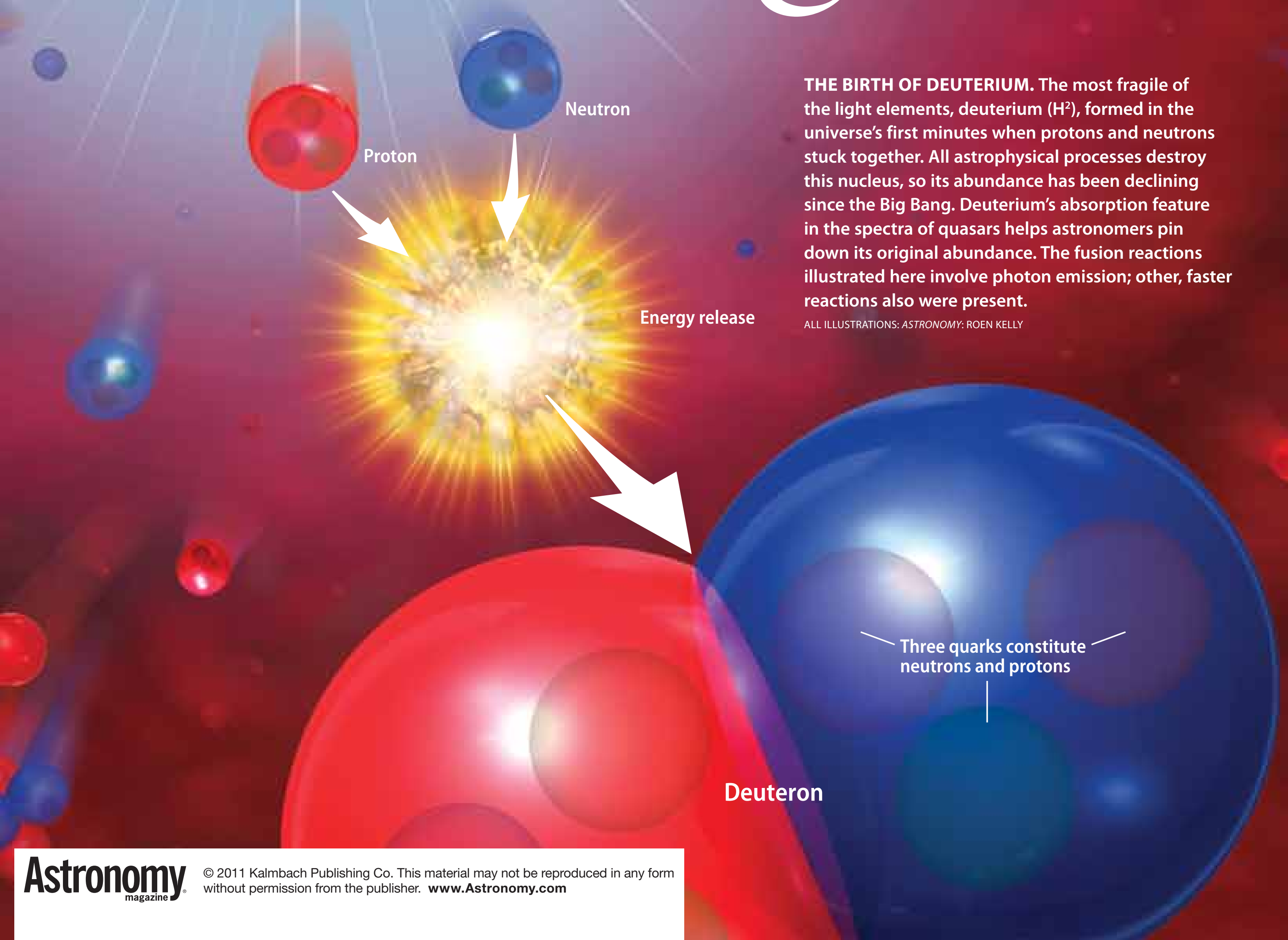
Nuclear reactions in the universe's first minutes made the lightest elements. How it happened laid the groundwork for everything that followed.

