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Enhancement of the Energy Gap in Superconducting Aluminum by Tunneling Extraction of Quasiparticles

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Al-Al_2O_3-Al-Al_2O_3-Al tunnel junctions have been used to induce and detect enhancements of up to 40% in the energy gap of superconducting aluminum. Quasiparticles are extracted from the middle aluminum film through the first tunnel junction into an aluminum film with a larger energy gap, and the gap enhancement in the middle film is measured from the characteristics of the second tunnel junction.

The energy gap, Δ, of superconducting aluminum can be enhanced by microwave[1,2] or phonon[3] irradiation. The enhancement arises from the excitation of low-energy quasiparticles to higher energies, thereby making additional pair states near the Fermi wave vector available for occupancy,[4,5] and increasing the condensation energy. Long before these experiments were performed, Parmenter[6] proposed that Δ could be enhanced by the extraction of quasiparticles through a tunnel barrier into a second superconductor with a larger gap. More recently, Peskovatskii and Seminozhenko[7] calculated the magnitude of the enhancement produced by quasiparticle tunneling between identical superconductors using a linearized quasiparticle kinetic equation with the assumption that the phonons remain in thermal equilibrium. Subsequently, Chang[8] also calculated the enhancement generated by tunneling between identical superconductors, but used the coupled kinetic equations for the quasiparticle and phonon distributions, thereby taking into account the effects of the non-equilibrium phonon distribution. In this Letter we report the experimental observation of gap enhancements of up to 40% in aluminum films by tunneling extraction of quasiparticles.[9]

We first comment on the theory of the steady-state distribution of quasiparticles in a tunnel junction. For the case of identical superconductors, at voltages $<2\Delta/e$ the tunneling process creates a quasiparticle branch imbalance[10] of opposite polarity in each superconductor. As a result, quasiparticles are transferred to higher energies in each superconductor, and, because the recombination rate increases with energy, the total number of quasiparticles in each superconductor decreases slightly. Both effects tend to increase Δ.[5,8] On the other hand, if the two superconductors have different gaps Δ_1 and Δ_2 ($\Delta_1 > \Delta_2$), at voltages less than $(\Delta_1 + \Delta_2)/e$ there is a net extraction of quasiparticles from film 2 and an equal net injection of quasiparticles into film 1.[6] The depletion of the quasiparticle population in film 2 and the resulting enhancement of Δ_2 can be much greater than in the case of equal gaps, particularly at voltages near $(\Delta_1 - \Delta_2)/e$. The enhancement of Δ_2 is reduced, however, by phonons of energy $\gtrsim 2\Delta_1$ produced by the recombination of the excess quasiparticles in film 1. These phonons can readily propagate from film 1 to film 2, where they have some probability (depending on the pair-breaking and phonon escape times) of breaking pairs. To minimize the phonon pair breaking in film 2, and also to increase the quasiparticle depletion density for a given extraction current, it is desirable to make film 2 as thin as possible, and to use superconductors with long electron-phonon scattering times. Thus we used thin aluminum films in our experiments, with film 1 doped with oxygen to make $\Delta_1 > \Delta_2$.

The experimental configuration is shown in the upper inset of Fig. 1. The first Al film (1), 1.5 mm wide, was evaporated slowly onto a glass substrate at a low pressure of air so that its transition temperature was enhanced by oxygen doping. Next, a film of SiO, 150 to 300 nm thick, was evaporated to produce a 0.5 × 0.5 mm window on the Al strip. The Al film was oxidized by briefly admitting air to the evaporator, and a relatively clean Al film (2) was deposited rapidly in a high vacuum. The sample was removed from the evaporator, and a thin layer of Duco cement was applied to mask off all the previous films except for a small window on the second Al film that lay completely inside the SiO window. The second Al film was oxidized in air for about 5 minutes during this process. The sample was returned to the evaporator, and the third Al film (3) was deposited in a low pressure of air. This procedure produced a low resistance extraction junction between Al(1) and

Al(2), and a relatively high resistance detection junction between Al(2) and Al(3), so that the detection current did not significantly perturb the quasiparticle population in Al(2). Furthermore, Δ_1 was greater than Δ_2, to achieve quasiparticle extraction from Al(2), and Δ_3 was also greater than Δ_2, so that Δ_2 could be measured at temperatures very close to the transition temperature of Al(2).

