The big squeeze

Exploring the world of ultra-high pressures

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Exhibitors:
Dr Miriam Marques Arias, Dr Craig Bull, Mr Alistair Davidson, Mr Shaun Evans, Dr Eugene Gregoryanz, Dr Malcolm Guthrie, Dr Ingo Loa, Dr John Loveday, Mr Lars Lundegaard, Ms Helen Maynard, Dr Malcolm McMahon, Professor Richard Nelmes FRS and Dr Colin Pulham,
The University of Edinburgh

Background

The pressure of the air in which we live is one atmosphere. This is also the pressure exerted by a column of water 10 metres high, and creatures in the deepest ocean live at a crushing 1,000 atmospheres. But some 90% of the mass of our solar system is at pressures of more than 100,000 atmospheres, the Earth's core is at three and half million atmospheres, and Jupiter has internal pressures of tens of millions of atmospheres. The pressure at the centre of the sun is one hundred billion (10^{11}) atmospheres, while that at the centre of a neutron star is an incredible 10^{30} – a thousand billion billion billion – atmospheres.

The 'normal' pressures of everyday life, and everyday science, are thus very unusual, as are the ways that materials behave under these 'normal' conditions. Pressure can cause extraordinary changes in all kinds of materials. It can turn oxygen gas into beautiful red crystals and change hydrogen into an exotic metal. And it can create completely novel materials – like the example of diamond in nature – and destroy bacteria to sterilise food.

At the Centre for Science at Extreme Conditions at the University of Edinburgh, we use extremes of pressure to discover exotic behaviour in simple metals, find out where the methane has gone in Saturn's moon Titan, solve puzzles in the structure of crystalline oxygen, explain the peculiar properties of water, look deep inside the Earth, explore crucial structural variations in pharmaceuticals, and probe the limits of life.

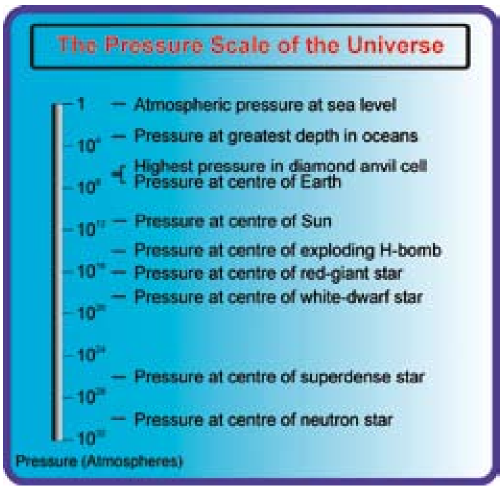

***Figure 1:** The high-pressure scale of the Universe covers a huge range of 10^{30} atmospheres*

Methodology

Pressure is defined as force per unit area, and we can therefore generate very high pressures using only moderate forces by concentrating them onto a very small area – the 'stiletto heels' effect. The ideal material for doing this is diamond, as it is both extremely hard and transparent. With the diamond anvil cell (DAC), a device small enough to hold in one hand, we can squeeze samples to pressures of millions of atmospheres between diamond tips and see the sample by looking through one of the diamonds. The sample volume is extremely small – much smaller than the size of a single grain of salt yet using lasers, x-ray beams and neutron beams, we can investigate how the atomic structures of materials changes with pressure, and how the magnetic, superconducting or chemical properties change.

The science behind the research

How do materials change at high pressure? Under 'normal' conditions, metals such as potassium can be regarded as a rigid array of positive ions surrounded by a 'sea' of negative electrons. But as the pressure is increased, the space available for the electrons is greatly reduced and, as a result, the atoms rearrange themselves into exotic new structures, unlike anything seen at ambient pressures.

Carbon exists under normal conditions as the flaky, opaque material graphite, but when subjected to very high pressure it changes into diamond – a completely different material that is transparent and very hard, as we know.

Simple gases such as oxygen first liquefy as the pressure is increased, and then solidify into a number of different structures which differ in the way in which the O_2 molecules are packed together. In one of these phases, oxygen forms beautiful dark red crystals, and we have recently shown that the structure comprises $(O_2)_4$ molecules – again, unlike anything seen at 'normal' ambient pressure. At higher pressures still, oxygen turns into a superconducting metal.

