Theoretical study of the spin dynamics in $CsNiF_3$, a one-dimensional ferromagnet with planar anisotropy, in an external magnetic field

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(Received 21 March 1996)

Using a Green's function technique we have studied the spin dynamics in the one-dimensional ferromagnetic $CsNiF_3$ with an external field. Taking into account damping effects, the longitudinal mode becomes purely imaginary and the transverse mode is underdamped for low temperatures and overdamped near and above the critical temperature. The spin wave energy and the damping strongly depend on the anisotropy energy and the magnetic field. We have calculated the dynamic structure factors S^{xx}, S^{yy}, and S^{zz} via the imaginary part of the Green's functions. The coupling between the transverse mode and the relaxing longitudinal mode produces a central peak in the dynamic structure factor, i.e., we obtain two spin wave scattering components and a central component. The temperature, magnetic field, anisotropy energy, and wave vector dependence of the three peaks are discussed and compared with the experimental data. [S0163-1829(96)06738-0]

I. INTRODUCTION

One of the important recent developments in solid state physics was the introduction of nonlinear aspects into this field. The soliton concept stimulated extensive theoretical and experimental work to elucidate characteristic features of this concept,[1,2] so for example, the appearance of the central peak in the energy spectrum of slow neutrons scattered on the quasi-one-dimensional (1D) ferromagnets $CsNiF_3$ and antiferromagnets $[(CH_3)_4N]MnCl_3$. It was clear from the beginning, that such features should be most prominent in low dimensional solids, since there long-range order is suppressed and short-range order dominates, which, if it becomes strong enough can give rise to nonlinear behavior. In this frame 1D systems are of special importance. The group of the 1D magnets appears to be most suitable for the study of the above mentioned nonlinear effects.

Detailed neutron scattering studies on different systems have revealed that all experimental results in zero magnetic field obtained for quasiclassical systems ($S \geqslant 1$) can be described by the results of linear classical theories. The situation is different in an external field. Restricting discussion on systems with more than one spin dimension n ($n \geqslant 2$), then an external field will introduce a gap E_0 at the zone center for the spin wave dispersion. For low temperatures, $kT < E_0$, we expect linear theory with corrections to be applicable, that means one has to deal with single spin wave and two spin wave processes but can neglect nonlinear effects. For higher temperatures, $kT \gg E_0$, in addition to the one and two spin wave processes one has to consider nonlinear effects especially the contribution of thermally excited solitons to the dynamics as was pointed out by Mikeska.[3]

$CsNiF_3$ is one of the most studied quasi-1D magnetic systems. Its magnetic properties have been studied by different experimental techniques, as well as by means of different theoretical approaches.[4] Recently three different experimental techniques revealed results in $CsNiF_3$, which were interpreted using nonlinear effects: optical measurements of spin waves,[5] NMR measurements,[6] and magnetic specific heat measurements.[7] Steiner *et al.*[8] have demonstrated that the spin dynamics of the 1D easy plane Heisenberg ferromagnet $CsNiF_3$ in a symmetry broken field is a combination of one and two spin wave processes and solitonlike excitations. Despite the fact that $CsNiF_3$ does not completely fulfill the requirements for sine-Gordon in the T and H range used, the nonlinear excitations seen in S^{xx} have properties very much like the sine-Gordon solitons. Their results suggest that one and two spin wave processes without mutual interaction dominate the low temperature, $T \leqslant E_{SW}$, spin dynamics, whereas at high temperatures, $E_{SW} < T$, nonlinear excitations, which are very similar to sine-Gordon solitons are necessary to describe the experimental results.

Since the experimental results obtained for $CsNiF_3$ in an external field,[8] which were interpreted in terms of Mikeska's soliton picture, there has been a steady increase of theoretical results on this problem indicating that the interpretation[9] might not be completely justified in the sense that two spin wave processes could explain part of the results.[10–16]

In order to understand and to elucidate the different contributions to the dynamics of the 1D ferromagnet $CsNiF_3$ in an external field we have carried out a detailed study of this system, using a Green's function technique of Tserkovnikov,[17] which goes beyond the random phase approximation (RPA) (or the Tyablikov decoupling) and takes into account the correlation functions and the damping effects. We shall discuss, what is the main aim of this paper; namely, the analysis of the central peak as found in the energy spectra of the scattered neutrons.[8]

II. MODEL AND METHOD

The present work is mainly concerned with $CsNiF_3$, in which the Ni^{2+} ions are ferromagnetically coupled in chains, along with the F^- ions. The chains are well separated from each other by large Cs^+ ions and are coupled by antiferromagnetic interactions. This arrangement causes a large anisotropy between the Ni ions, which is thus present in the magnetic properties. Such 1D magnets are usually described by the Hamiltonian:

$$H=-2J\sum_i \mathbf{S}_i\cdot\mathbf{S}_{i+1}+A\sum_i (S_i^z)^2-g\mu_B H\sum_i S_i^x. \quad (1)$$

As defined in Eq. (1) S^x and S^y are in the easy plane and would behave identically without an external field, whereas the S^z component behaves differently as a result of the anisotropy. If a magnetic field along x is applied the correlation functions S^{xx} and S^{yy} will behave differently. The positive anisotropy energy $A>0$ keeps the spins perpendicular to the chain axis and the positive exchange energy $J>0$ tries to align the spins within the chains parallel to each other. Spin correlations between different chains can be neglected. In zero field, the results are described by (1) with $J/k_B=11.8$ K, $A/k_B=4.5$ K, $S=1$, $g=2.4$, and $a=2.6$ Å.[3,4]

In the ferromagnetic phase we have $\langle S^x\rangle\neq 0$; therefore it is appropriate to choose a new coordinate system by rotating the original one used in (1) by an angle $\vartheta=\pi/2$ in the xz plane,

$$S_i^{z'}=-\tfrac{1}{2}(S_i^+ + S_i^-),$$

$$S_i^{x'}=S_i^z,$$

$$S_i^{y'}=S_i^y. \quad (2)$$

We have in the new coordinate system the order parameter $\langle S^{z'}\rangle=\sigma$.

