Title: Particle Physics 5

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Abstract:

Maxim Pospelov

Perimeter / University of Victoria

Particle Physics Catalysis of Thermal Big Bang Nucleosynthesis

Plan

1. BBN after WMAP. Lithium problem.
2. Modification of BBN by particle physics
3. BBN with metastable charged particles. Catalysis of BBN ^6Li output by $(^4HeX^-)$ bound states
4. Prospects for ^7Li. Conclusions

M.P., hep-ph/0605215

Main idea: many models of particle physics have charged relics that survive from the Big Bang until nucleosynthesis (charged staus, charged KK modes etc.)

At t after 1000 sec (T below 50 KeV), charged particles X^- recombine with nuclei (NX^-).

Existence of (NX^-) modifies reaction rates for N.

Standard mechanism for ^6Li

$$^4He + D \to {}^6Li + \gamma \quad (E2 \text{ transition}, Q \simeq 1.5 \text{ MeV})$$

Catalyzed mechanism

$$(^4He X^-) + D \to {}^6Li + X^-$$

Enhancement in the rate $\sim 10^8$

Gives a strong probe of X^-.

Steigman review, 2005

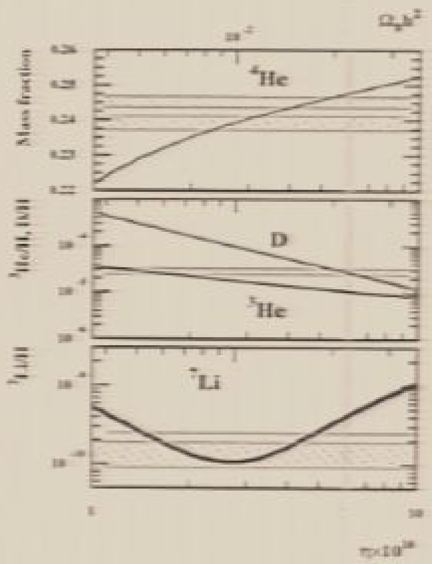


Fig. 1.— Abundances of ^4He (mass fraction), D, ^3He and ^7Li (by number relative to H) as a function of the baryon over photon ratio η or $\Omega_b h^2$. Limits (1-σ) are obtained from Monte Carlo calculations. Hatched area represent primordial ^4He, D and ^7Li abundances deduced from different primitive astrophysical sites (see Section 2): Izotov et al. (1999) (high area) and Luridiana et al. (2003) (low area) for ^4He, Kirkman et al. (2003) for D, and Ryan et al. (2000) for ^7Li (95% c.l.). Concerning ^7Li, we also show an upper limit derived from Bonifacio et al. (2002) observations (dashed line). The vertical stripe represents the (1-σ) $\Omega_b h^2$ limits provided by WMAP (Spergel et al. 2003).

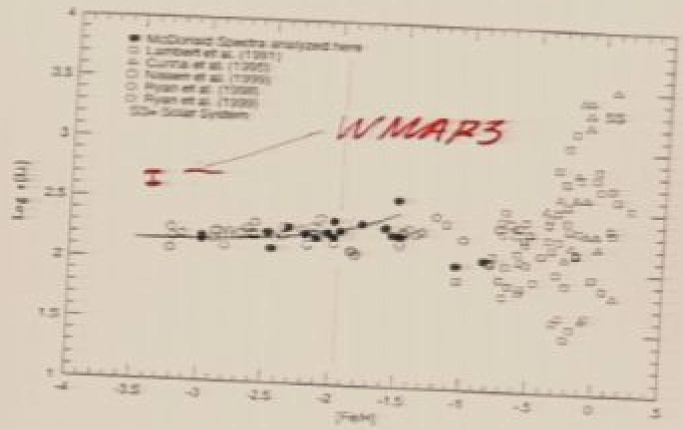
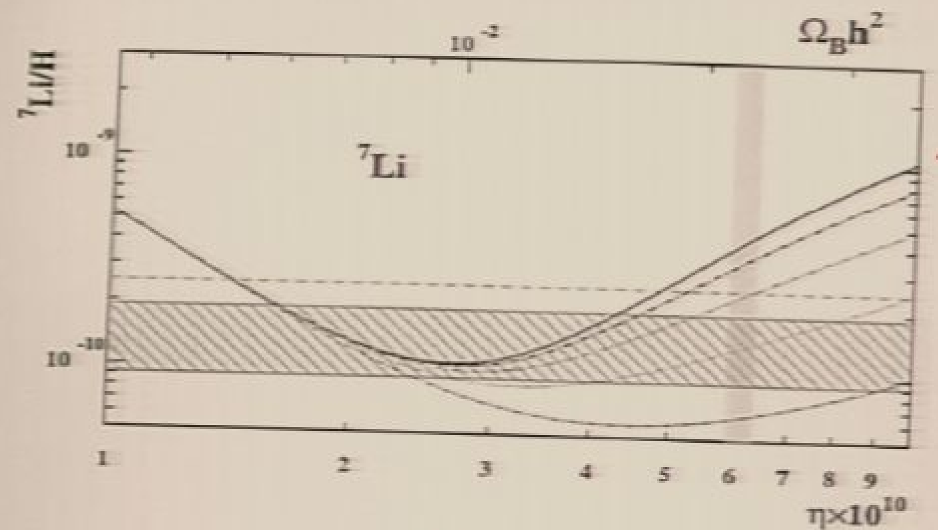


