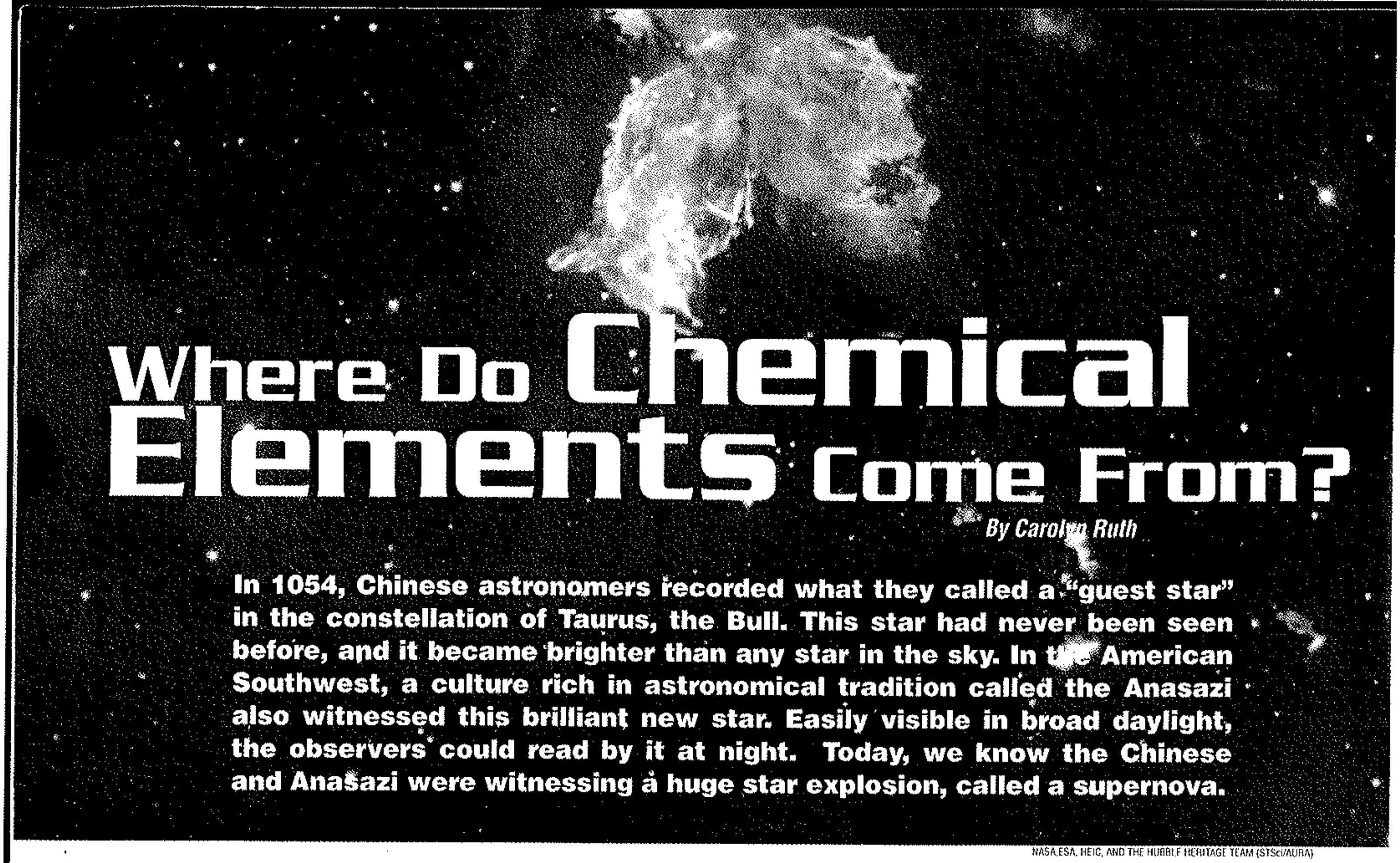


Where Do Chemical Elements Come From?

