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On the induction of the first-order phase magnetic transitions by acoustic vibrations in MnSi

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It was shown [1] that thermal expansion of the itinerant helical magnet MnSi as a function of temperature down to 5 K and magnetic field to 3 T has the small discontinuity at the magnetic phase transition in MnSi which decreases with application of magnetic field. In accord modern ideas [2, 3], a low-field anomaly H corresponds to the helical-conical (a spin-skyrmion phase) transition. The anomaly corresponding to the helical-paramagnetic phase transition at zero magnetic field was considered as a fluctuation-induced weak first-order transition [4, 5], but this explanation meets some difficulties [1]. A change at higher field $H_{\rm c}$ is the result of a transformation from the conical phase to a field-induced ferromagnetic phase.

The main result of the present paper contains the conclusion that the magnetic phase transition in MnSi always remains first order at any temperature and magnetic field. In these aims, a model of coupling parameter with other degrees of freedom is used. Its behavior essentially depends on the jump in the heat capacity $-\Delta C_P$.

The coupling of magnetic order parameters with long-wave acoustic phonons, in the presence of the nonsingular parts of the bulk and shear moduli (K_0 and μ), a first-order transition occurs, participle near the transition the heat capacity and the compressibility remain finite, if in the system without allowance of the acoustic phonons the heat capacity becomes infinite. It is assumed that in the system without allowance of the acoustic phonons the heat capacity becomes infinite according a law $f(T - T_{\rm c}^0)$ at a certain temperature $T_{\rm c}^0$, a second-order transition point. Near $T_{\rm c}^0$, the free energy depends only on the difference $T - T_{\rm c}^0$. For $T \to T_{\rm c}^0$, the function f has the form $A|T - T_{\rm c}^0|^{2-\alpha}$ where coefficient α depends on the proximity of temperature to the point $T_{\rm c}^0$, A is a positive phenomenological constant. The function f is related to one unit cell. If there is a region of applicability of the self-consistent field approximation, then in the zero-approximation (the Landau's phenomenological theory) the function f and corresponding part of the heat capacity of unit volume ΔC_P has a jump, but with approach of T to $T_{\rm c}^0$, correlation corrections proportional to $|T - T_{\rm c}^0|^{-1/2}$ become important (the first approximation of the Landau's theory) [6, 7]. In the immediate neighborhood of a transition point of the second kind, the heat capacity becomes infinite according to a law close to the logarithmic – $A(T - T_{\rm c}^0)^2 \ln |T - T_{\rm c}^0|$ [8].

The expression for Φ depending on the shear stress, i.e. giving rise to the singularity in the effective interaction between magnetic cells via exchange of low-momentum phonons [9], is written [10, 11] in the form

$$\Phi = \Phi_0 - \frac{P^2}{2K_0} + NT_{\rm c}^0 \left[-f(x) + \frac{\lambda}{2}(df/dx)^2 \right], \quad (1)$$

where N is the number of cells in unit volume, c is equal to the derivative of the first-order transition temperature $T_{\rm c}$ with respect to pressure P if the singular part of the potential Φ is symmetric with respect to the transition point,

$$T_{\rm c} = T_{\rm c}^0 + cP, \quad \lambda \propto \mu. \quad (2)$$

In (1) the parameter x must be expressed in terms of T by means of the minimization of Φ.

With allowance for interaction with long-wave acoustic phonons (for motion of the centers of the cells) [6, 9], a nonvanishing compression modulus K_0 and μ (the nonsingular parts of the bulk and shear moduli), a first-order transition occurs, participle near the transition all the quantities (the heat capacity, the compressibility, and susceptibility) remain finite [10, 11].

The dependence of the volume discontinuity of the thermal expansion on the applied magnetic field varies sufficiently broadly. It is assumed that the Frenkel concept of heterophase fluctuations [12, 13] may be relevant in the considered examples, which show that, for some phases, the heat capacity of the system remains continuous and finite at the transition point. Ultrasound studies [14, 15] have revealed a decrease of elastic moduli in the $T{-}H$ region corresponding to the proposed

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tricritical point [16], but no specific features identifying a tricritical point were observed in these experiments, for example, there was no tendency for the heat capacity to diverge. Instead, in accordance with [1], heterophase fluctuations smooth the transition to simulate a second-order phase transition. It is supposed that the transition is progressively smoothed by these fluctuations at the application of the magnetic field.

When anomalous parts of the heat capacity of unit volume, i.e. the values ΔC_P are large (in weak magnetic fields accordingly to [1]), they can be considered as the jumps in heat capacity, then first-order transitions can be described by the approximation of the self-consistent field [17]. If the values ΔC_P are very small (in sufficiently strong magnetic fields accordingly to [1]), then the asymptotic case takes place, and here $\Delta C_P \propto \ln|x|$. In the asymptotic region, in particular for a narrow range of temperatures near the phase boundary between the skyrmion phase and conical phase and for small applied magnetic fields, the derivative d^2f/dx^2 has, possibly, a form close to $-A\ln|x|$.

The impurity effect shows that, for some phases, the heat capacity of the system remains continuous and finite at the transition point. It should be noted that sufficiently high concentration of some impurities changes the nature of the transition, damping the large-scale fluctuations in the system, thereby weakening the singularity in the free energy F (an analog of the Frenkel concept) [18, 19]. Due to the number of impurity particles, the thermodynamic potential now is

$$\Phi = \Phi_0 - \frac{p^2}{2K_0} + NT_c^0\left[-f(x) + \frac{\lambda+\tilde{\lambda}}{2}(df/dx)^2\right], \quad (3)$$

where

$$\tilde{\lambda} = \frac{N}{T_c^0}\left(\frac{\partial T_c}{\partial \zeta}\right)^2_{\zeta=\zeta_0}\left(\frac{\partial^2\Omega}{\partial\zeta^2}\right)^{-1}_{\zeta=\zeta_0}.$$

$F(T,n)$ near T_c is written in the form $F(T,n) = F(T_c(\zeta)) + \Omega(\zeta)$, ζ is the chemical potential of the impurities, $F(T_c(\zeta))$ is a singular function of $T - T_c(\zeta)$, $T_c(\zeta)$ and $\Omega(\zeta)$ are smooth functions. In the first approximation, $n = -\left(\frac{\partial\Omega}{\partial\zeta}\right)$ at $\zeta = \zeta_0$. The Eq. (3) differs from analogous Eq. (1) by the presence of the coefficient $\lambda + \tilde{\lambda}$. When the effective coefficient $\lambda + \tilde{\lambda}$ can change its sign for the increasing number of impurities in corresponding phases. For example, this takes place for a transformation from the conical phase to a field-induced ferromagnetic phase. Its sign can be negative ($\lambda + \tilde{\lambda} < 0$) at sufficiently small λ and large $-\tilde{\lambda}$ (see Eq. (14)), since the quantity $\left(\frac{\partial^2\Omega}{\partial\zeta_0^2}\right) < 0$, which corresponds to an increase in the chemical potential with an increase in the number of impurity particles. This assumption means that for $\zeta =$ const the fluctuations in impurity concentration n can be arbitrarily large and, therefore, do not prevent critical fluctuations of the order parameter. This circumstance radically changes the thermodynamic properties of the system with a fixed average number of impurity particles n.

The approach taking into account a possibility of the acoustic oscillations and the fixed concentration of impurities simultaneously in the system can be plausible for consideration of phase transitions in various models including Ising [20].

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