$$\langle A_2\rangle=(1-\Delta)(P_3+\psi P_1)-P_1\beta\Delta \;,$$

$$\langle G_2\rangle=(\mu+\mu'\Delta)(P_3+\psi P_1)-P_1\beta\Delta\mu' \;;$$

$$\langle B_2\rangle=(\langle A_2\rangle\nu-\langle G_2\rangle)\left(1-\frac{1}{\epsilon}\right)\frac{\sin^2\theta}{2\cos\theta}+f\langle l_2\rangle-f'\langle l_2'\rangle+\tfrac{1}{2}(P_1-P_5) \;,$$

$$\langle H_2\rangle=(-\langle A_2\rangle+\langle G_2\rangle\nu')\left(1-\frac{1}{\epsilon}\right)\frac{\sin^2\theta}{2\cos\theta}+f\langle l_2\rangle\nu+f'\langle l_2'\rangle\nu'+\tfrac{1}{2}(P_1\nu+P_5\nu') \;;$$

$$f=1/(\cos^2\theta-\beta^{-2}) \;,\qquad f'=1/(\epsilon(\omega)-\sin^2\theta-\beta^{-2}) \;,$$

$$P_0=\exp[-i(\omega/c)(d/\beta)] \;,\qquad P_1=f'-f \;,$$

$$P_2=(f'/\epsilon-f)\Delta \;,\qquad P_-=P_1-P_2 \;,$$

$$P_+=P_1\nu+P_2\nu' \;,\qquad P_3=2(f'^2-f^2)/\beta$$

$$P_4=2\left(\frac{f'^2}{\epsilon}-f^2\right)\frac{\Delta}{\beta} \;,\qquad P_5=-(P_3+\psi P_1)\frac{\sin^2\theta}{\epsilon\cos\theta} \;,$$

$$\psi=i(\omega/c)\,\tfrac{1}{2}d \;,\qquad \Delta=1/\beta\cos\theta \;,$$

$$\delta=(\epsilon-\sin^2\theta)^{1/2}/\cos\theta \;,$$

$$\langle l_2\rangle=f\left(\tfrac{1}{2}\sin^2\theta+\frac{\psi\sin^2\theta}{\beta}+\frac{1}{\beta^2}\right)+\frac{2f^2\sin^2\theta}{\beta^2}+\tfrac{1}{2}\psi+\tfrac{2}{3}\psi^2,$$

$$\langle l_2'\rangle=f'\left(\tfrac{1}{2}\sin^2\theta+\frac{\psi\sin^2\theta}{\beta}+\frac{1}{\beta^2}\right)+\frac{2f'^2\sin^2\theta}{\beta^2}+\tfrac{1}{2}\psi+\tfrac{2}{3}\psi^2.$$

A detailed analysis of accurate experimental data in light of the present results will be given in the subsequent paper.

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Temperature Variation of the dc Josephson Current in Pb-Pb Tunnel Junctions*

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The temperature variation of the dc Josephson current $J_s(T)$ of Pb-Pb tunnel junctions has been investigated both experimentally and theoretically. The experimental data do not agree with the temperature dependence of the dc Josephson current derived by Ambegaokar and Baratoff for the case of two weak coupling superconductors. However, detailed numerical calculations of the temperature variation of the dc Josephson current for a Pb-Pb tunnel junction, which employ strong coupling superconductivity theory throughout, are in reasonably good agreement with the experimental measurements.

I. INTRODUCTION

The work to be described is a joint experimental and theoretical investigation of the temperature variation of the dc Josephson current for a Pb-Pb tunnel junction. The experimental work was carried out by the group at Waterloo, while the theoretical work was performed by the group at McMaster.

