gions with enhanced transition temperature are of sufficiently limited extent that their superconductivity can be quenched by the measuring currents. The critical field and critical currents were dramatically increased by the surface working, H_0 being increased 60 % beyond the value obtained in the unworked surfaces.

We have therefore shown both theoretically and experimentally that under conditions of a negative extrapolation length at a sample surface an enhancement of surface superconductivity to higher critical fields will take place.

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EFFECTS OF THE ELECTRON-MAGNON INELASTIC SCATTERING ON THE POLARIZATION OF PHOTOEMITTED ELECTRONS

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Polarization effects due to inelastic scattering from magnons is shown to alter significantly the original polarization of photoemitted electrons from the conduction bands of Gd.

The polarization of photoelectrons and field-emitted electrons from ferromagnets has been the topic of a number of papers. For a review of the field and references, see the article by Farago.[1] Recently two experiments successfully measured the polarization of field- and photoemitted electrons from a ferromagnet. The first experiment, reported by Hoffmann *et al.*,[2] measured the degree of polarization of field-emitted electrons from polycrystalline gadolinium. The polarization was found to be antiparallel to the direction of the magnetization and had a magnitude of about $(8 \pm 1.5)\%$. The second experiment, reported by Busch *et al.*,[3] measured the degree of polarization of photoelectrons from gadolinium. The polarization was also found to be antiparallel to the magnetization and had a magnitude of $(5.27 \pm 0.70)\%$. Müller, Siegmann, and Obermair,[4] using a parabolic-band model for Gd, predicted theoretically the polarization for field-emitted electrons to be 6% antiparallel to the magnetization, in qualitative agreement with Hoffmann's observation.

It has been suggested that the polarization of these emitted electrons can be correlated directly with the polarization of the electrons in the conduction band.[2-4] These attempts at direct correlation have neglected the polarization effects of inelastic magnetic scattering and of spin-dependent transmission at the interface of the crystal. In this paper we show that the polarization effects due to inelastic scattering from magnons can significantly alter the original polarization of photoemitted electrons from the conduction bands of Gd. In what follows we consider specifically the process of photoemission, although it is expected that similar considerations need to be made for field emission. Our aim in this paper is not to reinvestigate in detail the theories of photoemission for the purpose of accurately calculating the polarization of the emitted electrons, but rather to consider what corrections to the present simple theories are likely to be required by a more complete theory.

Photoemission from solids is described by a three-step process. Electrons are first optically excited into energy states above the crystal potential barrier, then they move to the surface of the solid, with or without scattering, and finally they are transmitted over the surface barrier.

Following Spicer[5] we write an expression for the photoemission current,

$$i^{\pm}(h\nu)=\int_{\varphi}^{h\nu}\int_0^{\infty}\alpha^{\pm}(E,h\nu)I(x,h\nu)\times P_{\mathrm{esc}}^{\pm}(x,E)dxdE, \qquad (1)$$

where $i^{\pm}(h\nu)$ is the photoemission current. The plus or minus signs refer to spin-up or spin-down electrons, respectively. The plus sign is taken parallel to the spin axis, i.e., antiparallel to the direction of magnetization of the crystal. $\alpha^{\pm}(E,h\nu)$ is the optical absorption coefficient for electrons excited to energy E per unit length per unit electron energy range dE, $I(x,h\nu)$ is the intensity of the light beam at a depth x from the surface, and $P_{\mathrm{esc}}^{\pm}(x,E)$ is the escape probability for the excited electrons of energy E, φ is the threshold energy, and $h\nu$ the photon energy. $P_{\mathrm{esc}}(x,E)$ as used here includes both transport effects from the excitation point to the surface and the probability of overcoming the surface potential barrier. In the work of Busch et al., $P_{\mathrm{esc}}^{\pm}(x,E)$ was assumed to be independent of the spin state of the electron. Two interactions in which the polarization of a conduction electron can be changed in an emission process from a ferromagnet are the inelastic electron-magnon scattering and transmission through a spin-dependent surface-barrier potential (which is a combination of the spin-independent Coulomb potential and spin-dependent exchange potential). If one is interested in total current rather than the degree of polarization, the electron-magnon scattering mechanism, because of the small amount of energy loss, can be considered as a quasielastic mechanism that increases the path length of the scattered electron resulting in a reduced escape probability.

First we consider the more important of the two interactions, the inelastic electron-magnon scattering. If the degree of polarization is to be correlated directly with the electronic density of states in the conduction band, then it is necessary that no spin-flip scattering events have occurred. A simple argument can be given to show that this will not be the case at low energies by considering the properties of the electron-magnon scattering cross section.[6] For simplicity we imagine the crystal at $T=0$ and consider first a spin-up photoexcited electron moving towards the surface. In a first approximation we can represent the physical situation by adding an extra electron to the system (in reality, however, the dynamics are expected to be more complicated, especially in a metal where a Heisenberg picture of the ferromagnetic state is known to be inadequate). Since at $T=0$ there are no equilibrium spin-wave excitations we expect the electrons polarized parallel to the ferromagnetic spin axis to be unscattered. This is due to the fact that electrons polarized parallel to the spin axis can only destroy magnons in a spin-flip process. On the other hand, an electron polarized antiparallel to the spin axis can create a magnon by reversing its spin direction. For $T\neq 0$ both creation and annihilation processes can take place, giving rise to a temperature dependence of the degree of polarization.

