Magnetization and magnetoresistance of common alloy wires used in cryogenic instrumentation

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We present magnetization and magnetoresistance data at liquid-helium and liquid-nitrogen temperatures for wire materials commonly used for instrumentation wiring of specimens, sensors, and heaters in cryogenic probes. The magnetic susceptibilities in *Systeme International* units at 4.2 K were found to be: Manganin 1.25×10^{-2}, Nichrome 5.6×10^{-3}, and phosphor bronze -3.3×10^{-5}, indicating that phosphor bronze is the most suitable for high-field applications. We also show the ferromagnetic hysteresis loop of Constantan wire at liquid-helium temperature. The magnetoresistance of these four wires was relatively small: the changes in resistance at 4 K due to a 10 T transverse magnetic field are –2.56% for Constantan, –2.83% for Manganin, +0.69% for Nichrome, and +4.5% for phosphor bronze, compared to about +188% for a typical copper wire under the same conditions. [DOI: 10.1063/1.2719652]

In cryogenic-probe construction, wire materials need to be chosen that are appropriate for the task. Depending on the application, instrumentation wires are commonly made from copper and copper alloys such as phosphor bronze (copper alloyed with tin and a small amount of phosphorus), Constantan (copper alloyed with nickel), or Manganin (copper with manganese and nickel). By contrast, a good choice for heater wire is usually the more resistive Nichrome (Ref. 1) (nickel alloyed with chromium). In general, the properties—and especially their change with temperature and/or magnetic field—will dictate the precise selection of the wire material. However, detailed "magnetofingerprints" of these wires at liquid-helium temperature have not been reported so far. In this note, we fill this gap by presenting our results on magnetization $M(H)$ (at 4, 76, and 295 K) and magnetoresistance $R(H)/R_0$ [at 4 K and in magnetic fields H up to 8000 kA/m (10 T)].

We tested commercially available American Wire Gauge No. 30 or No. 32 wires with the following compositions (by weight): Nichrome (80% Ni, 20% Cr), Manganin (83% Cu, 13% Mn, 4% Ni), Constantan (55% Cu, 45% Ni), and phosphor bronze (94.8% Cu, 5% Sn, 0.2% P).[1]

Magnetization was measured with a superconducting quantum interference device susceptometer. Pieces of wire 15–28 cm in length were shaped into coils 3–5 mm long and ~2 mm in diameter, so that the samples can be considered as localized dipoles aligned with the magnetic field. First, the samples were cooled to 4.2 K in zero field and then magnetization was measured while the field was increased to 127 kA/m (1600 Oe), with a resolution better than ±16 A/m (0.2 Oe).

Figure 1 shows the magnetic response $M(H)$ at 4.2 K of the four wires tested. Manganin and Nichrome wires present a small magnetic susceptibility χ, with values of 1.25×10^{-2} and 5.6×10^{-3}, respectively. This contrasts with the much stronger ferromagnetic response of Constantan (due to its nickel content), which has a remanent magnetization of 6.6 kA/m (83 Oe) and a coercive field of 1.1 kA/m (14 Oe). The phosphor bronze wire shows a very small diamagnetic signal with a value of $\chi=-3.34\times10^{-5}$. Phosphor bronze has the smallest magnetic susceptibility, at least two orders of magnitude less than that of the other wires. Data for these four materials plus copper are summarized in columns 5–7 of Table I along with susceptibilities at 76 and 295 K calculated from magnetization measured at $H=100$ Oe. Magnetization data at 4 K and room temperature for other materials, including aluminum, copper, brass, nylon, and quartz, are given by Fickett.[2]

Electrical conductivity is expected to change in a magnetic field, in part due to the effect of the Lorentz force on the charge carriers. In that case, the resistance is expected to increase with applied magnetic field (positive magnetoresistance), but it is also possible to observe a negative magnetoresistance (a decrease in resistivity with applied field), usually associated in some way with defects in the wire. In magnetic materials, one can observe effects due to anisotropic magnetoresistance and magnetic impurity scattering. A theoretical review of quantum corrections on conductivity is given by Lee and Ramakrishnan.[3] Here, we limit our study to determine experimentally whether or not wire materials commonly used in cryogenic apparatus present a significant magnetoresistance at liquid-helium temperature, since this effect could alter measurement values or lead to experimental artifacts. Magnetoresistance has been reported in many materials, but it is usually very small at room temperature and in most materials does not exceed a fraction of a percent, however, much higher values have been reported in high purity metals at lower temperatures.[4]

