Session I

Primordial Nucleosynthesis

Jean-Paul Zahn presenting state-of-the-art lithium depletion models, chaired by Margaret Burbidge.

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Lithium and Big-Bang Nucleosynthesis

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Abstract. Since the discovery of the "Spite plateau" in 1982, lithium observations in halo stars have been used to deduce the primordial ^7Li abundance. Compared with the results of Big Bang nucleosynthesis (BBN) it provided an estimate of the baryonic density of the Universe, together with the other cosmological isotopes. However, recently, the observations of the anisotropies of the Cosmic Microwave Background (CMB) radiation, by the WMAP satellite, has provided a determination of this baryonic density ($\Omega_b h^2$) with an unprecedented precision. There is a very good agreement with deuterium observed in cosmological clouds, but we note a discrepancy between the deduced ^7Li abundance and the one observed in halo stars. The origin of this discrepancy, observational, stellar, nuclear or more fundamental remains to be clarified. A recent nuclear physics experiment provided new results on the ^{7}Be(d,p)2α, an up to now neglected reaction in BBN. Unfortunately, this cannot solve the ^7Li discrepancy.

Keywords. Nuclear reactions, nucleosynthesis, abundances, cosmology: observations, cosmology: theory

1. Introduction

Since the pioneering work of Francois and Monique Spite (Spite & Spite (1982)) who found a value of Li/H$\approx 1.2 \times 10^{-10}$ independent of Fe/H (for [Fe/H]< -1.3), the so called "Spite plateau" (Figure 1), there have been many independent observations of Li confirming the existence of this plateau and suggesting a primordial origin for ^7Li. Big–Bang nucleosynthesis used to be the only method to determine the baryonic content of the Universe. However, recently other methods have emerged. In particular the analysis of the anisotropies of the cosmic microwave background radiation has provided $\Omega_b h^2$ values with ever increasing precision (as usual, Ω_b is the ratio of the baryonic density over the critical density and h the Hubble constant in units of 100 km $\cdot$ s^{-1} $\cdot$ Mpc^{-1}.) The baryonic density provided by WMAP (Spergel, Verde, Peiris *et al.* (2003)), $\Omega_b h^2 = 0.0224 \pm 0.0009$, has indeed dramatically increased the precision on this crucial cosmological parameter with respect to earlier experiments.

Many studies have been devoted to the calculation of the abundances of the light element isotopes produced in the big bang nucleosynthesis (Coc, Vangioni–Flam *et al.* (2002), Cyburt, Fields & Olive (2003), Coc, Vangioni-Flam, Descouvemont *et al.* (2004), Cuoco *et al.* (2004)). While the overall comparison between these theoretical predictions and the observational determinations of the abundances of D and ^{4}He are reasonably good, the theory tends to predict at present time a higher ^{7}Li abundance (of a factor 2 to 3) than is observed in the atmospheres of halo dwarf stars. Its BBN value is, according to Coc, Vangioni-Flam, Descouvemont *et al.* (2004) $^7Li/H = 4.15^{+0.49}_{-0.45} \times 10^{-10}$.

