Spin wave damping anisotropy in ferromagnetic EuO

1990 J. Phys.: Condens. Matter 2 6569

(http://iopscience.iop.org/0953-8984/2/31/010)

J. Phys.: Condens. Matter 2 (1990) 6569–6574. Printed in the UK

Spin wave damping anisotropy in ferromagnetic EuO

J M Wesselinowa and J Blagoev
Department of Physics, University of Sofia, 5 Boulevard Anton Ivanov, 1126 Sofia, Bulgaria

Received 22 August 1989

Abstract. A theoretical study of the s–f model is made on the basis of a Green function technique. The spin wave damping is numerically calculated using parameters appropriate to EuO. The temperature and wave vector dependence is in very good agreement with the experimental data.

1. Introduction

In the recent past much research effort has been focused on ferromagnetic 4f systems like Eu chalcogenides EuX (X = 0, S) [1], which are considered as almost ideal model substances for basic problems in the theory of magnetism. They are characterised by strictly localised magnetic moments stemming from the only partially filled 4f shell of the involved rare-earth (RE) ion. In insulators such as EuO and EuS these moments are coupled by a certain type of superexchange. The undoped EuX are therefore thought to be good realisations of the three-dimensional Heisenberg model. Still more spectacular than their purely magnetic properties are their magneto-optical properties. The drastic red shift of the optical absorption edge observed in the ferromagnetic compounds upon cooling below T_C [2] is a very frequently investigated effect in this connection. The physical properties of the magnetic and semiconducting EuX strongly depend on the concentration of free charge carriers, created for instance by doping with suitable impurities (Gd^{3+}) [3–5]. In EuS and EuO, the free carrier concentration exceeds 10^{18} cm^{-3}. This finds a natural interpretation in the existence and temperature dependence of quasiparticles in the conduction band of a ferromagnetic semiconductor EuX.

It is now well established [1] that a good description of ferromagnetic semiconductors, as for instance EuO, EuS, $CdCr_2S_4$ and $CdCr_2Se_4$, is provided by the s–f (or s–d) model. This model consists of a localised spin subsystem and a delocalised electron subsystem. The interaction between the two subsystems is intra-atomic. Unfortunately, exact results for the s–f model are available only for some limiting cases [6–8].

The influence of the s–f (or s–d) interaction I on the magnetic properties has been theoretically studied by many authors. Woolsey and White [3] calculated the electron and acoustic magnon energies in the limit of low temperatures where spin wave theory is valid. Babcenco and Cottam [9] have given a much more detailed description of the magnetic excitation spectrum using a field-theoretical perturbation formalism. They obtained the lifetime of the magnetic excitations but only in the first-order theory and discussed it at $T = 0$. Mauger and Mills [10] have investigated how the exchange

0953-8984/90/316569 + 06 $03.50

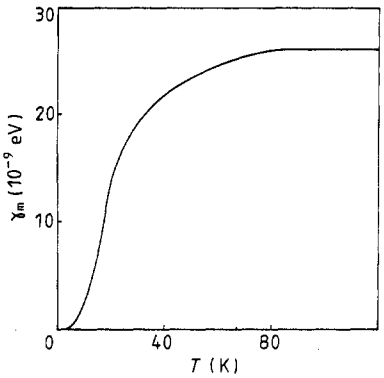

Figure 1. Temperature dependence of the magnon damping $\gamma_m(T)$ for $J_0 = 0.0001$ eV, $I = 0.2$ eV, $W = 2$ eV, $S = \frac{7}{2}$, $H = 0$, $n = 0.05$, $k = 3\pi/10$ in the direction [111].

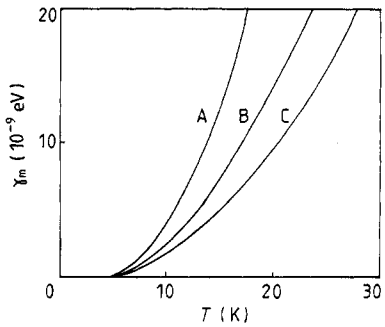

Figure 2. Temperature dependence of the magnon damping $\gamma_m(T)$ for $J_0 = 0.0001$ eV, $I = 0.2$ eV, $S = \frac{7}{2}$, $H = 0$, $n = 0.05$, $k = 3\pi/10$ in the direction [111] and for different band width values: A, $W = 1.5$; B, 2; C, 2.5 eV.

interaction I in ferromagnetic semiconductors modifies the dynamics of the spin excitations when the localised spins are no longer dilute. The time-dependent spin Green functions are calculated up to second-order in I. The damping of the two modes is shown to be small in the low-temperature limit. In the high-temperature limit, the expressions are shown to match the former results of the theory of spin resonance in dilute magnetic alloys.

