Nature of the glassy magnetic state in the Cu$_{2.84}$Mn$_{0.44}$Al$_{0.72}$ shape memory alloy

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Abstract – The magnetic ground state of the ferromagnetic shape memory alloy of nominal composition Cu$_{2.84}$Mn$_{0.44}$Al$_{0.72}$ was investigated. The sample shows the reentry of a glassy magnetic phase below the martensitic transition temperature, which is found to have complex character with two distinct anomalies in the temperature-dependent ac susceptibility data. The sample retains its glassy phase even below the second transition as evident from the magnetic memory measurements in different protocols. Existence of two transitions along with their observed nature suggest that the system can be described by the mean-field Heisenberg model of reentrant spin glass as proposed by Gabay and Toulous. The sample provides a fascinating example where a Gabay-Toulous-type spin-glass state is triggered by a first-order magneto-structural transition.

The nondiffusive thermoelastic martensitic transition (MT) in ferromagnetic shape memory alloy (FSMA) is a notable example of magneto-structural instability among metallic alloys. FSMAs are bi-ferroic materials which combine ferroelasticity and ferromagnetism through the MT and are often found to be quite intriguing due to the complex interplay between these two ferroic properties [1]. The present paper deals with a Cu-Mn-Al-based FSMA with particular focus on the magnetic ground state of the sample. The localized nature of Mn moment is responsible for the magnetism in this system [2], and the magnetic coupling is mediated through Rudermann-Kittel-Kasuya-Yosida (RKKY)–type exchange interaction between Mn atoms [3]. The stoichiometric Cu$_2$MnAl does not undergo MT and such instability in Cu-Mn-Al alloys occurs far from the Heusler stoichiometric region [2,4–6]. For compositions close to Cu$_{3-x}$Mn$_x$Al (0 < x < 1), the system generally crystallizes in a BCC $\beta$ phase at high temperature ($\sim$ 850°C). But with proper heat treatment, the cubic L2$_1$ phase can be stabilized above room temperature [7]. On further cooling, the cubic L2$_1$ phase undergoes MT to a more closed-packed phase 18R-type monoclinic structure [5,8].

The true magnetic nature of the Cu-Mn-Al system of alloys is still not thoroughly understood. For the off-stoichiometric Cu-Mn-Al alloys undergoing thermoelastic MT, the magnetic state is quite complex. In the literature there are reports on the observation of superparamagnetism and micromagnetism below the MT [2,9]. The off-stoichiometry alloys with random site occupancy can have both ferromagnetic (FM) and antiferromagnetic (AFM) correlations leading to spin frustration. In fact a spin-glass state is reported for Cu-Mn-Al alloys at low Mn concentration, which turns into a superparamagnetic-like state with increasing Mn [10,11]. Superparamagnetism is characteristically different from a spin-glass or FM state, as in the former case the superspin clusters are mutually noninteracting [12]. The reported metastability in Cu-Mn-Al alloys deserves further investigations to unveil the true nature of the glassy ground state. It is particularly important to address the origin of the low-$T$ spin-glass phase in Cu-Mn-Al, and to what extent it is intrinsic to the sample and corresponds to those of conventional spin...
glasses. Keeping all these aspects in mind, we chose the alloy Cu$_{2.84}$Mn$_{0.44}$Al$_{0.72}$ for the thorough characterization of its magnetic ground state. The sample can be thought of being derived from Cu$_3$Al with Mn substitution both in Cu and Al sites. In other words the sample can be written as Cu$_{1-x}$Mn$_x+y$Al$_{1-y}$ ($x = 0.16, y = 0.28$). Being high in Mn concentration, the sample undergoes long-range FM ordering rather than being a superparamagnet. The ground state is found to be more complex with spin-glass–like transition well below the region of MT.