By Carolyn Ruth

In 1054, Chinese astronomers recorded what they called a "guest star" in the constellation of Taurus, the Bull. This star had never been seen before, and it became brighter than any star in the sky. In the American Southwest, a culture rich in astronomical tradition called the Anasazi also witnessed this brilliant new star. Easily visible in broad daylight, the observers could read by it at night. Today, we know the Chinese and Anasazi were witnessing a huge star explosion, called a supernova.

NASA,ESA, HEIC, AND THE HUBBLE HERITAGE TEAM (STScI/AURA)

What these observers did not know is that during the explosion, the star not only emitted huge amounts of light—more light than a billion suns—but also released chemicals in space. Inside the star were most of the first 26 elements in the periodic table, from simple elements, such as helium and carbon, to more complex ones, such as manganese and iron; and the giant explosion sprayed them in space. During the explosion, other elements were created as well, and after the explosion, the chemicals in space combined with each other to form ions and molecules.

These elements travel in space and ultimately end up in planets like Earth, being part of everything we see around us and ourselves. The carbon in our cells, the oxygen in the air, the silicon in rocks, and just about every element, were all forged inside ancient stars before being strewn across the universe when the stars exploded.

During the past century, scientists have been studying how chemical elements form in stars and in outer space. Like genealogists—experts who study the origins of people and families—these scientists can track down where most chemical elements came from and how they descended from each other. And, similar to forming a family tree, studying the links between the chemical elements has brought—and keeps bringing—many surprises and interesting discoveries.

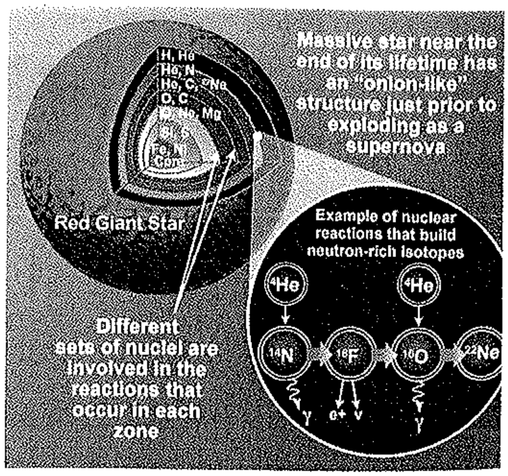
Stellar ovens

A young star is composed primarily of hydrogen, the simplest chemical element. This hydrogen ultimately leads to all known elements. First, the two constituents of each hydrogen atom—its proton and electron—are separated. The high pressure inside the star can literally squeeze together two protons, and sometimes, a proton will capture an electron to become a neutron.

When two protons and two neutrons band together, they form the nucleus of helium, which is the second element in the periodic table. Then, when two nuclei of helium fuse with each other, they form the nucleus of another element, beryllium. In turn, the fusion of beryllium with helium produces a carbon nucleus; the fusion of carbon and helium nuclei leads to an oxygen nucleus, and so on. This way, through successive fusion reactions, the nuclei of most elements lighter than iron can be formed (Fig. 1). Scientists call this process nucleosynthesis (for "synthesis of nuclei").

In stars, these fusion reactions cannot form elements heavier than iron. Up until the formation of iron nuclei, these reactions release energy, keeping the star alive. But nuclear reactions that form elements heavier than iron do not release energy; instead, they consume energy. If such reactions happened, they would basically use the star's energy, which would cause it to collapse.

Not all stars form iron, though. Some stars explode before creating that many ele-



LAWRENCE LIVERMORE NATIONAL LABORATORY

Figure 1. The chemical composition of a star before it explodes into a supernova.

ments. In stars less massive than the sun, the reaction converting hydrogen into helium is the only one that takes place. In stars more massive than the sun but less massive than about eight solar masses, further reactions that convert helium to carbon and oxygen take place in successive stages before such stars explode. Only in very massive stars (that are more massive than eight solar masses), the chain reaction continues to produce elements up to iron.

