The zero-bias anomaly of point contacts with ferromagnetic Ni and with the heavy-fermion antiferromagnet CeAl₂

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Abstract. We have investigated spear-anvil type point-contacts between ferromagnetic nickel as well as the heavy-fermion antiferromagnet CeAl₂ and various simple metals (Cu, Ta, Nb). Contacts with small resistance usually showed electron-phonon scattering, Andreev reflection in case of superconducting counter-electrodes, as well as anomalies due to magnetic ordering. With increasing contact resistance (decreasing contact size) a zero-bias anomaly appeared in both Ni and CeAl₂ contacts. It is conventionally attributed to resonant scattering at two-level systems or at magnetic impurities (Kondo effect). At contacts of ∼ 1 nm diameter it suppressed completely all other spectral features. We discuss whether those mechanisms are relevant here and what alternatives there might be.

1. Introduction

Point contacts between two pieces of metal provide a convenient means to investigate electronic excitations in the bulk material, like the electron-phonon interaction. However, quite often those contacts show an additional anomaly at zero bias which is not well understood, usually a maximum in the differential resistance $dV/dI$ at $V = 0$. It could be caused by electron scattering at magnetic impurities (Kondo effect) or at a two level system that resonantly scatters electrons at small energy. Naidyuk and Yanson [1] have recently reviewed this problem. An ideal point contact between two identical normal metals has a resistance of $R(T) \approx 2R_K/[(ak_F)^2 + \rho(T)/(2a)]$, where $R_K = h/e^2$ is the von Klitzing resistance, $k_F$ the Fermi wavenumber, and $a$ the contact radius, see [1] and references there. It depends on temperature $T$ via the specific resistivity $\rho(T)$. Since $\rho \cdot l = (3\pi R_K^2)/(2k_F^2)$ is a constant [2], one gets the bias-voltage dependence of the differential resistance at low temperature

$$\frac{dV}{dI}(V) \approx \frac{2R_K}{(ak_F)^2} \left( 1 + \frac{a}{l(eV)} \right)$$

(1)

to extract the mean free path $l(eV)$. Independent scattering processes can be separated according to Matthiessen’s rule. This is especially convenient for electron-phonon scattering, which sets in at energies above ∼ 15 meV, depending on the Debye energy, and Kondo scattering at magnetic impurities that is efficient only at small energies. Such an impurity polarizes the surrounding...
electron spins, forming a polarization cloud with an extension of about \( \xi_K \approx \hbar v_F/k_B T_K \) and a correspondingly large scattering cross-section. Here \( v_F \) is the Fermi velocity. The electrical resistivity due to scattering of electrons at Kondo impurities \[ \Delta \rho(T) = \Delta \rho_0 \left[ 1 - \frac{\ln(T/T_K)}{\sqrt{\ln^2(T/T_K) + S(S+1)\pi^2}} \right] \] depends on the Kondo temperature \( T_K \) and the effective spin \( S \). At low temperatures it reaches a maximum of \( \Delta \rho_0 = c \cdot 2R_K/k_F \) that equals the impurity concentration \( c \) (impurity per conduction electron) times the resistivity in the so-called unitary limit with ideal retro-reflection. Since a point contact is very small, even a single magnetic impurity can change dramatically the resistance. In this limit a better description might be the Fano model which considers two conducting channels, a direct and a resonant one, that interfere and give rise to a specific dependence of the conductance superposed on a smoothly varying background. This has been successfully applied recently to atomic contacts of the ferromagnets Fe, Co, and Ni \[4\].

![Figure 1. Typical dV/dI(V) spectra of a Ni - Ni, Ni - Cu, and CeAl\(_2\) - Cu contacts at 4.2 K.](image)

We have studied the zero-bias anomaly of point contacts with the heavy-fermion antiferromagnet CeAl\(_2\) (\( T_{N\text{eel}} = 3.8 \) K, see Ref. \[5\] for further information on material properties and break-junction experiments) as well as the bandferromagnet Ni (\( T_{\text{Curie}} = 627 \) K \[2\]) with other metals Cu, Ta (a BCS-type superconductor with \( T_c = 4.2 \) K), Nb (a BCS-type superconductor with \( T_c = 9.1 \) K), and Ni. We found a systematic variation of the magnitude of the anomaly as function of contact size, independent of the metals used as electrodes. This observation calls for a new and more generally valid explanation.

2. Experimental

We have measured the spear-anvil type point contacts at constant 4.2 K in liquid helium. The bulk resistivity at low temperature ensures electron mean free paths of at least 10 nm for all samples. That means contacts almost down 1 \( \Omega \) should be in the ballistic limit.

Figure 1 shows a series of typical spectra of Ni - Ni, Ni - Cu, and CeAl\(_2\) - Cu contacts. Low-resistance contacts usually had the zero-bias anomaly, unless it was below the noise level, together with the typical features of electron-phonon interaction, indicating ballistic transport. Low-resistance CeAl\(_2\) contacts had in most cases a minimum at zero bias inside a maximum. We attribute this feature to the onset of antiferromagnetic ordering in this compound because it...
Figure 2. Magnitude $\delta R$ of the zero-bias anomaly as function of resistance $R$ for the indicated metal contacts at 4.2 K. The thick solid lines are $\delta R = (9\pi/16)R^2/R_K$ as discussed in the text.

