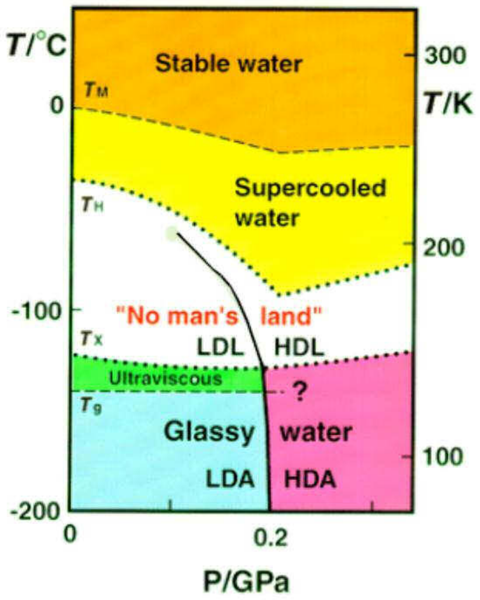
Glass-like arrested states across 1st order magnetic transitions

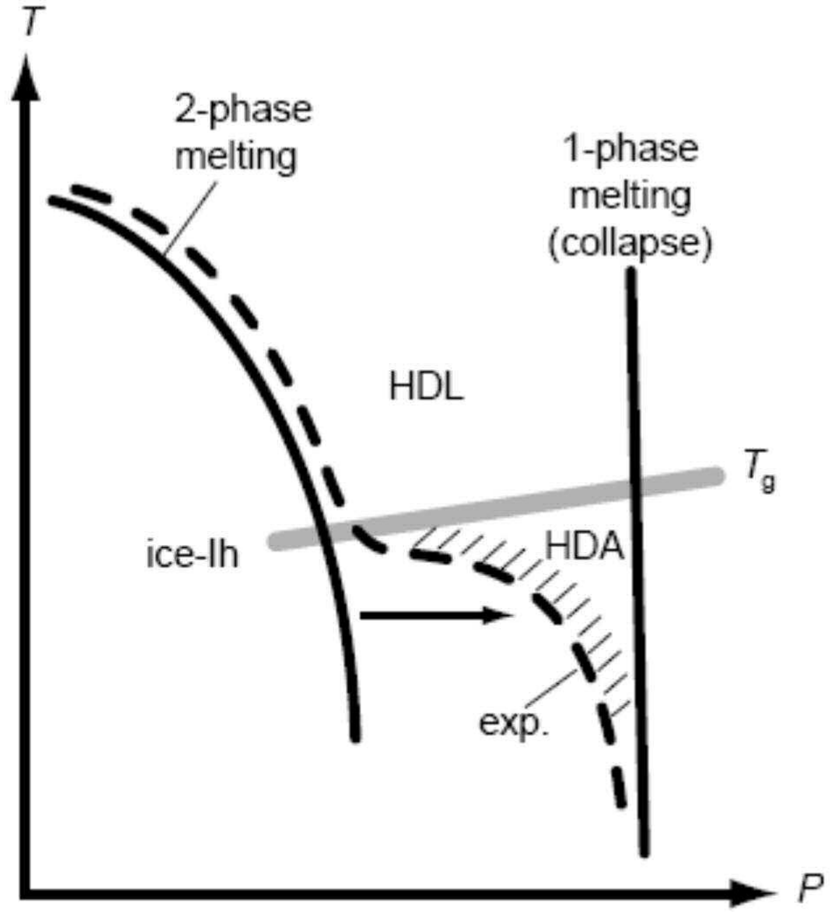
P. Chaddah *UGC-DAE Consortium for Scientific Research, Indore.*

We shall present our studies on various magnetic glasses including CMR manganites and magnetic shape-memory alloys. We have exploited the magnetic field as a second control variable to create and use new measurement protocols that may have analogies for structural glasses [1].

[1] P. Chaddah and A. Banerjee, arXiv:1107.0125 , and references therein

NATURE | VOL 396 | 26 NOVEMBER 1998 | www.nature.com





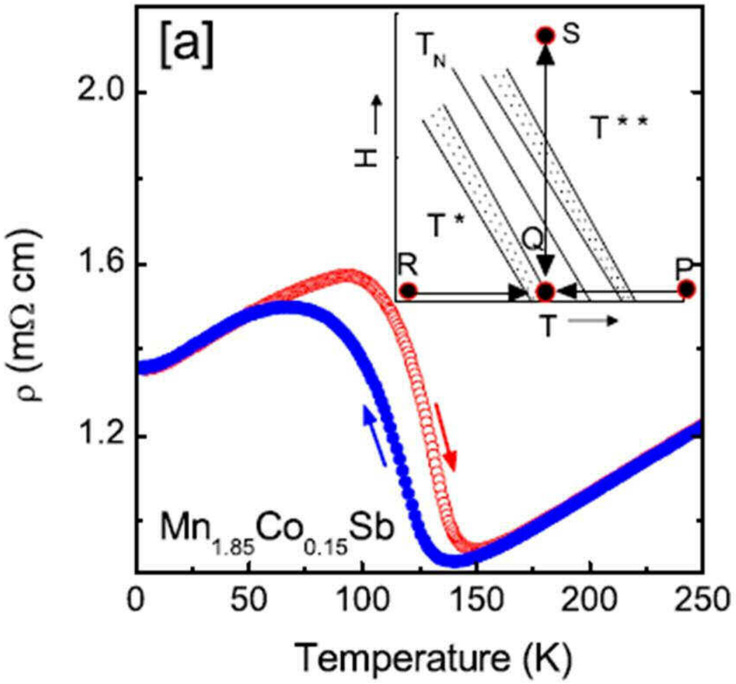
The relationship between liquid, supercooled and glassy water

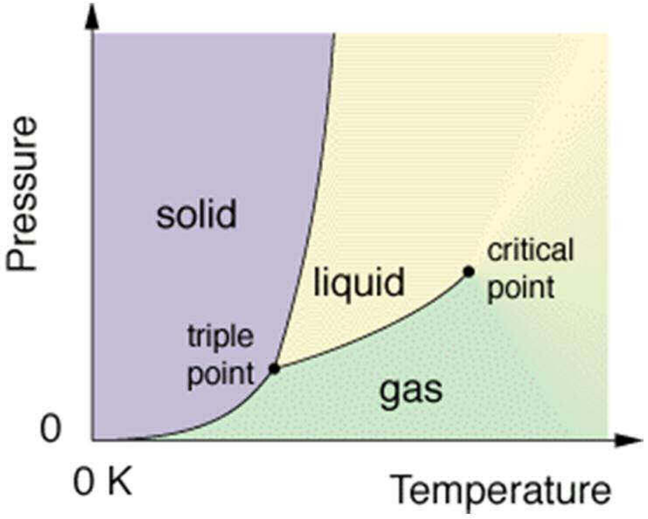
Osamu Mishima & H. Eugene Stanley

PHYSICAL REVIEW B **79**, 132402 (2009)

Real-space visualization of thermomagnetic irreversibility within supercooling and superheating spinodals in $Mn_{1.85}Co_{0.15}Sb$ using scanning Hall probe microscopy

Pallavi Kushwaha, Archana Lakhani, R. Rawat, A. Banerjee, and P. Chaddah
UGC-DAE Consortium for Scientific Research University Campus, Khandwa Road, Indore-452001, India





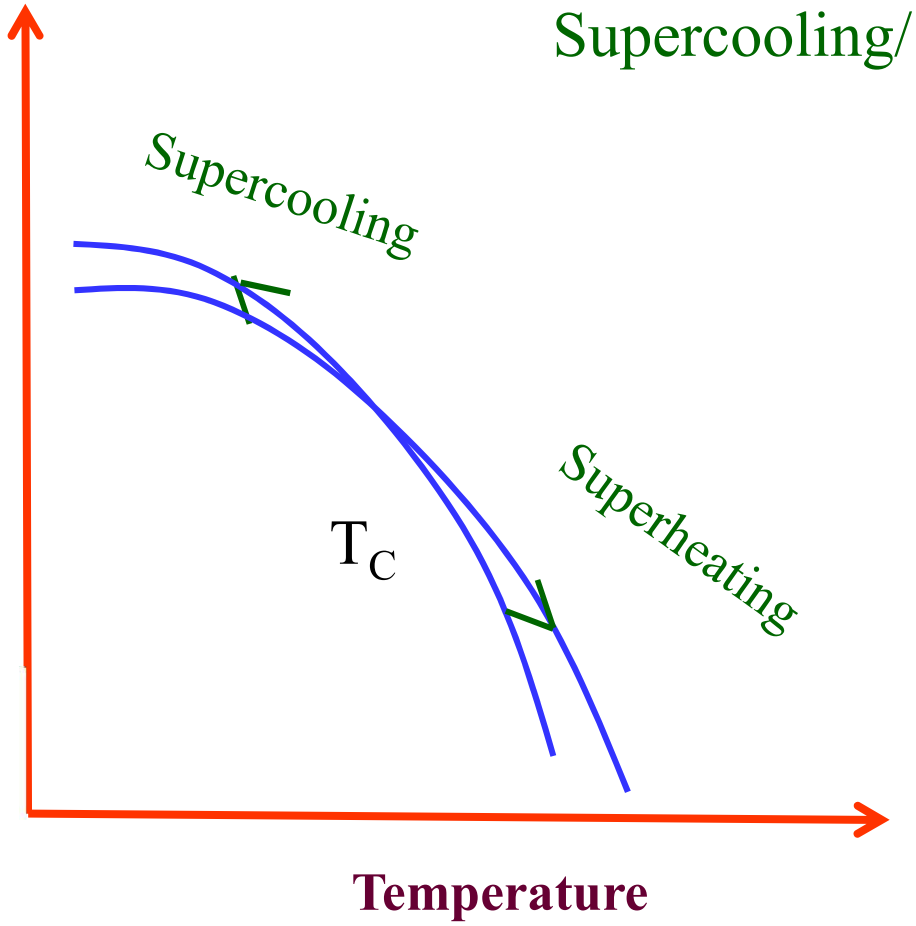
Study of 1^{st} Order transitions using magnetic field

larger variation of T_C with the experimentally available range of H than with the experimentally available range of P.

Signatures of 1st Order transitions

1st Order Transition allows
Supercooling/Superheating

**Free
Energy**



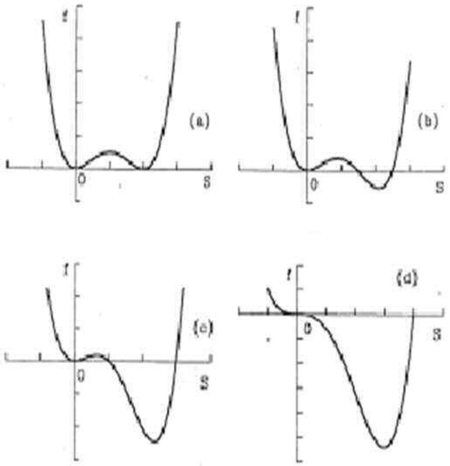
Supercooling

Superheating

T_C

Temperature

Phase transitions in vortex matter

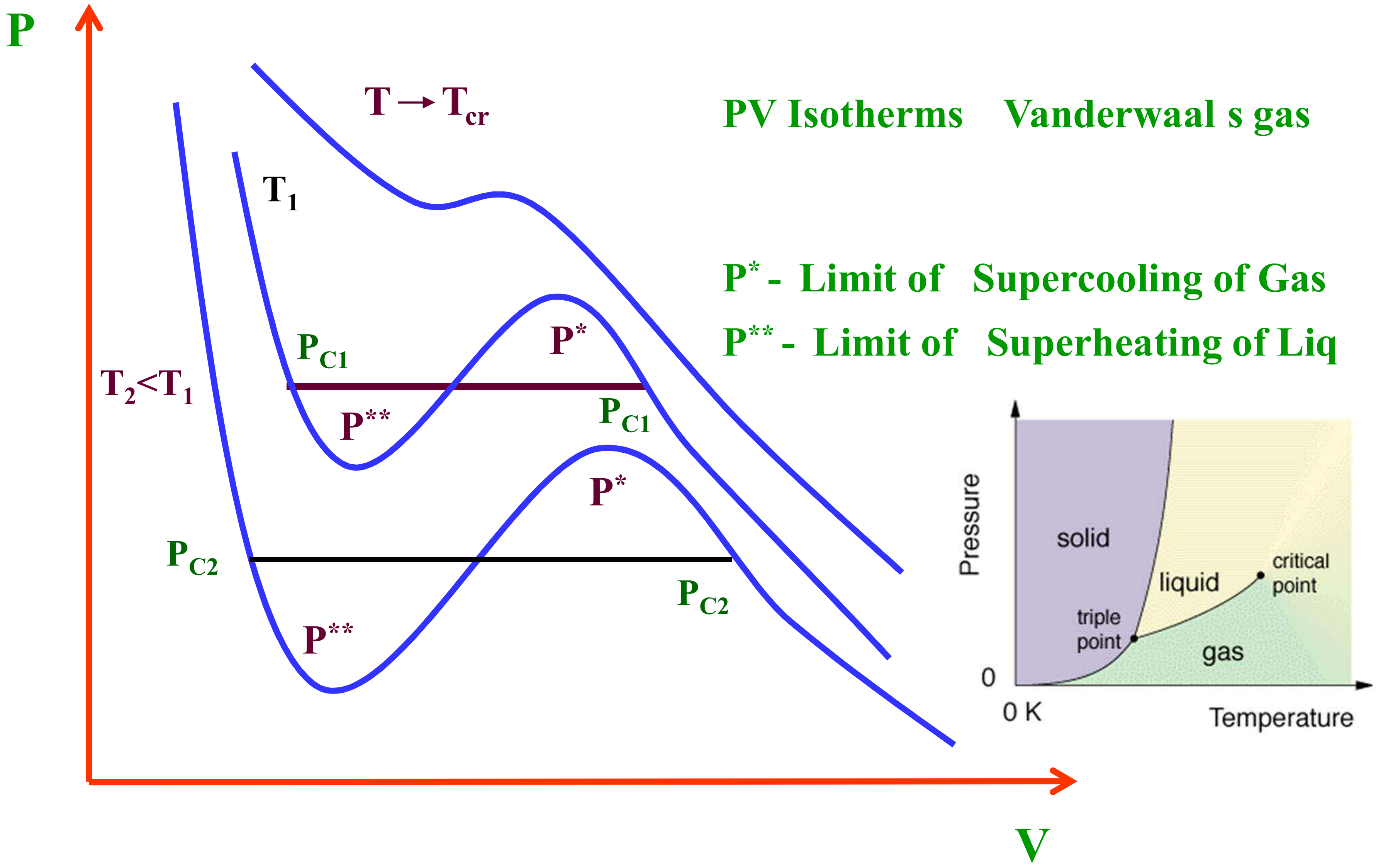


No Limits for supercooling or superheating?

PV Isotherms Vanderwaal s gas

P^* - Limit of Supercooling of Gas

P^{**} - Limit of Superheating of Liq



Supercooling/Superheating & hysteresis

Across a 1st Order transition, one can

Supercool the liquid (disordered state) or Superheat the solid (ordered state) → Observe hysteresis, supercooling.

Form a **Glass (arrest the kinetics)**

Glass is time held still → disorder can be other than structural

Magnetic Glass → a glass-like arrested state

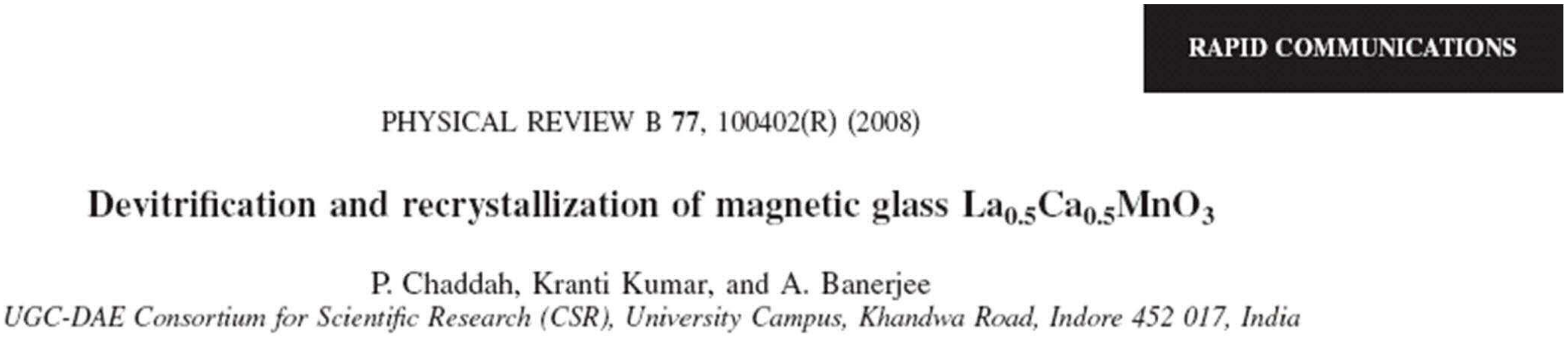
A glass-like arrested state is formed when we succeed in cooling across a 1st order transition while extracting the specific heat but without extracting the latent heat.

PHYSICAL REVIEW B **73**, 184435 (2006)

Relating supercooling and glass-like arrest of kinetics for phase separated systems: Doped $CeFe_2$ and $(La,Pr,Ca)MnO_3$

KUMAR *et al.*

[11] The metastable kinetically arrested (or glass) state is different from the metastable supercooled state in that the latter (but not the former) will undergo a metastable to stable transformation on lowering of temperature. In other words, the relaxation time decreases with the decrease in T for a supercooled state whereas the relaxation time increases with the decrease in T for the glassy state.

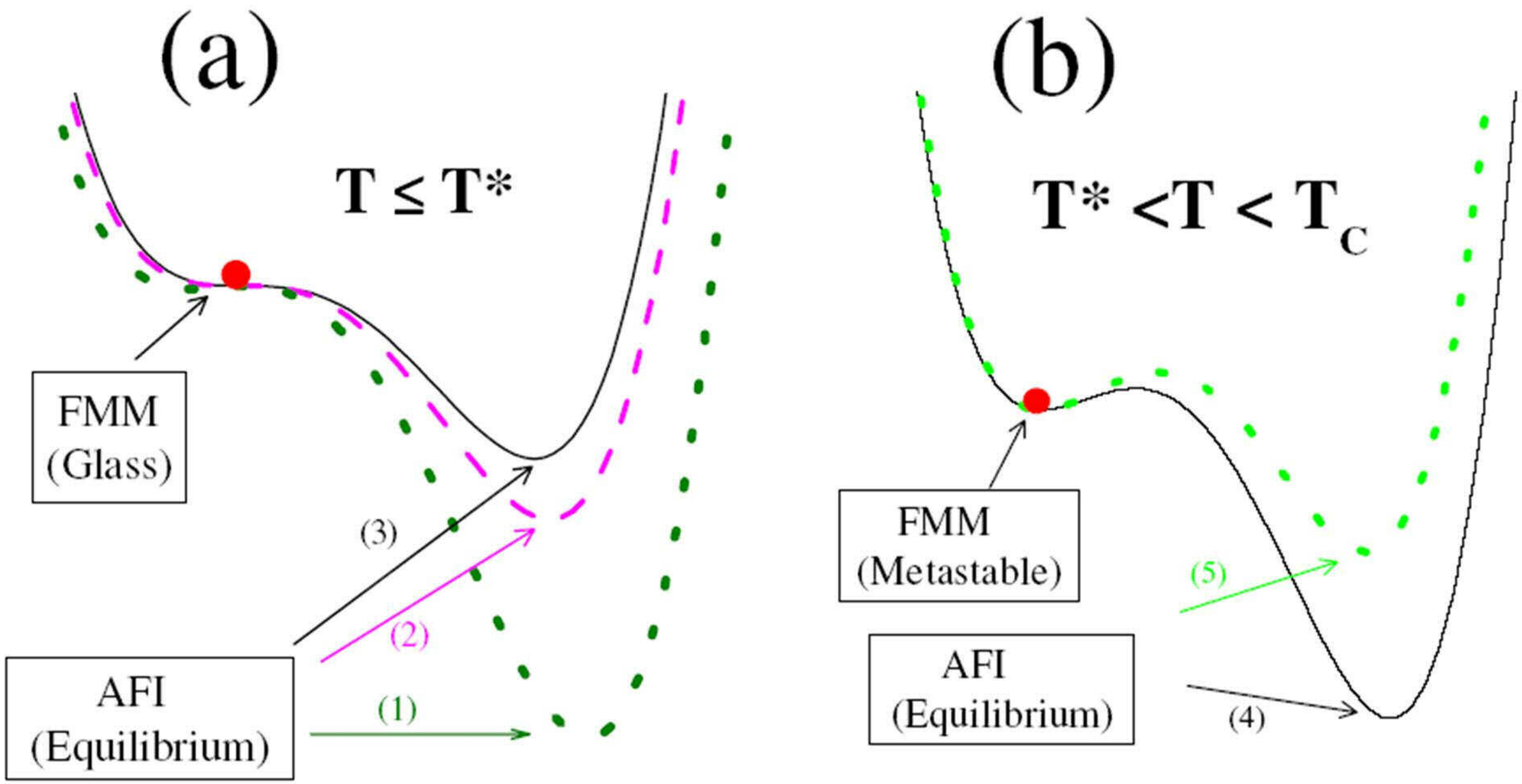


RAPID COMMUNICATIONS

PHYSICAL REVIEW B **77**, 100402(R) (2008)

Devitrification and recrystallization of magnetic glass $La_{0.5}Ca_{0.5}MnO_3$

P. Chaddah, Kranti Kumar, and A. Banerjee
UGC-DAE Consortium for Scientific Research (CSR), University Campus, Khandwa Road, Indore 452 017, India



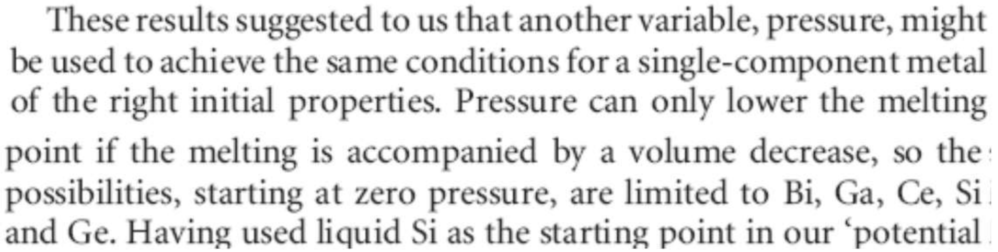
Barrier falls as one cools from T_C to T*, and relaxation rate will rise.