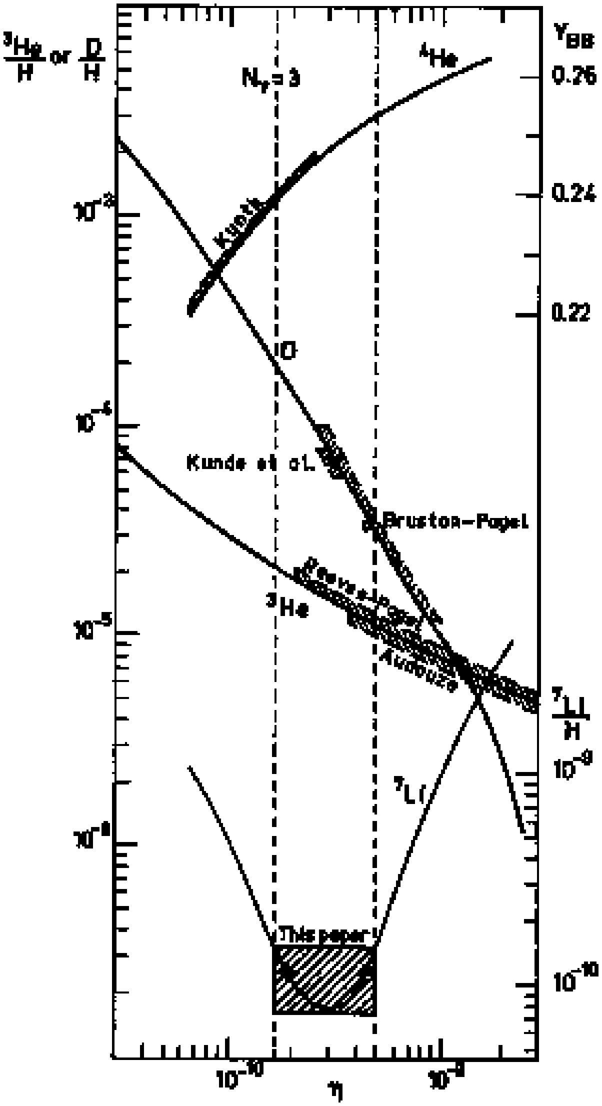

Figure 1. Figure extracted from the Spite & Spite (1982) paper showing the overall agreement between BBN calculations and observations for a range of baryonic densities, at that time.

2. Nuclear data

In 1999, the NACRE collaboration (Nuclear Astrophysics Compilation of REaction rates, (Angulo, Arnould, Rayet *et al.* (1999)) has provided a new set of reaction rates that were used to update the Big Bang Nucleosynthesis (Vangioni-Flam *et al.* (2000)). At that time, the baryonic densities obtained from CMB observations on the one hand and comparison between BBN calculations and spectroscopic data on the other hand were only marginally compatible (Coc, Vangioni–Flam *et al.* (2002)). In order to improve the nuclear network, Descouvemont, Adahchour, Angulo *et al.* (2004) have used the R-matrix theory to fit low-energy data on the 10 nuclear reactions involved in BBN and evaluated the rate uncertainties on statistic grounds. With this improved network, Coc, Vangioni-Flam, Descouvemont *et al.* (2004) have calculated BBN light element productions assuming for the baryonic density the precise value provided by WMAP (Bennett *et al.* (2003)) and confirmed the ^7Li discrepancy. However, it was argued that the $^7Be(d,p)2\alpha$ reaction, could destroy ^{7}Be (the source of ^{7}Li at high density) and solve the ^7Li problem if its cross section was much higher than assumed.

