19

HUBERT REEVES*

The origin of the light elements in the early Universe

Shortly after World War II, George Gamov and his collaborators (Alpher *et al*. 1948) considered the possibility that all chemical elements might have been generated by a succession of nucleon capture reactions in the cooling primordial Universe. The successful prediction of the existence of a fossil radiation left over from the earliest times of the Universe (Gamov 1946) emerged from the hypothesized formation of helium in the big bang. There are two steps to this argument: (1) in order to have nuclear reactions, the temperature must have been in the MeV range (10^{10} K), and (2) given the fact that a free neutron decays in approximately 15 minutes, the transformation of some but not all of the primordial nucleons into helium requires the mean free path for neutron capture (and hence the cosmic density) to lie in an appropriate range. At too low a density, the Universe would be of pure hydrogen; at too high a density it would be of pure helium. It is, in fact, about one-quarter helium and three-quarters hydrogen (in fractional mass). By combining these numbers, Gamov and his colleagues obtained the first estimate of the ratio of nucleons to photons (of the order of 10^{-10}). From there, they predicted the existence of a fossil radiation in the millimetric range (CMB, cosmic microwave background) and estimated its present temperature (a few kelvin). The theory of big bang nucleosynthesis (BBN) is essentially based on these arguments.

However, the hypothesis of a primordial origin of all the chemical elements soon ran into major difficulties. In the proposed chain of successive nucleon capture, extending from hydrogen all the way to uranium, the nuclear instability of aggregates containing five and eight nucleons constituted a fatal flaw: it could not be seen how the corresponding steps in the chain could be achieved, so the scheme was largely abandoned.

Around the same time, Fred Hoyle and his collaborators (Burbidge *et al*. 1957) proposed a stellar origin for the chemical elements. This scheme turned out to be highly successful in accounting for the chemical elements from carbon to uranium ($12 < A < 238$). However, it ran into problems with the lighter elements. Because of their small electric charges, these nuclides rapidly undergo self-destroying nuclear reactions at the high temperatures of stellar interiors. Other formation mechanisms were clearly needed to account for their presence and abundances in the cosmos.

One requirement for the selection of the formation mechanism of these fragile, light nuclides is that, after their formation by appropriate nuclear phenomena, they should be rapidly evacuated into low-temperature regions. Two different physical processes meet this requirement: (1) BBN, where the rapid cooling of the universe preserves the newly formed nuclei from further thermonuclear reactions; and (2) galactic cosmic-ray (GCR) bombardment of interstellar atoms (mostly C, N and O) ejecting spallation residues (mostly Li, Be and B) into the cold interstellar medium (ISM).

THE CASE FOR BIG BANG NUCLEOSYNTHESIS

The best evidence in favour of the BBN of the ligther nuclides can be seen from Figures 1–3. Figure 1 shows the abundance of ^{4}He as a function of the time-integrated stellar activity, represented by the oxygen abundance in various galaxies. Although an increase in helium from approximately 20 to 30% (fractional mass) is clearly visible,

