Break junctions of the heavy-fermion superconductors

K. Gloos\textsuperscript{a}, F. B. Anders\textsuperscript{a,b}, B. Buschinger\textsuperscript{a}, and C. Geibel\textsuperscript{a}

\textsuperscript{a} Institut für Festkörperphysik, Technische Hochschule Darmstadt, D-64289 Darmstadt, Germany
\textsuperscript{b} Department of Physics, The Ohio State University, Columbus, Ohio 43210-1106, USA

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Mechanical-controllable break junctions of the heavy-fermion superconductors can show Josephson-like superconducting anomalies. But a systematic study on the contact size demonstrates that these anomalies are mainly due to Maxwell’s resistance being suppressed in the superconducting heavy-fermion phase. Up to day, we could not find any superconducting features by vacuum-tunnelling spectroscopy, providing further evidence for the pair-breaking effect of the heavy-fermion interfaces.

Point contacts with heavy-fermion (HF) superconductors (SC) have attracted much interest during the past years. The finite contact resistance due to the small contact area allows charge carriers to be accelerated across the interface, and thus to observe the energy-dependent scattering processes. Andreev reflection (AR) and Josephson effect (JE) promise direct access to the still unknown SC order parameter of these compounds.

The most spectacular results have been obtained with SC counter-electrodes. Poppe et al. \cite{ref1}, Han et al. \cite{ref2} as well as Nowack et al. \cite{ref3} found JE-like anomalies with HFSC in contact with Al, Ta, Mo, Nb, and NbTi. He et al. \cite{ref4} verified that HFSC is really based on Cooper pairs, using a UPd\textsubscript{2}Al\textsubscript{3} sample as part of a SQUID. On the other hand, Moreland et al. \cite{ref5} could find neither supercurrents on metallic contacts nor SC features by vacuum-tunnelling spectroscopy on UBe\textsubscript{13} break junctions. This was attributed to the pair-breaking effect of the surface or interface.

Until recently, the SC anomalies of point contacts with HFSC and normal metals have been interpreted as clear evidence for the pair-breaking effect. But a systematic study on the contact size demonstrates that these anomalies are mainly due to Maxwell’s resistance being suppressed in the superconducting heavy-fermion phase.

To analyse those junctions one must distinguish the different processes that contribute to the contact resistance \(R\), and also to the SC anomalies. For details see Ref. \cite{ref6}. In the normal state \(R = dU/dI\) can be described by Wexler’s formula as a sum of Sharvin’s (\(R_{SH}\)) and Maxwell’s (\(R_{MAX}\)) resistance

\[
R(T) \approx 2R_K/(ak_F)^2 + \rho(T)/2a
\]

with \(R_K = \hbar/e^2 = 25.8\,\text{k}\Omega\), \(k_F\) the Fermi wave number, and \(a\) the contact radius. For the break junctions normal quasi-particle reflection and the effects of a normal interface layer should be negligible. We determine the radius by comparing the \(T\)-dependent part of the resistivity with that of the contact resistance. This method works excellently for the HF compounds because of their huge \(T\)-dependence of \(\rho(T) = \rho_0 + AT^2\) at low \(T\) due to the strong intrinsic electron-electron interactions.

Three different mechanism reduce \(R\) in the SC state: \(i\) The coherent coupling between the SC condensates from both sides of the contact can lead to the JE, and \(R\) disappears at low current densities. \(ii\) Single and multi AR enhance not only the JE supercurrent but also the normal quasi-particle reflection and the effects of a normal interface layer should be negligible. We determine the radius by comparing the \(T\)-dependent part of the resistivity with that of the contact resistance. This method works excellently for the HF compounds because of their huge \(T\)-dependence of \(\rho(T) = \rho_0 + AT^2\) at low \(T\) due to the strong intrinsic electron-electron interactions.

Three different mechanism reduce \(R\) in the SC state: \(i\) The coherent coupling between the SC condensates from both sides of the contact can lead to the JE, and \(R\) disappears at low current densities. \(ii\) Single and multi AR enhance not only the JE supercurrent but also the net current at finite bias voltage. \(iii\) \(R_{MAX}\) is frozen out. While the first two processes are boundary effects that scale with the inverse contact area, \(R_{MAX}\) scales with the inverse radius.

We apply Eq. \cite{ref6} at zero bias, and make a systematic study on the contact size. At \(U \approx 0\) local heating and the self-magnetic field of the current through the junction can be neglected. Thus the contact is at a well-defined condition. And by observing how the anomalies vary with radius, one gets an idea about the physics behind them.