We assume a functional form for $P_{\mathrm{esc}}^{\pm}(x,E)$ which has been found to be applicable in photoemission:

$$P_{\mathrm{esc}}^{\pm}(x,E)=G^{\pm}(E)e^{-(\mu_{\mathrm{e-e}}+\mu_{\mathrm{e-m}}^{\pm})x}, \qquad (2)$$

where $G^{\pm}(E)$ is the surface-barrier transmission probability, $\mu_{\mathrm{e-e}}$ and $\mu_{\mathrm{e-m}}^{\pm}$ are the reciprocals of the electron-electron and electron-magnon inelastic mean free paths which are assumed to be constants (over the small electron energy range considered). The plus-or-minus sign associated with the reciprocal of the electron-magnon mean free path and the transmission coefficient denotes the magnitudes of these quantities for electrons polarized parallel or antiparallel to the spin axis, respectively. In order to establish a lower bound of the effect of the electron-magnon scattering in Eq. (2) we have not allowed the scattered electrons whose spin direction has been changed to contribute to the emerging beam. Inserting Eq. (2) into Eq. (1) we have

$$i^{\pm}(h\nu)=\int_0^{\infty}I(x,h\nu)e^{-(\mu_{\mathrm{e-e}}+\mu_{\mathrm{e-m}}^{\pm})x}dx \times\int_{\varphi}^{h\nu}\alpha^{\pm}(E,h\nu)G^{\pm}(E)dE. \qquad (3)$$

Taking

$$I(x,h\nu)=I(0)e^{-\alpha_T(h\nu)x}, \qquad (4)$$

where $\alpha_T(h\nu)$ is the total optical absorption coefficient, we obtain, after inserting Eq. (4) into Eq. (3) and integrating over x, an expression for the photoemission yield,[5]

$$Y^{\pm}(h\nu)=\frac{\alpha_{\mathrm{av}}^{\pm}(h\nu)}{\alpha_T(h\nu)+\mu_{\mathrm{e-e}}+\mu_{\mathrm{e-m}}^{\pm}}, \qquad (5)$$

where

$$\alpha_{av}^{\pm}(h\nu)=\int_{\varphi}^{h\nu}\alpha^{\pm}(E,h\nu)G^{\pm}(E)dE. \tag{6}$$

The polarization is defined as

$$P=\frac{Y^+(h\nu)-Y^-(h\nu)}{Y^+(h\nu)+Y^-(h\nu)}. \tag{7}$$

We find after inserting Eq. (5) into Eq. (7) that

$$P=\left[P_0+P_0^-\frac{\mu_{e-m}^- -\mu_{e-m}^+}{\mu_{e-m}^- +\mu_{e-e}+\alpha_T(h\nu)}\right]\times\left[1-P_0^-\frac{\mu_{e-m}^- -\mu_{e-m}^+}{\mu_{e-m}^- +\mu_{e-e}+\alpha_T(h\nu)}\right]^{-1}, \tag{8}$$

where

$$P_0=\frac{\alpha_{av}^+(h\nu)-\alpha_{av}^-(h\nu)}{\alpha_{av}^+(h\nu)+\alpha_{av}^-(h\nu)} \tag{9}$$

and

$$P_0^-=\frac{\alpha_{av}^-(h\nu)}{\alpha_{av}^+(h\nu)+\alpha_{av}^-(h\nu)}. \tag{10}$$

In the above equations P_0 is the polarization that would be observed in the absence of electron-magnon scattering. Using a one-dimensional potential barrier[7] it can be shown that $G^+(E)$ and $G^-(E)$ can for all practical purpose be considered to be equal. This arises because the transmission coefficient for electron energies above the barrier is practically equal to unity.[7] Consequently P_0 will be essentially the polarization of the electrons in the conduction band.

It now remains to estimate $\mu_{e-m}^{\pm}$ and compare its value with μ_{e-e} and α_T which are known approximately for Gd.[8] The following estimate is not expected to be quantitatively correct for Gd, since a Heisenberg model is used to represent an itinerant system. The purpose of the calculation is simply to illustrate the fact that this polarization mechanism cannot a priori be neglected. For simplicity in what follows we restrict the calculation to $T=0$. For this case it follows from our earlier discussion that $\mu_{e-m}^+=0$ since there are no magnons present with which the electrons polarized parallel to the spin axis can couple. On the other hand, $\mu_{e-m}^-\neq 0$ since an antiparallel polarized electron can create a spin excitation at $T=0$. We write

$$\mu_{e-m}^-=N\int\frac{d\sigma^-}{d\Omega}d\vec{K}, \tag{11}$$

where $d\sigma^-/d\Omega$ is the inelastic differential scattering cross section for the excitation of a spin wave and $\vec{K}$ is the transferred wave vector. This differential cross section has been derived and discussed in an earlier paper.[6] At low electron energies and $T=0$

$$\mu_{e-m}^-\cong 4\pi\left(\frac{NS}{2}\right)\left(\frac{m}{2\pi\hbar^2}\right)^2\left[2J_{sf}v_a\right]^2, \tag{12}$$

where m is the mass of the electron, N is the atomic density, S is the atomic spin, J_{sf} is the exchange energy for the conduction electrons in Gd, and v_a is the atomic volume.

