Electronic damping of spin waves in disordered itinerant ferromagnets

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(Received 20 December 1988)

The effect of impurity scattering on the damping of spin waves in itinerant ferromagnets at zero temperature is studied. Spin-independent impurity scattering leads to a damping term proportional to q^4, and spin-flipping impurity scattering processes lead to an additional q^2 damping term. This, in light of the temperature-independent, q^4 spin-wave linewidth observed recently, indicates the significance of intrinsic spin-wave broadening mechanisms. Comparison of estimates made for the damping term with experimental results for the spin-wave linewidth strongly suggests that diffusive relaxation is the relevant mechanism for spin-wave broadening when only spin-independent scattering processes are present.

Recent inelastic neutron scattering experiments[1] on the spin dynamics of amorphous $Fe_{90-x}Ni_xZr_{10}$ have revealed a temperature-independent spin-wave linewidth and within experimental resolution the linewidth data have been shown to fit equally well a q^4 and a q^5 functional form. This insensitivity to temperature is contrary to the T^2 dependence expected from the contribution to damping of spin waves by magnon-magnon interaction.[2] The temperature independence of the spin-wave broadening was taken to be suggestive of the relevance of intrinsic broadening mechanisms arising possibly due to magnetic disorder in the system. It is known[3,4] that within a random Heisenberg model of localized spins, the scattering of spin waves off fluctuations in the exchange term leads to a temperature-independent spin-wave damping which goes as q^5. On the other hand, in a disordered, itinerant-electron system there exist, in the paramagnetic as well as in the weakly ferromagnetic phases, fluctuations in the spin density itself, the nature of which is rendered diffusive by impurity scattering processes. In the absence of any spin-flip impurity scattering process, spin diffusion is the only intrinsic mechanism for relaxation of the long-wavelength, low-frequency modes of spin-density fluctuations. This diffusive relaxation causes a damping of spin waves (proportional to the spin-diffusion constant) which, as we show here, goes as q^4.

Despite the fundamental differences between these two mechanisms for spin-wave damping, the closeness of the two functional forms makes it difficult to distinguish experimentally solely on the basis of the q dependence. Comparison of estimated magnitude of the damping term within the Heisenberg model with results for transition metal-metalloid systems has revealed an order-of-magnitude discrepancy.[3] Our estimate for the spin-wave damping term, relative to the spin-wave energy, compares well with the experimental linewidth data and clearly indicates the importance of diffusive relaxation in weak, itinerant ferromagnets as an intrinsic broadening mechanism for damping of spin waves at low temperatures.

Spin-flip processes associated with spin-dependent (spin-orbit or magnetic) impurity scattering provide an intrinsic spin-relaxation mechanism in addition to diffusive relaxation and this leads to an infinite-wavelength broadening of the spin response and an additional q^2 term in the spin-wave damping. We have extended our study of the combined effects of normal disorder and electronic correlation in an itinerant ferromagnetic system near the magnetic instability[5] by including spin-dependent impurity-scattering processes. The dynamical transverse magnetic susceptibility for the interacting system can be written in the form of a random-phase approximation-type expression:[5]

$$\chi^{-+}(\mathbf{q},\omega,\Delta)=\frac{\chi_{\mathrm{imp}}^{-+}(\mathbf{q},\omega,\Delta)}{1-U\chi_{\mathrm{imp}}^{-+}(\mathbf{q},\omega,\Delta)} . \tag{1}$$

Here $\chi_{\mathrm{imp}}^{-+}(\mathbf{q},\omega,\Delta)$ is the impurity-averaged transverse spin susceptibility for the noninteracting system, evaluated in the ferromagnetic phase. U is the Hubbard interaction strength and $\Delta=-U(n^{\uparrow}-n^{\downarrow})$, where n^{σ} denotes the electronic density. If no spin-flipping impurity scattering is present, Δ also measures the relative band shift between the majority and minority spin bands, and there are no minority spin states up to energy Δ measured from the bottom of the majority spin band. However, if spin-flip processes are present the band edges of the two spin bands have to coincide, although if spin-flip scattering is small the density of states in the minority spin band does become significant only outside this region.[6] For energies far from the band edge, Δ, apart from a renormalization, still measures the band shift.

