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Resonant surface scattering and dislocation flutter explain Kapitza resistance at a solid/solid ^{4}He interface

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In this report we investigate the Kapitza resistance R_K at an interface between a classical solid and a ^{4}He quantum crystal, as a function of temperature. We provide a premise for R_K based on a combination of two separate mechanisms which occur simultaneously. Owing to the fact that the phonon wavelengths in solid ^{4}He and in the superfluid are of the same order of magnitude, we infer that one mechanism is due to resonant scattering of phonons by nanoscale surface roughness as predicted by Adamenko and Fuks [1] for solid/superfluid interfaces. The other mechanism involves the interaction of thermal phonons with mobile vibrating dislocations within solid ^{4}He. The present analysis demonstrates the plausibility of these two mechanisms in solving the long outstanding problem of the Kapitza resistance anomaly of solid ^{4}He in contact with copper for temperatures ranging from 0.4 to 2 K.

Keywords: Kapitza resistance, quantum solid, interface.

Introduction

More than half a century ago Mezhov-Deglin (M-D) [2], and Folinsbee and Anderson (FA) [3] studied independently the evolution of the Kapitza thermal boundary resistance R_K before and after solidification of superfluid helium in contact with copper. Both experiments showed no evidence of a quantifiable shift in the Kapitza resistance when helium was either in the liquid or crystalline phase. These observations were rather unexpected since solid ^{4}He has a longitudinal and two transverse phonon branches like any classical solid; whereas superfluid ^{4}He has only a longitudinal branch. The roton excitation present in superfluid ^{4}He is absent in solid ^{4}He.

In the experiments performed by M-D, solid ^{4}He was grown to very high pressures. The measured R_K remained independent of the helium impedance which increased by a factor of 5 on going from He II to solid ^{4}He under high pressures. Also a strict T^3 behavior with solid ^{4}He is not observed. These findings refute the acoustic mismatch (AM) theory predictions applied to solid/solid interfaces. R_K at the solid/solid ^{4}He interface is therefore classified as being anomalous as in the case of superfluid. We recall that Khalatnikov [4] formulated the acoustic mismatch (AM) theory in which heat transmission across an interface is determined by the acoustic properties of each of the bulk materials, namely its density and sound velocities. The AM theory serves as a yardstick although it predicts thermal barriers for solid /superfluid interfaces which are generally larger by almost two orders of magnitude than the experimental results.

The quest to understand R_K between a solid and superfluid ^{4}He has overshadowed the enigmatic results of the R_K between a solid and solid ^{4}He. To our knowledge, the Kapitza resistance between a classical solid and solid ^{4}He has never been explained. In a recent experiment [5], a transition in the Kapitza resistance was observed upon solidifying superfluid helium at the minimum of its melting curve in contact with a Si crystal. This motivated the present study.

The aim of this paper is to provide a basis for a model to interpret the measurements of R_K between copper and solid ^{4}He. Our analysis leads to an explanation based on two independent recent findings. This paper is organized as follows. Firstly we shall show that it is highly plausible that the R_K at the solid (copper or silicon) /solid ^{4}He interface is due to resonant scattering of phonons by nanoscale surface roughness as described by Adamenko and Fuks (AF) in the case of superfluid/solid interfaces. Secondly, we shall study the influence of the interaction of phonons with mobile dislocations within solid helium, which leads to the phonon fluttering mechanism. This mechanism induces an additional thermal resistance which turns out to be as important as that

due to the AF resonant scattering process at the interface. Taking into account these two mechanisms provides a unified picture which explains the experimental results as a function temperature.

Finally, we note that the interest in R_K goes beyond the fundamental incentive to explain the thermal barrier at solidsuperfluid interfaces. Over the last decade the thermal interface resistance has gained increasing attention due to the rapid growth of miniaturization of electronic devices to nanoscales. The performance of devices at micro- and nanoscales is largely impacted by thermal transport across interfaces.

