Quantum Phase Transition in Fe/Cr Multilayers Tuned by a Magnetic Field

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We report on the spin dependent electron transport near the transition from a ferromagnetic into an antiferromagnetic (AFM) state. We find that in the $[Fe/Cr]_{10}$ multilayers the resistivity ρ_S associated with the AFM scattering at $4 < T < 100$ K varies as $\rho_S(T) = \rho_S(0) - AT^{\alpha}$ with $0.5 < \alpha(H) \leq 2$. As $T \rightarrow 0$ K, ρ_S saturates except for a magnetic field region near $H = H_S^0$, which tunes the AFM transition down to 0 K. For temperatures upwards from 20 mK with $H = H_S^0$ a crossover between two linear in T dependences of ρ_S is observed, indicating a possible transition from the critical quantum to the thermal spin fluctuations around 2–3 K. [S0031-9007(98)08049-1]

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A quantum phase transition (QPT) [1] occurs at 0 K in a quantum mechanical system due to variation of nonthermal control parameters which fundamentally change the ground state. The parameter used to tune QPT can be the chemical composition, pressure, or magnetic field [2–9]. Recently QPT's have attracted much interest because of their fascinating theoretical and experimental issues [7,10]. Since QPT cannot be studied at 0 K, its identification relies on finding the specific finite temperature scaling behavior as a function of temperature itself, frequency, or amplitude of various probes [7]. Quantum critical behavior may be different from the classical one since the ground state may be determined by quantum rather than thermal fluctuations [7,10]. The important difference between QPT and the finite temperature transition is that quantum fluctuations at QPT are present at all frequencies down to zero [7].

Study of the temperature scaling, especially in electron transport, is shown to be particularly important to identify QPT in nearly antiferromagnetic (AFM) metals [2,4,11,12]. In all of these systems, the QPT into the magnetically ordered phase occurs from the paramagnetic state and, to our best knowledge, quantum critical behavior with AFM fluctuations developed from the ferromagnetic state has not yet been reported. Moreover, so far no clear evidence for the quantum-thermal crossover has been observed, probably because of the difficulty to separate magnetic interactions at high temperatures.

In this Letter, we present an experimental study of the electron transport in a magnetic system in which the transition between *two magnetically different ground states* is tuned by an external magnetic field. The system we used is the antiferromagnetically coupled magnetic multilayer (MML) $[Fe/Cr]_{10}$ which demonstrates giant magnetoresistance effects (GMR) due to transition from AFM to ferromagnetic (FM) alignment of the Fe layers induced by a magnetic field [13]. Our important finding is that at sufficiently low temperatures the AFM/FM transition in MML is strongly affected by quantum fluctuations. Although our conclusions are based only on the study of the Fe/Cr system, we believe we have observed a general property of AFM coupled MML or other antiferromagnets with a well-defined characteristic field corresponding to the AFM/FM transition.

By using isothermal magnetoresistance (MR) measurements, we reconstructed the magnetic phase diagram for different orientations of the field with respect to the MML plane. The temperature dependence of the resistivity measured at different magnetic fields enables us to determine the spin dependent contribution ρ_S due to AFM coupling nearby and far away from the QPT point. We observe that over a wide temperature range above 4 K the spin dependent contribution varies as $\rho_S(T) = \rho_S(0) - AT^{\alpha}$, where α is a function of the magnetic field. On the other side, for the temperatures below 2 K the spin dependent scattering saturates: $\Delta\rho_S(T) = \rho_S(0) - \rho_S(T) \sim T^2$ except when the QPT is tuned exactly. In this case, ρ_S varies linearly as a function of temperature between 20 mK and 120 K $\Delta\rho_S(T) \sim \beta T$ with β changing around 2–3 K. This change of the slope β may be explained by a transition from the quantum to the thermal critical spin fluctuating regime.