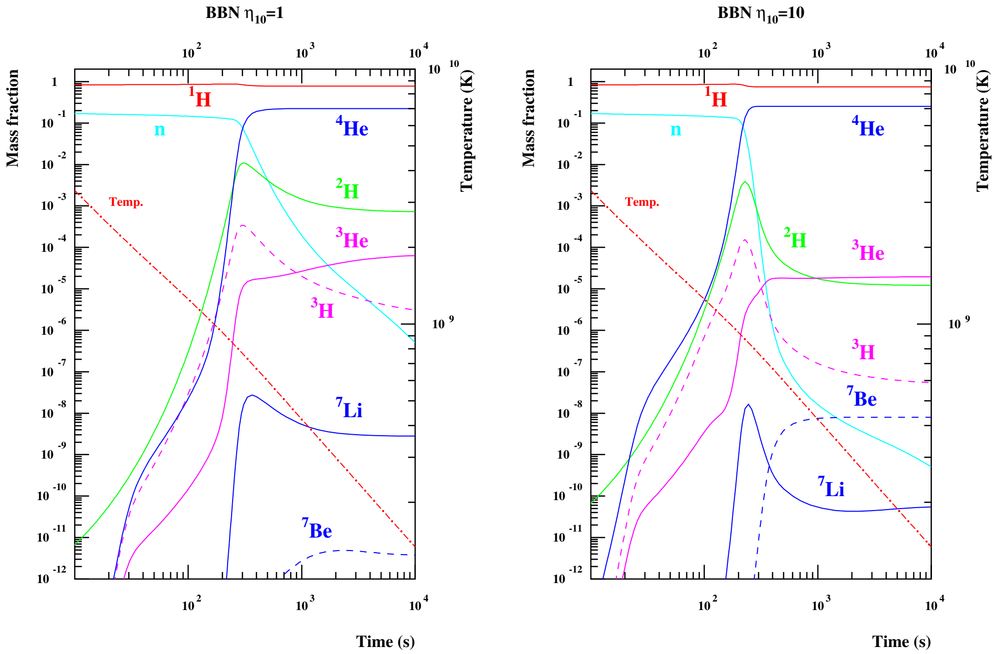

Figure 2. Evolution of the abundances as a function of time (left scale) for two extreme values of the baryonic density : $\eta = 10^{-10}$ (left panel) and 10^{-9} (right panel). It shows ^7Li direct production at low density or through ^{7}Be at high density. The right scale represent the temperature.

Several reaction-rate compilations involving the main SBBN reactions, are available in the literature. The latest Caltech version (Caughlan & Fowler (1988)) concerning isotopes up to silicon is now partially superseded by the NACRE compilation (Angulo, Arnould, Rayet *et al.* (1999)) but both are broad compilations not precisely aimed at SBBN. Compilations concerning specifically SBBN reaction rates have been performed by Smith, Kawano & Malaney (1993) and Nollet & Burles (2000). Cyburt, Fields & Olive (2001) have reanalyzed the NACRE compiled data and obtained in some cases a slightly different normalization. A very recent SBBN rate analysis was performed by Cyburt (2004) with a detailed analysis of uncertainties. However, all these analysis used polynomial or spline fits. Descouvemont, Adahchour, Angulo *et al.* (2004) have analyzed these low-energy cross sections in the R-matrix framework (Lane & Thomas (1958)) which provides a more rigorous energy dependence, based on Coulomb functions. This approach is more complicated than those mentioned above, and could not be considered for broad compilations covering many reactions. However, the smaller number of reactions involved in Big Bang nucleosynthesis makes the application of the R-matrix feasible. Evaluation of the uncertainties associated with the cross sections and reaction rates were performed by using standard statistical techniques (Particle Data Group (2002)) and new data, published after the NACRE compilation, were included.

