The Royal Society of Edinburgh

Conference

C T R Wilson, a Great Scottish Physicist: His Life, Work and Legacy

Friday 7 December 2012

Report by Sue Bowler

Introduction

This meeting was held to honour Charles Thomson Rees Wilson (CTR), the 1927 Physics Nobel Laureate, who invented the cloud chamber, described by Ernest Rutherford as "the most original and wonderful instrument in scientific history". Wilson conceived the cloud chamber initially to better understand the processes of water condensation – inspired by clouds seen from Scottish mountains – and quickly found that it could be used to detect ionisation produced by X-rays and radioactive sources. By 1912, Wilson had perfected his device and was able to take photographs that made visible representations of subatomic particles. His instrument was used across the world for intensive studies of cosmic rays, which were discovered in the same year. These efforts shaped the study of cosmic rays and the development of particle physics throughout the first 60 years of the 20th Century. Wilson was also deeply interested in atmospheric electricity, and his instruments and his ideas about thunderstorms and the global atmospheric electrical circuit remain at the heart of modern theories. His family knew him as a mild-mannered, thoughtful person, keen on hill-walking, with a lifelong scientific curiosity; his keen observation, persistence and patience made him a notably meticulous experimental physicist.

C T R Wilson was born on 14 February 1869, and in 1888 went up to Sidney Sussex College, Cambridge, from where he graduated in physics in 1892. He tried school teaching, briefly, but returned to Cambridge and to the Cavendish Laboratory, although it was a visit to the Ben Nevis Observatory in 1894 that sparked his interests in cloud formation. He continued his career as demonstrator, developing the apparatus that in 1912 became the cloud chamber. After showing that the cloud chamber could be used to see particle tracks, he concentrated much of his energies on meteorology and atmospheric electricity. In 1925, he became Jacksonian Professor at the Cavendish, remaining there for the rest of his career, before retiring to Edinburgh where he became friendly with Max Born who lived in the same street. Later, he went to live in the small village of Carlops, close to his birthplace. In 1956, at the age of 87, he published a paper on a theory of thunderstorm electricity in *Proceedings A of the Royal Society,* the oldest Fellow of the Society to have published there.

The cloud chamber, or Wilson Chamber, makes visible the mysterious world of subatomic physics, and has inspired many to take up the study of science. His contributions to physics shaped modern thinking about cosmic rays and climate, thunderstorms, particle physics and the search for the origin of cosmic rays, something about which CTR speculated over ten years before their discovery in 1912.

C T R Wilson: Reminiscences of a grandson

Andrew Wilson

Andrew Wilson began by recounting that visitors to The Cottage in Carlops would occasionally find CTR lying on the floor flat on his back, with Algernon, a black rabbit, chewing on the old man's hair, to the evident enjoyment of both. "I don't know if this is common among Nobel Prizewinners…" said the speaker.

Mr Wilson went on to describe CTR's early life, noting that the Thomson and Rees names came from two shepherds who were employed by his father John, a noted sheep breeder. CTR was very fit, thanks to his love of hill walking, particularly in Arran and, as a student at Sidney Sussex College, he had a cold bath every morning irrespective of the weather. He never carried any weight, always ate sparingly and did not drink at all for most of his life. CTR's mother was a founder member of the British Women's Temperance Association, while his brother-in-law was the 12th generation of Presbyterian ministers. Perhaps as a consequence, CTR's strongest expletive throughout his life was "tut tut".

CTR was a very private man who did not show his emotions, never laughing but occasionally smiling; as a consequence, he was difficult to know. However, he was very kind to his grandchildren, whom he was happy to take up Paties Hill at Carlops to look at beetles and other small creatures of which he seemed to have an encyclopaedic knowledge. He seemed to have liked most of his colleagues, but thought Einstein conceited and did not approve of Madam Curie's love life.

At 87, CTR was the oldest member of the Royal Society to publish a paper, although he confessed to being disappointed by its reception. His 90th birthday was marked by a well-attended party including many colleagues, notably Giuseppe Occhialini who had travelled all the way from Milan by train.

Mr Wilson concluded by drawing attention to the 27 boxes of notebooks in the Clerk Maxwell collection at Aberdeen University, and also that he recorded having seen a thunderstorm phenomenon now known as a sprite as early as 1924, but their existence was not confirmed until 1989.

Questions concerned whether Scotland was important to CTR; Mr Wilson thought that it was, without knowing CTR's politics. The fact that such an abstemious man had invented a device that depended on alcohol was also noted.