The epitaxial $[Fe(12\ \text{Å})/Cr(12\ \text{Å})]_{10}$ multilayers are prepared in a molecular-beam epitaxy system on MgO (100) substrates held at 50 °C and covered by a 12 Å thick Cr seed layer. The thickness of Cr film in the multilayer corresponds to the first AFM peak in the interlayer exchange coupling producing a maximum GMR in this system [14]. *In situ* reflection high-energy electron diffraction and *ex situ* x-ray diffraction measurements are used to control the structural quality of the multilayers. A detailed description of sample preparation and structural characterization has been reported elsewhere [15]. For the transport measurements the films were patterned by optical lithography. The electrical resistivity was measured by a standard four-probe ac method.

Figure 1a shows typical isothermal magnetoresistance curves measured in magnetic fields parallel ($H_{\parallel}$) and perpendicular ($H_{\perp}$) to the multilayer plane. The largest part of parallel MR is linear: $\rho(0) - \rho(H) \sim H$; the

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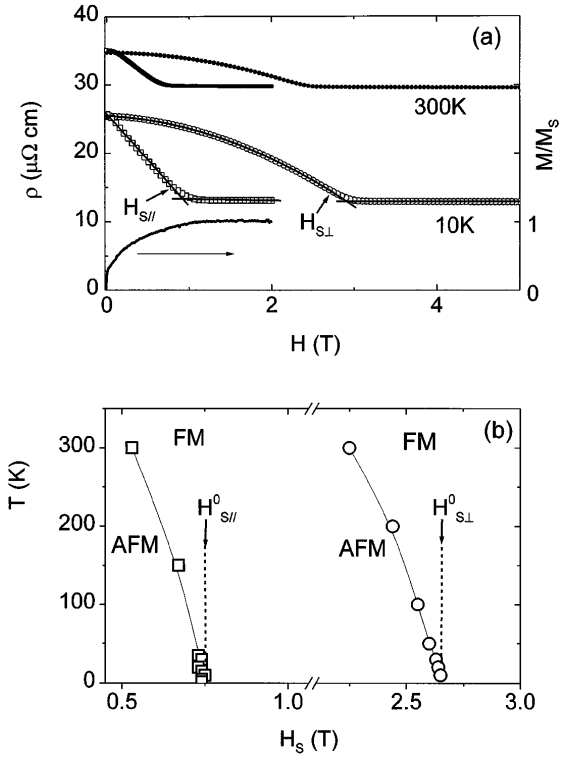

FIG. 1. (a) Isothermal magnetoresistance of $[Fe/Cr]_{10}$ in magnetic fields parallel ($H_{\|}$) and perpendicular ($H_{\perp}$) to the MML plane at $T = 10$ and 300 K. Also shown is the normalized by saturation value M_S in-plane magnetization M, measured at 10 K for the magnetic field decreased between 2 and 0 T. (b) Magnetic phase diagram of $[Fe/Cr]_{10}$ multilayers in parallel (squares) and perpendicular (circles) magnetic fields. The arrows show critical fields H^0_S which correspond to $T_{\mathrm{AFM}} = 0$ K. When the temperature decreases along the dashed lines, a QPT is approached.

perpendicular MR can be fitted by a parabolic field dependence $\rho(0) - \rho(H) \sim H^2$. Similar $\rho(H)$ dependences have been reported for Fe/Cr MML [16]. The characteristic saturation field $H_{S\|}$ ($H_{S\perp}$) is defined as the magnetic field which corresponds to the disappearance of the Néel vector $\mathbf{N} = (\mathbf{M}_1 - \mathbf{M}_2)/2M_0$ ($\mathbf{M}_1$ and $\mathbf{M}_2$ are the magnetization vectors of the coupled Fe layers and $\mathbf{M}_0 = |\mathbf{M}_{1,2}|$), i.e., as the field where the deviation from the linear (quadratic) decrease of MR starts (see Fig. 1a). We note that in the studied Fe/Cr multilayers the hysteresis effects in MR and magnetization are very small and do not affect the experimental data. Absence of low field saturation [17] of the in-plane magnetization (see Fig. 1a), which is characteristic for biquadratic exchange coupling (BC), proves that the bilinear antiferromagnetic coupling dominates over intrinsic BC or BC induced by spatial fluctuations of the Cr thickness [18].

