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The use of resonant Andreev tunneling via surface state in UTe_2 to nail down its pairing symmetry.

Pair Wavefunction Symmetry in UTe_2 from Zero-Energy Surface State Visualization

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Recommended with a Commentary by Patrick A. Lee, MIT

UTe_2 is a heavy fermion metal where unconventional superconductivity with a T_c around 1.6K was discovered in 2019.[1] It is now considered a leading candidate for spin triplet superconductor in 3D. Superconductivity (SC) survives up to a magnetic field $\approx 20T$, much beyond the Pauli limit, and even exhibits the so-called "Lazarus superconductivity" where SC revives when a magnetic field of 40T is applied along certain directions.[2] While evidence for triplet SC is accumulating, the precise nature of the pairing symmetry is still under debate. This is a complicated problem because the possibilities that are allowed by crystalline symmetry have been classified and known to be quite complex. Rather than attempting to survey this large field, I focus my attention in this commentary on a recent paper on this topic because both the experimental observations and the theoretical analysis strike me as novel.

The recommended paper employs a SC tip (Nb) to conduct scanning tunneling spectroscopy (STS) on a cleaved surface of UTe_2. Earlier STS data using a normal tip shows small peaks that correspond to the expected pairing gap, but the spectrum below the gap is largely filled in, making it is difficult to extract further information. As is often the case, an S-I-S junction with a SC electrode can greatly improve the resolution. In this case the STS spectrum indeed shows a number of features and is reproduced in Fig 1. The large peak at 1.4meV is reasonably assigned to be the sum of the Nb gap and the UTe_2 gap which are at ≈ 0.9 and ≈ 0.5 meV respectively. The smaller features at 0.5 and 0.9 meV may be interpreted as subgap Andreev processes commonly known as multiple Andreev reflection (MAR) peaks. What is unexpected is the peak at zero bias. It has a width comparable to the UTe_2 gap and its height is similar to the background conductance above the gap. This means that it scales as t^2 where t is the tunneling matrix element between the tip and sample. This scaling has been verified by varying the tip height.

What are the options for a zero bias peak in an S-I-S junction? At first glance one may want to interpret this peak as a broadened form of Josephson tunneling and the Josephson

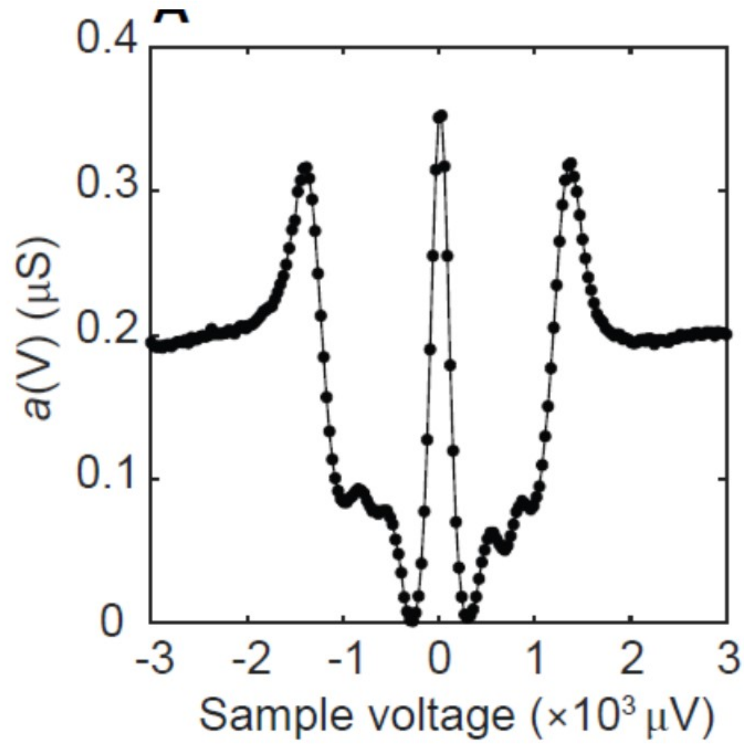

Figure 1: Measured STS conductance spectrum of UTe_2 using a superconducting Nb tip. Note the appearance of a peak at zero bias with a height comparable to the conductance above the gap.

