Kapitza conductance of niobium for superconducting cavities in the temperature range 1.6 K, 2.1 K.

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Introduction

The Kapitza conductance h_K is a limiting factor in removing heat from a metal to Helium II near 1.8 K the operating temperature of S.R.F Niobium cavities (1 to 3 GHz), but up to now the available theoretical h_K values, are one order of magnitude lower (Khalatnikov Acoustic Mismatch Theory [1]) or higher (Phonon Radiation Limit [2]) than the experimental h_K values. Moreover, in our knowledge, the few and relatively early publications [3-4] concerning the Kapitza resistance for Nb-He II systems concern Niobium specimens, surface of which are not prepared following the standard S.R.F. cavities procedure. Besides, the experimental apparatus used for measuring h_k in these previous works are not sufficiently accurate or even more difficult to realise. This lack of information leads us to build an experimental set-up to measure h_K. An experimental study is therefore carried out to measure the Kapitza resistance (R_K) as well as the purity (RRR) and chemical treatment of such specimens.

Experimental procedure

The analysis of existing measurement devices, by retaining only positive aspects, has allowed us to develop a new measurement device which presents the following advantages:

- The heat flux in the sample is one-dimensional.
- No disturbing of the temperature field in the sample.
- Easy assembling of the apparatus (simple samples mounting and dismounting procedure).

This experimental set up is shown on fig 1. It is composed of a stainless steel cylindrical support of 80 mm external diameter and 40 mm internal diameter. The test specimens are two plates of 50 mm diameter and 2 mm thickness each. They are mounted face to face on the cylindrical support and fixed by means of two stainless steel clamps. This assembly forms a cavity referenced here after as the internal bath, which can be filled with superfluid helium through a stainless steel capillary tube of 1 m long and 0.2 mm diameter. The internal bath can be heated using an electrical resistor (R_{ch1}). its temperature can be measured by a thermistance (AB_1), which is an Allen-Bradley carbon resistor. This thermistance is of high sensitivity in the experiment temperature range and of small dimension (which is necessary in view of the cell dimensions). The experimental cell is immersed in a helium filled cryostat, called the external or principal bath. The temperature in the external bath is controlled by a thermistance (AB_2) and a heating resistance (R_{reg}) within ± 0.1 mK.

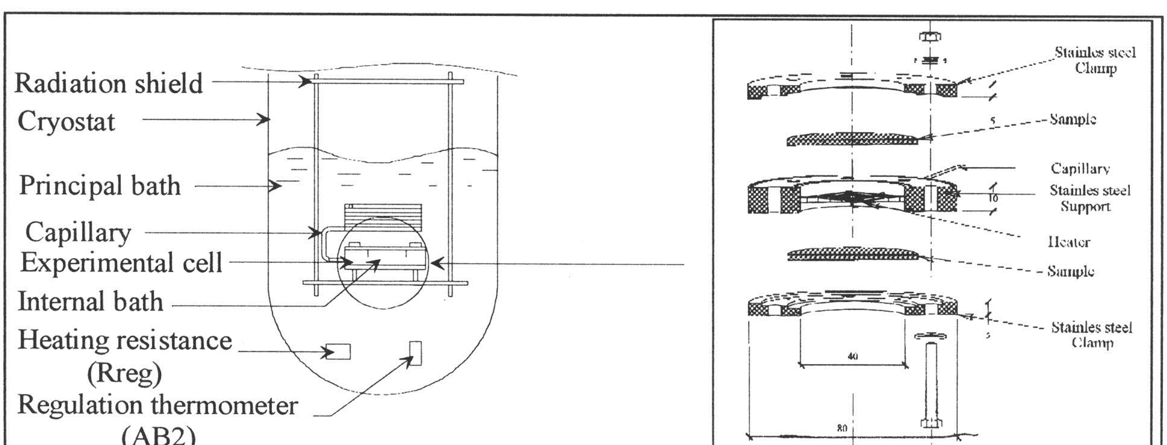

Fig. 1: Experimental set-up for measurement of Kapitza conductance

The experimental technique is based on temperature difference measurement between the internal and external baths, for different injected heat flux in the heater R_{ch1}. The relation between the heat flux Q and the temperature difference $\Delta T=T_{int}-T_0$, where T_0 is the external bath regulated temperature, takes into account heat transfer through:

- The specimen plates (Q_1).
- the stainless steel support and clamps (Q_2).
- the capillary tube (Q_3).
- The heater and Allen-Bradley thermometer measuring wires (Q_4).

