Comments and Addenda

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Spin-wave–Stoner-mode interaction in ferromagnetic metals above T_c †

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Although spin disorder should lead to a broadening out of the sharp spin-wave–Stoner-mode intersection point observed in iron and nickel above their Curie temperatures, no such broadening has been seen. In this article, the observed relatively rapid fall off of the spin-wave neutron scattering intensity when the spin wave enters the Stoner continuum is interpreted using a theory of broadening of the spin-wave line due to spin disorder proposed by Liu.

A couple of years ago Mook, Lynn, and Nicklow observed, by neutron scattering, spin waves in nickel[1] and iron,[2] which persisted for temperatures above the Curie temperature (T_c). Furthermore, they found that the spin-wave neutron scattering cross section dropped off quite sharply at about the same spin-wave energy as it did below T_c. This fall off was interpreted as being due to spin waves intersecting the continuum of Stoner excitations, which suggests that the excitations of sufficiently large wave vector do not differ much from those at low temperatures. The author proposed a model in which low-temperature excitations persist through T_c, because even in the unmagnetized state there always exist large fluctuating clusters or droplets.[3] Thus, excitations with frequencies low compared to the rate of fluctuation and with wavelengths short compared to the size of these droplets will look much like the corresponding low-temperature excitations. Liu has recently considered the broadening of the spin waves due to spin disorder.[4] Since the spin density that the neutrons couple to is disordered, considerable broadening of the observed spin wave is expected. Although this implies that the observed fall off of spin-wave scattering intensity should also be broadened, it is not. In this paper a way will be presented to interpret the sharp fall off on the basis of Liu's picture.

In Liu's model, the spin-spin correlation function is written as

$$\langle \vec{S}_i(t)\cdot\vec{S}_j\rangle = \rho_{ij}(t)\langle \vec{S}_i(t)\cdot\vec{S}_j\rangle_{SW} + [1-\rho_{ij}(t)]\langle \vec{S}_i(t)\cdot\vec{S}_j\rangle_{SD}\,, \quad (1)$$

where ρ_{ij} is the probability of sites i and j falling in the same droplet, the subscript SW signifies that the correlation function is calculated on the basis of zero-temperature spin-wave theory, and SD signifies that spin-diffusion theory is used. The probability ρ_{ij} is taken to be $\langle \vec{S}_i\cdot\vec{S}_j\rangle_{SD}$. Spin-diffusion theory should not be correct for the wave vector q and frequency ω at which the spin wave enters the Stoner continuum, but the first term in Eq. (1) should be a good representation of the spin-wave peak for q and ω not far from the spin-wave dispersion curve.

The approximations to be used in this article are the following:

$$\int dt\, e^{i\omega t}\sum_i e^{-i\vec{q}\cdot(\vec{R}_i-\vec{R}_j)}\langle \vec{S}_i(t)\cdot\vec{S}_j(0)\rangle_{SW} = \Theta(\omega-\omega_0)\delta(\omega-\omega(\vec{q}))/(1-e^{-\beta\omega})\,, \quad (2)$$

$$\rho(q,\omega)\propto\frac{1}{q^2+q_c^2}\,\frac{2\Lambda q^2}{\Lambda^2q^4+\omega^2}\,, \quad (3)$$

where Λ is the diffusion constant, $\omega(q)$ is the spin-wave dispersion relation, q_c is the inverse correlation length, ω_0 is the edge of the Stoner continuum, and

$$\Theta(x)=\begin{cases}1 \text{ if } x<0\,,\\ 0 \text{ if } x>0\,.\end{cases}$$

Thus, we assume that the unbroadened spin-wave intensity drops completely to zero at $\omega=\omega_0$. The spin-diffusion part [i.e., the second term in Eq. (1)] is assumed to be unimportant for ω and q near where the spin-wave intensity drops. As in Liu's model, the only broadening of the spin wave is that due to the fact that the spin density that the neutrons couple to is disordered. Intrinsic broadening of the spin wave and Stoner modes is not included. Then, the spin-wave contribution to the Fourier-transformed correlation function is found from Eqs. (1)–(3) to be proportional to

$$\sum_i e^{i\vec{q}\cdot(\vec{R}_i-\vec{R}_j)}\langle\vec{S}_i\cdot\vec{S}_j\rangle_{SW}$$

$$\propto\sum_{\vec{q}'}\frac{1}{q'^2+q_c^2}\frac{\Lambda q'^2}{\Lambda^2 q'^4+[\omega-\omega(\vec{q}+\vec{q}')]^2}\times\frac{1}{1-e^{-\beta\omega(\vec{q}+\vec{q}')}}\Theta(\omega(\vec{q}+\vec{q}')-\omega_0)\,. \quad (4)$$

The spin-wave scattering intensity as a function of q has been calculated using Eq. (4) for $T=673\,^\circ$K, $\Lambda=98$ meV Å^2, $q_c^{-1}=12.4$ Å (the parameters used in Liu's calculation) for various values of ω below and above ω_0. The results are given in Fig. 1. As can be seen in the figure, although the spin wave is quite broadened by spin disorder there exists a well-defined bump in the scattering intensity for ω less than ω_0, which goes away as soon as ω becomes greater than ω_0. Thus, it is easy to understand why the spin-wave intensity observed in the neutron scattering experiments drops off very rapidly when ω becomes greater than ω_0, if we assume that people who did the experiments on iron and nickel interpreted this bump to be the "spin-wave peak" and took the remainder of the spectrum to be "background."[1,2] The fact that this bump disappears completely at $\omega=\omega_0$ would then naturally be taken to mean that the spin-wave scattering intensity has vanished.

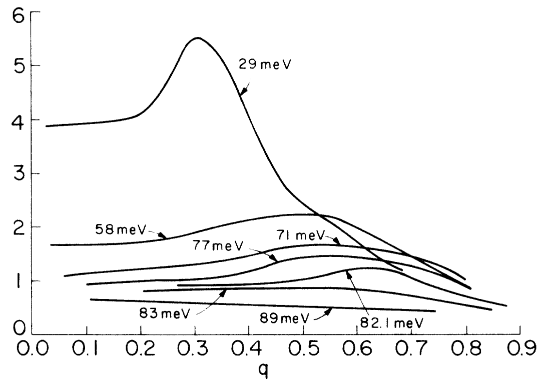

FIG. 1. Spin-wave neutron scattering intensity versus wave vector calculated from Eq. (4) is plotted for various neutron energy transfers. Intensity is in arbitrary units and wave vector is in units of Å^{-1}. The Stoner-continuum edge ω_0 is taken to be 82.4 meV.

Because the spin-diffusion form for $\rho(\vec{q},\omega)$ given in Eq. (3) is not expected to be valid for the large-q and -ω values which are needed to calculate the curves in Fig. 1, we expect these curves to be only qualitatively correct. Therefore, no attempt has been made to make a detailed fit of the experimental data. Another deficiency in the theory is that no intrinsic broadening of the spin wave and Stoner modes has been included. There is no reason to believe that there will not be strong broadening even at much lower temperatures, but in fact, the spin-wave peak is observed to vanish suddenly when ω reaches ω_0 at all temperatures.[1,2,5] The question that has been considered in this article is why despite the additional broadening due to spin disorder, the spin-wave peak still vanishes suddenly when a certain spin-wave energy ω_0 is reached.

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