The sample was immersed directly in liquid helium. The detection junction characteristics ($I_d - V_d$) were studied as a function of the extraction current, I_e. Gap enhancement was always observed in Al(2) provided that the extraction junction had negligible leakage current. Of the 11 samples in which we have observed enhancement, we present results on the two showing the greatest enhancement, A and B. Table I shows the film thicknesses, d_1, d_2, and d_3, and the transition temperatures T_{c1}, T_{c2}, and T_{c3}, (defined as the temperature at which Δ extrapolates to zero[11]) of the three Al films, and the extraction and detection junction resistances, R_e and R_d, measured at voltages much greater than the sum of the gaps. Figure 1 shows I_d vs. V_d and dV_d/dI_d vs. V_d for sample A at $T/T_{c2} = 0.986$, where T is the bath temperature. The labels indicate the bias points on the extraction junction characteristic (inset of Fig. 1) at which the various detector curves were obtained. As I_e is increased from zero to a point just below the cusp at $(\Delta_1 - \Delta_2)/e$, the $I_d - V_d$ curves show clearly that the sharp rise in current at $(\Delta_3 + \Delta_2)/e$ moves to a higher voltage while the cusp at $(\Delta_3 - \Delta_2)/e$ moves to a lower voltage. Thus, Δ_2 is enhanced. We associate the higher- and lower-voltage minima in dV_d/dI_d with $(\Delta_3 + \Delta_2)/e$ and $(\Delta_3 - \Delta_2)/e$ respectively. The derivatives in Fig. 1 show that, as I_e is increased from zero, there is no significant enhancement at b, while there is substantial enhancement at c and d. At e, an extraction voltage greater than $(\Delta_1 - \Delta_2)/e$, the enhancement of Δ_2 is much less than at d, indicating that the extraction rate is greatly reduced. Identical results were obtained when the extraction current was reversed.

A dc Josephson current was always observed in the extraction junction. The dc supercurrent was quenched by raising I_e to a large value, thereby trapping flux in the junction. It should be noted that the observed enhancement could not have been caused by photons[4] generated by ac Josephson currents since V_e $[\approx(\Delta_1 - \Delta_2)/e]$ was greater than Δ_2/e at temperatures near T_{c2} and the photon energy $(>2\Delta_2)$ was high enough to break pairs in Al(2).

From dV_d/dI_d vs. V_d, we obtained $\delta\Delta_2(V_e) \equiv \Delta_2(V_e) - \Delta_2(0)$ and $\delta\Delta_3 \equiv \Delta_3(V_e) - \Delta_3(0)$, where $\Delta_2(V_e)$ and $\Delta_3(V_e)$ are the steady-state gaps at an extraction voltage V_e. Figure 2 shows $\delta\Delta_2$ and $\delta\Delta_3$ vs. V_e for samples A and B, together with the characteristics of the extraction junctions. In both cases, $\delta\Delta_2$ is positive and sharply peaked near $(\Delta_1 - \Delta_2)/e$, reflecting the high rate of extraction near $(\Delta_1 - \Delta_2)/e$. For sample A, $\delta\Delta_3$ is negative and increases smoothly with increasing V_e, while for B, $\delta\Delta_3$ is essentially zero for $V_e \lesssim (\Delta_1 - \Delta_2)/e$ and negative for $V_e > (\Delta_1 - \Delta_2)/e$. We note that, at high currents, the voltage appears to switch on the $I_e - V_e$ curves, suggesting that part of Al(2) was made normal by the high current density in the extraction region. When the extraction junction was biased near the switching point, the dV_d/dI_d vs. V_d curve became very noisy, and its origin shifted abruptly along the V_d-axis. Therefore, we could obtain useful data only when V_e was below the switching voltage. Unfortunatley, the switching voltage decreased as the temperature approached T_{c2}, thus preventing us from obtaining data very close to T_{c2}, and removing the possibility of our observing an enhancement in T_{c2}.