Previous experimental work on the temperature variation of the dc Josephson current has been interpreted as supporting the temperature dependence derived by Ambegaokar and Baratoff[1] for the case of two weak coupling superconductors. For example, both Fiske[2] for Sn-Sn and Pb-Sn Josephson junctions and Hauser[3] for Pb-Pb Josephson junctions concluded that the temperature dependence of the dc Josephson current was described by the Ambegaokar-Baratoff formula. However, while Fiske's data for an Sn-Sn Josephson junction agree reasonably well with the calculation of Ambegaokar and Baratoff, his data for a Pb-Sn Josephson junction show rather large deviations from the theoretical curve. Similarly, Hauser's data for a Pb-Pb Josephson junction show a rather large amount of scatter around the curve of Ambegaokar and Baratoff.

The experimental work described here shows that for Pb-Pb Josephson junctions there is a systematic deviation from the temperature dependence of the dc Josephson current predicted by Ambegaokar and Baratoff. The theoretical work presented in this paper shows that the observed temperature variation of the dc Josephson current is caused by strong coupling effects.

We will present the experimental procedure in Sec. II, the theoretical calculations in Sec. III, and the experimental results and theoretical comparison in Sec. IV.

II. EXPERIMENTAL PROCEDURE

The Pb-Pb Josephson junctions used in this investigation were prepared in the following way. A Pb strip, 2400 Å thick and 0.08 mm wide, was evaporated onto a standard glass microscope slide. This Pb strip was exposed to 1 atm of dry air for 3 h to form the tunneling barrier. Then four cross strips of Pb, 2400 Å thick and 0.1 mm wide, were evaporated to complete the four tunnel junctions on each slide. The resistance of the tunnel junctions so formed was of the order of 0.1 Ω.

The sample holder consisted of a copper block that was thermally isolated from an enclosing vacuum jacket by a short section of thin-wall stainless-steel tubing. Up to six slides could be mounted on the copper block at one time. A thin layer of Apiezon N grease was used between the slides and the copper block to improve thermal contact. Electrical contact to the tunnel junctions was made by pressure contacts onto gold contacts evaporated onto the glass slides prior to the preparation of the tunnel junctions. The electrical leads which came down to the pressure contacts were thermally anchored at their place of entry into the vacuum jacket and again at the copper block to ensure that heat did not leak down the wires and into the junctions. Temperatures were measured by means of a calibrated germanium resistor.[4] A fixed current of 10 μA was passed through the germanium resistor and the voltage across it was measured with a Tinsley Type 4363A potentiometer. The absolute accuracy of the temperature measurement was $\pm 0.01\,^{\circ}$K. A heater and a carbon resistor were also mounted on the copper block for use with a temperature regulator.[5] The heater consisted of two separate windings in series, with one located at the top of the copper block and the other at the bottom of the copper block. This was done to ensure a uniform distribution of heat and fast thermal response when the heater is being used.

A temperature run was made in two parts. For temperature below 4.2 °K, a small amount of helium gas was introduced down a pumping tube into the vacuum jacket. In this way, good thermal contact was obtained between the copper block and the liquid-helium bath that surrounded the vacuum jacket. The temperature of the block was adjusted by varying the pumping rate on the liquid-helium bath. For temperatures above 4.2 °K, the helium gas introduced into the vacuum jacket was pumped out so that there was good thermal isolation between the copper block and the vacuum jacket. The temperature of the copper block was then adjusted by using the heater on the copper block and associated temperature regulator. If the heater was turned off, the temperature of the copper block would relax to that of the helium bath via thermal conduction along the stainless steel supporting tube and electrical wires. To determine whether this method of splitting a temperature run introduced any error, we repeated some runs using a lower changeover temperature between the two techniques. We found identical results. The only reason for not pumping the helium bath down to the lowest temperature, isolating the copper block, and using the heater and temperature regulator for the whole temperature range was that it would have used more liquid helium than splitting a run in two as we did.

