

## Temperature dependence of the Hall angle in a correlated three-dimensional metal

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The Hall coefficient,  $R_H$ , of the Mott-Hubbard system vanadium sesquioxide has a strong temperature dependence in the barely delocalized metal. As in the case of the cuprate superconductors, we find that the resistivity and the Hall angle of  $V_{2-y}O_3$  follow different power laws in temperature, implying different longitudinal and transverse scattering mechanisms. Far from half-filling, only one transport scattering rate is needed to describe the data, at which point the temperature dependence of  $R_H$  disappears. [S0163-1829(98)51922-4]

The peculiar temperature dependence of the Hall coefficient in the superconducting cuprates is a striking manifestation of their unconventional normal-state properties. With the magnetic field applied perpendicular to the  $CuO_2$  planes, the Hall coefficient rapidly increases with decreasing temperature, peaking just above the superconducting transition temperature. In studies of Zn-doped<sup>1</sup> and oxygen-reduced<sup>2</sup>  $YBa_2Cu_3O_{7-\delta}$ , Ong and co-workers have demonstrated that parametrization of the data in terms of the Hall angle,  $\theta_H = \tan^{-1}(\sigma_{xy}/\sigma_{xx})$ , reveals two separate relaxation rates for carrier motion. Whereas the planar resistivity varies linearly with  $T$ ,  $\cot \theta_H \sim T^2$ , implying different longitudinal and transverse ("Hall") scattering mechanisms. These experimental results have then been cited as evidence for Anderson's theoretical picture<sup>3</sup> of the decoupling of spin and charge in a highly correlated, two-dimensional system.

We find in the three-dimensional correlated metal,  $V_{2-y}O_3$ , a remarkably similar experimental situation. Vanadium sesquioxide has served as the prototype for the Mott-Hubbard metal-insulator transition, with coincident electronic, magnetic, and structural phase transitions.<sup>4,5</sup> With the magnetic field applied along any arbitrary direction, the Hall coefficient rapidly increases with decreasing temperature in the barely delocalized metal, peaking just above the Néel temperature. Parametrization of the data in terms of the Hall angle reveals two separate relaxation rates for carrier motion. Whereas the longitudinal resistivity  $\rho$  follows a  $T^{3/2}$  form consistent with scattering off spin fluctuations, again  $\cot \theta_H \sim T^2$ . The microscopic origin of an additional scattering rate is unclear, but it appears to be linked to the proximity of the Mott-Hubbard transition; the anomalous temperature dependence of the Hall coefficient (and the different power laws for  $\rho$  and  $\cot \theta_H$ ) disappear for crystals with large hole concentrations.

Single crystals of  $V_2O_3$  were grown using a skull melter and then were annealed in a CO-CO<sub>2</sub> atmosphere at 1400 °C for approximately two weeks to adjust the stoichiometry uniformly.<sup>6</sup> The stoichiometry of the  $V_{2-y}O_3$  crystals was

determined within 0.001 of  $y$  using thermogravimetric analysis.<sup>7</sup> Hall measurements were performed in the linear field regime on crystals with typical dimensions  $1 \times 1 \times 0.15$  mm<sup>3</sup>. Hydrostatic pressures up to 7 kbar were achieved using a BeCu piston-anvil self-locking pressure clamp with silicone oil as the pressure medium and a fragment of  $(V_{0.99}Ti_{0.01})_2O_3$  as the manometer.<sup>8</sup> All magnetotransport and magnetic susceptibility data were obtained in the ohmic and frequency-independent limits using standard lock-in techniques.

We plot in the top portion of Fig. 1 the temperature dependence of the Hall coefficient,  $R_H$ , for a series of vanadium sesquioxide crystals with different oxygen stoichiometries. Pure  $V_2O_3$  exhibits a striking first-order transition at  $T_{MI} \sim 150$  K, marked by a jump in the resistivity of seven orders of magnitude, a hysteresis loop of 10 to 12 K, a volume expansion of 1.4%, and antiferromagnetic ordering of the vanadium spins. Increasing the number of V vacancies stabilizes the metallic state at all temperatures by introducing holes into the  $3d$  band, with  $T_{MI} = 0$  at  $V_{1.985}O_3$  ( $y = 0.015$ ). For  $y > 0.015$ ,  $R_H$  increases rapidly with decreasing temperature below  $T = 200$  K and peaks a few K above the magnetic transition into an itinerant, reduced-moment spin density wave at  $T_N \sim 10$  K (Ref. 9). With the introduction of progressively more charge carriers and increasing deviations from half filling, the temperature dependence of  $R_H$  is suppressed. In fact, only a gentle maximum about  $T_N$  remains by  $y = 0.033$ .

