Спиновые стекла и им подобные: порядок, скрытый в беспорядке

- «Спиновые стекла» - магнитные сплавы типа

$Cu_{1-x}Mn_x$ или $Au_{1-x}F_x$ $(x << 1)$ и другие

$$E = \Sigma_{(ij)} J_{(ij)} S_i S_j$$

$$J(r) = J_0 \cos(2k_F r)/r^3$$

Знаки $J_{(ij)}$ случайны !

Другой пример - диполи:

$$V_{ij}^{ab} = (\delta_{ij}^{ab} - 3n_{ij}^{a} n_{ij}^{b})/r_{ij}^{3}$$

Какое состояние при низких темпер. ?

Основые ингредиенты для появления “спинстекла”

- Фрустрация – т.е. конкурирующие взаимодействия
- Беспорядок – отсутствие трансляционной инвариантности гамильтониана (хотя иногда можно и без этого)
- Квазиклассическое приближение – задачу можно описывать на языке классической статмеханики (хотя бывают и квантовые стекла – о них в конце курса)

Основные объекты (примеры)

- Металлические спиновые стекла (RKKY обмен)

$Cu_{1-x}Mn_x$ $Au_{1-x}Fe_x$ $Ag_{1-x}Mn_x$ $Y_{1-x}Gd_x$

- Диэлектрические спиновые стекла

$Eu_xSr_{1-x}S$ $Eu_xSr_{1-x}Se$ MnO Al_2O_3 SiO_2 $CdCr_{2-2x}In_{2x}S_4$

- Дипольные стекла

$LiHo_xY_{1-x}F_4$ (магнитное) $KCl:OH^-$ KCl:L (электрические)

- Электронные стекла

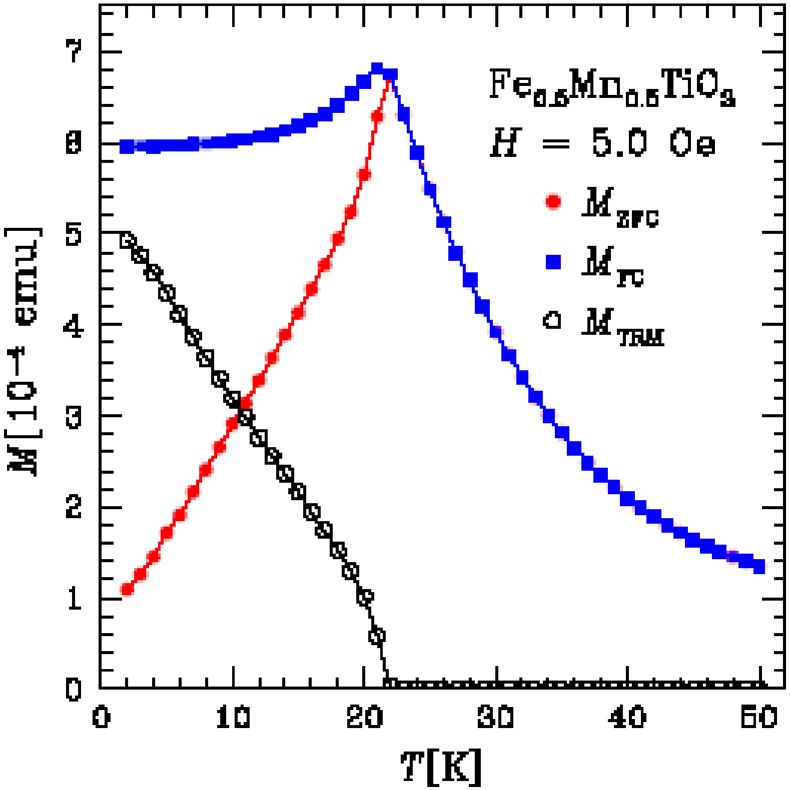
InOx (n ~ 10^{18}-10^{19}) ; granular Al (a ~ 3-5 nm)

- Сверхпроводящие стекла

Симметрии: Z_2 -Ising, O(2) – XY, или U(1) , O(3) - Heisenberg

Спиновое стекло: переход «замерзания»

первая теория – S.Edwards & P.W.Anderson 1975



[<S$_k$>] $=0$ - не ФМ

[<σ$_k$>] $= [(-1)^k < S_k >]=0$ – не АФМ

Однако локальные <S$_k$> $\neq 0$

Состояние зависит от истории !!

V.Canella and J.A.Mydosh
Phys Rev B6, 4220 (1972)

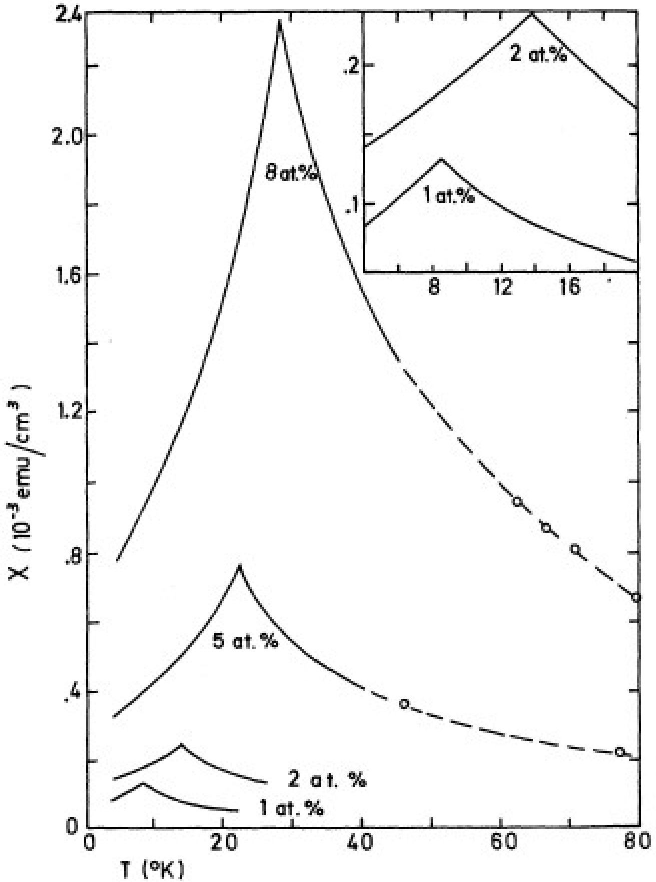


FIG. 9. Low-field susceptibility $\chi(T)$ for $1 \leq C \leq 8$ at.%. The data were taken every $\frac{1}{4}$°K in the region of the peak, and every $\frac{1}{2}$ or 1 °K elsewhere. The scatter is of the order of the thickness of the lines. The open circles indicate isolated points taken at higher temperatures.

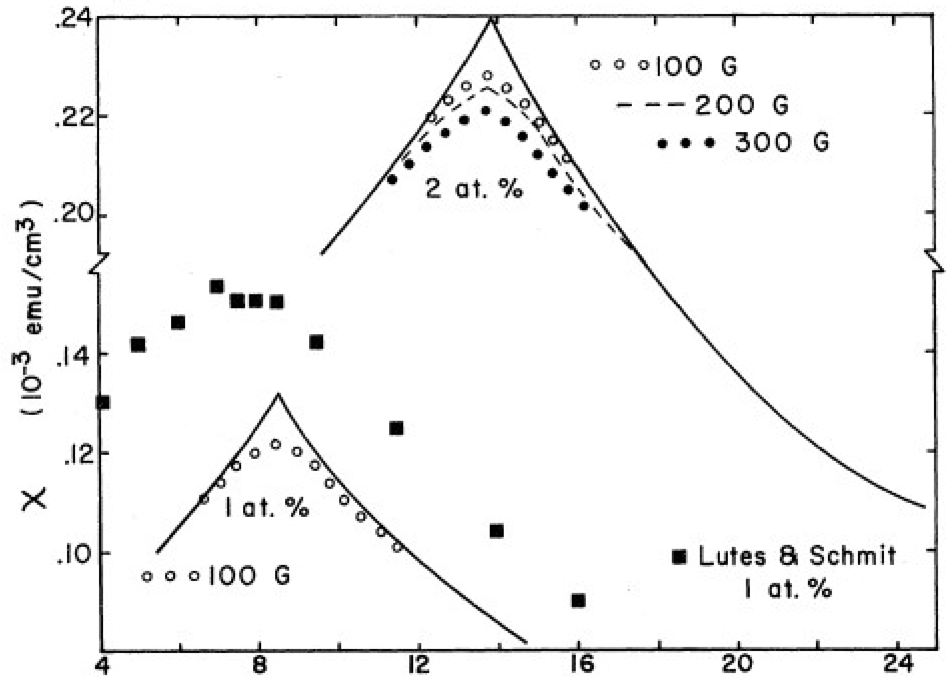


FIG. 11. Susceptibility vs T (°K) for samples with $C = 1$ and 2 at.%, showing the curves for zero field and for various applied fields, and including the data of Lutes and Schmit (Ref. 11) for $C = 1$ at.%.

