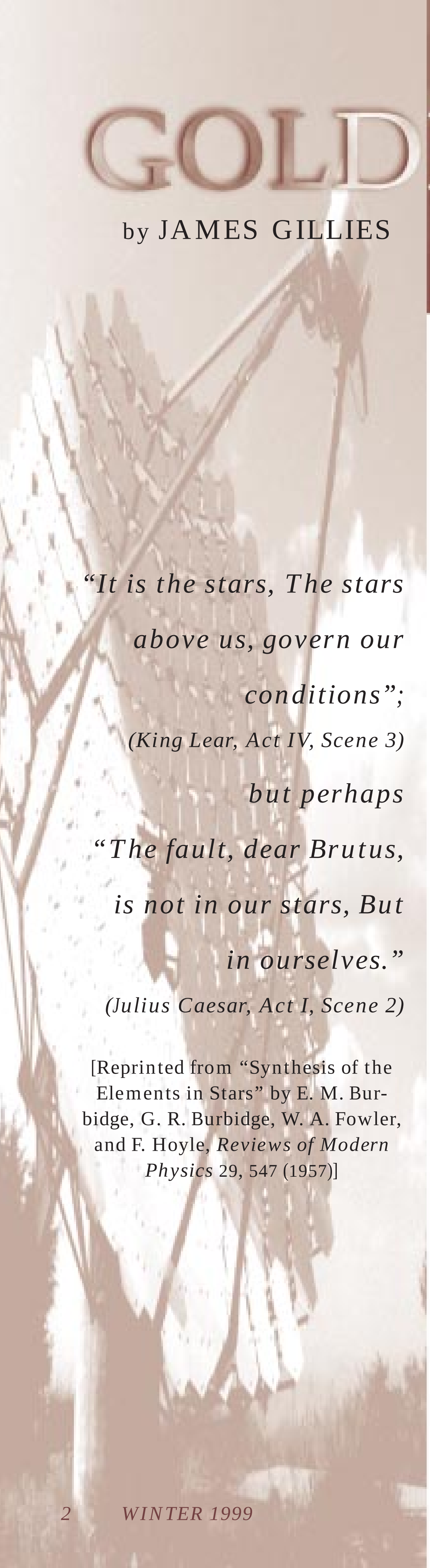


GOLDEN STARDUST

by JAMES GILLIES

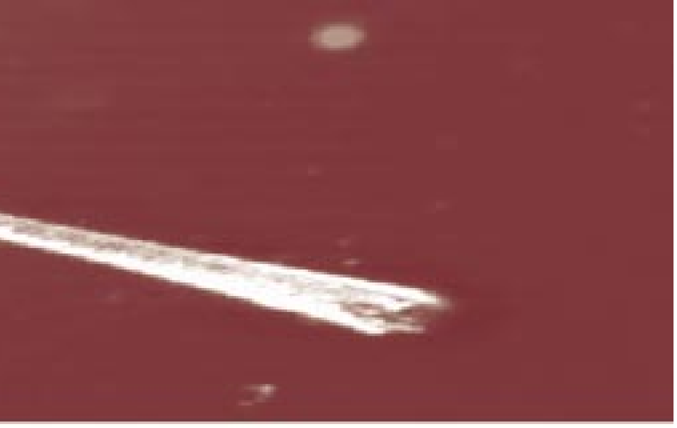
"It is the stars, The stars above us, govern our conditions";
(King Lear, Act IV, Scene 3)
but perhaps "The fault, dear Brutus, is not in our stars, But in ourselves."
(Julius Caesar, Act I, Scene 2)

[Reprinted from "Synthesis of the Elements in Stars" by E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle, *Reviews of Modern Physics* 29, 547 (1957)]

WHERE DO GOLD earrings come from? A simple answer is the local jewelry shop, but if you really want to know in depth, you'll have to dig a lot further. Gold is, quite literally, stardust. About half of it is forged in stars that burn normally, while the rest comes from large stars at the ends of their lives—in the cataclysmic explosions called supernovae. That much we know. But exactly how gold and all other elements heavier than iron are formed is still unclear. A new series of experiments at the ISOLDE facility at the European Laboratory for Particle Physics, CERN, in Geneva aims to find out.

