Large Zero Bias Conductance Peak in Dirac Semimetal-Superconductor Devices

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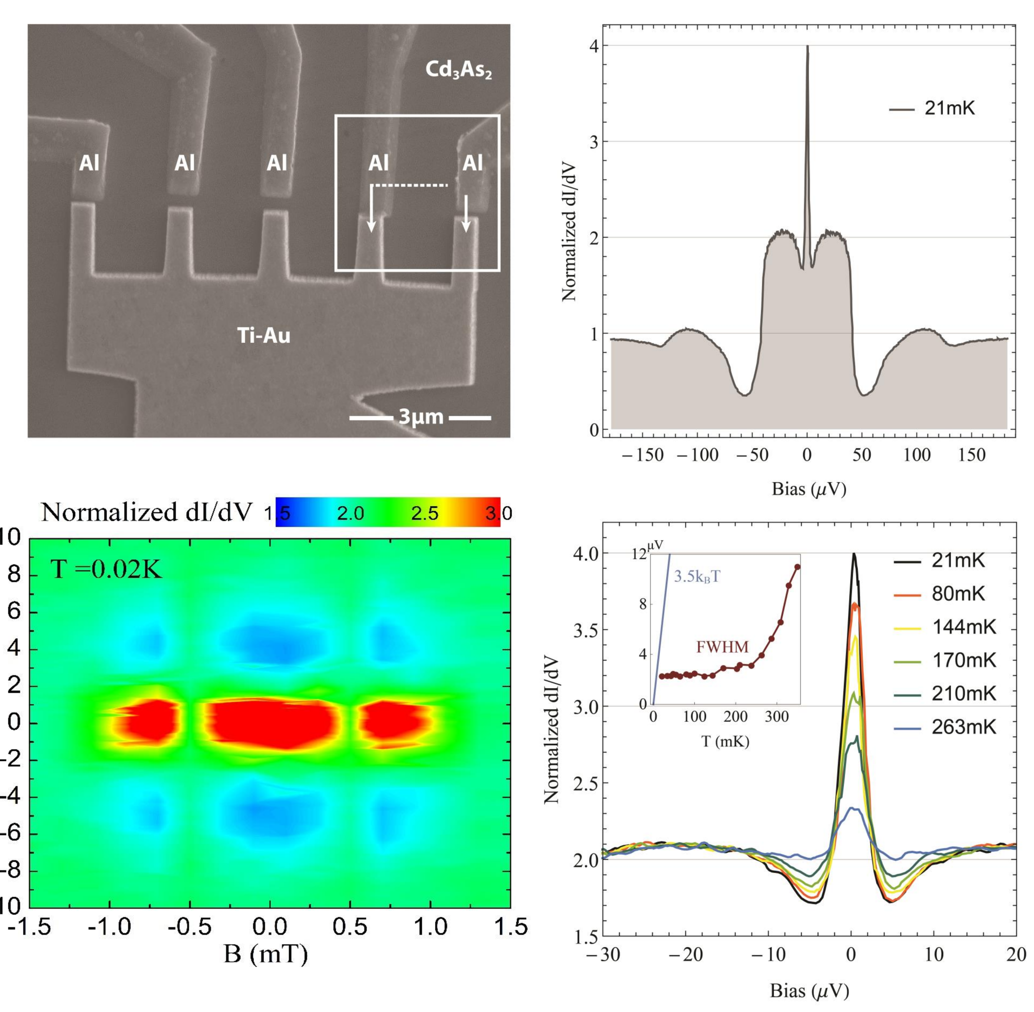
Summary

We report the observation of a large ZBCP in superconducting junction structures mediated by surface states of the Dirac semimetal Cd_3As_2. Our detailed analyses suggest that this large ZBCP is most likely not caused by MZMs. We attribute it, instead, to the existence of a supercurrent between two far-separated superconducting Al electrodes.

Experimental results

Majorana zero modes (MZMs) are widely seen as a promising route towards the realization of topological quantum computation. One of the experimental hallmarks of the presence of MZMs is a quantized zero bias conductance peak (ZBCP) in differential conductance measurements. Here, we report the observation of such a large ZBCP in transport measurements across a Ti/Au-Cd3As2-Al junction.
Below, we show the temperature and magnetic field dependence of the ZBCP. The data shown was measured on the rightmost junction.

