acta phys. slov. 36 (1986), No. 6

FRUSTRATION IN AMORPHOUS MAGNETIC SYSTEMS[1])

S. KOBE[2]), Dresden

A review is given of spin glass phenomena in amorphous magnetic systems. Amorphous spin glasses are classified as diluted systems, concentrated systems and systems around the percolation region. These last show a typical phase diagram with reentrant behaviour. Exact calculations for an amorphous Ising model help to understand some physical consequences of disorder and frustration.

ФРУСТРАЦИЯ В АМОРФНЫХ МАГНИТНЫХ СИСТЕМАХ

В работе дается обзор явлений в аморфных спиновых стеклах, которые подразделяются на системы с низкой концентрацией, высокой концентрацией и системы, находящиеся вблизи области перколяции. Для последних наблюдается типичная фазовая диаграмма с возвратным поведением. Точные вычисления в случае модели Изинга для аморфной системы позволяют понять некоторые физические следствия неупорядоченности и фрустрации.

I. SPIN GLASS PHENOMENA IN AMORPHOUS MAGNETIC SYSTEMS

Some of the amorphous alloys are good candidates for showing spin glass behaviour because they intrinsically possess the first ingredient for a spin glass: *disorder*. It is present not only as chemical disorder (the sole source in the crystalline case), but also as structural disorder. A second ingredient is *frustration*. This term summarizes a physical situation, which is characterized by a simultaneous appearance of ferromagnetic and antiferromagnetic interactions in a competitive manner. Thus one can expect that an amorphous alloy is an amorphous spin glass if either it contains also such atoms which preferably couple antiferromagnetically (Mn, Cr, ...) or the magnetic constituents interact long-ranged with alternating sign (e. g. the RKKY type of interaction) and are sufficiently diluted. The last situation resembles that in crystalline "canonical" spin glasses (e. g. **Au**Fe). A combination of both effects, antiferromagnetic interacting atoms and dilution, should be taken into consideration, too.

---

[1]) Contribution presented at the 7th Conference on Magnetism, Košice, June 5—8, 1984.
[2]) Technische Universität Dresden, Sektion Physik, Mommsenstrasse 13, 8027 DRESDEN, GDR.

Indeed, the search for spin glass properties in amorphous alloys has been carried out in the last years with increasing intensity. Typical experimental indications are, e. g., (i) a sharp cusp in the ac susceptibility for very low fields at a "freezing" temperature T_f (Fig. 1), (ii) no anomaly of the specific heat at T_f, (iii) field cooling effects and time relaxation phenomena below T_f, (iv) extreme field sensitivity of both the shape and the temperature of the susceptibility maximum.

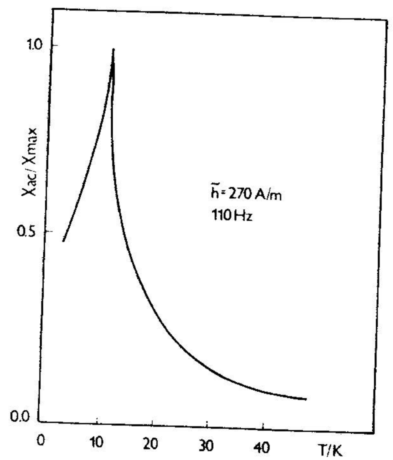


Fig. 1. χ_{ac}/χ_{max} vs. T for $(Fe_{0.05}Ni_{0.95})_{77}Si_{10}B_{13}$. χ_{max} — maximum of the ac susceptibility (after [1]).

Tab. 1 gives a survey on various series of amorphous spin glasses, for further information see also [53, 54]. More details are given in recent review papers by Durand [55] and Rhyne [56].

II. REENTRANT BEHAVIOUR

Recently, the second group in Tab. 1, which concerns substances with concentrations of the magnetic atoms around the percolation region, has been investigated by many authors. A strange "reentrant" behaviour has been found: In Fig. 2 the dc magnetization M of $(Fe_xMn_{1-x})_{75}P_{16}B_6Al_3$ for $x=0.65$ in a very low applied field (0.1 mT) is shown [26]. With decreasing temperature M rises at the Curie temperature ($T_C \approx 105$ K). However, at a lower temperature ($T_f \approx 52$ K) the magnetization falls again to zero. It appers that the system reenters a magnetic state with no long-range order. Both temperatures are very sensitive to applied fields with T_C increasing with H and T_f decreasing as H increases.

