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Microscopic theory of spin waves in ultrathin ferromagnetic films: Fe on W(110)

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Abstract

We present theoretical studies of the spin wave excitations in ultrathin Fe films adsorbed on the W(110) surface, within the framework of itinerant electron theory, and with use of a realistic electronic structure. The electronic structure of the films and the substrate, taken as semi-infinite, is described by the empirical tight-binding scheme with ferromagnetism in the film driven by intra-atomic Coulomb interactions within the d shell. We calculate the exchange stiffness directly, then explore spin wave dispersion relations and Landau damping throughout the surface Brillouin zone through use of the random phase approximation. We also compare dispersion relations so generated with results based on the adiabatic description of spin motions; the latter approach overlooks Landau damping, of course, which we find appreciable at the shorter wavelengths. We comment also on apparent hybridization gaps and 'optical' spin waves which have appeared in earlier theoretical studies of spin waves in the bulk transition metal ferromagnets.

1. Introductory remarks

For nearly two decades, the study of magnetism in ultrathin (few-atomic-layer) films has proved of fundamental interest, since these systems have properties very different to those encountered in the magnetism of bulk crystals, and also their properties can be controlled at the time of synthesis through choice of substrate, film thickness, growth conditions, and other variables as well. An example is the strong role played by crystalline and shape anisotropy; in ultrathin films, a large fraction of the atoms reside in low-symmetry surface or interface sites, with the consequence that the crystalline anisotropy can be stronger by one or two orders of magnitude, when compared to cubic forms of bulk magnetic matter [1]. The anisotropy can favour either an orientation of the magnetization perpendicular to the surfaces, or parallel depending of film thickness [2], temperature [3], and other variables as well. While the Mermin–Wagner theorem forbids long-ranged order in two dimensions, for the classical exchange Hamiltonian used so often in theoretical discussions of magnetism, in fact these films are commonly ferromagnetic at

elevated temperatures. This makes device applications possible when ultrathin ferromagnetic films are incorporated into multilayer structures such as spin valves. It is the anisotropy, weak compared to the very strong interatomic exchange, that drives ferromagnetic order in these quasi-two-dimensional systems [4].

It is the case that a very large fraction of the theoretical and experimental efforts in the field explore ground state properties of these materials. Anisotropy is one example of such a property. It is the excited states that actually control the response of the material to various external probes, of course. Magnetically ordered materials possess collective excitations, the spin waves or magnons, that enter importantly into the description of their response to diverse probes. Also, the study of the nature of the spin wave spectrum provides insight into and information on the interactions which control the magnetism of the material. In the case of ultrathin films, with the exception of two studies discussed below, the spin wave modes excited by the two methods utilized most commonly to date (ferromagnetic resonance spectroscopy, Brillouin light scattering) have wavelengths very long compared to both the underlying lattice constant and the film thickness. A consequence is that the properties of these low-frequency, long-wavelength modes may be described entirely in terms of ground state properties of the film (anisotropy, exchange stiffness, etc). It is of very great interest to find the means of exciting and studying short-wavelength spin wave modes, with wavelength comparable to the microscopic lengths in the system, since the dispersion relation and nature of such modes will provide deep insight into microscopic aspects of effective interatomic exchange interactions, and other properties as well.

One then enquires about the experimental means of exciting such short-wavelength spin wave excitations. Inelastic neutron scattering has been a widely used probe to study diverse low-lying collective excitations in solid materials for many decades, including spin waves in magnetically ordered crystals. However, this method encounters two serious difficulties if one contemplates using it to probe ultrathin films. First, of course, is the lack of surface sensitivity of the technique. One can in principle employ a glancing incidence geometry to achieve surface sensitivity, but to use the glancing incidence geometry while performing inelastic scattering measurements remains a major challenge. A more important limitation, which cannot be overcome even in principle, is the fact that the kinetic energy ($\sim$50 meV) of thermal neutrons is too low to excite short-wavelength spin waves in the transition metal ferromagnets, which typically lie in the range of a few hundred meV. Thus, if one explores the literature, we have very little detailed information in hand at this stage on even the short-wavelength spin waves in the bulk magnetically ordered 3d magnets.

