Thermal conductivity in glasses with a phononic crystal like structure

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Abstract. We investigated the thermal conductivity of two glass samples with a phononic crystal like structure at temperatures below 100 mK. The samples consist of glass with holes on a triangular lattice. The diameters of the holes are 5 µm and 25 µm and the porosities are 62 % and 45 % respectively. The thermal transport in glasses at low temperatures is generally believed to be carried by phonons. The holes in the sample limit the mean free path for the thermal phonons and therefore reduce the heat transport. By measuring samples with restricted geometries it might be possible to observe heat transport channels which are not based on propagating thermal phonons. Such an additional heat transport channel should exist in glasses because of the existence of tunneling systems that interact with each other and therefore allow for an energy diffusion via resonant flip-flop processes. We present experimental data down to 20 mK where the wavelength of the phonons becomes comparable to the lattice constant of the phononic crystal structure.

1. Introduction
The low-temperature properties of glasses are governed by atomic tunneling systems (TS). The Standard Tunneling Model (STM) [1, 2] has been developed to explain the these properties and it is quite successful in describing most of the experimental data at temperatures $T \leq 1$K. However, it was found that below 100 mK a number of experimental findings deviate from the predictions of the STM. Very often the interaction between tunneling systems, which are not included in the STM, were considered responsible for these findings [3]. The motivation for this work was to look for a possible influence of the interaction between tunneling systems on the thermal transport at very low temperatures. Measurements on bulk glass samples did not show any deviation from the STM [4]. In particular, the question was, whether interacting tunneling systems would provide an additional channel of heat transport beside the phonons. Measurements on bulk samples did not show any deviation from the STM and indicated that the heat transport is dominated by Phonons down to 5 mK. To reduce the thermal transport by phonons, and to look for a small additional transport channel via interacting TS we have investigated the thermal conductivity of porous glass samples. Here the heat flux via phonons is limited by boundary scattering [5].

2. Experimental setup
The samples used in this studies are so-called glass capillary arrays which consist of lead glass with circular holes on a 2-d hexagonal array. The parameters of the two samples are listed
in table 1. All steps of data analysis which are discussed in this publication are done with sample #1 as an example. Sample #2 shows a very similar behavior, therefore only the results will be discussed. Figure 1 shows a schematic drawing of the experimental setup. A contact free measuring technique allows to take data with very small residual heat flux[4]. The sample is heated optically. To do so, we couple light pulses from a pulsed-current-driven light emitting diode (LED) through a single core optical fiber which points directly on a black CuO absorber deposited on the sample. Two SQUID-based magnetization thermometers measure the temperature change of the sample. Therefore two paramagnetic alloy (i.e. ≃ 600 ppm of Er in Au) foils were attached to the sample. The magnetization changes in an applied magnetic field of about 10 G were inductively read out by two commercial dc-SQUIDs. For this purpose superconducting pickup coils were connected with Nb wires to the input coils of the dc-SQUIDS. The pickup coils were made of micro-structured Nb films which are sputtered on a sapphire plate. Because of the inductive read-out of the thermometers and the optical heating the method is contact-free and therefore parasitic heat inputs are minimized. In this experiments the setup was mounted on the mixing chamber of a dilution refrigerator.

### Table 1. Material parameters of the investigated glass samples.

| parameter                  | #1   | #2   |
|----------------------------|------|------|
| hole diameter d [µm]       | 5    | 25   |
| center-to-center [µm]      | 6    | 32   |
| porosity r                 | 0.620| 0.450|
| thickness t [µm]           | 300  | 300  |

3. Results and discussion

In figure 2 typical measuring cycles are shown. The relative magnetic flux change caused by one of the AuEr foils is plotted versus the relative time. At 100 mK a measuring cycle takes about \( t_{tot} \approx 1 \text{ h} \) and at 35 mK it takes already 8 h, because of the thermal relaxation times of the sample. Therefore the data are plotted versus the parameter \( t/t_{tot} \) as relative time. In figure 2 a positive flux change indicates a warming of the sample. The data set covers the temperature range between 35 mK and 100 mK. Usually a measuring cycle contains three phases: After setting the mixing chamber temperature the sample is thermalizing to the mixing chamber temperature \( T_{MC} \). Subsequently the LED is turned on and the sample is heated. After some time a stable temperature gradient in the sample is established and the LED is turned off again. The sample thermalizes back to the mixing chamber temperature. The heating power varies from 0.7 pW at 35 mK to 30 pW at 100 mK. The red squares and the region around represent the time period where the stable temperature gradient in the sample is reached. An important step in the analysis is the calibration of the magnetic flux change as a function of temperature.
For this, the region around the blue squares in figure 2 is used. In these regions the sample is supposed to be thermalized back to the thermal equilibrium and its temperature should be the same as the one of the experimental platform at the mixing chamber of the cryostat. In figure 3 the measured magnetic flux is plotted versus the inverse mixing chamber temperature (black squares). A cubic spline (blue line) through the data indicates the obtained calibration. The red line represents a numerical calculation of the temperature dependence of the magnetization of AuEr [7]. At high temperatures there is a very good agreement between the calculation and the measured data. At low temperatures a noticeable deviation arises. To understand this further one needs to have a closer look at the data at low temperatures.

