

# Legacies of the parallel worlds of Rutherford and Kamerlingh-Onnes, 1908\*

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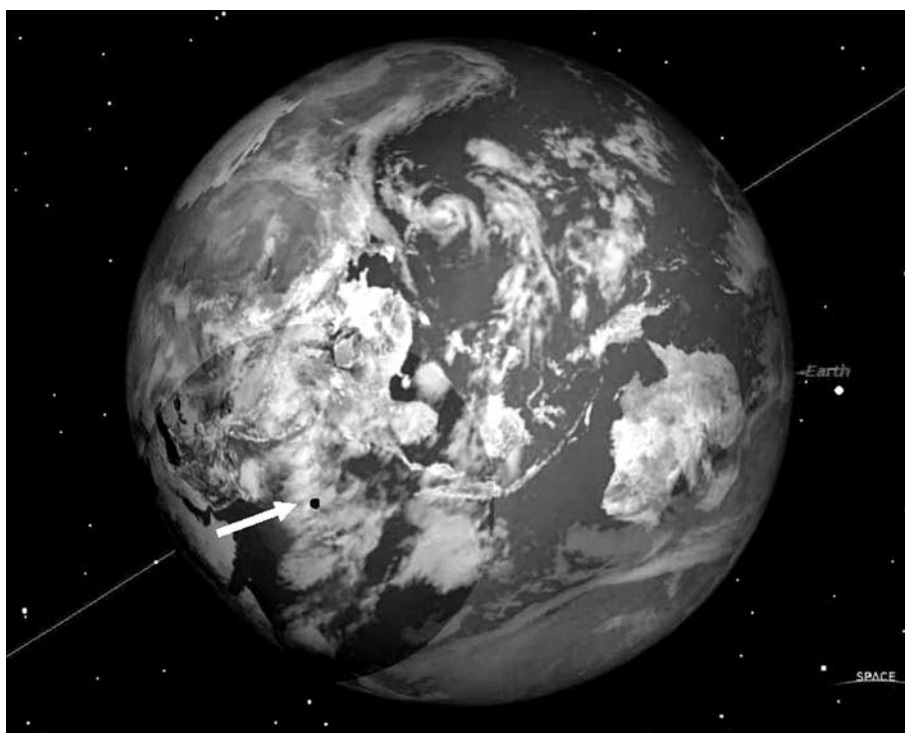
*This paper, on the occasion of the centennial of the award of the Nobel Prize to Rutherford, focuses on the simultaneous, but very different, achievements of Rutherford and Dutch physicist Kamerlingh-Onnes using atomic and bulk helium. One established the field of nuclear physics while the other the field of low-temperature physics and the discovery of superconductivity. The two are now inseparable in modern nuclear physics.*

Rutherford was awarded the Nobel Prize in Chemistry on 10 December 1908. But our particular story begins on 18 August 1868. The French astronomer, Pierre Jules César Janssen had travelled from Paris to the town of Guntoor on the east coast of India, just where the coastline swings sharply to the East. On that day, the sun's shadow cast by the moon swept across the south Arabian peninsular, across the Indian Ocean, and the *penumbra* made Indian landfall by 8:47 am. Janssen was there at Guntoor with a spectroscope to observe the total eclipse of the sun. Complete darkness fell on Guntoor at 10:10 am and lasted a mere 6 minutes (see Figure 1) – a very short time for the long trip from Paris, especially in those days.

Just before and after that eclipse, Janssen observed a yellow line of 587.5 nm wavelength in his spectroscope. The solar spectrum was his specialty and he recognised this yellow line to be previously unknown. Each gaseous element has its own distinctive set of spectral lines so Janssen made the bold conclusion that the yellow line originated from some new element contained within the sun's body. For this he was subsequently ridiculed by his peers, but later in the

year the English astronomer Norman Lockyer made the same observation and conclusion. He named the unknown element helium from the Greek name for the sun, *helios*.

Janssen was a remarkable individual and a model for any scientist. He travelled the globe to carry out his experiments. In 1857 he sailed to Peru to determine the magnetic equator. In 1861 and again in 1864 he travelled in Italy and Switzerland to study atmospheric absorption of the solar spectrum. In 1867 he was off to the Azores to carry out optical and magnetic ex-



**Figure 1.** The shadow of the sun over India on 18 August 1868 at 10:13 am as seen from the moon. The partial shadow (the penumbra) is 8200 km in diameter while the full shadow of complete darkness (the umbra, arrowed) is just 300 km across. Travelling at 3400 km/hour the umbral shadow lasted six minutes over Guntoor. The ecliptic is seen in the background.