Further information

The Centre for Science at Extreme Conditions at The University of Edinburgh
www.csec.ed.ac.uk

High-pressure Physics at The University of Edinburgh
www.ph.ed.ac.uk/cmatter/highpressure.html

High-pressure Chemistry at The University of Edinburgh
www.chem.ed.ac.uk/crp/highpressure.html

Nitrogen at pressures above a million atmospheres has been shown to turn into a remarkable polymer, with more stored energy than the most powerful known high explosives.

Water is a remarkably complex system even at ambient pressure, but exhibits a number of still more exotic forms at high pressures – including forms of ice that melt only above 1000°C. But perhaps the most striking of these exotic phases are the amorphous forms of ice found at high pressures and low temperatures. These glass-like structures exist in 'low', 'high' and 'very high' density forms, and we have used our detailed studies of the transitions between them to help understand the behaviour of water itself at high pressures.

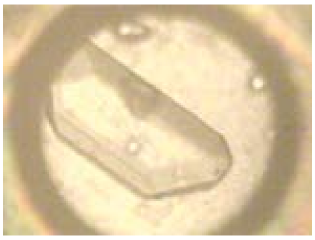

Figure 2: *A crystal of the high-pressure form of the pain-killer paracetamol*

The application of high pressures to more complex molecules such as pharmaceuticals is also an area of very active research. Under these conditions, the molecules pack together in different arrangements to give new forms that exhibit different properties such as solubility and density. Very high pressures are also generated when an explosive substance such as TNT undergoes detonation. Under these extreme conditions the properties of the explosive, such as density, crystal form, and reactivity, are dramatically changed.

Applications of the research

High-pressure science is a route to wholly new materials not found at ambient conditions. Because of its ability to radically alter inter-atomic distances, pressure can be used to continuously 'tune' electrical and magnetic properties, offering a rapid and powerful method of developing new optimised materials. Pressure can also polymerise gases such as methane and ammonia, while the recent conversion of CO_2 into a glass-like form could lead to a way of storing or disposing of carbon dioxide deep within the Earth's interior.

High pressure is also being used in the search for new crystal forms of pharmaceutical compounds with enhanced properties, such as improved uptake by the body and better processing characteristics. An understanding of the pressure-induced changes in explosives is crucial for the prediction and modelling of the performance of these materials, and in the design of new, safer explosives that are less sensitive to accidental initiation.

Pressure is increasingly used worldwide to sterilise food, and to alter the texture of foodstuffs. There is also potential for applications in destroying pathogens as part of therapeutic treatment.

Future research

Current high-pressure techniques using DACs are limited to about three million atmospheres, which is not high enough to find the 'holy grail' of high-pressure physics – the metallic phase of hydrogen. We are now developing techniques to push attainable pressures to five million atmospheres and temperatures of >5000K, opening the door to the study of astrophysical 'warm dense matter' and enabling us to pursue the study of exotic phases such as metallic nitrogen, polymeric oxygen and metallic fluid ammonia. Simultaneously, we are investigating methods by which we can grow very large gem-quality diamonds, and embed metallic circuitry into them in order to make 'smart' or 'designer' diamonds.

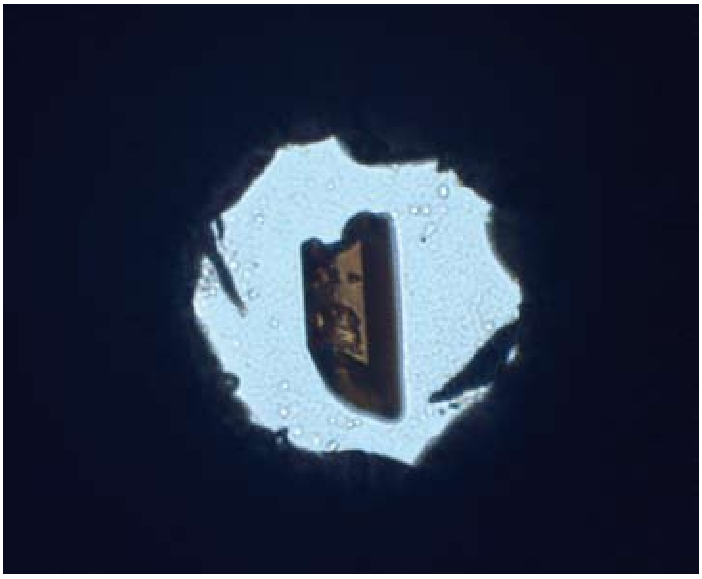

Figure 3: *A crystal of the high-pressure 'red' phase of oxygen at 176,000 atmospheres*