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Superconducting Pb-Pb Tunneling near T_c†

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We have measured electron tunneling from Pb films into (111) oriented Pb films at temperatures from 1.2 to 7.2°K. Above 6°K, structure in dV/dI at voltages greater than 2Δ is observed which is not the same as that found at low temperature. One new feature, a resistance maximum just outside 2Δ, is shown by a numerical calculation to arise from the occupation of excited states above the gap. The other, a resistance peak at 3.5 mV, is shown by further calculation to be associated primarily with the phonon-emission structure described by strong-coupling theory. We find that the effect of the previously predicted recombination process, also located at 3–4 mV, is too broad to be clearly identified.

INTRODUCTION

We report here on two new effects which are observed in tunneling with superconducting lead near its transition temperature. One of these can be understood from BCS theory, but has not previously been predicted or observed. The other is a strong coupling effect which arises from the presence of a high density of excited electrons above the gap.

Deviations from BCS theory have been observed[1] in tunneling from superconducting Pb since soon after Giaever's pioneering experiments.[2] The major departures from BCS theory which have previously been reported are observed at energies near $\Delta_0+\omega_{\mathrm{ph}}$, where Δ_0 is the superconducting energy gap and ω_{ph} is an energy range over which the phonon spectrum of the metal has a peak. For Pb there are two such energy ranges, one associated with transverse phonons (ω_T) and the other with longitudinal phonons (ω_L). This type of structure has been explained very well by the strong coupling theory. Schrieffer, Scalapino, and Wilkins (SSW)[3] assumed for Pb a constant electron-phonon coupling parameter α^2 and a phonon spectrum $F(\omega)$ approximated by the sum of two Lorentzians located to fit roughly the transverse and longitudinal phonon peaks observed in neutron scattering. They then calculated a density of states at zero temperature from the Eliashberg equations which agrees reasonably well with the conductance measured by Rowell, Anderson, and Thomas[4] for an Al-Pb junction at 1.3°K. McMillan and Rowell[5] inverted this type of calculation, and from their accurate measurements of dV/dI on Pb-Pb junctions calculated the phonon contribution $\alpha^2(\omega)F(\omega)$ to the Eliashberg equations. This calculation seems to account very well for all the observed low-temperature structure in the 3–20 mV range.

At higher temperatures, near T_c, one must take account of the presence of excited quasiparticles. Scalapino, Wada, and Swihart[6] (SWS) used a phonon spectrum of two Lorentzians similar to that of SSW to calculate the density of states at several temperatures. The major difference between the results of this calculation and those of the low-temperature calculations is a new structure in the density of states in the vicinity of $\omega_T-\Delta_0(T)$. They attribute this structure to recombination of the injected electron with an excited quasiparticle and decay of the pair to the Fermi surface via real-phonon emission. They estimated that the effect should be observable in normal-superconducting (NS) tunneling for $0.7<T/T_c<1.0$.

Franck and Keeler[7] performed such experiments with Pb-Al junctions and found that the predicted structure did not appear, or at least was too small to be separated from the phonon-emission structure at $\omega_T+\Delta_0(T)$. Vashishta and Carbotte[8] repeated the calculation of SWS using the experimentally determined effective phonon spectrum $\alpha^2(\omega)F(\omega)$ of McMillan and Rowell. Their results differ from those of SWS in certain details. In particular, they find that the structure at $\omega_T-\Delta_0(T)$ is considerably smaller than that of SWS. The NS differential conductance calculated from their data is in good agreement with the experimental results of Franck and Keeler for $0.9<T/T_c<1.0$.

We have performed experiments on tunneling with two Pb films, both superconducting (SS), at temperatures near T_c. Because of the sharp peak in the density of states at the gap edge, SS tunneling gives substantially higher resolution at high temperature than NS tunneling. Because of this better resolution we are able to observe structure around $\omega_{\mathrm{ph}}-\Delta_0(T)$, which may be in part a result of the SWS recombination process. In addition to this strong-coupling effect, we regularly observe a peak in dV/dI just outside the gap which has not previously been reported, and which we explain by BCS theory. Our experimental methods are described in the next section, followed by a discussion of experimental and theoretical results for temperatures near T_c. In an appendix we describe some of our low-temperature observations, and compare them with those reported by other investigators. We find a few differences between our data and those previously reported.