The retarded Green's function to be calculated is defined in matrix form as

$$\tilde{G}_{\mathbf{k}}(t)=-i\Theta(t)\langle[B_{\mathbf{k}}(t),B_{\mathbf{k}}^+]\rangle. \quad (3)$$

The operator $B_{\mathbf{k}}$ stands symbolically for the set $S_{\mathbf{k}}^+,S_{\mathbf{k}}^-,S_{\mathbf{k}}^z$. For an approximate evaluation of this Green's function, we use Tserkovnikov's method,[17] which is appropriate for spin problems. After a formal integration of the equation of motion for the Green function, one obtains

$$\tilde{G}_{\mathbf{k}}(t)=-i\Theta(t)\langle[B_{\mathbf{k}},B_{\mathbf{k}}^+]\rangle\exp[-iE_{\mathbf{k}}(t)t], \quad (4)$$

where

$$E_{\mathbf{k}}(t)=\epsilon_{\mathbf{k}}-\frac{i}{t}\int_0^t\left(\frac{\langle[j_{\mathbf{k}}(t),j_{\mathbf{k}}^+(t')]\rangle}{\langle[B_{\mathbf{k}}(t),B_{\mathbf{k}}^+(t')]\rangle}-\frac{\langle[j_{\mathbf{k}}(t),B_{\mathbf{k}}^+(t')]\rangle\langle[B_{\mathbf{k}}(t),j_{\mathbf{k}}^+(t')]\rangle}{\langle[B_{\mathbf{k}}(t),B_{\mathbf{k}}^+(t')]\rangle^2}\right) \quad (5)$$

with the notation $j_{\mathbf{k}}=[B_{\mathbf{k}},H_{int}]$. The time-independent term

$$\epsilon_{\mathbf{k}}=\langle[[B_{\mathbf{k}},H],B_{\mathbf{k}}^+]\rangle/\langle[B_{\mathbf{k}},B_{\mathbf{k}}^+]\rangle \quad (6)$$

gives the spin wave energy in the generalized Hartree-Fock approximation. The time-dependent term includes the damping effects.

III. THE SPIN WAVE SPECTRUM

The energy of the coupled system can be obtained from the following equation:

$$(\epsilon_{\mathbf{k}}^{33}-E)[(\epsilon_{\mathbf{k}}^{12})^2-(\epsilon_{\mathbf{k}}^{11})^2+E^2]-2E(\epsilon_{\mathbf{k}}^{13})^2=0 \quad (7)$$

with the matrix elements

$$\epsilon_{\mathbf{k}}^{11}=h+\frac{1}{2N\sigma}\sum_q ([4(J_q-J_{\mathbf{k}-q})+2A](2\langle S_q^zS_{-q}^z\rangle+\overline{n_q})-2A\overline{m_q}), \quad (8)$$

$$\epsilon_{\mathbf{k}}^{12}=\frac{1}{2N\sigma}\sum_q ([4(J_q-J_{\mathbf{k}-q})-2A]\overline{m_q}+4A(\langle S_q^zS_{-q}^z\rangle-\overline{n_q})), \quad (9)$$

$$\epsilon_{\mathbf{k}}^{33}=\frac{2}{N\langle S_{\mathbf{k}}^zS_{-\mathbf{k}}^z\rangle}\sum_q (J_{\mathbf{k}-q}\overline{n_q}-A\overline{m_q}), \quad (10)$$

$$\epsilon_{\mathbf{k}}^{13}=\frac{2}{N\sigma}\sum_q (J_q-J_{\mathbf{k}-q})l_q^+, \quad (11)$$

where $h=g\mu_BH$. $\sigma(T)$ is the relative magnetization:

$$\sigma=\frac{1}{N}\sum_{\mathbf{k}}\{(S+\tfrac{1}{2})\coth[(S+\tfrac{1}{2})\beta E_{\mathbf{k}}]-\tfrac{1}{2}\coth(\tfrac{1}{2}\beta E_{\mathbf{k}})\}. \quad (12)$$

For the transverse spin wave energy we have

$$E_{\mathbf{k}}^{tr}=\pm\sqrt{(\epsilon_{\mathbf{k}}^{11})^2-(\epsilon_{\mathbf{k}}^{12})^2}\equiv\pm E_{\mathbf{k}} \quad (13)$$

and for the longitudinal spin wave energy

$$E_{\mathbf{k}}^l=\epsilon_{\mathbf{k}}^{33} \quad (14)$$

with the correlation functions

$$\overline{n_q}=\langle S_q^-S_q^+\rangle=\frac{\sigma}{2\omega_q^2}\{[\omega_q^2-(\epsilon_q^{13})^2](\Phi_1+\Phi_2)+\omega_q\epsilon_q^{11}(\Phi_1-\Phi_2)\}, \quad (15)$$

$$\overline{m_q}=\langle S_{-q}^-S_q^-\rangle=\langle S_q^+S_{-q}^+\rangle=\frac{-\sigma}{2\omega_q^2}[\omega_q\epsilon_q^{12}(\Phi_1-\Phi_2)-(\epsilon_q^{13})^2(\Phi_1+\Phi_2)], \quad (16)$$

$$\langle S_q^zS_{-q}^z\rangle=(1+2\overline{n_q}+2\overline{n_q^2})/(1+3\overline{n_q}+3\overline{n_q^2}), \quad (17)$$

$$l_q^+=\langle S_q^+S_{-q}^z\rangle=\langle S_q^zS_q^-\rangle=\frac{\sigma^2\epsilon_q^{13}}{\omega_q^2}[\omega_q(\Phi_1-\Phi_2)+(\epsilon_q^{11}-\epsilon_q^{12})\times(\Phi_1+\Phi_2)]. \quad (18)$$

