Thermal conductivity of superfluid ^{3}He in aerogel

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Abstract

We report theoretical calculations of the thermal conductivity of superfluid ^{3}He impregnated into high-porosity aerogel and compare these results with available experimental data.

Key words: Quantum Fluids; Transport Properties; Thermal Conductivity, Superfluid ^{3}He; Aerogel

When ^{3}He is impregnated into high-porosity aerogel, a new scattering channel is available to ^{3}He quasiparticles, viz., elastic scattering off the aerogel strands. We examine the effects of elastic and inelastic scattering on the transport properties of ^{3}He in aerogel, and report new results for the thermal conductivity of superfluid ^{3}He in aerogel within the framework of homogeneous and isotropic scattering. This model predicts significant variations in the temperature dependence of the thermal conductivity as a function of pressure, scattering cross-section and aerogel density. Measurements of the thermal conductivity of ^{3}He in 98 % aerogel at $p = 7.4\,\text{bar}$ [1] are in good agreement with theoretical calculations based on either the BW or the ABM phase order parameters. At higher pressures, where pairbreaking effects are weaker, significant differences in the thermal conductivity for these two phases are predicted.

Figure 1 summarizes theoretical calculations for the thermal conductivity at a pressure of $p = 30\,\text{bar}$ over a temperature range, $0.01\,\text{mK} < T \le 30\,\text{mK}$. At high temperatures $T > T_*$ in the normal-state the transport mean-free path is determined by quasiparticle-quasiparticle scattering. Thus, we recover the bulk thermal conductivity of pure ^{3}He with $\kappa \propto 1/T$ for $T > T_*$ ($\approx 5.5\,\text{mK}$ at this pressure). The thermal conductivity crosses over in the normal state to a low-temperature regime determined by elastic scattering

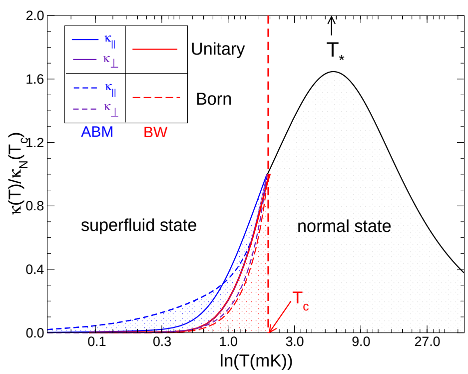

Fig. 1. Theoretical calculations of κ at $p = 30$ bar for a mean free path of $\ell = 180\,\text{nm}$ in both the Born and Unitary limits.

as shown in Fig. 1. This calculation is based on an exact solution to the Boltzmann-Landau transport equation with both elastic and inelastic scattering [3]. For $T \ll T_*$ in the normal-state $\kappa \propto T$ and the mean-free path in the aerogel, $\kappa = \frac{\pi^2}{9} N_f k_B^2 T v_f \ell$. For aerogel with a porosity of 98% we estimate $\ell \approx 180\,\text{nm}$ [4].

Scattering by the aerogel matrix leads to a suppression of the superfluid transition, pairbreaking [4] and the formation of a spectrum of low-energy quasiparticle states below the continuum gap edge. The spectrum of these excitations generally depends upon the symmetry of the order parameter, as well as the scattering cross-section and mean-free path [2] (see Fig. 2). In the unitary limit (strong scattering) a band of gapless excitations *at the Fermi level*, with energies $|\varepsilon| \le$

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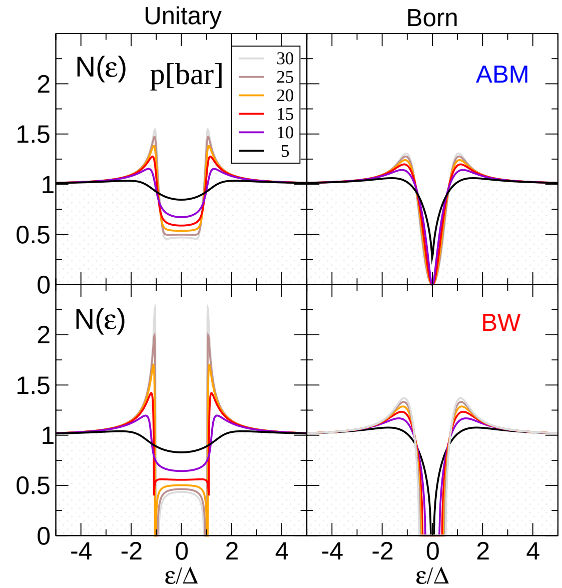

Fig. 2. Theoretical calculations of the density of states for ABM- and BW order parameters with aerogel scattering. The mean-free path is $\ell = 180\,\mathrm{nm}$ and the scattering is in both the unitary and Born limits. The spectra are calculated at reduced temperatures, $T/T_{ca} = 0.2$.