Figure 1b shows the T-H phase diagrams clearly indicating the transition between the AFM and FM states as deduced from the curves shown in Fig. 1a. For the in-plane configuration, measurements with the field parallel or perpendicular to the measurement current give almost identical results, indicating the domination of the spin scattering effects over the anisotropic MR. By linear extrapolation we find that $T_{\mathrm{AFM}} \approx 0$ K when $H_{S\|} = H^0_{S\|} \simeq 0.75$ T and $H_{S\perp} = H^0_{S\perp} \simeq 2.7$ T. At $H = 0$, the studied system is most probably a noncollinear antiferromagnet with a finite Néel vector $\mathbf{N} \sim 1$. When temperature is decreased along the dashed lines indicated in Fig. 1b, a $T = 0$ K phase transition from a FM to an AFM state may be approached resulting in a continuous enhancement of the effect of the AFM fluctuations. In our view, the FM state should be treated as "clean" ferromagnetism which could, however, have some degree of nonthermal disorder caused by the unavoidable presence of fluctuations of the Cr spacer layer thickness. On the other hand, the AFM state, which is approached along the above-mentioned line, is a noncollinear AFM with vanishing Néel vector.

Figure 2 shows total and spin dependent parts in electrical resistivity for $T > 4$ K at different magnetic fields. Because of similarity, we present only the data obtained for the perpendicular field orientation. For $H/H^0_{S\perp} > 1.2$, the $\rho(T)$ data (Fig. 2a) are almost field independent because in that field range the electron spins parallel to the Fe magnetic moment in the layers do not

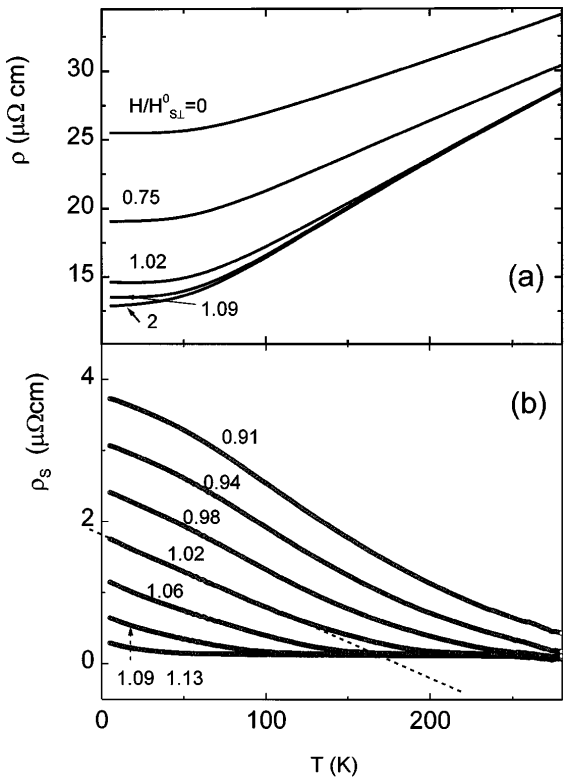

FIG. 2. (a) Temperature dependence of resistivity $\rho(T)$ for different perpendicular magnetic field values (in units $H/H^0_{S\perp}$). (b) Temperature dependences of the spin dependent contribution in resistivity $\rho_S(T) = \rho(T,H) - \rho(T,2H^0_{S\perp})$.

suffer magnetic scattering [13]. For magnetic fields $H < 1.2H^0_{S\perp}$, one observes a low temperature upward shift in $\rho_S(T)$ which at $H \sim H^0_{S\perp}$ transforms into an additional well-defined contribution. This MR was studied so far only in the form of the difference between ρ in the AFM (at $H = 0$) and FM ($H > H^0_S$) states [19]. Figure 2b shows the spin dependent part in electrical resistivity $\rho_S = \rho(T, H_\perp) - \rho(T, 2H^0_{S\perp})$ at different magnetic fields. We have found that for $0 < H \sim H^0_S$ the observed variation of spin dependent contribution with temperature $\Delta\rho_S(T) = \rho_S(T) - \rho_S(0)$ may be fitted to a power law: $\Delta\rho_S \sim T^\alpha$ in a wide temperature range below 100 K. For $H > H^0_S$, the temperature interval, where the power law may be obtained, is reduced. An important aspect of these data is an apparent linear variation of $\Delta\rho_S \sim T$ when temperature is varied by more than a decade in the vicinity of $H = H^0_S$, i.e., when tuning of the phase transition with $T_{\mathrm{AFM}} = 0$ K takes place.