* Centre National de Recherche Scientifique, Paris, France

Hubert Reeves, The Century of Space Science, 423–440

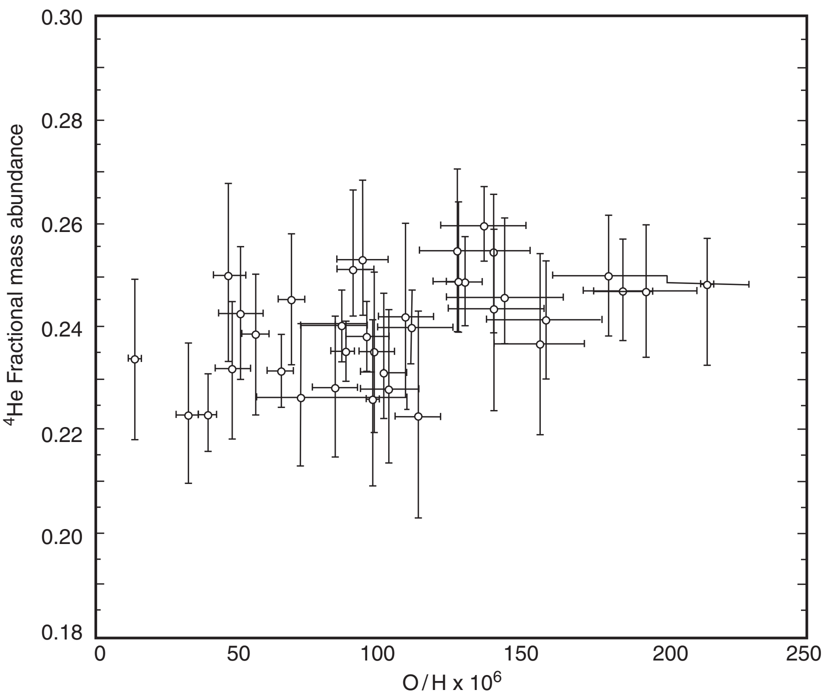

Figure 1 ^{4}He fractional mass abundances as a function of ^{16}O in chemically unevolved galaxies (after Pagel *et al.* 1992).

manifesting a stellar contribution, no celestial objects are known to have less than 20% helium (10 times less helium than hydrogen, in numbers of atoms).

A similar situation is found for ^{7}Li. As we go backward in time – by observing progressively older stars, representing the state of the ISM at the moment of their formation – the ^{7}Li to hydrogen ratio decreases progressively from 10^{-9} to 10^{-10}, where it levels off for all older stars (Figure 2). In the same fashion, the deuterium to hydrogen ratio appears to increase (Figure 3) with decreasing time.

These observations suggest that these light nuclides were already present in the primordial galactic gas. They point to a common origin: nuclear reactions in the hot big bang. Can this suggestion be made quantitative? Can the observed abundances be accounted for in terms of detailed computations? This is the subject of this chapter. It will appear that the answer is definitely yes, although some aspects are still obscure.

One important difficulty stems from the fact that the available observations (of galaxies, stars, interstellar gas, planets) cannot be readily compared with the computed primordial yields. Many factors have modified the abundances of the nuclides between the big bang and the moment at which they are observed in the history of the cosmos (e.g. the birth of the stars in which they are measured). Extrapolation from the observed data back to BBN has been a difficult task for many decades.

Another problem is the untangling, for each nucleus, of the relative contribution of different production mechanisms: BBN, GCR spallation and stellar nucleosynthesis. This is most important for the isotope ^{7}Li, for which the three mechanisms all contribute. For this reason, the cosmic-ray spallation processes and their resulting abundances will be reviewed in some detail.

NUCLEAR PHYSICS OVERVIEW

It is well known that many features of the universal abundance of chemical elements can be qualitatively understood through a knowledge of their nuclear properties. The iron peak (at $A=56$) corresponds to the most stable nuclear configurations. The secondary peaks correspond to nuclei with so-called magic numbers of neutrons (at $N=50$, 82 and 128), and also to the light nuclei with an integral number of alpha particles (at $A=12$, 16, 20, 24 and 28). In this respect, it is most informative to begin our study of the origin of the light elements with a brief review of their nuclear properties. Since the three elements lithium, beryllium and boron were potentially formed in the big bang, we shall extend this review up to $A<12$.

Two important factors play a crucial role in the nucleosynthesis of the light nuclei: their small electric charges and