Inelastic electron scattering has been widely used to probe a diverse array of excitations near the surface of crystals, and in very thin films. Electrons with kinetic energy in the range of 10–200 eV typically have mean free paths in matter the order of a few ångströms, so electron spectroscopies are highly surface sensitive. It has proved possible to achieve sufficient resolution to study short-wavelength phonon modes on surfaces, and in ultrathin films with the method [5]. One may enquire whether the spin polarized version of electron loss spectroscopy, described by the acronym SPEELS, may be used to excite spin waves with the electron spin exploited to confirm that in fact magnetic excitations have indeed been probed. For the past several years, we have been engaged in a theoretical effort to explore the feasibility of this method. We have performed absolute calculations of the excitation cross-section [6], finding it roughly three orders of magnitude weaker than that for exciting phonons on the surface. Thus, to excite spin waves, higher beam currents are required than are employed in phonon spectroscopy. This will make it more difficult to achieve the very high resolution used in the phonon studies, though since spin wave excitation energies are much higher than those of phonons, the very high resolution may not be necessary. Our microscopic studies of the

excitation of spin waves in Fe [7] predicted that the spin wave loss feature should stand out clearly in the spectrum, though in Ni the low-lying Stoner excitations obscure this feature [8], a result in accord with an earlier unsuccessful attempt [9] to excite spin waves on a Ni surface via inelastic electron spectroscopy.

We now have in hand two initial experimental studies in which spin waves have been observed in SPEELS, on Fe surfaces. Following the predictions in [7], Kirschner [10] successfully detected the loss feature produced by spin wave excitation by a polarized electron beam, for an ultrathin film of Fe on W(110). More recently, Vernoy and Hopster [11] have reported a band of spin wave losses, in a SPEELS study of a thick Fe film grown on GaAs. The shape of the feature that they observe is in excellent accord with the results of a simple model calculation presented many years ago [12]. In both experiments, the features found can be identified as spin wave losses as follows. In a saturated ferromagnet, excitation of a spin wave lowers the spin angular momentum of the substrate by precisely $\hbar$. If, then, the magnetization of the substrate points upward, only a down spin electron can excite spin waves, and flip its spin to up in the process. An up spin electron is forbidden to excite these modes, by conservation of angular momentum. Thus, the spin wave excitation features may be extracted from the total loss spectrum by measuring the losses with a beam polarized downward, and subtracting the loss spectrum for a beam polarized in the up spin direction. While neither of the two experiments just cited have yet to explore details of dispersion relations of the spin waves, signals are in hand, we hope to see detailed spectroscopy of these modes in the near future.

With this last point in mind, we have recently been engaged in theoretical studies of the spin wave excitations in candidate systems, with the aim of providing quantitative predictions of the dispersion relations, and the properties of the short-wavelength modes. Kirschner's experiment [10] has stimulated us to begin with ultrathin Fe films on W(110). We note also that Gradmann and co-workers have pointed out in their pioneering studies [13] that Fe wets W with the consequence that for this system, one finds uniform, high-quality ultrathin films. In this paper, we summarize some of our principal theoretical results. The focus here is on the Fe monolayer, for which we have found a number of issues to explore in detail. We make brief remarks on Fe multilayers. We have detailed calculations under way for the multilayers, it should be remarked. These will be reported elsewhere.

2. Summary of the method

We wish to explore the properties of spin waves of an ultrathin Fe film adsorbed on the W(110) substrate, for reasons just given. We begin with comments that motivate our choice of method. In this paper, we shall not describe explicitly details of our approach to the generation of the electronic structure of the system, nor our treatment of the spin excitations, which is based on use of the random phase approximation (RPA). We refer the reader to an earlier analysis [14] of spin excitations in bulk Fe and free-standing Fe(100) films, and to our recent paper on the Fe monolayer on W(110) for details [15]. Full details are found in these publications regarding the empirical tight-binding description of the electronic structure of the system that we use to describe the ferromagnetic ground state, and our means of computing the wavevector-and frequency-dependent susceptibility of the system through use of the RPA.

