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Influence of Pressure on the Electron–Phonon Interaction in Superconductors

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The electron–phonon interaction is a very important and ubiquitous process in solids, affecting almost all their physical properties. In metals, where the relaxation processes depend on both electrons and phonons, all thermodynamic and transport properties are dictated by the electron–phonon interaction. A very strong manifestation of the electron–phonon interaction is related with the superconducting state. Here we report the effect of high pressure on the transport electron–phonon interaction, λ_{tr}, in superconducting systems such as YB_6 ($T_c \approx 7.5$ K), Pb ($T_c \approx 7.2$ K), Nb bulk or thin film ($T_c \approx 9.2$ K), and in LaB_6 in which superconductivity was not yet observed. The expected pressure effect should correspond to the theoretically predicted negative pressure effect on T_c (except for Nb thin film and LaB_6). To determine the influence of pressure on λ_{tr}, we utilized the Bloch–Grüneisen fit (denoted also as "thermal spectroscopy") of the precise temperature dependence of resistivity measurements in the normal state up to a pressure of 2.8 GPa. Based on this fit the observed negative pressure effect on λ_{tr} values, $\mathrm{d}\lambda_{tr}/\mathrm{d}p$, are as follows: $\mathrm{d}\lambda_{tr}/\mathrm{d}p \approx -0.045$ GPa^{-1} for YB_6, $\mathrm{d}\lambda_{tr}/\mathrm{d}p \approx -0.13$ GPa^{-1} for Pb, $\mathrm{d}\lambda_{tr}/\mathrm{d}p \approx -0.019$ GPa^{-1} or –0.028 GPa^{-1} for Nb bulk or thin film, respectively, and $\mathrm{d}\lambda_{tr}/\mathrm{d}p \approx -0.003$ GPa^{-1} for LaB_6.

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1. Introduction

The electron–phonon interaction (EPI) exists in solids due to scattering of electrons on vibrating lattice ions (phonons). It affects their transport and thermodynamic properties, and is very significantly manifested in superconducting materials [1, 2]. EPI is characterized by the coupling parameter λ and it can be measured or calculated by various methods. Empirical λ values of some superconducting elements and compounds at ambient pressure received from transport (λ_{tr}) or spectroscopic measurements can be found e.g. in [1–6]. Experimental [7] or theoretical [1, 8, 9] studies of the pressure effect on EPI, however, are very rare and each new result is welcomed.

As to the materials, Pb ($T_c \approx 7.2$ K, $\lambda_{tr} \approx 1.48$) is a BCS type-1 superconductor which crystallizes in fcc lattice. Due to its pronounced and smooth pressure effect on T_c ($\mathrm{d}T_c/\mathrm{d}p = -0.360$ K/GPa) it is used as a manometer in high pressure cells. Nb is a type-2 superconductor ($T_c \approx 9.2$ K, $\lambda_{tr} \approx 1.06$), which crystallizes in *bcc* lattice. YB_6 and LaB_6 crystallize also in bcc structure, and LaB_6 ($\lambda \approx 0.19$) is an isostructural system to superconducting YB_6 ($T_c \approx 7.5$ K, $\lambda_{tr} \approx 1.03$).

Our investigation of the EPI under pressure was based on the method developed for YB_6 in [10], in which the normal state resistivity measurement, $\rho(T)$, as "thermal spectroscopy" was deconvolved into a spectrum of the EPI and the coupling constant λ_{tr}. Such an approach was successful because YB_6 happened to be an example of a superconductor with a dominant low-energy Einstein-like phonon mode (≈ 8 meV).

