

Universal distribution of transparencies in highly conductive Nb/AlO_x/Nb junctions

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 (November 1, 2013)

We report the observation of the universal distribution of transparencies, predicted by Schep and Bauer [Phys. Rev. Lett. 78, 3015 (1997)] for dirty sharp interfaces, in uniform Nb/AlO_x/Nb junctions with high specific conductance (10⁸ Ohm⁻¹cm⁻²). Experiments used the BCS density of states in superconducting niobium for transparency distribution probing. Experimental results for both the dc I-V curves at magnetic-field-suppressed supercurrent and the Josephson critical current in zero magnetic field coincide remarkably well with calculations based on the multimode theory of multiple Andreev reflections and the Schep-Bauer distribution.

The basic characteristic of a mesoscopic conductor is its set of transmission coefficients, or "transparencies", defined as the eigenvalues of the transfer matrix connecting all incoming electronic modes to outgoing modes (for a thorough review, see Ref. [1]). The set of transparencies for a given conductor determines all its transport properties including dc current and broadband current noise.

In 1982 Dorokhov showed [2] that the distribution of transparencies in disusive conductors is universal, i.e., does not depend on dimension, geometry, carrier density, and other sample-specific properties:

$$D = \frac{G}{2G_0} \frac{1}{D} \frac{1}{1-D}; \quad (1)$$

where G is the average conductance and $G_0 = 2e^2/h$. The universality of Eq. (1) is responsible in particular for the universal value $S_I(0) = 2eI/3$ of shot noise in disusive conductors [3,4] (here I is the dc current). This suppression of shot noise in comparison with its Schottky value has been observed experimentally [5-7] and may serve as an indirect confirmation of Eq. (1).

Recently, Schep and Bauer showed [8] that the distribution of transparencies of a disordered interface is also universal, but is given by an expression different from Eq. (1) [9]:

$$D = \frac{G}{G_0} \frac{1}{D^{3/2}} \frac{1}{1-D}; \quad (2)$$

(This distribution leads to a shot noise value of $S_I(0) = 2eI/2$ [8]). In this work we report a strong experimental evidence that the transparency distribution in sub-nm-thick aluminum oxide barriers is very close to Eq. (2) while being substantially different from Eq. (1).

The determination of the transparency distribution may be assisted by the fact that due to the BCS singularity in the density of states at the edges of the superconductor energy gap $2(T)$, both the Cooper-pair and quasiparticle transport through Josephson junctions are highly nonlinear. In particular, quasiparticle transfer strongly increases at the "gap voltage" $V_g = 2(T) = e$,

while below this threshold the transport is dominated by multiple Andreev reflections (MAR) [11-13], resulting in a pronounced sub-harmonic gap structure at $V_n = V_g/n$. This structure is very sensitive to the number and transparencies of the modes, and has been successfully used [14-16] to determine transparencies of atomic-size point contacts with a few propagating modes. However, as will be shown below, the fact that various features of MAR transport (the current jump at $V = V_g$, the excess current at $V > V_g$, and subharmonic structure at $V < V_g$) are sensitive to different ranges of the transparency distribution also allow probing of the distribution in junctions with a much larger area (and hence a very large number of propagating modes).

Our samples were made using in-situ-fabricated Nb/AlO_x/Nb trilayers which were deposited on oxidized Si wafers in a cryopumped vacuum system with a base pressure of $5 \cdot 10^{-8}$ Torr. A dc magnetron sputtered 150-nm niobium base electrode was covered by a 8-nm-thick aluminum film (also using dc sputtering). Without breaking the vacuum, an AlO_x layer was formed by thermal oxidation with well controlled dry oxygen exposure. For the junctions discussed below (specific normal conductance close to 10⁸ Ohm⁻¹cm⁻²), the oxidation was carried out at 1.0 mTorr of O₂ for 10 minutes. After the trilayer deposition was completed by sputtering of a 150-nm-thick Nb counter electrode, junctions of various areas (from 0.25 to 1 μm²) were formed by e-beam patterning - for details, see [17,18]. The resulting junctions were highly uniform; for example, for 1 μm² junctions the full spread of normal conductance was below 3%; a slightly larger (8%) spread of deep-submicron junctions may be readily explained by their area definition uncertainty. The junction homogeneity was further confirmed by the fact that the Josephson supercurrent could be almost completely suppressed by a magnetic field corresponding to the insertion of one flux quantum into the junction - see Fig. 1.