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periments, and he observed both transits of Venus: in 1874 in Japan and that of 1882 in Algeria. And then he led numerous expeditions to far-off places to observe solar eclipses including Trani (1867), the above-noted trip to Guntoor (1868), Algiers (1870), Siam (1875), the Caroline Islands (1883), and Alcosebre in Spain (1905). For the Algiers expedition Janssen was trapped in Paris, which was under siege during the Franco-Prussian war. But a scientist will always find a way round a research obstacle. He escaped by hot-air balloon! What made these travels remarkable was the fact that a childhood accident had left him a cripple for the remainder of his life. For solar spectrum studies he recognised the need to minimise atmospheric absorption and he duly constructed an observatory at the top of Mont Blanc to which he somehow climbed on numerous occasions.

The spectroscopic identification of helium in 1868 represents the first extraterrestrial discovery of an element. It began a race to find and isolate helium here on Earth. Twenty seven years were to pass before William Ramsay, in 1895, eventually extracted helium gas from cleveite, a mineral containing uranium. (Interestingly this was even before Becquerel had discovered radioactivity in uranium though the so-called Becquerel radiation and helium had a common origin in radioactive decay.) Ramsay was Professor of Chemistry at University College London. The natural person for him to turn to in order to determine the critical point of helium was (later, Sir) James Dewar, director of the Davy-Faraday Research Laboratory at the Royal Institution. But the previous year Ramsay had isolated argon and Dewar had published a letter in *The Times* expressing scepticism over the discovery, so Dewar was the last person Ramsay would turn to now for assistance. Instead he sent his gas samples to Karol Olszewski, who had established a low-temperature laboratory in Krakow, Poland. Olszewski found he was unable to liquefy the helium sample.

At about the same time that Ramsay made his discovery of helium gas, Rutherford was back home in Brightwater, Nelson, digging potatoes, or so the story goes. A telegram delivery at that moment informed him that he had been accepted on an 1851 Exhibition Scholarship for Doctoral study at Cambridge University. 'Those are the last potatoes I will dig', was his reported reply to the telegram delivery man.

Dewar, from whom we obtain the term of the same name to describe a thermos-like vacuum flask, provided the next chapter of the story. In 1898 he succeeded in cooling hydrogen gas to its boiling point of 20.3 K. There is a vivid painting of him at the Royal Institution the following year delivering one of the popular Friday evening public lectures in which he demonstrated the liquefaction of hydrogen. For this he used a system of *regenerative cooling* in which hydrogen gas was compressed, then cooled by expansion and the cooled gas used in a heat exchanger to cool the next cycle of compressed gas. In the same year he succeeded in solidifying hydrogen. But Dewar found that at liquid hydrogen temperatures helium still remained a gas and this then set in motion an international race between himself in London, Olszewski in Krakow, and Kamerlingh-Onnes in Leiden, to find a means to liquefy helium. That was to take another 10 years. We now know helium to be a closed S-shell atom, essentially non-reactive (hence the name 'noble gas') and displaying only weak interactions with other helium atoms due only to the polarisability of its S-electron orbitals. This, combined with its low mass, makes it an example of a

quantum fluid where, at low temperature, quantum fluctuations become more important than thermal fluctuations. This makes it difficult to liquefy and, at atmospheric pressure, it cannot be solidified, no matter how low the temperature.

In the meantime Rutherford had arrived at Cambridge and began working with J.J. Thompson on electrical conduction in gases at low pressure. These were heady years with the discovery of x-rays by Roentgen in 1895 and of radioactivity by Becquerel in 1896. Rutherford immediately began examining the effects of both forms of radiation on gas conduction, and so began a research career that laid the foundations for the entire field of nuclear physics. In 1898 he identified two components in Becquerel rays: one easily absorbed by paper, which he named  $\alpha$  radiation, and one more penetrating, which he named  $\beta$  radiation. Central to the story here, Rutherford proved in 1907 that an  $\alpha$ -particle is a helium nucleus, and many of his most important studies utilised the  $\alpha$ -particle. Perhaps his most famous work was carried out at Manchester in 1909, when he bombarded gold foil with  $\alpha$ -particles. Most passed right through but a small fraction, about one in a thousand, were reflected directly back. From this he concluded that the atom was mostly empty space with just a tiny nucleus at the centre. Rutherford's work pivoted on the  $\alpha$ -particle, which he himself had shown to be a helium atom stripped of its electrons<sup>1</sup>. He was awarded the Nobel Prize for Chemistry in 1908, and it is this that we commemorate in this symposium.

