Aust. J. Phys., 1980, 33, 881-95

# Magnetic Order in Spatially Disordered Systems

#### T. J. Hicks

Department of Physics, Monash University, Clayton, Vic. 3168.

#### Abstract

Magnetic order in metallic and nonmetallic binary alloys is discussed. A recent model, in which the breakdown of long-range magnetic order in metallic alloys is due to the cooperative change of the moment *magnitude* with concentration, is illustrated with examples from nickel alloy systems. Percolation at the critical concentration for long-range order plays a part in these alloy systems, as it does for nonmetallic alloys and metallic alloys in which the magnetic moment magnitude is not so environment dependent. Discussion of the magnetic state in the non long-range ordered composition range leads to a description of spin glasses. The results of recent experiments on the low temperature configuration, the AC susceptibility near the freezing temperature, and the dynamics at all temperatures are presented with the implications for the nature of the spin glass transition.

#### 1. Introduction

Although liquid ferromagnets and antiferromagnets are unknown there are a large number of magnetically ordered amorphous materials (e.g. amorphous CoP; see Bletry and Sadoc 1974, 1975). Another class of positionally disordered materials are the substitutional binary alloys, and in sufficient concentration of the magnetic species these too support long-range order.

Magnetic materials can be divided into electrical insulators and conductors. Of the latter class, in many materials the magnetically polarized electrons take part in the band and thus contribute to the electrical conduction. In these materials the magnetic moment associated with an atom is not necessarily due to an integral number of electrons and is susceptible to changes in electron structure in its neighbourhood.

This paper describes states of magnetic order observed in binary alloys, both metallic and nonmetallic. However, the emphasis is placed firstly on the modelling of the magnetic moment distribution in ferromagnetic alloys with electron band effects done by the author (Hicks 1977, 1980), and secondly on spin glasses to which the author and colleagues have contributed information on the structure (Ahmed and Hicks 1974, 1975; Davis and Hicks 1979).

## 2. Alloys with Magnetic Long-range Order

The simplest magnetic alloys are those formed by a mixture of magnetic and nonmagnetic compounds, like  $Mn_{1-x}Zn_xF_2$ . Compounds of elements from the 3d transition series are mostly antiferromagnetic and addition of a nonmagnetic atom randomly and substitutionally into the lattice gradually destroys the long-range magnetic order so that the material becomes paramagnetic at all temperatures. Tran-

sition metal compounds which are nonconducting have moments on the magnetic species which are closely similar to that expected of the isolated ion. Generally, the exchange interactions are via the second species or group and there is very little overlap between magnetic atoms.



Fig. 1. Variation of Neel temperature (solid line) and average sublattice magnetization (dashed line) for the  $Mn_{1-x}Zn_xF_2$  system (E. Bakshi, personal communication).

Addition of nonmagnetic atoms in place of the magnetic species weakens the coupling until it can no longer sustain long-range magnetic order and the compound becomes a paramagnet by the *directional* disordering of the atomic moments. The character of the disordering is stressed here because metallic systems in which the *magnitude* of the atomic moment depends on its environment will be discussed below. A guide to the concentration at which long-range order will disappear is given by percolation theory (Stauffer 1977) as the concentration at which there is just one path of interaction right through the structure. Values of the percolation concentration for first neighbour interactions for various simple structures as obtained by series expansion methods (Stauffer 1975) are given as follows:

Lattice	s.c.	b.c.c.	f.c.c.
Percolation concentration	0.307	0.243	0.195

An example of the variation of critical temperature and sublattice magnetization is given by the simple antiferromagnetic system  $(Mn/Zn)F_2$  in Fig. 1. The critical concentration is close to that predicted by percolation theory. One must be cautious here however because connectivity is not the only condition for the establishment of long-range order. For instance the linear chain coupled by Heisenberg exchange *JS.S* does not exhibit long-range order, and requires that some form of anisotropy be present before order is established (Steiner *et al.* 1976).