AF prediction of the Kapitza resistance between solids and superfluid helium

Adamenko and Fuks [1] first envisioned a model in which the physical mechanism of phonon transmission across a solid-liquid helium interface is controlled by the solid surface morphology. They anticipated the complexity of defining the morphology of any arbitrary surface by considering a surface with very small roughness heights which follow a Gaussian distribution. These conditions are generally satisfied for highly polished and clean surfaces. Roughnesses are considered as being "small" and uniform when the roughness height σ is comparable to the roughness correlation length ℓ_c and when σ is less than the dominant wavelengths λ of thermal phonons in liquid helium, that is, $\sigma \approx \ell_c < \lambda$. The effective surface area due to surface roughness is not of any importance here. The dominant phonon wavelength in liquid helium depends on pressure and temperature:

$$\lambda(P,T) = \frac{\hbar c_L(P,T)}{3.83 k_B T}. \tag{1}$$

In the AF model a frequency selection mechanism operates when thermal phonons incident from the superfluid interact with the surface roughness and undergo multiple scattering. This mechanism is governed by the geometrical relationship between the phonon wavelength and correlation length. In particular, under the condition $\lambda \approx \ell_c / 3$ phonon scattering becomes resonant and the energy transmitted across the interface is maximal. Now, surfaces have a distribution of roughness heights of different correlations lengths. At a given temperature, there is also a distribution of phonon wavelengths. Consequently, resonant scattering can persist in a wide temperature range and is not easily damped-out even at temperatures well below 1 K. The Kapitza resistance $R_{\sigma L}$ predicted by the AF model, normalized with respect to the AM theory, is given by

$$\frac{R_{\sigma L}^{-1}}{R_{AM}^{-1}} = \left[1 + \frac{1}{2}\gamma^2 f(\theta)\right], \tag{2}$$

where $\gamma = 2\sigma / \ell_c$ is the roughness inclination and $f(\theta) = 115.5\theta^2$ with $\theta = \ell_c / \lambda$ expresses phonon flux amplification across the interface. The numerical coefficient is due to physical constants.

In the recent study [5] the Kapitza resistance between a highly polished Si crystal surface in contact with the superfluid ^{4}He is conducted as a function of pressure (SVP to 24 bars) and temperature. The experiment validates the AF theory by establishing the relationship between the surface roughness heights and the dominant thermal phonon wavelengths in the superfluid. The study also reveals that the probability of resonant scattering increases with temperature, but is confined to smaller and smaller phonon wavelength scales. Two decades prior to this study, in Ref. 6 Zinov'eva *et al.* studied the resonant transmission of ultrasound (13–300 MHz) from liquid ^{4}He through a copper crystal at temperatures ranging from 100–400 mK. It is interesting to note that they had identified the surface acoustic modes to play an important role in the microscopic description of the Kapitza resistance.

Extending AF resonant scattering to solid/solid ^{4}He interfaces

As shown by Adamenko *et al.* [7] rotons in the superfluid contribute very little to heat transfer across interfaces and shall therefore not be considered here. Depending on pressure and temperature, the longitudinal phonon velocity in superfluid ^{4}He lies within the range $240\ \text{m/s} \le c_L < 360\ \text{m/s}$. In solid ^{4}He the longitudinal c_{SL} and two transverse c_{ST} phonon velocities [8] vary as a function of crystal orientation φ w.r.t. the c axis and lie, respectively, in the ranges $440\ \text{m/s} \le c_{SL} < 540\ \text{m/s}$ and $230\ \text{m/s} \le c_{ST} < 260\ \text{m/s}$. These values decrease by less than a factor of two with φ in their respective intervals and are of the same order as in superfluid helium. Consequently, thermal phonon wavelengths $\lambda_{S,j}(\varphi)$ in solid helium given by Eq. (1) (with appropriate sound velocities) therefore fall within the same range of values as for the superfluid. Further, the difference in the densities between the superfluid and solid helium is approximately 20%. In other words, the acoustic properties of longitudinal thermal phonon in the superfluid and solid helium are very similar. Also, sound velocities in solid helium are an order of magnitude smaller than in classical solids.

