COMMENT

ENVIRONMENT The age of cheap, abundant water is ending **p.27**

FILM Werner Herzog on cave painting and the brutality of nature **p.30**

POLICY Overhauling the NIH will not fix the broken US health pipeline **p.31**

COMMUNICATION Public mistrust of Japanese officials is not irrational but sensible **p.31**

D. TUFFS/THE GUARDIAN

Hans Geiger (left) and Ernest Rutherford's experimental work revealed the nucleus at the centre of atoms.

From isotopes to the stars

Creating more exotic isotopes will reveal the stellar formation of atoms — a fitting tribute to Ernest Rutherford, say **Michael Thoennessen** and **Bradley Sherrill**.

A hundred years have passed since Ernest Rutherford published his discovery of the atomic nucleus in May 1911 and started a journey to the centre of the atomic world. In Rutherford's famous experiment, a stream of α -particles was aimed at a very thin sheet of gold foil. Some of the particles were deflected at angles that suggested they had collided with a small, dense atomic core. As Rutherford remarked: "It was almost as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you." The experiment supported a planetary model of the atom — the idea that most of the mass is concentrated in a nucleus, with even smaller electrons orbiting it like planets around the Sun.

Over the century since, scientists have probed to sizes 1,000 times smaller than Rutherford managed — to the level at which quarks are important — and developed the

standard model to describe these particles and their interactions. This quest to find nature's ultimate building blocks is being led by experiments at CERN, Europe's particle-physics laboratory near Geneva, Switzerland.

Despite this progress, some basic questions remain unanswered. It is not known how Rutherford's nucleus can result from quarks and the strong force. It is not even known in detail how the strong force binds quarks to make neutrons and protons, or how it results in the forces that hold together protons and neutrons in the nucleus. Even simpler questions, such as how many elements might be possible, or how many neutrons a given number of protons can bind, are currently unanswerable.

So, away from the high-profile, high-energy frontier, a small army of machines is quietly advancing understanding of the atomic nucleus by generating new and rare

nuclides — atoms with a specific number of protons and neutrons in their nuclei. In 2010, for the first time, more than 100 new unstable isotopes — nuclides with different numbers of neutrons — were discovered in a single year (see "The nuclide trail"). We expect more than 1,000 new isotopes, including some of the most scientifically interesting to date, to be discovered over the next decade or so.

Initially, the search for new isotopes was driven by the quest for the unknown, to make something nobody else had made and the urge to understand the underlying forces. But they have enormous practical applications too: in nuclear energy, medical imaging and treatment, carbon dating and tracer elements. The international effort to create new isotopes will push our understanding of atom formation and nuclei to new levels, but may also lead to applications.

Even before Rutherford's experiment, ►

UNIV. MANCHESTER

THE NUCLIDE TRAIL

Isotope discovery over the past 100 years (below) has jumped with each introduction of new technology. Some 2,700 radioactive isotopes have been discovered so far (below right), but about 3,000 more are predicted to exist.

▶ radioactive-decay studies showed that a given element can exist in different forms. The discovery of the neutron in 1932 revealed that the nucleus of an atom was composed of protons and neutrons. Soon after, Irène Curie and Frédéric Joliot used α -particles from polonium and targets of boron, magnesium and aluminium to create the first radioactive isotopes in the laboratory. The new isotopes of nitrogen, aluminium and phosphorus had one neutron fewer than the normal stable nuclides of these elements.

Since then, researchers have been searching for the limits of nuclear existence, to discover what element may have the most protons and what are the largest (and smallest) number of neutrons for a given element. Even today, the limit to the number of neutrons that an element can bind is known only for the lightest elements, from hydrogen to oxygen. That is one very small corner of the possible nuclear landscape (see 'The nuclide trail').

There are almost 300 stable nuclides on Earth and another 2,700 radioactive isotopes have been identified so far. This represents perhaps only half of all predicted isotopes. Around 3,000 have yet to be discovered (it might be as many as 5,000 or as few as 2,000). Although the different masses of isotopes do not influence their chemistry much, the production and study of rare isotopes is crucial to understanding the process of nature that makes atoms in their birthplace.

Most of the elements in nature are created in stars and stellar explosions, and the isotopes involved are often at the very limits of stability. The next generation of rare-isotope accelerators will create, for the first time on Earth, most of the isotopes that are formed in stellar environments. Where physicists currently have to rely on theoretical models based on extrapolations, they will soon measure the properties of most of these isotopes directly. It could help to answer

other fundamental astrophysics questions on where in the cosmos these isotopes are created, why stars explode, the nature of neutron stars and what the first stars in the Universe were like.

MARCH OF MACHINES

The first particle accelerators, developed in the early 1930s, revealed many new isotopes. The Second World War delayed progress but, afterwards, neutron-capture and neutron-fission reactions in nuclear reactors continued the exploration. The next advance was the development of heavy-ion accelerators in the 1960s, which produced heavy neutron-deficient isotopes in fusion evaporation reactions.

With higher-energy accelerators in the 1990s, scientists could create more neutron-rich nuclei during in-flight fission or projectile fragmentation of high-energy heavy ions. This has been the most productive route to isotope discovery in recent times. But in the past decade, the rate of discovery dropped to levels not seen since the 1940s. It became obvious that dedicated rare-isotope accelerators were needed to make further progress.

The first of these facilities, the Rare Isotope Beam Factory, came online in 2007 in Wako, Japan. In 2010, it reported the discovery of 45 new neutron-rich isotopes.

To ensure that this is the beginning of a new era rather than just a discovery spike, it is crucial to continue efforts worldwide. Centres are under development, such as the Facility for Antiproton and Ions Research in Darmstadt, Germany, SPIRAL2 in Caen, France, and the Facility for Rare Isotope Beams at Michigan State University in East Lansing. Scientists in the United States have been trying to build a rare-isotope accelerator for almost 20 years. Funding for an earlier facility was halted during a previous period of austerity.

Today's difficult financial conditions must

not be allowed to halt the machine builders. The facility in Germany still needs to secure sufficient funding to start operations by the end of the decade. Isotope discovery over the past 100 years has been a worldwide effort, with more than 3,000 scientists in 125 laboratories in 27 countries contributing. It will be a shame if the German facility — an international collaboration from its outset — does not move forward expeditiously.

Pushing science to the limits produces surprises. We have already learned that rare nuclei with extreme proton-to-neutron ratios don't always follow the textbook behaviour of known stable isotopes. For example, the size of stable nuclei is proportional to their mass — it scales as $A^{1/3}$ (where A is the mass number of neutrons and protons). However, this simple relationship ignores any differences between neutrons and protons. Some rare nuclei that exist only fleetingly have proved to be significantly larger.

Other surprises may be in store. Hopefully, the next-generation facilities will create more than 1,000 new isotopes, and the limit of nuclear existence will be pushed towards heavier elements, up to zirconium (40 protons) but still some way from gold (79 protons). Fundamental phenomena are waiting to be discovered, and increased production of rare isotopes will bring new applications in medicine and other fields. We are confident that in the next 10–15 years, most of the isotopes needed to answer the question 'What is the origin of elements in the cosmos?' will be created in the lab for the first time. A fitting tribute to Rutherford. ■

Michael Thoennessen and Bradley Sherrill are at the National Superconducting Cyclotron Laboratory and the Department of Physics and Astronomy at Michigan State University, East Lansing, Michigan 48824, USA. e-mails: thoennessen@nscl.msu.edu; sherrill@frib.msu.edu