Experimental Evidence for a Nontrivial Number of Scattering Channels in a Dilute Alloy

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Magnetization measurements on a very dilute Au-V alloy yield evidence for the existence of a nontrivial power-law scaling at low temperatures. The n-channel Kondo model fits the data with $T_K = 60$ K and $n = 5$ for an impurity spin $S = \frac{3}{2}$.

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Recent theoretical developments have led to exact solution[1-3] of the so-called n-channel Kondo problem.[4] The model describes the scattering of conduction electrons by magnetic $3d$ impurities in a metal. The orbital structure of the impurity is taken into account, but the model only applies when the ground state has zero orbital angular momentum. This is the case for a half-filled $3d$ shell ($S = \frac{5}{2}$), but also for impurities with $3d^3$ or $3d^8$ configurations ($S = \frac{3}{2}$ and 1, respectively), where a strong cubic crystal field splits off an orbital singlet ground state (quenching of the orbital angular momentum). Because of this crystal field, some of the $2l+1=5$ orbital scattering channels may have very small amplitudes.[4] The number of effective scattering channels n (also called flavor) and the impurity spin S then parametrize the problem. For the first time, experimental evidence for the existence of a system with $n \neq 2S$ is presented in this Letter.

The solution of the model Hamiltonian reveals that the low-temperature properties depend crucially on the values of n and S, while the high-temperature behavior is unaffected by the presence of the flavor degrees of freedom. For temperatures much smaller than the Kondo temperature T_K (the characteristic energy scale of the problem), three distinct cases appear: (1) When $n < 2S$, the impurity spin is only partially screened in the ground state. The low-temperature properties are characterized by a logarithmic approach of the zero-temperature spin $S' = S - n/2$. (2) In the case $n = 2S$, the screening is complete and the zero-temperature susceptibility is finite. (3) A new asymptotic behavior arises for $n > 2S$. The low-temperature regime exhibits a scaling behavior characterized by nontrivial exponents. In all cases, the high-temperature limit is approached logarithmically.

It is generally believed[4-6] that in real life only the case $n = 2S$ occurs. The Au-V system is thought to be a characteristic example of an alloy exhibiting this behavior. The magnetization measurements of Van Dam, Grubbens, and Van Den Berg[7] show indeed a constant value at low temperatures. However, the lowest concentration of the alloys considered is 2000 ppm, and at these high values, interactions between the impurities have to be expected. We prove by our experiments on lower concentrations that $n > 2S$.

The impurity magnetization of a 32-ppm sample (with a 500-ppm alloy as a comparison) was measured in the temperature range 1.6–260 K and up to a magnetic field of 7 T. A Faraday balance apparatus with a resolution of $\simeq 10^{14}$ Bohr magnetons permitted sufficient accuracy, even for the 32-ppm sample. From the magnetization as function of the field, we deduced the zero-field susceptibilities by a numerical interpolation method. Figure 1 shows the susceptibility per impurity of both alloys as function of temperature. As expected, the two alloys behave quite differently, indicating interimpurity interactions in the 500-ppm sample. Although we cannot prove it, we assume only single-impurity effects in the lower-concentration alloy in the temperature range studied. No tendency towards a finite zero-temperature susceptibility is observed. Hence, this feature of the Van Dam data should be ascribed to interimpurity interactions. Hereafter, we concentrate on our 32-ppm alloy.

The high-temperature susceptibility is independent of flavor[1] and can be expressed as

$$p_{\rm eff}^2 = g^2 S(S+1)[1 - f(\ln(T/T_K))], \qquad (1)$$

where $p_{\rm eff}^2 = 3k_B \chi T / N\mu_B^2$ and N is the number of impurities. The function $f(\ln(T/T_K))$ has been calculated numerically by Wilson[8] for the case $S = \frac{1}{2}$ and $n = 1$. Expression (1) fits our 32-ppm data down to $\simeq 85$ K (Fig.

