

The Formation of the First Nuclei

CHO-003 · Cosmic History and Its Observers

A Chronological Scientific History from the Early Universe to the Present

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Structured abstract

Context. The “first nuclei” were not individually observed objects with recorded birth times. They were a changing population reconstructed from the expansion history, weak interactions, nuclear reaction rates, and later abundance evidence. CHO-003 treats Big Bang nucleosynthesis as an overlay from approximately one second to less than twenty minutes after the formal hot-Big-Bang coordinate boundary.

Mechanism. Weak reactions first establish and then fail to maintain the neutron-proton ratio. Expansion and neutron decay continue to alter the available neutron inventory. Deuterium does not accumulate as soon as temperature falls below its 2.23 MeV binding energy because photons greatly outnumber baryons and their energetic tail efficiently photodissociates it. When temperature falls to roughly 0.1 MeV, deuterium can survive in quantity and a rapid network builds helium-4, deuterium, helium-3, tritium, and mass-7 nuclei before falling density freezes reactions.

Evidence. Laboratory cross sections and the neutron lifetime constrain the network; CMB data constrain baryon density by an independent route [7]; low-metallicity absorption and emission systems and ancient stellar atmospheres provide later abundance evidence. The controlled PDG 2026 synthesis recommends $10^5(D/H)_P = 2.508 \pm 0.029$. The Cooke benchmark is distinguished in section 7. A precision calculation cited here predicted $\Upsilon_P = 0.24709 \pm 0.00017$. The controlled PDG 2026 synthesis recommends observational $\Upsilon_P = 0.245 \pm 0.003$ while warning that overlapping datasets and systematics prevent a simple precision-weighted combination. Deuterium provides a precise, input-dependent test of the CMB baryon density; helium agrees at lower precision, while lithium-7 remains discrepant [1].

Conclusion. BBN is a stringent and successful test of a hot early Universe, but its concordance is neither exact nor assumption-free. Nuclear rates, observational systematics, stellar processing, neutrino physics, and expansion all matter. The interval remains NO in the CHO observer framework: the surviving nuclei are traces used by much later observers, not evidence of contemporaneous awareness.

Keywords: Big Bang nucleosynthesis; first nuclei; deuterium bottleneck; helium-4; primordial abundances; baryon density; lithium problem; observer capacities

1. Chronological orientation

CHO-003 occupies the declared overlay [1 s, 20 min) tBB. It overlaps CHO-002 because the physical processes overlap. Neutrino decoupling, electron-positron annihilation, weak neutron-proton conversion, and nuclear assembly cannot be cut into non-interacting textbook boxes. Topic ownership supplies the separation: CHO-002 owns the particle thermal background, while CHO-003 owns the nuclear reaction network and its abundance consequences.

The interval is ordered through temperature and reaction state rather than exact seconds:

Stage	Temperature orientation	Cosmic-time orientation	Historical significance
Weak-rate departure	around the MeV regime	broadly near one second	neutron-proton ratio ceases to track equilibrium exactly
Neutron decay interval	cooling toward 0.1 MeV	seconds to minutes	free neutrons are lost before efficient assembly
Deuterium survival	roughly 0.1 MeV	minutes-scale onset	network can retain deuterium and move rapidly toward helium
Active light-nucleus network	below the bottleneck temperature	first several minutes	D, mass-3, helium-4, and mass-7 abundances evolve
Effective freeze-out	falling temperature and density	within the 20-minute containment bound	reaction rates become too slow to change yields materially

These are process ranges. The phrase “first three minutes,” common in reviews, summarises where most standard abundance setting occurs. It does not mean every reaction begins at one second and ends at exactly 180 seconds. The 20-minute article bound contains slower numerical convergence without claiming that a physical switch occurs there.

2. Initial state inherited from CHO-002

CHO-002 passes forward an expanding radiation-dominated environment containing photons, a neutrino background, electrons and positrons in diminishing abundance, and baryonic matter dominated by neutrons and protons. The matter-antimatter asymmetry itself was inherited from CHO-001 and remains mechanistically unexplained. BBN uses the surviving baryon density as an input; it does not explain its origin.

At sufficiently high temperature, weak reactions interconvert neutrons and protons rapidly enough that their ratio remains close to its equilibrium value. As the Universe expands and cools, the weak rate loses against the expansion rate. Freeze-out is gradual. Residual reactions continue, and free neutron beta decay lowers the neutron fraction before stable nuclear assembly becomes efficient. Because nearly every surviving neutron can later enter helium-4, the weak-rate history and neutron lifetime strongly influence the helium yield.