/// BY ADAM FRANK

How the Big Bang forged *the* first elements



THE BIRTH OF DEUTERIUM. The most fragile of the light elements, deuterium (H^2), formed in the universe's first minutes when protons and neutrons stuck together. All astrophysical processes destroy this nucleus, so its abundance has been declining since the Big Bang. Deuterium's absorption feature in the spectra of quasars helps astronomers pin down its original abundance. The fusion reactions illustrated here involve photon emission; other, faster reactions also were present.

ALL ILLUSTRATIONS: *ASTRONOMY*: ROEN KELLY

Moments after the Big Bang, as the universe quickly expanded from an unimaginably dense, impossibly hot state, something wonderful happened. Over the course of the first 3 minutes, the first elements were born.

Every instant of every day, evidence that the universe began in a cosmic fireball stares us in the face. Proof that the universe was once hot and dense resides in the very atoms from which the stars, planets, and we ourselves are built.

Big Bang nucleosynthesis — BBN, for short — is the field of astrophysics linking the observed abundances of the chemical elements to theoretical predictions based on the Big Bang. Along with the universal redshift of galaxies and the cosmic microwave background, BBN is one of the great pillars on which modern cosmology stands.

BBN is a remarkable mix of precise astronomical observation and exacting physical theory. Using only the abundances of the lightest elements, hydrogen and helium, BBN spins out a detailed picture of our cosmic beginnings. It is a remarkable tale and a grand triumph of science's power and precision. Most amazing of all, the events that drive this story, with consequences stretching across space and time, unfolded in little more than the span of a typical TV commercial break.

Elemental origins

We recognize more than 116 distinct chemical elements today. Each appears different to us — copper is metallic and shiny, while sulfur is yellow and powdery — because the atoms making each element differ. It's hard to believe scientists were still vigorously debating the reality of atoms even 100 years ago. But once researchers confirmed the reality of the atom in the early decades of the previous century, they began probing its internal structure.

Every atom, they found, contains a central nucleus composed of one or more protons, which carry a positive electric charge. Hydrogen, the simplest and most abundant element, has a single proton in its nucleus. It's the number of protons in a nucleus that distinguishes one element from another.

The nucleus also may contain another particle, called a neutron. It's slightly heavier than the proton and lacks an electrical charge. The number of neutrons in a nucleus is what distinguishes one variation of a single element — called an isotope — from another.

A third kind of particle, the negatively charged electron, orbits each nucleus at a great distance. Compared to protons and neutrons, electrons weigh next to nothing. The discovery of atomic, and then nuclear, structure answered questions about the nature of matter that had haunted philosophers and scientists for 2,000 years.

Until the 1930s, physicists could not explain elemental abundances. Why is it so much easier to find hydrogen atoms than, say, iron atoms? And good luck finding a lutetium atom. Hydrogen is vastly more abundant than iron, which is vastly more abundant than lutetium. Why?

In 1937, German-American physicist Hans Bethe (1906–2005) was returning by train to his Ithaca, New York, home following a nuclear physics conference in Washington. It just

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might have been the most productive train ride in history: By using the time to explore equations for the newly developing science of nuclear physics, Bethe discovered the secrets of stellar fusion. Taking into account the high temperatures and densities inferred by astronomers to exist at the centers of stars, Bethe showed how simple elements can be squeezed together to form more complex ones, a process that releases energy.

In a single stroke, Bethe showed how the fusion of elements fuels the stars, that stellar cores are alchemical furnaces transmuting one kind of matter into another. Bethe's success convinced physicists and astronomers that the handiwork of stars could explain all the elements and their abundances.

They were both right and wrong.

In 1957, British astronomers Geoffrey and Margaret Burbidge, American astronomer Willy Fowler, and British astrophysicist Fred Hoyle published a monumental work that put the theory of stellar nucleosynthesis on firm ground. Often known as B^2FH, the paper refined earlier studies into a single coherent picture that accounted for the observed abundances of elements — almost.