Figure 3 shows the dependence of α on the normalized field H/H^0_S for parallel and perpendicular field orientations for the field interval where $\rho_S(T)$ varies as $\Delta\rho_S \sim T^\alpha$ within a temperature interval of more than one decade. We can observe three different regimes: (i) for $H \approx H^0_S$ we find $\alpha \simeq 1$; (ii) for $H < 0.5H^0_S$ the exponent $\alpha \simeq 2$; and (iii) $\alpha \simeq 1.7$ for $H \simeq 0$. We note that for $H > 1.3H^0_{S\|}$ ($1.15H^0_{S\perp}$) one cannot determine $\alpha(H)$ because the data cannot be fitted by the power law. We believe that deviation from $\alpha \approx 2$ for $H < 0.1H^0_S$ is mainly due to the electron interaction with the AFM domain walls.

A peculiar character of the ground state realized at $H = H^0_S$ with $\alpha \approx 1$ is confirmed by the electrical resistivity measurements down to 20 mK. Figure 4 shows the temperature variation of $\rho_S(T)$ for $H_\|$ and close to the point where fine-tuning of the QPT is obtained by applying a magnetic field. For all magnetic fields, except those corresponding to $H \approx H^0_{S\|}$, the spin dependent contribution to the resistivity saturates at $T \to 0$ K. Again, as in the high temperature regime ($T > 4$ K), the ρ_S varies linearly with temperature when QPT is approached: $\rho_S(T) - \rho_S(0) \sim \beta T$. The slope β at very low temperatures is approximately half of the value observed at $T > 4$ K. This observation, together with completely different scaling of $\rho_S(T)$ with magnetic field near $H \approx H^0_S$ when T is above (Figs. 2 and 3) or below (Fig. 4) 2–3 K, indicates a possible fundamental change in the electron scattering mechanism. For the perpendicular magnetic fields, we observe similar behavior (see inset of Fig. 4) which is, however, complicated by the presence of relaxation effects in the electron transport below 100 mK.

The influence of the temperature on ρ in the AFM and FM states in Fe/Cr MML has been attributed to the variation of the mean free path [20], local spin excitations [21], magnons [19], and random exchange potentials [22]. In epitaxial Fe/Cr trilayers, the MR saturates at low temperatures and is linear as a function of T above 70 K [23]. These data, however, involve normalization of ρ_S by the total resistivity ρ which itself is temperature dependent. In sputtered Fe/Cr superlattices below $T \approx 100$ K,

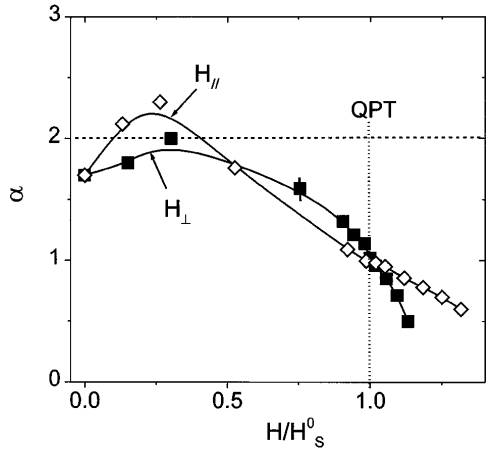

FIG. 3. The dependence of α on the normalized magnetic field H/H^0_S determined for parallel (open diamonds) and perpendicular (closed squares) field configurations. The dashed line corresponds to $\alpha = 2$, expected for the Fermi liquids. The vertical dotted line marks QPT. The vertical bars indicate the deviation in α which could be induced by variation in ρ_S determined as $\rho_S = \rho(T, H) - \rho(T, 80\ \mathrm{kG})$ and in parameter $\rho_S(0)$, or when employing another H_S definition (i.e., as a cross section between low field and high field asymptotics shown in Fig. 1).