Scene setting

Dr Tam Dalyell FRSE

Dr Dalyell recalled a soaking wet Saturday afternoon in the foothills of the Pentlands, when he was a 26-year-old Labour candidate, canvassing on a bicycle. He was extremely grateful for the offer of a cup of tea and a chat from an elderly man in a cottage in Carlops. "As he put the kettle on, I looked around," recalled Dr Dalyell. "One framed photograph, among the others on the wall, had me transfixed. It showed some familiar faces – Einstein, Bohr, Pauli, Planck, von Laue, Langevin, Madame Curie, Rutherford – and, standing in the second row at the end, somewhat diffidently, someone who was obviously my host, 30 years younger. I realised that he could only be C T R Wilson."

That photograph started a wide-ranging conversation. CTR said that he got on well with all of them, apart from Werner Heisenberg, whom he positively disliked. He remembered with respect

Peter Kapitsa and, many years later, when Dalyell visited the Soviet Academy of Sciences, Kapitsa had asked him if he had met C T R Wilson, whom he held in very high regard.

Dr Dalyell found CTR Wilson a very reflective man, and one who influenced his future life. As he left the cottage, CTR asked him if he would take a serious interest in science if he were ever elected. “I said that I would”, recounted Dr Dalyell, “and that is why I am here today.”

Glories seen at the Ben Nevis Meteorological Observatory

Ms Marjory Roy, Scottish Centre, Royal Meteorological Society

The Ben Nevis Observatory was a meteorological observatory that existed from 1883 to 1904 at an altitude of 1344m at the summit of Ben Nevis. It was established, in common with others across Europe, in order to get high-altitude data otherwise only very intermittently available at that time by using balloons or kites, from which recording instruments had to be retrieved. It was proposed by David Milner Horne, Chair of the Council of the Scottish Meteorological Society. Alexander Buchan, Secretary of the Scottish Meteorological Society, was involved in much of the planning, and the construction was funded by public subscription.

C T R Wilson spent two weeks there as a temporary observer, from the 8th to the 22nd September 1894. He noted while he was there that he saw a brockenspectre, or glory, a rainbow-like effect of sunlight on clouds, surrounding the observer’s shadow. Weather records quoted by Ms Roy show that he was lucky to have weather conditions to do so; Observatory records show that, on average, hill fog was present for 70% of the time in September, with just two hours of sunshine a day. But the weather on Ben Nevis when CTR was there was exceptionally good, with anticyclonic conditions, very low humidity at the summit and temperature inversions – ideal conditions to see glories. In 1895, when on holiday in the area, CTR also noted two other significant events. On 19 June, he saw lightning striking the Observatory and the next day when he visited, he saw some of the effects of the discharge. On 26 June 1895, when he was on Carn Mor Dearg, he felt his hair standing on end and saw St Elmo’s fire around his head and, realising that this was a direct experience of atmospheric electricity, he descended rapidly down the scree.

Some of the instruments in place at the BNO when C T R Wilson spent his time there would have been of interest, notably an Aitken Dustcounter, a device developed by John Aitken to investigate the ideas of Cuvier about the importance of condensation nuclei for the formation of clouds. At the time when C T R Wilson was at the Observatory, this instrument may have been in use, although CTR does not mention it.

Ms Roy concluded by noting that the observational log books from the Observatory are now in the Archive of the National Registry of Scotland (although not in digital form) and contain a lot of information not available in the published reports; showing for example, that Ormond, (the first Superintendent of the Observatory), was very interested in optical phenomena such as glories.

Medical impact of cosmic radiation

Professor Anne Glover CBE FRSE, Chief Scientific Advisor, European Commission

Professor Glover began by citing the inspirational effect of the work done by C T R Wilson. Seeing cosmic rays in a cloud chamber became part of what drove her into a career as a biologist.

Cosmic rays from the Sun and from the wider galaxy both have medical effects. Professor Glover cited solar X-ray data from the Geostationary Operational Environmental Satellite (GOES) spacecraft that showed the radiation dose going up by a factor of 1000 in just a few minutes. Solar radiation varies on the surface of the Earth, in line with the cycle of solar activity, and high latitudes are more vulnerable than low latitudes, because of the structure of the Earth's magnetic field. The levels of galactic cosmic rays are modulated by the solar cycle, but their effects are different, largely because they consist of ionised nuclei with high energies; in other words, their deeply penetrating radiation is hard to shield and has high biological impact. The effects of both are greater at high altitude. Altogether, this makes space a very dangerous place for humans – the Apollo astronauts missed instant death by just a few days.