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2. Thermal spectroscopy

The temperature dependence of electrical resistivity of simple superconductors in normal state can be described by the Bloch–Grüneisen (BG) formula [10]:

$$\rho_{BG}(T) = \rho_0 + \frac{4\pi m_b}{ne^2}\int_0^{\omega_{\max}} \alpha_{tr}^2 F(\omega)\frac{x\,\mathrm{e}^x}{(\mathrm{e}^x-1)^2}\,\mathrm{d}\omega, \quad (1)$$

where $x \equiv \omega/T$, T is temperature, ω — the frequency of phonons, m_b — the electron effective mass near the Fermi level, n — the electron concentration, e — the electron charge, $\alpha_{tr}^2 F(\omega)$ — the Eliashberg spectral function, ω_{max} — the maximum frequency in the phonon density of states (PDOS) and ρ_0 the temperature independent residual resistivity.

In materials with significant peaks in PDOS it is possible to approximate the PDOS by its decomposition into a set of the Einstein phonon modes [10]:

$$\alpha_{tr}^2 F(\omega) = \frac{1}{2}\sum_k \lambda_{tr,k}\omega_k \delta(\omega-\omega_k), \quad (2)$$

where $\lambda_{tr,k}$ is the electron–phonon transport coupling parameter for the k-th phonon mode and ω_k is its frequency. By substituting (2) into (1) one obtains the discrete version of BG formula [10]:

$$\rho'_{BG}(T) = \rho_0 + \frac{2\pi}{\varepsilon_0\Omega_p^2}\sum_k \lambda_{tr}\omega_k \frac{x_k\,\mathrm{e}^{x_k}}{(\mathrm{e}^{x_k}-1)^2} \quad (3)$$

where $x_k \equiv \omega_k/T$, $\Omega_p^2 = (ne^2/\varepsilon_0 m_b)$ is the unscreened plasma frequency and ε_0 — the permittivity of vacuum.

By taking into account the negative curvature of resistivity at high temperature, which is possibly related to the Mott limit $\rho_{\max}$ [10], one can obtain the fitting $\rho(T)$ dependence using the empirical "parallel resistor" formula

$$\frac{1}{\rho(T)} = \frac{1}{\rho'_{BG}(T)} + \frac{1}{\rho_{\max}}. \quad (4)$$

In our case the thermal spectroscopy method consisted of measuring the temperature dependence of resistivity at various pressures and fitting of the measured data by (4). From corresponding fit, values of the EPI parameter $\lambda_{tr,k}$ and the frequencies of Einstein modes ω_k were obtained.

3. Experimental details

Electrical resistance was measured by a standard four-wire method with lock-in amplifier. For pressure generation, a CuBe piston cylinder pressure cell with NiCrAl core and dielectric oil DAPHNE as pressure medium were used. Pressure was indicated from the superconducting transition of lead.

4. Results and discussion

In the temperature derivation of $\rho(T)$ of Pb (Fig. 1) there was observed a pronounced maximum, which is shifting with increase of pressure to higher temperatures. In thermal spectroscopy model this behaviour is observed when the Einstein-like phonon mode increases its frequency. This indicates the hardening of the Einstein-like phonon mode, which is responsible for the superconducting coupling. Electron–phonon transport coupling parameter $\lambda_{tr,1}$ for softer phonon mode in Pb (Fig. 2) has larger value than $\lambda_{tr,2}$ for higher frequency one.

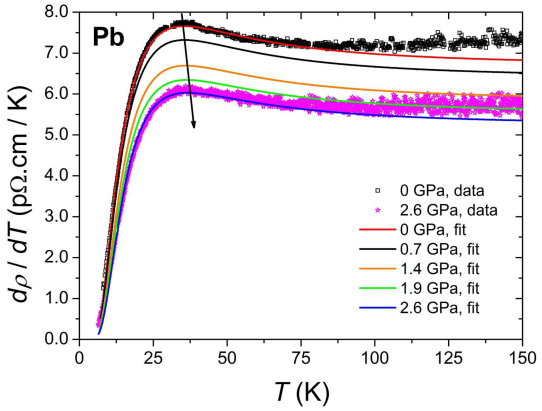

Fig. 1. Temperature dependences of $\mathrm{d}\rho(T)/\mathrm{d}T$ for Pb together with BG fits at various pressures. Inset shows $\rho(T)/\rho(0)$ dependences (for clarity not all data points are shown) at ambient and maximum pressures with fits.