Fig. 11. Lithium abundances, log ε(Li) ≡ [Li] ≡ 12+log(Li/H) versus metallicity (on a log scale relative to solar) from a compilation of stellar observations by V. V. Smith. The solid line is intended to guide the eye to the "Spite Plateau".

12+log(Li/H)) for $-3.5 \leq$ [Fe/H] ≤ -1, and they derive a primordial abundance of $[\mathrm{Li}]_P \approx 2.0-2.1$. This abundance is low compared to the value found by Thorburn[25], who derived $[\mathrm{Li}]_P \approx 2.25 \pm 0.10$. The stellar temperature scale plays a key role in using the observed equivalent widths to derive the ^{7}Li abundance. Studies of halo and Galactic Globular Cluster stars employing the infrared flux method effective temperature scale suggest a higher lithium plateau abundance[26], $[\mathrm{Li}]_P = 2.24 \pm 0.01$, similar to Thorburn's[25] value. Recently, Melendez & Ramirez[27] reanalyzed 62 halo dwarfs using an improved infrared flux method effective temperature scale. While they failed to confirm the [Li] – [Fe/H] correlation claimed by Ryan et al.[24], they suggest an even higher relic lithium abundance: $[\mathrm{Li}]_P = 2.37 \pm 0.05$. A very detailed and careful reanalysis of extant observations with great attention to systematic uncertainties and the error budget has been done by Charbonnel and Primas[28], who find no convincing evidence for a Li trend with metallicity, deriving $[\mathrm{Li}]_P = 2.21 \pm 0.09$ for their full sample and $[\mathrm{Li}]_P = 2.18 \pm 0.07$ when they restrict their sample to unevolved (dwarf) stars. They suggest the Melendez & Ramirez value should be corrected downwards by 0.08 dex to account for different stellar atmosphere

Coc et al. 2004



← SBBN

↑ Lines with
$^7Be + d \to 2\alpha + p$
cross sections scaled
up by 30
100
300
1000