Biological effects range from the transient lights seen by astronauts as individual accelerated particles flashing through their eyes, to cell damage from ionising radiation. Light ionising radiation tends to break single strands of DNA, which is relatively easy for the body to repair. If cells experience heavy ionising radiation, both strands of DNA may break, making the whole molecule shear apart. This is harder to repair and may lead to genetic damage in progeny.

Professor Glover described the Matryoshka experiment, in which a model human body, made of layers like a Russian doll, corresponding to the different layers of the human body, and packed with sensors, was exposed on the outside of the International Space Station. The results showed hot spots of high exposure within the doll, amid generally low exposures. But even low levels pose a problem, because of the duration and continuous nature of exposure in space.

Any further space exploration, whether it involves miners seeking rare earth elements on the Moon, or explorers visiting Mars, demands effective shielding; so far we have only water or aluminium to offer. Even with this, astronauts travelling to Mars and back would be likely to have 3% of their body cells hit by iron ions. Professor Glover described radiological studies of shielding as the cloud chambers of the future – technology that will allow us to explore further.

Among the **questions** was a query about the evolutionary effects of this natural radiation damage. Professor Glover agreed that it would be worth investigating whether cosmic rays might accelerate evolution in this way.

C T R Wilson at the Cavendish Laboratory

Professor Malcolm Longair CBE FRS FRSE, Jacksonian Professor of Natural Philosophy, University of Cambridge

Professor Longair began with Wilson's work on cloud formation, inspired by his observations on Ben Nevis. Paul-Jean Coulier and John Aitken had worked on the formation of artificial clouds, and Aitken was certain that a solid nucleus was needed for condensation to start; in other words, that dust in air was essential for clouds to form. CTR improved Aitken's apparatus and found that dust was not essential, but that clouds would not form in air free of dust unless the air was supersaturated with water vapour. He surmised in 1895 that some other form of condensation nuclei were present. In February 1896, CTR used X-ray tubes to illuminate his apparatus and saw not just a few droplets condensing, but a dense fog which, he subsequently established, was a result of the X-rays producing ions, which acted as condensation nuclei.

This significant result, that made possible the development of the cloud chamber, was the product of C T R Wilson's meticulous experimental work and the patience with which he met failure and carried on. This piece of apparatus would work only if all parts joined together in a perfect fit, requiring precision glass-blowing and grinding, and was a time-consuming process that involved very many failed attempts for each success.

Although Wilson spent the ten years from 1899 focusing largely on atmospheric electricity, he continued with his condensation experiments. He discovered that air appears to be spontaneously ionised, wherever he measured it. While staying with his brother in Peebles, he worked in the railway tunnel there and the results led him to suggest, in 1901, that there might be a source of ions with high penetrating power, outside the atmosphere. This was the first mention of the idea of cosmic rays in the literature, although he concluded at the time that such a source was unlikely.

By 1910, CTR was back at work on what would become his cloud chamber. He took seriously the possibility of being able to photograph the tracks of particles by photographing the streams of water droplets that condensed on the ions they formed, and devised a way to do it. It was, as Professor Longair put it “a typical Cavendish experiment, pure string and sealing wax.” The apparatus required a flash of light to take the photograph that was synchronised with the movement of the plunger. The solution was to use a weight on a string that broke when the plunger moved; the weight fell onto the electrical contacts, setting off the flash. “The whole thing depended on gravity,” said Professor Longair, “and the original weight used was a brass doorknob!”

String and sealing wax it may have been, but it worked. In 1912, CTR built the final version of his cloud chamber and with it obtained the first images of alpha and beta particles, and of ionisation by X-rays. He may also have produced the first images of cosmic rays without realising it; some of his 1911 photographs show their characteristic straight track.

Back at the Cavendish Lab, Rutherford and Blackett went on to use Wilson’s chamber to demonstrate the disintegration of the nucleus, to find high energy protons and to show nuclear interaction, in much the same way the Higgs boson experiments at CERN do today. By 1929, Wilson’s chamber was being used to take the first photographs of cosmic rays – discovered in1912 by Victor Hess – and the secondary electrons they produced.

C T R Wilson is recognised as a physicist of unusual skill and vision and an experimenter of genius. His great achievement – the cloud chamber – arose from his curiosity about the natural world and made possible so many discoveries in particle physics and cosmic ray research. And, as Professor Longair put it, “such a spectacular technical achievement does not happen without special amounts of effort, patience and enthusiasm.”