Substituting the values appropriate for Gd (using $N=3.0\times10^{22}$ cm^{-3}, $S=\frac{7}{2}$, $J_{sf}=0.085$ eV, and $v_a=3.3\times10^{-23}$ cm^3)[8-10] into Eq. (12) we find $\mu_{e-m}^-\cong(100\text{ Å})^{-1}$. Using this result and the order of magnitude estimates[8] $\alpha_T\cong\mu_{e-e}\cong(100\text{ Å})^{-1}$ in Eq. (8), we find

$$P_{Gd}\cong\frac{P_0+\frac{1}{3}P_0^-}{1-\frac{1}{3}P_0^-}, \tag{13}$$

or

$$P_0=\frac{P_{Gd}-\frac{1}{5}}{1-\frac{1}{5}P_{Gd}}. \tag{14}$$

If the electrons in the conduction band were essentially unpolarized, $P_0\cong0$ and $P_0^-\cong\frac{1}{2}$, and $P_{Gd}\cong0.2$ or 20%. On the other hand, using the polarization of $P_{Gd}\sim0.05$ measured by Busch et al., we estimate from our model the conduction-band polarization to be $P_0\sim-15\%$. One must remember that this large polarization estimate is valid only at the low energies (a few electron volts) and low temperatures that were used in these experiments. The polarization will decrease rapidly with increasing electron energy.

The above calculation clearly demonstrates that the degree of polarization deduced from the electronic energy bands is not conserved because of the strong electron-magnon scattering at low energies. In fact, the above estimate suggests that the polarization in the conduction band is negative which, in fact, was the theoretical prediction reached by Busch et al.[3] based on the density of states given by Blodgett, Spicer, and Yu[9] for the conduction electrons in Gd. However, the measurements by Busch et al. reveal a positive polarization of the photoemitted electrons. Both of these results are in qualitative agreement with our predictions if one assumes that the polarization obtained from the electron-magnon scattering dominates the negative polarization of the energy bands of Gd.

Finally, we would like to suggest a way in which the conduction-electron polarization can be measured directly. For electrons excited to high-energy states above threshold, the electron-magnon cross section is negligible (varying as $1/E^2$). Therefore, the conduction-band polarization could be measured directly by polarization measurements of high-energy photoelectrons. Experimental techniques are available for the very accurate measurement of photoelectron energies[11] thus making it possible to probe directly the polarization of electrons at various levels in the conduction band. In principle, by measuring the polarization as a function of the energy of the photoelectrons at low temperatures, it should be possible to deduce the value of $\mu_{e\text{-}m}^{-}$ as a function of energy. We would like to thank R. C. Eden for helpful discussions.

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DIRECT DETECTION OF NUCLEAR ACOUSTIC RESONANCE OF A MAGNETIC NUCLEUS IN AN ANTIFERROMAGNET: Mn^{55} in $RbMnF_3$†

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An intense, frequency-dependent absorption of ultrasound in antiferromagnetic $RbMnF_3$ has been observed and attributed to resonant phonon coupling to the Mn^{55} magnetic nuclei. The angular dependence at 4.3 K and the temperature dependence between 4.3 and 38 K of the absorption are reported.

In this paper we report an extraordinarily intense frequency-dependent absorption of ultrasonic energy in antiferromagnetic $RbMnF_3$, which we have identified as due to resonant acoustic coupling to the Mn^{55} nucleus. The resonant absorption (>40 dB/cm for certain magnetic field configurations) was accompanied by a dispersion (shift in the acoustic phase velocity) of greater than 0.1%. The techniques of nuclear acoustic resonance (NAR) were extended to the 600-MHz region and used to observe directly the dependence of the Mn^{55} absorption on frequency and on the direction of an external magnetic field in the temperature range 4.3 to 38 K. The present NAR technique provides a method of studying directly the nuclear spin-lattice interaction mechanisms in antiferromagnets.

Anomalies in the attenuation of 50- to 190-MHz ultrasound in antiferromagnetic MnTe as a function of temperature near the Néel temperature had previously been studied by Walther.[1] The results of the present work support Walther's tentative proposal that the attenuation anomalies observed by him were due to coupling of ultrasound to the Mn^{55} nucleus. There have been no other reports to our knowledge of coupling of ultrasound to magnetic nuclei in antiferromagnets or ferromagnets.

In the present work, the coupling of energy to the Mn^{55} nuclear spin system from longitudinal waves propagating along the [100] crystal axis was measured as a function of direction of applied field, frequency, and temperature. The specimen of $RbMnF_3$ was that used by Melcher et al.[2-4] in their studies of F^{19} NAR at lower frequencies. Measurements were made with a uhf transmission cw spectrometer, with broad-band thin-film CdS piezoelectric transducers evaporat-