The history of the elements is as old as the Universe itself. In the beginning, at the Big Bang, only the very lightest elements—hydrogen, helium, and a little lithium—were formed. Since then, so little heavier material has been created that even today hydrogen and helium make up over 99 percent of all the matter in the Universe. Everything else amounts to just a tiny fraction of 1 percent.

After the Big Bang, a billion years passed before any heavier elements appeared. They had to wait until the formation of stars, when gravity squeezed the light elements so tightly that they fused, igniting the stellar furnaces that forge heavier elements from lighter ones. In the normally burning part of their lives, these stars build elements as heavy as iron, producing energy from fusion as they do so. But then the process stops, because anything heavier than iron takes more energy to make than fusion gives out. That doesn't mean such elements can't be made in stars—the fusion process just uses some of the energy released by light-element fusion—



but the Universe simply hasn't been around long enough for all the heavy elements we observe to have been produced that way. Another process must be at work.

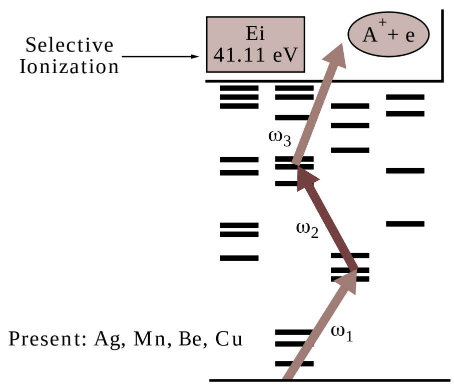
In 1957 the husband and wife team of Margaret and Geoffrey Burbidge working with Willy Fowler and the maverick British astronomer Fred Hoyle figured out what it could be. They published a paper which has since become legendary in the field of theoretical astrophysics and is known to aficionados simply as B2FH. In it, the Burbidges, Fowler, and Hoyle show how neutrons could provide the route to the heavier elements. B2FH describes the so-called s- and r-processes through which slow neutron absorption in stars could generate about half the present abundance of heavier-than-iron elements, with rapid neutron absorption, thought to occur in supernovae, making up the balance.

Left to right, Margaret and Geoffrey Burbidge, William Fowler, and Fred Hoyle, authors of the famous 1957 paper, "Synthesis of Elements in Stars." (Courtesy Astronomical Society of the Pacific)

The reason why neutrons can take over where fusion leaves off is that they are uncharged. There is no electrical repulsion resisting their entry into nuclei, and they can slip in more-or-less unnoticed. But only up to a point. When a nucleus becomes too neutron-rich it also becomes unstable and decays—nuclei tend to rearrange themselves into more energy-efficient configurations. Beta-decay turns a neutron into a proton, throwing out an electron in the process. The result is a nucleus with the same total number of constituent particles, but with one more proton and one fewer neutron.

In normally burning stars neutrons are released when helium nuclei fuse with other elements. There are relatively few of them around, and the probability that a nucleus will encounter one is consequently small. That's why B2FH named the neutron-capture process in stars the slow, or s-process: heavier-than-iron elements are built up slowly. What happens is that the neutron-capture chain marches steadily through the stable neutron-rich versions of an element until it reaches an unstable one. That nucleus then decays before it has a chance to absorb another neutron and the march towards heavier elements resumes in the element with one more proton.

Right, electrons orbit nuclei at well-defined energies which are unique to each element. The laser ion source (below) works by firing three laser pulses at a cloud of atoms in quick succession. The pulses are tuned so that the first lifts an electron from one orbit to another, the second lifts it again, and the third knocks it out completely. The combination of pulses is unique to the element required. Below, Michine Viatcheslav and Ulli Köster adjust the light bench for CERN's laser ion source.



