

Materials for Cutting-Edge Experiments in Astronomy and Particle Physics

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Abstract. Progress in fields such as astronomy and fundamental physics can require increasingly complex instrumentation operating at millikelvin temperatures. Such instruments often have demands on materials and components which have not been seen previously, particularly for space based instrumentation. The large scale of these projects and tight timescales forces as conservative design as possible. However, building these instruments with conventional techniques and materials is often impractical and sometimes impossible. It is therefore common for the design stage of such instruments to include test and measurement programmes. This adds risk to the development schedule, and such programmes also suffer from the problem that they are tightly focused on the exact needs of one particular instrument. We are setting up a laboratory to measure material properties and develop cryogenic components for general use in future large millikelvin instruments. By decoupling these measurements from a particular instrument programme, we have the freedom to make more speculative measurements, such as measuring new polymers whose cryogenic properties are completely unknown. We describe our set-up and the results of initial work.

1. Introduction

Many areas of experimental physics require instruments operating at cryogenic temperatures. The obvious examples are those in which the experiment is directly concerned with the properties of materials at low temperatures, such as investigations into superconductivity or the properties of liquid helium. However, many other areas require cryogenic instrumentation; examples include astronomical instruments operating over much of the electromagnetic spectrum [1], superconducting magnets in particle accelerators such as LHC at CERN [2], and sensitive detectors for rare events such as double beta decay [3].

In many areas, instruments are continually increasing in complexity. For example: a decade ago, state of the art instruments for sub-millimetre astronomy had around a hundred pixels, while instruments are now being constructed with thousands of pixels, each with greater sensitivity than those in previous instruments. The improvement in performance is achieved at the expense of a considerably more complex cryogenic design. Similarly, in particle physics, future accelerators will require superconducting magnets which generate higher fields, and must tolerate higher radiation environments, than existing instruments. A particularly challenging area is cryogenic instrumentation for operation in space; current experience in this area is somewhat limited, and missions currently being considered are likely to have significantly more demanding requirements than those already constructed [4].

A major difficulty in constructing complex cryogenic instruments is our limited knowledge of the precise properties of materials at cryogenic temperatures. Constructing successful instruments is a challenge when basic engineering data is not available. This is a particular issue at ultra-low

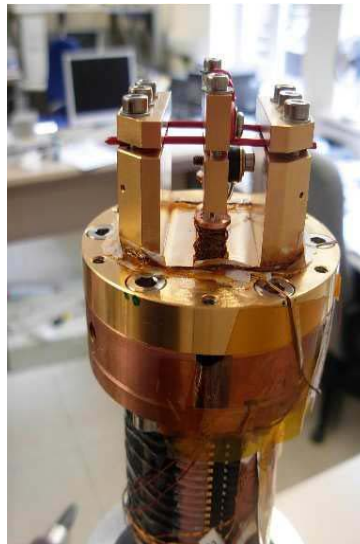


Figure 1. Test cryostat in the “small” configuration (left) and sample holder for measuring the low temperature thermal conductivity of thin wires (right)

temperatures (below 1 K). The result is that instruments are generally constructed from a small number of tried-and-tested materials. While this approach is entirely satisfactory for the majority of cryogenic instruments, it is insufficient for many large, complex instruments, particularly those operating at millikelvin temperatures.

In the past, measurements on materials have often been made as required during the design and construction of instruments. Where results have been written up, they are frequently not very useful as they only provide a solution to the exact requirements of that particular instrument, and the materials were not well enough characterised in order to exactly replicate them. This approach is inefficient, and hampers instrument design. The lack of accurate data often forces an initial design to be carried out using estimated values. These values then have to be confirmed by measurements during the design process, with the accompanying risk that the estimates are found to be incorrect. As instruments become increasingly complex, and schedules become tighter, this approach has become unsatisfactory.

We are therefore starting a programme of measurements on materials and components likely to be of use for future complex cryogenic instruments, so that results will be available at the start of the design stage.

2. Measurement system

Our current system consists of a mechanically cooled cryostat using a GM (Gifford McMahon) cooler.¹ The base temperature with no applied thermal load is ~ 2.5 K. Such a cryostat has the obvious advantage over a traditional helium bath cryostat of not requiring a supply of liquid helium, but is also particularly advantageous for measuring material properties as a function of temperature as it can operate easily at any stable temperature between the base temperature and room temperature. To give flexibility in measurements, two different configurations are available. The “small” configuration offers a sample volume of approximately 4 cm diameter and 4 cm height, with a cool-down time of around one hour (Fig. 1). A considerably larger sample space of 20 cm diameter and 40 cm height is also available, at the cost of an increased cool-down time of ~ 6 hours. A helium-3 sorption fridge² is available with the cryostat in the large configuration, offering additional cooling to temperatures below 300 mK.

