A series of nuclear reactions took place when the Universe was seconds old and made the lightest elements in the periodic table. The successful predictions of big-bang nucleosynthesis make it a cornerstone of the hot big-bang cosmology. It also leads to the most accurate determination of the baryon density of the Universe, provides the linchpin in the case for the existence of nonbaryonic dark matter, and permits the study of fundamental physics in regimes beyond the reach of terrestrial laboratories.

A BRIEF HISTORY

Two of the most pressing problems of the first half of this century were the energy source of stars and the origin of the chemical elements. In the 1930s the first puzzle was solved when Hans Bethe and others worked out the nuclear reactions that power stars like the sun. Nuclear physicists then turned to the stars to solve the second puzzle. However, by the end of the 1930s, they were ready to abandon them. In 1938 von Weizsäcker articulated the dominant view: “··· no element heavier than $^4$He can be built up to any appreciable extent. Therefore we must assume that the heavy elements were built up before the stars · · ·”

In 1942 George Gamow began talking about the big-bang origin of the elements. In the 1948 paper that marks the beginning of big-bang nucleosynthesis (BBN), Gamow, his student Ralph Alpher, and Hans Bethe proposed that the periodic table was built up by neutron capture minutes after the big bang. Critical physics corrections made by Chushiro Hayashi, Enrico Fermi and Anthony Turkevich led to the seminal 1953 paper of Alpher, Robert Herman and James Follin that described correctly the big-bang synthesis of large amounts of $^4$He and little else. As Fermi and Turkevich had pointed out, Coulomb barriers and the lack of stable nuclei with mass 5 and 8 preclude significant nucleosynthesis beyond $^4$He. BBN required a hot beginning, and in 1949 Alpher and Herman predicted a 5 K temperature for the relic radiation now known as the Cosmic Microwave Background (CMB).

\footnote{Text of a poster on the theme “Great Discoveries in Astronomy in the Last 100 Years” produced for the APS centennial meeting.}
In 1957 Fred Hoyle, E. Margaret and Geoffrey Burbidge, and William Fowler and independently A.G.W. Cameron showed that essentially all of the elements beyond $^4\text{He}$ can be made in stars, but under very different conditions than von Weizsäcker and others considered. Interestingly enough, Hoyle was impelled to work on stellar nucleosynthesis because of his attachment to the steady-state cosmology which lacked an explosive beginning. Years later, Hermann Bondi, another father of the steady state, referred to the work of Hoyle and collaborators as the most important achievement of the steady-state theory.

A year before the discovery of the CMB, Hoyle and Roger Tayler made the observational case for a large primeval abundance of $^4\text{He}$ (around 25% by mass) and suggested a big-bang explanation. After the discovery of the CMB by Penzias and Wilson in 1965, the BBN calculations were refined by P.J.E. Peebles and Robert Wagoner, Fowler and Hoyle. Explaining the large primeval abundance of $^4\text{He}$ was a striking triumph of the hot big-bang theory. In 1973 Hubert Reeves, Jean Audouze, Fowler and David N. Schramm focused attention on deuterium, whose big-bang production depends sensitively on the density of ordinary matter (baryons). The reasoning in this paper together with the detection of deuterium in the interstellar medium (ISM) led to an upper limit to the baryon density of no more than 10% of the critical density.

By the early 1980s, primordial abundances of all four light elements cooked in the big bang, D, $^3\text{He}$, $^4\text{He}$ and $^7\text{Li}$, had been determined, and the concordance of the predicted abundances with the measured abundances was used both as a test of the big-bang framework and a means of constraining the baryon density. The hot big-bang model had become the standard cosmology and BBN was one of its cornerstones. Further, BBN began to play an important role in probing fundamental physics. In their influential 1977 paper, Gary Steigman, David Schramm and James Gunn used big-bang $^4\text{He}$ production to constrain the number of light neutrino species. Not only was their limit an important one, but it also helped to open the field of cosmology and particle physics.

In 1998 the first accurate measurement of the primordial deuterium abundance by David Tytler and Scott Burles marked the beginning of a new, precision era of BBN. This measurement fixes the baryon density to a precision of around 7%, and in turn, leads to accurate predictions of the primeval abundances of the other light elements. This development promises to extend and sharpen the power of BBN to probe cosmology, fundamental physics and
astrophysics.
HOW IT WORKS

Big-bang nucleosynthesis is very different from the stellar nucleosynthesis that produces the heavier elements. It is a nonequilibrium process that took place over the course of a few minutes in an expanding, radiation-dominated plasma with high entropy (10^9 photons per baryon) and lots of free neutrons. In contrast, much of stellar nucleosynthesis occurs in equilibrium over billions of years at relatively low entropy (less than one photon per baryon) and no free neutrons. The densities in stars are around 10^2 g cm^{-3}, while in the big bang they were closer 10^{-5} g cm^{-3}. The theoretical description of BBN requires only a few basic assumptions – general relativity, the standard big-bang cosmology, and the standard model of particle physics – along with a dozen nuclear cross sections which are well measured at the relevant energies.

