Primordial Nucleosynthesis

In addition to the expansion of the Universe and the Cosmic Microwave Background, the Big Bang theory is based on a third fundamental pillar: primordial nucleosynthesis.

This stage, which cannot be observed directly, is crucial for understanding a key period in the history of the Universe, when the first atomic nuclei formed. We now understand that atoms – the building blocks of all known matter, including ourselves – result from the evolution of the Universe. The simplest, hydrogen and helium, emerged from the Big Bang 13.8 billion years ago. These elements serve as fuel for the nuclear reactors that stars are, which then synthesise more complex nuclei.

In its earliest moments, the Universe was extremely hot and dense, consisting primarily of radiation and elementary particles. This is why physics of the infinitely small applies so admirably to this period. From the very first second after the Big Bang, temperature and density of the Universe decreased as it expanded, allowing for nuclear physics to take over: the Universe became a massive nuclear fusion reactor.

Protons p (hydrogen nuclei) and neutrons n from the primordial soup of elementary particles fused into a set of more complex nuclei. These include:

• deuterium D (hydrogen-2), a stable isotope of hydrogen, whose nucleus combines one proton and one neutron;

• tritium T (hydrogen-3), a radioactive isotope of hydrogen, whose nucleus combines one proton and two neutrons;

• helium-3, ^{3}He, with two protons and one neutron;

• helium-4, ^{4}He, with two protons and two neutrons;

• lithium-7, ^{7}Li, with three protons and four neutrons.

Nucleus	Hydrogen	Deuterium	Helium-3	Helium-4	Lithium-7
Abundance ratio	92%	10^{-5}	10^{-5}	8%	10^{-10}

Nuclei ratios

Abundance ratios of elements at the end of primordial nucleosynthesis, approx. 200 seconds after the Big Bang.

Only these few nuclei had time to form directly. As the Universe continued expanding, the temperature continued to drop, soon halting further nuclear reactions.

The chain of nuclear reactions producing the first nuclei is as follows:

p + n → D

D + n → T

D + p → 3He

3He + D → 4He + p

4He + T → 7Li

4He + 3He → 7Be

The final product of this nucleosynthesis chain, beryllium-7, is a radioactive nucleus that decays into lithium. By comparing the measured abundances of these primordial nuclei with theoretical predictions, scientists can estimate a key cosmological parameter, namely the total amount of atomic matter in the Universe – approximately one atom per cubic metre today. When primordial nucleosynthesis ended, 200 seconds after the Big Bang, the ratios of nuclei in the Universe remained fixed until the first stars appeared.

The Big Bang nucleosynthesis theory, which is now well understood and sufficiently robust, is used today to pave the way for a new physics as it helps address some of the fundamental questions raised by physicists: are the laws of physics immutable, or have they changed over the Universe's evolution?

Translated from 'La nucléosynthèse primordiale',* Passeport pour les deux infinis, *IN2P3/Dunod, https://pass2i.ijclab.in2p3.fr/ (French); updated with ICHEP2024 conference (https://ichep2024.org) for IPPOG