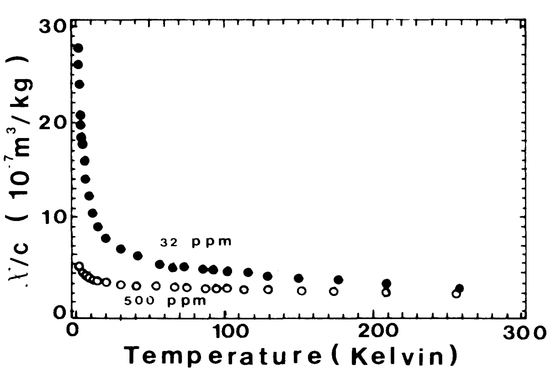

FIG. 1. Susceptibility per impurity vs temperature for 32- and 500-ppm Au-V. The nonscaling behavior suggests interimpurity interactions in the 500-ppm sample.

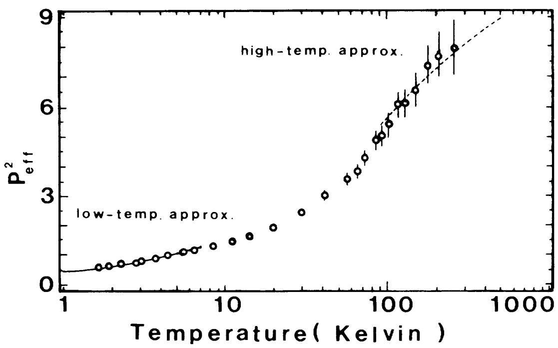

FIG. 2. $p_{\text{eff}}^2 = 3k_B\chi T/N\mu_B^2$ vs temperature for 32-ppm Au-V. The dashed line indicates high-temperature expansion [Eq. (1)], and the solid line indicates the low-temperature power law [Eq. (2)].

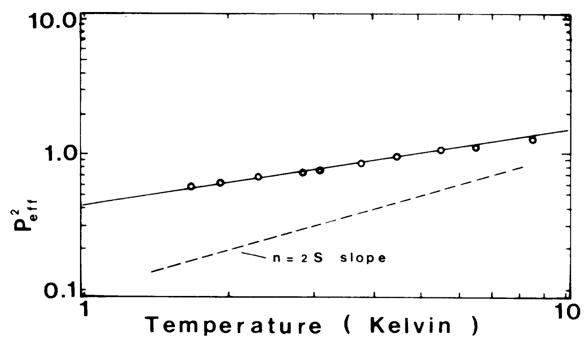

FIG. 3. Log-log plot of the low-temperature regime of 32-ppm Au-V. The straight solid line represents the power-law Eq. (2). For comparison, an arbitrary line (dashed) indicates a slope 1 corresponding to the $n=2S$ case.

2) with $T_K = 60 \pm 5$ K and $S = \frac{3}{2}$. A χ^2 test gives $\chi_\nu^2 = 0.36$ for $\nu = 8$ degrees of freedom, giving a probability of exceeding χ_ν^2 equal to $P_\chi = 94\%$.

At low temperatures, the possibility $n < 2S$ can be ruled out immediately: In this case, the zero-temperature spin S' equals at least $\frac{1}{2}$. From Fig. 2 it can be seen that p_{eff}^2 drops below the value 3 corresponding to $S' = \frac{1}{2}$. Because no tendency to a constant susceptibility is observed, $n = 2S$ is only possible when T_K lies below our experimental temperature range; this hypothesis is inconsistent with the high-temperature result.

