Nonlocality in superconducting metals: An ultra-high precision magnetic penetration depth study

Ismardo Bonalde [a,1], Brian D. Yanoff [b], Myron B. Salamon [c] Elbert E. M. Chia [c]

[a] *Centro de Física, Instituto Venezolano de Investigaciones Científicas, Apartado 21874, Caracas 1020-A, Venezuela*
[b] *General Electric, Schenectady, NY, USA*
[c] *Physics Dept., University of Illinois at Urbana-Champaign, 1110 W. Green St., Urbana, IL 61801, USA*

Abstract

In previous reports the temperature dependence of the penetration depth $\lambda(T)$ of some nonlocal superconducting metals has been found to be in disagreement with the behavior expected from the nonlocal BCS theory. Instead, $\lambda(T)$ was close to the local BCS prediction. Here we present high-precision measurements of $\lambda(T)$ in Al, Cd, and Zn down to 30 mK, which are in excellent agreement with the prediction of the nonlocal BCS electrodynamics without using adjustable parameters.

Key words: nonlocal; superconductivity; metals; penetration depth

1. Introduction

The electrodynamics of superconductors is studied basically in two limiting cases in which analytic results can be obtained: The local and the nonlocal limits. In the local limit the coherence length ξ_0 is much smaller than the magnetic penetration depth $\lambda(0)$ ($\kappa = \lambda(0)/\xi_0 \gg 1$), and the contrary establishes the nonlocal limit. In most of the pure metal superconductors the coherence length is much larger than the magnetic penetration depth and, therefore, they are classified theoretically as nonlocal superconductors. However and surprisingly, there is no experimental evidences of nonlocality in superconducting metals.

The magnetic penetration depth is the most direct probe of the electrodynamics of superconductors. Several studies of λ in superconducting aluminum, the classic example of a nonlocal superconductor with $\kappa \approx 0.03$, have been carried out [1,2], yielding results close to local behavior. No attention has been paid to this contradiction for several decades.

Here we report on high-precision measurements of the temperature dependence of λ in pure aluminum, cadmium, and zinc from T_c down to 30 mK. Cadmium is in the intermediate nonlocal range, $\kappa \approx 0.1$, and zinc is deep in the nonlocal regime, $\kappa \approx 0.03$. We were not able to find in the literature previous studies of the electrodynamics of superconducting cadmium and zinc. For all three superconducting elements the temperature dependence of the magnetic penetration depth is in excellent agreement with the prediction of the nonlocal BCS electrodynamics *without* using fitting parameters.

2. Experiment

The samples used in the experiment were 99.999% pure, and chemically polished with $3HCL{:}1HNO_3$ to remove the oxide film from the surface. Measurements of the magnetic penetration depth were performed utilizing a 28 MHz tunnel diode oscillator with a very low noise level [3]. $T_c = 1.175$K, $T_c = 0.521$K, and $T_c = 0.855$ K for aluminum, cadmium, and zinc, re-

[1] Corresponding author. E-mail: bonalde@ivic.ve

spectively, were determined from the onset of superconductivity in the penetration depth measurements.

3. Results and discussion

We compared the data to the nonlocal BCS approximation

$$\frac{\lambda^2(0)}{\lambda^2(T)} = \left[\frac{\Delta(T)}{\Delta_0}\tanh\frac{\Delta(T)}{2k_BT}\right]^{\frac{2}{3}} . \quad (1)$$

Here Δ_0 is the energy gap a $T = 0$. We have assumed for the T-dependent gap function the weak-coupling interpolation formula $\Delta(T) = \Delta_0 \tanh\left(\frac{\pi k_B T_c}{\Delta_0}\sqrt{a(T_c/T-1)}\right)$ with $a \approx 0.953$ and $\Delta_0 = 1.76 k_B T_c$.