While the astronomers could nail down elements like carbon, oxygen, and iron, their model couldn't get the simplest elements right. The theory predicted hydrogen and helium proportions that were completely different from what astronomers observe.

Stellar nucleosynthesis predicted a cosmos with too little helium. Observations show that helium makes up about 24 percent of the universe's normal matter. Everything heavier accounts for less than 2 percent of the total, and all the rest is hydrogen. For years, astronomers were left scratching their heads at this glaring failure in the midst of a spectacular success.

In fact, the answer had already been found and forgotten. Hiding in their journals was a paper that could solve the light-element puzzle. But accepting the solution it offered meant opening a door to the dawn of time.

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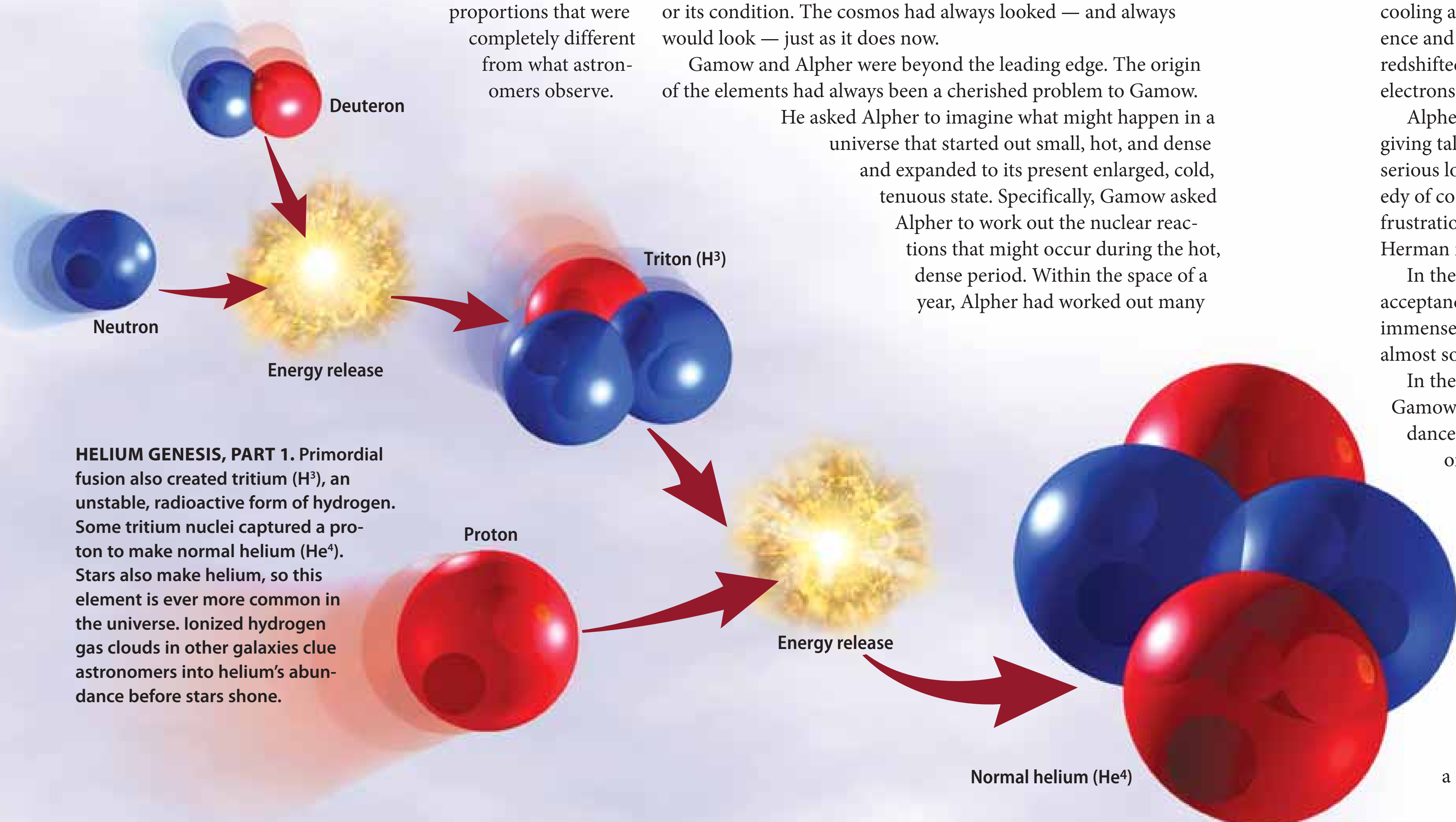
Beyond steady state