Our setup is similar to that described by Muller et al. \cite{ref7}. The samples were cut into \(5 - 10\,\text{mm}\) slabs of about \(1 \times 1\,\text{mm}^2\) cross section, a \(\sim 0.5\,\text{mm}\) deep nut defines the break position. They were glued electrically isolated onto a 0.5 mm thick gold-plated copper-bronze bending beam. A screw, driven by two thin (0.3 mm diam.) cotton threads, breaks the sample and makes the coarse adjustment. Vertical resolution is about \(2\,\mu\text{m}\). A piezo tube serves for fine adjustment (2 nm resolution). The whole setup sits in the vacuum region of the refrigerator. A magnetic field can be applied perpendicular to the current flow.

Here we present the results for two UNi\textsubscript{2}Al\textsubscript{3} polycrystals (batch no. 27 100), the other HFSC behave - in most respect - quite similar \cite{ref8}. Fig. \ref{fig:1} (a) shows typical \(R(T)\)-traces, recorded while continuously increasing \(T\). The step-like increase \(\delta R\) indicates the SC transition.
at \( T_c = 1.2 \) K. Comparing the slope of \( R \) vs. \( T^2 \) above \( T_c \) with \( A = 0.25 \mu \Omega \text{cm}/K^2 \) yields the radius \( a \). On increasing the force on the bending beam, the contact area becomes smaller and \( R \) increases. Finally, the sample breaks and the contact has to be re-adjusted. However, the size of the SC signal relative to the slope in the normal state remains almost the same, indicating their common origin.

Only two out of 50 low-\( R \) contacts had unresolvably small residual resistances \( R_0 = R(T \to 0) \ll 0.1 \) m\( \Omega \) like that in Fig. 1 b). \( R_0 \) vanishing below \( T_c \) might result from a supercurrent, but Fig. 2 (a) shows that \( \delta R \propto 1/a \) like Maxwell’s resistance. Since the average \( 2a\delta R \approx 6 \) µ\( \Omega \text{cm} \) is near the bulk \( \rho_0 = 2.9 \) µ\( \Omega \text{cm} \), contributions from a supercurrent or AR are hard to resolve. Note, immediately before breaking the samples had \( 2a\delta R \approx 4 \) and 6 µ\( \Omega \text{cm} \), respectively, and a residual resistance ratio of 25.

\( R_0 \propto 1/a^2 \) is strongly enhanced with respect to \( R_{SHA} \), see Fig. 3 (b). This corresponds to a rather small effective Fermi wave number \( k_{F,eff} \approx 1 \text{ nm}^{-1} \). The transition from the ballistic to the thermal regime takes then place at \( R_0 \approx 0.01 \) \( \Omega \), and a huge elastic mean-free path of \( l \approx 2 \mu \text{m} \). An alternative explanation for the large \( R_0 \) is a normal interface layer. Direct information about it could be obtained from high-\( R \) junctions, that have zero-bias maxima (probably from scattering at disordered U magnetic moments), but no SC features.

Fig. 3 shows spectra of a contact in the intermediate regime with both SC features of width \( 4\Delta_0 \approx 0.8 \text{ meV} \), and zero-bias maxima when the contact is driven normal. From the size of the SC anomaly \( \delta R \approx 3 \) \( \Omega \) we estimate \( a \approx 10 \text{ nm} \). Driving the contact normal to above \( T_c \) or \( B_{c2} \) increases \( R \) by about 0.5 \( \Omega \). What we directly ‘see’ from the normal layer is then only \( 1-2 \) \( \Omega \), i. e. a fraction of the total resistance. This layer must be thinner than the radius to observe the SC anomalies. It may add to the pair-breaking effect of the interface and explain why we could not find SC features by vacuum tunnelling.

In summary, the break junctions support our previous findings with HF heterocontacts. The brickwall to understand these junctions seems to be the interface itself. To recover the energy-dependent SC gap from the spectra of low-\( R \) contacts will require at least detailed knowledge of the mean-free path effects described by \( R_{MAX} \).

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FIG. 1. a) $R(U = 0)$ vs $T^2$ of two different UNi$_2$Al$_3$ junctions. b) $I$ vs $U$ of contact 1 of Fig. a). At low $T$ this contact is probably driven normal due to the contact resistance of the current leads.
FIG. 2. a) Size of the SC anomalies $\delta R$ vs radius $a$. The solid line is $R_{\text{Max}} = \rho \rho_0 / 2a$. b) Residual resistance $R_0$ vs $a$. The solid line is $R_0 = 2R_K(ak_F)^2$ at $k_F = 10^{-1}$.
FIG. 3. $dU/dI$ vs $U$ at (a) $B = 0$ Tesla and (b) $T = 0.1$ K. Both in the normal and SC state. The hatched area marks tentatively the contribution from the interface layer. Also indicated is the width of the SC anomaly $4\Delta_0$ as well as the signal size at $4\mu V$ excitation.