figure 1(d) shows the data measured under the same conditions except $H < 0$. The data show almost the same characteristics as those in Fig. 1(c) except an opposite voltage sign. This sign change is consistent with the facts that the YIG magnetization direction dictates the polarization of the spin currents, and a flip in the polarization leads to a sign change of V [43–45]. The signal might contain a circuit-associated background as well as contributions from nonmagnetic effects (e.g., the Seebeck effect) [60]. These contributions are H independent and can be easily removed by subtracting the signals measured using opposite fields.

The data in Figs. 1(c) and 1(d) were obtained at an input microwave power $P_{\text{in}} = 100$ mW. To ensure that spin pumping is performed in a linear regime, the measurements using different P_{in} are compared. Figure 1(e) shows the frequency-domain data $(V_{H>0} - V_{H<0})/2$ obtained using different P_{in} . The (1,0) mode is the strongest for all P_{in} , consistent with the data in Figs. 1(c) and 1(d). From the data in Fig. 1(e) one can plot the peak voltage of the (1,0) mode, $V_{1,0}$, as a function of P_{in} , as in Fig. 1(f). The data in Fig. 1(e) show that the peak frequencies do not change with P_{in} , while those in Fig. 1(f) show linear behavior, suggesting that measurements involve neither microwave

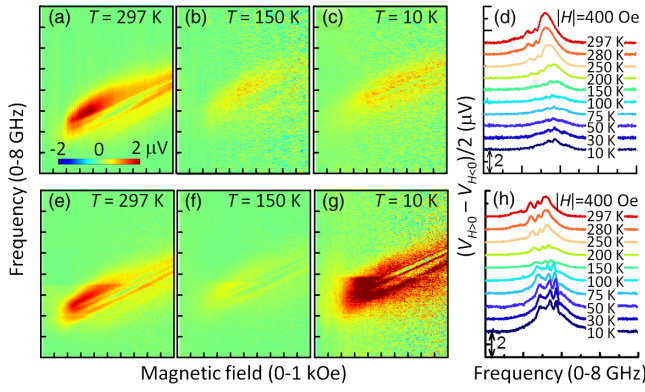


FIG. 2. Evidence for nontrivial TSS. The first and second rows present the data for SmB₆(20 nm)/YIG and SmB₆(120 nm)/YIG, respectively. In each row, the color maps present the signals measured for $H > 0$ at different T , while the rightmost diagram shows the $(V_{H>0} - V_{H<0})/2$ signals measured for $|H| = 0.4$ kOe at different T . All the color maps use the same scale shown by the color bar in (a).

heating nor nonlinear spin pumping. The data below were taken at $P_{\text{in}} = 100$ mW.

The above-described approach facilitates the use of spin pumping to explore the TSS in SmB₆. The key point is that when nontrivial TSS are present, the spin-momentum locking enhances SOC in SmB₆ and thereby results in strong voltage signals.

Figure 2 presents the spin-pumping data for SmB₆(20 nm)/YIG (top row) and SmB₆(120 nm)/YIG (bottom row). For SmB₆(20 nm)/YIG, the signal diminishes as T decreases from 297 to 10 K. This is mainly because the damping in polycrystalline YIG becomes stronger at low T due to the enhancement in porosity- and anisotropy-associated two-magnon scattering [61]. The larger damping results in weaker spin waves in the YIG and, consequently, a smaller spin current in the SmB₆. In contrast, SmB₆(120 nm)/YIG shows different behavior—the signal becomes weaker as T is reduced from 297 to 150 K, but a further decrease in T leads to a substantial increase in the signal. This enhancement is attributed to the TSS, as discussed below. The data also indicate that with decreasing T , the peaks shift to higher frequencies. This shift results from the increase of magnetization with decreasing T [62,63].

Similar measurements were performed on other samples with different d . The data were analyzed with two approaches. One uses the amplitude of the main mode $V_{1,0}$ to represent the signal strength and examines how $V_{1,0}$ varies with T and d . The other examines the area (A) under the V profile and explores its T and d dependences. The $V_{1,0}$ data are given in Fig. 3. The A data (see Fig. S3 [52]) show the same results as the $V_{1,0}$ data.