Cusp in χ(T) and slow frequency-dependence

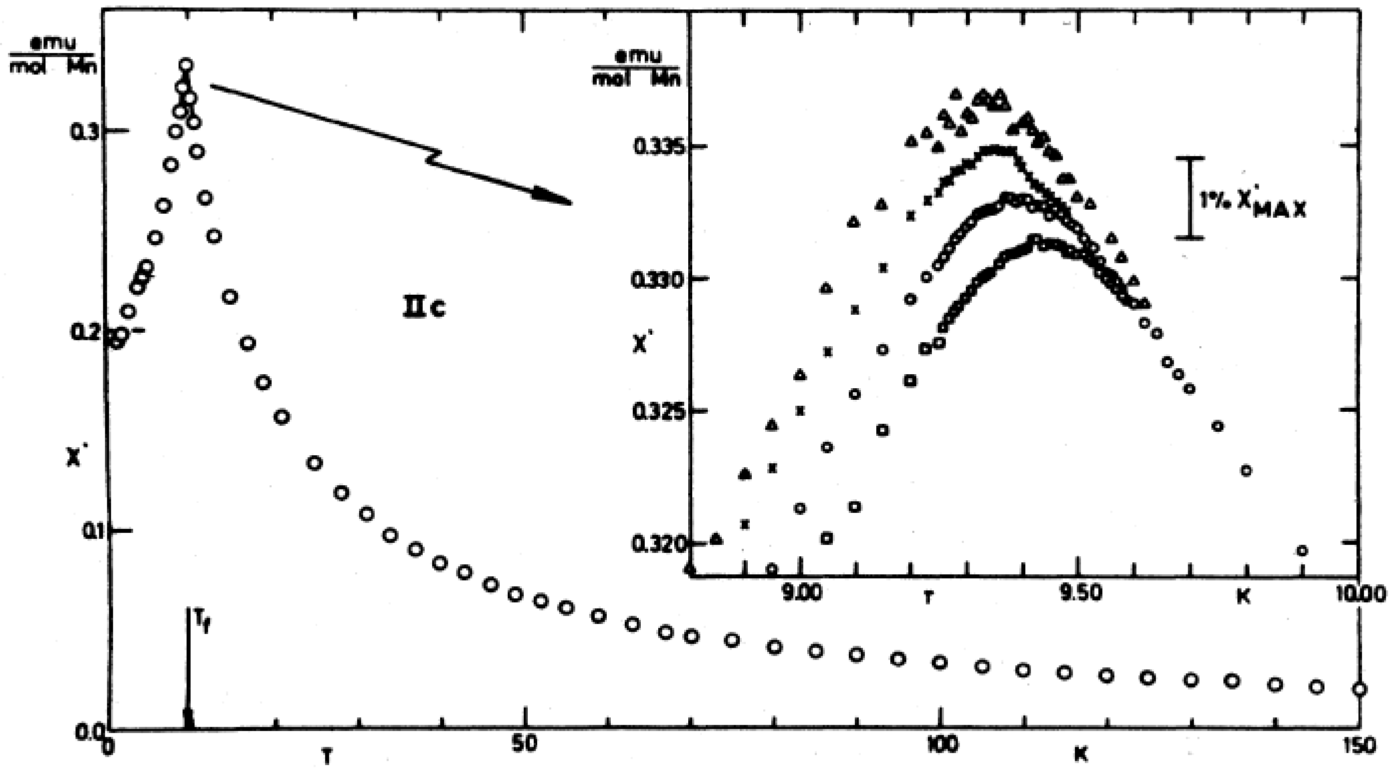


FIG. 1. Real part χ' of the complex susceptibility $\chi(\omega)$ as a function of temperature for sample IIc (*Cu*Mn with 0.94 at. % Mn, powder). Inset reveals frequency dependence and rounding of the cusp by use of strongly expanded coordinate scales. Measuring frequencies: □, 1.33 kHz; ○, 234 Hz; ×, 104 Hz; △, 2.6 Hz. From Mulder *et al.* (1981).

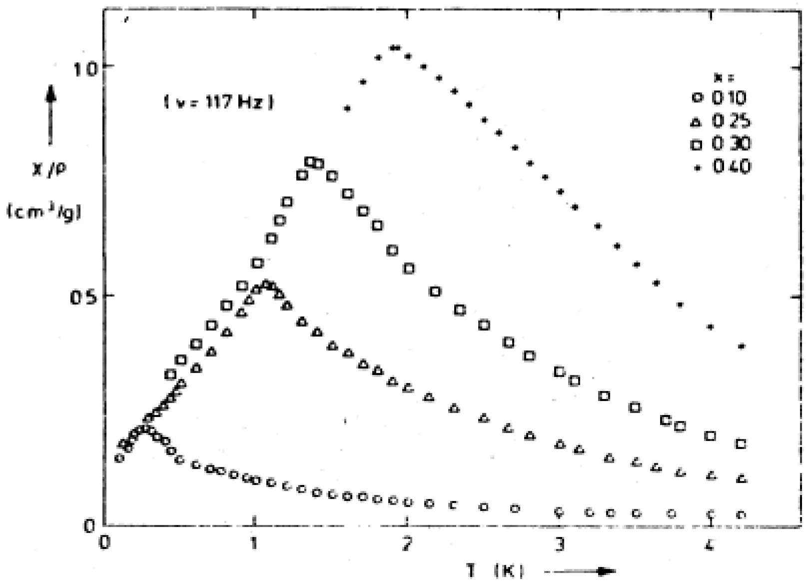


FIG. 2. Real part χ' of the complex susceptibility $\chi(\omega)$ as function of temperature for $Eu_xSr_{1-x}S$, at $\omega = 117$ Hz and var ous Eu concentrations as indicated in the figure. From Malett and Felsch (1979).

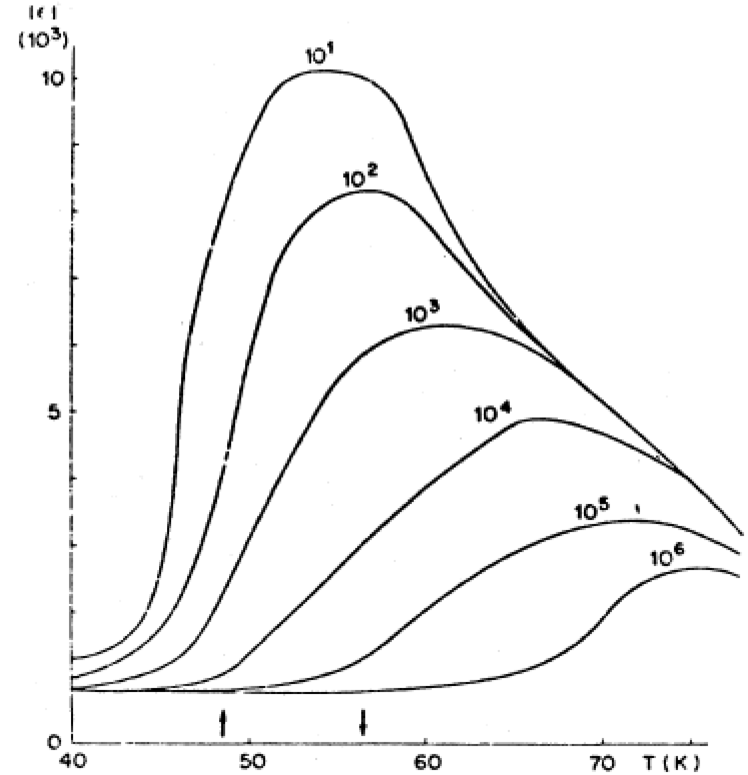


FIG. 3. Dielectric susceptibility of $K_{0.974}Li_{0.026}TaO_3$ as a function of temperature. Labels stand for the measuring frequencies, arrows for the maximum of the dielectric dispersion step (49 K) and the stability limit of remanent polarization (56 K). From Höchli (1982).