$\gamma \approx 0.67\Delta\sqrt{\xi_0/\ell}$, forms which is relatively insensitive to the symmetry of the order parameter, particularly at lower pressures where ξ_0/ℓ is largest.

The transition to the superfluid state is evident in Fig. 1 as a change in the slope of the thermal conductivity. Calculations of κ/T for the ABM and BW-phases with aerogel scattering included are shown in more detail in Fig. 3 also for $\ell = 180\,\mathrm{nm}$. These results were obtained from solutions to the quasiclassical transport equations, following Graf et al. [2], for spin-triplet, p-wave pairing. Note the difference in the limiting $T \to 0$

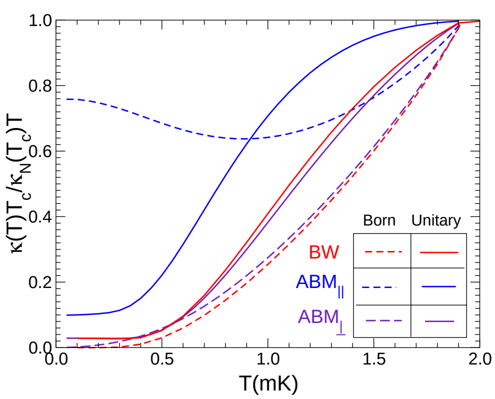

Fig. 3. Thermal conductivity for models of superfluid ^{3}He in aerogel for Born and unitary scattering at $p = 30\,\mathrm{bar}$.

behavior in the Born and unitary limits, and the sensitivity of κ/T to the order parameter at $p = 30\,\mathrm{bar}$. However, in zero field the anisotropy of the thermal conductivity for the ABM state is likely to be averaged out by the orientational disorder of the $\boldsymbol{\ell}$-texture.

At lower pressures, e.g. $p = 10\,\mathrm{bar}$ ($\xi_0/\ell = 0.16$), the excitation spectrum, and therefore the thermal conductivity, are expected to be less sensitive to the pairing symmetry. In the unitary limit the spectrum of gapless excitations leads to a linear T-dependence of the thermal conductivity at low temperatures, $k_B T \ll \gamma$, with a slope, $\lim_{T\to 0} \kappa/T$ that is determined by ξ_0/ℓ.

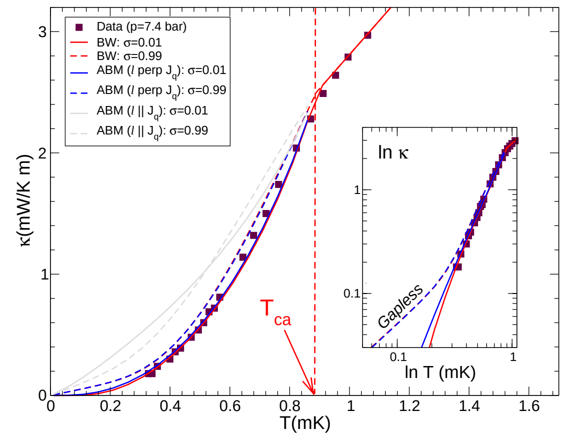

Fig. 4. The theoretical results for κ (solid and dashed curves) are compared to data taken at Lancaster [1] (squares) at $p = 7.4\,\mathrm{bar}$. The calculations are for the BW and ABM states with a mean free path of $205\,\mathrm{nm}$ in the Born ($\sigma = 0.01$) and unitary ($\sigma = 0.99$) scattering limits. Inset: Log-scale comparison between the unitary and Born calculations for the BW and ABM state with $\boldsymbol{\ell} \perp \mathbf{J}_q$.

In Fig. 4 we compare our calculations to experimental data at $p = 7.4\,\mathrm{bar}$ from the Lancaster [1] group. At this pressure pairbreaking is sufficiently strong that the thermal conductivity is only weakly dependent on the symmetry of the order parameter. The data, including $T_{ca} \simeq 0.88\,\mathrm{mK}$ for 98% aerogel, are accounted for by a mean free path of $205\,\mathrm{nm}$ for either the BW phase or the ABM state with $\boldsymbol{\ell} \perp \mathbf{J}_q$ (consistent with $\mathbf{B}||\mathbf{J}_q$), in the Born limit. At this pressure the difference between unitary and Born scattering is significant only at very low temperatures, $T \lesssim 0.2\,\mathrm{mK}$ (inset of Fig. 4). Thus, measurements at lower temperatures could provide evidence for gapless excitations ($\kappa \propto T$); measurements at higher pressures are more sensitive to the pairing symmetry.

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