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Theory of ultrasonic attenuation in metallic rare earth systems

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Résumé. — Nous étudions comment l'atténuation ultrasonore dans les alliages et composés des terres rares dépend de la température, du champ magnétique et du champ cristallin.

Abstract. — We investigate the temperature and magnetic field dependence of the ultrasonic attenuation in rare earth alloys and compounds with crystalline field split energy levels.

In rare earth (RE) metallic systems we have to consider two different attenuation mechanisms:

1. The conduction electron-phonon coupling: The transfer of energy from the sound wave to the conduction electrons depends strongly on the electronic mean free path, which is determined by inelastic electron scattering from RE ions.

2. The magnetoelastic coupling: The interaction between the distortion of the crystalline electric field (CEF) by the sound wave and the deformable 4f-shell of the RE ions allows a direct transfer of sound energy to the RE system. In RE alloys normally both attenuation mechanisms are present. In order to distinguish between them we investigate the attenuation in an applied magnetic field which splits the CEF levels.

In the following sections we will discuss separately the attenuation by electron-phonon interaction and magnetoelastic coupling for dilute alloys. In the last section we will investigate ultrasonic attenuation in RE compounds, where structural phase transitions and a very pronounced increase of the attenuation near $T_c$ have been observed [1].

1. Ultrasonic attenuation by conduction electron-phonon interaction in RE-alloys. — The attenuation of long wavelength sound due to the electron-phonon interaction in metals can be written as a generalization of the Pippard formula [2, 3]. For longitudinal waves we obtain

$$\xi_{ef} = \frac{nmv_L}{\rho v_L} \sum_{\alpha}^{+\infty} \int_{-\infty}^{+\infty} \frac{d\delta}{d\delta} \left( -\frac{\partial f}{\partial \delta} \right) \frac{1}{l_e} \times$$

$$\times \left\{ \frac{1}{3} \left( \frac{q_{l_e}^2}{q_{l_e}^2 - \arctan q_{l_e}^2} - 1 \right) \right\}$$

(1)

Here $v_L$ is the sound velocity, $\rho$ the ionic mass density; $n, m, v_F$ are the density, mass and Fermi velocity of the conduction electrons. $l_e^*\Delta$ is an energy and spin dependent electronic mean free path which depends on the scattering rate from the RE ions. Note that $\alpha$ is small and prop. to $q \langle l \rangle$ when $q \langle l \rangle \ll 1$ and large and independent of $l$ when $q \langle l \rangle \gg 1$. We have studied the scattering from RE ions with $J = 5/2$ (Ce$^{3+}$, Sm$^{3+}$) in a cubic CEF. The Zeeman

(Continued on next page)
splitting of the $\Gamma_7, \Gamma_8$ level system is shown in figure 1. Figure 2 shows the calculated attenuation $\varepsilon_\text{P}$. At low temperatures we find a minimum at the field strength where the two states of the $\Gamma_7$ ground state cross, and which corresponds to a minimum of the electronic mean free path.

2. Magnetoelastic attenuation in RE-alloys. — The attenuation due to the magnetoelastic coupling between the sound wave and the quadrupole moments of the RE ions can be written as [3]

$$\varepsilon_{\mu} = c \frac{g_\mu^2}{\rho v_\mu} \frac{1}{\omega} U_0'(\omega)$$

where $c$ is the RE concentration, $g_\mu$ the magnetoelastic coupling constant, and $U_0'(\omega)$ is the quadrupole susceptibility of the RE ions. $U_0'(\omega)$ can be represented by a sum of Lorentzians with positions corresponding to the transitions between different 4f-levels and widths determined by the interactions with conduction electrons. For the ultrasonic attenuation we need only its value at $\omega = 0$. We expect a strong attenuation when the sound wave couples to a degenerate ground state level of the RE ions. This is demonstrated in figure 3 for the $\Gamma_7-\Gamma_8$ level system, where a maximum appears at the field strength where the two states of the $\Gamma_7$ doublet cross. Note that the matrix elements of the quadrupole moment within the $\Gamma_7$ states are field induced, and that therefore, no attenuation occurs at $H = 0$.

The situation is different, when the $\Gamma_8$ level is the ground state. Here nonvanishing matrix elements exist for $H = 0$, and the attenuation decreases with increasing Zeeman splitting.

3. Ultrasonic attenuation in RE compounds. — In RE compounds the same two attenuation mechanisms are present as in alloys, but in systems with a degenerate ground state (like TmCd and TmZn) we expect the Pippard mechanism to be of less importance because of the short mean free path of the conduction electrons. Therefore we will discuss only the magnetoelastic attenuation in the following.

In a compound we have to consider the coupling between different RE ions. In this case the ultrasonic attenuation is given by

$$\varepsilon_{\mu} = q^2 \left( \frac{g_\mu^2}{\rho v_\mu} \right) \chi_0^{0}(q, \omega)/\omega$$

where $v_\mu$ is the sound velocity of the coupled lattice-RE-conduction electron system and $\chi_0^{0}(q, \omega)$ is the quadrupole susceptibility of the RE system coupled to the conduction electrons.

Let us assume that the sound wave couples to a degenerate ground state of the RE system, and the energy of excited states is large enough that we may neglect the coupling to excited states. Then for small $\omega$ and $q$ we have to consider only elastic scattering processes for which $\chi_0^{0}/\omega$ takes the general form

$$\chi_0^{0}(\omega)/\omega = \chi_0^{0} \frac{\gamma}{\omega^2 + \gamma^2} \approx (\chi_0^{0})^2/M.$$ 

Here $\gamma = M/\chi_0^{0}$ is the relaxation rate of the coupled system. In this approximation $M$ is the transition probability between the degenerate states of single RE ions due to exchange and aspherical Coulomb interaction with the conduction electrons, and is temperature independent. The static susceptibility contains an effective quadrupole interaction $g'$ between different RE ions induced by the conduction electrons and is given in MFA by $\chi_0^{0} = U_0^{0}/(1 - g' U_0^{0})$ where $U_0^{0}$ is the single ion susceptibility.

A very strong temperature dependence is obtained for the ultrasonic attenuation of the soft acoustic mode. In particular, if the experiment is performed at a fixed frequency $\omega$ we obtain

$$\varepsilon_{\mu} = \frac{\omega^2}{\rho} \frac{g_\mu^2}{\rho v_\mu} \frac{1}{\omega} \chi_0^{0}(T)^2/M$$

where

$$v_\mu(T) = v_0 \sqrt{1 - \frac{g_\mu^2}{\rho v_\mu} \chi_0^{0}(T)}$$

vanishes at $T_c$ for a second order phase transition

$$\left( \frac{g_\mu^2}{\rho v_\mu} \right) = \frac{g_\mu^2}{\rho v_\mu} \chi_0^{0}(T).$$

Lüthi has analyzed his experiments on TmCd and TmZn in this manner (1). The qualitative features are well reproduced by this simplified theoretical description, but for a quantitative comparison one

(1) Lüthi, B., Private communication.
has to include excited states of the RE system. In that case Eq. (4) no longer holds, and one has to include an additional damping mechanism due to the dynamical nature of the effective interaction $g'$ induced by the conduction electrons.

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