Experimental Physicist: Sir Paul Callaghan

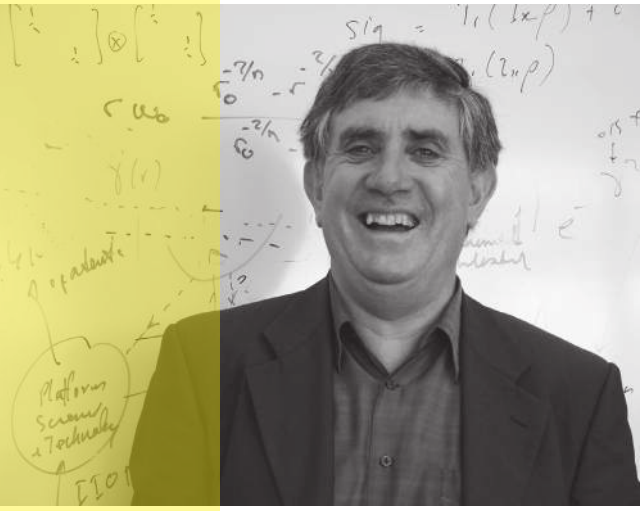
At the heart of matter

Look around you. Inside every object you can see lie hidden worlds as detailed and busy as the one we live in and as unfamiliar as outer space. Zoom in a thousand times and a piece of paper would transform into a tangled network of fibres. A thousand times further and the fibres would open up to reveal long molecules twisted together like the wires in an electric cable. Zoom inside a molecule and you would find yourself in a vast expanse of empty space. Shimmering clouds of electrons would form intricate patterns around you. Dotted throughout space, almost invisibly small, you might spot an atomic nucleus – a tiny solid clump at the centre of the atom.

No one has ever seen the atomic nucleus. But this is the world that Paul Callaghan lives in. Like an explorer he is constantly drawn further in.

Finding the meaning behind the magic

"As a boy growing up in Wanganui, physics seemed to surround me," Paul remembers. "I made my first crystal set radio at primary school and was delighted to pick up two channels. When I was ten years old Sputnik was launched, with many more satellites following. Some you could see with the naked eye, repeating their orbit every 90 minutes. In my early teens I was a boy chemist with a backyard laboratory, pursuing adventures that would today be considered foolhardy at best, criminal at worst."



All these experiences took on meaning and magic once Paul started to learn science and maths at school.

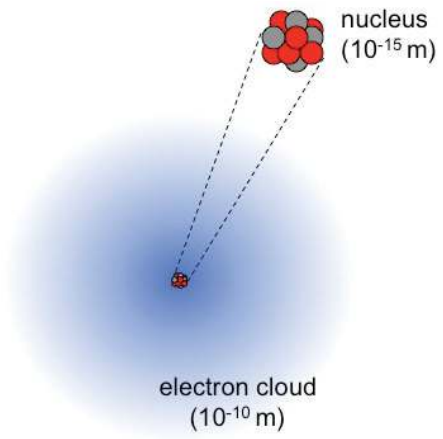
"I remember the precise moment I met calculus," he recalls. "It totally blew me away! Suddenly I could see the relationship between things: the curves of power lines hanging from telegraph poles, a cricket ball arching through the air and a swing swaying from side to side were suddenly brought together by a universal law of gravity described by a mathematical formula."

Paul realised he could use formulae like this to predict how objects would behave in different situations. It was magic! As if he had discovered the language of Nature.

It has taken scientists hundreds of years to construct theoretical models to describe and explain almost

Atoms - Nature's Building Blocks

If the atom in this picture were drawn to scale then the closest electrons would be orbiting around half a kilometre away. And yet the actual diameter of an atom is so small that it would take around fifty million atoms lined up side by side to form a centimetre long line.



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every aspect of Nature. They have discovered universal laws such as quantum physics and gravity that help us understand and control the world around us. But there is still so much to find out. It is the job of scientists to coax Nature into revealing more. They do this by studying the current theories and models, looking for gaps or contradictions, developing new models and designing experiments to test them The process requires an open-mind, creativity and persistence.

Using magnetism to understand matter

Paul's speciality is called Nuclear Magnetic Resonance (NMR), a technique for probing materials to find out what they're made of and how they're put together. In his lab are two round white tanks about a metre across. Inside each is a massive magnet made out of a coil of superconducting wire. Inside each magnet sits a small sample of matter (it could be detergent, oil-bearing rocks or biological tissue), and inside that sample, billions of atomic nuclei hover, spinning like tops around the magnetic field lines. NMR works by applying tiny bursts of energy that throw the nuclei out of equilibrium so they rotate wildly around the magnetic field. This sudden change of movement creates a small magnetic field that can be detected and the data decoded to reveal valuable information about the atoms and molecules inside the material.

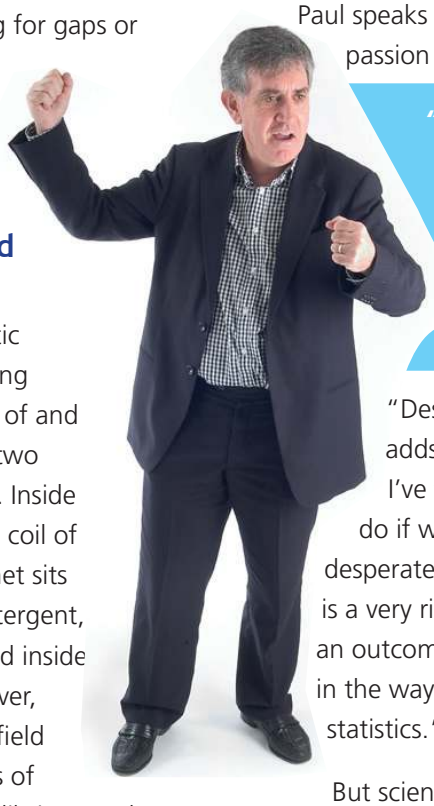
Paul is famous for discovering a way to use NMR to measure how atoms and molecules move around inside soft matter and porous materials such as rock or body tissue. The techniques he developed are now used in hospitals to take high-resolution brain scans. They are also used to find the most efficient way of extracting oil from the ground, to develop tasty low-fat foods and to improve the consistency of skin-care products.