The polycrystalline sample of nominal composition Cu$_{2.84}$Mn$_{0.44}$Al$_{0.72}$ was prepared by argon arc melting of the constituent elements. The ingot was homogenized at 800 °C for 20 minutes followed by a rapid quenching in ice water, which helps to stabilize the desired L2$_1$ phase at room temperature [10,11]. The sample was characterized by x-ray powder diffraction using Cu K$_\alpha$ radiation at room temperature. The crystal structure is found to be of cubic L2$_1$ type with lattice parameter $a = 6.039$ Å. The dc magnetization ($M$) of the sample was measured on a Quantum Design SQUID magnetometer (MPMS, Ever-cool model). The ac susceptibility ($\chi_{ac}$) was measured on a commercial cryogen free low-temperature system (Cryogenic Ltd., UK) using the mutual inductance bridge technique.

Figure 1(a) depicts the temperature ($T$) variation of $M$ recorded in zero-field–cooled heating (ZFCH), field cooling (FC) and field-cooled heating (FCH) protocols in the presence of 100 Oe of applied dc magnetic field ($H$). On cooling from 300 K, $M$ shows a sudden upturn around $T_C = 270$ K which signifies the development of an FM-like state. The signature of MT is visible below about 150 K where the FC and FCH data show thermal hysteresis. Separation of FCH and ZFCH data starts to emerge below $T_s = 65$ K. However, significantly large irreversibility is only observed below $T_s$ = 35 K. Similar fall in $M$ below the MT was earlier observed in several Ni-Mn-Z (Z = Sb, Sn, In) alloys [13–15] and it was found to be related to the onset of the glassy magnetic state and exchange bias effect [13,14,16].

We measured isothermal $M$ as a function of $H$ at different $T$ (see inset of fig. 1(a)). The isotherms show typical FM-like behavior with an initial rise at low field followed by a tendency to saturation at higher fields. However, the $M(H)$ isotherm recorded at 5 K does not show complete saturation. This indicates that either the magnetic anisotropy of the FM phase is very high or there is phase separation with some other magnetic phase coexisting with the majority FM fraction. All the isotherms show small but finite coercivity ($H_{coer}$) at least below $T_C$. Extrapolation of the high-field part of the Arrot plot ($M^2$ vs. $H/M$) [17] shows a finite intercept on the vertical axis below $T_C$. This signifies nonzero spontaneous magnetization expected for a ferromagnetically ordered sample. Figure 1(b) shows the variation of $H_{coer}$ with $T$. At high temperature (down to 50 K), the observed coercivity is small and almost independent of $T$. $H_{coer}$ starts to decrease below 50 K and it goes through a minimum at around 30 K with its value almost turning to zero. On further cooling, $H_{coer}$ rises and attains a value of 80 Oe at 5 K. This minimum point matches closely with the temperature $T_s$ which signifies the onset point for large thermomagnetic irreversibility. The enhanced coercivity below $T_s$ can be reconciled with the added anisotropy from random spin freezing [18].

We performed ac susceptibility measurement at different constant frequencies to ascertain the presence of any spin-glass–like state in the studied alloy. The real ($\chi''_{ac}$) and imaginary ($\chi''_{ac}$) parts of the ac susceptibility data in the $T$ range 10–88 K are depicted in fig. 2(a) and (b), respectively. The frequency dispersion of $\chi''_{ac}(T)$ and $\chi''_{ac}(T)$ is expected to be similar as long as the frequency is low enough (well below 1 kHz). The anomalies near $T_f$ and $T_s$ observed in dc magnetization data are also present in the ac measurements. In $\chi''_{ac}(T)$ data, $T_f$ is associated with the onset of a sluggish drop, while $T_s$ is characterized by a change in slope. The corresponding anomalies are more prominent in the $\chi''_{ac}(T)$ data, where broad
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Fig. 2: (Colour on-line) Real (a) and imaginary (b) parts of the ac susceptibility as a function of temperature measured at three different applied frequencies of the ac signal. During measurement the dc magnetic field was kept zero, whereas the magnitude of the applied ac field was 10 Oe. In the inset of (b) the relaxation time ($\tau$) is plotted as a function of $T_{f}$. The solid line indicates fitting in accordance with the dynamical scaling model to the experimental data (see text for details).