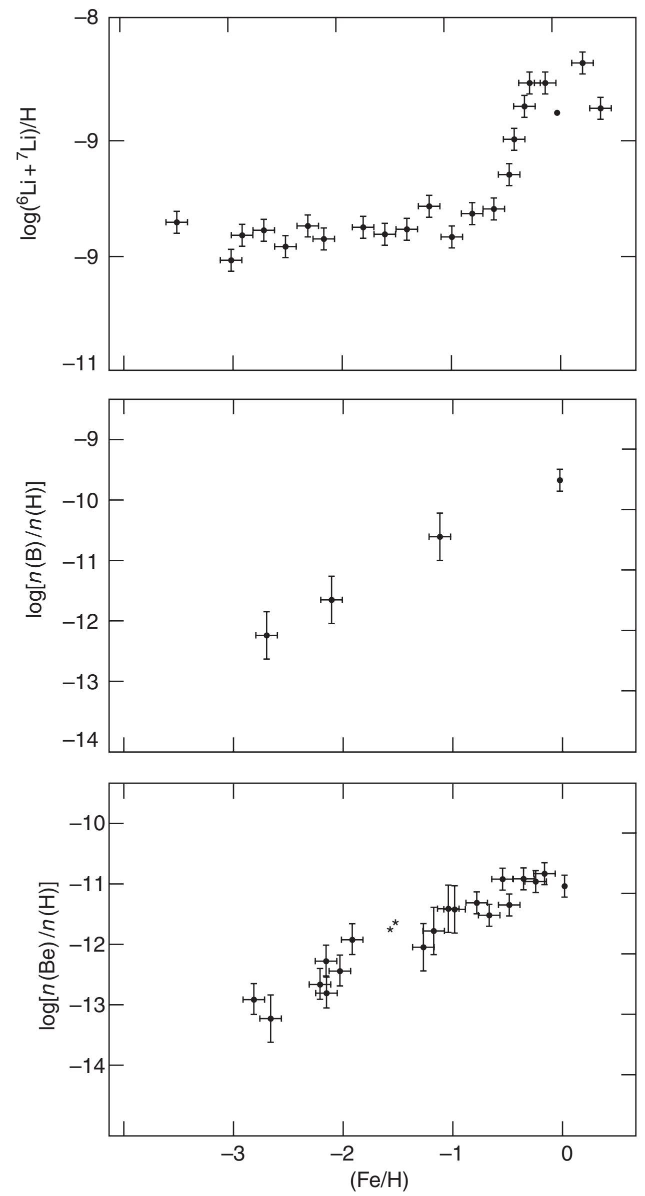

Figure 2 Li/H, Be/H and B/H stellar abundances as a function of Fe/H abundances. The logarithmic scale of the *x*-axis is in units of fractional solar iron abundance. For more data, see Cunha and Smith (1999) (after Gilmore 1992).

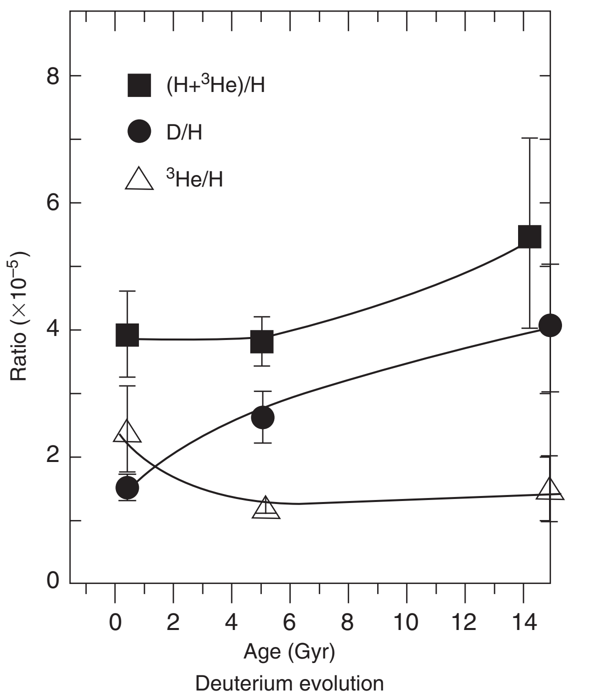

Figure 3 D and ^{3}He abundances as functions of time from the big bang (14 Gyr ago) to the present. The value of ^{3}He at 14 Gyr is not an observation but results from BBN calculations. The apparent variation of this nuclide at later times is well within the uncertainties (adapted from Geiss and Gloeckler 1998).

the large binding energy of alpha particles two relative to other nuclear arrangements.

