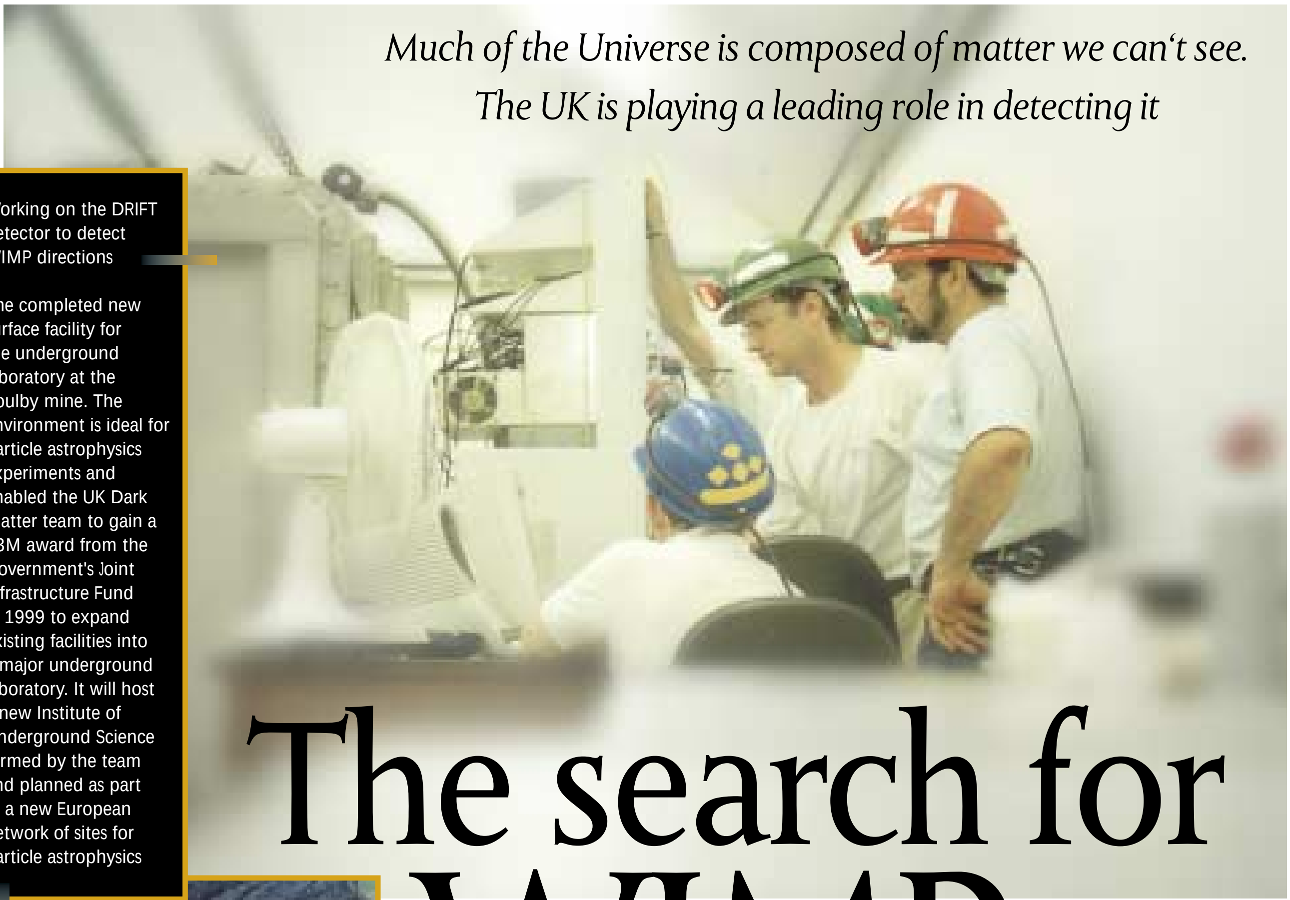
Much of the Universe is composed of matter we can't see. The UK is playing a leading role in detecting it



Working on the DRIFT detector to detect WIMP directions

The completed new surface facility for the underground laboratory at the Boulby mine. The environment is ideal for particle astrophysics experiments and enabled the UK Dark Matter team to gain a £3M award from the Government's Joint Infrastructure Fund in 1999 to expand existing facilities into a major underground laboratory. It will host a new Institute of Underground Science formed by the team and planned as part of a new European network of sites for particle astrophysics

The search for WIMPs

Neil Spooner

Measurements of the motions of galaxies and galaxy clusters indicate that there is much more matter in the Universe than observed in the form of luminous stars and galaxies. In fact, both observations and cosmological theory (see p.10) suggest that 90 per cent of matter must be in the form of so-called dark matter. Around the world the race is now on to detect this dark matter, and UK researchers are front-runners with a series of experiments of great technological ingenuity based in a unique deep underground site at Boulby, North Yorkshire. Earlier this year, one of the Boulby experiments, called ZEPLIN I, produced some of the best results. With this detector, new experiments just started – and further more sensitive devices on the way – the UK looks set to continue its high-profile leading role in the field.