The opposite extreme class of magnetic alloys are those in which the main effect on the long-range ordered state is to reduce the *magnitude* of the moment of magnetic atoms in the environs of the substitutional nonmagnetic impurity. The classic example is the ferromagnetic Ni–Cu system. The critical concentration for ferromagnetism is approximately 44 at. % Ni (Ahern *et al.* 1958), well in excess of that predicted by percolation theory for the f.c.c. lattice with first neighbour interactions. This is no surprise because Ni does not carry a moment when dissolved in Cu and therefore there are no individual moments to couple at the percolation concentration. The Ni atoms acquire a moment by virtue of their surroundings before ferromagnetism can be established.



Fig. 2. Schematic diagram of the nickel and copper 3d and 4s electron bands (after Mott 1935). The rigid band model assumes a common fixed band is formed in Ni-Cu alloys.

The earliest idea of how Ni loses moment and ferromagnetism when alloyed with Cu was due to Mott (1935). Fig. 2 shows his electron band picture in which the effect of adding Cu to Ni is simply to donate one electron per added atom to the electron bands without changing their shape (rigid band model). The addition goes mainly to the deficient electron spin, because in that band the density of states at the Fermi level is largest. It requires an addition of  $\sim 0.6$  electrons to completely fill the minority spin band thus ensuring loss of moment and ferromagnetism at approximately a composition of 60% of Cu (cf.  $\sim 56$  at. % observed). This model lasted for 30 years until evidence for the non-rigidity of the electron bands emerged from photoelectron emission studies (see e.g. the recent work of Durham *et al.* 1979) and evidence for the inhomogeneity of the ferromagnetism (Aldred *et al.* 1973) came from neutron diffraction.

The details of the inhomogeneity of the ferromagnetism in Ni–Cu alloys have subsequently been well explained in two similar models by Medina and Cable (1977) and Hicks (1977). Both models are phenomenological in the sense that the moment at each site is described by a set of parameters which are determined by the variation of spontaneous moment with composition and/or the details of the distribution of ferromagnetic moment. The physics employed however is to determine each atomic moment as a function of its *atomic* environment and also of its *magnetic* environment via an exchange field. The response to the exchange field is due to the local electron structure, which, although it varies from atom to atom, is nevertheless part of the electron bands of the alloy as a whole. Progress towards the band theory of substitutional alloys has been made using the coherent potential approximation and its derivatives (see e.g. Frollani *et al.* 1975). The phenomenology of the models presented here is in the spirit of such electron band structure calculations.

The inhomogeneous ferromagnetic alloy model described below is that of Hicks (1977). It differs from that of Medina and Cable (1977) in the assumption of a fixed saturating function for moment at each site, which allows a prediction of the details of the moment distribution from a fit of the variation of spontaneous moment with composition, and relatively easy insertion of nonrandom alloy statistics. The moment at any site is assumed to be

$$m(\mathbf{R}) = p(\mathbf{R}) \alpha(\mathbf{R}) h(\mathbf{R}) / \{1 + B h(\mathbf{R})\},\$$

where  $p(\mathbf{R})$  is 0 or 1 depending whether or not a magnetic atom is at  $\mathbf{R}$ ,  $\alpha(\mathbf{R})$  is the zero field susceptibility at the site,  $h(\mathbf{R})$  is the exchange field, and B is a parameter controlling the rate of saturation. The  $\alpha(\mathbf{R})$  and  $h(\mathbf{R})$  are respectively functions of the atomic and magnetic environments in the following manner:

$$\alpha(\boldsymbol{R}) = \sum_{\boldsymbol{R}'} a(\boldsymbol{R} - \boldsymbol{R}') p(\boldsymbol{R}'), \qquad h(\boldsymbol{R}) = \sum_{\boldsymbol{R}''} \mathscr{I}(\boldsymbol{R} - \boldsymbol{R}'') m(\boldsymbol{R}'').$$

By substituting these expressions into that for  $m(\mathbf{R})$ , and Fourier transforming, an implicit integral equation for the Fourier transform of  $m(\mathbf{R})$  is obtained. By separating this into its average and fluctuating parts, and ignoring some convoluted terms, separate equations for the average moment and for the spatial distribution of the moment can be obtained. By fitting the former to the average moment data all the constants in the expressions are determined, and thus the distribution of moment is determined except for the range of the bare interaction  $\mathscr{I}(\mathbf{R} - \mathbf{R}'')$ , for which a choice of predominantly first neighbour or longer range interactions must be made.