A star is a balancing act between two huge forces. On the one hand, there is the crushing force of the star's own gravity trying to squeeze the stellar material into the smallest and tightest ball possible. On the other hand, there is tremendous heat and pressure from the nuclear reactions at the star's center trying to push all of that material outward.

The iron nucleus is the most stable nucleus in nature, and it resists fusing into any heavier nuclei. When the central core of a very massive star becomes pure iron nuclei, the core can no longer support the crushing force of gravity resulting from all of the matter above the core, and the core collapses under its own weight.

NASA/CXC/ASU/J. HESTER ET AL.

Combined X-ray and optical images of the Crab Nebula.

The collapse of the core happens so fast that it makes enormous shock waves that blow the outer part of the star into space—a supernova. It is during the few seconds of the collapse that the very special conditions of pressure and temperature exist in the supernova that allow for the formation of elements heavier than iron. The newly created elements are ejected into the interstellar dust and gas surrounding the star.

"The amount of elements released through a supernova is truly phenomenal," says Stan Woosley, professor of astronomy and astrophysics at the University of California at Santa Cruz. "For example, SN1987A, a supernova seen in 1987, ejected 25,000 Earth masses of iron alone."

How stars make elements heavier than iron

Elements that are heavier than iron can be assembled within stars through the capture of neutrons—a mechanism called the "s" process. The process starts when an iron nucleus captures neutrons, thus creating new nuclei. These nuclei can be either stable, that is, they do not change, or radioactive, meaning that they transform, or decay, into another element after a certain amount of time, which can be as short as a fraction of a second and as long as a few million years.

Also, the newly formed nuclei can be different versions of a given element. These different versions of an element are called isotopes. They all contain the same number of protons in their nucleus but have different numbers of neutrons. Some isotopes are radioactive, while others are stable and never change.

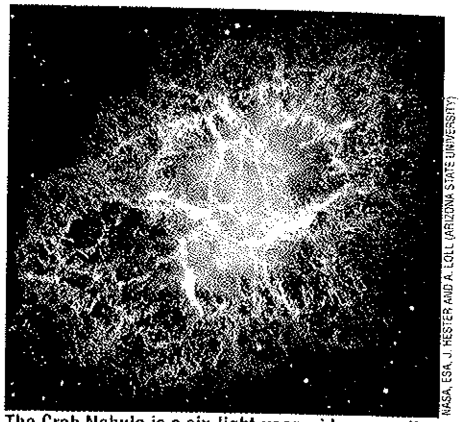
For example, nickel can appear in the form of 23 different isotopes. They all have 28 protons, but each isotope contains between 20 and 50 neutrons. Of these 23 isotopes, only five are stable, while the others are radioactive.

If a nucleus produced through the "s" process is stable, it may capture another neutron. If it is radioactive, it transforms into another nucleus. This other nucleus can, in turn, absorb another neutron, leading to a heavier nucleus.

For example, nickel-64, which contains 28 protons and 36 neutrons, can absorb a neutron, leading to nickel-65, which contains 28 protons and 37 neutrons:

Ni-64 (28 protons, 36 neutrons) + neutron → Ni-65 (28 protons, 37 neutrons)

Nickel-65 is radioactive. It exists for only 2 and a-half hours, and then transforms into copper-65—the next element in the periodic table, which contains 29 protons and 36 neutrons. This is a process called beta decay, in which a neutron transforms into a proton and an electron:



NASA, ESA, J. HESTER AND A. LOLL (ARIZONA STATE UNIVERSITY)

The Crab Nebula is a six-light-year-wide expanding remnant of a star's supernova explosion.

Ni-65 (28 protons, 37 neutrons) → electron + Cu-65 (29 protons, 36 neutrons)

Copper-65 is stable, so nothing happens after that.

This neutron capture mechanism, called the "s" process, is extremely slow. Hundreds or thousands of years might elapse between neutron strikes. But another process, called the "r" process, which stands for "rapid," allows for the rapid capture of neutrons. Unlike the "s" process, which occurs inside a star before it explodes, the "r" process happens only during the explosion of a star.