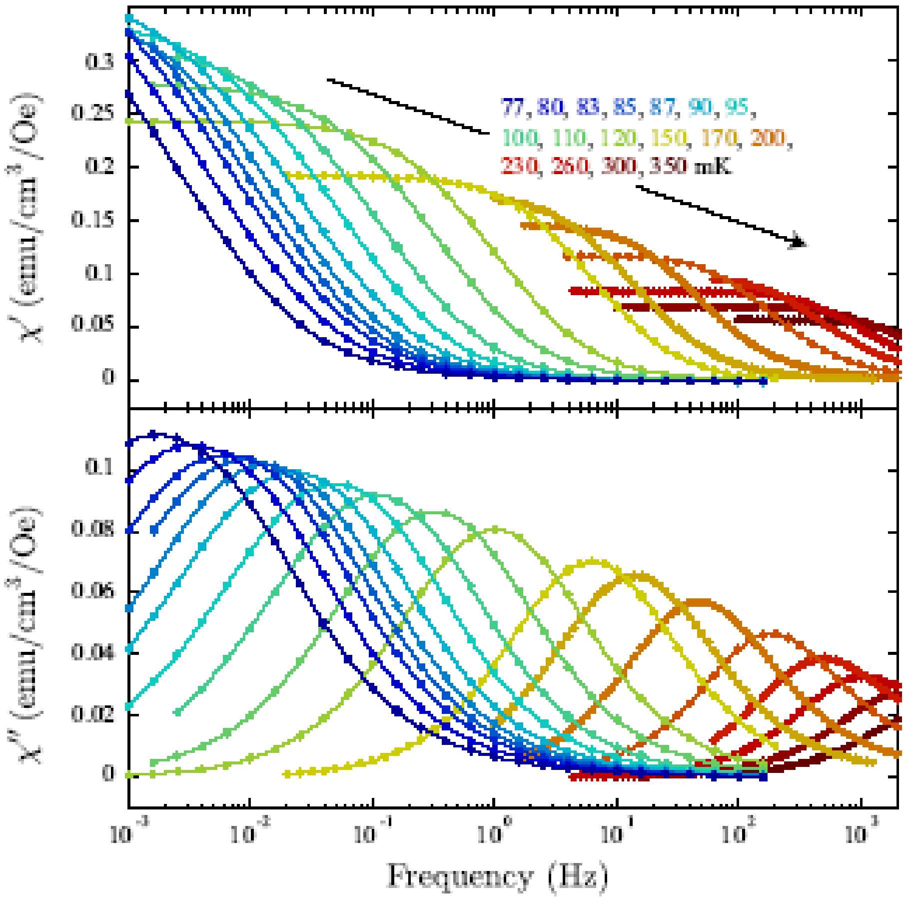


FIG. 1: AC susceptibility of the $x = 0.045$ sample showing in-phase $\chi'(f)$ and out-of-phase $\chi''(f)$ components. The spectra were obtained at temperatures 77, 80, 83, 85, 87, 90, 95, 100, 110, 120, 140, 150, 170, 200, 230, 260, 300 and 350 mK from left (blue) to right (red).

Спиновое стекло: *очень* медленная динамика

$LiHo_xY_{1-x}F_4$:

магнит.диполи

Фазовый переход
или постепенное замерзание ?

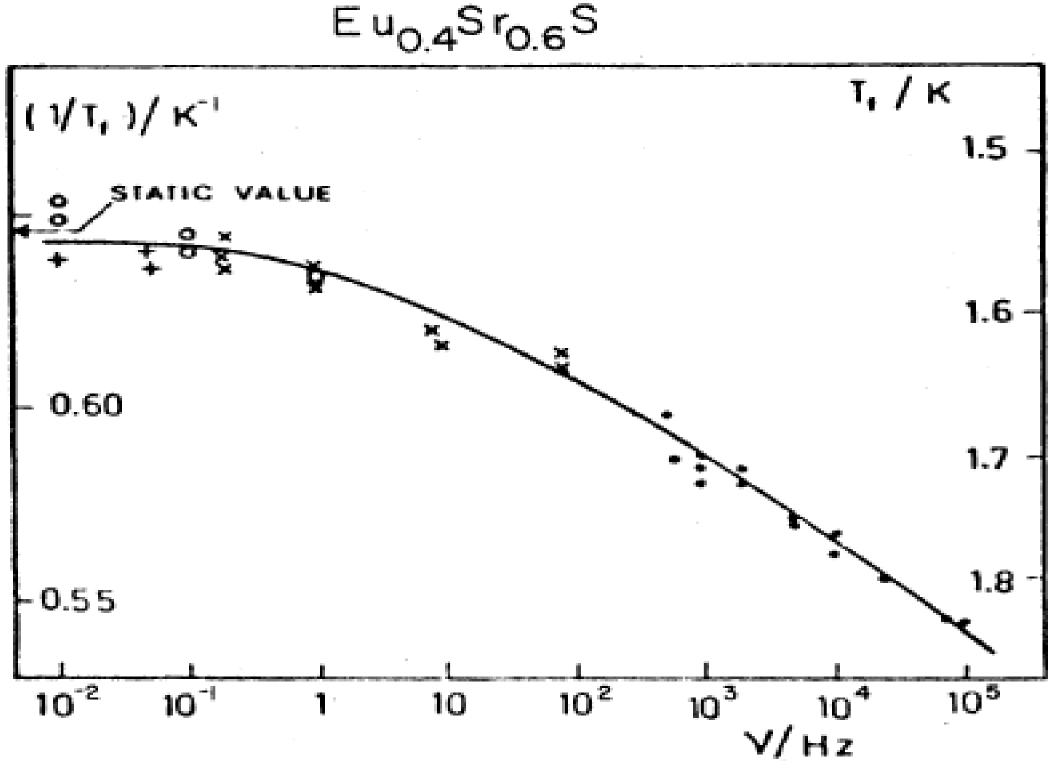


FIG. 9. Inverse freezing temperature $T_f^{-1}(\omega)$ of $Eu_{0.4}Sr_{0.6}S$ plotted vs logarithm of measurement frequency. Different symbols indicate different measurement techniques. From Ferré *et al.* (1981).

Spin Glasses: A transition in plain ordinary space

J. Souletie Ann.Phys.Fr. **10**, 69-84 (1985)

Abstract. — We are living a fascinating moment where theorists, faced to ample experimental and (more recent) simulation evidence seem to have little choice other than to accept that the transition which they described, actually occurs in our ordinary space at 3 *d*. We review here some of the experimental arguments, based on critical measurements performed at equilibrium in the high temperature phase, and we stress the similarities and the differences with superparamagnetism and with an ordinary phase transition. By contrast, the slow relaxations which are observed in the low temperature phase below T_c are interpreted in terms of activation over finite energy barriers and would suggest little more than ordinary superparamagnetism. Some features of the Fulcher law which describes the edge between the equilibrium and the non equilibrium regimes, would allow to conciliate both points of view : it is the *critical* divergence of the barrier heights, on approaching T_c from above, which is responsible for the fact that the system appears blocked at a temperature $T_g(t)$ slightly larger than T_c for all experiments performed in a finite time t.

Какая величина сингулярна в T_c ?

$$M/H = \chi_0(T) - H^2 \chi_{nl}(T) + O(H^4) \, .$$

$$G_{ik} = \langle\langle \overline{S_i S_k} \rangle\rangle^2, \quad K_{ik} = \langle\langle \overline{S_i^2 S_k^2} \rangle\rangle \qquad K_{ik} = -2G_{ik}.$$

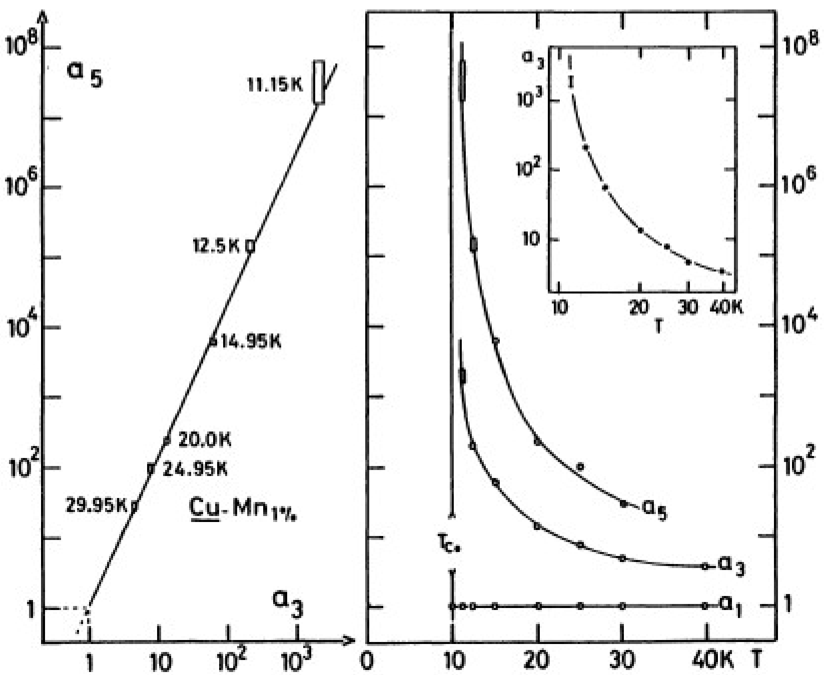


Fig. 3. — The first, second and third order Curie constants a_1, a_3, a_5 involved in the expansion of the magnetization in terms of $\mu H/kT$ are represented *vs.* temperature in a semi-log plot on the right hand side. The insert shows a log-log representation of the $a_3(T)$ dependence. On the left hand side we have represented log a_5 *vs.* log a_3 (Ref. [24]).

