Relaxation of uniform magnetization precession in collinear cubic ferrimagnets in the paramagnetic neighborhood of T_c

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(Submitted 5 July 1990; resubmitted 3 October 1990)
Pis'ma Zh. Eksp. Teor. Fiz. **52**, No. 9, 1085–1088 (10 November 1990)

The characteristic features of the critical spin dynamics of the cubic ferrimagnets $Y_3Fe_5O_{12}$ and $MnFe_2O_4$ in the exchange temperature region above T_c have been studied. The magnetic-dipole relaxation of the uniform magnetization of these ferrimagnets is shown to be suppressed. The relaxation channel due to the local uniaxial anisotropy, with a new temperature dependence, is the dominant channel.

Experimental studies of a series of basic static magnetic characteristics of collinear cubic ferrimagnets have shown that their critical properties are the same as those of ferromagnets, and that they are described by the static scaling theory.[1–4] Experiments have shown, however, that the critical dynamic behavior of these magnets, at least in the homogeneous limit, has fundamental differences. In a ferromagnet the spin relaxation rate (Γ_0) increases, in accordance with the theory developed by Huber,[5] in the exchange temperature region ($4\pi\chi \ll 1$) as $T \to T_c$ (Refs. 6–8). In a ferrimagnet the magnetic resonance linewidth, $\Delta B \propto \Gamma_0$, decreases monotonically as $T \to T_c$ (Refs. 4–9). The value of Γ_0 was not observed to increase in them even in the study of the homogeneous susceptibility in a zero external magnetic field.[3]

The goal of our study was to determine why the dynamic behavior of the magnets does not correspond to their typical behavior. As the typical examples of ferrimagnets we chose perfect crystals of the manganese spinel $MnFe_2O_4$ and of yttrium iron garnet $Y_3Fe_5O_{12}$ (Ref. 4). Both magnets contain Fe^{3+} and Mn^{2+} ions which are identical in their magnetic properties and which occupy two nonequivalent sites: (a) the octahedral site and (d) the tetrahedral site. The ferrites we are analyzing differ in the number of these ions and in their position in the magnetic primitive cell: $MnFe_2O_4$ contains six ions ($4a + 2d$) and six magnetic modes, respectively. The yttrium iron garnet contains 20 ($8a + 12d$).

Figure 1 shows a $\Delta B(T)$ curve of yttrium iron garnet at a frequency of 9.21 GHz. A $\Delta B(T)$ curve of a ferromagnet $CdCr_2S_4$ is shown for comparison in the inset. The latter curve is typical of the behavior of $\Delta B(T)$ for a ferromagnet in a static magnetic field, where the increase in $\Delta B(T)$, which occurs in a zero field upon approaching T_c, is restricted by a field in the exchange region. This leads to the formation of a maximum, whose position with respect to τ is determined by the field. To the left of the maximum the behavior of $\Delta B(T)$ is characteristic of a strong-field regime.[8]

In the ferrimagnets which we studied the curves of $\Delta B(T)$, measured at frequencies of 9 and 35.5 GHz, were the same in the exchange temperature region. Furthermore, the values of Γ_0 for yttrium iron garnet, determined from the resonance data,

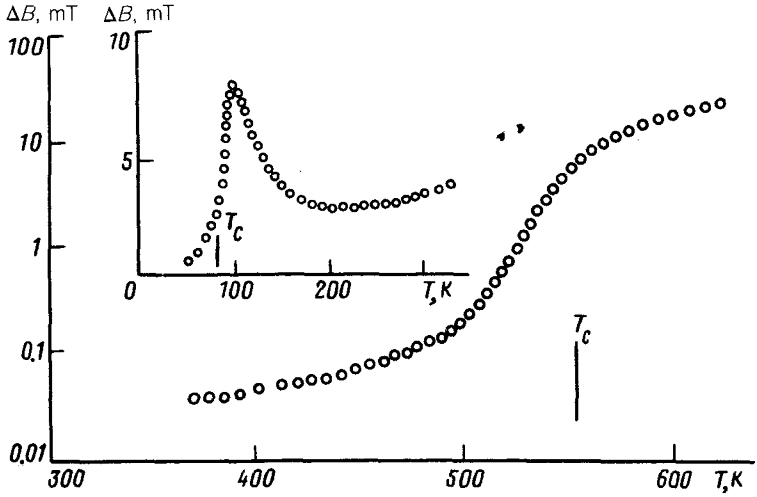

FIG. 1. Temperature dependence of the resonance absorption linewidth for an yttrium iron garnet near T_c at a frequency of 9.21 GHz. The inset shows the same functional dependence for a cubic $CdCr_2S_4$ ferromagnet.

were the same as the results[3] obtained in a zero field for the exchange region. This circumstance makes it possible to analyze the $\Gamma_0(\tau)$ dependence of a ferrimagnet in a zero field approximation and to compare it with a corresponding dependence for a ferromagnet.