current indeed scales as t^2. However, in STS experiments, the tip area is so small that the total Josephson energy that locks the phase difference across the junction is much less than the thermal energy kT. In this case the phase difference fluctuates, the Josephson conductance peak acquires a width and its hight scales as t^4. [3, 4]. This possibility is therefore ruled out. A second option, illustrated in Fig 2A, is to consider Andreev tunneling, where an electron and a hole tunnel in opposite directions, effectively transferring a pair in a process which, unlike quasi-particle tunneling, does not require paying the gap energy. It is well known that this leads to a zero bias conductance peak with a width corresponding to twice the energy gap. However, since this involves the incoherent transfer of two particles, its amplitude also scales as t^4. So how do we get a peak height that scales as t^2 ?

The recommended paper presents an interesting solution to this puzzle. They point out that the 3D triplet SC is expected to be topological and host topological surface state. Two examples of these surface state dispersion are sketched in Fig 2A and B. Depending on whether time reversal symmetry is broken or not, the surface state is either chiral or helical. The latter option consists of two counter-propagating modes whose crossing is protected by T-reversal. The surface states lie inside the gap and offer the possibility of resonant tunneling between the SC electrodes, using the surface states as stepping stones. The formula is given in Eq. S8 in the recommended paper. It takes the usual form for resonant tunneling where the overall magnitude in the numerator scales as t^4 as expected, but the width appears in the

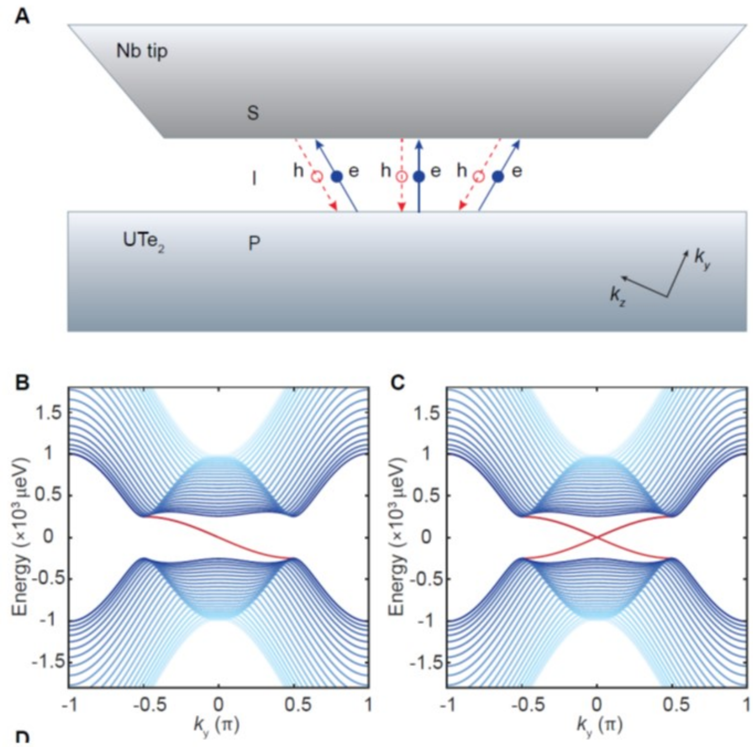

Figure 2: A. Illustration of Andreev tunneling of an electron and a hole in opposite direction that can give rise to a zero bias peak. However, its amplitude is too small. B. The band dispersion projected to the surface showing (in red) a chiral surface state that corresponds to broken time reversal symmetry. C. A pair of non-chiral surface states with zero crossing in the absence of time reversal breaking. It is proposed that the Andreev process shown in A goes through these surface states as an intermediate step, resulting in resonant enhancement of the amplitude.

denominator and scales as t^2. Therefore at resonance the conductance scales as t^2 and nicely explains the data. An example of a calculation based on a simplified model is shown in fig. 3. The very narrow peak at zero energy has to do with an enhancement of the density of states near the end of the "Fermi arc" where the gap vanishes. This narrow peak is not seen in the data and may have been smeared out. The other aspect is that its full width is twice the UTe_2 energy gap, while in the experiment the width seems to be considerably smaller. Apart from these issues which may require refinement of the model, the overall picture of resonant tunneling seems like a compelling explanation, in part because alternatives are hard to come by.

