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Author(s)	A. Nowack, A. Heinz, F. Oster, D. Wohlleben, C. Guntherodt, Z. Fisk, A. Menovsky
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Point-contact spectra of the heavy-fermion superconductors UBe_{13} and UPt_3

A. Nowack, A. Heinz, F. Oster, D. Wohlleben,* and G. Güntherodt
II. Physikalisches Institut, Universität Köln, 5000 Köln 41,
Federal Republic of Germany

Z. Fisk
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

A. Menovsky
Natuurkundig Laboratorium, Universiteit van Amsterdam,
1018 XE Amsterdam, The Netherlands

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We have measured the current-voltage characteristics of point contacts between UBe_{13} or UPt_3 and the normal metals W or Pt (metallic point contacts) or GaAs (Schottky-barrier tunneling contact) in the temperature range between 50 mK and 1 K. In the metal-point-contact characteristics (dV/dI vs V) there appear zero-bias minima of width 2Δ below T_c. The ratio $2\Delta/k_BT_c$ is close to the BCS value. The tunneling spectra of UPt_3 exhibit weak additional structure below T_c. A value 2Δ has been estimated, which is a factor of 2 larger than that for the metal point contacts.

In the investigation of the unusual superconductivity of the heavy-fermion systems UBe_{13} and UPt_3 point contact and tunneling experiments play an important role. The absence of a Josephson effect in UPt_3 and the anomalous proximity-induced Josephson effects in point contacts between UBe_{13} and normal superconductors[1,2] give evidence for an unusual pairing mechanism. So far no tunneling data are available; such data would allow a determination of the energy gap in the density of states (DOS) of UBe_{13} and UPt_3, if there is any.[3] We report here the observation of slight changes in the characteristics of a GaAs-UPt_3 tunneling point contact below T_c. The difference between the spectra in the normal and superconducting state yields an energy gap 2Δ, which exceeds the BCS value by a factor of more than 2. A determination of the energy gap 2Δ of the above two heavy-fermion superconductors seems also to be possible by means of metallic point contacts with normal metals as the counterelectrodes. We report here the appearance of distinct minima of width 2Δ in the dV/dI-vs-V characteristics of such contacts below T_c.

We used polycrystalline samples of UBe_{13} and UPt_3. The point contacts were realized by the "needle-anvil" technique. A sharply etched wire (W or Pt) or a GaAs tip were carefully pressed against the freshly cleaved surface of the sample by a Cu-Be spring. Eight such contacts were mounted in a ^{3}He-^{4}H dilution refrigerator. On the average two of them "survived" the cooling procedure and gave results, while the others opened. The tunneling spectra of GaAs-UPt_3 were measured by the Schottky-barrier point-contact tunneling technique described in Refs. 4 and 5. In our investigation we used p-type GaAs with a Zn-doping level of 2×10^{19} cm^{-3} and hence a barrier height of $V_B=0.46$ eV, independent of the material of the counterelectrode. The differential resistance dV/dI of the contacts was measured by the usual lock-in technique as a function of the bias voltage V. The voltage is always measured from the sample to the needle, i.e., at positive voltages electrons are flowing into the sample.

Figure 1(a) shows the dV/dI-vs-V characteristic of a UBe_{13}-W point contact at $T=1$ K, normalized to the differential resistance at $V=0$ mV. The zero-bias minimum and the asymmetry are features which UBe_{13} has in common with intermediate-valence materials (see, e.g., Refs. 6-9). Below T_c (0.89 K) another narrower minimum appears within the minimum of Fig. 1(a), which becomes more pronounced with decreasing temperatures, as seen in Fig. 1(b). (Note that the V axis is expanded and the dV/dI axis is compressed.) In addition, an oscillating structure appears at the edges of the minimum. The characteristics of Fig. 1(c), measured at a different contact, show similar behavior, but the structure at the edges of the minimum is different. The distinct peaks at the edges of the minimum move to smaller voltages with increasing temperatures. They are accompanied by smaller peaks at higher voltages.

Similar results were obtained for the characteristics of UPt_3-Pt at $T=1$ K and below T_c (0.46 K) as shown in Figs. 2(a) and 2(b). In contrast to UBe_{13}, the curves are almost symmetric with respect to zero bias. Note that the nonlinearities of the low-temperature curves due to the superconductivity are much smaller than those of UBe_{13}. Normal-state point-contact spectra of UBe_{13} and UPt_3 have been published earlier, in Refs. 10 and 11, respectively.