Jedamzik 2004

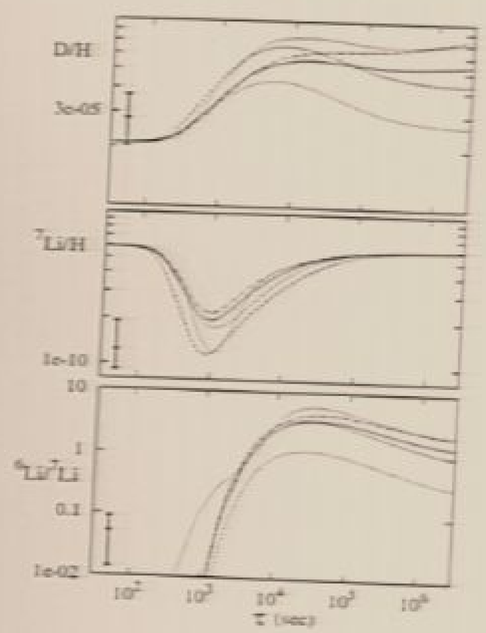


FIG. 2: Abundance yields of D/H, ^{7}Li/H, and ^{6}Li/^{7}Li in an $\Omega_b h^2 = 0.026$ Universe as function of the hadronic decay time τ of a putative primordial relic. The models are decay of a $m_\chi = 10\,\mathrm{GeV}$ particle (long-dashed), decay of a $m_\chi = 200\,\mathrm{GeV}$ particle (solid), decay of a $m_\chi = 4\,\mathrm{TeV}$ particle (dashed-dotted), injection of monoenergetic nucleons of $E_{kin} = 250\,\mathrm{MeV}$ (short-dashed), and extended power-law injection due to a $m_\chi = 200\,\mathrm{GeV}$ particle (dotted). Also shown are the two-sigma ranges of the inferred primordial D/H and ^{7}Li/H abundances [3, 10] as well as the ^{6}Li/^{7}Li ratio as inferred in the low-metallicity star HD84937 [25]. See text for further details.

scatterings an interconversion of protons to neutrons occurs frequently, such that energetic protons produce secondary neutrons. For example, though the decay of a 200 GeV particle generates only about ≈ 1 neutron per annihilation, around $\approx 1, 0.6$ secondary neutrons result at $T \approx 20, 40\,\mathrm{keV}$, respectively [39], and ≈ 3.5 asymptotically at low temperatures $T \sim 0.1-1\,\mathrm{keV}$. Here at higher temperatures the number of secondary neutrons reduces due to the rapid Coulomb losses of protons. Neutrons, on the other hand, do not possess a significant bias towards producing secondary neutrons in np inelastic interactions. Excess neutrons at $T \approx 40\,\mathrm{keV}$ are mostly due to inelastic processes on ^{4}He, accompanied by the production of D and ^{3}He (i.e. $n + {}^4\mathrm{He} \to \mathrm{D} + p + 2n, ...$), with a comparatively smaller amount of neutrons removed in pionic fusion processes (i.e. $np \to \mathrm{D}\pi^0, ...$). One thus obtains approximately a ratio n/D ≈ 3.6 for a 200 GeV particle at $T \approx 40\,\mathrm{keV}$, with similar ratios for n/^{3}H and n/^{3}He. As the ^{3}H and ^{3}He are energetic they may yield the production of ^{6}Li. Nevertheless, ^{6}Li production (and survival) may only be efficient at somewhat lower temperatures. Due to Coulomb losses of energetic ^{3}H and ^{3}He production is only efficient at $T \lesssim 20\,\mathrm{keV}$, whereas survival of the freshly synthesized ^{6}Li against destruction via ^{6}Li$(p,\alpha)^3$He is only nearly complete for $T \lesssim 10\,\mathrm{keV}$. The production of ^{6}Li at temperatures $T \approx 10-20\,\mathrm{keV}$ for a 200 GeV particle is found to be approximately 2×10^{-4} per decaying particle, becoming significantly lower at lower temperatures (e.g. 3×10^{-5} at $T \approx 1\,\mathrm{keV}$). Cascade yields are subject to some nuclear physics data uncertainties which in the case of ^{6}Li may be of the order of a factor two. In particular, it may be that ^{6}Li yields are underestimated due to an experimentally incomplete determination of the high-energy tail of the energy distribution of energetic ^{3}H and ^{3}He produced in ^{4}He spallation.