It becomes therefore clear that the condition for phonon resonant scattering to occur at solid/superfluid interfaces, namely that $\lambda \approx \ell_c / 3$, must now also be naturally fulfilled when the superfluid solidifies into a crystal. Off-course the prerequisite of the AF theory that the solid surface has a Gaussian distribution of roughness on scale lengths of ^{4}He thermal phonon wavelengths remains valid since properties of the solid surface do not change as the pressure is increased. Since the density of states g_s in solid ^{4}He is larger than the density of states g_L in the superfluid, one can surmise that the thermal interface resistance $R_{\sigma S}$ with solid ^{4}He is weaker by the ratio g_s / g_L. Based on these arguments the thermal interface resistance between a classical

solid and solid ^{4}He, $R_{\sigma S}$ can be scaled in the temperature range where resonant scattering prevails as

$$R_{\sigma S} = \frac{R_{\sigma L}}{g_s / g_L}. \quad (3)$$

The ratio $g_s / g_L \approx 3\rho_s / \rho_L = 3.92$, where $\rho_L = 0.145$ g/cm^3 is the superfluid density at SVP and $\rho_s = 0.19$ g/cm^3 is the solid ^{4}He density on the melting curve.

Thermal phonons interacting with vibrating mobile dislocations in solid ^{4}He

In this section we point-out another important feature which is inherent in all direct measurements of the Kapitza resistance between a classical solid and solid ^{4}He. Indeed, the interaction of thermal phonons with mobile dislocations in solid ^{4}He plays a crucial role in explaining, at least partially, the quantum nature of solid ^{4}He. During the search for "supersolidity" in ^{4}He crystals, the group of Balibar *et al.* [9,10] studied its elastic properties. They measured the shear modulus of pure ^{4}He crystals as a function of temperature. Their measurements show that the shear modulus gradually increases with temperature from ~0.3 K which they identified as being due to the interaction of thermal phonons with vibrating dislocations on the basal plane in solid ^{4}He. For completeness we note that for temperatures between 0.1 and 0.3 K they demonstrated that the shear modulus attains a minimum value owing to freely mobile dislocations which lead to the "giant plasticity" [11] of ^{4}He crystals. As the temperature decreases below 0.1 K the shear modulus increases once again, due here to the pinning of the dislocations by ^{3}He impurities. These last two features are not of relevance to our analysis here but could serve as test in future experiments to define relaxation times as discussed later.

The interaction of thermal phonons with mobile dislocations was studied by Ninomiya [12]. In this process thermal phonons, which are incident on mobile dislocations, are absorbed. The dislocations flutter and in turn emit thermal phonons at a frequency that is Doppler shifted. In summary, during the fluttering mechanism a "type of viscous dynamic scattering" occurs where phonons exchange energy with vibrating dislocations. The mean free paths of phonons and therefore of the lattice thermal conductivity are modified. The rate of energy exchange defines the relaxation time [13] $\tau_{Fl} = BL^2 / \pi C$, where $C \simeq 1.7 \cdot 10^7 b^2$ is the dislocation energy per unit length (in J/m), $b = 0.367$ nm is the Burgers vector in solid ^{4}He [8], L is the typical length between dislocations (network length) in the absence of the pinning effect and $B = 14.4 k_B^3 T^3 / \pi^2 \hbar^2 v_D^3$ is the phonon damping coefficient derived by Ninomiya [12]. The scattering rate then takes the form: $\tau_{Fl}^{-1} = 4.95 \cdot 10^7 \times b^2 v_D^3 \, (N_d / \alpha) / T^3$, where we have used the connectedness relationship $L^2 N_d = \alpha$. The numerical coefficients are in SI units. In the Debye approximation, the inverse thermal resistivity is given by

$$W_{Fl}^{-1} = \frac{1}{3} \sum_j \int \hbar \omega_j \frac{\partial N(\omega, T)}{\partial T} c_j^2 \tau_{Fl} d\omega_j .$$