In itinerant ferromagnets, in general spin wave excitations of short wavelength are damped rather strongly because they can decay to a particle–hole continuum in which the spin wave excitation is embedded. The spin wave can decay by exciting an electron from a partially filled majority spin band to an unfilled state in a minority spin band, transferring its crystal moment to this spin triplet particle–hole pair in the process. These particle–hole excitations, in which such a spin flip is involved, are referred to in the literature as Stoner excitations, and the

damping mechanism is called Landau damping, a term introduced in the discussion of similar decays experienced by the collective plasmon modes of the electron gas.

In the limit of long wavelengths or small wavevectors, a general theorem of many-body theory ensures that the Landau damping is negligible in magnitude; one can prove rigorously that in the limit of zero wavevector, the lifetime of the spin wave is infinite (provided spin–orbit coupling effects are overlooked), and by continuity the damping remains small at long wavelengths. An important question is whether, at short wavelengths, the Landau damping is so severe that well defined spin waves fail to exist as collective excitations. We note that a recent theoretical study of seven-layer free-standing Fe(100) films found Landau damping so severe for short-wavelength standing spin wave modes that they failed to give a well defined signature in the relevant spectral density functions [14]. Thus, an important question is the degree of Landau damping experienced by short-wavelength modes for a film adsorbed on a substrate such as W, where the particle–hole spectrum associated with the 5d band complex overlaps the domain of frequency and wavevector (parallel to the surface) in which the spin wave modes are to be found.

To assess the extent of this damping accurately, in our view one should describe a film adsorbed on a semi-infinite substrate, wherein the final state particle–hole manifold is a true continuum; use of a film on a substrate modelled as a limited number of layers, as done often in *ab initio* electronic structure studies, may not prove accurate. For this reason, in addition to reasons of computational convenience, we have utilized an empirical tight-binding description of the d bands, and the sp band complex of both the adsorbed film and the underlying substrate. Within this scheme, the single-particle propagators required for the construction of the irreducible particle–hole propagator that enters centrally into the study of the spin dynamics can be generated efficiently, for the case where the substrate is semi-infinite in nature. As remarked above, full details of the methods that we use to describe the electronic band structure, and to carry out the computations reported below, are given elsewhere [14, 15], so the comments here are qualitative in nature.

Ferromagnetism is driven in the ferromagnetic film via on-site intra-atomic Coulomb interactions, within the 3d shell in our analysis, while the electrons in the substrate are treated as non-interacting band electrons. One may thus view our model as a multi-band generalization of the Hubbard model. We generate the ground state through use of mean field theory and, as described above, the spin waves are studied via the RPA. We must model the Coulomb interaction through use of empirical parameters deduced from ground state properties of bulk ferromagnetic Fe. One then must enquire about how sensitive the results may be to the choice of model for the intra-atomic Coulomb interactions. To explore this issue, we have utilized two different schemes, finding rather small quantitative differences between the numerical results produced by each. The first scheme is rather simple, and involves only one adjustable parameter that sets the overall strength of the Coulomb repulsion in the 3d shell. This scheme was used many years ago in a classic study by Lowde and Windsor [16], and has the virtue of simplicity. The second scheme uses a group theoretic based description used in the literature on atomic physics [17]. This has the virtue that in the limit of separated atoms, the model Hamiltonian correctly reproduces the structure of the intra-d-shell excitations of the free atom; three parameters are involved whose values are deduced by fitting ground state magnetic properties of bulk crystalline Fe. This scheme has been used in recent studies of the spin wave excitations of bulk Fe, and those of free-standing Fe(100) films [14]. In the new calculations reported here, we have used the ground state parameters reported in [14]. Interestingly, we find only minor quantitative differences between the spin wave spectra calculated with these two different schemes, for the Fe monolayer on W(110), so it would appear that our results are not sensitive to the details of the means used to describe the intra-atomic Coulomb interactions.

