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Quality factor of a superfluid ^{3}He weak link resonator

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Abstract

We measure the quality factor, Q for an oscillating membrane, which is in parallel with a superfluid ^{3}He weak link array. We have constructed an effective cell model to help explain these results and find reasonable agreement between the experimental data and our theoretical model. The familiar effects of first and second viscosity have been considered as well as a new intrinsic dissipation that acts as a linear shunt conductance G across the weak link. Although the viscous terms dominate, as seen in single orifice weak links [1], the "shorting" effects of the shunt conductance noticably suppress the quality factor, especially at low temperatures. © 2000 Published by Elsevier Science B.V. All rights reserved.

Keywords: ^{3}He superfluid; Josephson effect; Second viscosity

An array of apertures acts collectively as superfluid ^{3}He weak link, with $I(\phi) = I_c \sin(\phi)$, for temperatures near T_c [2,3]. The experimental cell, described more thoroughly in Ref. [2], contains two metalized flexible membranes and a weak link array, immersed in a bath of superfluid ^{3}He–B at 0 bar. This system forms a two-membrane superfluid resonator. We explore several sources of dissipation in the system by measuring the quality factor Q of the resonator.

The experimental cell can be treated in a simplified manner by considering the two membranes to act together as a single membrane with an effective spring constant, $k_{\mathrm{eff}} = k_1 k_2/(k_1 + k_2)$, at a distance d_{eff} from the nearest cell wall. A schematic representation is shown in Fig. 1.

Dissipative effects coming from first and second viscosity, η and ζ_3, thoroughly studied using a single membrane superfluid resonator [4], have been included in our model of the system. We have also included a linear conductance G, that shunts the superfluid ^{3}He weak link. This was determined by measuring, as a function of temperature, the DC current through the weak link for a given constant pressure across it (i.e., I versus P). The slope from a linear fit of I versus P defines G (i.e., $I = GP$) [5]. Because we measure the absolute pressure across the weak link using the Josephson frequency, we can extract the parallel conductance G independent of any series effects that occur at the membrane (e.g., first and second viscosity).

Following Ref. [4], the linearized equations of motion can be expressed in terms of x, the average displacement of the membrane. For small displacements and an arbitrary current-phase relation for the weak link we find,

$$\ddot{x} + \left[\frac{2m_3}{\hbar}\left(\frac{\mathrm{d}I}{\mathrm{d}\phi}\right)\frac{(\frac{4}{3}\eta + \rho^2\zeta_3)}{\rho^2 A d_{\mathrm{eff}}} + \frac{k_{\mathrm{eff}} G}{\rho^2 A^2}\right]\dot{x} + \left[\frac{2m_3}{\hbar}\left(\frac{\mathrm{d}I}{\mathrm{d}\phi}\right)\frac{k_{\mathrm{eff}}}{\rho^2 A^2}\right]x = 0, \quad (1)$$

where $(\mathrm{d}I/\mathrm{d}\phi)$ is taken about $\phi = 0$. This gives a quality factor,

$$Q = \omega_{\mathrm{p}}\left[\frac{2m_3}{\hbar}\left(\frac{\mathrm{d}I}{\mathrm{d}\phi}\right)\frac{(\frac{4}{3}\eta + \rho^2\zeta_3)}{\rho^2 A d_{\mathrm{eff}}} + \frac{k_{\mathrm{eff}} G}{\rho^2 A^2}\right]^{-1}, \quad (2)$$

where $\omega_{\mathrm{p}}^2 = (2m_3/\hbar)(\mathrm{d}I/\mathrm{d}\phi)k_{\mathrm{eff}}/\rho^2 A^2$ is the natural frequency.

We initiate oscillations about $x = 0$ by applying a small step voltage to either flexible membrane. The output of a DC SQUID displacement transducer records the damped oscillations as a function time. The quality factor Q was extracted by taking the FFT of the low amplitude oscillations and by fitting the peaks of these

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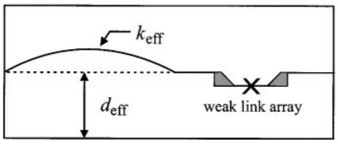

Fig. 1. Schematic representation of the effective cell.

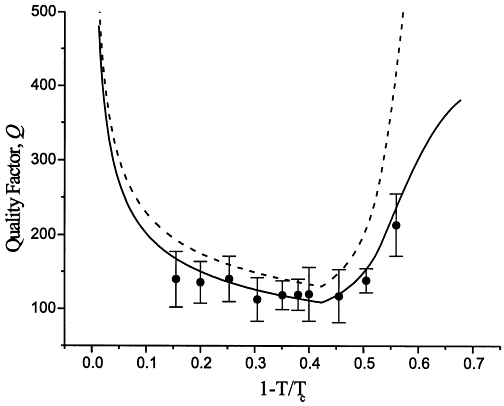

Fig. 2. Measured values of the quality factor, Q, as a function of $1 - T/T_c$. The solid curve was generated using Eq. (2) with $d_{eff} = 113$ μm. The quantities $(dI/d\phi)$, G, and $(\frac{4}{3}\eta + \rho^2\zeta_3)$ were fitted as functions of temperature from experimental data [5–7]. The dashed curve represents predictions for Q neglecting the effects from the shunt conductance G.

oscillations to an exponentially decaying function of time. Fig. 2 shows experimental values for the quality factor for temperatures from $0.845T_c$ down to $0.44T_c$.

Experimental data of the current-phase relation was used to measure $(dI/d\phi)$ about $\phi = 0$ [6]. The values for $(\frac{4}{3}\eta + \rho^2\zeta_3)$ were taken from the experimental data of Cook et al. [7]. This information along with the measurements of G and Q were used in Eq. (2) at 10 temperatures to generate a best-fit value for the effective cell wall distance, $d_{eff} = 113 \pm 31$ μm which is consistent with the dimensions in the experimental cell.

The solid curve in Fig. 2 was generated using Eq. (2), the fit value for d_{eff} and the experimental data for $(dI/d\phi)$, G, and $(\frac{4}{3}\eta + \rho^2\zeta_3)$ fitted as functions of temperature [5–7]. The difference between the prediction including G (the solid curve) and that based purely on viscous damping (the dashed curve) shows a noticable suppression of the quality factor, especially at low temperatures. The majority of the damping, at high temperatures, is due to viscous effects. As the temperature falls, a competition arises between the decreasing viscous terms which tend to increase Q and the increasing shunt conductance which reduces Q. The shunt conductance G essentially tries to "short out" any pressure differences in the system.

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