Vol 448 | 16 August 2007 | doi:10.1038/nature06044 nature

LETTERS

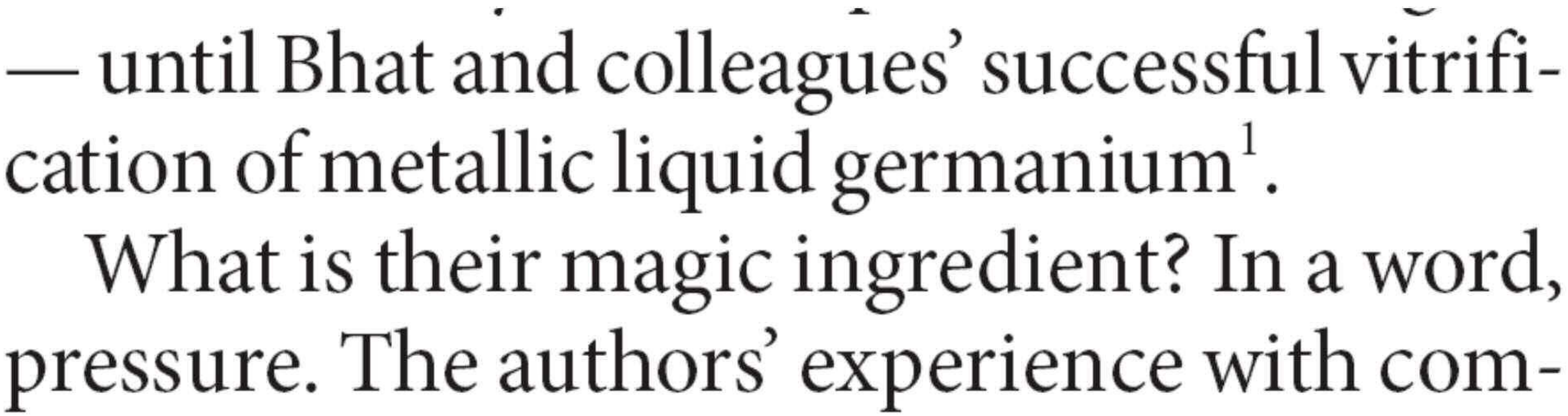
Vitrification of a monatomic metallic liquid

M. H. Bhat[1], V. Molinero[1,2], E. Soignard[1], V. C. Solomon[1], S. Sastry[3], J. L. Yarger[1] & C. A. Angell[1]



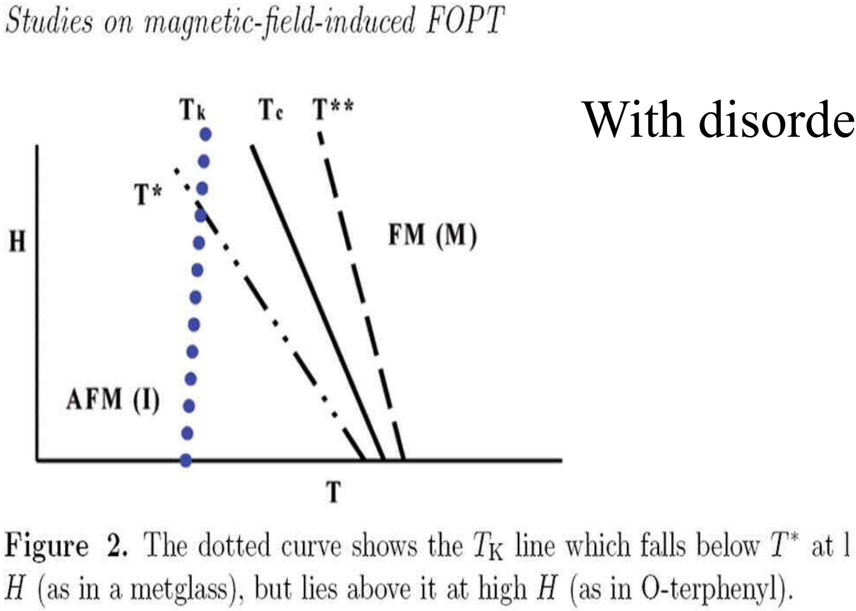
These results suggested to us that another variable, pressure, might be used to achieve the same conditions for a single-component metal of the right initial properties. Pressure can only lower the melting point if the melting is accompanied by a volume decrease, so the possibilities, starting at zero pressure, are limited to Bi, Ga, Ce, Si and Ge. Having used liquid Si as the starting point in our 'potential

Giles Tarjus



— until Bhat and colleagues' successful vitrification of metallic liquid germanium[1].

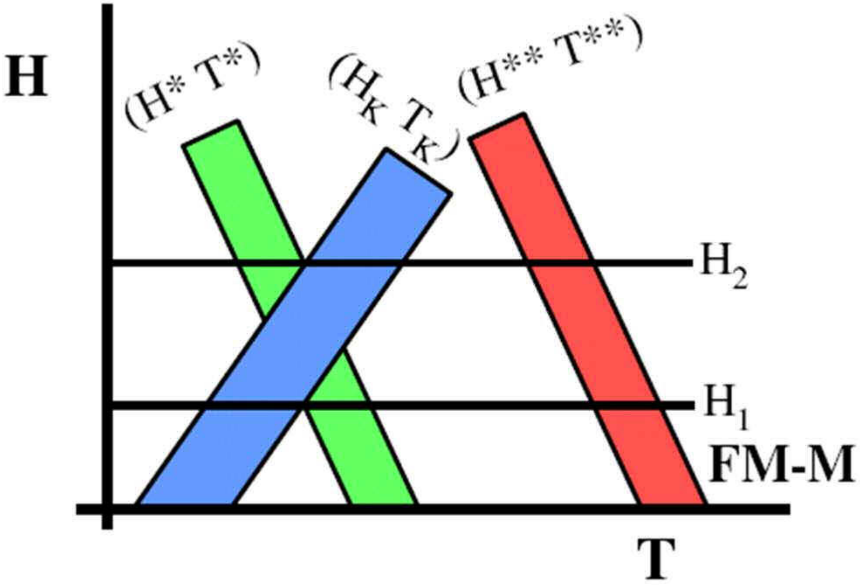
What is their magic ingredient? In a word, pressure. The authors' experience with com-



Studies on magnetic-field-induced FOPT

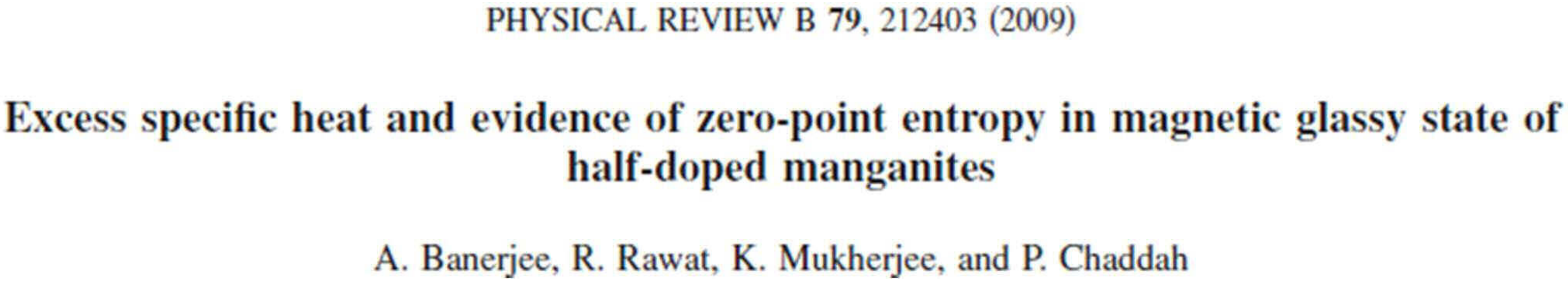
Figure 2. The dotted curve shows the T_K line which falls below T^* at l
H (as in a metglass), but lies above it at high H (as in O-terphenyl).

With disorder broadening



Chaddah   Pramana-J Phys 67 (2006)

CHUF (cooling & heating in unequal fields)



PHYSICAL REVIEW B **79**, 212403 (2009)

Excess specific heat and evidence of zero-point entropy in magnetic glassy state of half-doped manganites

A. Banerjee, R. Rawat, K. Mukherjee, and P. Chaddah

PHYSICAL REVIEW B, VOLUME 64, 104416

First-order transition from antiferromagnetism to ferromagnetism in $Ce(Fe_{0.96}Al_{0.04})_2$

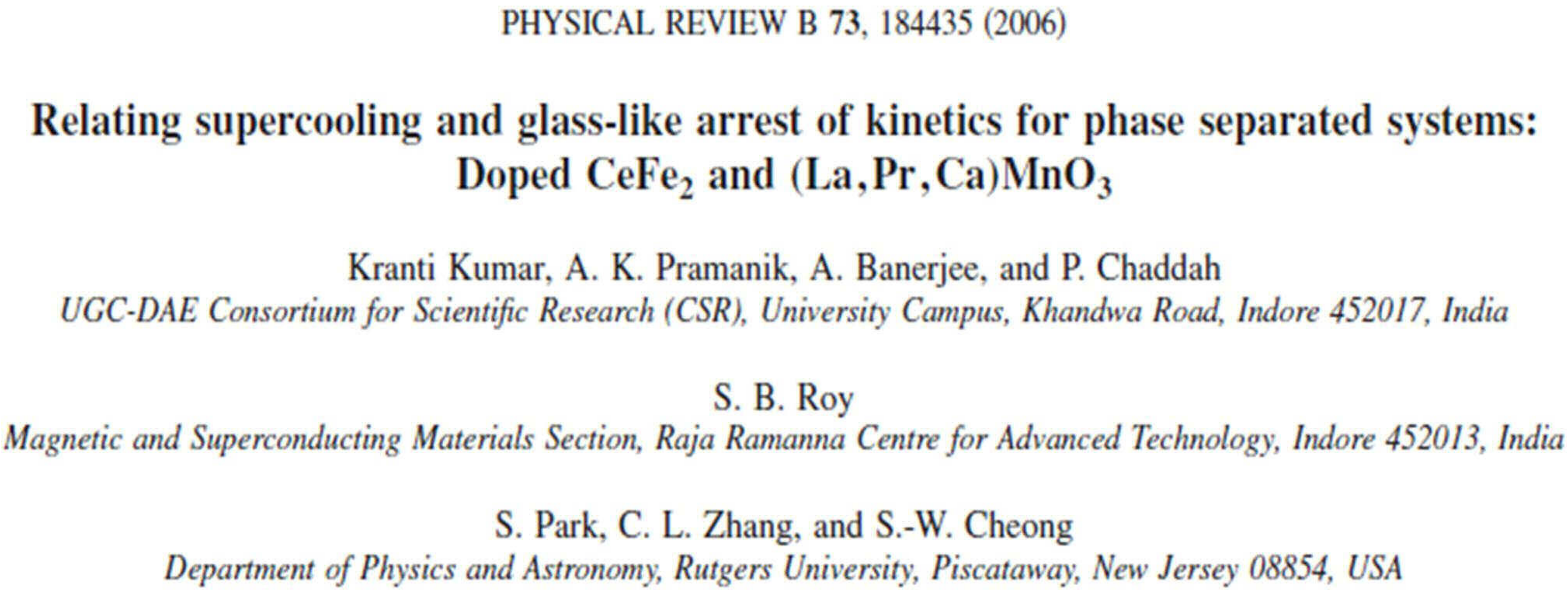
M. A. Manekar, S. Chaudhary, M. K. Chattopadhyay, K. J. Singh, S. B. Roy,* and P. Chaddah
Low Temperature Physics Laboratory, Centre for Advanced Technology, Indore 452013, India

(Received 23 April 2001; published 22 August 2001)

Taking the pseudobinary C15 Laves phase compound $Ce(Fe_{0.96}Al_{0.04})_2$ as a paradigm for studying a ferromagnetic to antiferromagnetic phase transition, we present interesting thermomagnetic history effects in magnetotransport as well as magnetization measurements across this phase transition. A comparison is made with history effects observed across the ferromagnetic to antiferromagnetic transition in $R_{0.5}Sr_{0.5}MnO_3$ crystals.

cussed similarities with earlier single-crystal data on $R_{0.5}Sr_{0.5}MnO_3$ across another first-order FM-AFM transition.

FM-AFM transitions can be used as paradigms to study various interesting aspects of first-order transitions such as nucleation and growth, supercooling and superheating, hindered kinetics, etc. in a relatively easy and reproducible manner.



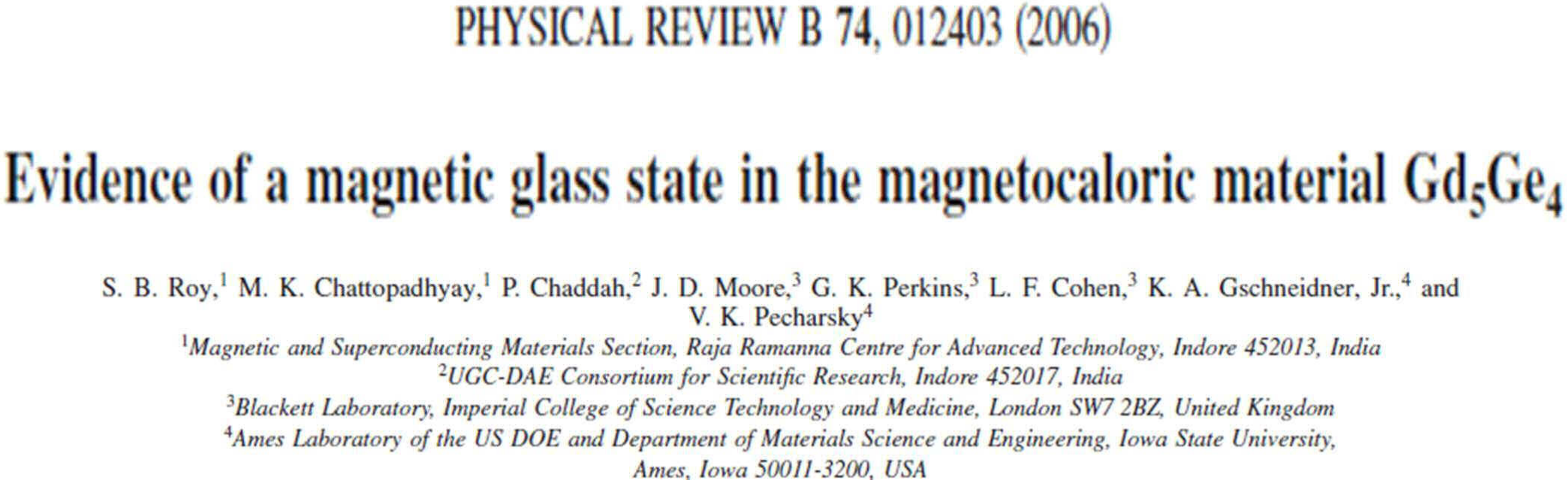
PHYSICAL REVIEW B **73**, 184435 (2006)

Relating supercooling and glass-like arrest of kinetics for phase separated systems: Doped $CeFe_2$ and $(La,Pr,Ca)MnO_3$

Kranti Kumar, A. K. Pramanik, A. Banerjee, and P. Chaddah
UGC-DAE Consortium for Scientific Research (CSR), University Campus, Khandwa Road, Indore 452017, India

S. B. Roy
Magnetic and Superconducting Materials Section, Raja Ramanna Centre for Advanced Technology, Indore 452013, India

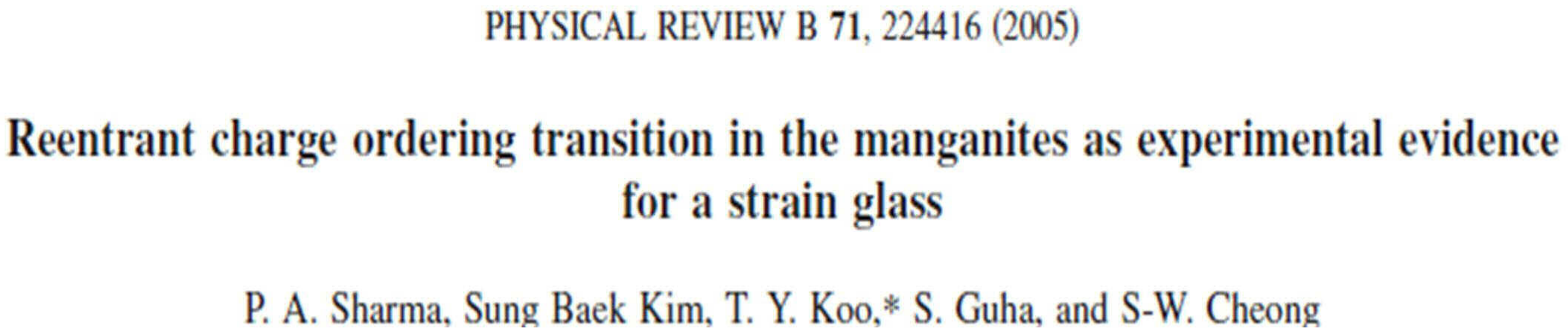
S. Park, C. L. Zhang, and S.-W. Cheong
Department of Physics and Astronomy, Rutgers University, Piscataway, New Jersey 08854, USA



PHYSICAL REVIEW B **74**, 012403 (2006)

Evidence of a magnetic glass state in the magnetocaloric material Gd_5Ge_4

S. B. Roy,[1] M. K. Chattopadhyay,[1] P. Chaddah,[2] J. D. Moore,[3] G. K. Perkins,[3] L. F. Cohen,[3] K. A. Gschneidner, Jr.,[4] and V. K. Pecharsky[4]
[1]*Magnetic and Superconducting Materials Section, Raja Ramanna Centre for Advanced Technology, Indore 452013, India*
[2]*UGC-DAE Consortium for Scientific Research, Indore 452017, India*
[3]*Blackett Laboratory, Imperial College of Science Technology and Medicine, London SW7 2BZ, United Kingdom*
[4]*Ames Laboratory of the US DOE and Department of Materials Science and Engineering, Iowa State University, Ames, Iowa 50011-3200, USA*



PHYSICAL REVIEW B **71**, 224416 (2005)

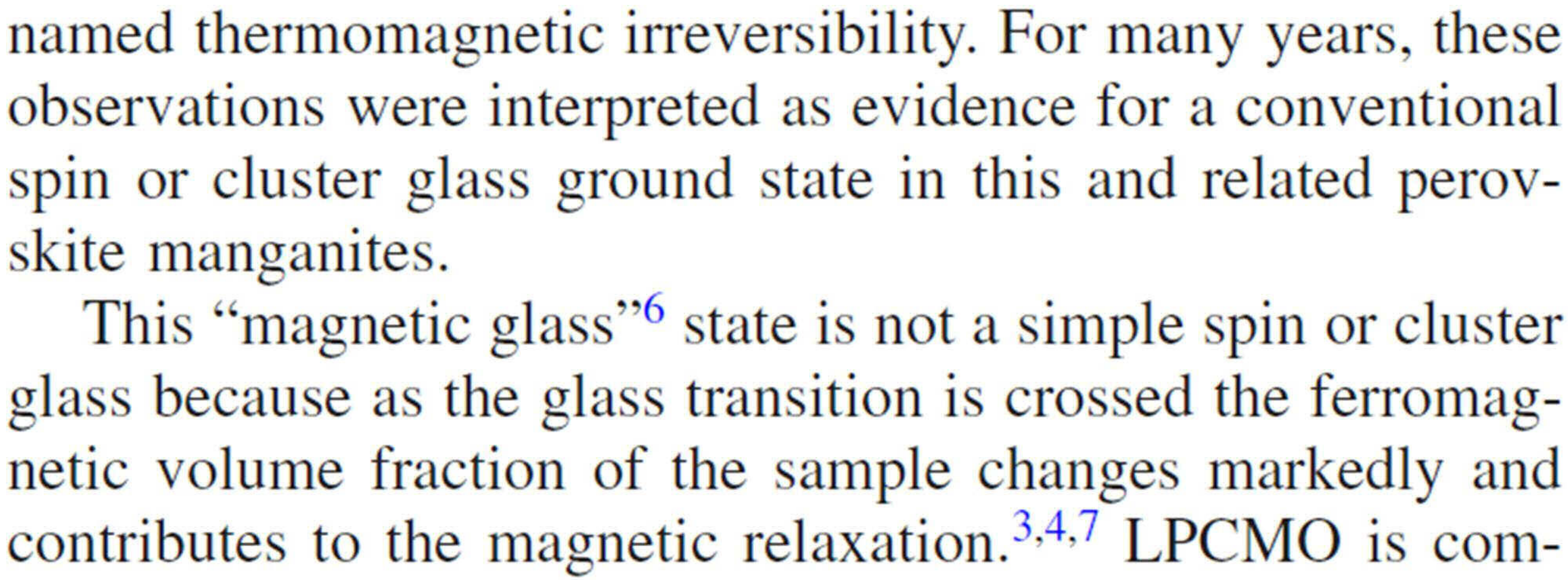
Reentrant charge ordering transition in the manganites as experimental evidence for a strain glass

P. A. Sharma, Sung Baek Kim, T. Y. Koo,* S. Guha, and S-W. Cheong

PHYSICAL REVIEW B **78**, 134205 (2008)

Phase-segregated glass formation linked to freezing of structural interface motion

P. A. Sharma,[1,*] S. El-Khatib,[2] I. Mihut,[3] J. B. Betts,[3] A. Migliori,[3] S. B. Kim,[4] S. Guha,[4] and S.-W. Cheong[4]



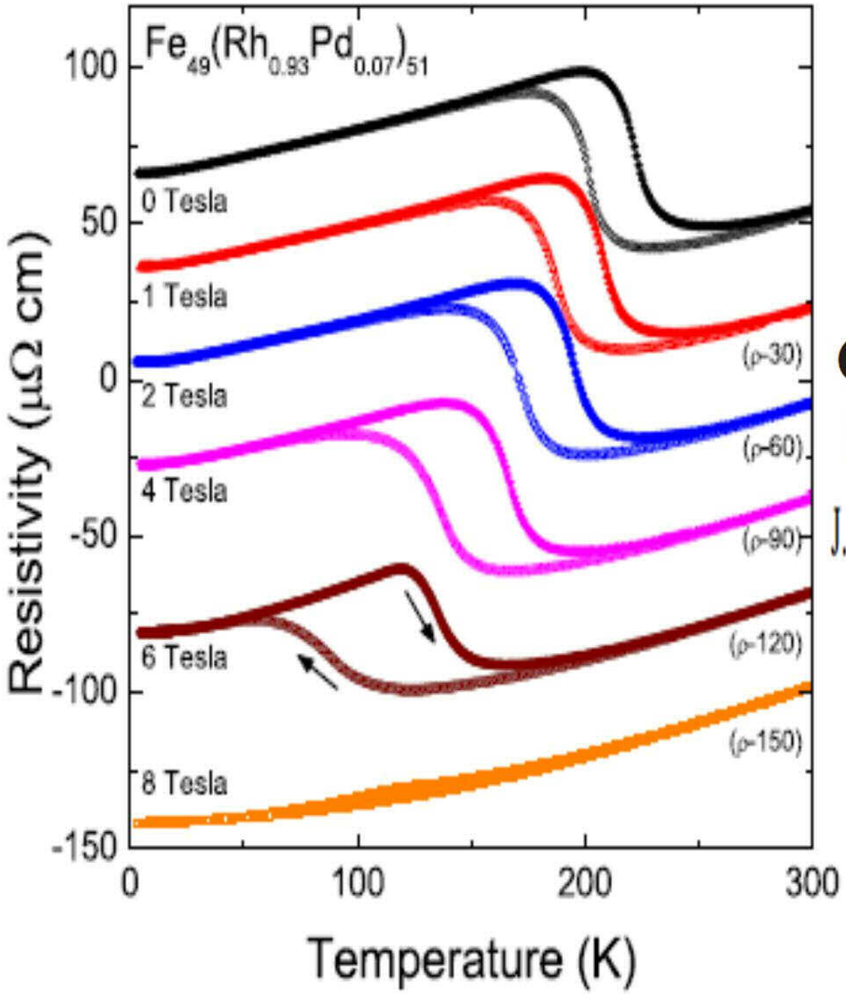
named thermomagnetic irreversibility. For many years, these observations were interpreted as evidence for a conventional spin or cluster glass ground state in this and related perovskite manganites.