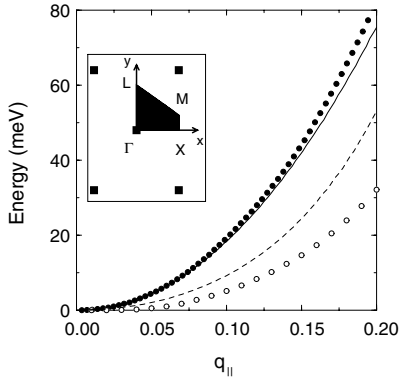

Figure 1. The filled dots form the dispersion curve for the adsorbed monolayer along the ΓX direction, and the open dots describe spin wave dispersion along ΓY also for the adsorbed film. The thin solid curve and the dashed curve describe the free-standing film dispersion relation, again along ΓX and ΓY respectively. All calculations are done within the adiabatic approximation.

A detailed comparison between the two schemes is given elsewhere [15], and we shall not comment further on this matter here. We turn next to our results.

3. Results and discussion

We first begin with a discussion of spin waves with wavelength long compared to a lattice constant; the dispersion relation of such modes necessarily varies quadratically with the wavevector of the mode. In this regime, as discussed many years ago [18], a quasi-static method rigorously described the exchange stiffness associated with the long-wavelength spin wave modes. We have extended this scheme so we can utilize it to calculated directly the exchange stiffness for the adsorbed film [15].

A striking feature of the Fe monolayer on W[110] is that in the long-wavelength limit, we find the exchange stiffness highly anisotropic. The dispersion relation is given by

$$\hbar\omega(\vec{q}_\parallel) = D_{xx}q_x^2 + D_{yy}q_y^2 \tag{1}$$

where in our coordinate system, in real space the x-axis is directed along the long side of the two-dimensional unit cell. The dispersion relation for the adsorbed monolayer in the long-wavelength limit for the two principal directions is illustrated by the dotted curves in figure 1, with the solid dots describing propagation along the x-direction. There is a remarkably large four-to-one asymmetry in the spin wave exchange stiffness, as the wavevector scans the xy-plane. We find $D_{xx} = 400$ meV Å^2, while $D_{yy} = 107$ meV Å^2. The indirect spin interactions through the W substrate play a major role in producing this large anisotropy. The dashed and solid curves in figure 2 are calculations for the free-standing monolayer. Here we have $D_{xx} = 392$ meV Å^2, a value very close to that realized for the adsorbed film, whereas now $D_{yy} = 192$ meV Å^2. Interestingly, if one consults the prediction of the nearest-neighbour Heisenberg model for the geometry of the [110] film, one expects the ratio D_{xx}/D_{yy} to assume the value 2, very close to our finding for the free-standing film.

If one considers long-wavelength spin wave propagation within the [110] plane of bulk crystalline Fe, then the cubic symmetry of the crystal dictates that the dispersion relation should be isotropic, with $D_{xx} = D_{yy}$. Thus, as we add layers of Fe to the monolayer, at some point the dispersion relation should become isotropic. We have studied the variation of exchange stiffness constants with the number N of Fe layers in the film; a set of empirical tight-binding

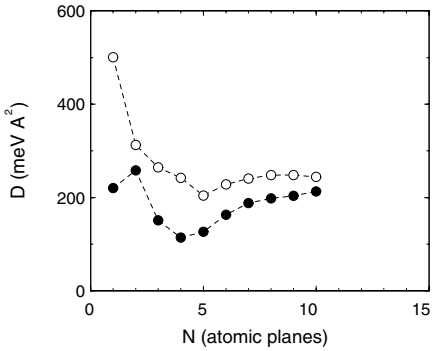

Figure 2. The open circles are the exchange stiffness as a function of film thickness for spin wave propagation along the ΓX direction and the solid circles are the exchange stiffness for propagation along ΓY. Both are normalized to the bulk value.