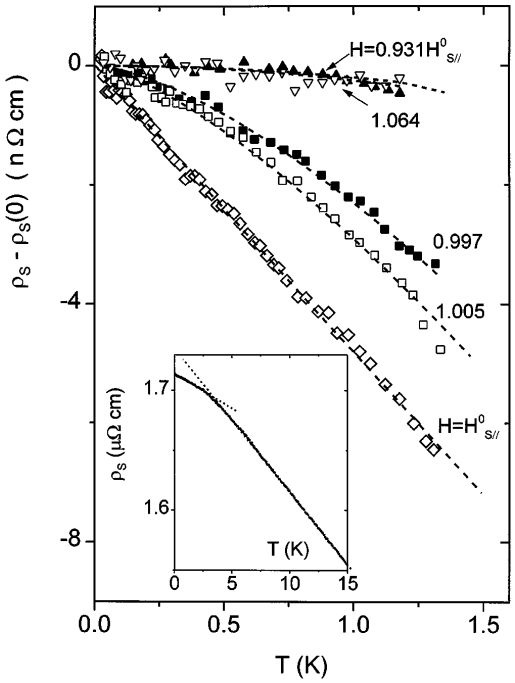

FIG. 4. Variation of the spin dependent contribution to resistivity, $\rho_S(T) - \rho_S(0)$, at temperatures between 20 mK and 1.3 K. This contribution is measured in the parallel magnetic fields (in units $H/H^0_{S\|}$) which provide fine-tuning of the quantum magnetic phase transition. The inset shows the low temperature part in $\rho_S(T)$ for $H_\perp \simeq H^0_{S\perp}$.

$\rho_S(T) - \rho_S(0) \sim T^2$ [19]. We also note that critical behavior in divergent resistivity near T_N in Dy was found to be described by a power law with $\alpha \approx 0.7$ [24].

Although a non-Fermi liquid (NFL) variation of the electrical resistivity has been observed in some correlated electron systems, a satisfactory theoretical explanation is lacking [25]. The nearly antiferromagnetic Fermi-liquid model [26], which does not involve any quantum critical point, predicts a transition from linear to quadratic temperature dependence in the resistivity. Near $T = 0$ K, magnetic phase transition spin-fluctuation theories [27–29] predict $\rho_S(T) - \rho_S(0) \sim T^n$ with $4/3 < n < 5/3$ determined by the type (ferro/antiferro) of paramagnons and degree of disorder. Three-dimensional spin fluctuations in a heavy electron system near their AFM instability should result in $n = 3/2$ at very low T followed by a crossover to a certain range where ρ_S varies almost linearly with temperature [30].

According to Hertz [1], a quantum mechanical system in d dimensions is similar to a classical system in $(d + z)$ dimensions, where $z = 1$ or 2 [28] is the dynamic critical exponent. If this statement is valid only for $z = 1$ [31], the transition between two different linear versus T dependences in spin dependent electron transport may reflect a quantum-classical crossover [7,32] from a dominating one(two)-dimensional quantum to a two(three)-dimensional classical spin fluctuation. Quantum fluctuations in reduced dimensions [33] could develop to prevent dissipation into a surrounding Fermi sea.

Finally, the narrow field range, where QPT is observed, is consistent with theoretical predictions [7] and contradicts an explanation in terms of a disorder induced NFL [34]. The nature of the ground state at $H/H_S^0 \gg 1$, where a spin gap could appear [7], as well as the limit $H/H_S^0 \ll 1$ will be addressed in forthcoming publications.

In summary, we have demonstrated the importance of quantum effects for spin dependent electron transport in the vicinity of a FM/AFM transition suppressed by an external field. In the AFM coupled $[Fe/Cr]_{10}$ MML for the interval of magnetic fields where formation of the Néel vector at $T = 0$ K is expected, we observe a linear vs temperature variation of the spin dependent part in resistivity over almost two decades variation of T above 20 mK. This behavior is followed by quantum-classic crossover above 2–3 K and the extended temperature region with also a linear dependence $\Delta\rho_S \sim T$, which could be due to electron scattering on critical thermal spin fluctuations.

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