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Low-temperature magnetization of $FeCl_3$ intercalated graphite

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Abstract

We report magnetization measurements on ferric chloride intercalated graphite in the temperature range $1\ K < T < 4\ K$ for stages of index $n = 1$–6 and 8. All stages exhibit a sharp increase in $M(T)$ at $T = 1.7$ K as the temperature decreases and a subsequent saturation below 1.4 K. The saturation magnetization, when normalized to the iron contents, exhibits a strong stage dependence ($M(1\ K) \sim e^n$), up to stage 5 and then deviates for higher stages. For the stage 6 sample $M(1\ K)$ has a linear dependence on the trapped applied field ($H < 0.5$ G) and long relaxation times ranging from under one to more than 4 min. The relaxation time $\tau(T)$ has a lambda shape with a peak temperature of 1.45 K, with similar results for stage 3.

Keywords: Intercalation; Magnetization; Relaxation; Stage

1. Introduction

Graphite intercalation compounds are formed by the insertion of atomic or molecular layers of guest species into a graphite host [1]. This process occurs in a highly anisotropic manner and results in the staging phenomenon, where the stage number n is the number of graphite layers sandwiched between two intercalant layers. Here, the intercalant is a magnetic salt and as a result of intercalation magnetic layers are separated by a number of diamagnetic graphite layers. The control of the stage is a direct control of the distance between the magnetic layers, thereby changing their interlayer magnetic interaction. Previously, in-plane AC magnetic susceptibility [2,3] and specific heat measurements [4] showed a peak at ~ 1.8 K, with a weak stage variation. The susceptibility peak can be supressed by a ~ 20 G field. Here, we report measurements of in-plane DC magnetic susceptibility and its stage and low-field dependence.

2. Experimental details

The samples were synthesized in a two-zone oven, and characterized with respect to stage using the $(0\,0\,l)$ diffractograms. A flux-locked RF squid coupled to a gradiometer coil was used to measure the sample's magnetization in a low magnetic field that is trapped by a superconducting cylinder. Extreme care was taken in setting and measuring the low applied field, H_a. The temperature was controlled through the vapor pressure of the liquid helium. Care was taken to change the temperature in discrete steps of 10–30 mK, while the signal was recorded at 1 s intervals. The resulting points were fitted to an exponential, from which the relaxation times were extracted. The relaxation time, τ, exhibited a temperature dependence; $1/\tau$ is the rate at which the moments line up with H_a, as opposed to the time lag they exhibit following an AC field.

3. Results

The magnetization, $M(T)$, exhibits an increase as the temperature decreases below 2 K, for all stages studied. It saturates below 1.4 K, as shown in Fig. 1, where $M(T)$ of each stage is labeled by its index, n, at a field $H_a = 0.5$ G. The temperature of the inflection point, T_c, occurs in the range 1.62–1.72 K depending on stage, and averages to $T_c = 1.67\ K \pm 3\%$, just 8% below that of the susceptibility and the specific heat anomalies. For $2.4\ K < T < 4\ K$, $M(T)$ is very flat and featureless, thus not shown here.

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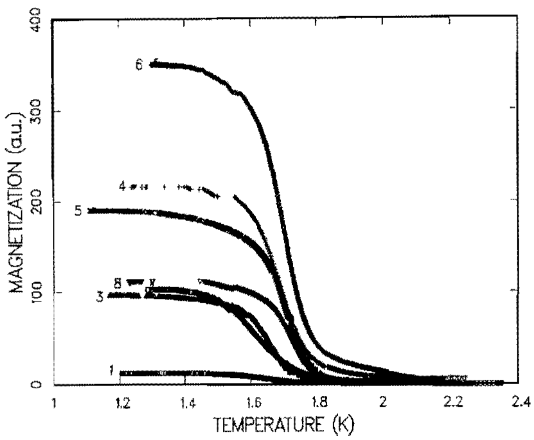

Fig. 1. $FeCl_3$ GIC's in-plane magnetization as a function of temperature for stages 1–6, and 8 as labeled, at a field $H_a = 0.5$ G.

The data show similar behavior for all stages, with one distinct difference. The saturation moment $M(1\ \text{K})$ has a strong stage dependence. After normalization to the iron contents, $M(1\ \text{K}) = 0.00036 \times e^n \mu_B/\text{Fe}$ ion for $1 \leqslant n \leqslant 5$, same behavior as that of the susceptibility peak, and deviates due to island formation in high stages.

Stage 6 was studied with respect to the applied field. The results of $M(T)$ at different fields were similar with one exception, the saturation moment, $M(1\ \text{K})$, exhibits a linear increase with the field up to $H_a = 1.0$ G; $M(1\ \text{K}) \sim 0.03 H_a \mu_B/\text{Fe}$ ion. The susceptibilty peak is reduced as the applied field is increased above 1.1 G [3].

The relaxation time measurements were carried out on stages 3 and 6. The data are shown in Fig. 2. Both stages

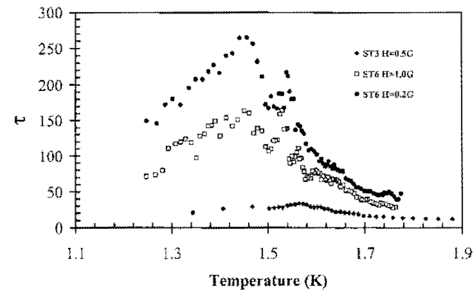

Fig. 2. The magnetization relaxation time $\tau(T)$, in seconds, around the transition temperature for stage 3 ($H_a = 0.5$ G) and stage 6 ($H_a = 0.2$ and 1.0 G), as labeled.

exhibit a maximum, at $T = 1.56$ K for $n = 3$ and at $T = 1.45$ K for $n = 6$, less than 14% below $T_c = 1.67$ K, as defined above. The peak's height decreases with field for stage 6 and is reduced further for stage 3. This is an indication of the fact that for stage 3 the mean field seen by the iron moments is higher than for stage 6.

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