

There is now a rich variety of amorphous magnetic materials that exhibit spontaneous long-range magnetic ordering below a critical temperature being characteristic to each substance. That is to say, although the long-range order for the distribution of magnetic atoms does not exist, a magnetic long-range order is possible in these systems. Therefore, these amorphous magnets can be mainly classified into three categories according to the nature of long-range magnetic order. In the next section, we present general information and definitions about the natures of these three categories.

1.2 General Information and Definitions

Crystalline magnetic materials are in general classified into four categories according to the nature of long-range magnetic order. These are called ferromagnetic, antiferromagnetic, ferrimagnetic, and helimagnetic systems and correspond, respectively, to parallel, antiparallel, uncompensated antiparallel, and spiral alignment of magnetic moments. Because of the structurally disordered nature, there exists a number of amorphous magnets with new-type spin orderings not classified by those of crystalline systems. In this section,

let us at first adumbrate some important physical properties of the three categories in amorphous magnets.

A. Ferromagnet

In an amorphous ferromagnet the spins are oriented in the same direction but the topological arrangement of spins is not regular. Some typical examples of amorphous ferromagnetic materials are alloys of transition metals (Fe, Co, Ni) with metalloid elements (B, C, Si, Ge, P), containing approximately 20 at % of the latter, such as $\text{Fe}_{80}\text{B}_{20}$ and $(\text{Fe}_x\text{Ni}_{1-x})_{80}\text{B}_{10}\text{P}_{10}$. Below the critical (Curie) temperature T_c , all the spins are, on the average, oriented parallel to one another, giving rise to a large spontaneous magnetization of the sample in some arbitrary direction if the system is isotropic. In real amorphous materials, there is always some anisotropy, although it may be weak, and the bulk magnetic moment $M(T)$ is oriented along one of the easy magnetization axes. The spontaneous magnetization decreases continuously as the temperature rises, and, in the absence of the external magnetic field, disappears at and above the critical temperature. In the vicinity of the Curie temperature ($T \leq T_c$), the temperature dependence of the spontaneous magnetization is given by the expression

$$M(T) \cong \text{const} \times \left(1 - \frac{T}{T_c}\right)^\beta, \quad (1.5)$$

where β is called the critical exponent. The value of β in amorphous ferromagnets is close to 0.4. In the low-temperature region, i.e., for $T \rightarrow 0$, the temperature dependence of $M(T)$ has the

power form given by

$$M(T) = M(0)[1 - BT^{3/2} - CT^{5/2} - \dots] , \quad (1.6)$$

where $M(0)$ is the saturation magnetization and corresponds to complete alignment of moments. The values of B in amorphous ferromagnets are typically larger than those in related crystalline ferromagnets. The range of the $T^{3/2}$ variation extends more widely than that expected for the related crystalline ferromagnet. Above the Curie temperature ($T \gg T_C$), an amorphous ferromagnet behaves like a classical paramagnet and the paramagnetic susceptibility χ obeys the Curie-Weiss law

$$\chi = \frac{\text{constant}}{T - T_C} \quad (1.7)$$

For T close to T_C , however, some departure from the above behavior is observed ; it can be described by

$$\chi \propto (T - T_C)^{-\gamma} , \quad (1.8)$$

where γ is another critical exponent. The value of γ in amorphous ferromagnets is scattered around the value $\gamma \cong 1.36$. Another prominent difference between the amorphous and crystalline ferromagnets is also found in the temperature dependence of the paramagnetic susceptibility. The inverse paramagnetic susceptibility of amorphous ferromagnets shows a large downward curvature. The transition region to the Curie-Weiss law ($\chi^{-1} \propto (T - T_C)$) extends over $100 \sim 200$ K in amorphous ferromagnets, whereas in crystalline ferromagnets this transition takes place within a temperature range of $\sim T_C/25$. The phenomenon is ascribed as a characteristic of highly disordered systems. The spin

arrangement of an amorphous ferromagnet is schematically described in Fig.1.1 (a).

