Two weeks near Absolute Zero

Alex Mason

Foreword

The purpose of my visit to Daresbury Labs has been to gain experience in the work environment and prepare myself for the future. However, over my two weeks I have gained more than just experience, I have gained knowledge in the field of superconductivity and cryogenics, the opportunity to be taken on a tour of the scientific facilities here and also the chance to perform a fascinating experiment involving levitation.

Before I came here I honestly didn't know what to expect, as I hadn't really thought about it much. However, I was still pleasantly surprised to find that it really is a fantastic here and was an excellent place to come for work experience.

The project assigned to me was to create a booklet about everything I have learned and done in my two weeks at Daresbury Lab. This was to include: super conductivity, cryogenics, the uses and applications of low temperatures, what is absolute zero, health and safety issues, an experiment and finally, the history of it all.

Overall the project was an extremely beneficial and enjoyable two weeks. The tours were interesting, the experiments were entertaining, the atmosphere was pleasant and although sometimes my eyes grew tired from large amounts of writing, it was a small price to pay to be able to have my work experience here.

I would like to thank the staff at Daresbury Lab for being so considerate towards my situation and just being generally kind. I would mainly like to thank the lab staff for letting me use their liquid nitrogen and facilities and above all I'd like to thank Shrikant Pattalwar as for the last two weeks he has gone out of his way to help me on this project and to make my experience here at Daresbury Labs as wonderful as it could be.

Alex Mason
27th May 2011

Two weeks near Absolute Zero

Introduction

MRI Scanner [1]

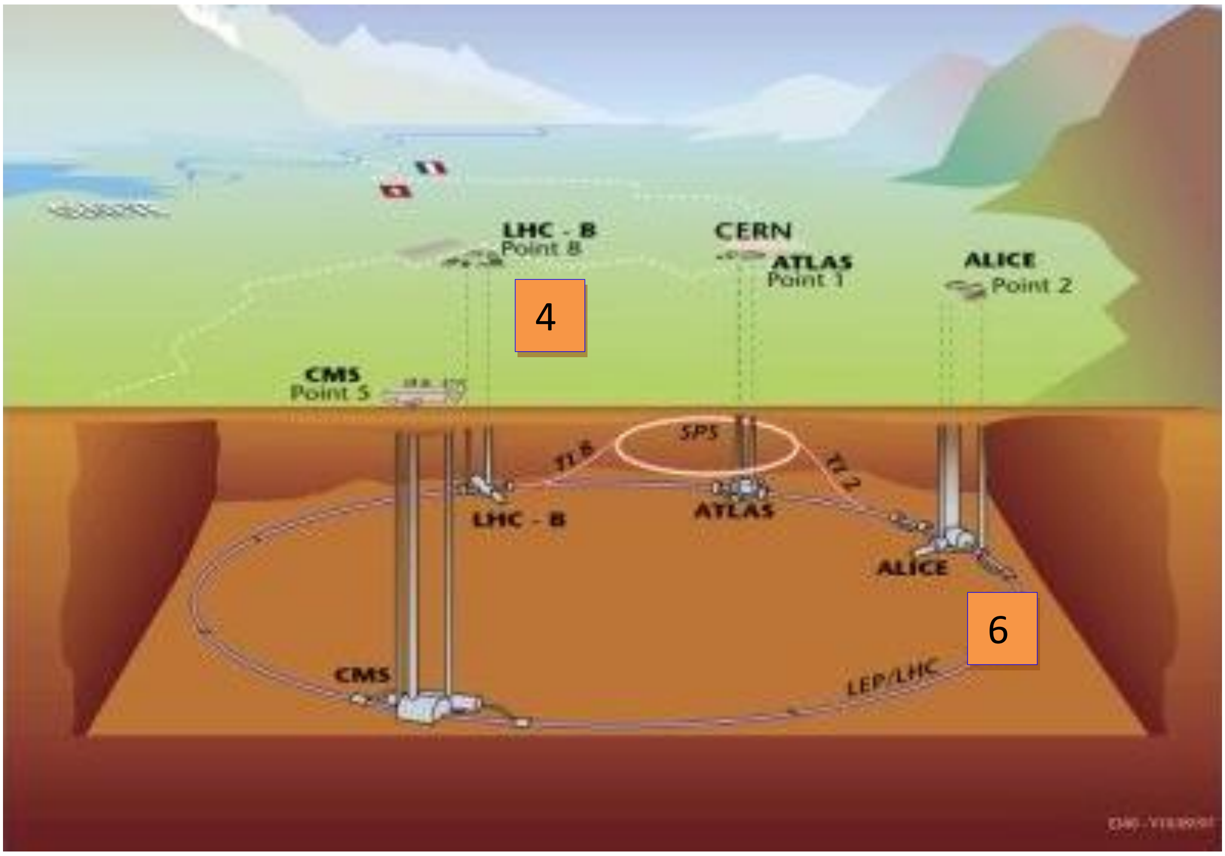
The patient lies inside a large, cylinder-shaped magnet [2]. Radio waves are sent through the body surrounded by a magnetic field 10,000 to 30,000 times stronger than the magnetic field of the earth. This affects atoms inside the body, forcing the nuclei into a different position. As they move back into place they send out radio waves of their own. The scanner picks up these signals and a computer turns them into a picture [3]. These pictures are based on the location and strength of the incoming signals.

Our body consists mainly of water, and water contains hydrogen atoms. For this reason, the nucleus of the hydrogen atom is often used to create an MRI scan in the manner described above.

