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The critical pressure of chromium

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Abstract

We present first results of high-pressure resistivity measurements on pure chromium. Two pieces of evidence show that spin density wave magnetism is suppressed at a critical pressure $p_c \approx 10\,\text{GPa}$, namely, the evolution of the ordering temperature $T_N(p)$ and the rapid decrease of the residual resistivity close to p_c. Our discussion profits from the comparison between pressurized-Cr and the $Cr_{1-x}V_x$ alloy, for which a large amount of information on its electronic properties is available.

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The widespread interest in quantum phase transitions has recently motivated a restudy of the magnetic properties of elemental chromium [1,2]. In Cr, long-range spin density wave (SDW) order develops below $T_N = 311\,\text{K}$ through a weakly first-order, largely strain-dependent, phase transition [3]. As itinerant magnetism sets in, a gap opens at portions of the Fermi surface, which results in the characteristic changes of the transport properties immediately below T_N [3]. Pressure [4–6] or alloying [3] strongly affect magnetism. Only 3.5% of V-doping is necessary to continuously drive $Cr_{1-x}V_x$ to a $T = 0$ magnetic critical point [1,3,7]. This has been exploited by the authors of Refs. [1,2] to study a quantum phase transition in a simple cubic system very close to stoichiometry.

Alloying inevitably induces disorder which, even in small amounts, can modify the phase diagrams of magnetic systems close to a $T = 0$ critical point. Pressure, on the other hand, is a parameter that allows suppressing magnetism without drastically modifying the amount of quenched disorder. We have thus undertaken the study of a *clean* system, by performing resistivity measurements in pressurized-Cr. Here we report a first analysis of our data, aimed at determining the critical pressure at which the SDW phase of chromium is suppressed.

The chromium sample was cut from a high-purity crystallite (Alfa Aesar 4N+) and mechanically polished to an approximate final dimension of $20 \times 20 \times 600\,\mu\text{m}^3$. High-pressure four-probe dc electrical resistivity measurements were performed up to 24 GPa in a clamped Bridgman anvil cell using steatite as the p-transmitting medium. The superconducting transition of Pb was used as a low-temperature manometer and allowed us to estimate a typical gradient in the cell, $\delta p/p \sim 5$–10%. The temperature sweeps were extended down to 70 mK at some selected pressures.

Our high-pressure resistivity measurements can be qualitatively described by the two conduction-channels model of Ref. [5]. We consider two parallel channels and approximate the total resistivity as $1/\rho = 1/\rho_c + 1/\rho_{nc}$, where $1/\rho_c$ describes the conductivity due to the carriers that condense within the SDW phase and $1/\rho_{nc}$ relates to the portion of the Fermi surface that is unaffected by magnetism. It is assumed that both contributions have the same T-dependence in the non-magnetic phase. We first focus on $\rho(T)$ measured at the highest pressure of 23.9 GPa. The Bloch–Grüneisen resistivity, $\rho_{BG}(T)$, describes our data using a Debye temperature $\Theta_D = 580\,\text{K}$. The excess resistivity $\rho(T) - \rho_{BG}(T)$ at $p = 23.9$ is presented as the dashed "baseline" in Fig. 1. No features that can be associated to a magnetic transition are found. The weak broadened maximum around 90 K is most probably

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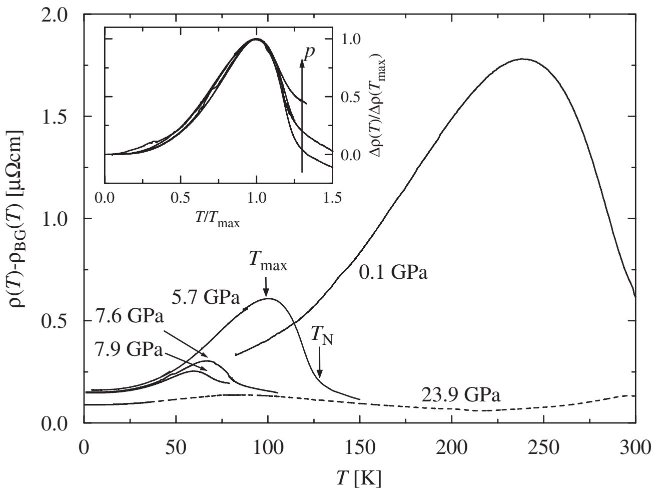

Fig. 1. Excess resistivity in the SDW-phase of chromium at high pressures, estimated as $\rho(T)-\rho_{BG}(T)$. The dashed baseline corresponds to $\rho(T)-\rho_{BG}(T)$ at $p=23.9$ GPa. Inset: normalized $\Delta\rho(T)=\rho(T)-\rho_{BG}(T)-\rho_0$ vs. T/T_{max}, where T_{max} is the temperature of the maximum in $\Delta\rho(T)$.

