Multiple magnon modes in the \( \text{Co}_3\text{Sn}_2\text{S}_2 \) Weyl semimetal candidate

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Abstract – We experimentally investigate electron transport in the kagome-lattice ferromagnet \( \text{Co}_3\text{Sn}_2\text{S}_2 \), which is regarded as a time-reversal symmetry broken Weyl semimetal candidate. We demonstrate \( dV/dI(I) \) curves with pronounced asymmetric \( dV/dI \) spikes, similar to those attributed to current-induced spin-wave excitations in ferromagnetic multilayers. In contrast to multilayers, we observe several \( dV/dI \) spikes' sequences at low, \( \approx 10^4 \text{A/cm}^2 \), current densities for a thick single-crystal \( \text{Co}_3\text{Sn}_2\text{S}_2 \) flake in the regime of fully spin-polarized bulk. The spikes at low current densities can be attributed to novel magnon branches in magnetic Weyl semimetals, which are predicted due to the coupling between two magnetic moments mediated by Weyl fermions. The presence of spin-transfer effects at low current densities in \( \text{Co}_3\text{Sn}_2\text{S}_2 \) makes the material attractive for applications in spintronics.

Introduction. – A strong area of interest in condensed matter physics is topological semimetals [1]. Dirac semimetals host the 4-fold degenerate topologically protected Dirac points, which are the special points of the Brillouin zone with three-dimensional linear dispersion. In Weyl semimetals (WSM), by breaking time reversal or inversion symmetries, the 4-fold degeneration of Dirac points declines to the 2-fold one, so every Dirac point splits into two Weyl nodes with opposite chiralities. Similarly to topological insulators and quantum Hall insulators, Weyl semimetals have topologically protected surface states, which are Fermi arcs connecting projections of Weyl nodes on the surface Brillouin zone [1]. The first experimentally investigated WSMs were noncentrosymmetric crystals with broken inversion symmetry. Spin- and angle-resolved photoemission spectroscopy data indeed demonstrate spin-polarized surface Fermi arcs [2,3].

Also, ferromagnetic and antiferromagnetic WSMs with broken time-reversal symmetry can be discussed [1]. There are only a few candidates of magnetically ordered materials for the realization of WSMs [4–7]. Recently, a giant anomalous Hall effect was reported [8,9] for the kagome-lattice ferromagnet \( \text{Co}_3\text{Sn}_2\text{S}_2 \), as an indication for the existence of a magnetic Weyl phase. Fermi arcs were also visualized [10] for \( \text{Co}_3\text{Sn}_2\text{S}_2 \) by scanning tunneling spectroscopy. Another specifics of time-reversal symmetry broken WSMs is a large anomalous Hall conductivity [8,9]. The anomalous Hall effect (AHE) manifests itself as non-zero Hall conductance in zero magnetic field. AHE is known in a large class of magnetically ordered materials due to the two qualitatively different microscopic mechanisms: extrinsic processes due to scattering effects, and an intrinsic mechanism connected to the Berry curvature [11–13]. The latter variant is realized for WSMs, where the Berry curvature is enhanced at Weyl nodes [1].

It is well known that the magnetically ordered materials allow spin-wave excitations. For example, current-induced excitation of spin waves, or magnons, was demonstrated in ferromagnetic multilayers at large electrical current densities [14–20]. Spin-wave excitations are observed only for one current polarity and are presented as a sharp peak in differential resistance [14–20]. Electric field assisted magnetization dynamics was also predicted [21,22] for WSMs, which requires experimental investigations. In particular, novel magnon branches are predicted [21] in magnetic Weyl semimetals, which can be understood as a result of the coupling between two magnetic moments mediated by Weyl fermions.