Hence the thermal resistivity generated by the fluttering mechanism is calculated to be $W_{Fl} = 1.21 \cdot 10^{-3} v_D^4 b^2 \times \times (N_d / \alpha) T^{-6}$. Thermal resistivity associated to phonon scattering from static (core and screw) dislocations were calculated [14] and their contributions are two to four orders of magnitude smaller. Here phonon wavelengths are much larger than the dislocation core size.

Explaining the Kapitza resistance between copper and solid ^{4}He

In Fig. 1 we display two sets of Kapitza resistance measurements at a copper/solid ^{4}He interface performed independently by Mezhov-Deglin [2] (crossed-squares) and by Folinsbee and Anderson [3] (full squares). Only data above 0.4 K are plotted since this temperature range is of interest to us. For clarity, only one series of measurements performed by M-D is represented in the Fig. 1. The data given by the open circles in the figure correspond to measurements by Folinsbee *et al.* with helium in the superfluid phase. Comparing the different data reveals clearly

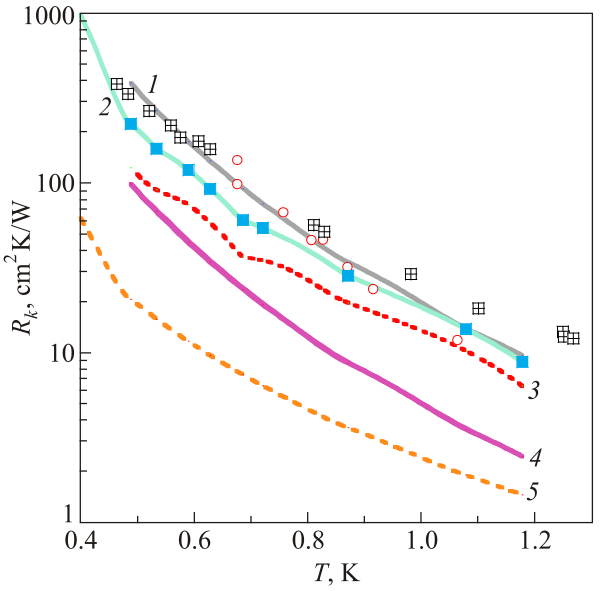

Fig. 1. The open circles and full squares correspond to measurements of Folinsbee and Anderson [3] for the Kapitza resistance between copper and, respectively, superfluid and solid ^{4}He. The gray curve *1* fitting the open circles is obtained using the AF model with σ-values shown in Fig. 2. Curves *4* and *5* are respectively $R_{\sigma,S}$ and R_{DMS}. The dotted curve *3* is the estimated contribution due to the flutter mechanism and is obtained using Eq. (4). The squares with crosses correspond to measurements of R_K between Cu and solid ^{4}He under pressure done by Mezhov-Deglin (see text).

that the difference in the Kapitza resistance when helium is either in the solid or superfluid phase is barely quantifiable at low temperatures and at $T > 1$ K, where these values are confounded (open circles are below full squares in Fig. 1). Similar results (not shown in figure) have been obtained by M-D who periodically measured the Kapitza resistance at the Cu-superfluid interface before undertaking measurements with solid ^{4}He under different high pressures [see data sets in Fig. 3a in Ref. 2). M-D concluded that the effect of the bulk resistance of solid ^{4}He is negligible on R_K and a decisive role must be played by surface properties at the interface and/or by, perhaps, the intervention of an additional heat transfer mechanism. It is therefore well established that the Kapitza resistance at Cu/solid ^{4}He interfaces is "anomalous" since it cannot be accounted for by the AM theory adapted for solid/solid interfaces.

