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Acoustic coupling and effective quasiparticle lifetimes of superconducting films*

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Our results on the acoustical coupling of thin superconducting films are recalculated using the phonon-enhanced electronic density of states. The acoustic coupling of lead to tin is smaller than previously reported. Recent revised measurements of the quasiparticle lifetimes in lead indicate that it is not necessary to assume additional inelastic processes in lead as previously reported. We find that the acoustic coupling of lead to tin is smaller than the acoustic coupling of lead to helium.

In an earlier paper[1] we reported two observations which relate to phonons in thin superconducting films. The first was an independent measurement of the acoustic coupling from a lead to a tin film. The second involves existing measurements of the effective lifetime in superconducting lead films. These results could not be explained in terms of conventional theories of phonon escape so we postulated additional inelastic phonon processes in lead films. In this paper we comment on each of these observations.

In order to determine the acoustic coupling we illuminated a superconducting film that was part of a tunnel junction, and studied the subsequent change in the energy gaps in both films. We were able to separate the contribution in each film by determining the excess number of quasiparticles ΔN in each film as

$$\Delta N = f(N(T), N'(T), \delta\Delta_{\text{expt}}, \epsilon) , \tag{1}$$

where f is an algebraic function of its variables, $N(T)$ and $N'(T)$ are the thermal equilibrium quasiparticle numbers in the illuminated and nonilluminated films, as calculated from BCS theory, $\delta\Delta_{\text{expt}}$ is the experimentally measured change in the energy gaps due to illumination, and ϵ is a coupling parameter between the two films. By comparing the temperature dependence of ΔN obtained from (1) for various values of ϵ with the theoretically determined temperature dependence, we were able to determine ϵ. This ϵ could then be related to the coupling parameters between the two films.

It was pointed out to us[2] that $N(T)$ is correctly calculated using the phonon-enhanced density of states at the Fermi surface, $(1+\lambda)N(0)$, and not the bare band-structure density $N(0)$ that we used. We have recalculated the values of ϵ using a method suggested by Jaworski *et al.*[3] The calculation is slightly more complicated because the phonon-enhanced densities of states in lead and tin are not equal, as assumed earlier. The value of ϵ determined in this way is $\epsilon = 0.75 \pm 0.3$, compared to the previously reported result of 1.1 ± 0.4. This is related to the phonon coupling of the two films by an equation derived in Ref. 1:

$$\epsilon = 2\frac{\beta' R}{R'\beta}\frac{\gamma_{\text{PbSn}}}{\gamma'} , \tag{2}$$

where β is the pair-breaking probability of phonons, R is the recombination coefficient, γ_{PbSn} is the probability for losing phonons from lead into tin, and γ' is the total probability for losing phonons in the tin film. The use of the phonon-enhanced density of states also affects β/R; so we determine that $\gamma_{\text{PbSn}} = 3.1\times10^{7}\ \text{sec}^{-1}$ whereas we previously reported $7.7\times10^{8}\ \text{sec}^{-1}$. The value of the phonon transmission coefficient α_{PbSn} is smaller by a factor of 6 than that determined from Little's theory, indicating substantial phonon reflection at the oxide barrier between the two films.

We now consider our suggestion of additional inelastic phonon processes in lead. This was a necessary conclusion of the existing measurements of effective quasiparticle lifetimes in lead,[4] which measure the phonon escape time, and were more than an order of magnitude too small to be understood by conventional phonon escape mechanisms. Recently a better measurement of effective lifetime[3] has revised this values by a factor of 25, making it compatible with phonon escape and removing the necessity to postulate these additional inelastic phonon processes.

The discrepancy between the original quasiparticle lifetime measurements[5] of Parker and Williams (PW) in lead and the recent measurements of Jaworski *et al.* is not so great if the results are analyzed consistently. The results of PW measure the excess quasiparticle-distribution relaxation, which is $\tau_{\text{eff}}/2$. In the determination of τ_{eff}, PW used the bare band-structure density of states and only considered the thickness of one film. With all these corrections, the PW value is within a factor of 5 from the recently measured value of Jaworski *et al.*

Parker and Williams had to assume a value for r, the number of quasiparticles produced for

