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

R. B. Schwartz, D. J. Kim, and R. B. Frankel
National Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts

and

X. A. Blum
NASA Electronics Research Center, Cambridge, Massachusetts

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 $\mu_B^T \approx KT_K$, where $KT_K$ is on the order of the energy change associated with the formation of the spin-compensated state.

In a previous paper\textsuperscript{1} 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 alloys\textsuperscript{2} 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,\textsuperscript{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 data\textsuperscript{4} 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 introduced\textsuperscript{4} the concept of a field- and temperature-dependent moment, $\mu^T(\mathbf{H}_0, T) = f(\mathbf{H}_0, T)\mu^F$, where $\mu^F$ is the free Fe moment and $f(\mathbf{H}_0, T)$ is a factor to be fit to the Mössbauer data. Under this assumption, the temperature- and field-dependent hyperfine field is given by

$$H_{hf}(\mathbf{H}_0, T) = f(\mathbf{H}_0, T) 80B_{ab}[1.9f(\mathbf{H}_0, T)\mu_B/\sqrt{gT_K}]$$

kOe, where the impurity spin\textsuperscript{2} is taken to be 3/2 and the constant 80 kOe has been obtained by fitting the high-temperature hyperfine-field measurement where $f(\mathbf{H}_0, T \gg T_K)$ is assumed to be unity. $T_K$ is of the order of the Kondo temperature.\textsuperscript{5} Previously\textsuperscript{4} we plotted the $T=0$ hyperfine field obtaining $f(\mathbf{H}_0, 0)$ as a function of $\mathbf{H}_0$ between 42 and 136 kOe and included some earlier Mössbauer measurements\textsuperscript{4} to obtain $f(\mathbf{H}_0, 0)$ for fields below 42 kOe. In a simple model we take $f(\mathbf{H}_0, 0)$ to be proportional to the $T=0$ magnetization of the iron spin which is a measure of the magnitude of the effective moment.\textsuperscript{6} Since the low-field magnetization $M(\mathbf{H}_0) = M(\infty) - a\mathbf{H}_0(1-\beta^2\mathbf{H}_0^2)$, we have plotted in Fig. 1:

$$f(\mathbf{H}_0, 0) = \frac{80\text{kOe}}{\mathbf{H}_0} = H_{sat}(\mathbf{H}_0)/\mathbf{H}_0$$

and have obtained the coefficients $a$ and $b$; a best linear fit gives $a = 0.1/151$ kOe and $b = 0.2/77$ kOe. The coefficients $a$ and $b$ should reflect the Kondo field $H_K$ and are approximately

$$a \approx c_1(H_K) \approx c_1(\mu_B g\mathbf{H}_0/\sqrt{gT_K})$$

and

$$b \approx c_2(H_K) \approx c_2(\mu_B g/\sqrt{gT_K})$$

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.\textsuperscript{7} The critical field obtained\textsuperscript{4} by extrapolating $f(\mathbf{H}_0, 0)$ to unity was considered to be the field for which the spin-compensated

\textsuperscript{4} A similar proposal has recently been made by L. Dewing (private communication). He suggested the expression

$$80B_{ab}[c\mathbf{H}_0/\sqrt{g(T+T_K)}]$$

for the hyperfine field which gives a qualitative fit to $f(\mathbf{H}_0, 0)$ with $T_K \approx 19\text{k}$; however, this one parameter fit gives a more realistic temperature dependence of the hyperfine field than is actually measured.\textsuperscript{4}
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 humpyne measurements\(^1\) for three values of \(H_0\). The temperature dependence for all three fields are similar, with \(f(H_0, T)\) being relatively flat for \(T < T_K\), changing rapidly (and perhaps logarithmically) for \(T \approx T_K\) and approaching 1 for \(T > T_K\). There seems to be a close resemblance between the temperature dependence of \(f(H_0, T)\) and the resistivity data of Daybell and Steyert.\(^3\) A correspondence between susceptibility and resistivity has been noted by Knapp\(^4\) 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.\(^5\) We are also re-examining our data on Fe–Au Mössbauer experiments.\(^6\) 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, since \(g\mu_B H_0 \gg kT\) and our lowest \(T\) value, 1.2 K, is on the order of the Kondo temperature.\(^7\)

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.\(^8\) 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.

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\(^1\) G. Knapp, Phys. Letters 25A, 114 (1967); M. A. Jensen (private communication).