For the above model, in which only one magnetic species is treated, the variation of average moment is quadratic, and any critical concentration for ferromagnetism can be obtained. This is because in this model the breakdown of ferromagnetism is not due to the dilution of bonds and the consequent disordering of integral moments, but rather due to the loss of moment on the magnetic sites. The fit of average moment for Ni–Cu is shown in Fig. 3a. The distribution of moment is expressed as the amplitude of the Fourier components of the deviations of the moment from the mean. This information is available from diffuse neutron scattering, and Fig. 3b shows a comparison between the predictions of the model for Ni–Cu moment distribution and data obtained from diffuse scattering of both polarized and unpolarized neutrons. The similar model of Medina and Cable (1977) has a similar success.



**Fig. 3.** Variation of (a) the average moment with nickel concentration for Ni–Cu alloys and (b) the amplitude of moment fluctuations with wave vector  $\kappa$  for Ni–Cu alloys of different composition (c is the nickel fraction). In (a) the curve is the fit of the magnetic environment model. The data points are from five different studies. In (b) the lines are parameter free predictions of the magnetic environment model. The points are from eight different studies using unpolarized (closed symbols) and polarized neutrons (open symbols). (Note 1 Å =  $10^{-10}$  m.)

Inclusion of a moment on the second species in a magnetic alloy complicates the model, for instance because it is necessary to include three different exchange interactions among other parameters. However, this has been done with some success for Ni–Pd and Ni–Rh alloys (Hicks 1980). The Ni–Rh case is more clear cut because it is known that the alloys are reasonably random. The fitting of the average moment for two species requires eight parameters and the fit to Ni–Rh is shown in Fig. 4*a*. Fig. 4*b* shows the comparison of the predicted moment distribution (using the eight parameters determined from the fit of average moment) with the data again from diffuse neutron scattering experiments. The model can also predict the individual average moments on the two species simply from the fit of average total moment, and this is shown in Fig. 5 for the Ni–Rh system. Notice that even the extreme behaviour of the Rh moment can be predicted by the model.

There seems little doubt that the mechanisms for moment change incorporated in the above model are applicable to nickel alloys. The model explains the wide range of ferromagnetic critical concentrations observed for nickel alloys as having nothing to do with the percolation concentration. The next step is to try and relate the various parameters of the model to features of alloy electron band structures which are presently being calculated. Coherent potential approximation band structures have been used to predict average species moments in binary ferromagnetic alloys (see e.g. Kajzar 1977) with some success, but as yet there appears to be no attempt to calculate the complete moment distribution.

The situation with respect to iron alloys is more complex. Iron is a conductor in which magnetically polarized electrons take part in the conduction process, and

885



Fig. 4. Variation of (a) the average ferromagnetic moment with composition and (b) the predicted moment disturbance with scattering vector for Ni–Rh alloys (*c* is the nickel fraction). In (*a*) the curve is the fit of the two moment, eight parameter, magnetic environment model. The open circles are from Crangle and Parsons (1960) and the solid circles are from Muellner and Kouvel (1975). In (*b*) the first neighbour interactions only are assumed, and no further parameters than those generated by the fit of average ferromagnetic moment. The dashed curves are the modulus of the disturbance. The experimental data are those of Cable (1977) for unpolarized (open circles) and polarized (solid circles) neutron results.



Fig. 5. Average moments of the individual magnetic species predicted from the magnetic environment model for the Ni–Rh system; the solid curve is for nickel and the dashed curve is for rhodium. The experimental points are from Cable (1977).

the magnitude of the atomic moment can be modified by the addition of impurities (Collins and Low 1965). On the other hand, in many dilute alloys isolated iron atoms carry a moment. For Au-Fe, for instance, isolated iron atoms have a moment of  $\sim 3 \mu_B$  (Tholence and Tournier 1971) and the critical concentration for ferro-magnetism is close to that expected for percolation via first neighbour interactions (Coles *et al.* 1978). Isolated nickel atoms in dilute alloys carry no moment and it must be for this reason that the simple model outlined above is particularly applicable to nickel alloys.