3. What controls the network

Standard BBN combines general-relativistic expansion, Standard Model weak physics, thermodynamic distributions, and measured or evaluated nuclear reaction rates. Its principal inputs are compact but not trivial.

The baryon-to-photon ratio controls how often nuclei encounter one another in an overwhelming photon bath. The expansion rate controls the time available for reactions and depends on radiation energy density, including neutrinos and any additional relativistic species. Weak rates and the neutron lifetime control the neutron-proton history. Nuclear cross sections control how material flows through deuterium and mass-3 intermediates into helium-4 and the mass-7 channels.

The network is not a march straight up the periodic table. It is a coupled set of forward and reverse reactions in a rapidly changing environment. Early on, photodissociation prevents net assembly. Later, falling density and Coulomb barriers prevent reactions from continuing indefinitely. The outcome is a narrow window in which light nuclei can be built efficiently.

4. The deuterium bottleneck

The deuteron is bound by about 2.23 MeV, yet a temperature just below that energy is not enough for deuterium to accumulate. Photons vastly outnumber baryons. Even when the average photon energy is lower, the high-energy tail contains enough photons above the dissociation threshold to destroy newly formed deuterium. The relevant condition depends on the photon-to-baryon ratio as well as binding energy.

Only after cooling to roughly 0.1 MeV does photodissociation become sufficiently ineffective for a sustained deuterium population to form [1] [2]. Calling this the “first deuterium” time would still be misleading. Transient deuterons can form earlier and be destroyed. What changes is the balance: deuterium becomes a viable reaction bridge rather than a short-lived exception.

Once the bottleneck opens, two-body reactions rapidly process neutrons and protons through deuterium and mass-3 nuclei. Examples include $D(p,\gamma)3\text{He}$, deuterium-deuterium branches leading to helium-3 or tritium, and subsequent reactions feeding helium-4. Reaction notation summarises changes in nuclear species; it does not imply that the plasma was spatially uniform down to every collision. Standard BBN assumes large-scale homogeneity for the calculation and can be extended to test departures.

5. Helium-4, residual light nuclei, and the mass gaps

Helium-4 is exceptionally tightly bound. Once the network runs, most surviving neutrons are incorporated into helium-4. A simple neutron-counting estimate therefore already places its mass fraction near one quarter, while precision work must follow weak rates, radiative and finite-temperature corrections, neutron lifetime, and the reaction network. Pitrou and collaborators reported $Y_P = 0.24709 \pm 0.00017$ under their stated inputs and calculation [2]. That narrow uncertainty is a model-calculation result, not the full uncertainty of every astronomical inference.

Deuterium and helium-3 survive as residual products because expansion eventually makes further burning inefficient. Tritium decays to helium-3. Much of primordial mass 7 is produced initially as beryllium-7, which later becomes lithium-7 by electron capture. The final numbers are sensitive to different reactions; the label “light-element abundance” must not conceal different uncertainty budgets.

Efficient primordial construction of substantially heavier nuclei is blocked by several effects. The density falls rapidly, Coulomb barriers suppress charged-particle reactions, and there are no stable mass-5 or mass-8 nuclei that would provide easy bridges. Standard BBN can predict extremely small trace production beyond lithium, so “no heavy elements” should be read as no significant cosmic inventory, not mathematical zero. The major production of carbon, oxygen, iron, and many heavier species belongs to stellar and explosive histories owned by CHO-007.

6. Laboratory evidence and calculational reconstruction

BBN is sometimes described as an observational window onto minutes after the Big Bang. The description is valid only if the inference chain remains visible. No detector was present in the plasma. Instead, laboratory experiments measure cross sections at energies overlapping or extrapolated into the relevant range. Nuclear theory turns those measurements into thermally averaged rates. A network code evolves abundances while a cosmological model supplies temperature, density, and expansion.

The $D(p,\gamma)3\text{He}$ reaction illustrates the chain. The PDG 2026 review identifies the LUNA measurement [3] as an improvement in the precision of predicted deuterium abundance, while noting that nuclear-rate uncertainties still exceed observational D/H errors and that the deuterium-deuterium channels require further experimental refinement [1]. A laboratory cross section is measured in its experimental domain; a cosmological abundance or baryon density follows only after the rate enters a specified nuclear network and expansion model.

No single reaction closes the entire abundance calculation. Rate correlations, experimental normalisation, plasma corrections, neutron physics, and numerical integration all contribute. A credible precision statement must identify which inputs are varied and which model assumptions are fixed.