The difference in the behavior of $\Gamma_0(\tau)$ of a ferromagnet and a ferrimagnet indicated above is sufficiently nontrivial. In a ferromagnet the critical component of $\Gamma_0(\tau) \propto \tau^{-1}$ in the exchange region is, as we know, accounted for by the dipole forces in the perturbation theory and is determined by the decay of the homogeneous mode into two critical modes.[5] This component must be present in ferrimagnets since they contain a critical mode which is identical to the ferromagnetic mode and which corresponds to the fluctuations of the conserved total momentum. The corresponding expression has the form[7,8]

$$\Gamma_F(\tau) = \Gamma_d(\tau) + \Gamma_{nc}(\tau), \quad \Gamma_d(\tau) = c_0 \frac{\omega_0^2}{T_c} \tau^{-1}, \quad \Gamma_{nc} = \gamma_{nc} \tau^{4/3}. \tag{1}$$

Here c_0 is a coefficient, $\omega_0 = 4\pi(g\mu)^2/v$ is characteristic dipole energy, v is the volume of the magnetic primitive cell in a magnetic ion, Γ_{nc} is the noncritical component which takes into account the interaction with the phonons, and γ_{nc} is its amplitude.

The $\Gamma_0(\tau)$ dependence of ferrimagnets, however, cannot be described by expression (1). To explain this dependence, it is necessary to take into account the characteristic features of the properties and dynamics of the ferrimagnets. We note that the "optical" modes of ferrimagnets are not directly linked with the fluctuations of the order parameter, are noncritical, and contribute only to Γ_{nc} (this feature and other features of the dynamics of ferrimagnets will be considered in a separate study). The critical amplitude χ, which is governed by the antiparallel orientation of the sublattice spins and which is small in comparison with that of ferromagnets, is characteristic for ferrimagnets. The indicated small value for the ferrites with identical magnetic ions is characterized by the coefficient ϵ, and χ can be represented in the form

$$4\pi\chi = \epsilon \frac{S(S+1)}{3} \frac{\omega_0}{T_c} \tau^{-\gamma}, \tag{2}$$

where $\gamma \approx 4/3$. From the experimental data of Ref. 4 we find $\epsilon \approx 6.87 \times 10^{-2}$ in $MnFe_2O_4$ and $\epsilon \approx 3.62 \times 10^{-2}$ in yttrium iron garnet. In ferromagnets we have $\epsilon \sim 1$ (Ref. 8). The origin of the small values of ϵ can be understood by calculating ϵ in the mean-field approximation. Restricting the analysis to an a–d exchange, we have $\epsilon = 1/2(1-\delta^{1/2})^2/(1+\delta)$, $\delta = N_a/N_d$, where $N_{a,d}$ is the number of magnetic ions at the a and d sites. This estimate gives $\epsilon \approx 3 \times 10^{-2}$ in $MnFe_2O_4$ and $\epsilon \approx 10^{-2}$ in yttrium iron garnet.

We know that the local crystallographic anisotropy, which is characteristic only for ions at the a sites, leads to an interaction which does not conserve the total spin or the dipole forces. The corresponding single-ion Hamiltonian is $H = DS_\xi^2$, where ξ is the direction of the local trigonal axis of the given ion. Analysis of the decomposition of the homogeneous mode into two critical modes, which is governed by this interaction, gives the following component in Γ_0:

$$\Gamma_A(\tau) = c_A \frac{D^2}{T_c} \tau^{1/3}, \tag{3}$$

where c_A is a dimensionless coefficient. It can be shown that the main component of Γ_A, which is proportional to τ^{-1}, is not present since the coefficient of this component vanishes upon averaging over various orientations of the local axis. The cancellation stems from the fact that the total critical part of the Green's function of a ferrimagnet, $\hat{G}$, has a two-sublattice structure and does not depend on the indices of the sublattice ions: $G_{ij}^{(PQ)}(q,\omega) = \Phi(q,\omega) G_0^{(PQ)}(q)$, where P and Q are the indices of the a and d sublattices, i and j are the numbers of ions in them, Φ is the dynamic form factor, $G_0^{(PQ)}(q) = A^{(PQ)} G_0(q)$ are the static correlators, $A^{(PQ)}$ are the dimensionless amplitudes, and Φ and G_0 have the same properties as the functions of the ferromagnets. The nonzero component of Γ_A arises due to the partial mixing of the critical motion and noncritical "optical" motion of the spins, which is described for the a sublattice by the increment in $\hat{G}^{(aa)}$ of the type $\Phi(q,\omega) R_{ij}^{(aa)}$, where $R_{ij}^{(aa)}$ is the noncritical matrix for $q = \tau = 0$ which depends on the ion indices. Allowance for this increment in the form of a function of the perturbation-theory plot leads, because of the independence of $\hat{R}^{(aa)}$ of τ and q, to $\Gamma_A \propto \tau^{-1+4/3} = \tau^{1/3}$.