Exploding and cooking elements at the same time

When a star explodes into a supernova, it produces a huge amount of light and releases an extremely high number of neutrons (on the order of 10 thousand billion billion neutrons per square inch per second). These neutrons are then rapidly captured by the various nuclei that are also released by the exploding star, producing new nuclei through the "r" process.

In this process, even though many neutrons are available, only a limited number can be added to a given nucleus; otherwise, a nucleus becomes radioactive and breaks up. Neutrons in a nucleus are thought to occupy shells—similar to successive shells on a hard candy. When a nucleus gets "saturated" with neutrons, that is, when its shells are filled up, it undergoes a beta decay process to become the nucleus of the next element on the periodic table. This new nucleus, in turn, absorbs as many neutrons

Finding Chemicals Inside Stars

To determine which chemical elements are formed inside stars, scientists use a technique known as visible spectroscopy. It is based on a device, called a spectroscope, which spreads visible light into its component colors by passing it through a prism or grating.

These colors are called an emission spectrum, and their position and intensity differ according to the chemical element that emits the light. For example, the hydrogen's emission spectrum consists of four lines: purple, blue, green, and red, located at positions that correspond to their wavelengths. The emission spectrum of helium consists of six lines that are purple, cyan, green, yellow, orange, and red. In other words, atoms and molecules produce their own "fingerprint" or "signature" when the light they emit is spread in a spectroscope.

Astronomers also measure how much light is present at each spectral line. The overall strength or weakness of all the lines of an element depends on the number of atoms of that element. The percentage composition of the atoms in a stellar body can also be determined. For example, by looking at the light emitted by the sun, scientists have been able to determine the relative number of atoms from specific elements and infer their percentage by mass.

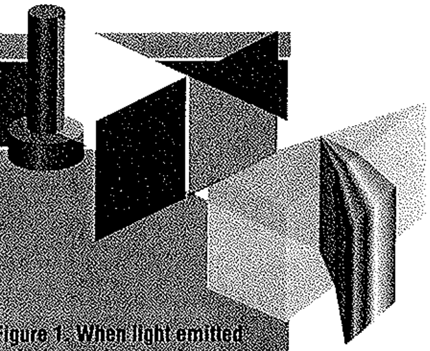


Figure 1. When light emitted by hydrogen is spread through a spectroscope, it reveals a characteristic emission spectrum specific only to hydrogen.

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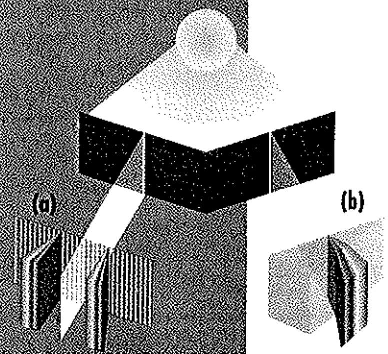


Figure 2. Sketch of a spectroscope and how it forms a spectrum. The light emitted by a source from space goes through a narrow slit to form a beam of light, which is then spread into its components by a grating (a) or a prism (b), resulting in the light's spectrum.

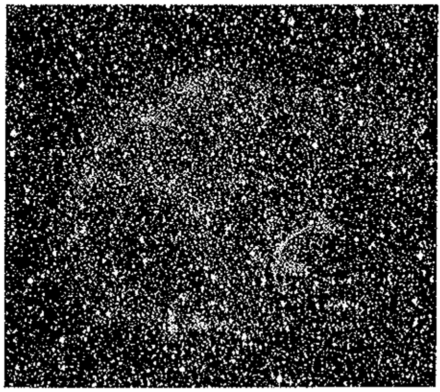
as it can hold, and then decays when it is "saturated" with neutrons, and the cycle starts again. When an element formed through the "r" process becomes really heavy (total number of protons and neutrons close to 270), it spontaneously breaks apart through a process called nuclear fission.

"The neutrons add very rapidly at a temperature of a few billion degrees, going from iron to uranium in less than 1 second," Woosley says.