Further we have used the abbreviations

$$\omega_q=\sqrt{(E_q^{tr})^2+2(\epsilon_q^{13})^2},\quad \Phi_1=\exp(\omega_q/T)^{-1},$$

$$\Phi_2=[\exp(-\omega_q/T)-1]^{-1}.$$

If we neglect the transverse correlation functions (15), (16), and (18), and if we decouple the longitudinal correlation function $\langle S_q^zS_{-q}^z\rangle\rightarrow\langle S^z\rangle^2\delta_{q0}$, then we get the result of the RPA (i.e., the Tyablikov approximation):

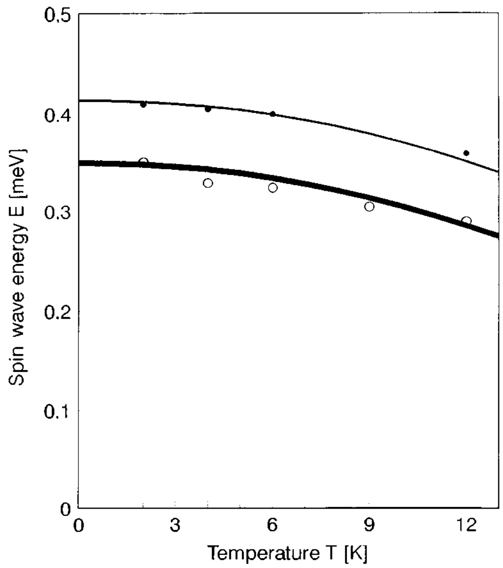

FIG. 1. Temperature dependence of the spin wave energy $E_{\mathbf{k}}$ for $A/k_B=4.5$, $h=10$ kOe and for different k_c values: $k_c=0$ (lower curve) and $k_c=0.05$ (upper curve). Points and circles are the experimental data from Steiner *et al.* (Ref. 8).

$$\epsilon_{\mathbf{k}}^{11}=h+\sigma[4(J_0-J_{\mathbf{k}})+2A], \tag{19}$$

$$\epsilon_{\mathbf{k}}^{12}=2\sigma A, \tag{20}$$

$$\epsilon_{\mathbf{k}}^{33}=0, \tag{21}$$

$$\epsilon_{\mathbf{k}}^{13}=0, \tag{22}$$

where $J_{\mathbf{k}}=J\cos ka$. There is a solution with $\epsilon^{33}=0$. It corresponds to the longitudinal mode, i.e, a relaxation of the spin components parallel to the mean field. In the RPA we obtain no coupling between the transverse and the longitudinal mode, because of $\epsilon^{13}=0$.

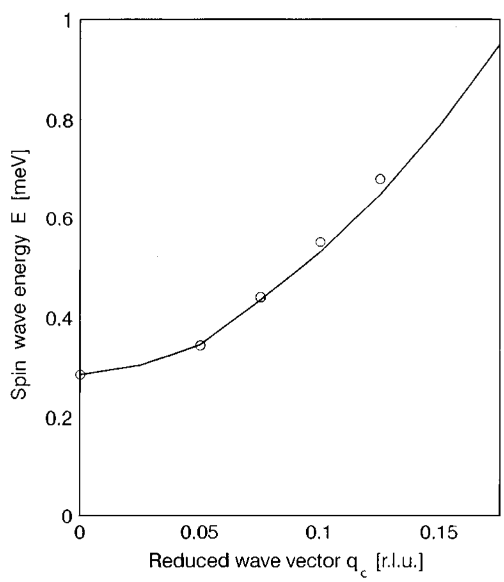

FIG. 2. Wave vector dependence of the spin wave energy $E_{\mathbf{k}}$ for $T=12$ K and $A/k_B=4.5$ K. The points are the experimental data from Steiner *et al.* (Ref. 8).

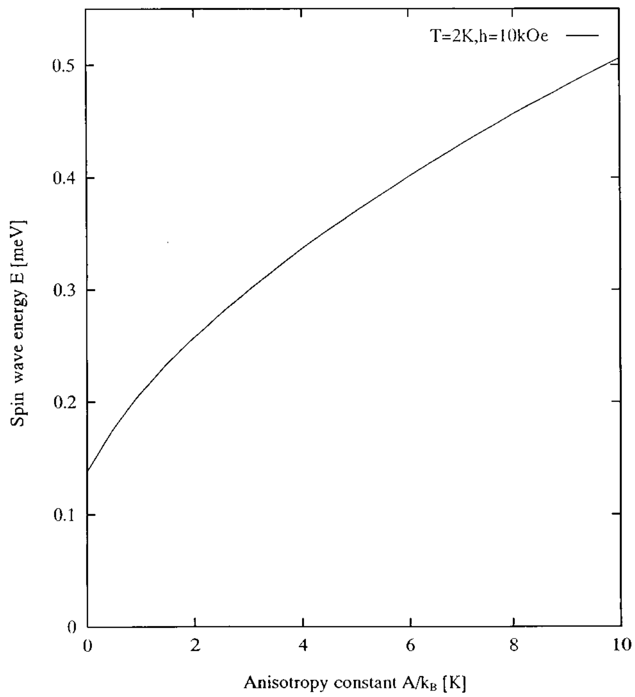

FIG. 3. The spin wave energy $E_{\mathbf{k}}$ as a function of the anisotropy constant A for $T=2$ K, $k_c=0$ and $h=10$ kOe.