Peak-like structures are observed around $T_{f}$ and $T_{s}$. In the frequency ($f$)-dependent ac measurement, $T_{f}$ shows a strong variation with $f$. This indicates the onset of a spin freezing phenomenon or a blocking (in the case of superparamagnetic clusters) around this anomaly. The shift in $T_{f}$ is found to be as high as 10 K for $f$ changing from 19 Hz to 191 Hz. The relative shift in $T_{f}$ can be expressed as $P_{T_{f}}=\frac{\Delta T_{f}}{T_{f}}=\frac{1}{2\pi f}$, where $\omega = 2\pi f$ is the angular frequency of the ac excitation. $P$ is typically found to be between 0.005 and 0.01 for CSG [18–20] and somewhat between 0.03 and 0.06 in the case of cluster glasses. In superparamagnetic systems, $P$ is generally $\geq 0.1$ [18]. Systems associated with complex spin freezing phenomena can also give rise to a large value of $P$ as observed in the case of disordered antiferromagnetic spin chain compounds, [21,22] or spin ice systems [23]. For the present sample, $P$ was found to be 0.19 which may apparently indicate a superparamagnetic-like state in the alloy. The subsequent investigation shows a more complex spin freezing phenomenon in the system.

We have investigated the dynamical scaling (DS) behavior of the frequency shift observed in $\chi''_{ac}$ data (see the $\tau$ vs. $T_{f}$ curve in the inset of fig. 2(b)). The relaxation time $\tau$ (for the decay of the fluctuations to the spin correlation length) can be expressed as $\tau = \tau_0(T_f/T_g - 1)^{-z\nu}$ [24], where $z$ is the dynamic critical exponent, $\nu$ is the spin-correlation length exponent, $T_g$ is the zero-frequency spin freezing temperature, and $\tau_0$ is the characteristic spin flipping time. Taking $\tau = 1/(2\pi f)$, the parameters $\tau_0$, $T_g$ and $z\nu$, are found to be $7.5 \times 10^{-4}$ s, 43.56 K and 1.63, respectively from the experimental $T_f$ vs. $f$ data. For CSG, the value of $\tau_0$ was reported to be $\sim 10^{-13}$ s [18]. Such high values of $\tau_0$ obtained for the present sample indicate a slower rate of spin flipping as observed for several cluster glass and reentrant spin-glass systems [25–28]. In addition, the fitted value of $z\nu$ (=1.63) is found to be considerably lower than values (4–12) reported for different SG systems [18]. In recent times, low values of $z\nu$ were reported in few systems such as LaMn$_{0.5}$Fe$_{0.5}$O$_3$ and BiFeO$_3$ [25,26]. We failed to fit the $T_f$ vs. $f$ data to a simple Arrhenius-type law ($f = f_0 \exp[-E_a/k_B T_f]$) with physically meaningful value of $f_0$. Arrhenius type of behavior is generally expected for noninteracting superparamagnetic systems.

To shed more light on the low-temperature glassy state of the sample, we recorded $\chi_{ac}$ at different amplitudes of the applied ac magnetic field ($h_{ac}$) keeping the frequency of the ac signal constant at 97 Hz (see figs. 3(a) and (b)). $h_{ac}$ has little effect on $\chi_{ac}$ below $T_s$, however both the
Fig. 4: (Colour on-line) Panel (a) shows the field-cooled field stop memory effect in dc magnetization vs. temperature data for the Cu$_{2.84}$Mn$_{0.44}$Al$_{0.72}$ alloy. The memory measurement was performed by cooling the sample in $H$ = 100 Oe with intermediate zero-field stops at $T$ = 35, 25, and 15 K ($M_{\text{mem}}^\text{FC}$) followed by uninterrupted heating in 100 Oe ($M_{\text{mem}}^\text{FCH}$). The reference curve ($M_{\text{ref}}^\text{FCH}$) was measured on heating after the sample was field-cooled in 100 Oe without intermediate stops. Panel (b) shows the time-dependent magnetic memory measurement in the presence of 100 Oe of applied field. The time variation of $M$ was measured in three consecutive segments viz. $pq$ (15 K), $rs$ (10 K) and $tu$ (15 K) with the duration of each segment being 5400 s. Here the $t'_{u}$ segment is obtained by simply shifting $tu$ to merge its starting point with the end point of $pq$. The inset of (b) shows the positive $T$ cycling or rejuvenation measurement of magnetic relaxation.