Fert and Levy have ascribed the anomalous behavior of the Hall effect in heavy fermion compounds to skew scattering.<sup>10</sup> Although  $V_{2-y}O_3$  has strong electronic correlations and a significant spin-fluctuation spectrum for temperatures up to  $10 T_N$ ,<sup>9</sup> it is clear from the inset in Fig. 1 that this explanation cannot account quantitatively for our data. Compared in the inset are the actual Hall data for  $y = 0.027$  and a skew scattering form:  $R_H = \gamma \chi(T) \rho(T)$ , where  $\chi$ , the magnetic susceptibility, and  $\rho$ , the electrical resistivity, are measured on the same crystal, and  $\gamma$  is a constant chosen to

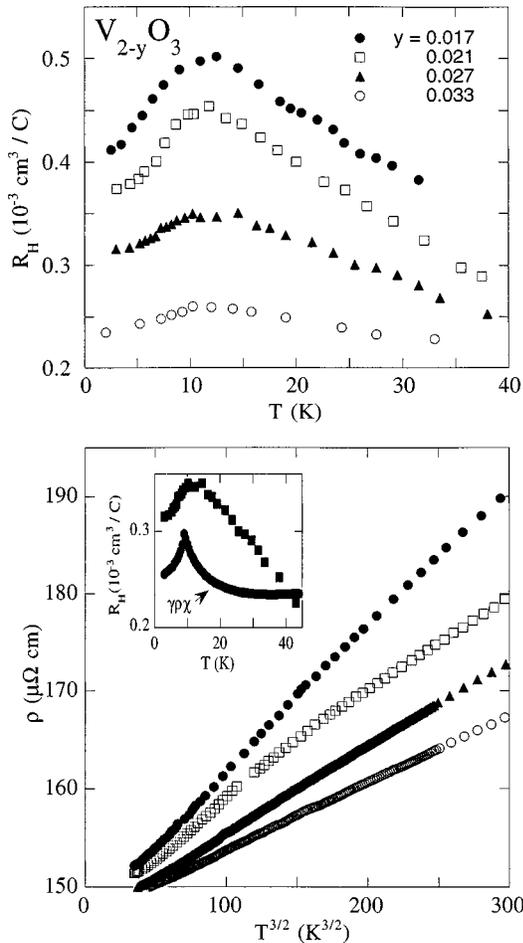


FIG. 1. Temperature dependence of the Hall coefficient  $R_H$  (top) and the electrical resistivity (bottom) in metallic vanadium sesquioxide doped away from half filling. Inset: Failure of a skew scattering form (circles) to account for the Hall data for  $y=0.027$  (squares).

normalize the two curves at  $T=40$  K. Independent of the normalization, the skew scattering form has the wrong curvature and it will always peak at a lower temperature than  $R_H(T)$ .

We plot in the bottom portion of Fig. 1 the longitudinal resistivity for a series of  $V_{2-y}O_3$  crystals vs  $T^{3/2}$  over the same temperature range as the Hall data. This functional form is motivated by the self-consistent renormalization (SCR) theory for itinerant magnetism in the small moment limit;<sup>11</sup> the same SCR theory successfully describes the magnetic correlations in the metallic phase of  $V_{2-y}O_3$  as measured by neutron diffraction.<sup>12</sup> Over a limited temperature range, the electrical resistivity obeys a  $T^{3/2}$  law well at all four hole concentrations. We note that any tendency to deviate from the simple model of scattering off spin fluctuations is in the direction of a power smaller than  $\frac{3}{2}$  (slight downward curvature).

The transport scattering rate  $1/\tau_{tr}$  that appears in the resistivity of paramagnetic  $V_{2-y}O_3$  differs from the transverse scattering rate  $1/\tau_H$ . The Hall angle demonstrates this contrast most readily because  $\theta_H = \tan^{-1}(\sigma_{xy}/\sigma_{xx}) \sim (\tau_H \tau_{tr}/\tau_r)$  is a function of  $\tau_H$  alone. As is shown in Fig. 2,  $\cot \theta_H \sim 1/\tau_H$  follows a  $T^2$  law for the crystals closest to half filling. Deep in the metal at  $y=0.033$ ,  $1/\tau_H$  approaches the  $T^{3/2}$  depen-

