Magnetically stable zero-bias anomaly in Andreev contact to the magnetic Weyl semimetal Co$_3$Sn$_2$S$_2$

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Abstract – Being encouraged by the interplay between topology, superconductivity and magnetism, we experimentally investigate charge transport through the interface between the Nb superconductor and the time-reversal symmetry breaking Weyl semimetal Co$_3$Sn$_2$S$_2$. In addition to the proximity-induced superconducting gap, we observe prominent subgap zero-bias anomaly. The anomaly demonstrates an unusual robustness to external magnetic fields: its width is absolutely stable up to the critical field of Nb, while its amplitude exhibits a weak non-monotonous variation. As the promising scenario of emergence of the zero-bias anomaly in transport characteristics, we consider the proximity-induced zero-energy Andreev bound states interfaced with the half-metallic Co$_3$Sn$_2$S$_2$ and influenced by the strong spin-orbit coupling and large Zeeman splitting.

Introduction. – A magnetic Weyl semimetal (WSM) with broken time-reversal symmetry can be interpreted as a 3D heterostructure consisting of the layers of Chern insulators [1]. For WSM, the coupling between the layers closes the bulk band gap at isolated points of the Brillouin zone. These band touching points with linear dispersion, also called Weyl nodes, are topological objects [2,3]. Their topological protection is guaranteed by a non-zero Chern number defined on a sphere in momentum space enclosing a given Weyl node.

There are only a few candidates of time-reversal symmetry breaking WSMs [3–6]. In transport studies, an anomalous Hall effect (AHE) is the hallmark of a WSM phase [7]. AHE originates from the topologically protected chiral surface states residing in the Fermi arcs, which connect projections of Weyl nodes on the surface Brillouin zone and inherit the chiral property of Chern insulator edge states [2,3]. The Fermi arc states can play an important role in forming the transport properties of WSM not only when the bulk contribution is strongly suppressed or absent for a special reason, as in AHE. The anomalous contribution to a number of transport coefficients from the Fermi arcs can be of the same order as from the bulk states even in large systems [8].

Physics becomes even more exciting if one considers a magnetic WSM in proximity to an s-wave spin-singlet superconductor. The unusual band structure of WSM and its nontrivial topological properties modify Andreev reflection processes and result in new proximity-induced effects [9–16]. It is worth mentioning that a variety of possible unusual intrinsic superconducting phases has been theoretically identified in magnetic WSM (see, for example, [17–22]), although the intrinsic superconductivity has not yet been determined in the materials. On the other hand, if the exchange field is parallel to the interface of the junction between the magnetic WSM and the conventional s-wave superconductor, the Andreev reflection should be suppressed for the bulk excitations near a certain Weyl node due to chirality blockade [23]: a change in chirality is required in order to preserve spin-singlet pairing with its transfer of zero-spin and zero-momentum. The types of proximity-induced inhomogeneous superconducting correlations that can be present in this case, including the even-frequency spin-triplet p-wave and odd-frequency spin-triplet s-wave order parameters with intra- and interorbital pairings [24]. The proximity-induced superconductivity in Fermi arcs has been predicted to show up even if the superconductivity in the bulk is substantially suppressed and found to emerge, in the simplest cases, as a pure triplet state or a singlet-triplet mixture [25]. The appearance of chiral zero-energy Majorana bound states has been identified for the triplet pairing. The topologically
protected surface states of WSM are considered as a potential platform for realization of chiral Majorana bound states [2].

Recently, the giant AHE has been reported [26,27] for the kagome-lattice half-metallic ferromagnet Co$_3$Sn$_2$S$_2$ as an anomalous Hall conductance in zero magnetic field. The existence of Fermi arc surface states in the material was confirmed by angle-resolved photoemission spectroscopy [27,28] and scanning tunneling microscopy [29]. The magnetic moments of cobalt become ferromagnetically ordered out of kagome-lattice Co$_3$Sn planes below 175 K. Here, we experimentally investigate charge transport through the interface between a Nb superconductor and a magnetic WSM Co$_3$Sn$_2$S$_2$. Aside from Andreev reflection, we observe prominent zero-bias anomaly (ZBA). Unlike the superconducting gap, the anomaly’s width possesses absolute robustness to external magnetic fields up to the critical field of Nb. We discuss possible scenarios that could result in magnetically stable ZBA under the conditions studied, taking into account the topological nature of WSM and its interfaces as well as the presence of the spin-orbit coupling and large Zeeman splitting, which are intrinsic for the half-metallic WSM.