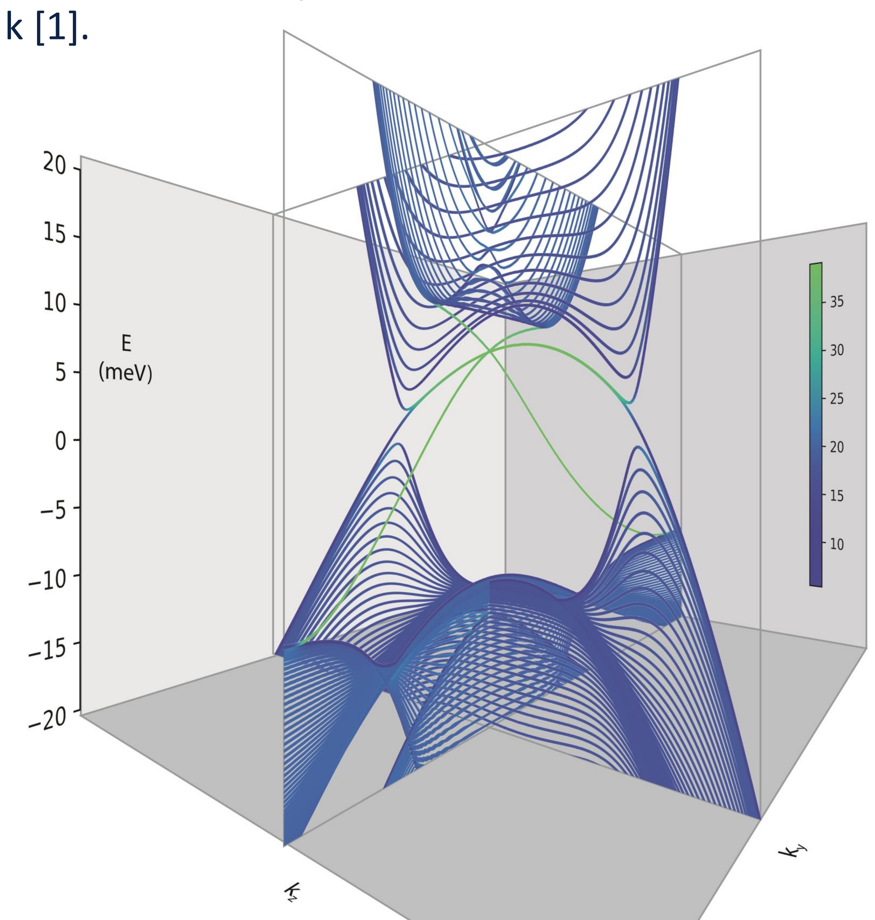


Model

We model the Dirac semimetal Cd_3As_2 by the effective low energy theory

$$H_0(\boldsymbol{k}) = \epsilon_0(\boldsymbol{k}) + \begin{pmatrix} M(\boldsymbol{k}) & Ak_- & 0 & 0 \\ Ak_+ & -M(\boldsymbol{k}) & 0 & 0 \\ 0 & 0 & -M(\boldsymbol{k}) & -Ak_- \\ 0 & 0 & -Ak_+ & M(\boldsymbol{k}) \end{pmatrix}$$

where $k_\pm = k_x \pm k_y$ and $M(\boldsymbol{k}),\ \epsilon(\boldsymbol{k})$ are even functions in k [1].



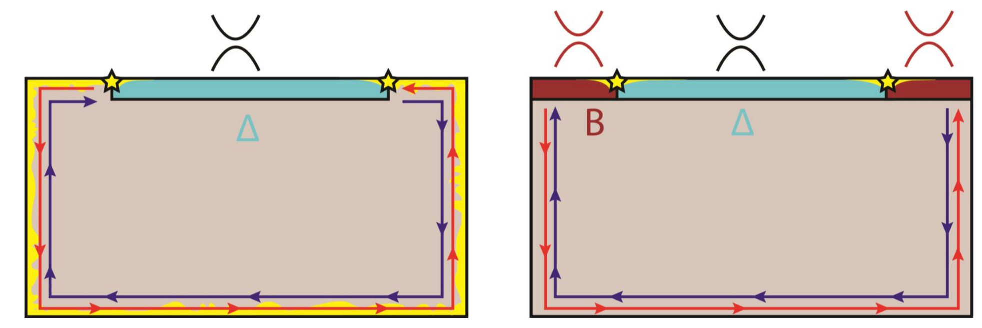
BdG Hamiltonian

To account for the junction geometry, we regularize the Hamiltonian on a lattice and add a spatially dependent superconducting meanfield parameter Δ to obtain the BdG-Hamiltonian