Fig. 1 shows $[\lambda(0)/\lambda(T)]^2$ vs T/T_c for the data of Al, Cd, and Zn along with the numerical evaluation of Eqs. (1). Because from our experiment we cannot find $\lambda(0)$, in the cases of aluminum and cadmium we utilized the values of $\lambda(0)$ obtained from other experimental techniques. We used $\lambda(0) = 515$ Å [4] and $\lambda(0) = 1100$ Å [5,6] for aluminum and cadmium, respectively. We noticed that small deviations from these values do not make a significant change in the temperature dependence of $[\lambda(0)/\lambda(T)]^2$. For zinc $\lambda(0)$ needed to be calculated. From ultrasonic shear wave experiments we know that the London penetration depth $\lambda_L(0) \approx 300$ Å [7]. Using the formula $H_0 = \Phi_0/\sqrt{8\pi}\lambda(0)\xi_0$, where Φ_0 is the flux quantum and $H_0 = 54$ Oe [8], together with the nonlocal expression $\lambda(0) = 0.578(\xi_0\lambda_L^2(0))^{\frac{1}{3}}$, we obtained $\lambda(0) \approx 603$ Å.

The excellent agreement without adjustable parameters between our data and Eq. (1) over the entire temperature range is a strong evidence for nonlocality in superconducting aluminum, cadmium, and zinc. In the case of aluminum, such a result contrasts to the ones of Tedrow *et al.* [1] and Behroozi *et al.* [2], which showed significant deviation from the nonlocal BCS superconductivity.

It has been suggested theoretically that zinc has three energy gaps associated to the three bands of its electronic structure [9]. Several experiments on zinc, which used techniques other than penetration depth, have been explained using a two-gap model with a ratio $\Delta_1/\Delta_2 \approx 1.3$ [9]. This ratio is so small that it hardly yields a difference with respect to the one gap model in the nonlocal $[\lambda(0)/\lambda(T)]^2$. The high-resolution $\lambda(T)$ measurements reported here could distinguish in principle between the one- and two-gap models, if $\lambda(0)$ were known with high certainty. Because we do not know $\lambda(0)$ with high accuracy (we have estimated it), it makes no sense to discuss the two-gap model. It is noteworthy that this does not invalidate the conclusions about the electrodynamics.

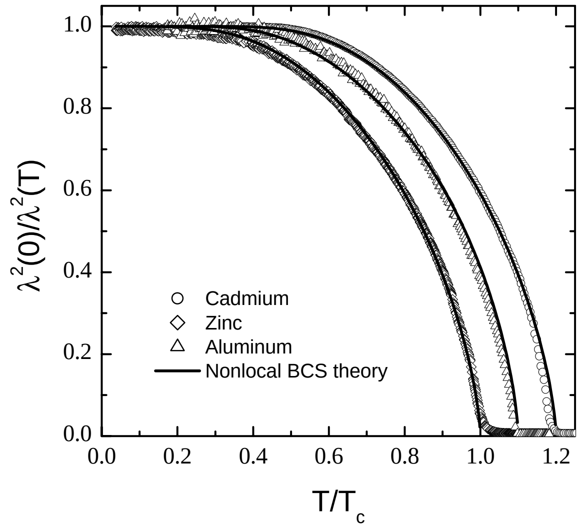

Fig. 1. $[\lambda(0)/\lambda(T)]^2$ against T/T_c for the experimental data and the numerical evaluation of the nonlocal BCS expression of the penetration depth. The data of aluminum and cadmium have been shifted along the horizontal axis in the sake of clarity.

In summary our measurements of the magnetic penetration depth indicate strongly that aluminum, cadmium, and zinc are certainly nonlocal superconductors.

References

[1] P. M. Tedrow, G. Faraci, and R. Meservey, Phys. Rev. B **4**, (1971) 74.

[2] F. Behroozi, M. P. Garfunkel, F. H. Rogan, and G. A. Wilkinson, Phys. Rev. B **10**, (1974) 2756.

[3] I. Bonalde, B. D. Yanoff, M. B. Salamon, D. J. V. Harlingen, E. E. M. Chia, Z. Q. Mao, and Y. Maeno, Phys. Rev. Lett. **85**, (2000) 4775.

[4] M. A. Biondi and M. P. Garfunkel, Phys. Rev. **116**, (1959) 862.

[5] D. P. Almond, M. J. Lea, and E. R. Dobbs, Proc. Phys. Soc. London, Series A **343**, (1975) 537.

[6] M. S. Khaikin, Sov. Phys. JETP **34**, (1958) 961.

[7] E. R. Dobbs and M. J. Lea, Proc. of the 14th International Conference on Low Temperature Physics, Otaniemi, Finland, 1975, pp. 203.

[8] D. U. Gubser and J. E. Cox, Phys. Rev. B **7**, (1973) 4118.

[9] S. Auluck, J. Low Temp. Phys. **12**, (1973) 601.