If this picture is correct, the large zero bias peak provides strong evidence for the existence of a surface mode. The authors did not stop there and went further to build on this picture. They discovered that as they move the tip closer to the sample, the zero bias peak begins to split, as shown in Fig. 4. They propose that this spitting can be used to discriminate between the two versions of surface state shown in Fig. 2B and C, namely, whether time reversal symmetry is broken or not. In the chiral case the mode cannot be gapped and is always

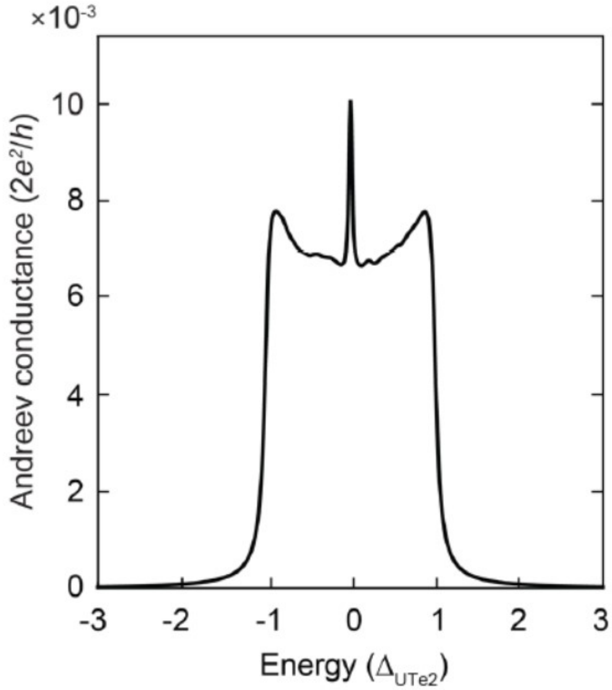

Figure 3: Calculate conductance due to the resonant Andreev process. The broad peak is to be compared with the central peak in fig 1. The sharp peak at zero energy may be broadened and is not observed in the experiment.

available for resonant tunneling. On the other hand, the crossing point of the non-chiral states shown in Fig. 2B is gapped in the presence of time reversal breaking and can result in the splitting of the zero bias peak. To make the case stronger, we need to understand why T breaking arises when the tip is pushed closer to the surface. The authors propose the following mechanism. When the Josephson coupling is strong, a phase difference is generated across the junction which breaks T symmetry. In a planar junction the energy is minimized by a phase of $\pi/2$. However, as mentioned earlier, in an STM junction, the Josephson energy is too small compared with the thermal energy to pin this phase. Nevertheless, the authors argue that since every instance of phase difference leads to T breaking, an avoided crossing will still occur upon averaging over these phases. Whether the reader accepts this specific proposal is perhaps not that important. The key idea that a T breaking order parameter cannot lead to peak splitting and is therefore ruled out is robust.

With these observations, the authors narrow down the order parameter symmetry to three options, B_{1u}, B_{2u} and B_{3u} and rule out all options which breaks T reversal. They employ further arguments based of quasi-particle interference to nail down the paring symmetry to be B_{3u}. The last step may require further experimental confirmations, but the important progress is that by a combination of novel experimental observation and theoretical analysis, the authors have ruled out time reversal symmetry breaking and determined (or greatly limited) the order parameter symmetry in a complex system. Hopefully this work opens up

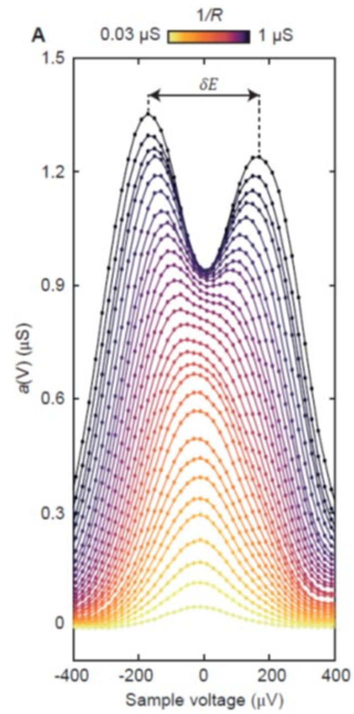

Figure 4: The central peak is split as the tip is pushed closer to the surface and the averaage coonductance is increased, as seen in the traces from bottom to top.

a new direction in the study of unconventional superconductivity.

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