The most likely explanation for dark matter appears to be that it is composed of so-called weakly interacting massive particles, or WIMPs. These are relic particles produced in the Big Bang and now distributed throughout the Universe. It is these WIMPs that the Boulby experiments aim to be the first to detect.

Importance of dark matter

There is much circumstantial evidence that WIMPs exist. For instance, they are predicted by certain theoretical extensions to the currently accepted description of matter and forces, the Standard Model of Particle Physics. But also their presence would go a long way to explaining the structure of the Universe we observe – the galaxies and clusters of galaxies. So both particle physicists and cosmologists are excited about the prospect of detecting these particles.

Meanwhile, alternative possibilities have, over the years, been increasingly ruled out. One such idea is that of MACHOs – massive astronomical compact halo objects. Some astronomers have suggested that these objects, which might typically be the size of large planets but do not emit sufficient radiation to be seen directly, could fill our Galaxy. However, if MACHOs exist their gravity would bend light from background stars (according to Einstein's General Relativity theory). Extensive searches for such 'microlensing' events have revealed that MACHOs probably do exist, but only in sufficient numbers to account for at most 20 per cent of the dark matter. So the hunt for WIMPs is on.

Unfortunately, detecting WIMPs is not an easy task. First, although many billions pass through your body everyday they ➤

hardly interact with ordinary matter. They can be detected only through very occasional collisions with the nuclei of a suitable target – a collision causes the nucleus to recoil slightly, which can be detected and measured in various ways.

Secondly, interactions with the many other forms of radiation coming from space – gamma-rays, alpha particles, electrons and cosmic rays – are likely to swamp any signal unless extreme measures are taken. The first such precaution is to go deep underground, at least 1 kilometre, to where the rock above provides sufficient shielding against this background radiation. The UK is exceptionally fortunate in that we have one of the deepest mines in Europe. At 1.2 kilometres, the Boulby mine, operated by Cleveland Potash, not only provides the depth required but, with caverns in salt rock easy to excavate, it also offers a safe and adaptable environment in which to build underground laboratories.

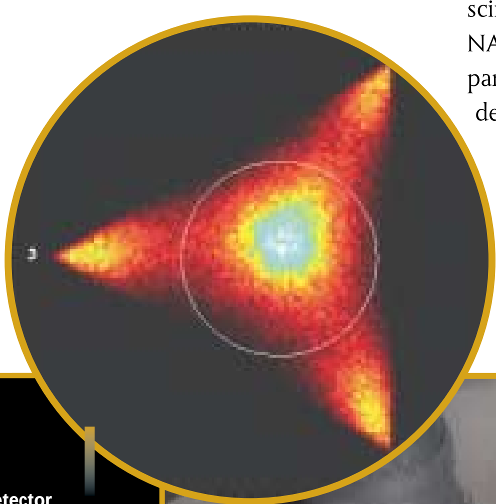
A further advantage of Boulby is that salt rock is relatively low in natural radioactivity. This is helpful with the next stage in the challenge to remove all extraneous background, which is to surround the detector by a dense, high-purity material to shield out gamma-rays from the rock. The best materials are lead and copper, so all the detectors at Boulby are placed within massive lead or copper 'castles' of up to 30 centimetres thick, sufficient to reduce the background by a factor of a million.