In our experimental setup, the magnetic field was applied perpendicular to the wire by a commercial split-pair magnet, and the resistance was measured by a standard four-lead technique. In contrast to the magnetization data pre-

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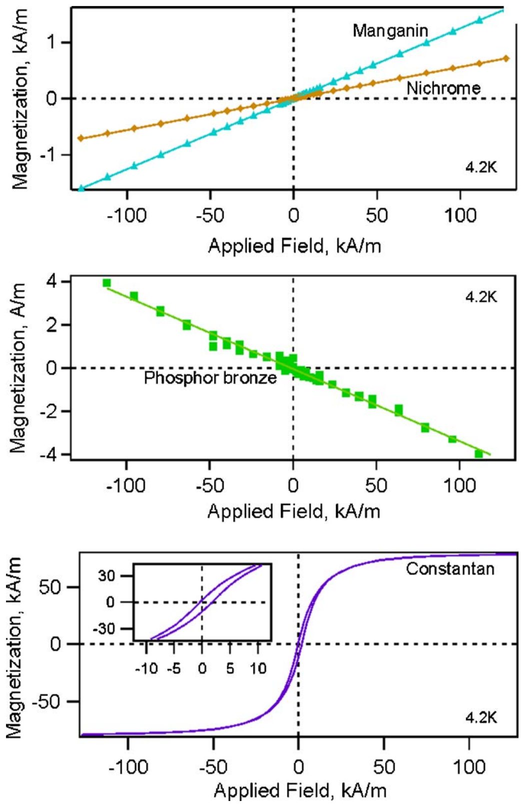

FIG. 1. Magnetization data $M(H)$ at 4.2 K of Manganin and Nichrome (top), phosphor bronze (middle), and Constantan wires (bottom). Note the different ordinate scales. The solid lines represent a linear fit from which the χ values were extracted, except for the ferromagnetic Constantan wire, where the solid line exactly links the data points (which have been removed for clarity).

sented above, where the temperature was controlled at 4.2 K, in this experiment the samples were immersed in a helium bath whose temperature was 4.0 K (due to the altitude of our

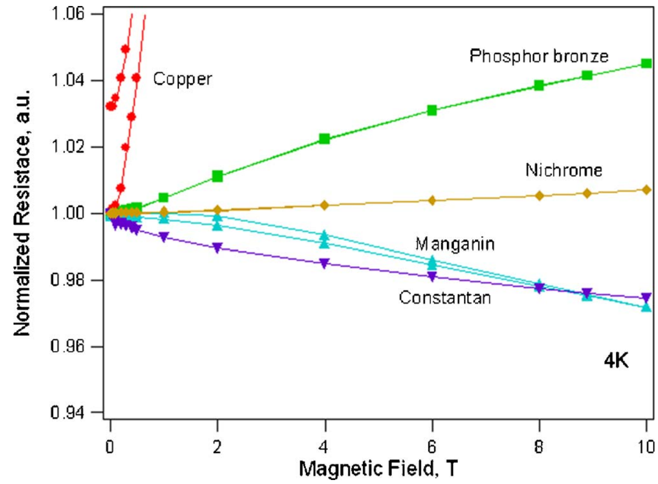

FIG. 2. Normalized magnetoresistance $R(H)/R_0$ of phosphor bronze, Nichrome, Manganin, Constantan, and copper.

laboratory). For the voltage taps, we used pure indium solder (T_c=3.5 K) that is not superconducting at 4 K (standard eutectic Pb-Sn solder is superconducting at 4 K, and produces experimental artifacts when the applied fiels reaches the low critical field of the solder).

Measurements were taken using a 100 mA direct current source. To minimize the effects of thermoelectric voltages, the current was reversed and the average value of the voltage for positive and negative excitations was recorded. We estimate the upper limit of uncertainty to be about ±0.02% of the measured value.

Figure 2 presents the normalized resistance (R/R_0) for selected field values between 0 and 10 T, where R_0 is the zero-field. The variation ($\Delta R/R_0$) is monotonic for each wire, either positive as for phosphor bronze (+4.5% at 10 T) and Nichrome (+0.69%), or negative as for Constantan (–2.56%) and Manganin (–2.83%). All these values are far

TABLE I. Magnetoresistance and magnetic susceptibility of common alloy wires used in cryogenic instrumentation.