The composition region close to the onset of ferromagnetism is an interesting one. It appears that even in Ni–Cu alloys, where for almost all the ferromagnetic concentration range the breakdown of ferromagnetism is due to the collapse in the magnitude of the nickel moment, the final transition to the paramagnetic state is due to the directional disorientation of large regions in which the moment is more than the average. In fact just to the ferromagnetic side of the critical concentration, the distribution in magnetism can be described as large widely spaced inhomogeneities (Hicks *et al.* 1969; Hicks 1976). Just inside the paramagnetic concentration range, susceptibility studies indicate the presence of similar sized superparamagnetic moments (Kouvel and Comly 1970). Some sort of percolation limit is therefore responsible for the final breakdown, but in this case it is a percolation between superparamagnetic regions rather than between individual moments.

The antiferromagnetic elements in the 3d transition series Mn and Cr also form alloys with long-range magnetic order and with critical concentrations which are not the percolation limit for the structure with first neighbour interactions. The most studied of these is the f.c.c. form of manganese alloyed with copper which has a critical concentration of about 28 at. % Cu (Cowlam *et al.* 1978). It is not clear at the moment whether the breakdown of antiferromagnetism in this system is due to percolation between individual moments. Some preliminary diffuse neutron scattering measurements on a 10 at. % Cu alloy have been interpreted in terms of a change in *magnitude* of the manganese moment (Davis and Hicks 1977), but isolated manganese atoms in copper do have a good moment. So it appears that manganese may be complex in the same manner as iron. Chromium on the other hand may be more like nickel, but most of the work on chromium alloys has concentrated on the unusual incommensurate antiferromagnetic structure rather than surveying the whole longrange ordered magnetic phase to the critical concentration.

Beyond the critical concentration for long-range magnetic order in disordered alloy systems, whether compounds or metals, is the paramagnetic phase. Or is it quite paramagnetic? The next section outlines some of the properties of spin glasses.

### 3. Spin Glasses

The most surprising of the types of magnetic order observed in binary solid solutions containing a good magnetic species is that of the 'spin glass'. Until the early seventies it was not recognized that all the indications of a magnetic ordering process, coming especially from the temperature variation of susceptibility, pointed towards, not the onset of long-range order, but rather the freezing in of short-range order.

It is instructive to look at one early piece of work on CuMn and AgMn alloys (Owen *et al.* 1957) in which the magnetic manganese ion is present in dilute quantities. Fig. 6 shows that in these alloys there is a broad maximum in the susceptibility versus



Fig. 6. Inverse volume susceptibility versus temperature for CuMn and AgMn alloys (after Owen *et al.* 1957).

temperature curve, reminiscent of the maximum in susceptibility at the Neel temperature of an antiferromagnet. Owen *et al.* analysed their results on the assumption that at low temperatures the alloys became antiferromagnetic. At the same time, Meneghetti and Sidhu (1957) and Bacon *et al.* (1957) using neutron diffraction showed that the onset of long-range antiferromagnetism did not occur for compositions less than about 70 at. % Mn. Another puzzling feature for Owen *et al.* was that from fitting their high temperature susceptibility results to a Curie–Weiss law they found that the interaction was predominantly *ferromagnetic* even though they had assumed *antiferromagnetic* order at low temperatures.

An exhaustive search for Bragg peaks which could indicate long-range antiferromagnetic order in a 5 at. % CuMn crystal was made by Arrott (1965) using neutron diffraction. Arrott looked through much of reciprocal space driven on by the idea (based on a theory of the ground state of an electron gas due to Overhauser 1960) that the antiferromagnetic order need not be commensurate with the lattice. He found nothing, and put a limit on the average moment contributing to antiferromagnetic long-range order of  $0.03 \mu_{\rm B}$  per atom. This is to be compared with a moment of  $4 \mu_{\rm B}$  on each Mn ion inferred from the high temperature susceptibility measurements of Owen *et al.* (1957).