The contribution of Γ_A and Γ_0 competes with Γ_d if $c_0 \omega_0^2 \ll c_A D^2$. In the magnets under consideration $\omega_0 > D$, while $c_0/c_A \sim \epsilon^3 \ll 1$. The small value of the latter ratio can be explained as follows. The quantity Γ_d is determined by the decay into two critical modes which correspond to the fluctuations of the total moment; their amplitude and χ contain ϵ. At the same time, Γ_A depends on the spin fluctuations of the a sublattice, whose amplitude is not proportional to ϵ. Furthermore, it appears that $R_{ij}^{(aa)} \propto \Gamma_{AF}^{-1} \propto \epsilon^{-1}$, where Γ_{AF} is generally a complex gap in the spectrum of the

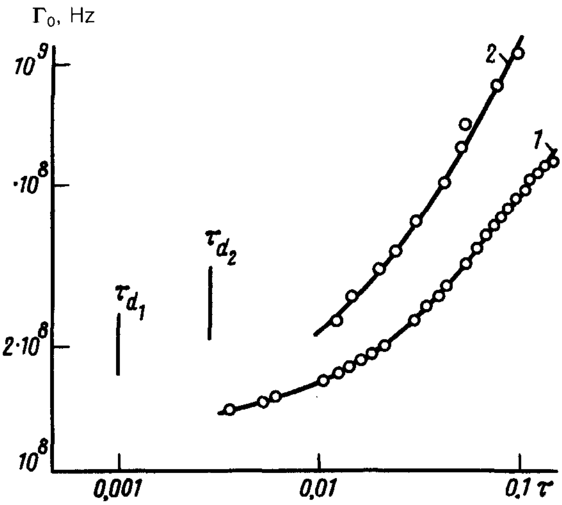

FIG. 2. Temperature dependence of the spin relaxation rate of cubic ferrimagnets in the paramagnetic neighborhood of T_c. 1—Yttrium iron garnet; 2—$MnFe_2O_4$. The values $\tau_{d_1} \approx 10^{-3}$ and $\tau_{d_2} \approx 3 \times 10^{-3}$ are the limits of the exchange regions, where $4\pi\chi(\tau_d) = 1$. Solid line—Calculation results.

antiferromagnetic mode. Because of the two-sublattice critical part of $\hat{G}$, only this mode is linked with a ferromagnetic mode, and hence with $\chi \propto \epsilon$. For this reason $|\Gamma_{AF}| \sim \epsilon T_c$. Furthermore, because of the softening of Γ_{AF}, the characteristic energy of the critical fluctuations in ferrimagnets is $\propto \epsilon^{-1/2}$, which gives the final estimate: $c_0 \sim \epsilon^{3/2}$ and $c_A \sim \epsilon^{-3/2}$.

The curve of $\Gamma_0(\tau)$ for the single crystals which we studied is shown in Fig. 2. Using the limits of τ_d (Fig. 2), we chose the intervals $3 \times 10^{-3} \leqslant \tau \leqslant 10^{-1}$ in yttrium iron garnet and $10^{-2} \leqslant \tau \leqslant 10^{-1}$ in $MnFe_2O_4$, where Γ_0 is given in the form $\Gamma_0(\tau) = \Gamma_F(\tau) + \Gamma_A(\tau)$. Analysis of experimental data give the following values of the coefficients: $c_0 = (1.11 \pm 0.01) \times 10^{-2}$ $(c_0/\epsilon^{3/2} \approx 1.6)$, $c_A = 196 \pm 2$ $(c_A \epsilon^{3/2} \approx 1.35)$, $\gamma_{nc} \equiv c_{nc}\omega_0^2/T_c$, and $c_{nc} = 219 \pm 2$ for yttrium iron garnet and $c_A = 241 \pm 2$ $(c_A \epsilon^{3/2} \simeq 4.3)$ and $c_{nc} = 269 \pm 3$ for $MnFe_2O_4$. Here we used the values $\omega_0 = 0.66$ K, $T_c = 554.8 \pm 0.1$ K (yttrium iron garnet); $\omega_0 = 1.22$ K, $T_c = 556.2 \pm 0.1$ K ($MnFe_2O_4$) and a typical value of D ($D \approx 0.3$ K).[10] The values of T_c for the given samples were measured in Ref. 4. The quantity γ_{nc} is assigned to the scale ω_0^2/T_c. The coefficients c_{nc} and c_A are determined by the intervals of abrupt change in $\Gamma_0(\tau)$ and c_0 is determined by the region $\tau < 10^{-2}$, where the $\Gamma_0(\tau)$ dependence becomes more moderate. The values of the coefficients c_0 and c_A obtained by us are approximately equal to the estimates given above. The value of c_0 in $MnFe_2O_4$ could not be determined because Γ_d affects the behavior of $\Gamma_0(\tau)$ only slightly at $\tau > 10^{-2}$. The large values of c_{nc} are due primarily to that fact that $\gamma_{nc} \propto \chi^{-1} \propto \epsilon^{-1}$.

The critical relaxation in ferromagnets is characterized by the suppression of the dipole component ($c_0 \sim \epsilon^{3/2}$) and by the fact that the component attributable to the local anisotropy is strengthened ($c_A \sim \epsilon^{-3/2}$) and at $D \sim \omega_0$ becomes the dominant critical component of Γ_0 in virtually the entire exchange region.

We wish to thank I. E. Dzyaloshinskiĭ for the valuable remark which stimulated us to give our interpretation of the results.

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Translated by S. J. Amoretty