The measurement

\[ C = \frac{\Delta Q}{\Delta T} \]
How to measure $C_p$?

**Principle**: apply $P$, read $T$ and time

**adiabatic**: isolated sample and pt by pt

$$C = \frac{\Delta Q}{\Delta T}$$

**quasi-adiabatic**, continuous heating $P = C \frac{dT}{dt}$

**relaxation**: heat pulse, thermal link to $T$ bath

large relaxation, dual slope, ...

**modulation**: alternative heating at $\omega$

$$T_{ac} = \frac{P}{K + jC\omega}$$
very demanding T measurements!!

\[ \frac{DC}{C} \sim 10^{-3} \]

\[ T = 9.104785 \]

\[ \frac{DT}{T} \sim 10^{-3} \]

and TIME

calibrations of
thermometers is a
nightmare!!
and fitting procedure
Thermodynamic thermometers

Figure 1. Primary thermometers recently used or currently under development with temperature ranges. For the abbreviations see the text.

Figure 2. Principles of CVGT, AGT and DCGT (for the symbols cf table 1, the simple relations are valid for an ideal gas).

Temperature metrology

3. Gas thermometers

The three kinds of GT currently practised are constant-volume GT (CVGT), AGT and DCGT, and they are all based on different simple relations between the properties of an ideal gas and thermodynamic temperature (see figure 2). Though many gases exhibit a nearly-ideal behaviour at and above the TPW, in view of the desired level of accuracy, even at these temperatures, the small departures from the ideal behaviour must be carefully considered. This is done by measuring the relevant property as a function of the density. Then, the ideal behaviour is deduced by an extrapolation to zero density applying an appropriate virial expansion. The results are usually transferred to resistance thermometers as...
Thermometers

- What is a good thermometer?
- primary / secondary
- accuracy
- resolution/sensitivity
- reproducibility
- easy to use
- time response
Thermometers actually used in low temperature laboratory
ADIABATIC

heat pulse and isolated sample

- Excellent precision and accuracy

\[ \lambda \text{ transition in space shuttle} \]

but

- method point by point (tenuous)

- how to cool the sample?

- limited to large samples (parasitic non-adiabaticity)
Apparatus used for calorimetric measurements in the adiabatic demagnetization range

Superconducting switch

Mechanical heat switch

Sample
Apparatus used for calorimetric measurements in the adiabatic demagnetization range

Prof. N.E. Phillips
University of California
BERKELEY

100mK–40K
accuracy a few %
ΔC/C a few 10⁻³

100mg–1g Heavy Fermion
QUASI-ADIABATIC

heat pulse continuous heating and still isolated sample

\[ P = \text{Cste} <> 0 \]

\[ P = C \frac{dT}{dt} \]

\[ \frac{dT}{dt} \]

\[ T \text{ (Kelvin)} \]

\[ P \text{ (Watts)} \]

\[ \text{time (s)} \]
QUASI-ADIABATIC

heat pulse continuous heating and still isolated sample

Double radiation shields but still

\( P_{\text{parasitic}} \) a few \( 10^{-7} \)W

with

\( \Delta T \) measured via Cr-Cn thermocouples and nanovoltmeter
QUASI-ADIABATIC

heat pulse continuous heating and still isolated sample

10K-300K
accuracy 1-5 %
ΔC/C a few 10^{-3}
10mg-100g HTSC
QUASI-ADIABATOMIC in dilution range

$\Delta T$ measured via Au:Fe thermocouples and SQUID !!

SQUID + Chopper = 1–2 pA/(Hz)$^{1/2}$

R. Calemczuk
CEA-grenoble

P

I

V

$\Delta T=0$

T

$P = C \frac{dT}{dt}$

$P = C_{\text{ste}} \neq 0$

$\Delta T$ measured via Au:Fe thermocouples and SQUID !!
QUASI-ADIABATIC in dilution range

R. Calemczuk
CEA-grenoble

\[ V = \sqrt{4k_B T R} = 0.5 \text{ pV/} \sqrt{\text{Hz}} \]
\[ I = \sqrt{4k_B T / R} = 10 \text{ pA/} \sqrt{\text{Hz}} \]
\[ \Delta T = 2 \text{ } \mu\text{K/} \sqrt{\text{Hz}} \]
\[ P_{\text{parasitic}} = \frac{L}{S/T} \sqrt{I^2} = 10^{-13} \text{ W} \]
QUASI-ADIABATIC in dilution range

R. Calemczuk
CEA-grenoble

1-10% of 10mg Cu
BUT !!
no calibration of S
(null detector)
\[ \Delta T = 0 \]
therefore thermometer in compensated area
RELAXATIONS Methods

heat pulse or steplike, heat link to thermal bath at $T_b$
PPMS Quantum Design: $^4$He and $^3$He
Set-up at ultra-low T (10mk-1K)

J.P. Brison
CEA-grenoble

21/09/2011
CryoCourse Chichiliane
(Dis)Advantages,

- popular, reliable, and widely used at low T
- extended down to below 10mK (J.P. Brison)
- good accuracy (5%), but not excellent resolution
- mass down to a fraction of a mg
- relaxation time $\geq 1$ s

- $C_p$ can vary by orders of magnitude between the interesting $T$-range, so does relaxation time

- Point by point, long and tenuous, 1 pt at 100K = 20 mns
AuCrS$_2$ : antiferromagnetic + structural

Courtesy:
F. levy
CNRS-grenoble
Options

- define internal and external time constants
- choose duration time vs $T_{int}$ and $T_{ext}$
- fitting procedure: introduce constraints
- Large relaxations and local $dT/dt$ (A. Demuer) faster, larger current, ...
- Dual Slope method (dynamic, no calibration of $\kappa$)
Modulation (alternative)

ac-power

\[ T_{ac} = \frac{P}{K + jC\omega} \]

\[ T_{dc} = \frac{P}{K} \]

\[ P \propto \cos^2(\omega t/2) \]

\[ T \xrightarrow{C} k \]

\[ T_{base} \]
Characteristics

- lock-in detection, filters, noise rejection (true for all modulation technics)

- excellent resolution (typical $10^{-4}$), lesser accuracy but $\Delta C = \text{a few } 10^{-12} \text{ J/K}$

- 100 nanogram $< m < \text{a few milligram}$

- continuous: during $H$ and/or $T$ sweeps

- easy to extend a differential configuration

- extrem conditions: 45T-DC, pulsed 60T, 15Gpa, 10kHz
transformer at room T:
a few 0.1 mK/(Hz)$^{1/2}$

transformer at 4K:
a few 10 $\mu$K/(Hz)$^{1/2}$

Squid detection:
a few 0.1 $\mu$K/(Hz)$^{1/2}$