Impurities in a superconductor with a highly anisotropic gap: Universal correlation between the residual resistivity and T_c in doped UPd_2Al_3

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We have studied the effect of doping on the superconducting transition temperature T_c and on the residual resistivity ϱ_0 of the heavy-fermion superconductor UPd_2Al_3. We have found a general correlation between the increase of ϱ_0 and the decrease of T_c which seems to be independent of the type of dopant. We interprete this correlation as a further evidence for a large anisotropy of the superconducting order parameter.

The symmetry of the superconducting order parameter in the heavy fermion and in the cuprate superconductors is presently controversely discussed. In this context the effect of impurity scattering on a highly anisotropic order parameter has gained increasing interest. In classical superconductors with weak anisotropy scattering by non-magnetic impurities leads at low concentration to a correlation between increasing residual resistivity and decreasing T_c which is independent of the type of impurity [1]. This question has never been investigated thoroughly in heavy fermion superconductors, although they present strong evidence for a large anisotropy of the superconducting order parameter. We have undertaken a systematic study of doping in the heavy fermion superconductor UPd_2Al_3, which presents the advantage of having the highest T_c among these compounds and a comparatively unproblematic preparation process. Specific heat [2] and NMR [3] measurements at $T \ll T_c$ indicate the presence of nodes or lines of zero of the order parameter on the Fermi surface of UPd_2Al_3.

The samples were prepared by arc melting followed by an annealing process of 120 hours at 900 °C. U was substituted by several rare earth elements (Y, Pr, Gd, Dy) and Th, Pd was substituted by Rh, Ni, Pt and Au, and Al by Ga. T_c was determined by means of ac-susceptibility or resistivity measurements. Preliminary results for doping with Y, Gd and Ni were already reported elsewhere [4].

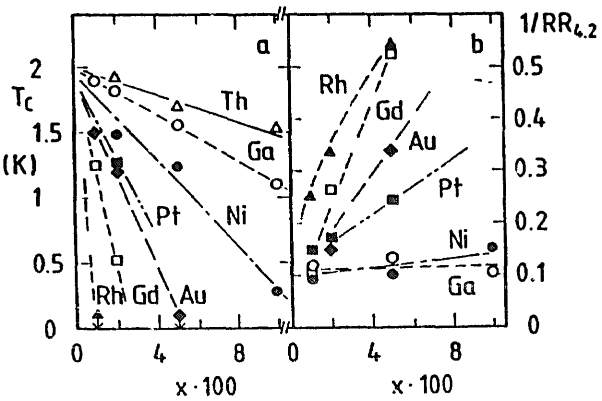

Fig.1a T_c vs dopant content x for different types of dopants: Ga(○), Rh(▲), Ni(●), Pt(■), Au(◆), Gd(□) and Th(△).
Fig.1b Reciprocal resistivity ratio at 4.2K, $1/RR_{4.2}$ vs x for various dopants (same symbols as in fig.1a).

All dopants lead to a reduction of T_c, which size however is strongly dependent on the type of dopant: the critical concentration x_c at which superconductivity is completely supressed ranges from less than 1% for Rh to more than 20% for Th. In Fig. 1a the dependence of T_c on the dopant concentration x is shown for Ga, for all dopants on the Pd-site, for Th and for Gd. All other rare earth dopants show a rather fast T_c depression similar to that of Gd ($x_c \approx 3\%$), independently of the atomic volume or the value of the magnetic moment of the rare earth element. The large Curie-tail observed in the susceptibility even at low contents (1%) of those rare earth elements with a large moment had no additional effect on T_c. Thus there seems to be no correlation between the effect of dopants on the magnetic properties and the effect on T_c. A similar conclusion can also be drawn for doping results at the Pd-site. Rh and Ni lead to a slight increase of the antiferromagnetic ordering temperature T_N whereas Au leads to a reduction of T_N. By contrast T_c is strongly reduced by Rh but only weakly by Ni, the effect of Au being in between.