Figure 3(a) presents $V_{1,0}(T)$ for nine samples. Obviously, the signals from different samples show different T dependences. To better present this, Fig. 3(b) gives

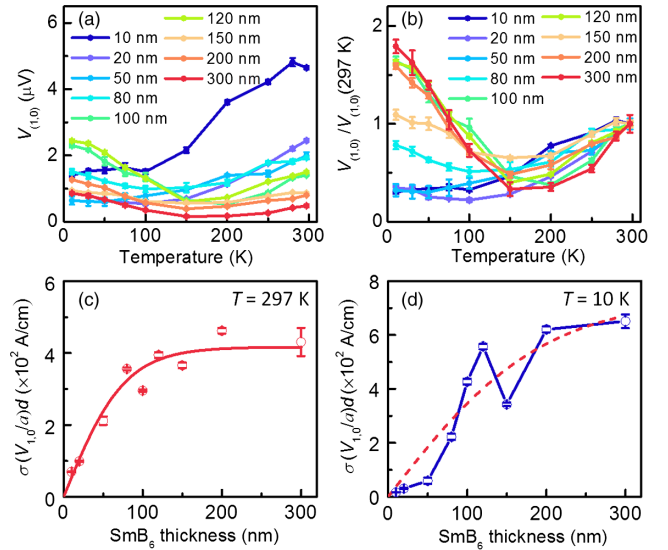


FIG. 3. Temperature and length characteristics of TSS. (a) Amplitude of the (1,0) mode, $V_{1,0}$, as a function of T for nine samples with different d . (b) The same $V_{1,0}$ data in (a) but normalized by the $V_{1,0}$ values at $T = 297$ K. (c) and (d) give the $\sigma(V_{1,0}/a)d$ data at 297 and 10 K, respectively, as a function of d , with the error bars estimated from the noise level of the signals. The red curves in (c) and (d) are fits to Eq. (2).

the $V_{1,0}$ values normalized by that measured at $T = 297$ K. Three observations are evident in Fig. 3(b). (i) For samples with $d \leq 50$ nm, the ratio “ $V_{1,0}/V_{1,0}(297 \text{ K})$ ” decreases monotonically as T decreases. (ii) For the one with $d = 80$ nm, the ratio drops when T decreases from 297 to 150 K, but surprisingly increases as T is further lowered. (iii) For those with $d \geq 100$, the ratio decreases first, just like in thinner samples, but then increases substantially. As T changes from 150 to 10 K, the ratio is enhanced by a factor of 4.1 for SmB₆(120 nm)/YIG and a factor of 5.4 for SmB₆(300 nm)/YIG.

The results from Figs. 2, 3(a), and 3(b), together with those from Figs. S3 and S8 in the Supplemental Material [52], provide strong evidence for the nontrivial nature of the TSS in SmB₆. Specifically, due to damping enhancement in YIG at low T [61], a decrease in T leads to weaker spin pumping and accordingly a weaker voltage signal. As a result, the signal intensity in HM/YIG decreases monotonically with decreasing T , as shown in Fig. S8 [52] and reported previously [48,49]. Note that SOC in HM is insensitive to T and is therefore not responsible for the monotonic voltage decrease. For SmB₆/YIG samples, the signal intensity also decreases when T is reduced from 297 to ~ 150 K, as shown in Figs. 3(b) and S3(b) of Ref. [52]. However, when T is further reduced, in samples with $d \geq 80$ nm the TSS start to be present and the spin-momentum locking start to enhance SOC, resulting in low- T signal enhancement. Without the spin-momentum locking, one would expect a monotonic T dependence just as in HM/YIG. Indeed, the signal does decrease with

decreasing T in samples with $d \leq 50$ nm in which the nontrivial TSS are absent because the films are so thin that the top and bottom surface states overlap [see Figs. 5(a) and 5(b)]. Note that the low- T enhancement starting from ~ 150 K is consistent with previous observations in which the TSS start to appear at ~ 150 K and become stronger with a further decrease in T [23,24].

The data in Fig. 3(b) also suggest notable d dependences. To better show this, the $V_{1,0}$ data for $T = 297$ and $T = 10$ K are plotted as a function of d in Figs. 3(c) and 3(d). The vertical axis shows $\sigma(V_{1,0}/a)d$ (σ -SmB₆ conductivity), which represents the signal strength that is independent of the sample dimensions and the resistivity. The red curves show fits to [47,50]

$$\sigma \frac{V_{1,0}}{a} d = C \lambda_{sd} \tanh\left(\frac{d}{2\lambda_{sd}}\right), \quad (2)$$

which has been widely used to evaluate the spin-pumping signals in the HM/ferromagnet [64].