The impact of C T R Wilson on particle physics

Professor Don Perkins CBE FRS, Emeritus Professor of Physics, University of Oxford

Professor Perkins considered that cloud chamber images of the tracks of charged particles, pioneered by C T R Wilson in 1911, were of great significance in the development of particle physics, playing a significant role in the discovery and understanding of subatomic particles and inspiring the development of instruments that used visual images, such as the bubble chamber.

In 1930, Paul Dirac predicted the existence of a particle with the mass of an electron, but with a positive charge. Blackett and G P S Occhialini (a former research student of C T R Wilson’s) found pairs of particle tracks that could be explained by positively and negatively charged particles, but their mass was uncertain. Measurements by C D Anderson at Caltech in 1932 suggested that the mass of the positively charged particle was less than that of a proton; but it was not until Andersen and then Blackett and Occhialini, independently in 1933, were able to show that the positive particle had the same mass as the electron, that the first anti-matter particle – the positron – was detected.

The visual images of particles and their tracks were also instrumental in the discovery of mesons. In 1935, H Yukama suggested that there were particles acting as carriers of the strong force within the atomic nucleus, with masses of around 200–300 times the electron mass. Yukama's particle could, in theory, be detected in the interactions of cosmic rays with atmospheric molecules, although it was expected to be very short-lived (10^{-8} seconds). It was not until 1947 that the pion was found, using particle tracks caught in photographic emulsion.

Professor Perkins recalled the advent of nuclear emulsion, when he was a graduate student. Ilford produced photographic plates using silver iodide which, when hit by charged particles, ionised and when the plates were developed, led to a trail of tiny black dots along the tracks. Stacks of such plates recorded the paths of charged particles in three dimensions. In 1947, the speaker sent some stacks of plates to high altitude on photoreconnaissance flights from RAF Benson. "While I never saw the flight logs and so I didn't know how high they flew or for how long," said Professor Perkins, "the plates did show evidence of nuclear disintegration. I wondered if the light particle I saw was the Yukama particle (the pion), but had to wait for further experiments with better emulsion." His work, along with further detections by C F Powell and Occhialini in 1949, established the existence of the pion. Professor Perkins noted that Powell and Occhialini referred to the cloud chamber as the "Wilson Chamber" throughout their work.

Wilson's invention led to major discoveries in cosmic ray science and initiated the global progression of detector and accelerator development that led directly to the current standard model of the Universe. But the standard model applies to the 4% of the Universe that is made of matter, antimatter and electromagnetic radiation; the rest is dark matter and dark energy. Professor Perkins concluded that "the work that Wilson started 100 years ago gave us a new understanding of the Universe, but we have got a long way to go, because we are only 4% of the way there."

In **questions**, Arnold Wolfendale recounted that Blackett, his Professor at Manchester, told him he had seen a positron, but he had thought that the magnetic field was in the other direction. C T R Wilson, Wolfendale felt, would have known which way the magnetic field was!

Alan Watson asked about the delay in publication of the positron results and wondered if it suggested some confusion over the interpretation of the data. Perkins said that there had been probably six months delay while the paper was repeatedly revised – 14 times in all!

C T R's contributions to atmospheric electricity

Professor Giles Harrison, Department of Meteorology, University of Reading

CTR's work on atmospheric electricity was most productive and important in the period 1920–1925, but he had been interested in the origin of the fair weather electric field from 1903, when the prevailing view was that the upper atmosphere had a static electric charge. Wilson realised that if the air was continually being ionised, as it appeared to be, there had to be current flow; the fair weather field could not be entirely electrostatic. If current flow occurred – and Wilson measured it in 1906 – how was it sustained and how was the charge conveyed? CTR's work on ions and cloud condensation led him to consider how raindrops could convey the charge to the ground during thunderstorms.

Understanding the vertical distribution of charge on electrified clouds was needed to develop a theory of the current flow. C T R Wilson and Sir George Simpson disagreed about the interpretation of the charge on raindrops and the position of positive and negative charge in thunderclouds; both of them developed instruments to measure the arrangement of charge in thunderstorms. The tripolar model of thunderclouds that eventually emerged includes elements of both men's work.

CTR was very interested in charge transfer from clouds downwards to the ground and upwards to the ionosphere. He adapted his instruments and set them up in west Cambridge where, from 1915 to 1917, he carried out kite experiments, hoping to learn more about the changes in charge associated with lightning strikes. By 1921, Wilson was describing a global circuit deriving current from thunderstorms. By 1925, he hypothesised that thunderstorms operated as particle accelerators, citing dielectric breakdown above thunderstorms as a discharge mechanism. The idea of a global current flow preoccupied Wilson; he developed ideas on limiting potentials, on the growth of potential in thunderstorms and on the production of ionising particles, all of which have been proved sound with modern instrumentation.

