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Rapid Communication

Vibrating Wire Measurements in Superfluid ^{3}He at the Melting Curve down to 0.53 mK

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Measurements of the vibrating wire spectrum have been carried out in superfluid ^{3}He along the melting curve down to 0.53 mK. We have observed that at temperatures below 0.3 T_c the width of the mechanical resonance of the wire decreases exponentially with $1/T$, indicating the ballistic regime of collisions with quasiparticles. The value of the superfluid energy gap was found to be (1.99±0.05) T_c, in good agreement with the values obtained from heat capacity measurements. The vibrating wire was thereby calibrated for further experiments at temperatures below 0.5 mK, where the sensitivity of the melting curve thermometry becomes rather poor.

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1. INTRODUCTION

Thermometers based on measuring the ^{3}He melting pressure are widely used down to about 0.5 mK. The steep slope of the melting curve and the three well-known fixed points (A, B–A superfluid and Néel transitions) make this method very reliable in this region. However, at temperatures lower than the Néel transition point ($T_N = 0.934\,\mathrm{mK}$[1]) the slope of the melting curve rapidly decreases as T^3,[1,2] becoming less than 1 bar/K at 0.45 mK, and that sets the practical limit for melting curve thermometry.

In contrast, the vibrating wire resonance method is very sensitive in this temperature range. Moreover, at temperatures lower than about 0.3 T_c

($\approx 0.75\,$mK at the melting curve) the vibrating wire should enter the ballistic regime of collisions with quasiparticles where the width of the resonance should obey a simple $e^{-\Delta/T}$ law. Such behavior has been observed at 0 bar and at 7.3 bar by Guénault *et al.*[3,4]

As one can see, there is a wide temperature range in which it is possible to calibrate a vibrating wire by the melting curve thermometer in order to use it at temperatures below 0.5 mK, where the melting curve thermometry is no longer sensitive. To the best of our knowledge, the vibrating wire spectra along the melting curve at such low temperatures were never measured before. We are aware only of the measurements of the viscosity and the normal component density that were done with vibrating wire technique by Alvesalo *et al.*[5,6] However, these measurements were limited to 1.2 mK in temperature.

In this paper we present the experimental observations on the vibrating wire spectra along the melting curve at temperatures down to 0.53 mK.

2. EXPERIMENTAL SETUP AND PROCEDURES

Our cryostat is designed for optical observations on ^{3}He crystals at ultra-low temperatures. The low temperature part of the experimental setup and the optical cell are shown in Fig. 1. For a detailed description of our optical scheme and methods, see our previous publications.[7,8]

Our vibrating wire is a 50 μm diameter tantalum wire bent into a semicircle of radius 2.3 mm. The cavity that the wire is contained in is a cylinder of a 6.5 mm diameter and a 8 mm length. The axis of the cylinder lies in the plane of the vibrating wire. The channel connecting the vibrating wire cavity with the sample cell has a 4 mm diameter and a 40 mm length. The magnetic field in the vibrating wire cavity, supplied by a superconducting solenoid, was 36 mT.

All vibrating wire measurements were conducted in the linear regime, in which the width of the resonance did not depend upon the excitation current. The measured vibrating wire spectrum normally contains 100 data points, one step in frequency being about 10 % of the linewidth. The heat produced by the wire, evaluated as $\vec{I} \cdot \vec{U}$, was well below 1 pW.

The pressure of the liquid was monitored by a Straty-Adams type strain gauge.[9] The resolution of our pressure gauge at 34 bar is about 2 μbar.

One should take special precautions to nucleate a crystal in the optical space of the cell because the magnetic field in the vibrating wire unit decreases the crystallization pressure. We use a sharp tungsten tip operated by a high voltage for crystal nucleation.