The Large Hadron Collider (LHC)

The Large Hadron Collider is the world's largest and highest-energy particle accelerator. It is supposed to help address some of the most fundamental questions of physics and has the potential to show what happened after the big bang up to a billionth of a second

Built inside a tunnel 100 meters underground [4] in Geneva it consists of 2000 superconducting magnets [5] arranged in a 23 km long circle [6]


LHC - B
Point 8
CERN
ATLAS
Point 1
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LHC - B
ATLAS
ALICE
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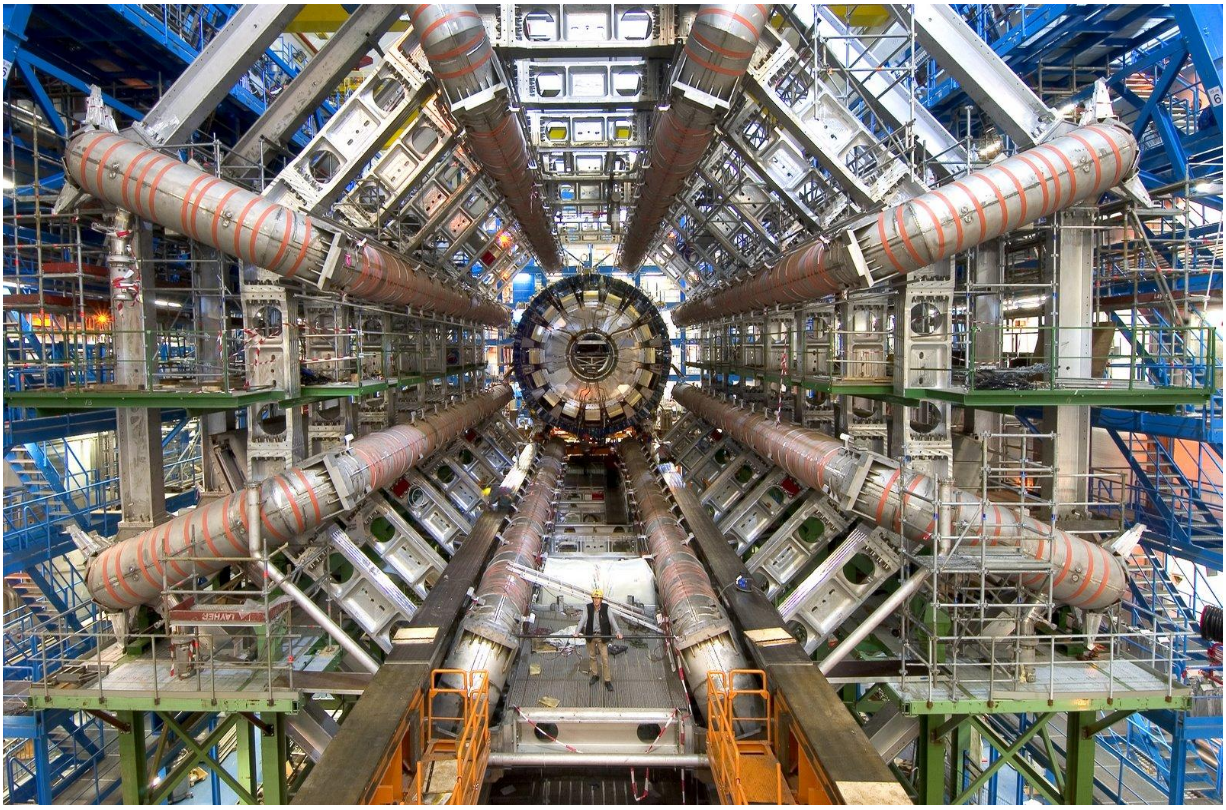
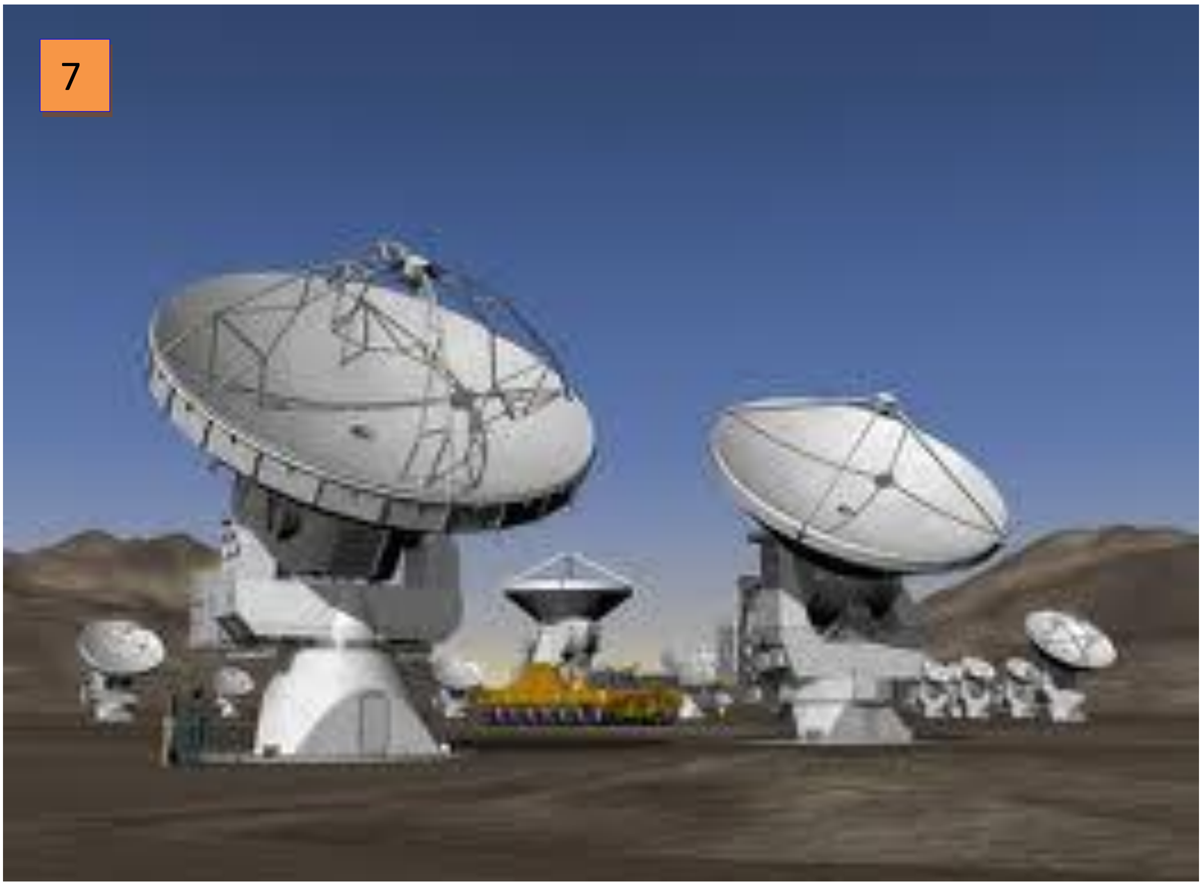
CMS
LEP/LHC



Atacama Large Millimetre Array (ALMA)

ALMA is the largest radio telescope ever constructed [7] which operates at very high radio frequencies, between 30 and 1000 GHz at the high-altitude Llano de Chajnantor site in Chile's Atacama desert. ALMA represents the largest assembly of superconducting electronics ever built, and will allow astronomers to observe cold regions of the universe with unprecedented clarity.