Neutron spectroscopy investigations of Pb show two significant peaks in PDOS at ≈ 4.3 meV and ≈ 9 meV [1], which are responsible for its EPI and superconductivity. In our case $\rho(T)$ at ambient pressure was at first fitted by the two-term-discrete BG formula (3) using as starting parameters for the Einstein frequencies of phonon modes $\hbar\omega_{E,1} = 4.3$ meV and $\hbar\omega_{E,2} = 9$ meV. From performed fit the parameters $\lambda_{tr,1}$ and $\lambda_{tr,2}$ for each phonon mode were obtained (Fig. 2).

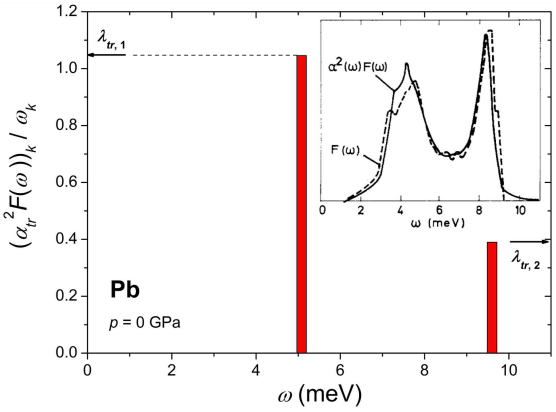

Fig. 2. Transport electron–phonon coupling parameters, $\lambda_{tr,1}$ and $\lambda_{tr,2}$, of Pb deconvolved from the temperature dependence of resistivity at ambient pressure. In the inset, the phonon density of states, $F(\omega)$, and the Eliashberg spectral function, $\alpha^2F(\omega)$, of Pb from neutron spectroscopy investigation are shown [1].

The same fitting procedure was used for all applied pressures and from them the total parameters, $\lambda_{tr} = \lambda_{tr,1} + \lambda_{tr,2}$, were obtained. Based on λ_{tr} data (Fig. 3) a negative pressure effect on the transport EPI parameter of Pb, $\mathrm{d}\lambda_{tr}/\mathrm{d}p \approx -0.13$ GPa^{-1}, was observed. This value is in good agreement with the theoretical value, $\mathrm{d}\lambda_{tr}/\mathrm{d}p \approx -0.17$ GPa^{-1}, received from theoretical prediction in [9], where a multiple-cutoff Lorentzian model of PDOS was used.

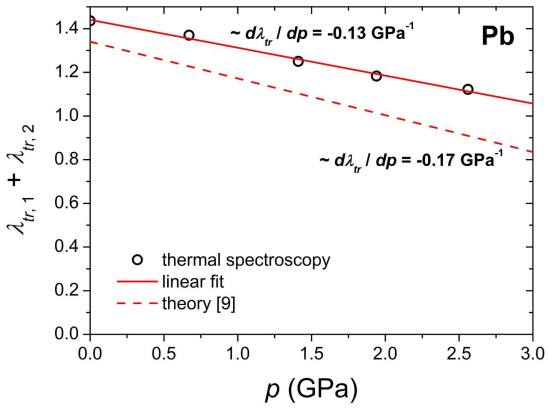

Fig. 3. Pressure dependence of the transport EPI parameter, λ_{tr}, of Pb obtained from thermal spectroscopy (circles) and given by theoretical calculation from [9] (dashed line).

The same procedure was used for other studied samples, YB_6, LaB_6, Nb bulk and Nb thin film (100 nm), respectively. From pressure dependences of the difference between critical temperature at applied and ambient pressure (Fig. 4) one can see that T_c of YB_6, Pb and of bulk Nb decreases with pressure linearly up to 2.8 GPa.

On the other hand, for the Nb thin film $T_c(p)$ increases with pressure. For LaB_6, no superconducting transition was observed down to 1.6 K.