Upper atmosphere discharges were finally unambiguously observed from photographic evidence in 1989. These transient luminous effects, known as sprites and jets, include charge transfer between the top of clouds and the upper atmosphere. Wilson's synthetic global circuit concept involved the current generated during storms flowing upwards to the ionosphere, via sprites, and downwards to the Earth via rain. In his notebooks, Wilson made calculations to balance the global circuit. He saw thunderstorms as batteries separating charge to yield a potential at the ionosphere of +300kV relative to the surface, permitting current flow from disturbed weather regions through the ionosphere to the rest of the planet – ideas subsequently confirmed by close agreement between variation in thunderstorm area and the fair weather field elsewhere on the globe.

In summary, CTR Wilson's legacy for atmospheric electricity lies in the influential students he taught, the establishment of meteorological physics, his instruments, his global synthesis of atmospheric electricity and the power of his approach that linked the microscale to the macroscale. He was, as Professor Harrison put it "remarkably right about a lot of things".

Climate change and the Cosmos

Professor Sir Arnold Wolfendale FRS, Emeritus Professor, Department of Physics, Durham University

In common with many of the speakers, Professor Wolfendale had been inspired by C T R Wilson; in his case by the experience of using a cloud chamber when he started research at the University of Durham in 1956. "I was astonished that he got such good results – he really was an excellent experimenter!" Durham at that time had Alan Chambers working on cloud physics, and it was there that the speaker came across the idea of an array of electric field mills to pick up air showers, but the noise was too great.

These early interests meant that Professor Wolfendale was in a good position to assess the idea, put forward by Henrik Svensmark, that cosmic rays may have a role in climate change, through the formation of clouds. While sceptical, he supported an experiment at CERN (CLOUD) to investigate the interaction of radiation with aerosols, but was also able to apply some of the common sense and global thinking that C T R Wilson used so successfully. The suggestion was that the cloud cover at low levels should correlate with cosmic ray intensity. Observational data show that it does, in some cases, but the effect is not reproducible and not replicated. And such a correlation does not imply cause and effect. But the effect of ionisation on cloud formation requires air that is supersaturated with water vapour at 25%; the levels measured are around 1%, which is far too low.

Professor Wolfendale stressed the importance of taking a critical approach. For example, the overall measures of temperature rise when cosmic ray intensity falls, leading to suggestions of cause and effect. But when the solar cycle moves on and cosmic ray intensity increases, the temperature still goes up. There is also the opportunity to think laterally: there was, for example, no increase in cloud cover following the 1950s bomb tests or the Chernobyl reactor accident.

Chernobyl released some 2 Mt of fallout, but the processes involved in going from ionisation to cloud droplets have at most 3% efficiency.

In addition, if cosmic rays were to affect clouds, then there should be some variation over the surface of the Earth, because of the structure of the magnetic field. The cloud cover data shows a dip that correlates with the solar cycle, but the magnetic field means that the effect should be smaller at the Equator, and larger at the poles. There is no such signal in the cloud cover data.

Where there is a strong effect is in the stratosphere, where solar proton events affect aerosols, ozone and temperature, noctilucent clouds, the polar mesospheric clouds at altitudes of 56–85 km that include water ice, also contain heavy cosmic ray nuclei, which might have an effect. It would also be worth considering Neptune, for example, a cloudy planet where solar modulation is less significant, and thus cosmic ray effects on clouds may be clearer. Overall, around 1% of cloud cover on Earth is affected by cosmic rays – the effect of cosmic rays on climate change is negligible.

In **discussion**, the speaker said that the experiments at CERN using sulphuric acid vapour showed that there still is a lot of good exciting physics to be done on aerosols and clouds. A question concerned what, if not cosmic rays, was causing climate change? Professor Wolfendale said he could see nothing other than man-made emissions, and a show of hands indicated that the majority of the audience agreed.

The many uses of the rare isotopes produced by cosmic rays

Professor Finlay Stuart, Isotope Geosciences Unit, Scottish Universities Environmental Research Centre

Primary cosmic rays are dominantly extremely high energy protons. When they penetrate the Earth’s atmosphere, they cause a cascade of secondary particles that bathes the Earth surface. The high-energy secondary neutrons interact with atomic nuclei in the atmosphere and shallow Earth, forming an array of daughter products. Spallation reactions result in the formation of isotopes. Where the cosmogenic isotopes are naturally in low abundance, but the cosmogenic contribution can be measured, they can be used as chronometers and tracers of processes at the Earth’s surface.