Investigations into different concentrations x have suggested a phase diagram which has the same characteristics for all alloys in this group. An example is given in Fig. 3 for $(Fe_xNi_{1-x})_{75}P_{16}B_6Al_3$ [17, 18]. The nature of the different

Table 1

Amorphous spin glass system

system	example	reference
I. Diluted systems		
Fe—Pd—Si	$(Fe—Pd)_{80}Si_{20}$	[2—5]
	$(Fe—Pd)_{82}Si_{18}$	[6—8]
Co—Pd—Si	$(Co—Pd)_{80}Si_{20}$	[2—4]
Fe—Ni—P—B	$(Fe—Ni)_{80}P_{12}B_8$	[9]
	$(Fe—Ni)_{79}P_{13}B_8$	[9—11]
	$(Fe—Ni)_{80}P_{14}B_6$	[11—12]
	$Fe_{1.6}Ni_{78.4}P_{10}B_{10}$	[13]
Mn—Ni—P—B	$(Mn—Ni)_{78}P_{14}B_8$	[14]
La—Gd—Au	$(La—Gd)_{80}Au_{20}$	[15]
II. Systems around the percolation region		
$(TM—TM')_{75}P_{16}B_6Al_3$	TM = Fe, TM′ = Ni	[16—22]
	TM = Co, TM′ = Ni	[18, 21]
	TM = Fe, TM′ = Mn	[18, 21—28]
	TM = Co, TM′ = Mn	[21, 29]
Fe—Ni—Si—B	$(Fe—Ni)_{77}Si_{10}B_{13}$	[30]
	$(Fe_{0.05}Ni_{0.95})_{77}Si_{10}B_{13}$	[1]
	$(Fe—Ni)_{78}Si_9B_{13}$	[31]
Fe—Sn		[32]
Co—Sn		[33]
III. Concentrated systems		
Mn—Me	Me = Si	[34—37]
	Me = C	[38]
	Me = Ge	[36, 38, 39]
Fe—Zr	$Fe_{92}Zr_8$	[40]
Dy—Cu		[41]
Gd—Al		[42—46]
Gd—Y—Al	$(Gd—Y)_{33}Al_{67}$	[47]
Ce—Au	$Ce_{80}Au_{20}$	[48]
Ce—Cu	$Ce_{72}Cu_{28}$	[48]
Y—Fe		[49—51]
Fe—F	FeF_3	[52]

low-temperature magnetic phases is a subject of present controversies. A possible explanation is given by Gabay and Toulouse [57]. They have investigated a three-component Heisenberg spin-glass model with infinite-ranged interactions. The model is similar to a mean-field theory. It is discussed that ferromagnetism below T_C involves only one spin component. The transverse spin components freeze into a spin glass state at T_f. The results shows that ferromagnetism and spin glass order can coexist at low temperatures.

A lot of further problems in this field are not yet clear, e. g., the role of anisotropy for the spin glass state, the existence of spin wave excitations in reentrant systems [28, 58, 59], the behaviour in the vicinity of the tricritical point [60], the relations between Hopkinson's maximum in the susceptibility and the cusp at T_f [1, 17], and the role of the metalloid elements, having in mind that no spin-glass phase has so far been found in amorphous $(Fe—Mn)_{75}P_{15}C_{10}$ [61] or $(Fe—Mn)_{80}B_{20}$ [62].

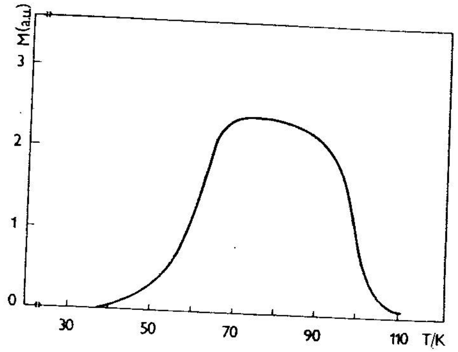


Fig. 2. Very low field dc magnetization of amorphous $(Fe_{0.65}Mn_{0.35})_{75}P_{16}B_6Al_3$ vs. temperature showing the rise at T_C and the lower temperature "reentrant" transition at T_f (after [26]).