Figure 3(a) shows the maximum gap enhancement $\delta\Delta_2^{max}$ and $\delta\Delta_2^{max}/\Delta_2(T)$ [$\Delta(T)$ is the equilibrium gap] at $V_e = (\Delta_1 - \Delta_2)/e$ as functions of T/T_{c2} for samples A and B. The absolute magnitude of the gap enhancement, $\delta\Delta_2^{max}$, increases sharply as T approaches T_{c2}. For sample B, the gap is enhanced by over 40% at $T/T_{c2} = 0.998$, and there is no indication that this enhancement is leveling off. Therefore, we suspect that an enhancement of T_{c2} would be possible if it were not for the switching induced by I_e. Figure 3(b) shows $\delta\Delta_3$ at $V_e = (\Delta_1 - \Delta_2)/e$ vs. T/T_{c2}. For A, $\delta\Delta_3$ is always zero or negative, while for B, $\delta\Delta_3$ is zero at low temperatures and becomes positive at temperatures close to T_{c2}. We believe that the changes in Δ_3 shown in Figs. 2 and 3(b) are induced by non-equilibrium phonons. To a first approximation, the steady-state phonon distribution is uniform across all three films because the total thickness is less than the phonon mean free path, and the phonon transmission coefficient between the Al films is close to unity. When $V_e = (\Delta_1 - \Delta_2)/e$, there is an excess of phonons with energies $\gtrsim 2\Delta_1$, generated by the recombination of excess quasiparticles in Al(1). For sample A, $\Delta_1 > \Delta_3$, so that the $2\Delta_1$ phonons can break pairs in Al(3), thereby reducing Δ_3 at all temperatures and extraction voltages. On the other hand, for sample B, Δ_3 is slightly greater than Δ_1, the difference increasing as the temperature is raised towards T_{c1}. As the temperature is increased, a growing fraction of the recombination phonons from Al(1) have energies between $2\Delta_1$ and $2\Delta_3$, and are unable to break pairs in Al(3). In fact, for $T > 0.995T_{c2}$, it appears that the predominant action of the phonons is to excite quasiparticles in Al(3) to higher energy states in such a way that Δ_3 is enhanced.[3,4]

Unfortunately, the only calculation of tunneling enhancement to take into account the effects of the non-equilibrium phonons assumes that $\Delta_1 = \Delta_2$, and we cannot, therefore, make any quantitative comparison of our results with theoretical predictions. We hope that a calculation for different gaps will become available in the near future.

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11. Δ_2 and Δ_3 were measured with $I_e = 0$. With $V_e = (\Delta_1 - \Delta_2)/e$, we deduced the value of Δ_1 using the (enhanced) value of Δ_2 determined from the detector junction. The depression of Δ_1 by quasiparticle injection should be negligible because d_1 is relatively thick, and the reduced temperature of Al(1) is relatively low, <0.91 for A, and <0.97 for B.

TABLE I. Parameters of samples A and B

Sample	1st Al film		2nd Al film		3rd Al film		Extraction junction resistance	Detection junction resistance
	d_1(nm)	T_{c1}(K)	d_2(nm)	T_{c2}(K)	d_3(nm)	T_{c3}(K)	R_e(Ω)	R_e(Ω)
A	56	1.49	37	1.353	28	1.40	0.019	3.5
B	79	1.36	45	1.321	40	1.38	0.037	12

Figure Captions

Fig. 1 (upper) I_d vs. V_d and (lower) dV_d/dI_d vs. V_d for sample A for the various extraction bias points a, b, c, d, and e shown in the lower inset. The temperature was 0.986 T_{c2}. Upper inset: (left) plan view of sample configuration; (right) section CC' of sample (film thicknesses greatly exaggerated).

Fig. 2 $\delta\Delta_2$ and $\delta\Delta_3$ vs. V_e, and I_e vs. V_e for sample A at $T = 0.986\ T_{c2}$ (upper), and sample B at $T = 0.995\ T_{c2}$ (lower).