The data in Fig. 3(c) can be fitted nicely. This is expected as SmB₆ is known to have no TSS and show metallic behavior at RT. The saturation response is typical in the HM/ferromagnet [47,50] and is not due to the electromagnetic shielding of the SmB₆ (see the Supplemental Material [65,66]). The fitting yields $\lambda_{sd} = 38.7 \pm 1.8$ nm, which is longer than in HM [50,51].

Interestingly, the data in Fig. 3(d) cannot be fitted by Eq. (2). In fact, over $d = 10$ – 100 nm the experimental response shows a clear positive curvature, opposite to the expectation of Eq. (2). The different features indicated by the data in Figs. 3(c) and 3(d) suggest that SmB₆ behaves like a HM at RT but differs from HMs at low T . This can be attributed to the presence of the TSS at low T . Specifically, at RT, as the TSS are absent in SmB₆ and the SOC is similar to that in HMs, the d dependence for SmB₆ is expected to be similar to that for HMs; at low T , since the nontrivial TSS are absent in very thin SmB₆ films but are present in thicker films, one would expect a jump in the “ $V_{1,0}$ vs d ” response that cannot be described by Eq. (2). The data in Fig. 3(d) indeed show a jump response. When d increases, the signal strength increases slightly over $d = 10$ – 50 nm but starts to rise sharply at $d = 50$ – 80 nm, suggesting $d_{TSS} = 25$ – 40 nm or ~ 32 nm. In samples with $d > 2d_{TSS}$, the TSS at the top and bottom surfaces of the SmB₆ film are decoupled and show a nontrivial feature, resulting in enhanced SOC. When $d < 2d_{TSS}$, the wave functions of the two surfaces overlap, suppressing the TSS.

Transport measurements were conducted on all nine samples. Figure 4(a) gives representative resistance $R(T)$. For both SmB₆(100 nm)/YIG and SmB₆(300 nm)/YIG, with decreasing T , R increases monotonically first and then reaches a plateau at ~ 10 K. SmB₆(20 nm)/YIG shows a very similar response, except that the plateau is not as flat as those of the other two. These results are consistent with

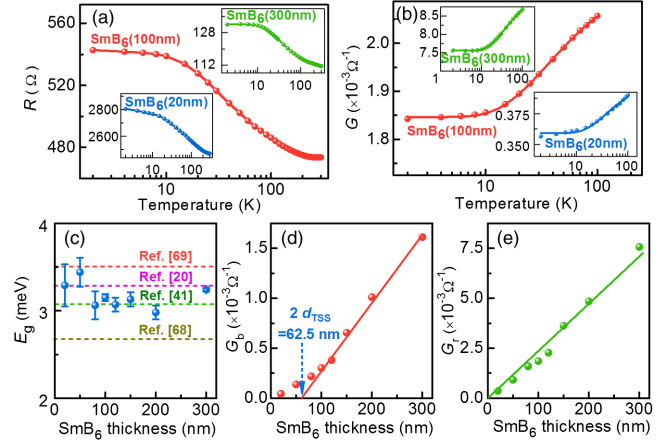


FIG. 4. Transport measurements confirming SmB₆ film quality and TSS depth. (a) Resistance R vs T . The curves are guides for the eye. (b) Conductance G vs T . The curves are fits to Eq. (3). (c), (d), and (e) The fitting-yielded gap energy E_g , bulk conductance G_b , and residual conductance G_r , respectively. The lines in (c) indicate the values reported previously. The line in (d) is a linear fit to the five points on the right side of the kink. The line in (e) is a linear fit.

previous reports [67,68]. The increase of R with decreasing T is a common feature of KIs and results from the gap opening due to hybridization between conduction electrons and f electrons, while the low- T plateau may be associated with the TSS [14]. With decreasing T , the TSS start to present at ~ 150 K [23,24], but the thermal excited bulk conductivity does not reduce to be a very small value till ~ 10 K. The overall R increase is close to that reported previously for SmB₆ films [40–42], but is notably smaller than in bulk SmB₆ [14,67,68]. This difference is likely because defects in polycrystalline films may serve as additional conducting channels, while the density of defects is low in SmB₆ single crystals.