The term 'spin glass' was first used to describe magnetic systems of the CuMn type by B. R. Coles, as quoted by Anderson (1973), but the first direct demonstration of the glassy nature of the microscopic spin structure was that of Ahmed and Hicks

(1974, 1975) using neutron scattering. Because there is no long-range magnetic order in a spin glass there are no Bragg peaks of magnetic origin in a neutron diffraction pattern. All the information is in the background structure of such a pattern. Ahmed and Hicks were able to separate out the magnetic part of that background by analysing the polarization of the scattered neutron beam in a polarized neutron experiment.



Fig. 7. Nuclear (open symbols) and magnetic (full symbols) scattering cross sections for neutrons at  $4 \cdot 2$  K for  $4 \cdot 7$  at. % CuMn along the three crystal directions.

This was important as the majority of the background diffuse scattering from **Cu**Mn alloys is not magnetic and contains structure of its own. The work of Ahmed and Hicks showed that, at low temperature in **Cu**Mn alloys containing less than 10 at. % Mn, the spin correlations are predominantly but weakly ferromagnetic and that the moment associated with each Mn ion is 4  $\mu_B$ , in agreement with the high temperature susceptibility results. In Fig. 7 the later results of Davis and Hicks (1979) are shown on a 4  $\cdot$  7 at. % **Cu**Mn single crystal. The nuclear defect scattering is angle independent indicating that the solution of Mn atoms in Cu is closely random. The magnetic scattering rises toward small angles indicating the overall spin correlation is weakly ferromagnetic. In fact, the magnetic cross sections are reasonably fitted by just a first neighbour correlation which, as  $\langle 110 \rangle$  is the first neighbour direction, also explains the difference between the  $\langle 110 \rangle$  results and those in the other two directions. No doubt there are longer range spin correlations, but data at smaller scattering again confirms that a moment of 4  $\mu_B$  is associated with each manganese atom.

Further interest in the nature of the spin glass transition was raised by the susceptibility results of Canella and Mydosh (1972) when they discovered that the broad peak sharpened into a cusp shape as the applied field was lowered to zero. Their results for CuFe alloys are shown (Fig. 8*a*) along with an earlier result (Lutes and Schmit 1962) measured in a field of 1 kOe. Canella and Mydosh measured the



Fig. 8. Temperature variation of (a) the AC susceptibility versus temperature for 1 and 2 at. % CuMn specimens in zero and various applied fields (after Canella and Mydosh 1972, including the data of Lutes and Schmit 1962) and (b) the magnetic specific heat of  $1 \cdot 2$  at. % CuMn versus temperature (after Wenger and Keesom 1976). The arrow in (b) indicates the freezing temperature determined from susceptibility measurements.

susceptibility by AC techniques at a frequency of 155 Hz, but no dependence on frequency of the susceptibility for spin glass systems has been noted in the literature for frequencies accessible to the AC technique (see e.g. the recent work of Dahlberg *et al.* (1979) on AgMn spin glasses). The sharpness of the susceptibility cusp and

its apparent independence of frequency raised the question of whether the spin glass transition could be regarded as a cooperative phase transition. However, no support for the phase transition hypothesis has come from specific heat measurements, which reveal no anomaly at the freezing temperature (Wenger and Keesom 1976), as shown in Fig. 8b.



**Fig. 9.** (a) Temperature dependence of the AC susceptibility in  $\operatorname{Eu}_x \operatorname{Sr}_{1-x} S$  with Eu content x. (b) The time dependence of the thermoremanent magnetization in  $\operatorname{Eu}_{0.2} \operatorname{Sr}_{0.8} S$  at two temperatures and various cooling fields (after Maletta and Felsch 1979).

The other peculiar features of spin glasses are the remanent magnetization that can be induced by cooling through the freezing temperature in an applied field (Guy 1977), and the displaced hysteresis loops first observed by Kouvel (1961, 1963) on varying the field for such field-cooled samples. A detailed discussion of these effects cannot be made here.