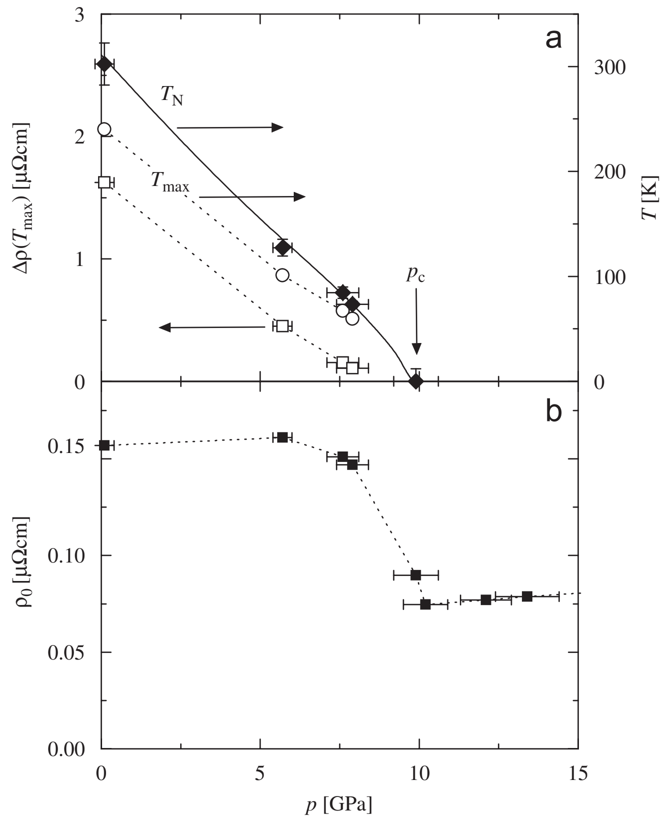

Fig. 2. Panel (a): Pressure evolution of T_N, T_{max} and the excess resistivity at T_{max}, $\Delta\rho(T_{max})$. The full line represents $T_N(x)$ measured in the $Cr_{1-x}V_x$ alloy [7]. Panel (b): The residual resistivity $\rho_0(p)$. Dotted lines are guides to the eyes.

related to an extra contribution to the low-T resistivity which is not described by $\rho_{BG}(T)$. Note that at $p=23.9$ GPa the "excess" resistivity is mainly the residual $\rho_0=0.088\,\mu\Omega$cm.

We now consider the $\rho(T)$ measurements performed at $p<10$ GPa. In this p-range, the onset of a "hump" in $\rho(T)$ signals the approximate position of $T_N(p)$ [5]. Again, we define an excess resistivity $\rho(T)-\rho_{BG}(T)$ as previously described, but in this case we fit to $\rho_{BG}(T)$ only the data for $T>T_N(p)$. The excess resistivity is displayed as full lines in Fig. 1. The humps observed at different pressures have very similar characteristics, see also the inset of Fig. 1 displaying the normalized $\Delta\rho=\rho(T)-\rho_{BG}(T)-\rho_0$ as a function of T/T_{max}. Within the picture of two parallel conduction channels the humps result from an initial abrupt increase in ρ_c as a gap opens at $T_N(p)$, which is overcome below $T\sim T_{max}$ by the (parallel) metallic-dependence of ρ_{nc}. These anomalies seem to emerge from a baseline defined by the $p=23.9$ GPa curve, although a "tail" is always observed above $T_N(p)$. These tails could relate to magnetic fluctuations near the transition, although the effects of p-inhomogeneities could also be present.

Above $p=7.9$ GPa we cannot detect in our $\rho(T)$ measurements any feature unambiguously associated to a magnetic anomaly. As it can be observed in Fig. 2a, $\Delta\rho(T_{max})\to 0$ slightly above this pressure, while $T_{max}(p)$ seems to join $T_N(p)$. Indeed, $\rho(T)$ at $p=9.9$ GPa displays an extremely weak temperature dependence (not shown), similar to what has been observed in alloys like $Cr_{1-x}V_x$ for $x\approx x_c$ [7]. Tentatively, we associate this characteristic to the imminent suppression of magnetism at a critical pressure $p_c\approx 10$ GPa.

In the upper panel of Fig. 2 we compare the suppression of T_N in pressurized-Cr with that induced by doping in $Cr_{1-x}V_x$. Along with our data we plot the V-doping data from Ref. [7] (full line). The common p-scale was obtained simply by matching $T_N(x\approx 0.031)\approx T_N(p=7.6\,\mathrm{GPa})=85$ K. The correspondence between both sets of data is noteworthy, suggesting that a negative curvature of $T_N(p)$ is to be expected close to p_c. A similar conclusion follows from the analysis performed by Lee et al. [2].

We finally focus on the evolution of $\rho_0(p)=\rho(T\to 0,p)$ presented in Fig. 2b. The residual resistivity rapidly increases when crossing p_c from the paramagnetic into the SDW phase. This is again an indication that a gap opens in a portion of the Fermi surface at $p\sim p_c$: For $p<p_c$, only the non-condensing channel, $1/\rho_{nc}$, conducts at $T=0$. If we assume the simplest (Drude) picture in which *only* the number of carriers changes across p_c, the value $\rho_0(p\sim 0)/\rho_0(p>p_c)\approx 2$ is very close to $R_H(x=0)/R_H(x>x_c)\approx 2$ determined from Hall resistivity measurements in the $Cr_{1-x}V_x$ alloy [1]. This suggest that roughly half of the carriers condense in the SDW phase of pressurized-Cr. However, the magnitude of the change of $\rho_0(p)$ we measure at p_c seems to be larger than the change in $\rho_0(x)$ at x_c of $Cr_{1-x}V_x$ [7]. Rather than a linear relation, the quadratic relation $R_H(x=0)/R_H(x>x_c)=(\rho_0(x=0)/\rho_0(x>x_c))^2$ seems to hold in the alloy [8]. The origin of this difference should be verified by careful simultaneous $\rho(T)$ and $R_H(T)$ measurements in chromium under pressure.

In summary, we have presented evidence suggesting that the SDW order of chromium is suppressed at a quantum phase transition at $p_c \approx 10\,\mathrm{GPa}$. Previous reports on the high-pressure properties of chromium have either been limited to lower pressures [4,5] or a higher p_c has been proposed [6]. Strain induced by different types of pressure-mediums could play an important role in modifying the measured critical pressure of chromium. Measurements in softer mediums could give important clues concerning this issue.

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