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

The kagome-lattice ferromagnet Co$_3$Sn$_2$S$_2$ has the (0001) cleavage plane, but bonds between the layers in the crystal are quite strong. Thus, only rather thick flakes (about 100 µm size and 1 µm thick) can be exfoliated by rough mechanical cleavage. We selected the flattest flakes with a clean surface, which was verified by an optical microscope.

Then, a small Co$_3$Sn$_2$S$_2$ flake is transferred to the Nb leads pattern, see fig. 1(a). The leads pattern is defined on an insulating SiO$_2$ substrate by a lift-off technique after magnetron sputtering of 150 nm Nb. The leads are separated by 2 µm intervals. Further, a Co$_3$Sn$_2$S$_2$ flake is pressed to the leads slightly with another oxidized silicon substrate. A weak pressure is applied with a special metallic frame, which keeps the substrates strictly parallel. This procedure provides transparent contacts, stable in different cooling cycles, without mechanical polishing or chemical treatment [30–32]. For our sample preparation technique, Andreev spectroscopy has been demonstrated in refs. [30,31,33]. Moreover, direct experimental comparison of Andreev and thermal regimes can be found in ref. [31]. Although the interface quality allows us to observe the Andreev physics in the Nb-Co$_3$Sn$_2$S$_2$ junctions, it prevents the proximity-induced Josephson current [33] to flow across the WSM Co$_3$Sn$_2$S$_2$ connecting 2 µm spaced superconducting Nb contacts.

It has been shown previously that our samples show a giant AHE [32], which is a hallmark of Co$_3$Sn$_2$S$_2$ Weyl semimetal [26,27]. The bulk of the samples is fully spin-polarized [32] above 0.5 T.

A standard three-point technique is used to study electron transport across a single Nb-Co$_3$Sn$_2$S$_2$ junction, see fig. 1(b): one Nb contact (C1) is grounded and two other contacts are used for applying current (C2) and measuring potential (C3). To obtain dV/dI(V) characteristics, dc current is additionally modulated by a low (below 5 µA, f ≈ 1 kHz) ac component. We measure both dc (V) and ac (∼ dV/dI) components of the potential with a dc voltmeter and a lock-in, respectively, after a broadband preamplifier. We checked that the lock-in signal is independent of the modulation frequency. The obtained dV/dI(V) characteristics are verified to be independent of mutual positions of current/voltage probes (e.g., changing C2 to C4 or C3 to C4 in fig. 1(b)), so they reflect transport parameters of the Nb-Co$_3$Sn$_2$S$_2$ interface with negligible admixture of the sample’s bulk resistance. We also checked that dV/dI(V) characteristics are well reproducible in different cooling cycles. The measurements are performed in a dilution refrigerator (30 mK–1.2 K) and in a standard He$^+$ cryostat (1.4 K–4.2 K).

Experimental results. – The blue curve in fig. 2 shows the dV/dI(V) characteristic of the Nb-Co$_3$Sn$_2$S$_2$ junction at the lowest temperature 30 mK and zero
In addition, the blue curve in fig. 2(a) shows several features both inside and outside the gap at zero magnetic field and 30 mK temperature. There are sharp periodic peaks outside the Nb gap, which are likely to be geometrical resonances, known for Andreev contacts [37–39]. Also, there is a wide (±0.45 meV width) central structure, which is denoted by the dashed rectangle in fig. 2(a) and can be understood [40–42] as the proximity-induced soft [43] superconducting gap $\Delta_S$ at the surface of Co$_3$Sn$_2$S$_2$. Figure 2(c) shows the temperature dependence of the normalized $\Delta_S$ (the black rectangles) and ZBA normalized width (red diamonds). The gap $\Delta_S$ has approximately the BCS-like temperature dependence [10] and nearly satisfies the BCS relation $\Delta_S \approx 1.76 k_B T_{c_S}$, where $T_{c_S} = 3.5$ K in fig. 2(c) and $\Delta_S = 0.45$ meV in fig. 2(a).