real and imaginary $\chi_{ac}$ components become highly sensitive to $h_{ac}$ above $T_s$. A large shift in $T_f$ ($\sim$ 10 K) for $h_{ac}$ changing from 4 to 8 Oe is observed in the $\chi''_{ac}(T)$ data. The $h_{ac}$-dependence of $\chi_{ac}$ is not unexpected and it has been reported earlier in the case of reentrant spin-glass materials, phase-separated manganites and magnetic superconductors [29–31]. Interestingly, for low amplitude of the ac excitation field ($h_{ac}$ = 1 Oe) no peak-like feature around $T_f$ is observed in $\chi''_{ac}(T)$. The $h_{ac}$-dependence of $\chi''_{ac}(T)$ indicates strong nonlinearity particularly around $T_f$ [32]. Below a certain threshold ac field, the frozen spins remain almost unperturbed by the ac excitation. The shift of $T_f$-peak with $h_{ac}$ is due to the competition between temperature and the driving ac field. The stronger the ac excitation, it can perturb the frozen spins down to lower temperature, and subsequently $T_f$ shifts to lower $T$ with increasing $h_{ac}$. It is to be noted that the anomaly associated with $T_s$ is quite prominent in $\chi''_{ac}(T)$ data, although it is quite insensitive to $h_{ac}$ or $f$. The $h_{ac}$-dependence in $\chi''_{ac}(T)$ emerges only above $T_s$ signifying the presence of this characteristic temperature even in $\chi''_{ac}(T)$.

The observed anomalies in $\chi_{ac}$ measurements indicate a frozen metastable state in the sample at least below $T_f$. Tempted by this observation, we performed magnetic memory measurements (see figs. 4 and 5) which can independently support the nonergodic nature of the ground state as well as its probable origin. The field-cooled field-stop memory measurement (see fig. 4(a)) in the $M$ vs. $T$ data were recorded following the protocol described by Sun et al. [33]. Here the sample was cooled down to 5 K in 100 Oe with intermediate stops for $t_w$ = 3600 s at 35, 25 and 15 K. Subsequent heating in 100 Oe produces characteristics wiggles at those selected temperatures confirming the presence of field-cooled memory. No signature of memory was observed above $T_f$ indicating that the frozen nonergodic state only exists below $T_f$. 

Fig. 5: (Colour on-line) Panel (a) shows the memory measurement in the zero-field–cooled condition recorded on dc magnetization vs. temperature data for the Cu$_{2.84}$Mn$_{0.44}$Al$_{0.72}$ alloy. The sample was first cooled in $H$ = 0 down to 5 K, with intermediate stops at 42 and 15 K of 14400 s each. The sample was then reheated in $H$ = 100 Oe up to 70 K ($M_{\text{ZFCH}}^\text{mem}$). A zero-field–cooled reference curve ($M_{\text{ZFCH}}^\text{ref}$) without intermediate stops during heating is shown as a dotted line. The difference in magnetization $\Delta M = M_{\text{ZFCH}}^\text{mem} - M_{\text{ZFCH}}^\text{ref}$ is plotted in (b).
The presence of magnetic memory in the alloy was confirmed by the relaxation memory measurements with negative $T$ cycling (fig. 4(b)) [34,35]. Here relaxation data ($M$ vs. time ($t$)) were recorded in 100 Oe of field at three consecutive segments $\overline{\mathbf{P}}$, $\overline{\mathbf{S}}$, and $\overline{\mathbf{T}}$ with the sample being held at 15 K, 10 K and 15 K, respectively, for 5400 s each. The segment $\overline{\mathbf{T}}$ shows a continuation of $\overline{\mathbf{P}}$. This memory effect reflects that the state of the system before cooling is recovered when the sample is cycled back to the initial $T$. To confirm the reliability of the observed memory, we performed positive $T$ cycling or rejuvenation, where the sample was heated to a higher value of $T$ for the intermediate relaxation [34,36]. Such rejuvenation measurement has been depicted in the inset of 4(b). Here $M$ vs. $t$ was measured consecutively at 15 K ($\overline{\mathbf{P}}$), 20 K ($\overline{\mathbf{S}}$), and 15 K ($\overline{\mathbf{T}}$). Clearly, $\overline{\mathbf{T}}$ does not follow the trend of $\overline{\mathbf{P}}$, signifying that the magnetic state is lost on intermediate heating. This is a typical signature of glassy or superparamagnetic state below the freezing or blocking temperature.