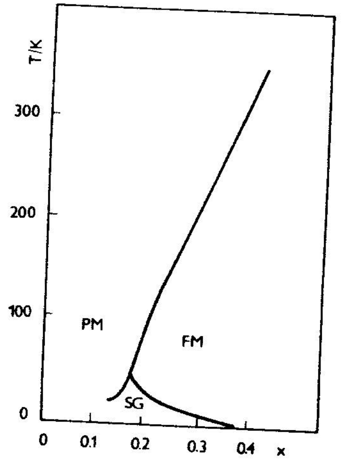


Fig. 3. Magnetic phase diagram for $(Fe_xNi_{1-x})_{75}P_{16}B_6Al_3$ obtained from very low field magnetization data (after [17, 18]).

Further questions concern both the crystalline and the amorphous spin glasses: What is the nature of the phase boundaries and the tricritical point? Does T_f represent a true second order phase transition point or do the spin enter at T_f a frozen state with experimentally inaccessible long time constants. The actual state of experimental and theoretical investigations is summarized in the proceedings of a recent Colloquium [63].

III. GROUND STATE PROPERTIES OF AMORPHOUS ISING SYSTEM WITH FRUSTRATION [64]

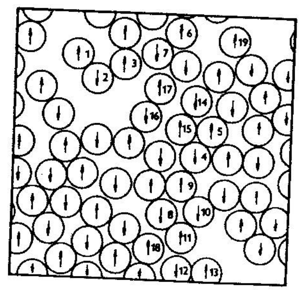
At present there is a large "gap" between experimental results and theoretical explanations. The most theoretical spin glass models are far from the real physical situation. Moreover, the difficulties to handle disorder, frustration and metastability in a theoretical way require serious approximations and simplifications, which

can lead to artifacts. The aim of our investigation is to obtain first impressions of the ground state properties for a more realistic model concerning the amorphous structure, putting up with a very simple description of the magnetism in the form of the Ising model and with the finiteness of the used system.

We start with the Ising Hamiltonian ($S=1/2$)

$$\mathcal{H} = -\sum_{i<j}^{i\ldots N} I_{ij} S_i^z S_j^z - \mu g H \sum_i^{i\ldots N} S_i^z \tag{1}$$

and consider a two-dimensional finite amorphous one-component system with a fixed structure (dense random packing of hard disks, computer-built using Finney's algorithm [65] with the packing fraction 0.68). Periodical boundary conditions are chosen. A short-range antiferromagnetic interaction decreasing linearly with distance is assumed. The range of interaction is a 1.36 times hard core diameter. Although this model does not fulfil all of the strict demands necessary for a spin glass [66], it involves frustration and disorder as the basic ingredients because of the combination of amorphous structure and antiferromagnetic interaction.



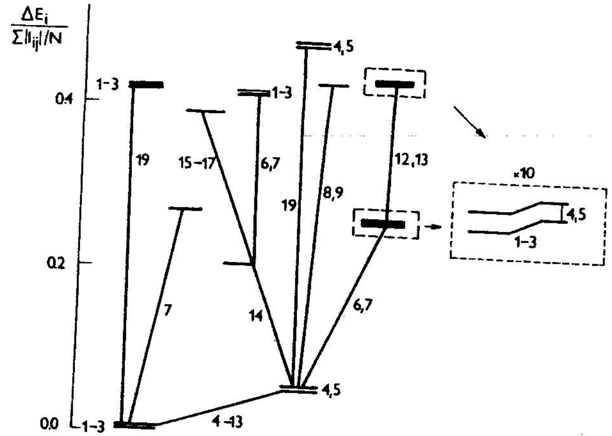


Fig. 4a. Ground state ($N=60$) for zero field.
Fig. 4b. Energy levels of the 22 lowest states of the system of Fig. 4a. The numbers denote the flipped spins.

