acoustic detection of the magnetocaloric effect

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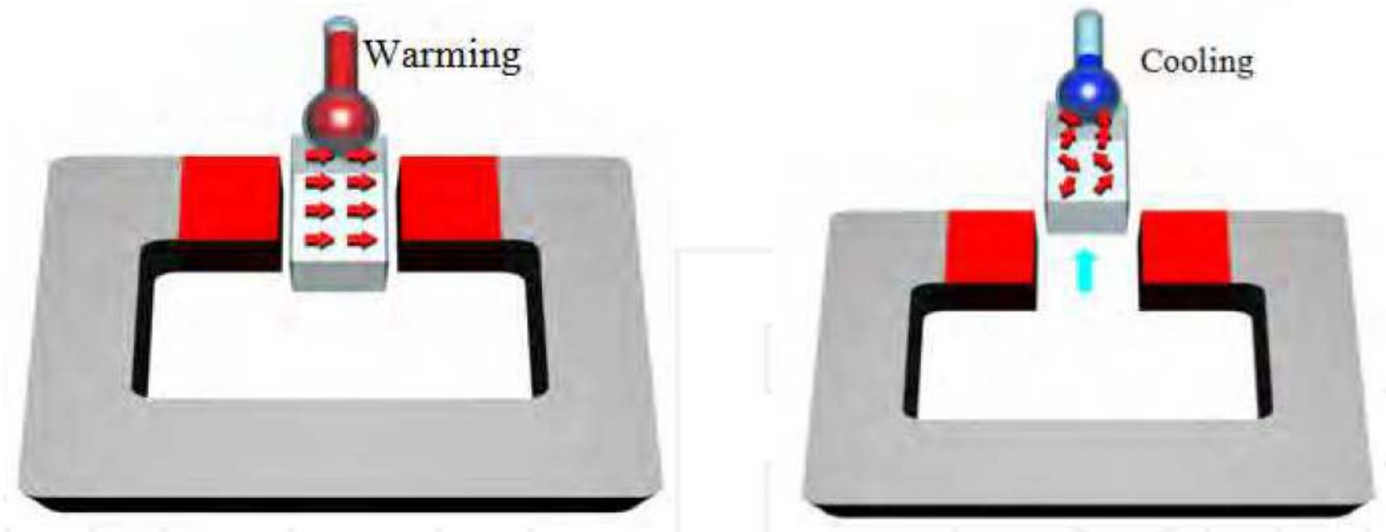
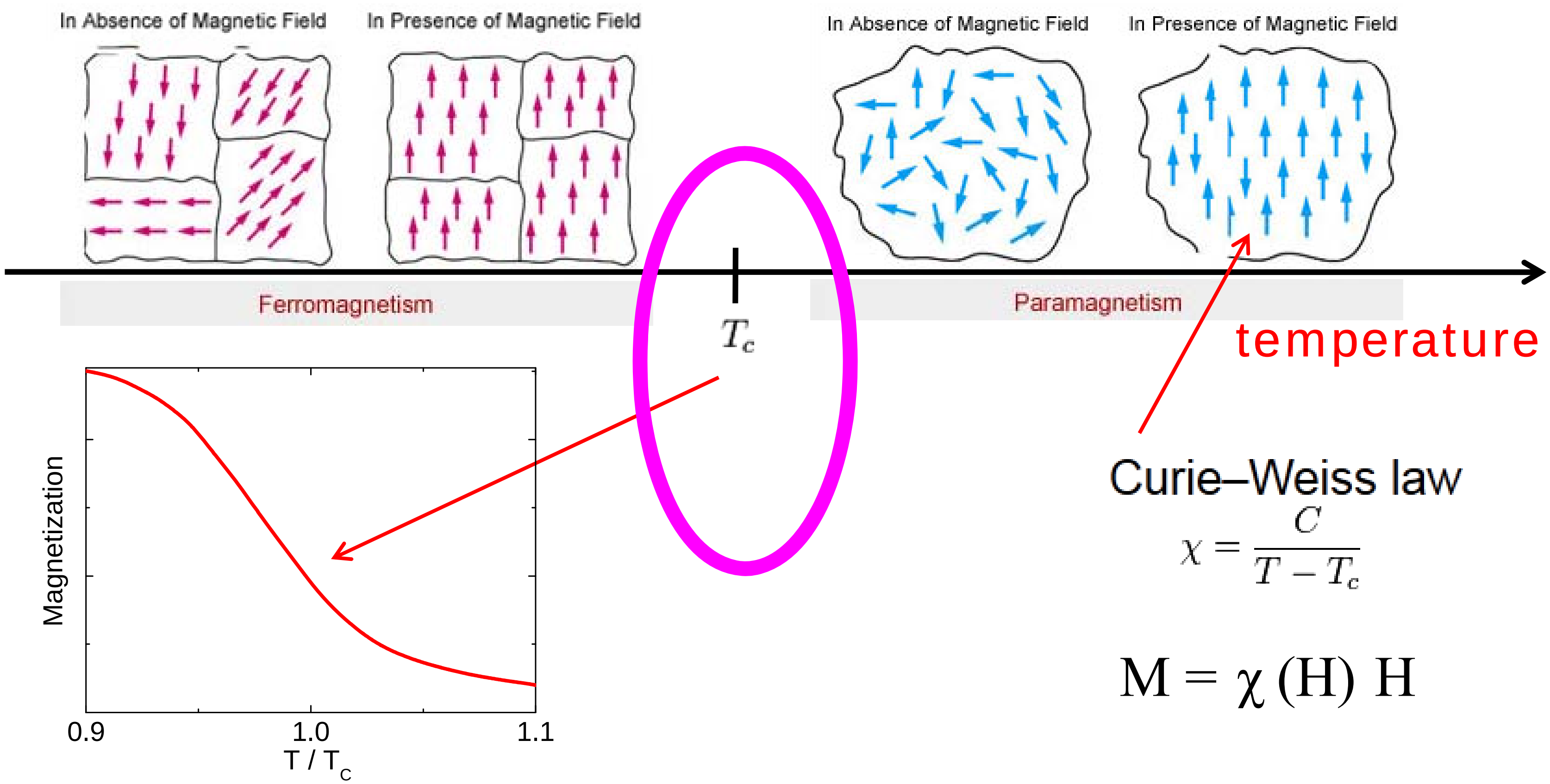
the magnetocaloric effect: what is it?



the magnetocaloric effect: strategic/ideal conditions



Curie–Weiss law

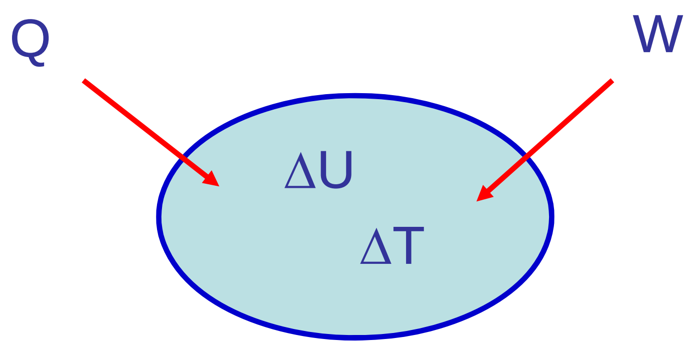
$$\chi = \frac{C}{T - T_c}$$

$$M = \chi(H)\, H$$

objectives of the presentation

- to introduce the magnetocaloric effect (mce) and its potential applications: magnetic refrigeration;
- to establish thermodynamic relations between magnetic field, temperature and entropy; discuss the conventional characterization of the mce;
- to introduce the photoacoustic effect: detection of small changes in the temperature of the sample;
- to use the acoustic detection to determine the mce;

the first law of thermodynamics: internal energy U



the zero law states the existence of the temperature

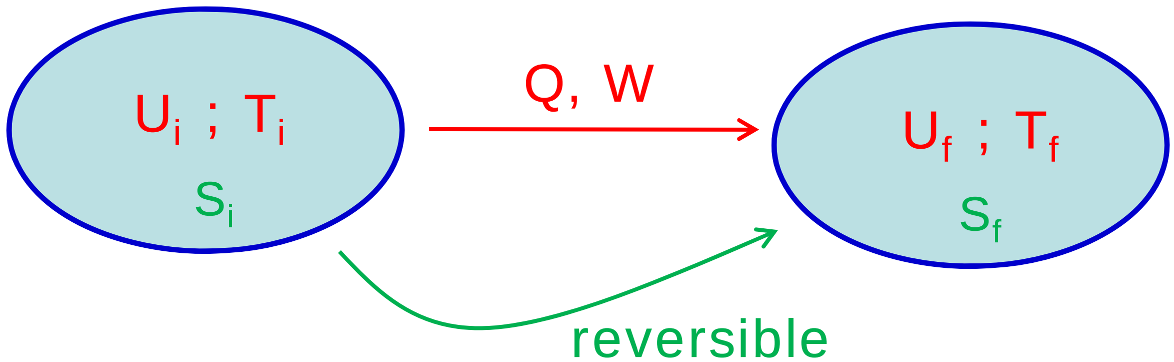
$$\begin{cases} \Delta U = Q + W \\ dU = \delta Q + \delta W \end{cases}$$

If $\delta W = 0$, them:

$$dU = C_{V,\, M,\, \ldots}\, dT$$

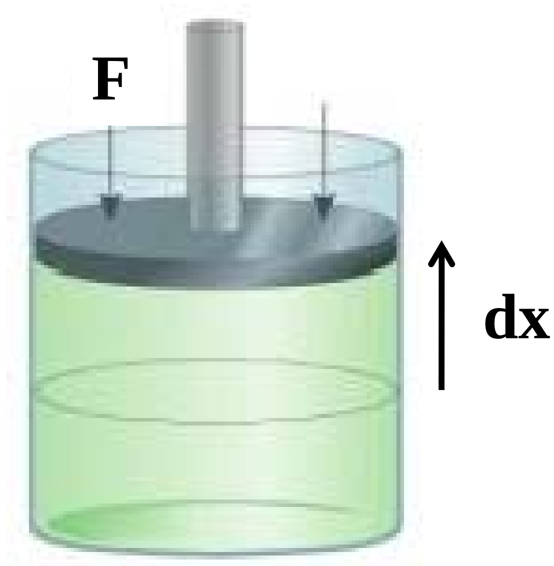
extensive coordinates: volume, magnetization etc.

the second law of thermodynamics: entropy S



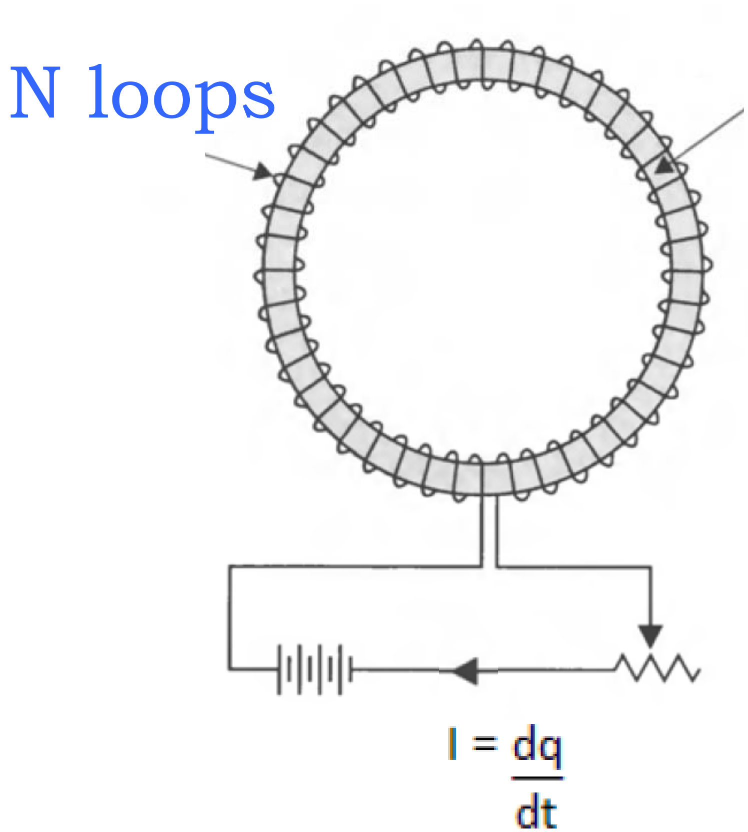
$$\begin{cases} dS = \dfrac{\delta Q_{\text{reversible}}}{T} \\[2ex] \Delta S = S_f - S_i = \displaystyle\int_{\substack{i \\ \text{reversible} \\ \text{path}}}^{f} \frac{\delta Q}{T} \end{cases}$$

work on a hydrostatic system: a gas, for example



$$\delta W = - F\, dx = - P\, A\, dx = - P\, dV$$

work on a magnetic system



$$\varepsilon = -\frac{1}{c} N \frac{\partial \Phi}{\partial t} \quad \text{(gaussian units)}$$

$$\Phi = \oint \vec{B} \cdot \hat{n} da = B A \quad \text{(thin toroid)}$$

$$\varepsilon = -\frac{1}{c} N A \frac{dB}{dt}$$

work on a magnetic system

work done by the battery: $\delta W' = - \varepsilon\, dq = - \varepsilon\, I\, dt = \dfrac{NAIdB}{c}$

Ampère law: $\oint_C \vec{H}.dl = \dfrac{4\pi}{c} I_{enc} \Rightarrow H = \dfrac{4\pi}{c}\dfrac{NI}{L} \Rightarrow (NI) = \dfrac{HLc}{4\pi}$

$$\delta W' = \frac{(NI)AdB}{c} = \frac{HLc}{4\pi}\frac{AdB}{c} = \frac{V\,H}{4\pi} dB$$

$$B = H + 4\pi M \quad \Rightarrow \quad dB = dH + 4\pi\, dM$$

$$\delta W' = \frac{V\,H}{4\pi} dH + V\,H\,dM$$

vacuum — material — magnetization

work on a magnetic system

$$\delta W = V\, H\, dM = H dm$$

total magnetic moment

$$\vec{m} = V\, \vec{M} = \sum_i \vec{m}_i$$

a magnetic system:
the first law of thermodynamics

$$\boxed{dU = \delta Q - PdV + H\,dm}$$

magnetic work

mechanical work

practical conditions:

i) atmospheric pressure (p = cte)
ii) solids: volume ~ cte

Therefore, p and V are taken as constants: $\boxed{dU = \delta Q + H\,dm}$

the magnetocaloric effect: the formal concept

$$dU = \delta Q + H\,dm$$

work

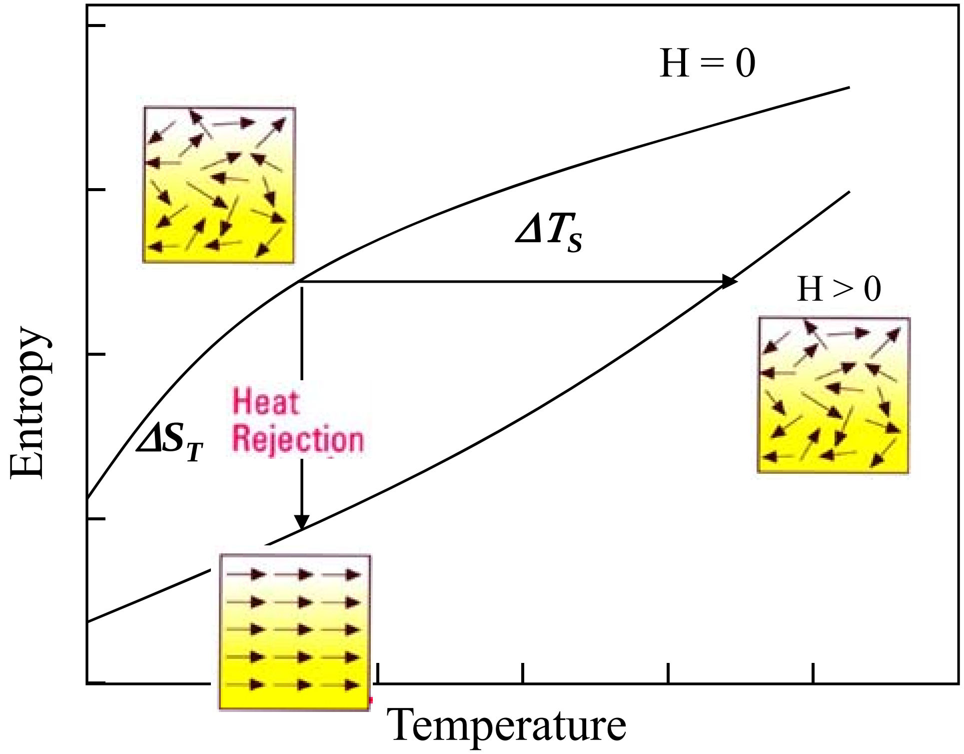
$$\delta Q = 0 \quad \text{(adiabatic)}$$

$$H \uparrow \quad T \uparrow \quad (\Delta T_S > 0)$$

$$T = cte \quad \text{(isothermal)}$$

$$H \uparrow \quad \delta Q = TdS \downarrow \quad (\Delta S_T < 0)$$

the magnetocaloric effect



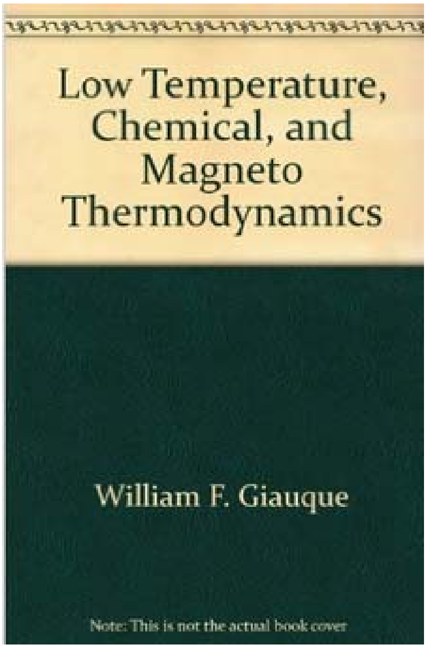
one slide of history

- 1881: discovery by the German physicist Emil Gabriel Warburg. He observed a few millikelvins increase in an iron sample [1].