MAGLEV

Maglev (short for Magnetic Levitation) trains [8] are an innovative form of transport that uses magnets for levitation and propulsion. The highest speed a Maglev train has ever reached is 361mph in Japan 2003. They have the potential to be smoother, faster and as they do not burn fossil fuels they are cleaner.

All these are the tools of Science and Technology of the 21st century. They help doctors to identify anomalies in human body and cure diseases like cancer, scientists to explore the universe, engineers to build high speed trains and supercomputers.

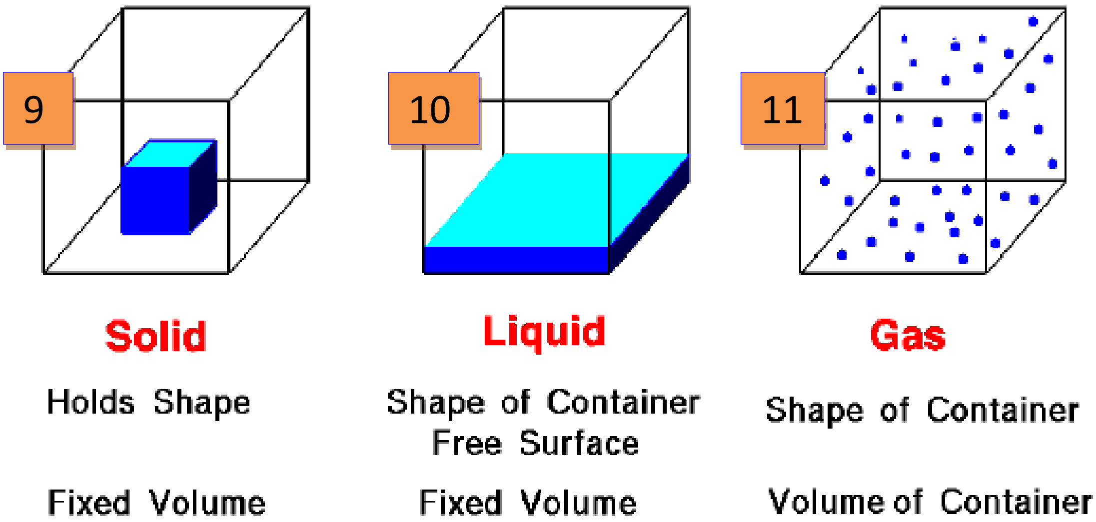
What do they have in common?

They all work only at extremely low temperatures, known as **Cryogenic Temperatures**, where all the known matter is frozen and behaves very differently.

I found myself lucky to spend two weeks at the Daresbury Laboratory as a part of the work experience while studying GCSE. **Two weeks near Absolute Zero** is a record of my experience on a journey to the exciting world of Cryogenic Temperatures. Shrikant Pattalwar took me on a guided tour where I was fascinated to handle liquefied nitrogen and perform an experiment in Superconductivity.

Three states of matter

Matter exists in three states – solid [9], liquid [10] and gas [11]. We see the matter in all the three states around us: the air as gas, water as liquid and many other objects made up of glass, metal etc. as solids. Solid when heated to high temperatures melts into liquid and liquid when heated further turns in to gas. Similarly when a gas is cooled sufficiently it converts (condenses) in to liquid and eventually freezes as solid.



In science the temperatures are indicated in units of 'Kelvin' or 'K'. 0^0C, the freezing point of water is equivalent to 273.15 K. 100^0C, the boiling point of water is equivalent to 373.15 K. '-273.15 ^{0}C' or '0 K' is the lowest temperature than can be achieved.

Such a temperature scale is called the **Absolute Temperature Scale** on which, the lowest temperature is 0K, and is also known as **absolute zero**.

The air we breathe is made up of several gases.

Table 1 – Composition of air

Nitrogen	Oxygen	Argon	Carbon Dioxide	Neon	Helium	Krypton	Xenon
78.08%	20.95%	0.93%	0.03%	0.0018%	0.0005%	0.0001%	0.00001%.

Boiling point of gases

If the air is cooled sufficiently a temperature is reached when majority of the gases in the air, mainly nitrogen and oxygen, condense into liquid. There is hardly anything that can exist as a gas below such a temperature. The temperatures below about 100 K are called cryogenic temperatures.