The solid lines in Fig. 1 show the experimental dc I-V curves of two junctions of different area at a bath temperature of $T_0 = 1.8$ K, with the Josephson critical current suppressed by a magnetic field parallel to the film plane,

while the solid lines in Fig. 2 show the measured differential conductances of the same samples. These curves exhibit well pronounced sub-gap structure, indicative of MAR transport. However, the conduction peak positions V_n at higher voltages deviate gradually from the expected dependence $1/n$, indicating self-heating of the samples. This heating was higher in larger junctions and may be calculated with good accuracy using a simple model where the main temperature gradient between the self-heated junction and the bath is parallel to the substrate, in the niobium electrodes adjacent to the junction; from this picture one should expect overheating to scale roughly as the junction area divided by its perimeter, in agreement with experiment.

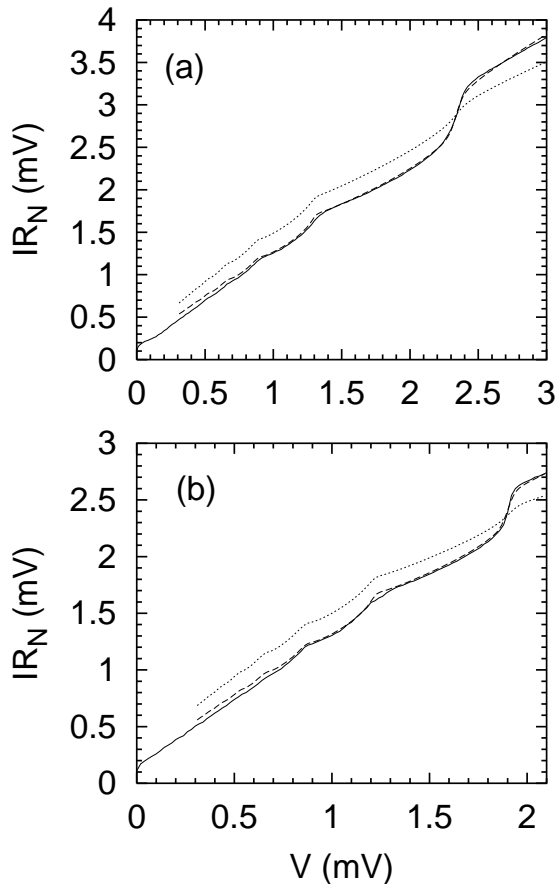


FIG. 1. DC I-V curves for two samples of area (a) 0.25 m^2 and (b) 1.0 m^2 . Solid lines: experimental results normalized with $1/G = R_N = R_N^{\text{expt}}$. Dashed lines: MAR theory using Eq. (2), (a) $R_N = 1.01R_N^{\text{expt}}$, (b) $R_N = 1.04R_N^{\text{expt}}$. Dotted lines: MAR theory using Eq. (1), (a) $R_N = 0.82R_N^{\text{expt}}$, (b) $R_N = 0.84R_N^{\text{expt}}$.

The points in Fig. 3 show the dependence of the energy gap $\Delta(T)$, where T is the junction temperature including self-heating, on the power $P = IV$ dissipated in the junction, read off from the peak positions. Assuming the BCS temperature dependence of the energy gap, the

data show that at $V = V_g(T)$ the junction temperature is close to 6.2 K and 7.6 K for, respectively, the 0.25 m^2 and 1.0 m^2 junctions. The solid and dashed lines in Fig. 3 show the theoretical dependence of the gap on P assuming a specific heating model. In this model we approximate the experimental temperature dependence of the heat conductance $\kappa(T)$ of superconducting niobium [19] with a one-parameter parabolic expression. The resulting dependences provide a reasonably good, smooth interpolation of the experimental heating data.