With years of experience Paul has learnt to slip easily between the human-sized world and the secret world of the nucleus.

"On one level I could be thinking about the signal that's coming out," he explains, "but at the same time my mind is down there with the nucleus. What's it doing? Is it responding to these things? How can I find out more? As the data comes out I'm analysing it and adjusting the experiment accordingly. We have models of what the nuclei do in their interaction with the environment and they're actually real to me."

The joy of experimenting

Paul speaks about experimental physics with the passion of an artist.



"It's a process that requires total commitment of body and soul. It's utterly exhausting. I'm very involved. That's why I enjoy it. That's why I love doing experiments." – Paul Callaghan

"Designing a new NMR experiment," he adds, "is like writing a score for an orchestra. I've thought about what the nuclei might do if we play these new tricks on them and I'm desperately hoping they're going to do that. This is a very risky way to go when you're hoping for an outcome. You need to be totally meticulous in the way you handle the data and the noise and statistics."

But science needs risk-takers and visionaries too. Many of the greatest discoveries have happened this way. Take Watson and Crick who discovered the structure of the DNA molecule:

"They had this idea of a helix," says Paul. "They were obsessed with it! They were looking for anything that justified it. And in the end they succeeded."

One of Paul's role models in experimental physics is the Kiwi Nobel Prize-winning physicist Ernest Rutherford. In the 1890s, when Rutherford started his career, scientists thought that atoms were solid lumps. Rutherford devised an experiment proving they are almost entirely space. And it is in this space that Paul has spent his rich career.

Coming home

Paul studied Physics at Victoria University in Wellington with a few papers in English and Chemistry. He won a scholarship to do a PhD at Oxford University in England and after that was offered a prestigious job in a Canadian University. But with a wife and young family he decided to return home, accepting a job at Massey University in Palmerston North. He joined a small group of physicists within a chemistry department.

"The rest of it all happened by accident," he says. "Suddenly I was surrounded by chemists and biochemists and I had to get into that world and see the opportunities. Having been a narrowly focussed physicist I began to see the wonders of chemistry, the world of molecules, with all the opportunities for physics that this field presented. It couldn't have turned out better for me."

Early in his career Paul developed an NMR tool, which accurately tracked the movement of molecules for the first time. Later, by applying physics models of wave diffraction to NMR experiments he developed transformative new theories and methods that are now used across the world.

"As a physics student you get given a tool kit of model examples, like a mass on a spring or waves diffracting over water," Paul explains. "These simple examples are like metaphors for so much we can see around us. When you bring them to another field like chemistry you can make a big difference. You don't need to know everything to be a scientist, just have a bag of tricks and know how to use them really well."

Being in New Zealand, away from the world centres of science, allowed Paul the space and confidence to find his own niche and follow his intuition.

"It pushed me into a field which was far more productive than the area of my PhD," he says. "I'm doing beautiful physics in a field where I can make a big difference."

Out into the world

While Paul dug further into the secret world of atomic nuclei, his breakthrough discoveries in NMR were winning him international acclaim. The techniques he was developing had a vast number of useful applications in the food, cosmetics and oil industries and he had written a book on NMR techniques which is now the main reference for the field.

In 2001 something happened that changed the course of Paul's career. He had just moved to Wellington to take a job at Victoria University when he met the famous Kiwi chemist Alan MacDiarmid. The previous year Alan had won the Nobel Prize in Chemistry and returned home to give a lecture tour.

"Everywhere he went he filled venues to capacity," says Paul. "He wasn't just a chemist. He was a poet! He had the showman's craft of capturing people's hearts. He spoke about why science is beautiful and told stories in his down-home Kiwi accent that moved people to tears. For me the penny dropped!"

Paul had always loved writing and was a natural performer. Suddenly he saw the possibility to combine those interests with his science. He started giving radio interviews, writing popular science books, engaging with the public through lectures and dialogues and even collaborating with poets.

He was also inspired by Alan's political stance, how he promoted the value of science and technology to society and wasn't afraid to make politically provocative statements.

Paul has since become an advocate for science in New Zealand, realising that unless we pool our resources and start working together New Zealand won't have the critical mass to compete internationally. In 2002 he helped establish the MacDiarmid Institute for Advanced Materials and Nanotechnology – one of eight centres of research excellence selected by the Government for special support. The Institute is based on the principles of collaboration and communication inspired by Alan MacDiarmid.

Paul believes that science and technology have the potential to transform New Zealand's culture and economy and provide exciting new job opportunities for young people. In partnership with three colleagues, he started a high-tech export company, *Magritek*, which employs several science graduates and sells portable NMR equipment to the oil industry and researchers worldwide. His example has been an inspiration to a generation of young scientists and entrepreneurs.

Paul Callaghan loading a sample into the superconducting magnet