- 1918: Weiss and Piccard explained the effect [2].

- 1926/1927: Debye [3] and Giauque [4] proposed a new method to reach ultra low temperatures (below 1 K) using adiabatic demagnetization.

- 1933: experimental proof of the method by Giauque [5]. A temperature of 0.25 K was attained, and the use of the effect in magnetic refrigeration at low temperatures became important. *William Francis Giauque was an American chemist and Nobel laureate recognized in 1949 for his studies in the properties of matter at temperatures close to absolute zero.*



- 1976: Brown demonstrated the usefulness of the method at room temperature [6]. He obtained a temperature variation of 47 K by cycling Gd following a suitable pathway. The maximum mce in Gd at 7 T is about 16 K.

- 1997: Pecharsky and Gschneidner discovered a new alloy ($Gd_5Si_2Ge_2$) that presents a giant mce near room temperature (~ twice the pure Gd) [7].

history key references

1. E. Warburg, *Magnetische Untersuchungen uber einige Wirkungen der Koerzitivkraft*, Ann. Phys. **13** (1881) 141–164.

2. P. Weiss, A. Piccard, *Sur un nouveau phénomène magnétocalorique*, Compte Rendu Ac. Sci. **166** (1918) 352.

3. P. Debye, *Einige Bemerkungen zur Magnetisierung bei tiefer Temperatur*, Ann. Phys. **81** (1926) 1154–1160.

4. W.F. Giauque, *A thermodynamic treatment of certain magnetic effects. A proposed method of producing temperatures considerably below 1º absolute*, J. Am. Chem. Soc. **49** (1927) 1864–1870.

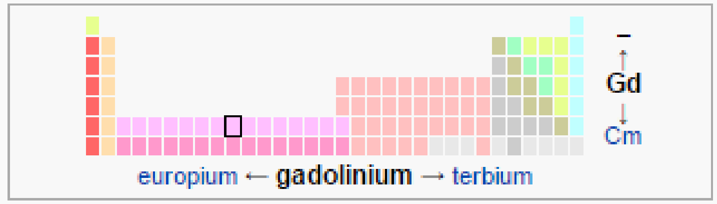
5. W.F. Giauque, D.P. MacDougall, *Attainment of temperatures below 1º absolute by demagnetization of* $Gd_2(SO_4)_3.8H_2O$, Phys. Rev. Lett. **43** (9) (1933) 768.

6. G.V. Brown, *Magnetic heat pumping near room temperature*, J. Appl. Phys. **47** (1976) 3673–3680.

7. V. K. Pecharsky, K. A. Gschneidner Jr., *Giant Magnetocaloric effect in* $Gd_5(Si_2Ge_2)$, Phys Rev Lett **78** (23) (1997) 4494–4497.

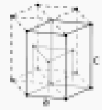
gadolinium

Gadolinium in the periodic table	

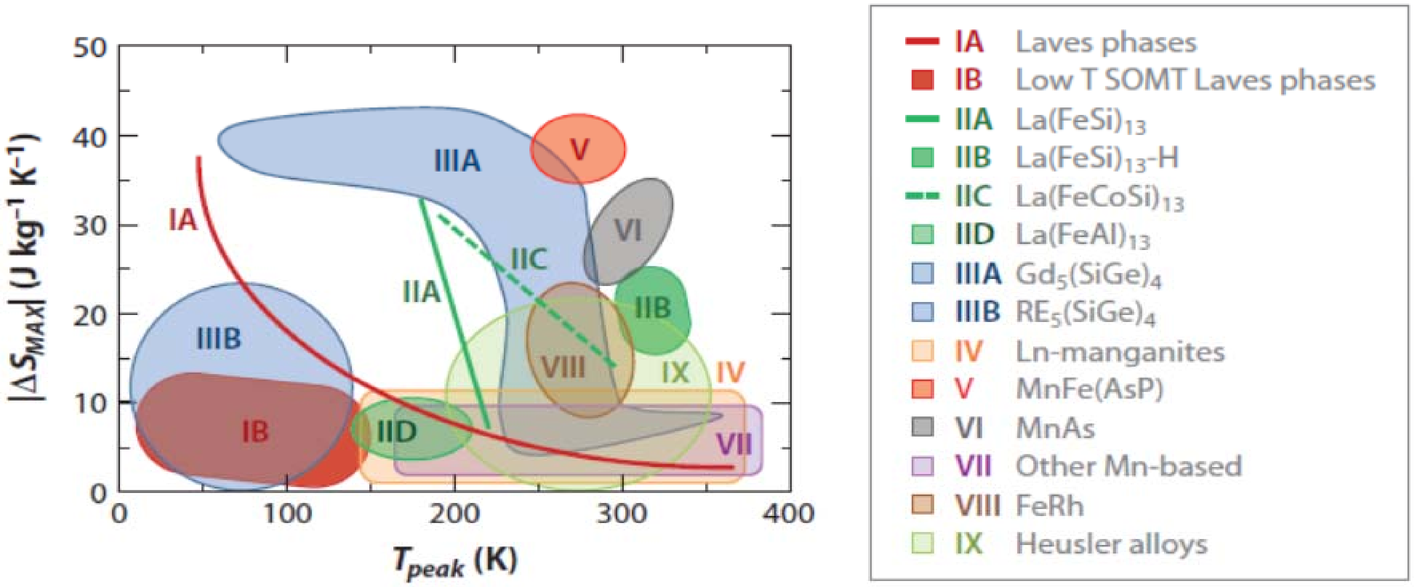


Atomic number	64
Standard atomic weight (±) (A_r)	157.25(3)[1]
Element category	lanthanide
Group, block	group n/a, f-block
Period	period 6
Electron configuration	[Xe] $4f^7\ 5d^1\ 6s^2$
per shell	2, 8, 18, 25, 9, 2
Physical properties	
Phase	solid
Melting point	1585 K (1312 °C, 2394 °F)
Boiling point	3273 K (3000 °C, 5432 °F)
Density near r.t.	7.90 g/cm^3
when liquid, at m.p.	7.4 g/cm^3
Heat of fusion	10.05 kJ/mol
Heat of vaporization	301.3 kJ/mol
Molar heat capacity	37.03 J/(mol·K)

gadolinium

Miscellanea	
Crystal structure	hexagonal close-packed (hcp) 
Speed of sound thin rod	2680 m/s (at 20 °C)
Thermal expansion	α poly: 9.4 µm/(m·K) (at 100 °C)
Thermal conductivity	10.6 W/(m·K)
Electrical resistivity	α, poly: 1.310 µΩ·m
Magnetic ordering	ferromagnetic-paramagnetic transition at 293.4 K
Young's modulus	α form: 54.8 GPa
Shear modulus	α form: 21.8 GPa
Bulk modulus	α form: 37.9 GPa
Poisson ratio	α form: 0.259
Vickers hardness	510–950 MPa
CAS Registry Number	7440-54-2
History	
Naming	after the mineral Gadolinite (itself named after Johan Gadolin)
Discovery	Jean Charles Galissard de Marignac (1880)
First isolation	Lecoq de Boisbaudran (1886)

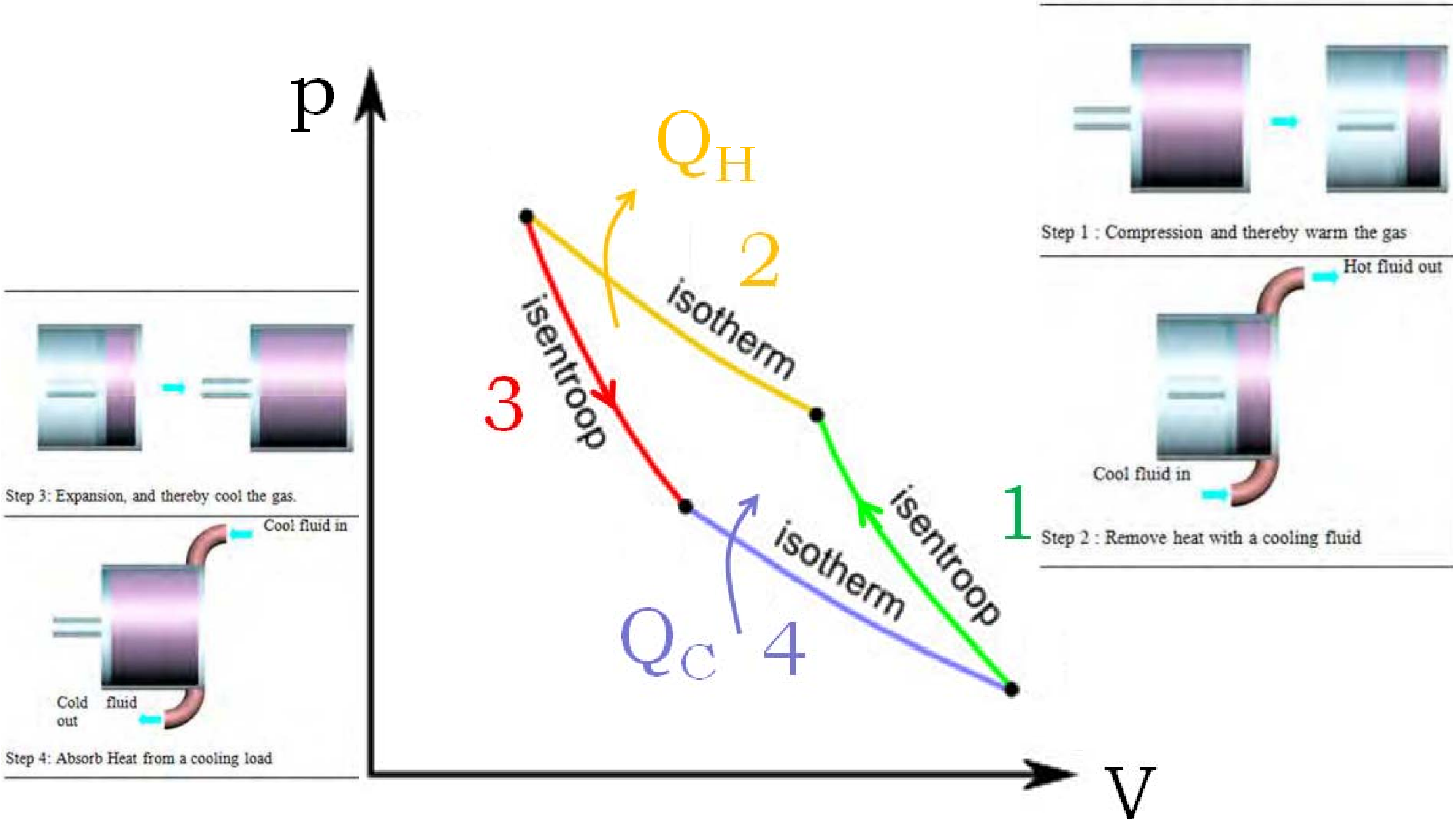
materials



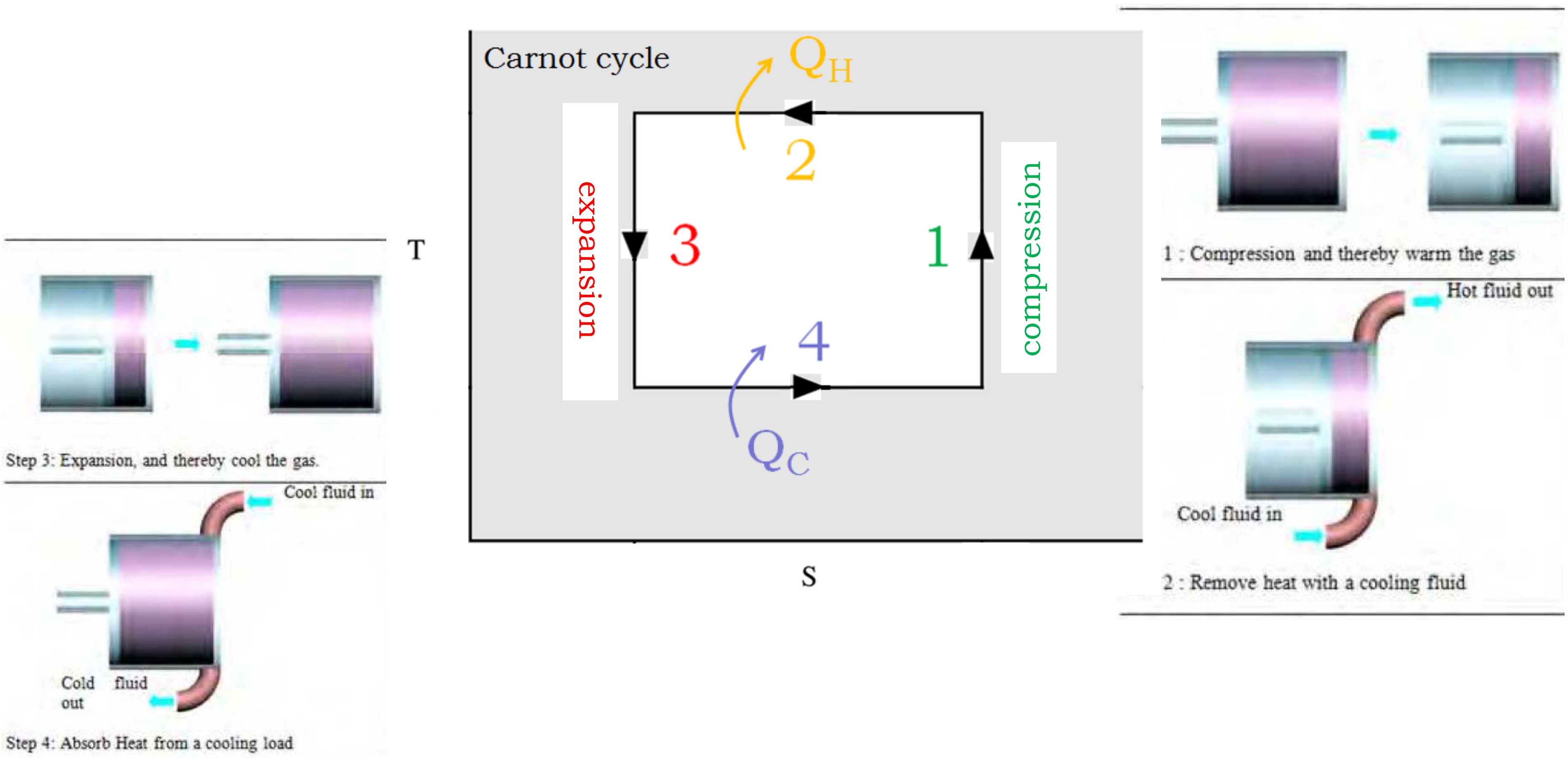
Maximum magnetic entropy change for $\Delta H = 5$ T versus peak temperature for different families of magnetocaloric materials.