We return to the properties of spin glasses in vanishing fields. It has long been accepted (see e.g. Mydosh 1977) that the spin glass state is a result of the long-range oscillatory exchange coupling (RKKY) via the host conduction electrons in the above and very many more well-investigated metallic systems. However, recent work on the insulator  $Eu_xSr_{1-x}S$  (Maletta and Felsch 1979) has revealed all the characteristic spin glass behaviour already seen in metals, except that the freezing is frequency dependent. The exchange interactions in this material are thought to be restricted to first and second neighbours (Kasuya 1970) and to be ferromagnetic and antiferromagnetic respectively. So even if the interaction is not long range at least it is mixed. As an example of the results from this insulating system, Fig. 9a shows the low field AC susceptibility measured on a number of (Eu, Sr)S compositions, while Fig. 9b shows that this system also acquires a remanent magnetization on cooling in a field through the freezing temperature. The behaviour with temperature of each property is exactly the same as for metallic spin glasses. Spin glass behaviour also occurs for concentrated amorphous systems (Mizoguchi et al. 1977), where the randomness is due partially or, in the case of amorphous compounds, entirely to the randomness of interatomic distances.

Theories of the spin glass state fall into two categories. In the first category the freezing temperature is treated as a phase transition temperature below which an order parameter develops (see e.g. Edwards and Anderson 1975). Such theories have been heavily influenced by the sharpness of the susceptibility cusp at the freezing temperature in low fields. The second category of theories regards the spin glass as a paramagnet in which the spin relaxation times are very long. These theories group the spins into clusters (see e.g. Tholence and Tournier 1974, 1977) and explain the cusp in the susceptibility as occurring when the largest (which contribute most to the susceptibility) spin clusters are just too sluggish to respond to the applied field. It is fair to say that both theoretical streams have had their problems. The phase transition theories tend to predict anomalies in properties other than susceptibility, such as specific heat; but the variation of magnetic specific heat with temperature is free of any sharp anomalies. The theories in which the freezing process is controlled by a spectrum of relaxation times predict that there should be some frequency dependence of the susceptibility, in particular a shift in the freezing temperature with frequency. This has not been observed. Dahlberg et al. (1979) followed the AC susceptibility of AgMn up to 109 kHz and looked at the e.s.r. at 1.6 and 9.2 GHz without finding any characteristic temperature which varied with frequency.

Relaxation times spanning the range  $10^{-12}$ - $10^{-8}$  s are now open to measurement by neutron spectroscopy using the spin echo technique (Mezei 1972). With this technique one looks at  $S(\mathbf{k}, t)/S(\mathbf{k}, 0)$  where  $S(\mathbf{k}, 0)$  is the scattering coming from the Fourier component of the magnetization of wave vector  $\mathbf{k}$  at time zero and  $S(\mathbf{k}, t)$  is the same thing at a later time t. Mezei and Murani (1979) have measured the time decay of this function for 5 at. % CuMn at various temperatures. Their results are shown in Fig. 10 for a Fourier component wavelength of 70-80 Å (7-8 nm). There is no observable decay up to  $10^{-8}$  s at 5 K but, as the temperature is increased through the freezing temperature of 27 K, most of the decay occurs within  $10^{-8}$  s. On raising the temperature to 100 K the decay is over in  $10^{-11}$  s. Apart from the wide time range of the relaxation processes at various temperatures, the significant point about these results is that the decay is not exponential. The bold curve in Fig. 10 shows the shape expected for a simple relaxation process  $exp(-\gamma t)$  with  $\gamma = 0.5$  meV. The shape is preserved, but the curve is simply shifted along the t axis for different  $\gamma$ . So at each temperature there is no single relaxation time, but rather a spectrum of relaxation times. This is at variance with the simple phase transition theories of the spin glass state which predict a simple exponential relaxation (Binder 1977). It is consistent with a spread of relaxation times required by the cluster model, and the almost linear time variation on the semilog plot is reminiscent of the Binder and Schröder (1976) Monte Carlo computer simulations of Ising spin glasses. Mezei and Murani (1979) suggest that at high temperatures the relaxation may be exponential with the time constant being determined by the Korringa mechanism via the conduction electrons.