TABLE I. Relevant physical properties of tin and lead. $\Delta(0)$ is the zero-temperature energy gap, $\bar{S}_T$ is the mean transverse sound velocity; we use $N_T = 4N(0)\Delta(\pi/2)^{1/2}(kT/\Delta)^{1/2}e^{-\Delta/kT}$, $\tau = \tau_0 T^{-1/2} e^{\Delta/kT}$, $R_{\text{eff}} = 1/\tau_{\text{eff}} N_T$, $\beta/R = N_T^2/N_{\omega T} = (1+\lambda)^2 N^2(0) h^3 \bar{S}^3/4\Delta$, $\gamma = (\beta/2R) R_{\text{eff}}$, γ_{PbSn} from Eq. (2), and $\alpha = 4d\gamma/\bar{S}_T$. The calculations in tin are done only on the measurement of Ref. 11 since this is a direct measurement. The letters in parentheses indicate which of the following corrections were applied to the reported effective lifetimes: (a) used only the thickness of one film in the calculation of τ_{eff}; (b) τ_{eff} was determined using the band structure value for $N(0)$ [include enhancement $(1+\lambda)$]; (c) experiment measures $\frac{1}{2}\tau_{\text{eff}}$ not τ_{eff}; (d) the value of $N(0)$ used does not agree with Ref. 8.

Parameter	Tin	Lead	Units
$\Delta(0)$	0.60×10^{-3}	1.35×10^{-3}	eV
$N(0)$ (Ref. 8)	0.89×10^{22}	0.92×10^{22}	$\text{eV}^{-1}\text{cm}^{-3}$
$\bar{S}_T$	1.67×10^{5}	0.9×10^{5}	cm/sec
λ (Ref. 9)	0.72	1.55	
τ_0 (quoted)	9.2×10^{-10} (c)	4×10^{-12} (a, b, c)	$\text{sec K}^{1/2}$
(Refs. 3, 5, 10, 11)	2.3×10^{-9} (b, d)	2×10^{-10}	
R_{eff}	3.1×10^{-11}	1.3×10^{-10}	$\text{eV cm}^3\text{sec}^{-1}$
β/R	3.2×10^{19}	5.3×10^{18}	$\text{eV}^{-1}\text{cm}^{-3}$
γ	5.0×10^{8}	3.4×10^{8}	sec^{-1}
γ_{PbSn}	3.1×10^{7}		sec^{-1}
α_{PbSn}	2.3×10^{-2}		
α_{PbHe}	0.53		

every absorbed photon. Clearly, the maximum value of r is the ratio of photon energy to the energy gap, which in this case is 1500. On weaker grounds, they suggested a lower limit of ~220, and used a value of 1000. A value of 200 gives very good agreement between the two experiments, with the assumption of a film thickness of 3500 Å. This can perhaps be considered as an experimental determination of the value of r. This parameter is of importance in the effect of light illumination on superconductors.

An additional point involves whether it is necessary to include longitudinal phonons in these considerations. Rothwarf and Cohen[6] long ago showed that the coupling of quasiparticles to longitudinal phonons in lead was much smaller than to transverse phonons. Jaworski *et al.* have included them in a calculation of the phonon density N_ω whereas we have neglected them. The density of phonon states is proportional to S^{-3}, where S is the speed of sound, and for most metals $S_{\text{long}} \sim 2S_{\text{trans}}$. Since there are two transverse modes, we find that the longitudinal modes only contribute about 6% to N_ω and will not significantly affect the results.

If in the experiments of Jaworski *et al.* we assume that most of the phonons are lost into helium we obtain a coupling coefficient of lead to helium $\alpha_{\text{PbHe}} = 0.53$. Calculations using the experimentally determined Kapitza[7] resistance in conjunction with Little's theory give $\alpha_{\text{PbHe}} = 0.11$. Table I summarizes the data we have used in this paper.

In summary, the acoustic coupling experiments of Schuller and Gray are corrected by the enhancement of the density of states by the electron-phonon interaction. The quasiparticle lifetime measurements of Parker and Williams in lead are in agreement with the most recent measurements of Jaworski *et al.* if we assume that every photon produces 200 quasiparticles on the average. There is *no* additional mechanism for the loss of phonons in lead, and the phonon coupling of lead to helium is higher than the coupling of lead to tin.

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