3. SBBN primordial abundances compared to observations

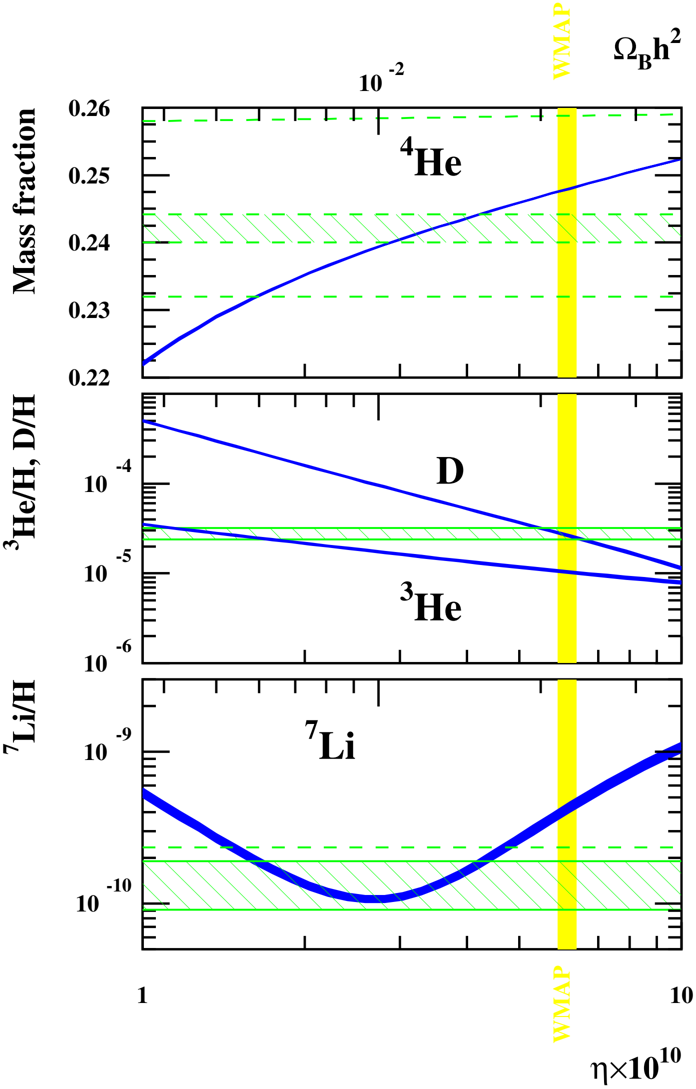

Figure 3. Abundances of ^4He (mass fraction), D, ^3He and ^7Li (by number relative to H) as a function of the baryon over photon ratio η or $\Omega_b h^2$. Limits (1-σ) are obtained from Monte Carlo calculations. Horizontal lines represent primordial ^4He, D and ^7Li abundances deduced from observational data (see text). The vertical stripe represent the (68% c.l.) $\Omega_b h^2$ limits provided by WMAP (Spergel, Verde, Peiris *et al.* (2003)).

Coc, Vangioni-Flam, Descouvemont *et al.* (2004) performed Monte-Carlo calculations using Gaussian distributions with parameters provided by the new compilation (Descouvemont, Adahchour, Angulo *et al.* (2004)) and calculated the ^4He, D, ^3He and ^7Li yield range as a function of η, fully consistent with our previous analysis (Coc, Vangioni–Flam *et al.* (2002)). Using these results and the WMAP $\Omega_b h^2$ range (quoted WMAP + SBBN in the following), it is now possible to infer the primordial ^4He, D,

^3He and ^7Li abundances. The results were compared to observations that are thought to be representative of the corresponding primordial abundances. The deuterium primordial abundance obtained (WMAP + SBBN) is $D/H = (2.60^{+0.19}_{-0.17}) \times 10^{-5}$ [ratio of D and H abundances by number of atoms] which is in perfect agreement with the average value $(2.78^{+0.44}_{-0.38}) \times 10^{-5}$ of D/H observations in cosmological clouds (Kirkman, Tytler, Suzuki, *et al.* (2003)). These clouds at high redshift on the line of sight of distant quasars are expected to be representative of primordial D abundances. The exact convergence between these two independent methods is claimed to reinforce the confidence in the deduced $\Omega_b h^2$ value. Figure 3 displays the resulting abundance limits (1-σ) from SBBN calculations compared to primordial ones inferred from observations. The other WMAP + SBBN deduced primordial abundances are $Y_P = 0.2479 \pm 0.0004$ for the ^4He mass fraction, $^3\mathrm{He/H} = (1.04 \pm 0.04) \times 10^{-5}$ and $^7\mathrm{Li/H} = (4.15^{+0.49}_{-0.45}) \times 10^{-10}$.

