Voltage in a Charge-Imbalance Experiment, Taking into Account the Approximate Charge Neutrality in the Superconductor*

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We consider the two-fluid model description of the "branch imbalance" experiment first carried out by Clarke and interpreted by Tinkham. We show that when approximate charge neutrality is taken into account, the analysis of the tunneling process has to be slightly modified to allow for the shifts in the pair chemical potential when imposing energy conservation. As a consequence we find that near $T_c$, most of the voltage difference $V_d$ measured between the superconducting and normal probes develops across the nonequilibrium region and not across the junction coupled to the normal probe. We show that as the temperature is lowered more of the measured voltage $V_d$ develops across the junction as the shift of the pair chemical potential $\delta \mu_s$ decreases and the corresponding quasiparticle chemical potential shift $\delta \mu_n$ increases. Our expression for the measured voltage $V_d$ agrees with the ones obtained previously, but we note that at lower temperatures it can no longer be identified with the difference between the pair and quasiparticle chemical potentials in the nonequilibrium region.

1. INTRODUCTION

In recent years there has been increased interest in nonequilibrium superconductivity. Therefore a search has been made for simple systems where theory can be understood and experiments performed. One such system is generated by tunneling electrons into a superconducting film and extracting them as pairs, creating in the film a steady-state nonequilibrium region. This system was first probed in the pioneering work of Clarke, in which a voltage difference $V_d$ was measured between a normal probe coupled to the nonequilibrium region through a tunnel junction, and the

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far side of the superconducting film. Using a generalized tunneling model, Tinkham\textsuperscript{3} related this voltage to the nonequilibrium properties of the system. Since then similar systems have been used to gather more detailed information about relaxation times related to the transverse mode\textsuperscript{4} of nonequilibrium phenomena in superconductors.\textsuperscript{5,6} A complete review of this work was recently presented by Clarke.\textsuperscript{7}

The introduction of a two-fluid model by Pethick and Smith (PS)\textsuperscript{8} has enhanced the physical understanding of nonequilibrium superconductivity. Among other things, they treated Clarke’s experiment in the context of the two-fluid model and pointed out that the departure from equilibrium was related to the appearance of quasiparticle charge. Recently, following the treatments of Waldram\textsuperscript{9} and PS,\textsuperscript{8} Kadin \textit{et al.}\textsuperscript{10} introduced a model to treat the transverse mode of nonequilibrium in superconductors near their critical temperature $T_c$, where the importance of considering approximate charge neutrality was emphasized.

In this paper we consider the two-fluid model description of Clarke’s experiment, but we follow Kadin \textit{et al.} to include charge neutrality. Although most of our results agree with the ones obtained previously, we believe that our approach gives a clearer idea of what is happening in the system as a whole.

\section{2. Charge Imbalance and Approximate Charge Neutrality}

We summarize some basic ideas of the two-fluid model in its various versions. The total charge in a BCS superconductor can be divided into the sum of a quasiparticle charge $Q_n$ and a condensate charge $Q_s$ given by\textsuperscript{8}

$$Q_s = 2 \sum_k v_k^2$$  \hspace{1cm} (1)

$$Q_n = 2 \sum_k (u_k^2 - v_k^2) f_k = 2 \sum_k q_k f_k$$  \hspace{1cm} (2)

where $u_k$ and $v_k$ are the familiar coherence factors, $q_k$ is the effective charge associated with a quasiparticle, and $f_k$ is the quasiparticle distribution function. The effective charge can be written in terms of the quasiparticle excitation energy $E_k$ and the normal state excitation energy $\varepsilon_k$ measured with respect to the chemical potential $\mu$ as

$$q_k = \xi_k / E_k$$  \hspace{1cm} (3)

$$E_k = (\xi_k^2 + \Delta^2)^{1/2}$$  \hspace{1cm} (4)

$$\xi_k = \varepsilon_k - \mu$$  \hspace{1cm} (5)