Figure 3 shows a zero-bias maximum of a GaAs-UPt_3 tunneling point contact which becomes narrower near the top with decreasing temperature, as shown for $T=900$ and 54 mK. The shape of both maxima is symmetric with respect to zero bias, in spite of the fact that GaAs usually produces an asymmetric background in the tunneling characteristics. Following Refs. 12 and 13 this symmetrization can be explained by resonant tunneling via local-

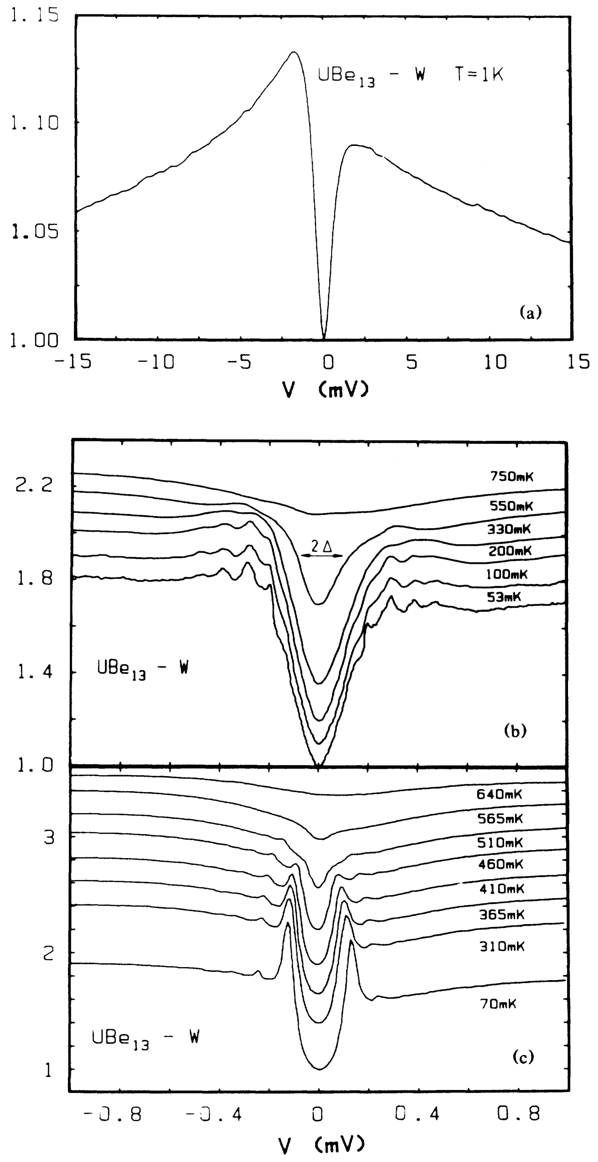

FIG. 1. (a) Normalized dV/dI-vs-V characteristic of a UBe$_{13}$-W contact at $T=1$ K. The differential resistance at $V=0$ mV (R_0) is approximately 3 Ω. (b) Temperature dependence of the characteristic of the UBe$_{13}$-W contact of Fig. 1(a) in the vicinity of zero bias. The 750-mK curve corresponds to the expanded minimum of Fig. 1(a). The differential resistance at $V=1$ mV is the same for all curves and has a value of approximately 3 Ω. (c) Temperature dependence of a Josephson-like characteristic of a UBe$_{13}$-W contact. The differential resistance at $V=1$ mV is 5.4 Ω for each curve.