Figure 1 shows the circuit that was used to measure the magnitude of the dc Josephson current. The principle of the method of measurement was to drive the Josephson junction with a low-frequency (120 Hz) ac current source and plot the resulting I-V characteristic on an oscilloscope. The junction voltage was plotted on the X axis of the oscilloscope and the voltage across a 10-Ω precision resistor in series with the junction, which measures the current through the junction, was plotted on the Y axis of the oscilloscope. By using a relay operating at 60 Hz and an adjustable dc reference voltage, it was possible to alternate the display of the voltage proportional to the junction current and the reference voltage on the Y axis of the oscilloscope. The reference voltage appeared on the I-V characteristic as a horizontal line, produced by the voltage across the junction which was swept through one cycle while the reference voltage, rather than the junction current, was displayed on the scope. The dc Josephson current appeared on the oscilloscope display as a vertical line at zero voltage. By adjusting the horizontal reference voltage line, it was possible to make

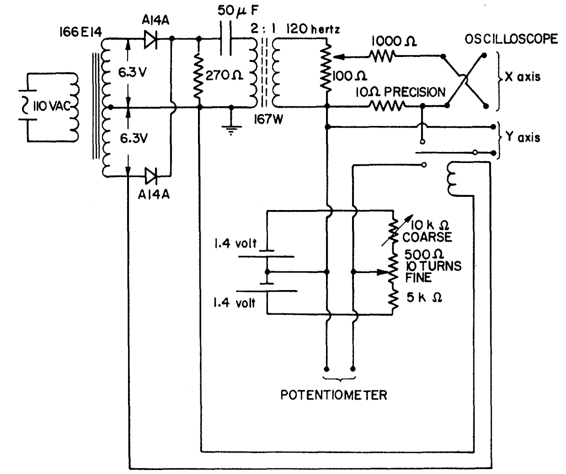

FIG. 1. Circuit for measuring the magnitude of the dc Josephson current. The relay was a Potter and Brumfield Mercury Wetted JML 8130 81, and the oscilloscope was a Tektronix 502A.

the reference voltage equal to the voltage across the current sensing 10-Ω resistor, as determined by the horizontal reference voltage line just passing through the top of the vertical dc-Josephson-current line. By adjusting the reference voltage it was possible to measure the peak-to-peak height or the zero-to-peak height. We ended up using the latter because it simplified the data taking. The reference voltage was displayed on an X-Y recorder which was just used as a plotting potentiometer. In this way the magnitude of the dc Josephson current could be determined quite accurately, since the oscilloscope was used only as a null detecting device and the vertical gain could be turned up so that only a section of the dc Josephson current was displayed on the oscilloscope. The limiting factor on the accuracy of determining the magnitude of the dc Josephson current was the thickness of the trace and the small amount of fluctuation in the dc Josephson current itself. We conclude that the absolute accuracy of the current measurement is better than $\pm 0.2\%$.

A magnetic coil was located in the nitrogen Dewar surrounding the sample in the helium Dewar. A Mumetal shield surrounded the lower section of the nitrogen Dewar. At each temperature, we adjusted the magnetic field to maximize the dc Josephson current. This was necessary because of a small amount of the earth's magnetic field leaking through our Mumetal shield and/or a small amount of field produced by the tunneling currents flowing in the leads of the junction. The maximum magnetic field needed to maximize the dc Josephson current was typically 56 mG at the lowest temperature and decreased as the temperature was increased. This was approximately 10 times less than the field needed to maximize the dc Josephson current in some earlier work on junctions which showed self-limiting effects.[6] At higher temperatures close to T_c, sometimes the dc Josephson current would show a sudden decrease. We attributed this to some stray flux being trapped in the junction. Once we had warmed the junction above T_c in a zero magnetic field and cooled down again to the same temperature, the junction regained its original value of dc Josephson current. The transition temperature T_c was taken to be the temperature at which the dc Josephson current first vanished.