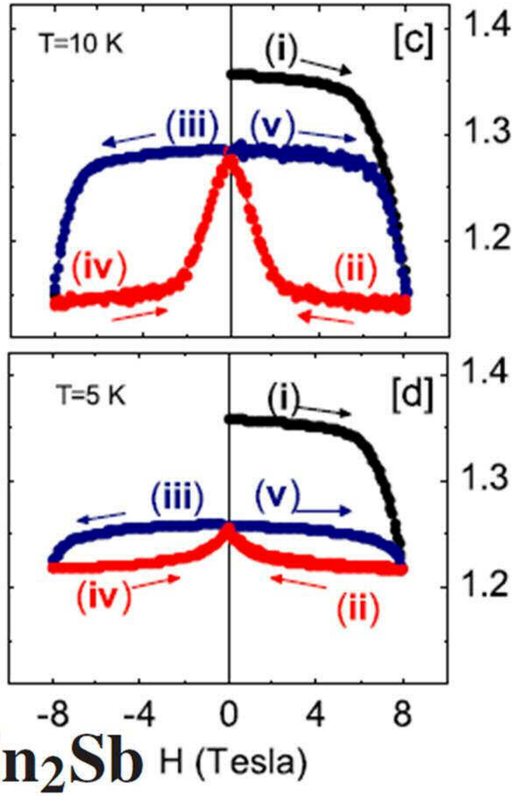
This “magnetic glass”[6] state is not a simple spin or cluster glass because as the glass transition is crossed the ferromagnetic volume fraction of the sample changes markedly and contributes to the magnetic relaxation.[3,4,7] LPCMO is com-

PHYSICAL REVIEW B 80, 174413 (2009)

Low-temperature study of field-induced antiferromagnetic-ferromagnetic transition in Pd-doped Fe-Rh

Pallavi Kushwaha, Archana Lakhani, R. Rawat, and P. Chaddah





Co substituted Mn_2Sb

Pallavi Kushwaha, R Rawat and P Chaddah

J. Phys.: Condens. Matter 20 (2008) 022204

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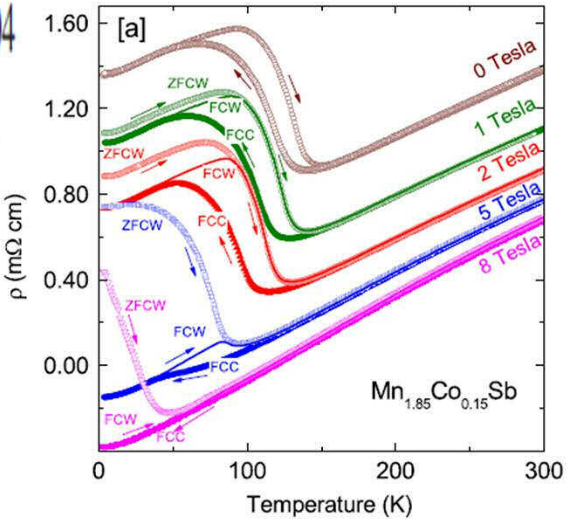
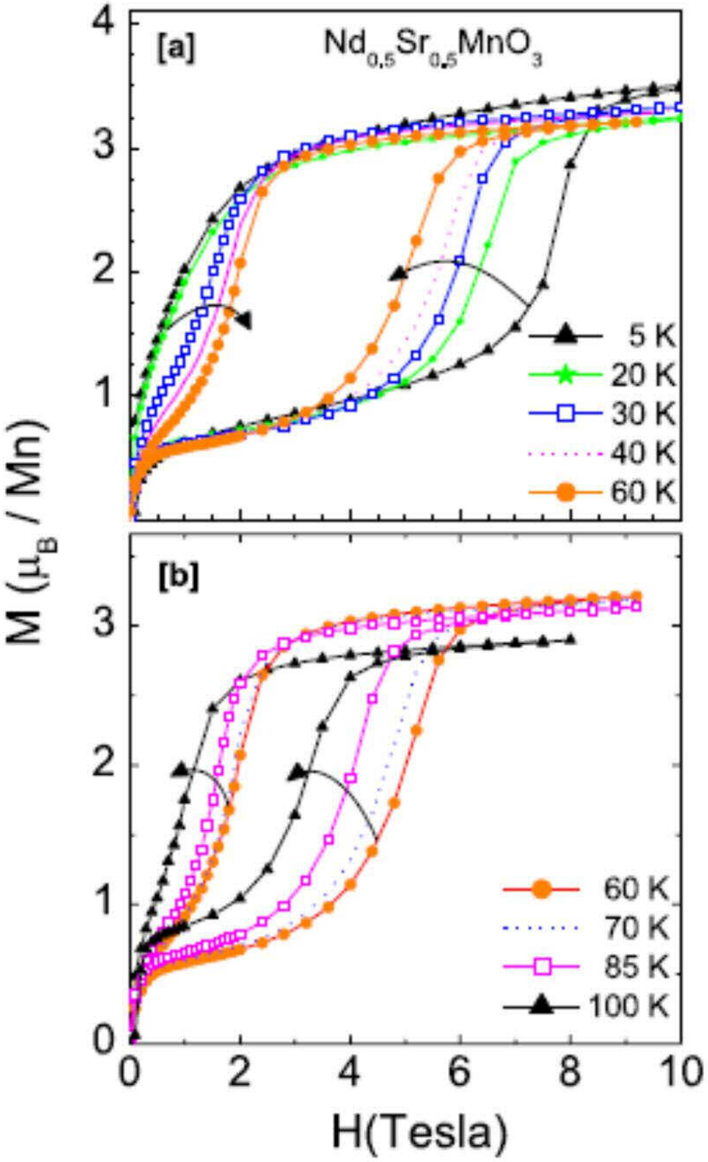
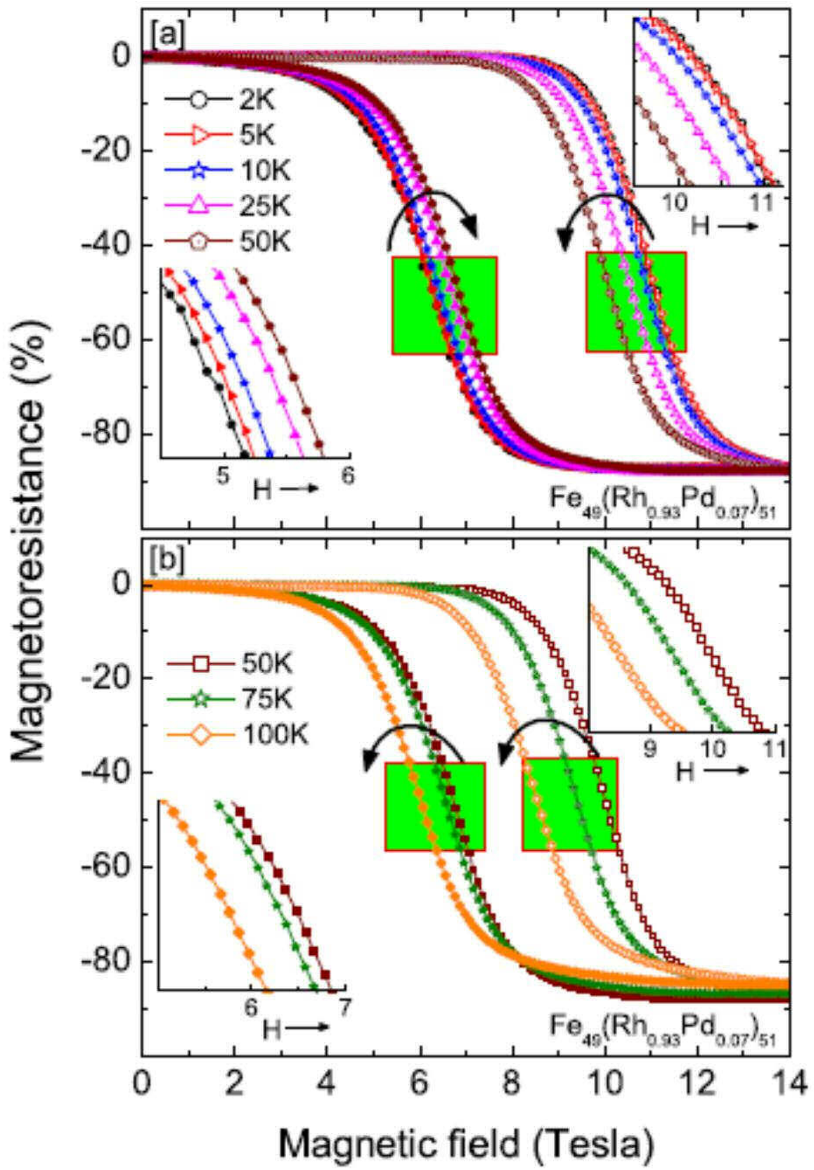


PHYSICAL REVIEW B **80**, 174413 (2009)

J. Phys.: Condens. Matter **19** (2007) 256211

KUSHWAHA *et al.*





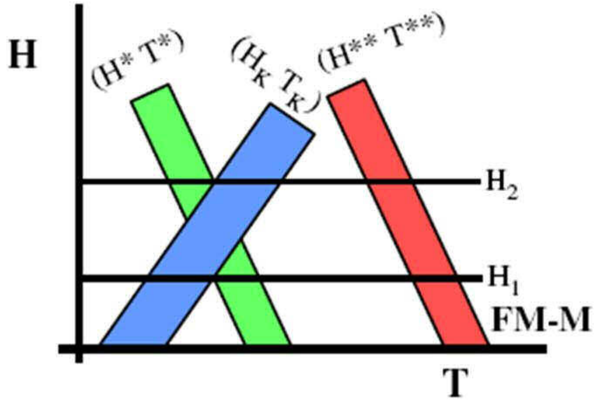
PHYSICAL REVIEW B **84**, 214420 (2011)

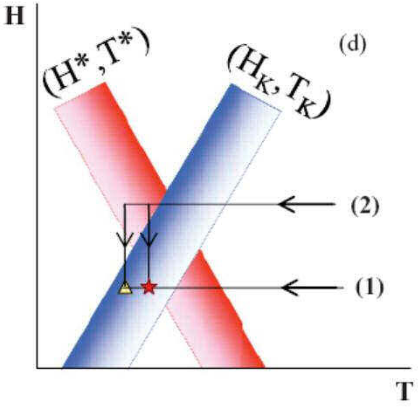
History-dependent nucleation and growth of the martensitic phase in the magnetic shape memory alloy $Ni_{45}Co_5Mn_{38}Sn_{12}$

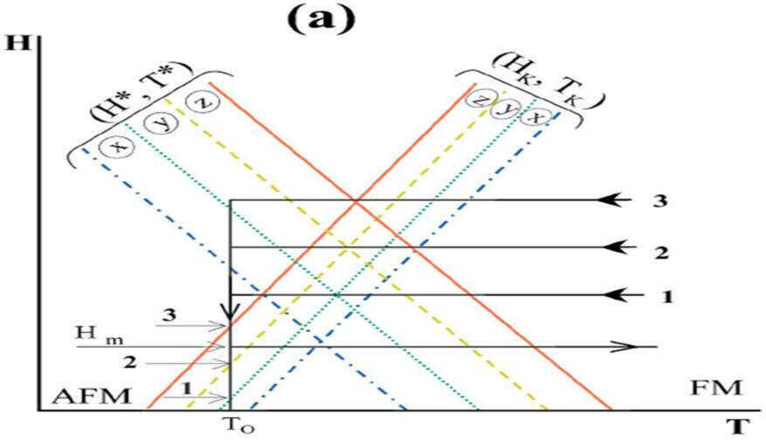
A. Banerjee, P. Chaddah, S. Dash, Kranti Kumar, and Archana Lakhani
UGC-DAE Consortium for Scientific Research, University Campus, Khandwa Road, Indore 452001, Madhya Pradesh, India

X. Chen and R. V. Ramanujan
School of Materials Science and Engineering, Nanyang Technological University, N4.1-01-18, 50 Nanyang Avenue, Singapore 639798

transformation kinetics in monatomic Ge can be inhibited by the "magic ingredient" of pressure[20] and for magnetic systems it is magnetic field H which can be used as the "magic ingredient." It is indeed found that H as a second control variable has a decisive role both for the magnetic first-order transition and on the kinetic arrest of such transformation







FAST TRACK COMMUNICATION

Field dependence of temperature induced irreversible transformations of magnetic phases in $Pr_{0.5}Ca_{0.5}Mn_{0.975}Al_{0.025}O_3$ crystalline oxide

IOP select

Archana Lakhani, Pallavi Kushwaha, R Rawat, Kranti Kumar,
A Banerjee and P Chaddah

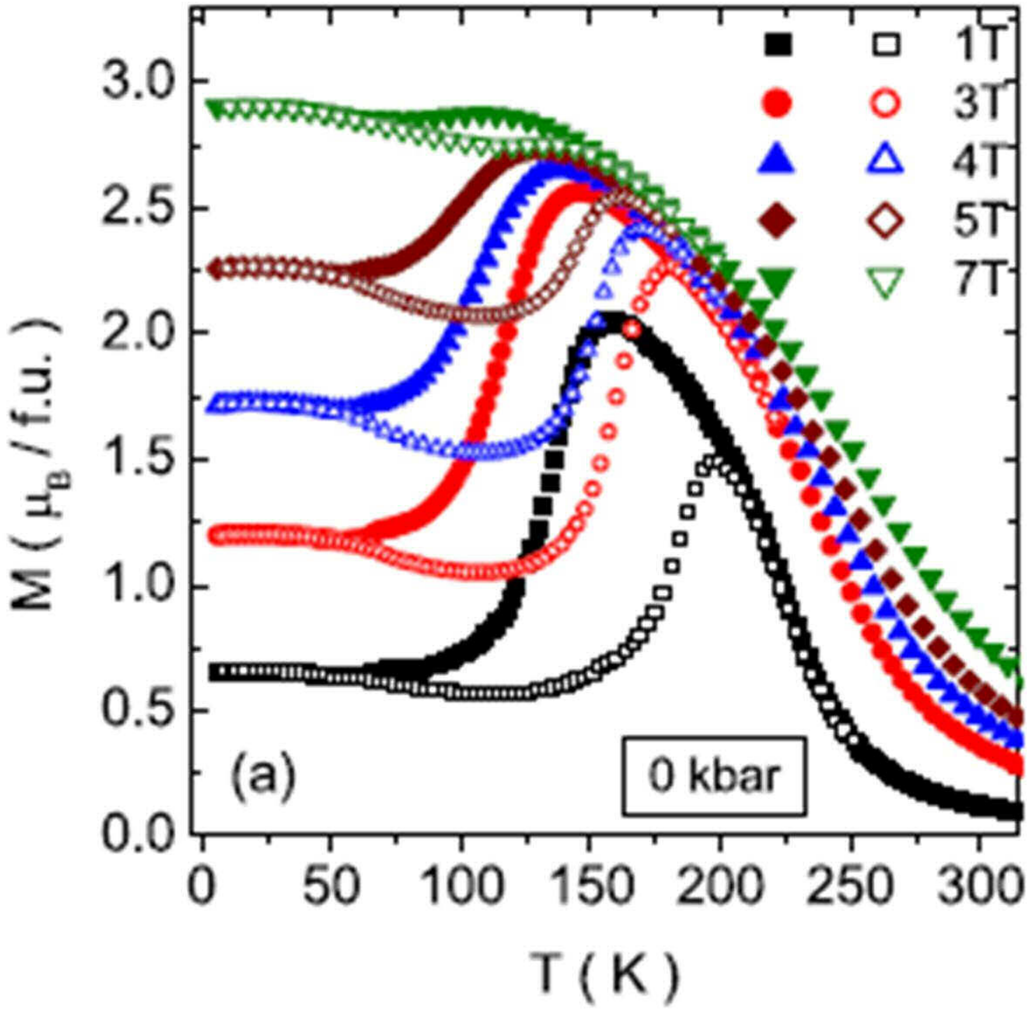
Abstract. Glass-like arrest has recently been reported in various magnetic materials. As in structural glasses, the kinetics of a first order transformation is arrested while retaining the higher entropy phase as a non-ergodic state. We show visual mesoscopic evidence of the irreversible transformation of the arrested antiferromagnetic–insulating phase in $Pr_{0.5}Ca_{0.5}Mn_{0.975}Al_{0.025}O_3$ to its equilibrium ferromagnetic–metallic phase with an isothermal increase of magnetic field, similar to its iso-field transformation on warming. The magnetic field dependence of the non-equilibrium to equilibrium transformation temperature is shown to be governed by Le Chatelier's principle.

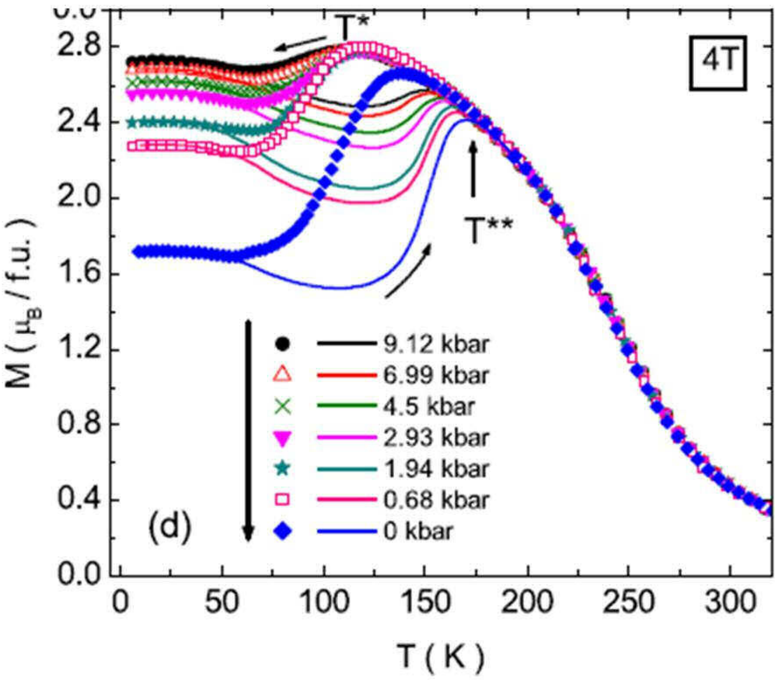
J. Phys.: Condens. Matter **22** (2010) 032101

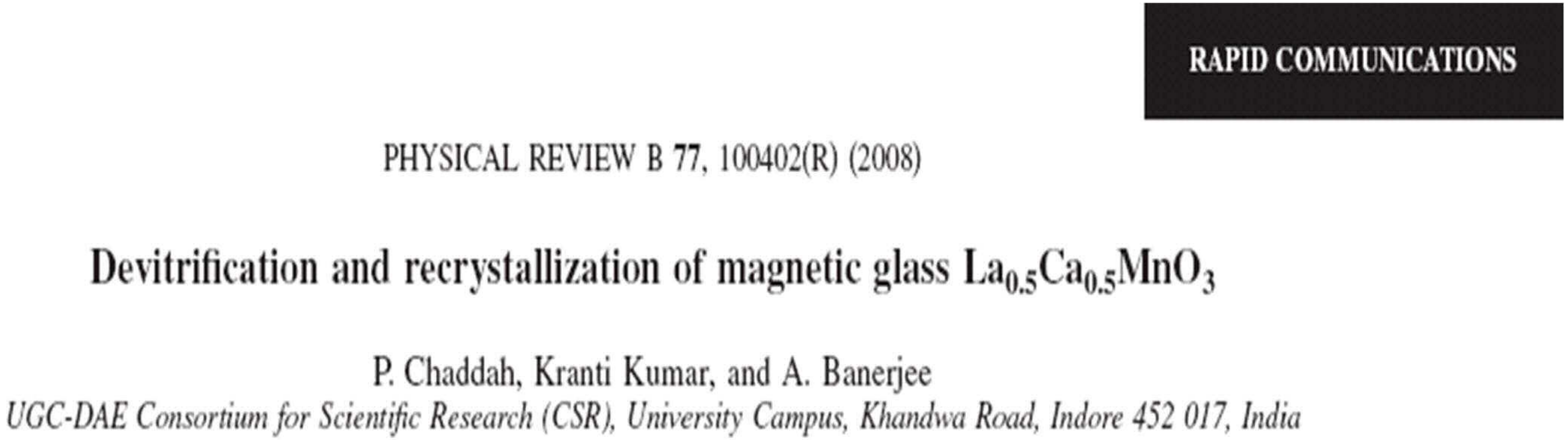
PHYSICAL REVIEW B **82**, 172412 (2010)