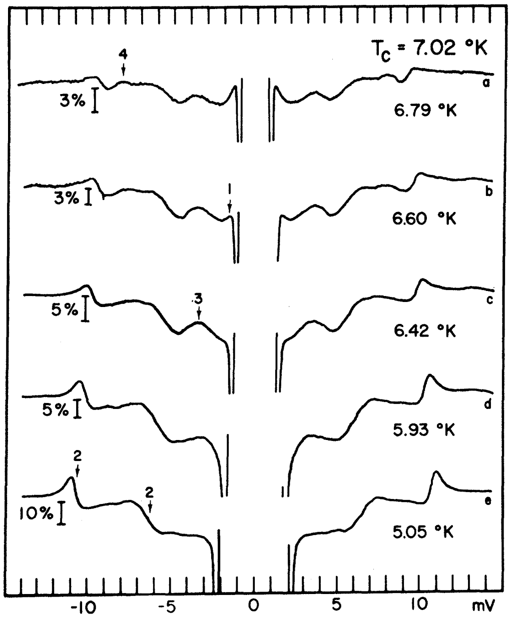

FIG. 1. dV/dI-versus-voltage curves for several temperatures on the same sample. Horizontal scale is identical for each curve, vertical scale is expanded for the higher temperatures as indicated by marker, labeled as percent of normal-state junction resistance at $V=0$, $R_N(V=0)$. Numbers refer to type of structure as described in the text.

EXPERIMENTAL PROCEDURE

Tunneling samples are prepared in an oil-diffusion-pump vacuum system, with a liquid-nitrogen-cooled titanium sublimation pump operating during evaporations. The system is equipped with a mask and substrate changer, multiple evaporation sources, and a built-in oxygen bottle with needle-valve control, so that the complete fabrication is done without exposure to air. During and between evaporations the pressure does not exceed 10^{-7} Torr.

The first Pb film is evaporated onto air-cleaved mica, heated to about 270°C. This procedure results in smooth epitaxial films. We have studied the crystal structure by reflection high-energy electron diffraction, and find mosaic films with a (111) plane parallel to the substrate.

To eliminate short circuits or tunneling at the edge of the film, crossed strips of ZnS a few hundred Angstroms thick are deposited as a thick insulator, leaving uncovered four windows about 0.2 mm square. Pure dry oxygen is bled into the system and the samples are oxidized in a glow discharge for ~10 sec at ~30 mTorr pressure. The system is then pumped down and four strips of Pb are deposited across the first strip, making four junctions on each sample. The Pb films are typically 2000 Å thick. We believe that the glow discharge technique with edge masking produces junctions of quality at least equal to those of other investigators. In support of this belief we report in the Appendix some of our low-temperature observations and compare them with those of other investigators.

The data recorded are current, dV/dI, and d^2V/dI^2 versus voltage, measured by the standard ac modulation technique. The ac voltage is fed by a transformer and high-impedance amplifier to a lock-in amplifier which can read either fundamental or second harmonic, and whose output drives the y axis of an x–y recorder. Detection frequency is 1 kHz. The dc voltage is amplified by another high-impedance amplifier and drives the recorder x axis. Structure in dV/dI of 0.1% is easily observable above the noise with a signal level of 30 μV rms. dc voltage calibration is about $\pm 2\%$ absolute, with relative accuracy much better than 2%. All measurements are made by a four-probe technique.

The sample is mounted on a copper block in a chamber which is immersed in liquid helium. Pressure in the chamber is adjusted to about 1 Torr of He gas. The copper block and sample are heated resistively and temperature measured with a germanium resistance thermometer. Temperature can be measured to better than 0.5% accuracy with resolution of better than 0.005°K at T_c (7°K). Temperature above 4.2°K is held constant to within this resolution for ample time to record several curves, except in cases when the junction resistance is very low and voltage high enough that current in the copper leads produces substantial Joule heating.

