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Interplay between Kondo effect and superconductivity in a carbon nanotube quantum dot

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Abstract

When Kondo effect and the superconductivity coexist, the two quantum many-body effects compete with each other and bring intriguing physics. A superconductor / quantum dot / superconductor junction with the Kondo effect presents ideal platforms to study such an interplay. In a carbon nanotube quantum dot with superconducting leads, we addressed two Kondo effects with *SU*(2) and *SU*(4) symmetries in the superconducting state using conductance and shot noise measurements. Our experiment revealed that the Kondo effect enhances multiple Andreev reflections and that this enhancement is larger in the *SU*(4) case than in the *SU*(2) one.

1. Introduction

Kondo effect is one of the most typical many body effects, where a localized spin is screened by the surrounding conduction electrons. It has been one of the central topics in physics as extensively studied in heavy fermion systems [1], quantum dots [2], cold atoms [3], and quantum chromodynamics [4]. The advantage of using a quantum dot to explorer the Kondo physics is that we can access the non-equilibrium regime with tuning this effect by gate voltages and magnetic field.

Shot noise measurement is a powerful tool to study transport properties in mesoscopic physics [5]. For example, we investigate the shot noise in the Kondo-correlated quantum dot and successfully confirm that the Fermi liquid theory can be extended to the non-equilibrium regime [6-8]. Also, we realized two Kondo effects with different symmetries, namely the *SU*(2) and *SU*(4) Kondo effects, in a carbon nanotube quantum dot and clarified how the quantum crossover takes place between the different symmetries [8].

Now, it is interesting to ask what happens when the electrodes are superconductor. We expect that the Kondo effect and the superconductivity compete with each other and bring exciting physics (see Fig. 1). Combining the conductance and shot noise measurements, we studied this competition where the Kondo effect is realized for both *SU*(2) and *SU*(4) symmetries. While there are several experimental works regarding this topic in the literature [9-12], our work is unique as we for the first time investigated the unitary limit case, which is the ideal Kondo state, by the noise measurement.

2. Experimental setup

The device consists of a single-wall carbon nanotube and Pd/Al superconducting leads [6, 8]. The measurement was carried out in a dilution refrigerator at 20 mK. We measured differential conductance (dI/dV) using a lock-in technique and detected shot noise (S_{shot}) with two amplifiers and a resonant *LC* circuit [6]. We can set the leads of the device either in the normal state or in the superconducting state with or without applying a small magnetic field of 0.08 T, respectively.

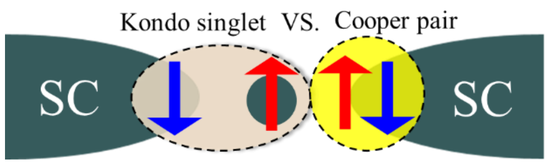

Fig. 1: Scheme of a Kondo-correlated quantum dot coupled to superconducting leads. Two different singlet pairs compete with each other.

3. Conductance: normal vs. superconducting states

Figure 2 shows dI/dV as a function of eV/k_BT_K at the same filling factor for the *SU*(2) and *SU*(4) Kondo effect in the normal state, where k_B and T_K are the Boltzmann constant and Kondo temperature, respectively. The Kondo resonance behaviors are almost the same since the conductance reaches the

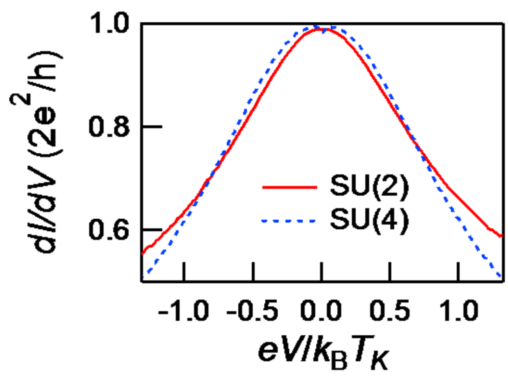

Fig. 2: Conductance for the *SU*(2) and *SU*(4) Kondo states at the same filling factor.