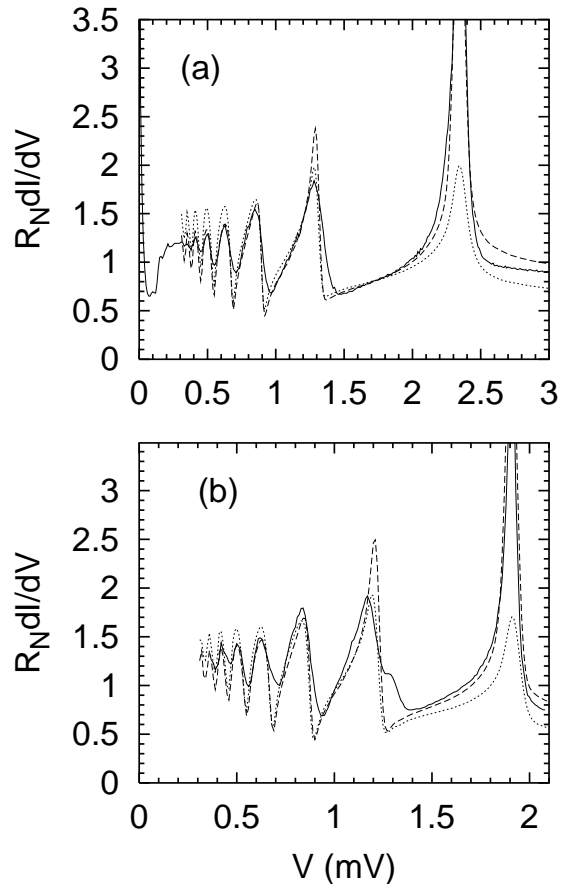


FIG. 2. Differential conductance for the same samples, and with the same fitting values of R_N , as in Fig. 1.

Dashed curves in Figures 1 and 2 show the theoretical dependences which were obtained by averaging the results of the MAR theory [12,13] over the distribution of transparencies given by Eq. (2) [20]. Apart from the incorporation of the heating model described above, two additional minor adjustments were made when calculating these curves. First, the assumed value of normal resistance R_N was allowed to differ by a few percent (within experimental uncertainty [21]) from the experimentally determined value R_N^{expt} . Second, we have introduced a Gaussian distribution of $\Delta(T)$ with an r.m.s. spread of 2%. Such a spread is typical for any superconductor junction and may be readily attributed to the

anisotropy of the superconducting gap in polycrystalline electrode films.

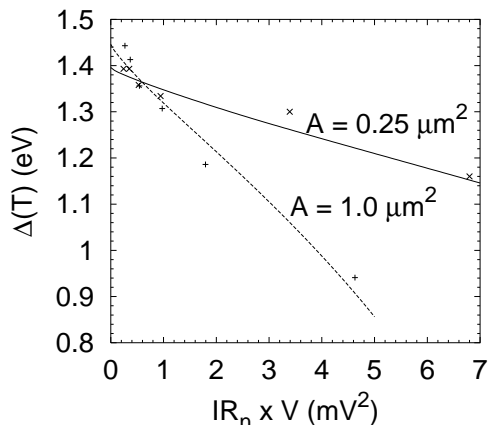


FIG. 3. Dependence of the superconducting gap $\Delta(T)$ on the dissipated power $P = IV$ for the same two samples as in Figs. 1 and 2. Points: fit to positions of the peaks in Fig. 2 (see the text). Lines: Calculated $\Delta(T)$ based on our heating model and the BCS gap temperature dependence.

We believe that the agreement of the experimental data and theoretical curves based on the Schep-Bauer distribution is remarkable. In order to see that this agreement could not result from the fitting procedure described above, dotted curves in Figs. 1 and 2 show the results of our best attempt to fit the data with the MAR theory results averaged using the Dorokhov distribution (with a similar account of self-heating). It is evident that these curves are rather far from the data. Moreover, in this best fitting attempt we have selected the values of R_N rather distant from R_N^{expt} (see the Fig. 1 caption); if the latter values were used, the theoretical lines would pass considerably higher than the experimental plots. This is immediately visible from the values of the "excess current" defined as $I_{\text{exc}} = I(V) - GV$ at $V = V_g$. Averaging the results of Ref. [12] for $T = 0$ with the Schep-Bauer distribution Eq. (2), we get

$$I_{\text{exc}} = \frac{G(0)}{e} \frac{7}{4} \frac{P}{2} = 1.055 \frac{G(0)}{e}; \quad (3)$$

while for the Dorokhov distribution the excess current is substantially higher, $I_{\text{exc}} = 1.467G(0)e$ [22].

Another (though less spectacular) evidence of the validity of the MAR theory combined with the Schep-Bauer distribution comes from the temperature dependence of the Josephson critical current (in zero magnetic field), which is also sensitive to the mode transparency distribution. Points in Fig. 4 show the measured temperature dependence of the critical current in the same samples as in Figs. 1 (3. Lines show the Ambegaokar-Barato dependence for tunnel junctions (upper curve), the MAR theory using the Dorokhov distribution (lower curve), and the MAR theory using the Schep-Bauer distribution

(middle curve) [23]. It is evident that the experimental data agree with the Schep-Bauer distribution.

