Evidence for charge Kondo effect in superconducting Tl-doped PbTe

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Phys. Rev. Lett. **94**, 157002 (2005)

AND

Superconductivity in charge Kondo systems

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Phys. Rev. Lett. **94**, 157003 (2005)

Recommended and a Commentary by Elihu Abrahams, Rutgers University.

It has been known since the early 1980s that Tl doped PbTe (a small-gap semiconductor) superconducts with modest Tl concentrations corresponding to carrier densities only of order 10^{20} cm^{-3}. Considering the low carrier concentration, the T_c, ≈ 1.5K is remarkably high, and this has been a topic of some discussion, much of it concerning the possibility that the Tl impurities act as negative-U centers and as such whether they can enhance superconductivity.

Tl($6s^2 6p^1$) in a polarizable host, here PbTe, which is nearly ionic, is known to be a valence skipper. That is, it prefers the two closed shell configurations Tl^{3+}, Tl^{1+} over Tl^{1+} by several eV. This was discussed later in the 1980s by C.M. Varma, who calculated, for a number of cases, the effective negative-U (on-site electron-electron interaction) that results from valence skipping. He pointed out that this purely electronic attractive interaction could be responsible for enhanced superconductivity in some compounds.

Another interesting property of a negative-U center, such as a valence skipping ion, is that it can lead to a "charge Kondo effect", which was first mentioned by F.D.M. Haldane (1977). This idea was discussed by several groups and was elaborated by A. Taraphder and P. Coleman in 1991. In the present context, when the two favored charge states become degenerate the situation is directly analogous to the two degenerate spin states of a conventional spin Kondo impurity.

All this interesting physics comes together in the experimental paper of Matsushita, et al and the theory contribution of Dzero and Schmalian. Superconductivity and resistivity in single crystals of $Pb_{1-x}Tl_xTe$ was investigated. Superconducting T_c's increased linearly to ≈ 1.5K with $0.3 < x < 1.5$. At the same time, at higher T , characteristic Kondo behavior in temperature of the resistivity was seen (with a Kondo temperature $T_K \approx 6$ K) . A 5 Tesla magnetic field did not eliminate the Kondo behavior; this shows that it is not a spin Kondo effect and it also eliminates some other possible explanations for the resistance anomaly. As discussed above, a charge Kondo effect is a natural explanation for the transport behavior and the negative-U due to valence skipping for the superconductivity.

Dzero and Schmalian have given a complete theoretical framework for this scenario for $Pb_{1-x}Tl_xTe$. (Aspects of the general $U < 0$ case were discussed theoretically by A.G. Mal'shukov in 1989,91.) They explain why it is possible to have $T_c \lesssim T_K$, where one might have expected the pairing fluctuations to be quenched. They also show how the two low-lying charge states of the Tl impurity [1+ (acceptor), 3+ (donor) remain degenerate when the impurity concentration exceeds a critical value. After establishing this degeneracy for $x > x^*$, they discuss superconductivity in the charge Kondo situation by generalizing an approach used successfully by Müller-Hartmann and Zittartz (1971) for spin Kondo impurities in a superconducting host. An interplay between pair-breaking and pairing occurs in the charge Kondo case and complicates somewhat the analysis. Interesting behavior at low T is predicted, including the reappearance and disappearance of a reentrant normal phase at low concentration. Their results agree in order of magnitude and in concentration dependence with experiment and they suggest that the reentrant behavior might be a fingerprint for charge Kondo superconductivity.