We have studied the temperature dependence of the transverse spin wave energy $E_{\mathbf{k}}^{tr}$ from Eq. (13) using following model parameters for $CsNiF_3$ (Ref. 3): $J/k_B=11.8K$, $A/k_B=4.5$, and $S=1$. The results of the temperature dependence of $E_{\mathbf{k}}$ for different wave vector values, $\mathbf{k}=(0,0,k_c)$, $k_c=0$ (lower curve) and $k_c=0.05$ (upper curve) are shown in Fig. 1. We obtain a very good agreement between the experimental data (points and circles) obtained by Steiner *et al.*[8]

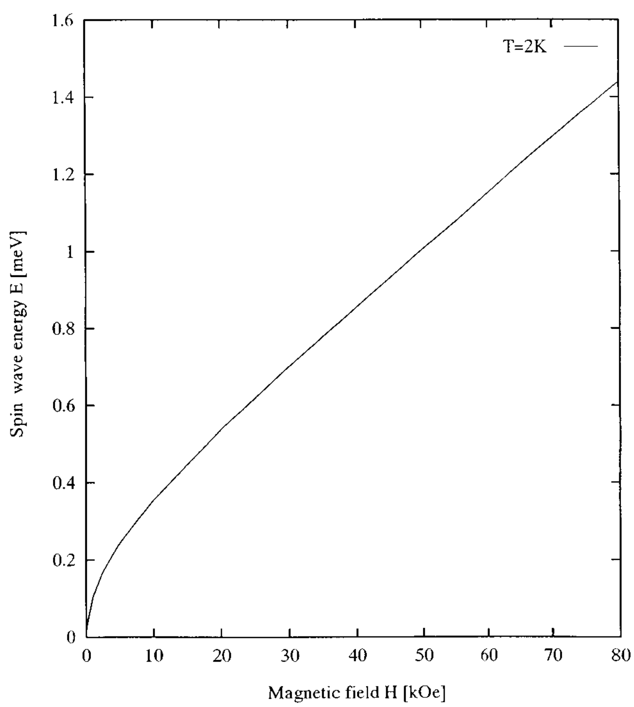

FIG. 4. The spin wave energy as a function of the magnetic field h for $T=2$ K, $A/k_B=4.5$ K and $k_c=0$.

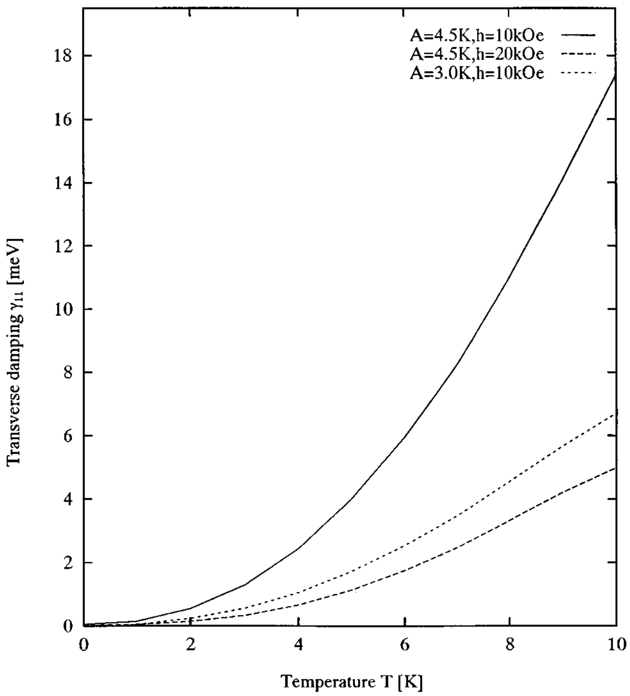

FIG. 5. Temperature dependence of the transverse damping γ_{11} for different h and A values.

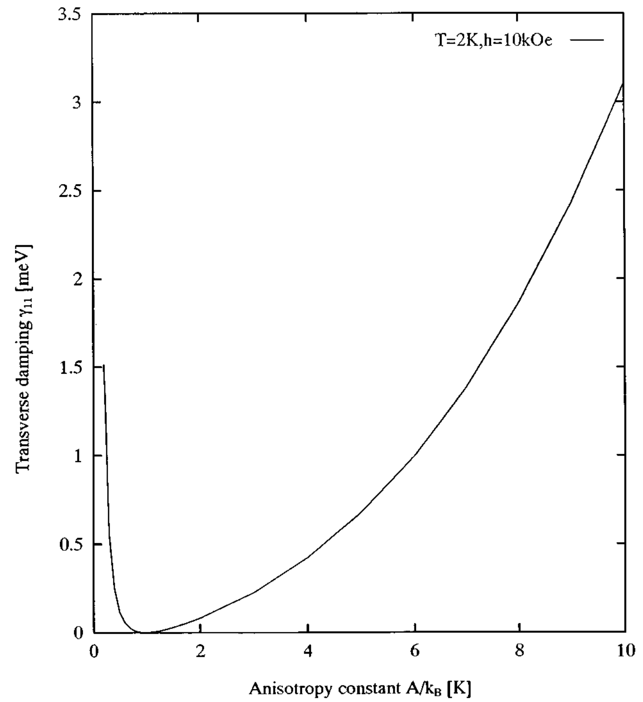

FIG. 7. The transverse damping γ_{11} as a function of the anisotropy constant A/k_B.

with inelastic neutron scattering and the calculated data using the Green's function method in this paper (solid line). The spin wave energy increases with k_c (Fig. 2). In this figure the circles represent the experimental data from Steiner *et al.*[8]

$E_{\mathbf{k}}$ depends very strongly on the anisotropy energy A (Fig. 3). With increase of A, the spin wave energy increases too. The spin wave energy grows with increase of h for