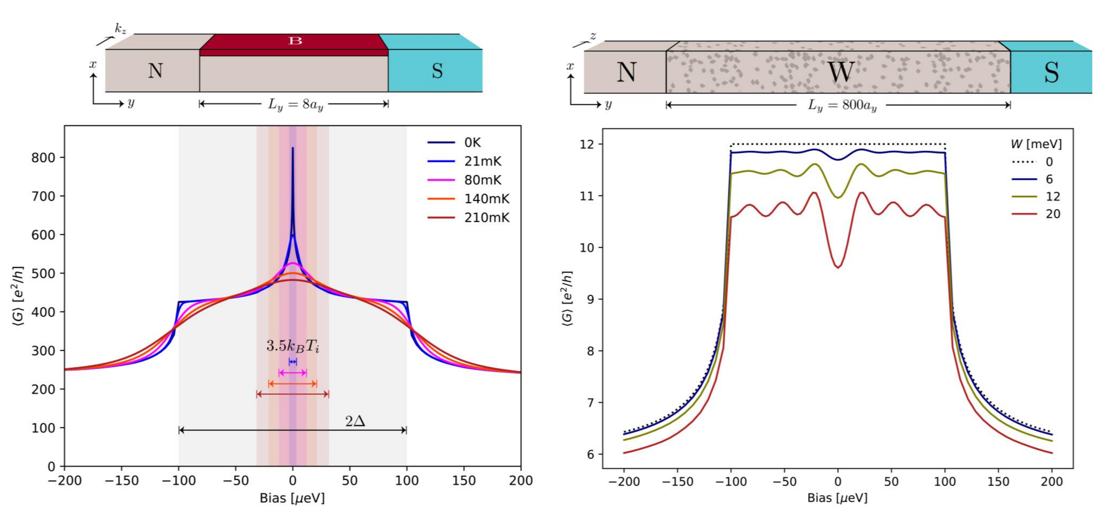
$$H = \begin{pmatrix} H_0 - \mu & \Delta(x) \\ \Delta^\dagger(x) & -(\tau H_0 \tau^{-1} - \mu) \end{pmatrix}.$$

τ is the time-reversal operation with $\tau^2 = -1$, μ is the chemical potential. In numerical simulations, we further add terms that are consistent with symmetry class DIII.

Majorana Zero Modes



When the momentum k_z is treated as a parameter, the Hamiltonian describes a 2D Quantum Spin Hall insulator (QSHI). In proximity to an s-wave superconductor, the low energy edge theory is equivalent to a Kitaev chain which admits Majorana zero modes at its ends.
The QSH edge states, however, do not have ends. MZMs exist at the boundaries of superconducting regions but delocalize over the gapless part of the edge.
Below, we examine two mechanisms of localizing the MZMs: a τ-breaking magnetic field (left) and disorder that couples QSHI at different k_z (right).