Fig. 10. Measured time dependent spin correlation function for 5 at. % CuMn at various temperatures. The thick curve corresponds to the simple exponential decay; the thin curves are guides to the eye (after Mezei and Murani 1979).

No attempt is made here to choose between the two main streams of spin glass theory at this early stage. The phase transition approach in its present approximations however has problems both with describing the specific heat results and with the form of the relaxation observed. Unfortunately the paramagnetic slow relaxation picture also has problems in defining the entities which are relaxing in any more than a qualitative way. That is why after 10 years of intensive effort there is still much to do.

# 4. Conclusions

This paper has concentrated on two aspects of spatial disorder in binary solid solutions of magnetic atoms. The first of these concerned the modelling of systems supporting long-range magnetic order in which the loss of the order is predominantly an electron band effect. The best examples to date of such systems are ferromagnetic nickel alloys. Although the magnetic long-range order is much more complicated (incommensurate antiferromagnetic), chromium alloys promise also to be good examples. Cobalt, iron and manganese alloys also show band effects on the moment magnitude if alloyed with other species, but the loss of magnetic order is probably due to moment disorientation rather than moment loss due to band effects. Secondly, for those magnetic species that in dilute quantities retain an atomic moment, paramagnetism changes to static short-range order at low temperatures. Spin glasses can be metallic and sometimes nonmetallic, but their common magnetic properties show a very sharp anomaly in low field susceptibility at a temperature interpreted as the glass freezing temperature. Whether the behaviour of spin glasses is best explained by theories approaching the glass regime as a phase with an order parameter, or as simply a very sluggish paramagnet, is still controversial. Experiments are being performed to look at the dynamics of spin glass systems in the hope of either distinguishing between the two approaches or showing the way to a more sophisticated theory.

# Acknowledgments

I would like to thank Dr R. Cywinski and Dr E. Gray for discussion on the frequency dependence of the spin glass susceptibility, and Mr E. Bakshi for permission to use his recent results on the  $Mn_{1-x}Zn_xF_2$  system.

#### Note added in proof

Since this article was written some frequency dependence of the magnetic properties of metallic spin glasses has been claimed. In particular Tholence (1980) fits the observed variation with a Fulcher law which confirms the spin glass transition as analogous to the normal glassy transition.

#### References

Ahern, S. A., Martin, M. J., and Sucksmith, W. A. (1958). Proc. R. Soc. London A 248, 145.

Ahmed, N., and Hicks, T. J. (1974). Solid State Commun. 15, 415.

Ahmed, N., and Hicks, T. J. (1975). J. Phys. F 5, 2168.

Aldred, A. T., Rainford, B. D., Hicks, T. J., and Kouvel, J. S. (1973). Phys. Rev. B 7, 218.

Anderson, P. W. (1973). In 'Amorphous Magnetism' (Eds H. O. Hooper and A. M. de Graaf) (Plenum: New York).

Arrott, A. (1965). J. Appl. Phys. 36, 1093.

Bacon, G. E., Dunmur, I. W., Smith, J. H., and Street, R. (1957). Proc. R. Soc. London A 241, 223.

Binder, K. (1977). Festkörperprobleme XVII, 55.

Binder, K., and Schröder, K. (1976). Phys. Rev. B 14, 2142.

Bletry, J., and Sadoc, J. F. (1974). Phys. Rev. Lett. 33, 172.

Bletry, J., and Sadoc, J. F. (1975). J. Phys. F 5, L110.

Cable, J. W. (1977). Phys. Rev. B 15, 3477.

Canella, V., and Mydosh, J. A. (1972). Phys. Rev. B 6, 4220.

Coles, B. R., Sarkissan, B. V. B., and Taylor, R. H. (1978). Philos. Mag. B 37, 489.