parameters slightly different to those used for figure 1 were employed. In Fe, exchange is well known to be very sensitive to details of the electronic structure, so for $N = 1$ we do not quite obtain the values just quoted, though the very large anisotropy remains. In figure 2, for this choice of band structure, which differs very slightly from that used to generate figure 1, we show the behaviour of both D_{xx} and D_{yy} as a function of the number of Fe layers. We see that the film has indeed to be quite thick for nearly isotropic behaviour to be realized. Of particular interest are the oscillations in both these quantities. Interestingly, within a two-layer film, we realize almost isotropic behaviour, but this is just a consequence of the oscillatory approach of these quantities to the bulk limit. The fact that the film has to be quite thick to realize isotropic behaviour is, in our view, a consequence of the long range of the effective exchange interactions in an itinerant ferromagnet such as Fe.

As we move out into the surface Brillouin zone, away from the long-wavelength regime, the Landau damping discussed above asserts itself. The spin waves no longer have infinite lifetime, but rather are damped by virtue of the fact that they may decay to the continuous manifold of Stoner excitations. As noted in the previous section, a general theorem of many-body theory based on spin rotation invariance of the underlying Hamiltonian ensures that right at $\vec{q}_{\parallel} = 0$, the lifetime of the spin wave, a simple spatially uniform rotation of the spins, is infinite. (The theorem assumes that spin–orbit coupling is neglected, so only Coulomb interactions are present.) The damping rate is small in the long-wavelength regime, but becomes quite strong as we move out into the surface Brillouin zone. We illustrate this in figure 3, where we show the spin wave spectral densities as a function of wavevector for the Fe monolayer on W(110). The wavevector is directed along the ΓL direction of the surface Brillouin zone, and the plots explore reduced wavevectors between 0.1 and 0.7, as described in the figure caption. At the largest value of the wavevectors displayed, the 'Q' of the mode is only in the region of 4 or 5.

In the literature on spin wave excitations in the itinerant electron ferromagnets, quite often the adiabatic approximation is utilized to calculate spin wave dispersion relations throughout the surface Brillouin zone. One method of proceeding is to calculate effective exchange couplings J_{ij} between spin i and spin j by a spin analogue of the 'frozen phonon' method of calculating effective force constants in phonon dispersion relation analyses. In the magnetic case, one rotates spin i and freezes it in position, then calculates the torque on spin j, to extract an effective exchange coupling constant from the result. Various pairwise interactions are computed in this fashion, and from this one builds up a dispersion relation used for all wavevectors in the Brillouin zone. Various other equivalent formulations are employed. In any such quasi-static theory, the resulting spin wave has infinite lifetime, and thus the strong

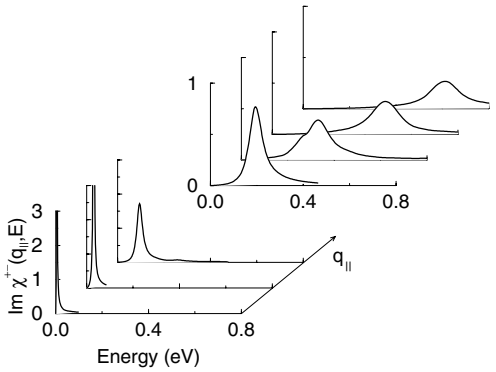

Figure 3. For a series of wavevectors along the ΓL direction, we show the spin wave spectral densities to illustrate the degree of Landau damping. The calculations are for the adsorbed film, and the reduced wavevectors illustrated are $q_{\|} = 0.1$, 0.2, 0.3, 0.4, 0.5, 0.6, and 0.7.