In 1948, Ralph Alpher (1921–2007), a wiry, young graduate from George Washington University, wrote a doctoral thesis that began, for the first time, at the beginning. Under the tutelage of George Gamow (1904–1968), a Russian-refugee physicist known as much for his heavy drinking as for his genius, Alpher set out to describe nuclear physics in the realm of an infant expanding universe.

It's difficult to imagine now how bold, how radical this endeavor was. In 1948, few scientists were thinking about cosmology, and those who were had locked themselves into the so-called steady-state model. Steady-state cosmology held that, even with expansion, the universe never changed its appearance or its condition. The cosmos had always looked — and always would look — just as it does now.

Gamow and Alpher were beyond the leading edge. The origin of the elements had always been a cherished problem to Gamow. He asked Alpher to imagine what might happen in a universe that started out small, hot, and dense and expanded to its present enlarged, cold, tenuous state. Specifically, Gamow asked Alpher to work out the nuclear reactions that might occur during the hot, dense period. Within the space of a year, Alpher had worked out many of the crucial aspects with meticulous attention to mathematical detail. It was a triumphant physics tour de force — but one the scientific establishment promptly forgot. While Alpher's first calculations contained some missteps, they got the fundamentals of Big Bang nucleosynthesis correct.



HELIUM GENESIS, PART 1. Primordial fusion also created tritium (H^3), an unstable, radioactive form of hydrogen. Some tritium nuclei captured a proton to make normal helium (He^4). Stars also make helium, so this element is ever more common in the universe. Ionized hydrogen gas clouds in other galaxies clue astronomers into helium's abundance before stars shone.

AIP EMILIO SEGRÈ VISUAL ARCHIVES

GEORGE GAMOW, a Russian-American scientist and a pioneer in nuclear physics, suggested the universe originated from a hot sea of radiation and particles.

AIP EMILIO SEGRÈ VISUAL ARCHIVES

RALPH ALPHER and Gamow found that observed abundances of light elements, like hydrogen and helium, are a consequence of a hot, expanding early universe.

NUCLEAR SPEAK

BIG BANG
The event that spawned space, time, and the expanding universe.

DEUTERON
A hydrogen nucleus (proton) bound to a neutron; a nucleus of deuterium.

FUSION
The merger of protons and neutrons to form atomic nuclei, accompanied by a characteristic energy release. The fusion of hydrogen into helium powers the Sun.

NUCLEON
A proton or neutron.

NUCLEOSYNTHESIS
Processes in stars and the early universe that create new atomic nuclei from existing protons and neutrons.

TRITON
A hydrogen nucleus (proton) bound to two neutrons; a nucleus of tritium.

Alpher, along with collaborator Robert Herman, spent the next few years refining his models and examining the implications of a cooling and expanding universe. The team even predicted the presence and temperature of a cosmic microwave background from the redshifted light released when the universe had cooled enough that electrons could combine with nuclei to form atoms.

Alpher said he and Herman expended "a hell of a lot of energy" giving talks to convince astronomers that the results deserved a serious look. But their work received little attention, and, in a tragedy of cosmic proportions, the two physicists ultimately gave up in frustration. Alpher left academia to work for General Electric while Herman moved on to General Motors Research Laboratories.