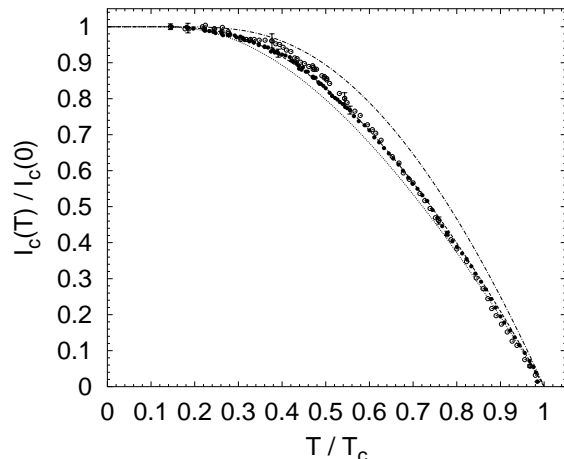


FIG. 4. Temperature dependence of the critical current I_c in the two samples of Figs. 1 (3. Open circles: $A = 0.25 \mu\text{m}^2$; filled circles: $A = 1.0 \mu\text{m}^2$; dashed-dotted line: the Ambegaokar-Barato result for tunnel junctions; dashed line: MAR theory using Eq. (2); dotted line: MAR theory using Eq. (1).

The absolute value of the low-temperature critical current is different in all three models used in Fig. 4: $I_c(0) = G(0)e = 1.57; 1.92; 2.08$ for, respectively, a tunnel junction, disordered barrier with the Schep-Bauer distribution of transparencies, and SNS junctions with Dorokhov's distribution [26]. The observed value lies within a few percent of the prediction for the Schep-Bauer distribution; the difference can again be attributed to the error in the normal resistance definition [21].

The fact that transport in disordered AlO_x barriers of finite thickness (of the order of 1 nm, i.e., much thicker than the Fermi wavelength λ_F in the junction electrodes) is described by Eq. (2) so well may seem rather surprising, since its derivation in Ref. [8] assumed that the barrier is a strongly-disordered region with thickness d much smaller than λ_F . However, this distribution may be derived from a different model which does not rely on this assumption.

It is well known that resonant tunneling through a single localized site leads to the following transparency:

$$D = \frac{1}{[(\epsilon - \epsilon_F) = \epsilon] + \cosh^2(x/a)}; \quad (4)$$

where ϵ is the state energy, ϵ_F is the Fermi level in the junction electrodes, ϵ is the tunneling width for a site in the barrier center, x is the site deviation from the center, and a is the localization radius. If ϵ is so large that the first term in the denominator is unimportant, for a system with a uniform spatial distribution of sites, Eq. (4) immediately gives the Dorokhov distribution. On

the other hand, if $x \ll 0$ while the spread of ϵ is much broader than ϵ_F , Eq. (4) yields the distribution (2). This condition applies to strongly disordered barriers like ours [27] if their thickness d is smaller than a (though possibly much larger than ϵ_F) and their spread of atomic localization energies is larger than ϵ_F .

In summary, the excellent agreement between the experimental data and the results of the MAR theory combined with the Schep-Bauer distribution of transparencies provides very strong evidence that our Nb/A_{1-x}Nb_x junctions are well described by this distribution, while being far from, e.g., the Dorokhov distribution. Since the distribution (2) has the same universal nature as Eq. (1), this result is of considerable general importance for mesoscopic physics [28].

Our result is also of substantial importance for applications. It shows that transport in niobium-trilayer Josephson junctions with high specific conductance and hence high critical current density (up to at least 200 kA/cm²) may be due to a fundamental mechanism rather than rare defects such as pinholes, etc. This gives every hope that these junctions may be even more reproducible than in our first experiments: assuming that the barrier transparency is only correlated at distances of the order of its thickness (about 1 nm), we may estimate that the minimum rms. spread of the critical current is below 1% even for deep-submicron junctions. Together with the fact that such junctions are intrinsically overshunted [18], this makes them uniquely suitable for several important applications in superconductor electronics, including ultrafast digital RSFQ circuits of very high integration scale – see, e.g., Ref. [31].

We would like to thank A. A. Golubov and Yu. V. Nazarov for useful discussions. This work was supported in part by DoD and NASA via JPL, and by ONR.