It is now essential to distinguish between superparamagnetism and a spin-glass–like ground state for the studied sample. We performed zero-field–cooled memory measurements in the $M$ vs. $T$ data (see fig. 5) [34–36]. Here the sample was cooled from 300 to 5 K in $H = 0$ with intermediate stops for 14400 s at 42 K and 15 K (points $S_{ZFC}$, and $S_{FCH}$, respectively, in fig. 5(a)). After that the sample was heated back to 70 K in the presence of $H = 100$ Oe. Substantially strong signatures of anomalies are observed on the difference curve $\Delta M(T) = M_{ZFC}(T) - M_{FCH}(T)$ at the stopping temperatures providing positive signature of memory (fig. 5(b)). This is a clear indication that the ground state of the system is spin-glass-like.

Our investigation indicates that the studied alloy $\text{Cu}_{2.84}\text{Mn}_{0.44}\text{Al}_{0.72}$ undergoes long-range FM ordering below $T_C = 270$ K and it attains a glassy magnetic state below $T_f = 65$ K. The magnetic state between $T_C$ and $T_f$ is certainly FM as evident from finite coercivity and spontaneous magnetization rather than a superparamagnetic state claimed previously for certain Cu-Mn-Al alloys [2,9,10]. Development of a glassy magnetic state out of a long-range magnetically ordered state is referred to as a reentrant spin-glass (RSG) transition [37–40]. The RSG state occurs due to the competition between FM and AFM interactions arising from site or bond randomness [40], although the mean interaction has to have a nonzero FM character for the realization of an RSG phase. The magnetic phase below the spin freezing transition (here occurring at $\sim T_f$) is a mixed phase with the coexistence of FM and spin-glass orderings.

The magnetic phase in $\text{Cu}_{2.84}\text{Mn}_{0.44}\text{Al}_{0.72}$ is substantially different from the conventional RSG systems such as Fe-Au or Fe-Mn alloys. The glassy phase in conventional RSG develops from an ordered FM phase, whereas in the present alloy the spin freezing is preceded by a first-order structural transition which itself modifies the high-$T$ FM phase. In the case of Cu-Mn-Al alloys the sign of the magnetic interaction depends on the Mn-Mn distance (due to the RKKY mechanism). For the stoichiometric Heusler compound $\text{Cu}_2\text{MnAl}$ with ordered $L_2_1$ structure, the Mn-Mn distance is of next-nearest-neighbor (nnn) type and this gives rise to FM interaction. For the present sample, some excess Mn is doped randomly at the Al and Cu sites. This will reduce the Mn-Mn distance in some sites paving the path for random AFM-type bonds in the backdrop of FM correlations. It has been argued by Prado et al. [5] that the percentage of Mn-Mn AFM bonds enhances in the presence of chemical disorder below the MT, due to the increased nearest-neighbor Mn-Mn occupancy. The occurred glassy state in $\text{Cu}_{2.84}\text{Mn}_{0.44}\text{Al}_{0.72}$ just below the MT is supposedly connected to the structural transition-induced random AFM bond formation.