The last three thermal powers are heat losses, and can be precisely estimated, then we can deduce Q_1 according to heat balance:

$$Q_1 = Q - \sum_{i=2}^{4} Q_i \qquad (1)$$

Low level amplifiers with adjustable offset, developed in the Laboratory, are used for conditioning only the temperature difference signal (few mK). Assuming that $\sum_{i=2}^{4} Q_i << Q_1$ and that the test specimens diameters is large compared to their thickness, the heat flow across the plates can be considered as one dimensional. On the other hand, as the two specimens used at each test are prepared from the same Nb sheet and their surfaces prepared following exactly the same process, the heat flux through each plate can be obtained by dividing Q_1 in two equal parts. So an experimental curve $Q_1=f(\Delta T)$ leads directly to the value of the global thermal resistance given by:

$$R_g = R_K + \frac{R_{Nb}}{2} \qquad (2)$$

where:

- R_K is the Kapitza resistance at the Nb-He II interface.
- $R_{Nb} = \frac{e}{KS}$, the thermal resistance due to the Niobium thermal conductivity.
- e and S are respectively the specimen thickness and helium II cooled surface area.

The Kapitza resistance at the temperature T_0,is simply given by:

$$R_K = R_g - \frac{e}{2KS} = \frac{1}{h_K} \qquad (3)$$

This expression shows that the specimen thermal conductivity (K) should be known. This thermal conductivity is determined by F. Koechlin [5] prior to our tests.

Sample preparation and experimental results.

As pointed out in nearly every publication on Kapitza conductance, the sample and especially its surface preparation influence strongly h_K; a factor two is not unusual for samples with different surface preparation. For this raison, we measured h_K for niobium sample with different surface treatment. We, also carried out measurement on samples with different purity, which is electrically characterised by the RRR.
Tested samples are referred by the name of the manufacturer as well as by the value of their RRR.

- Niobium Wah-Chang RRR 40 (Sheet).
- Niobium Heraeus RRR 180 (Sheet).
- Niobium Wah-Chang RRR 270 (Ingot)

For each sample, several tests were performed in order to get statistics and to check the reproducibility. We have, in a first time, undertaken measures on samples having a crude surface state, (i.e. as received from the manufacturer), but with different RRR.
We have then, realised measures of h_k on a sample of niobium Heraeus RRR 180 that has been submitted to the surface chemical treatment of superconducting cavities.
Finally, we investigate on the effect of the "titanification" on h_K.
All the results are reported on fig. 2. Values of h_k obtained vary from 0.180 to 0.859 W/cm²K at 1.8 K and from 0.224 to 1.226 W/cm²K at 2 K. The temperature dependence varies for the different samples between $T^{2.6}$ and $T^{3.6}$. We can see that all the values are limited by the two available theories i.e. Acoustic mismatch theory and phonon radiation limit.

