

# Point Contact Spectroscopy Study of $\text{ZrZn}_2$

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**Abstract.** We have performed point contact spectroscopy on spark-cut single crystals of ferromagnetic  $\text{ZrZn}_2$ , using normal-metal tips in a dilution refrigerator down to 100mK. The differential conductance spectra show low-energy peak structures which evolve systematically with temperature below 1.1 K. We associate these state-conserving peak spectra with the surface superconductivity recently observed in  $\text{ZrZn}_2$ . Implications of our data on the electron pairing in  $\text{ZrZn}_2$  are discussed.

**Keywords:** superconductivity, ferromagnetism, inter-metallics, tunneling spectroscopy, Andreev interference

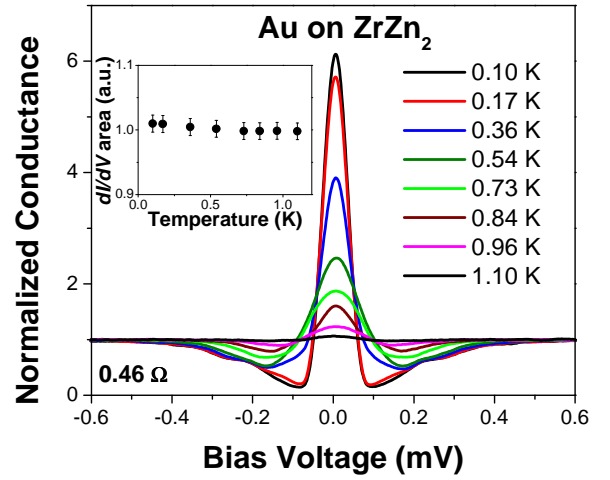
**PACS:** 74.20.Rp, 74.50.+r, 74.70.Ad

Superconductivity and ferromagnetism tend to be competing types of order. The intermetallic ferromagnetic compound  $\text{ZrZn}_2$  has recently been shown to display surface superconductivity under some circumstances [1, 2] in the ferromagnetic state, suggesting their possible coexistence and complex interplay [3, 4]. A proposed scenario for this coexistence involves spin-mediated electron pairing, which could produce a spin-triplet, odd-parity superconducting order parameter (OP) with nodes in  $k$ -space [5].

Experimentally, the presence of OP nodes can be detected by tunneling spectroscopy, in the form of zero-bias conductance peaks, which are a manifestation of surface states due to Andreev interference resulting from the sign change about nodes in the OP [6, 7]. This Andreev phenomenology has been used to reveal OP nodes in several unconventional superconductors, ranging from  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  [8, 9] to  $\text{Sr}_2\text{RuO}_4$  [10, 11] and  $\text{CeCoIn}_5$  [12].

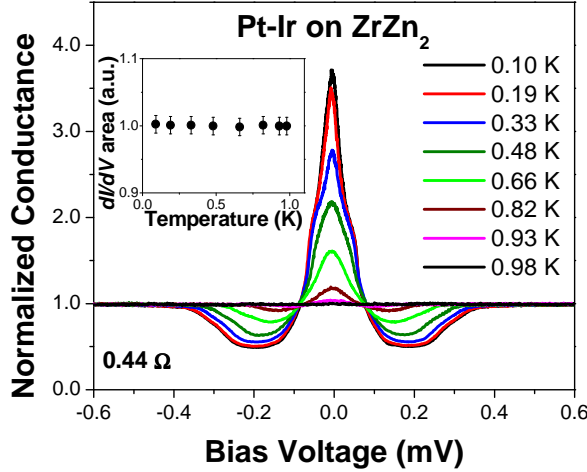
To look for evidence of a nodal OP in  $\text{ZrZn}_2$ , we have performed point-contact spectroscopy (PCS) on single-crystal samples. The  $\text{ZrZn}_2$  crystals were grown using a directional-cooling technique and cut to expose (111)-faces by spark-erosion [2]. These crystals show bulk ferromagnetic susceptibility below  $\sim 30\text{K}$ , and a resistive downturn below  $\sim 0.3\text{K}$  [1]. The PCS measurements were made in a dilution refrigerator, using either Pt-Ir or Au tips with a pulsed-signal technique to minimize Joule heating [12].

Typical  $dI/dV$  conductance spectra measured are plotted in Figures 1 and 2. Figure 1 plots the data taken with a Au tip, showing the spectral evolution with temperature up to 1.1K, above which the conductance becomes independent of bias voltage. Figure 2 plots the data for a Pt-Ir tip, showing a similar evolution up to 0.98K. The spectra



**FIGURE 1.** Normalized conductance vs. voltage as a function of temperature for a  $0.46\Omega$  Au/ $\text{ZrZn}_2$  point-contact junction. Shown in the inset is the  $dI/dV$  spectral area, integrated between  $\pm 0.5$  mV, as a function of temperature.

shown in each plot are normalized relative to the highest temperature data. The generic similarities between the two plots attest to the reproducibility of our measured spectra, as well as to their independence on tip material. At base temperature in each plot, a pronounced low-energy peak structure is observed, flanked by symmetric dip structures. With increasing temperature these spectral features evolve such that the total integrated  $dI/dV$  spectral area is conserved, as shown in the inset of each figure. The spectral details and their evolutions varied slightly between junctions and samples. In some cases, discernible peak-and-dip structures persisted to as high as  $\sim 1.8\text{K}$ .



**FIGURE 2.** Normalized conductance vs. voltage as a function of temperature for a  $0.44\Omega$  Pt-Ir/ZrZn<sub>2</sub> point-contact junction. Shown in the inset is the  $dI/dV$  spectral area, integrated between  $\pm 0.5$  mV, as a function of temperature.

The conductance spectra we observed provide further support for the existence of a superconducting surface layer in spark-cut ZrZn<sub>2</sub>, although the composition of this layer is still unknown [2]. The observed spectral peaks can be interpreted as a distinct signature of Andreev surface states arising from a nodal OP. First, the spectral peaks were generally taller than twice the normalized spectral background, as is expected from the generalized Blonder-Tinkham-Klapwijk formalism [6, 7, 9, 13]. Second, the conservation in the  $dI/dV$  spectral area is entirely consistent with the conservation of quasiparticle states which mediate the Andreev interference process [6]. Third, the microscopic scale of our probe [14] largely rules out spurious scenarios based on material inhomogeneity, especially those involving conventional superconductivity with a non-nodal OP symmetry [4].

In conclusion, the apparent robust formation of Andreev surface states could be regarded as strong evidence for local pairing correlations on the surface in ZrZn<sub>2</sub>. It is remarkable that these Andreev surface states seem to persist above the apparent resistive transition [1]. This observation suggests that in ZrZn<sub>2</sub> it is easier for the electrons to pair microscopically than for them to phase-condense macroscopically. This picture would be consistent with the fragile nature of the resistive transitions reported thus far [2]. More detailed studies, correlating the spectral and transport data with the surface preparation, are under way to elucidate this picture.

## ACKNOWLEDGMENTS

Work supported by NSERC, CFI/OIT, MMO/EMK and the Canadian Institute for Advanced Research.

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14. Using the Sharvin formula,  $R = 4\rho\ell/3\pi a^2$ , with  $\rho \sim 0.6 \mu\Omega \cdot \text{cm}$  and  $\ell \sim 55$  nm for ZrZn<sub>2</sub> [2], the point-contact radius for a  $0.4 \Omega$  junction is estimated to be  $a \sim 20$  nm.