The most intriguing result of the present study are the anomalies observed in the $\chi''$ data on and around the spin freezing temperature. In $\chi''$ vs. $T$ data, two distinct features were seen, one at $T_f$ and another at slightly low temperature denoted by $T_s$. As evident from our previous discussion, $T_f$ denotes a spin freezing point characterized by large frequency shift in the ac $\chi$ measurement. This is approximately the onset point of thermomagnetic irreversibility between the ZFCH and the FCH curve in $M$ vs. $T$ measurements. The irreversibility starts to grow rapidly only when the sample is cooled approximately below $T_s$.

The two major theoretical models which describes the RSG state are i) mean-field treatments of Heisenberg spins with infinitely long-range interaction [18,41–43] commonly known as Gabay-Toulous (GT) model and ii) a phenomenological random field model [44]. In the mean-field model it has been argued that spin freezing in the RSG phase in the presence of a magnetic field takes place through set of transitions lines in the $J_f-T$ phase diagram, where $J_0$ is the exchange interaction averaged over all the magnetic bonds. It was predicted that there exist three characteristics temperatures $T_C$, $T_{GT}$ and $T_{AT}$. Below $T_C$, the FM phase develops from the paramagnetic state. Below $T_{GT}$, the system enters into a mixed phase $M_1$, where the transverse component of the spins (with respect to the direction of $H$) freezes keeping the longitudinal components ferromagnetically ordered. On further cooling below $T_{AT}$, a crossover to a second mixed phase ($M_2$) occurs which is associated with strong magnetic irreversibility in the longitudinal component of the spins. Experimental support for such model is found in several metallic spin-glass systems [40,45]. It is to be noted that $T_{AT}$ is a crossover temperature rather than a transition below which nonergodicity sets in gradually in the longitudinal spin components.

For the present sample, the observation of two anomalies presumably indicate an RSG phase similar to the prediction of the mean-field Heisenberg model. In that situation $T_f$ and $T_s$ of our sample correspond to $T_{GT}$ and $T_{AT}$, respectively. The large peak-shift in $\chi''(T)$ with $f$ and $h_{ac}$ and the onset of irreversibility between ZFCH-FCH
magnetization at or around $T_f$ certainly signifies the spin freezing. On the other hand, $T_\nu$ shows an almost negligible peak shift with $f$ or $h_{ac}$ along with strong irreversibility in $M$ mimicking the properties of the crossover point $T_{AT}$. Our memory measurements (both in field-cooled and zero-field–cooled protocols) show positive signature below $T_f$ as well as below $T_s$. Therefore the glassy state that develops below $T_f$ continues to exist at the lowest temperature.

The exponent $\nu$ obtained from the dynamical scaling analysis of frequency shift in $\chi_{ac}$ data is quite low for the present alloy. The spin freezing temperature $T_f$ of Cu$_{2.84}$Mn$_{0.44}$Al$_{0.72}$ actually falls within the region of thermal hysteresis associated with MT. A possible mechanism related to domain wall dynamics was mooted for the observed low value of $\nu$ in BiFeO$_3$ [25]. The MT give rise to low-temperature martensite with structural variants, which can actually have similar effect on the dynamics of spin freezing.

In conclusion, we present a comprehensive view of the glassy magnetic state of the Cu$_{2.84}$Mn$_{0.44}$Al$_{0.72}$ alloy. The glassy state is of reentrant type and it is likely to be connected to the first-order structural phase transition observed in this ferromagnetic shape memory alloy. This is a unique example where an RSG phase arises from the result of a martensitic-type first-order structural transition showing GT-like character of the reentry. It is to be noted that previous reports on Cu-Mn-Al alloys by Obradó et al. [10] indicated a superparamagnetic ground state for a large Mn concentration. The presently studied sample has different Cu:Mn:Al ratio, it shows a spin-glass–like state even for large concentration of Mn. This indicates that the glassy state in Cu-Mn-Al alloys may depend on factors other than Mn concentration.