Six junctions were measured in some detail. The junctions showed a constant maximum current below 2.3 °K (i.e., T/T_c less than 0.3). Therefore, the maximum dc Josephson current at 1.8 °K was taken as $J_s(0)$. The value of $J_s(0)$ and T_c was used to normalize the data, in that the raw data were plotted up finally as curves of $J_s(T)/J_s(0)$ versus T/T_c. The energy gap was measured directly from the oscilloscope, but the accuracy of this determination was not great. However, the value of the energy gap does not come into the measurements, only into a characterization of the samples. The normal-state resistance of the tunnel junction was determined from the oscilloscope display. Once again this determination was not too accurate because of the small scale of the oscilloscope face, but we only wanted the resistance to characterize the sample, and in particular to determine the efficiency of the junctions.

The reasons for employing the circuit of Fig. 1 rather than plotting the dc I-V characteristic on an X-Y recorder are the following: In plotting out the maximum dc Josephson current by increasing a dc current through the junction and observing the current at which the junction voltage suddenly switched from zero to 2Δ, a small amount of noise can cause the junction to trigger prematurely at a lower current than the true maximum. Also in adjusting the magnetic field to maximize the dc Josephson current, one would have to make several I-V plots for different magnetic fields to find the optimum field. By using the ac method of sweeping out the I-V characteristic continuously, one is in effect performing a number of separate determinations of the I-V characteristic. Thus, the effects of any noise just show up as a little jitter of the top of the vertical dc-Josephson-current trace. Also, the effect of varying the magnetic field can be clearly seen, since it results directly in the magnitude of the vertical dc-Josephson-current trace increasing or decreasing.

III. THEORETICAL CALCULATIONS

A general expression for the dc Josephson current J_s has been derived by Ambegaokar and Baratoff,[1] who discuss in some detail the temperature variation of $J_s(T)$ for the case of two weak coupling superconductors. More recently, Nam[7] as well as Fulton and McCumber[8] have emphasized the case of junctions made of strong coupling superconductors. The work of Nam is formal. Fulton and McCumber present results of detailed numerical calculations for the current J_s at $T=0$. For a Pb-Pb junction they conclude that strong coupling effects reduce $J_s(T=0)$ by more than 20%. Here we extend the work to finite temperatures and calculate the temperature variation of $J_s(T)$ for the Pb-Pb case.

Fulton and McCumber[8] quote a formula for $J_s(T)$ valid at finite temperatures and for strong coupling superconductors:

$$J_s(T)=\frac{2}{\pi e R_N}\int_0^\infty d\omega_1$$

$$\times\int_0^\infty d\omega_2\left(\frac{f(\omega_1)-f(\omega_2)}{\omega_1-\omega_2}+\frac{1-f(\omega_1)-f(\omega_2)}{\omega_1+\omega_2}\right) \tag{1}$$

$$\times\ \mathrm{Re}\left(\frac{\Delta(\omega_1,T)}{[\omega_1^2-\Delta^2(\omega_1,T)]^{1/2}}\right)\ \mathrm{Re}\left(\frac{\Delta(\omega_2,T)}{[\omega_2^2-\Delta^2(\omega_2,T)]^{1/2}}\right)\ .$$

In Eq. (1), R_N is the normal-state junction resistance and $f(\omega)$ is the Fermi function

$$f(\omega)=(1+e^{(\omega/kT)})^{-1}\ .$$

For a Pb-Pb junction $\Delta(\omega, T)$ is the frequency-dependent gap parameter for Pb at temperature T. For a derivation of Eq. (1) the reader is referred to Refs. 1 and 8 as well as Nam's papers.[7] We are only interested in the numerical evaluation of Eq. (1) to obtain the Josephson current as a function of temperature. The most difficult part of such a problem is to determine the gap function $\Delta(\omega, T)$. This requires the solution of the Éliashberg[9] gap equations at finite temperature. We have iterated these equations at a number of temperatures using the numerical data of McMillan and Rowell[10] for the kernels entering the gap equations. The kernels are completely determined in terms of a frequency-dependent phonon part $\alpha^2(\omega)F(\omega)$ and a Coulomb pseudopotential U_C. In principle, these two normal-state parameters completely determine the superconducting properties of Pb. They can be obtained from quasiparticle tunneling data using an inversion technique of the Éliashberg equations which is now well known.[10]