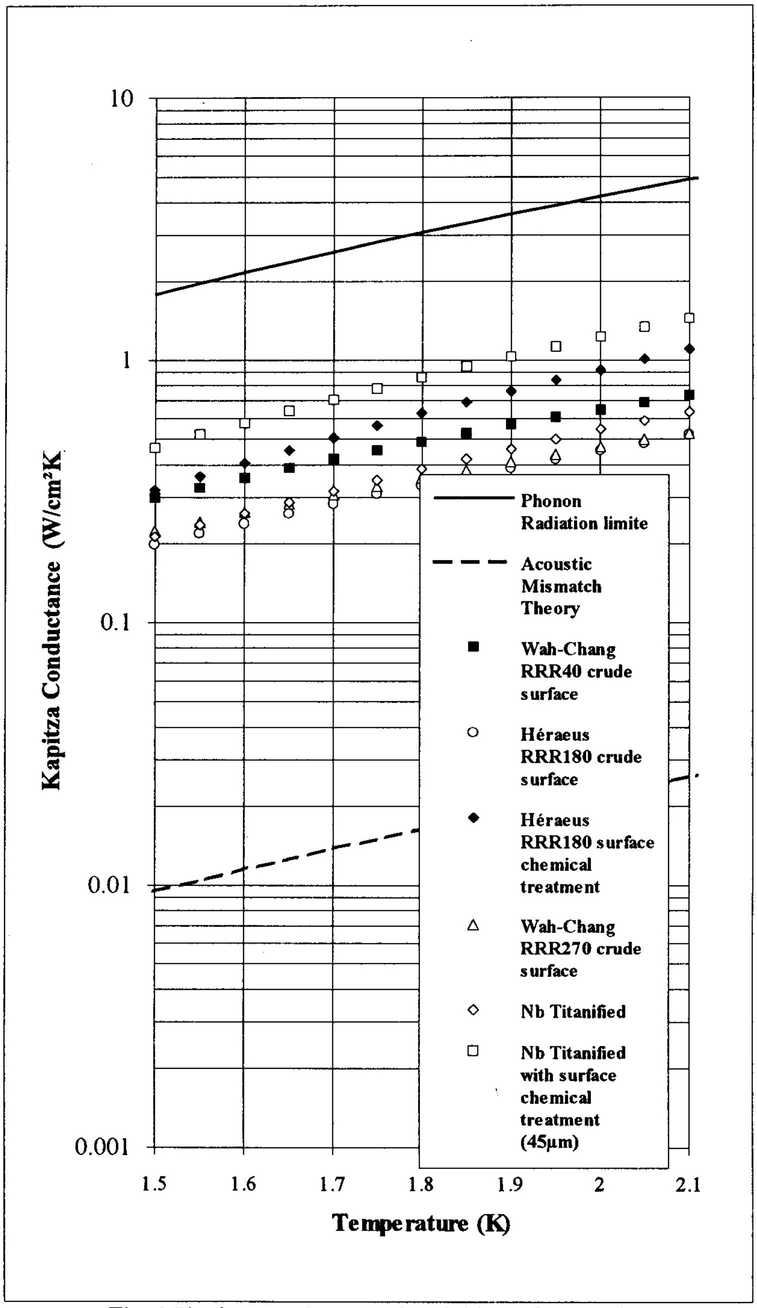

Fig. 2 Kapitza conductance for niobium. Our results.

Effect of bulk purity

We are looking for a relation between h_K and the purity of the material which is characterised by the RRR. Fig 3 gives the results for niobium with different purity and rough surface. The sample Wah-Chang RRR40 and Heraeus RRR180 are as received from the manufacturer (Laminated). The sample Wah-Chang RRR270 is machined. So it is thought that the last sample has a different state surface from the other two samples.

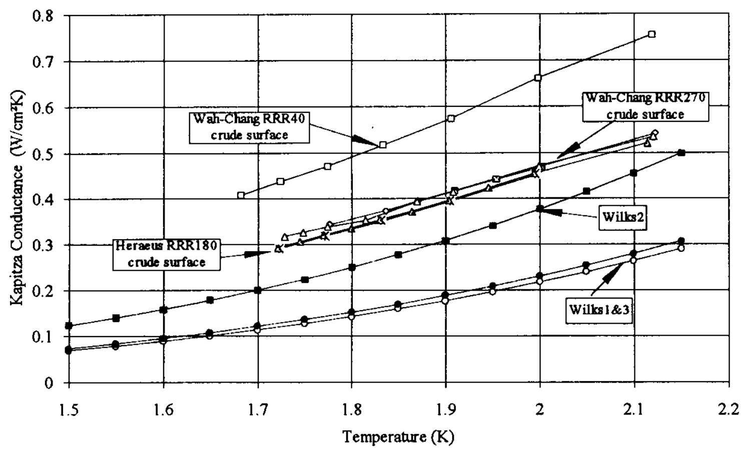

Fig. 3.-.Kapitza Conductance of niobium for crude samples of different purity (our results). Comparison of our results with Wilkes data [1]. Wilkes1 and Wilkes3 are for pure niobium samples (99.98%). Wilkes2 pure niobium samples (99.8%).

At first glance, we can't obtain a conclusion. As a matter of fact, the niobium Wah-Chang RRR40 which is less pure has the higher values of h_K, but the niobium of RRR 270 which is more pure has higher conductance than the niobium Heraeus RRR180 (intermediate purity). Except the Wah-Chang RRR270 niobium, it can be said that the Kapitza conductance decreases with the purity. The results obtained by Wilkes [1] (Fig 3)seems to follow this tendency. More measurements should be carried out to confirm the results and getting more statistics.

Influence of surface chemical treatment.

The chemical treatment following the standard process used on S.R.F. cavities has been applied to a sample of niobium Heraeus RRR180. The values of h_K have been measured before and after this treatment. The results are shown in fig 4. It can be seen that the chemical treatment increases h_K by a factor 2. These results are confirmed by Mittag [2] (Fig 4).

