High Resolution Thermometers Based on Pd(Mn) for Studies of Critical Phenomena aboard the ISS

Peter Day, Mary Jayne Adriaans
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA

Beverly Klemme, Dmitri Sergatskov, and Robert Duncan
Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87102, USA

Abstract

A high resolution thermometer was developed using a dilute alloy of Mn in Pd as the magnetic sensing element instead of the traditional paramagnetic salt. Use of the alloy material facilitated a significant decrease in the total mass of the device to about 3.5g. The noise and drift of the device were measured and found to be comparable with that of the larger HRTs used on past flight experiments. The origin of the noise observed in state-of-the-art HRTs and the potential of the new thermometric material for achieving lower noise figures is discussed.

1. Introduction

Thermometers with sub-nanokelvin resolution [1,2,3] have been developed for the investigation of thermodynamic behavior around critical points, such as the lambda transition in liquid helium [4]. These high-resolution thermometers (HRTs) allow measurements to be made at temperatures very close to the critical point and thereby extend the number of decades in reduced temperature over which the characteristic power-law diverges in the thermodynamic quantities may be studied. The highest resolution measurements in this respect have been conducted in microgravity aboard the space shuttle, because the hydrostatic pressure gradient through the sample in an earth-bound laboratory spreads the transition over a range of temperatures, limiting the nearness with which the transition can be approached. In microgravity, the Lambda Point Experiment (LPE) [4] observed that the superfluid transition remains sharp to within 1 nK of the lambda point. That experiment measured the divergence in the heat capacity of liquid helium over seven orders of magnitude in reduced temperature and rigorously tested the results of renormalization group calculations that underpin the theory of critical phase transitions in general. Further measurements planned for the international space station include studies of the ^{3}He critical point [5], the tricritical point in ^{3}He-^{4}He mixtures, the lambda transition in the presence of perturbing conditions such as steady heat flow [6] and confinement to one and two dimensions, and the superfluid density in ^{4}He at various pressures along the lambda line [7].

The HRTs used so far in such experiments rely on a precise measurement of the magnetization of the paramagnetic salt Copper Ammonium Bromide (CAB), although thermometers using another paramagnetic salt, $GdCl_3$, have also been reported [3]. These materials have ferromagnetic transitions at 1.8 and 2.2K respectively, so near those temperatures the magnetic susceptibility exhibits a sharp maximum. The highest thermometric resolution [2,3] has been obtained using a SQUID magnetometer to measure the magnetic induction in the sensing material in a very stable DC magnetic field maintained by trapping a magnetic flux inside a superconducting tube.

In this paper we discuss the potential of advancing the state-of-the-art in high resolution thermometry by replacing the paramagnetic salts with the dilute magnetic alloys Pd(Mn), Pd(Fe) and Pd(Co). Additionally, we report the results of tests on a miniature HRT based on Pd(Mn).

2. Advantages of the magnetic alloys for high resolution thermometry

Dilute quantities of magnetic materials in Pd exhibit a giant magnetic moment in the range of $10\mu_B$ [8] because magnetism is induced in the palladium in the vicinity of the impurities. At concentrations up to several percent, a transition to a ferromagnetic phase is observed. At both higher concentrations and ultra-low concentrations, the transition is to a spin glass phase. This phenomenon has been studied extensively in the past for its own right, and Pd(Fe) has already been used as a thermometric material for thermometry at sub-millikelvin temperatures [9]. In the case of ultra low temperatures, nominally pure palladium is used so that the magnetic ordering temperature of the remnant iron impurities is depressed as low as possible. The magnetic susceptibility in the very dilute case is comparable with that of CMN at low temperature. With added impurity concentrations of a few percent for Pd(Mn) and a few tenths of a percent for Pd(Fe), the transition moves to the range of a few kelvin, and the susceptibility is comparable to that of CAB and $GdCl_3$ [10].