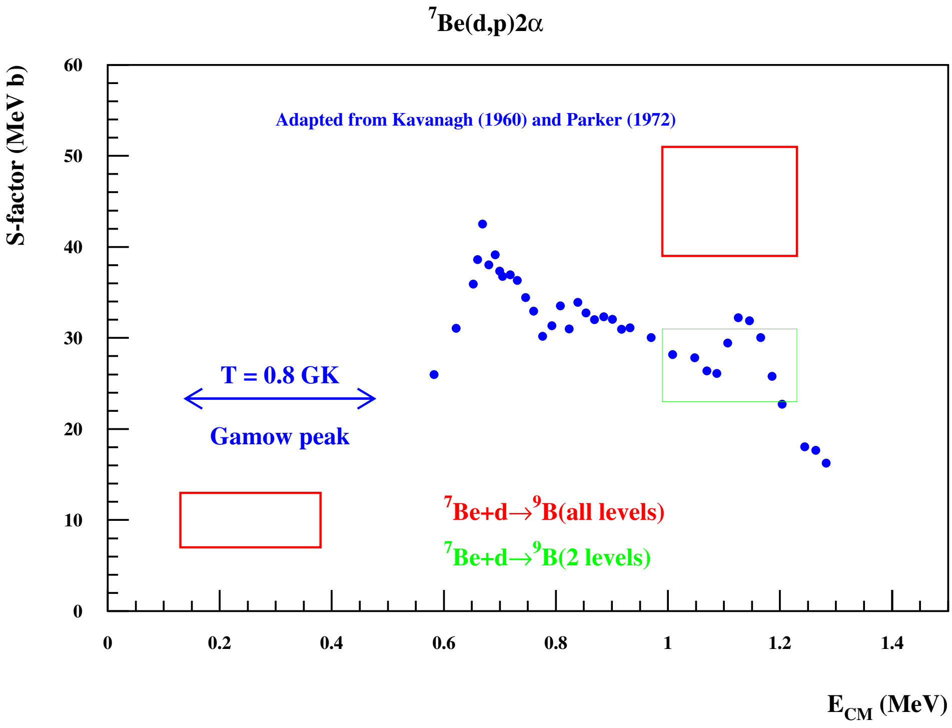

Figure 4. Recent lithium observations in halo stars Ryan *et al.* (1999), Ryan, Beers, Olive *et al.* (2000), Melendez & Ramirez (2004) and in a globular cluster NGC 6397 (Thévenin *et al.* (2001), Bonifacio *et al.* (2002)).

We leave aside ^3He whose primordial abundance cannot be reliably determined because of its uncertain rate of stellar production and destruction (Vangioni–Flam, Olive, Fields & Cassé (2003)). The observed ^4He abundance, Y_p (mass fraction), is derived from observations of metal–poor extragalactic, ionized hydrogen (H II) regions. Recent evaluations gave relatively narrow ranges of abundances: $Y_p = 0.2452 \pm 0.0015$ (Izotov, Chaffee, Foltz, Green *et al.* (1999)), 0.2391 ± 0.0020 (Luridiana *et al.* (2003)). However, recent observations by Isotov & Thuan (2004) on a large sample of 82 H II regions in 76 blue compact galaxies have lead to the value of $Y_p = 0.2421 \pm 0.0021$. With this range, WMAP and SBBN results are hardly compatible. Nevertheless, as systematic uncertainties may prevail due to observational difficulties and complex physics leading to a broader range of values (Olive & Skillman (2004)) (dashed lines in Figure 3). The ^7Li abundance measured in halo stars of the Galaxy is considered up to now as representative of the primordial abundance since it displays a plateau (Spite & Spite (1982)) as a function of metallicity. Recent observations (Ryan, Beers, Olive *et al.* (2000)) have led to (95% c.l.) $\mathrm{Li/H} = (1.23^{+0.68}_{-0.32}) \times 10^{-10}$. These authors have extensively studied and quantified the various sources of uncertainty: extrapolation, stellar depletion and stellar atmosphere parameters. This Li/H value, based on a much larger number of observations than the D/H one was considered (Coc, Vangioni–Flam *et al.* (2002)) as the most reliable constraint on SBBN and hence on $\Omega_b h^2$. However, it is a factor of 3.4 lower than the WMAP + SBBN value. Even when considering the corresponding uncertainties, the Li/H values differ. It is surprising that the major discrepancy affects ^7Li since it could a priori lead to a more reliable primordial value than deuterium, because of much higher observational statistics and an easier extrapolation to primordial values. One should note however that very recently, Melendez & Ramirez (2004)) have observed many halo dwarf stars showing a flat lithium plateau with mean abundance $\mathrm{Li/H} = 2.34 \times 10^{-10}$ (dashed line in Fig 3, higher than the Ryan *et al.* (Ryan, Beers, Olive *et al.* (2000)) value. This would reduce the discrepancy to a factor of ≈2, but not remove it. In Figure 4, is represented Li data as a function of [Fe/H] including Ryan *et al.* (1999) and Melendez & Ramirez (2004) observations together with the WMAP + SBBN value (Coc, Vangioni-Flam, Descouvemont *et al.* (2004)). Note that other recent calculations (Cyburt, Fields & Olive (2003), Cuoco *et al.* (2004)) using other compilations of reaction rates also display a similar discrepancy for ^7Li.