The Magnetocaloric Effect and Magnetic Refrigeration Near Room Temperature: Materials and Models, V. Franco, J.S. Blázquez, B. Ingale, and A. Conde Annual Review of Materials Research **42**: 305-342 (2012)

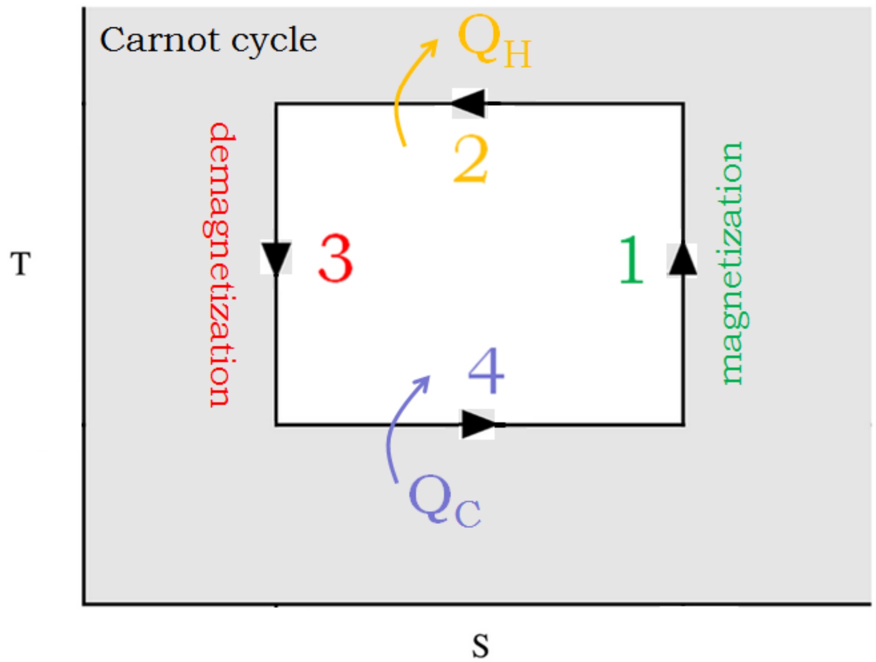
conventional refrigeration: ideal gas Carnot cycle

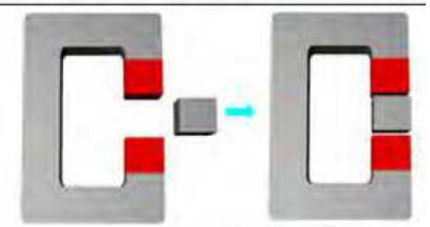


conventional refrigeration: ideal gas

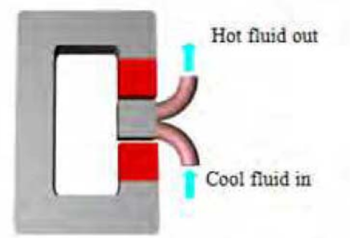


magnetic refrigeration

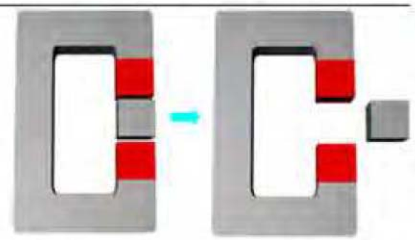




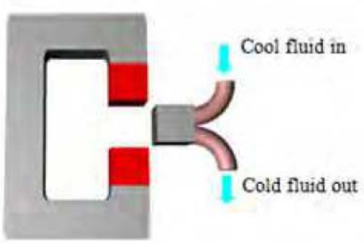
Step 1 : Magnetize, and thereby warm the solid



Step 2 : Remove heat with a cooling fluid



Step 3 : Demagnetize, and thereby cool the solid



Step 4: Absorb Heat from a cooling load.

magnetic refrigeration

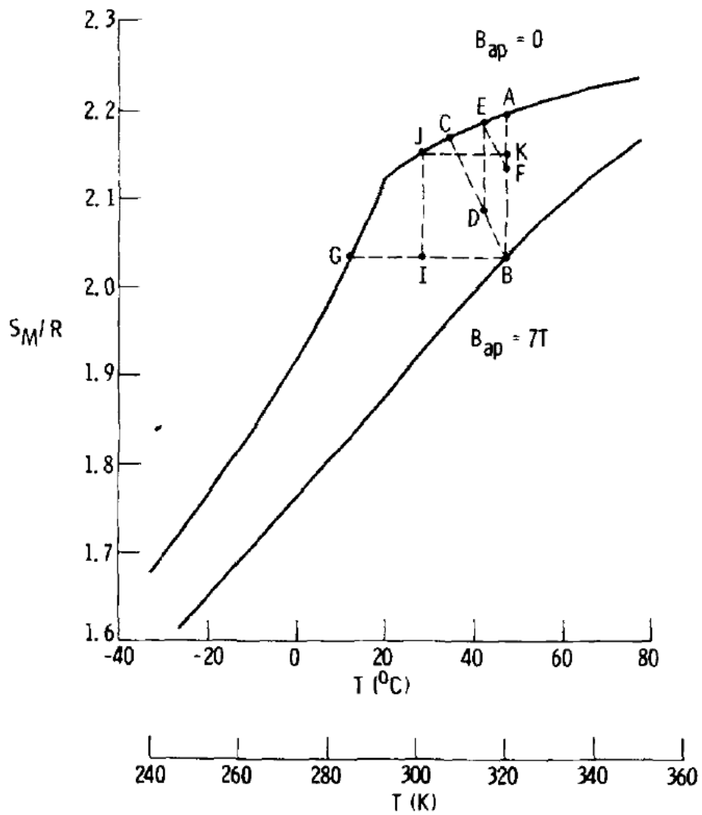


FIG. 6. Magnetic entropy S_M of Gd as a function of temperature T for two applied field strengths B_{ap}.

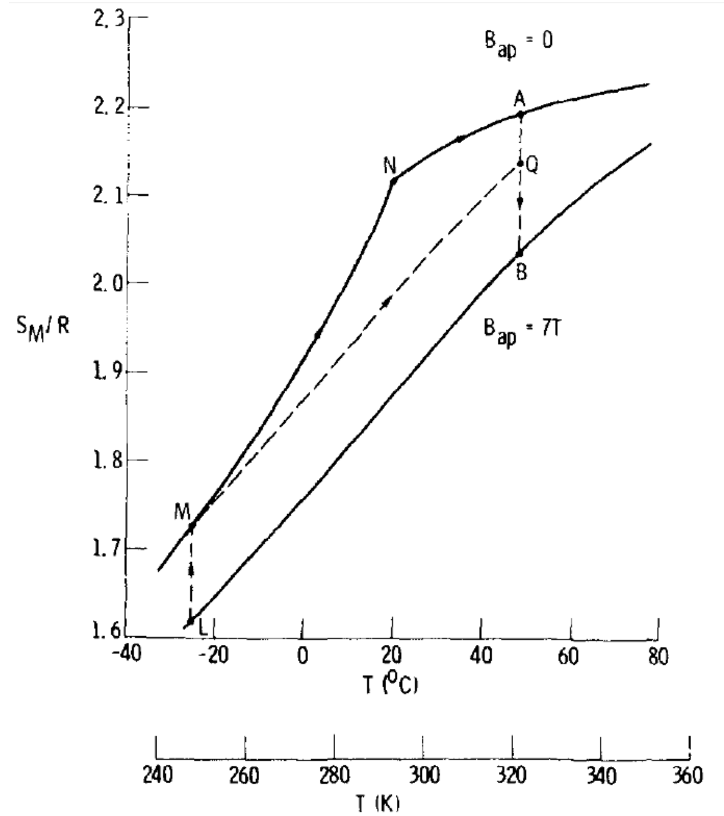
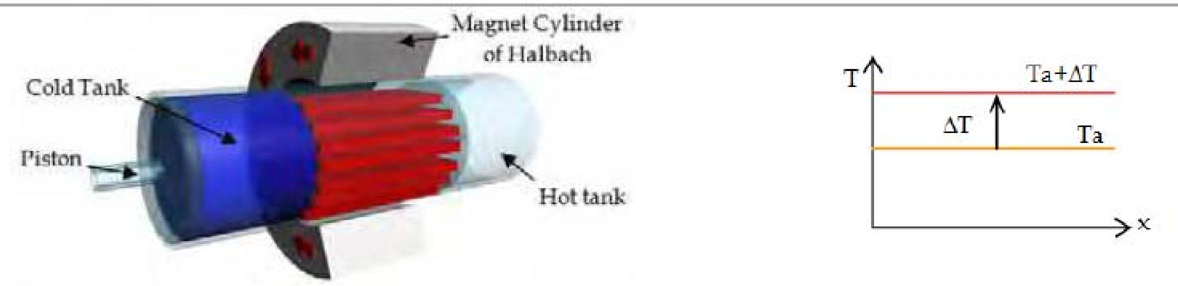


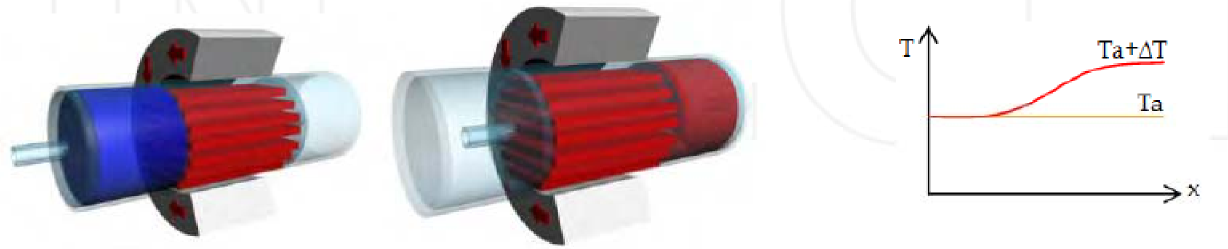
FIG. 8. The magnetic Stirling cycle QBLMQ plotted in the magnetic entropy-temperature plane.

G.V. Brown, J. Appl. Phys. **47** (1976) 3673–3680.

regenerative magnetic refrigeration



Step 1: Magnetization of the material from an initial state where the entire system is at temperature T_a. Each point of the regenerator material sees its temperature increase by ΔT following the application of the magnetic field.



Step 2: Flow of the fluid from the cold source to the hot source. The heat produced by the magnetization step is removed by the fluid flowing from the cold source T_c to the hot source T_h. This creates a temperature gradient along the bed.

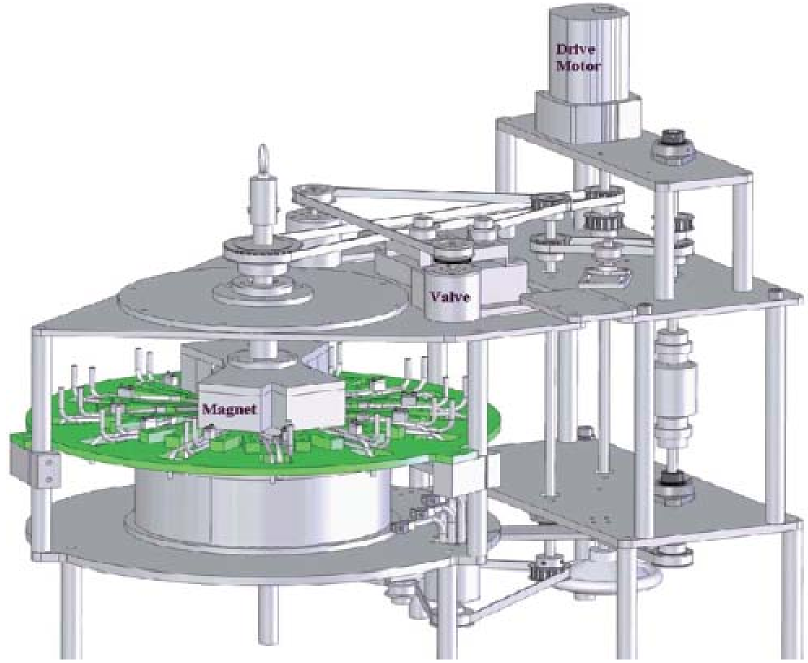
regenerative magnetic refrigeration

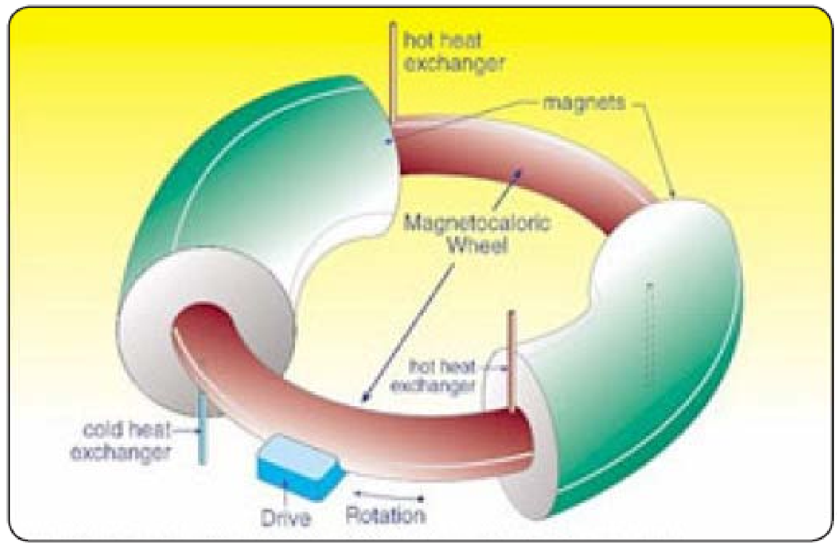
Step 3: demagnetization of the material. The temperature of Each point of the regenerator decreases by ΔT due to the demagnetization.

Step 4: Flow of fluid from the hot source to cold source. The flow of the fluid from the hot source T_h to the cold source T_f transfers its heat to the regenerator. The temperature gradient is amplified.

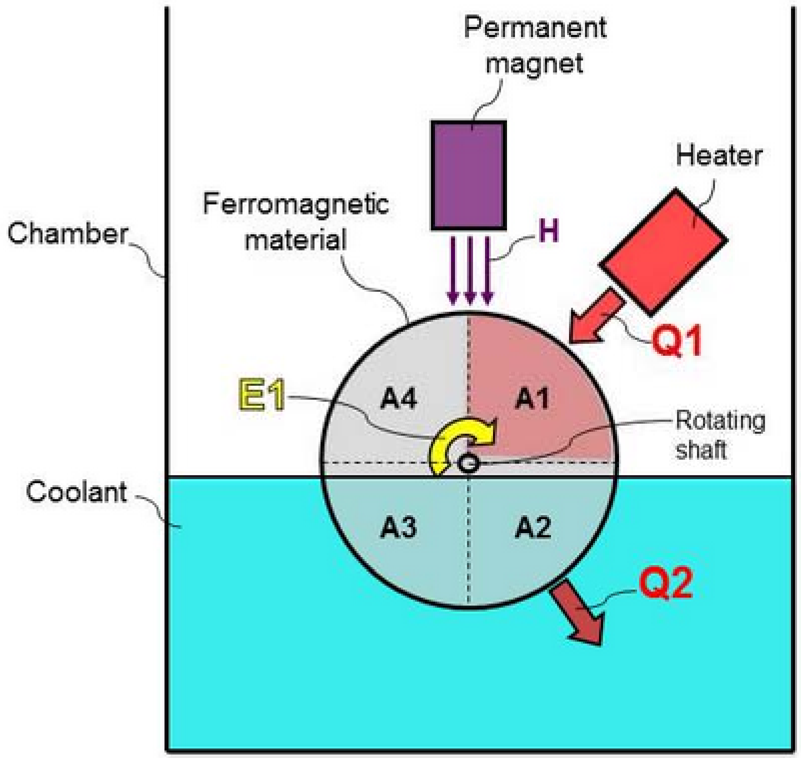
rotating magnetic refrigerator

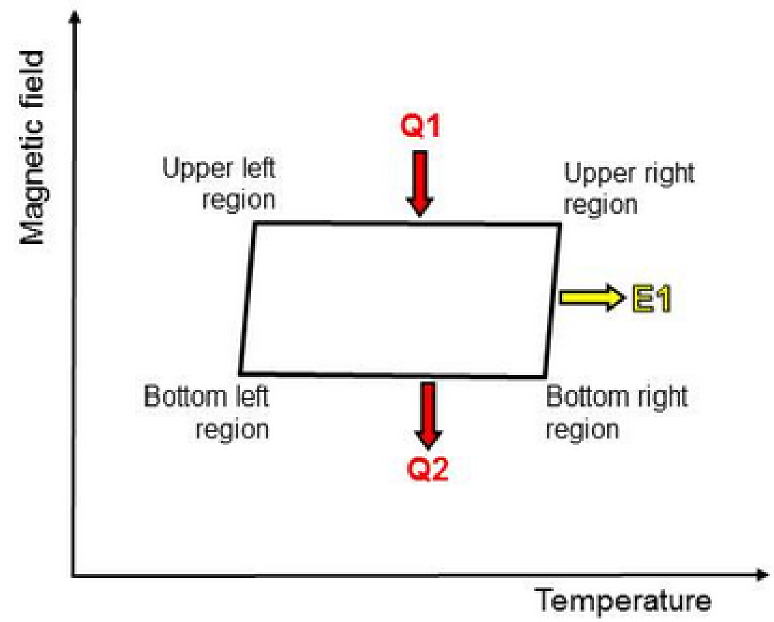
A rotating magnetic refrigerator developed by Astronautics Corporation of America Ltd. in collaboration with the Ames Laboratory.





thermo magnetic engine





thermodynamic relations

hydrostatic system

simple thermodynamic system:

3 coordinates among
T, P, V (the natural coordinates),
U, S and others…

+ 1 equation of state ➔
➔ 2 independent coordinates

ideal gas: PV = nRT

$$U = U(T,V)$$

$$dU = \left(\frac{\partial U}{\partial T}\right)_V dT + \left(\frac{\partial U}{\partial V}\right)_T dV$$

$$V = cte \;\Rightarrow\; dU = \delta Q = TdS$$

$$\text{and} \; \left.\frac{\delta Q}{dT}\right|_V = C_V = \left(\frac{\partial U}{\partial T}\right)_V$$

$\lambda = V$ or P

$$C_\lambda = \left.\frac{\delta Q}{dT}\right|_\lambda = \left.\frac{TdS}{dT}\right|_\lambda = \frac{T}{dT}\left[\left(\frac{\partial S}{\partial T}\right)_\lambda dT + \left(\frac{\partial S}{\partial \lambda}\right)_T d\lambda\right]$$

$$\text{For } \lambda = cte\text{:} \quad C_\lambda = T\left(\frac{\partial S}{\partial T}\right)_\lambda$$

$$C_V = T\left(\frac{\partial S}{\partial T}\right)_V \quad \text{and} \quad C_P = T\left(\frac{\partial S}{\partial T}\right)_P$$

hydrostatic system

thermodynamic relations

first law: $dU = dQ + dW$

$$\begin{cases} dQ = TdS \\ dW = -\,PdV \end{cases}$$

$$dU = TdS - PdV$$

$$U = U(S,V)$$

$$dU = \left(\frac{\partial U}{\partial S}\right)_V dS + \left(\frac{\partial U}{\partial V}\right)_S dV \Rightarrow \left(\frac{\partial U}{\partial S}\right)_V = T \text{ and } \left(\frac{\partial U}{\partial V}\right)_S = -P$$

$$\text{Since } \left(\frac{\partial^2 U}{\partial V \partial S}\right) = \left(\frac{\partial^2 U}{\partial S \partial V}\right) \Rightarrow \left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial P}{\partial S}\right)_V \text{ (Maxwell equation)}$$

magnetic system

thermodynamic relations

the natural coordinates are: T, H and m

paramagnetic system:

the equation of state is the Curie law: $M = (m/V) = C_C\ (H/T)$

first law: $dU = TdS + Hdm$

Maxwell equation: $$\left(\frac{\partial T}{\partial m}\right)_S = \left(\frac{\partial H}{\partial S}\right)_m$$

$$C_m = \left(\frac{\partial U}{\partial T}\right)_m = T\left(\frac{\partial S}{\partial T}\right)_m \quad \text{and} \quad C_H = T\left(\frac{\partial S}{\partial T}\right)_H$$

thermodynamic relations

hydrostatic system

magnetic system

entalpy E and magnetic entalpy E^*

$E = U + PV$

$dE = dU + PdV + VdP = TdS + VdP$

$P = cte \quad \Rightarrow \quad dE = \delta Q$

Maxwell equation: $\left(\frac{\partial T}{\partial P}\right)_S = \left(\frac{\partial V}{\partial S}\right)_P$

$E^* = U - Hm$

$dE^* = dU - Hdm - mdH = TdS - mdH$

$H = cte \quad \Rightarrow \quad dE^* = \delta Q$

Maxwell equation: $\left(\frac{\partial T}{\partial H}\right)_S = -\left(\frac{\partial m}{\partial S}\right)_H$

Helmholtz free energy: $F = U – TS$

$dF = dU – TdS - SdT$

$T = cte \quad \Rightarrow \quad dF = \delta W$

$dF = -SdT - PdV$

Maxwell equation: $\left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial P}{\partial T}\right)_V$

$dF = -SdT + Hdm$

Maxwell equation: $\left(\frac{\partial S}{\partial m}\right)_T = -\left(\frac{\partial H}{\partial T}\right)_m$

thermodynamic relations

XXX

hydrostatic system

Gibbs free energy G and
magnetic Gibbs free energy G^*
$G = E – TS$; $G^* = E^* – TS$
$dG = dE – TdS – SdT$
$dG^* = dE^* – TdS - SdT$

magnetic system

$dG = -SdT + VdP$

Maxwell equation: $\left(\frac{\partial S}{\partial P}\right)_T = -\left(\frac{\partial V}{\partial T}\right)_P$

$dG^* = -SdT - mdH$

Maxwell equation: $\left(\frac{\partial S}{\partial H}\right)_T = \left(\frac{\partial m}{\partial T}\right)_H$

$T = cte$ and $P = cte \Rightarrow dG = 0$

$T = cte$ and $H = cte \Rightarrow dG^* = 0$

$T = cte$ and $P = cte \Rightarrow dG = \delta W_{non-mechanical}$

thermodynamic relations:
TdS equation

$$S = S\,(T, H)$$

$$TdS = T\left(\frac{\partial S}{\partial T}\right)_H dT + T\left(\frac{\partial S}{\partial H}\right)_T dH$$

$$TdS = C_H\, dT + T\left(\frac{\partial m}{\partial T}\right)_H dH$$

thermodynamic relations

$$TdS = C_H\, dT + T\left(\frac{\partial m}{\partial T}\right)_H dH$$

adiabatic process (dS = 0):

$$dT_S = -\frac{T}{C_H}\left(\frac{\partial m}{\partial T}\right)_H dH \;\Longrightarrow\; \Delta T_S = -\int_{H_i}^{H_f} \frac{T}{C_H}\left(\frac{\partial m}{\partial T}\right)_H dH$$

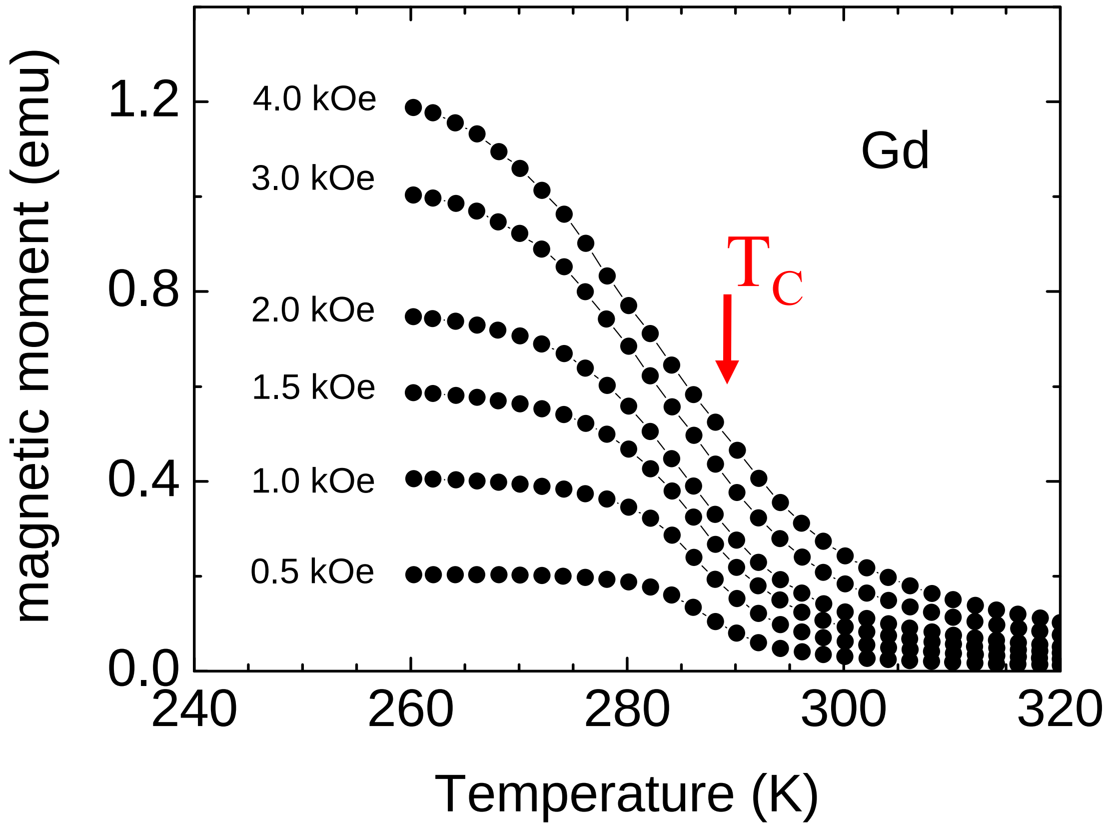
isothermal process (dT = 0):

$$dS_T = \left(\frac{\partial m}{\partial T}\right)_H dH \;\Longrightarrow\; \Delta S_T = \int_{H_i}^{H_f} \left(\frac{\partial m}{\partial T}\right)_H dH$$

cte magnetic field (dH = 0):

$$dS_H = C_H \frac{dT}{T} \;\Longrightarrow\; \Delta S_H = \int_{T_i}^{T_f} C_H(T')\frac{dT'}{T'}$$

conventional characterization: magnetic moment and entropy

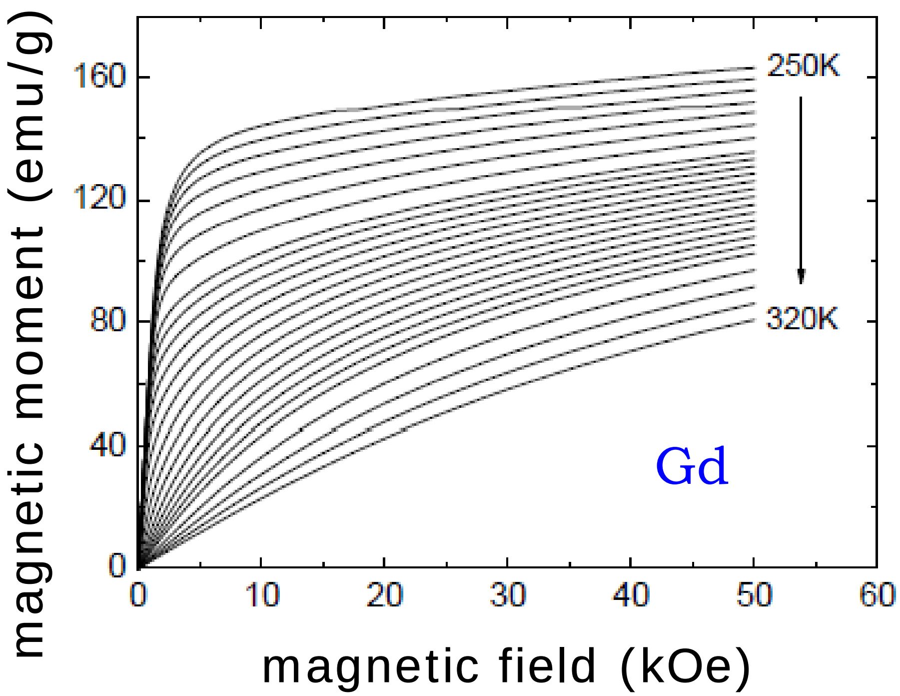


$$\Delta S_T = \int_{H_i}^{H_f} \left(\frac{\partial m}{\partial T} \right)_H dH$$

$$\Delta T_S = -\int_{H_i}^{H_f} \frac{T}{C_H} \left(\frac{\partial m}{\partial T} \right)_H dH$$

$$\Delta T_S \simeq -\frac{T}{C_H} \Delta S_T$$

conventional characterization: magnetic moment and entropy

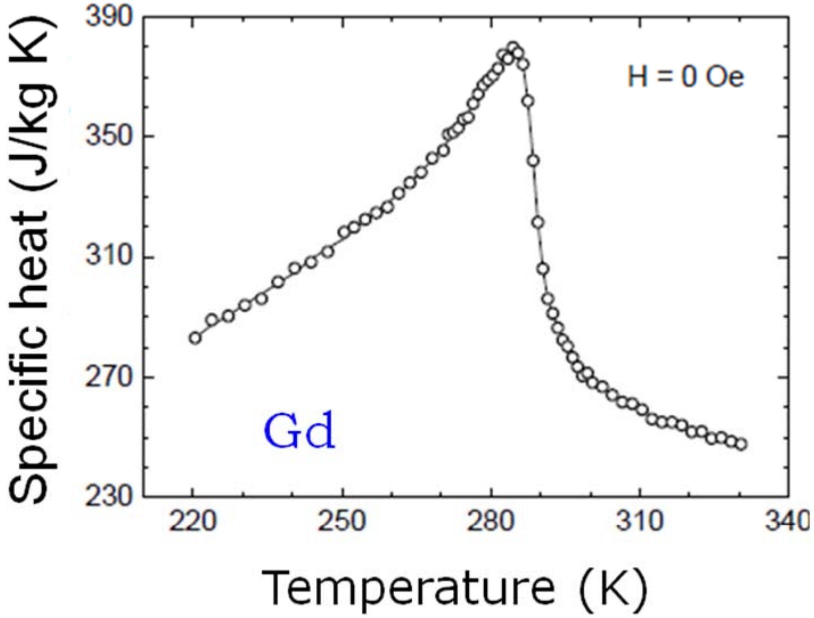


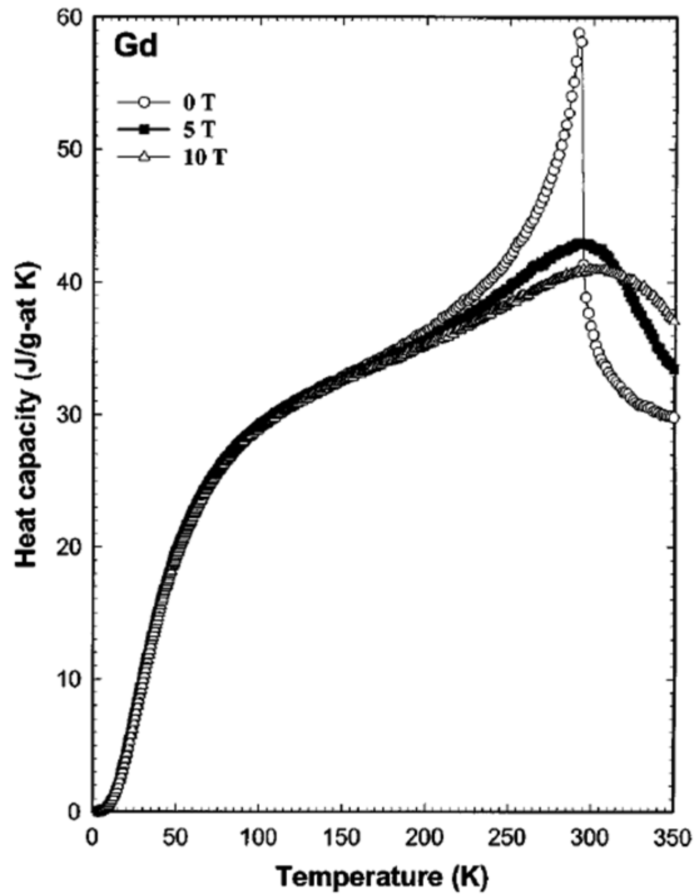
$$\Delta S_T = \int_{H_i}^{H_f} \left(\frac{\partial m}{\partial T}\right)_H dH$$

$$\Delta T_S = -\int_{H_i}^{H_f} \frac{T}{C_H} \left(\frac{\partial m}{\partial T}\right)_H dH$$

$$\Delta T_S \simeq -\frac{T}{C_H} \Delta S_T$$

conventional characterization: specific heat and entropy





$$\Delta S_T^{0\rightarrow H_2} = \int_0^T \left(C_{H_2}(T') - C_{H_1=0}(T') \right) \frac{dT'}{T'}$$

conventional characterization: other techniques

- direct measurement of the temperature (thermocouple)

- direct measurement of the entropy (heat) flow: Seebeck (thermopower) effect

$$\mathbf{E}_{\mathrm{emf}} = -S\boldsymbol{\nabla}T$$

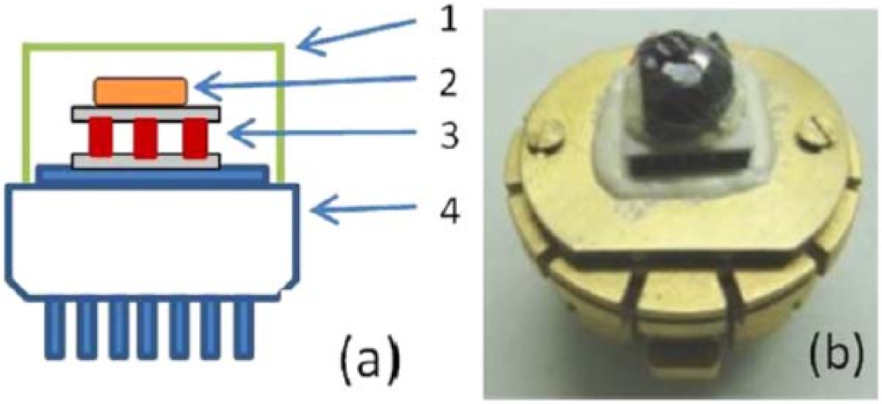


FIG. 1. (a) Schematic drawing of the Peltier element mounted on the PPMS puck: 1—heat shield; 2—sample; 3—Peltier element; and 4—puck. (b) Picture of the actual puck with a $Gd_5Ge_2Si_2$ sample.