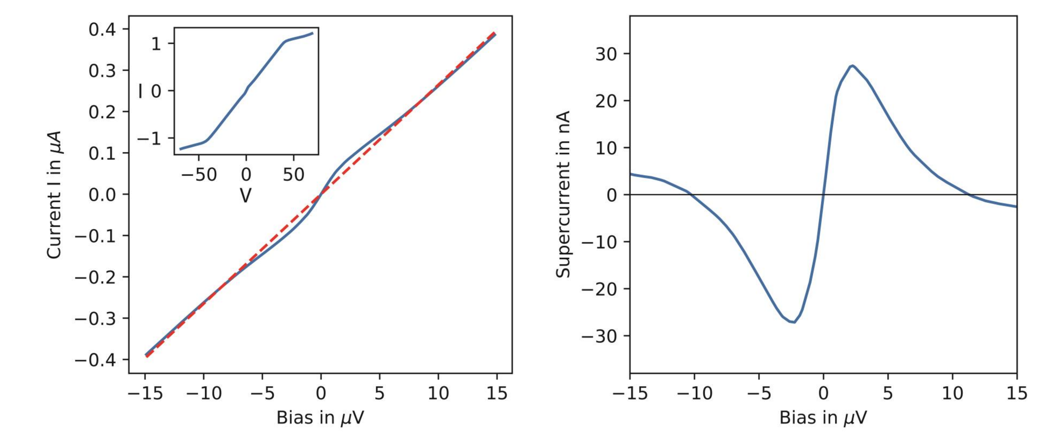


ZBP from supercurrent

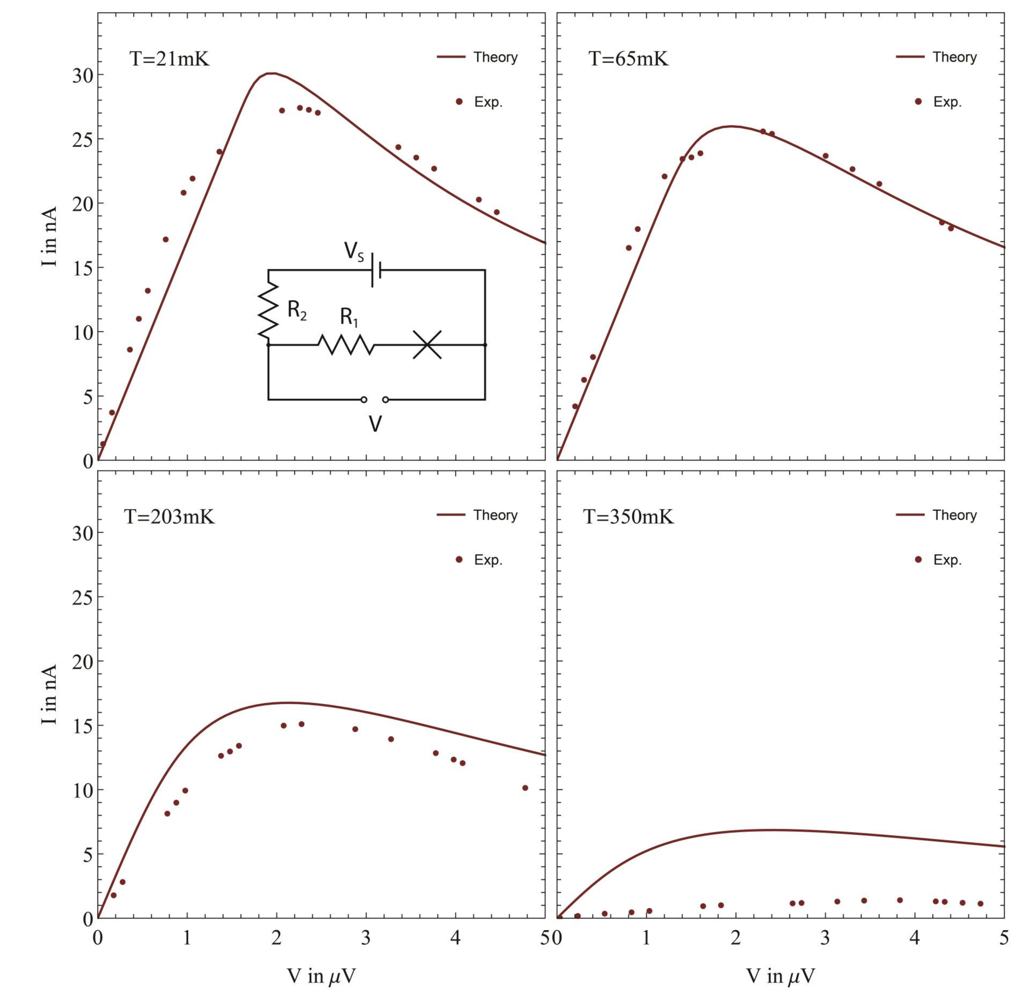
Finite-temperature smearing should yield a ZBCP of width $3.5k_BT$. However, the experimentally observed width is much narrower. This strongly suggests that the ZBCP is not caused by any single-particle mechanism.
We are motivated to investigate a different origin of the the ZBCP: a supercurrent channel that exists between two neighboring Al-electrodes. The IV relationship for a Josephson junction in the presence of thermal Nyquist noise has been derived in [2]:

$$I(V) = I_0 Im\left[\frac{I_{1-2i\beta(V+R_2 I)\hbar/(2e(R_1+R_2))}\left(\beta\frac{\hbar}{2e}I_0\frac{\Delta(T)}{\Delta(0)}\right)}{I_{-2i\beta(V+R_2 I)\hbar/(2e(R_1+R_2))}\left(\beta\frac{\hbar}{2e}I_0\frac{\Delta(T)}{\Delta(0)}\right)}\right]$$