The calculation and investigation of spin wave damping is a topic of great interest for theorists as well as experimentalists. The spin wave damping in ferromagnetic semiconductors was observed experimentally by Anisimov *et al* [11] in $CdCr_2Se_4$ and $CdCr_2S_4$, and by Gurevich *et al* [12] in EuO. In fact the imaginary parts of the energies corresponding to lifetime broadening effects are usually not considered because of the mathematical difficulties in their calculations. Karmakar *et al* [13] have studied the electronic damping rate $\gamma(\boldsymbol{k} = 0)$ of the s–f model in the paramagnetic phase close to T_C. Wesselinowa [14–16] has extended the theory to higher order and determined for the first time beyond the RPA the corrections to the electron and magnon energies and the damping over the whole temperature region. The theoretical results were applied to $CdCr_2Se_4$. The band occupation dependence of the conduction electron magnetisation of the energy gap and of the electronic damping for $I > 0$ and $I < 0$ was obtained in [15]. The influence of an external magnetic field H on the magnon and electronic damping is discussed in [16] but for wave vector $\boldsymbol{k} = 0$.

The aim of the present paper is to study the wave vector dependence of the magnon damping in the interval from 0 to 2π and for different directions in the system for the ferromagnetic and paramagnetic phases in application to EuO.

2. The Hamiltonian

The Hamiltonian of the system is given by

$$H = H_M + H_E + H_{ME}. \tag{1}$$

H_M is the Heisenberg Hamiltonian for the ferromagnetically ordered f or d electrons:

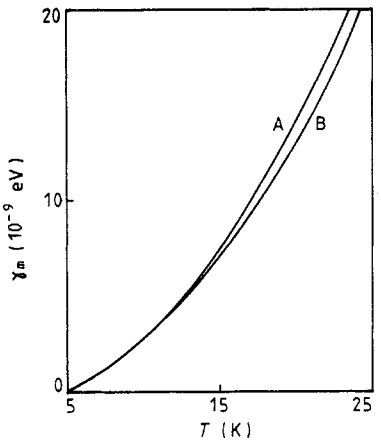

Figure 3. Temperature dependence of the magnon damping $\gamma_m(T)$ for $J_0 = 0.0001$ eV, $I = 0.2$ eV, $W = 2$ eV, $S = \frac{7}{2}$, $H = 0$, $n = 0.05$ and $k = 3\pi/10$ for two different directions: A, [111]; B, [100].

$$H_M = -\tfrac{1}{2}\sum_{i,j} J_{ij} S_i S_j - g\mu_B H \sum_i S_i^z \tag{2}$$

where S_i is the spin operator. The exchange interaction J_{ij} is a function of the lattice constant. H is an external magnetic field applied in the z direction.

H_E represents the usual Hamiltonian of the conduction band electrons

$$H_E = \sum_{q,\sigma} (\varepsilon_{q\sigma} - \mu) a_{q\sigma}^+ a_{q\sigma} \tag{3}$$

where $a_{q\sigma}^+$ and $a_{q\sigma}$ are the Fermi creation and annihilation operators in the state $q\sigma$, μ is the chemical potential, and $\varepsilon_{q\sigma}$ are the Bloch energies

$$\varepsilon_{q\sigma} = \varepsilon_q - \sigma\mu_B H \qquad \sigma = \pm 1.$$

The most important term in (1) is the operator H_{ME} which couples the two subsystems (2) and (3) by an intra-atomic exchange interaction

$$H_{ME} = -\frac{I}{2N}\sum_{q,p} [S_{q-p}^+ a_{p-}^+ a_{q+} + S_{q-p}^- a_{p+}^+ a_{q-} + S_{q-p}^z (a_{p+}^+ a_{q+} - a_{p-}^+ a_{q-})] \tag{4}$$

where I is the constant interaction energy.

3. Magnon damping

To study the magnetic excitation spectrum of the system, we evaluate the Green function corresponding to the excitation of a transverse spin component defined in matrix form as

$$\tilde{G}_k(t) = -\mathrm{i}\theta(t)\langle [B_k(t), B_k^+] \rangle$$

where the operator B_k stands symbolically for the set S_k^+, $\Sigma_p a_{p+k+}^+ a_{p-}$. Using a Green

function method proposed by Tserkovnikov [17] we obtain for the magnon damping $\gamma_m(\boldsymbol{k})$ [16]:

$$\gamma_m(\boldsymbol{k}) = \frac{\pi}{2N^2}\sum_{q,p} V_{kqp}^2[\bar{N}_p(2\langle S^z\rangle + \bar{N}_{k-q} + \bar{N}_{p+q}) - \bar{N}_{k-q}\bar{N}_{p+q}]$$