Collins, M. F., and Low, G. G. (1965). Proc. Phys. Soc. London 86, 535.

Cowlam, N., Gillot, L., and Shamah, A. M. (1978). Proc. Int. Conf. on Transition Metals, Toronto 1977: Inst. Phys. Conf. Ser. Vol. 39, p. 619.

Crangle, J., and Parsons, D. (1960). Proc. R. Soc. London A 255, 509.

Dahlberg, E. D., Hardiman, M., Orbach, R., and Souletie, J. (1979). Phys. Rev. Lett. 42, 401.

Davis, J. R., and Hicks, T. J. (1977). J. Phys. F 7, 2153.

Davis, J. R., and Hicks, T. J. (1979). J. Phys. F 9, 753.

Durham, P. J., et al. (1979). J. Phys. F 9, 1719.

Edwards, S. F., and Anderson, P. W. (1975). J. Phys. F 5, 65.

Frollani, G., Menzinger, F., and Sachetti, F. (1975). Phys. Rev. B 11, 2030.

Guy, C. N. (1977). J. Phys. F 7, 1505.

Hicks, T. J. (1976). Phys. Rev. Lett. 37, 719.

Hicks, T. J. (1977). J. Phys. F 7, 481.

Proceedings of Fourth AIP Congress

Hicks, T. J. (1980). J. Phys. F 10, 879.

Hicks, T. J., Rainford, B. D., Kouvel, J. S., Low, G. G., and Comly, J. B. (1969). *Phys. Rev. Lett.* 22, 531.

Kajzar, F. (1977). J. Phys. F 7, 1623.

Kasuya, T. (1970). IBM J. Res. Dev. 14, 214.

Kouvel, J. S. (1961). J. Phys. Chem. Solids 21, 57.

Kouvel, J. S. (1963). J. Phys. Chem. Solids 24, 795.

Kouvel, J. S., and Comly, J. B. (1970). Phys. Rev. Lett. 24, 598.

Lutes, O. S., and Schmit, J. L. (1962). Phys. Rev. 125, 433.

Maletta, H., and Felsch, W. (1979). Phys. Rev. B 20, 1245.

Medina, R. A., and Cable, J. W. (1977). Phys. Rev. B 15, 1539.

Meneghetti, D., and Sidhu, S. S. (1957). Phys. Rev. 105, 130.

Mezei, F. (1972). Z. Phys. 255, 146.

Mezei, F., and Murani, A. P. (1979). J. Mag. Mag. Mat. 14, 211.

Mizoguchi, T., McGuire, T. R., Kirkpatrick, S., and Gambino, R. J. (1977). Phys. Rev. Lett. 38, 89.

Mott, N. F. (1935). Proc. Phys. Soc. London 47, 571.

Muellner, W. C., and Kouvel, J. S. (1975). Phys. Rev. B 11, 4522.

Mydosh, J. A. (1977). Proc. 2nd Int. Symp. on Amorphous Magnetism (Eds A. A. Levy and R. Hasegawa) (Plenum: New York).

Overhauser, A. W. (1960). Phys. Rev. Lett. 4, 462.

Owen, J., Browne, M. E., Arp, V., and Kip, A. F. (1957). J. Phys. Chem. Solids 2, 85.

Stauffer, D. (1975). J. Phys. C 8, L172.

Stauffer, D. (1977). In 'Amorphous Magnetism', Vol. II (Eds A. A. Levy and R. Hasegawa) (Plenum: New York).

Steiner, M., Villain, J., and Windsor, C. G. (1976). Adv. Phys. 25, 87.

Tholence, J. L. (1980). Solid State Commun. 35, 113.

Tholence, J. L., and Tournier, J. (1971). J. Phys. C 32, 1, 211.

Tholence, J. L., and Tournier, J. (1974). J. Phys. C 35, 4, 229.

Tholence, J. L., and Tournier, J. (1977). Physica B, C 86-88, 873.

Wenger, L. E., and Keesom, P. H. (1976). Phys. Rev. B 13, 4053.

Manuscript received 20 August 1980, accepted 19 September 1980

