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Magnetic field independent capacitance thermometers at very low temperatures

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Abstract

We have established the magnetic field independence up to 20 T of two capacitance thermometers based on different dielectric materials: amorphous borosilicate and the incommensurate ferroelectric (Pb_{0.45}Sn_{0.55})\textsubscript{2}P\textsubscript{2}Se\textsubscript{6}. The obtained sensitivity of the thermometers, d\ln C/d\ln T, is 8 \times 10^{-4} and 5 \times 10^{-3} for the borosilicate and the (Pb_{0.45}Sn_{0.55})\textsubscript{2}P\textsubscript{2}Se\textsubscript{6} samples, respectively.

1. Introduction

Almost all thermometers used at low temperatures are influenced by the application of a magnetic field, which makes them essentially unsuitable for high field experiments. Clearly, it would be desirable to develop a type of thermometer that is completely magnetic field independent up to the highest presently attainable fields and down to mK temperatures.

Negligible coupling to a magnetic field is expected for dielectric materials where no free electrons or magnetic dipoles are present. For this reason capacitance thermometers based on dielectric materials are the most suitable candidates for low temperature thermometry [1] in high magnetic fields [2]. A second advantage of capacitative thermometers is the low self-heating even with a few volts excitation, which makes these thermometers especially useful for low temperature measurements in a noisy environment.

We have studied the magnetic field dependence of two capacitance thermometers based on different dielectric materials: a crystalline (Pb_{0.45}Sn_{0.55})\textsubscript{2}P\textsubscript{2}Se\textsubscript{6} sample which already proved to be a good and sensitive capacitance thermometer for temperatures above 1 K [3] and an amorphous sol-gel derived borosilicate sample, reported in Ref. [4]. The low temperature behaviour of the dielectric constant of (Pb_{0.45}Sn_{0.55})\textsubscript{2}P\textsubscript{2}Se\textsubscript{6} is expected to be glass-like. The reason for this is that due to the pinning of the incommensurate modulation of defects induced by the introduction of lead atoms into the cation sub-lattice of the pure compound Sn\textsubscript{2}P\textsubscript{2}Se\textsubscript{6}, the incommensurate phase is transformed to a state which is similar to the so-called cluster glass.
2. Setup

The \((\text{Pb}_{0.45}\text{Sn}_{0.55})_2\text{P}_2\text{Se}_6\) was grown using a Bridge- 
man technique. The crystal (typical size 10 mm \(\times\) 25 mm) 
was cut and polished to obtain platelets (size \(5 \times 5 \times 0.8 \text{ mm}^3\)) perpendicular to the 1 0 0 direction. The 
sample had gold sputtered electrodes and was connected 
to SS coaxial wiring with silver paint and a small amount 
of epoxy. The borosilicate glass was prepared by the 
sol-gel process [4] and also had gold plated electrodes 
soldered to SS coaxial wires.

The two samples were mounted inside the mixing 
chamber of an adapted SHE dilution refrigerator, placed 
in a 20 T Bitter magnet [5]. The original metal mixing 
chamber had been replaced by a home-made, Kapton foil 
mixing chamber to avoid eddy current heating. The silver 
sintered heat exchangers were located about 1 m above 
the field centre, where the magnetic field is reduced by 
a factor of about 100. The lowest achieved temperature 
with this dilution refrigerator at 20 T was 16 mK.

Three types of thermometers were mounted in the 
mixing chamber: Speer 100 \(\Omega\) carbon resistors, a CMN 
thermometer [6] and a vibrating wire thermometer [7]. 
Also in the entrance and exit tubes of the mixing chamber 
Speer 100 \(\Omega\) resistors were mounted. The CMN 
thermometer was calibrated with the mixing chamber Speer 
resistor above 100 mK and reproduced the thermody- 
namically correct cooling power of the dilution refrig- 
erator below 100 mK.

A reliable but somewhat cumbersome temperature ref- 
ence in magnetic fields is given by the field independent, 
but temperature dependent, viscosity of the \(^3\text{He}-\text{He}\) 
mixture in the mixing chamber and this was probed by 
the vibrating wire thermometer in magnetic fields above 
1 T.

The vibrating wire was a 100 \(\mu\)m manganine wire, 
shaped in a semi-circle with radius 2 mm. This device has 
a mechanical resonance at a few kHz, which can be 
excited by a small alternating current through the wire in 
the presence of a magnetic field. The quality factor of the 
resonance is a measure of the viscosity of the surrounding 
medium. The magnetic field dependent quality factor in 
vacuum was measured at 4 K and the quality factor 
measured with the mixture present, \(Q_{3-4}\), has been cor-
rected for this.

3. Results and discussion

In Fig. 1, the capacitance of both samples is shown as 
a function of the temperature. Our measurements at 
different frequencies subscribe to the common behaviour 
of dielectric materials extensively reported in the litera-
ture and in our case \(T_{\text{min}}\) shifts with frequency approxim-
ately as \(\omega^{0.3}\). The straight parts of the curves in Fig. 1 
to the left of the minimum have sensitivities 
\(\frac{\text{d} \ln C}{\text{d} \ln T} = 5 \times 10^{-3}\) and 
\(8 \times 10^{-4}\) for the 
\((\text{Pb}_{0.45}\text{Sn}_{0.55})_2\text{P}_2\text{Se}_6\) and the borosilicate sample, 
respectively. The reproducibility of the studied thermometers 
after warming to 1 K and cooling back is better than our 
measurement resolution. However, upon cycling between 
room temperature and 10 mK, slight changes in the value 
of the capacitance at the minimum and even in the slope 
for \(T < T_{\text{min}}\) have been observed.
In Fig. 2 the most sensitive part of the capacitance curve is plotted for the ferroelectric sample measured at different excitation voltages. The excitation voltage dependence shown in Fig. 2 provides a useful property, namely the tunability of the most sensitive range of the thermometers to other temperature ranges. Alternatively, it should always be kept in mind that the calibration for these thermometers depends on the excitation voltage, at least on the low temperature side of the minimum.

In Figs. 3 and 4 the capacitance of the two samples is shown for magnetic fields ranging from 1 to 20 T as a function of $Q_{3-4}$, the vacuum corrected quality factor of the resonance of the vibrating wire thermometer. The upper horizontal axis is a conversion of $Q_{3-4}$ to temperature using viscosity data from Ref. [7]. These temperatures are in agreement with the temperatures deduced from the Speer resistor in the exit tube of the mixing chamber and from the zero field calibration of the capacitance thermometers. Furthermore, the values of the capacitances at the minimum do not change from 0 to 20 T.

In conclusion, it has been shown that the capacitance thermometers are field independent for magnetic fields ranging from 0 to 20 T at least down to temperatures of 30 mK.

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References