At BBN or stellar temperatures, the kinetic energy factors are well below the Coulomb barrier. Coulomb penetration factors, proportional to the electric charge, govern the destruction rate of the light nuclei by proton capture. Because of its low Z and low nuclear stability, deuterium is doubly fragile. It disappears at 0.5 million K (MK). Next comes ^{6}Li at 2.0 MK, ^{7}Li at 2.5 MK, ^{9}Be at 3.5 MK, ^{11}B at 5.0 MK and ^{10}B at 5.3 MK. As a result, the light elements (except ^{4}He and, to a certain extent, ^{3}He) cannot resist the heat of stellar interiors. However, in view of the particle instability of ^{4}Li and ^{5}Li, the helium isotopes cannot be destroyed in nucleon-induced reactions, but only by helium-induced reactions, resulting in an appreciably higher Coulomb barrier energy and higher thermal resistance (Figure 4).

The second important nuclear property is the large binding energy of ^{4}He, due to the large pairing effect of nuclear forces when the nucleons are paired four by four: neutron–proton; spin up, spin down. As a result, every nucleus in this mass range is quite unstable toward a rearrangement involving ^{4}He nuclei. No nucleus of mass 5 manages to be stable; the lifetimes are 10^{-21} s. The isotopes ^{8}Li and ^{8}B are beta-unstable with respect to ^{8}Be, which quickly (10^{-16} s) breaks into two alpha particles.

The nuclear stability situation at a mass of 9 is deeply marked by the alpha stability. ^{9}B is unstable against two alphas + p (10^{-19} s), but ^{9}Be barely escapes disintegration (it has a very small binding energy). This weak stability of ^{9}Be is reflected in the fact that the endothermic Q values

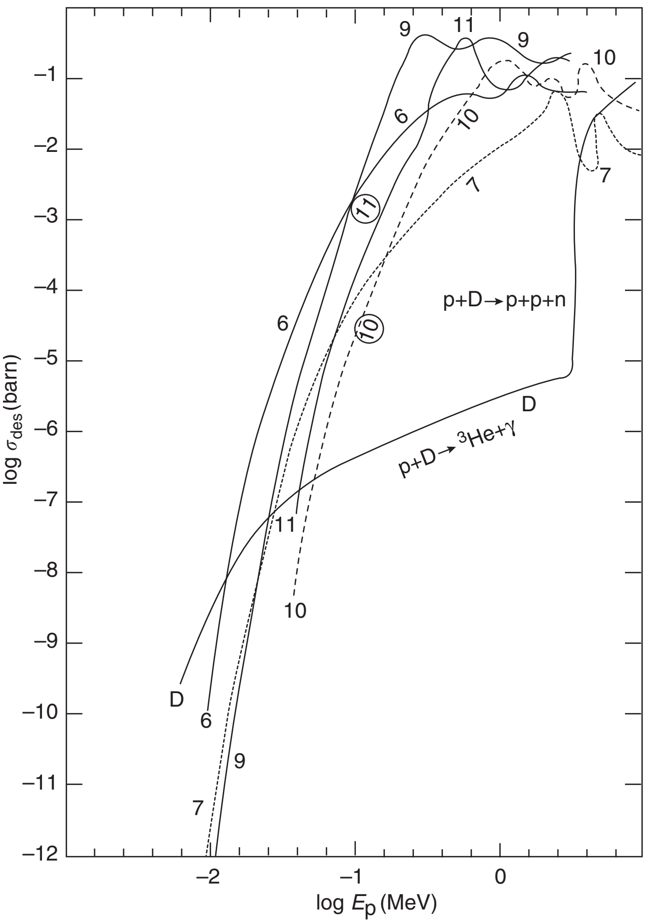

Figure 4 Total destruction cross-sections of light nuclides by protons in barns (10^{-24} cm^{-2}) as a function of energy. The number close to each curve refers to the mass number of the corresponding nuclide (after Reeves 1974).

corresponding to its formation by spallation reactions are remarkably large, and the exothermic *Q* values corresponding to its destruction are small. It is also reflected in the fact that it has only one 'bound' state; all the excited states are unstable against particle break-up. These facts are instrumental in explaining the low natural abundance of ^{9}Be (one of the lowest in nature). The isotopes ^{6}Li, ^{7}Li, ^{10}B and ^{11}B fare better but all remain comparatively fragile; in high-energy proton-induced reactions they all quickly break down into alpha particles and other products.