The method of calculation is based on the mathematical theory of discrete optimization. In the past decades a remarkable progress has been attained in this field, connected with numerical algorithms for such standard problems as "the travelling salesman problem", "the Chinese postman problem", etc.

An application of the problem to the determination of the exact ground state of an Ising model is given first by Kobe and Hartwig [67] for amorphous systems with antiferromagnetic interactions, next by Bieche et al., Barahona et al., Angles d'Auriac and Maynard [68—71], who have investigated the $\pm I$ spin glass model.

Here, as a continuation of [67], a recursive branch-and-bound algorithm is developed, described in detail elsewhere [72].

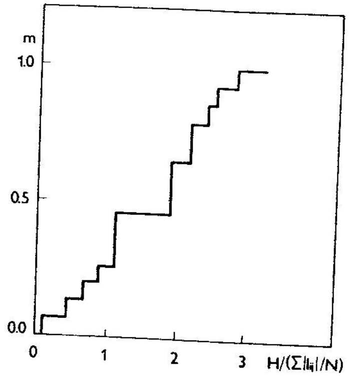


Fig. 5. Magnetization vs. field at zero temperature; $N=30$ (after [73]).

Fig. 4a shows the ground state for a system ($N=60$) in the zero field. By comparison with the "term scheme" of the low-lying states in Fig. 4b highly frustrated regions (clusters) can be recognized. The first excitation belongs to a flip of the spin no. 1—3 because of a large „inner surface", but already the second excitation (spins no. 4—13 are flipped) represents such a low-lying cluster excitation. Starting from such "valleys in the configuration space" further one-, two-, ..., -spin excitations occur.

Fig. 5 shows the magnitization vs. field curve for a system with $N=30$ [73] at zero temeprature. Jumps of the magnetization for intermediate fields arise because of the clusters, which have a high cluster magnetization and simultaneously a low excitation energy. With an increasing field such a cluster is flipped early and the resulting state represents the ground state for a wide field region. It plays the role of a „microdomain".

IV. SUMMARY

It is hoped that this review will partially acquaint the reader with the great diversity of phenomena and problems connected with amorphous spin glass systems and the physical understanding of their unusual properties.

REFERENCES

[1] Takahashi, M.: INTERMAG 1984 Digest, Hamburg, paper FA-O6.
[2] Zentko, A., Duhaj, P., Potocký, L., Tima, T., Bánsky, J.: Phys. Stat. Sol. (a) *31* (1975), K 41.

