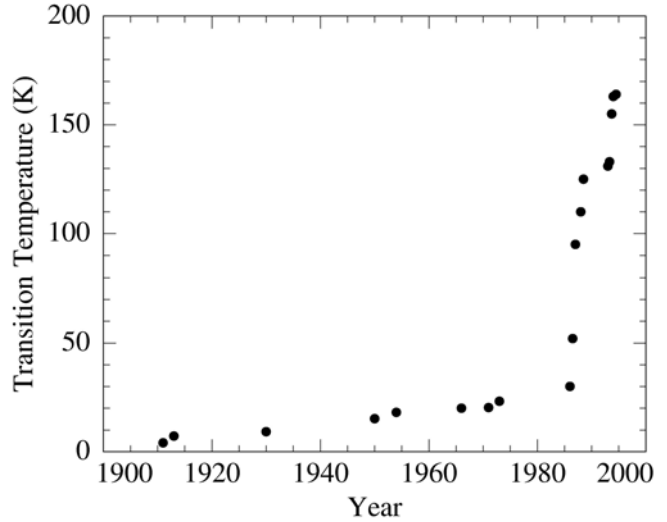


# Superconductors and Cryogenics

## PHYS 312

### 1. Superconductivity

One of the most profound and unexpected phenomena in low temperature physics is the effect of superconductivity, in which the electrical resistance of a material becomes *exactly* equal to zero if it is cooled below a certain temperature. A Dutch physicist Heike Onnes first discovered this effect in 1911 in Hg at 4 K. Since then a number of new superconductors have been discovered with progressively higher transition temperatures, as shown in the figure on the right. In 1986 a new class of high-temperature superconductors was discovered with chemical formulas like  $\text{YBa}_2\text{Cu}_3\text{O}_7$  and  $\text{BiPbSr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$ . Their superconductivity is particularly surprising because at higher temperatures they are ceramic materials with poor electrical conductivity. Another surprise came in 2001 when  $\text{MgB}_2$  was found to superconduct at 39 K. While this temperature is not as high as in other materials, this superconductor is simple, cheap, and easy to synthesize.

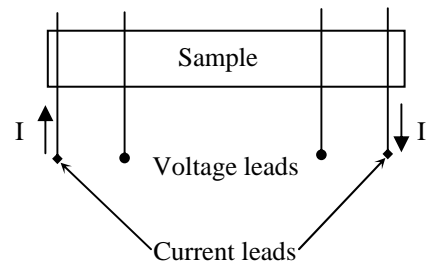


The superconducting state has a number of interesting properties. In addition to zero resistance it is also perfectly diamagnetic and completely expels the magnetic field. As a result a superconductor can float above a permanent magnet, as you may have seen in a demonstration. Other material properties, such as thermal conductivity and heat capacity also have discontinuities at the superconducting transition temperature.

A theory of superconductivity was proposed by Bardeen (the same Bardeen who invented the transistor), Cooper and Schrieffer in 1957. They proposed that interactions between electrons in these materials become effectively attractive due to the influence of the lattice. The electrons then form bound pairs, known as Cooper pairs, with a zero total spin. The Cooper pairs are bosons and can undergo a Bose-Einstein condensation. Thus, the phenomenon of superconductivity is related to the phenomenon of superfluidity (zero viscosity) observed in liquid  $^4\text{He}$ . The BCS theory of superconductivity works well in low-temperature superconductors, however it cannot explain the behavior of high-temperature ceramic superconductors. Despite many years of intensive research there is still no completely satisfactory theoretical explanation for high-temperature superconductivity.

### 2. Experimental Techniques

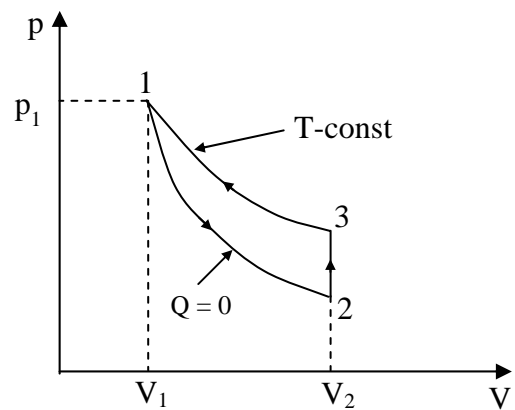
- a) 4-wire resistance measurements



To observe superconductivity one needs to measure the resistance of the sample as a function of temperature. The first issue that you might have noticed already is that sample has to be connected to a measuring circuit using wires that are not superconducting. Therefore in a simple measurement using an ohmmeter it would be hard to tell if the resistance of the sample is exactly equal to zero. A common technique used in this situation is a 4-wire or Kelvin probe measurement. Four contacts are made to the sample as shown on the right. The outer contacts are used to drive a current through the sample and the inner contacts are used to measure the voltage across the sample. It is important that the voltmeter does not draw any significant current from the voltage leads. Under these conditions the voltage will be proportional to the resistance of the sample and will be independent of the wire and/or contact resistance. If the sample is superconducting, the voltage between the voltage leads should be exactly equal to zero.

### b) Cryocooler

One also needs to cool samples to relatively low temperatures and do it in a controlled fashion. One can use liquid nitrogen (77K) or liquid helium (4K) or this purpose. However, increasingly people are using cryocoolers, a closed cycle refrigerator using helium as the working substance. An approximate P-V diagram of the cryocooler cycle is shown on the right. Modern systems often use two consecutive stages cleverly constructed to share a common piston. Such closed-cycle cryocollers can reach temperatures down to about 10 K.



### c) Temperature Measurements

A number of sensors are available in this temperature range. For example, an undoped semiconductor has electrical resistance that changes exponentially with temperature and can serve as a sensitive sensor. Another type of temperature sensor is a “thermocouple”, which works on the basis of the Seebeck effect: generation of voltage in a junction between two dissimilar metals. It is essentially due to temperature-dependent changes in the work function of dissimilar metals.