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Udai Pratap (Autonomous) College, Varanasi

E-learning Material

Module/ Lecture	**10**
Topic	**Adiabatic Demagnetization**
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Adiabatic Demagnetization

During the study of Magneto-Caloric effect we have seen that adiabatic demagnetization always produces cooling. Temperature very near the absolute zero may be obtained by adiabatic demagnetization of certain paramagnetic salts. Fig. 1 shows the experimental arrangement for cooling by adiabatic demagnetization.

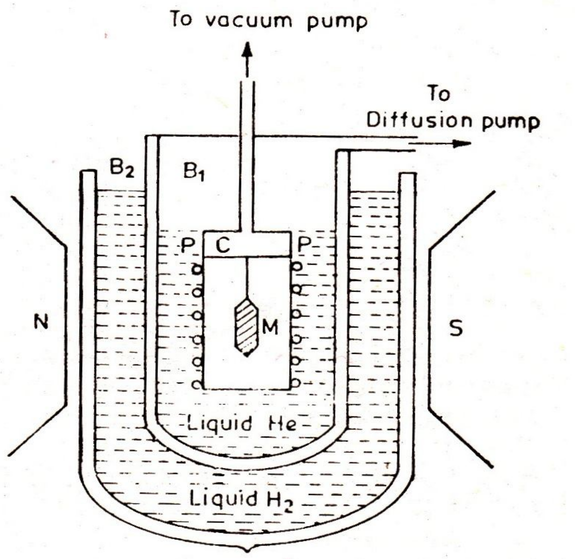

Fig. 1

The paramagnetic salt e.g. gadolinium sulphate, ferrous chloride etc are taken in the form of powder. It is pressed into the form of a cylinder or spheroid M. It is suspended by a silk or nylon fibre inside a cylindrical chamber **C** which is surrounded by a liquid helium bath B_1. Around B_1 we have a liquid hydrogen bath $\mathbf{B_2}$ and the whole arrangement is put inside the poles NS of a strong electromagnet, producing a powerful magnetic field of the order of 30,000 Gauss. *C* has only one opening which is connected to a vacuum pump and bath B_1 is connected to a diffusion pump.

First the Chamber C containing the paramagnetic salt is filled with helium gas at a pressure of 0.1 mm of Hg and a temperature of 1 K is maintained in the liquid helium bath B_1. At this temperature, the helium gas is a good conductor of heat, therefore a quick thermal equilibrium established between the salt and the liquid helium and salt acquires a temperature of 1 K.

Now the external magnetic field is switched on, the specimen (salt) is magnetized. The heat due to magnetization is removed by the helium gas at low pressure and is passed to the liquid helium at 1 K filled in bath $B_{1.}$ Thus the temperature of the salt is maintained at 1 K. Now the helium gas filled in the chamber C is removed with the help of vacuum pump, so that the sample is thermally isolated.

The magnetic field is now switched off so the adiabatic demagnetization of the paramagnetic salt takes place and its temperature falls to a very low value. The mechanism of lowering of temperature can be understood as below:

Each atom of the paramagnetic salt may be considered to be a tiny magnet. In the initial condition when magnetic field is not ON then all its atoms or the magnets are randomly oriented such that the net magnetic force is zero. If the paramagnetic salt is exposed to a strong magnetic field, the atoms will align themselves to the direction of magnetic field. This requires work and the temperature increases during this process. As the salt is kept in a container having helium gas which conducts the heat to the bath B which is filled with liquid helium, the heat will be absorbed by liquid helium. After removing the helium gas from chamber C, if the magnetic field is suddenly removed, the atoms will come back to the original random orientation. This requires work to be done by the atoms. As there is no heat transfer from surroundings, the internal energy of the salt will decrease as it does work and therefore the salt will be cooled.

