Mössbauer Effect in ^{57}Fe in Copper and the Spin-Compensated State

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The results of Mössbauer experiments on dilute Fe in Cu in high external magnetic fields (42–146 kOe) are presented here as evidence for significant destruction of the spin-compensated state by a magnetic field for which $\mu H_0 \sim kT_K$, where kT_K is on the order of the energy change associated with the formation of the spin-compensated state.

In a previous paper¹ we presented evidence based on Mössbauer measurements of ^{57}Fe in Cu consistent with the formation of a spin-compensated state in dilute Fe-Cu alloys² at low temperatures. The saturation hyperfine field extrapolated to its value at zero temperature was found to be a monotonically increasing function of the applied field. We interpreted the growth of the saturation field with applied field as resulting from a perturbation of the spin-compensated state leading to a field-dependent effective moment about the Fe impurity. Using a linear extrapolation of the high-field saturation moment to what one would expect for a free Fe moment in Cu,³ we concluded that a field on the order of 235 kOe would be necessary to destroy significantly the correlations leading to the spin-compensated state. In this paper we discuss the data¹ in more detail and will concentrate on clarifying the meaning of the critical or Kondo field and the temperature dependence of the hyperfine field.

In order to discuss our Mössbauer hyperfine measurements in the spin-compensated state, we introduced¹ the concept of a field- and temperature-dependent moment, $\mu_{\text{eff}}(H_0, T) = f(H_0, T)\mu^0$, where μ^0 is the free Fe moment and $f(H_0, T)$ is a factor to be fit to the Mössbauer data. Under this assumption, the temperature- and field-dependent hyperfine field is given by

$$H_{\text{hf}}(H_0, T) = f(H_0, T) 80 B_{3/2} [1.9 f(H_0, T) \mu_B H_0 / kT] \text{ kOe},$$

where the impurity spin³ is taken to be 3/2 and the constant 80 kOe has been obtained by fitting the high-temperature hyperfine-field measurement where $f[H_0, (T \gg T_K)]$ is assumed to be unity. T_K is of the order of the "Kondo temperature." Previously¹ we plotted the $T \rightarrow 0$ hyperfine field obtaining $f(H_0, 0)$ as a function of H_0 between 42 and 136 kOe and included some earlier Mössbauer measurements⁴ to obtain $f(H_0, 0)$ for fields below 42 kOe. In a simple model we take $f(H_0, 0)$ to be proportional to the $T=0$ magnetization of the iron spin which is a measure of the magnitude of

the effective moment.⁵ Since the low-field magnetization $M(H_0)/M(\infty)$ may be expressed in the form $aH_0(1-b^2H_0^2)$, we have plotted in Fig. 1:

$$f(H_0, 0) (80 \text{ kOe}/H_0) = H_{\text{sat}}(H_0)/H_0 \text{ vs } H_0^2,$$

and have obtained the coefficients a and b ; a best linear fit gives $a = 1/(151 \text{ kOe})$ and $b = 1/(77 \text{ kOe})$. The coeffi-

FIG. 1. A plot of $-H_{\text{sat}}(H_0)/H_0 = -[f(H_0, 0)/H_0] 80 \text{ kOe}$ vs H_0^2 . In a linear fit to $f(H_0, 0)/H_0 = a(1-b^2H_0^2)$, the intercept gives $a \times 80 \text{ kOe}$ and the slope is b^2 (see text).

cients a and b should reflect the Kondo field H_K and are approximately

$$a = c_1/H_{K1} \simeq c_1(g\mu_B/kT_K)$$

and

$$b = c_2/H_{K2} \simeq c_2(g\mu_B/kT_K),$$

respectively, where c_1 and c_2 are constants on the order of 1. The values for H_{K1} and H_{K2} obtained assuming c_1 and c_2 are unity are 151 kOe and 77 kOe, which are in qualitative agreement with each other and with the Kondo temperature derived by Daybell and Steyert from the resistivity measurements.² The critical field obtained¹ by extrapolating $f(H_0, 0)$ to unity was considered to be the field for which the spin-compensated

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¹ R. B. Frankel, N. A. Blum, B. B. Schwartz, and D. J. Kim, Phys. Rev. Letters **18**, 1051 (1967).

² M. D. Daybell and W. A. Steyert, Phys. Rev. Letters **18**, 398 (1967).

³ C. M. Hurd, Phys. Rev. Letters **18**, 1127 (1967).

⁴ T. A. Kitchens, W. A. Steyert, and R. D. Taylor, Phys. Rev. **138**, A467 (1965).

⁵ A similar proposal has recently been made by L. Dworkin (private communication). He suggested the expression

$$80 B_{3/2} [g\mu_B H_0 / k(T + T_K)]$$

for the hyperfine field which gives a qualitative fit to $f(H_0, 0)$ with $T_K \simeq 19^\circ \text{K}$; however, this one parameter fit gives a more rapid temperature dependence of the hyperfine field than is actually measured.¹

state is destroyed. Actually, this field more nearly corresponds to the temperature for which the resistance anomaly is quite small.²

In Fig. 2 we show the temperature dependence of $f(H_0, T)$ by fitting the temperature dependence of the Mössbauer hyperfine measurements¹ for three values of H_0 . The temperature dependence for all three fields are similar, with $f(H_0, T)$ being relatively flat for $T \ll T_K$, changing rapidly (and perhaps logarithmically) for $T \approx T_K$ and approaching 1 for $T \gg T_K$. There seems to be a close resemblance between the temperature dependence of $f(H_0, T)$ and the resistivity data of Daybell and Steyert.² A correspondence between susceptibility and resistivity has been noted by Knapp⁶ in Fe-Rh alloys.

At the present time there is insufficient experimental evidence to conclude that the observed magnetic behavior for Fe in Cu is a general property of the dilute alloys systems which display the Kondo resistivity anomaly. Therefore, we are continuing similar Mössbauer measurements on dilute Fe-Rh alloys which are believed to form a spin-compensated state with a Kondo temperature in the neighborhood of a few degrees.⁶ We are also re-examining our data on Fe-Au Mössbauer experiments.⁷ Although there seems to be some indication of an increase in the saturation hyperfine field with H_0 , we are in the limit where $f(H_0, T)$ is close to 1,

FIG. 2. The function $f(H_0, T)$ as a function of temperature for three values of the external field as fit to the Mössbauer hyperfine measurements.¹

since $g\mu_B H_0 \gg kT$ and our lowest T value, 1.2°K, is on the order of the Kondo temperature.⁸

It would be instructive to measure directly the low-temperature magnetization of Fe-Cu alloys in high fields in order to obtain the field dependence of the effective moment for comparison with Mössbauer results and NMR measurements.⁹ Further, it would be interesting to correlate the concept of an effective moment with the anomalies in the low-temperature magnetoresistance caused by the Kondo effect.

⁸ N. E. Alekseevskii and Iu. P. Gaidukov, Zh. Eksperim. i Teor. Fiz. **31**, 947 (1956) [English transl.: Soviet Phys.—JETP **4**, 807 (1957)].

⁹ M. A. Jensen, A. J. Heeger, L. B. Welsh, and G. Gladstone, Phys. Rev. Letters **18**, 997 (1967).

⁶ G. Knapp, Phys. Letters **25A**, 114 (1967); M. A. Jensen (private communication).

⁷ N. A. Blum, R. B. Frankel, and A. J. Freeman, Bull. Am. Phys. Soc. **11**, 236 (1966).