In the mid-1960s, the weight of new data finally forced the acceptance of Big Bang cosmology. But, even then, Alpher's immense contribution was largely ignored, with credit given almost solely to Gamow.

In the years since, others have refined the picture Alpher and Gamow first glimpsed. Its predictions of simple-element abundances prove that we understand something about cosmic origins. The secret of BBN, the secret Alpher, Gamow, and Herman knew first, occurs just after the cosmos began.

Fusion and the Big Bang

Astronomers see galaxies rushing away from one another in today's expanding universe. But if we could run cosmic evolution backward, everything would draw together. The cosmos would become denser and hotter. As the clock runs backward toward the Big Bang, structures like galaxies melt into a thickening soup of primordial gas. Run the clock back further, and the gas also breaks down into a smooth, ultrahot sea of protons, neutrons, and other subatomic particles. At this point, the universe has a temperature of about 100 billion kelvins. A teaspoon of cosmic matter weighs more than 100,000 tons.

This is where BBN begins. By going back only to about 0.01 second after the beginning, physicists limit themselves to a temperature and density domain they can work with comfortably. More than 60 years of particle accelerator experiments validate their understanding. Running the clock forward from 0.01 second, BBN describes the universe's next 3 minutes in astonishing detail.

From the chaos of those first moments, fusion physics leaves an unalterable imprint on the universe. To choreograph this dance, BBN requires two critical components — an understanding of fusion processes and the physical conditions in the young cosmos.

A hydrogen nucleus (denoted H) is a single proton. Helium nuclei (denoted He^4) have two protons and two neutrons. Fusing hydrogen into helium is a battle between electromagnetism and the strong nuclear force, two of the four forces that govern the cosmos.

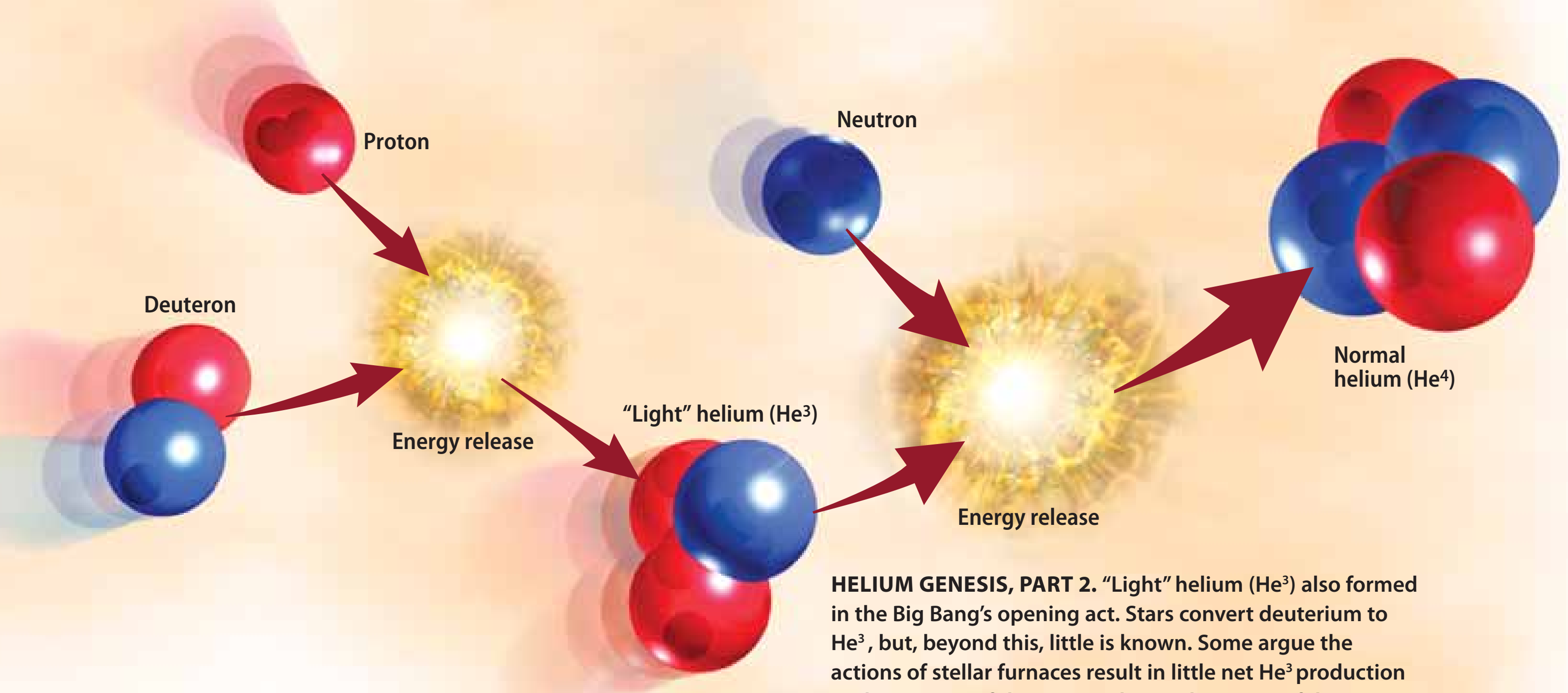
While it's easy to push neutral neutrons together, every proton carries a positive electric charge. Like charges repel via the electromagnetic force, which gets stronger as the particles get closer. (It's like trying to force the same poles of two magnets together.) To fuse into more complex nuclei, protons must overcome this electromagnetic barrier.