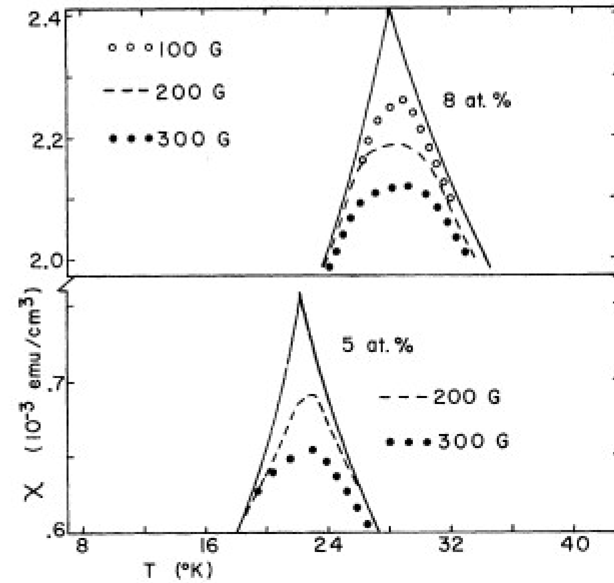


FIG. 12. Susceptibility data for samples with $C = 5$ and 8 at. %, showing the curves for zero field, and for various applied fields.

Canella & Mydosh

J. Souletie

$$\mathfrak{R} = \frac{\partial G}{\partial \eta} = \theta^{\beta} f\left(\frac{\eta}{\theta^{\gamma+\beta}}\right).$$

$\gamma = 3.26$ and $\beta \simeq 1$

FM transition $\eta = \frac{H}{T_c}$ and $\theta = \frac{T - T_c}{T_c}$.

SG transition $\eta = (H/T_c)^2$

$\mathfrak{R} = M/\eta$ $X = \eta^2/\theta^{\gamma+\beta}$

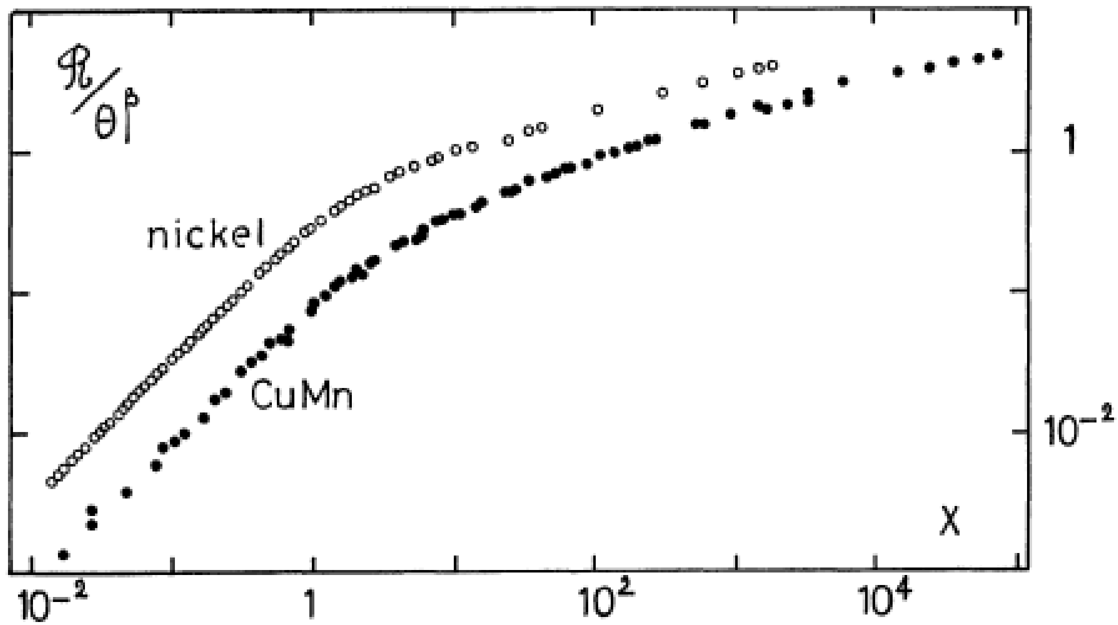


Fig. 4. — The scaled magnetization of Nickel and the scaled *equivalent magnetization* of CuMn 1 at % in a universal plot $\mathfrak{R}/\theta^{\beta}$ *vs.* X. In nickel $\mathfrak{R} = M$ and $X = \eta/\theta^{\gamma+\beta}$. In CuMn $\mathfrak{R} = M/\eta$ and $X = \eta^2/\theta^{\gamma+\beta}$ with $\theta = (T - T_c)/T$ and $\eta = H/T$ [Ref. 24].

Souletie 1985

Determination of the critical exponents in the AgMn spin glass

H. Bouchiat *J. Physique* **47** (1986) 71-88

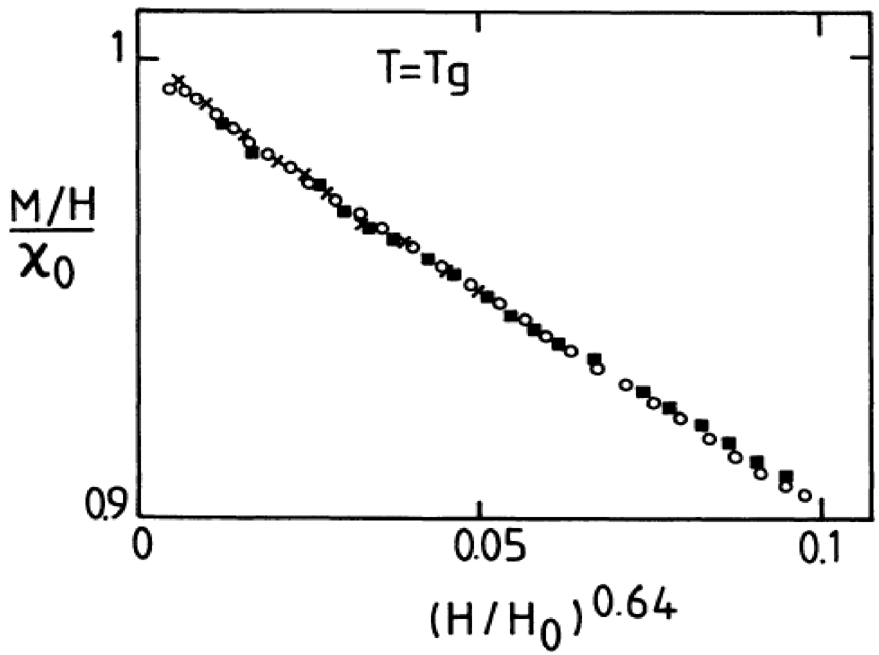


Fig. 8. — M/H scaled to the linear susceptibility at T_g is plotted *versus* reduced magnetic field $(H/H_0)^{0.64}$ for three different concentrations : ■ AgMn 0.4 %; ○ AgMn 0.5 %; × AgMn 20.5 %.

$$M_{NL}/H \propto H^{2/\delta}$$

$$2/\delta = 0.64 \pm 0.02 .$$

$$\delta = 3.1 \pm 0.1 .$$

$$a(T) \propto (T - T_g)^{-\gamma}$$

with

$$\gamma = 2.1 \pm 0.1 \text{ for the } 0.5 \text{ at.\% sample}$$
$$\gamma = 2.3 \pm 0.1 \text{ for the } 20.5 \text{ at.\% sample}.$$

In conclusion we have shown that the nonlinear magnetization of the AgMn system can be consistently described by scaling theory with a nonzero transition temperature. The values of critical exponents $\gamma = 2.2 \pm 0.2$ and $\delta = 3.1 \pm 0.2 = 1 \pm 0.1$ are obtained when the analysis is restricted to the range of temperatures and fields $(T - T_g)/T_g < 0.1$ and $M_{NL}/M < 0.1$.

