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To cite this version:


HAL Id: jpa-00217517
https://hal.archives-ouvertes.fr/jpa-00217517
Submitted on 1 Jan 1978

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TUNNELLING AS A MECHANISM FOR THE ANOMALOUS KAPITZA RESISTANCE

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Abstract.- We try to explain the anomalous Kapitza resistance introducing tunnelling states of He atoms close to the boundary between a solid and liquid or solidified He. It is emphasized that tunnelling states of "quantum atoms" in the first few layers may play an important role in the anomalous heat conduction. We suggest further experimental aspects to verify the theory.

Thermal boundary resistance has by now been reported for interface between solids and quantum media at low temperatures including solid $^{3}\text{He}$, $\text{H}_2$, $\text{D}_2$. Above 0.1 K there is general disagreement with all aspects of the acoustic mismatch theory /2/. In recent years, considerable progress has been made in understanding the heat transfer from various experiments. Summing up the situations /1/, we need a consistent explanation of the following experimental features: (1) The mechanism must be independent of the quantum statistics, i.e., it must work for either $^{3}\text{He}$ or $^4\text{He}$. (2) With increasing frequency above about 20 GHz ($\sim 1$ GHz), phonons have an increasing probability of transferring energy across the interface. (3) The first few adsorbed layers of He play a significant role. (4) The mechanism must be applicable to liquid, solidified or gaseous $^{3}\text{He}$ and $^4\text{He}$, or solid $\text{H}_2$ or $\text{D}_2$, but not to other 'ordinary' solids. (5) We must explain why anomalous heat transfer appears above 0.1 K ($\sim 2$ GHz) and the anomalous absorption of 'quasi-monochromatic phonons' occurs above about 20 GHz ($\sim 1$ K). (6) The mechanism must inject phonons into liquid He at all angles. (7) The transverse phonons are absorbed effectively to the quantum media. (8) The unknown mechanism must be relatively weakly influenced by the physical condition of the interface and work for the uneven surface.

Recently, the author /3/ proposed the mechanism to explain consistently the eight experimental features mentioned above. The first layer of He atoms (or $\text{H}_2$ molecules) is bound strongly at the solid surface under the action of van der Waals forces. The second or third layer of these atoms, however, are rather weakly bound to the solid due to van der Waals forces. In these layers the states of atoms differ fundamentally from those in the first layer or the bulk. These layers are misfitted to the atomic arrangement of the solid surface since the effective radius of an atom of a solid is much larger than that of He atoms (or $\text{H}_2$ molecules). In view of the unavoidable spatial randomness of the solid surfaces He atoms (or $\text{H}_2$ molecules) will be randomly distributed at the solid surface and misfitted to the atomically rough surface in the first few layers. We can expect that a number of vacancies or voids are contained in the first few layers. The presence of the vacancies or voids indicates that tunnelling, corresponding to two neighbouring equilibrium positions, could occur naturally in He atoms (or $\text{H}_2$ molecules) close to the boundary. A theoretical description of this kind of defect is made by the two-level system with a distribution of level splitting. The properties of a quantum mechanical two-level system are characterized by the energy difference $E=\left(c^2+\alpha^2\right)^{1/2}$, where $\epsilon$ stands for the energy difference between the localized groundstates which is the sum of the energy difference between the two potential minima and the difference in zero-point energy of the two oscillators. $\Delta$ can be written as $\Delta=\hbar \omega_0 \exp(-\lambda\lambda)$, where $\hbar \omega_0$ is of the order of the zero-point energy for the motion of an atom around one potential minimum, and $\lambda$ is roughly proportional to the square root of the height $V$ of the potential barrier and...
to the distance \( \lambda \) between the two potential minima, that is, \( \lambda = (\frac{\hbar}{2m})^{1/2} R \). We must note that because of the random character of the tunnelling site, the quantities like barrier height \( V \) and tunnelling distance \( \lambda \) can be expected to be statistical variables dependent on such factors as the particular configurations of atoms surrounding the two minima. Taking the suitable values of mass, barrier height \( V \) and tunnelling distance \( \lambda \) we can roughly estimate the acceptable range of the energy distribution. If we take the potential wells to be identical, the minimum energy difference \( E_{\text{min}} \) due to the overlapping of the wavefunctions is obtained. Using the mass of He atoms with the high potential barrier height \( V \approx 10 \text{ K} \) between wells, which should correspond to the desorption energy of the second atomic layer, and a separation \( \lambda \) of 1 Å, the minimum energy difference is about 0.5 K, taking a zero-point energy \( \hbar \omega_0 = 1.5 \times 10^{-6}\text{eV} \). This energy difference is sensitive to the exact value chosen for these parameters but as we have chosen the possible mass together with a high-potential barrier height, the contributing energy distribution \( n(E) \) has the acceptable range between \( E_{\text{min}} \approx 0.5 \text{ K} \) and \( E_{\text{max}} \approx E_{\text{max}} \) will be much higher than the temperature of interest. We do not mean, of course, that no tunnelling states appear below the energy difference below \( E_{\text{min}} \), but the density of tunnelling states with energy difference \( E_{\text{min}} \) is very low. From the tunnelling mechanism, we can obtain excellent agreement with the experimental data /3/. Of particular significance is the fact that it is possible to explain all the experimental features ( (1) - (8) ) with this mechanism.

Finally, we would like to mention about some further experimental aspects in order to verify the theory. These are quite analogous to the experimental situation of the glassy materials. First, the experiments on saturation effect enable us to obtain the information of the presence of tunnelling states. When a relatively strong high frequency ultrasonic pulse propagates through the boundary, one would expect a saturation of the tunnelling states where energy splitting is sufficiently close to the energy of the incident phonons. Also these experiments provide information on the mutual interactions between neighbouring tunnelling states. Second, experiments on the phonon echoes are quite valuable. This gives us information about the 'transverse' relaxation time \( T_2 \). Third, incident angle-dependence of reflection or transmission coefficient of bulk transverse waves gives the detailed knowledge of the coupling between phonons and tunnelling states. In these experiments, it is desirable carefully to fix the polarization direction of the mode to the boundary plane. It should be emphasized that the transverse mode with horizontal polarization (SH-mode) also contributes to the heat transfer through the coupling changing the distance \( \lambda \) between potential minima.

The author is indebted to Dr. W. Arnold for enlightening discussions.

References

/1/ See, for examples, Challis, L.J., J. Phys. C 7 (1974) 481
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