Landau damping evident in figure 3 is completely absent. It is the case as well that the frequency of the spin wave is also poorly accounted for by this method, at short wavelengths where the damping is strong. One may appreciate this from the following reasoning. The spin wave is an elementary excitation of the system, and its interactions may be accounted for by introducing an appropriate self-energy. The Landau damping may be viewed as arising from the imaginary part of the spin wave self-energy. But the proper self-energy has a real part related to the imaginary part as a Kramers–Kronig transform. Thus, the presence of Landau damping necessarily introduces a frequency shift correlated with the damping rate. This shift is clearly omitted in any quasi-static or adiabatic description, and thus the dispersion relation generated by such an approach is not quantitatively reliable, save at long wavelengths where the damping is very weak. This point is not new. We remind readers of a discussion presented many years ago, in which it was demonstrated that the adiabatic approach provides a proper account of the dispersion relation only to order $(q_{\|})^2$ [18]. That is to say, it provides a proper value of the exchange stiffness (a tensor in the case of the monolayer, as we have seen), but beyond this long-wavelength regime it is quantitatively unreliable.

In the particular case explored here, the Fe monolayer on W(110), the Landau damping is particularly severe, because the spin wave dispersion relation overlaps the particle–hole excitation spectrum of the underlying W substrate. We illustrate this in figure 4, where for a selected wavevector well out in the surface Brillouin zone, we compare the spin wave spectral density on the adsorbed Fe monolayer, and that for a free-standing monolayer. Note that not only is the spin wave in the isolated monolayer much more long lived than that on the adsorbed layer, but also there is a substantial frequency shift with its origin in the indirect interaction between Fe spins mediated by the substrate.

We conclude with comments on our experience with an issue that has been discussed in the literature for quite a number of years now. Suppose that we consider the dispersion relation of spin waves in a bulk ferromagnet of simple crystal structure, with one magnetic ion per unit cell. Then, as is known very well indeed from elementary textbook discussions, any localized spin representation of the excitation spectrum will produce a single, continuous dispersion relation that extends throughout the Brillouin zone. However, some years ago, Cooke and collaborators, in early studies of spin waves in Ni and Fe, within an itinerant electron description of spin waves, reported regimes of wavevector where a high-frequency spin wave branch existed, in addition to the classical acoustic spin wave branch. They referred to such modes as 'optical spin waves'. We see new calculations which explore bulk spin waves within the framework of more sophisticated schemes. These report apparent hybridization gaps in the dispersion

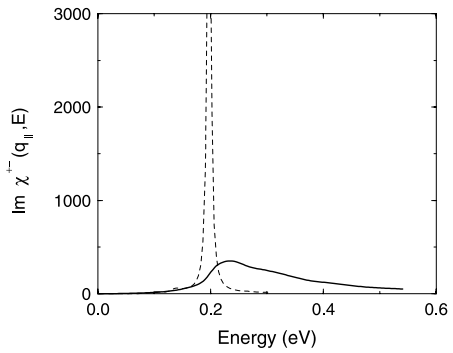

Figure 4. For the reduced wavevector of 0.35 along the ΓX direction, we show the spin wave spectral density for the free-standing film (dotted line) and the adsorbed Fe monolayer.

relation of the acoustic branch [20, 21]. Yet we find other studies [14, 22] in which such interesting features fail to appear. A comparison between results displayed in papers in which such structures appears shows that no two authors find them in the same direction or region of the Brillouin zone.

Our experience with this matter is summarized in figure 5. We display here calculations of the spin wave spectral density for the Fe monolayer on W(110), for three selected wavevectors along the ΓX direction of the surface Brillouin zone. In figure 5(a) we show results for $q_x = 0.25$, in figure 5(b) the results are for $q_x = 0.5$, and finally in figure 5(c) we show results for $q_x = 0.35$. First examine the dotted curves in figure 5. These are calculated with a mesh of 262 points in the irreducible surface Brillouin zone. We see a single feature in figure 5(a), a single feature in figure 5(b), but a doublet in figure 5(c). If we arrange the information in a sequence of such figures into a dispersion relation plot, we find a dispersion relation with a hybridization gap in the vicinity of the reduced wavevector of 0.35. Our search for a physical origin of this feature proved vexing. One might think that there is structure in the Stoner spectrum which introduces such a feature, yet at these low frequencies we see nothing of significance in the irreducible particle–hole propagators that we employ in the calculation.