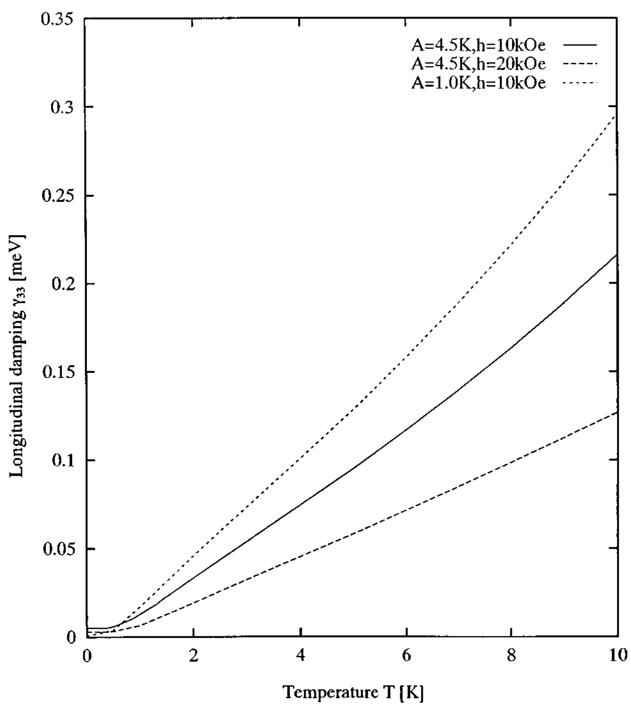

FIG. 6. Temperature dependence of the longitudinal damping γ_{33} for different h and A values.

$T=$const (Fig. 4), which is in agreement with Steiner.[2] The critical temperature increases with the increase of the magnetic field h, which is in agreement with the results of Harada *et al.*[18] for the 1D magnet *TMMC*, $(CH_3)_4NMnCl_3$.

Taking into account damping effects, we obtain for the spin wave energy in the simplest approximation

$$E_{1/2}(\mathbf{k}) = \pm E_{\mathbf{k}}^{tr} - i\gamma_{\mathbf{k}}^{11}, \tag{23}$$

$$E_3(\mathbf{k}) = -i\gamma_{\mathbf{k}}^{33}, \tag{24}$$

where $E_{\mathbf{k}}$ is from Eq. (13). The complex energy (23) belongs to the damped motions of the spins processing in a spin wave around the mean field. Equation (24) gives the relaxation of the spin components parallel to the mean field. The longitudinal mode is therefore of diffusive type for all temperatures.

Calculations yield the following expressions for the transverse γ_{11} and longitudinal γ_{33} damping, respectively,

$$\begin{aligned}\gamma_{11}(\mathbf{k}) = \frac{\pi}{N^2}\sum_{q,p} &[4(J_q - J_{\mathbf{k}-q}) + 2A] \\ &\times[4(J_q - J_{\mathbf{k}-q} + J_{\mathbf{k}-q-p} - J_{q+p}) + 4A] \\ &\times[\overline{n_p}(\sigma + \overline{n_{p+q}} + \overline{n_{\mathbf{k}-q}}) - \overline{n_{p+q}}\,\overline{n_{\mathbf{k}-q}}] \\ &\times\delta(E_{p+q} - E_p + E_{\mathbf{k}-q} - E_{\mathbf{k}}) \\ &+ \frac{4\pi A}{N^2}\sum_{q,p}[4(J_q - J_{\mathbf{k}-q}) + 2A]\overline{m_{\mathbf{k}-q}}(\overline{n_p} - \overline{n_{p+q}}) \\ &\times\delta(E_{p+q} - E_p + E_{\mathbf{k}-q} - E_{\mathbf{k}})\end{aligned} \tag{25}$$

and

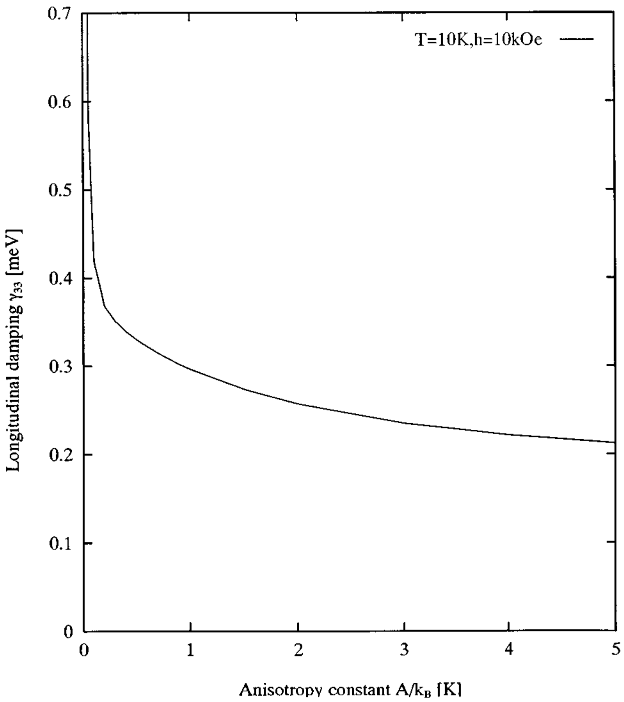

FIG. 8. The longitudinal damping γ_{33} as a function of the anisotropy constant A/k_B.

$$\gamma^{33}(\mathbf{k})=\frac{\pi}{N\sigma}\sum_q (J_q-J_{\mathbf{k}+q})[4(J_q-J_{\mathbf{k}+q})(\overline{n_q}-\overline{n_{\mathbf{k}+q}})+2A(\overline{m_q}-\overline{m_{\mathbf{k}+q}})]\delta(E_{\mathbf{k}+q}-E_q-E_{\mathbf{k}})+\frac{\pi A}{2N\sigma}\sum_q [2(J_q-J_{\mathbf{k}-q})(\overline{m_{\mathbf{k}-q}}-\overline{m_q})+A(\sigma+\overline{n_q}+\overline{n_{\mathbf{k}-q}})]\delta(E_{\mathbf{k}-q}+E_q-E_{\mathbf{k}}). \qquad (26)$$