J. C. B. Monteiro, R. D. dos Reis, A. M. Mansanares, F. C. G. Gandra, Appl. Phys. Lett. **105**, 074104 (2014).

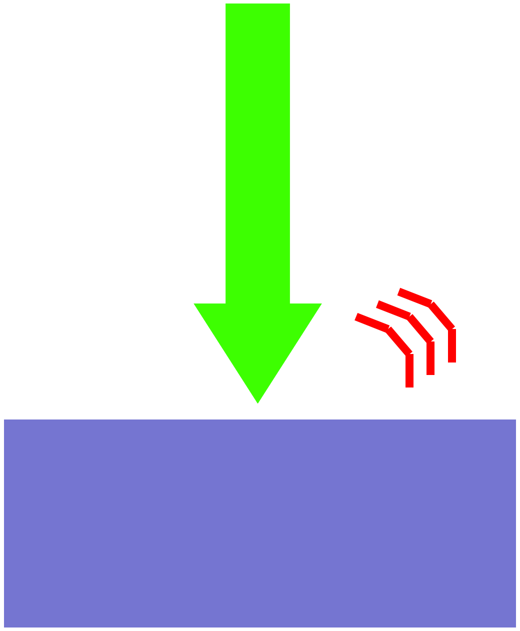
photoacoustic effect

the photophone (1880):
optical fibers precursor

alexander graham bell

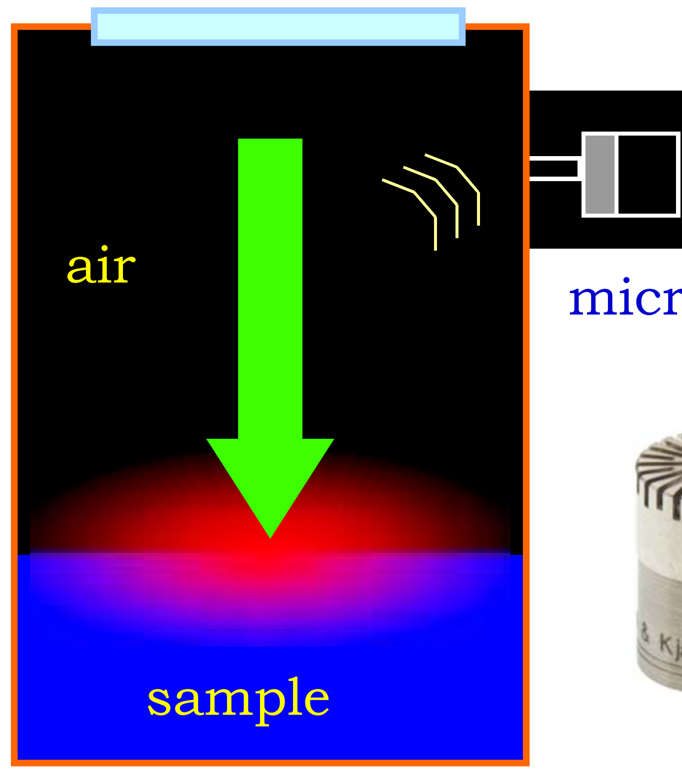
photoacoustic effect

the photophone

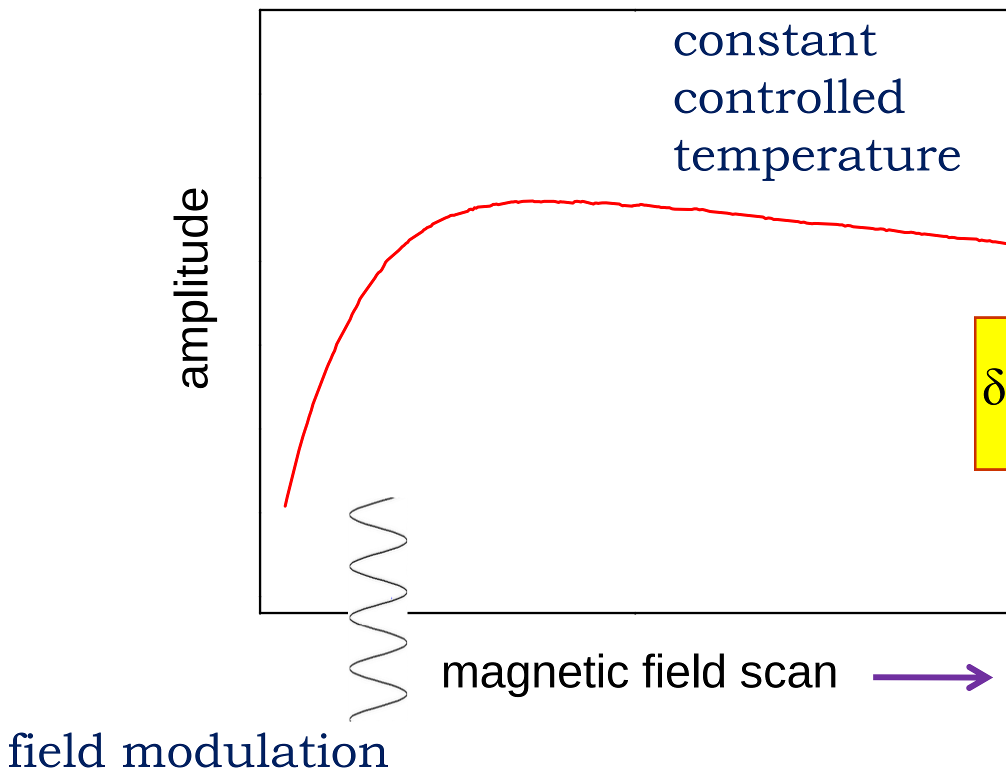


photoacoustic effect

- light absorption
- heat propagation:
  to the sample's bulk and
  to the surrounding air
- surrounding air expansion
- air column compression:
  acoustic wave generation

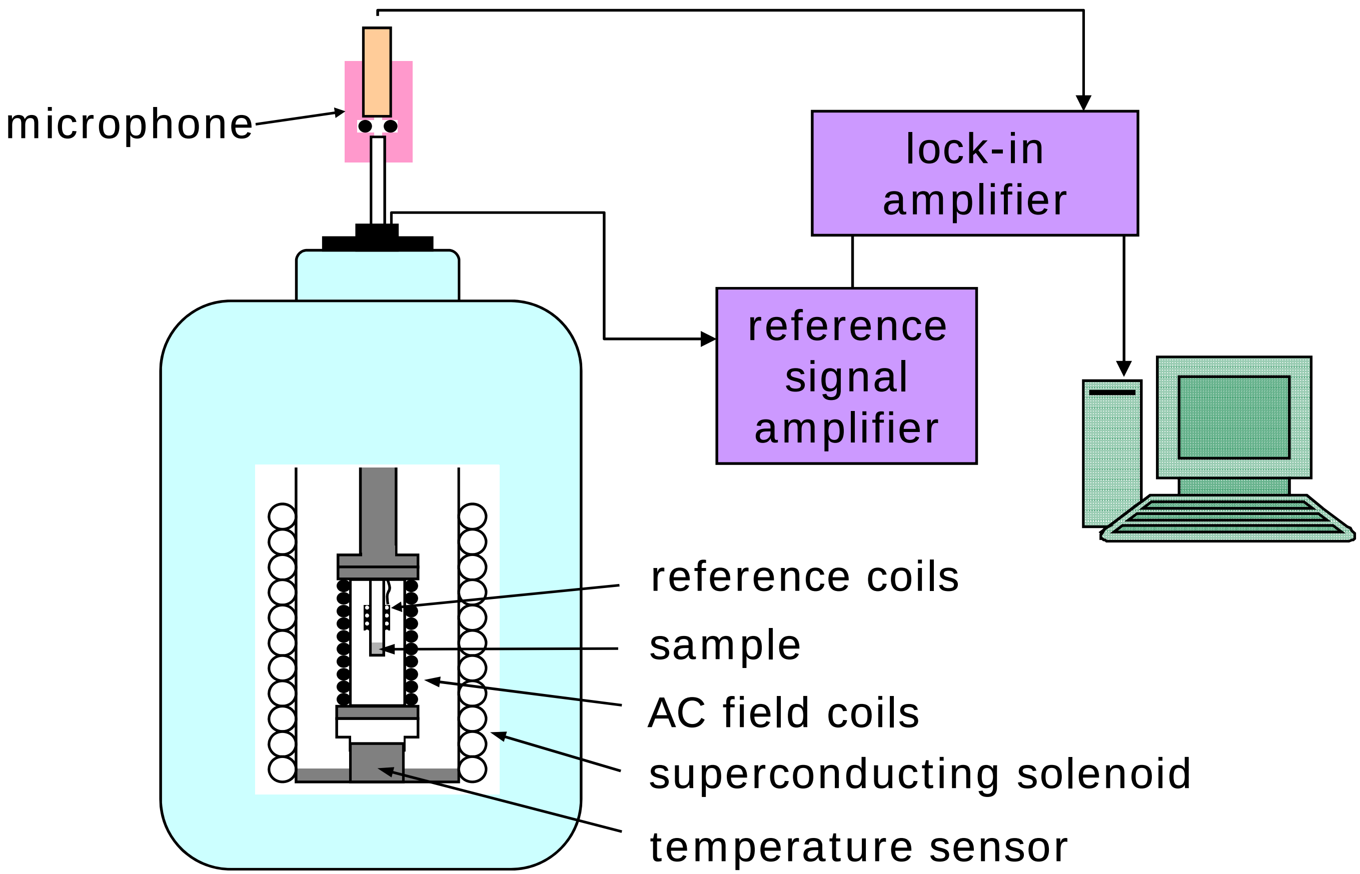


magnetoacoustic signal



$$\delta T_S = -\frac{T}{C_H}\left(\frac{\partial m}{\partial T}\right)_H \delta H$$

experimental setup

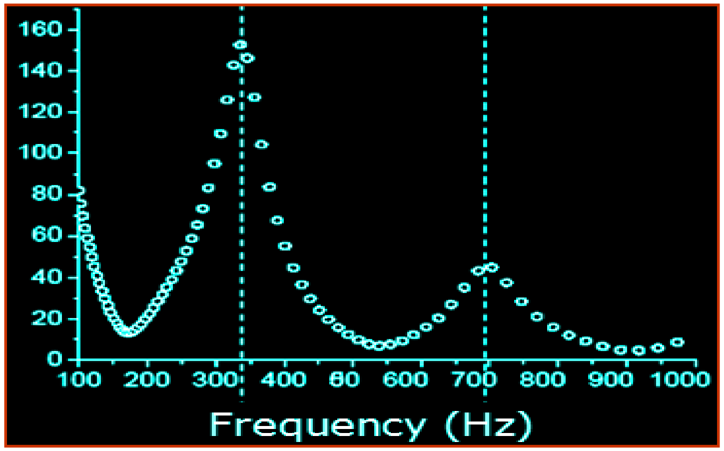


experimental setup

PPMS (0-50 kOe)

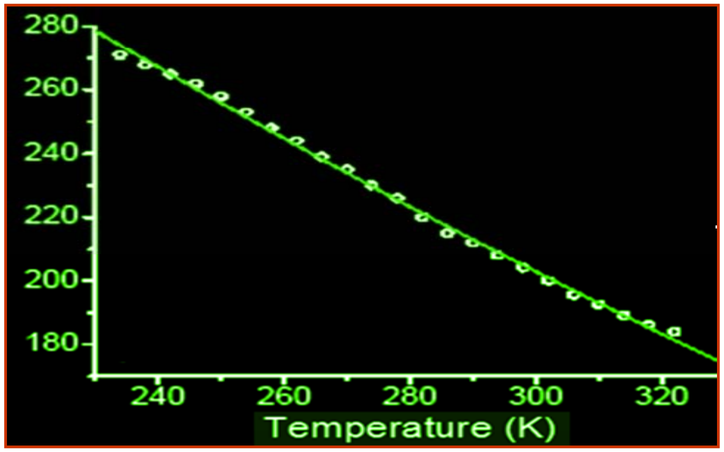
ESR spectrometer (0-20 kOe)