Now examine the structures in the three figures described by the thin solid lines. These have been calculated through use of 1036 points in the irreducible surface Brillouin zone. There is little change in what we see in figures 5(a) and (b), so one may reach the reasonable conclusion that the first choice of grid, 262 points, was quite sufficient to ensure numerical convergence. However, when we increase the grid density at the reduced wavevector of 0.35, in figure 5(c) we now see a most dramatic change. Instead of a doublet, we see a single peak only, with a modest shoulder at higher energy. The heavy solid line in figure 5(c) is a calculation with a grid of 4120 points in the irreducible zone, and the shoulder itself has disappeared, with only minor structure left of little physical significance; so far as we know, these mild undulations in the spectral density may also be a product of incomplete convergence.

Thus, while in our calculations, we did initially encounter hybridization gaps in the spin wave dispersion relation of the Fe monolayer rather similar in nature to those illustrated in the literature for bulk Fe and Ni, in every case we encountered (see one exception below), these structures disappear after a careful check of convergence. In the numerical work, the issue is subtle. As we see clearly from figure 5, if one achieves convergence at particular wavevectors in the Brillouin zone, this does not ensure convergence even at rather nearby points. Our procedure has been to perform careful convergence checks every time that anomalous structures are found in the spectral densities, and we find that they disappear. It is our view that in these materials, one should find a single branch in the dispersion relation, and 'optical spin waves' or

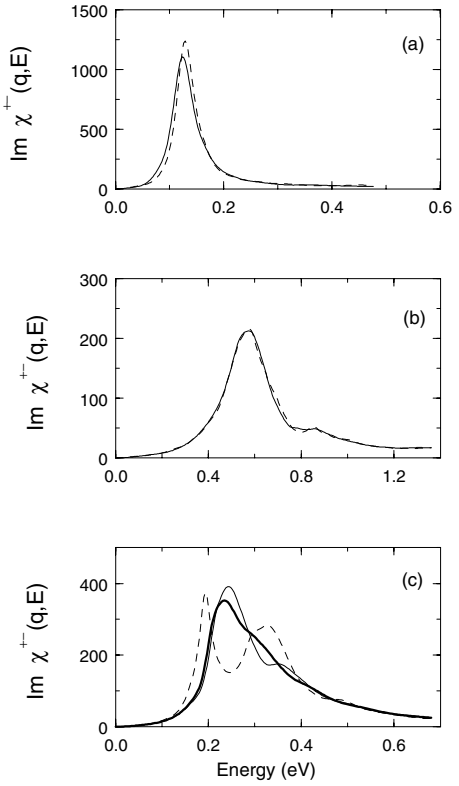

Figure 5. An illustration of requirements for converged calculations, for various wavevectors along the ΓX direction. The results in (a) and (b) are for reduced wavevectors of 0.25 and 0.50 respectively. In these figures, the dashed curves employ 262 special points in the reduced Brillouin zone, and the solid curve employs 1036 special points. In (c) we have results for the reduced wavevector of 0.35, and the heavy solid curve is a calculation with 4120 special points.

hybridization gaps should be absent. At rather short wavelengths, of course, where the features in the spin wave spectral densities are quite broad, there may be modest structures in the wing of the main features, but these are not necessarily collective modes, defined as a zero crossing of the denominator of the appropriate response function. Previous calculations suggest [14] that a broad weak feature interpreted [23] as a possible 'optical spin wave mode' is of such an origin.

We referred to one exception above. In the early work of Cooke and collaborators, a particularly simple representation of the on-site Coulomb interaction was utilized. This had one diagonal matrix element within the t_{2g} manifold of 3d states, and a second within the manifold of e_{2g} states. Here we find a complex array of hybridization gaps which persist, even as numerical convergence is increased. We believe that this is a special feature of this particular model, which introduces effective local crystal field excitations via the Coulomb interaction, which mix with the spin waves in the ferromagnetic state. We note that this particular model is unphysical, in that the on-site Coulomb interaction is not form invariant under the operations of the cubic point group [24].