The s-process is responsible for a lot of heavy elements, but it can't account for them all. There are many stable heavy elements which are highly neutron rich. To reach them involves passing through unstable isotopes on the way. That means that neutrons have to be so abundant that an unstable nucleus can absorb several before it gets a chance to decay, and that is where the rapid r-process comes in. R-process element generation happens in places where the neutron density is staggering—the sort of places, in fact, which are only found in certain stars when they reach the ends of their lives in the most violent explosions known in the Universe—supernovae.

Most stars finish their careers in unspectacular fashion, retiring peacefully from energy production before slowly fading away into darkness. Our own Sun is one of these. It has enough fuel to burn its way up to carbon, and in a few billion years from now it will end its days as a slowly cooling lump of ash. Heavier stars don't all go so quietly, and some of them, the James Deans of the cosmos, instead go out in spectacular style. A supernovae happens when a heavy star has completely burned up its insides. With its fuel source exhausted, there is nothing left to support it and the star collapses in on itself. Protons in the star resist the collapse because of the repulsive electric force between them, but the gravitational pull of all the matter in the dead star is stronger and the charge is literally squeezed out of the protons in the form of positive electrons (positrons), turning them into neutrons. The star's collapse generates a shock-wave traveling outwards which blows the outer layers of the star out into space in an explosion accompanied by copious neutrons. In this extremely neutron-rich environment, an unstable nucleus has a good chance of catching another neutron before it decays. Rapid neutron capture ensues, generating a wide range of unstable heavy isotopes. When this explosive burning is over, these unstable isotopes cascade through a chain of beta-decays ending up as stable neutron-rich isotopes. This all takes place in just a few seconds, and when it is over, the newly formed elements are sprayed out into the Universe where eventually gravity, that ultimate cosmic master of ceremonies, marshals them into new stars and planets.

IT HAS TAKEN 40 years for terrestrial experiments to catch up with B2FH. That's not too surprising, since stars and supernovae are not the easiest things to bring into the laboratory. Nevertheless, the paper's ability to predict the observed abundances of heavy elements has made it so widely accepted that it has become the stuff of textbook astrophysics. In 1997, new developments at CERN's veteran unstable-particle beam facility, ISOLDE, allowed physicists to put B2FH to the laboratory test for the first time. They began to measure the binding energies and half-lives of some of the unstable elements vital to the r-process.

ISOLDE can produce a wide range of unstable isotopes covering most of the elements. In 1997 it was complemented by a device, called the laser ion-source, which allows extremely pure beams to be created. The laser ion-source works like a key in a lock by selecting just the element of interest. At ISOLDE a beam of protons strikes a target. The impact causes a range of unstable atoms to be created. These are evaporated from the target and allowed to find their way into a small tube. Atoms are electrically neutral, and can not be transported to experiments using electric fields and magnets. First they must be ionized, losing an electron so they become electrically charged. This is where the laser ion source comes in. It works by firing three precisely tuned laser pulses into the tube in quick succession. The first pulse has just the right energy to lift an electron into a higher orbit around the nucleus; the second lifts it again; and the third knocks it out completely. The combination of laser energies is unique to the ion required—just as a key fits only one lock. Once ionized, an electric field pulls the atoms out of the tube, sending an ion beam on its way to a waiting experiment.

One of the first experiments to use the laser ion source in October 1997 was code named IS-333. It studied the properties of highly neutron-rich silver isotopes. For the first time, silver-129, an isotope with 22 more neutrons than the most common stable isotope of silver, was identified and its half-life measured. Silver-129 plays an important role in the r-process because it builds up in higher quantities than many other elements.

The half-life of silver-129 pins down one link in the supernova event-building chain, but it is nevertheless just one of myriad parameters in element generation calculations. Since that first experiment, IS-333 and successor experiments have

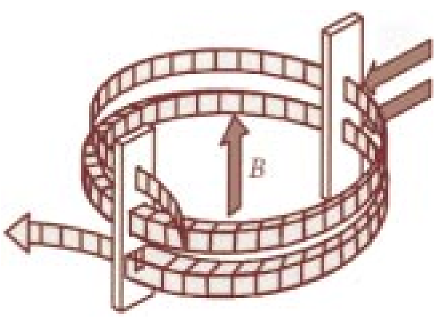
What Makes an Element an Element?