Table 2 - Boiling point of gases

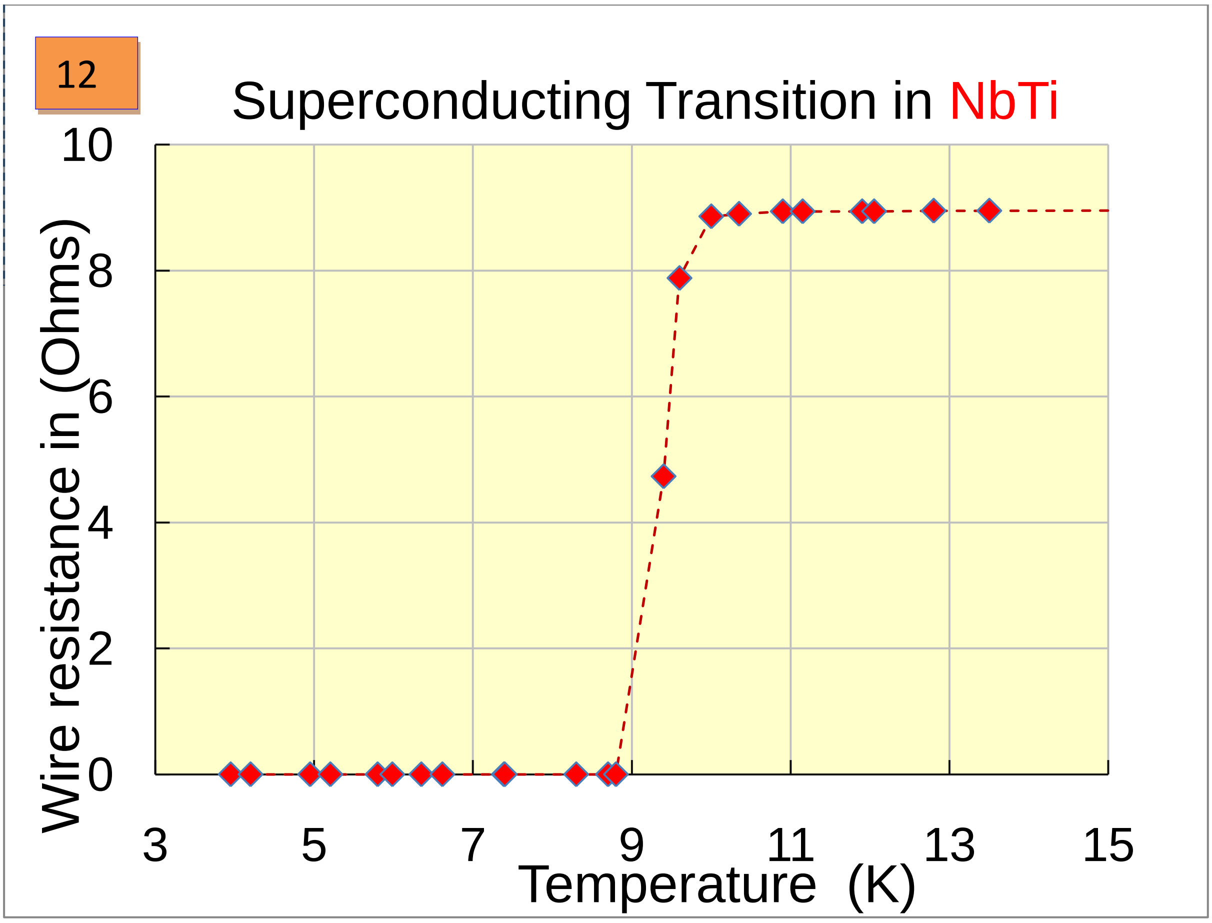
Gas	Boiling Point in K (Kelvin)	Boiling Point in ^{0}C (Celsius)
Chlorine	239.11	-34.04
Radon	211.25	-61.8
Xenon	165.03	-108.12
Oxygen	90.20	-182.95
Argon	87.45	-185.7
Fluorine	85.03	-188.12
Nitrogen	77.36K	-195.79
Neon	27.05	-246.1
Krypton	20.85	-252.3
Hydrogen	20.28	-252.87
Helium	4.22	- 268.93

Among all the gases helium has a lowest boiling point of 4.2K. Liquid Nitrogen and liquid Helium are mostly used in creating very low temperatures.

Superconductivity

Zero Resistance

The phenomenon of superconductivity was discovered by Heike Kamerlingh Onnes in 1911. Below a certain temperature the electrical resistance of a superconductor suddenly reduces to 'zero' [12]. Zero resistance means a large current can be circulated through a superconducting wire without generating any heat at all. This is an amazing property as very large magnets like those used in MRI can be built and run without consuming any power at all. There are many materials which become superconductor but the wires of NbTi and Nb_3Sn are mostly used to construct powerful magnets. These materials show superconductivity below 10K, the temperatures which can only be achieved using liquid helium.

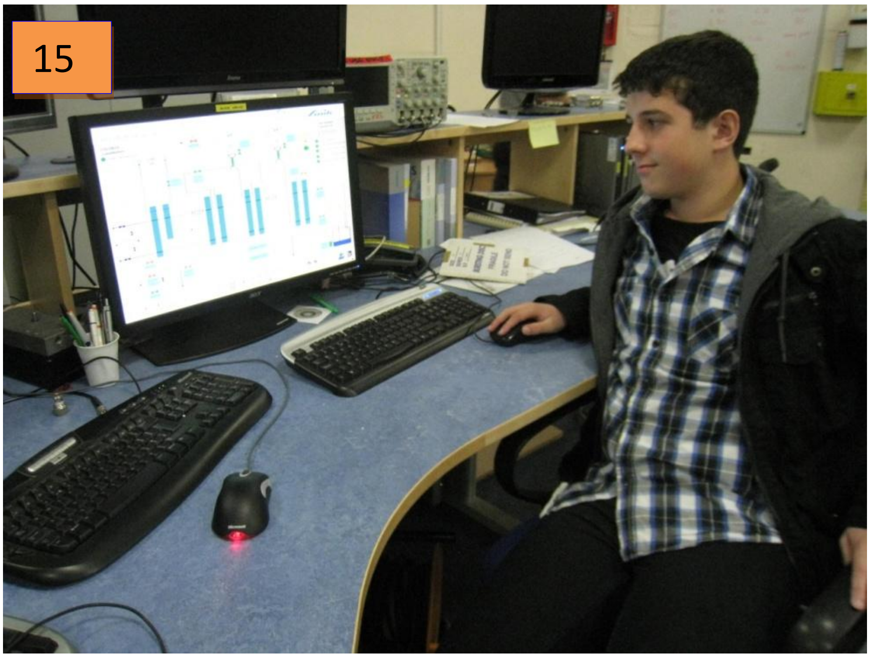


Helium is a rare and expensive gas. Liquefying helium is also an expensive process. But operating the powerful superconducting magnets without using any electrical power at all makes the whole process much cheaper. Without the use of superconductivity the complex and ambitious experiments like LHC at CERN and ALICE at Daresbury laboratory would not be possible.

Accelerator and Lasers in Combined Experiments (ALICE)

Located under the famous Daresbury tower is ALICE [13], an experimental accelerator to develop and test the concepts of future particle accelerators. At the heart of ALICE are four Superconducting Radio Frequency (SRF) cavities operating at 2K. Each cavity consists of 9 cells [14]. These cavities are made from pure niobium.

