Discussion

In LaCe alloys the Kondo effect arises from a mixing of the localized $4f$ electron with conduction electron states. The $4f$ level lies a small energy E below the fermi level so that the resonance scattering mechanism dominates the normal exchange scattering. Consequently the effective exchange parameter J_{eff} is negative. According to the Schrieffer-Woolf transformation it is given by

$$J_{\text{eff}} = |V_{kf}|^2/E \tag{2}$$

where V_{kf} is the matrix element of mixing between $4f$ electrons and conduction electrons.

With the application of pressure, the energy difference E becomes smaller and, assuming a nearly constant mixing parameter V_{kf}, the exchange parameter $|J_{\text{eff}}|$ increases. Therefore, when the pair breaking effect is treated only in the Born approximation[2], the depression of the superconducting temperature ΔT_c increases as

$$\Delta T_c = -\frac{c \cdot \pi^2}{8 k_B} N(0)\, S(S+1)\, J_{\text{eff}}^2 . \tag{3}$$

Due to Maple *et al.*[6,7] the $4f$ level eventually overlaps the Fermi level upon further application of pressure, initiating a transition from a magnetic to a nonmagnetic impurity state, which causes a decrease in the pair breaking effect at higher pressures.

In what follows, we will discuss the experimental facts which indicate, in our opinion, that the maximum in ΔT_c follows from the above mentioned theories of Zuckermann or Müller-Hartmann and Zittartz, in which, as a main result, ΔT_c exhibits a maximum by its relationship to T_k/T_{c0} when T_k increases monotonically from values of $T_k \ll T_{c0}$ to $T_k \gg T_{c0}$. For the increase of T_k the same model given above is used (Eq. (2)). However, the transition of the cerium ion from a magnetic to a nonmagnetic state is not needed for this discussion; it may arise at higher pressures.

First we point out that the maximum of ΔT_c is found at about 13 kbar, whereas the resistance anomaly, typical for the Kondo effect, still exists, at least up to 21 kbar, i.e. the Kondo effect is still present (Fig. 2).

For a more detailed discussion of the resistance anomaly we consider Hamann's expression[11]

$$\frac{R(T/T_k)}{R(0)} = \frac{1}{2}\left[1 - \frac{\ln T/T_k}{|(\ln T/T_k)^2 + \pi^2 S(S+1)|^{1/2}}\right]. \tag{4}$$

11 Hamann, D. R.: Phys. Rev. 158, 570 (1967).

One sees immediately that, at a fixed temperature T_0, the slope of the R vs. $\ln T$ curve goes through a maximum if the Kondo temperature T_k, which is less than T_0 at zero pressure, increases with pressure and finally exceeds T_0. This was observed in our experiments and is shown in Figs. 2 and 4a. Further, under the same conditions, it is easily deduced from Eq. (4) that, at a fixed temperature T_0, the resistance varies monotonically with T_k, showing a turning point when T_k equals T_0. As seen in Fig. 3, such a behaviour was also observed in our experiments for the pressure dependence of $R(p)$ at T_0 (Fig. 3). This correlation again is most naturally explained by a continuous increase of T_k with pressure. To illustrate this, and to compare it with the results of the first procedure given in Fig. 4a, we have plotted both the derivatives of the measured curves, i.e. $1/R(p=0) \cdot \Delta R/\Delta p$ at 4.2 K and of the theoretical function (Eq. (4)), i.e. $1/R(T=0) \cdot dR/d \ln T_k$ at 4.2 K, in Figs. 4b and c, respectively. The maxima in Fig. 4b are again located near 13 kbar.

Comparison with Fig. 4c shows, as marked by points B, that a pressure of approximately 13 kbar has raised the Kondo temperature from 0.2 K (points A) to 4 K. The fact that the $R(p)$ curves do not coincide for both concentrations may be interpreted as due to a stronger interaction between the impurity spins at the higher concentration. In principle, an empirical function $T_k(p)$ can be determined from the theoretical and experimental curves in Fig. 4. However, one sees immediately that a simple relation like $\ln(T_k(p)/T_k(0)) = K \cdot p$, with $K = 0.50 \pm 0.05\ \text{kbar}^{-1}$, holds only in a limited pressure regime (about ± 5 kbar) around the maximum.

If one accepts the Hamann function as describing the resistance anomaly correctly, one then expects a slight curvature in the R versus $\ln T$ dependence, especially for zero pressure and for 21 kbar (Fig. 2). Because of the small temperature interval, bordered by the onset of superconductivity and lattice resistivity, this could not be resolved within experimental accuracy.

In Fig. 5 we summarize our results on the depression $\Delta T_c(p) = T_{c0}(p) - T_c(p)$. One notes that its magnitude is much larger than reported by Maple *et al.* for comparable Ce concentration, indicating a phase mixture or inhomogenity in their "as cast" samples. We mention that the measurements of Maple *et al.* show the largest decrease of $\Delta T_c(p)$ near 25 kbar, which might be interpreted by the transition to a nonmagnetic state. However, since *we* see no such kink, it is most likely that it is due to the dhcp-fcc phase change in La. The maximum depression for our La 1% Ce alloy amounts to $\Delta T_{c\,\max} = 6.4$ K*, which is in

* If the depression of the transition temperature due to cold work is taken into account, the $\Delta T_{c\max}$ becomes 5.7 K.