7. Later observations as evidence of primordial production

Primordial abundances are measured indirectly at much later times. Astronomers seek environments that have undergone little chemical processing or model how processing changes an abundance. Each element requires a different observational strategy.

Deuterium is destroyed in stellar interiors and is therefore especially useful in low-metallicity gas. Cooke, Pettini, and Steidel analysed high-redshift quasar absorption systems and combined seven high-precision, homogeneously treated measurements to infer $10^5(D/H)_P = 2.527 \pm 0.030$ [4]. The spectral absorption is directly observed; identifying the combined value as primordial is a reconstruction supported by low metallicity, chemical-evolution arguments, and consistency across systems.

The controlled PDG 2026 synthesis recommends $10^5(D/H)_P = 2.508 \pm 0.029$, based on twelve measurements [1, Eq. (24.2) and Table 24.1]. Its quoted uncertainty is inflated by the review’s scale factor $S = 1.08$ to account for the scatter, with $\chi^2/(N - 1) = 1.160$. This is the synthesis recommendation used here; the Cooke value is retained as the expli-

citly attributed historical benchmark for the following comparison, not as the uniquely current recommended abundance.

This precision does not imply exact agreement with every modern standard-BBN calculation. Launders, Giovanetti, and Liu used data-driven nuclear-rate fits with the Planck baryon density and obtained $10^5(D/H) = 2.442 \pm 0.040$, reported as 1.70σ below the Cooke measurement [10]. This is a study-specific comparison under its stated nuclear-rate and cosmological assumptions and its chosen observational abundance input. The reported 1.70σ is specifically relative to Cooke and is not a significance computed against the PDG recommendation. The magnitude of the discrepancy also depends on which observational abundance is adopted; it is not universal across BBN input choices.

Helium-4 is commonly inferred from emission lines in low-metallicity ionised regions. Electron temperature and density, stellar absorption, optical depth, collisional excitation, atomic emissivities, reddening, and chemical enrichment all enter. Aver, Olive, and Skillman reported $Y_p = 0.2449 \pm 0.0040$ in 2015 [5]. Post-2015 determinations compiled in the controlled PDG 2026 review span central values from about 0.2430 to 0.2462; its table distinguishes statistical and total uncertainties, so those error columns are not interchangeable. The review recommends $Y_p = 0.245 \pm 0.003$ and cautions that overlapping datasets cannot be combined naively [1]. Yanagisawa and collaborators reported $Y_p = 0.2402 \pm 0.0040$ in EMPRESS XV [8]. Aver and collaborators reported $Y_p = 0.2458 \pm 0.0013$ in the LBT Yp Project IV after their stated quality screening [9]. The LBT estimate uses a weighted mean of fifteen low-metallicity, unflagged targets rather than the same regression procedure used by all other studies. These study-specific results are not naively combined because samples, emissivities, modelling choices, and systematic budgets overlap or differ. Helium therefore agrees with standard BBN at materially lower observational precision than deuterium.

Lithium-7 is the conspicuous exception to simple concordance. Warm, metal-poor halo stars show a relatively flat lithium abundance over part of their metallicity range, but at the lowest metallicities the plateau breaks down and scatter grows. Sbordone and collaborators reported a mean $A(Li) = 2.199$ with sample dispersion 0.086 for their 3D non-LTE plateau subset at $[Fe/H] \geq -2.8$ and established a lower-metallicity “meltdown” in their sample [6]. Standard BBN calibrated by CMB baryon density predicts materially more lithium-7 than the classic stellar plateau suggests. Stellar depletion, diffusion, mixing, nuclear-rate revisions, observational modelling, and non-standard physics have all been investigated. No single explanation has been established.

Helium-3 is harder to use as a clean primordial test because stellar production and destruction complicate its later history. The uneven quality of the four abundance probes is itself part of the result. “BBN agrees with observation” is most precisely tested by deuterium, with the study-dependent tension noted above, broadly supported but systematically limited for helium-4, weak as a precision primordial test for helium-3, and unresolved for lithium-7.

8. Observer capacities present

The production interval is N0. Nuclear reactions respond to physical conditions; they do not detect, interpret, value, or communicate information. A nucleus can preserve a consequence of an early reaction history without becoming an observer under CHO’s operational framework.

Observer capacity enters billions of years later. Scientific communities build spectrographs, calibrate atomic models, measure underground reaction rates, compare independent baryon-density inferences, and revise networks. These activities turn surviving abundances into evidence. The historical claim therefore links two times: nuclei were produced during the first minutes, while the observations that support the reconstruction occur in stars, gas clouds, laboratories, and scientific institutions much later.