Wire material	Composition[a] (by weight)	$R_{295\ K}/R_{4\ K}$	$\Delta R/R_0$ at 4 K and 10 T (perpendicular to wire) (%)	χ at 4 K [c] (SI)[g]	χ at 76 K (SI)	χ at 295 K[d] (SI)
Copper	100% Cu	76[b]	188[b]	⋯	⋯	⋯
Constantan	55% Cu 45% Ni	1.17	–2.56	Ferromagnetic	Ferromagnetic.	Ferromagnetic.
Manganin	83% Cu 13% Mn 4% Ni	1.25	–2.83	1.25×10^{-2}	2.2×10^{-2}	2.7×10^{-3}
Nichrome	80% Ni 20% Cr	1.09	0.69	5.6×10^{-3}	8.3×10^{-4}	5.2×10^{-4}
Phosphor bronze	94.8% Cu 5% Sn 0.2% P	1.67	4.5[e,f]	-3.3×10^{-5}	-4.7×10^{-5}	-5.2×10^{-5}

[a]Small, but unknown quantities of impurities may be present.
[b]The magnetoresistance of pure copper is strongly dependent on sample purity; it can be determined from a normalized "Kohler" plot, such as that shown in Fig. 5.16 in Chap. 5 of Ref. 4.
[c]Susceptibilities at 4.2 and 76 K were determined from magnetization vs. magnetic field data.
[d]Room-temperature susceptibilities were calculated from the magnetization measured at H=100 Oe.
[e]The magnetoresistance of phosphor bronze varies with (trace) impurities in the wire.
[f]At 76 K and 10 T, the magnetoresistance of phosphor bronze is much smaller than at 4 K, decreasing to about $\Delta R/R_0$=0.08%.
[g]*Système International*.

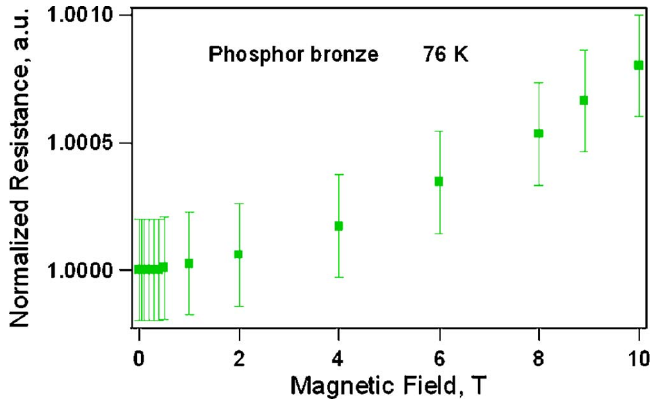

FIG. 3. Magnetoresistance of phosphor bronze at 76 K.

lower than that of standard copper wire (typically about +188%). The data points measured in increasing field are the same as those measured in decreasing field, except for Manganin and copper. The small hysteresis in the latter two materials were confirmed by several measurements on different sections of these wire and could be attributed to magnetic elements or impurities in these commercial materials, or it may be due to spin-glass effects.

In some applications, magnetoresistance changes on the order of a few percent at 4 K should not be neglected. The phosphor bronze result (+4.5%) is much higher than that previously reported for a phosphor bronze wire with a different composition[5] ($\Delta R/R_0 \leq 5\times10^{-3}\%$ for $P_{0.05}Cu_{0.95}$). At higher temperatures the effect is much less, however Fig. 3 shows that at 76 K, the resistance change due to a 10 T field is only 0.08%, less that one fiftieth that at 4 K.

We also oriented one of the wires (Manganin) parallel to the field. It showed a rather insignificant anisotropy: the resistance value dropped an additional 0.16% at 10 T, which means the resistance change is 5.6% bigger when the wire is aligned with the field compared to when it is perpendicular to the field.

The higher the residual resistance ratio ($RRR \equiv R_{295\ \mathrm{K}}/R_{4\ \mathrm{K}}$, an index of purity), the higher the magnetoresistance at low temperature. As a consequence, if a metal is made very pure to lower its resistance at low temperature, it will be more prone to a larger magnetoresistance effect.

A summary of these magnetoresistance and magnetization results is given in Table I, including additional data obtained at liquid-nitrogen and room temperatures.

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