4. Possible origins of ^7Li discrepancy between SBBN and CMB

4.1. *Stellar*

Both observers and experts in stellar atmospheres agree to consider that the abundance determination in halo stars, and more particularly that of lithium requires a sophisticated analysis. The derivation of the lithium abundance in halo stars with the high needed precision requires a fine knowledge of the physics of stellar atmosphere (effective temperature scale, population of different ionization states, non LTE (Local Thermodynamic Equilibrium) effects and 1D/3D model atmospheres (Asplund, Carlsson & Botnen (2003)). Even though the 3D hydrodynamical models with non–LTE abundances give very similar results comparing to the 1D, non–LTE models, 3D models are now compulsory to extract lithium abundance from metal poor halo stars (Barklem, Belyaev & Asplund (2003)). Modification of the surface abundance of Li by nuclear burning all along the stellar evolution has been discussed for a long time in the literature. There is no lack of phenomena to disturb the Li abundance: rotational induced mixing, mass loss,...(Theado & Vauclair (2001), Pinsonneault *et al.* (2002)). However, the flatness of the plateau over three decades in metallicity and the relatively small dispersion of data represent a real challenge to stellar modeling. For a detailed analysis, see Ryan, this proceedings and Charbonnel & Primas (2005). In addition, recent observations of ^6Li in halo stars (an even more fragile isotope than ^7Li) constrain more severely the potential destruction of lithium (Rollinde *et al.* (2005)). Concerning this isotope see the papers of Inoue and Rollinde in this proceedings. (Note also that the large nuclear uncertainty concerning its production in SBBN has been significantly reduced thanks to a recent experiment (Hammache *et al.* (2005))).

4.2. *Cosmology and particle physics.*

Recent theories that could affect BBN include the variation of the fine structure constant (Nollet & Lopez (2002)), the modification of the expansion rate during BBN induced by quintessence (Salati (2003), modified gravity (Navarro, Serna & Alimi (2002)), or leptons asymmetry (Orito, Kajino *et al.* (2002)). However, their effect is in general more significant on ^4He than on ^7Li. Recently, Ellis, Olive & Vangioni (2005) have reconsidered the effects of the radiation from the decays of unstable particles on the production/destruction of the primordial isotopes in order to reconcile the high primordial ^{7}Li abundance deduced from BBN+WMAP, with the abundance of ^{7}Li observed in halo stars. This study has demonstrated that the potential destruction of ^{7}Li in this physical context, is strongly constrained by observations of Deuterium (D), ^{3}He and ^{6}Li. They conclude that late particle decay is unable to explain both the discrepancy of the calculated ^7Li abundance and the observed ^7Li plateau.

4.3. *Pregalactic evolution*

We note that between the BBN epoch and the birth of the now observed halo stars, a few 10^8 years have passed. Primordial abundances could have been altered during this period. For instance, cosmological cosmic rays possibly generated by first generation stars (Population III), assumed to have been born in a burst at some high redshift, could have modified these primordial abundances in the intergalactic medium (Montmerle (1977)). Specifically, very recent observations of the ^6Li isotope in halo stars reveal a ^6Li plateau about 1000 times above the predicted BBN abundance. Rollinde *et al.* (2005) have shown that pregalactic production of this isotope via cosmological cosmic rays (CCRs) can account for the observed ^6Li plateau. This process is indeed able to produce the required abundance of ^6Li without the additional over-production of ^7Li. Consequently, the derived relation between the amplitude of the CCR energy spectra and the redshift of the initial CCR production puts constraints on the physics and history of the primitive objects, possibly responsible for these early cosmic rays. But, in all cases, these processes cannot reconcile the BBN and the Spite plateau.