That separation blocks a common confusion. Measurement changes what investigators can justifiably say about BBN; it did not bring the primordial nuclei into existence. No conscious-observer postulate is used in the network.

9. Contingency and contemporaries

The broad outcome is constrained but not logically inevitable. A different baryon density would change deuterium burning. A different expansion rate would alter the time available for weak and nuclear reactions. Additional radiation, neutrino asymmetry, changed neutron lifetime, altered binding energies, or new decays could shift yields. The joint comparison of deuterium and helium with independently constrained cosmology therefore limits many alternatives, while retaining the study-dependent deuterium tension.

Contemporaneous processes included neutrino transport, electron-positron annihilation, neutron decay, electromagnetic thermalisation, nuclear reactions, and expansion. Their overlap means causal explanations must resist isolated “epoch” stories. The helium yield, for example, carries information about weak freeze-out and expansion even though its assembly proceeds later.

Alternative nuclear pathways also existed without becoming major inventories. Mass-3 and mass-7 branches persisted; heavier paths were strongly suppressed. Later stellar history selected a very different reaction environment and opened routes unavailable during BBN. Cosmic chemical complexity was delayed, not prohibited in principle.

10. Competing interpretations and unresolved questions

The principal disagreements concern precision and anomaly, not whether a hot nuclear phase occurred. Nuclear evaluations continue to refine rates and correlations. Neutron-lifetime measurements using different techniques remain relevant to precision helium prediction. Astronomical helium analyses differ in sample selection, atomic data, temperature structure, and treatment of systematics. Deuterium samples are precise but small and require complex absorption modelling.

The lithium problem crosses disciplinary boundaries. If stellar surfaces have depleted primordial lithium, models must reproduce both the plateau and its low-metallicity behaviour without erasing other abundance constraints. If nuclear inputs are responsible, revised rates must remain consistent with laboratory data. If new particles or altered expansion are invoked, deuterium, helium, CMB, and other cosmological evidence constrain the change. The discrepancy is evidence of an unresolved problem, not permission to select any preferred mechanism.

The retained source comparisons distinguish historical predictions, the PDG synthesis, and the newer study-specific helium estimates. The different samples, estimators and systematic assumptions prevent a simple combined value from replacing that comparison.

11. Claim-class statement

Class	CHO-003 use
E1, directly measured	Laboratory cross sections; spectral line fluxes and absorption profiles within stated analyses
E2, reconstructed	Primordial abundance estimates from later environments; broad existence of a hot nuclear phase
E3, model-dependent	Network yields, time-temperature mapping, baryon density inferred from BBN, and sensitivity to radiation content
E4, actively contested	Cause and full significance of the lithium discrepancy; some precision helium systematics
E5, speculative/open	Specific new-physics solutions not selected by current convergent evidence

The codes classify propositions, not papers or entire paragraphs. Verification status is kept separate from evidential class.

12. Boundaries and exclusions

CHO-003 owns nuclear assembly and primordial abundance tests within [1 s,20 min) . It does not re-own neutrino decoupling, electron-positron annihilation, or the full hadronic thermal history from CHO-002. It inherits their effects as inputs. It does not own the origin of the baryon asymmetry from CHO-001.

Later element production in stars, supernovae, compact-object mergers, and cosmic-ray spallation belongs to CHO-007. Later galaxies and stars supply abundance evidence but do not acquire ownership of the primordial network. The title does not claim an observed individual first nucleus, an exact instant of nuclear birth, production of all elements in the Big Bang, or exact agreement among all light-element observations.

13. Closing state passed to CHO-004

At effective BBN freeze-out, the expanding Universe contains photons, neutrinos, electrons, baryonic matter dominated by hydrogen nuclei and helium-4, residual deuterium and helium-3, and trace mass-7 nuclei. It does not yet contain neutral atoms. Charged nuclei and electrons remain embedded in a radiation-coupled plasma.

CHO-004 inherits that composition and follows a much longer interval through matter-radiation equality, acoustic evolution, recombination, and photon decoupling. The elemental mixture affects electron density and recombination, while the CMB later provides an independent test of the baryon density used in BBN. The next handoff therefore retains causal continuity without duplicating the nuclear network.

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Disclosure

This document is a scholarly synthesis; it is not primary research and has not been peer reviewed. Juan Segurola is the sole author. He approved the final text and is responsible for its content.