The colormaps in fig. 3(a), (b) show the stability of ZBA against magnetic fields at two different temperatures. At both temperatures, the width of ZBA is robust to magnetic fields, while its depth has a small (less than 5%) non-monotonous variation. Suppression of ZBA starts only close to the critical field of the superconducting gap: after 3.3 T at 30 mK (fig. 3(a)) and after 2.2 T at 1.4 K (fig. 3(b)). Figure 3(c) shows the enlarged ZBA region for magnetic fields 0, 1.67 T and 2.5 T. The ZBA width is about 0.1 mV, while the ZBA width change is within 0.01 mV. On the other hand, the superconducting gap $\Delta(B)$ is diminished more than twice in the 2.5 T field. Due to the sharp edges of the ZBA in fig. 3(c), the noise level should be estimated below this 0.01 mV value for voltage. This is the reason to conclude that the width of ZBA stays unaltered in a wide magnetic field range.

Apart from the ZBA stability, the data in fig. 3(a), (b) allow the detailed analysis of the Nb superconducting gap. The temperature $\Delta(T)$ and the magnetic field $\Delta(B)$ dependencies are shown in fig. 3(d). The niobium gap $\Delta$ shows clear BCS-like temperature dependence [10], which firmly confirms our general dV/dI(V) analysis. Qualitatively the same behavior is demonstrated by another Nb-Co$_3$Sn$_2$S$_2$ junction, showing a larger interface scattering, see fig. 4(a), (b). The blue curve in fig. 4(a) at zero magnetic field and 30 mK shows a well-defined gap $\Delta = 1.3$ meV, denoted by the blue dashed lines, and a subgap structure with a sharp ZBA in the center. Neglecting the ZBA we have the normal resistance approximately equal to the dV/dI(0), which gives $T = 0.76$ from the BTK as a crude estimation. Higher interface scattering should diminish the gap suppression by the ferromagnet, so $\Delta = 1.3$ meV is closer to the bulk niobium gap.

Again, the width of ZBA is stable even in high magnetic fields, e.g., see the red curve at $B = 1.67$ T in fig. 4(a). The colormap in fig. 4(b) shows the stability of the ZBA width in moderate magnetic fields and its independence from the field’s sign. There is also non-monotonous variation of the ZBA depth in fig. 4.

**Discussion.** – Our main observation is the zero-bias anomaly, which is unusually robust over a wide range

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**Fig. 2:** (a) dV/dI(V) characteristics for one of the Nb-Co$_3$Sn$_2$S$_2$ junctions at 30 mK. The external magnetic field $B$ is normal to the sample’s plane. It is zero for the blue curve, and equal to ±1.67 T for the black and red curves, respectively. The superconducting gap, marked by the blue (zero field) and red (±1.67 T) dashed lines, is suppressed in magnetic fields. The subgap structure is marked by the black dashed rectangle, it is diminishing proportionally to the superconducting gap in magnetic fields. ZBA, on the contrary, is robust to magnetic fields, while the proximity-induced superconducting gap is still observable. The curves are shifted for clarity both in (a) and (b). (c) Normalized width of the subgap structure (the black rectangles) and ZBA (the red diamonds) vs. temperature.

**Fig. 3:** (a) dV/dI(V) characteristics for one of the Nb-Co$_3$Sn$_2$S$_2$ junctions at 30 mK. The external magnetic field $B$ is normal to the sample’s plane. It is zero for the blue curve, and equal to ±1.67 T for the black and red curves, respectively. The superconducting gap, marked by the blue (zero field) and red (±1.67 T) dashed lines, is suppressed in magnetic fields. The subgap structure is marked by the black dashed rectangle, it is diminishing proportionally to the superconducting gap in magnetic fields. ZBA, on the contrary, is robust to magnetic fields, while the proximity-induced superconducting gap is still observable. The curves are shifted for clarity both in (a) and (b). (c) Normalized width of the subgap structure (the black rectangles) and ZBA (the red diamonds) vs. temperature.