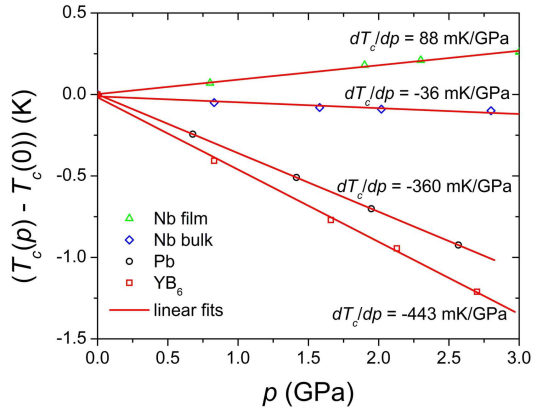

Fig. 4. Pressure dependences of the difference between the critical temperature at applied and at ambient pressure for all studied samples.

From pressure dependences of the difference between transport EPI parameter at applied pressure, $\lambda_{tr}(p)$, and at ambient pressure, $\lambda_{tr}(0)$, shown in Fig. 5, one can see that it decreases with pressure for all our studied samples as follows: $\mathrm{d}\lambda_{tr}/\mathrm{d}p \approx -0.13$ GPa^{-1} for Pb, $\mathrm{d}\lambda_{tr}/\mathrm{d}p \approx -0.045$ GPa^{-1} for YB_6, $\mathrm{d}\lambda_{tr}/\mathrm{d}p \approx -0.019$ GPa^{-1} for Nb bulk, $\mathrm{d}\lambda_{tr}/\mathrm{d}p \approx -0.028$ GPa^{-1} for Nb thin film, and $\mathrm{d}\lambda_{tr}/\mathrm{d}p \approx -0.003$ GPa^{-1} for LaB_6. The received value for Nb agrees with that theoretically calculated using a full potential LMTO (linear muffin-tin orbital) method in [8].

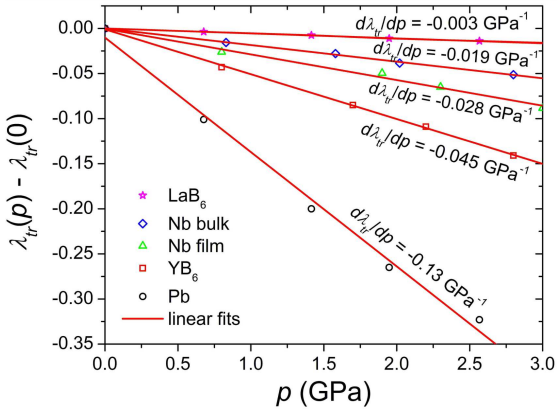

Fig. 5. Pressure dependences of the difference between the transport EPI parameter at applied and at ambient pressure for all studied samples.

As it was shown, for YB_6, Pb, Nb (bulk), both T_c and λ_{tr} decrease with pressure, as theoretically predicted. Therefore, we can conclude that in these materials mainly the EPI is responsible for their superconducting properties. In Nb thin film, on the contrary, T_c increases with pressure but λ_{tr} drops with pressure. Therefore, in Nb thin film some additional mechanism which influences superconductivity, like surface electron–phonon coupling, may be present. In LaB_6 no superconducting transition under pressure up to 2.8 GPa was observed and λ_{tr} decreases with increasing pressure. From it follows that in this compound superconductivity will likely not be induced by pressure.

5. Conclusions

Electrical resistivity based thermal spectroscopy was successfully used to determine the pressure dependence of the EPI parameter in YB_6, LaB_6, Pb, Nb bulk and Nb thin film up to 2.8 GPa. Pressure dependences of T_c and λ_{tr} indicate that in YB_6, Pb and Nb bulk superconductivity is mediated mainly by bulk phonons, and that in Nb thin film it might be influenced also by surface phenomena.

Acknowledgments

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