The best known cosmogenic isotope is ^{14}C, commonly called radiocarbon. It is formed from nitrogen in the atmosphere and incorporated into living things – plant and animal tissue – along with the dominant stable carbon isotopes during life. The ^{14}C is radioactive, with a half-life of 5,730 years. When the animal or plant dies, ^{14}C ceases to be absorbed, and that present starts to decay – the radiocarbon clock starts ticking. The amount of ^{14}C in organic compounds provides the most common way of determining age. It is useful for dating up to about 50,000 years ago, making it especially useful for understanding environmental change on a timescale that is very relevant to climate change.

Because the cosmic ray flux to Earth varies, the rate that ^{14}C is produced in the atmosphere also varies. Consequently the radiocarbon clock needs to be calibrated against absolute chronometers. As a result of considerable international effort using tree rings, sediment layers in lakes or speleothems, in which there are annual markers, the radiocarbon timescale is now calibrated for thousands of years into the past. This means high precision dating. For example, radiocarbon dating has shown that the Turin Shroud originated in medieval times rather than 2000 years ago.

A range of cosmogenic isotopes is produced in rocks and soils at the Earth’s surface. Both stable (^{3}He) and radioactive (^{10}Be, ^{26}Al and ^{36}Cl) isotopes are used to provide powerful techniques for measuring the time rocks or artifacts have been exposed at the surface of the Earth; for example, dating when glaciers retreated or landslips took place. Application of these techniques requires measuring very low concentrations of cosmogenic isotopes (a few tens of thousands of atoms) and requires state-of-the-art mass spectrometers. They are particularly useful for determining the time of eruption of lava flows, for example. These in turn can be used to determine the exposure of fault scarps, revealing the history of fault movements over longer time periods than the earthquake record.

In **discussion**, Professor Perkins commented that the distribution of radiogenic isotopes was important in the production of the bubble chamber. The first bubble chambers used the boiling of superheated diethyl ether, but it turned out to work only because of the ^{14}C in the diethyl ether used in the US, which had been produced from petroleum, that contained natural radiogenic carbon. When Glazer tried it with diethyl ether produced in Europe from alcohol, with a different diethyl ether content, the prototype chamber did not produce the bubbles.

Astronomy with dustbins and light buckets

Dr Paula Chadwick, Durham University

Despite the ubiquity and energy of cosmic rays, we don't know where they come from. The Sun produces plenty at low energies, but the rest must come from other objects within our Galaxy or, at the very highest energies, outside it. The galactic cosmic rays do not travel in straight lines; because they are charged particles, they are deflected by the galaxy's magnetic field. But any process that can accelerate particles to the energies observed will also produce gamma rays, which, as electromagnetic radiation, travel in straight lines. "If we can catch the gamma rays", said Dr Chadwick, "we will know where the cosmic rays come from."

Efforts to do this over the past quarter century show that it is not so simple. Gamma rays do not penetrate the Atmosphere, so they are detected with orbiting observatories such as Fermi. However, very high energy (VHE) gamma rays, which provide the best tracers of cosmic rays, are so rare that it would take a detector the size of a football stadium in Space to detect enough of them – and this is not technically or financially feasible. VHE gamma ray astronomers have had to try alternative approaches, and they use the Cherenkov radiation that arises when a charged particle moves at speeds faster than the speed of light in the Atmosphere.

Patrick Blackett suggested that Cherenkov radiation should be visible in the Atmosphere, and W Galbraith and J V Jelley built the first ground-based detector by placing a photomultiplier at the focus of an army-surplus searchlight mirror, which was put in the bottom of a dustbin to keep out the background light. This is essentially the design of modern ground-based gamma ray telescopes, albeit with much more sophisticated mirrors, detectors and electronics. However, there is considerably more Cherenkov light from cosmic rays than from high-energy gamma rays, which makes picking out the gamma rays from the cosmic ray background difficult. However, the air showers are distinct in each case.

That distinction also means that high-energy gamma rays can be detected on the ground and their sources identified. Imaging atmospheric Cherenkov telescopes use arrays of detectors to map the elongated pool of light on the ground arising from a gamma ray air shower. Its long axis corresponds to the long axis of the shower, giving an indication of the direction of origin of the shower and hence of the gamma rays. This is what telescopes such as VERITAS, MAGIC and HESS are designed to do, and their detections are leading to new science in fields such as cosmology, pulsars and black holes.