Effect of simultaneous application of magnetic field and pressure on magnetic transitions in $La_{0.5}Ca_{0.5}MnO_3$

S. Dash, Kranti Kumar, A. Banerjee, and P. Chaddah
UGC-DAE Consortium for Scientific Research, University Campus, Khandwa Road, Indore 452001, Madhya Pradesh, India







RAPID COMMUNICATIONS

PHYSICAL REVIEW B **77**, 100402(R) (2008)

Devitrification and recrystallization of magnetic glass $La_{0.5}Ca_{0.5}MnO_3$

P. Chaddah, Kranti Kumar, and A. Banerjee

UGC-DAE Consortium for Scientific Research (CSR), University Campus, Khandwa Road, Indore 452 017, India

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PHYSICAL REVIEW B **84**, 214420 (2011)

History-dependent nucleation and growth of the martensitic phase in the magnetic shape memory alloy $Ni_{45}Co_5Mn_{38}Sn_{12}$

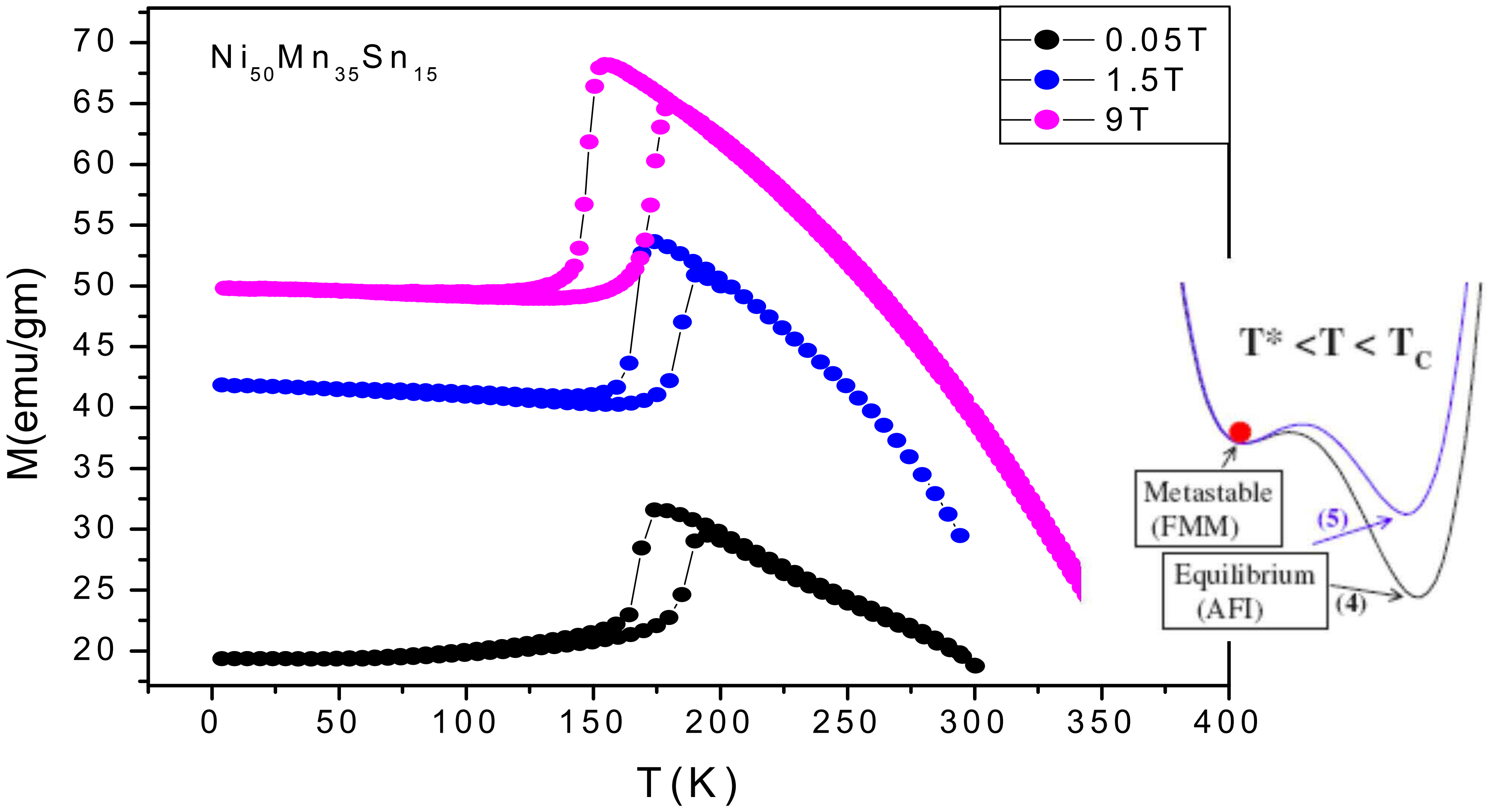
A. Banerjee, P. Chaddah, S. Dash, Kranti Kumar, and Archana Lakhani

UGC-DAE Consortium for Scientific Research, University Campus, Khandwa Road, Indore 452001, Madhya Pradesh, India

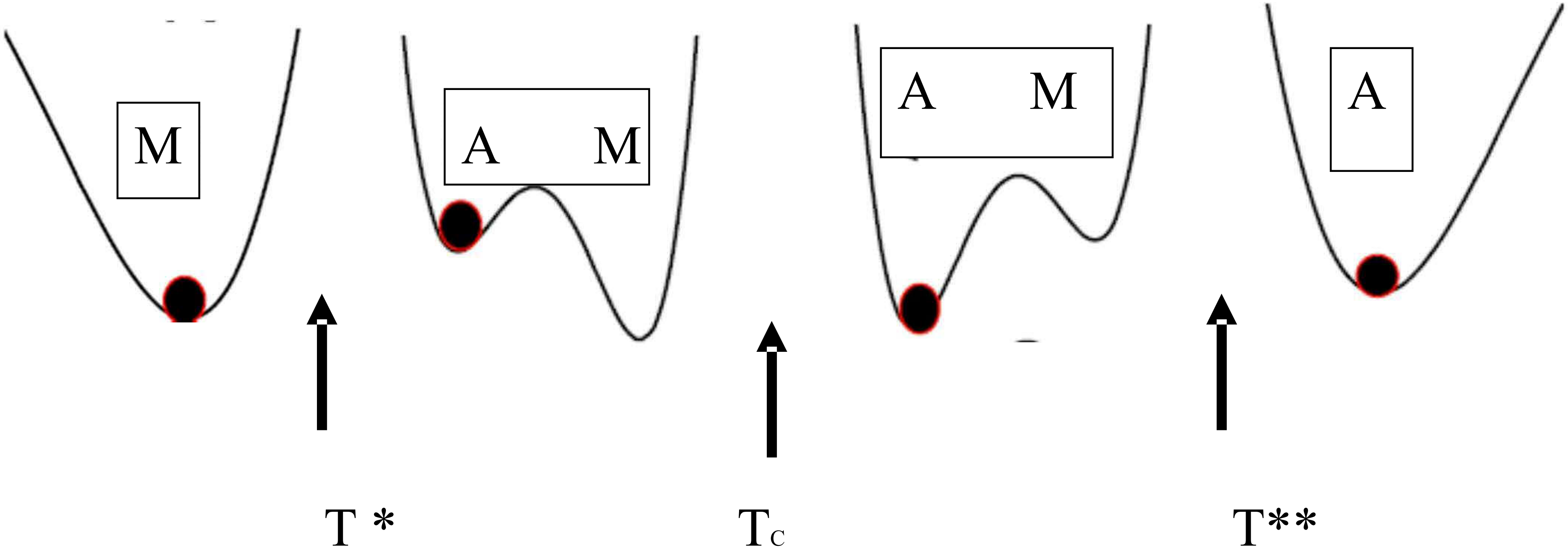
X. Chen and R. V. Ramanujan

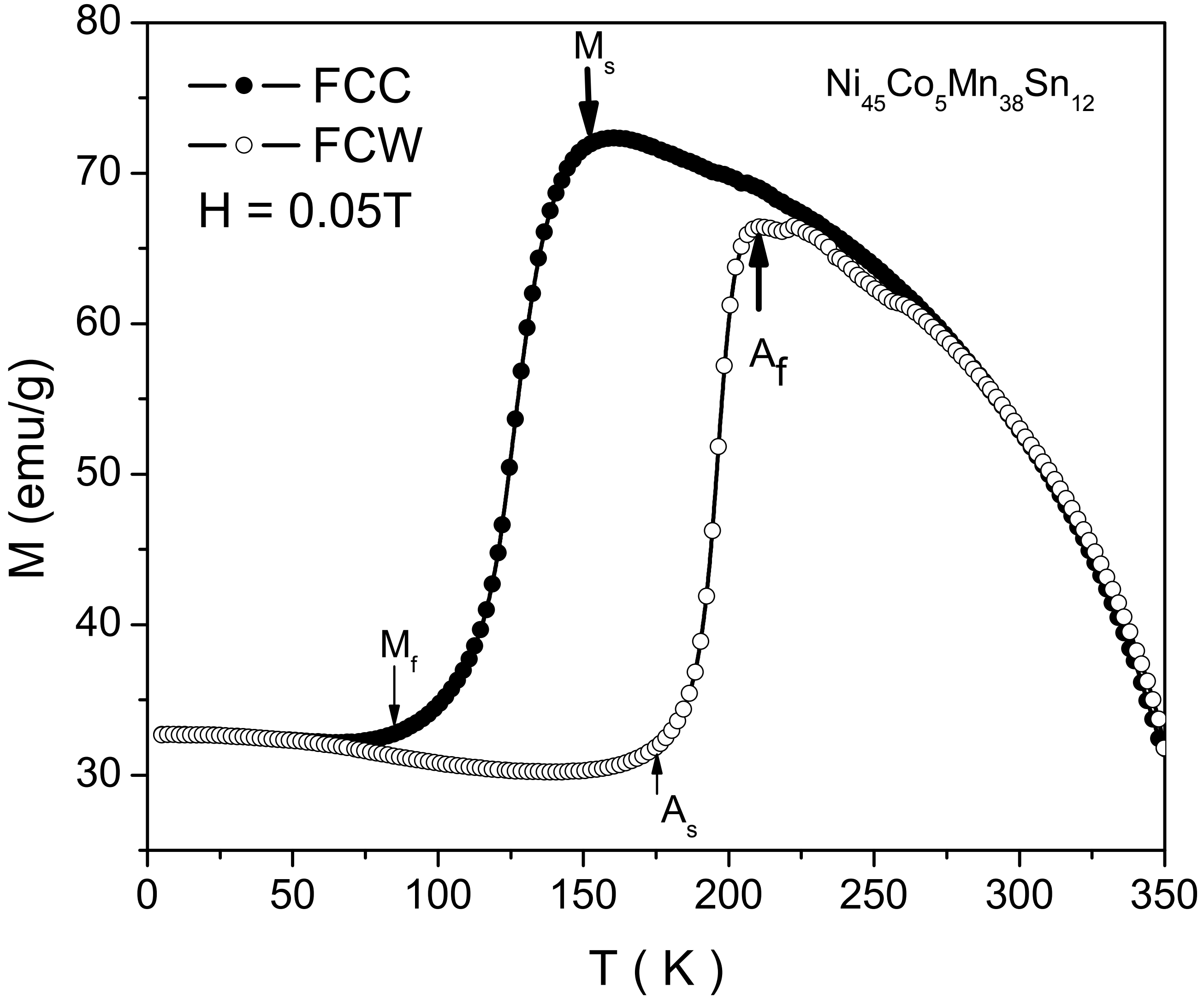
School of Materials Science and Engineering, Nanyang Technological University, N4.1-01-18, 50 Nanyang Avenue, Singapore 639798

Magnetization Measurements on $Ni_{50}Mn_{35}Sn_{15}$ Ribbon (prepared by Melt spinning)



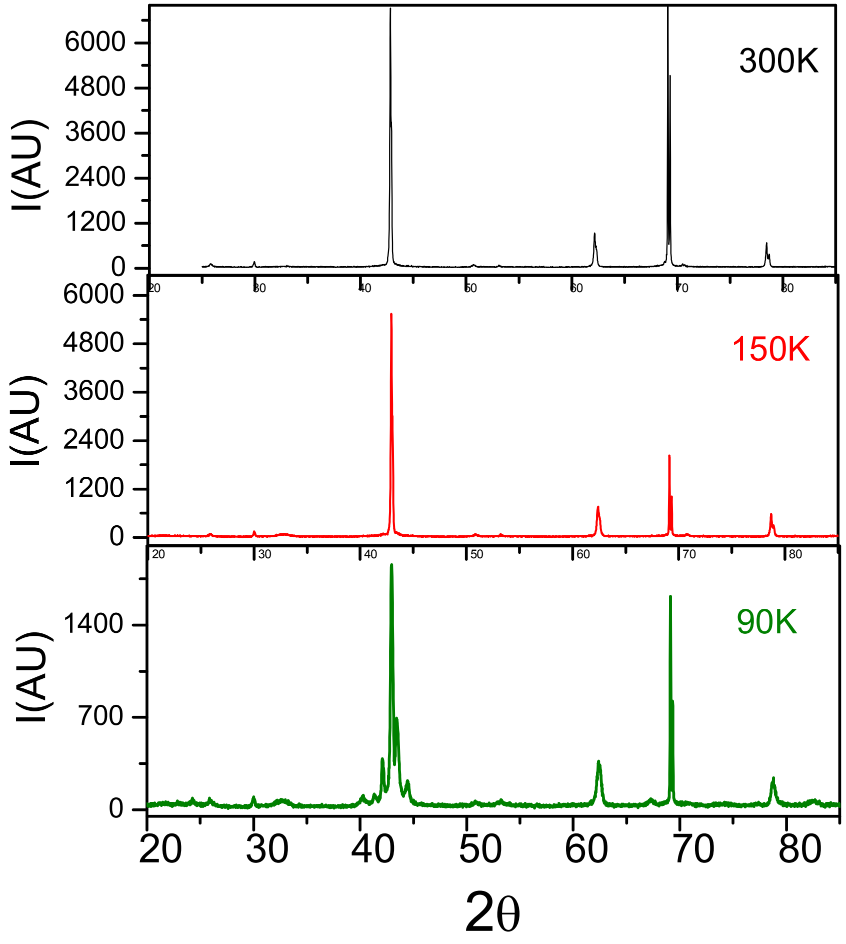
Alok Banerjee, S Dash, Archana Lakhani, Ramanujan et al

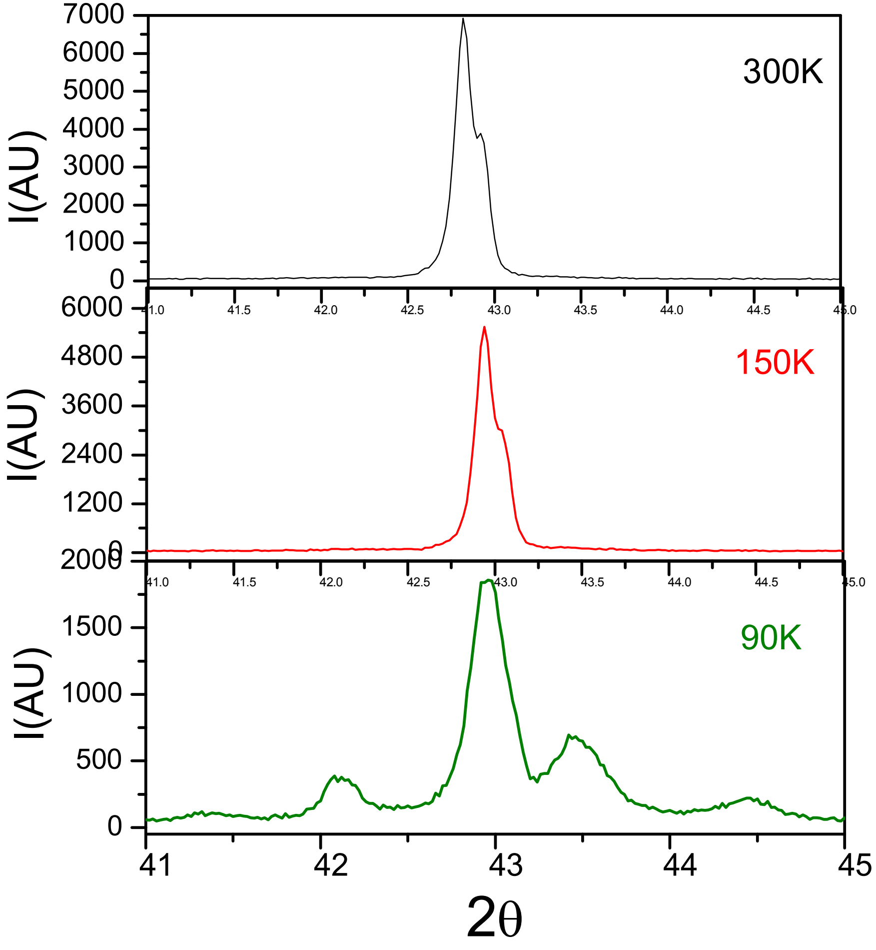

M
A M
A M
A
T *
T_C
T**



Alok Banerjee, S Dash, Archana Lakhani, Prof Ramanujan et al

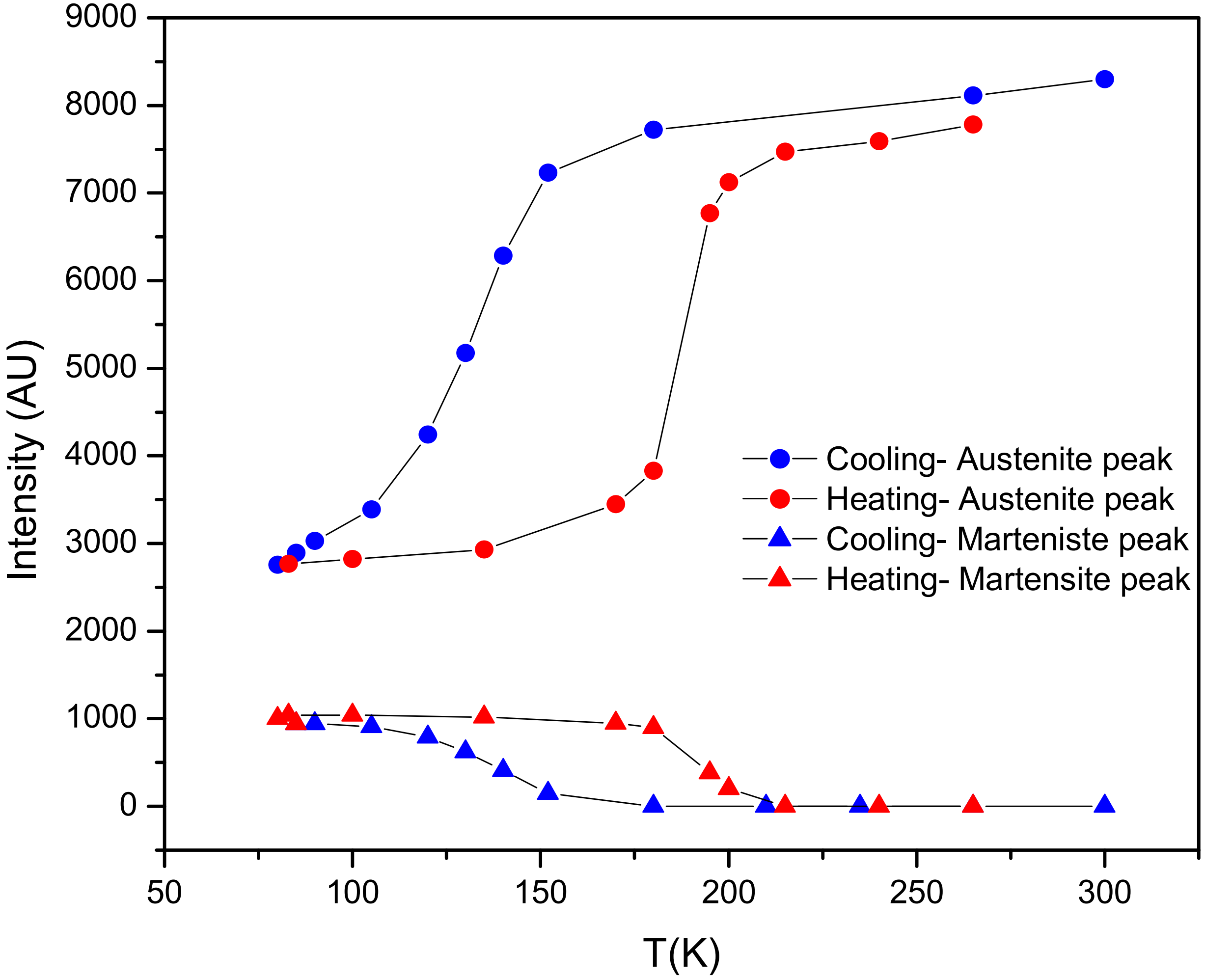
$Ni_{45}Co_5Mn_{38}Sn_{12}$ Ribbon XRD





N P Lalla et al

Intensity vs. Temperature plot for Austenite and Martensite peak height in $Ni_{45}Co_5Mn_{38}Sn_{12}$



N P Lalla et al

Can measure thru structure → both crystal & magnetic →Both X-ray and neutron diffrcn.

