METHODOLOGICAL NOTES

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Notes on phase transitions and the role of spin fluctuations

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Abstract. **The physical properties of two chiral systems with localized and delocalized magnetic moments, Cu_2OSeO_3 and MnSi, are reviewed. It is concluded that the longitudinal fluctuations of magnetic moments have no strong effect on the qualitative picture of phase transitions and the magnetic phase diagrams of chiral systems.**

Keywords: chiral magnetic systems, phase transitions, longitudinal fluctuations of the magnetic moment

The Heisenberg model based on the exchange interaction between localized spins has explained the nature of magnetic ordering in dielectric crystals and a number of metallic crystals [1]. The spin excitations or fluctuations characteristically occurring in Heisenberg magnets are spin waves, spin flips, and critical fluctuations [2]. As follows from the time reversal symmetry, magnetic phase transitions are usually second-order transitions. Because of the short range of the exchange force interaction, fluctuation effects are highly pronounced in magnetic phase transitions and are therefore a subject of intense study [3, 4].

Stoner [5] showed that under certain conditions (high density of states on the Fermi level, d-metals), the exchange interaction splits the system of itinerant electrons into two subbands (majority and minority bands) with oppositely directed spins and different numbers of electrons [5]. Clearly, this last factor produces a magnetic moment. The magnetic moment of such a system vanishes at the Curie point T_C due to the individual thermal spin-flip excitations (Stoner excitations) [6].

The key point of difference between the two models of a ferromagnet is whether magnetic moments completely vanish at T_C (Stoner) or persist at temperatures above T_C (Heisenberg). In the latter case, the magnetic moment vanishes when the system loses its long-range order.

Because of the absence of free magnetic moments, the magnetic susceptibility of a nonmagnetic phase in the Stoner model cannot be described by the Curie law. Also, the Stoner model overestimates the Curie temperature. These conclusions of the Stoner theory cannot be reconciled with experimental observations.

The breakthrough came in 1972, when Murata and Doniach [7] showed in the framework of a scalar model that including magnetic fluctuations into the theoretical description of magnetic metallic systems provides a much better agreement with experimental observations. According to [7], the phase transition in a weak metallic ferromagnet results from the interaction of fluctuating modes. In the framework of the Landau expansion, this should imply that the fourth-order term is negative and therefore the magnetic phase transition occurs via a first-order phase transition. Moriya and Kawabata [8], apparently independently, modified the Stoner model by including transverse spin fluctuations, which lowered the Curie temperature and provided an approximate applicability of the Curie–Weiss law for the magnetic susceptibility.

Lonzarich and Taillefer [9] used the Ginzburg–Landau formalism to develop a quantitative model for the magnetic properties of weak ferromagnets. The vector nature of the order parameter, which exhibits both transverse and longitudinal fluctuations, is taken into account in the model in Ref. [9] (see also Ref. [10]). The role of the transverse (orientation) fluctuations of the magnetic moment in metallic magnets is clear: including them results in the magnetic order being lost at a much lower temperature than the temperature at which magnetic moments themselves vanish (as is the case in the Stoner model).

As regards the longitudinal magnetic moment fluctuations, their role is very significant in weak band magnets such as MnSi. According to Moriya [11], the saturation of longitudinal magnetic fluctuations is responsible for the applicability of the Curie–Weiss law in the paramagnetic phase of weak ferromagnets. Weak fluctuations of magnetic moments also occur in Heisenberg magnets, but they likely have a different nature from those in band magnets (see, e.g., Refs [11–13]).

At the same time, the effect of longitudinal magnetic fluctuations on the physical properties of materials has received insufficient treatment in the literature. It is unclear, in particular, what the role of longitudinal fluctuations is in magnetic phase transitions. Fortunately, it has now become possible to answer this question, at least partially, by comparing the behavior patterns of two chiral magnets, MnSi and Cu_2OSeO_3 [14, 15] (Figs 1 and 2). Both these compounds crystallize in a noncentrosymmetric space group $P2_13$, which leads to the appearance of the Dzyaloshinskii–Moriya term in the energy of the corresponding systems. As a result, the magnetic structures of MnSi and Cu_2OSeO_3 are spirals with respective pitches of 180 Å and 616 Å. Cu_2OSeO_3

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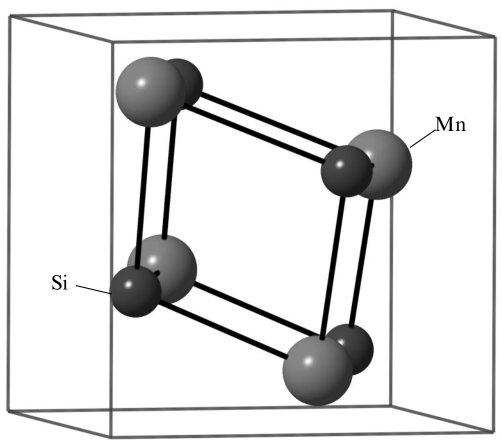

Figure 1. Crystal structure of chiral magnet MnSi [14].