Figure 3. Full width at half maximum $\delta V$ of the zero-bias anomaly as function of resistance $R$. The thick solid lines are $\delta V = 2hv_F/ea$ when $\xi_K = a$. The thin lines through the data points represent when $\xi_K = 100 \cdot a$.

was also present at CeAl$_2$ break junctions at very low temperatures [5]. Similarly, low-resistance contacts with Nb showed the double-minimum structure of Andreev reflection. When the contact radius was reduced and the resistance increased, the relative magnitude of the zero-bias anomaly grew and at the same time the spectroscopic features of electron-phonon interaction, magnetism, and superconductivity became suppressed. In general, the zero-bias anomaly appeared to be more robust than the structure due to electron-phonon scattering.

We have found that the differential resistance increases logarithmically towards zero bias as expected for Kondo scattering Eq. 2. One can then directly read off the Kondo voltage $V_K = \delta V/2$, and thus the Kondo temperature $T_K$, from the half width $\delta V$ of the zero-bias anomaly. However, the effective spin $S \approx 0.2$ was always smaller than the expected $S = 0.5$. Figure 2 shows that over a wide range of contact resistances $\delta R \sim R^2$. Here $R$ is the (extrapolated) zero-bias resistance without zero-bias anomaly and $\delta R$ the additional resistance of the anomaly. This dependence contrasts the typical spectroscopic features which vary like $\delta R \sim \sqrt{R}$ according to Eq. 1. Since the behaviour does not change between small and large contacts, the barely resolved tiny zero-bias anomalies at small $R$ develop directly into the huge anomalies at large $R$, indicating that they are caused by the same mechanism. Also the width of the anomaly in Figure 3 increases with resistance.

3. Discussion

One can always reconstruct the zero-bias anomalies using specific assumptions, like the type of magnetic impurities and their concentration. But the systematic variation of the size of the zero-bias anomaly with contact resistance poses rather strong constraints on those mechanisms, especially on how the impurity density varies with resistance. In addition, those mechanisms would have to be the same for all investigated metals. This can be savely discarded. For the case of contacts with a superconductor we can directly exclude a tunneling barrier as the origin of the anomaly because this did not show up in the Andreev reflection spectra. The source of this strong electron-electron scattering at zero bias could be magnetic impurities as indicated by the shape of the spectra. One way to describe the effects of such a hypothetical impurity is the so-called unitary limit of Eq. 2. With the impurity concentration $c$ the zero-bias resistance should increase by $\delta R = c\sqrt{2R_K \cdot R}$, in clear contradiction with the experimental results in
Figure 2. To fit the data would require to vary the impurity concentration from contact to contact, as already mentioned above. The width of the anomalies in Figure 3 is typically around $\sim 10 \text{ mV}$, corresponding to Kondo temperatures of $\sim 100 \text{ K}$ and Kondo lengths of $\sim 0.1 \mu \text{m}$. This is much larger than the contact radius, meaning that it is unlikely to find more than one of those impurities in the contact volume $v_C \approx 4\pi a^3/3$ that contributes to the resistance through backscattering. With the electron density $n = k_F^3/3\pi^2$ the number of impurities at the contact $N = cnv_C \approx (16/9\pi)R_K\delta R/R^2$ depends only on the size $\delta R$ of the zero-bias anomaly and the contact resistance $R$. The magnitude of the zero-bias anomaly for a single impurity ($N = 1$)

$$\delta R = \frac{9\pi}{16} \frac{R^2}{R_K}$$

(3)

describes the experimental data in Figure 2 quite well. It is consistent with what we have deduced from the width of the anomaly. This leads us to believe that indeed a single impurity determines the zero-bias anomalies.

Kondo phenomena at atomic size contacts have been observed for tunneling into a single magnetic atom on a metallic surface [6] as well as for small contacts with ferromagnets [4]. However, magnetic impurities are not really needed. Electrons also have a spin and therefore spin-spin scattering should be possible, and lead to the Kondo effect if the number of participating electrons is small. This happens in quantum-point contacts and quantum dots in a two-dimensional electron gas, where a single electron sits either in the dot [7, 8, 9, 10] or in a shallow potential minimum near the center of the point contact [11].

We suggest here a similar picture that one or few electrons are trapped near the point contact and polarize the conduction electrons in the contact region. This polarization cloud does not sit in the center of the contact, but on one or on both sides in the electrodes. Some of the contacts had indeed a zero-bias anomaly apparently composed of two different parts, as if each electrode had its own polarization cloud with different extension. One might further speculate that if the two clouds are coupled well enough through the contact that the spins on both sides are aligned, electrons would flow through the contact region with reduced scattering. This would offer a rather straightforward explanation for the more rarely observed zero-bias minima.

4. Conclusion

The suggested spontaneous electron spin polarization at the contact interface would have serious consequences for the interpretation of a number of point-contact experiments, for example those that use Andreev reflection to measure the surface polarization of magnetic samples. In future work one should try to find out how the intrinsic magnetism of the samples is involved in the zero-bias anomalies. For example for Cu - Cu contacts we have found the same kind of zero-bias anomaly as reported above, but not for In - In contacts.

5. References

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