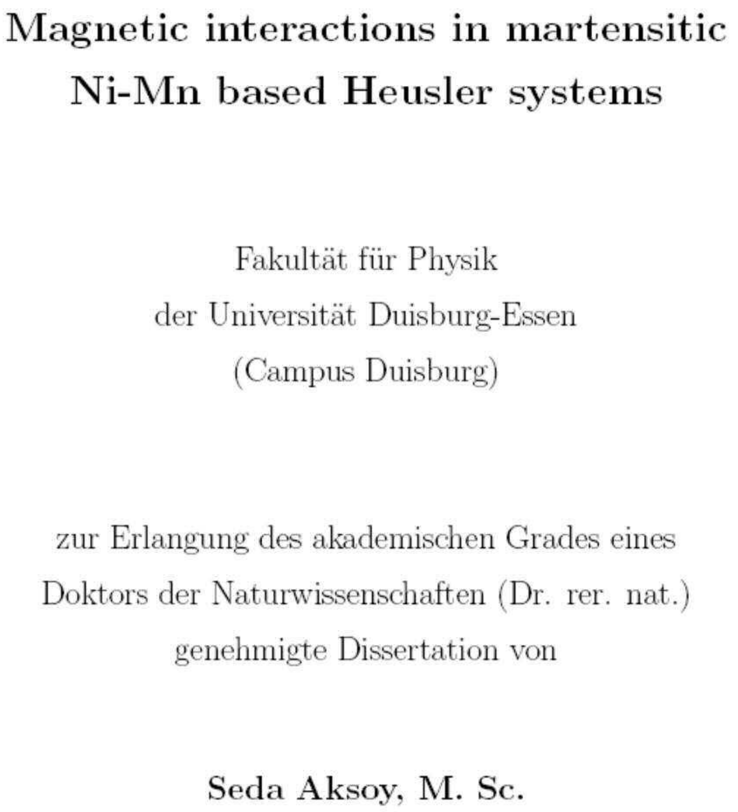
PHYSICAL REVIEW B 75, 184412 (2007)

Cooling and heating by adiabatic magnetization in the $Ni_{50}Mn_{34}In_{16}$ magnetic shape-memory alloy

Xavier Moya, Lluís Mañosa,* and Antoni Planes
Departament d'Estructura i Constituents de la Matèria, Facultat de Física, Universitat de Barcelona, Diagonal 647, E-08028 Barcelona, Catalonia

Seda Aksoy, Mehmet Acet, Eberhardt F. Wassermann, and Thorsten Krenke†
Fachbereich Physik, Experimentalphysik, Universität Duisburg-Essen, D-47048 Duisburg, Germany

(Received 17 January 2007; published 14 May 2007)

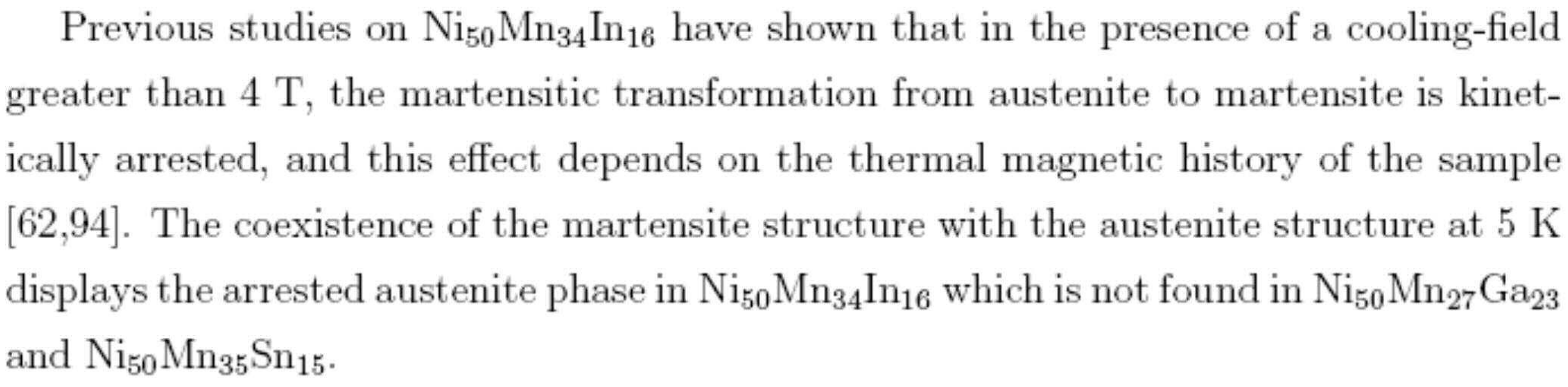


Magnetic interactions in martensitic Ni-Mn based Heusler systems

Fakultät für Physik
der Universität Duisburg-Essen
(Campus Duisburg)

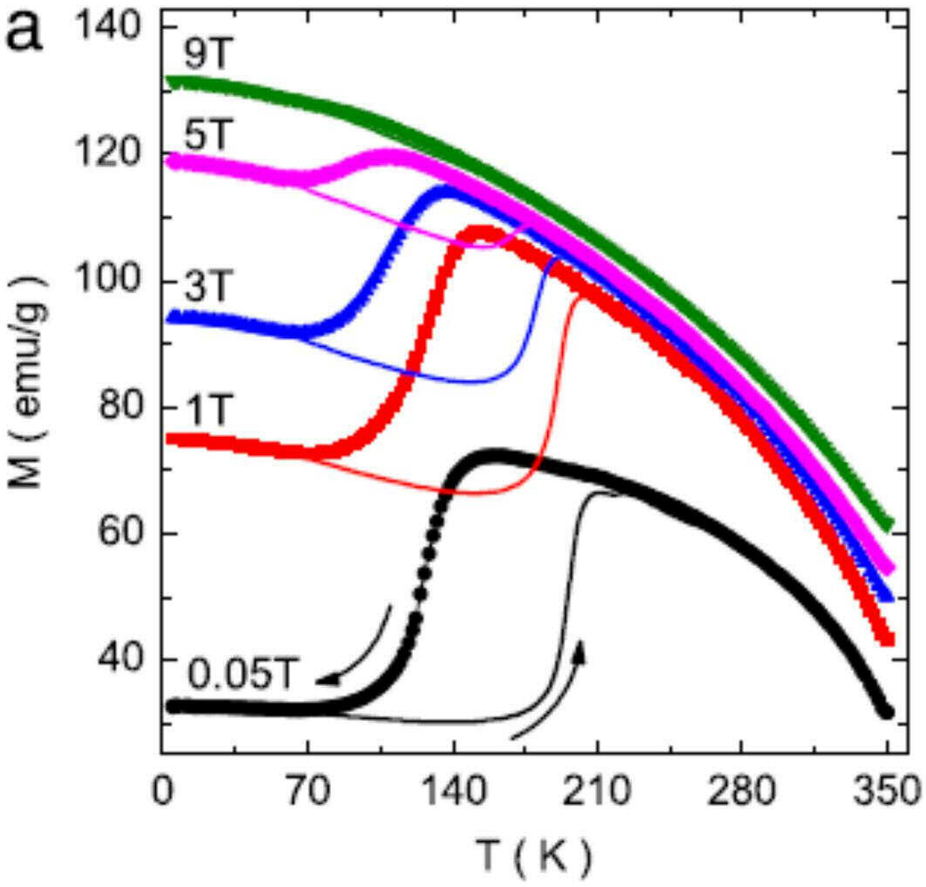
zur Erlangung des akademischen Grades eines
Doktors der Naturwissenschaften (Dr. rer. nat.)
genehmigte Dissertation von

Seda Aksoy, M. Sc.



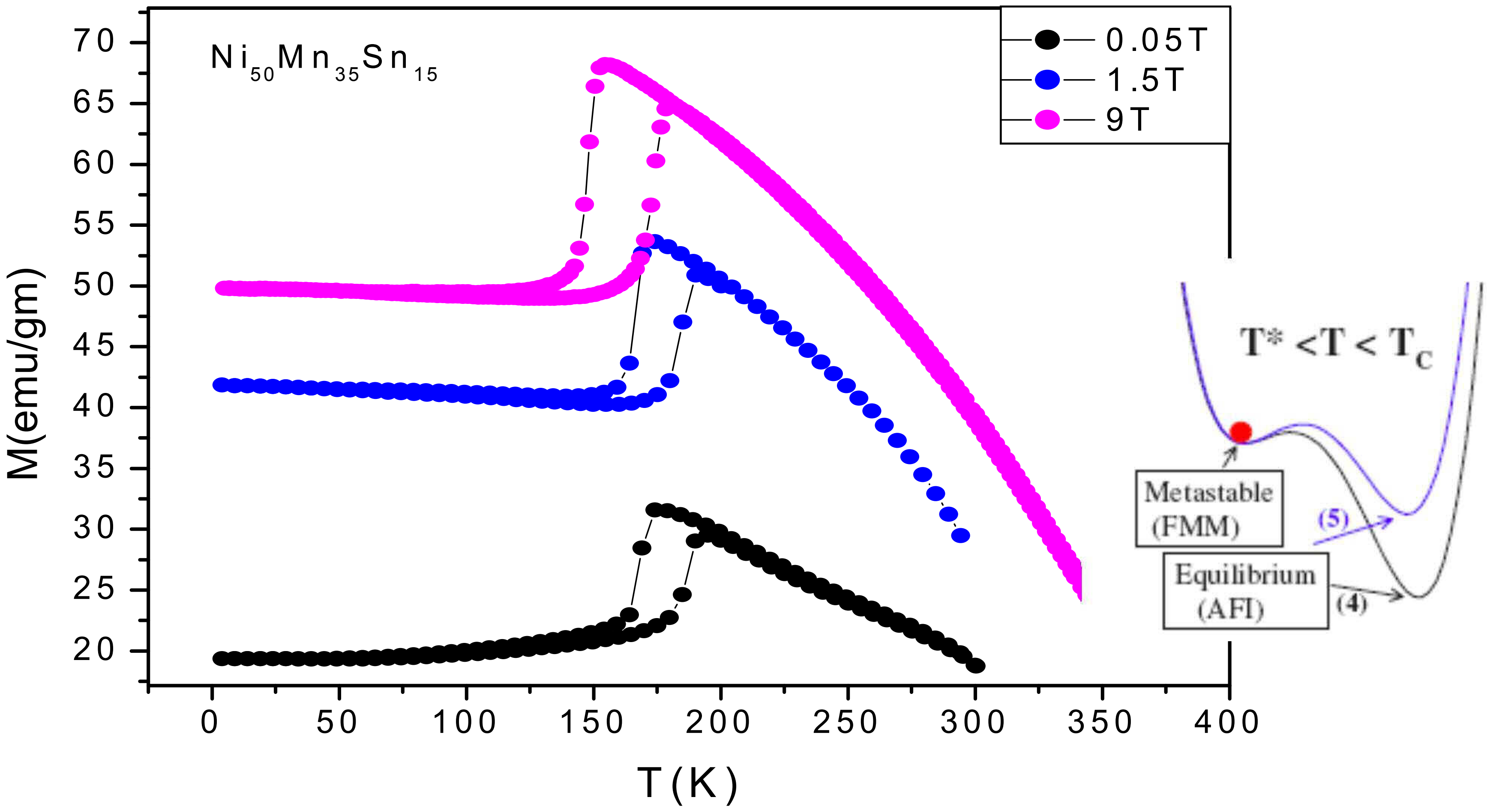
Previous studies on $Ni_{50}Mn_{34}In_{16}$ have shown that in the presence of a cooling-field greater than 4 T, the martensitic transformation from austenite to martensite is kinetically arrested, and this effect depends on the thermal magnetic history of the sample [62,94]. The coexistence of the martensite structure with the austenite structure at 5 K displays the arrested austenite phase in $Ni_{50}Mn_{34}In_{16}$ which is not found in $Ni_{50}Mn_{27}Ga_{23}$ and $Ni_{50}Mn_{35}Sn_{15}$.

alloy $Ni_{45}Co_5Mn_{38}Sn_{12}$



A. Banerjee et al. / Solid State Communications 151 (2011) 971–975

Magnetization Measurements on $Ni_{50}Mn_{35}Sn_{15}$ Ribbon (prepared by Melt spinning)



Alok Banerjee, S Dash, Archana Lakhani, Ramanujan et al

A. Banerjee et al. / Solid State Communications 151 (2011) 971–975

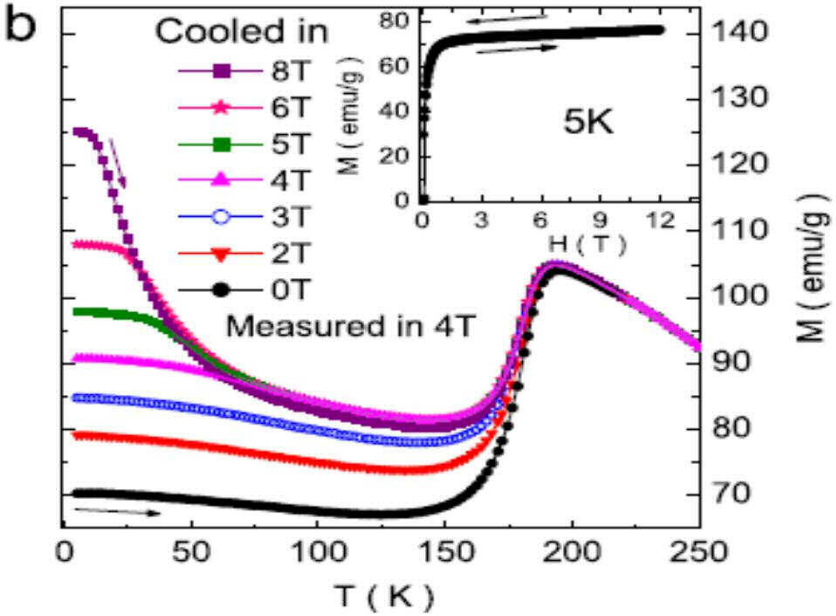


Fig. 3(b) shows a representative measurement following CHUF protocol where magnetization is measured in 4 T while warming after cooling in different fields. While cooling in higher fields, larger fraction of austenite is accrued which remains as a metastable arrested phase at low *T*. If the measuring (warming) field is lower, then this metastable austenite will dearrest to the stable martensitic phase at low *T* while warming and the magnetization will show a sharp fall. This will be followed by usual conversion of martensitic to austenite phase at higher temperature showing a double (re-entrant) transition. On the contrary, if the measuring (warming) field is higher than the cooling field then the sharp fall corresponding to dearrest will not occur. The smaller fraction of the

PHYSICAL REVIEW B **84**, 214420 (2011)

History-dependent nucleation and growth of the martensitic phase in the magnetic shape memory alloy $Ni_{45}Co_5Mn_{38}Sn_{12}$

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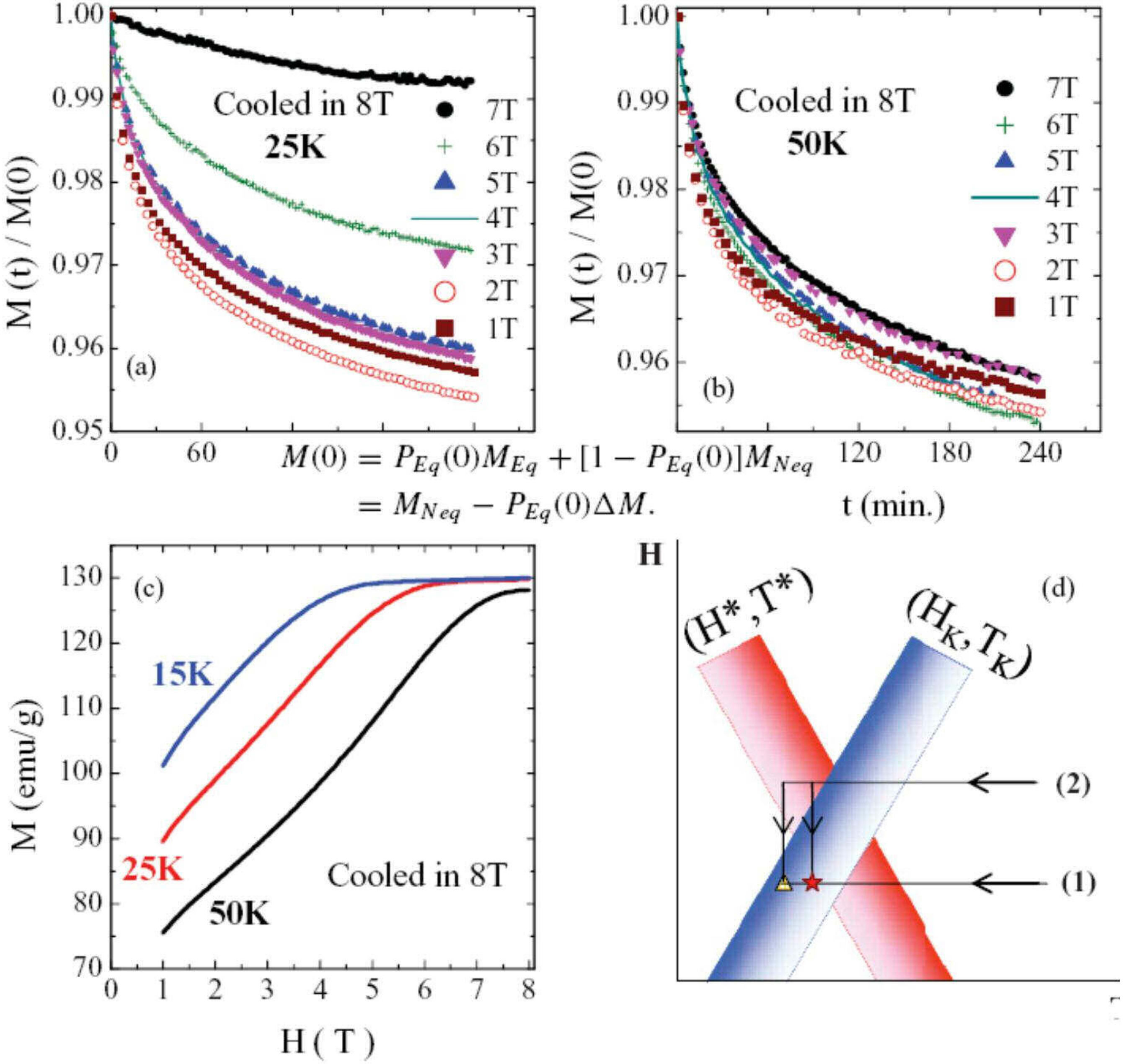
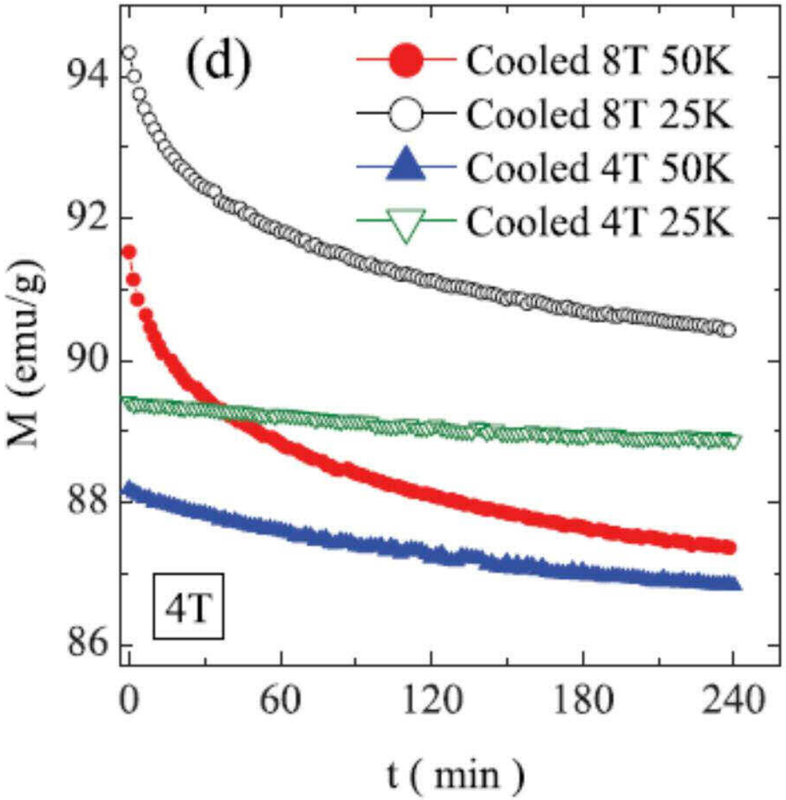
parameter H and allows us to initiate nucleation at much lower temperatures by traversing different H-T paths. Recently, it has been shown for a CMR manganite that even for the same degree of metastability or the same fraction of nonequilibrium phase the rate of growth depend on the H-T history.[31] This is attributed to the H-T path dependent critical radius of