The strong nuclear force is more powerful than electromagnetism. But it has the odd property of kicking in only when protons and neutrons get really close to each other.

At a high enough density and temperature, protons whiz around fast enough that some collisions have the energy to push them past the electromagnetic barrier and trigger fusion. But because the universe is expanding and cooling, Big Bang nucleosynthesis becomes a race against time.

Beat the clock

The universe's rapid expansion and cooling leaves only a brief window for nuclear fusion to occur. Einstein's theory of relativity specifies the expansion rate; nuclear physics specifies the temperature and density at each moment in cosmic history. But as the young



HELIUM GENESIS, PART 2. "Light" helium (He^3) also formed in the Big Bang's opening act. Stars convert deuterium to He^3, but, beyond this, little is known. Some argue the actions of stellar furnaces result in little net He^3 production or destruction. If this is true, the total amount of deuterium and He^3 remains approximately constant.

universe ages, each temperature and density regime allows only certain particles to exist and certain kinds of reactions between those particles.

Fusion can't start until protons and neutrons — collectively, nucleons — form. A millionth of a second after the Big Bang, when the temperature is a mere 2 trillion K, the universe has cooled enough that quarks can coalesce into protons and neutrons.

About 1 second after the Big Bang, the ratio of neutrons to protons becomes fixed, and fusion reactions can begin. But this window of opportunity lasts only 3 minutes. After this time, the cosmos will have expanded and cooled so much, it won't support fusion reactions at all.

As BBN begins, protons outnumber neutrons 7 to 1. The difference emerges because neutrons are slightly heavier than protons, and this mass difference allows a neutron to decay spontaneously into a proton, electron, and a ghostly particle called a neutrino. Left to its own devices, a lone neutron will, on average, decay into a proton and an electron in just 15 minutes.

Save the neutron

Fusion saved the neutrons. They collided with the abundant protons and fused together as a deuteron — the simplest compound nucleus. A deuteron, a nucleus of deuterium (denoted H^2), is a second stable isotope of hydrogen.

Deuteron formation can't start up in earnest until about 100 seconds after the Big Bang. Once it does, it triggers a cascade of reactions that leads to nuclei with 2 protons and 2 neutrons — helium. For example, a deuteron may collide with a neutron to make tritium (H^3), which then collides with a proton to make normal helium (He^4). Or the deuteron could collide with a proton to make a nucleus of light helium (He^3), which then collides with a neutron to make He^4.