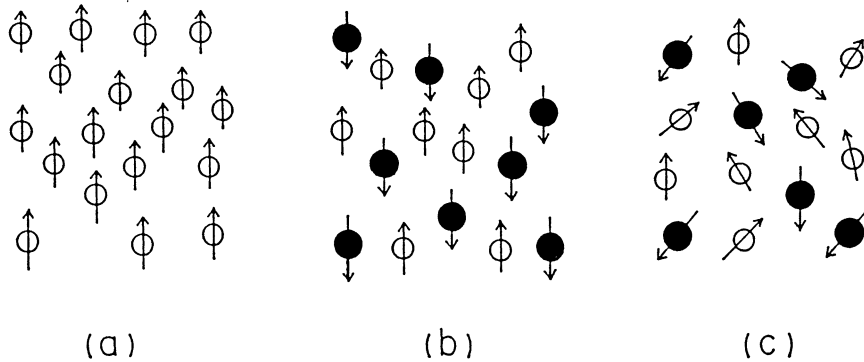


Fig.1.1 The arrangements of magnetic moments in (a) a ferromagnet, (b) a ferrimagnet and (c) a noncollinear (sperimagnetic) ferrimagnet.

B. Ferrimagnet

As shown in Fig.1.1 (b), ferrimagnets have several subnetworks with a finite resultant moment, comparable with the spontaneous moments of the subnetworks; Some typical examples are the transition metal-rare earth Gd alloy systems with rare earth moments (black circles) pointing oppositely to the transition metal moments (white circles) forming a two-subnetwork structure. In amorphous $GdCo_3$, for example, there is strong positive Co-Co exchange coupling, producing a ferromagnetic cobalt "sublattice". The Co-Gd is negative and much weaker, so that the gadolinium "sublattice" is coupled antiparallel to the cobalt.

The resulting ferrimagnetic order is analogous to that found in similar crystalline alloys. Since the atomic moments on the two - "sublattices" are unequal, we have a resultant spontaneous magnetization as in a ferromagnet. Above the transition temperature T_C ferrimagnets show paramagnetic behavior. In contrast with a ferromagnet, there is an interesting possibility of the existence, under certain conditions, of a compensation temperature T_{comp} ($T_{comp} < T_C$), at which the resultant magnetization vanishes. The appearance of a compensation point is due to the fact that the magnetic moments of the "sublattices" compensate each other completely at $T = T_{comp}$, due to the different temperature dependences of the sublattice magnetizations. Above this temperature, the compensation is no longer obtained, and the resultant moment does not disappear until the Curie point is reached. Above the transition temperature, the temperature dependence of susceptibility is described by the Curie-Neel law;

$$\chi^{-1} = \chi_0^{-1} + \frac{T}{C} + \frac{\Delta}{T-\theta} \quad (1.9)$$

where χ_0 , θ , C and Δ are constants. In amorphous $Gd Co_3$, the Gd moment falls more rapidly with temperature than the Co moment, producing a compensation point at 350 K. In general, the T_{comp} of all amorphous ferrimagnetic alloys are lower than the T_{comp} of the corresponding crystalline materials.

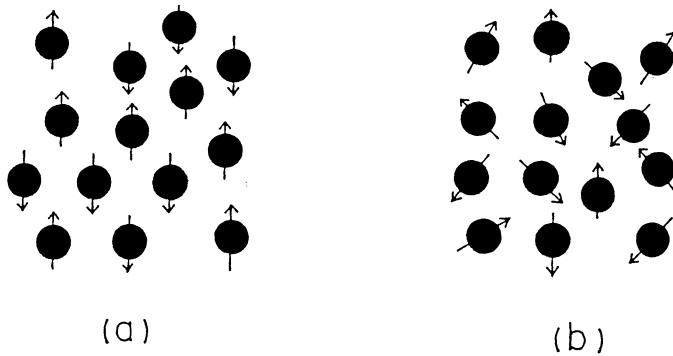


Fig.1.2 The spin arrangements in (a) an amorphous antiferromagnet and (b) in a spin glass (or speromagnet).

In a standard textbook of magnetism in crystalline systems it is common to comment on antiferromagnetism before adumbrating some physical properties of ferrimagnetism. An antiferromagnetic crystalline system consists of two or more interpenetrating equivalent magnetic sublattices. The sublattices are ferromagnetic and their moments are collinear but in opposite directions, giving zero resultant moment. On the other hand, if the exchange coupling between neighboring spins is negative, the spin arrangement of the amorphous magnet may be a collinear structure having the zero net moment, as shown in Fig.1.2 (a). However, an antiferromagnet is particularly sensitive to the sort of structural disorder present in an amorphous solid. In fact, there is a few experimental evidences for antiferromagnetic structures in amorphous materials with negative interactions, such as the high iron content glass $(\text{Fe}_2\text{O}_3)_{0.79}\text{P}_2\text{O}_5$ with the

finite Neel temperature T_N ($T_N = 7$ K). In amorphous magnets, the existence of antiferromagnetic couplings often leads to random, non-collinear magnetic structures and a multiplicity of nearly-degenerate quasi ground states. These facts are sharply in contrast to those in crystalline magnets where most of the insulators have collinear antiferromagnetic sublattice structures.