Elements created this way include transuranium elements—elements whose number of protons is higher than that of uranium—such as curium-250, californium-252, californium-254, and fermium-257.

Our stellar origins

When a supernova spews its newly made elements into space, the elements become part of an enormous cloud of gas and dust, called an interstellar cloud. The gas is made of 90% hydrogen, 9% helium, and 1% heavier atoms. The dust contains silicates (compounds made of silicon), carbon, iron, water ice, methane (CH_4), ammonia (NH_3), and some organic molecules, such as formaldehyde (H_2CO).



NASA

Supernova remnant ejected from the explosion of a massive star that occurred some 3,000 years ago.

Such clouds are found so often between stars in our galaxy that astronomers think that all stars and planets have formed from them. Except for hydrogen, which appeared when the universe formed through the Big Bang explosion, all of the elements on Earth have been cooked for billions of years in stars and then released in the universe through supernova explosions. The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, and the carbon in our apple pies were all made in the interiors of stars. The gold in jewels, tungsten in light bulbs, and silver in cookware were all produced during stellar explosions. We ourselves are made of "star stuff." ▲

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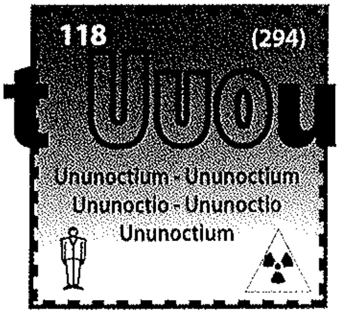

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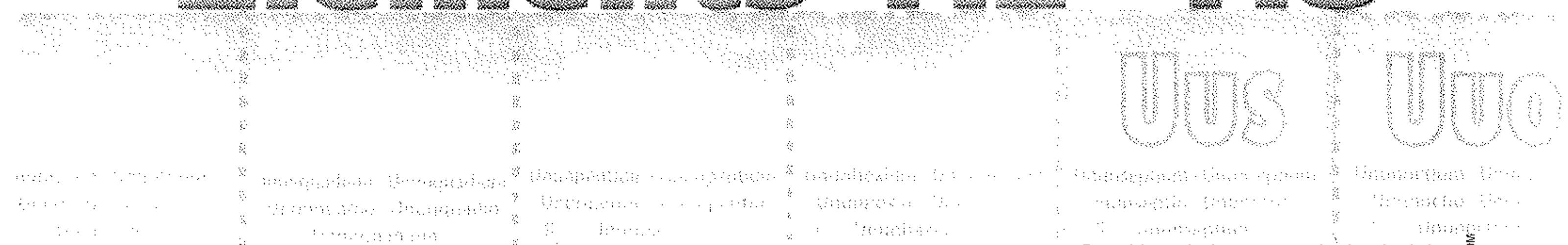
Wha Uuought to Know About Elements 112–118



By Christen Brownlee

With all of the time that you have spent using the periodic table, you may be feeling pretty chummy with most of its elements. By now, some of them, such as oxygen or helium, feel like old friends whom you have known your whole life. Others, such as hafnium or molybdenum, are not as familiar, though you are learning to get along. But there is one group of elements that are still weird, no matter how many times you have seen their chemical symbols: those oddities at the bottom of the periodic table, from element 112 to element 118.

Why can't they have real names like the rest of the elements, instead of tongue-twisters, such as ununbium or ununtrium? How come you have never heard of them being used in any experiments or as part of any chemical formulas? And what's up with that sketchy element 117—does it even exist?

Read on to get the straight scoop from experts on these odd elements: What they are and how we know they exist.

Discovering superheavy elements

Elements 112–118 are relative newcomers to the periodic table. “When I was in high school, the periodic table ended at element 103, now known as lawrencium,” says Ken Moody, a nuclear chemist at the Lawrence Livermore National Laboratory in California. “By the time I graduated in 1972, there was a dotted box at element 104 (rutherfordium) based upon then-preliminary work done by Russian scientists.”

