ELECTRON-MAGNON SCATTERING AND POLARIZATION OF THE SCATTERED BEAM

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We discuss use of electron-magnon scattering as a probe of the magnon spectrum and as a means of producing polarized electron beams.

Recently Boersch, Geiger, and Stickel[1] have demonstrated the feasibility of measuring small energy losses (~0.006 eV) for electrons of energies up to 60 keV. (For additional material, see Kuyatt and Simpson.[2]) Consequently, the contribution of low-energy inelastic processes, such as electron-phonon[1] and electron-magnon scattering, to the scattered beam is now experimentally accessible. The purpose of this Letter is to report the results of the electron-magnon inelastic coherent scattering cross section and to examine the possibility of using this scattering process as a probe of the magnon spectrum and as a means for producing polarized electron beams.

Unlike neutron-magnon scattering, where the only contribution to the interaction Hamiltonian comes from the dipole-dipole interaction,[3] the most important mechanism for electron-magnon scattering at moderate energies arises from the exchange interaction. The ratio of the dipole-dipole to the exchange differential scattering cross section can be shown to be of order $(E_e/m_e c^2)$,[2] where E_e is the incoming electron energy, m_e is its mass, and c is the velocity of light.

The exchange scattering for a general magnetic (antiferromagnetic, ferrimagnetic, or ferromagnetic) system depends in a nontrivial way on the number, distribution, and magnitude of the spins in a unit cell. We are currently completing a detailed calculation of the electron-magnon cross section, including all these factors. However, for a ferromagnet with one spin per unit cell, one finds the simple result that the differential scattering cross section for one-magnon processes arising from the local exchange potential in the Born approximation is[4]

$$\left(\frac{d\sigma}{d\Omega}\right)^{(\pm)}_{\text{exch}} = \left(\frac{NS}{2}\right)\left(\frac{m_e}{2\pi\hbar^2}\right)^2 \frac{k_e'}{k_e} |G(K)|^2 \exp[-2W(\vec{K})]\,|\langle f_e|S_e^{(\pm)}|i_e\rangle|^2] \frac{\sigma_M(T)}{\exp(\hbar\Omega_{\vec{K}}/k_B T)-1} A^{(\pm)}, \tag{1}$$

where

$$A^{(+)} = \exp(\hbar\Omega_{\vec{K}}/k_B T),$$

$$A^{(-)} = 1,$$

and

$$G(K) = \left(\frac{31\pi}{180}\right)\left(\frac{Z_{\text{eff}} e^2}{k_e^{\,2}}\right)(1 - K^2/4\alpha^2). \tag{2}$$

Here S is the magnitude of the spin of each of the N host atoms; $S_e^{\pm}$ is the raising and lowering operator for the incident electron spin; $\vec{K} = \vec{k}_e' - \vec{k}_e$, where $\vec{k}_e'$ and $\vec{k}_e$ are the wave vector for the scattered and incident electron, respectively; $\exp[-2W(\vec{K})]$ is the familiar Debye-Waller factor; $|i_e\rangle$ and $|f_e\rangle$ are the initial and final spin states of the incoming electron; $\Omega_{\vec{K}}$ is the angular frequency associated with a magnon of wave vector $\vec{K}$; k_B is the Boltzmann constant; T is the temperature of the crystal; $\sigma_M(T)$ is the magnetization[5] relative to its value at $T = 0$, which vanishes for $T \geq T_c$ where T_c is the Curie temperature; $Z_{\text{eff}} e$ is the electronic charge of the electrons contributing to the net magnetic moment of the scattering atom; and α^{-1} is the mean radius of the orbits of the interacting host electrons (~0.3 Å). The upper sign in Eq. (1) refers to magnon-creation processes while the lower sign refers to magnon-destruction processes. In Eqs. (1) and (2), $G(\vec{K})$ is the Fourier transform of the exchange potential $G(\vec{r})$, which is derived starting from Thompson's form of the exchange potential.[4] The assumptions for representing the exchange by local potentials are fully discussed by Thompson and Wolfram.[4] Equation (2) is valid only for small-angle scattering, and $k_e \gg \alpha \gg K$.

Presently, $G(\vec{K})$ is being calculated numerically for arbitrary values of α, $\vec{k}_e$, and $\vec{K}$.

Since the differential scattering cross section for more general magnetic systems has a form similar to Eq. (1), the following remarks are formulated to include cases with more than one atom per unit cell. The familiar electron-electron scattering need not be considered since this scattering leads to characteristic energy losses much larger than magnon energies.[6] Under these conditions the only other scattering mechanism in this energy region is that from phonon scattering. The scattering cross section for electron-phonon scattering processes has been calculated elsewhere[7,8] and, unlike the electron-magnon cross section, is found to vanish in the forward direction ($\vec{K} \to 0$). Therefore, even in cases where the excited optical phonons and magnons have the same energy, the phonon contribution can be made negligible by restricting the observations to sufficiently small scattering angles. Also, the drastically different energy and temperature dependence of these two differential cross sections should make it possible to isolate the two effects even for scattering angles where their magnitudes are comparable.