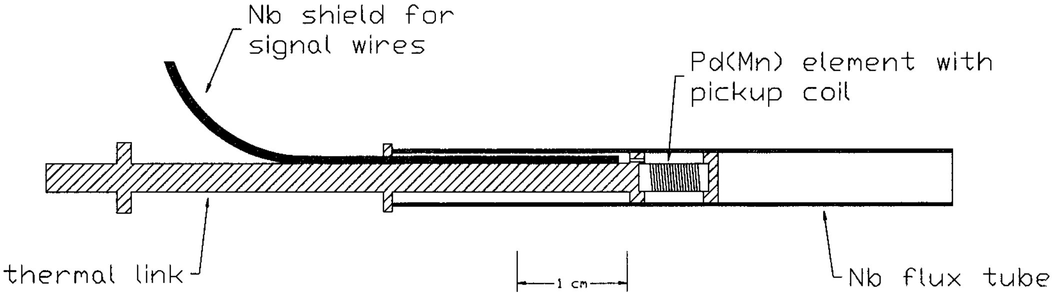


Figure 1. Drawing of the Pd(Mn) high resolution thermometer.

The use of the magnetic alloys in place of the paramagnetic salts in high-resolution thermometry offers many advantages. First, the transition temperature is tunable by varying the magnetic impurity concentration so that it ma the range of varied from millikelvins to tens of kelvins by increasing impurity concentration. A second advantage is that the magnetic alloys are chemically more robust than the paramagnetic salts. CAB is a hydrated crystal so that it cannot be exposed to vacuum at room temperature and must be sealed into a hermetic container if pump-out is to be performed before cool-down. On the other hand, it reacts with nearly all metals, which leads to difficulty with making thermal contact. Similarly $GdCl_3$ crystals react with water and must be hermetically sealed. The impracticality of precisely controlling the crystal's dimensions and the necessary sealing layer degrade the coupling to the magnetometer pick-up coil and complicate the task of miniaturizing the thermometer.

The dilute alloy materials, on the other hand, are simple to manufacture and may be precisely machined and bonded to other metallic elements of the HRT. The technique of making intimate thermal contact between the sensing element and the object to be measured is of central importance to the reduction of noise in HRTs. It has been demonstrated that the noise in the current state-of-the-art HRTs is limited by 'thermal fluctuation noise', [1,3] which arises from the statistical uncertainty in the energy of a finite subsystem of a larger thermal system. That source of noise may be compared with phonon noise in very sensitive bolometers. The noise contributed by the magnetic measurement is currently only about 10% of the statistical noise source. Reduction of the statistical noise has been shown to be only possible through reduction of een sensing element and frequency of the thermal fluctuations, allowing a greater amount of averaging in a given time interval [3]. The dilute alloy materials should allow a greater conductivity between sensing element and sample to be achieved. For example, foils of the alloy may be interleaved with foils of high conductivity copper and diffusion bonded together.

3. Miniature HRT results

To demonstrate the feasibility of using dilute magnetic alloys for high-resolution thermometry, we have constructed and tested a miniature HRT using Pd(Mn). Figure 1 shows a cross-sectional view of the sensor. The sensing element is a 0.25 cm diameter by 0.54 cm long rod of Pd(Mn). It is bonded to an annealed aluminum post, which provides the thermal contact to the sample. Surrounding the sensing element is a 0.025 cm wall niobium tube that serves both to maintain the trapped DC magnetic field in the thermometer and to provide magnetic shielding. The magnetic induction in the sensing element is coupled into a SQUID magnetometer with the aid of a superconducting flux transformer. The wires that make up the flux transformer are carefully shielded by passing them through a niobium capillary. Typically a field on the order of 2mT is trapped in the device.