Since then, scientists—including Moody—have filled out nearly the rest of the periodic table up to the next noble gas (element 118).

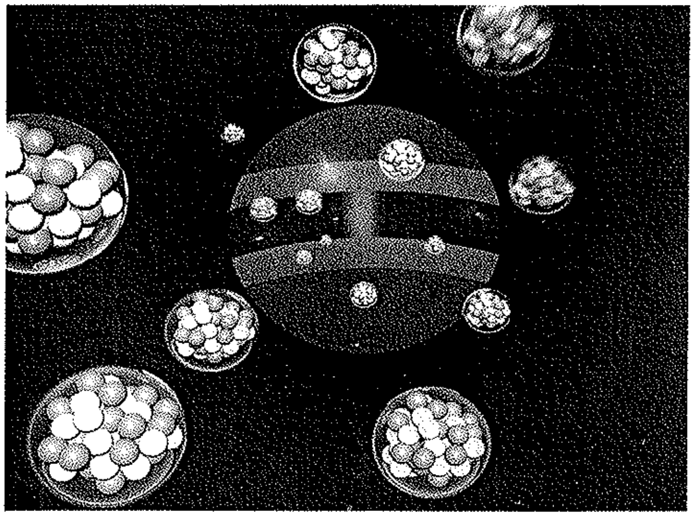
In the case of elements 112–118, Moody says the discovery process is more like manufacturing than actual discovery. Unlike the 90 or so elements that exist in nature, these superheavy elements can only be made in a laboratory.

How does one “discover” an element?

To make a superheavy element, such as 118 (also called ununoctium, or Uuo), you first need to find two elements whose atomic numbers add up to 118, such as krypton (Kr) and lead (Pb), whose atomic numbers are 36 and 82, respectively, or xenon (Xe) and gadolinium (Gd), whose atomic numbers are 54 and 64, respectively.

Once you find the right nuclei, you hurl one toward the other so hard that the nuclei collide and stick together. “It's not much more high tech than that,” Moody says. “The concept is really simple.”

But although the concept *is* simple, it is the underlying details that make the process tricky. The main problem is that nuclei are positively charged, and the heavier they are, the higher the positive charge they carry. When two such nuclei are sent toward each other, they repel each other, because their electrical charges are the same (only particles with opposite charges attract each other). So, these nuclei need to collide with each other at very high speed. But they also need to have just the right amount of energy to combine with each other instead of just hitting each other.



SABRINA FLETCHER AND THOMAS TEGGE/LLNL

Artist's conception of calcium ions traveling down the accelerator at high velocity toward the californium target.

Scientists also find it more convenient not to throw two separate packets of nuclei at each other, but to have one packet moving while the other sits in one place. In other words, they create a beam of one type of nuclei and hurl it toward a fixed target made of the other type of nuclei. This way, their work is divided by half: They only have to work on the moving beam of nuclei (while the other set of nuclei is a fixed target).

The next challenge is to find the right energy for the beam so that both types of nuclei combine with each other when the beam hits the target.

Preparing the projectile and target

The nuclei in the beam and in the target need to contain the right number of protons to add up to your goal. But, because some neutrons are lost, both projectile and target also need to contain the highest possible number of neutrons. This is because the probability that a nucleus breaks apart depends upon its internal structure.

Nuclei that do not break apart easily have a specific number of protons (Z = 2, 8, 20, 28, etc.) and neutrons (N = 2, 8, 20, 50, etc.), also called magic numbers of protons and neutrons. For the superheavy elements, those that satisfy the combination (Z = 108 and N = 162) and (Z = 114 and N = 184) are the most stable, and scientists try to create elements whose numbers of neutrons and protons are as close as possible to these combinations—which are also called islands of stability; the word "island" refers to a particular (Z, N) combination. This is why the highest possible number of neutrons is needed—scientists are aiming for 184 neutrons. The closer the synthesized heavy nucleus is to 184 neutrons, the greater the chance that it will not break apart as soon as it is formed.