RESULTS

A typical set of resistance-versus-voltage curves is shown in Fig. 1. The lowest-temperature curve, for 5.05°K, is very similar to those published elsewhere[9] for temperatures down to 1°K. A number of changes with increasing temperature are apparent: (1) A maximum in resistance appears at voltages a little greater than $2\Delta(T)$. (2) The structure which exists at 5.05°K moves to lower voltage. (3) A broad bump appears, centered at 3.5 mV, which moves very little with temperature. (4) Another broad, smaller bump appears around 8 mV. These features are indicated in the figure by the numbers 1–4.

In order to check theoretical predictions against these results numerical calculations were done using first a modified BCS density of states and later the strong-coupling density of states calculated by SWS. We assume the usual SS tunneling equation[1]

$$IR_N=\int_{-\infty}^{\infty} dE\, \rho(E)\rho(E+eV)[f(E)-f(E+eV)],$$

where ρ is the density of states and R_N is the junction resistance in the normal state. It should be emphasized that R_N is not a constant, but depends on both voltage and temperature in a manner which can, of course,

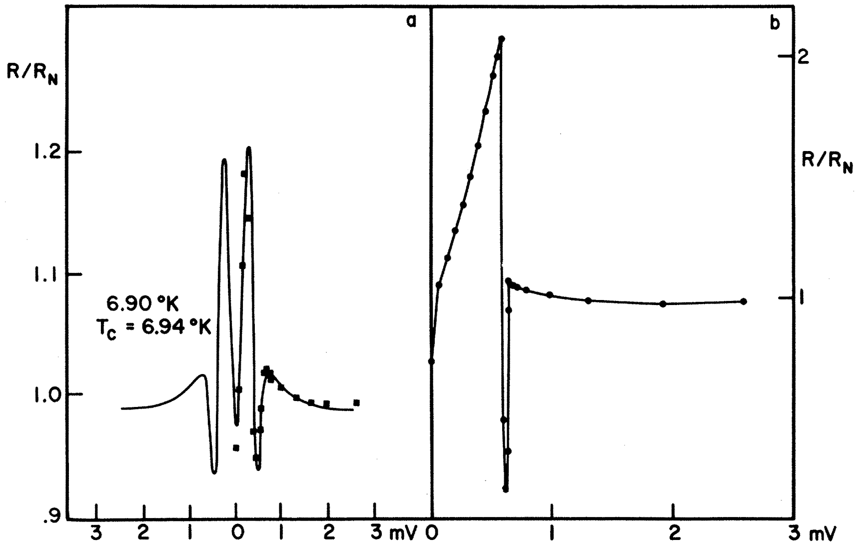

FIG. 2. dV/dI versus voltage. (a) Experimental curve, $T=6.90°\mathrm{K}$, $T_c=6.94°\mathrm{K}$. Calculated points from modified BCS density of states, $T=7.0°\mathrm{K}$, $T_c=7.0001$–$7.1°\mathrm{K}$. (b) Modified BCS calculation, $T=7.0°\mathrm{K}$, $T_c=7.09$–$7.1°\mathrm{K}$, with points joined by an arbitrary curve.

be measured, but not rigorously understood. Fortunately for the study of superconductivity, the main effect of $R_N(V)$ is to introduce a background curvature in dV/dI on which the structure associated with superconductivity is superimposed.

The large peak in resistance just outside the gap appears in all samples, including those made on glass substrates and those made without the ZnS edge masks. It is surprising that it has not previously been reported. A peak in this same position has been reported in tunneling from niobium,[10] but it is seen at low temperature, not near T_c, and so clearly is not the same effect. We find that BCS theory predicts the high-temperature peak and that with a small modification described in the next paragraphs, agreement with experiment is good.

BCS theory predicts a step in current at voltage 2Δ with zero width and infinite differential conductance. Experimentally a step with 0.1–0.2 mV width and finite conductance is observed, such that this deviation from BCS cannot be explained by thermal smearing. The origin of the finite slope is not quantitatively understood. In order to fit experiment near the gap edge, some means of smearing the square root singularity must be invoked. We have assumed a distribution of the gap, such as might arise from spatial inhomogeneity on a scale large compared to the coherence length but small compared to the junction dimensions.