experimental conditions

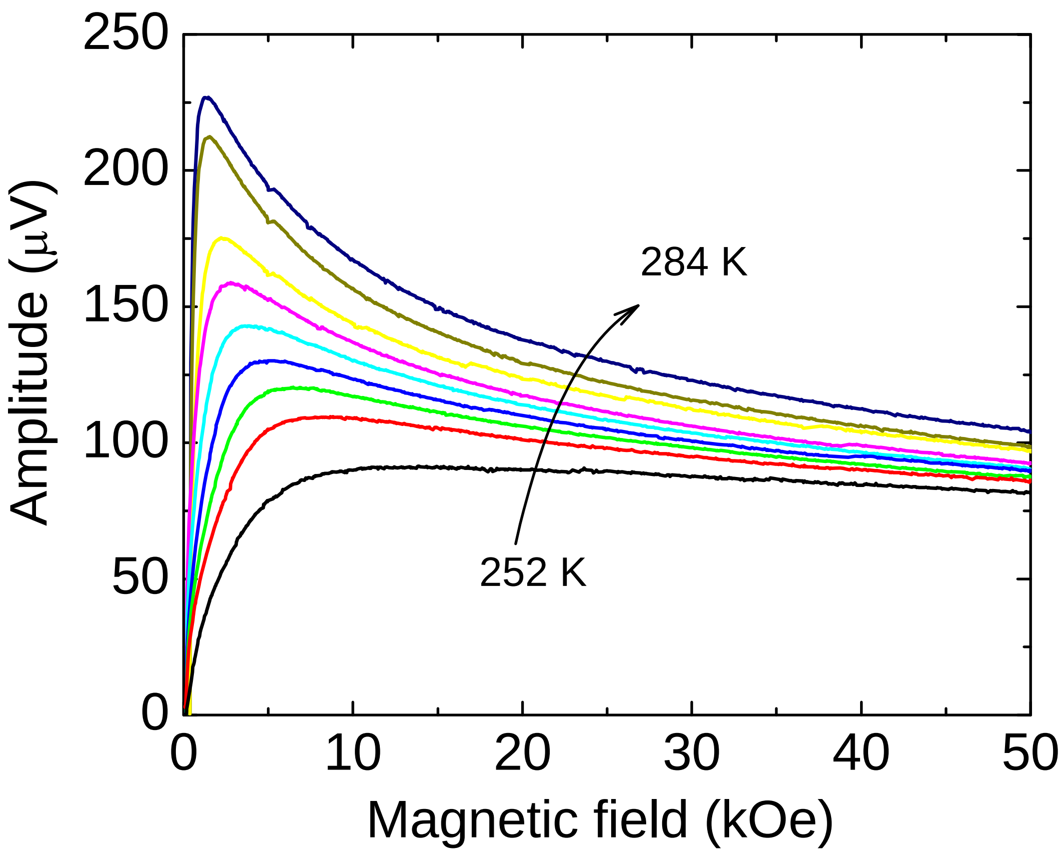


$\delta H = 30$ Oe
$f = 270$ Hz

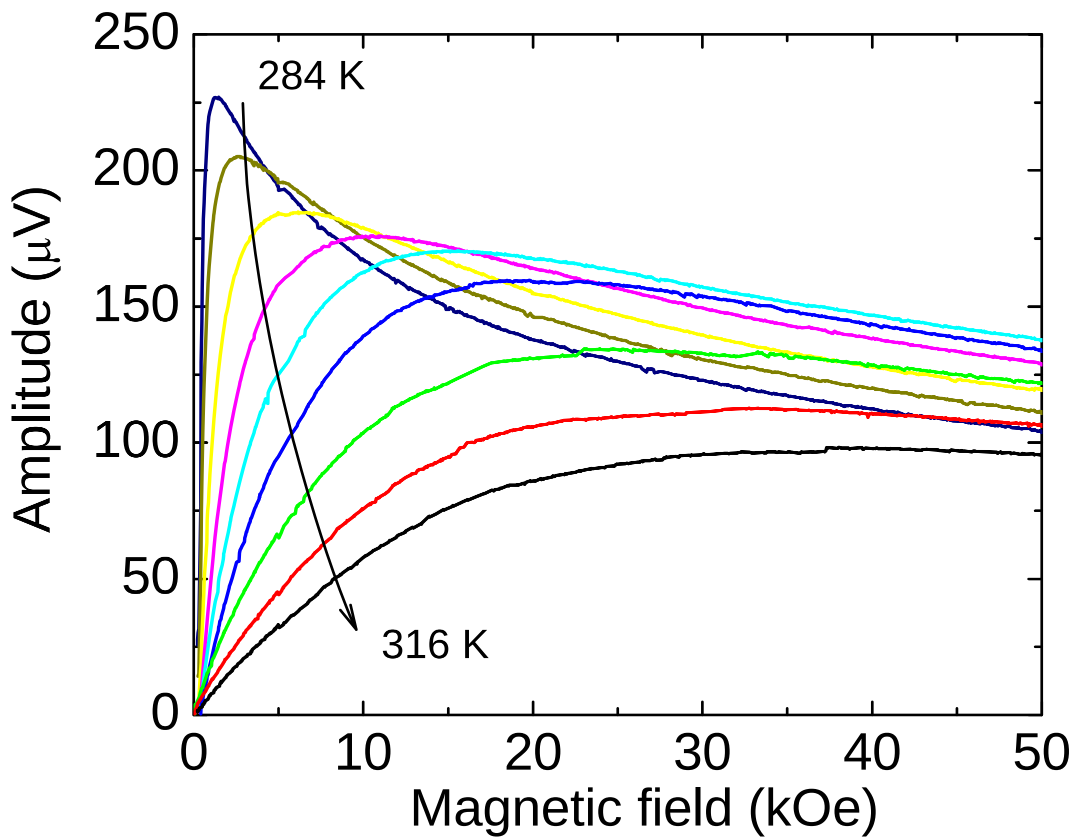
cell response



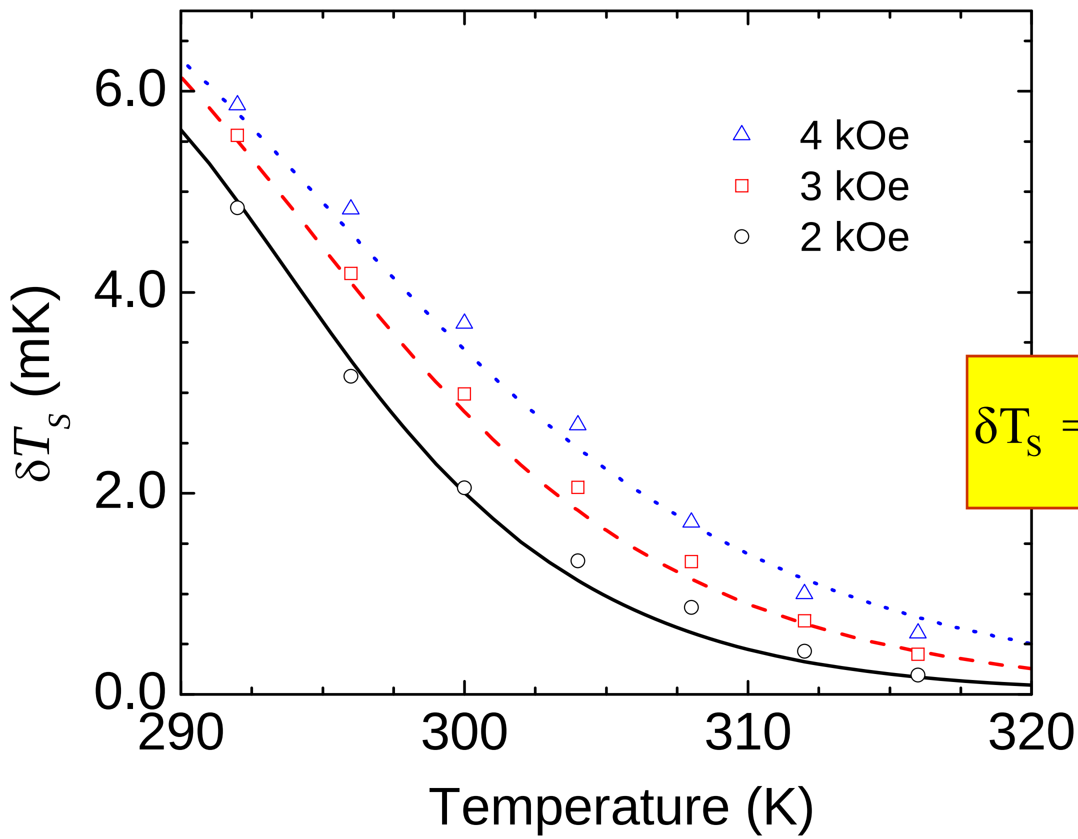
magnetoacoustic signal for Gd



magnetoacoustic signal for Gd

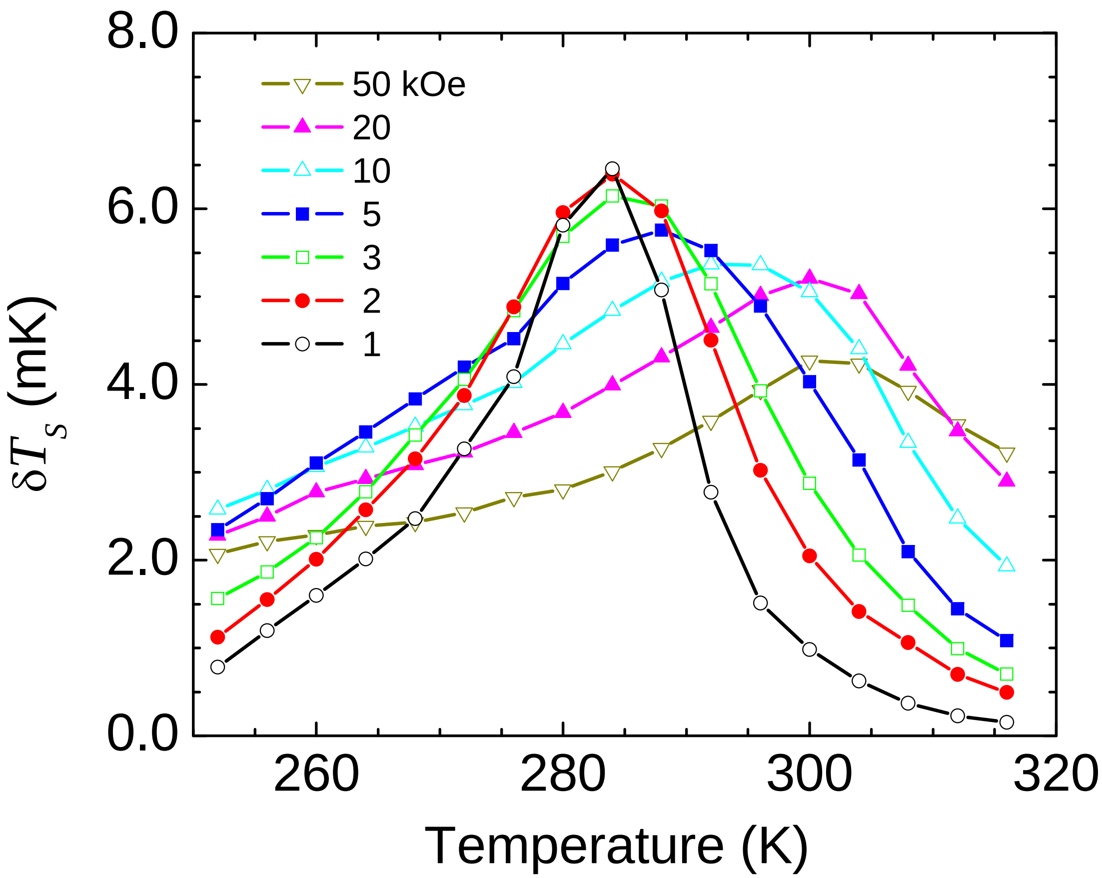


calibration using Gd reference values

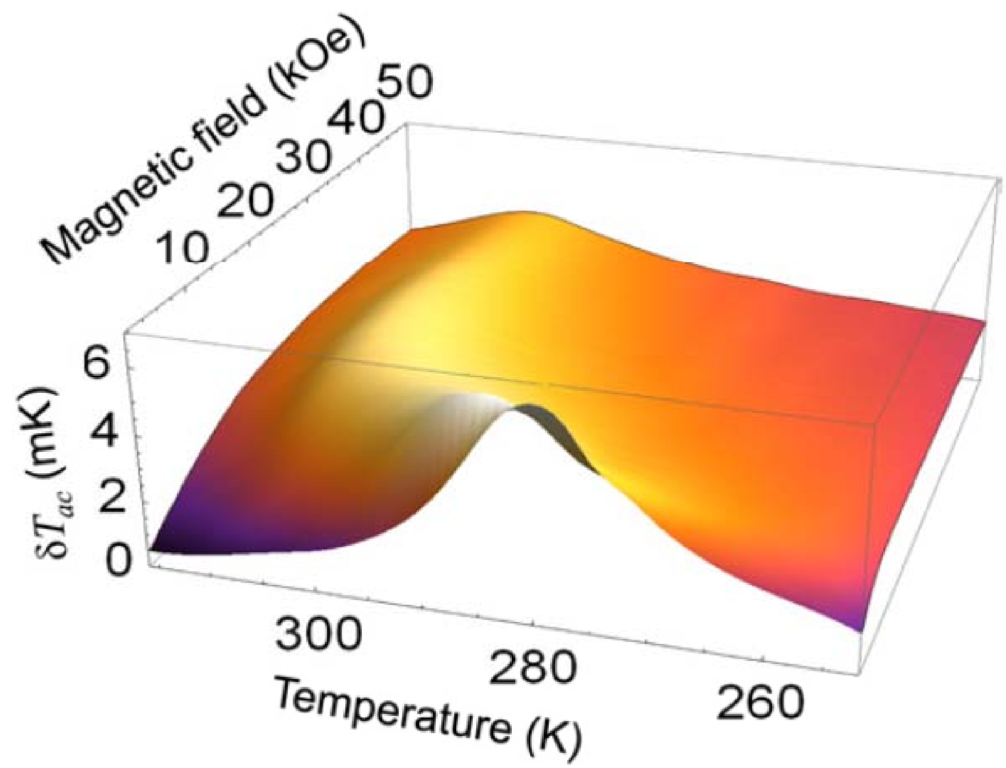


$$\delta T_S = -\frac{T}{C_H}\left(\frac{\partial m}{\partial T}\right)_H \delta H$$

temperature rise for Gd

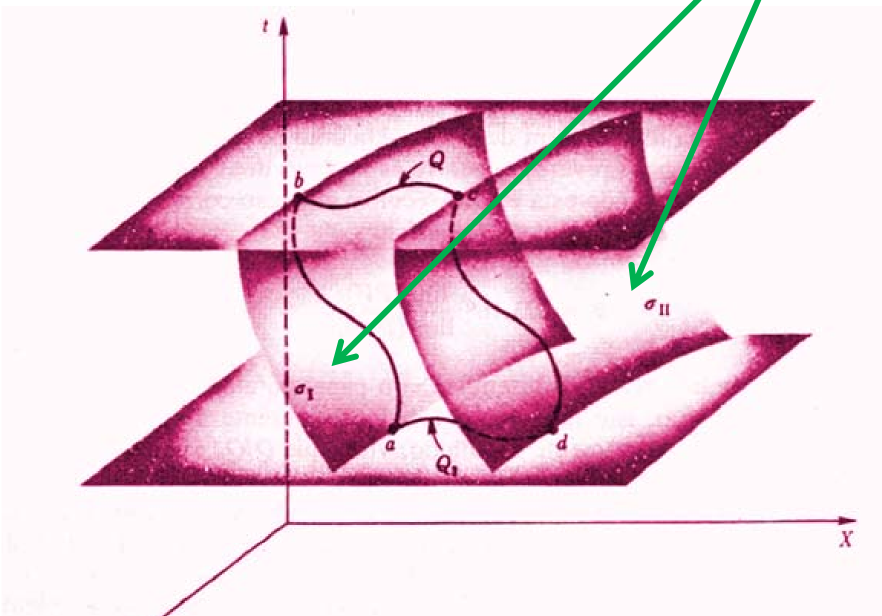


temperature map for Gd



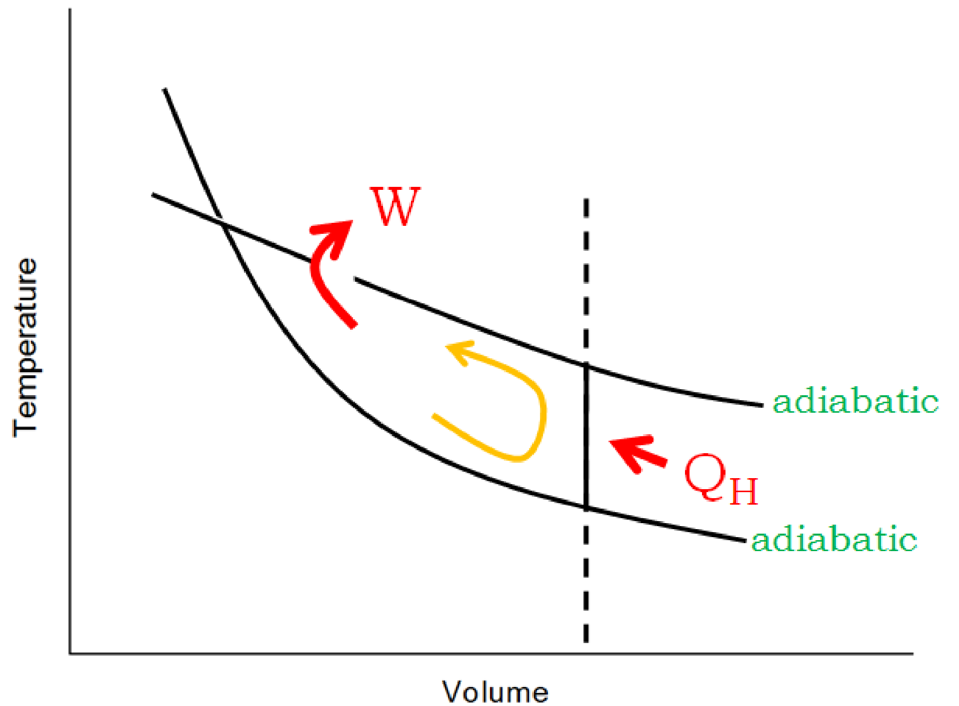
ΔT_S and ΔS_T ???

adiabatic surfaces



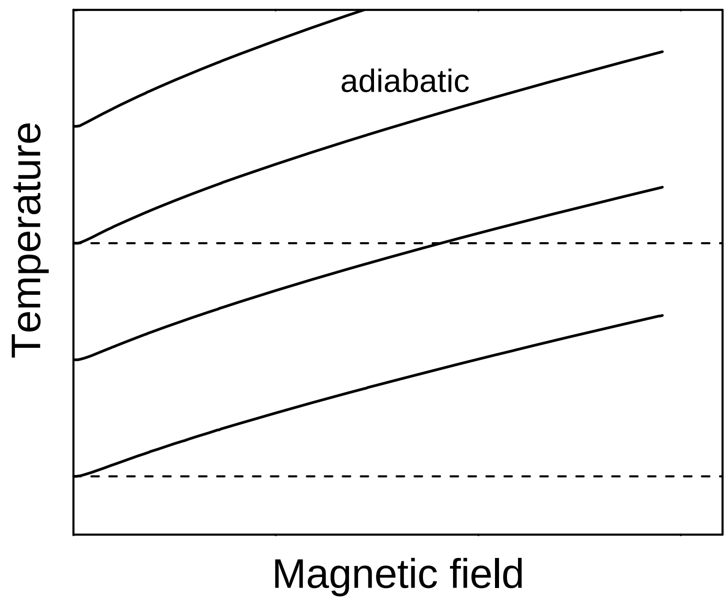
Caratheodory axiom ➔

➔ adiabatic surfaces
do not cross each other
(second law)