Other reactions create a small amount of lithium and beryllium. But that's as far down the periodic table as we can go before fusion grinds to a halt. More complex elements must await the first stars — several hundred million years in the future.

Scientists must follow all possible reactions, their pace, and all their products. Most importantly, physicists must perform these calculations in a cosmic background of continually changing temperature and density. It is a tremendous task. But when the smoke clears, BBN predicts exactly how much hydrogen, helium, deuterium, and other light elements exist in the cosmos.

FUSION reactions begin about 1 second after the Big Bang and last only 3 minutes.

From H to us

While stellar nucleosynthesis could not match the observation that helium makes up one-quarter of the cosmos' mass, Big Bang nucleosynthesis nails it right out of the gate. BBN's main prediction is the copious early production of He^4. This result ends up being remarkably insensitive to details in the calculation. Barring major changes to the basic scenario, BBN always leads to helium production close to the observed amount. Fundamentally, all that really matters is that a Big Bang occurred.

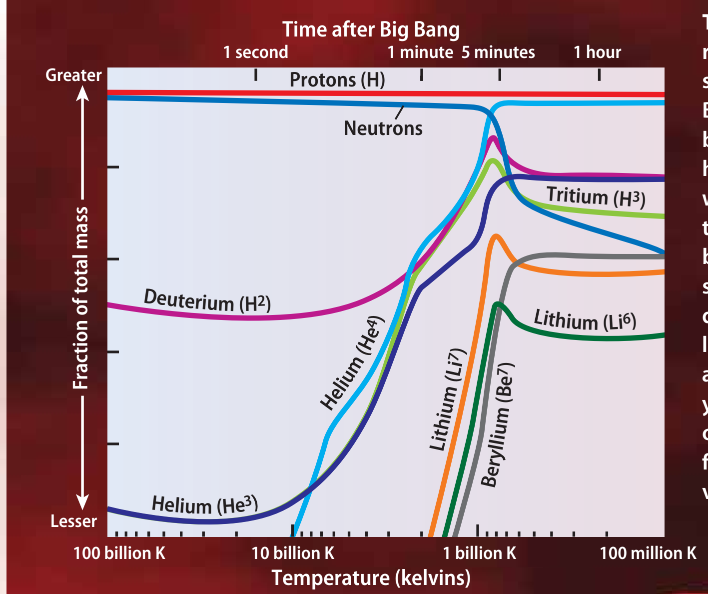
Helium abundance isn't all that sensitive to conditions in the early universe, but deuterium is another story. The denser the early universe was at the beginning of the fusion era, the more likely it is that all the deuterium would end up in helium nuclei. That some deuterium remains — even 0.01 percent relative to hydrogen — tells physicists something about the young universe.

This and other trace elements let physicists determine the universe's baryonic density — a measure of matter like protons and neutrons — with high accuracy. Using precise measurements of light-element abundances in regions as diverse as stars and intergalactic clouds, astrophysicists now can claim that the density of normal matter in the cosmos is only around 2 percent of the value needed to halt the universe's expansion in the future. Most astronomers and cosmologists believe the universe's total density (the sum of all kinds of matter and energy) exactly equals this critical density.