Deviations towards higher apparent values of the critical exponents are observed outside this range. These deviations explain the discrepancy between the values of the critical exponents determined by Omari *et al.* on CuMn and ours. Such deviations due to the presence of regular terms are also present in the mean

Table II. — *Measured values of critical exponents on various spin glass systems. Some of these values were directly measured like γ and δ others are the result of the optimization of the scaling like ϕ and β.*

System	Technique	Range of temperature $(T^{max} - T_g)/T_g$	Range of field M_{NL} max$/M$	δ	ϕ	γ	β	Reference
CuAlMn (1 % Mn)	A.C.		0.15	2.9 ± 0.4				[1]
CuMn (2 % Mn)	A.C.		0.02	1.9 ± 0.1				[36]
CuMn (4.6 % Mn)	D.C.	1	0.5	1.15 ± 0.15	5 ± 0.5	3.4	1	[2]
CuMn (0.25 % Mn)	D.C.	0.7		4.5		3.5	1	[4]
CuMn (1 at. % Mn)	D.C.	2	0.5	4.4		3.3 ± 0.05	1	[5]
AgMn (10.6 % Mn)	D.C.	0.4	0.1			1.5 ± 0.5		[3]
AgMn (0.4 %, 0.5 %, 0.7 %, 20.5 %)	D.C.	0.1	0.1	3.1 ± 0.2	3.3 ± 0.2	2.2 ± 0.2	1 ± 0.1	this work
AuFe (1.5 % Fe)	A.C.-3 ω	0.1	0.01	2 ± 0.2		1.1 ± 0.2	0.9	[38]
GdAl (37 % Gd)		1	0.6	6.1 ± 0.2	4 ± 0.5	3.8 ± 0.5		[2]
GdAl (37 % Gd)	D.C.	0.16	0.3	5.7 ± 0.2	3.3 ± 0.4	2.7 ± 0.1		[39]
$Fe_{10}Ni_{70}P_{20}$	A.C.-3 ω	0.3	0.15	5.2 ± 0.5		2.3 ± 0.2		[8]
$Al_2O_3MnOSiO_2$(15 % Mn)	A.C.	0.4	0.05	3.2	4.5	3.1 ± 0.1	1.4 ± 0.1	[7]
$CsNiFeF_6$	D.C.	0.1	0.5	3.5	4.2	3 ± 0.5	1.2 ± 0.1	[9]

STATIC SCALING IN A SHORT-RANGE ISING SPIN GLASS

PHYSICAL REVIEW B
43 8199 1991

$\chi_2 \propto t^{-\gamma}$

$\chi_{nl} = t^{\beta} G(H_0^2 / t^{\beta+\gamma})$.

$Fe_{0.5}Mn_{0.5}TiO_3$

$\gamma = 4.0.$

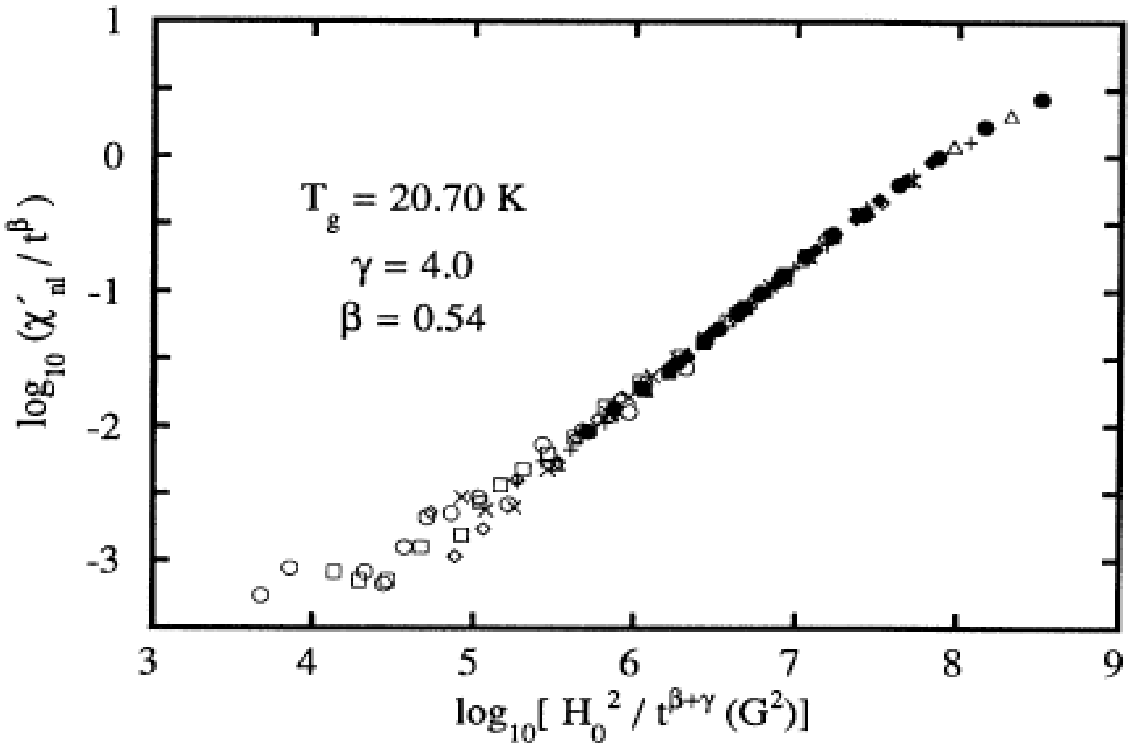


FIG. 4. $\log_{10}(\chi'_{nl}/t^{\beta})$ vs $\log_{10}(H_0^2/t^{\beta+\gamma})$. The figure shows the data collapsing obtained using $T_g = 20.70$ K, $\gamma = 4.0$, and $\beta = 0.54$.

Journal of Physics: Conference Series **320** (2011) 012051 doi:10.1088/1742-6596/320/1/012051

Critical Phenomena in Long-Range RKKY Ising Spin Glasses

Yoshikazu Tabata, Satoshi Kanada, Teruo Yamazaki[A], Takeshi Waki, Hiroyuki Nakamura

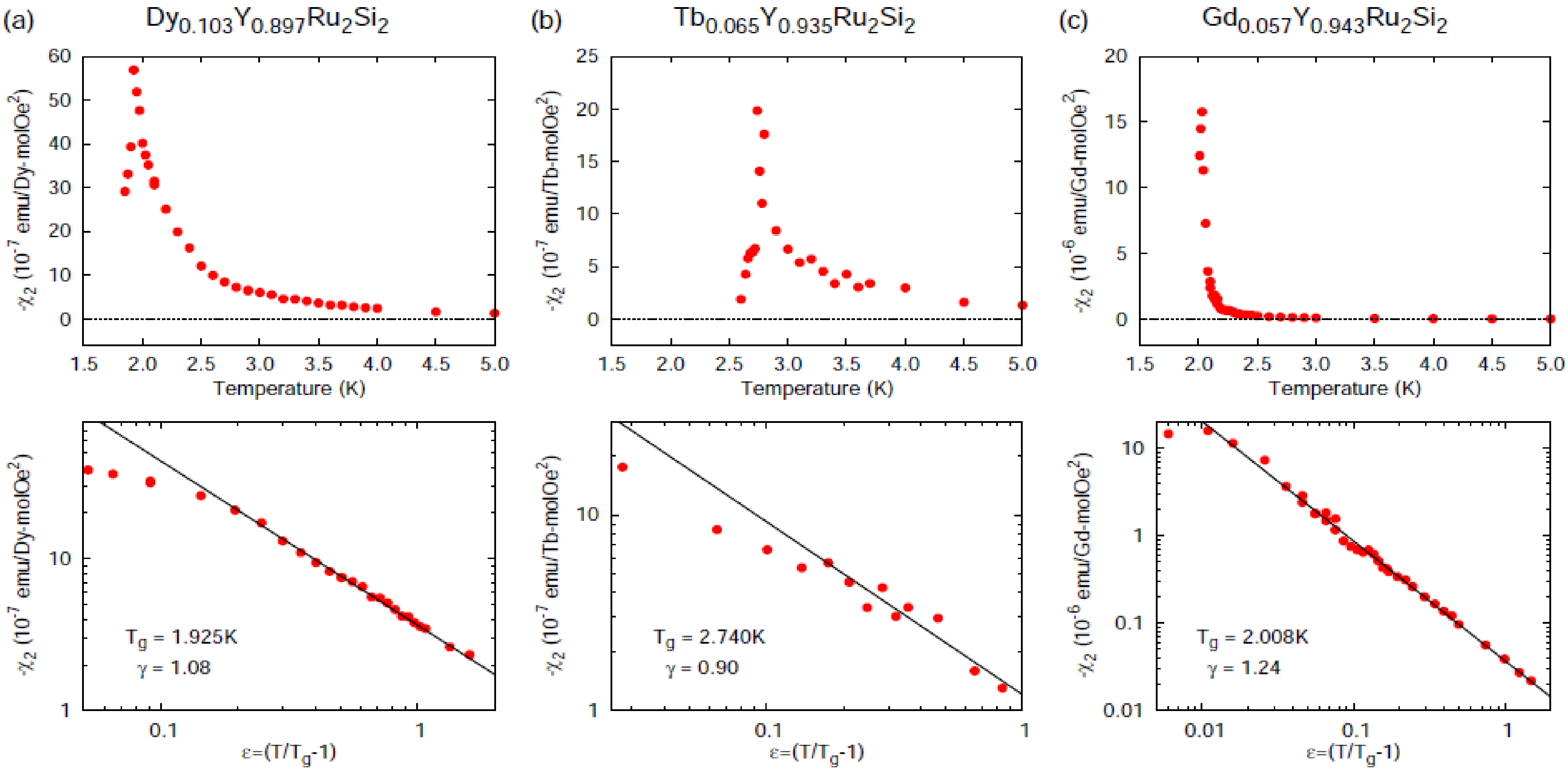


Figure 2. T dependences of second nonlinear susceptibilities of (a) $Dy_{0.103}Y_{0.897}Ru_2Si_2$, (b) $Tb_{0.065}Y_{0.935}Ru_2Si_2$, and (c) $Gd_{0.057}Y_{0.943}Ru_2Si_2$. Lower figures are the log-log plots of $-\chi_2$ vs ε ($\equiv T/T_g - 1$).