![Figure 2](image2.png)  
**Figure 2.** (color online) Measuring cycles between 35 mK and 100 mK. The heating power varies between 0.7 pW and 30 pW.

![Figure 3](image3.png)  
**Figure 3.** (color online) Thermometer calibration. Comparison between measured data and numerical calculation.

At temperatures below 30 mK one observes small peaks on top of the magnetization signal. In figure 4 a four hour section of the measured data of one of the thermometers on the glass sample at 19 mK is shown. The unexpected peaks occur with a rate of about four per hour and cause a sudden temperature jump up to about $\Delta T = 0.5$ mK, which correspond to energy depositions of up to 10 MeV. The origin of these heat inputs is not yet fully understood. Plausible explanations could be either cosmic rays hitting the sample [8], small cracks in the sample [9] or its environment or natural radioactivity from the environment. It is conceivable that these heat inputs lead to the fact that the sample cannot thermalize completely to the bath temperature at low temperatures. Therefore we use for the further data analysis the calculated magnetization of AuEr (simulation) as calibration curve.

In figure 5 the results for the thermal conductivity of both samples is plotted versus temperature. The error bars indicate the uncertainty in temperature that results from the uncertainties in the calibration of the Au:Er thermometers. At first the results of the sample with the small holes will be discussed. At higher temperatures the thermal conductivity decreases almost linearly in the double logarithmic plot and around 50 mK it shows a weaker temperature dependence. If one assumes that the thermal conductivity in this temperature range can be described as a superposition of a $T^3$ behavior and a $T^{4/3}$ dependence of the contribution by interacting tunneling systems one obtains the red line, which fits the data quite well. The black line indicates the $aT^3$ contribution. If one assumes that the contribution of interacting tunneling
systems to the thermal conductivity for both samples is nearly the same than it is possible to describe the temperature dependence of the sample with the big holes in the same way, by just modifying the $T^3$ contribution. At temperatures above 70 mK data are not described by this curve, because there the thermal conductivity is not longer determined by boundary scattering of phonons. The black line again shows the $T^3$ dependence.

Although this is a consistent way to describe the thermal conductivity of these two porous glass samples, we cannot exclude other possible explanations. One obvious scenario is that the weak temperature dependence of $\lambda$ for the porous sample with small holes come about because the wavelength of the dimensions of the holes (6 $\mu$m). For the sample with the larger holes this effect is expected to occur at temperatures five times lower, which would be consistent with the existing data. Therefore, we cannot draw a final conclusion on the relevance of the heat transport via interacting tunneling systems in glasses. Further experiments with samples of different geometries and at low temperatures have to be performed to solve this question.

References
[1] Phillips W A 1972 *J. Low Temp. Phys.* 7 351
[2] Anderson P W, Halperin B I and Varma C M 1972 *Philos. Mag.* 25 1
[3] Enss C 2002 *Physica B* 316-317 12
[4] Hao H -Y, Neumann M, Enss C and Fleischmann A 2004 *Rev. Sci. Instr.* 75 2718
[5] Zaitlin M P and Anderson A C 1975 *Phys. Rev. B* 12 4475
[6] Hao H -Y, Fleischmann A, Enss C and Hunklinger S 2004 *phys. stat. sol. (c)* 1 2908
[7] Fleischmann A, Schönefeld J, Sollner J, Enss C, Adams J S, Bandler S R, Kim Y H and Seidel G M 2000 *J. Low Temp. Phys.* 118 7
[8] Nazaretski E, Merithew R D, Kostroun V O, Zehnder A T, Pohl R O and Parpia J M 2004 *Phys. Rev. Lett.* 92 245502
[9] Åström J et al. 2006 *Phys. Lett. A* 356 262
[10] Burin A L, Maksimov L A and Polishchuk I Ya 1989 *JETP Lett.* 49 784
[11] Würger A and Bodea D 2004 *Chem. Phys.* 296 301