[1] C. W. J. Beenakker, Rev. Mod. Phys. 69, 731 (1997).
 [2] O. N. Dorokhov, JETP Lett. 36, 318 (1982).
 [3] C. W. J. Beenakker and M. Buttiker, Phys. Rev. B 46, 1889 (1992).
 [4] E. V. Sukhorukov and D. Loss, Phys. Rev. Lett. 80, 4959 (1998).
 [5] A. H. Steinbach, J. M. Martinis, and M. H. Devoret, Phys. Rev. Lett. 76, 3806 (1996).
 [6] M. Henny, H. Birk, R. Huber, C. Strunk, A. Bachtold, M. Kugler, and C. Schonenberger, Appl. Phys. Lett. 71, 773 (1997).
 [7] R. J. Schoelkopf, P. J. Burke, A. Kozhevnikov, D. E. Prober, and M. J. Rooks, Phys. Rev. Lett. 78, 3370 (1997).
 [8] K. M. Schep and G. E. W. Bauer, Phys. Rev. Lett. 78, 3015 (1997); Phys. Rev. B 56, 15860 (1997).

[9] The distribution (2) was derived [10] for the first time for a system that is physically very much different from disordered interface: long ballistic double-barrier structure with symmetric uniform tunnel barriers. The reasons for coincidence between the two systems are not completely clear.
 [10] J. A. M.elsen and C. W. J. Beenakker, Physica B 203, 219 (1994).
 [11] E. N. Batus, V. S. Shumeiko, and G. Wendin, Phys. Rev. Lett. 74, 2110 (1995).
 [12] D. V. Averin and A. Bardas, Phys. Rev. Lett. 75, 1831 (1995).
 [13] A. Bardas and D. V. Averin, Phys. Rev. B 56, R8518 (1997).
 [14] N. van der Post, E. T. Peters, I. K. Yanson, and J. M. van Ruitenbeek, Phys. Rev. Lett. 73, 2611 (1994).
 [15] E. Scheer, P. Joyez, D. Esteve, C. Urbina, and M. H. Devoret, Phys. Rev. Lett. 78, 3535 (1997).
 [16] E. Scheer, N. Agrait, J. C. Cuevas, A. Levi Yeyati, B. Ludoph, A. Martin-Rodero, G. R. Bollinger, J. M. Van Ruitenbeek, and C. Urbina, Nature 394, 154 (1998).
 [17] M. B. Hushan, Z. Bao, B. Bi, M. Kemp, K. Lin, A. O. Iiva, R. Rouse, S. Han, and J. E. Lukens, in Extended Abstracts of the 5th International Superconductive Electronics Conference (Nagoya, Japan, 1995), p. 17.
 [18] V. Patel and J. E. Lukens, IEEE Trans. Appl. Supercon. 9, 3247 (1999).
 [19] P. H. Kes, J. G. A. Rolfes, and D. de Klerk, J. Low Temp. Phys. 17, 341 (1974).
 [20] Similar calculation for the double-barrier junctions was performed by A. Brinkman and A. A. Golubov, cond-mat/9912109.
 [21] The latter value was measured in a narrow temperature interval below T_c where the junction dc $I-V$ curves are almost linear while the junction electrodes are still superconducting. This procedure may easily give a few percent error.
 [22] S. N. Artemenko, A. F. Volkov, and A. V. Zaitsev, Sov. Phys. JEPT 49, 924 (1979).
 [23] The two latter curves may be readily calculated from the current-phase relation for a single channel [24,25] by its averaging with the respective weight (1), (2) and then maximizing the current over the Josephson phase difference.
 [24] W. H. Aberkom, H. K. Nauer, and J. Richter, Phys. Status Solidi A 47 K161 (1978).
 [25] C. W. J. Beenakker, Phys. Rev. Lett. 67, 3836 (1991).
 [26] I. O. Kulik and A. N. Omelyanchuk, JETP Lett. 21, 96 (1975).
 [27] Preliminary measurements of the nonlinearity of dc $I-V$ curves of our junctions at large voltages, combined with the independent measurements of their specific capacitance, indicate that the effective height of the effective tunnel barrier is close to 2 eV, while the average dielectric constant is about 5. Both parameters are substantially different from those of crystalline Al₂O₃, indicating that the aluminum oxide structure is highly disordered.
 [28] Results of previous experiments with large-area, multimode Josephson junctions in the MAR regime could be interpreted as an evidence of either a small number of high-transparency pinholes [29], or of percolation paths

through localized states [30]. In both cases, the samples were much less uniform than our junctions, so that apparently such explanations were adequate.

[29] A. W. Kleinsasser, R. E. Miller, W. H. Mallison, and G. B. Arnold, *Phys. Rev. Lett.* 72, 1738 (1994).

[30] A. Frydman and Z. Ovadyahu, *Phys. Rev. B* 55, 9047 (1997).

[31] K. K. Likharev, in *Applications of Superconductivity*, ed. by H. Weinstock (Kluwer, Dordrecht, 2000), p. 247.