In contrast a clear correlation is observed between the residual resistivity ϱ_0 and T_c. In fig. 2a the composition dependence of the reciprocal resistivity ratio $1/RR_{4.2} = (\varrho(300K)/\varrho(4.2))^{-1}$ is shown. At 300K the resistivity is dominated by spin disorder scattering and should therefore only weakly depend on the composition. Then $1/RR_{4.2}$ is roughly proportional to the residual resistivity and thus inversely proportional to the electron mean free path ℓ. Those dopants which strongly depress T_c also lead to a strong increase of $1/RR_{4.2}$ whereas those dopants which have a weak effect on T_c also show a weak increase of $1/RR_{4.2}$. One exception is Th, where already a small content leads to a pronounced increase of ϱ(4.2K). Since the Th we used had a lower purity than the other dopants (We observed traces of ThO_2 in the powder diffraction pattern of $ThPd_2Al_3$ made from the same batch) we suspect that this large increase of ϱ_0 is not intrinsic but due to the presence of ThO_2 at the grain boundaries.

We therefore plotted in Fig.2 T_c versus $1/RR_{4.2}$ with the composition as an implicit parameter for all dopants investigated up to date. We included results for non-stoichiometric $U_{1+x}Pd_{2+y}Al_3$ samples as well as for the many stoichiometric polycrystalline samples and single crystals produced in our laboratory during the last years [5]. Despite the strong differences in the effect of different dopants on T_c, most of the data are close together within a band which starts from the point T_c=2K, $1/RR_{4.2} \approx 0.04$ and reaches the x-axis at $0.17 < 1/RR_{4.2} < 0.33$. Only the Th-doped samples and three UPd_2Al_3 samples are far away from this band. In both cases the origin of this discrepancy is probably related to oxide layers as already discussed for Th. From the value of $1/RR_{4.2}$ at which T_c=0, one can estimate a corresponding ℓ of 60Å, which is comparable to the coherence length $\xi_0 \approx 85$Å [4]. Thus superconductivity disappears when ℓ gets smaller than ξ_0. This general relation between T_c and $1/RR_{4.2}$ suggests, in analogy to the effect in classical superconductors, that the reduction of T_c is mainly related to the smearing out of a strongly anisotropic order parameter. The present experiments are however not able to clarify whether we have to deal in the case of UPd_2Al_3 with a strongly anisotropic s-wave superconductor, a d-wave superconductor or whether this anisotropy has to be interpretated in the sense that different sheets of the Fermi surface have completely different values of the order parameter.

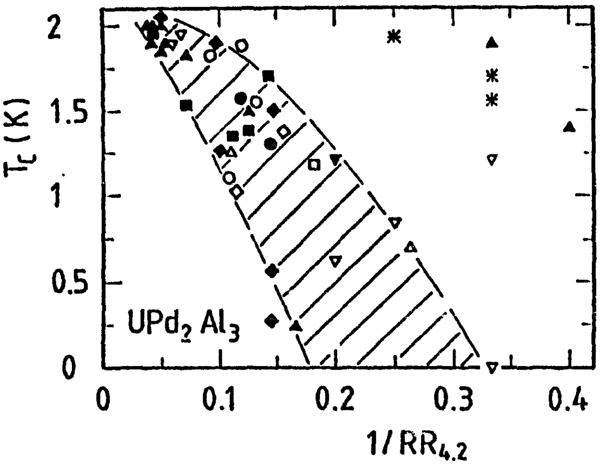

Fig.2 T_c versus $1/RR_{4.2}$ for all dopants investigated up to now: Y(□), Pr(◇), Gd(△), Th(*), Ni(◆), Pt(▼), Au(●), Ga(○). Included are results for stoichiometric (▲) and non-stoichiometric(▽) polycrystalline samples as well as single crystals(■).

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