ANDREW T. OGIELSKI

PHYSICAL REVIEW B 32 7384 1985

Dynamics of three-dimensional Ising spin glasses in thermal equilibrium

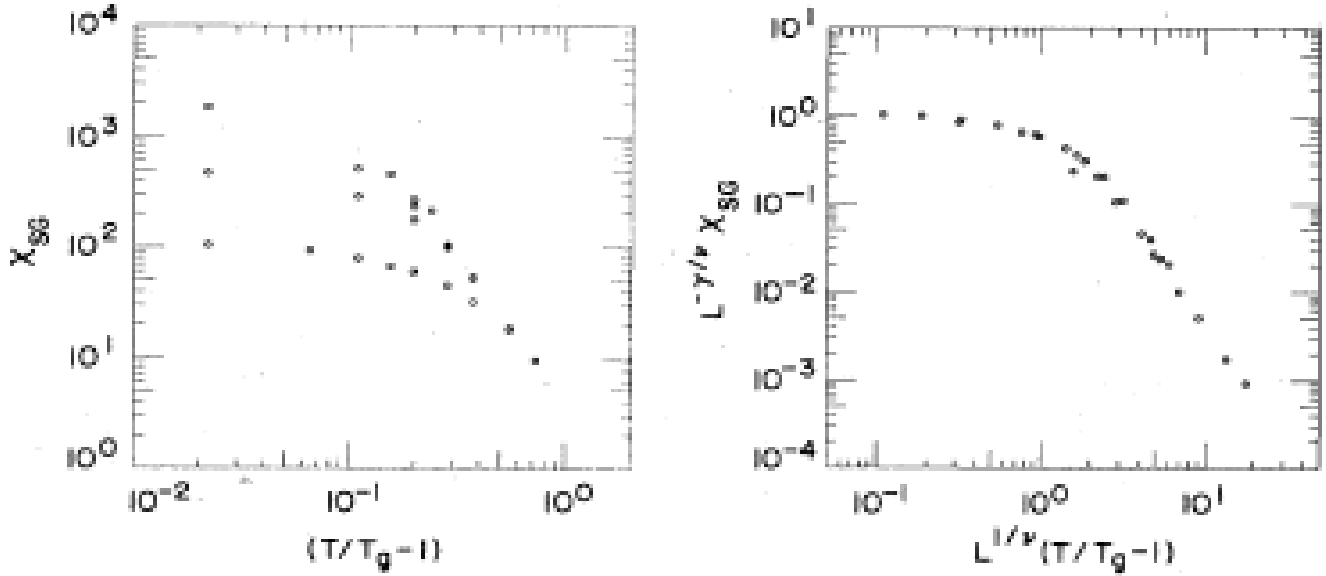


FIG. 4. Static nonlinear susceptibility χ_{SG} for lattices of size 8^3, 16^3, 32^3, and 64^3 (left) is plotted in the scaling form (right). The parameters are $T_g=1.175$, $\nu=1.3$, and $\gamma=2.9$.

Critical parameters of the three-dimensional Ising spin glass 2013

M. Baity-Jesi,[1,2,3] R. A. Baños,[3,4] A. Cruz,[4,3] L.A. Fernandez,[1,3] J. M. Gil-Narvion,[3] A. Gordillo-Guerrero,[5,3] D. Iñiguez,[3,6] A. Maiorano,[2,3] F. Mantovani,[7] E. Marinari,[8] V. Martin-Mayor,[1,3] J. Monforte-Garcia,[3,4] A. Muñoz Sudupe,[1] D. Navarro,[9] G. Parisi,[8] S. Perez-Gaviro,[3,6] M. Pivanti,[7] F. Ricci-Tersenghi,[8] J. J. Ruiz-Lorenzo,[10,3] S.F. Schifano,[11] B. Seoane,[2,3] A. Tarancon,[4,3] R. Tripiccione,[7] and D. Yllanes[2,3]

40^3

$\alpha = -5.69(13)$
$\beta = 0.782(10)$
$\gamma = 6.13(11)$

Есть ли универсальность критического поведения ?

Critical exponents in Ising Spin Glasses

1307.5247

P. H. Lundow[1] and I. A. Campbell[2]

Нет !

PHYSICAL REVIEW E **92**, 022128 (2015)

Universal dynamic scaling in three-dimensional Ising spin glasses

Cheng-Wei Liu,[1] Anatoli Polkovnikov,[1] Anders W. Sandvik,[1] and A. P. Young[2]

Да !

Study	Model	Exponent z
Pleimling and Campbell (Ref. [22])	$\pm J$	5.7(2)
	G	6.2(1)
Nakamura (Ref. [23])*	$\pm J$	5.1(1)
Katzgraber and Campbell (Ref. [24])*	G	6.80(15)
Rieger (Ref. [25])*	$\pm J$	$\simeq 6$
Ogielski (Ref. [26])	$\pm J$	6.0(8)
Belletti *et al.* (Ref. [27])*	$\pm J$	6.86(16)
This study	$\pm J$	5.85(9)
	G	6.00(10)

Аномальная релаксация выше T_c

[11] F. Mezei and A. P. Murani, J. Magn. Magn. Mater. **14**, 211 (1979).

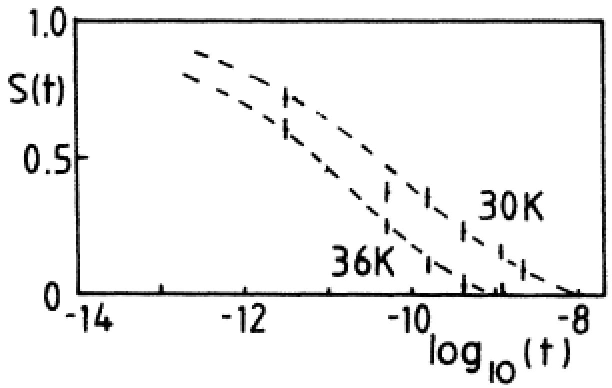


FIG. 3. Neutron spin-echo data from Ref. 11 on Cu–5 at.% Mn at two temperatures just above T_g = 28.5 K. The curves are stretched exponential fits with β = 0.33 and 0.37.

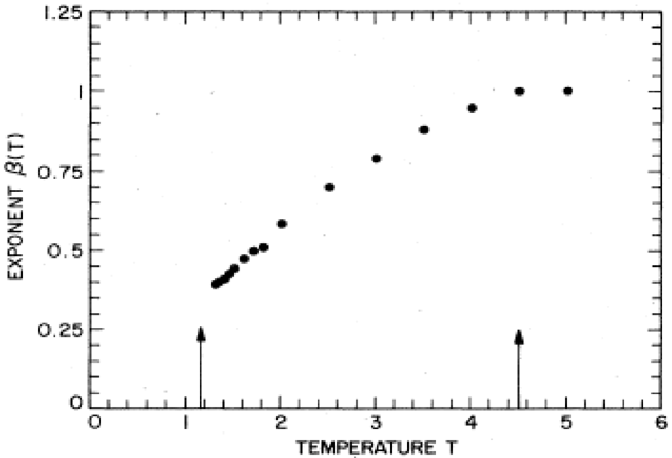
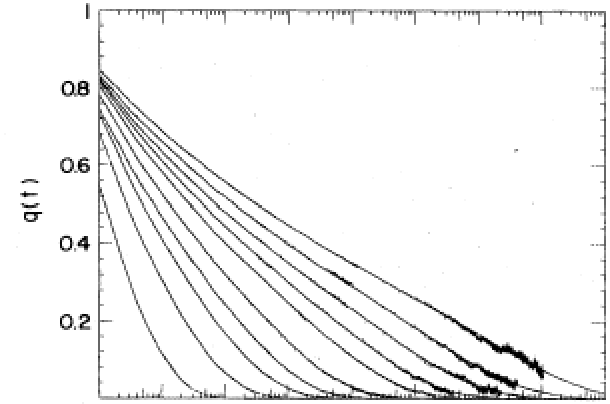


FIG. 11. Temperature dependence of the exponent β defined in Eq. (13). The arrows mark the spin-glass transition temperature T_g and the Curie point T_c of nonrandom Ising model.