Evaluation of the impurity-averaged susceptibility, $\chi_{\mathrm{imp}}^{-+}(\mathbf{q},\omega,\Delta)$, has been discussed earlier.[5,6] The collective modes representing the spin-wave instability are obtained by setting the denominator in Eq. (1) to zero,[7] from which we obtain the equation for the spin-wave mode:

$$\omega=\frac{(\bar{\Delta}-i\{(4/3)\tau_{\mathrm{SF}}^{-1}+Dq^2/[1+(\bar{\Delta}\tau)^2]\})\alpha q^2}{12k_F^2} . \tag{2}$$

The relaxation rates are given by $\tau_N^{-1}=2\pi N(0)\gamma_N$, $\tau_{\mathrm{SF}}^{-1}=2\pi N(0)\gamma_{\mathrm{SF}}$; γ_N and γ_{SF} being the strengths of normal and spin-flip impurity scattering processes. $\tau^{-1}=\tau_N^{-1}+\tau_{\mathrm{SF}}^{-1}$ is the total relaxation rate, $D=l^2/3\tau$ is the diffusion constant, l is the mean free path, and $\bar{\Delta}$ is the renormalized relative band shift given by $\bar{\Delta}=\Delta/[1+(2/3k_Fl_{\mathrm{SF}})^2]$.

The factor α, which is the coefficient of the q^2 term in the static susceptibility, is 1 in the pure limit and decreases with increasing disorder. Its behavior with increasing $(k_F l_{SF})^{-1}$ for different values of $(k_F l)^{-1}$ has been studied by direct evaluation of the static susceptibility.[6] In the case when only normal impurity scattering is present, the static susceptibility $\chi_{imp}^{-+}(0,0)$ for $q=0$ is independent of disorder strength. Thus the behavior of α with disorder indicates that for nonzero q the static susceptibility is enhanced by disorder—a simple example of disorder-induced enhancement of spin fluctuations. The factor α also effectively sets the length scale for the paramagnon correlation length in the very dirty limit $(k_F l \ll 1)$.[5,8]

The spin-wave stiffness constant is proportional to the factor α which, in view of its behavior with disorder, indicates that the spin-wave mode becomes softer with increasing impurity scattering strength. The presence of an imaginary part indicates that spin waves in this system are damped and this leads to broadening and to an intrinsic spin-wave linewidth Γ_q.

In the absence of any spin-flip impurity scattering, Γ_q is proportional to q^4 and may be rewritten, in units of the Fermi energy, as:

$$\Gamma_q^N = \frac{1}{18}\left[\frac{(k_F l)^{-1}\alpha}{(k_F l)^{-2}+(\Delta/2\omega_F)^2}\right]\left[\frac{q}{k_F}\right]^4 . \tag{3}$$

The q^4 damping term is seen to be vanishing both in the pure limit $[(k_F l)^{-1}\rightarrow 0]$ as well as in the dirty limit $[(k_F l)^{-1}\rightarrow \infty]$. The behavior of the coefficient $\Gamma_q^N/(q/k_F)^4$ with increasing $(k_F l)^{-1}$ is shown in Fig. 1 for different values of Δ/ω_F.

Information about the Fermi energy, Fermi momentum, mean free path, and the band shift can enable one to evaluate the damping term from Eq. (3) and make quantitative comparison with experimental data possible. The ratio of the damping term to the spin-wave energy can simply be written as

$$\Gamma_q/\omega_q = Dq^2/\Delta \tag{4}$$

in the limit when $(\Delta\tau)^2 \ll 1$. In view of the fact that diffusion constant is proportional to the mean free path [in atomic units $(\hbar = m = 1)$, $D = k_F l/3$ to lowest order], correlation with resistive measurement can be done to establish the intrinsic nature of spin-wave broadening due to normal disorder.

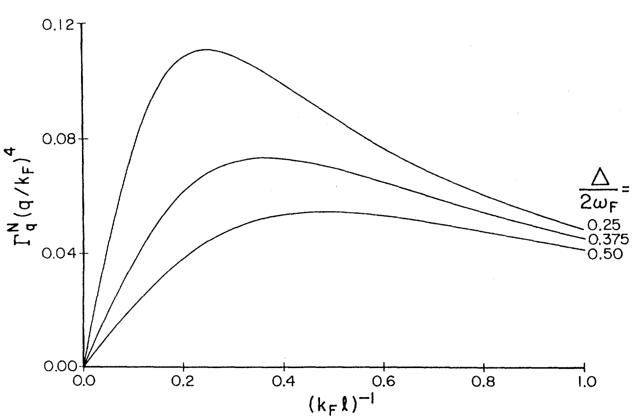

FIG. 1. Variation of spin-wave damping coefficient, $\Gamma_q^N/(q/k_F)^4$, with increasing normal scattering strength.