The resulting modified BCS density of states is

$$\rho(E)=\int_0^E d\epsilon\, g(\epsilon)\,\frac{|E|}{(E^2-\epsilon^2)^{1/2}}\,.$$

The results shown in Fig. 2 are based upon a parabolic gap distribution,

$$\begin{aligned} g(\epsilon)&=(3/4a)\{1-[(\Delta-\epsilon)^2/a^2]\}, && \Delta-a<\epsilon<\Delta+a\\ &=0, && \text{otherwise.}\end{aligned}$$

We have also used a rectangular distribution, without substantially modifying our results.

The width parameter a can be expressed near T_c in terms of a range of T_c. In Fig. 2(a) we plot an experimental curve together with points calculated for $T=7.0°\mathrm{K}$, and a T_c range of 7.0001–7.1°K. The observed and predicted resistance peaks outside the gap agree very well. At lower temperatures agreement is not as good. We believe that this arises from our assumed sharp cutoff of the gap distribution at $\Delta\pm a$. To illustrate the effect of a major change in the gap distribution, Fig. 2(b) shows calculated points for $T=7.0°\mathrm{K}$, $T_c=7.09$–$7.10°\mathrm{K}$. This narrower distribution produces a sharp corner in dV/dI at a voltage $2(\Delta+a)$, and a somewhat higher peak. The resistance minimum at twice the gap edge is also greatly sharpened. For zero width, which is simply a pure BCS model, this sharpening is increased, and the resistance becomes discontinuous, with the minimum and maximum both located at voltage 2Δ. This resistance peak cannot be simply attributed to any single feature in the density of states, such as a minimum in the density of empty states above Δ. Such a minimum does exist at high enough temperatures but its position in energy does not correspond to the position in voltage of the resistance peak. The peak is an average effect of a large number of occupied states extending far above the gap.

It is not clear whether or not the idea of a gap distribution is a correct representation of the physical situation. We use it here only as a mechanism to

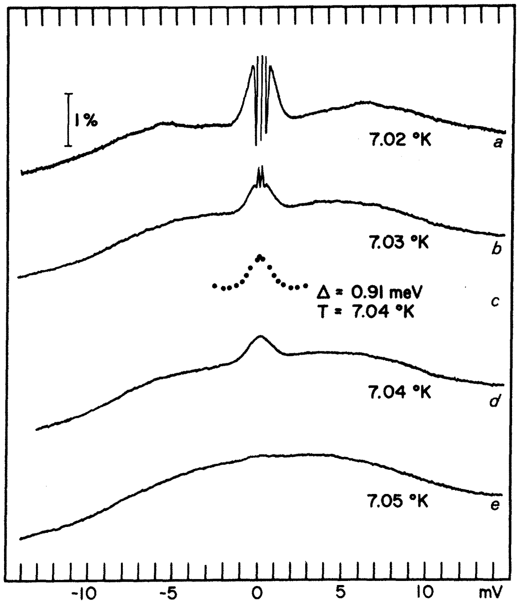

FIG. 3. dV/dI versus voltage for a narrow range of temperature, all the same sample. c is the calculated normal-superconductor tunneling resistance for appropriate temperature and gap. Note that a change in Δ would change the height of the peak but not its width. Marker indicates 1% of $R_N(V=0)$.

produce a reasonable slope in the current-voltage curves at 2Δ. Our experiments do yield one other bit of information in support of the idea of a range of T_c. Figure 3 shows that as temperature increases the SS gap disappears, but the two resistance peaks remain and merge into one. This single peak then disappears at about 0.02°K higher temperature, leaving the broad bump associated with normal tunneling. Using Bermon's program[11] to calculate the conductance in tunneling between a normal metal and a BCS superconductor, we find the points of curve c of Fig. 3. The calculated shape is the same as curve d, so we conclude that the peak is the energy gap observed by NS tunneling. There are two plausible explanations for this NS tunneling. Either one of the films goes normal while the other is still superconducting, or some areas of each are normal while some are still superconducting. The range of critical temperatures required for the latter explanation is a few tens of millidegrees, in rough agreement with the range required to fit the increase of current at 2Δ in SS tunneling.