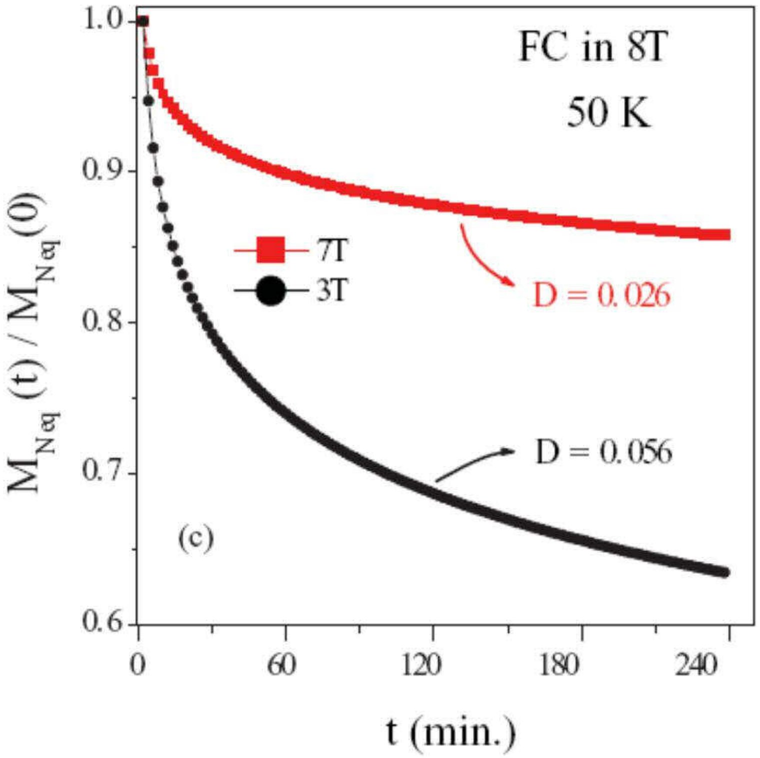


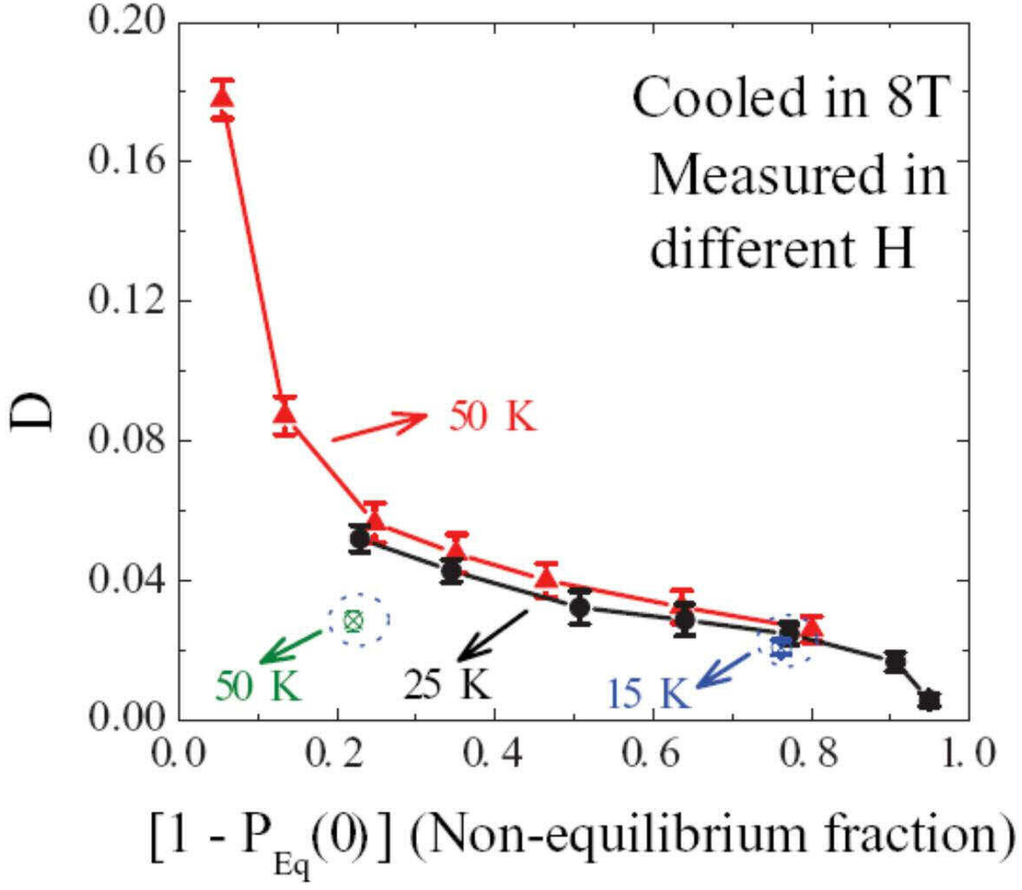
$$M(0) = P_{Eq}(0)M_{Eq} + [1 - P_{Eq}(0)]M_{Neq}$$
$$= M_{Neq} - P_{Eq}(0)\Delta M.$$

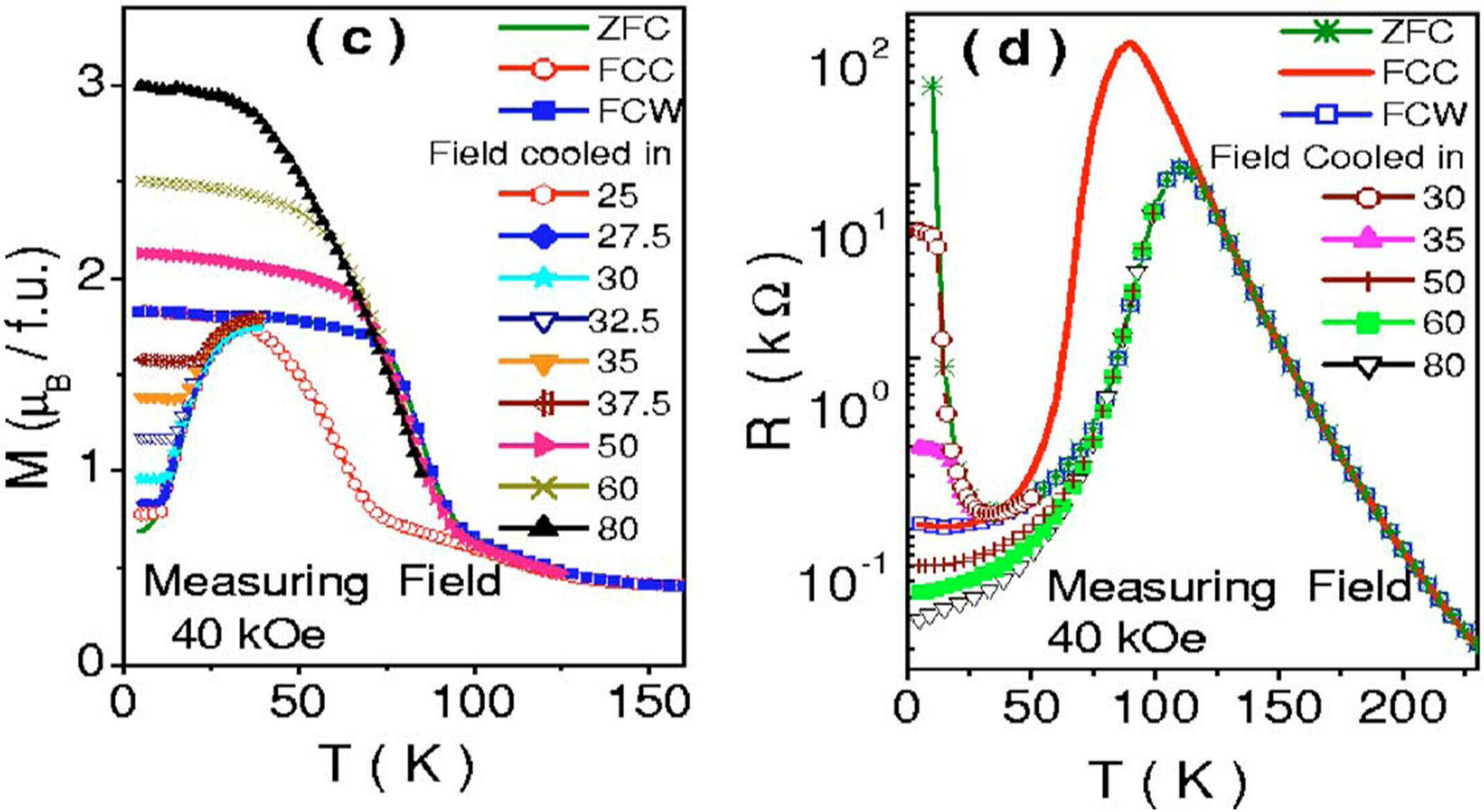


$$\begin{aligned} M(0) &= P_{Eq}(0)M_{Eq} + [1 - P_{Eq}(0)]M_{Neq} \\ &= M_{Neq} - P_{Eq}(0)\Delta M. \end{aligned}$$

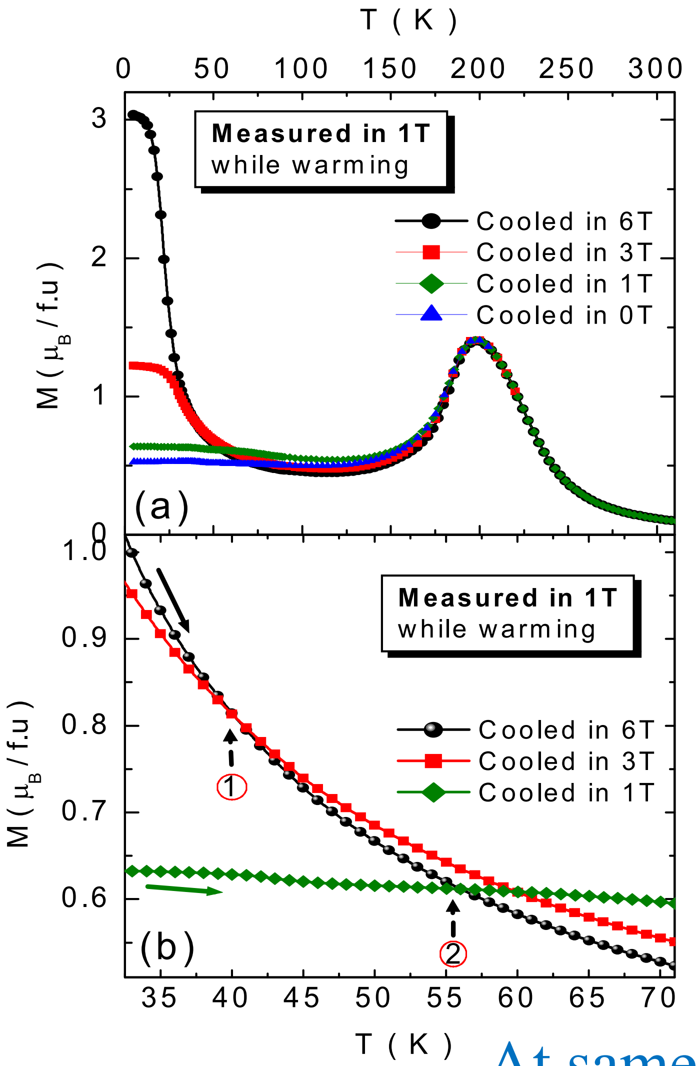
$$P_{Neq}(t) = P_{Neq}(0)\,[1 - D\ln(t/t_0)],$$

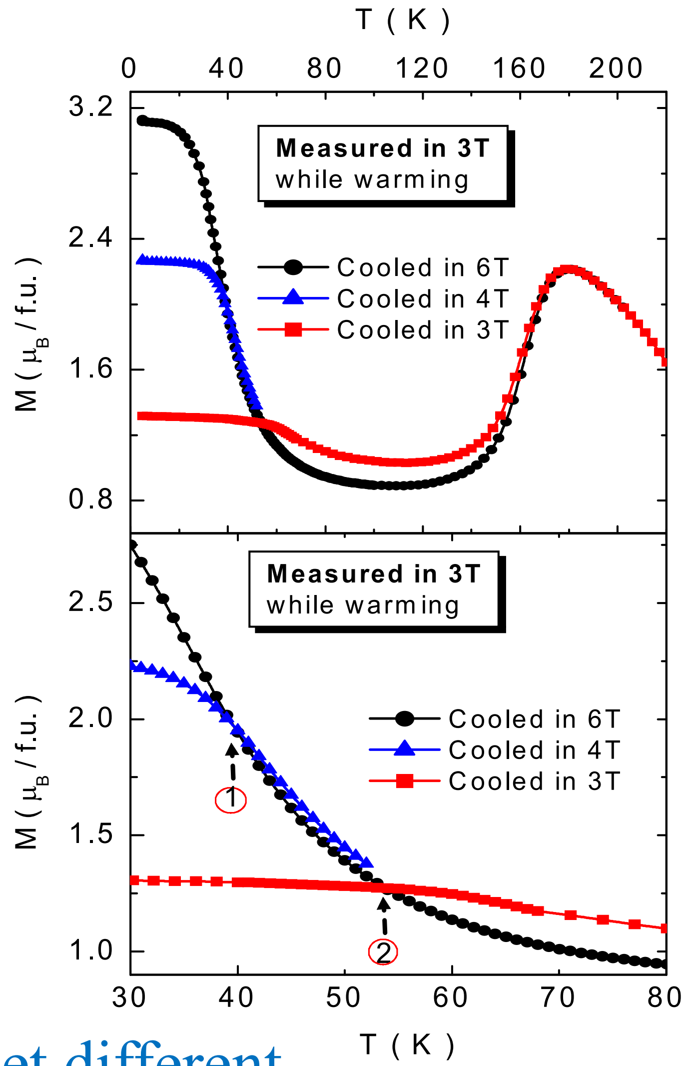



Cooled in 8T
Measured in
different H
D
0.20
0.16
0.12
0.08
0.04
0.00
0.0
0.2
0.4
0.6
0.8
1.0
50 K
50 K
25 K
15 K
[1 - P_Eq(0)] (Non-equilibrium fraction)



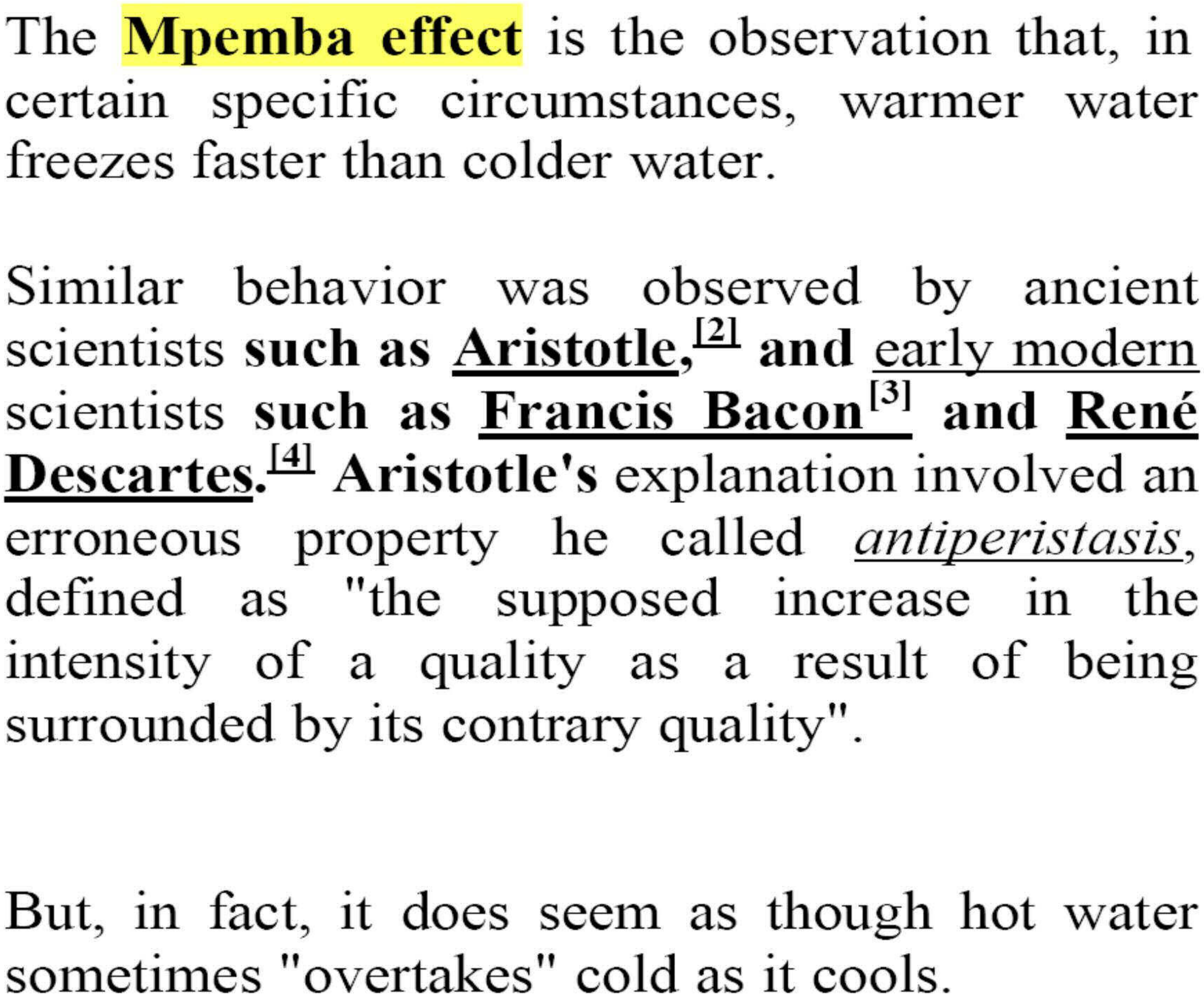
BANERJEE *et al.* PHYSICAL REVIEW B **74**, 224445 (2006)





At same (T,H) we get different values of M depending on the history. At same (T,H,M) we get different .

Alok Banerjee



The **Mpemba effect** is the observation that, in certain specific circumstances, warmer water freezes faster than colder water.

Similar behavior was observed by ancient scientists **such as Aristotle,**[2] **and** early modern scientists **such as Francis Bacon**[3] **and René Descartes.**[4] **Aristotle's** explanation involved an erroneous property he called *antiperistasis*, defined as "the supposed increase in the intensity of a quality as a result of being surrounded by its contrary quality".

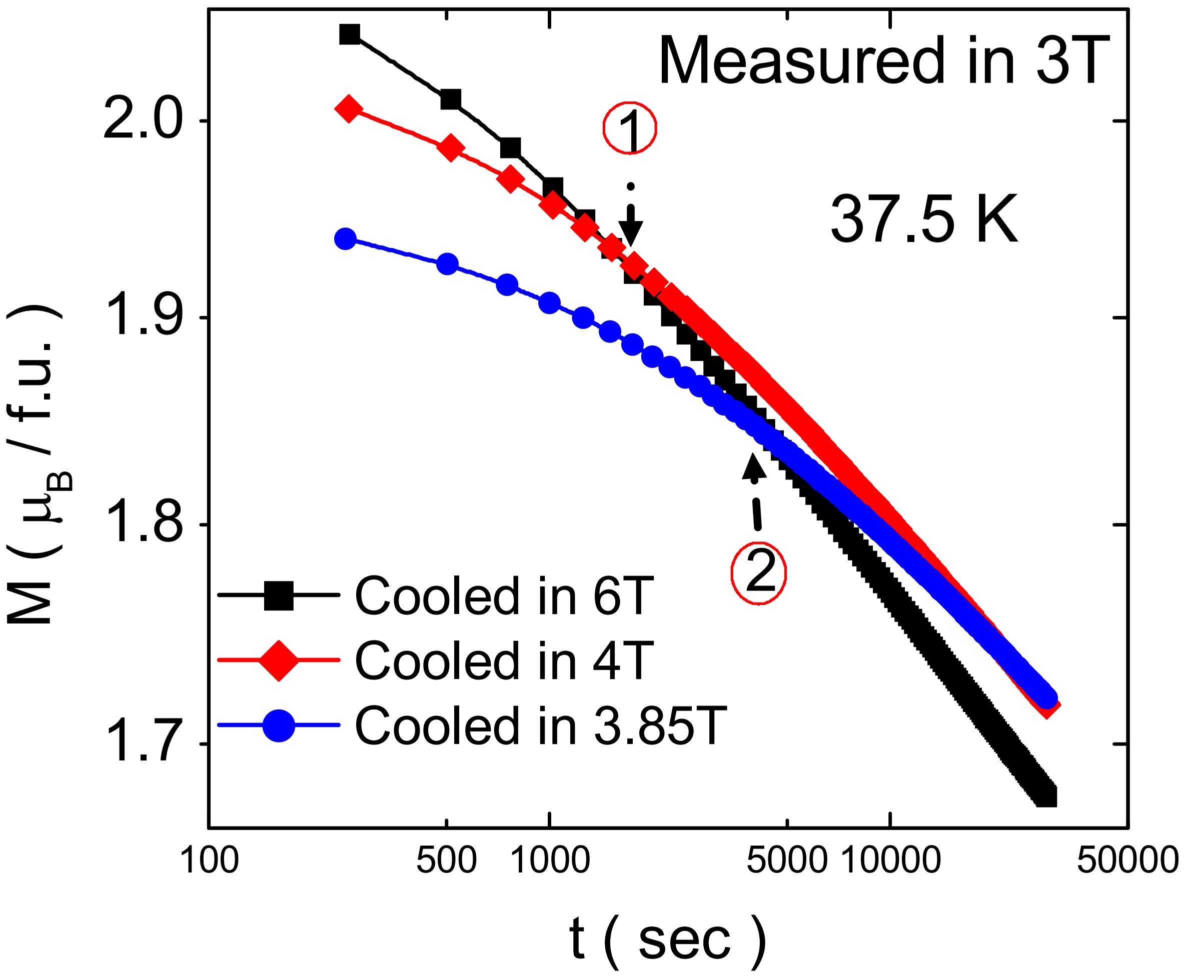
But, in fact, it does seem as though hot water sometimes "overtakes" cold as it cools.

Water shows supercooling, superheating, glass state & Mpemba effect!!

Does hot water freeze first?

Mar 29, 2006

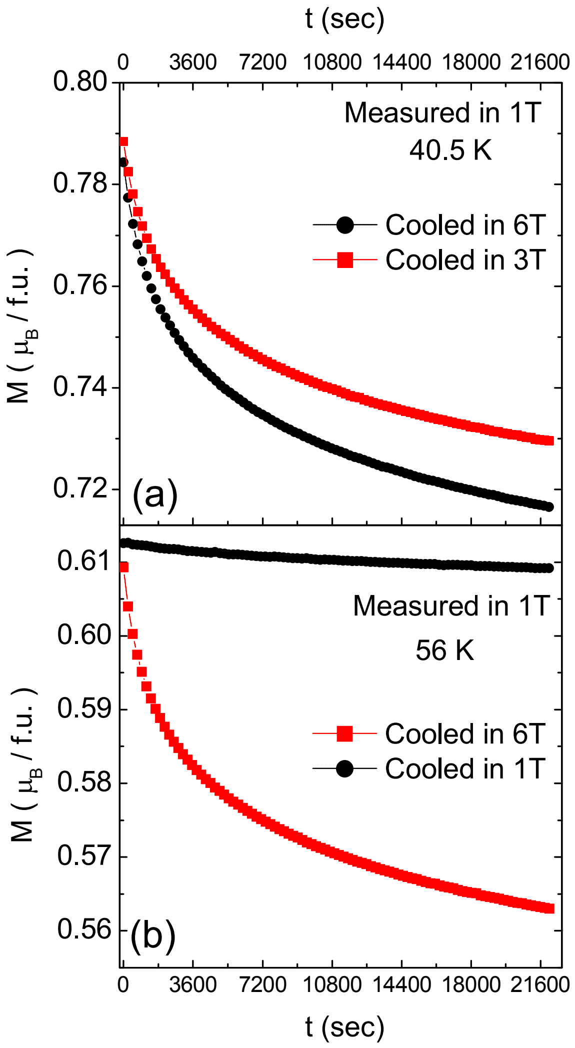
Since the time of Aristotle, some scientists have claimed that hot water freezes faster than cold. Philip Ball looks at current attempts to shed light on this puzzling phenomenon. It sounds like the kind of question you would be dismayed to hear schoolchildren getting wrong: which takes less time to freeze, cold or hot water? Common sense and the laws of thermodynamics appear to insist that cold water must freeze first.