In Fig. 2(a), we present results for the real

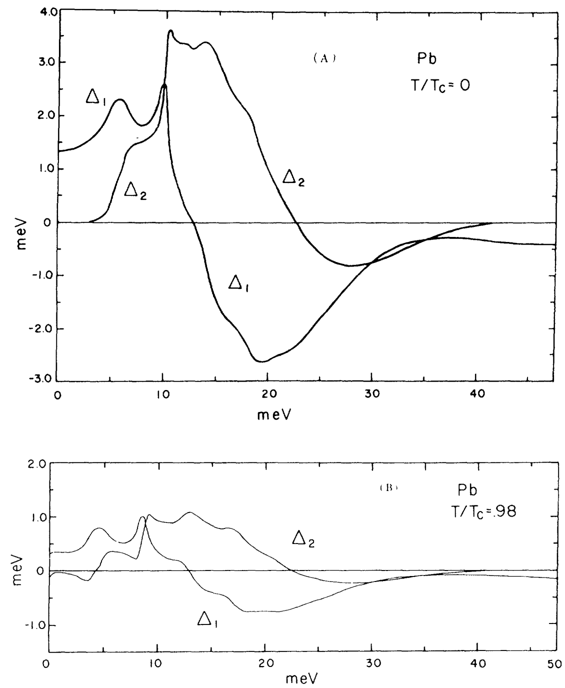

FIG. 2. Frequency dependence of the real $\Delta_1(\omega, T)$ and imaginary $\Delta_2(\omega, T)$ parts of the gap for (a) $T=0$; (b) $T=0.98T_c$. The zero-temperature results are for reference only. The McMillan and Rowell $\alpha^2(\omega)F(\omega)$ is used in both cases.

and imaginary part of $\Delta(\omega, T)$ at zero temperature,

$$\Delta(\omega, 0)=\Delta_1(\omega, 0)+i\Delta_2(\omega, 0)\ .$$

Such solutions are not new and are given by McMillan and Rowell. Our results agree well with theirs. Denoting by $J_{sw}(T)$ the Josephson current predicted by the weak coupling formula

$$J_{sw}(T)=[\pi\Delta_0(T)/2eR_N]\tanh[\Delta_0(T)/2kT]\ , \tag{2}$$

where $\Delta_0(T)$ is the BCS temperature-dependent gap, we obtain for the ratio

$$J_s(T=0)/J_{sw}(T=0)$$

the value 0.80. Fulton and McCumber using the McMillan-Rowell data obtain a value 0.788 for the above ratio.[11]

In Fig. 2(b), we show the frequency dependence of $\Delta_1(\omega, T)$ and $\Delta_2(\omega, T)$ for a temperature near the critical temperature T_c. Our results differ in details from the finite-temperature solutions obtained by Swihart, Scalapino, and Wada.[12] Since we have used a more realistic spectrum for the phonon part $\alpha^2(\omega)F(\omega)$, our work represents an improvement. In this connection we mention that the calculated gap edge at zero temperature is 1.385 meV with a calculated critical temperature of 7.29 °K.

