CRYOGENICS AND ULTRA LOW TEMPERATURES

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Summary

This article describes the scientific and technical aspects of low and ultra low temperatures. The article includes the historical background, explanation of temperature scales, description of different cooling methods, and the modern problems of ultra low temperature physics as well low temperature applications.

1. Introduction

Cryogenics is the technical discipline which studies and uses materials at very low temperatures, as well as the methods for producing low temperatures. The temperature achieved depends on the type of liquefied gas, known as “cryogens.” This word, formed from the Greek κρυοζ (cold) and γευεζ (generated from,) was introduced by Kamerlingh Onnes, who liquefied helium for the first time and who can thus be regarded as the progenitor of cryogenics as known today.

The field of cryogenics involves the production and application of low temperatures in science and technology. In the industrial sector, cryogenics includes the preparation and storage of food and biological materials, the liquefaction of liquid oxygen and hydrogen for the space program, as well as delivery and storage of oxygen and other gases to industry, and to medical and metallurgical facilities. The modern technical application of low temperatures, which is currently under development, is the generation, storage, and transmission of electrical energy using the phenomena of superconductivity in metals.

In experimental physics, low temperatures are applied for studying the phenomena, the observation and theoretical interpretation of which can be easily done under the conditions of a reduction of thermal motion, as well as the phenomena that occur only at low temperatures, which include superconductivity, and the superfluid phases of liquid ^{3}He and ^{4}He. Since these phenomena can be understood only in terms of quantum mechanics, cryogenics provides the conditions for the investigation of quantum–mechanical phenomena in condensed matter.

The recent progress of ultra low temperatures physics has made possible many unique experiments; for example, the experiment in which the mechanism of cosmic cords were created after the “Big Bang” has been simulated in superfluid ^{3}He at the extremely low temperature of about 100 mkK, or experiments of nuclear magnetic ordering at temperatures in the nanoK region above and below absolute zero.

2. Temperature Scales

In order to measuring low temperatures, the absolute or Kelvin scale of temperature is generally used. This scale is based on thermodynamic law, which introduces the low limit of temperature that is chosen as an absolute zero of the Kelvin temperature scale. On this scale the freezing and boiling point of water are approximately 273 and 373 K, respectively. To appreciate the Kelvin scale and, in fact, to understand the importance of cryogenics in physics, it is necessary to recognize that it is often the ratio of two temperatures, not the difference, that plays a significant role in physical processes. That is why it is useful to consider the logarithmic scale of temperature, in which physical phenomena are distributed more homogeneously than on the simple linear scale.

The upper limit of cryogenic temperatures has not been agreed on, but according to the International Institute of Cryogenics (1971) the term cryogenics can be applied to all temperatures below the boiling temperature of oxygen –183 °C (90° above absolute zero on the Kelvin scale).

The term “low temperature physics” is applied to the range of temperatures that can be achieved by pumping cryogenic liquids. The lowest limit is the 0.3 K, the temperature of boiling of liquid ^{3}He at a small pressure. The even lower temperatures are the subject of “ultra low Temperatures physics.”

In order to cool a substance down to these temperatures, different methods of experimental physics can be applied, and these are considered below. Nowadays, the limits of cooling strictly depend on the considered system, since the lower the temperature the more difficult it is to make a good thermal contact between the different subsystems. Consequently, even inside one piece of matter, the subsystem of electrons can be thermally disconnected from its nuclei and different temperatures characterize these subsystems. The lowest temperatures are obtained for the nuclear subsystems and are equal to about 10^{-9} K, and for electrons in metals about 10^{-6} K, and for quantum liquid like ^{3}He about 10^{-4} K.

3. History

Between 1823 and 1845 the British chemists Sir Humphry Davy and Michael Faraday carried out pioneering work in low-temperature physics, thus preparing the way for the development of cryogenics. They generated gases by heating an appropriate mixture at one end of a sealed tube shaped like an inverted **V**. The other end was chilled in a salt–ice mixture. The combination of reduced temperature and increased pressure caused the evolved gas to liquefy. When the tube was opened, the liquid was evaporated rapidly and cooled to its normal boiling point. By evaporating solid carbon dioxide mixed with ether, at low pressure, Faraday finally succeeded in reaching a temperature of about 163 K (about –110 °C).

If a gas, which is initially at a moderate temperature, is expanded through a valve, its temperature increases. But if its initial temperature is below the inversion temperature, the expansion will cause a temperature reduction as the result of what is called the "Joule–Thomson effect." It may, in a sense, be regarded as a method of making the gas perform "internal work" against attractive interatomic forces. The technique would not, therefore, work for an ideal gas, but for real gases, cooling can be obtained provided that the starting temperature is less then the inversion temperature, which is different for different gases.