Differences between this design and the model used in recent shuttle experiments [1,2] are an overall reduction in dimension of approximately four times, substitution of the copper thermal link with one made of aluminum, and a reduction in the thickness of the niobium shield by a factor of two. The overall mass was decreased by over a factor of ten to less than four grams, which was accomplished for the purpose of decreasing susceptibility to cosmic rays on orbit. In an earthbound laboratory, HRTs are virtually dissipationless. On orbit, however, a significant source of heat generation results from cosmic ray strikes on the HRT itself. These events result in an extra source of thermometry noise that can exceed the intrinsic noise of the sensor by an order of magnitude. Additionally, the average heat deposited by the cosmic rays strikes results in a parasitic heat flow of approximately 1-2 pW per gram of material between thermometer and sample, which, for the 40 gram HRTs used on past flight experiments, would be intolerable for some of the sensitive experiments planned for the ISS, such as DYNAMX [6, 11].

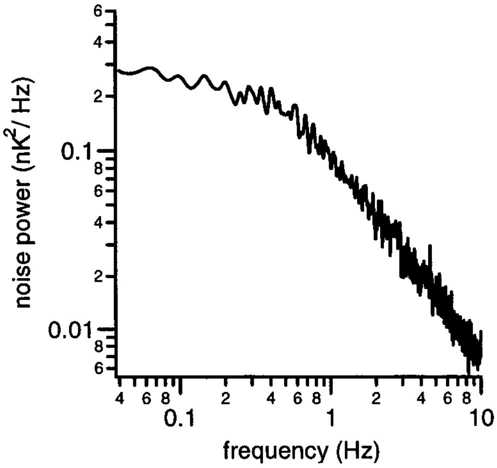
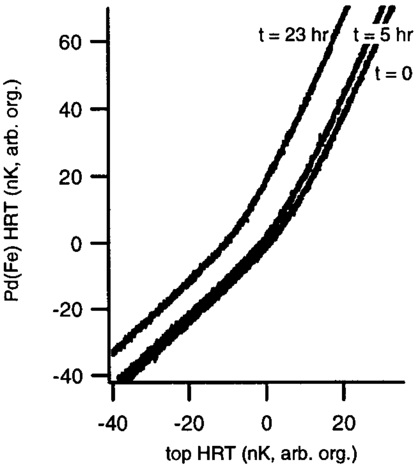


Figure 2. Noise power spectrum of the Pd(Mn) HRT

Experimental characterization of the miniature HRT included measurements of sensitivity, noise and drift and was carried out at 2.177K on a multistage temperature controlled platform similar to that which will be part of the International Space Station's Low Temperature Microgravity Physics Facility. The HRT under test was mounted on the innermost stage of the temperature controlled platform, which contained a large volume of liquid helium that was isolated with a cryogenic valve located on the same stage. The sensitivity of the HRTs was determined by comparing with a standard germanium resistance thermometer and corresponded to 0.5 Φ_0 measured by the SQUID per microkelvin. The transition temperature of the Pd$_{.994}$Mn$_{.006}$ sample used was found to be 1.4K in separate measurements, which was lower than optimal for application at the lambda point, although the thermal fluctuation noise still dominated other sources.

The noise figure of the Pd(Mn) HRT was obtained by controlling the temperature of the helium volume with a separate HRT that used GdCl$_3$ as the sensing element. With the helium volume controlled to 0.15nK RMS, the total noise of the Pd(Mn) HRT was found to be 0.4nK RMS in a 1Hz bandwidth. This noise figure is larger than what should be achievable, because the thermal contact to the helium volume was not optimized. The noise power spectrum up to 10 Hz is shown in fig. 2. We observe an absence of "Johnson noise" from magnetic coupling of thermally driven electrical currents in the metallic sensor. This phenomenon is readily observable if, for example, a pickup coil were wound on a highly conducting metal such as copper, but a flat noise spectrum is seen.