An inspection of Eq. (1) reveals that for ferromagnetic systems the magnon creation and annihilation processes give rise to polarized scattered electrons. The polarized electron current is given by

$$I_p^{(\pm)} = (d\sigma/d\Omega)_{\text{exch}}{}^{(\pm)} I_{\text{eff}} \Delta\Omega, \qquad (3)$$

where I_{eff} is the effective incident electron current, corrected for all losses resulting from experimental configurations.[2] The scattering angle θ_s is chosen to correspond to magnon energies near the zone boundary since they are more easily measured. For $E \cong 10^3$ eV this θ_s will typically be ~0.07 rad. Using conservative values of $I_{\text{eff}} \simeq 10^{-8}$ A/cm^2, $\Delta\Omega \simeq 4 \times 10^{-3}$ rad^2, $E \simeq 10^3$ eV, and $Z_{\text{eff}} \simeq 5$, we obtained $I_p^{(+)} \cong 10^{-9}$ A per cm^3 of sample. For a typical thin-film sample of 1-cm^2 area and 1000-Å thickness, $I_p^{(+)} \simeq 10^{-14}$ A. Since $(d\sigma/d\Omega)_{\text{exch}}{}^{(\pm)} \sim E_e^{-2}$, larger polarized currents should be attainable at lower energies where, if necessary, experiments could be carried out in the reflection mode. Other techniques of polarizing electrons[9] yield, at best, polarized currents of 10^{-9} A. One possible advantage of the magnon polarization technique, even at relatively low currents, is that the degree of polarization can be nearly 100%, in contrast to what is found for other techniques.

This calculation also suggests that the electron-magnon scattering can be used as a probe for measuring dispersion curves of magnons. Some advantages over the neutron technique are as follows: (a) It provides a means for investigating systems not accessible by neutron scattering (e.g., materials with large neutron capture cross sections), (b) crystals of smaller dimensions can be used since the cross section resulting from the exchange potential is much larger than dipole-dipole cross-sections, and (c) the electron technique should be more easily applicable since it does not require high-flux reactors.

For a ferromagnetic system, as is displayed in Eq. (1), the exchange differential scattering cross section is proportional to the magnetization of the crystal. Therefore, in view of the disagreement found in some metals between the host exchange as determined from neutron scattering and that from macroscopic magnetization measurements,[10] it would be interesting to measure this exchange via the temperature dependence of the electron-magnon differential scattering cross section. Furthermore, it would be interesting to measure the predicted energy dependence of the effective exchange interaction between the incident electron and host electrons in Eq. (1) because of its importance in the formulation of the many-body problem.[4]

Yttrium iron garnet should be a good ferrimagnet for study since there are several optical magnon branches[11] in the energy region of 0.05 eV.

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scattering from magnetic materials which is being prepared for publication. The starting point for this calculation is an effective one-electron Hamiltonian deduced from the basic Hartree-Fock equations derived by E. D. Thompson, Ann. Phys. 22, 309 (1963), and T. Wolfram and J. Callaway, Phys. Rev. 127, 1605 (1962).

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DIRECT MEASUREMENT OF THE ELECTRON VELOCITY AND MEAN FREE PATH IN GALLIUM

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The Fermi velocity has been measured by a heat-pulse time-of-flight technique near the *a* axis in gallium. Also, the electron mean free path has been measured in several gallium samples between ~1.8 and 4.0°K.

Previously reported work on the propagation of heat pulses in insulating materials[1,2] has shown that the dynamics of the heat-flow process can be investigated in more detail than is possible with conventional thermal conductivity techniques. For example, it was shown that in some insulators at low enough temperatures, phonon scattering events are sufficiently infrequent that the ultimate velocities of the carriers of the thermal energy (i.e., the energy velocities of the phonons) can be determined by a measurement of the arrival times of the heat pulses.

In most normal metals, the heat flux is carried predominantly by the electrons. Heat-pulse measurements on metals should thus give information on electron scattering processes, and, in cases where the electron mean free path is particularly long (that is, for very pure metal single crystals at very low temperatures), it should be possible to measure directly the Fermi velocity of the electrons by a determination of the transit time of the heat pulse.

We have measured the electron mean free path (mfp) and the electron thermal transport velocity as a function of temperature between ~1.8 and 4.0°K in single-crystal gallium samples near two principal axes. The heat-pulse measurements were made by heating the electrons at one face of the gallium sample by the absorption of optical radiation from a pulsed laser and then detecting the arrival of the thermal energy at the opposite face with a thin-film superconducting bolometer. The shapes and arrival times of the detected heat pulses give information on the mfp's and velocities of the thermal carriers (i.e., electrons). For reasons to be described below, it is believed that at the lowest temperatures the arrival time gives a direct measure of the Fermi velocity for at least a certain group of electrons.

The two gallium samples were grown in Lucite molds from 99.9999% pure starting materials. Heat-pulse data were taken for sample I along a direction located ~20° from the *c* axis, ~104° from the *a* axis, and 76° from the *b* axis. For samples IIa and IIb, this direction was ~18° from the *a* axis and in the *ab* plane. An angular spread of about 20° was also present due to the finite sizes of the source and detector. Sample IIb was the same as sample IIa except that the heater-to-detector distance was reduced by 50% by carefully milling a $\frac{1}{4}$-in. hole into the sample. The laser light was then directed into this hole.

The laser used was a chloroaluminum phthalocyanine (CAP) cell side-pumped with a giant-pulse ruby laser.[3] The rise time of this CAP laser was measured to be ~3 nsec with a decay time of ~20 nsec. The heat-pulse detector was an evaporated thin-film bolometer of In-Sn alloy, ~2000 Å thick, similar in geometry to those previously described.[4] A 3000-Å-thick layer of evaporated Pyrex insulated the detec-