The SRF cavities are kept cooled by a largest liquid helium refrigerator in the UK. It keeps the SRF cavities cool at 2K, day and night, by circulating liquid helium at the rate of 200 litres per hour. The refrigerator consists of a series of heat exchanges, control valves and a variety of sensors. All of them are continuously monitored and controlled remotely by a computer located in a control room [15].

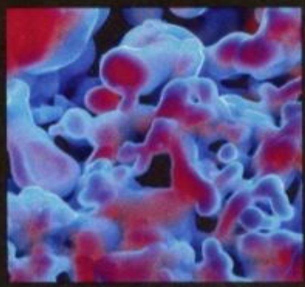


High Temperature Superconductors

25 years ago a new family of materials was discovered which showed superconductivity at relatively higher temperatures- between 90K and 150K. These temperatures can be obtained by using liquid nitrogen, which

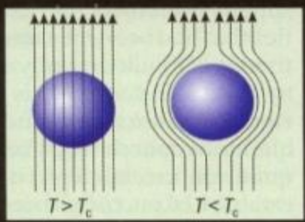
Superconductivity at 100

1908 and 1911
Heike Kamerlingh Onnes wins the race against James Dewar to liquefy helium (1908), then discovers zero resistance in mercury with Gilles Holst (1911)



1931
Wander Johannes de Haas and Willem Keesom discover superconductivity in an alloy

1957
John Bardeen
Schrieffer pu
builds on the
the previous
electrons tog
The theory pr
cannot occur



1933
Walther Meissner and Robert Ochsenfeld discover that magnetic fields are expelled from superconductors. This "Meissner effect" means that superconductors can be levitated above magnets

1935
Brothers Fritz and Heinz London make a long-awaited theory breakthrough, formulating two equations that try to describe how superconductors interact with electromagnetic fields

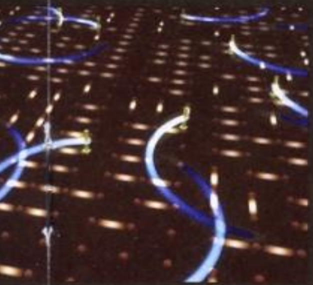
1913
Heike Kamerlingh Onnes

superconducting transition temperature, T_c (K)

140, 120, 100, 80, 60, 40, 20, 0

1900, 1910, 1920, 1930, 1940, 1950

In the 100 years since the discovery of superconductivity, progress has come in fits and starts. The graphic below shows various types of superconductor sprouting into existence, from the conventional superconductors to the rise of the copper oxides, as well as the organics and the most recently discovered iron oxides. Experimental progress has relied on fortuitous guesses, while it was not until 1957 that theorists were finally able to explain how current can flow indefinitely and a magnetic field can be expelled. The idea that the theory was solved was overturned in 1986 with the discovery of materials that superconduct above the perceived theoretical limit, leaving theorists scratching their heads to this day. In this timeline, *Physics World* charts the key events, the rise in record transition temperatures and the Nobel Prizes for Physics awarded for progress in superconductivity.



een, Leon Cooper and Robert
publish their (BCS) theory, which
he idea of Cooper pairs proposed
s year, and describes all the
ogether as one wavefunction.
predicts that superconductivity
ur much above 20 K

1987
Paul Chu and his team break the 77 K liquid-nitrogen barrier and discover superconductivity at 93 K in a compound containing yttrium, barium, copper and oxygen, now known as "YBCO"

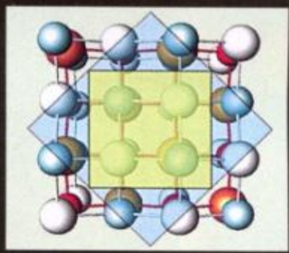
1987
Georg Bednorz
Alexander Müller

2003
Alexei Abrikosov
Vitaly Ginzburg

1973
Brian Josephson

1972
John Bardeen
Leon Cooper
Robert Schrieffer

1962
Lev Landau



2006
Hideo Hosono and colleagues discover superconductivity in an iron compound. The highest T_c found in these materials to date is 55 K

boiling point of liquid nitrogen

1962
Brian Josephson predicts that a current will pass between two superconductors separated by an insulating barrier. Two of these "Josephson junctions" wired in parallel form a superconducting quantum interference device (SQUID) that can measure very weak magnetic fields

1986
Georg Bednorz (right) and Alexander Müller (left) find superconductivity at 30 K, over the 20 K limit of BCS theory, and not in a metal, but a ceramic

2001
Jun Akimitsu announces that the cheap and simple chemical magnesium diboride (MgB_2) superconducts up to 39 K

1981
Superconductivity is found by Klaus Bechgaard and colleagues in a salt – the first organic material to superconduct at ambient pressure. To date the organic superconductor with the highest T_c is Cs_3C_{60} at 38 K

is much cheaper than helium as 78% of air is composed of nitrogen. This class of superconductors is known as High Temperature Superconductors or HTSC.

Zero resistance also means that the electrical current can be transported without any loss for long distances [16] and can be used to create a more efficient and smart national grid of the future.

In addition to zero resistance one more property of a superconductor is to levitate a magnet, also known as Meissner effect. A superconductor becomes a perfect diamagnet which means it does not allow magnetic field to pass through. In other words it always keeps itself away from a magnet. This is a very interesting property and is used in Maglev trains. On the third day of my journey I conducted an experiment to demonstrate this exciting phenomenon of magnetic levitation with High Temperature Superconductor (HTSC).

An Experiment with Superconductivity

Health and Safety

Safety is extremely important in cryogenic engineering as personnel and property need to be properly protected. In working with any cryogenic fluid, hazards that can arise include those that are physiological and those that originate from physical behaviour of the fluids.

Physiological hazards happen because of the very low temperatures of the cryogens, which can cause the freezing of human tissue or hypothermia. The very cold temperatures are an obvious hazard if it is allowed to come into contact with human tissue. Such contact can cause instantaneous freezing, the resulting damage of which is similar to thermal burn, which is why it is often referred to as cryogenic burn.