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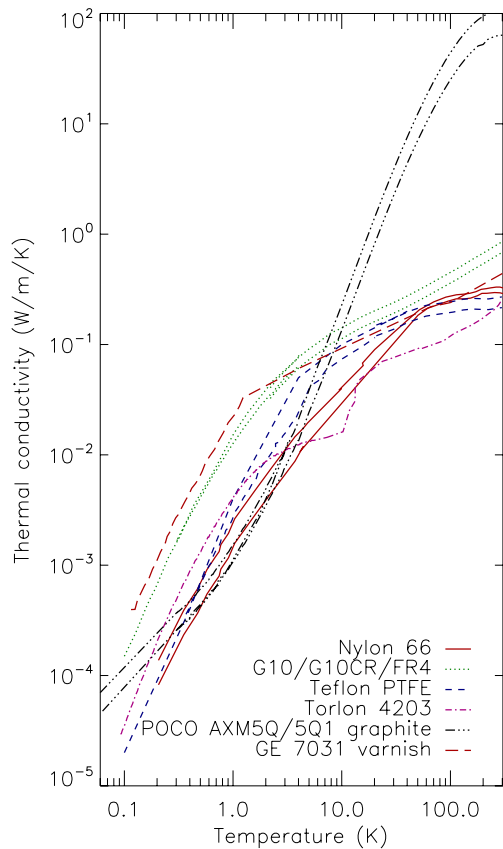


Figure 2. Recommended thermal conductivity values for various materials used as thermally isolating supports in cryogenic instruments. For each material apart from GE varnish and Torlon[®] 4201, upper and lower limits are shown, corresponding to the range of values obtained from the literature.

Calibrated Cernox thermometers,³ read out with an AVS-47 cryogenic resistance bridge,⁴ enable accurate measurements of sample temperature over a range from 300 mK to room temperature with a single thermometer. Along with resistive heaters, this enables electrical and thermal conductivity and heat capacity of samples to be measured as a function of temperature. Optical measurements are also possible, with four windows provided in each configuration.

3. Critical analysis

As well as making measurements on new materials, we are interested in consolidating existing knowledge. There is considerable scope for this; thermal property measurements are scattered across the literature, and little effort has been made to systematically examine them, particularly in recent years. As an example of the potential for improving our understanding of existing data, Ref. [5] gives a method for predicting the temperature dependence of the thermal conductivity of any aluminium alloy, developed almost entirely using measurements made in the 1960's and 1970's. In Fig. 2, we show initial results for the recommended thermal conductivity values for various materials of interest for insulating supports in cryogenic instruments, obtained by collating measurements from the literature.

The values for GE varnish should be taken as an approximate upper limit, since the composition of the varnish once set is likely to depend on the drying conditions and quantity of solvents present before drying. In addition, preparing a bulk sample for measurements is difficult. We have taken values below 1 K from Ref. [6], since the measured sample appears to have been prepared with extreme care. Above 1 K we have taken datasheet values [7], which appear to join smoothly to the lower temperature

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data. Lower values have been reported below [8] and above [9] 1 K; these results support the change in temperature dependence shown around 1 K.

Sample preparation by the user is not an issue for the other materials shown. However, correctly characterising materials *is* important. For example, the trade name Teflon[®] is usually taken to mean PTFE (polytetrafluoroethylene), but in fact various different polymers are sold under the name Teflon, with PTFE being properly described as Teflon-PTFE (and even then, there are different grades of Teflon-PTFE). We have had to assume here that any material described simply as Teflon is indeed PTFE of some kind. Measurements over the full temperature range shown [8, 9, 10, 11, 12, 13] are in reasonable agreement; we show the limiting values found from the literature. Similar agreement is seen for measurements on Nylon 66 [14] (and references therein), [8, 15], except at room temperature where significantly lower values have been reported (references in [14]), possibly due to measurements suffering from radiative losses. Fibre-reinforced Nylon [15] appears to have very similar conductivity, at least below 4 K. Measurements on POCO AXM-5Q and 5Q1 graphite [16, 17, 18] (the two types have similar composition) also show reasonable agreement; it is known that the conductivity of this material has significant ($\pm 10\%$) variation from lot to lot, and even within a single sample. Again, we show the limits of the values reported. The Torlon[®] 4203 measurements are taken from papers by the same research group covering different temperature ranges [19, 20], with good agreement.

The material G10 is an extreme example of the need for proper characterisation. This is a fibreglass epoxy laminate, commonly used for manufacturing printed circuit boards. However, the specifications do not define the actual composition; they are primarily specifications on the (room temperature) *electrical and mechanical properties*, not on thermal properties or the actual material itself. Moreover, the composition and manufacture is generally proprietary to a particular manufacturer [21]. Since G10 is of such use at cryogenic temperatures, a cryogenic grade, G10-CR is available. Unlike regular G10 (or FR4, a flame retardant alternative to G10), this is made with a well specified formulation and manufacturing procedure, determined by the US National Bureau of Standards (NBS, now NIST) [21]. Measurements in the literature do in fact show good agreement for G10 [22], G10-CR [21, 22] and FR4 [17], but there is a risk involved in assuming this remains true for an arbitrary sample of G10. The common conclusion that there is no advantage to using G10-CR is therefore *not* supported by these results.

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