The high binding energy of ^{4}He is also responsible for the fact that, at all but the lowest temperatures, hydrogen is transformed rapidly into ^{4}He. The nuclei D and ^{3}He are intermediate steps in this chain of reactions; very small amounts of them remain at the end of the process. These facts dominate the scenario of BBN and also of main sequence stellar energy generation.

The influence of these nuclear properties on the formation rate of the light elements is reflected in their formation cross-sections of the spallation reactions resulting from the bombardment of atoms of C and O by protons (Figure 5). The link is best illustrated by phase-space arguments. In the high-energy region, the break-up of the excited nuclei into a given configuration is proportional to the number of possible channels, which is itself a function of the binding energy, and also of the number of bound excited states for the given configuration. Above 100 MeV or so, the cross-sections reach a plateau which is maintained all the way up to the highest energies. As expected, the cross-sections for the formation of 9Be are the smallest, while for Li and B isotopes they have higher values.

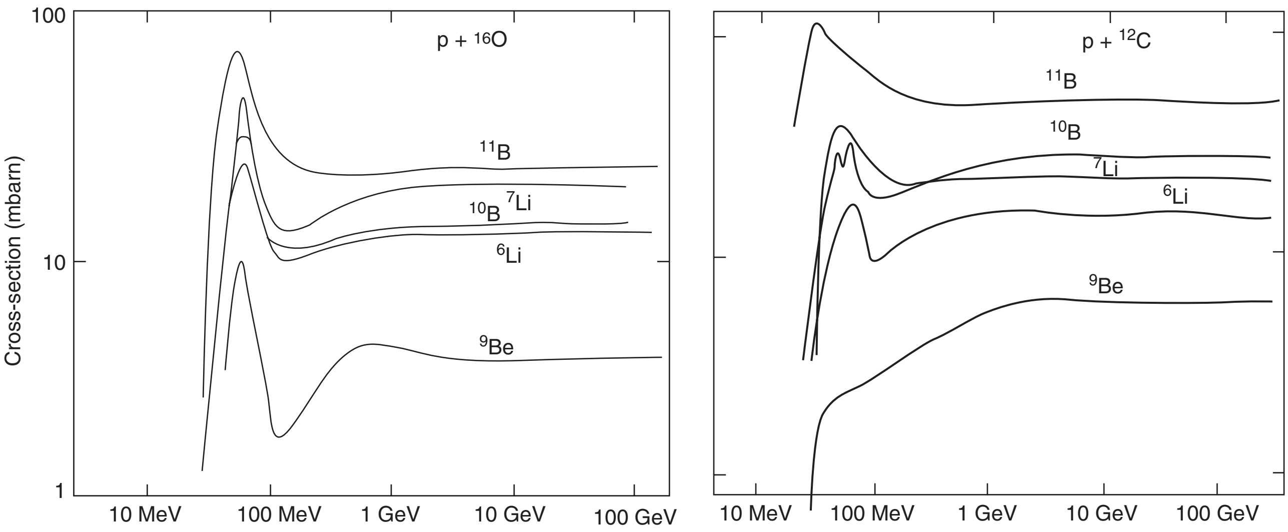

Figure 5 Spallation cross-sections in millibarns (10^{-27} cm^{-2}) for the formation of the Li, Be and B isotopes by proton-induced reactions on ^{12}C and ^{16}O (after Reeves 1974).

The Century of Space Science
Bleeker, J.A.; Geiss, J.; Huber, M. (Eds.)
2001, XLIX, 1846 p., Hardcover
ISBN: 978-0-7923-7196-0