The remaining structure described at the beginning of this section cannot be explained by BCS theory. We have, therefore, compared our experiments with numerical calculations of I and dV/dI versus voltage for several temperatures using the functions $\Delta(\omega)$ calculated by SWS, and the strong coupling density of states

$$\mathrm{Re}\{E/[E^2-\Delta^2(E)]^{1/2}\}.$$

The structure which exists at low temperature reflects decreases in the density of states due to emission of phonons. These decreases are located around $\omega_{\mathrm{ph}}+\Delta_0(T)$. For Pb, neutron scattering data indicate two ranges of high density of phonon states, $\omega_T=$ 3.5–5 meV and $\omega_L=8.5$–9 meV.[12] Structure in the electron density of states at an energy E appears in the SS tunneling measurement at a voltage corresponding to $E+\Delta_0(T)$, so this damping structure is located at $2\Delta_0(T)+\omega_{\mathrm{ph}}$. Thus, it moves with temperature as $2\Delta_0(T)$, staying a constant voltage away from the gap edge. Inspection of Fig. 1 shows that this indeed is the case, with 2Δ equal about 2.2 meV at 5.05°K and about 1.0 meV at 6.79°K.

Figure 4 shows theoretical points for three temperatures, together with experimental curves chosen to have matching gaps. The theoretical phonon-emission structure agrees well with experiment, except that the calculated peaks are about $\frac{1}{3}$ too big, and the ω_L structure is located about 0.1 mV too high. These differences are confirmed at low temperature and are assumed to arise from the approximate nature of the theoretical phonon spectrum.

For the structure in the range 3–4.5 mV, agreement between theory and experiment is not as good, as may also be seen from Fig. 4. Experimentally there is a single symmetric, broad peak, centered at 3.5 mV. From the experimental curves a–c of Fig. 1 and a and b of Fig. 4, this peak remains essentially stationary with temperature, moving by no more than 0.1 mV, while 2Δ changes by 1.0 mV. The calculation yields a broad peak, centered at 3.5 mV with a superimposed

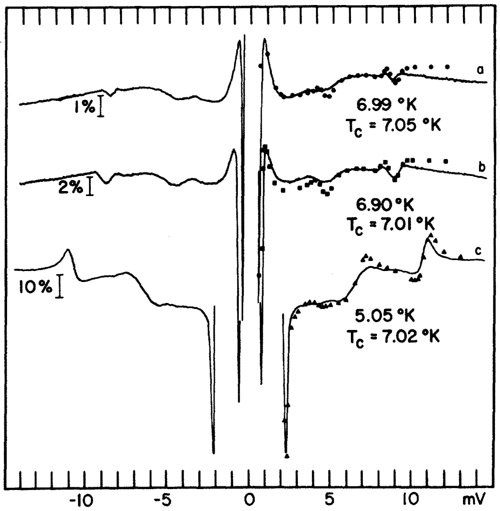

FIG. 4. dV/dI versus voltage for different temperatures, different samples. a—Solid line: experimental curve for $T=6.99$°K, $T/T_c=0.991$; dots: calculation from SWS strong-coupling-theory data for $T=7.11$°K, $T/T_c=0.990$. b—Solid line: experiment for $T=6.90$°K, $T/T_c=0.985$; squares: calculation for $T=7.02$°K, $T/T_c=0.977$. c—Solid line: experiment for $T=5.05$°K, $T/T_c=0.719$; triangles: calculation for $T=5.16$°K, $T/T_c=0.715$.

sharper peak at somewhat higher voltage, near 4.0 mV. This theoretical structure changes position and shape more rapidly with temperature than does the experimental structure. We believe, however, that the theoretical and experimental structures are related, and that the discrepancy again arises from the approximate theoretical model for the phonon spectrum.