Here, we experimentally investigate electron transport in the kagome-lattice ferromagnet \( \text{Co}_3\text{Sn}_2\text{S}_2 \), which is regarded as a time-reversal symmetry broken Weyl
semimetal candidate. We demonstrate $dV/dI(I)$ curves with pronounced asymmetric $dV/dI$ spikes, similar to those attributed to current-induced spin-wave excitations in ferromagnetic multilayers. In contrast to multilayers, we observe several $dV/dI$ spikes’ sequences at low, $\approx 10^4$ A/cm$^2$, current densities for a thick single-crystal Co$_3$Sn$_2$S$_2$ flake in the regime of fully spin-polarized bulk. The spikes at low current densities can be attributed to novel magnon branches in magnetic Weyl semimetals, which are predicted due to the coupling between two magnetic moments mediated by Weyl fermions. The presence of spin-transfer effects at low current densities in Co$_3$Sn$_2$S$_2$ makes the material attractive for applications in spintronics.

Samples and technique. – Co$_3$Sn$_2$S$_2$ single crystals were grown by the gradient freezing method. Initial load of high-purity elements taken in stoichiometric ratio was slowly heated up to $920$ °C in the horizontally positioned evacuated silica ampoule, held for 20 h and then cooled with the furnace to the ambient temperature at the rate of 20 degree/h. The obtained ingot was cleaved in the middle part. The Laue patterns confirm the hexagonal structure with (0001) as cleavage plane. The electron probe micro-analysis of cleaved surfaces and X-ray diffractometry of powdered samples confirmed the stoichiometric composition of the crystal.

Despite it is possible to form contacts directly on the cleaved Co$_3$Sn$_2$S$_2$ crystal plane, large samples are not suitable for transport experiments: it is impossible to create high current density in a thick sample, which is crucial for the current-induced magnetization experiments.

Instead, the leads pattern is formed on the insulating SiO$_2$ substrate by the lift-off technique after thermal evaporation of 100 nm Au. The gold leads are separated by 5 µm intervals, see fig. 1(a), and (b). Since the kagome-lattice ferromagnet Co$_3$Sn$_2$S$_2$ can be easily cleaved along the (0001) crystal plane, small (about 100 µm size and 1 µm thick) Co$_3$Sn$_2$S$_2$ flakes are obtained by a mechanical cleaving method. Then we select the most plane-parallel flakes with a clean surface, where no surface defects could be resolved with the optical microscope. They are transferred to the Au leads pattern and pressed slightly with another oxidized silicon substrate. A special metallic frame allows us to keep the substrates parallel and apply a weak pressure to the sample. No external pressure is needed for a Co$_3$Sn$_2$S$_2$ flake to hold onto a substrate with Au leads afterward. This procedure provides reliable Ohmic contacts, stable in different cooling cycles, which has also been demonstrated before [23–25].

We check by standard magnetoresistance measurements that our Co$_3$Sn$_2$S$_2$ flakes demonstrate a giant anomalous Hall effect [11–13] in the normal to the flake’s plane magnetic field. Figure 2(a) shows hysteresis behavior and sharp switchings in the Hall resistance $R_{xy}$, the switchings’ positions $\approx 0.5$ T even quantitatively coincide with the previously reported ones [8,9]. Figure 2(b) shows positive, non-saturating longitudinal magnetoresistance, which is also consistent with the reported behavior [8] for the Co$_3$Sn$_2$S$_2$ semimetal. Thus, magnetoresistance measurements confirm the high quality of our Co$_3$Sn$_2$S$_2$ samples.

We study electron transport along the Co$_3$Sn$_2$S$_2$ surface by a standard four-point technique. The principal circuit diagram is depicted in fig. 1(b). To obtain $dV/dI(I)$ characteristics, a large (up to 3 mA) dc current $I$ is additionally modulated by a low ($\approx 5$ µA) ac component. We measure both dc ($V$) and ac ($\sim dV/dI$) components of the voltage drop in fig. 1(b) with a dc voltmeter and a lock-in, respectively, after a broadband preamplifier. The lock-in signal is checked to be independent of the modulation frequency. The obtained $dV/dI(I)$ curves are qualitatively independent of the particular choice of current and voltage probes. We check by comparison of the four- and three-point $dV/dI(I)$ curves, that the contact resistance is negligible, see also, refs. [23–25] for details.