At times much less than one second after the beginning, the Universe was a hot (\gg 10^{10} K), rapidly expanding plasma, with most of its energy in radiation and relativistic particles. In particular, there were roughly equal numbers of electrons, positrons, neutrinos and antineutrinos (of each species), and photons. Nucleons were outnumbered by more than a billion to one. There were essentially no composite nuclei, and weak processes like \( \nu + n \leftrightarrow p + e^- \) maintained the ratio of neutrons to protons at its thermal equilibrium value of around unity.

At about one second, the temperature had dropped to around 10^{10} K. The weak processes became ineffective, and the neutron/proton ratio leveled off at about 1/6. Growing amounts of D, ^3He, ^3H, and ^4He were present in amounts dictated by nuclear statistical equilibrium. The processes maintaining this equilibrium slowed relative to the temperature evolution (because of decreasing temperatures and densities). After five minutes, most neutrons were in ^4He nuclei, and most protons remained free (see Figure). Much smaller amounts of D, ^3He, and ^7Li were synthesized, but the low density, growing Coulomb barriers, and stability gaps at masses five and eight worked against the formation of larger nuclei. The elemental composition of the Universe subsequently remained unchanged until the formation of the first stars several billion years later. The yields of primordial nucleosynthesis, with 2\sigma theoretical errors, are shown as a function of the baryon density in the central Figure.
The big-bang predictions for the light-element abundances depend only upon the mean baryon density. The primeval abundances of the four light elements are not measured easily or simultaneously. Here is a brief summary.

1. **Helium-4**: Since the big bang its abundance has grown because stars make $^4$He. The primordial abundance is inferred from measurements of the $^4$He/H ratio in regions of hot, ionized gas (HII regions) in other galaxies. The Figure shows a compilation of these measurements as a function of the Oxygen abundance, an indicator of stellar processing. Izotov and Thuan infer $Y_P = 0.244 \pm 0.002$.

2. **Deuterium**: It is the most fragile of the light elements – all astrophysical processes destroy D – and so its abundance has been declining since the big bang. In 1973 Rogerson and York measured the deuterium abundance in the local ISM; this measurement provided a lower limit to the big-bang production and an upper limit to the baryon density. In 1998, Tytler and Burles determined the primeval deuterium abundance by measuring the D/H ratio in several high ($z > 3$) redshift hydrogen clouds, $(D/H)_P = (3.4 \pm 0.3) \times 10^{-5}$. These hydrogen clouds are “seen” by their distinctive Ly-$\alpha$ absorption features in the spectra of QSOs, with the deuterium feature isotopically shifted (to the blue) by $0.33(1 + z_{\text{cloud}})$ Å (see Figure). The primeval deuterium abundance pins down the baryon density, $(3.6 \pm 0.2) \times 10^{-31}$ g cm$^{-3}$.

3. **Lithium**: Some stars destroy lithium and others produce it. The primeval value is inferred from the $^7$Li abundance in the atmospheres of the oldest (pop II) stars in the halo of our galaxy, $(^7$Li/H)$_P = (1.7 \pm 0.15) \times 10^{-10}$. While the less massive halo stars have depleted some of their lithium, the “lithium plateau” for stars with higher surface temperatures suggests that these stars have not (see Figure). However, stellar models indicate that there could have been up to a factor of two depletion on the lithium plateau.

4. **Helium-3**: Stars burn primeval deuterium to $^3$He; beyond that little is certain. It has been argued that the net destruction or production beyond this is small. If so, then the sum of D + $^3$He remains relatively constant (measurements support this idea). Under this assumption, the primeval deuterium abundance together with the measured abundance of D + $^3$He in the ISM imply that $(^3$He/H)$_P = (0.3 \pm 1) \times 10^{-5}$.
Since the 1980s cosmologists have spoken of a concordance interval for the baryon density where the predicted and measured abundances for all four light elements are consistent (within their uncertainties). Because the abundances span nine orders of magnitude, this is no mean feat, and it establishes the validity of the standard cosmology when the Universe was seconds old and a billion times smaller. The accurate determination of the primeval deuterium abundance changed the strategy. It pegged the baryon density, and led to accurate predictions for the other light elements. When the $^4\text{He}$ abundance is known better, a comparison with the predicted abundance, $Y_P = 0.246 \pm 0.001$, will be an important consistency test. When the issue of stellar depletion is settled and the theoretical errors are reduced, lithium will offer a similar test. On the other hand, $^3\text{He}$ will serve best to probe of galactic and stellar evolution. The central Figure summarizes the present situation, showing concordance intervals for each element (based upon $2\sigma$ uncertainties) and the baryon density predicted by the deuterium measurement (vertical band). A remarkable cross check of BBN will be possible when precision measurements of CMB anisotropy made by the MAP and Planck satellites determine the baryon density to similar accuracy, based upon the completely independent physics of gravity-driven acoustic oscillations (see Figure).
PROBING COSMOLOGY AND PARTICLE PHYSICS