ANDREW T. OGIELSKI



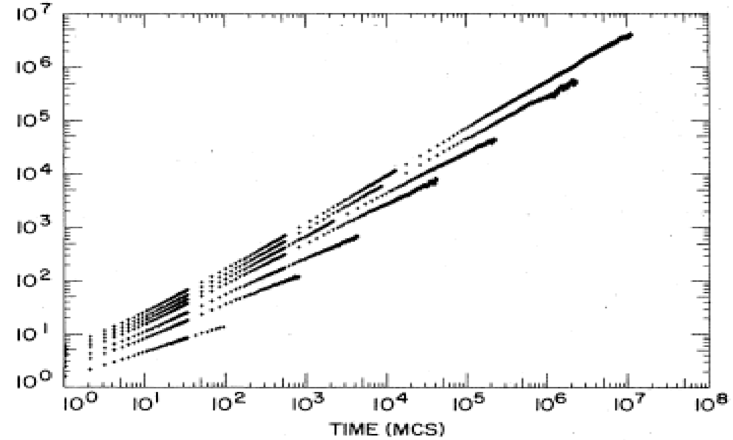


FIG. 10. Correlation functions $q(t)$ shown before in Fig. 7 are converted into a plot of $-t/\ln q(t)$ vs t on the log-log scale. Data points would appear as horizontal lines if $q(t) \sim \exp(-t/\tau)$; this is not seen here. Asymptotically straight lines seen in the graph indicate the Kohlrausch behavior $\exp(-\omega t^{\beta})$ instead, with $\beta < 1$. The temperatures are t = 2.50 (bottom), 2.00, 1.80, 1.60, 1.50, 1.40, and 1.30 (top).

Рост времени релаксации

$$\frac{T_g(t)}{T_g(t) - T_c} \sim 1 + 25\,\frac{kT_c}{E_a}$$

$$kT_g(t) = W_{max}/(\ln t - \ln \tau_0)\,. \quad kT_g(t) = kT_0 + E_a/\ln \frac{t}{\tau_0}\,. \quad W_{max}(T_g(t)) = kT_g(t)\ln\frac{t}{\tau_0} = \frac{E_a\,T_g(t)}{T_g(t) - T_0}\,.$$

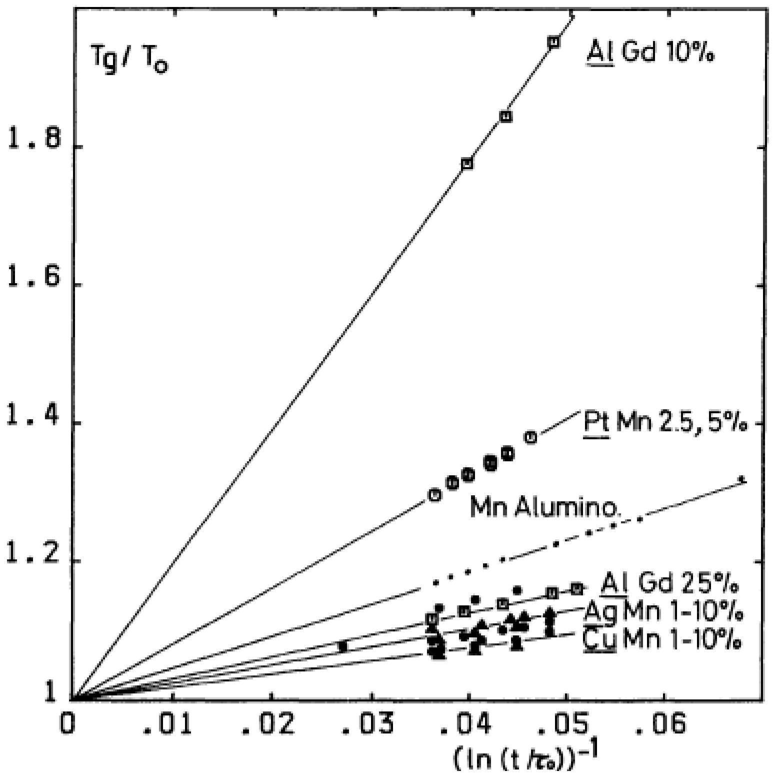
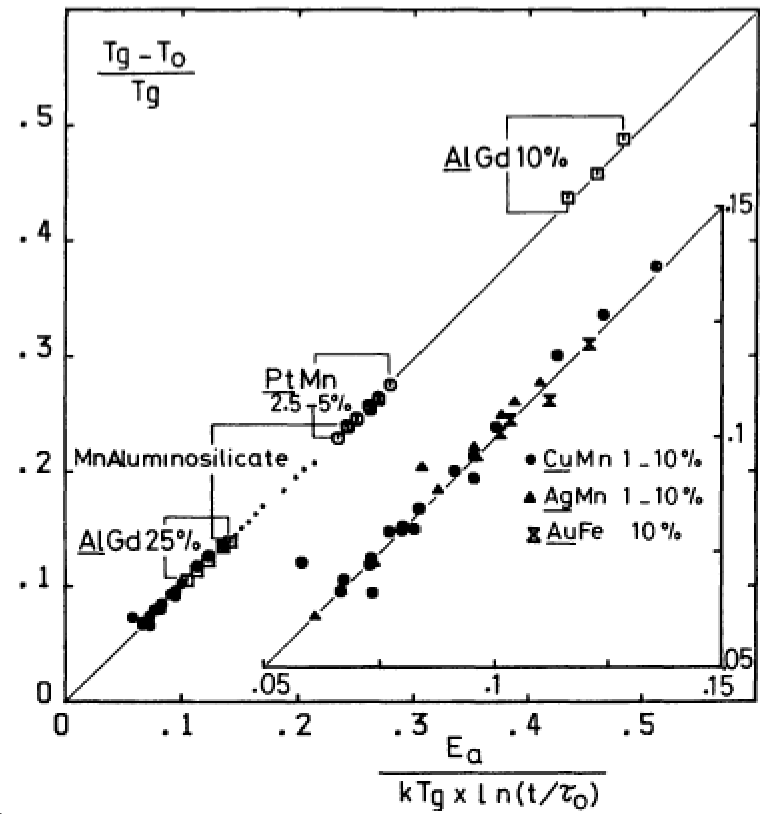


Fig. 7. — The temperature of the susceptibility maximum measured at different frequencies in different R.K.K.Y. system and in Mn aluminosilicate, is shown to follow rather well a Fulch[e]r law $T_{g(t)} = T_0 + E_a/(\ln t - \ln \tau_0)$ for the same value of $\tau_0 \sim 10^{-13}$ s. The temperatures hav[e] been normalised to T_0.



The inverse reduced energy barrier (in abcissa)

$$w_m^{-1} = E_a/W_{max} = E_a/kT_g(t)\ln t/\tau_0$$

Неэргодическое поведение

Spin glass CuMn

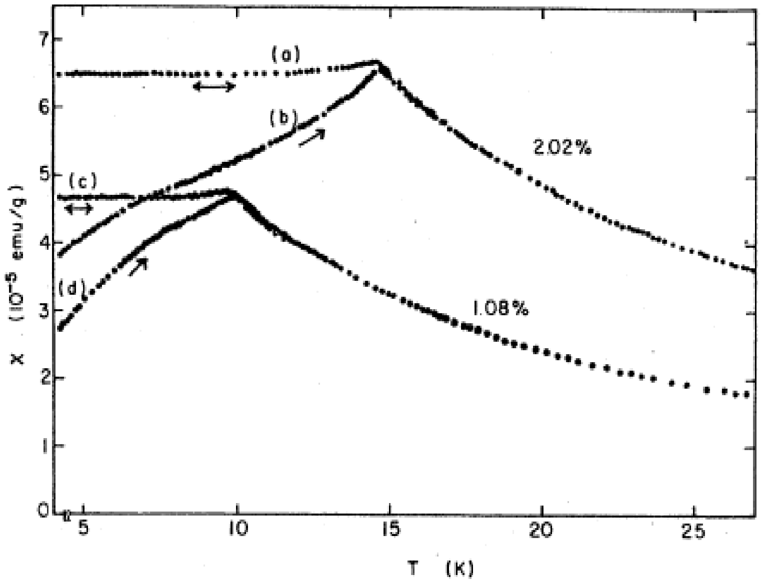
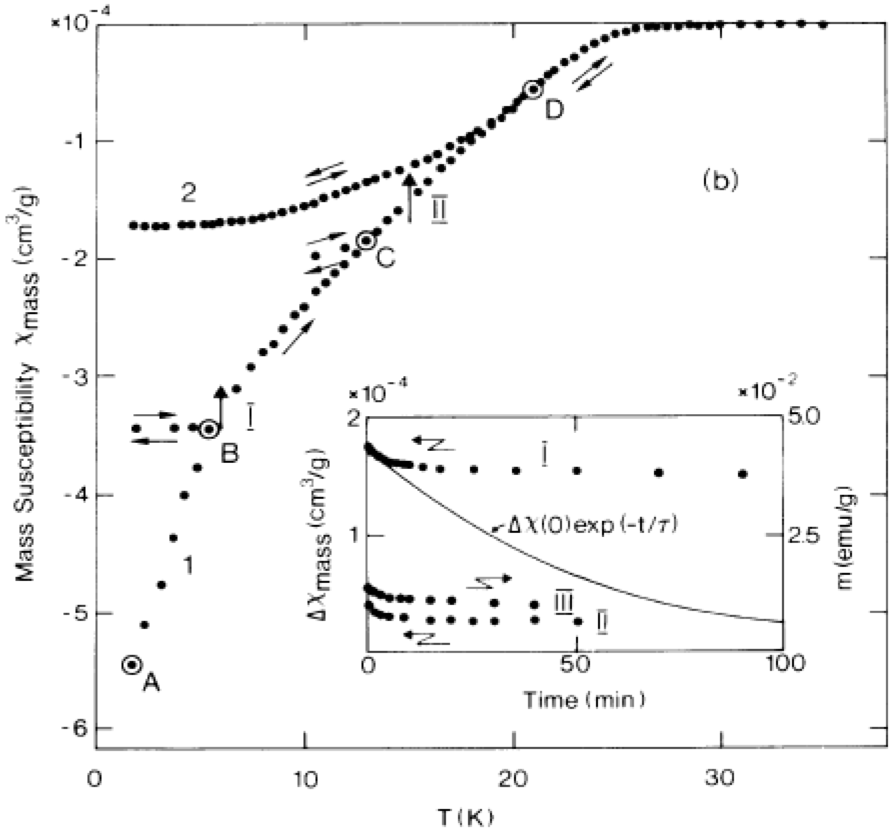