$$\times \delta(E_{p+q} + E_{k-q} - E_p - E_k) + \left(\frac{\pi I^2}{N^3}\sum_{q,p,r}(\bar{N}_p - \bar{N}_{p+k+q})\right.$$

$$\left.\times \bar{n}_{q+r+}(1-\bar{n}_{r-}) + \frac{\pi I^2}{2\langle S^z\rangle N^3}\sum_{q,p,r}\bar{N}_{p+k+q}(2\langle S^z\rangle + \bar{N}_p)(\bar{n}_{q+r+} - \bar{n}_{r-})\right)$$

$$\times \delta(E_{p+k+q} - E_p + \omega_{q+r+} - \omega_{r-} - E_k)$$

$$+ \left(\frac{\pi I^2}{4N^2}\sum_{q,p}\bar{n}_{p+q+}(1-\bar{n}_{p+}) + \frac{\pi I^2}{8\langle S^z\rangle N^2}\sum_{q,p}\bar{N}_{k-q}(\bar{n}_{p+q+} - \bar{n}_{p+})\right)$$

$$\times \delta(E_{k-q} + \omega_{p+q+} - \omega_{p+} - E_k) + \frac{\pi I^2\langle S^z\rangle}{2N}$$

$$\times \sum_q (\bar{n}_{q-k+} - \bar{n}_{q-})\delta(\omega_{q-k+} - \omega_{q-} - E_k) \tag{5}$$

where

$$V_{kqp} = (J_q + J_{k-q-p}) - (J_{k-q} + J_{p+q})$$

$$\bar{N}_q \equiv \langle S_q^+ S_q^-\rangle = (\langle S^z\rangle/2)[(\varepsilon_q^{11}/E_q)\coth(E_q/2k_BT) - 1] \tag{6}$$

$$\bar{n}_{q\sigma} \equiv \langle a_{q\sigma}^+ a_{q\sigma}\rangle = 1/(\exp(\omega_{q\sigma}/k_BT) + 1). \tag{7}$$

The expressions $E_q = E_1(\boldsymbol{q})$ and $\omega_{q\sigma}$ are the spin-wave energy and the electron energy in the generalised Hartree–Fock approximation, respectively

$$E_{1/2}(\boldsymbol{k}) = 0.5(\varepsilon_{11} + \varepsilon_{22} \pm \sqrt{(\varepsilon_{11} - \varepsilon_{22})^2 + 4\varepsilon_{12}\varepsilon_{21}}) \tag{8}$$

with

$$\varepsilon_{11} = g\mu_B H + \langle S^z\rangle(J_0 - J_k) + I\rho \qquad \varepsilon_{22} = 2\mu_B H + I\langle S^z\rangle$$

$$\varepsilon_{12} = -I\langle S^z\rangle \qquad \varepsilon_{21} = -I\rho$$

and

$$\omega_\sigma(\boldsymbol{k}) = \varepsilon_k - \mu - \sigma(\mu_B H + 0.5I\langle S^z\rangle) \qquad \sigma = \pm 1 \tag{9}$$

where ε_k is the conduction band energy in the paramagnetic state. For a face-centred cubic lattice ε_k is equal to

$$\varepsilon_k = -(W/3)(\cos(ak_x/2)\cos(ak_y/2) + \cos(ak_y/2)\cos(ak_z/2)$$

$$+ \cos(ak_z/2)\cos(ak_x/2))$$

where W is the conduction band width. The band occupation n is given by $n = \bar{n}_+ + \bar{n}_-$. Equation (9) together with (7), (8), (10) and (11) build a closed, non-linear set of equations for the determination of the chemical potential μ.

$\langle S^z \rangle$ and ρ are the relative localised-spin magnetisation and the conduction-electron magnetisation, respectively:

$$\langle S^z \rangle = \frac{1}{N} \sum_k \{(S+0.5) \coth[(S+0.5)\beta E_k] - 0.5 \coth(0.5\beta E_k)\} \tag{10}$$

$$\rho = (\bar{n}_+ - \bar{n}_-)/2N = (1/2N) \sum_{q,\sigma} \sigma \langle a^+_{q\sigma} a_{q\sigma} \rangle. \tag{11}$$

$\langle S^z \rangle$ and ρ were self-consistently calculated in [14] for different W and T values. With increasing W, $\langle S^z \rangle$ and the Curie temperature T_C decrease, but very slightly. If W is constant and I increases, then T_C increases too, due to the indirect coupling of the localised spins via the conduction electrons.

