Kondo effect in P-wave Superconducting Junctions

Tomosuke Aono[1], **Anatoly Golub** [1] **and Yshai Avishai** [1,2]
[1]*Department of Physics and* [2]*Ilse Katz Center,*
Ben-Gurion University, Beer-Sheva 84105, ISRAEL

The Kondo effect has been observed in electron transport through semiconductor quantum dots. [1] Localized spin of electrons in the dot acts as magnetic impurity, interacting with electrons in leads. When the temperature T is lower than the Kondo temperature T_K, electrons in the leads and the dot forms a singlet state, and consequently, the local density of states shows a sharp peak structure at the Fermi energy E_F in the leads (the Abrikosov-Suhl resonance). This resonance result an enhancement of the conductance G, approaching the unitary limit, $G = 2e^2/h$ as T decreases below T_K [2].

When one or both electrodes are superconductor (S) instead of normal metal (N), a novel transport mechanism, the Andreev reflection plays a dominant role both in and out of equilibrium. In the former case it is responsible for occurrence of direct Josephson current for two superconducting leads while in the latter case it is the cause of dissipative currents at sub-gap voltages. In such systems, the interplay between the Andreev reflection and the Kondo effect leads to a rich structure of electron transport. A natural candidate for this system is that in which the role of the quantum dot is played by a Carbon nano-tube (CNT), where T_K is rather high ($T_K > 1K$) [3, 4] and competes with a superconducting gap Δ. Indeed, in a recent experiment, a superconducting junction through CNT in the Kondo regime has been realized with $T_K > \Delta$ [4].

In this research, we investigate electron transport through quantum dot in the Kondo regime (K) with superconducting leads, namely SKN and SKS junctions, especially when $T_K > \Delta$ [5], where the interplay between Andreev reflection and the Kondo effect is prominent. We further elucidate the distinction between (conventional) s-wave and (unconventional) p-wave superconductor, the latter has recently been discovered in Sr_2RuO_4. [6] For p-wave superconductor, the pairing potential is anisotropic and also reverses its sign: $\Delta(\theta) = -\Delta(\pi - \theta)$, where θ is the azimuthal angle. This property induces mid-gap zero-energy states (ZES) near the interface between the lead and the dot while no such states appear for s-wave superconductor. This difference becomes important when the Kondo effect takes place, because ZES strongly interact with the Kondo resonant state which appears also at $E_\mathrm{F} = 0$.

We adopt the Anderson model with superconducting leads within the slave boson mean field formalism, which gives an adequate description of the Kondo effect. For p-wave superconductor, we choose $\theta = 0$ because the dot is almost point-like. The conductance, shot-noise power and Fano factor of SKN junctions are calculated as functions of the applied bias voltage V in the sub-gap region $eV < \Delta$. We also investigate the Josephson current. (Details are given in Ref. [5].)

Figure. 1 shows the $G-V$ curves of SKN junctions for both s-wave and p-wave superconducting leads for several values of $t_K \equiv T_K/\Delta$. In the limit of large t_K the $G-V$ curve is almost independent of t_K and shows no difference between s-wave and p-wave superconductors; $G = 4e^2/h$ when $eV < \Delta$ and G decreases gradually when $eV > \Delta$. In this limit, the Kondo resonance reaches the unitary limit, and consequently, this SKN junction reduces to an SN junction with pure ballistic contact, which has been analyzed by the BTK theory [7]. For lower values of t_K the distinction between s-wave and p-wave leads becomes prominent.

For s-wave superconductor, as t_K decreases, the Kondo state is driven away from the unitary limit and the actual value of the Kondo temperature is suppressed accordingly. For $t_K = 5$ the $G-V$ curve noticeably deviates from the one of $t_K = 100$, reflecting the suppression of the Kondo effect due to both Δ and V. For $t_K = 2$ the competition between gap-related suppression of the Kondo effect and the effective transparency of the junction becomes essential, leading to further decrease of the conductance.

For p-wave superconductor, the $G-V$ curves are less influenced by variations of t_K in contrast to s-wave superconductor, indicating superconductivity plays a minor role in the suppression of the Kondo resonance and BTK behavior persists for smaller values of t_K. This result shows that the ZES support the formation of a Kondo singlet for lower values of t_K, and effectively turn the junction to be more transparent, approaching the BTK limit [7].

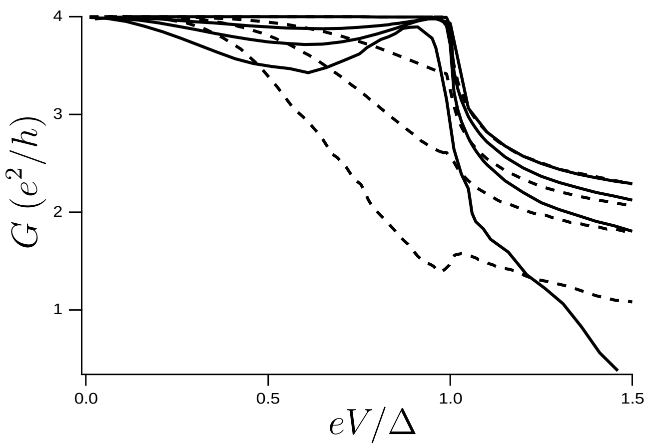

Fig. 1 The conductance G (in units of e^2/h) versus the bias V (in units of Δ/e) for an s-wave SKN (broken lines) and p-wave SKN (solid lines) junctions at sub-gap voltages with $\Gamma/T_K = 200$. (Γ is the dot-lead coupling.) The parameter $t_K \equiv T_K/\Delta$ =2,3,5, and 100 (from down to top). The upper line corresponds to t_K =100 coincides for s-wave and p-wave superconducting leads.

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