efficiency = (W/Q_H) = 100% ➔
➔ the second law would be violated

adiabatic curves



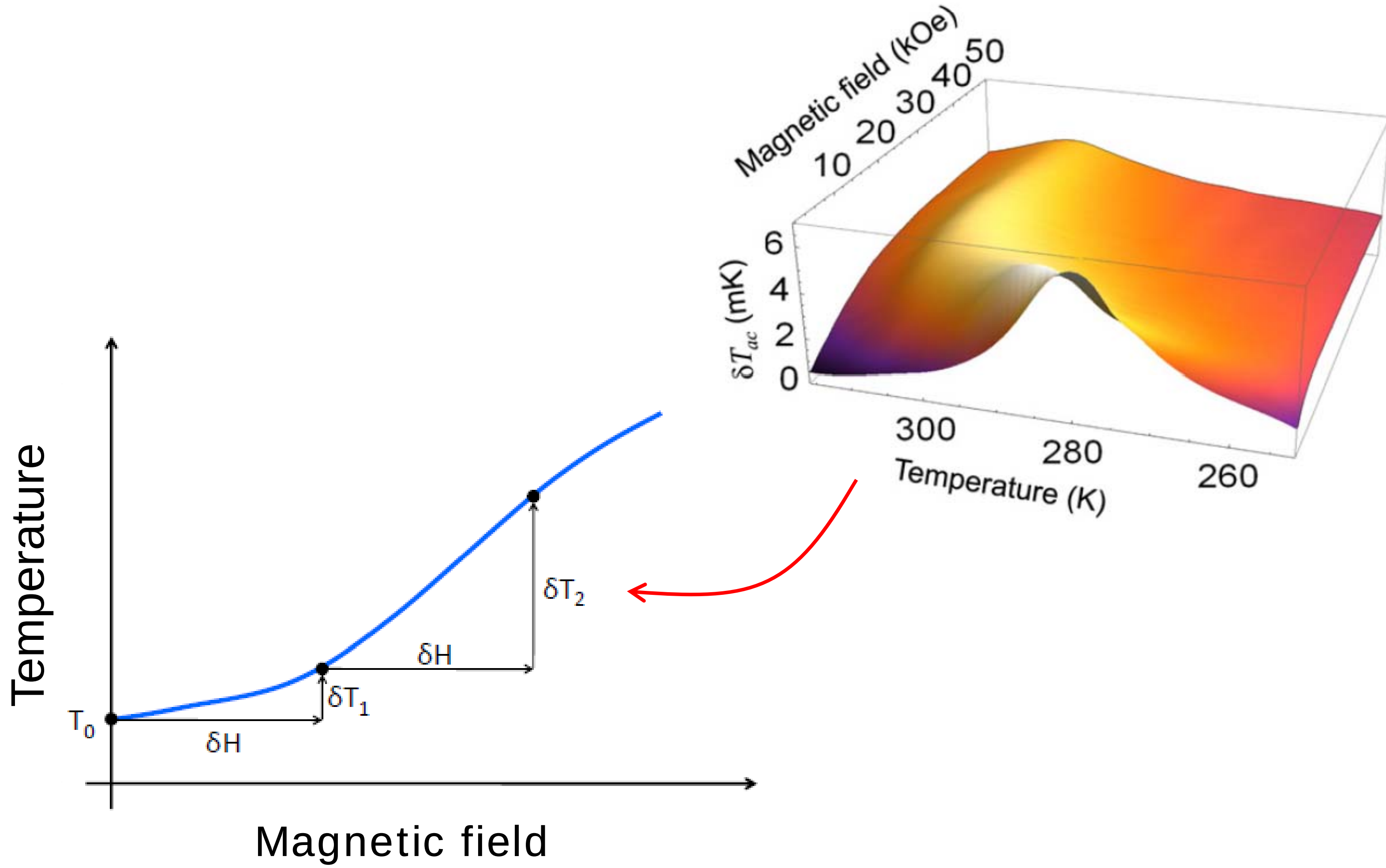
Adiabatic process:

$$dT_S = -\frac{T}{C_H}\left(\frac{\partial m}{\partial T}\right)_H dH$$

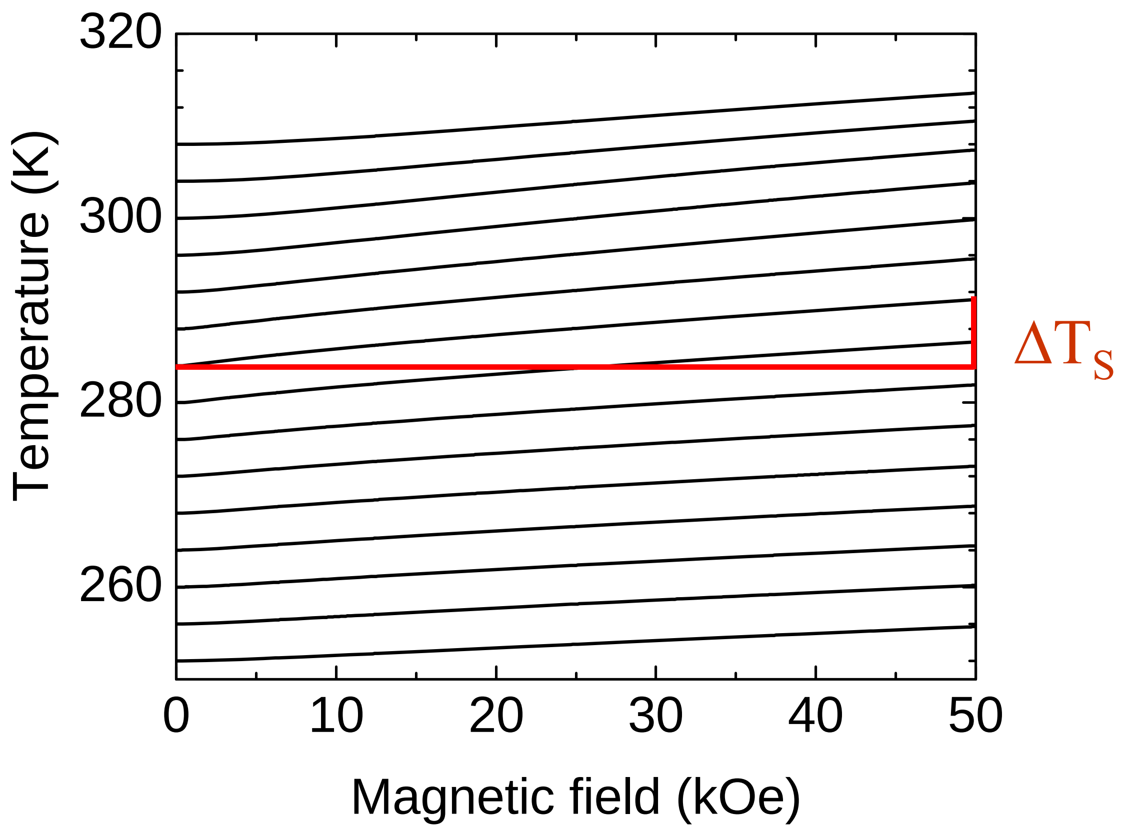
measured signal gives the slope of the adiabatic curves

acoustic detection of the violation of the second law of thermodynamics

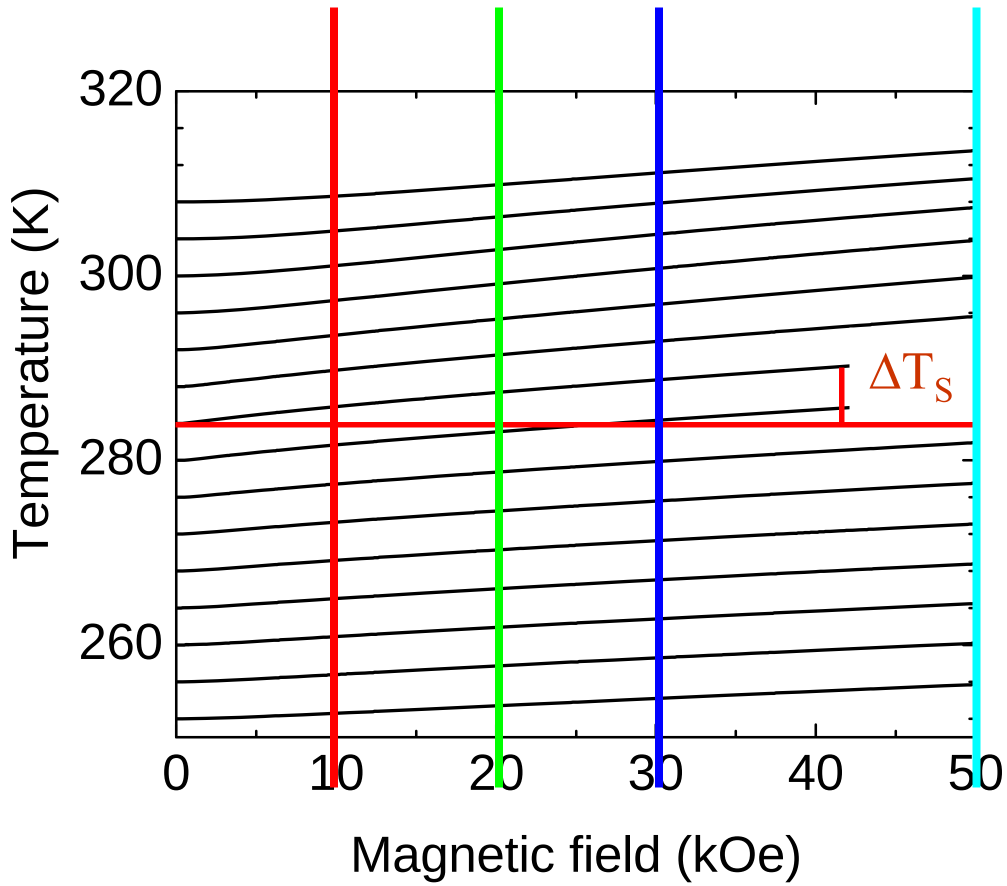
building adiabatic curves



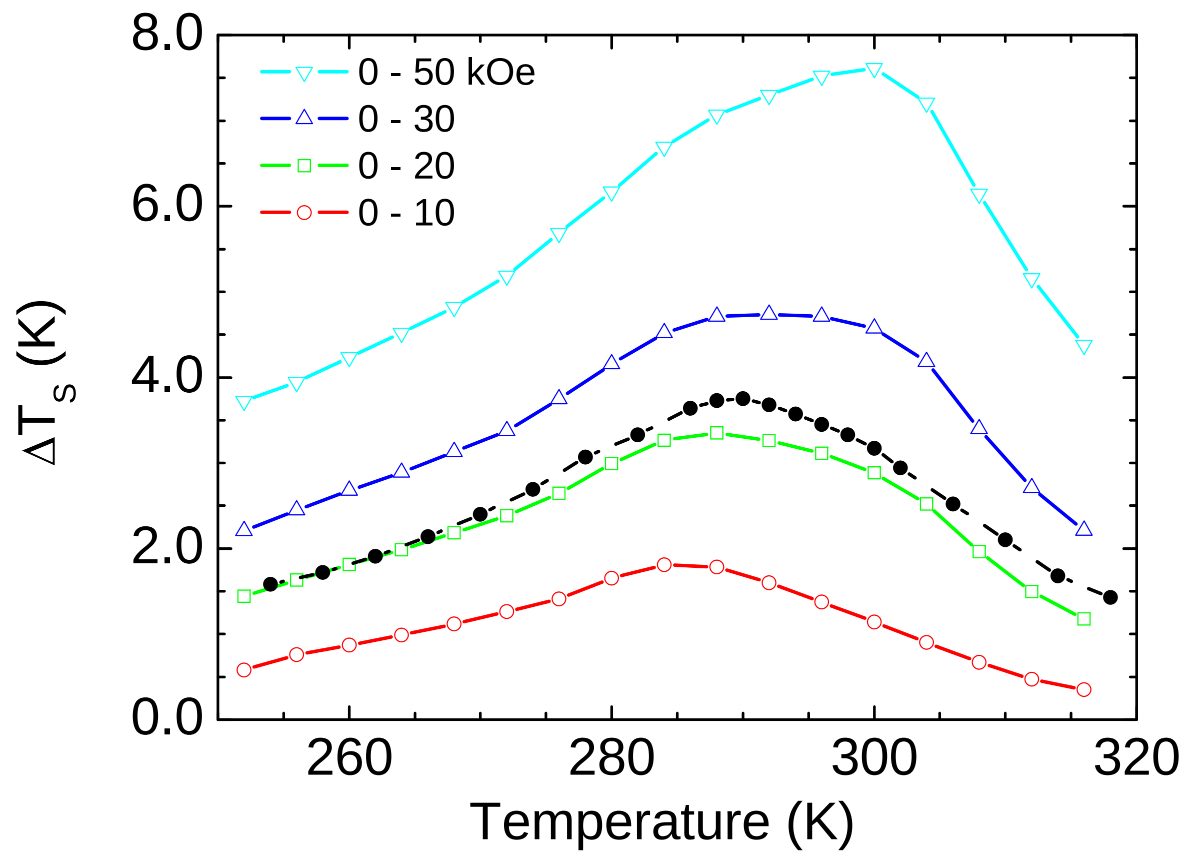
adiabatic curves for Gd



adiabatic curves for Gd



adiabatic temperature change for Gd



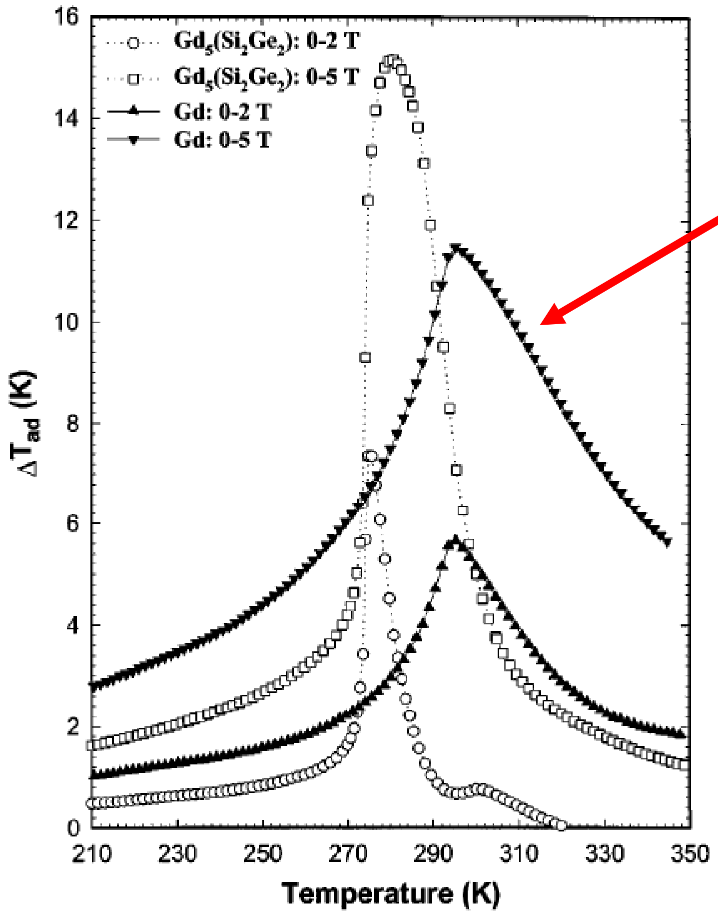


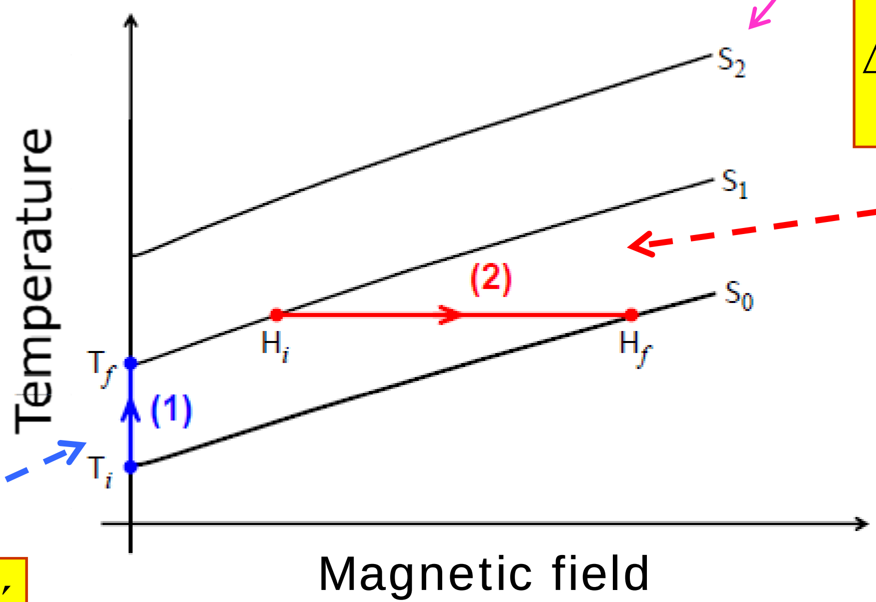
FIG. 6. The magnetocaloric effect in $Gd_5(Si_2Ge_2)$ from 210 to 350 K in comparison with that of pure Gd for magnetic field change from 0 to 2 and from 0 to 5 T.