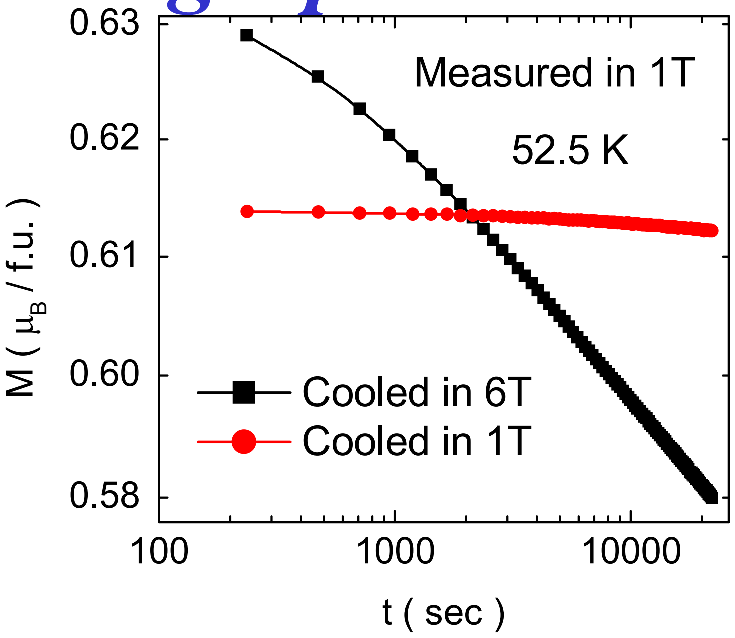


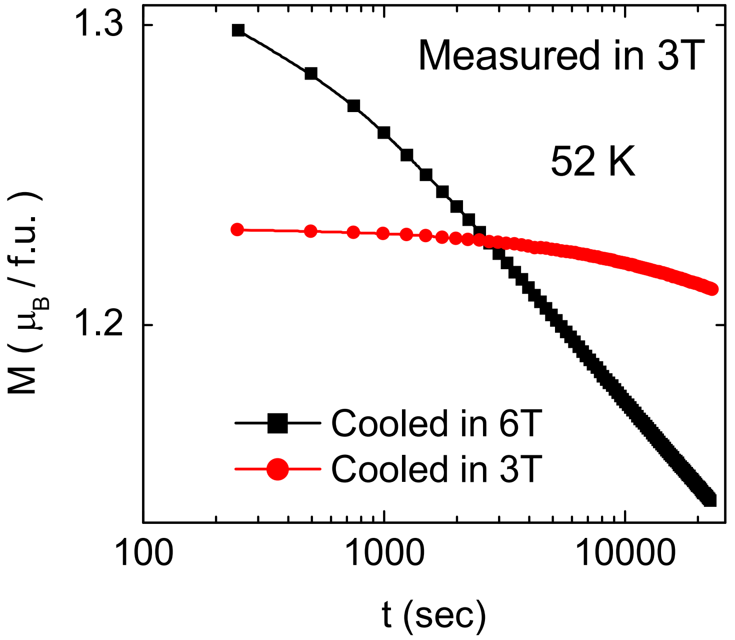
Overtaking, while approaching equilibrium

Chaddah et al arXiv.org:1011.3598

Overtaking, while approaching equilibrium

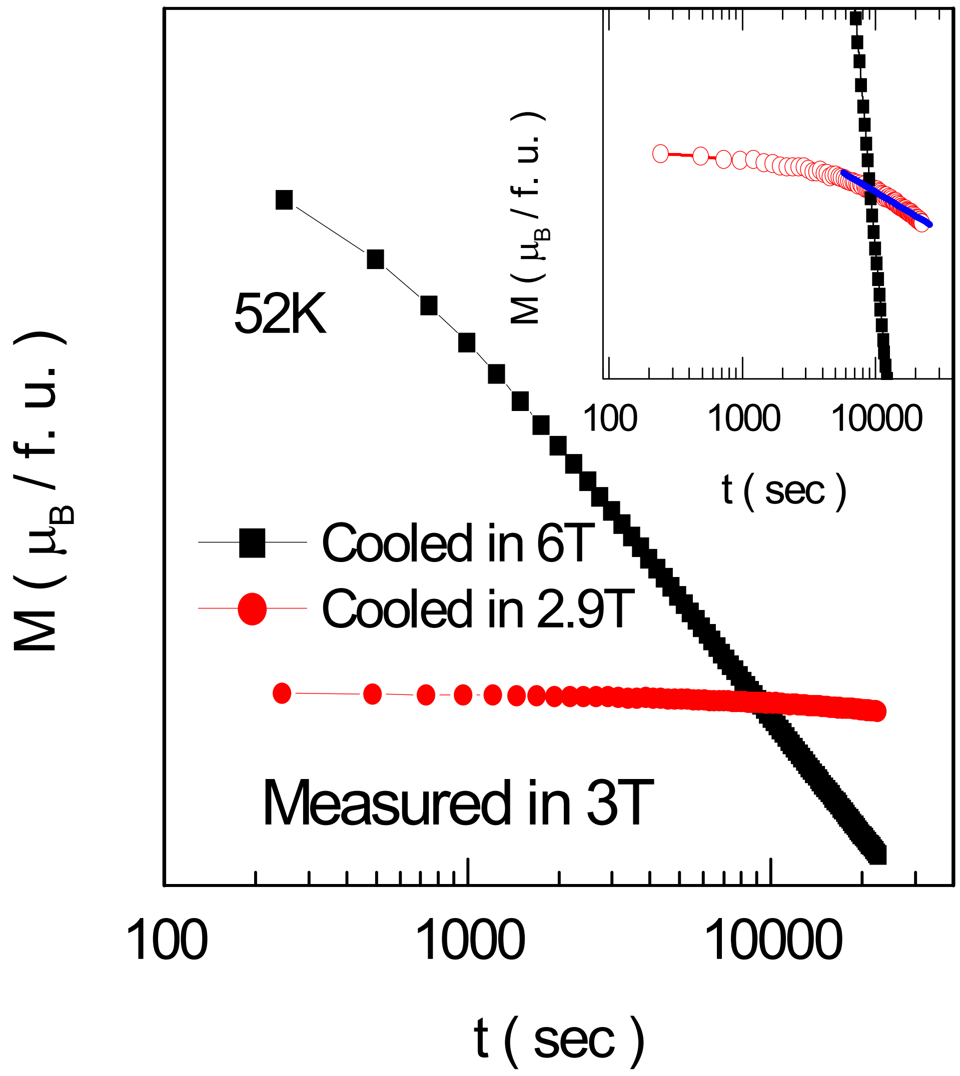






Chaddah et al   arXiv.org:1011.3598

Overtaking, while approaching equilibrium



Chaddah et al   arXiv.org:1011.3598

A second control variable , other than temperature, will help understand glass physics .

Magnetic field is a good control variable (cf pressure).

CHUF, a new protocol to study **g**lass-**l**ike **a**rrested **s**tates

Vision Statement

To see what others have seen, but ..

To think what others have not thought.

To pursue those new thoughts, and then

To see what others have not seen.

PHYSICAL REVIEW B 83, 214428 (2011)

Formation of magnetic glass in calcium-doped $YBaCo_2O_{5.5}$ cobaltites

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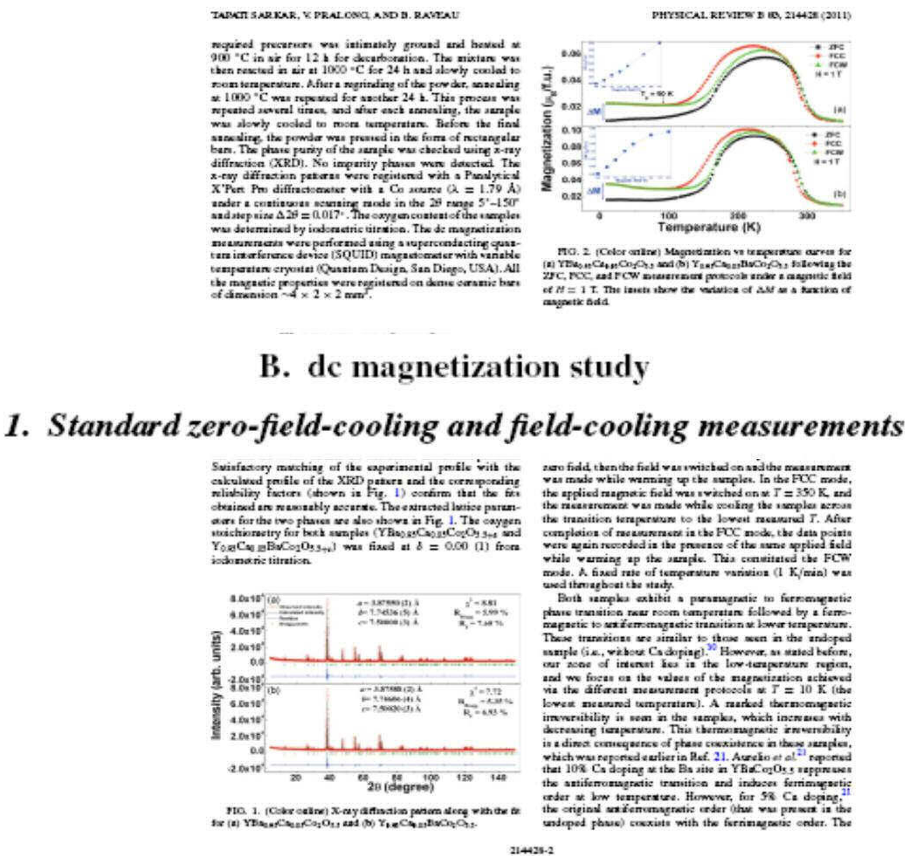
(Received 26 April 2011; published 30 June 2011)

used all 3 (kinetic arrest, magnetic glass, CHUF) keywords



required precursors was intimately ground and heated at 900 °C in air for 12 h for decarbonation. The mixture was then reacted in air at 1000 °C for 24 h and slowly cooled to room temperature. After a regrinding of the powder, annealing at 1000 °C was repeated for another 24 h. This process was repeated several times, and after each annealing, the sample was slowly cooled to room temperature. Before the final annealing, the powder was pressed in the form of rectangular bars. The phase purity of the sample was checked using x-ray diffraction (XRD). No impurity phases were detected. The x-ray diffraction patterns were registered with a Panalytical X'Pert Pro diffractometer with a Co source ($\lambda = 1.79$ Å) under a continuous scanning mode in the 2θ range 5°–150° and step size $\Delta 2\theta = 0.017°$. The oxygen content of the samples was determined by iodometric titration. The dc magnetization measurements were performed using a superconducting quantum interference device (SQUID) magnetometer with variable temperature cryostat (Quantum Design, San Diego, USA). All the magnetic properties were registered on dense ceramic bars of dimension ~4 × 2 × 2 mm³.

B. dc magnetization study

1. Standard zero-field-cooling and field-cooling measurements

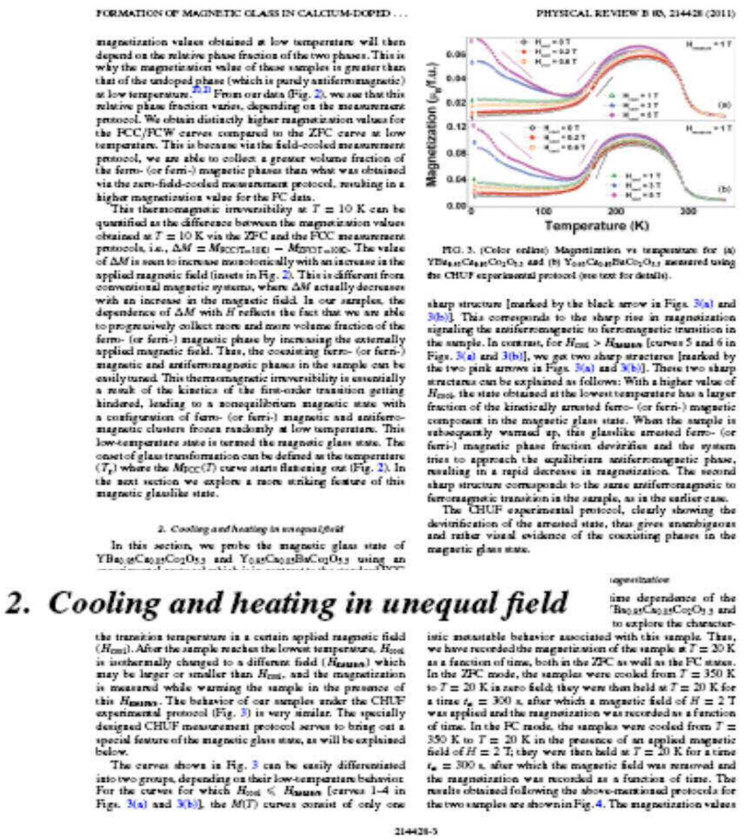
Satisfactory matching of the experimental profile with the calculated profile of the XRD pattern and the corresponding reliability factors (shown in Fig. 1) confirm that the fits obtained are reasonably accurate. The extracted lattice parameters for the two phases are also shown in Fig. 1. The oxygen stoichiometry for both samples ($YBa_{0.95}Ca_{0.05}Co_2O_{5.5+\delta}$ and $Y_{0.95}Ca_{0.05}BaCo_2O_{5.5+\delta}$) was fixed at $\delta = 0.00$ (1) from iodometric titration.

FIG. 1. (Color online) X-ray diffraction pattern along with the fit for (a) $YBa_{0.95}Ca_{0.05}Co_2O_{5.5}$ and (b) $Y_{0.95}Ca_{0.05}BaCo_2O_{5.5}$.

FIG. 2. (Color online) Magnetization vs temperature curves for (a) $YBa_{0.95}Ca_{0.05}Co_2O_{5.5}$ and (b) $Y_{0.95}Ca_{0.05}BaCo_2O_{5.5}$ following the ZFC, FCC, and FCW measurement protocols under a magnetic field of $H = 1$ T. The insets show the variation of ΔM as a function of magnetic field.

zero field, then the field was switched on and the measurement was made while warming up the samples. In the FCC mode, the applied magnetic field was switched on at $T = 350$ K, and the measurement was made while cooling the samples across the transition temperature to the lowest measured T. After completion of measurement in the FCC mode, the data points were again recorded in the presence of the same applied field while warming up the sample. This constituted the FCW mode. A fixed rate of temperature variation (1 K/min) was used throughout the study.

Both samples exhibit a paramagnetic to ferromagnetic phase transition near room temperature followed by a ferromagnetic to antiferromagnetic transition at lower temperature. These transitions are similar to those seen in the undoped sample (i.e., without Ca doping).[30] However, as stated before, our zone of interest lies in the low-temperature region, and we focus on the values of the magnetization achieved via the different measurement protocols at $T = 10$ K (the lowest measured temperature). A marked thermomagnetic irreversibility is seen in the samples, which increases with decreasing temperature. This thermomagnetic irreversibility is a direct consequence of phase coexistence in these samples, which was reported earlier in Ref. 21. Aurelio *et al.*[21] reported that 10% Ca doping at the Ba site in $YBaCo_2O_{5.5}$ suppresses the antiferromagnetic transition and induces ferrimagnetic order at low temperature. However, for 5% Ca doping,[21] the original antiferromagnetic order (that was present in the undoped phase) coexists with the ferrimagnetic order. The



magnetization values obtained at low temperature will then depend on the relative phase fraction of the two phases. This is why the magnetization value of these samples is greater than that of the undoped phase (which is purely antiferromagnetic) at low temperature.[20,21] From our data (Fig. 2), we see that this relative phase fraction varies, depending on the measurement protocol. We obtain distinctly higher magnetization values for the FCC/FCW curves compared to the ZFC curve at low temperature. This is because via the field-cooled measurement protocol, we are able to collect a greater volume fraction of the ferro- (or ferri-) magnetic phases than what was obtained via the zero-field-cooled measurement protocol, resulting in a higher magnetization value for the FC data.

This thermomagnetic irreversibility at $T = 10$ K can be quantified as the difference between the magnetization values obtained at $T = 10$ K via the ZFC and the FCC measurement protocols, i.e., $\Delta M = M_{FCC(T=10K)} - M_{ZFC(T=10K)}$. The value of ΔM is seen to increase monotonically with an increase in the applied magnetic field (insets in Fig. 2). This is different from conventional magnetic systems, where ΔM actually decreases with an increase in the magnetic field. In our samples, the dependence of ΔM with H reflects the fact that we are able to progressively collect more and more volume fraction of the ferro- (or ferri-) magnetic phase by increasing the externally applied magnetic field. Thus, the coexisting ferro- (or ferri-) magnetic and antiferromagnetic phases in the sample can be easily tuned. This thermomagnetic irreversibility is essentially a result of the kinetics of the first-order transition getting hindered, leading to a nonequilibrium magnetic state with a configuration of ferro- (or ferri-) magnetic and antiferromagnetic clusters frozen randomly at low temperature. This low-temperature state is termed the magnetic glass state. The onset of glass transformation can be defined as the temperature (T_g) where the $M_{FCC}(T)$ curve starts flattening out (Fig. 2). In the next section we explore a more striking feature of this magnetic glasslike state.

2. Cooling and heating in unequal field

In this section, we probe the magnetic glass state of $YBa_{0.95}Ca_{0.05}Co_2O_{5.5}$ and $Y_{0.95}Ca_{0.05}BaCo_2O_{5.5}$ using an

FIG. 3. (Color online) Magnetization vs temperature for (a) $YBa_{0.95}Ca_{0.05}Co_2O_{5.5}$ and (b) $Y_{0.95}Ca_{0.05}BaCo_2O_{5.5}$ measured using the CHUF experimental protocol (see text for details).

sharp structure [marked by the black arrow in Figs. 3(a) and 3(b)]. This corresponds to the sharp rise in magnetization signaling the antiferromagnetic to ferromagnetic transition in the sample. In contrast, for $H_{cool} > H_{warm}$ [curves 5 and 6 in Figs. 3(a) and 3(b)], we get two sharp structures [marked by the two pink arrows in Figs. 3(a) and 3(b)]. These two sharp structures can be explained as follows: With a higher value of H_{cool}, the state obtained at the lowest temperature has a larger fraction of the kinetically arrested ferro- (or ferri-) magnetic component in the magnetic glass state. When the sample is subsequently warmed up, this glasslike arrested ferro- (or ferri-) magnetic phase fraction devitrifies and the system tries to approach the equilibrium antiferromagnetic phase, resulting in a rapid decrease in magnetization. The second sharp structure corresponds to the same antiferromagnetic to ferromagnetic transition in the sample, as in the earlier case.

The CHUF experimental protocol, clearly showing the devitrification of the arrested state, thus gives unambiguous and rather visual evidence of the coexisting phases in the magnetic glass state.

2. Cooling and heating in unequal field

the transition temperature in a certain applied magnetic field (H_{cool}). After the sample reaches the lowest temperature, H_{cool} is isothermally changed to a different field (H_{warm}) which may be larger or smaller than H_{cool}, and the magnetization is measured while warming the sample in the presence of this H_{warm}. The behavior of our samples under the CHUF experimental protocol (Fig. 3) is very similar. The specially designed CHUF measurement protocol serves to bring out a special feature of the magnetic glass state, as will be explained below.