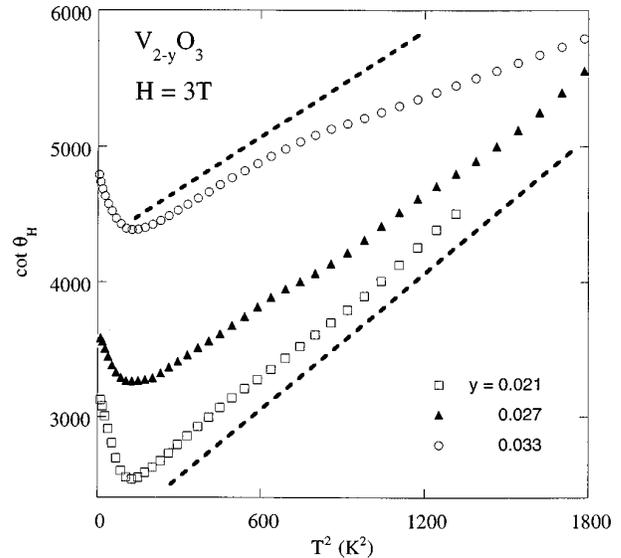


FIG. 2. Near the  $T=0$  Mott-Hubbard metal-insulator boundary at  $y=0.015$ , the Hall angle follows a  $T^2$  form, as compared to a  $T^{3/2}$  dependence for the longitudinal resistivity (Fig. 1), implying different scattering mechanisms. Deep in the metal ( $y=0.033$ ),  $\cot \theta_H$  approaches a  $T^{3/2}$  form (downward curvature) and  $R_H$  approaches temperature independence (Fig. 1). The dashed lines are guides to the eye.

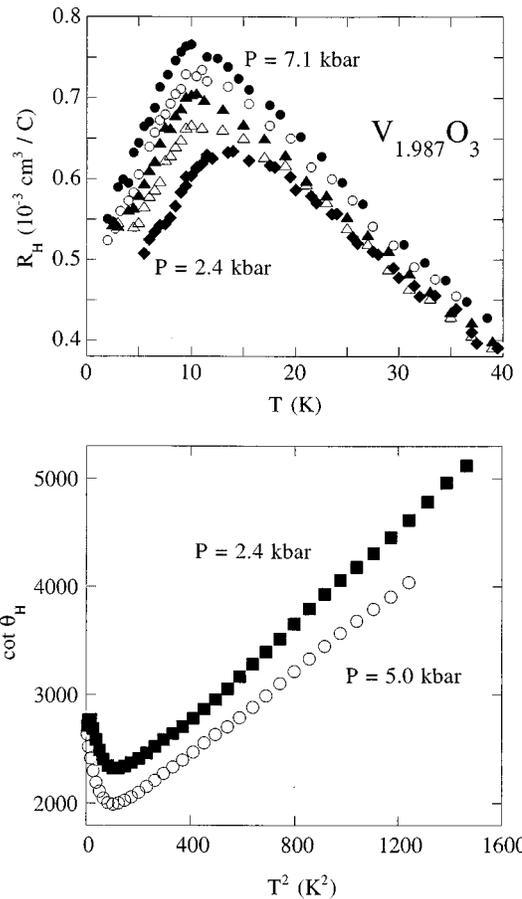


FIG. 3. Temperature dependence of the Hall coefficient (top) and the Hall angle (bottom) for insulating vanadium sesquioxide driven metallic by hydrostatic pressure  $P$ .  $R_H$  data are for  $P = 2.4, 2.9, 4.1, 5.0,$  and  $7.1$  kbar.

dence characteristic of  $1/\tau_{tr}$ ; at this point the temperature dependence of  $R_H$  essentially disappears (Fig. 1). We underscore the fact that although the difference between power laws of  $\frac{3}{2}$  and 2 is not large, the strong temperature dependence of  $R_H$  at smaller V vacancy concentrations would not exist without that difference, providing a powerful self-consistency check.

The application of hydrostatic pressure is an alternative method for driving insulating vanadium sesquioxide metallic. In this case there are no large deviations from half filling and the classic signature of a diverging effective mass on the metallic side of the transition is retained.<sup>13</sup> We plot in Fig. 3 the temperature dependence of the Hall coefficient (top) and the Hall angle (bottom) at a series of pressures  $P$ . Once again,  $R_H(T)$  rises dramatically with decreasing temperature in the paramagnetic metal, peaking a few K above  $T_N$ . Over the same temperature range,  $\cot \theta_H \sim T^2$ . Up to  $P = 7.1$  kbar, the highest pressure we have explored, both the  $T^2$  dependence of the Hall angle and the  $T^{3/2}$  behavior of the resistivity (not shown) are still in evidence.

In this discussion of vanadium sesquioxide, we have adopted the language used to describe the normal-state prop-

erties of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ .<sup>1-3</sup> Elements of Mott-Hubbard physics are involved in both the cuprates and the transition-metal oxides, but the special properties of a Luttinger liquid clearly cannot be applied to the three-dimensional  $\text{V}_2\text{O}_3$  system. The  $\text{V}_2\text{O}_3$  data appear to indicate, however, that there is a generalizable notion of separate scattering rates for the longitudinal and transverse (Hall) transport over a well-defined temperature range. An extra scattering mechanism survives in  $\text{V}_{2-y}\text{O}_3$  as long as deviations from half filling are not too severe and may reflect the presence of an underlying quantum critical point (in this case the  $T = 0$  metal-insulator transition). It appears that an analysis of scattering mechanisms could be profitably undertaken for heavy fermion materials where the Hall coefficient is known to be strongly temperature dependent<sup>10</sup> and where unusual behavior of the spin and charge degrees of freedom may be manifest in non-Fermi-liquid behavior.<sup>14</sup>

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