In our analysis of the R_K measurements at the Cu/solid ^{4}He interface, we begin by fitting the data of FA for the Cu/superfluid interface (open circles) with Eq. (2). Figure 2 shows σ and σ/λ values which are determined as a function of temperature from the experimental data. The surface roughness values are of the order of ~1 nm and we have $0.2 < \sigma/\lambda < 0.4$. The latter clearly supports a predominance of AF-resonant scattering at the Cu/superfluid interface. Using Eq. (3), the tendency of the Kapitza resistance between Cu and solid ^{4}He is then determined and represented by the curve *4* in Fig. 1. All experimental data of R_K (full and crossed squares) between Cu and solid ^{4}He are stronger than our prediction of $R_{\sigma S}$. For completeness, curve *5* shows the diffuse mismatch (DM) model prediction [15] for Cu/solid ^{4}He interface $R_{DMS} = 2.4T^{-3}$ cm^{2}K/W. Since the scattering conditions at the interface in the DM model are less stringent than in the AF model, the R_{DMS} prediction is smaller by a factor which varies from ~5 at 0.4 K to a factor of ~2 as 1.2 K, as shown in the figure.

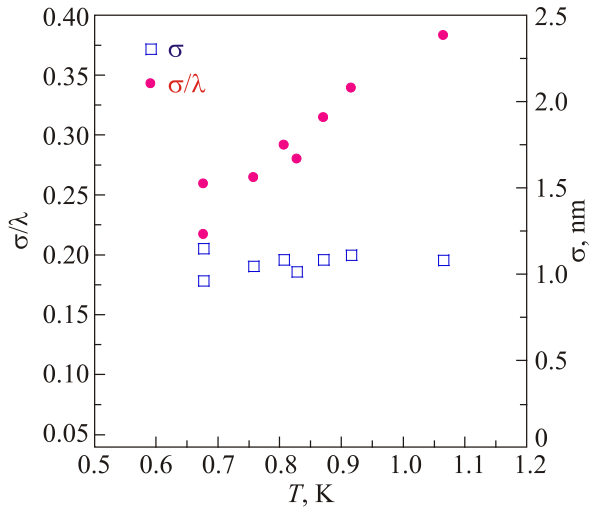

Fig. 2. Roughness height σ and σ/λ determined from AF theory for R_{KL} measurements of Folinsbee *et al.* [3] at Cu/superfluid interface.

Now, in the experiments performed by FA, and for a set of measurements done by M-D, the ^{4}He crystals were grown between cylindrical walls. In both experiments the temperature gradient across solid ^{4}He was considered to be negligible, that is, the crystals were taken to be pure and the bulk thermal resistance of solid ^{4}He was supposed to be negligible compared to the measured R_K. But the presence of dislocations plays an important role on the elastic properties of solid ^{4}He as confirmed by the recent studies by Balibar *et al.*, and in earlier investigations of the thermal conductivity of solid ^{4}He by Mezhov-Deglin [16]. In particular, the flutter mechanism, discussed in the previous section, induces an additional thermal resistance $R_{Fl} = W_{Fl}t$ which takes the form

$$R_{Fl} = 1.21\cdot 10^{-7}\left(\frac{N_d}{\alpha}\right)T^{-6}\ (\text{cm}^2\text{K/W}), \qquad (4)$$

where the dislocation density N_d is now in cm^{-2} and the thickness of the solid ^{4}He in studies of FA and M-D is taken to be $t \approx 0.1$ cm. R_{Fl} must therefore be inherent in all the measurements displayed in Fig. 1. The measured thermal resistance R_{KS} can now be cast as $R_{KS} = R_{\sigma S} + R_{Fl}$.