4.4. *Nuclear physics and the $^7Be(d,p)2\alpha$ experiment*

Before suggesting that new physics may be needed, effects related to uncertainties in the SBBN reaction rates have to be considered. Large systematic errors on the 12 main nuclear cross sections are excluded (Coc, Vangioni–Flam *et al.* (2002), Descouvemont, Adahchour, Angulo *et al.* (2004), Coc, Vangioni-Flam, Descouvemont *et al.* (2004)). However, besides the 12 reactions classically considered in SBBN, first of all the influence of *all* nuclear reactions needs to be evaluated. It is well known that the valley shaped curve representing Li/H as a function of η is due to two modes of ^7Li production. One, at low η is the production of ^7Li directly via ^{3}H$(\alpha,\gamma)^7$Li while ^7Li destruction comes from ^{7}Li(p,α)^{4}He. The other one, at high η, leads to the formation of ^{7}Be through ^{3}He$(\alpha,\gamma)^7$Be while ^{7}Be destruction by ^{7}Be(n,p)^{7}Li is inefficient because of the lower neutron abundance at high density (^7Be later decays to ^7Li). Since the WMAP results point toward the high η region, a peculiar attention should be paid to ^{7}Be synthesis. In particular, the ^{7}Be+d reactions could be an alternative to ^{7}Be(n,p)^{7}Li for the destruction of ^7Be, by compensating the scarcity of neutrons at high η. An increase of the ^{7}Be(d,p)2^{4}He reaction rate by factors of 100 to 300 would remove the discrepancy. The rate for this reaction (Caughlan & Fowler (1988)) can be traced to an estimate by Parker (Parker (1972)) who assumed for the astrophysical S–factor a constant value of 10^5 keV-barn based on the single experimental data available (Kavanagh (1960)). To derive this S–factor, Parker used this measured differential cross section at 90° and assumed isotropy of the cross section. The estimate of the ^{7}Be(d,p)2α cross sections at the SBBN Gamow window ($T = 0.1 - 1$ GK, $E = 0.11 - 0.56$ MeV) implies an extrapolation of about two orders of magnitude. Since Kavanagh measured only the p_0 and p_1 protons (i.e. feeding the ^{8}Be ground and first excited levels), Parker introduced an additional but arbitrary factor of 3 to take into account the possible population of higher lying levels. Indeed, a level at 11.35 MeV is also reported (Ajzenberg-Selvone (1988)). In addition, one should note that *no* experimental data for this reaction was available at energies relevant to ^{7}Be Big Bang nucleosynthesis (Figure 5), taking place when the temperature has dropped below 10^9 K. A seducing possibility to reconciliate, SBBN, ^7Li and CMB observations could be that new experimental data below E_d = 700 keV ($E_{cm} \approx 0.5$ MeV) for ^{7}Be(d,p)2^{4}He [and ^{7}Be(d,α)^{5}Li] would lead to a sudden increase in the S–factor as in ^{10}B(p,α)^{7}Be (Angulo, *et al.* (1993), Angulo, Arnould, Rayet *et al.* (1999)). This is not supported by known data, but considering the cosmological or astrophysical consequences, an experiment was performed recently.