**Fig. 4:** (a) dV/dI(V) characteristics for one of the Nb-Co$_3$Sn$_2$S$_2$ junctions at 30 mK. The external magnetic field $B$ is normal to the sample’s plane. It is zero for the blue curve, and equal to ±1.67 T for the black and red curves, respectively. The superconducting gap, marked by the blue (zero field) and red (±1.67 T) dashed lines, is suppressed in magnetic fields. The subgap structure is marked by the black dashed rectangle, it is diminishing proportionally to the superconducting gap in magnetic fields. ZBA, on the contrary, is robust to magnetic fields, while the proximity-induced superconducting gap is still observable. The curves are shifted for clarity both in (a) and (b). (c) Normalized width of the subgap structure (the black rectangles) and ZBA (the red diamonds) vs. temperature.

The most prominent result is the ZBA, which appears as a narrow (±0.06 meV width) dV/dI drop. The width of the ZBA exhibits absolute robustness to external magnetic fields, which is demonstrated in fig. 2(a). In contrast to that, the superconducting Nb gap is diminishing in the magnetic field, as well as the other subgap structures. This behavior is independent on the field’s sign, as demonstrated by the black (+1.67 T) and red (−1.67 T) curves in fig. 2(a). In contrast to the magnetic field, an increase in temperature has a dramatic influence on ZBA: it shrinks and disappears completely at about 3.5 K, while the superconducting gap is still observable, see fig. 2(b).

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Fig. 3: (a), (b): evolution of $dV/dI(V)$ characteristic of the Nb-Co$_3$Sn$_2$S$_2$ junction in magnetic fields at $T = 30$ mK and at $T = 1.4$ K. At both temperatures, the width of ZBA (the violet stripe around zero bias) is stable against magnetic fields. ZBA shrinks only close to the critical field of the superconducting gap. (c) Enlarged ZBA region for magnetic fields 0, 1.67 T and 2.5 T. The ZBA width is about 0.1 mV, while the ZBA width change is within 0.01 mV. The superconducting gap $\Delta$ is diminished more than twice in the 2.5 T field. (d) The temperature $\Delta(T)$ and the magnetic field $\Delta(B)$ dependencies, respectively, for the normalized niobium superconducting gap $\Delta$. It demonstrates clear BCS-like temperature dependence [10], which firmly confirms our general $dV/dI(V)$ analysis.

A number of mechanisms resulting in ZBA in mesoscopic physics can be ruled out for our experiment. This in particular concerns the effects known for superconducting-normal contacts of a large area [44,45]. As a most important argument, we observe standard $dV/dI(V)$ Andreev curve [10], with clearly defined superconducting niobium gap $\Delta$. Despite the fact that the gap is partially suppressed by the proximity with a ferromagnet, it shows standard, well-known dependencies on temperature and magnetic field in fig. 3(c) and (d). A similar BCS-like behavior is demonstrated for the proximity-induced superconducting gap in fig. 2(c). Thus, the observed ZBA should be connected with spectrum specifics and it cannot be ascribed to current-induced effects. Also, i) a rough estimation of heating in the contact area may be done by using the bias voltage (mV) by a factor of 3.2 K/mV [46]. For the observed ZBA $V = 0.06$ mV gives much less heating than Nb $T_c$, so we cannot attribute the ZBA to the heating effects; ii) the effects of the Oersted field can be excluded since ZBAs caused by the Oersted field are sensitive to an external magnetic field [44] and they exist almost till the superconductor’s $T_c$ [44], in contrast to the temperature dependence in fig. 2(c). The junction resistance is about 1 ohm, which is inconsistent with touching only in a few points. Moreover, this value is more or less stable for different samples (about 1 ohm), which is inconsistent with multiple point-contact touching. Thus, the bottom flake surface is smooth, we can estimate the junction area of the externally applied magnetic field and appears in the proximity-induced charge transport through the junctions involving the magnetic Weyl semimetal Co$_3$Sn$_2$S$_2$ connecting the superconducting Nb leads.