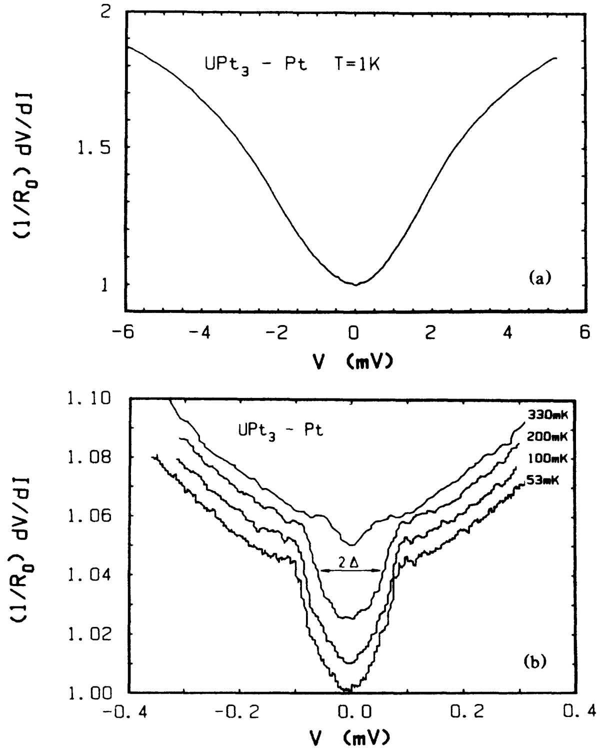

FIG. 2. (a) Normalized dV/dI-vs-V characteristic of a UPt$_3$-Pt contact at $T=1$ K. $R_0 \approx 0.3$ Ω. (b) Temperature dependence of the characteristic of (a) in the vicinity of zero bias. The curves are identical outside the minima; the resistance is approximately 0.3 Ω at $V=0.4$ mV.

ized states introduced into the barrier by surface contaminations. Below 400 mK an additional structure appears in the tunneling spectra, which can be detected more clearly in the difference between the 54- and the 900-mK curve as shown in the inset of Fig. 3. This structure is probably due to the superconductivity. In order to deduce an approximate value of a possible energy gap 2Δ we took the full width at half maximum (FWHM) of the maximum in the inset. Thus a value of ~0.5 meV was obtained for the 54-mK curve, yielding $2\Delta/kT_c \approx 10$, which is much larger than the BCS value of 3.52 and exceeds even values of strong-coupling superconductors by a factor of at least 2.

Point contacts between normal (N) and superconducting (S) metals allow a measurement of the energy-gap parameter of a superconductor, just as do tunneling contacts. Comparing tunneling and metallic N-S point contacts there are differences especially in the following points.

(i) In a tunneling experiment the gap is measured directly, because the tunneling probability and therefore the current is proportional to the quasiparticle DOS. The result is a maximum of width 2Δ in the dV/dI-vs-V characteristics.

(ii) According to the theory of Blonder, Tinkham, and Klapwijk (BTK),[14] a metallic point contact (barrier strength parameter $Z=0$ in the BTK model) allows a measurement of the probability of Andreev reflections at the N-S interface. An Andreev reflection is the reflection of a hole for each electron moving from N to S, which becomes one part of a Cooper pair. This probability A is given as a function of energy E approximately by $A(E)=1$, if $E<\Delta$ and $A(E)=0$ otherwise. For more details, see Ref. 14. A thermally smeared version of the function $[1+A(E)]^{-1}$ (minimum of width 2Δ) should

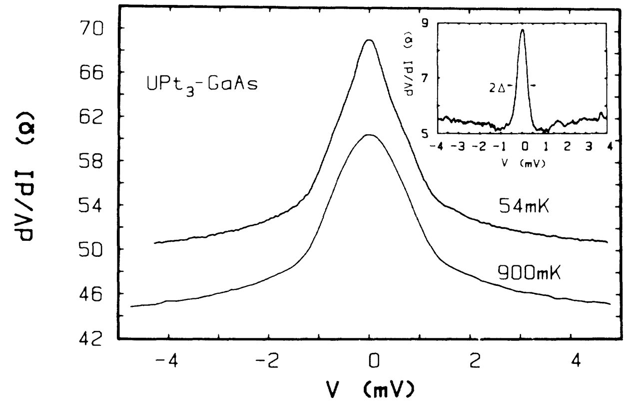

FIG. 3. dV/dI-vs-V characteristics of a UPt$_3$-GaAs contact at $T = 900$ mK and 54 mK. The inset shows the difference between both curves.

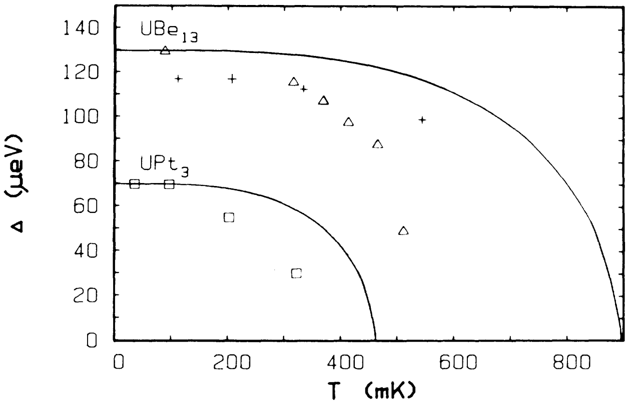

FIG. 4. Temperature dependence of the gap parameter of UBe$_{13}$ and UPt$_3$ as extracted from the metal point contact characteristics. +: from Fig. 1(b); △: from Fig. 1(c) (UBe$_{13}$, $T_c = 0.89$ K); □: from Fig. 2(b) (UPt$_3$, $T_c = 0.46$ K); ——: corresponding BCS curves.