One can perform more quantitative analyses by plotting the conductance $G(=1/R)$ vs T , as in Fig. 4(b), and modeling G as the combination of two contributions—one decreases with decreasing T and goes to zero at $T = 0$, while the other is T -independent residual conductance [20,41,68,69],

$$G = G_b e^{-(E_g/k_B T)} + G_r. \quad (3)$$

The exponential term describes the bulk conductivity change due to the gap opening. G_b is the bulk conductance in the high T limit. E_g is the gap energy. Defining σ_0 as the high- T bulk conductivity limit, G_b can be evaluated as $\sigma_0(w/l)(d - 2d_{TSS})$ (w , sample width; l , sample length). G_r is the residual conductance, consisting of a metallic surface contribution and a defect-associated, T -independent bulk contribution.

The curves in Fig. 4(b) show fits to Eq. (3). The fits are good for all three samples. The fitting-yielded E_g , G_b , and

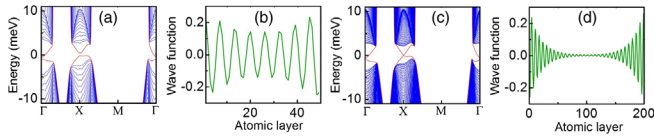


FIG. 5. Theoretical analysis of TSS in SmB_6 . (a) and (b) The band structure and wave function of the surface states of a 50-layer film (21 nm), respectively. (c) and (d) The results of a 200-layer film (83 nm).

G_r are presented in Figs. 4(c)–(e), respectively. In Fig. 4(c), the dashed lines indicate E_g values reported previously for SmB_6 bulks [20,68,69] and films [41]. The fitting-yielded E_g values are close to each other, suggesting no d dependence, and are also consistent with the previous values. G_b increases with d , with a kink at $d \approx 120$ nm. The linear fitting of the five points on the right side of the kink to $\sigma_0(w/l)(d - 2d_{\text{TSS}})$ yielded $d_{\text{TSS}} \approx 31$ nm, which is surprisingly close to that from spin-pumping measurements. The fitting also yielded $\sigma_0 = 2.7 \times 10^4 \Omega^{-1} \text{m}^{-1}$, which is almost the same as that for bulk SmB_6 [68,69]. The data in Fig. 4(e) show an approximately linear response, indicating that the defect-associated conductivity dominates over the metallic surface contribution. The existence of the low- T R plateaus, the nice fitting of $G(T)$, and the agreement of E_g and σ_0 with the values for single-crystal SmB_6 together confirm the high quality of the SmB_6 films.

The spin-pumping results were further supported by tight binding model-based analyses [36,70–72]. Figure 5 shows the main results. The interaction between the top and bottom surface states across a 21-nm film is very strong, as manifested by the gap opening for the surface states shown in (a) and the long-range distribution of the wave functions in (b). As d increases, the two surface states eventually decouple and the gap closes, as displayed by the results for the 83-nm film. With this band structure, the spin-momentum locking feature is recovered and produces the low- T enhancement of the spin-pumping signal. Further simulations indicate $d_{\text{TSS}} = 30\text{--}40$ nm, consistent with the experimental values.

Previous studies showed $d_{\text{TSS}} \approx 16$ [39] and $d_{\text{TSS}} \approx 6$ nm [41], which are smaller than the above-discussed values. The reason for this is currently unknown and may be due to different qualities of the SmB_6 films, but it should be mentioned that the values were determined through transport measurements only, with no evidence of the nontrivial nature of the TSS provided. All of those d_{TSS} values are larger than prototypical topological insulators [73,74]. This is understandable as d_{TSS} is roughly proportional to $1/E_g$ [Fig. S6(b)]. Spin-pumping experiments were previously conducted on a structure consisting of a Permalloy film grown on a SmB_6 bulk [75]. The signals were limited to very low T (2 K), inconsistent with the expected T dependence of the TSS in SmB_6 [23,24]. The use of bulk SmB_6 and the signals measurable only

at low T make it impossible to determine whether the TSS is responsible for the spin-to-charge conversion and what d_{TSS} is.

In summary, spin-pumping measurements have been conducted on SmB_6/YIG . The low- T spin-pumping signal enhancement likely provides evidence for the nontrivial feature of the TSS in SmB_6 , while the d dependence of the signals indicates $d_{\text{TSS}} \approx 31$ and $\lambda_{sd} \approx 39$ nm. The results were supported by transport measurements and theoretical analyses.

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