The range of values of Γ_q shown in Fig. 1, measured with respect to the spin-wave energy ω_q, and evaluated using parameters for a typical dirty ferromagnetic metal are indeed of the same order of magnitude as seen in the experiments.[1] If one takes $\Delta/2 \sim T_c$ (≈ 300 K for these alloys[1]), then from the measured values of the stiffness constant $(=\Delta/12k_F^2)$ of ~ 50 meV Å^2 we obtain $k_F \sim 0.2$ Å^{-1}. Using $q = 0.12$ Å^{-1} from Ref. 1, $k_F l = 1$, $\Delta/2\omega_F = 0.25$, we find $\Gamma_q/2\omega_q \sim 0.2$, which is roughly where the experimental results seem to extrapolate to at zero temperature.

Comparison for the intrinsic spin-wave linewidth observed in experiments has been made in Ref. 1 with the functional form q^5 as well as with q^4 and within experimental resolution the fitting indicates that both forms seem to adequately represent the linewidth data. As noted in Ref. 1 temperature-independent spin-wave damping proportional to q^5 has been predicted by the works of Singh and Roth[3] and Iskhakov[4] in random Heisenberg models. However, comparison of estimates for Γ_q/ω_q made by Singh and Roth within their random Heisenberg model[3] with results for a transition metal-metalloid alloy indicates that their estimates are an order of magnitude smaller than the observed values. We now discuss these earlier works as they differ from the present theory based on the itinerant electron model of spin-wave damping in weak ferromagnets.

The works in Refs. 3 and 4 deal with a random Heisenberg model of localized spins and the damping of spin waves in such a system arises from their scattering-off fluctuations in the exchange term. An approximate but particularly simple way to understand the q^5 result is to transform the Heisenberg Hamiltonian into a free-bosonic Hamiltonian (representing spin waves) by using the Holstein-Primakoff transformation. The spectrum of the nonrandom part of the one-particle Hamiltonain gives the spin-wave dispersion relation and fluctuations in the exchange term appear as random diagonal and off-diagonal terms which are, however, correlated. These impurity terms lead to scattering of spin waves and, as a result of the correlation, one finds that in momentum space the scattering amplitude for low-momentum spin waves goes as q^2. Impurity averaging of the self-energy correction in the conventional manner and evaluation of the imaginary part leads to a q^5 result for spin-wave damping.

Unlike the case of a localized spin model, in an itinerant electron system there exist fluctuations in the spin density in the paramagnetic and the weakly ferromagnetic phases. These spin-density fluctuations are strongly affected by impurity scattering and in the diffusive limits of small momentum $(q \ll 1/l)$ and low frequency $(\omega\tau \ll 1)$, the mechanism of diffusion provides a mode for spin relaxation leading to a damping of spin-density fluctuations which goes as Dq^2/Δ relative to the spin-wave energy. A description of spin-wave damping in terms of an itinerant electron model is more appropriate physically for metallic weak ferromagnets in which the impurity parameter $k_F l$ and the band shift Δ/ω_F play important roles. Many transition-metal–metalloid systems are believed to be itinerant, weakly ferromagnetic (unsaturated) systems[9] and the Invar behavior exhibited by the $Fe_{90-x}Ni_xZr_{10}$ alloys studied[1] are one of the characteristics of such systems.[9] That our estimate for $\Gamma_q/2\omega_q$ is close to the observed values in these systems strongly supports the conclusion of our theory that diffusion of spin-density fluctuations plays an important role in spin-wave damping.

Spin-wave damping in the itinerant ferromagnetic system is much stronger if spin-flip impurity scattering is present, and in this case the damping term Γ_q^{SF} is proportional to q^2. The coefficient $\Gamma_q^{SF}/(q/k_F)^2$ in units of the Fermi energy, may be written as $\frac{2}{9}(k_F l_{SF})^{-1}\alpha$. Variation of $(k_F l_{SF})^{-1}\alpha$ with increasing spin-flip impurity scattering strength is shown in Fig. 2 and indicates that spin-wave damping appears to saturate with increasing strength of spin-flip scattering.