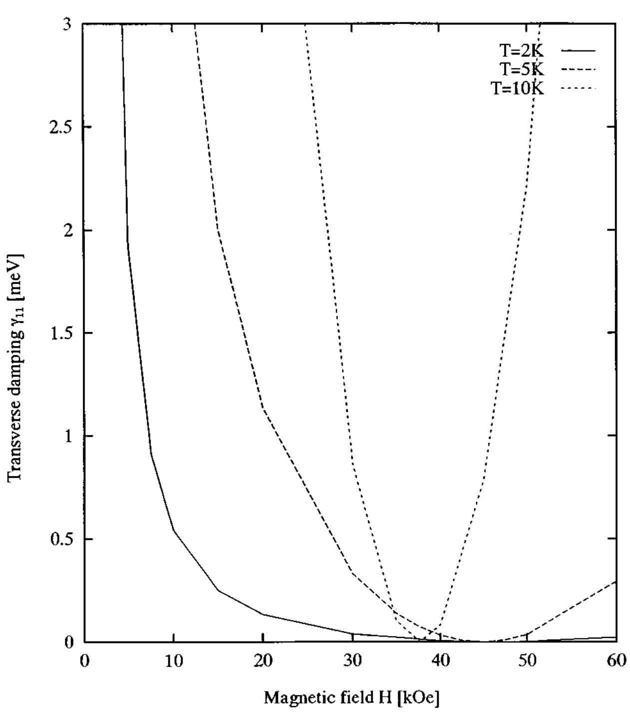

FIG. 9. Magnetic field dependence of the transverse damping γ_{11} for different temperature T values.

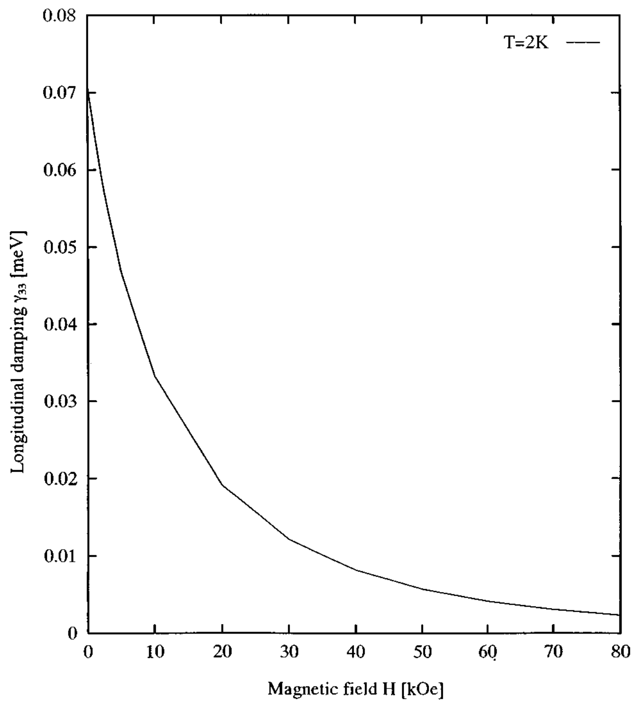

FIG. 10. Magnetic field dependence of the longitudinal damping γ_{33}.

We have studied the temperature, anisotropy constant, wave vector, and magnetic field dependence of the magnon damping. At $T=0$ Eqs. (25) and (26) simplify to

$$\gamma_{11}(T=0)=0, \qquad (27)$$

and

$$\gamma_{33}(T=0)=(\pi/2)A^2\delta(E_{\mathbf{k}-q}+E_q-E_{\mathbf{k}}). \qquad (28)$$

Provided that the δ function can be satisfied, we obtain a longitudinal damping at $T=0$ due to the anisotropy energy A. γ_{11} and γ_{33} are very small at low temperatures, then they grow on with increasing temperature (Figs. 5 and 6). Taking into account the damping, the longitudinal mode becomes purely imaginary (24) and the transverse mode is underdamped for low temperatures and overdamped near and above the critical temperature. The transverse damping is much greater compared with the longitudinal damping, $\gamma_{11}\gg\gamma_{33}$.

For $k=0$ we obtain the following expressions:

$$\gamma_{11}(\mathbf{k}=0)=\frac{8\pi A^2}{N^2}\sum_{q,p}[\overline{n_p}(\sigma+\overline{n_{p+q}}+\overline{n_{\mathbf{k}-q}})-\overline{n_{p+q}}\,\overline{n_{\mathbf{k}-q}}+\overline{m_{\mathbf{k}-q}}(\overline{n_p}-\overline{n_{p+q}})]\delta(E_{p+q}-E_p+E_{\mathbf{k}-q}-E_{\mathbf{k}}) \qquad (29)$$

and

$$\gamma_{33}(\mathbf{k}=0)=\frac{\pi A^2}{2N\sigma}\sum_q(\sigma+\overline{n_q}+\overline{n_{\mathbf{k}-q}})\delta(E_{\mathbf{k}-q}+E_q-E_{\mathbf{k}}). \qquad (30)$$

For $\mathbf{k}=0$ only the anisotropy terms give contribution to the damping. Both damping decrease with decreasing wave vector $\mathbf{k}$.

Figure 7 shows the dependence of the transverse damping on the anisotropy energy A. γ_{11} has a minimum which shifts with increasing h to higher A values. The damping is asymmetric in the single-ion parameter A. The longitudinal damping decreases with A (Fig. 8). The behavior of the damping is in agreement with the results of Tucker,[19] which obtained that γ_{33} first decreases with A and then remains finite.

