Certain properties of diffusion-magnetized metals

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It is shown that the polarization of the conduction electrons (CE) of a diamagnetic metal in contact with a ferromagnet leads to a number of interesting effects that can be observed by various methods.

The contact between a metallic film and a conducting ferromagnet in a strong magnetic field causes diffusion of the polarized conduction electrons (CE) of the ferromagnet into the metal, as well as diffusion of the partly depolarized CE from the metal into the ferromagnet. Strong polarization in the metal becomes noticeable at a depth on the order of the CE mean free path L without a change in the spin direction, which amounts to many thousands of atomic distances for certain metals at sufficiently low temperature. Denoting by p_0 the degree of polarization of the CE at the boundary of the ferromagnet, we obtain

$$p = p_0 \exp(-x/L), \qquad (1)$$

where p is the degree of polarization of the CE in the metal at a distance x from the boundary with the ferromagnet.

A magnetic moment of like magnitude can be obtained by a metal only in an ultrastrong magnetic field H_0, the value of which depends on p

$$H_0 \approx \frac{p}{1-p}\,\frac{k\Theta}{\mu}, \qquad (2)$$

where μ is the magnetic moment of the electron, k is the Boltzmann constant, and Θ is the degeneracy temperature. An estimate shows that $H_0 \approx 10^8 - 10^9$ Oe. However, an external magnetic field can produce a moment directed along the field, whereas the direction of the moment induced by the ferromagnet[1] is determined by the polarization of the CE in the ferromagnet.

Let us examine certain properties of a diffusion-magnetized metal.

1. The polarization of the CE in a diamagnetic metal causes a weakening of the virtual magnetic fields H_i produced by the magnetic moment of the CE. It is known that

$$H_i \approx \frac{\mu}{r^3} + \frac{\mu_i}{r_j^3},$$

where r and r_j are the distances between the CE and accordingly between the nuclei of the atoms, and μ_j is the magnetic moment of the nucleus. The decrease of H_i is determined by the value of p and depends as $p \to 1$ only on the fields produced by the nuclei. Therefore at $\mu_j = 0$ and $p = 1$ the decrease of H_i can amount to several orders of magnitude. This, however, can be hindered by the microscopic and macroscopic inhomogeneities of the fields at the boundary of the metals. If L is large, however, and $L \approx x$, then their role will be small.

The decrease of H_i seems to afford a unique opportunity of assessing the scattering of conduction electrons by H_i and the contribution of this scattering to the electric conductivity of metals. It is difficult as yet to estimate this effect, but we know that in metals the spin-spin and spin-lattice relaxation times are equal, and a decrease of H_i weakens the coupling between the spins and the lattice; this is frequently accompanied (for example, when the temperature is lowered) by a decrease in the translational coupling between the CE and the lattice. We note that it would be of interest to perform experiments of this kind with TTF-TCNQ films, since in this substance the dependence of the electron paramagnetic resonance (EPR) width is similar to the temperature dependence of the electric conductivity,[2] and the narrowing of the EPR curve would make it possible to separate the magnon component of the resistance.

It is quite probable that the inhomogeneities of the magnetic field at the metal boundaries will affect the electric conductivity of the metal less than the EPR spectrum. We note also that a lengthening of the spin-lattice relaxation time of the CE as a result of a lowering of H_i leads to an increase of L. This nonlinear effect can make the relation (1) more complicated.

2. An increase should be observed in the EPR signal. The maximum increase can be determined from the ratio a of the energy $2pn\mu H$, where n is the CE density, to the Pauli paramagnetic energy of the CE in the field H

$$a \approx 4pn\mu H(\chi H)^{-1} .$$

where

$$\chi \approx 3n\mu^2(2k\Theta)^{-1}.$$

An estimate of a shows that even when x exceeds L by one order of magnitude we have $a \gtrsim 1$. On the other hand, if the metal thickness is equal to or less than L, we have naturally $a \gg 1$. We note that if the skin-layer thickness exceeds x, then processes due to the interaction of the high-frequency field with the ferromagnet can become superimposed on the EPR spectrum of the metal.

3. The change of the g factor of the EPR line is determined by the magnetic flux due to the polarization of the CE in the metal. At saturation (partial or complete) of the CE of the metal, the resonance curves will shift in a direction such that the absolute value of Δg decreases. Pulsed saturation of the EPR seems to be a good method of measuring the time of establishment of the CE polarization in a metal.

4. In blocks consisting of many interleaved metal and ferromagnet layers, strong effects of acoustic paramagnetic resonance are possible. The estimate of the signal in the metal is of the order of that calculated in (2). This effect should make it easier to obtain polarized nuclear targets.

5. A maser effect on the CE of the metal can be produced in the case of negative polarization of the CE of the metal, or in the case of positive polarization but using an auxiliary short microwave pulse (or rapid reversal of the magnetic field), which transfers the spins to the upper Zeeman level. If the degree of polarization of the CE in the metal is large, and the width of the EPR curve is small, then the conditions of resonance will become violated, in the case of intense induced transitions between the Zeeman sublevels, owing to the change in the magnetization of the metal. To maintain resonance conditions, we can modulate the magnetic field with a period on the order of or larger than the recovery time of the CE polarization. The resonance conditions that are produced at a certain magnetic field strength can then be maintained automatically so long as the condition

$$dH / dt = 0,$$

is satisfied in the metal, where H is the intensity of the magnetic field in the metal and includes, generally speaking, also the field due to the induced currents. Modulation of the magnetic field ensures a periodic maser effect and energy balance.

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[2]Y. Tomkiewicz, B. A. Scott, L. J. Tao, and R. S. Title, Phys. Rev. Lett. **32**, 1363 (1974).