These instruments have detected 140 sources of gamma rays in our Galaxy and beyond (compared to the ten sources known in 2004). The sources include many different types of objects such as binary star systems involving neutron stars, or black holes with jets. Yet the basic question of where cosmic rays come from remains unanswered. Supernova remnants are detected by VHE gamma ray telescopes and are thought likely to provide the shocks that accelerate particles to such prodigious energies, but conclusive proof that they are the main source of the galactic cosmic rays remains elusive.

It will take new instruments to find out, and there are two being planned: HESS II has added a much larger telescope to the HESS array, collecting more light but also more of the lower energy gamma rays; and the Cerenkov Telescope Array, will be bigger still and will detect more of the really highest energy radiation.

Questions included whether it is possible to see Cherenkov light. Astronauts have reported seeing the flashes within their eyes, and Lovell claimed that Blackett tried to see air showers by lying outside in a field for protracted periods.

Tam Dalyell asked if workers at HESS in Namibia are working to involve people in the region in the work. The speaker said that this was an important part of their work, with well-attended open days, links to universities and research exchanges.

The future of astronomy at high energies

Professor Jim Hinton, Department of Physics & Astronomy, University of Leicester

C T R Wilson’s pioneering instrument to detect ionising particles, the cloud chamber, has a direct legacy in two current instruments, the ATLAS detector on the Large Hadron Collider at CERN, and the Fermi gamma ray telescope orbiting Earth. Both these instruments detect relativistic ionising charged particles, although Fermi works at much higher energies than are achievable at CERN. And both are making discoveries. Fermi has found enormous structures associated with our Galaxy that appear to be bubbles 40,000 light years across, inflated by the supermassive back hole at the centre of our Galaxy and filled with cosmic rays. These enormous structures are on our cosmic doorstep, yet we have only just discovered them.

High-energy astrophysics has enormous potential for astronomy, applying the technology that has been developed for particle physics and cosmic ray detection to astronomy. Astroparticle physics – using gravitational waves, fundamental particles and high-energy gamma rays – offers an opportunity to examine extreme physical environments. The innovative approaches demanded to detect gravitational waves, dark matter and neutrinos make gamma ray astronomy, with its successful current instruments, look fairly easy. But improving detection from current levels demands bigger arrays with more telescopes – very much a brute force way forward, but one that is achievable in the next decade through the Cherenkov Telescope Array.

The Cherenkov Telescope Array (CTA) will combine a few large telescopes to work at low light levels, with a large area of smaller telescopes to capture the rarer high-energy events. The project builds on the instrument heritage built up in this field, including how best to deploy small telescopes over large areas. CTA will survey large patches of the sky for a census of particle accelerators in the Universe and it will do so 300 times faster than HESS has done. HESS was limited to the nearest few thousand light years; CTA can look anywhere in our Galaxy and will see blazars out at redshifts of 4 or 5. CTA will also bring an increase in precision, seeing structures as small as an arcminute across. The CTA will involve two sites, more than 100 telescopes and more than 1000 people in, so far, 27 countries, including everyone from HESS, MAGIC and VERITAS. Construction is expected to be complete in 2020.

The science that CTA will address ranges from the origin of galactic cosmic rays and their role in the Universe to fundamental particle physics, the nature of dark matter, the behavior of matter at high energies, cosmology and signs of quantum gravity. Some of the biggest bubbles in the Universe, five times the size of the Fermi bubbles, have recently been discovered around an active galactic nucleus at the centre of a galaxy cluster. It is thought that cosmic ray protons and neutrons are holding these bubbles up; if this is the case, CTA will see them. In summary, this is a very exciting time for the new field of astroparticle physics and the message from the past is to expect the unexpected.

Questions addressed the striking amount of time C T R Wilson spent working on his own instruments; who in the UK is building these instruments now? Professor Hinton said that instrument building is a UK strength, but we have to work in order to maintain that capability, and if we want to continue to have technical roles in such projects, we have to provide the resources and the infrastructure.

Meeting overview and the future of high-energy cosmic rays

Professor Alan Watson FRS, Emeritus Professor of Physics, University of Leeds

Professor Watson counted himself among those people influenced by C T R Wilson, not directly, but through two people who knew CTR well, George Evans at Edinburgh and J G Wilson at Leeds.