The Coulomb part U_C was taken to be 0.149 and the phonon cutoff in the Eliashberg kernels adjusted to $\omega_c = 55$ meV. The numerical spectrum was employed on a 45-point mesh because of the computer time limitations. As trial gap the BCS value was used and 18 iterations performed to get a stability in the calculated gap edge in the third figure after the decimal. Using 51 instead of 45 points changed U_C but did not appear to alter any of our conclusions. At finite temperature and in strong coupling theory, the gap edge $\Delta_0(T)$ is defined as the solution of

$$\Delta_1(\Delta_0(T), T) = \Delta_0(T) .$$

The temperature variation for the reduced gap ratio $\Delta_0(T)/\Delta_0(0)$ obtained is shown in Fig. 3 as a function of the reduced temperature T/T_c. It is also compared with the BCS variation. For temperatures less than roughly $\sim 0.84T_c$, our results are above BCS whereas beyond they seem to be slightly below BCS. This general behavior is in agreement with the experimental data of Gasparovic *et al.*,[13] although we predict more deviation in the low-temperature region than they seem to pick up. We point out, however, that the graphical construction they use to deduce a gap value from tunneling result is different from that employed more recently by McMillan and Rowell.[10] This may have some effect on the results.

IV. EXPERIMENTAL RESULTS AND THEORETICAL COMPARISON

The six junctions that were measured in detail had the following T_C's: 7.19, 7.23, 7.25, 7.27, 7.28, and 7.35 °K. The uncertainty in the determination of T_c was ±0.01 °K. The normal-state junction resistances R_N ranged from 0.08 to 0.26 Ω. The experimentally observed values of $J_s(T=0)$ ranged from 5.6 to 12.8 mA. The

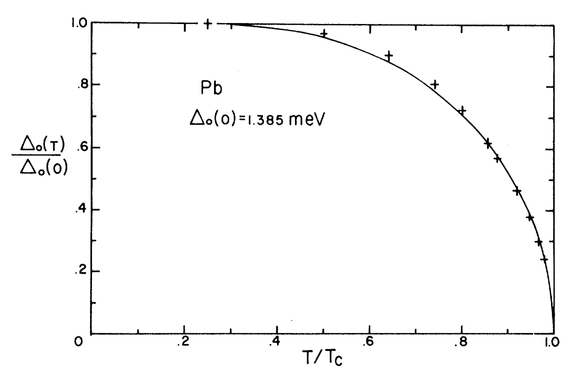

FIG. 3. Variation with reduced temperature T/T_c of the gap ratio $\Delta_0(T)/\Delta_0(0)$. The BCS variation is also shown (solid line) for comparison.

ratio $J_s(T=0)/J_{sw}(T=0)$ for four of the junctions was between 0.55 and 0.66 and for two junctions was 0.40. Theoretically, for a Pb-Pb junction this ratio should be 0.80 as was stated in Sec. III; however, experimentally this ratio is always found to be lower than the theoretical value, but the reason for this discrepancy is not known. The value of the ratio $J_s(T=0)/J_{sw}(T=0)$ did not have any systematic effect on the temperature variation of $J_s(T)$ for these Pb-Pb junctions. Similarly, we have observed that the value of this ratio does not affect the temperature variation of $J_s(T)$ for weak coupling junctions. The junctions all had a zero-temperature Josephson penetration length λ_J equal to slightly less than the length of the junction L. Since size effects barely become noticeable until $L/\lambda_J > 2$,[14] and using the usual temperature dependence of λ_J,[6] this situation does not occur for our junctions until $T/T_c > 0.985$, we do not believe that our results are affected by size effects.

In Fig. 4, we show the experimental temperature variation of the dc Josephson current for Pb-Pb junctions studies in this experiment. The data for the different junctions were normalized for different $J_s(T=0)$ and T_c, by plotting $J_s(T)/J_s(T=0)$ versus T/T_c. The normalized data for the six junctions were then averaged to yield the solid experimental curve. Error bars have not been shown on the curve for the sake of clarity, but they were assigned in the following way. The vertical error bars were taken to be the *maximum* deviation of the six junctions from the average value. Following this procedure, the vertical error bars are ±0.002 for $0 < T/T_c < 0.45$, ±0.005 for $0.45 < T/T_c < 0.80$, and ±0.010 for $0.80 < T/T_c < 1.00$. The horizontal error due to temperature uncertainty is ±0.0014, and is completely negligible.