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REFERENCES

[1] Ullakko K. et al., Appl. Phys. Lett., 69 (1996) 1966.
[2] Pardo M. O. et al., Acta Mater., 46 (1998) 137.
[3] Webster P. J. and Ziebeck K. R. A., Magnetic Properties of Metals (Springer-Verlag, Berlin) 1988.
[4] Winkler R. and Wachtel E., J. Magn. & Magn. Mater., 9 (1978) 270.
[5] Prado M. O. et al., Acta Mater., 46 (1997) 137.
[6] Kainuma R. et al., J. Alloys Compd., 266 (1998) 191.
[7] Obradó E. et al., Phys. Rev. B, 58 (1998) 14245.
[8] Wang R. et al., Acta Mater., 50 (2002) 1835.
[9] Yeﬁmova T. V. et al., Phys. Met. Metallogr., 64 (1987) 189.
[10] Obradó E. et al., Phys. Rev. B, 59 (1999) 11450.
[11] Obradó E. et al., Mater. Sci. Eng. A, 273–275 (1999) 586.
[12] Bedanta S. and Kleemann W., J. Phys. D: Appl. Phys., 42 (2009) 013001.
[13] Khan M. et al., Appl. Phys. Lett., 91 (2007) 072510.
[14] Khan M. et al., J. Appl. Phys., 102 (2007) 113914.
[15] Li Z. et al., Appl. Phys. Lett., 91 (2007) 112505.
[16] Chatterjee S. et al., Phys. Rev. B, 79 (2009) 092410.
[17] Arrott A., Phys. Rev., 108 (1957) 1394.
[18] Mydosh J. A., Spin Glasses: An Experimental Introduction (Taylor & Francis, London) 1993.
[19] Mahendirar R. et al., Phys. Rev. B, 68 (2003) 104402.
[20] Tiwari S. D. and Rajeev K. P., Phys. Rev. B, 72 (2005) 104433.
[21] Sampathkumaran E. V. and Niazi A., Phys. Rev. B, 65 (2002) 180401(R).
[22] Flahaut D. et al., Eur. Phys. J. B, 35 (2003) 317.
[23] Snider J. et al., Nature (London), 413 (2001) 48.
[24] Souletie J. and Tholence J. L., Phys. Rev. B, 32 (1985) 516.
[25] Singh M. K. et al., Phys. Rev. B, 77 (2008) 144403.
[26] De K. et al., J. Appl. Phys., 99 (2006) 013908.
[27] Hanasaki N. et al., Phys. Rev. Lett., 99 (2007) 086401.
[28] Viswanathan M. and Kumar P. S. A., Phys. Rev. B, 80 (2009) 024110.
[29] Jonason K. et al., Phys. Rev. B, 53 (1996) 6507.
[30] Mugerjee S. et al., Phys. Rev. B, 54 (1996) 9267.
[31] Kumar A. et al., J. Appl. Phys., 110 (2012) 043926.
[32] Andersson J.-O. et al., Phys. Rev. B, 54 (1996) 9912.
[33] Sun Y. et al., Phys. Rev. Lett., 91 (2003) 167206.
[34] Bhattacharyya A. et al., Phys. Rev. B, 83 (2011) 134427.
[35] Chattopadhyay S. et al., EPL, 98 (2012) 27004.
[36] Dolinšek J. et al., Phys. Rev. B, 77 (2008) 064430.
[37] Abiko S. et al., Phys. Rev. Lett., 94 (2005) 227202.
[38] Mathieu R. et al., Europhys. Lett., 52 (2000) 441.
[39] Dhom J. et al., Phys. Rev. Lett., 89 (2002) 027202.
[40] Mirebeau I. et al., Phys. Rev. B, 41 (1990) 11405.
[41] Gabay M. and Toulouse G., Phys. Rev. Lett., 47 (1981) 201.
[42] Cragg D. M. et al., Phys. Rev. Lett., 49 (1982) 158.
[43] Binder K. and Young A. P., Rev. Mod. Phys., 58 (1986) 801.
[44] Aeppli G. et al., Phys. Rev. B, 28 (1983) 5160.
[45] Kim T. H. et al., Phys. Rev. B, 53 (1996) 221.