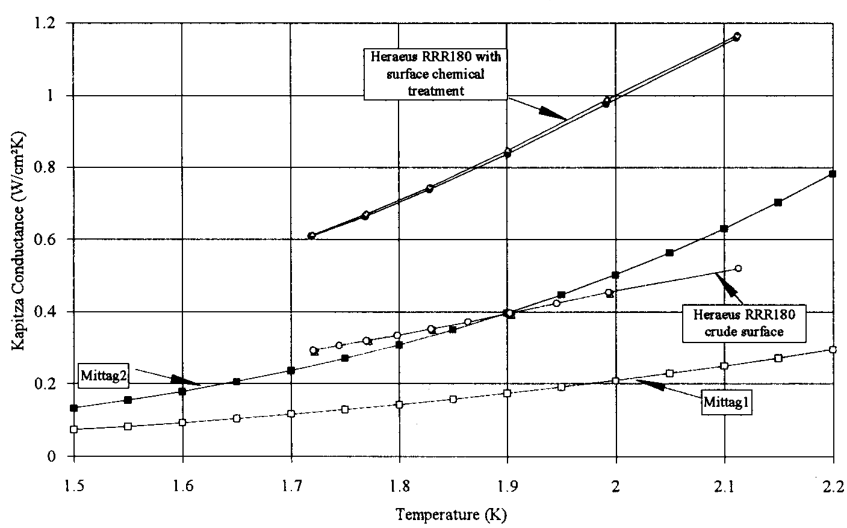

Fig. .4.-.Kapitza Conductance of niobium. Effect of surface chemical treatment. Comparison of our results with Mittag data [2]. Mittag1 without chemical treatment. Mittag2 with chemical treatment.

Titanification effect.

We have made measurements of h_K on a sample which has been titanified. The sample was then subjected to the chemical treatment and during this operation we removed from each face a layer of a few µm thickness, to eliminate the titanium from the surface. Then measurements of h_K were performed. The sample was submitted again to the chemical surface treatment and the layer removed has 45 µm thickness on each face and measurement of h_K were made again. The results of these measurements are shown in fig. 5.

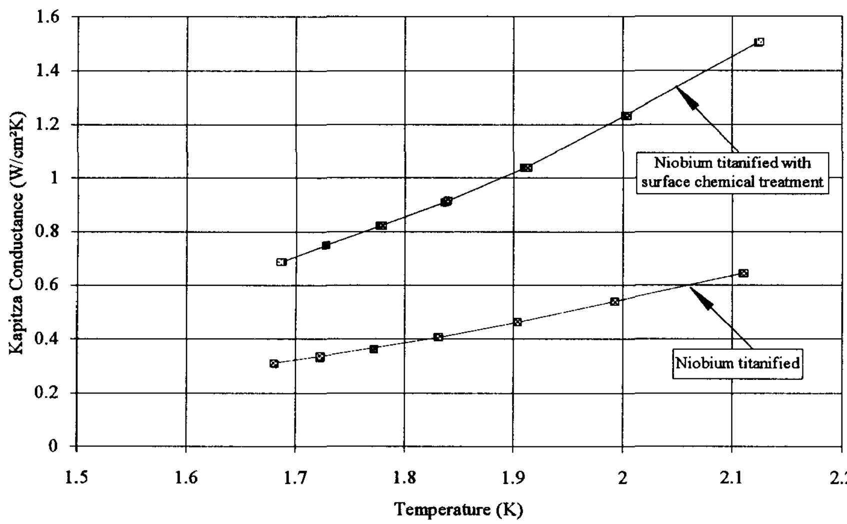

Fig. 5.-.Titanification effect on the Kapitza conductance.

The Kapitza conductance h_K obtained for the titanified niobium were found to be within the smaller mesured values. the first surface chemical treatment has increased h_K by a factor 2.2. It can be seen that the second chemical surface treatment (45 µm on each face) gives no more variation of h_K. The highest h_K values for all the specimens tested, were obtained for the titanified sample with chemical surface treatment.
These results allow to conclude that the titanium layer should not exceed 4 or 5 µm.

Conclusion

Measurements were made on several niobium samples with different surface preparations. The highest values of Kapitza conductance were obtained for the titanified sample. A characterisation of the sample surface state (Roughness, grains dimension,...) should be necessary to give a better interpretation of the Kapitza phenomena.

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