[3] Zentko, A., Potocký, L., Marko, P., Duhaj, P., Tima, T.: prepr. INTERMAG Conf., London 1975.
[4] Zentková, A., Duhaj, P., Zentko, A., Tima, T.: Physica *86—88B* (1977), 787.
[5] Chien, C. L.: Phys. Lett. *68 A* (1978), 394.
[6] Dublon, G., Lin, C. H., Bevk, J.: J. Appl. Phys. *50* (1979), 7650.
[7] Dublon, G.: Phys. Stat. Sol. (a) *60* (1980), 287.
[8] Dublon, G.: J. Appl. Phys. *52* (1981), 1871.
[9] Durand, J.: in: *Amorphous Magnetism II*, ed.: R. A. Levy and R. Hasegawa, Plenum Press, New York 1977, p. 305.
[10] Durand, J., Poon, S. J.: Journ. de Physique *39* (1978), C 6—953.
[11] Krause, J. K., Long, T. C., Egami, T., Onn, D. G.: Phys. Rev. B *21* (1980), 2886.
[12] Prater, J. T., Egami, T.: J. Appl. Phys. *50* (1979), 1706.
[13] Záveta, K., Schneider, J., Handstein, A., Zounová, F.: in: *Rapidly Quenched Metals* III. ed. Cantor, B., The Metals Soc. London 1978, Vol. 2, p. 156.
[14] Amamou, A.: in: *Amorphous Magnetism II*, ed.: R. A. Levy and R. Hasegawa, Plenum Press, New York 1977, p. 265.
[15] Poon, S. J., Durand, J.: Phys. Rev. B *16* (1977), 316.
[16] Bhagat, S. M., Geohegan, J. A., Chen, H. S.: Solid State Comm. *36* (1980), 1.
[17] Bhagat, S. M., Geohegan, J. A., Spano, M. L., Chen, H. S.: J. Appl. Phys. *52* (1981), 1741.
[18] Geohegan, J. A., Bhagat, S. M.: J. Magn. Magn. Mater. *25* (1981), 17.
[19] Rao, K. V., Malmhäll, R., Bhagat, S. M., Bäckström, G., Chen, H. S.: IEEE Trans. Magn. MAG-*16* (1980), 896.
[20] Lynn, J. W., Erwin, R. W., Rhyne, J. J., Chen, H. S.: J. Appl. Phys. *52* (1981), 1738.
[21] Yeshurun, Y., Salamon, M. B., Rao, K. V., Chen, H. S.: Phys. Rev. B *24* (1981), 1536.
[22] Chu, C. W., Wu, M. K., Jin, B. J., Lai, W. Y., Chen, H. S.: Phys. Rev. Lett. *46* (1981), 1643.
[23] Chien, C. L., Hsu, J. H., Stokes, J. P., Bloch, A. N., Chen, H. S.: J. Appl. Phys. *50* (1979), 7647.
[24] Salamon, M. B., Rao, K. V., Chen, H. S.: Phys. Rev. Lett. *44* (1980), 596.
[25] Yeshurun, Y., Salamon, M. B., Rao, K. V., Chen, H. S.: Phys. Rev. Lett. *45* (1980), 1366.
[26] Manheimer, M. A., Bhagat, S. M., Chen, H. S.: Phys. Rev. B *26* (1982), 456.
[27] Keller, H., Rao, K. V., Debrunner, P. G., Chen, H. S.: J. Appl. Phys. *52* (1981), 1753.
[28] Aeppli, G., Shapiro, S. M., Birgeneau, R. J., Chen, H. S.: Phys. Rev. B *28* (1983), 5160; Phys. Rev. B *29* (1984), 2589.
[29] Kramer, B., Rao, K. V.: Bull. Am. Phys. Soc. *25* (1980), 177.
[30] Hilscher, G., Haferl, R., Kirchmayr, H., Müller, M., Güntherodt, H. J.: J. Phys. F *11* (1981), 2429.
[31] Manns, V., Brand, R. A., Keune, W., Marx, R.: Sol. Stat. Comm. *48* (1983), 811.
[32] Teirlinck, D., Piecuch, M., Geny, J. F., Marchal, G., Mangin, P., Janot, C.: IEEE Trans. Magn. MAG-*17* (1981), 3079.
[33] Marchal, G., Teirlinck, D., Mangin, P., Janot, C., Hübsch, J.: J. de Physique *41* (1980), C 8 — 662.
[34] Cochrane, R. W., Ström-Olsen, J. O., Rebouillat, J. P.: J. Appl. Phys. *50* (1979), 7348.
[35] Hauser, J. J.: Solid State Commun. *30* (1979), 201.
[36] Hauser, J. J.: J. Magn. Magn. Mater. *15—18* (1980), 1387.
[37] Hayes, T. M., Allen, J. W., Boyce, J. B., Hauser, J. J.: Phys. Rev. B *23* (1981), 4691.
[38] Hauser, J. J.: Phys. Rev. B *22* (1980), 2554.
[39] Hauser, J. J., Hsu, F. S. L.: Phys. Rev. B *24* (1981), 1550.
[40] Hiroshi, H., Fukamichi, K.: Phys. Lett. *85 A* (1981), 242.
[41] Coey, J. M. D., von Molnar, S.: J. de Physique *39* (1978), L-327.