Two processes may give rise to structure in this voltage range. One is the recombination process described by SWS, which modifies the density of states, while the other is a thermal effect involving no new features in the density of states. The recombination effect produces structure in the density of states at $\omega_T - \Delta_0(T)$, which then should appear in SS tunneling at a voltage corresponding to ω_T, independent of temperature. In the thermal effect, electrons excited above the gap in one superconductor tunnel into empty states above the gap in the other. For BCS superconductors this process adds a monotonically decreasing term to the conductance. But for lead at a voltage corresponding to ω_T the high density of occupied states at $\Delta_0(T)$ in the first superconductor sees the peak in density of states at $\omega_T + \Delta_0(T)$ in the second, resulting in a conductance maximum at a voltage somewhat less than ω_T. Thus, both processes are expected to produce structure in approximately the same place, near ω_T, 4.4 meV in the SWS model.

In order to separate the two processes we have performed a number of calculations of tunneling resistance using (a) the SWS density of states modified in such a way as to approximately eliminate the recombination effect, and (b) the correct high-temperature SWS density of states with the Fermi function for a very low temperature, thus eliminating the thermal effect. These calculations are not absolutely conclusive, but they indicate that in the calculations the sharper peak is entirely due to the thermal effect. Its sharpness, which does not agree with experiment, indicates that the transverse peak in the phonon spectrum assumed by SWS is too sharp. This conclusion is confirmed by the McMillan-Rowell[5] effective-phonon spectrum. The remainder of the calculated structure at 3.5 mV may be an indication of the recombination effect, but we cannot at present rule out the possibility that it may arise from thermal smearing in conjunction with the phonon-emission structure. The recombination process has a major effect on $\Delta(\omega)$, but only a broad, smooth effect on the density of states. Hence, at these relatively high temperatures no dramatic new structure can be expected.

As the temperature is raised, the shape of the longitudinal structure also changes. The point on this structure which can be identified with the emission process is the center of the steep rise in resistance located at $2\Delta(T) + 8.4$ mV. This inflection point, which is a peak on our second derivative curves, remains separated from the gap edge by a constant 8.4 ± 0.1 mV for all $T < T_c$. Near $T_c (T \gtrsim 0.95\, T_c)$ the peak just above this steep rise becomes flattened, and a new peak appears just below the rise. This new peak is readily apparent in curves *a* and *b* of Fig. 4 and agrees very well in position with our calculation. At lower temperature, the peak becomes so broad it is impossible to localize, so its temperature behavior cannot be accurately described. A calculation using the high-temperature density of states with a low-temperature Fermi function yields no peak at this point, indicating that the peak is due to thermally excited electrons at the gap edge in one superconductor tunneling into the longitudinal phonon peak in the density of states of the other, as discussed above for the transverse phonon peak.

At voltages above the longitudinal phonon structure in curves *a* and *b* of Fig. 4, the experimental resistance seems to be dropping away from the theoretical value. This is due to the nonconstant R_N described above. For extremely accurate work it can easily be measured and divided out of the experimental data, but the effect is small enough that we have not done so. The background normal tunneling curve is roughly parabolic with some smooth, very broad structure which is shown in curve *e* of Fig. 3. The superconducting structure very near T_c is about the same size as the normal structure, but it is much sharper and so can easily be separated from the background.

We have shown earlier in this section that the peak outside the gap is not a strong coupling effect, but simply a thermal one. It is caused by the occupation of an appreciable fraction of the states above the gap. However, its detailed shape is related to the density of states. Referring again to curve *b* of Fig. 4 we see that the peak calculated from strong coupling theory is somewhat bigger than that observed experimentally. Although it is not shown in curves *a* and *b* of Fig. 4, the calculated dip in resistance at 2Δ for T near T_c is much too deep, extending well below the bottom margin of the figure. This implies that the step in current is too steep. In fact, at zero temperature the step is vertical just as in BCS theory. So it is still necessary to assume some sort of distribution of gap. Such an assumption would make the dip at 2Δ shallower and a little wider and would also tend to reduce the size of the peak outside 2Δ without changing its shape significantly.