The conduction electron magnetisation ρ shows different behaviour in the cases when $W \lessgtr 0.5IS$. For $W < 0.5IS$, ρ reaches the highest value at $T = 0$ ($\rho = 0.5$) and then decreases with $T \to T_C$. At $T = T_C$, ρ is zero. If $W = 0.5IS$ then ρ shows the same behaviour as for $W < 0.5IS$, only the curve is not so steep and starts at $\rho = 0.25$ for $T = 0$. For $W > 0.5IS$, ρ is zero at $T = 0$, then increases with increasing temperature, and at $T = T_C$ is zero, again.

Babcenco and Cottam [9] and Nolting and Oles [5] obtained only the last term in $\gamma_m(\boldsymbol{k})$ (5), which corresponds to the lowest-order approximation, which is equivalent to the generalised mean-field theory or to the first-order of a $1/Z$ expansion (where Z is the number of nearest neighbours). However, as it turns out in our calculations, the scattering terms give more important contributions to the damping than the decay terms, i.e. the contribution to the damping of order $1/Z^2$ is larger than that of order $1/Z$.

4. Numerical calculations

The magnon damping $\gamma_m(\boldsymbol{k})$ was numerically calculated using parameters for EuO [1] ($J_0 = 0.0001$ eV, $I = 0.2$ eV, $W = 2$ eV, S = $\frac{7}{2}$, $T_C = 69.33$ K) for $H = 0$, $n = 0.05$ for different temperature T, band width W and wave vector $\boldsymbol{k}$ values in the interval from 0 to 2π and for different directions in the system: [111], [110] and [100]. The band filling increases the Curie temperature T_C which is in agreement with the results of Nolting and Nolting [18]. In our case for $n = 0.05$, we obtain $T_C = 80$ K.

At low temperatures the damping is extremely small, approaching T_C, γ_m increases very strongly (figure 1). The magnon damping above T_C arises from the s–f (or s–d) interaction. For $I = 0$, $\gamma_m(\boldsymbol{k})$ is zero, too. In the disordered phase $\langle S^z \rangle$ and ρ vanish. As a consequence of this, the expression for the damping $\gamma_m(\boldsymbol{k})$ is simpler than for the ordered phase. The magnon damping above T_C is nearly temperature-independent, it increases very slowly (figure 1).

Figure 2 shows the band width dependence of γ_m. The damping is maximum for $W = 0$. With increasing W, γ_m decreases.

The magnon damping increases with wave vector $\boldsymbol{k}$ and is maximum for the direction [111] (figure 3), which is in very good agreement with the experimental data for EuO of Gurevich *et al* [12]. For small $\boldsymbol{k}$ ($\boldsymbol{k} \simeq 0$) the spin wave damping anisotropy is rather small. The anisotropy is due to intrinsic and not to extrinsic relaxation processes (scattering on inhomogeneities, ionic processes, etc), the contribution of which can be made negligible.

References

[1] Nolting W 1979 *Phys. Status Solidi* b **96** 11
[2] Busch G and Wachter P 1966 *Phys. Kondens. Mater.* **5** 232
[3] Woolsey R B and White R M 1970 *Phys. Rev.* B **1** 4474
[4] Schoenes J and Wachter P 1974 *Phys. Rev.* B **9** 3097
[5] Nolting W and Oles A M 1981 *Z. Phys.* B **43** 37
[6] Izyumov Y A and Medvedev M V 1971 *Zh. Eksp. Teor. Fiz.* **32** 302
[7] Nolting W 1979 *J. Phys. C: Solid State Phys.* **12** 3033
[8] Nolting W, Dubil U and Matlak M 1985 *J. Phys. C: Solid State Phys.* **18** 3687
[9] Babcenco A and Cottam M G 1981 *J. Phys. C: Solid State Phys.* **14** 5347
[10] Mauger A and Mills D L 1984 *Phys. Rev.* B **29** 3815
[11] Anisimov A N, Shukyurov A S, Gurevich A G and Emiryan L M 1983 *Zh. Eksp. Teor. Fiz.* **84** 1407
[12] Gurevich A G, Anisimov A N, Samokhvalov A A and Solin N I 1985 *Acta Phys. Pol.* A **68** 467
[13] Karmakar S N, Roy G K and Chaudhuri P 1986 *Phys. Lett.* **114A** 145
[14] Wesselinowa J M 1984 *J. Phys. C: Solid State Phys.* **17** 3737
[15] Wesselinowa J M 1988 *Phys. Status Solidi* b **146** K55
[16] Wesselinowa J M 1987 *J. Phys. C: Solid State Phys.* **20** 4639
[17] Tserkovnikov Yu A 1971 *Teor. Mat. Fiz.* **7** 250
[18] Nolting V and Nolting W 1988 *Phys. Status Solidi* b **149** 313