In our analysis N_d/α is taken to be a variable fitting parameter. Details of the experimental conditions under which the ^{4}He crystals were grown are not known. It is also unknown if all measurements were conducted on the same crystal or on crystals having similar qualities. Furthermore ^{4}He crystals tend to anneal with time and generally improve due to recrystallization. Consequently, it is highly probable that N_d and α vary as a function of temperature for these samples in the both studies.

Figure 3 shows N_d/α as a function of T for the R_K data represented by the full squares in Fig. 1. N_d/α varies from

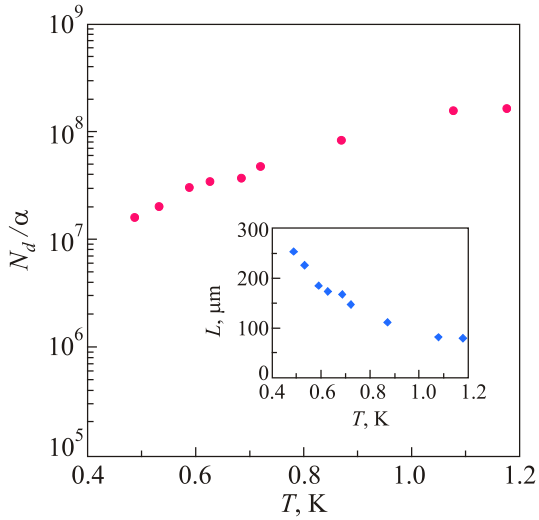

Fig. 3. N_d/α as a function of temperature from the thermal resistance due to the flutter mechanism is given by Eq. (4). The insert shows the evolution of the estimated dislocation network length L as a function of temperature. Small values of L at high temperatures are due to a higher dislocation density.

a value of $2\cdot10^7$ cm^{-2} at 0.4 K to $15\cdot10^7$ cm^{-2} at 2 K. The value of α depends on the crystal quality and can theoretically vary from $1/\sqrt{2}$ to 20–60 for high quality hcp crystals [17]. Taking plausible values of α from experiments to lie within the range 1 to 10, estimates of the dislocation density N_d are found to be within 10^7–10^8 cm^{-2}. This is in agreement with typical values for relatively good quality crystals [16,18]. Puech *et al.* [19] also found dislocation densities of the order of $2\cdot10^7$ cm^{-2} for their ^{4}He crystals grown between two cylindrical tubes, separated by distance of 1 mm as in the case of AF and M-D.

With these values of N_d/α the thermal resistance due to the flutter effect is given by dotted curve *3* in Fig. 1. The predominance of R_{Fl} over the thermal interface resistance $R_{\sigma S}$ is clearly highlighted. Indeed, R_{Fl} restores the expected drop in Kapitza resistance upon solidifying ^{4}He. This artifact is effective only when R_K is measured with the aid of two thermometers positioned at distances greater than the mean free path of phonons on either side of the interface. Dislocations in the classical solid [27] can also have an effect on the measured R_K. From the connectedness relation for dislocation N_d/α corresponds to L^2. The insert in Fig. 3 shows the typical values of L we obtain and its evolution with temperature. The increase in the dislocation density (decrease in network length) indicates a deterioration of the crystal quality with temperature. It highly likely that this finding is related to the cell geometry and/or sample history of the FA experiment, as explained later.

Comments

We have limited our analysis to temperatures in the range of 0.4–1.2 K. In this range the importance of dislocation flutter mechanism in describing the elastic properties of solid ^{4}He is well established. Moreover, the importance of the flutter effect on the thermal properties of solid ^{4}He was demonstrated by Levchenko and Mezhov-Deglin (LM-D) [16,20]. Their work was conducted after the measurements of the Kapitza resistance between Cu and solid ^{4}He by M-D. They studied the thermal conductivity of perfect and plastically deformed ^{4}He crystals grown in a narrow capillary. Their results clearly show a decrease in the thermal conductivity with an increase in the N_d due to bending of the solid ^{4}He crystal. However this effect is damped at temperatures above ~1 K. But on samples which have undergone a thermal shock, the diminution of the thermal conductivity is observable in the whole temperature range (see Fig. 5 in Ref. 16), that is, above the temperature at which the thermal conductivity attains a maximum. These results provides the clues as to how the evolution of N_d by an order of magnitude, observed in Fig. 2, is plausible under certain experimental conditions. Unfortunately, in the FA study the history of the sample treatment during measurements is not available. Finally, the present analysis also shows that the phonon-dislocation interaction is preponderant in the Poiseuille and Umklapp regions of the thermal conductivity of solid ^{4}He.