Fig. 1: (a) A top-view image of the sample. A flat (about 100 µm size and 1 µm thick) single-crystal Co$_3$Sn$_2$S$_2$ flake is weakly pressed on the insulating SiO$_2$ substrate with 100 nm thick, 5 µm separated gold leads. The leads are of 40 µm, 20 µm, 10 µm and 10 µm width from up to down for the left side of the sample. (b) The sketch of a sample with electrical connections. Non-linear $dV/dI(I)$ curves are measured by a standard four-point technique, so a large dc current $I$ is additionally modulated by a low ac component.

Fig. 2: (a) Giant anomalous Hall effect, which confirms [8] the high quality of our kagome-lattice semimetal Co$_3$Sn$_2$S$_2$ samples [8,9]. The Hall resistance $R_{xy}$ demonstrates hysteresis behavior and sharp switchings at $\approx 0.5$ T. Arrows indicate the scanning directions. (b) Positive, non-saturating longitudinal magnetoresistance in the normal magnetic field, which is a hallmark of compensated semimetals [8,9]. The measurements are performed at 4.2 K.
The measurements are performed in a usual He4 cryostat equipped with a superconducting solenoid. Co$_3$Sn$_2$S$_2$ magnetic properties arise from the kagome-lattice cobalt planes, whose magnetic moments order ferromagnetically [8] out of plane below 175 K. We do not see noticeable temperature dependence in the interval 1.4–4.2 K, so all the results below are obtained at 4.2 K.

**Experimental results.** – Examples of $dV/dI(I)$ characteristics are shown in fig. 3(a) and (b). The curves demonstrate a clear non-Ohmic behavior: $dV/dI$ is rising with both bias current polarities without any saturation at high biases. This behavior is inconsistent with trivial reasons like tunneling through different sample defects, which generally leads to decreasing $dV/dI(I)$. Moreover, the experimental $dV/dI(I)$ curves are well reproducible for different samples with very different zero-bias resistance, cf. fig. 3(a) and (b). On the other hand, an overall symmetric increase in $dV/dI(I)$ is usually attributed to electron scattering in the magnetically ordered materials [14,26].

For the curves in fig. 3 we observe well-developed $dV/dI$ spikes for certain (positive) current polarity. These $dV/dI$ features are well reproducible in different cooling cycles. The spike position is sensitive to the magnetic field, as depicted in fig. 3, it moves to higher currents with increasing magnetic field. At the same time, there is no noticeable hysteresis with the current sweep direction, see the inset to fig. 3(a). This behavior is very similar to one reported for ferromagnetic multilayers [14–20], where the $dV/dI$ spikes have been attributed to spin-wave excitation modes.

In addition, small spikes are sometimes present at the counter (negative) current polarity, as depicted in fig. 3(a) for $B = 2.5$ T and for $B = 2.7$ T in the inset. These minor spikes have qualitatively the same magnetic field behavior, so we regard only the major ones at positive currents below.

The colormap in fig. 4(a) demonstrates the evolution of $dV/dI$ spikes with magnetic field, which is applied normally to the Co$_3$Sn$_2$S$_2$ flake. Since the general $dV/dI(I)$ shape is practically independent of the magnetic field, see fig. 3, it is subtracted from the data. Thus, the colors correspond only to the spikes’ amplitudes in fig. 4(a). It is clear, that the $dV/dI$ spikes’ positions depend linearly on the magnetic field, as has been also demonstrated [14–20] for magnons [17] in multilayers. In contrast to multilayers, we observe several excitation branches, which are highlighted by white dashed lines on the colormap. The line slopes coincide within experimental accuracy, they also independent of the field direction. The spikes are better visible at highest currents, where they can be demonstrated even in zero magnetic field.

On the other hand, the relative amplitudes of the spikes are different for different branches, the spikes even vanish and reappear in some regions of the map. Also, we observe the splitting of a particular branch in high magnetic fields, see also fig. 4(b): while increasing the magnetic field, the spike’s amplitude is diminishing, an additional spike appears at different current position; in higher fields, two spikes coexist, see fig. 4(b). Such interplay generally reflects the ground-state reconstruction [27–29].