CONCLUSIONS

Other authors have shown that the structure observed in Pb-Pb superconducting tunneling for voltages of 3–20 mV at low temperature is accurately explained by the Eliashberg equations. The present work shows that the temperature behavior of the phonon-emission structure is also well understood, and that two new effects exist near T_c. One of these, the resistance peak just outside the gap, is a thermal effect which is

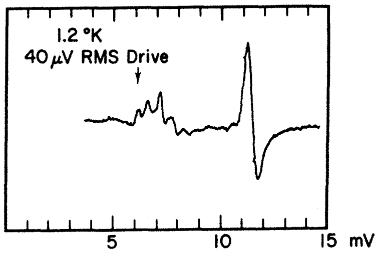

FIG. 5. d^2V/dI^2 versus voltage. The arrow marks the extra bump reported by Blackford and March (see Ref. 13).

predicted and fit rather well by either BCS or strong coupling theory. The other, a pair of peaks at 3.5 and about 8 mV, is primarily a thermal effect involving the phonon-emission structure. A modification in the density of states due to recombination of two excited quasiparticles to form a Cooper pair may contribute to the 3.5-mV structure, but as yet it has not been possible to separate any contribution due to this process from the effect of thermal occupation.

ACKNOWLEDGMENTS

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APPENDIX: LOW-TEMPERATURE OBSERVATIONS

Considerable experience has been gained by a number of groups in Pb-Pb tunneling at low temperature. In this section we describe some of our 1.2°K results in order to allow comparison of junction quality, and to point out a few small differences from previously reported results.

We have measured samples with good superconducting gaps with junction resistances from less than 0.1 Ω to greater than 1 MΩ. No difference in any of the observed effects, except Josephson tunneling, is seen between high- and low-resistance samples. Most samples exhibit the so-called subharmonic structure reported by a number of authors.[13] This complicated series of peaks inside the gap is not understood but is believed to be associated with tiny metallic bridges through the oxide. If we define a gap resistance ratio as the average resistance inside the gap divided by the resistance outside the gap, then for many samples this ratio is around 100, indicating about 1% nontunneling current. Even these samples usually exhibit some subharmonic peaks. It should be noted that other samples with much lower gap resistance ratios, even approaching 2, have all the same structure outside the gap as the "good" samples, with no additional structure. The only differences are that low-ratio samples are usually noisier, the relative size of structure is smaller, and the resolution is poorer, with peaks tending to round into shoulders. Thus, while some high-ratio samples are necessary to properly describe a new effect, other samples may be of considerable value in confirming structure observed in a small number of high-ratio ones.

Second-Harmonic Data

At low temperature, second-harmonic data recorded here (Fig. 5) agree in the smallest detail with the excellent curve published by Rowell and Kopf (Fig. 8 of Ref. 14) over the range 3–15 mV, except that we observe an extra dip at 6.0–6.1 mV (arrow in Fig. 5). This dip has previously been reported by Blackford and March[9] in tunneling from bulk single-crystal Pb into a Pb film. We observe this dip on some samples, including some deposited on glass as well as those on mica, but on others it appears only as a shoulder. Thus, the dip cannot be due to using bulk single-crystal Pb, as suggested by Blackford and March. We believe that its absence from some samples may be due to broadening of the peak in density of states at Δ_0. As discussed previously, we must assume such broadening to fit the finite width of the current step at $2\Delta_0$. This effect reduces the resolution of the measurement, and may be expected to vary between samples.

Normal Tunneling at 1.2 K

When a magnetic field large enough to quench superconductivity is applied, not all the structure in dV/dI disappears. Rowell, McMillan, and Feldmann (RMF)[15] have extensively analyzed their data on normal Pb at 1°K in terms of even and odd conductance. They observe a big (10%) bump in resistance between plus and minus 60 mV from which they draw a "barrier phonon density" spectrum, as shown in Figs. 4 and 5 of Ref. 15. Superimposed on this large anomaly is a smaller (1%) resistance bump between plus and minus 10 mV with very small (0.1%)

