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MAGNETIC STUDIES OF AMORPHOUS Fe-RICH Fe-Sc-Zr ALLOYS

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Abstract. – We present Mössbauer studies of the magnetic properties of amorphous Fe$_{90}$Zr$_{10-x}$Sc$_x$ alloys for $0 < x < 10$. Alloys with low Sc content show a ferromagnetic, and at lower temperatures a spin-glass like transition. For alloys with low Zr content there is only a transition to a cluster spin-glass behaviour.

1. Introduction

The detailed nature of the ferromagnetic and in particular of the low-temperature state in amorphous Fe-rich Fe-Zr alloys near 90 at. % Fe is still controversial. Contradicting microscopic explanations have been suggested [1] for the low temperature state. Recently, a new system of amorphous Fe-rich Fe-Sc alloys was prepared by the rapid quenched method [2]. Amorphous Fe$_{90}$Sc$_{10}$ and Fe$_{90}$Zr$_{10}$ have the same non-random distributions of quadrupole splittings. This means that the local short-range order of Fe-atoms is similar in both systems. In order to obtain more information about the magnetic behaviour of Fe-rich alloys we combined for the first time Fe-Sc and Fe-Zr alloys in a Fe$_{90}$Zr$_{10-x}$Sc$_x$ system.

Results of Mössbauer and magnetization measurements show that alloys with low Sc concentration undergo a transition to a spin-glass-like magnetic state at a temperature $T_f$ ($T_f < T_c$). This is shown by an anomalous increase in the average magnetic hyperfine field $B_{hf}$ ($T_f$) below $T_f$. Our observation can be explained in context of the spin canting model based on the mean field theory [3, 4]. No evidence of spin canting was found for amorphous Fe$_{90}$Zr$_{10-x}$Sc$_x$ alloys with very low Zr content. The amorphous Fe$_{90}$Sc$_{10}$ alloys undergo a transition from a cluster spin-glass to a super-paramagnetic state with increasing temperature. The average cluster moment is about $\mu = 200 \mu_B$ at $T = 100$ K [5].

The ribbon samples were prepared by single roller melt quenching. The amorphous structure of ribbons was examined by X-ray measurements. Mössbauer measurements were performed using a conventional constant acceleration-type spectrometer.

2. Results and discussion

The Mössbauer spectra are similar for all amorphous Fe$_{90}$Zr$_{10-x}$Sc$_x$ alloys at $T = 4.2$ K. Figure 1 shows the Mössbauer spectrum and corresponding magnetic hyperfine field distribution $P(B_{hf})$ at a representative concentration ($x = 2$). The method of analysis and details of Mössbauer parameters for the determination of $P(B_{hf})$ have been discussed in reference [1]. The shape of $P(B_{hf})$ for all Fe$_{90}$Zr$_{10-x}$Sc$_x$ alloys at $T = 4.2$ K shows a broad low field tail down to $B_{hf} \approx 0$ and a high field maximum. The variance $\Delta B_{hf}$ of $P(B_{hf})$ at $T = 4.2$ K increases with increasing Sc content ($\Delta B_{hf} \approx 6.5$ T for $x = 0$ and 7.4 T for $x = 10$). Thus Sc atoms create larger inhomogeneity in the magnetic state than Zr atoms. The temperature dependence of $B_{hf}$ for three representative alloys are shown in figure 2. For $x > 0$ there is a definite break in the slope of $B_{hf}(T)$ at a temperature which we denote as $T_f$. The observed values of $T_f$ agree well with the temperature of the anomaly in the magnetization [6]. According to the spin canting model [4] we attribute the anomalous increase in $B_{hf}(T)$ below $T_f$ to the freezing of the transversal component $S_z$ of the local magnetic moment [1]. Above $T_f$, the spin precession around the direction of the spontaneous magnetization results in an effective moment $S_z$ and a collinear ferromagnetic state. In this state, $B_{hf}(T)$ is proportional to $\langle S_z \rangle$, but as $\langle S_z \rangle$ progressively freezes below $T_f$, the effective spin $\langle S \rangle$ (vector sum of $\langle S_z \rangle$ and $\langle S_z \rangle$), and thus $B_{hf}(T)$, increases in magnitude. In the infinite-range model [3] the variance of exchange interactions $J$ determines the value of $T_f$. The increase of $T_f$ with the Sc concentration can be interpreted within this model [4] as indicating an increase in the fraction of the antiferromagnetic exchange interactions. Thus decreasing
At $x = 10$, the fraction of antiferromagnetic exchange is sufficient to cause a spin-glass behaviour. This is shown by Mössbauer measurements in a longitudinal external field of $B_{ex} = 5$ T shown in figure 3. These results show that the Fe moments in amorphous Fe$_{90}$Sc$_{10}$ are not aligned parallel to the $\gamma$-ray direction and to the magnetic field at $T = 4.2$ K. This can be obtained from the non-vanishing relative intensities of the second and fifth line corresponding to the $\Delta m = 0$ nuclear transitions. An applied field ($B_{ex} = 5$ T) rotates the Fe spins of Fe$_{90}$Zr$_{10-x}$Sc$_x$ ($0 < x < 10$) into the direction of $B_{ex}$. However in the case of Fe$_{90}$Sc$_{10}$, the competing antiferromagnetic exchange interactions is strong and prevents the alignment of Fe-spins. In a previous paper [5] we have shown that the spins are distributed in clusters with an average size of about $\mu = 200 \mu_B$. The spins in the clusters are in a frustrated state and show a cluster spin-glass behaviour. Based on percolation problems Aeppli et al. [7] have shown that the frustration of spins may lead to the formation of isolated spin clusters.

With increasing of Zr content the competing exchange and the magnetic inhomogeneity decreases. This results in a transition from spin-glass ordering to a re-entrant spin-glass state.

The conclusion is that the theoretical spin canting models originally developed for more dilute alloys near the percolation concentration are more universal, and may be applied to concentrated magnetic systems like Fe$_{90}$Zr$_{10-x}$Sc$_x$ alloys with competing ferromagnetic and antiferromagnetic exchange interactions.

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Fig. 2. – Average hyperfine field as a function of temperature for three different concentrations.

Fig. 3. – Mössbauer spectra of amorphous Fe$_{90}$Zr$_{10-x}$Sc$_x$ alloys measured in an applied magnetic field of $B_{ex} = 5$ T at $T = 4.2$ K. The positions of lines 2 and 5 are marked with arrows.

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