The temperature of the specimen is determined by fitting a coaxial solenoid coil round the cylinder C, shown by small circles around C in fig.1 and measuring the self-inductance and hence susceptibility (χ) of the substance at the beginning and at the end of experiment. Then temperature is calculated by Curie law

$$\chi = \frac{C_c}{T}, \qquad \text{where } C_c \text{ is the Curie constant.}$$

or

$$\chi_1 T_1 = \chi_2 T_2$$

Theory: When a paramagnetic salt is placed in a magnetic field H, the intensity of the magnetization changes by an amount, say dM. Thus the work done by the magnetic field on the substance is HdM (Magnetic field does a work on the system so that magnetic dipoles are aligned in the direction of field against a nonalignment tendency due to their thermal motion). So that from 1st and 2nd laws of thermodynamics

$\delta Q = \delta W + dU$ with $\delta Q = TdS$ and $\delta W = -HdM$ we get

$$TdS = dU - HdM$$

i.e.

$$dU = TdS + HdM \tag{1}$$

The Eqn. (1) is similar to equation $dU = TdS - pdV$ except that p is replaced by –H and V is replaced by M. Hence Maxwell's Equations can be used.

Now if S=S (T, H)

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

$$TdS = T\left(\frac{\partial S}{\partial T}\right)_H dT + T\left(\frac{\partial S}{\partial H}\right)_T dH \qquad (2)$$

Now

$$T\left(\frac{\partial S}{\partial T}\right)_H = \left(\frac{T\partial S}{\partial T}\right)_H = \left(\frac{\delta Q}{\partial T}\right)_H = C_H \qquad (3)$$

Where C_H is molar specific heat of salt at constant H.

Using Maxwell's Equation $\left(\frac{\partial S}{\partial p}\right)_T = -\left(\frac{\partial V}{\partial T}\right)_p$ we have similar relation

$$\left(\frac{\partial S}{\partial H}\right)_T = \left(\frac{\partial M}{\partial T}\right)_H \qquad (4)$$

Using Eqs. (3 & 4) we get from Eqn. (2)

$$TdS = C_H dT + T\left(\frac{\partial M}{\partial T}\right)_H dH \qquad (5)$$

Now for the adiabatic process, i.e. $\delta Q = TdS = 0$, we get from Eqn. (5)

$$0 = C_H dT + T\left(\frac{\partial M}{\partial T}\right)_H dH \qquad (6)$$

Thus $dT = -\frac{T}{C_H}\left(\frac{\partial M}{\partial T}\right)_H dH$ (7)

The derivative $\left(\frac{\partial M}{\partial T}\right)_H$ is a measure of the change in alignment of a system of magnets due to a change in temperature (disordering effect) when the external magnetic field (ordering effect) is kept constant. Thus this derivative will be negative.

Since $\left(\frac{\partial M}{\partial T}\right)_H = -\text{ve}$ and if H is reduced (demagnetization) i.e. if dH=-ve , it follows from Eqn. (7) that $dT = -\text{ve}$.

Thus adiabatic demagnetization will always result in cooling.

Now since paramagnetic susceptibility is defined as

$$\chi = \frac{M}{H} \tag{8}$$

According to Curie law;

$$\chi \propto \frac{1}{T}$$

or

$$\chi = \frac{C_c}{T} \tag{9}$$

where C_c is the Curie constant. From Eq. (8) and Eq. (9) we get

$$\frac{M}{H} = \frac{C_c}{T} \tag{10}$$

Differentiating Eq. (100 with respect to T at constant field H, we get

$$\frac{1}{H}\left(\frac{\partial M}{\partial T}\right)_H = -\frac{C_c}{T^2} \tag{11}$$

Using Eq. (11), Eq. (6) gives

$$C_H dT - \frac{C_c H}{T} dH = 0$$

or

$$TdT = \frac{C_c}{C_H} HdH \tag{12}$$

let the initial magnetic field be H and temperature be T_i. On reducing the final magnetic field to zero let temperature becomes T_f. On integrating Eq. (12) between initial and final states we get,

$$\int_{T_i}^{T_f} TdT = \frac{C_c}{C_H}\int_H^0 HdH$$

or $$T_f^2 - T_i^2 = -\frac{C_c}{C_H} H^2 \tag{13}$$

Obviously , $T_f \langle T_i$ as Right Hand side of the Eq. (13) is negative. From Eq. (13) it is clear that the value of the final temperature will be lowest i.e. maximum cooling will take place when

1. The initial magnetic field H is large.
2. The paramagnetic salt has large value of Curie constant C_c and small value of specific heat at constant magnetic field.
3. The initial temperature is sufficiently low.