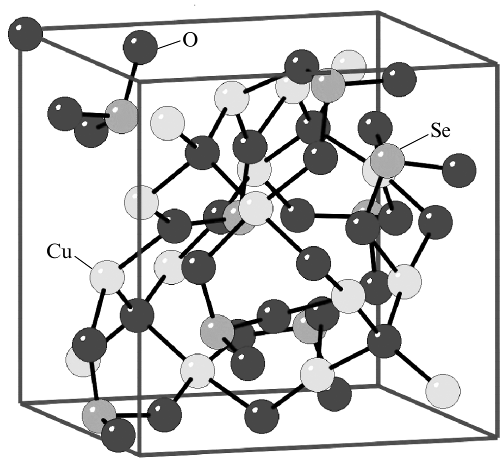

Figure 2. Crystal structure of chiral magnet Cu_2OSeO_3. It is seen that Cu ions form a three-dimensional network of distorted tetrahedra. (See Ref. [16] for details.)

is a magnetic dielectric with localized spins, whereas MnSi is a weak itinerant magnet. In the latter case, longitudinal spin fluctuations can justifiably be expected to manifest their effects.

We recall that MnSi is a model helicoidal magnet whose properties have been studied sufficiently well [14]. Figure 3 illustrates some of these properties near a phase transition. The presence of a peak (delta function) on the curves of the heat capacity, the thermal expansion coefficient, and the thermal electrical resistivity coefficient is a characteristic feature of the phase transition in MnSi, which provides evidence in favor of a first-order transition.

Another salient phase transition feature in MnSi is a shoulder or a small maximum to the right of the peak in Fig. 3. As neutron studies suggest, this side maximum corresponds to intense chiral fluctuations [17, 18].

In Fig. 4, the Cu_2OSeO_3 and MnSi heat capacity and magnetic susceptibility curves are compared near the phase transition. Curiously, the characteristic features inherent in the transition in MnSi is reproduced almost fully in Cu_2OSeO_3. Notably, both compounds exhibit a skyrmion phase (Figs 5 and 6). We emphasize that the magnetic phase diagram of a chiral system (including the existence of the

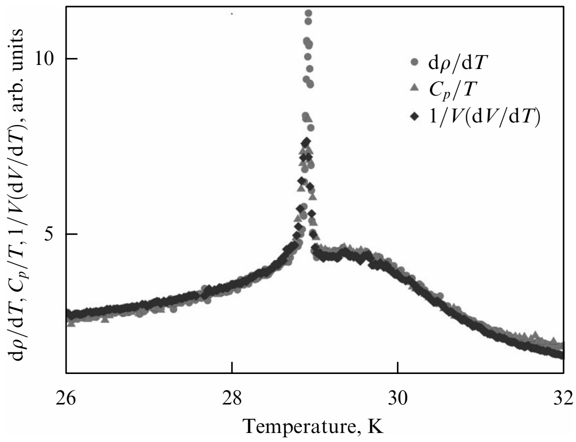

Figure 3. The thermal electrical resistivity coefficient, the heat capacity, and the thermal expansion coefficient at the phase transition in MnSi in reduced units [14].

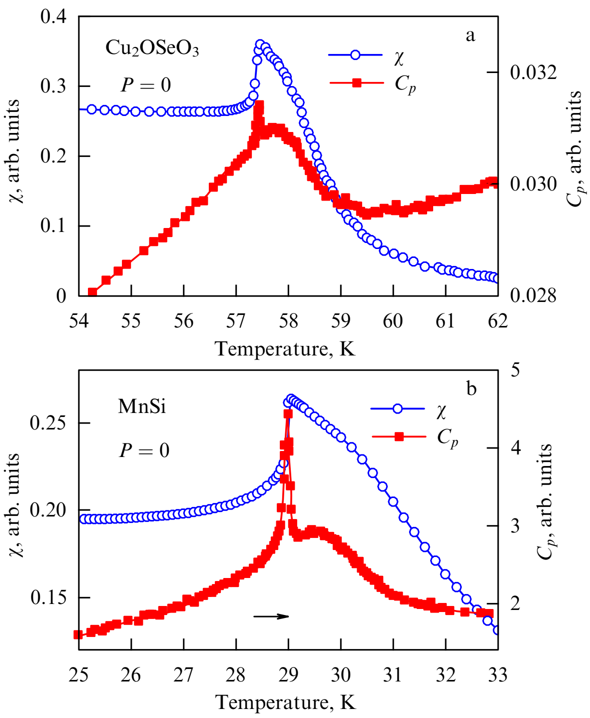

Figure 4. The magnetic susceptibility χ and the heat capacity C_p of (f) Cu_2OSeO_3 and (b) MnSi at the phase transition [19].

skyrmion phase) can be reproduced by the Monte Carlo simulation of a classical system of local spins (Fig. 7).