C. Amorphous Magnets with Canted (Noncollinear) Spin Structures

Typical examples of this type of ordering are the transition metal - heavy rare earth alloy systems. Figure 1.1 (c) shows such a spin arrangement where white and black circles have the same meanings as those of Fig.1(b). Amorphous Dy Co₃ is taken as an example. The exchange interactions are similar to those in amorphous Gd Co₃, but in addition there is a strong influence of the local crystal field on the dysprosium. The arrangement of the neighboring atoms defines a local preferred direction for the dysprosium moment, and the combined effect of this interaction and the exchange interactions results in the sperimagnetic structure depicted in Fig.1.3 (a). The dysprosium "sublattice" has a net moment antiparallel to that of the cobalt, yet it is not ferromagnetic (collinear). The T_{comp} of Dy Co₃ is observed near $T = 230$ K. In sperimagnets, furthermore, the following spin structure is included; spins of each "sublattice" (or subnetwork) have a random, non-collinear structure, but the sublattices are coupled parallel. As illustrated in Fig.1.3 (b), amorphous Nd_xCo_{1-x} alloys are such an example.

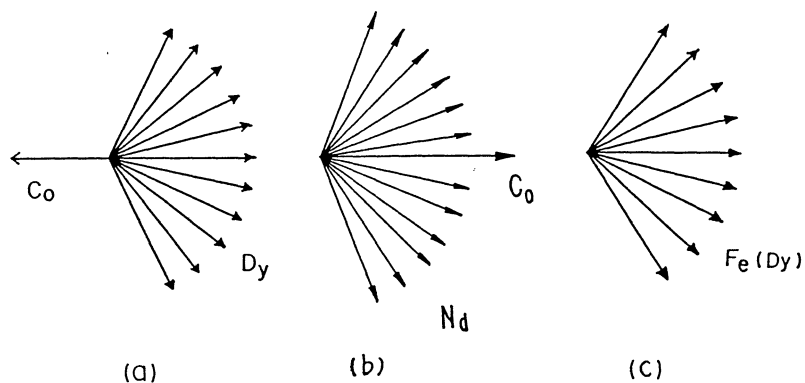


Fig.1.3 Schematic magnetic structures for (a) sperimagnetic DyCo_3 , (b) sperimagnetic $\text{Nd}_x\text{Co}_{1-x}$ and (c) asperomagnetic Fe_3Y and DyNi_3 .

Now, when white (or black) circles are replaced by black (or white) circles in Fig.1.1 (c), the amorphous magnet is called a speromagnet or an asperomagnet with a random, non-collinear spin structure. For example, amorphous YFe_2 is speromagnetic and has the spin structure of Fig.1.2 (b), in which the atomic moments of Fe are directed randomly to different directions. The speromagnet can be also defined as an ordering having short-range correlations of spin directions within small noncrystalline region but no average long-range correlation. Experimentally, a sharp cusp has been reported in the low-field susceptibility at $T = 55 \text{ K}$ for amorphous YFe_2 and hyperfine splitting appears in the Mossbauer measurement around this temperature. The magnetic ordering of "spin glass", which are a class of crystalline alloys containing a few percent of magnetic impurity atoms, is most

likely of this type. On the other hand, amorphous YFe_3 and $DyNi_3$ are asperomagnetic and the spin structure is illustrated in Fig.1.3 (c). In the asperomagnetic structure, the moments are distributed at random but have some long-range preferred orientation in direction. In other words, an asperomagnet has a spontaneous magnetization but a speromagnet does not. The speromagnet resembles a random antiferromagnet or spin glass state, whereas the asperomagnet can be thought as a random ferromagnet. The speromagnetic spin arrangement may be classified as the concentrated spin glass like ordering.

1.3 Hamiltonians and Exchange Interactions

To describe the behavior of an amorphous magnet, it is necessary to know the explicit form of the Hamiltonian of the system. But, it is a many-body system and no attempt can be made to include all the features of the system in the Hamiltonian. Instead, we usually consider a simplified system in which the most important characteristics of the real substance are included.

In the theory of magnetism, a magnetic substance is frequently considered as a system of spins localized at lattice