AN ATOM IS MADE UP of three kinds of particles: protons, neutrons, and electrons. Positively charged protons and electrically neutral neutrons compose the nucleus while negatively charged electrons orbit the outside and balance the charge of the protons in the nucleus.

The defining feature of an element is how many protons its nucleus contains. This is because the number of protons equals the number of electrons, and it is the electrons that determine an element's chemical properties.

Several versions of the same element can exist; these are called isotopes, and they differ in the number of neutrons in the nucleus. Similarly, different elements can have the same total number of protons and neutrons in the nucleus, but a different ratio. These are called isobars.

The nuclei important to element building in supernovae are unstable. They tend to decay rapidly by emitting electrons in a process known as beta decay. This is a random process and is characterized by a half-life—if you start off with a certain number of unstable nuclei, then after one half-life, there will be half as many left.



Top, David Lunney sets up the MISTRAL apparatus at the ISOLDE facility. Above, an isotope beam enters at the top and follows a spiraling path through the apparatus. Only isotopes of a particular mass escape through the exit slit at the bottom of the apparatus.

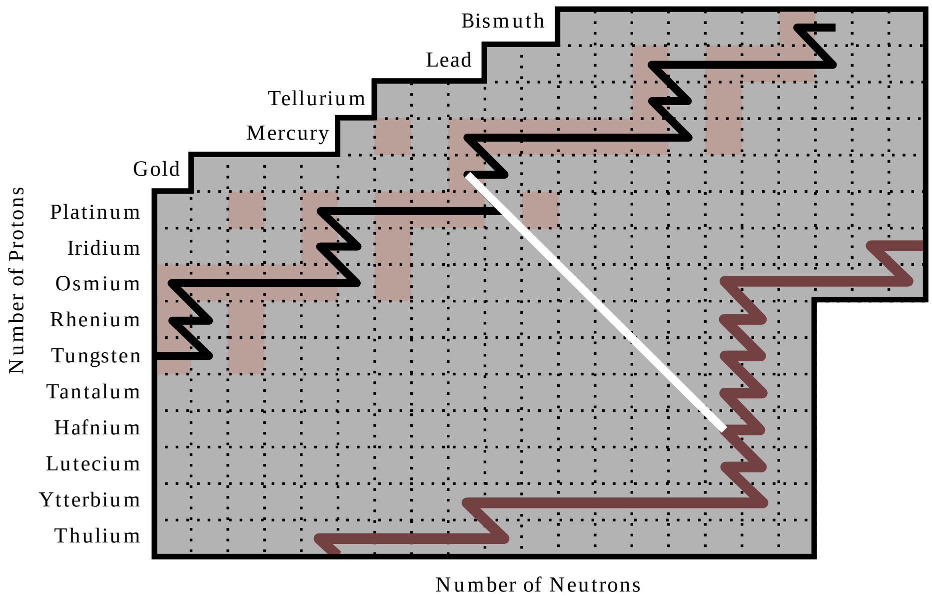
added a few more links in the form of the half lives of isotopes of cadmium, copper, and manganese which are also on the r-process path.

HALF-LIVES of unstable elements are just one important ingredient in understanding supernovae. They determine how long an atom will retain its identity, and so give an indication of how likely it is that the atom will absorb another neutron before it decays. But there's another vital ingredient too, and that is the subject of another ISOLDE experiment called MISTRAL. The goal of this experiment is to measure the masses of these unstable isotopes.