We add that although the purity of ^{4}He is unknown in the R_K experiments of FA and M-D, it does not affect our analysis here. On the other hand, at temperatures below 0.1 K the presence of ^{3}He impurities leads to the pinning of dislocations. Here the phonon-dislocation relaxation time should deviate from the one we have used and Eq. (4) would no longer be valid.

Kink-phonon interactions

The phonon-dislocation flutter mechanism is present in other materials like Li, Be and Pb. Ostaay *et al.* [26] proposed a model in which phonons scatter from kinks on a mobile dislocation. Different temperatures dependences for the thermal conductivities of solids are proposed in different temperature regimes which are classified according to the nature of phonon-kink interactions. In reality the latter must depend on the thermal phonon wavelength λ with respect to the size of the kink s_k and on the orientation of a dislocation. Indeed, for $\lambda > s_k$ the scattering must be coherent and when $\lambda < s_k$ scattering is incoherent. Their model serves to explain the observed thermal conductivity anomalies in Pb. However, it is not straightforward to apply this model equations to solid ^{4}He since the expressions defining the temperature regimes contain adjustable parameters which need to evaluated first, other than the kink mass which has been determined in Ref. 21. Nevertheless, to emphasize the importance of the kink-phonon interactions, we cite a previous study [22] of the growth dynamics of surfaces of ^{4}He crystals on the melting curve. In this study it is clearly demonstrated that, depending on the crystal orientation and therefore on the kink density on a step, the mobility of the ^{4}He crystal surface is governed by the nature of the interaction determined by phonon wavelength λ to kink size s_k ratio. As before when $\lambda > s_k$ the scattering process is insensitive to the kink structure and hence the scattering is specular.

On a matching layer at the interface between the solid and superfluid ^{4}He

One of the first attempts to explain the anomalous R_K is attributed to the binding of ^{4}He atoms at the surface. The key idea is that the van der Waals force between surface atoms in the solid and ^{4}He creates a pressure gradient perpendicular to the interface. This leads to a variation of the superfluid density over a distance of ~0.8 nm from the solid surface. The calculated thickness of the hypothetical solid ^{4}He layer does not exceed 0.24 nm (see supplementary material in Ref. 5). This is smaller than the thickness of a monolayer of ^{4}He. The solid ^{4}He layer is so thin that it cannot smoothen-out the surface roughness. Consequently, thermal phonon-surface roughness interactions as envisioned by AF remain unaltered.

More recently, Yu.A. Kosevich *et al.* [28,29] proposed new mechanism in which the presence of an absorbed 2D monolayer (due to impurity atoms) with an internal dynamical degree of freedom forms a meta-interface between the two media. By tuning the dissipative nature of the meta-interface the model predicts a maximum transmission of phonons from all angles of incidence by 3 orders of magnitude compared to an ideal interface. For a non-dissipative meta-interface the maximum transmission reaches only an order of magnitude compared to an ideal interface. The model also predicts a very sharp increase in the transmission as $T^{\approx 6}$ to reach a maximum at a "resonant" temperature of ~1.5 K. It would be interesting to study these model features using a prepared solid surface. We note that in the experiments of FA, M-D and in Ref. 5 the meta-interface, if it exists, must be present before and after solidification of ^{4}He. Therefore, the analysis relevant to the role of dislocations in solid ^{4}He as discussed in this paper remains unchanged.