There was another event in 1908 that forms the counterpoint to our story. The struggle to liquefy helium had continued for 10 years by then. There were almost insurmountable technical problems with fabricating seals that could still operate effectively at the extremely low temperatures, and there was also the issue of securing enough helium to work with<sup>2</sup>. But in that same year Kamerlingh-Onnes, working at the University of Leiden, succeeded in liquefying helium at just 4.2 degrees above absolute zero. In fact for 15 years he possessed the only helium liquefier in the world and researchers travelled from around the globe to use his facilities. Rutherford's lab at the Cavendish Laboratory did not begin to develop such capability until after 1921, when Peter Kapitza cajoled Rutherford into accepting him in his group<sup>3</sup>. Kamerlingh-Onnes was himself awarded the Nobel Prize in 1913 'for his investigations on the properties of matter at low temperatures which led, *inter alia*, to the production of liquid helium'<sup>4</sup>.

<sup>1</sup> Helium is the second most abundant element in the universe. Almost all of it was formed about 200 seconds after the big bang. In these early moments all nuclei were fully ionised, so helium took the form of  $\alpha$ -particles. It took another 300 000 years for it to cool sufficiently for  $\alpha$ -particles to capture electrons and form helium atoms. Only then did the young universe become transparent to light.

<sup>2</sup> At the time, helium was extracted from thorium-bearing monazite sand and very rare. Later it was found in natural gas and for a long time vast quantities of helium were simply lost to the atmosphere.

<sup>3</sup> Rutherford is reported to have protested that his budget could not afford to include Kapitza. The Russian then asked Rutherford what were his typical experimental error bars. When he answered 'about 3%' Kapitza insisted that if Rutherford took him on he would still be within 3% of budget! Kapitza's own contribution, in Moscow in 1937, was to show that liquid helium possessed essentially zero viscosity. He discovered superfluidity.

<sup>4</sup> For a full description of his achievements, see D. van Delft. 2008. Little cup of helium, big science. *Physics Today* 61(3): 36–43.



**Figure 2. Members of the Solvay Conference of 1911 drawn together to discuss the emerging quantum mechanics of the day. Rutherford and Kamerlingh-Onnes (circled) are seen standing side by side, perhaps for the only time in their research careers. Einstein is immediately to their left.**

Figure 2 shows the well-known picture of some of the world's greatest scientists of the time at the Solvay Conference of 1911. Next to Rutherford stands Kamerlingh-Onnes. As far as we know they never corresponded and never collaborated, but for a moment in a photograph they stand together. They are nonetheless forever linked by the helium atom, which they each used as a tool in totally different ways to achieve their ground-breaking discoveries. For Kamerlingh-Onnes it was to be the discovery of superconductivity in 1911, and it is superconductivity that now provides the ongoing link between the legacies of these two great scientists.

That link was underscored by several other related events in 1908. On 22 January, Lev Landau was born. He was the co-developer of the so-called Ginzburg-Landau theory of superconductivity<sup>5</sup>. This was an extremely general thermodynamic theory, still used today. On 23 May, John Bardeen was born. He, with Cooper and Schrieffer developed the so-called BCS microscopic theory of superconductivity<sup>6</sup>, regarded by many as one of the greatest intellectual achievements of the 20<sup>th</sup> century. He is the only physicist to have been awarded two Nobel Prizes in physics, the second being for developing the transistor<sup>7</sup>. And then, on 25 August, Henri Becquerel died. That year closed several chapters in radioactivity and paved the way for opening several new ones in superconductivity.