same unitary value $2e^2/h$ [6]. However, the situation becomes totally different in the superconducting state (Fig. 3). The $SU(2)$ conductance at zero bias is enhanced in the superconducting state, showing that transport takes place through a single perfect channel. On the other hand, the $SU(4)$ conductance presents multiple Andreev reflections (MAR) at voltages $2\Delta/n$, demonstrating that transport occurs through two partially-transmitted channels. Here, Δ and n are superconducting gap and an integer number.

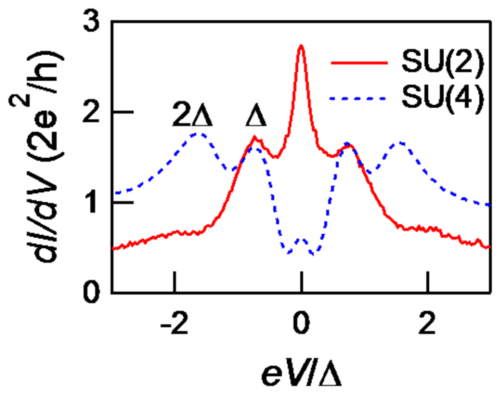

Fig. 3: Conductance in the superconducting state at the same filling factor.

3. Shot noise in the superconducting state

We carried out the shot noise measurement for the $SU(2)$ and $SU(4)$ cases and found that the shot noise around zero bias is enhanced. Figure 4 shows $S_{shot}/2e|I|$ as a function of $1/|V|$. First, we show the theoretical prediction for a superconductor / quantum point contact / superconductor junction whose transmission is almost perfect. In this case, $S_{shot}/2e|I| = 2\Delta/e\times\alpha/|V|$ is predicted where $\alpha = 0.9$ is the enhancement factor of MARs. However, the experimental slope for the $SU(2)$ case is higher ($\alpha = 2.2$) than the expected one. Furthermore, MARs enhances more in the $SU(4)$ case (α = 4.3). These results suggest that the Kondo correlation helps MAR transport and show $SU(4)$ symmetry leads to more enhancement than $SU(2)$ [13].

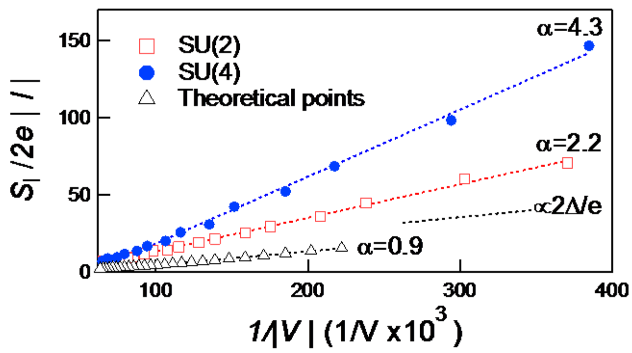

Fig. 4: $1/|V|$ dependence of $S_{shot}/2e|I|$ for the $SU(2)$ and $SU(4)$ Kondo cases in the superconducting state. The triangle points show the theoretical prediction. The points are fitted with $S_{shot}/2e|I| = 2\Delta/e\times\alpha/|V|$.

4. Conclusion

We report the $SU(2)$ and $SU(4)$ Kondo effects coexisting with the superconductivity. The difference in the conductance at the same filling is explained with the transmission of channels which participate in Kondo transport. In addition, our shot noise measurement suggests that Kondo effect enhances MAR. Interestingly, this enhancement is more significant in the $SU(4)$ case than in the $SU(2)$ one. These experimental studies afford new perspectives on a competing system between two kinds of singlet, that is, Kondo singlet and Cooper pair. Our work will contribute to further understanding of electron correlation in various competing systems.

Acknowledgements

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