4. Concluding remarks

Recent developments in spin polarized electron spectroscopy (SPEELS) now allow access to short-wavelength spin wave excitations in ultrathin ferromagnetic films, and on ferromagnetic

surfaces. We hope that in the near future we shall see detailed studies of the dispersion relations of such modes, far out in the surface Brillouin zone, in ultrathin-film structures of current interest. With this possibility in mind, we have undertaken calculations of the properties and nature of spin waves in candidate structures. In this paper, we have presented a summary of our initial results for a classic system, Fe films on W(110). A complete account of this rather extensive series of calculations is found in [15], along with a detailed summary of the model that we have employed, and a number of formal details.

It will be interesting to compare the properties of spin waves in the system considered here with other film/substrate combinations. To our mind, of particular interest will be studies of Landau damping of spin waves in Fe films adsorbed on noble metal substrates. We expect that the damping will be much less severe than that found here, since the spin waves will overlap a much lower density of states in the substrate. Meanwhile, we hope that results such as those presented here will stimulate new experimental activity in this most interesting new field.

Acknowledgments

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References

[1] For a discussion of the physical origin of the strong anisotropy associated with low-symmetry sites, see section 2 of
Mills D L 1991 *J. Magn. Magn. Mater.* **100** 515
[2] Schultz B and Baberschke K 1994 *Phys. Rev.* B **50** 13467
[3] Pappas D P, Kamper K P and Hopster H 1990 *Phys. Rev. Lett.* **64** 3179
[4] Bander M and Mills D L 1988 *Phys. Rev.* B **38** 12015
[5] For an example of such a study, see
Hall B M, Mills D L, Mohammed M H and Kesmodel L L 1988 *Phys. Rev.* B **38** 5856
[6] Gokhale M P, Ormeci A and Mills D L 1992 *Phys. Rev.* B **46** 4172
[7] Plihal M and Mills D L 1998 *Phys. Rev.* B **58** 14407
[8] Hong J and Mills D L 2000 *Phys. Rev.* B **61** R858
[9] Ibach H 1983 private communication
[10] Plihal M, Mills D L and Kirschner J 1999 *Phys. Rev. Lett.* **82** 2579
[11] Vernoy M and Hopster H 2002 *Mtg of the American Physical Society (Indianapolis, IN, March 2002)* paper W2.007
[12] Mills D L 1967 *J. Phys. C: Solid State Phys.* **28** 2245
[13] See, for example,
Przybylski M, Korecki J and Gradmann U 1991 *Appl. Phys.* A **52** 33
[14] Tang H, Plihal M and Mills D L 1998 *J. Magn. Magn. Mater.* **187** 23
[15] Muniz R B and Mills D L 2002 *Phys. Rev.* B **66** 17717
[16] Lowde R D and Windsor C G 1970 *Adv. Phys.* **19** 813
[17] Tinkham M 1964 *Group Theory and Quantum Mechanics* (New York: McGraw-Hill) ch 6
[18] Edwards D M and Muniz R B 1985 *J. Phys. F: Met. Phys.* **15** 2339
[19] Cooke J F, Lynn J W and Davis H L 1980 *Phys. Rev.* B **21** 4118
[20] Savrasov S Y 1998 *Phys. Rev. Lett.* **81** 2570
[21] Karlsson K and Aryasetiawan F 2000 *Phys. Rev.* B **62** 3006
Karlsson K and Aryasetiawan F 2000 *J. Phys.: Condens. Matter* **12** 7617
[22] Hong J and Mills D L 1999 *Phys. Rev.* B **61** R858
[23] Perring T G, Boothroyd A T, Paul D M^{c}K, Taylor A D, Osborn R, Newport R L, Blackman J A and Mook H A 1991 *J. Appl. Phys.* **69** 6219
[24] Allan S R 1982 The effects of electron–magnon interaction on the band structure of ferromagnets *PhD Thesis* Imperial College, London