For the recently discovered ununoctium, the right combination was calcium-48, which contains 20 protons and 28 neutrons; and californium-249 (Cf-249), which consists of 98 protons and 151 neutrons.

Let the collisions begin!

Once you have the right target and determined the right energy to throw the projectiles, you need a machine that accelerates the projectiles and throws them hard enough. Scientists use big, circular machines, known as cyclotrons (Fig. 1).

Once the ions have reached a velocity that gives them the right energy, electrical and magnetic forces are used to extract these ions from the cyclotron and send them flying toward the target nuclei, which are plated on thin titanium foils.

All done. You have made your new ununbium or ununquadrium—right? Not so fast. These hurtling projectiles hit lots of things, and not necessarily the target nuclei. Only a very select few—about 10^{-17} %—hit the target nuclei and fuse, creating the product—a new superheavy nucleus—the researchers are interested in. During the 6 months that the Russian team continuously ran their cyclotron, they created only two (!) detectable nuclei of element 118.

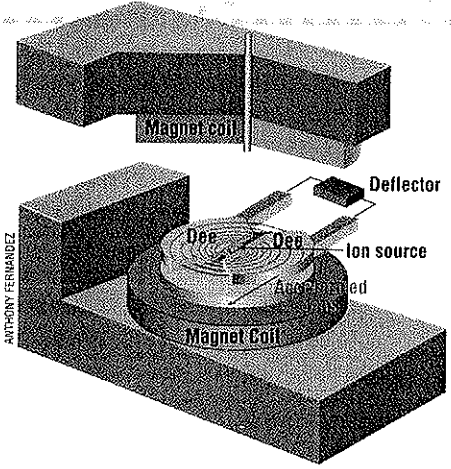


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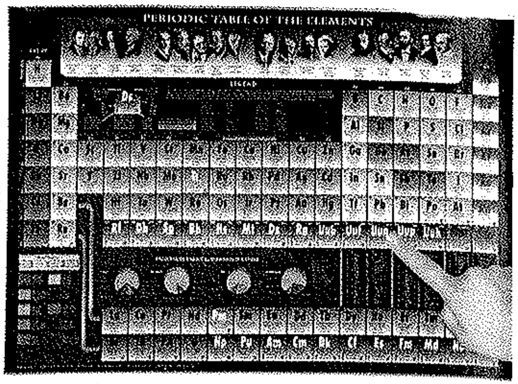
Figure 1. Schematic representation of a cyclotron.

"Detectable" is a key word here. With these fusions happening at the atomic level, it is—needless to say—impossible to watch the reactions taking place with the naked eye. That is why researchers have created a sophisticated system to detect when they have actually discovered a new element and distinguished it from other products that are not as exciting, such as nuclei that reacted with the titanium foil instead of the target.

You created a new element. Now what?

If all goes well—the right projectile and target are in place, they fuse in the right way, and the detector registers their presence—then, high-five! You have created your new superheavy element. But what to name it?



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Those awkward names—elements 112–118—are not real names. They are just placeholders until the discoverers are allowed to choose names for these elements. So, before elements get a real name, they get a temporary one made of Latin or Greek words that spell out the number. For example, ununoctium (for element 118) is "one, one, eight" in Latin. Also, being allowed to give elements permanent names can be a long process: The discovery must be confirmed by other scientists, but only a few labs have the necessary equipment.

But what about element 117? "The box for this element has remained unfilled for so long because this element is uniquely difficult to create," Moody says. Coming up with the right combination of projectile and target nuclei has been tricky because one of the most likely candidates for a target—berkelium-249—has a very short half-life. Moody and colleagues are currently trying to get a large supply of berkelium-249 to combine with calcium-48 as their projectile. If all goes well, the newest element on the periodic table could be discovered by this year's end! ▲

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Christen Brownlee is a science writer in Baltimore, Md. Her latest article, "Using Chemistry to Protect the Environment: Interview with Christopher Reddy, Environmental Chemist at the Woods Hole Oceanographic Institution," appeared in the April 2009 issue of *ChemMatters*.