V. K. Pecharsky and
K. A. Gschneidner Jr.,
Phys. Rev. Lett. 78, 4494 (1997)

$$\Delta T_S = -\int_{H_i}^{H_f} \frac{T}{C_H}\left(\frac{\partial m}{\partial T}\right)_H dH$$

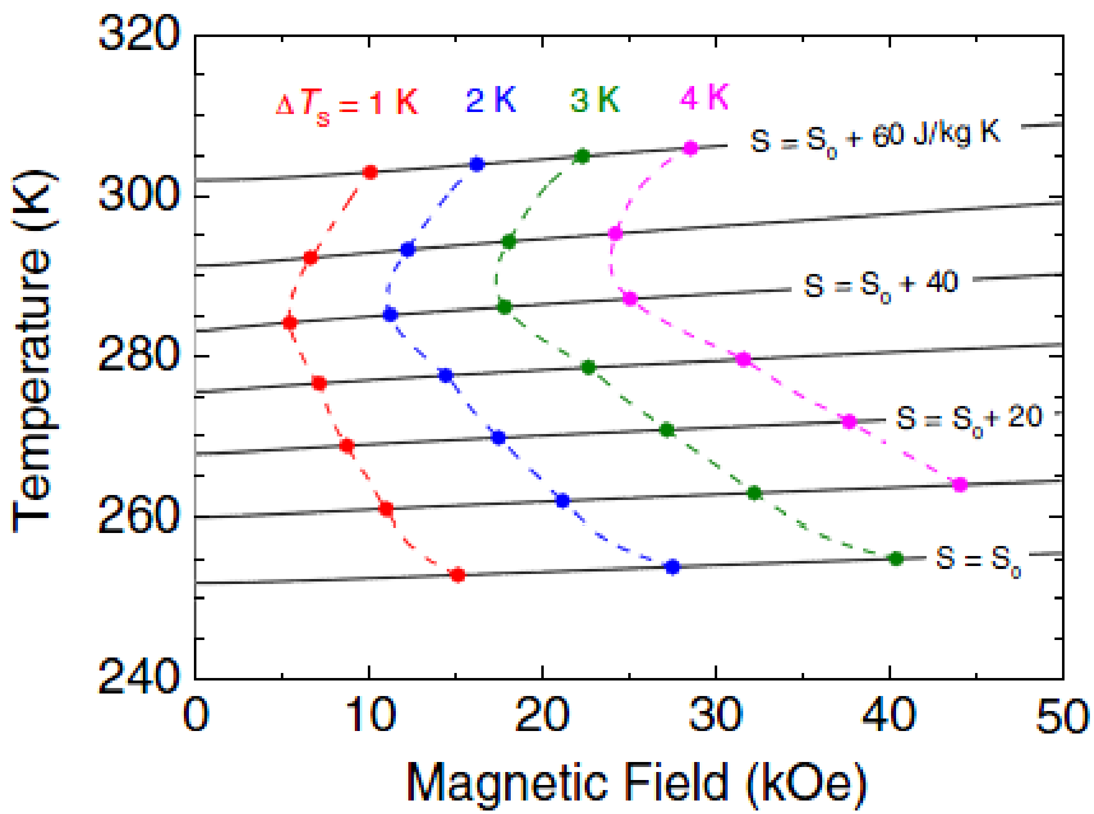
assigning the entropy

$$\Delta S_T = \int_{H_i}^{H_f} \left(\frac{\partial m}{\partial T} \right)_H dH$$

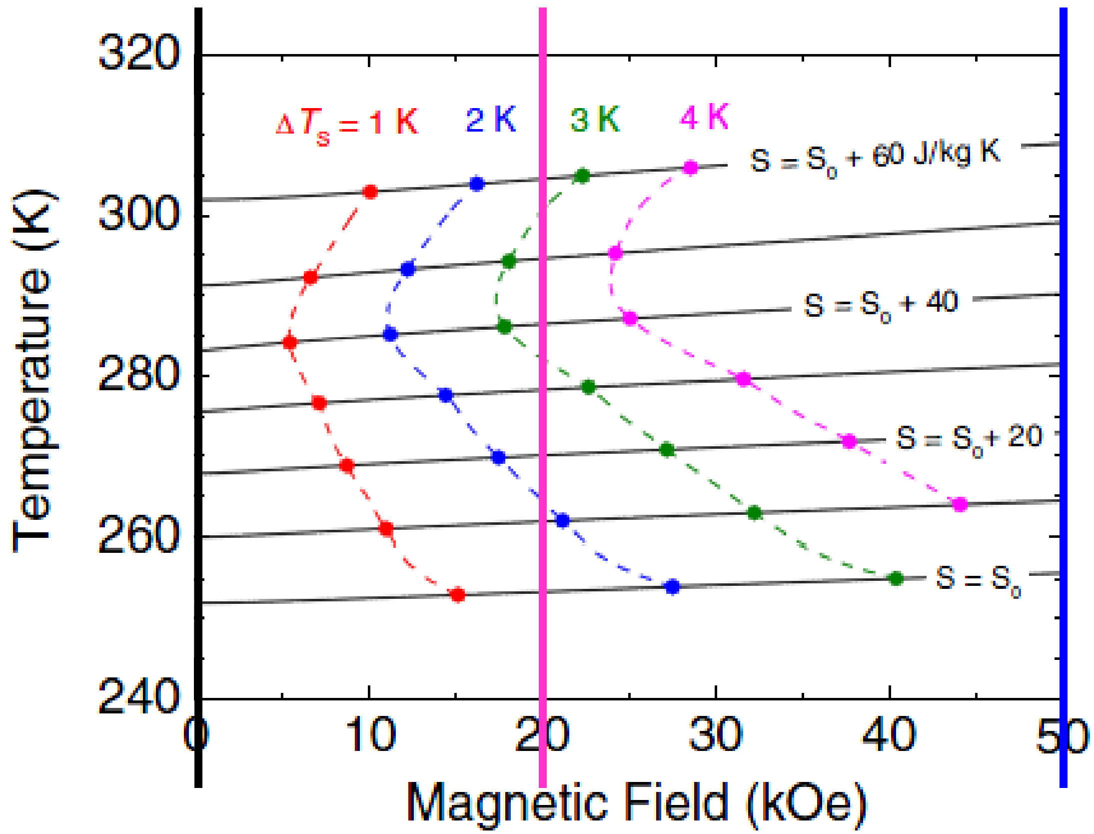


$$\Delta S_H = \int_{T_i}^{T_f} C_H(T') \frac{dT'}{T'}$$

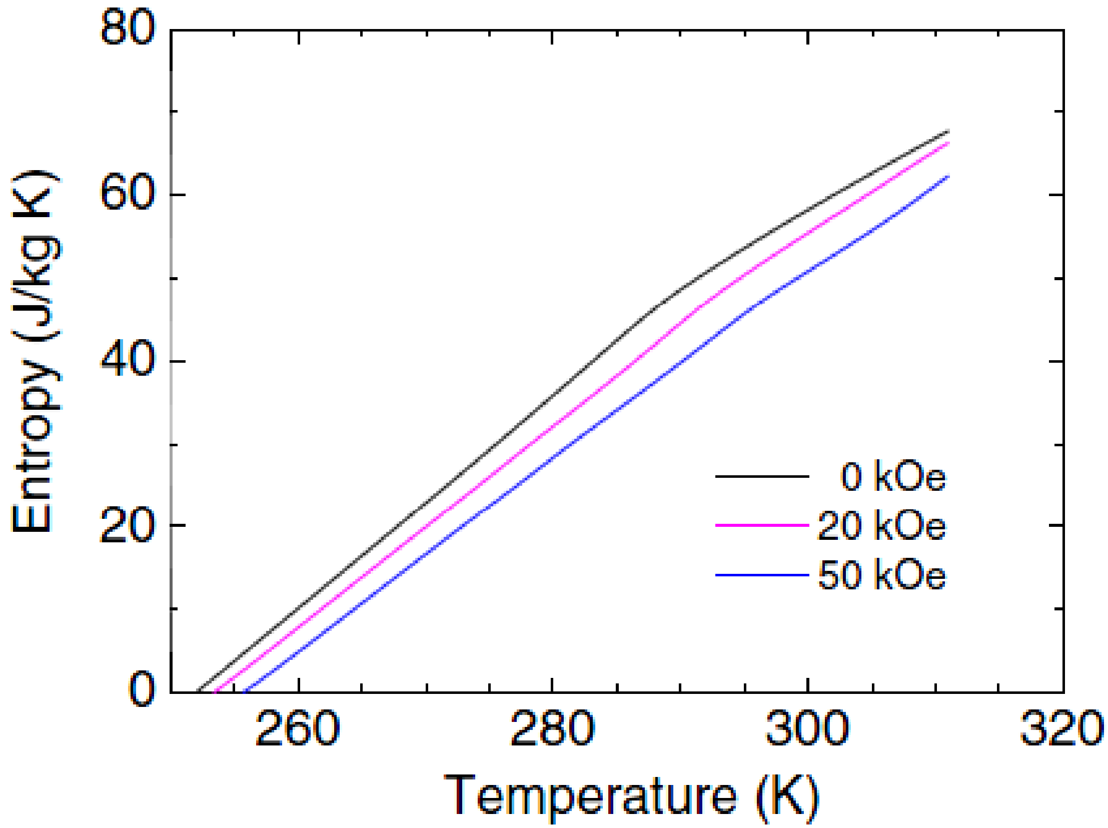
adiabatic curves for Gd



adiabatic curves for Gd

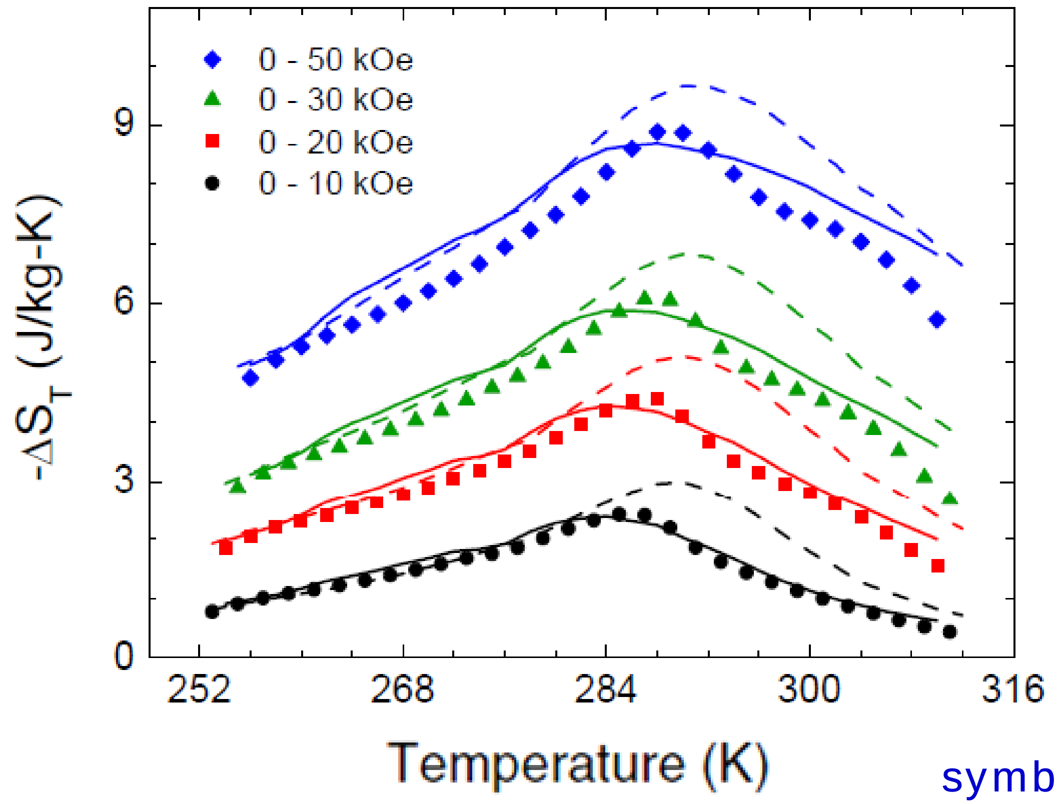


Gd entropy



Entropy (J/kg K)
80
60
40
20
0
260
280
300
320
Temperature (K)
0 kOe
20 kOe
50 kOe

isothermal entropy change for Gd



symbols: acoustic + specific heat
solid lines: acoustic + magnetization
dashed lines: magnetization

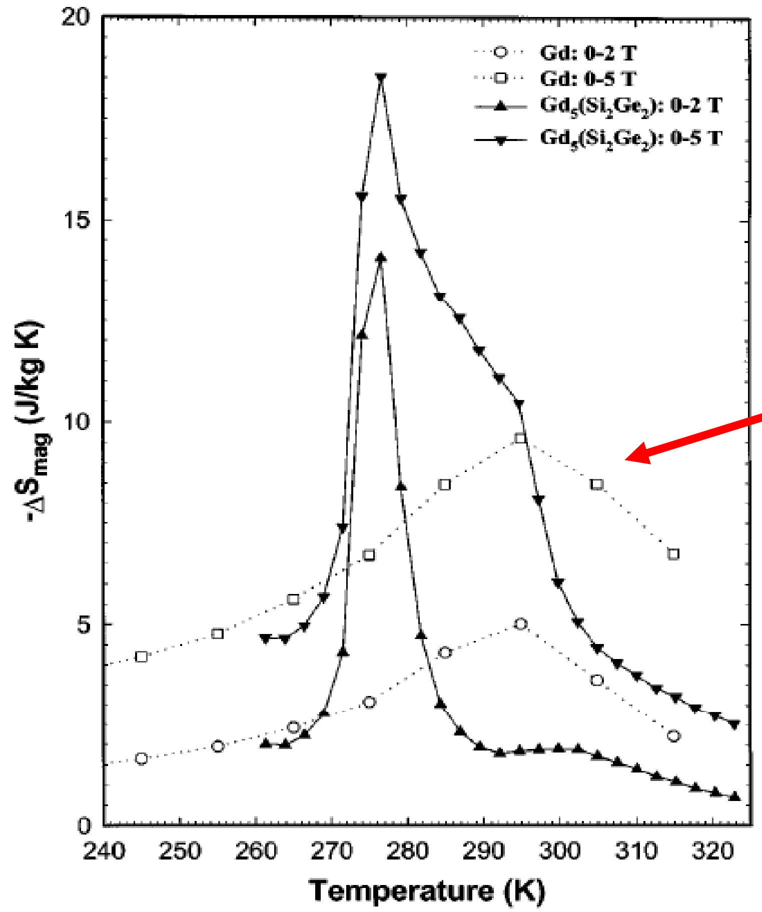


FIG. 4. Magnetic entropy change of the $Gd_5(Si_2Ge_2)$ between 240 and 325 K for a magnetic field change 0 to 2 and 0 to 5 T, respectively, compared to that of pure Gd as determined from magnetization measurements.

V. K. Pecharsky and
K. A. Gschneidner Jr.,
Phys. Rev. Lett. 78, 4494 (1997)

acoustic detection summary

- direct determination of the adiabatic temperature variation
- calibration: no further information about the sample is necessary
- suitable for measuring the magnetocaloric effect under very small magnetic field steps (high sensitivity)
- able to measure very small amounts of samples → application to magnetic thin films
- determination of the isothermal entropy variation provided $C_H(T)$ is known for a single value of H (H = 0, for instance)

published articles

1. A. O. Guimarães, M. E. Soffner, A. M. Mansanares, A. A. Coelho, A. Magnus G. Carvalho, M. J. M. Pires, S. Gama, E. C. da Silva, *Acoustic detection of the magnetocaloric effect : application to Gd and* $Gd_{5.09}Ge_{2.03}Si_{1.88}$, Phys. Rev. B **80**, 134406 (2009).
2. A. O. Guimarães, A. M. Mansanares, A. Magnus G. Carvalho, A. A. Coelho, S. Gama, M. J. M. Pires, E. C. da Silva, *Photoacoustic based technique for measuring the magnetocaloric effect*, Journal of Physics: Conferences Series **214** (2010) 012137.
3. A. O. Guimarães, M. E. Soffner, A. M. Mansanares, A. A. Coelho, A. Magnus G. Carvalho, M. J. M. Pires, S. Gama and E. C. da Silva, *Magnetocaloric effect in GdGeSi compounds measured by the acoustic detection technique: influence of composition and sample treatment*, J. Appl. Phys. **107**, 073524 (2010).
4. M. E. Soffner, A. M. Mansanares, F. C. G. Gandra, A. A. Coelho, S. Gama, A. Magnus G. Carvalho, M. J. M. Pires, A. O. Guimarães and E. C. da Silva, *Determination of entropy change using the acoustic detection in the investigation of the magnetocaloric effect*, J. Phys. D: Appl. Phys. **43** 445002 (2010).

published articles

5. A. Magnus G. Carvalho, J. C. G. Tedesco, M. J. M. Pires, M. E. Soffner, A. O. Guimarães, A. M. Mansanares and A. A. Coelho, *Large magnetocaloric effect and refrigerant capacity near room temperature in as-cast Gd5Ge2Si2-xSnx compounds*, Appl. Phys. Lett. **102**, 192410 (2013).
6. A. M. Mansanares, F. C. G. Gandra, M. E. Soffner, A. O. Guimarães, E. C. da Silva, H. Vargas, E. Marin, *Anisotropic magnetocaloric effect in gadolinium thin films: magnetization measurements and acoustic detection*, J. Appl. Phys. **114**, 163905 (2013).
7. J. C. B. Monteiro, R. D. dos Reis, A. M. Mansanares, F. C. G. Gandra, *Determination of the magnetocaloric entropy change by Field sweep using a heat flux setup*, Appl. Phys. Lett. **105**, 074104 (2014).
8. U. Nogal, A. M. Mansanares, F. C. G. Gandra, M. E. Soffner, A. O. Guimarães, E. C. da Silva, H. Vargas, E. Marín and A. Calderón, *Acoustic detection of the magnecaloric effect in gadolinium thin films: influence of the substrate*, Int. J. of Thermophysics **36**, 1099-1105 (2015).

thanks

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