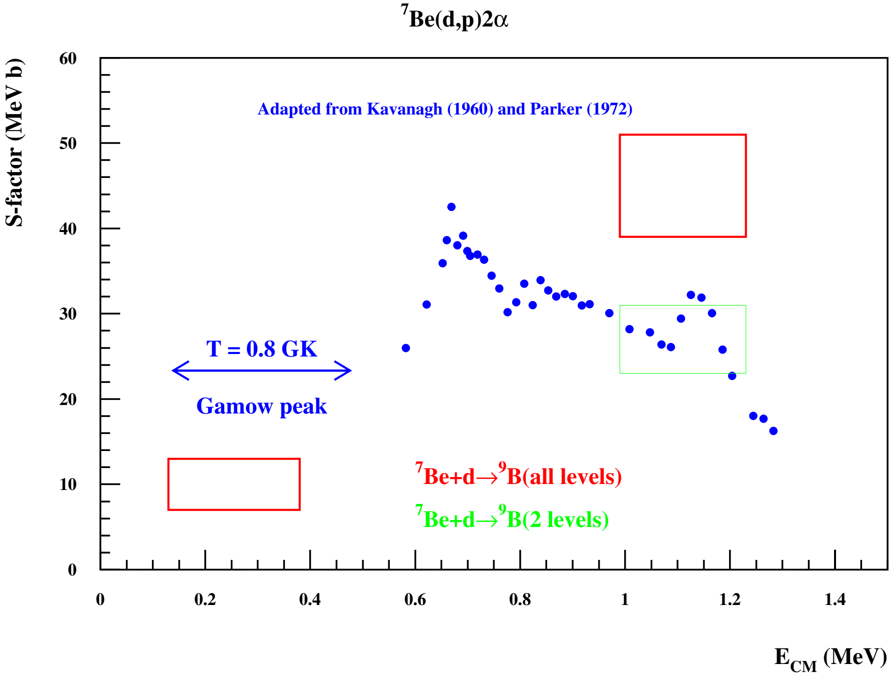

Figure 5. The only experimental data available for the ^{7}Be(d,p)2^{4}H reaction from Kavanagh (1960). The displayed S–factor is calculated as in Parker (1972) from the differential cross section at 90° ($\times 4\pi$) leading to the ground and first ^{8}Be excited states. Note that no data were available at SBBN energies as shown by the Gamow peak for a typical temperature of T_9 = 0.8. Boxes represent the new experimental data (integrated energy range × error bars on cross–section) at high (for comparison with existing data) and low (BBN) energies (Angulo *et al.* (2005)).

The experiment (Angulo *et al.* (2005)) was performed using a ^{7}Be^{1+} radioactive beam (Gaelens *et al.* (2003)) at the lowest energy of 5.545 MeV provided by the CYCLONE110 cyclotron at the CYCLONE RIB facility at Louvain-la-Neuve (Belgium). This energy was degraded down to 1.710 MeV using a 6 μm Mylar foil situated at about 50 cm from the target. The target consisted of a 200 μg/cm^2 (CD$_2$)$_n$ self-supporting foil. The reaction products were detected using a stack of two silicon strip detectors (Davinson *et al.* (2000)) covering an angular range of $\theta_{\rm lab} = 7^\circ - 17^\circ$. With such a set-up, we were able to investigate the center-of-mass energy ranges (see Figure 5) between 1.2 and 0.96 MeV (for a beam energy of 5.545 MeV) and between 0.38 and 0.15 MeV (for 1.710 MeV). High energy protons corresponding to the ground state and the first excited state in ^{8}Be were not completely stopped in the $\Delta E_1 - \Delta E_2$ telescope, while protons corresponding to other higher excited states in ^{8}Be were stopped. α particles, recoil and scattered particles were completely stopped in ΔE_1. The results (Angulo *et al.* (2005)) are displayed in Figure 5 (the three boxes) showing that the cross–section averaged over the energy loss in the target is not higher than expected at BBN energies. (For comparison with Kavanagh (1960), at high energy, the contribution of the ground and first exited states only are also displayed). Finally, since the cross section value is found to be smaller than estimated, the ^7Li discrepancy remains.

5. Conclusions

^7Li plays a key role as a bridge between big bang nucleosynthesis, stellar evolution and galactic cosmic ray nucleosynthesis. Using a new set of reaction rates and related uncertainties, obtained within the R-matrix model, light element primordial abundances are calculated within the standard model of Big–Bang theory to be compared with spectroscopic observations. The baryonic density of the Universe as determined by the analysis of the Cosmic Microwave Background anisotropies is in very good agreement with Standard Big–Bang Nucleosynthesis compared to D primordial abundance deduced from cosmological cloud observations. However, at present, there is a significant discrepancy between the BBN-predicted ^7Li abundance assuming a baryon density consistent with the concordance model derived from observations of anisotropies in the microwave background, and the abundance determined from the observations of ^7Li in the atmospheres of halo stars. The discrepancy is large enough that it appears impossible to be resolved at the level of the nuclear physics inputs to BBN calculations. The last option, a higher than expected ^{7}Be(d,p)2α cross section is now ruled out by recent experimental data.

The remaining conventional options (i.e., not invoking physics beyond the Standard Model) are an adjustment of the stellar input parameters needed to extract a ^7Li abundance from observations, or stellar depletion of ^7Li. That certainly remains a possibility, though models must be constructed to avoid dispersion in the ^7Li abundances over a wide range of stellar parameters. Consequently, the origin of the discrepancy of Li, not nuclear, is a challenging issue, probably of stellar origin.

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