Fig. 3(a) $\delta\Delta_2^{max}$ (solid line) and $\delta\Delta_2^{max}$ (dashed line) vs. T/T_{c2}, and (b) $\delta\Delta_3$ vs. T/T_{c2} for samples A and B, for $V_e = (\Delta_1 - \Delta_2)/e$.

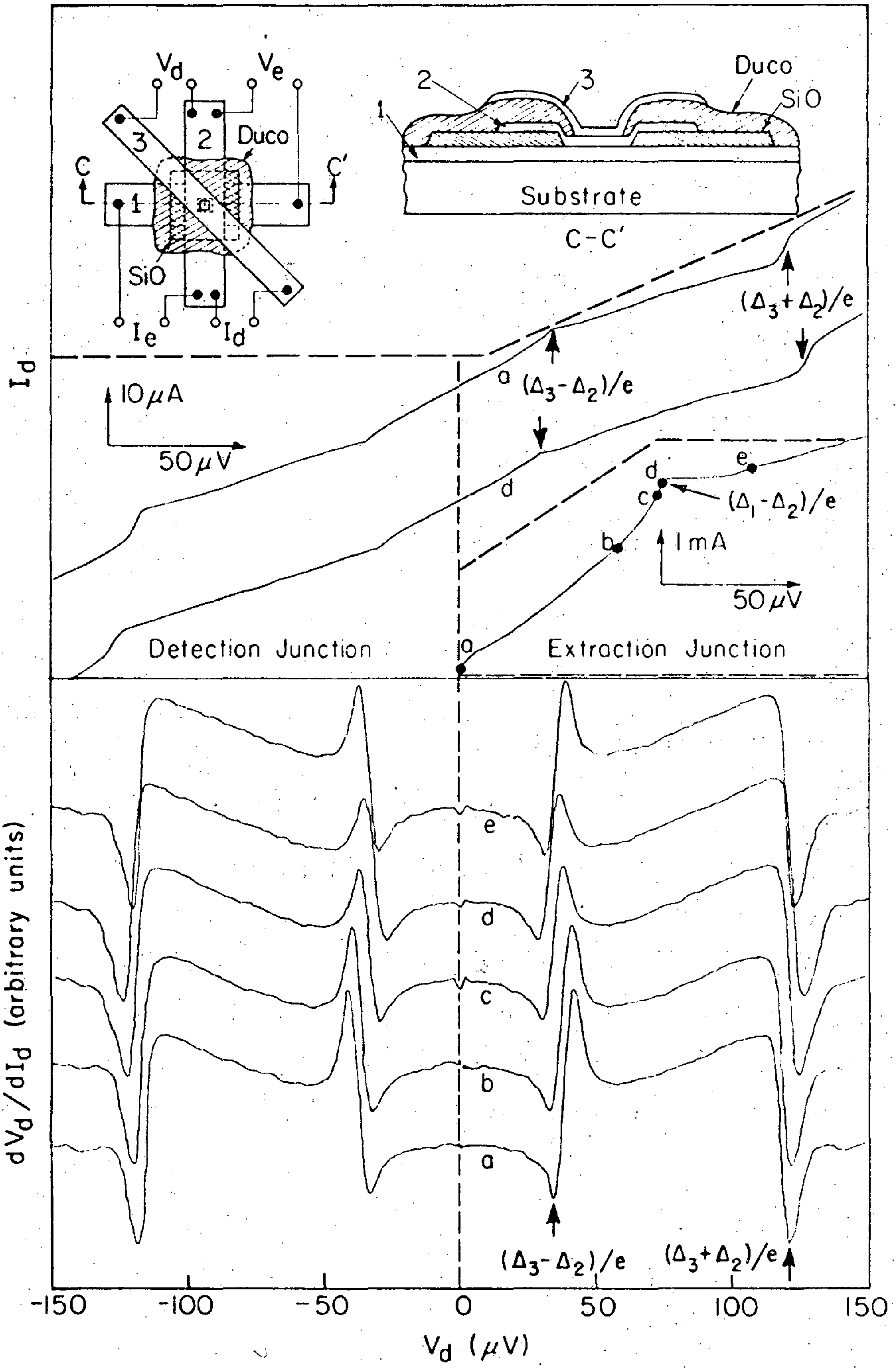

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Fig. 1

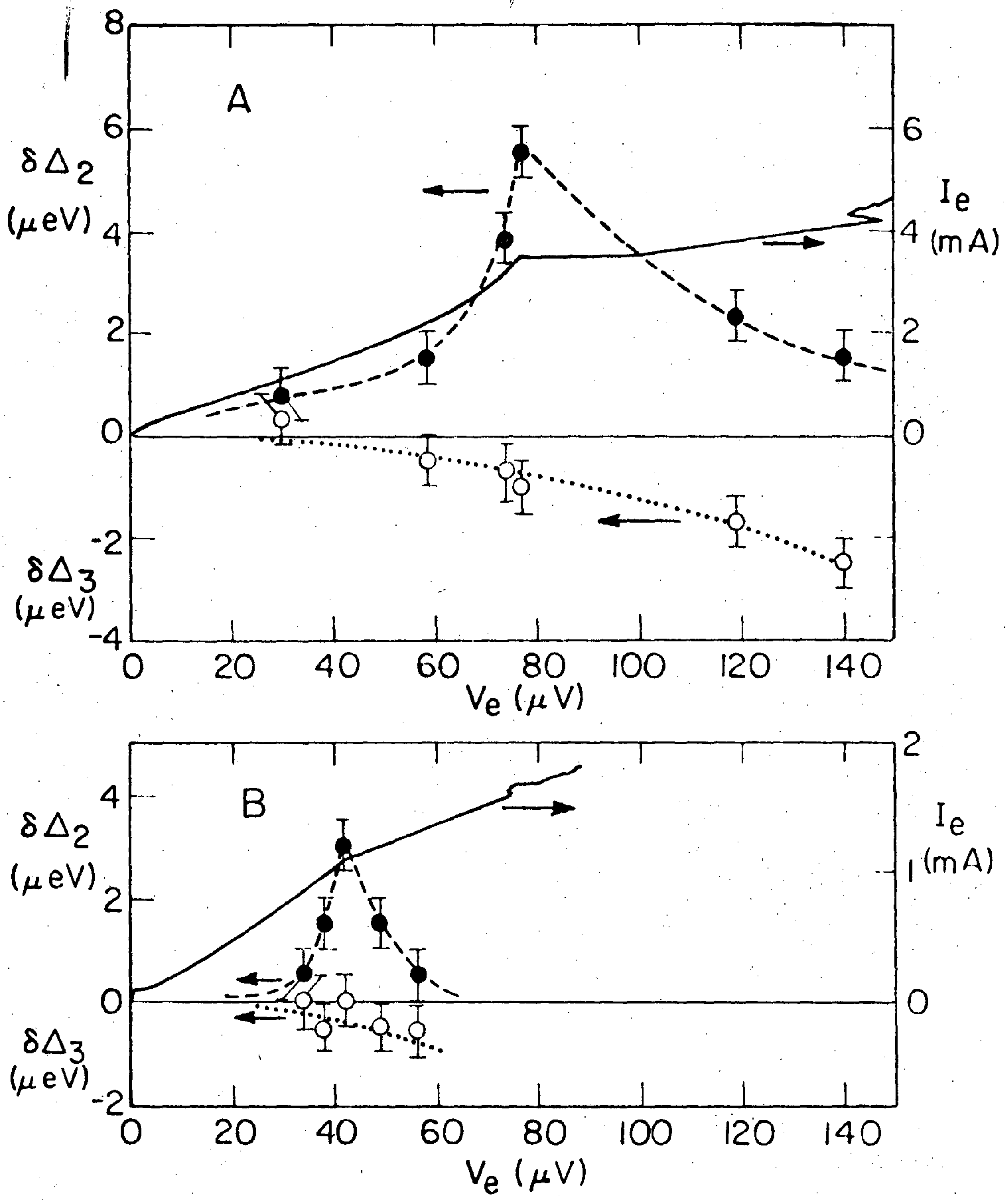

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Fig. 