FIG. 7. Static susceptibilities of *Cu*Mn vs temperature for 1.08 and 2.02 at. % Mn. After zero-field cooling ($H < 0.05$ Oe), initial susceptibilities (b) and (d) were taken for increasing temperature in a field of $H = 5.9$ Oe. The susceptibilities (a) and (c) were obtained in the field $H = 5.9$ Oe, which was applied above T_f before cooling the samples. From Nagata *et al.* (1979).

Flux Trapping and Superconductive Glass

: in La_2CuO_{4-y}:Ba

K. A. Müller, M. Takashige,[a] and J. G. Bednorz



Спиновое стекло: «старение»

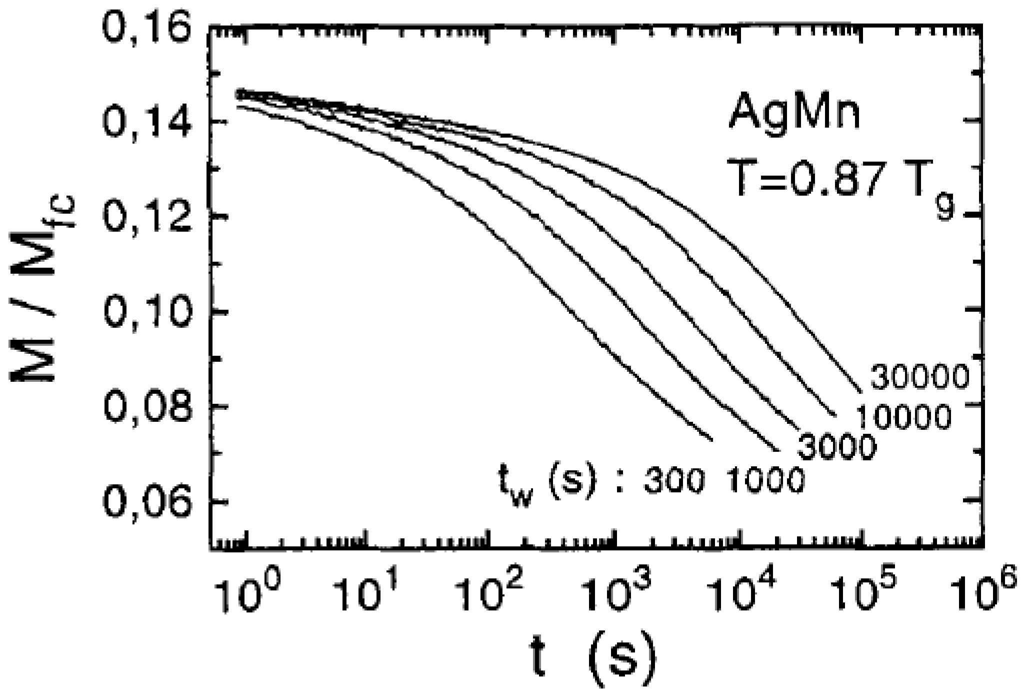


Fig. 1. a. Thermo-remanent magnetization M, normalized by the field-cooled value M_{fc}, *vs.* $t(s)$ ($\log_{10}$ scale) for the $Ag : Mn_{2.6\%}$ sample, at $T = 9K = 0.87T_g$. The sample has been cooled in a $0.1\ Oe$ field from above $T_g = 10.4K$ to 9K; after waiting t_w, the field has been cut at $t = 0$, and the decaying magnetization recorded.

Это никогда не кончается !

Temperature Variation Experiments

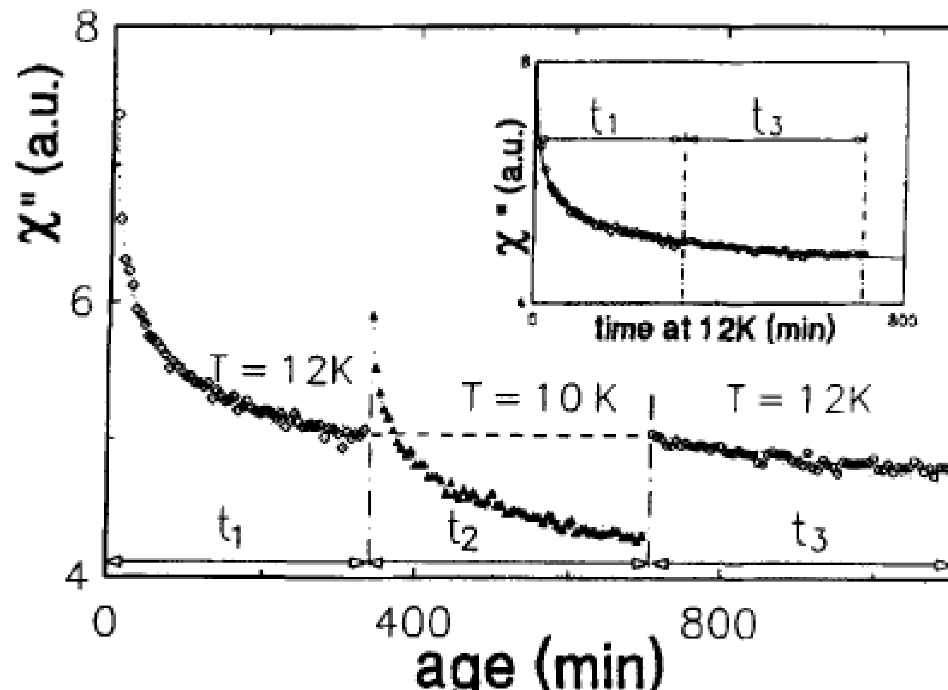


Fig. 4. Out of phase susceptibility $\chi''(\omega, t_a)$ of the $CdCr_{1.7}In_{0.3}S_4$ sample ($T_g = 16.7K$) during a temperature cycle. The frequency ω is 0.01 Hz, and t_a is the time elapsed from the quench. The inset shows that, despite the strong relaxation at 10 K, both parts at 12 K are in continuation of each other.

Главные вопросы

- Есть ли универсальность в точке перехода, и как найти индексы ?
- Как понимать не-экспоненциальное поведение при $T>T_c$?
- Как описать параметр порядка, возникающий при $T<T_c$?
- Очень медленная релаксация.
- Зависимость от истории (нет термодинамики!)
- Старение (зависимость от скорости движения по траектории).
- Параллельная или иерархическая динамика ?

Книги и обзоры

- K.Binder, A.Young Rev. Mod. Phys. **58**, 801 (1986)
- J. Souletie Ann.Phys.Fr. **10**, 69-84 (1985)
- Mezard, M., Parisi, G. and Virasoro, M .A . (1987) Spin Glass Theory and Beyond. Singapore: World Scientific.
- Vik.Dotsenko, M. Feigel'man, L.Ioffe, Sov. Sci. Rev. A. Phys. Vol. 15, (1990), pp. 1-250
- E.Vincent, *in Ageing and the Glass Transition* (Lecture Notes in Physics, 716) Springer (2007) Eds.M.Henkel,M.Pleimling,P.Sanctuary

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Задание к лекции №1

Найти наиболее свежие (последние 3-4 года) экспериментальные или численные работы по описанным в лекции свойствам спиновых

(и других) стекол