In Fig. 9 is plotted the dependence of the transverse damping on the magnetic field h. γ_{11} has a minimum which shifts with increasing temperature T to smaller h values. The magnetic field dependence of the longitudinal damping is demonstrated in Fig. 10. γ_{33} decreases with increasing of h.

IV. THE DYNAMICAL STRUCTURE FACTOR

We obtain for the transverse Green's function:

$$G^{xx}_{(yy)}(\mathbf{k},E)=\frac{2\sigma(\epsilon_{11}\mp\epsilon_{12})}{E^2-E_{\mathbf{k}}^2+iE\Gamma_{\mathbf{k}}} \tag{31}$$

with the frequency dependent

$$\Gamma_{\mathbf{k}}(E)=2\gamma_{11}+\frac{i\epsilon_{13}^2}{E+i\gamma_{33}}. \tag{32}$$

The transverse dynamical structure factor (DSF) is calculated via the imaginary part of the Green's function (31). We obtain it in the form

$$\begin{aligned}S^{xx}_{(yy)}(\mathbf{k},E)=&\{2\sigma(\epsilon_{11}\mp\epsilon_{12})E/[1-\exp(-E/T)]\}\\ &\times\{[2\gamma_{11}E^2+\gamma_{33}(2\gamma_{11}\gamma_{33}+\epsilon_{13}^2)]/(E^2+\gamma_{33}^2)\}/([E^2-E_{\mathbf{k}}^2-E^2\epsilon_{13}^2/(E^2+\gamma_{33}^2)]^2\\ &+E^2\{[2\gamma_{11}E^2+\gamma_{33}(2\gamma_{11}\gamma_{33}+\epsilon_{13}^2)]/(E^2+\gamma_{33}^2)\}^2).\end{aligned} \tag{33}$$

For the longitudinal Green's function we obtain

$$G^{zz}(\mathbf{k},E)=\frac{2\langle S^z_{\mathbf{k}}S^z_{-\mathbf{k}}\rangle}{(E+i\gamma_{33})-[E\epsilon_{13}^2/(E^2-E_{\mathbf{k}}^2+2i\gamma_{11})]}. \tag{34}$$

The longitudinal DSF is calculated to

$$\begin{aligned}S^{zz}(\mathbf{k},E)=&\{2\langle S^z_{\mathbf{k}}S^z_{-\mathbf{k}}\rangle/[1-\exp(-E/T)]\}\\ &\times\{\gamma_{33}+2E^2\gamma_{11}\epsilon_{13}^2/[(E_{\mathbf{k}}^2-E^2)^2+(2E\gamma_{11})^2]\}/(E^2\{1+\epsilon_{13}^2(E_{\mathbf{k}}^2-E^2)/[(E_{\mathbf{k}}^2-E^2)^2+(2E\gamma_{11})^2]\}^2\\ &+\{\gamma_{33}+2E^2\gamma_{11}\epsilon_{13}^2/[(E_{\mathbf{k}}^2-E^2)^2+(2E\gamma_{11})^2]\}^2).\end{aligned} \tag{35}$$

We obtain in the DSF S^{xx} a central peak (CP) around $E=0$, the width of which is

$$\Gamma_c=\gamma_{33}\,\frac{E_{\mathbf{k}}^2}{E_{\mathbf{k}}^2+2\epsilon_{13}^2}, \tag{36}$$

and two spin wave peaks of the width

$$\Gamma_s=2\gamma_{11}+\gamma_{33}\,\frac{2\epsilon_{13}^2}{E_{\mathbf{k}}^2+2\epsilon_{13}^2} \tag{37}$$

which are situated at

$$\omega_s=\pm\sqrt{E_{\mathbf{k}}^2+2\epsilon_{13}^2}. \tag{38}$$

The temperature, magnetic field and anisotropy constant dependences of the DSF's have been numerically calculated. The temperature dependence of the transverse DSF S^{xx} is shown in Fig. 11. For low temperatures, S^{xx} exhibits only the sharp spin wave mode peak (SWP). As T increases, the SWP becomes lower and wider, and a CP appears in addition to the SWP. Approaching T_c, the intensity moves from the SWP to the CP. The CP becomes very narrow. From the results it is obvious that the quasielastic peak is thermally induced because it is weak at low temperatures becoming strong at higher temperatures only, in agreement with Steiner *et al.*[8] The CP is due to the coupling of the transverse and longitudinal relaxing mode. Due to the anisotropy A/k_B, S^{xx} and S^{yy} are quite different.

The temperature dependence of the longitudinal DSF S^{zz} is obtained too. The SWP is very small, if not absent. It is clearly seen, that the CP at $k_c=0$ in S^{zz} (and S^{yy}) is much smaller than in S^{xx}, in agreement with the experimental data of Steiner *et al.*[8] This is a very important result already and we emphasize that S^{xx} is due to longitudinal spin fluctuations (parallel to the external field or the induced magnetization σ), whereas S^{yy} and S^{zz} represent spin fluctuations perpendicular to the applied field or σ. Clearly the spectra at $k_c=0$ are completely different; while the S^{xx} spectrum is dominated by the SWP alone, the S^{zz} spectrum is dominated by the CP.