George Evans lectured on physical optics, and somehow inserted some meson physics within it. He enthused him through discussions of CTR's work related to the subject and cosmic rays. Watson studied many cloud chamber pictures taken by Evans in high-pressure argon and thus gained an important insight into cosmic ray processes. He showed one photograph in which an argon nucleus was shattered by a cosmic ray with the outgoing particles leading to the build-up of a cascade of particles, just as happens in an air shower in the atmosphere.

In 1964, Professor Watson moved to the University of Leeds to work with J G Wilson, who had been a research student of C T R Wilson's, and to help establish the Haverah Park water-Cherenkov detector array, of which J G Wilson was the founder. The major effort at this time was to try to discover whether there were excesses of particles from some regions of the sky, but the focus changed when, following the discovery of microwave background radiation, it was predicted that the abundance of the highest-energy cosmic rays should fall rapidly above 5×10^{19}eV.

By the end of the 1980s, a range of different techniques to detect these high-energy cosmic rays were producing a range of different results. However, most agreed that less than one particle reached the surface of the Earth per square kilometre, per century, the equivalent of roughly ten per minute reaching the outside of the Earth's atmosphere. This suggested that a detector much bigger than Haverah Park (12 km^2) would be needed to measure sufficient events to find out more.

In 1991, Professor Watson and Professor Jim Cronin of the University of Chicago started an international collaboration to design and build a much bigger instrument, eventually 3000 km^2. They used the water-Cherenkov technique that had been successful at Haverah Park and combined it with fluorescence detectors to pick up the ultraviolet, auroral-like emission from the air shower. They found the large flat area with clear skies they needed in western Argentina, which is now home to the Pierre Auger Observatory, completed in 2008: an array of 1600 water-Cherenkov detectors 1.5km apart, plus four fluorescence telescopes, spread over a near-circular area with a diameter similar to the distance from Edinburgh to Glasgow.

Collecting and combining the data from all these detectors proved critical to the success of the Observatory, solved in part by using GPS and adaptions of cellular telephone technology. The detectors fire 20 times per second, and each time they send a time signal to a central location where a computer is used to search for coincidences from three or more detectors that fire simultaneously. The footprint of the shower defined by the tanks shows the orientation of the shower, and the light curve from the fluorescence telescopes indicates the energy. The signalling used to coordinate data collection for this bluest of blue skies research was developed by Paul Clark at the University of Leeds; he now heads his own company, with an early contract being to use his Auger technology to improve the safety of single-track railway lines in the Scottish Highlands.

Another parallel that came out of the meeting was CTR's observation of *sprites* in 1927, but which was largely ignored at the time; the Pierre Auger Observatory also has an interest in *elves*, a related form of emission, which are common in the data but which were found quite unexpectedly.

Despite the audacious size of the Pierre Auger Observatory, it is too small to answer the biggest questions concerning the directional distribution of the particles and the details of the flux reduction now clearly observed. While the Observatory has been successful in locating events, around 30 that originate close to active galactic nuclei, few of these lie close to the galactic plane where the high-energy gamma ray sources are found, and there are no strong signals from astronomical objects thought likely to accelerate particles to high energy. There is potential for the future in combining data with the Cherenkov Telescope Array, to look at Centaurus A for example, or with telescopes in Space. The alternative would be to build an array 30 times the size of the Auger Observatory, something that has been proposed for the next decade.

In **discussion**, questions and comments focused on ways that the legacy of C T R Wilson could become more recognised, and used to promote interest in physics amongst school students and the general public. There was general agreement that CTR deserves better national recognition.

Professor Watson focused first on the visual appeal of the images produced by the cloud chamber. Professor Harrison and others noted that they have been pivotal to the development of similar techniques in other branches of physics, as today's speakers have shown, but they are also very appealing to people outside science – artists, for example.

Perhaps, Professor Watson suggested, we should all now refer to the cloud chamber as the Wilson Chamber, as is commonly done in France, and gain recognition for CTR in the way that Geiger's name is widely known from the Geiger Counter.

It would be useful to improve the display in the National Museum of Scotland, where refurbishment is planned for 2016, and to have recognition of CTR in the room devoted to Scottish Nobel Laureates in the Scottish National Portrait Gallery. It might also be worth investigating initiatives such as getting his image on the back of a banknote.

Questioners wondered if the lack of recognition over the past few decades had something to do with CTR not having a memorial in Westminster Abbey, or in the Scottish equivalent. It was noted that there is a blue plaque on a dyke by Glencorse Farm, CTR's birthplace, but something in central Edinburgh would be seen by many more people. The meeting place of the Alcovian Club was suggested as suitable location, while the placement of blue plaques on the houses lived in by CTR Wilson and Max Born in Grange Loan are under discussion.