# Thermal Impedance Spectroscopy: A New Tool to Study Thermodynamics of Metals

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Unlike transport measurements, which constitute significant fraction of user experiments at the MagLab, specific heat measurements are slow. Very slow. This is because they require waiting for thermal equilibrium between the sample and the thermometer to set in. This waiting time is determined by the macroscopic size of the sample and calorimeter platform, rather than by microscopic timescales as is the case for transport measurements. So far, the specific heat measurements at the MagLab used large calorimeters with time constants of tens of seconds, which in practice means each specific heat measurement takes fraction of an hour. Whether user's magnet time is measured in hours or megawatts, the specific heat measurements are a significant challenge.

*This experimental roadblock has been recently broken by introducing ultra-fast nanocalorimeters -- which have millisecond time constants at cryogenic temperatures. This 4+ order of magnitude change in the timescale of the measurement are a complete game changer and, for the first time, open a practical use of specific heat as a technique available for users, The specific heat can now be measured at the fastest field-sweep rates, continuously as the field and angle is swept. Just like an electrical transport measurement,*

Typically, when a breakthrough improvement of a technique occurs, it opens entirely new uses not possible or even imagined before. Use of nanocalorimeters is not an exception. MagLab scientists imagined, tested and put to good scientific use an entirely new technique -- "thermal impedance spectroscopy" (TISP) – that is enabled by ultrafast nanocalorimeters. It provides, for the first time, a way to measure nuclear spin-lattice relaxation rates without use and restrictions of nuclear magnetic resonance (NMR) techniques. In metals, thermal impedance spectroscopy provides two independent way to measure electronic density of states – in the same measurement – through electronic specific heat and through nuclear spin-lattice relaxation rate.

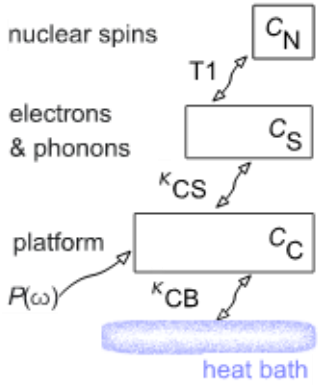
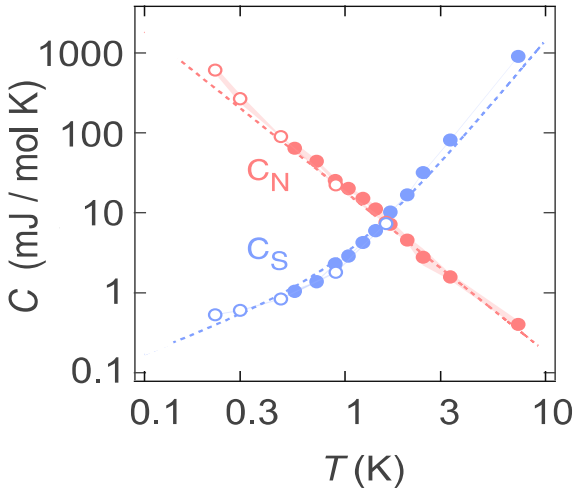



**Fig. 1:** Thermal circuit of the calorimeter-sample assembly: noting thermal couplings between the sample's nuclear spins ($C_N$), the sample's electrons and phonons ($C_S$), and calorimeter ($C_C$).



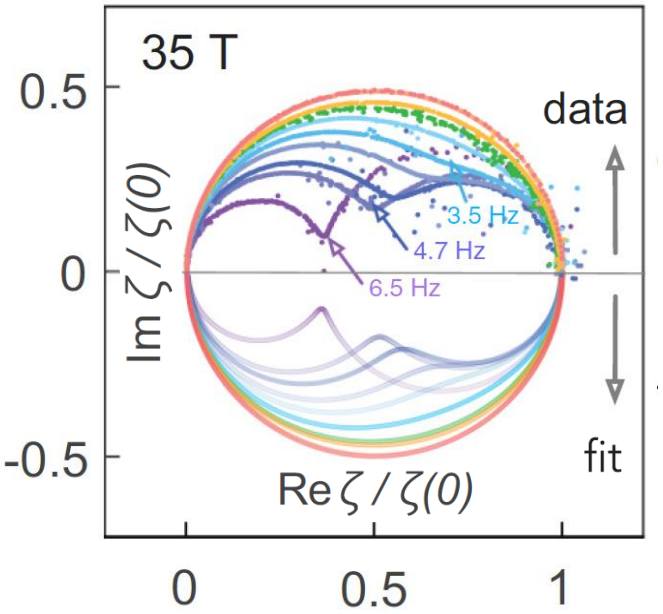




**Fig. 2:** Measured thermal impedance of the calorimeter-sample assembly (the dense sets of data points that form seemingly solid lines in the upper half of the figure) as measured at various frequencies, compared to the fits to the data (lower half of the figure) that determine the temperature and magnetic field dependence of the six parameters denoted in Fig.1.

**Fig. 3:** Experimental values of heat capacity showing the ability of TISP to measure the heat capacity of the electrons and phonons separately from the nuclear heat capacity.

**Facilities and instrumentation used:** DC-Field Facility, Cell 12

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