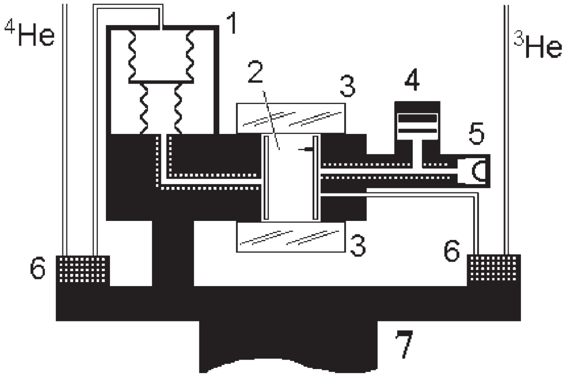

Fig. 1. Principal scheme of the low temperature part of the experimental setup: 1 – Pomeranchuk cell, 2 – optical space with a nucleator inside, 3 – optical windows, 4 – capacitive pressure gauge, 5 – vibrating wire unit, 6 – heat exchangers, 7 – nuclear stage.

The ^{3}He crystal was nucleated at a temperature slightly below T_N, and was then cooled down to the lowest possible temperature of 0.53 mK. The crystal was then grown to a roughly 4 mm size, and was maintained at the lowest temperature for about a week during which time optical measurements were carried out. The cell was then allowed to warm slowly with the nuclear refrigerant under the ambient heat leak of about 5 nW in a 40 mT field. The calibration of the pressure gauge was performed during the same

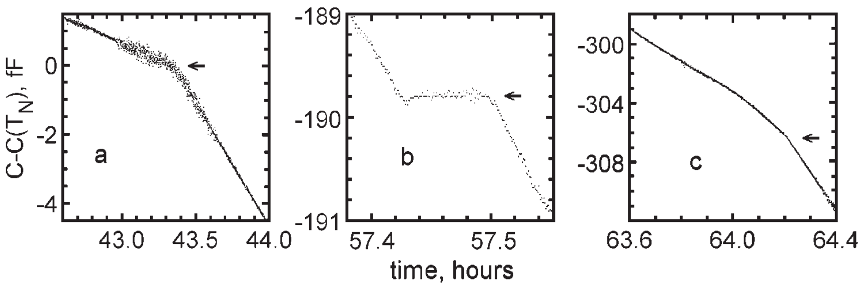

Fig. 2. Manifestation of the fixed points on the trace of the capacitive pressure gauge during a slow warmup: a – the Néel transition in solid ^{3}He, b – the B–A superfluid transition, c – the superfluid A transition. Zero time corresponds to the beginning of the warmup.

warmup (see Fig. 2).

It can be seen from the trace of capacitance versus time, that the Néel and the superfluid B–A transitions can be located with much higher accuracy than the A transition (see Ref. 10 for discussion), and these two transitions were chosen for calibration. The origin of the additional noise in the vicinity of the Néel transition (Fig. 2a) is not clear, but definitely this noise is not connected to the transition itself.

The melting pressure values were converted to temperature using the relations reported by Ni *et al.*[1]

3. RESULTS AND DISCUSSION

The observed dependence of the full width of the resonance curve at half of its maximum upon temperature, plotted as ln (FWHM) vs. T_c/T is presented in Fig. 3. The scatter of the experimental points at the lowest temperatures is due to the error of the melting curve thermometer; this error rapidly decreases with increasing the temperature (see Introduction). At the highest temperatures the scatter of the experimental points is due to the uncertainty in the measured width of the resonance curve, which becomes comparable with the resonance frequency close to T_c.

It was shown by Fisher *et al.*[11] that the damping of slowly moving vibrating wire in the ballistic regime of collisions with quasiparticles is simply proportional to the $e^{-\Delta/T}$, Δ being the superfluid energy gap. The exponential behavior of the width of the resonance curve is clearly seen in our data at temperatures below $0.3\,T_c$, where the mean free path of quasiparticles becomes longer than the diameter of the wire.[12] It should be also mentioned here, that at temperatures lower than $\approx 0.4\,T_c$ the difference between $\Delta(T)$ and $\Delta(0)$ is negligible.[13]

A further indication that the vibrating wire is in the ballistic regime is that its resonance frequency doesn't depend on temperature,[4] which was also observed (see the insert in Fig. 3).