STFC has introduced a special safety procedure, (SHE code 2), which must be followed while working with cryogens. For example, Personal Protection Equipment (PPE): thermal gloves and a face mask must be worn. In addition before conducting the experiment we conducted a risk assessment [17]

STFC STANDARD RISK ASSESSMENT

17

Title: **Magnetic Levitation Demo** Assessed By: **Shrikant Pattalwar** Date of Assessment: **18/5/2011,**

Assessment No 1398

Purpose –
An experiment to be conducted by Alex Mason to demonstrate magnetic levitation using HTSC sample dipped in LN2, under the complete supervision of Shrikant Pattalwar.

Procedure –
A small piece of HTSC will be kept cooled with a very small quantity of LN2 (less than 50 cc at any given time) held in a flat insulating dish.
LN2 will be topped up periodically at about 10 minute's interval to keep the sample cool.
Once cold a small piece of permanent magnet will be dropped onto to HTSC sample which will levitate as long HTSC is held at T<90K

Step 1 What are the hazards?	Step 2 Who might be harmed and how?	What are you already doing?	Step 3: What further action is necessary?	Step 4: How will you put the Assessment into action?		
Hazard/Task or Situation				Action by whom	By when	Done
Hazards identified in SHE for Cryogen handling	Staff/ student	Follow SHE code STFC SHE Code 2	None	SP	18/5/2011	
LN 2 spillage	Staff /student	Use minimum quantity of LN2 at any given time (less than 50 cc)	The activity will always be manned by a trained staff	SP	18/5/2011	
LN 2 spillage	Staff/student	Use containment so that LN2 will evaporate before spillage occurs	Display a warning sign indicating possible hazards	SP	18/5/2011	

Demonstration of Magnetic Levitation (Meissner effect)

On the third day of my two weeks near absolute zero I was given the exciting opportunity to perform an experiment using a small amount of liquid nitrogen [18]

The experiment involve pouring liquid nitrogen into a Petri dish which had a square of iron inside of it, then placing a magnet in and cooling it down with liquid nitrogen, the liquid nitrogen boils and evaporated quickly, so the dish had to be refilled several times. When the two objects were cold enough, it was possible to see the magnet repel and attract the square of iron at the same time. The magnet always stayed slightly away from as if it were repelling it, but at the same time would not move away from it as if it were attracted to it. The best part of the experiment was the ending, where the magnet was placed on top of the square of iron. The magnet literally floated in mid-air just above the iron. It did not waver or hover up and down, it just stayed completely still. The magnet would only move when touched by something else and when it warmed up and started to float back down.


18

Although it is impossible to see in a picture you could also make the magnet spin [19] by touching it and because no energy is lost from friction (heat, sound etc.) it could keep spinning for a while. If it was in the right environment it could keep spinning for longer possibly even forever, but in this environment it heated up again and air currents from us moving slowed it down.

It was a truly fascinating experiment.

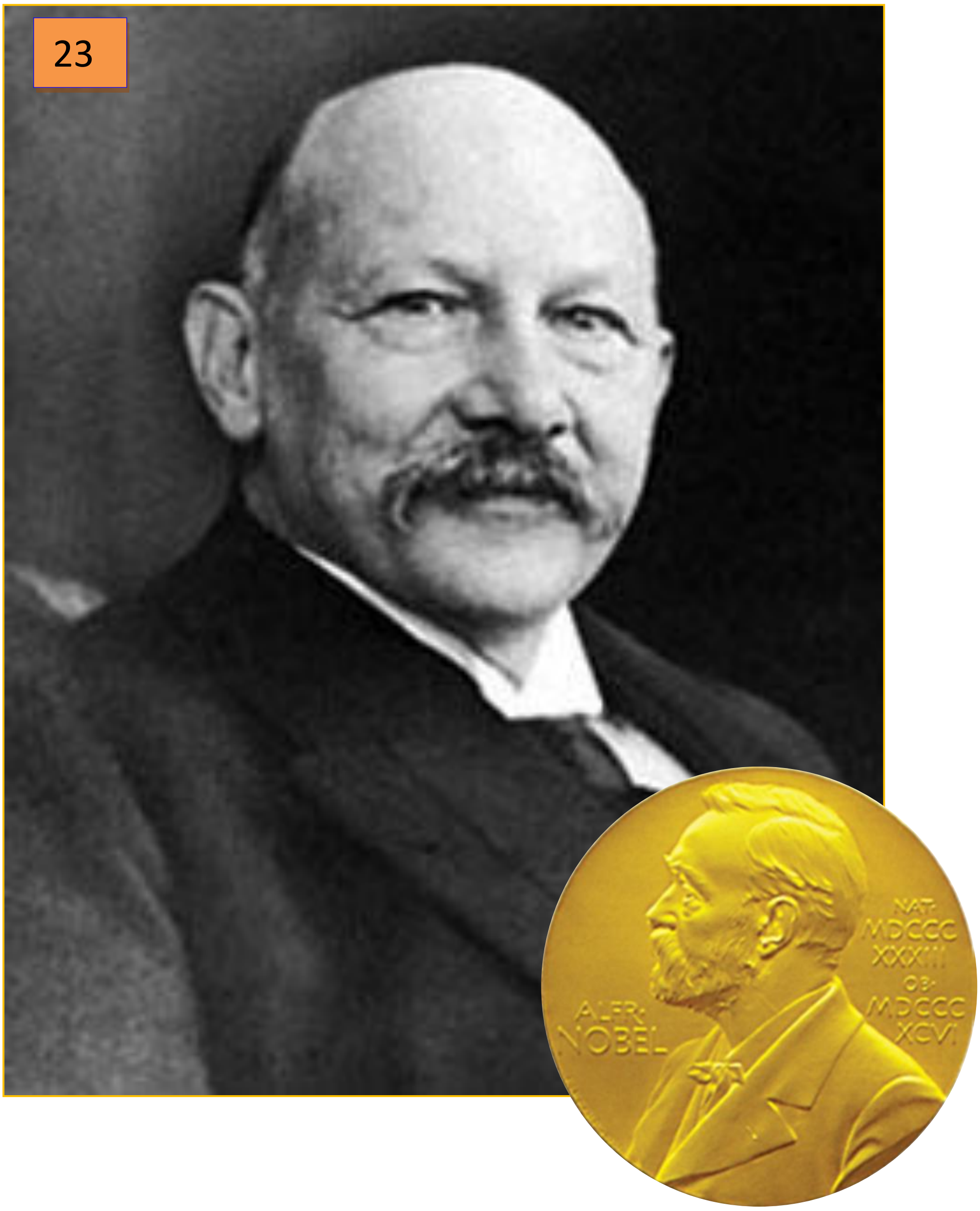
It all started when Sir James Dewar invented a vacuum flask in 1890. We call it a thermos flask [20]. It consists of a double wall which is silvered and in between there is nothing, literally, it's a vacuum.