appear in the dV/dI-vs-V characteristics of a N-S point contact.

Qualitatively, the shape of the curves in Figs. 1(b), 1(c), and 2(b) agrees well with the BTK theory. For the ratio of the resistivities at $V = 0$ and at $V > \Delta$ a value of 2 is expected, because the Andreev reflections double the number of transferred charges. The UBe$_{13}$ characteristics in Figs. 1(b) and 1(c) at the lowest temperatures reach nearly this value, while the UPt$_3$ curves [Fig. 2(b)] show much smaller ratios. Serial resistances to the proper point-contact resistance might give a simple explanation for ratios lower than 2. Alternatively, the averaging over an anisotropic gap (caused by the band structure and/or points or lines of zeros in the case of unconventional superconductors) could also account for this experimental observation.

The UBe$_{13}$ characteristics of Fig. 1(c), with the distinct maxima at the edges of the zero-bias minimum, cannot be considered as due to a proper N-S contact at all. They are reminiscent of the shape of characteristics found for S-S contacts (Josephson-like characteristics). Indeed, due to proximity-induced superconductivity in the tungsten tip a N-S′-S contact would result and explain the characteristics.

For extracting 2Δ from the metal-point-contact spectra, the following procedure was chosen: The FWHM's of the curves of Fig. 1(b) (UBe$_{13}$) and Fig. 2(b) (UPt$_3$) were determined. The distance between the sharp peaks in the curves of Fig. 1(c) was determined. The results are shown in Fig. 4, where for comparison a BCS curve is plotted for each $\Delta(T)$.

For the UBe$_{13}$ data in Fig. 1(c) distinct marks could be used for the determination of Δ, which correlates for $T \rightarrow 0$ exactly with the BCS value. At higher temperatures Δ decreases faster towards zero than expected from BCS theory. Although this behavior may be intrinsic, one should note that the high current density in the point contact might cause a depression of the gap parameter, either by approaching the critical current or via a (small) heating effect. The other data [Figs. 1(b) and 2(b)] show also a good correlation with the BCS values; at least parts of the deviations may be due to the uncertainty in the method of determining Δ. We estimate an uncertainty of about 50% for the values extracted from these curves. In contrast to this, the GaAs probe tunneling yields a value of Δ, which is by a factor of about 2.5 larger compared to the BCS value. Presumably the background resonant tunneling causes a smearing of the gap structure. The additional structure in the characteristics of UBe$_{13}$ may be explained by harmonics of Δ. Another explanation for the oscillating structure in the curves of Fig. 1(b) might be the generation of standing waves in a small crystallite of the polycrystalline sample.

The normal-state effects, i.e., the minima in the curves of UBe$_{13}$ [Fig. 1(a)] and UPt$_3$ [Fig. 2(a)] and the asymmetry in the characteristics of UBe$_{13}$ cannot yet be explained satisfactorily. The asymmetry is regarded as a normal-state feature, because all the structures appearing below T_c are symmetric with respect to zero bias (each peak appears at positive and negative voltages).

Interesting questions arise from a comparison of point-contact and tunneling data. Why do metallic point contacts give clear and distinct results, while the tunneling experiments seem to be more or less insensitive to the superconductivity? A possible answer is that a tunneling contact is sensitive to the first few atomic layers of the sample (a depth of a few Å), while a point contact "sees" a region down to a depth of approximately the same value as the contact diameter (a value between 50 and 500 Å is appropriate). Surface effects might therefore play an important role for the tunneling data. On the other hand, the unusual Josephson effect found in point contacts by Han, Ng, and Wolf^2 seems to be rather independent of surface conditions.

Further work should be done on single crystals of UPt$_3$ to check on possible gap anisotropies.

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*Present address: Los Alamos National Laboratory, Los Alamos, New Mexico 87545.

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