The inversion temperatures of hydrogen and helium, two primary cryogenic gases, are extremely low, that is why these gases must first be cooled below their inversion temperatures to achieve a temperature reduction through expansion. The hydrogen is cooled by liquid air and the helium by liquid hydrogen. This method is generally unable to bring about liquefaction in one step, but by cascading the effects, the French physicist L. P. Cailletet (1832–1913) and the Swiss scientist R.P. Pictet (1846–1929) were able in 1877 to produce droplets of liquid oxygen. The success of these experimenters marked the end of the idea of permanent gases and established the possibility of liquefying any gas by moderate compression at temperatures below the critical temperature.

The Dutch physicist H. Kamerlingh Onnes set up the first liquid-air plant in 1894, using the cascade principle. During the following 40 years investigators in Great Britain, France, Germany, and Russia developed various improvements to the process of liquefaction. The British chemist Sir J. Dewar first liquefied hydrogen in 1898, and in 1908, H. Kamerlingh Onnes liquefied helium, the most difficult of the gases to liquefy. Since then increased attention has been given to studying phenomena at low temperatures. The increased efficiency of having a refrigerant gas operated in a reciprocating engine or in a turbine continues to be a challenge. The work of the Russian physicist P.L. Kapitza (1894–1984) and the American mechanical engineer S. Collins (1898–1984) has been noteworthy. A helium-liquefier machine has provided the opportunity for many laboratories to conduct experiments at the boiling temperatures of helium, 4.2–1 K.

4. The Methods of Refrigeration

4.1. Evaporation Cryostats

Nowadays cryostats with boiling liquid helium or other gases can be found in many branches of human activity, like cryophysics, cryobiology, cryosurgery, and so on.
For storing liquids at cryogenic temperatures, Dewar flasks have proved useful. Such vessels consist of two flasks, one within the other, separated by an evacuated space. Substances colder than liquid air cannot be handled in open Dewar flasks because air would condense in the sample or form a solid plug to prevent an escape of released vapors; the accumulated vapors would eventually rupture the container.

For lower temperatures, cryostats which consist of closed Dewar flasks with a pumping line are in use.

The cryostats with liquid helium are used in the space programs to maintain telescopes and scientific instruments at temperatures about 2 K and higher for a nominal lifetime of as long as 18 months. In this case, some of the detectors are directly coupled to the helium tank and are at 2 K. The other units are cooled using the cool boil-off gas from the liquid helium. This gas is first routed through the optical support structure where it cools the telescope and the scientific instruments to 3-4 K. It then passes the baffles and radiation shields before it is vented into space. A sunshield, which prevents direct sunshine on the cryostat, is mounted on the outside of the vacuum vessel.

4.1.1. ^{3}He Evaporation Cryostat

Even lower temperatures can be achieved by pumping liquid 3He. In this case the cooling stage takes place inside the evacuated jacket, surrounded by liquid 4He. A small amount of gaseous 3He is condensed inside the heat exchangers which are cooled down to 2 K by evaporated 4He. After an impedance it flows to the cell, from which its pumped out. Owing to a small latent heat, only about 10% of 3He is boil-off as the liquid is cooled down. This method can maintain a temperature of about 0.3 K permanently; but the problem is the strong decrease of saturated gas pressure on cooling. Consequently powerful pumping systems are required to reach a temperature close to 0.3 K.

This problem can be avoided in the dilution refrigerators, where 3He “evaporates” into the 4He.

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Biographical Sketch

Yuriy Mikhailovich Bunkov graduated from the Moscow Institute of Physics and Technology (MIPT) in 1974, becoming candidate of sciences in 1979, and doctor of physico-mathematical sciences in 1985. From 1974 until 1975 he worked at the P.L. Kapitza Institute for Physical Problems, Russian Academy of Sciences. From 1995 until the present he is working in France at the National Center of Scientific Research, at the Very Low Temperature Laboratory, Grenoble, where he is the director of research of this institute. In a framework of scientific collaboration, Bunkov has conducted research work in low temperature physics at Helsinki University of Technology, Finland; Lancaster University, England; Kosice University, Slovakia; and Bayreuth University, Germany. His scientific interests include: the physics of superfluid ^{3}He, particularly the formation and properties of the magnetically excited coherent quantum states that were discovered by Bunkov with co-workers (Russia State Prize 1993). In last years Bunkov is known for his investigations into fast superfluid transitions in ^{3}He after a single neutron fusion reaction. This process models the fast transitions in the universe after the “Big Bang”. In 2000 he was made Professor (Honorarius Causa) of Kosice University, Slovakia. Professor Bunkov has published more than 120 papers in scientific journals.