Baryonic and Nonbaryonic Dark Matter

For more than a decade, the “BBN concordance interval” has stood as the most accurate determination of the baryon density. The measurement of the primordial D abundance ushered in a new level of precision: expressed as a fraction of the critical density, the baryon density is $\Omega_B = 0.043 \pm 0.003$ (for $H_0 = 65 \text{ km sec}^{-1} \text{ Mpc}^{-1}$ – it varies as $H_0^{-2}$). This has several important implications: first, since stars contribute a mass density that is about ten times less, it implies that most of the baryons must be dark (most likely in the form of diffuse, hot gas). Second, measurements of the total matter density indicate that it is eight times larger, $\Omega_M = 0.4 \pm 0.1$. BBN leads us to the remarkable conclusion that most of the matter is something other than baryons. The leading candidate is elementary particles (such as axions or neutralinos) left over from the earliest, fiery moments. While a self-consistent picture of structure formation also argues for nonbaryonic dark matter, BBN is truly the linchpin in the case.

Using Helium to Count Neutrinos

The conditions at the time of big-bang nucleosynthesis are very different than those available in terrestrial laboratories, and so it is not surprising that BBN has been used as a heavenly laboratory to probe physics in regimes that go beyond the reach of earthly laboratories. BBN has constrained the properties of neutrinos, nucleons and nuclei, axions and other hypothetical particles, as well as tested general relativity and the predictions of theories that attempt to unify the forces and particles of Nature. The most striking example of the power of the heavenly laboratory is the well-known limit to the number of neutrino species.

The physics works like this. At the time of BBN, the energy density of the Universe, which controls its expansion rate, was dominated by a thermal bath of relativistic particles including neutrinos and antineutrinos. More neutrino species means a higher energy density and faster expansion. This leads to more neutrons, and hence more $^4\text{He}$ production (see Figure). Thus, the $^4\text{He}$ abundance can be used to constrain the number of neutrino species and thereby the number of families of quarks and leptons since there is one neutrino for each family. In 1977 when Steigman, Schramm and Gunn obtained a limit of no more than 7 neutrino species, the direct laboratory limit was around 5000 – a truly impressive improvement. By the time the $e^+e^-$
colliders at SLAC and CERN showed directly that the number of neutrino species was 3, the BBN limit stood at no more than 4. Today, the BBN limit stands at no more than 3.2 (at 2σ) and is used to constrain the possible existence of other new, light weakly interacting particles.

Selected Bibliography

**Beginnings:** G. Gamow, Phys. Rev. 22, 153 (1946); R. Alpher, H. Bethe, and G. Gamow, Phys. Rev. 73, 803 (1948)

**Ready to Go:** R. Alpher, J. Follin and R. Herman, Phys. Rev. 92, 1357 (1953)

**The Helium Clue:** F. Hoyle and R.J. Tayler, Nature 203, 1108 (1964)

**The Modern Era:** R.V. Wagoner and D.N. Schramm, Ann. Rev. Nuc. Sci. 27, 37 (1977)

**The Concordance Era:** A.M. Boesgaard and G. Steigman, Ann. Rev. Astron. Astrophys. 23, 319 (1985)

**The Precision Era:** D.N. Schramm and M.S. Turner, Rev. Mod. Phys. 70, 303 (1998); S. Burles, K. M. Nollett, J. W. Truran, and M. S. Turner, Phys. Rev. Lett. (submitted), astro-ph/9901157
QSO 1937–1009

$z_{\text{abs}} = 3.572$
Temperature ($10^9$ K)

Mass Fraction

- $n$
- $\text{p}$
- $^7\text{Li, }^7\text{Be}$
- $^6\text{Li}$
- $^4\text{He}$
- $^3\text{H, }^3\text{He}$

Minutes:

- $1/60$
- $1$
- $5$
- $15$
- $60$
Spherical Harmonic on Sky

$\Omega_B$

- 0.039
- 0.045
- 0.051

(Temperature Fluctuation)$^2$

Spherical Harmonic on Sky
