Peculiar behavior of the electrical resistivity of MnSi at the ferromagnetic phase transition

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The intermetallic compound MnSi experiences a second order phase transition at temperature \(T_c\) slightly below 30 K, acquiring helical magnetic structure and becoming a weak itinerant ferromagnet. On application of pressure the transition temperature \(T_c\) decreases and tends to zero at a pressure of about 1.4 GPa [1]. As was noticed for the first time in ref. [2] (see also [3]), a \(\lambda\)-type singularity of the AC magnetic susceptibility \(\chi_{AC}\) at the phase transition in MnSi deforms gradually with pressure and becomes a simple step at pressures more than 1 GPa. That was ground to claim existence of a tricritical point with the coordinates: \(\sim 1.2\) GPa, \(\sim 12\) K [2,3]. This conclusion was partly disputed in ref. [4], where new measurements of \(\chi_{AC}\) of MnSi at high pressures, created by compressed helium, were reported. These authors [4] confirmed the existence of a tricritical point on the phase transition line in MnSi but placed it at much lower pressure \((P_{Tr} \approx 0.355\) GPa, \(T_{Tr} \approx 25.2\) K).

To resolve that somewhat controversial issue we have carried out precise resistivity measurements of a MnSi single crystal across the phase transition line at ambient pressure. Sharp peaks of the temperature coefficient of resistivity \(d\rho/dT\) at the transition line. Analysis of these data shows that at pressures to \(\sim 0.35\) GPa these peaks have fine structure, revealing a shoulder at \(\sim 0.5\) K above the peak. It is symptomatic that this structure disappears at pressures higher than \(\sim 0.35\) GPa, which was identified earlier as a tricritical point.

The electrical resistivity of a single crystal of MnSi was measured across its ferromagnetic phase transition line at ambient and high pressures. Sharp peaks of the temperature coefficient of resistivity characterize the transition line. The resistivity measurements of MnSi were carried out along 24 quasi isobars [12] in the pressure range from zero to 1.5 GPa. Selected experimental data are displayed in Fig. We have tried to describe the resistivity curves in the temperature range from zero to the phase transition region by various polynomials that contained potentially important \(T^2\) and/or \(T^5\) terms accounting for scattering by spin and density fluctuations (phonons) [13,14]. The overall results appeared to be quite satisfactory though we observed small but systematic deviations of the experimental data points from the corresponding approximations at low temperatures. Replacing the \(T^2\) term with \(T^n\) improves the situation but does not correct it entirely, though always leads to a value of \(n < 2\). On the other hand, as is seen in Fig. the pressure derivatives of resistivity are positive below the Curie point and negative above (see also [2]). This implies a dominant role of order parameter fluctuations in the electron scattering in MnSi. Hence, any analysis of the resistivity behavior in MnSi should take into account this significant factor.

We will discuss this issue elsewhere. However, it is important to emphasize here that the residual resistivity of
MnSi, derived from reasonable extrapolations, decreases monotonically from 2.25 to 2.11 $\mu\Omega\text{cm}$ over all the pressure range studied on compression. This indicates that many cycles of pressure loading and unloading, cooling and warming do not introduce additional defects into the sample. The temperature-dependent resistivity of MnSi above the phase transition line shows clear signs of resistivity saturation at $T \rightarrow \infty$ [15].

Now we turn to an analysis of the temperature coefficient of resistivity $d\rho/dT$ in the vicinity of the phase transition boundary. Temperature derivatives of resistivity $\rho$ were taken by averaging the slopes of two adjacent points of the raw experimental data. The outcome of this procedure is illustrated in Fig.2 where also the smoothing lines are shown. As is seen from the figure at ambient pressure the curve $d\rho/dT(T)$ has a distinct shoulder on the high temperature side of $T_c$ which disappears at high pressure. The evolution of the shape of the peaks of $d\rho/dT$ with applied pressure is shown in Fig.3. The overall trend is that at low pressure structure in $d\rho/dT$ consists of two components: one sharp and another broad, separated only by half a degree or so. Because of lack of $a$ priori knowledge of the peak forms and uncertainty with background subtraction, we could not separate these peaks in a reliable way. The obvious overlapping of the peaks makes also unreliable attempts to obtain a critical exponent, based on behavior $d\rho/dT$ [3,4]. Nevertheless, we have found that an approximation of $d\rho/dT$ at $T < T_c$ with the expression

$$
\frac{d\rho}{dT} = a + bT + c(T_c - T)^{-m}
$$

(1) gives $m \approx 0.25$ in case of the low pressure isobars, which is a reasonable value for an exponent characterizing critical behavior of heat capacity near helical spin ordering [16,17]. At pressures more than 0.3-0.4 GPa, the fitting became unstable and did not lead to realistic values of the exponents.
FIG. 3: (Color online) Evolution of temperature derivatives of resistivity $d\rho/dT$ with pressure. The pressures in GPa are shown at the left side of the figure.

FIG. 4: (Color online) Pressure dependence of the Curie temperature of MnSi according to the current resistivity measurements and the AC susceptibility data [4]. The inset shows that the average mismatch of the two sets of the data is less than 0.1K.

temperature side of $d\rho/dT$ (Fig 4). Thus, the observed shoulder in $d\rho/dT$ could be connected with short range spin order or with the spin texture [12, 20]. However, it does not appear that the shoulder in $d\rho/dT$ marks any kind of a conventional phase transition. Nevertheless, one cannot exclude that a topological phase transition takes place at a temperature above the magnetic transformation. In the latter case, instead of a tricritical point there would be a special kind of a multicritical point in the phase diagram of MnSi. But, if the scenario with a topological phase transition is not appropriate, then the shoulder in $d\rho/dT$ disappears, being adsorbed by the volume instability gap, which is opened at a tricritical point [21].

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