**Discussion.** – $dV/dI(I)$ curves with an overall symmetric increase in $dV/dI$ and asymmetric $dV/dI$ spikes

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Fig. 3: Examples of $dV/dI(I)$ characteristics for two different samples, (a) and (b), respectively. The curves are shifted upward for clarity. $dV/dI$ is rising with both bias current polarities without any saturation at high biases. There are well-developed $dV/dI$ spikes for certain (positive) current polarity, their positions are sensitive to the magnetic field. The inset to (a) demonstrates a lack of hysteresis for different current sweep directions. The magnetic field is perpendicular to the flake’s plane. The measurements are performed at 4.2 K.

Fig. 4: Evolution of $dV/dI$ spikes’ positions with magnetic field. The monotonous $dV/dI(I)$ is subtracted from the data, the colors correspond only to the spikes’ amplitudes. There are several excitation branches with the linear field dependence, which are highlighted by white dashed lines. The slopes coincide within experimental accuracy, but the spikes vanish and reappear in some regions of the map. (b) An example of splitting of a particular branch in high magnetic fields, the curves are shifted downward for clarity. While the amplitude of one spike is decreasing, the other spike is emerging at higher current, see also the corresponding region in (a).
have been reported for spin valves [14–20]. The spin valves are the sandwich structures, where spin-dependent scattering affects the magnetic moments of two spin-polarized layers, while their mutual orientation defines the differential resistance. We observe qualitatively similar effects in the bulk properties of single-crystal Co$_3$Sn$_2$S$_2$ flakes. Since Co$_3$Sn$_2$S$_2$ is a quasi–two-dimensional ferromagnet, it can be regarded as a layered structure consisting of multiple Co monolayers. Thus, possible spin-transfer effects in a single Co layer should be discussed firstly.

For spin valves, the hysteresis in dV/dI(I) curves in low magnetic fields indicates current-induced switching in the orientation of layers’ magnetic moments between parallel and antiparallel orientations. In the high-field regime, the high-bias dV/dI spikes correspond to a precessing spin-wave state with increasing deviations from the parallel alignment, which leads to increases in dV/dI resistance. In experiments on multilayers [14–20], spin-waves are excited by injection of extremely high (10$^9$ A/cm$^2$) current density for thin, 2–4 nm, Co layers.

We estimate the maximum current density as $\approx$10$^4$ A/cm$^2$ for $I = 1$ mA through $S \sim 1 \times 10^{15}$ cm$^{-2}$ contact area, since the current density is maximal near the contact. Below, we rely on the model of Slonczewski [30], which was successfully adapted for the quantitative analysis of spin-transfer effects in Co/Cu/Co nanopillars [17]. All the model parameters are well known for Co [17].

Within the model [17,30], the dV/dI spikes positions $I_{sw}$ are described by

$$I_{sw}(H) = \frac{\alpha \gamma e \sigma [H + H_{an} - H_{ex} + 2\pi M]}{g(0)}, \quad (1)$$

where $\alpha$ is the damping parameter, $\gamma$ is the gyromagnetic ratio, $\sigma$ is the total spin of the free layer, $M$ is the magnetization, $H_{ex}$ and $H_{an}$ are the exchange and the anisotropy fields, respectively. The total spin is $\sigma = MV/\gamma h$, where $V = Sd$ is the free layer’s volume. $g(0) \leq 0.25$ is the scalar function, which depends on the mutual orientation of the free and static layers’ magnetization [30]. The d$I_{sw}$/dH slope is defined by $\alpha \gamma e \sigma / g(0)$, so all the branches are parallel in fig. 4(a).

A single Co monolayer plays the role of the free layer and the rest of the sample is the static layer. Then, one may estimate the free layer thickness as $d = (dI_{sw}/dH) \cdot h g(0)/\alpha e M S$. For known Co parameters [17], $\alpha = 0.005$, $g(0) = 0.14$, and $M$ can be estimated as $\approx$100 emu/cm$^3$ for Co$_3$Sn$_2$S$_2$. It gives inappropriately small $d \approx 3 \times 10^{-2}$ Å. The damping parameter $\alpha$ can only be larger in a ferromagnet [15,16,18], which leads to even smaller $d$. To obtain realistic $d \sim 4$ Å, which is approximately equal to the distance between the Co layers in Co$_3$Sn$_2$S$_2$, one should use very small $S \approx 100 \times 100$ nm$^2$, which is impossible even for inhomogeneous large $1 \times 10^{15}$ cm$^{-2}$ planar contacts. We wish to note, that dV/dI spikes are observed for different samples and are independent of the particular contacts, see fig. 3(a) and (b).