The silver is used to reflect infra red energy back inside so no energy is lost and the vacuum prevents both conduction and convection as there are no molecules in between the outside of the flask and the inside.

Thermos flasks are often used to store liquid nitrogen and other very cold substances to protect them from the heat outside. But as glass is extremely fragile material now a days metallic thermos flasks are used. They are known as Cryostats or Dewars. In the last two weeks I saw many of them in variety of shapes and sizes [21], from very small to be used in a laboratory to a very large which supplies liquid nitrogen to the whole campus [22].

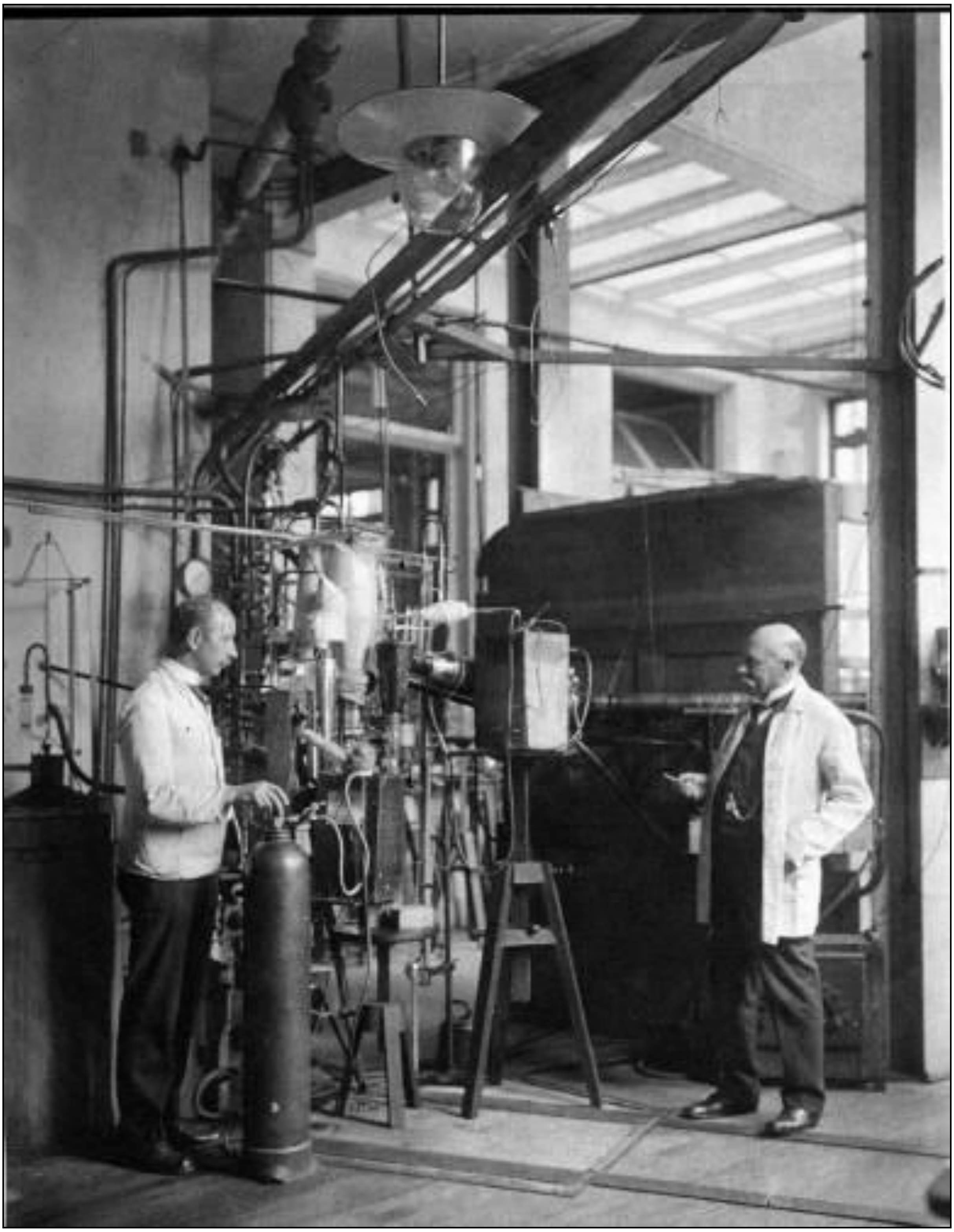
22

By the end of the 19th century helium was the only gas which could not be liquefied. There was an intense race to reach lower and lower temperatures which was won by a Dutch scientist, Heike Kamerlingh Onnes [23] by liquefying helium in 1908. Kamerlingh Onnes also discovered Superconductivity in 1911, **100 years ago from today.** He was awarded a Nobel Prize in Physics for this discovery in 1913. In the last 100 years [24] Superconducting technology has made huge progress and is still playing a key role in improving our lives, with MRI scanners, high speed communication, high speed transportation and efficient national grids. The year 2011 is thus an important year for the scientists and engineers working in the field of Superconductivity.