The experimental data can be analyzed quantitatively with use of the low-temperature expressions for the case $n > 2S$. This regime is characterized by power-law scaling:

$$p_{\text{eff}}^2 = \alpha_1 (T/T_K)^{4/(n+2)}, \quad T \ll T_K, \tag{2}$$

and

$$M = \alpha_2 (B/T_K)^{2/n}, \quad k_B T \ll g\mu_B B \ll k_B T_K, \tag{3}$$

where α_1 and α_2 are numerical coefficients which are not calculated theoretically. A fit of expression (2) to our low-temperature susceptibility data gives excellent results up to 5.5 K (see Figs. 2 and 3), as can be judged from $\chi_\nu^2 = 0.20$ for $\nu = 6$, giving $P_\chi = 98\%$. From the exponent, flavor can be calculated:

$$n(\text{from } T \text{ dependence}) = 5.3 \pm 0.2. \tag{4}$$

TABLE I. Results of the fit of Eq. (3) to the magnetization data of the 32-ppm Au-V sample.

T (K)	B range (T)	$\alpha_2 T_K^{-2/n}$ (SI units)	n	ν	χ_ν^2	P_χ (%)
1.66	3–7	9.7 ± 0.2	4.9 ± 0.1	3	0.39	76
1.91	3–7	9.0 ± 0.2	4.5 ± 0.2	3	0.47	70
2.29	3–7	8.5 ± 0.2	4.4 ± 0.2	3	0.74	54

From Fig. 3, it is also evident that the hiterherto believed reality $n = 2S$ (a slope equal to unity in the figure) can by no means describe our data.

The high-field, low-temperature magnetization data were analyzed with Eq. (3). Acceptable fits could be obtained for the lowest three temperatures in the field range 3–7 T. The results are shown in Table I and Fig. 4. From the figure and from the χ^2 tests, the quality of the fits can be judged as rather good for the 1.66-K fit, but a decreasing probability of exceeding χ_ν^2 for increasing T is noticed. Besides, the parameters show a weak temperature dependence. Both tendencies are probably due to the fact that the condition $k_B T \ll g\mu_B B$ is not fulfilled to a sufficient extent. The lowest-temperature fit, being the most representative for the limit studied, gives a second estimate of flavor:

$$n(\text{from } B \text{ dependence}) = 4.9 \pm 0.1, \tag{5}$$

in excellent agreement with (4).

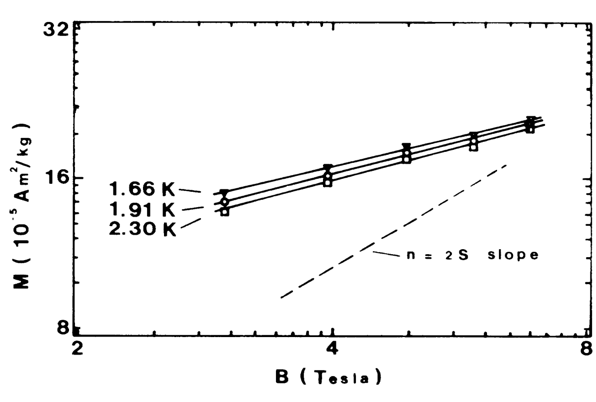

FIG. 4. Log-log plot of the low-temperature, high-field regime of 32-ppm Au-V. The straight solid lines represent the power-law Eq. (3) at constant temperature. The dashed line indicates a slope 1 corresponding to the case $n = 2S$.

Finally, we note that also the observed field dependence rules out the $n=2S$ possibility. Since in the limits $T \ll T_K$ and $g\mu_B B \ll k_B T_K$, the magnetization is proportional to the magnetic field,[2] the $n=2S$ case corresponds to a straight line with slope 1 in Fig. 4; the figure shows that the experimental data behave quite differently.

As a conclusion, it can be stated that very dilute Au-V is an example of a multichannel Kondo system. The evidence that emerges from both the temperature dependence and the field dependence points unexpectedly but unambiguously to the $n > 2S$ case. Fittings of the nontrivial power laws that govern this regime yield $n=5$ for the number of scattering channels: All orbital one-electron states of the impurity participate in the interaction with the conduction electrons. From the high-temperature behavior of the susceptibility, the Kondo temperature can be deduced: $T_K = 60 \pm 5$ K with spin $S=\frac{3}{2}$. These results underline the existence of a Kondo alloy with a nontrivial number of scattering channels.

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