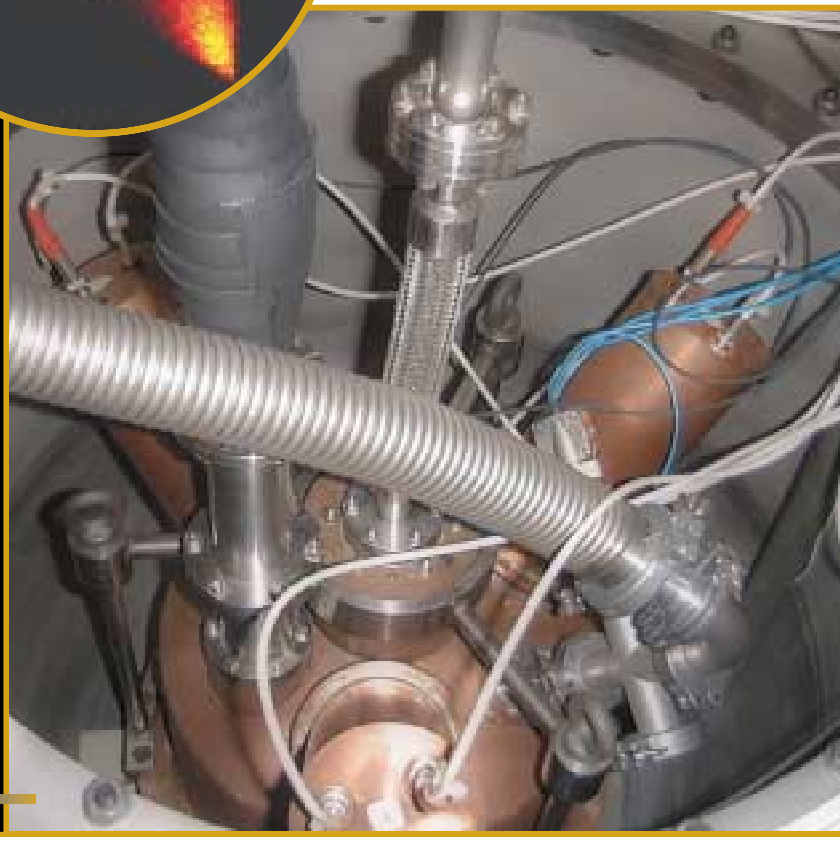
Winning technologies

Fifteen years ago, we did not really know how to build a detector for WIMPs, or whether it was even possible. So many technologies, with the help of several high-tech companies such as the UK-based Electron Tubes (*Frontiers* 7, p.22), have had to be investigated around the world. However, a winning combination of ideas has now emerged at Boulby, comprising a liquid xenon scintillator, a sodium iodide scintillator and a gas-based detector. In the first two detectors, the small amount of energy from the recoil causes photons of light to be released from scintillator material which can then be measured. In the third system, a low-pressure gas is ionised by the effects of the WIMP interaction. Most important is that all these detector systems fulfil a prime requirement for a successful WIMP detector – that it should be able to distinguish between nuclear recoils (the signal for WIMPs) and electron recoils (produced by the remaining background radiation).

The detector based on liquid xenon, ZEPLIN I, which was completed in 2000, is now yielding the best sensitivity to WIMPs of any currently running underground detector in the world.

In parallel with ZEPLIN I, an array of detectors called NAIAD (NaI Advanced Array), using sodium iodide (NaI) scintillation crystals, is also now running. NAIAD is potentially sensitive to WIMP particles of lower mass than ZEPLIN I. This detector has a particularly important role at the moment. We are using it to investigate a claim by the Italian-Chinese DAMA collaboration that they have detected a WIMP signal in their more massive NaI array in the Gran Sasso tunnel near Rome. This





The ZEPLIN I detector
The device consists of 4 kilograms of liquid xenon contained in a high-purity copper vessel viewed by three photomultipliers, which sense the scintillation light possibly produced by a WIMP event, and amplify the signal. Typical data are produced in plots as shown in the inset. Here, each event, comprising coincident signals from all three photomultipliers, is plotted in a position weighted according to the size of the signal in each channel. Points nearer to one photomultiplier than the others are likely to be background events from the glass in that tube and so can be rejected. In liquid xenon, it turns out that the scintillation light produced by nuclear recoil events emerges over a period about 50 per cent faster than for electron recoils – thereby allowing the electron background to be rejected on a statistical basis

team was looking for a signal that varies during the year. Such a modulation is predicted for WIMPs because the Earth's orbit around the Sun results in a small change in our velocity relative to the WIMPs in our Galaxy. However, the effect is small and could be mimicked by seasonal background changes in the detector. The ability of NAIAD to separate genuine recoil events from background should resolve the issue.

Ultimately it will be necessary to check that a nuclear recoil signal, such as from ZEPLIN, is genuinely due to WIMPs in the Galaxy. The best way to do this is to correlate the response of a detector with our motion through the WIMPs. The annual modulation technique above is one, though weak, possibility. A much more powerful technique is to measure the directions of nuclear recoil events. For instance, it is estimated that because of our orbit around the Galaxy at about 230 kilometres per second there will be a difference between the forward and backward directions of the recoils of as much as 1 to 100. The third and final experiment at Boulby aims to measure this difference using a low-pressure gas in which individual events produce ionisation tracks. The DRIFT (Directional Recoil Identification From Tracks) detector (*Frontiers* 12, p.5) can achieve this by imaging the tracks on a type of 2-dimensional detector which uses wires held at an electrical potential to register the charge from the ions. DRIFT was installed in part of the new JIF laboratory at Boulby last summer and is now undergoing preliminary runs to search for a directional signal.

It may be that the Boulby experiments are on the brink of a discovery. However, we know that WIMPs could be very elusive. So the Boulby team has built up an international network of collaborators from the US and Europe which together are developing a third generation of much more sensitive detectors for Boulby. Xenon experiments ZEPLIN II and ZEPLIN III, currently under construction, will improve sensitivity by100 times. Plans are already being drawn up for a much larger experiment, the 1- tonne ZEPLIN-MAX. This device should be capable of answering once and for all the question: do WIMPs make up most of the material in the Universe – the dark matter? ✥

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UK researchers are front-runners with a series of experiments of great technological ingenuity

A cut-away drawing of the new ZEPLIN II detector currently being constructed

The NAIAD detector
This comprises a set of eight high purity sodium iodide (NaI) scintillation crystals, each 5 to 10 kilograms in mass. Like ZEPLIN I, the array is surrounded by lead and copper. Again, nuclear recoils produce a different statistical signal from that of background electron recoils