Here, $I_n(z)$ is the modified Bessel function of the first kind. The critical current I_0 and the resistances R_1, R_2 are treated as fit parameters.
To compare with the experiment, we first subtract the linear current contribution from the NS channel, denoted by a red-dashed line below, to isolate the supercurrent as shown exemplary in the right panel.

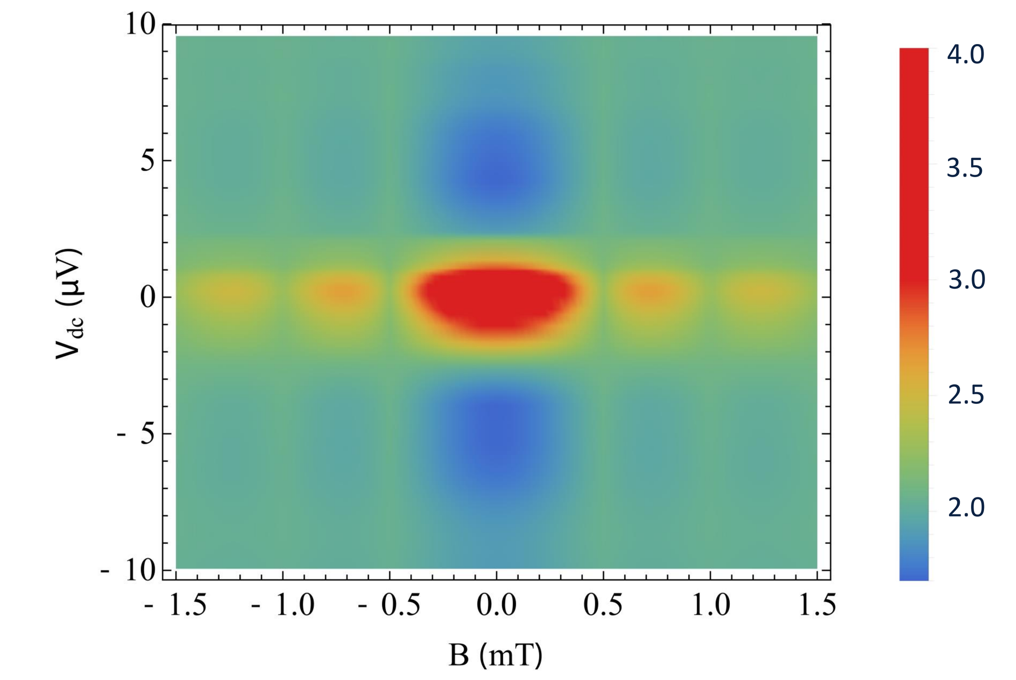


Supercurrent



Experimentally measured IV curves (dots) agree well with the model (red lines) for a wide range of temperatures. This strongly suggests that the ZBCP is the result of a supercurrent that is supported by neighboring Al contacts in the device geometry.
Fit parameters are I_0 = 35 nA, R_1 = 59Ω, R_2 = 88 Ω. The effective circuit is depicted in the inset.

Magnetic field dependence



Assuming a diffusive Josephson junction, the magnetic field dependence of the supercurrent follows the Fraunhofer interference pattern

$$I(\Phi) = I_0 \left|\frac{\sin(\pi\Phi/\Phi_0)}{\pi\Phi/\Phi_0}\right|$$

Above figure shows the resulting simulated differential conductance assuming a junction area of $4\ \mu m^2$, consistent with the experimental geometry. The result is in good agreement with the experimental data.

References

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[4] Anffany Chen, D I Pikulin, and M Franz. Josephson current signatures of Majorana flat bands on the surface of time-reversal-invariant Weyl and Dirac semimetals. *Physical Review B, 95 174505, 2017*