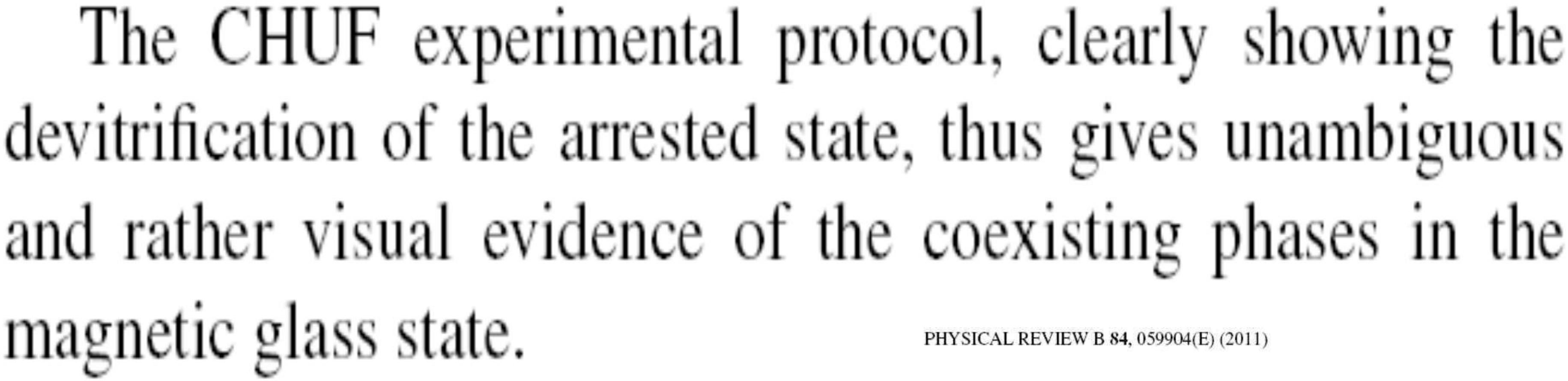
The curves shown in Fig. 3 can be easily differentiated into two groups, depending on their low-temperature behavior. For the curves for which $H_{cool} \leqslant H_{warm}$ [curves 1–4 in Figs. 3(a) and 3(b)], the $M(T)$ curves consist of only one

agnetization

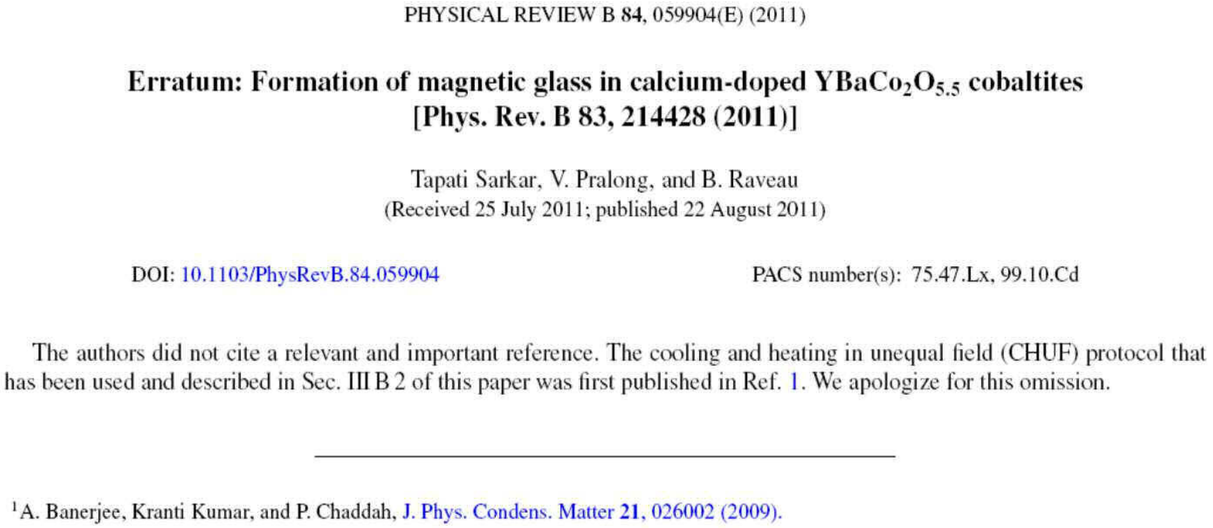
time dependence of the
$Ba_{0.95}Ca_{0.05}Co_2O_{5.5}$ and
to explore the characteristic metastable behavior associated with this sample. Thus, we have recorded the magnetization of the sample at $T = 20$ K as a function of time, both in the ZFC as well as the FC states. In the ZFC mode, the samples were cooled from $T = 350$ K to $T = 20$ K in zero field; they were then held at $T = 20$ K for a time $t_w = 300$ s, after which a magnetic field of $H = 2$ T was applied and the magnetization was recorded as a function of time. In the FC mode, the samples were cooled from $T = 350$ K to $T = 20$ K in the presence of an applied magnetic field of $H = 2$ T; they were then held at $T = 20$ K for a time $t_w = 300$ s, after which the magnetic field was removed and the magnetization was recorded as a function of time. The results obtained following the above-mentioned protocols for the two samples are shown in Fig. 4. The magnetization values

They used all 3 keywords (kinetic arrest, magnetic glass, CHUF) multiple times each. Referred only once!!

Praised the CHUF protocol, which is based on a new understanding of the physical process involved.



The CHUF experimental protocol, clearly showing the devitrification of the arrested state, thus gives unambiguous and rather visual evidence of the coexisting phases in the magnetic glass state.



PHYSICAL REVIEW B **84**, 059904(E) (2011)

Erratum: Formation of magnetic glass in calcium-doped $YBaCo_2O_{5.5}$ cobaltites [Phys. Rev. B 83, 214428 (2011)]

Tapati Sarkar, V. Pralong, and B. Raveau

(Received 25 July 2011; published 22 August 2011)

DOI: 10.1103/PhysRevB.84.059904 PACS number(s): 75.47.Lx, 99.10.Cd

The authors did not cite a relevant and important reference. The cooling and heating in unequal field (CHUF) protocol that has been used and described in Sec. III B 2 of this paper was first published in Ref. 1. We apologize for this omission.

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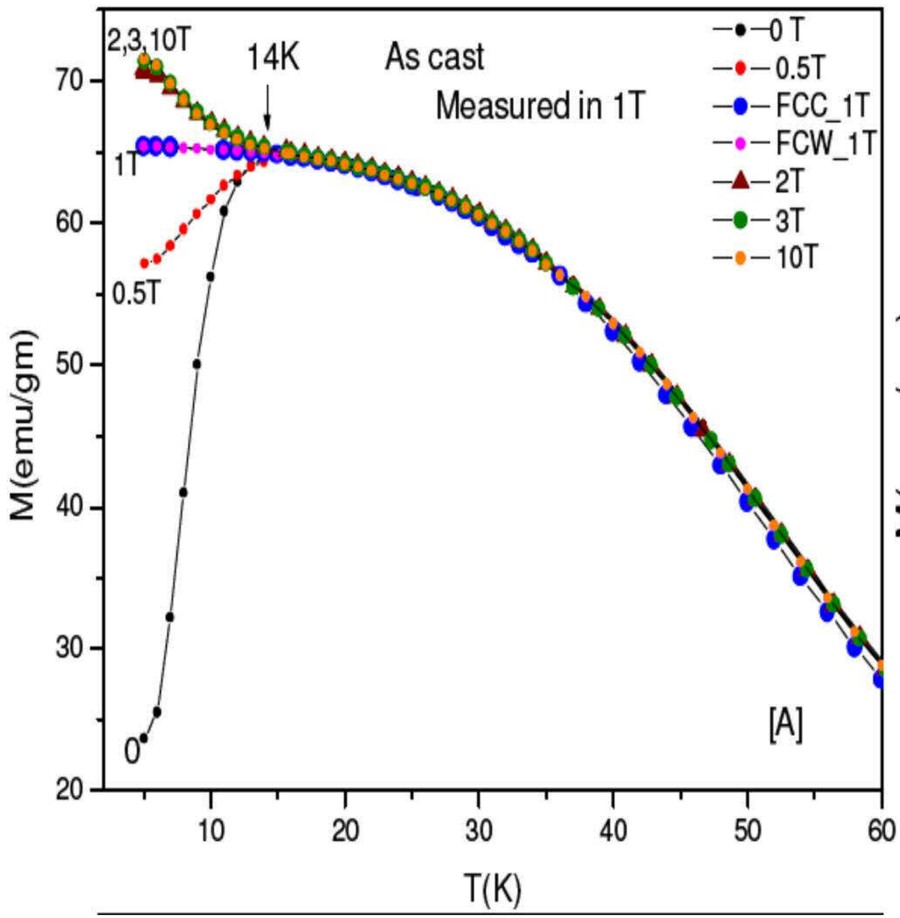
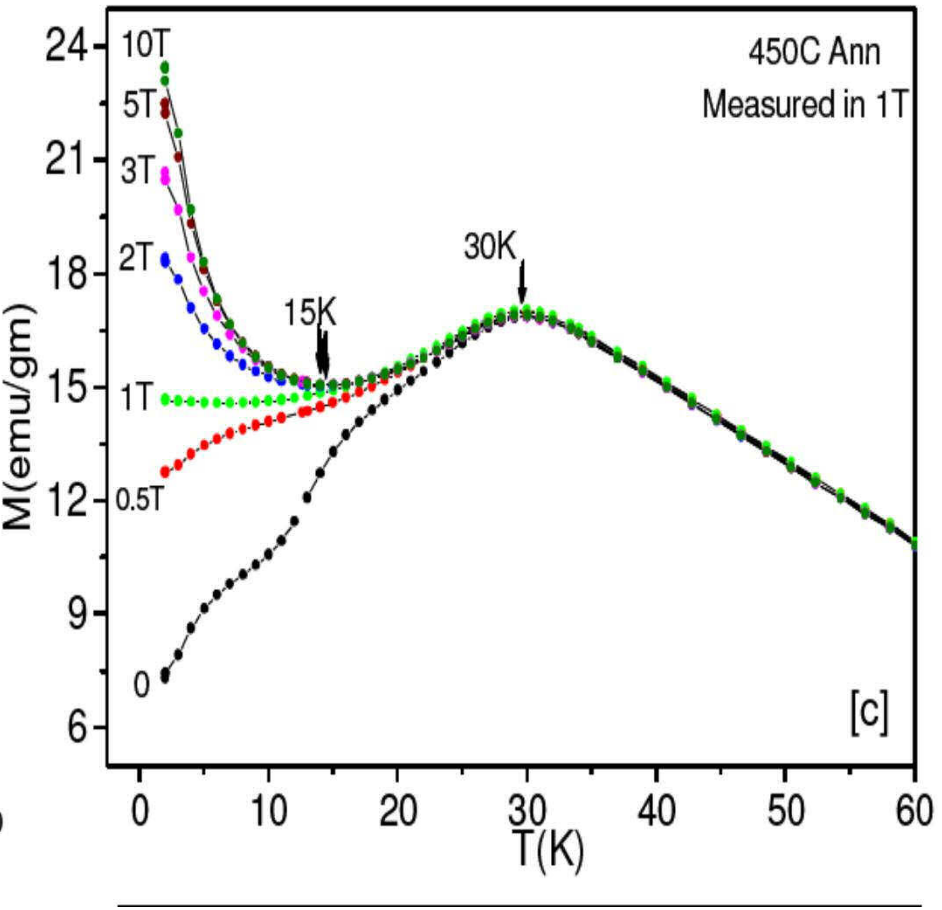
[1] A. Banerjee, Kranti Kumar, and P. Chaddah, J. Phys. Condens. Matter **21**, 026002 (2009).





Evolution of Magnetic Glass on partial crystallization of a Bulk Metallic Glass: $Tb_{36}Sm_{20}Al_{24}Co_{20}$

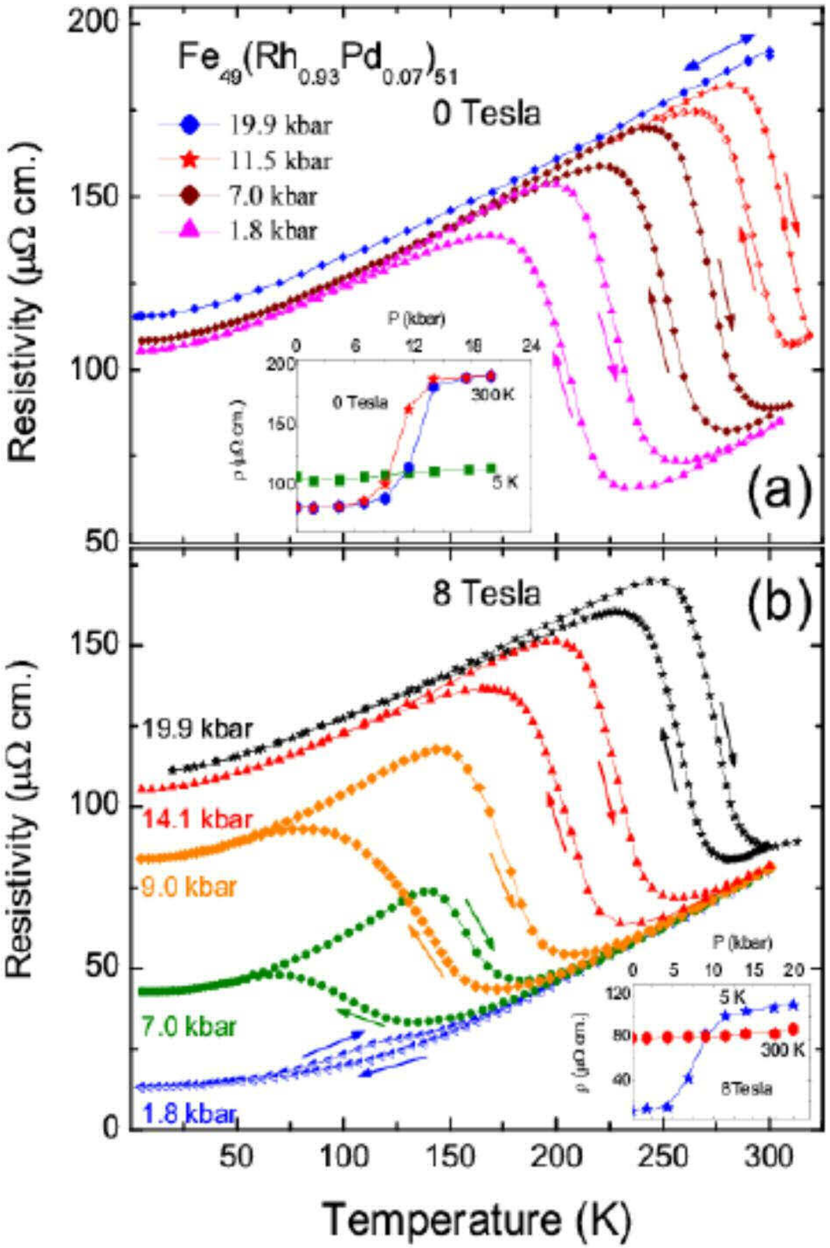
Archana Lakhani [a*], A. Banerjee [a] and P. Chaddah [a]
and
J.Q. Wang [b] and W.H Wang [b]

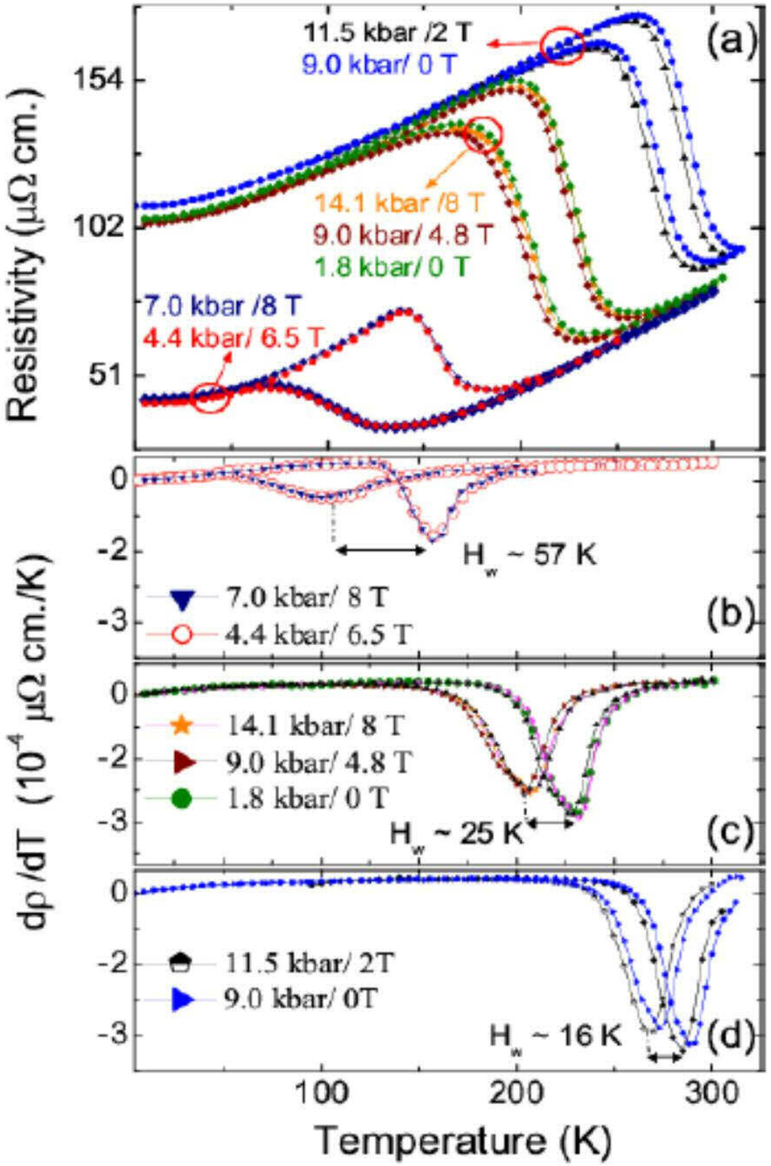
arXiv:1201.5255

Pallavi Kushwaha, Pallab Bag, R Rawat*, and P Chaddah

1108.4117 Both H & P together

JPCM(in press)

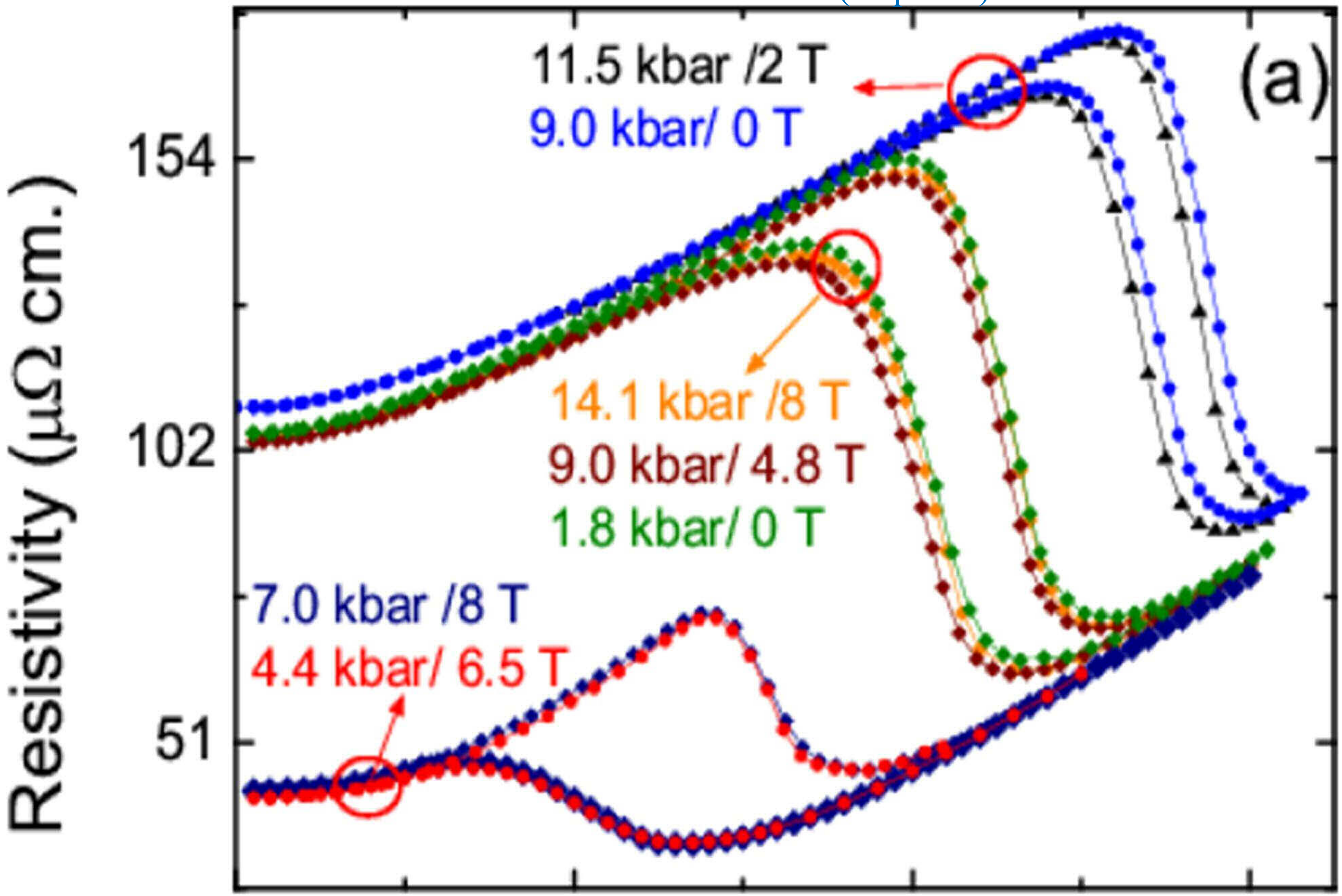




Pallavi Kushwaha, Pallab Bag, R Rawat*, and P Chaddah

1108.4117 Both H & P together

JPCM(in press)



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J. Phys.: Condens. Matter **20** (2008) 022204 (7pp)
doi:10.1088/0953-8984/20/02/022204

FAST TRACK COMMUNICATION

Metastability in the ferrimagnetic–antiferromagnetic phase transition in Co substituted Mn_2Sb

Pallavi Kushwaha, R Rawat and P Chaddah

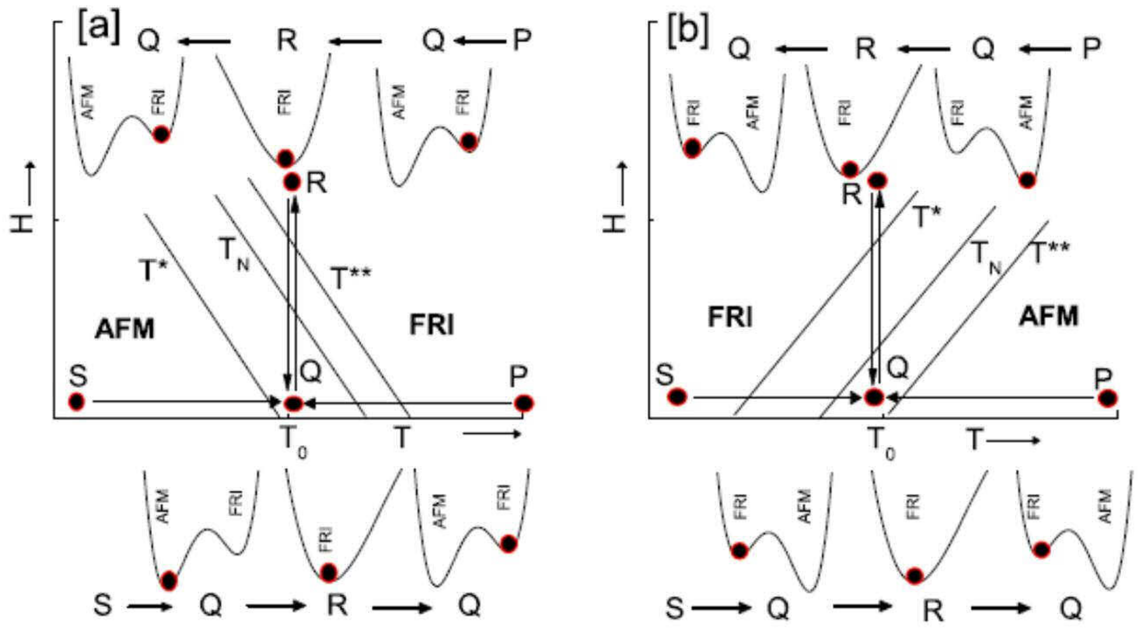

Figure 3. Transformations in the supercooling or superheating regime for different paths are demonstrated along with a corresponding schematic of the free energy diagram. The state in