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EXPERIMENTAL DETERMINATION OF THE ENERGY AND TEMPERATURE DEPENDENCES OF QUASIPARTICLE RELAXATION TIMES IN A NONEQUILIBRIUM SUPERCONDUCTOR *

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Résumé.- La dépendance en énergie et température du temps de relaxation inélastique des quasi-particules et du temps pour produire un mélange élastique des branches a été mesuré dans un supraconducteur en employant l'effet tunnel pour mesurer la population de non-équilibre des quasi-particules maintenues par l'injection de quasi-particules.

Abstract.- The energy and temperature dependences of the quasiparticle inelastic relaxation time and the quasiparticle elastic branch-mixing time have been measured in a superconductor, using a tunnel probe of a nonequilibrium quasiparticle population maintained by tunnel injection of particles.

We have previously reported experimental observation of nonthermal branch-imbalanced quasiparticle distributions in a tunnel-injected nonequilibrium superconductor /1/. Chang has recently shown how the energy and temperature dependences of both the quasiparticle inelastic relaxation time and the quasiparticle elastic branch-mixing time can be extracted from such experiments /2/. We show here that this method can yield high-resolution ($\sim 25 \mu\text{eV}$) measurements of the energy region above the gap edge, free of complications due to phonon-trapping effects.

Our measurements were made using asymmetric Al-Al-PbBi (1-2-3) double-tunnel-junction structures as described in Ref. /1/. Sharp structures ($\sim 25 \mu\text{V}$ wide) were observed in the detector junction (2-3) second-derivative signal at voltages $|V_d| = (\Delta_3 \pm \Delta_1 \mp |eV_i|)/e$ when the injector junction (1-2) was biased at voltage V_i . The structure above the current step (at $|V_d| = (\Delta_3 + \Delta_2)/e$) corresponded to a small cusp in the detector current-voltage characteristic and that below the cusp (at $|V_d| = (\Delta_3 - \Delta_2)/e$) corresponded to a small step in the characteristic. These structures result from a small peak in the energy distribution of the excess quasiparticles in the injected film (2), which in turn has

its source in the gap-edge peak in the density of states of the injecting film (1). The structures were superimposed on a smooth background corresponding to an increased effective quasiparticle temperature which was determined by measuring the Al gap with injection and then raising the bath temperature without injection until the same gap resulted. The amplitudes of the two types of structure depended oppositely on the sign of the injector bias in the manner expected for a branch imbalance in the injected film. The structure above the current step was approximately five times smaller than that below the cusp and contained the same information, so we measured amplitudes of the latter exclusively.

Using Chang's theory /2/, we find that the elastic branch-mixing time $\tau_e(E, T)$ in the injected Al film is essentially independent of quasiparticle energy E and temperature T and approximately equal to 1×10^{-9} s. The inelastic relaxation time $\tau_i(E, T)$ however, is strongly energy and temperature dependent. Figure 1 shows our experimentally determined τ_i as a function of normalized quasiparticle energy for several bath temperatures corresponding to $0.51 \leq T_b/T_c \leq 0.90$. Comparison of these experimental results with theory is complicated by the dependence of the effective quasiparticle temperature on the injection bias as well as on the bath temperature. Figure 2 shows a set of curves based on the theory of Kaplan *et al.* /3/, including corrections for injection-induced effective quasiparticle temperature increases. The experimental data do have

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the qualitative features predicted by the theory : τ_i is relatively strongly temperature dependent at low energies, where quasiparticle relaxation is dominated by recombination, but only weakly temperature dependent at higher energies where scattering dominates, and it decreases roughly exponentially with increasing energy at high energies.

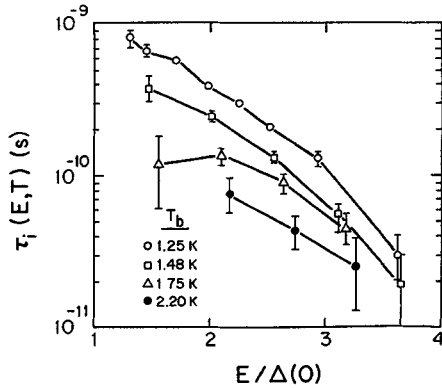


Fig. 1 : Measured quasiparticle inelastic relaxation time versus normalized quasiparticle energy $E/\Delta(0) = [eV_i - \Delta(T)]/\Delta(0)$ for several bath temperatures.

However, the quantitative agreement between experiment and theory is only fair. An attempt at a global least-squares fit of experiment to theory yielded a value of 2.1×10^{-9} s for the scale time τ_0 of the Kaplan *et al.* theory /3/.

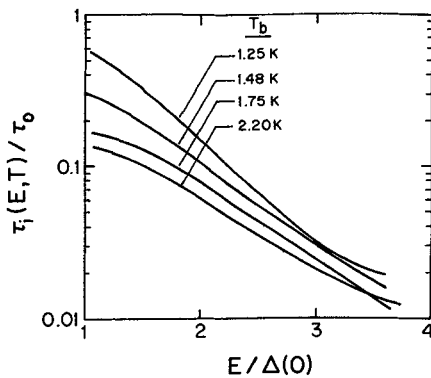


Fig. 2 Theoretically predicted quasiparticle inelastic relaxation time for the same conditions as Fig. 1. These curves include corrections for the increase in effective quasiparticle temperature with increasing injector power for fixed bath temperature.

This is about 200 times smaller than the theoretical estimate /3/ for pure Al. This result is perhaps not

unreasonable, because τ_0 is inversely proportional to both T_c^3 and the strength of the electron-phonon coupling constant for weak-coupling superconductors /3/. The high T_c (~ 2.4 K) of our dirty Al would indicate a reduction of τ_0 by a factor of about 9. We would expect a further reduction from the increased electron-phonon coupling constant which should accompany the increased T_c /4/. Finally, recent measurements of τ_0 for clean Al /5/ indicate that it is roughly 7 times smaller than Kaplan *et al.*'s theoretical estimate.

We have also estimated from our data the phonon-trapping factor for the injected Al film. It is surprisingly large, ~ 20 . This is difficult to understand in terms of existing simple models, and may be a consequence of the complexity of our multilayer tunnel-junction structure. It should be noted, however, that the phonon-trapping factor does not enter into the experimentally determined quasiparticle relaxation times in this experiment, as it does in many others.

We conclude from these results that experiments of the type described here provide a powerful tool for the detailed study of the energy and temperature dependences of quasiparticle relaxation times in a nonequilibrium superconductor.

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