Turning now to the present, 2008, Rutherford's centennial year, marks the commissioning of the Large Hadron Collider (the LHC). The LHC represents the ultimate state-of-the-art embodiment of Rutherford's nuclear physics legacy. It accelerates protons<sup>8</sup> around a 27 km track comprising 1232 superconducting 15 m-long dipole magnets, which induce the necessary curvature in the proton path. There are an additional 1800 superconducting magnets in the beam line with, in total, some 7 million metres of superconducting wire. This facility shows in the extreme that superconductivity and nuclear physics are today inseparable. Each proton is accelerated to an energy of 14 million million eV and a velocity of 99.9999991% of the speed of light, completing 11 000 circuits around the 27km track every second. Protons propelled with these velocities in opposite directions collide with a combined energy that reproduces the first fraction of a second of the 'big bang'. Of course at such speeds the protons are highly relativistic and their mass has grown to nearly 7500 times their rest mass. Fittingly, in the Solvay Conference photograph, Rutherford and Kamerlingh-Onnes stand immediately next to Einstein. These three are inseparable in modern nuclear physics.

The wires in the superconducting magnets are conventional low-temperature superconductors (LTS) comprising niobium-tin and niobium-titanium. These, and until recently, all superconducting magnets use liquid helium as a coolant. Twenty years ago a revolution took place that promised to change all this. This was the discovery of high-temperature superconductors (HTS). In the space of a few years transition temperatures rose by a factor of 7 over the previous record, from 23 K to 160 K. We at Industrial Research Ltd discovered a compound,  $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$ <sup>9</sup>, which still is the only HTS material used in commercial HTS applications.

<sup>5</sup> Ginzburg, V.L.; Landau, L.D. 1950. On the theory of superconductivity. *Journal of Experimental and Theoretical Physics (USSR)* 20: 1064.

<sup>6</sup> Bardeen, J.; Cooper, L.N.; Schrieffer, J.R. 1957. Microscopic theory of superconductivity. *Physics Reviews* 106: 162–164.

<sup>7</sup> Half a century later it was Bardeen who warned the US government that the world's supplies of helium would run out by 1980 unless something was urgently done. Congress reacted by declaring helium to be a national strategic resource. A US\$1 billion separation plant was built in Amarillo, Texas, for extracting helium from natural gas and, from then, helium was stored in disused gas wells.

<sup>8</sup> In another mode the LHC accelerates and collides Pb ions.

<sup>9</sup> Tallon, J.L.; Buckley, R.G.; Gilberd, P.W. *et al.* 1988. High- $T_c$  superconducting phases in the series  $\text{Bi}_{2,1}(\text{Ca},\text{Sr})_n\text{Cu}_n\text{O}_{2n}$ . *Nature* 333: 153–156.

**Figure 3. A dipole magnet for the Brookhaven National Laboratory synchrotron, with retro-fitted HTS superconducting coils manufactured by HTS-110 Ltd. The coils are conduction-cooled using refrigerators seen at each end. Neither liquid helium nor liquid nitrogen is used as a cryogen.**



It took 16 years to secure the US and European patents and we eventually spun out two companies for manufacturing HTS products. One of these, *HTS-110 Ltd*<sup>10</sup>, is manufacturing magnets, coils and whole systems such as NMR for the scientific, oil, electronics, health and energy markets. In the last year or so they have completed a 5 T (tesla) magnet for neutron scattering at the Australian Nuclear Science and Technology Organisation, Sydney, a 5.4 T magnet for x-ray scattering at the Hahn-Meitner Institute, Berlin, and a retro-fitted dipole magnet for the synchrotron at Brookhaven National Laboratory (Figure 3). The company now offers magnets up to 16 T and is currently designing for the 19 T range. With the advent of a second-

generation HTS wire, fields over 20 T are anticipated. This activity is globally unique and it is clear that we are now witnessing the long-promised eclipse of LTS by HTS, with a wide range of very significant advantages: price, size, field magnitude and stray field. HTS products will soon be impacting on accelerators for nuclear physics and already they are used as current leads in the 7000 to 10 000 amp range for existing LTS magnets.

The legacies of Rutherford (the New Zealander) and Kamerlingh-Onnes (the Old Zealander) flowing from 1908 continue to impact on leading-edge science in new and exciting ways. And we here in New Zealand are making our own unique contribution to the ongoing revolution. These two, who during their lives had so little to do with each other are now forever linked both by their discoveries and by the second element of the Periodic Table.

<sup>10</sup> [www.hts-110.com](http://www.hts-110.com)