Thus, the longitudinal fluctuations of the magnetic moment appear to have little or no effect on the qualitative picture of the phase transition and the magnetic phase diagram of chiral systems. On a quantitative level, however, their contribution cannot be estimated from a comparative analysis of the two discussed systems because of the fundamental difference between them.

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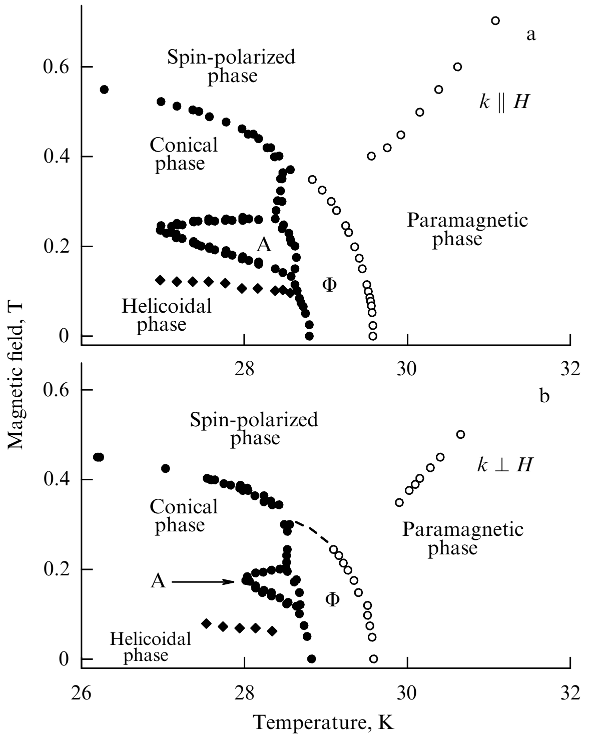

Figure 5. MnSi magnetic phase diagram from ultrasound data [20]. A is the skyrmion phase, Φ is the region of strong chiral fluctuations. The difference between diagrams a and b is due to the difference in the geometry-specific demagnetization factor of the sample.

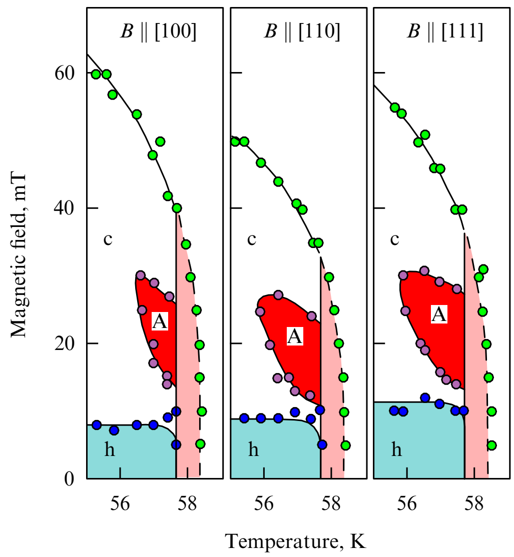

Figure 6. Magnetic phase diagram of Cu_2OSeO_3 [15]; h is the helicoidal phase, c is the conical phase, and A is the skyrmion phase. Diagrams for different magnetic field directions differ due to different demagnetization factors.

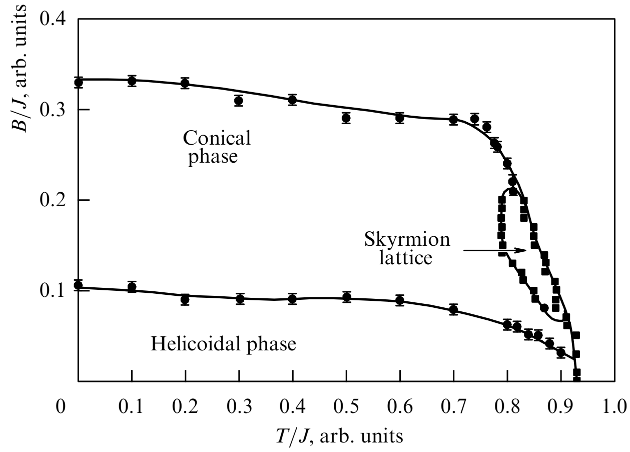

Figure 7. Magnetic phase diagram of a three-dimensional system of chirally interacting classical spins from Monte Carlo simulation data. B, magnetic field; T, temperature; J, exchange coupling constant [21].

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