Because of the very low drift rates that can be achieved, drift in the HRT is often difficult to measure except in the most exacting experiments. The drift of the Pd(Mn) HRT was determined by mounting it on the bottom of a thin walled stainless steel cylinder that was filled with liquid helium. A steady heat current could be made to flow upwards through the cylinder of helium by driving a heater that was also mounted on the cylinder's bottom. The temperature of the top of the cylinder of helium was measured and controlled with a separate HRT and heater and could be scanned at a rate of 40pK/second through the lambda transition temperature. Below the transition, helium conducts heat very efficiently through counterflow of the normal and superfluid components, so the temperature of the helium in the column remains uniform. As the transition is approached, a helium I/ helium II interface is formed at the bottom of the column, and the thermal conductivity changes by several orders of magnitude, giving rise to an abrupt temperature gradient. By repetitively sweeping through the transition, the apparent lambda point temperature can be monitored as a function of time. If the pressure of the helium volume is maintained constant, apparent drifts in the lambda point temperature must be a result of drift in the thermometer. Three such scans through the transition temperature taken over a 23 hour period are shown in fig. 3. The miniature Pd(Mn) HRT was found to drift by no more than 2×10^{-14} Kelvin per second using this method, which is comparable to the best reported results with larger devices. The source of drift in HRTs has been attributed to relaxation of the magnetic flux trapped in the niobium shield. Our result indicates that the field trapped in a 0.025cm wall flux tube is adequately stable for the most demanding experiments so far proposed.

4. Conclusion

In conclusion, we have discussed a promising new sensor material that advances the state-of-the-art of high-resolution temperature measurement below 10K. This advance allows for a ten-fold reduction in the mass of an HRT without sacrifice in performance. The lower mass should improve performance on orbit with regard to the disturbing influence of cosmic rays. These HRTs have the advantage of being easier to construct and use than previous versions, and, because the transition temperature of the sample may be varied, they may be used for a wide variety of critical phenomena studies planned for the ISS.

Acknowledgment

The research described in this paper was partially carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

References

[1] T.C.P. Chui, D.R. Swanson, M.J. Adriaans, J.A. Nissen, and J.A. Lipa, *Phys. Rev. Lett.* **23** 3005 (1992).

[2] X. Qin, J.A. Nissen, D.R. Swanson, P.R. Willianson, D.A. Stricker et. al. *Czech Journal of Physics,* **46**(supplement 5), 2857 (1996).

[3] Peter Day, Inseob Hahn, Talso Chui, Alexa W. Harter, David Rowe and John Lipa, *Journal of Low Temperature Physics* **107** 359 (1997).

[4] J. Lipa, D.R. Swanson, J.A. Nissen, T. Chui and U.E. Isrealsson, *Phys. Rev. Lett.* **76** 944 (1996).

[5] M. Barmatz, I. Hahn and F. Zhong, *Journal of Low Temperature Physics* (to be published).

[6] M.J. Adriaans, W.A. Moeur, S.T.P. Boyd, D.M. Strayer, R.V. Duncan, *Cryogenics* **36**(10), 787 (1996 Oct).

[7] J.A. Nissen, D.R. Swanson, Z.K. Geng, V. Dohm, U.E. Isrealsson, M.J. Dipirro and J.A. Lipa, *Low Temperature Physics* **24**(2) 86 (1998 Feb).

[8] See, for example, I.Y. Kornblit and E.F. Shender, *Sov. Phys. Usp.* **21** 832 (1978); B.M. Boerstoel, J.E. Van Dam, and G.J. Niewenhuys, in *Magnetism: Selected Topics,* Ed. S. Foner, Gordon and Breach, New York (1976), p. 207.

[9] M. Jutzler, B. Scgroder, K. Gloos, and F. Pobell, *Z. Phys, B* **64** 115 (1986).

[10] B.J.Klemme, M.J. Adriaans, R.V. Duncan, P.K. Day, D.A Sergatakov, T.L. Aselage, P.T. Ton-Nu and T.D. McCarson, (to be published).

[11] P.K. Day, W.A. Moeur, D.A. Sergatakov, F-C. Liu, R.V. Duncan, *Physical Review Letters* **81** 2674 (1998).