Thus, possible spin-transfer effects between Co layers cannot explain the experimental results. The bulk of the sample is fully spin-polarized [8] above $\approx0.5$ T, see fig. 2, so we cannot attribute dV/dI spikes to any bulk spin structures like domains. The domains are always accompanied by hysteresis in dV/dI(I) curves [14,17], which cannot be seen in the inset to fig. 3(a). We have to search for Weyl specifics of the Co$_3$Sn$_2$S$_2$ flake. In principle, there are two possibilities, which refer to surface or bulk WSM properties, respectively:

i) Broken time-reversal symmetry WSMs are characterized by topologically protected Fermi–arc surface states, which survive in high magnetic fields [1]. Low current density $\approx$10$^4$ A/cm$^2$ can reflect the small total spin $\sigma$ in the surface state, which is unreachable in traditional ferromagnets.

ii) An additional bulk magnon branch is predicted [21] in magnetic WSMs. Physically, this magnon excitation can be understood as a direct result of the coupling between two magnetic moments mediated by Weyl fermions. The branch is also described by the modified Landau-Lifshitz equation [21], so $I_{sw}(H)$ is still linear [17,30]. However, the gapless nature of Weyl fermions leads to the long-range correlation of this magnon excitation [21], which results in the dramatic decrease [22] in the damping parameter $\alpha$. Thus, the observation of low current density $\approx$10$^4$ A/cm$^2$ well correspond to the predicted [21] novel magnon mode in magnetic WSMs.

In both cases, the spin-unpolarized current from Au leads is injected into the magnetically ordered WSM, which creates spin precession, or, in other words, spin-wave excitation. The process is somewhat similar to the tip experiments [15,16,18], while the current density is much smaller in our case. In multilayers, the asymmetry of dV/dI spikes reflects the intrinsic asymmetry of the spin diode. The real Co$_3$Sn$_2$S$_2$ flakes are also not symmetric, see fig. 1(a), which creates higher current density for one region of the sample and is responsible for the spikes asymmetry in fig. 3. The latter variant ii) is based on the solid theoretical background [21,22,31] and seems to be more realistic. In the terms of eq. (1), different modes in fig. 4(a) are characterized by different fields $H_{ex}$ and $H_{an}$, due to the complicated band structure of the real Co$_3$Sn$_2$S$_2$ WSM [10], which is reflected in a different onset current at zero magnetic field. Moreover, band bifurcation has been predicted in the magnetic field [21], which can be an origin of the dV/dI spikes’ interplay in fig. 4(b).

Conclusion. – As a conclusion, we experimentally investigate electron transport in the kagome-lattice ferromagnet Co$_3$Sn$_2$S$_2$, which is regarded as a time-reversal symmetry broken Weyl semimetal candidate. We demonstrate dV/dI(I) curves with pronounced asymmetric dV/dI spikes, similar to those attributed to current-induced spin-wave excitations in ferromagnetic multilayers. In contrast to multilayers, there are several dV/dI spikes that...
spikes' sequences at low, \( \approx 10^4 \text{A/cm}^2 \), current densities for a thick single-crystal \( \text{Co}_3\text{Sn}_2\text{S}_2 \) flake in the regime of fully spin-polarized bulk. We attribute \( dV/dI \) spikes at low current densities to novel magnon branches in magnetic Weyl semimetals, which can be understood as a direct result of the coupling between two magnetic moments mediated by Weyl fermions. In this case, the observed splitting of the magnon branches in magnetic field may reflect the predicted band bifurcation for a magnetic Weyl splitting of the magnon branches in magnetic field.

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