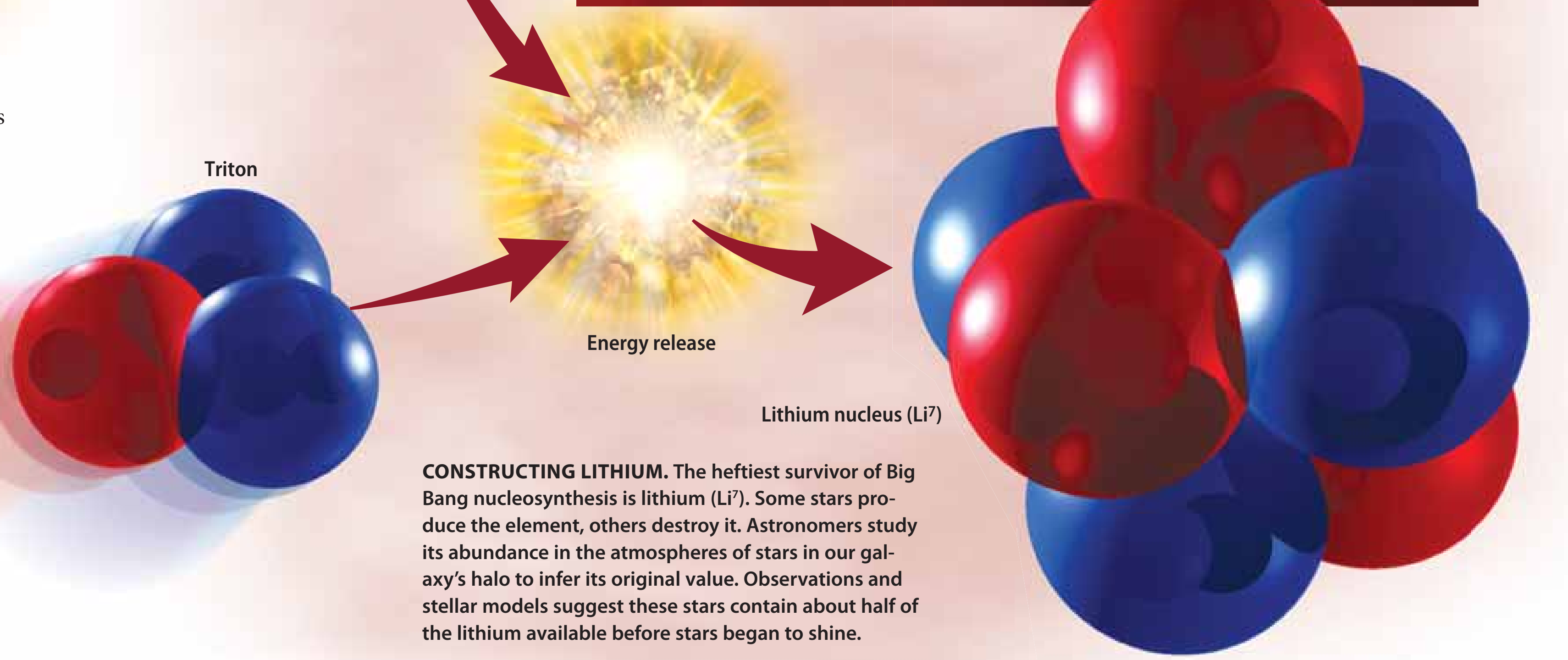
Because BBN predicts such a tiny fraction for stuff like us, the rest of the universe must be composed of dark matter and dark energy — "dark" in the sense that astronomers don't yet understand what they are. In this way, BBN not only has provided proof that a Big Bang must have occurred, but it also gives us strong evidence that we have much to learn about our universe.

Much has changed from Alpher and Gamow's first calculations 60 years ago to the current era of precision cosmology. Now, a wealth of high-quality data lets scientists test competing cosmological models. But while astronomers have firm reasons for believing in the reality of the Big Bang, they don't need to rely on cutting-edge physics to do so. Big Bang nucleosynthesis shows us that a brief period of well-understood physics has consequences that trickle down 13.7 billion years to the universe we observe.

The early universe's chemical content



THE AMOUNT of deuterium peaks about 100 seconds after the Big Bang, but much of it becomes swept into helium nuclei. Fusion with these helium nuclei then builds lithium and beryllium. But Be^7 isn't stable, and the nucleus decays to Li^7 with a half-life of 53 days. Tritium also decays, with a 12-year half-life, to He^3. None of the beryllium or tritium formed during BBN survives today.



CONSTRUCTING LITHIUM. The heftiest survivor of Big Bang nucleosynthesis is lithium (Li^7). Some stars produce the element, others destroy it. Astronomers study its abundance in the atmospheres of stars in our galaxy's halo to infer its original value. Observations and stellar models suggest these stars contain about half of the lithium available before stars began to shine.