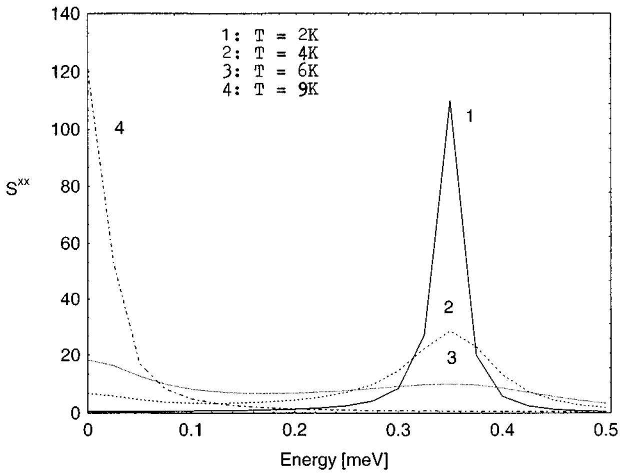

FIG. 11. The dynamical structure factor S^{xx} as a function of the energy E for different temperatures T.

The DSF S^{xx} depends strongly on the anisotropy constant A. This is demonstrated in Fig. 12. With increasing of A the SWP becomes lower and wider, and shifts to smaller E values, whereas the CP becomes higher. The intensity of the SWP increases strongly with increasing magnetic field h and the peak shifts to smaller E values (Fig. 13).

V. CONCLUSIONS

We have studied the spin dynamics in the 1D ferromagnetic $CsNiF_3$ with an external magnetic field using the Green's function method of Tserkovnikov.[17] In the generalized Hartree-Fock approximation we calculated the transverse and longitudinal spin wave energy. The transverse energy increases with increasing wave vector **k** and magnetic field h, which is in agreement with the experimental data of Steiner *et al.*[8]

The transverse and longitudinal spin wave damping have been calculated too, where the first is much greater compared with the latter. They are very small at low temperatures and then increase with T. Taking into account the damping, the longitudinal mode becomes purely imaginary and the transverse mode is underdamped for low temperatures and overdamped near and above the critical temperature. For $k_c=0$ only the anisotropy terms give contribution to the damping. The transverse damping shows a minimum as a function of the anisotropy constant A, whereas the longitudinal damping decreases with A. The damping is asymmetric with respect to the single-ion parameter A, in agreement with the result of Tucker.[19] γ_{11} has a minimum in the dependence of the magnetic field h, whereas γ_{33} decrease with increasing of h.

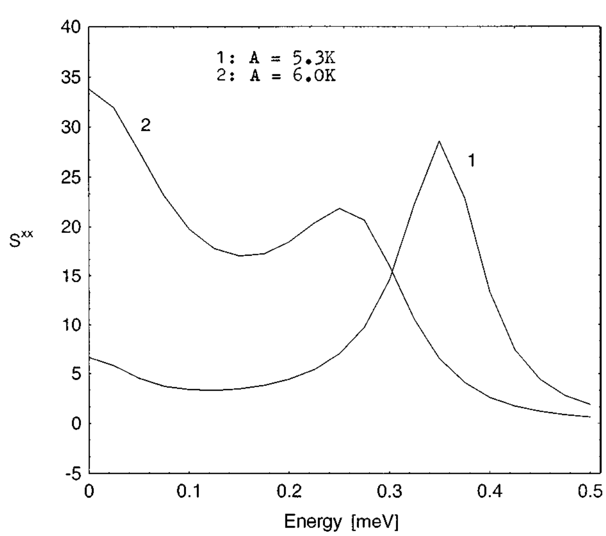

FIG. 12. The dynamical structure factor S^{xx} as a function of the energy E for $T=2$ K and different A values.

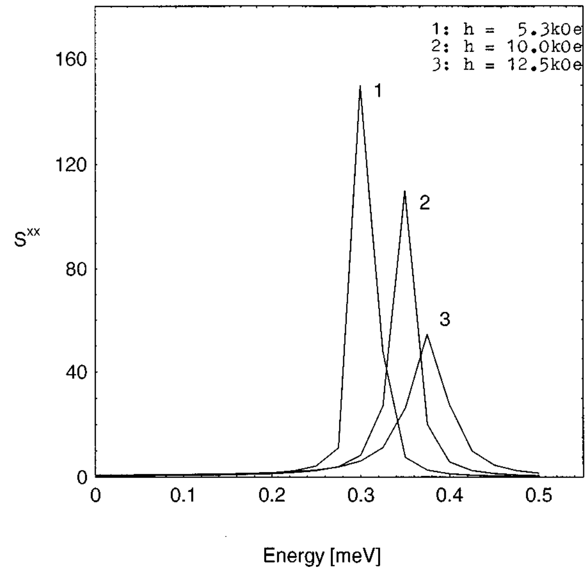

FIG. 13. The dynamical structure factor S^{xx} as a function of the energy E for $T=1$ K and for different h values.

The dynamical structure factors S^{xx}, S^{yy}, and S^{zz} were calculated via the imaginary part of the Green's functions. We obtain two spin wave scattering components and a central component. The T, h, and A dependence of the three peaks are discussed. From the results it is obvious that the CP is thermally induced because it is weak at low temperatures becoming strong at higher temperatures only. It is clearly seen, that the CP at $k_c=0$ in S^{zz} is much smaller than in S^{xx}, in agreement with the experimental data of Steiner *et al.*[8] Therefore we emphasize that S^{xx} is due to longitudinal spin fluctuations, parallel to the external field, whereas S^{yy} and S^{zz} represent spin fluctuations perpendicular to the applied magnetic field. The experimental evidence of a CP in the 1D ferromagnet $CsNiF_3$ may be explained with the help of this model with the Hamiltonian (1) only. We obtain the CP without coupling to other degrees of freedom, in particular, without coupling to other phonon branches or heat diffusion modes. It may be concluded, that the CP in the 1D magnetic system with an external field is due to the coupling between the transverse spin wave mode and the longitudinal relaxing mode.

ACKNOWLEDGMENTS

We gratefully acknowledge very helpful and stimulating discussions with Professor L. Hirst from the Institute of Theoretical Physics of Frankfurt/Main. The research work was supported in part by the Deutscher Akademischer Austauschdienst (DAAD), Germany.

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