The solid triangles in Fig. 4 show values of $J_{sw}(T)/J_{sw}(T=0)$ that result from using the BCS $\Delta_0(T)$ in Eq. (2). As can be seen from Fig. 4 the experimental $J_s(T)/J_s(T=0)$ versus T/T_c is significantly different from the weak coupling prediction of Eq. (2). Even if one attempts to incorporate some strong coupling effects into Eq. (2), by using the strong coupling $\Delta_0(T)$ calculated in Sec. III rather than the BCS $\Delta_0(T)$, the resulting points shown on Fig. 3 as solid circles still do not agree with the experimental results.

The crosses in Fig. 4 show values of $J_s(T)/J_s(T=0)$, at a number of values of T/T_c, calculated from Eq. (1) following the procedure outlined in Sec. III. As can be seen from Fig. 4, Eq. (1) predicts that strong coupling effects are much larger than what one would expect on the basis of Eq. (2) even if the strong coupling $\Delta_0(T)$

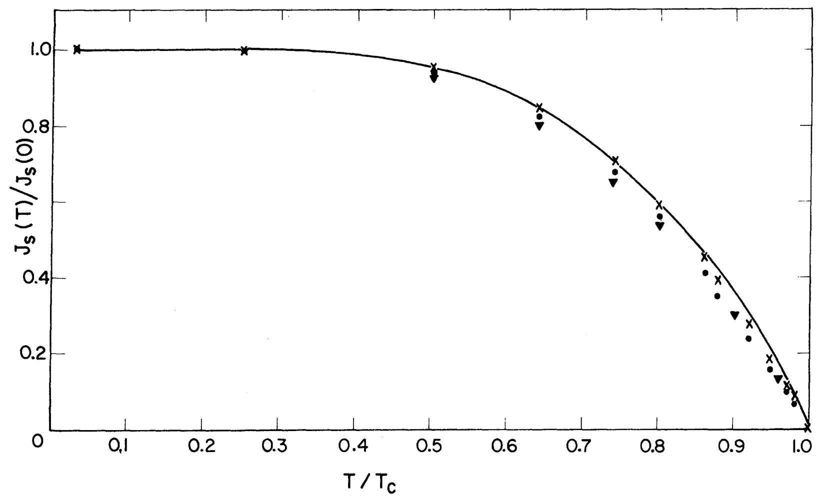

FIG. 4. Plot of the normalized dc Josephson current, $J_s(T)/J_s(T=0)$ versus reduced temperature T/T_c. The solid line is the experimental temperature variation that is observed in this experiment. The crosses are the strong coupling values calculated from Eq. (1), following the procedure outlined in Sec. III. The solid triangles are the predictions of Eq. (2) using the BCS $\Delta(T)$, while the solid circles are the result of putting the strong coupling $\Delta(T)$ from Sec. III into Eq. (2).

is used. The values of $J_s(T)/J_s(T=0)$ calculated from Eq. (1) are in excellent agreement with the experimental data over most of the temperature range. However, for T/T_c greater than 0.8, the values of $J_s(T)/J_s(T=0)$ calculated from Eq. (1) are significantly lower than the experimental curve, but are still in much better agreement with the experimental results than the predictions of Eq. (2). Whether this discrepancy between the predictions of Eq. (1) and the experimental results is due to experimental error, a limitation of the numerical calculations, or an additional physical mechanism is unknown at the present time.

In conclusion, the temperature variation of the dc Josephson current in Pb-Pb tunnel junctions has been shown experimentally to deviate significantly from the prediction of Ambegaokar and Baratoff. Detailed numerical calculations, which employ strong coupling superconductivity theory throughout, have shown that the deviation is the result of strong coupling effects. These calculations are in excellent agreement with the experimental data over most of the temperature range, but differ from the experimental curve over a narrow temperature range near T_c where experiment is higher than theory.

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