Spin-orbit effects show up experimentally when the impurity atoms have a large atomic number (e.g., Au, Pb, etc.). However, with such impurities one needs to consider the disorder in the strength of the Hubbard correlation term also. This has been shown to lead to infinite-wavelength damping of spin waves[10] which will probably overwhelm any q^2 dependence in damping for small momentum. Spin-dependent scattering processes, in general, tend to work against ferromagnetism due to spin flipping and furthermore when magnetic impurities are present systems tend to form more complicated ground states such as spin glasses. This may account for why it is hard to see the q^2 dependence of spin-wave damping.

Due to the quantum mechanical interference of scattering amplitudes of a diffusing particle, weak-localization effects lead to a reduction in the diffusion constant from its bare value $(l^2/3\tau)$. Therefore, in view of Eq. (4) wherein the spin-wave damping is proportional to the diffusion constant, it is important to study weak-localization effects. Weak-localization corrections are very significant experimentally and lead to well-known dependences of the diffusion constant on system scale, temperature, and frequency.[11]

Effects of weak-localization corrections in the ferromagnetic phase have recently been studied for normal disorder.[5] Localization corrections to the transverse magnetic susceptibility in the ferromagnetic phase have a qualitatively different nature from those in the paramagnetic phase due to the presence of the band shift Δ. For the transverse magnetic susceptibility the relevant propagator involves antiparallel spins and so in the diffusion pole ω gets replaced by $\omega-\Delta$. For the Cooper propagator in the antiparallel spin channel one obtains,[5]

$$C_d^{\uparrow\downarrow}=\frac{\gamma}{\tau}\int\frac{d^dQ}{(2\pi)^d}\left[\frac{1}{DQ^2-i(\omega-\Delta)}\right]. \tag{5}$$

Therefore, as $\omega\rightarrow 0$, the presence of Δ removes the infrared singularity, and the system-size (L) dependence which comes in the localization correction through the lower limit of the Q integral is removed provided $\Delta\gg D/L^2$. Localization corrections to the diffusion constant thus lead to a reduction in the spin-wave damping; however, these corrections are not singular due to the presence of Δ and do not lead to any scale dependence (or temperature dependence) as long as $\Delta\gg D/L^2$ (or τ_{in}^{-1}, the inelastic scattering rate). On the other hand, for Stoner excitations which have energies of the order of Δ, the localization corrections are singular. This results in a quantum-mechanical suppression of the diffusion constant associated with Stoner excitations.

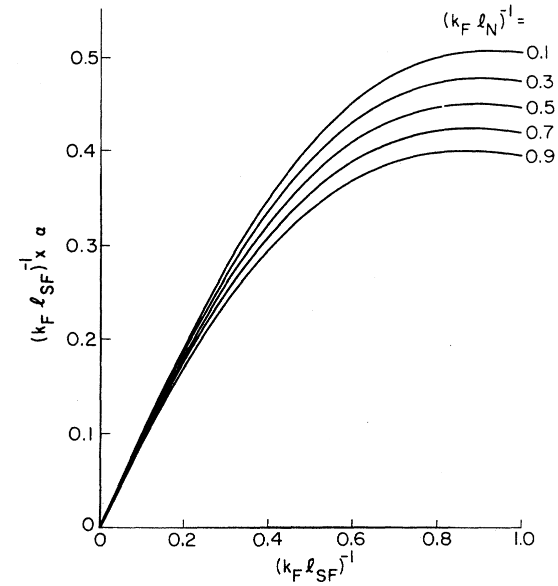

FIG. 2. Variation of $(k_F l_{SF})^{-1}\alpha$, with increasing spin-flip scattering strength.

In conclusion, it has been shown that impurity scattering processes lead to damping of spin waves in disordered itinerant ferromagnets. This is the prominent broadening mechanism at low temperatures as the contribution due to magnon-magnon interaction goes as T^2. In the weakly ferromagnetic limit spin-independent impurity scattering has been shown to lead to a zero-temperature damping term proportional to q^4 which, in light of the recent observation in $Fe_{90-x}Ni_xZr_{10}$ of a temperature-independent spin-wave linewidth which goes as q^4, seems to corroborate the significance of intrinsic broadening mechanisms. Our estimate for $\Gamma_q/2\omega_q$ is close to the experimentally observed values for spin-wave broadening in these systems and strongly supports the conclusion of our theory that diffusive relaxation of spin-density fluctuations in weakly ferromagnetic systems plays an important role in spin-wave damping.

This work was supported in part by the National Science Foundation Grant No. NSF-DMR-86-12860 at the Materials Research Laboratory (Illinois). One of us (A.S.) is thankful to Professor E. Fradkin and Professor M. B. Salamon for helpful discussions.

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