The superfluid energy gap obtained from the data presented in Fig. 3 is $\Delta = (1.99 \pm 0.05)\,T_c$. The enhancement of the BCS weak coupling energy gap $\Delta_{\mathrm{BCS}} = 1.76\,T_c$ is described by the strong-coupling parameter κ, so that $\Delta = \kappa^{-1/2}\Delta_{\mathrm{BCS}}$.[14] Our value of the gap enhancement $\kappa^{-1/2} = 1.13$ is very close to the values extracted from the specific heat jump measurements by Halperin *et al.*[15] at melting pressure, by Greywall[16] at 34.0 bar, and by Alvesalo *et al.*[17] at 32.5 bar, $\kappa_{\Delta C}^{-1/2} = \sqrt{\Delta C_{NS}/(1.43\,C_N)} = 1.15 \div 1.17$.

It was first suggested by Serene and Rainer,[18] that the major strong coupling correction to the BCS weak coupling model for most purposes can

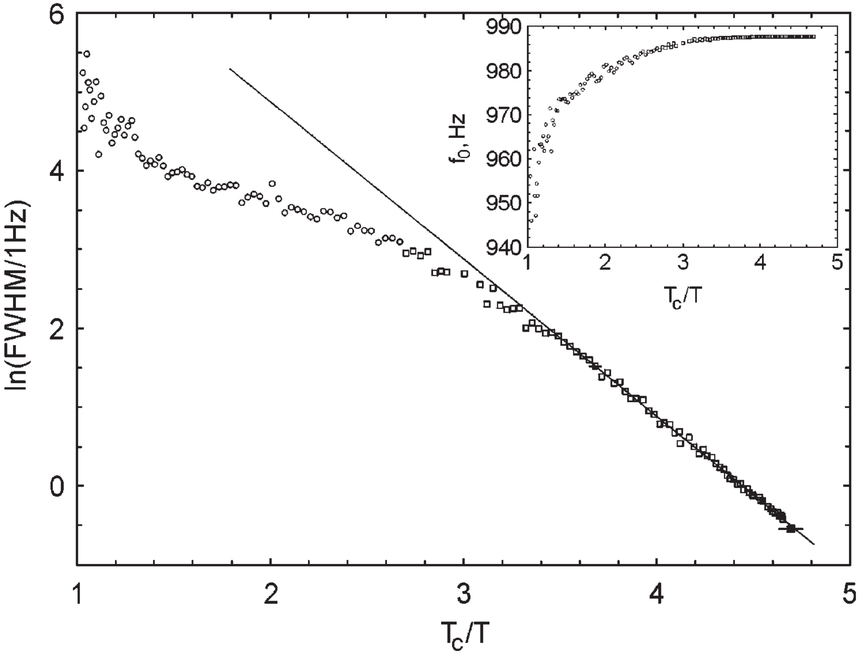

Fig. 3. The width of the resonance of the vibrating wire in superfluid ^{3}He along the melting curve as a function of temperature, plotted as $\ln(\mathrm{FWHM}/1\,\mathrm{Hz})$ vs. T_c/T. The slope of the solid line is -1.99. The insert shows the resonance frequency vs. T_c/T. The scatter of the experimental points is discussed in the text.

be taken into account by the renormalization of the superfluid energy gap. It is important to note that our measurements in the low temperature limit and measurements of the specific heat jump at $T = T_c$ show practically the same gap enhancement, which provides some base for such a "trivial" strong coupling approach.

Since we have calibrated the vibrating wire by the primary (melting curve) thermometer, it can be used at lower temperatures as a very sensitive thermometer. The natural limit of the vibrating wire thermometry will be reached when the damping provided by the liquid ^{3}He becomes much less than the vacuum damping of the wire. From the measurements of the vibrating wire damping at zero pressure by Guénault *et al.*[3,4] and by Carney *et al.*[19] one can expect the limiting temperature to be about $0.1\,T_c$.

As mentioned above, we used the values of pressure and temperature at fixed points reported by Ni *et al.*,[1] namely $T_N = 0.934\,\mathrm{mK}$, $P(T \to 0) - P_N = 1.987\,\mathrm{mbar}$, $P_N - P_{BA} = 32.4\,\mathrm{mbar}$, and $T_c = T_A = 2.505\,\mathrm{mK}$. If we apply the values of the fixed points suggested by the new temperature scale PLTS-2000,[20] we obtain about 1 % decrease of the measured value of Δ/T_c, which is within the limit of our experimental errors.

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