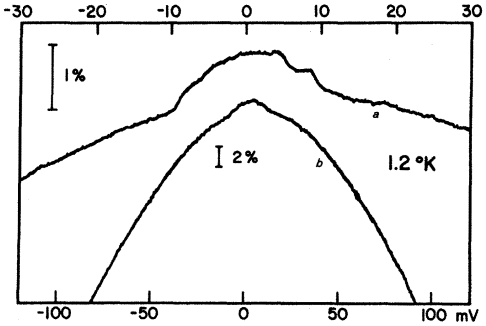

FIG. 6. dV/dI versus voltage at 1.2°K with magnetic field high enough to eliminate superconductivity. a: top voltage scale; b: bottom voltage scale. Markers indicate vertical scale of each curve as a percentage of $R_N(V=0)$.

bumps at about ±4 and ±8 mV, which they attribute to phonon emission in the surface layers of the metal and to self-energy effects in the Pb films. As shown in Fig. 6, we observe essentially identical structure to that of RMF in the ±10-mV range, but the big peak is totally absent. Beyond about 10 mV the conductance follows the usual approximately parabolic form of normal tunneling with no bump as big as 0.5%, and beyond about 40 mV the curves for normal and superconducting Pb at 1.2°K are identical to within 0.2% of the zero voltage normal resistance.

Another difference between our normal Pb data and that of RMF is the large (100 mV) offset from zero voltage of the conductance parabola in their data, compared to the much smaller offset shown in Fig. 6. This is simply an indication of different barrier shapes in the two experiments. The data of RMF indicate a high degree of asymmetry in the barrier, while our Fig. 6 indicates a much more symmetric barrier.[16,17]

There are several major differences in fabrication between our samples and those of RMF. Their samples are made on glass; most of ours are on mica. Theirs are simple crossed strips, while most of ours have masked edges. Their junctions are thermally oxidized at atmospheric pressure outside their evaporator; ours are oxidized by glow discharge in low-pressure pure oxygen. These are substantial differences, and the fact that the small structure below 10 mV is reproduced in size as well as position indicates that it is indeed fundamental and probably is due to the Pb electrodes rather than to the barrier. The total absence of the big peak in our samples indicates, however, that it is certainly not fundamental, and it seems unwarranted to attribute this effect specifically to barrier phonons.

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[1] I. Giaever, H. R. Hart, Jr., and K. Megerle, Phys. Rev. **126**, 941 (1962).

[2] I. Giaever, Phys. Rev. Letters **5**, 147 (1960).

[3] J. R. Schrieffer, D. J. Scalapino, and J. W. Wilkins, Phys. Rev. Letters **10**, 336 (1963).

[4] J. M. Rowell, P. W. Anderson, and D. E. Thomas, Phys. Rev. Letters **10**, 334 (1963).

[5] W. L. McMillan and J. M. Rowell, in *Superconductivity*, edited by R. D. Parks (Marcel Dekker, New York, 1969), p. 561.

[6] D. J. Scalapino, Y. Wada, and J. C. Swihart, Phys. Rev. Letters **14**, 102 (1965).

[7] J. P. Franck and W. J. Keeler, Phys. Rev. **163**, 373 (1967).

[8] P. Vashishta and J. P. Carbotte, Solid State Commun. **8**, 161 (1970).

[9] B. L. Blackford and R. H. March, Phys. Rev. **186**, 397 (1969).

[10] M. L. A. MacVicar and R. M. Rose, Phys. Letters **26A**, 510 (1968).

[11] S. Bermon, University of Illinois Technical Report No. 1, NSF-GP-1100, 1964 (unpublished).

[12] B. N. Brockhouse, T. Arase, G. Caglioti, K. R. Rao, and A. D. B. Woods, Phys. Rev. **128**, 1099 (1962).

[13] J. M. Rowell and W. L. Feldmann, Phys. Rev. **172**, 393 (1968).

[14] J. M. Rowell and L. Kopf, Phys. Rev. **137**, 907 (1965).

[15] J. M. Rowell, W. L. McMillan, and W. L. Feldmann, Phys. Rev. **180**, 658 (1969).

[16] A. Gruodis and R. C. Barker (unpublished).

[17] W. F. Brinkman, R. C. Dynes, and J. M. Rowell, J. Appl. Phys. **41**, 1915 (1970).