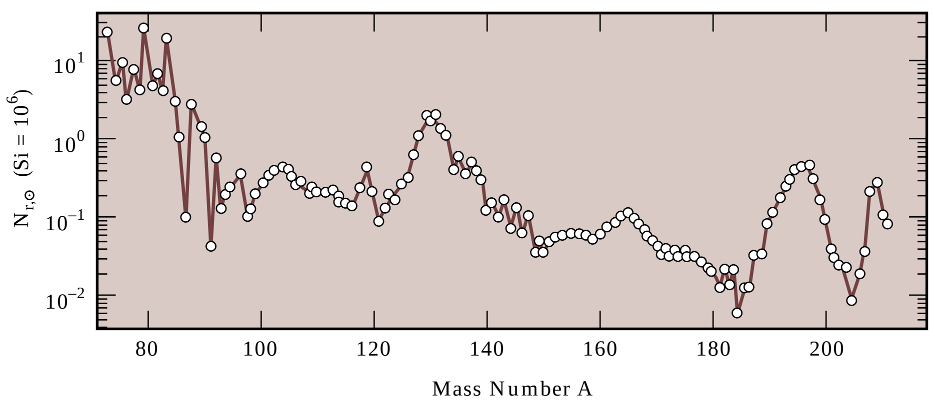
The mass of a nucleus is made up of two parts, the individual masses of the protons and neutrons within it, and the so-called binding energy which holds them all together. Iron has the highest binding energy per nucleon of any nucleus, which is what makes it so stable. In the highly neutron-rich nuclei important in supernova element-building chains, the energy binding the excess neutrons into the nucleus is small. And since it is this neutron binding energy which determines the energy needed to capture another neutron, it must be measured if scientists are to understand these processes fully. The MISTRAL apparatus has the unique capacity to measure the masses of the particularly short-lived isotopes involved in supernova element-building.

MISTRAL works by bending a beam of incoming ions in a spiraling path using a uniform magnetic field. This is done for stable ions of well known mass as well as for the unstable ions whose mass is to be measured. Then by comparing the time it takes for an unstable ion to complete an orbit with that of a known reference ion, the mass can be measured. Ions are injected into MISTRAL and vertically deflected so that they make two spiraling turns inside a magnetic field. An applied oscillating voltage modifies the trajectories of the ions such that only those with a particular mass escape from the apparatus through a narrow slit. By varying the applied voltage and counting the transmitted particles, precise mass measurements are made. The speed of this process enables the measurement of very short-lived isotopes, and the resolution of the apparatus is so good that it can cleanly separate the signals arising from isotopes of different elements having the same number of protons and neutrons but in different proportions. The tiny

On this plot of heavy elements, stable isotopes are marked by colored squares. The s-process path is shown by the black line and the r-process path by the dark brown line. On the s-process path, isotopes absorb neutrons slowly. When an unstable isotope is reached, it decays by emitting an electron, and the path takes a diagonal step up to the next element. On the r-process path which happens in supernovae, neutrons are rapidly consumed. When the process stops and the supernova blasts isotopes into space, unstable elements decay through a cascade of electron emission until they reach stability. One example is shown by the white diagonal line (the r-process path to gold).



The abundances of isotopes produced by the r-process. The mass number is just the total number of protons and neutrons in the nucleus. Some elements build up in greater numbers than others, like those in the bump around mass number 130. This is why studying unstable isotopes, such as silver-129, in the same mass range is particularly important.



difference in the mass of such isotopes, isobars as they are known, arises from binding energy determined by the configuration of the nucleus.

Once the mass has been measured, the binding energy can be calculated by remembering Einstein's lesson that $E = mc^2$, energy and mass are interchangeable. The combined mass of all the protons and neutrons in the nucleus can be added up and compared with the measured mass, the difference between the two is the binding energy.

MISTRAL's first measurements were made in November 1997 and continued through 1998. So far, several masses have been measured, some with extremely short half-lives. Further measurements which started in November 1998 will soon begin to feed into the recipes proposed in B2FH. So far, the Burbidges, Fowler, and Hoyle seem to have got it right.

The CERN results bear out their predictions and are starting to fill in the gaps between the forging of iron in stars, and the gold baubles to be found in the jeweler's shop around the corner.