2

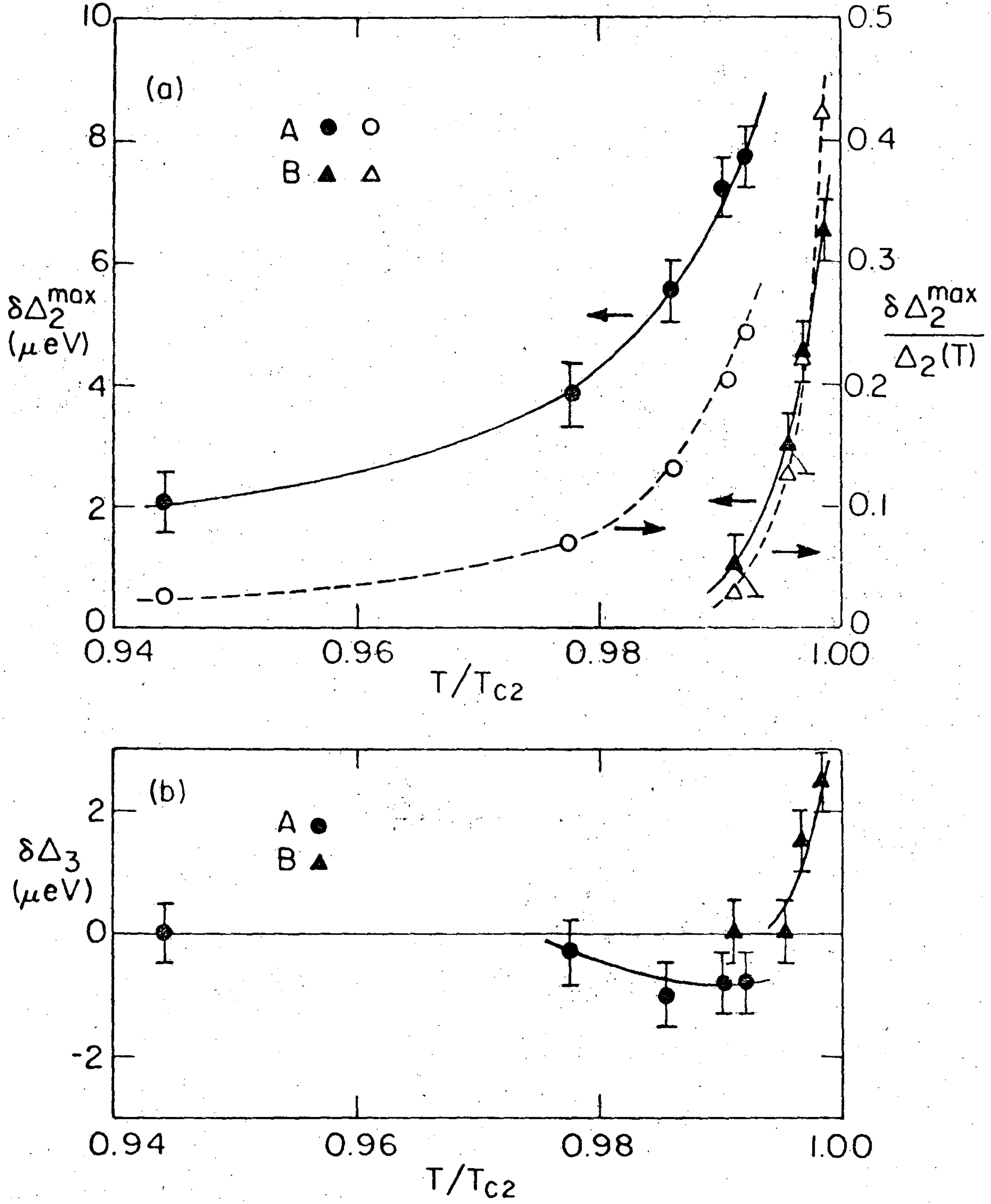

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Fig. 3

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