Possibility of observing an acoustic spin resonance of conduction electrons in a metal

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(Submitted 30 January 1982)

Pis'ma Zh. Eksp. Teor. Fiz. **35**, No. 5, 214–216 (5 March 1982)

A narrow line of the Dyson type should be observed against the background of the line corresponding to resonant absorption of sound, broadened by electron diffusion. The transverse magnetization induced by an acoustic wave is derived.

PACS numbers: 43.35.Rw, 76.30. – v

Acoustic-resonance methods may have definite advantages for studying spin systems.[1] It is generally believed, however, that the diffusion of spin carriers greatly broadens the line of the acoustic spin resonance (ASR; or the acoustic paramagnetic resonance) of conduction electrons in a metal. Gerasimenko[2] has shown that the width of the APR line is given by

$$\Gamma_q = T_2^{-1} + q^2 D, \tag{1}$$

where T_2^{-1} is the rate of transverse spin relaxation of the conduction electrons if diffusive broadening is ignored, D is the diffusion coefficient of these electrons, and $\mathbf{q}$ is the wave vector of the sound. It follows that the condition under which the resonance line can be resolved, $\Gamma_q \ll \omega$, means that there is only a narrow window of acoustic frequencies within which the ASR can be observed:

$$T_2^{-1} \ll \omega \ll S^2 D^{-1}, \tag{2}$$

where S is the sound velocity.

Actually, the situation is even worse, because attempts to reduce the spin relaxation (by lowering the temperature or using pure samples) automatically increase D; i.e., in many cases the window in (2) is always closed. Condition (2), the condition under which an ASR can be observed, has been satisfied in all the recent studies (see the review in Ref. 3).

An important circumstance has escaped general attention, however: If, in the course of diffusion, an electron leaves the region where the sound wave has a given phase and does not return, then the spin "sees" a change in this phase over a time $\sim 1/Dq^2$. This effect leads to the broadening of the ASR line which was described above. Actually, some of the conduction electrons may return to the point where the wave has the same phase during the lifetime of the spin state, T_2, so that the width of the ASR line for such electrons is determined exclusively by the time T_2. This situation evidently becomes more likely with increasing diffusion coefficient D, in contradiction of condition (2). This effect is analogous to that which occurs in the ordinary electron spin resonance in metals,[4] except that in the ESR case the spin of an electron which has crossed the spin layer "sees" an abrupt change in both the phase and amplitude of the electromagnetic wave, while in ASR the change is basically in the phase alone.

Let us examine the ASR for a sound wave which is propagating along the normal to a plate of thickness of **L**. The interaction of the conduction electrons with the sound may be thought of as the interaction of the spin moment of the charge carrier with an effective magnetic field $\mathbf{H}_1 = \mathbf{h}_1 \exp[-i(\omega t + qx)]$ which is produced by the sound wave and which depends on the particular mechanism for the spin-phonon coupling.[2] By introducing the magnetic field $\mathbf{H}_1$, we can study the ASR by calculating the magnetization caused by the spins of the conduction electrons from a modified Bloch equation,

$$\dot{\mathbf{M}} = \gamma [\mathbf{M} \times \mathbf{H}] - \mathbf{M} T_2^{-1} + D \nabla^2 \mathbf{M}, \tag{3}$$

where $\mathbf{H} = \mathbf{H}_0 + \mathbf{H}_1$, γ is the gyromagnetic ratio for the conduction electrons, and D is the (generally anisotropic) diffusion coefficient of the conduction electrons, which depends on the orientation of the constant field $\mathbf{H}_0$. Equation (3) applies if the mean free path of the conduction electrons satisfies $l \ll 1/q$.

Assuming that there is no surface relaxation of the magnetization at the boundaries of the sample ($x = 0, L$), we find the following expression for the transverse component of the oscillatory magnetization $M \sim \exp[-i\omega t]$:

$$M(x, t) = \frac{i\omega_0 \chi h_1 e^{-i\omega t}}{(\Gamma_q - i\Delta\omega)} \left[e^{-iqx} + \frac{q}{k} \frac{\operatorname{ch} ikx}{\operatorname{sh} ikL} e^{-iqL} - \frac{q}{k} \frac{\operatorname{ch} ik(x-L)}{\operatorname{ch} ikL} \right], \tag{4}$$

where χ is the Pauli susceptibility, $\omega_0 = \gamma H_0$ is the resonant frequency of the conduction electrons, $\Delta\omega = \omega - \omega_0$, Γ_q is given by (1), and

$$k^2 = D^{-1}(i\Delta\omega - T_2^{-1}). \tag{5}$$

When the ASR is to be detected through measurements of the magnetization, we would like to study the signal which has passed through a plate of sufficient thickness under the condition $|ikL| \gg 1$, since under this condition the parasitic signal caused by the electromagnetic wave, which is excited along with the sound, is completely damped. From (4) we then find the magnetization at the boundaries ($x = 0, L$):

$$M_{0,L} = \frac{i\omega_0 \chi H_1(x, t)_{0,L}}{(\Gamma_q - i\Delta\omega)} \left[1 \mp \frac{iq\sqrt{2DT_2}}{(\eta - i\xi)} \right] \tag{6}$$

$$\eta = (\sqrt{1 + T_2^2 \Delta\omega^2} + 1)^{1/2}, \qquad \xi = (\sqrt{1 + T_2^2 \Delta\omega^2} - 1)^{1/2} \operatorname{sign} \Delta\omega \cdot$$

The minus sign corresponds to $x = 0$, and the plus sign to $x = L$.

Analysis of expression (6) shows that against the background of a resonance of width Γ_q we should find a narrow line, of width T_2^{-1} caused by the second term in brackets. The shape of the narrow ASR line is similar to that of a Dyson line corresponding to ordinary ESR in a metal. It is not difficult to see that the narrow line will essentially always be predominant, since near the resonance we have

$$\left|\frac{q}{k}\right|^2 = \frac{2DT_2q^2}{\eta^2+\xi^2} \sim (\omega T_2)\frac{\omega D}{S^2} >> 1. \tag{7}$$

In particular, for some typical numerical values of the quantities in (7) ($\omega = 10^{10}$ s^{-1}, $S = 3 \times 10^5$ cm/s, $T_2 = 10^{-8}$ s, $D = 10^2$ cm^2/s), we find $|q/k| \simeq 30$.

These results thus show that there is the possibility of observing an acoustic spin resonance of conduction electrons with a line width set by the spin-relaxation time of the conduction electrons. It is a simple matter to arrange conditions under which the narrow component of the absorption line can be observed well. We hope that this paper will stimulate an experimental study of acoustic resonances of conduction electrons in metals.

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Translated by Dave Parsons
Edited by S. J. Amoretty