On solid/liquid ^{3}He interfaces

Measurements of R_K between copper and liquid ^{3}He were conducted by Anderson *et al.* [23] in a wide temperature range. These results remain essentially unexplained. Analysis of R_K for these interfaces goes beyond the scope of this paper and the applicability of the AF theory. Indeed, liquid ^{3}He is a viscous Fermi liquid with unique properties. For example, measurements of the thermal boundary resistance [24] between solid and liquid ^{3}He on the melting curve between 50 and 250 mK, are explained by taking into account the zero sound modes [25] present in liquid ^{3}He. In view of the confirmation of role of zero sound, we believe that the Kapitza resistance of solids in contact with liquid ^{3}He remains to be reinterpreted.

Conclusions

From the arguments based on the criteria relating surface roughness and phonon wavelengths, established by AF for solid/superfluid interfaces, we have proposed that resonant scattering is the preponderant mechanism at the interface between a classical solid (Cu) and solid ^{4}He. The discrepancy between the $R_{\sigma,S}$ values predicted by our model and the measurements are then explained by an artifact in the measurements, attributed to the role of mobile dislocations in solid ^{4}He. Our analysis highlights the importance of a thermal resistance due to the phonon-flutter mechanism and correctly predicts the required dislocation densities as corroborated by other experiments. Taking into account these two mechanisms provides a coherent picture of the Kapitza resistance as a function of temperature at the Cu/solid ^{4}He interface. Our analysis provides the motivation to establish a full theoretical picture of the resonant scattering mechanism at solid/solid ^{4}He interfaces.

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Пояснення опору Капіци на інтерфейсі твердого тіла та твердого ^{4}He резонансним поверхневим розсіюванням і флатером дислокацій

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Досліджено опір Капіци R_K на інтерфейсі між класичним твердим тілом і квантовим кристалом ^{4}He як функція температури. Зроблено припущення, що R_K базується на комбінації двох окремих механізмів, що відбуваються одночасно. Завдяки тому факту, що довжини хвиль фононів у твердому та надплинному ^{4}He є величинами одного порядку, припускається, що один з механізмів — це резонансне розсіювання фононів на наномасштабних нерівностях поверхні, як передбачили Адаменко та Фукс (АФ) [1] для інтерфейсів тверде тіло/надплинний гелій. Інший механізм враховує взаємодію термічних фононів з коливаннями мобільних дислокацій усередині твердого ^{4}He. Представлений аналіз демонструє правдоподібність цих двох механізмів у вирішенні давньої проблеми аномалії опору Капіци для контакту твердого ^{4}He з міддю в температурному інтервалі від 0,4 до 2 К.

Ключові слова: опір Капіци, квантовий кристал, інтерфейс.

Объяснение сопротивления Капицы на интерфейсе твердого тела и твердого ^{4}He резонансным поверхностным рассеянием и флаттером дислокаций

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Исследовано сопротивление Капицы R_K на интерфейсе между классическим твердым телом и квантовым кристаллом ^{4}He как функция температуры. Сделано предположение, что R_K базируется на комбинации двух отдельных механизмов, совершающихся одновременно. Благодаря тому факту, что длины волн фононов в твердом и сверхтекучем ^{4}He имеют один порядок величины, предполагается, что один из механизмов — это резонансное рассеяние фононов на наномасштабных неровностях поверхности, как предсказали Адаменко и Фукс (АФ) [1] для интерфейсов твердое тело/сверхтекучий гелий. Другой механизм учитывает взаимодействие термических фононов с колебаниями мобильных дислокаций внутри твердого ^{4}He. Представленный анализ демонстрирует правдоподобие этих двух механизмов в решении давней проблемы аномалии сопротивления Капицы для контакта твердого ^{4}He с медью в температурном интервале от 0,4 до 2 К.

Ключевые слова: сопротивление Капицы, квантовый кристалл, интерфейс.