Heike Kamerlingh Onnes

Sir James Dewar with his vacuum flask



Kamerlingh Onnes with first helium liquefier

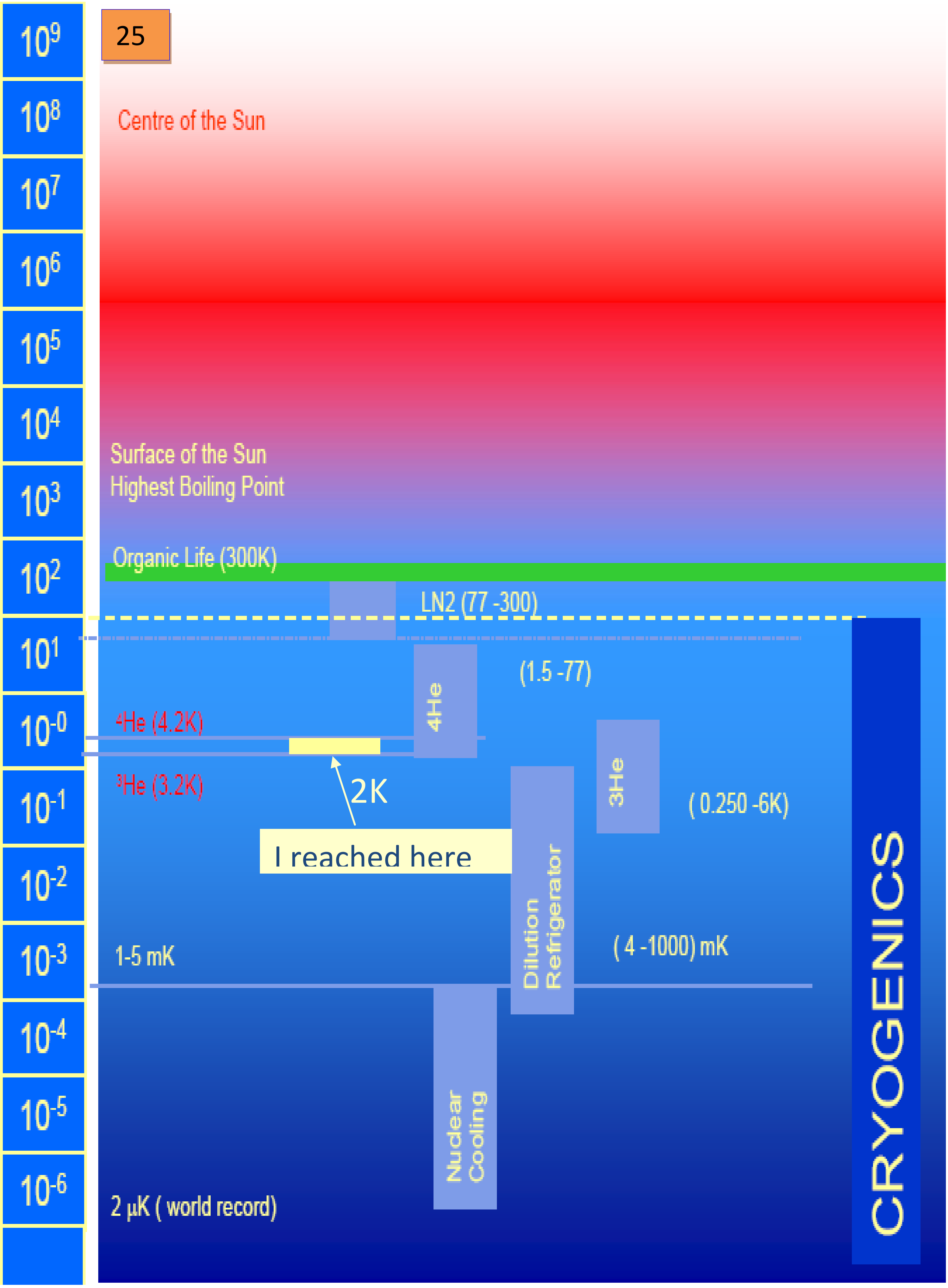
Absolute Zero

Having reached a temperature just 2^0 above absolute zero on ALICE are we really closer to the absolute zero? The absolute temperature scale is a ratio scale. Which means the temperature shown by a step at a higher level is 10 times higher than the previous one and one step below is 10 times lower. In other words instead of incrementing the steps on the scale in a sequence like 10, 20, 30... on the absolute temperature scale [25] each step increases like 1, 10 , 100, 1000, 10000 and so on. While cooling it reduces as 100, 10, 1, 0.1, 0.01, 0.001, 0.0001 and so on.

On this scale 1 is represented as 10^0, 10 as 10^1, 100 as 10^2 and 0.1 as 10^{-1}, 0.01 as 10^{-2}, 0.001 as 10^{-3} and so on. Note that there is no 'zero' on such a scale which means Absolute Zero can never be reached. Interesting!

But this also means that cryogenic temperatures cover a very large region of the temperature scale, much more than we experience near room temperature. It is amazing to see that Scientists have already reached the temperatures just 2 micro-Kelvin above absolute zero and still it appears far away.

Cryogenics is certainly very exciting. On my journey in the last two weeks I reached a temperature of 2K and yet there is so much more to go.



25
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^{-0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Centre of the Sun
Surface of the Sun
Highest Boiling Point
Organic Life (300K)
LN2 (77 -300)
(1.5 -77)
4He
^{4}He (4.2K)
^{3}He (3.2K)
2K
I reached here
3He
(0.250 -6K)
Dilution Refrigerator
(4 -1000) mK
1-5 mK
Nuclear Cooling
2 µK (world record)
CRYOGENICS

Two Weeks Near Absolute Zero Project Plan

Activity	May 16	May 17	May 18	May 19	May 20	May 23	May 24	May 25	May 26	May 27
Introduction and site tour										
Project Organisation and Planning										
Risk Assessment and H&S training										
Experiment with Superconductivity										
Literature survey and information gathering										
Report Writing										
Insert pictures, hyperlinks and Revise										
Visit to ALICE control room										
Proof read, edit, Final print										
Publish										

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Two weeks near Absolute Zero is an experiment to introduce the exciting fields of **Cryogenics and Superconductivity** to teenagers as a part of the centennial programme to celebrate 100 years of the discovery of Superconductivty. **Alex Mason** spent two weeks at STFC's Daresbury Laboratory as a work experience student and carried out this project under the supervision of Shrikant Pattalwar. Alex reports his first experience with Superconductivity in this publication.

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