[42] Mizoguchi, T., McGuire, T. R., Gambino, R. J., Kirkpatrick, S.: Physica *86—88 B* (1977), 783.
[43] Mizoguchi, T., McGuire, T. R., Kirkpatrick, S., Gambino, R. J.: Phys. Rev. Lett. *38* (1977), 89.
[44] McGuire, T. R., Mizoguchi, T., Gambino, R. J., Kirkpatrick, S.: J. Appl. Phys. *49* (1978), 1689.
[45] Malozemoff, A. P., Hart, S. C.; Phys. Rev. B *21* (1980), 29.
[46] Barbara, B., Malozemoff, A. P., Imry, Y.: Physica B+C *108* (1981), 1289.
[47] Malozemoff, A. P., Krusin-Elbaum, L., Taylor, R. C.: J. Appl. Phys. *52* (1981), 1773.
[48] Löhneysen, H. v., Schink, H. J., Felsch, W., Samwer, K., Schröder, H.: Physica *107 B* (1981), 631.
[49] Forester, D. W., Pala, W. P., Segnan, R.: in *Amorphous Magnetism II*, ed. R. A. Levy and R. Hesegawa, Plenum Press, New York 1977, p. 135.
[50] Forester, D. W., Koon, N. C., Schelleng, J. H., Rhyne, J. J.: J. Appl. Phys. *50* (1979), 7336.
[51] Coey, J. M. D., Givord, D., Rebouillat, J. P., Lienard, A.: J. Phys. F *11* (1981), 2707.
[52] Férey, G., Varret, F., Coey, J. M. D.: J. Phys. C *12* (1979), L 531.
[53] Ferchmin, A. R., Kobe, S.: *Amorphous Magnetism and Metallic Magnetic Materials Digest, Selected Topics in Solid State Physics*, Vol XVII, ed. E. P. Wohlfarth. North Holland, Amsterdam 1983, p. 55.
[54] Kobe, S., Fechmin, A. R., Nosé, H., Stobiecki, F.: Supplement A of 53: J. Magn. Mat. 60 (1986), 1.
[55] Durand, J.: in: *Glassy Metals. Magnetic, Chemical and Structural Properties*. Ed. R. Hasegawa, CRC Press, Boca Raton, Florida 1983, Chapter 4, p. 109.
[56] Rhyne, J. J.: *Magnetic Phase Transitions*. Springer Series in Solid State Sciences. Vol. 48, ed. M. Ausloos and R. J. Elliott. Springer Verlag, Berlin 1983, p. 241.
[57] Gabay, M., Toulouse, G.: Phys. Rev. Lett. *47* (1981), 201.
[58] Lynn, J. W., Erwin, R. W., Chen, H. S., Rhyne, J. J.: Solid State Commun. *46* (1983), 317.
[59] Hennion, B., Hennion, M., Hippart, F., Murani, A. P.: J. Phys. F *14* (1984), 489.
[60] Moorjani, K., Ghatak, S. K., Rao, K. V., Kramer, B., Chen, H. S.: Journ. de Physique *41* (1980), C 8 — 718.
[61] Wieser, E.: Journ. de Phys. *41* (1980), C 1 — 259.
[62] Onodera, H., Yamamoto, H.: J. Phys. Soc. Japan *50* (1981), 3575.
[63] *Heidelberg Colloquium on Spin Glasses, Lecture Notes in Physics*, Vol. 192, ed. J. L. van Hemmen and I. Morgenstern. Springer Verlag, Berlin 1983.
[64] Kobe, S.: Wiss Zeitschr. Hochschule für Verkehrswesen, Dresden, Sonderheft *13* (1984), 43.
[65] Finney, J. L.: Mater. Sci. Eng. *23* (1976), 199.
[66] Mydosh, J. A.: Wiss Zeitschr. Hochschule für Verkehrswesen, Dresden, Sonderheft *13* (1984), 25.
[67] Kobe, S., Hartwig, A.: Comput. Phys. Commun. *16* (1978), 1.
[68] Bieche, I., Maynard, R., Rammal, R., Uhry, J. P.: J. Phys. A *13* (1980), 2553.
[69] Barahona, F., Maynard, R., Rammal, R., Ugry, J. P.: J. Phys. A *15* (1982), 673.
[70] Barahona, F. J.: Phys. A *15* (1982), 3241.
[71] Angles d'Auriac, J. C., Maynard, R.: Sol. Stat. Commun. *49* (1984), 785.
[72] Hartwig, A., Daske, F., Kobe, S.: Comput. Phys. Commun. *32* (1984), 133.
[73] Daske, F., Kobe, S.: J. Magn. Magn. Mater. *31—34* (1983), 1317.

Received October 8th, 1985
Revised version received January 27th, 1986