Fig. 4: (a) $dV/dI(V)$ characteristic for another Nb-Co$_3$Sn$_2$S$_2$ junction at 30 mK for zero external magnetic field (blue) and for $B = 1.67$ T. The width of ZBA stays unaltered in high magnetic fields, while its height is diminished. (b) Evolution of $dV/dI(V)$ characteristic in magnetic field. The width of ZBA (the dark blue stripe around zero bias) is stable and independent of the sign of the magnetic field.

of the externally applied magnetic field and appears in the proximity-induced charge transport through the junctions involving the magnetic Weyl semimetal Co$_3$Sn$_2$S$_2$ connecting the superconducting Nb leads.
to be not less than $1 \times 10 \, \mu m^2$. Also, ZBAs in fig. 2(a) and fig. 4(a) cannot arise due to the Kondo effect, since they are symmetric and do not show a double-peak structure under the applied magnetic field [44,47,48]. Furthermore, one should point out a possibility for the impurity-induced ZBA, which was actively studied with regard to semiconductor nanowires [49–55]. A detailed analysis has shown that disorder-induced ZBA is generally not so stable with varying strength of the Zeeman splitting [54], as compared to the experimental results in figs. 3 and 4.

At the same time, there is another possible scenario resulting in ZBA that cannot be excluded yet from the list of relevant physical mechanisms [56]. In particular, if there is a spatially inhomogeneous confining potential inside a proximitized nanowire, there are subgap Andreev bound states (ABSs). In the absence of the intrinsic Zeeman splitting as well as the external magnetic field, ABSs usually appear as two symmetric subgap conductance peaks. With increasing external magnetic field in the presence of a strong spin-orbit coupling, ABSs can merge to form a single zero-energy state producing a single zero-bias conductance peak [56–73]. Analogous effects can take place even for highly transparent contacts between a superconductor and a chiral channel [64].

A similar physical mechanism can be assumed to form zero-energy ABSs at the surface of Co$_2$Sn$_2$S$_2$ in proximity to a Nb superconductor. Fortunately, the applicability to two-dimensional systems of the main qualitative theoretical statements regarding the Majorana and Andreev states in the one-dimensional case, is known to be usually justified [12,15,69,71].

i) Although Weyl surface states are two-dimensional, they inherit the chiral property of the Chern insulator edge states, so a preferable direct ion is defined by Fermi arcs on a particular crystal surface.

ii) The condition of a strong spin-orbit interaction is obviously satisfied for the Co$_2$Sn$_2$S$_2$ WSM [26]. A sufficiently large intrinsic Zeeman splitting in the half-metallic Co$_2$Sn$_2$S$_2$ can be tuned by applying the external magnetic field. In the experiment, we observe no evidences of the finite-energy Andreev states. This could indicate that the inherent Zeeman splitting substantially exceeds its critical value, above which the finite-energy Andreev states coalesce together and form near-zero-energy midgap states. We wish to note that no stable ZBA has been observed [30] in a similar setup for Andreev reflection at the interface between Nb and WTe2, which is a non-magnetic Weyl semimetal. In ref. [30], any subgap features have been suppressed below 0.85 T magnetic field.

iii) An inhomogeneous potential is expected at the surface of Co$_2$Sn$_2$S$_2$, providing a platform for confined ABSs. After a mechanical cleavage, one expects to have multiple layer steps in the contact region for the Nb-Co$_2$Sn$_2$S$_2$ junctions. Cleavage mostly occurs between the Sn and S layers, but the topological surface states were revealed at the Sn layers [29,74,75]. In addition, it has also been shown that there are Co$_2$Sn terraces at the surface of Co$_2$Sn$_2$S$_2$ [76].

**Conclusion.** – In conclusion, we have experimentally investigated charge transport through the interface between the Nb superconductor and magnetic WSM Co$_2$Sn$_2$S$_2$. Aside from Andreev reflection, we observe several additional features, among which the most notable is the prominent subgap ZBA, stable against external magnetic fields up to the critical field of Nb. Possible mechanisms of emergence of magnetically stable ZBA under the given conditions should include the topological nature of WSM and its interfaces together with the effects of the strong spin-orbit coupling and large Zeeman splitting, intrinsic to the half-metallic WSM. As the promising scenario for ZBA observed in the transport measurements, we consider the proximity-induced zero-energy ABSs interfacing between the superconducting Nb and Co$_2$Sn$_2$S$_2$.

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