The developed code allows me to present detailed predictions on the BBN in the presence of decaying particles. Figure 2 shows the light-element yields for a variety of decaying particles as a function of particle life time τ. The panels show, from top-to-bottom, final abundances of D/H, ^{7}Li/H, and ^{6}Li/^{7}Li, with the understanding that Y_p is virtually unchanged when compared to SBBN at the same $\Omega_b h^2$. In all models $\Omega_b h^2 = 0.026$ has been assumed. Hadronically decaying particle yields (with the simplifying assumption that $\chi \to q\bar{q}$ yields the production of a pair of quarks, the up-quark for definiteness) are shown for three particle masses: $m_\chi = 10\,\mathrm{GeV}$ with $\Omega_\chi h^2 = 7.5 \times 10^{-5}$ (long-dashed), $m_\chi = 200\,\mathrm{GeV}$ with $\Omega_\chi h^2 = 1 \times 10^{-4}$ (solid), and $m_\chi = 4\,\mathrm{TeV}$ [40] with $\Omega_\chi h^2 = 6 \times 10^{-4}$ (dashed-dotted). It is evident that for decay times around $\tau \approx 10^3\mathrm{s}$ an efficient destruction of ^{7}Li is obtained. For τ much shorter than $10^3\mathrm{s}$ the destroyed ^{7}Be is regenerated, whereas for τ much longer, incomplete ^{7}Li burning in the reaction chain ^{7}Be$(n,p)^7$Li$(p,\alpha)^4$He results in only partial reduction of the total ^{7}Li yield. As anticipated, the destruction of ^{7}Li is accompanied by production of D. When compared to the injection of thermal neutrons, D/H yields are higher. This is due to D generated in the nuclear cascade itself (i.e. by ^{4}He spallation and pionic fusion). Cascade generated deuterium (as well as ^{3}H, ^{3}He, and ^{6}Li) is substantially reduced per injected neutron for sources which inject nucleons with a soft spectrum. For example, I have also employed a soft source with monoenergetic nucleons of 250 MeV. Results for this case are shown by the short-dashed line, assuming $\Omega_\chi h^2/m_\chi = 7.5 \times 10^{-7}\,\mathrm{GeV}^{-1}$ and the injection of one np pair per decay [41]. A cascade n/D ≈ 10 ratio at $T \approx 40\,\mathrm{keV}$ is obtained in such scenarios. The ...

The reason why $^6Li/H < 10^{-14}$ in SBBN

$2.20 \times 10^4 T_9^{-2/3} exp(-3.569/T_9^{1/3})$
$\times(1 + .108T_9^{1/3} + 1.68T_9^{2/3} + 1.26T_9 + .551T_9^{4/3} + 1.06T_9^{5/3})$

12. $Li_6 + p \rightarrow \gamma + Be_7(65.062)$
→ $6.69 + 5T_{9a}^{1/6} T_9^{-3/2} exp(-8.413/T_{9a}^{1/3})$

13. $Li_6 + p \rightarrow He_4 + He_3(46.653)$
$3.73 \times 10^{10} T_9^{-2/3} exp(-8.413/T_9^{1/3} - (T_9/5.50)^2)$
$\times(1 + .050T_9^{1/3} - .061T_9^{2/3} - .021T_9 + .006T_9^{4/3} + .005T_9^{5/3})$
$+1.33 \times 10^{10} T_9^{-3/2} exp(-17.763/T_9) + 1.29 \times 10^9 T_9^{-1} exp(-21.820/T_9)$

14. $Li_7 + p \rightarrow He_4 + He_4(201.321)$
$6.13 \times 10^8 T_9^{-2/3} exp(-8.473/T_9^{1/3} - (T_9/30.068)^2)$
$\times(1 + .0492T_9^{1/3} + 1.56T_9^{2/3} + .539T_9 - .966T_9^{4/3} - .545T_9^{5/3})$
$+1.07 \times 10^{10} T_9^{-3/2} exp(-30.443/T_9) + 1.54 \times 10^6 T_9^{-3/2} exp(-4.479/T_9)$

15. $d + He_4 \rightarrow \gamma + Li_6(17.100)$
$30.1T_9^{-2/3} exp(-7.423/T_9^{1/3})$
$\times(1 + .056T_9^{1/3} - 4.85T_9^{2/3} + 8.85T_9 - .585T_9^{4/3} - .584T_9^{5/3})$
$+85.5T_9^{-3/2} exp(-8.228/T_9)$

16. $H_3 + He_4 \rightarrow \gamma + Li_7(28.63)$
$1.10 \times 10^6 T_9^{-2/3} exp(-8.08/T_9^{1/3})$
$\times(1 + .0516T_9^{1/3} - .408T_9^{2/3} - .148T_9 + .102T_9^{4/3} + .0940T_9^{5/3})$

17. $He_3 + He_4 \rightarrow \gamma + Be_7(18.407)$
$5.79 \times 10^6 T_{9B}^{5/6} T_9^{-3/2} exp(-12.826/T_{9B}^{1/3})$

18. $d + d \rightarrow n + He_3(37.938)$
$3.97 \times 10^8 T_9^{-2/3} exp(-4.258/T_9^{1/3})$
$\times(1 + .098T_9^{1/3} + .876T_9^{2/3} + .600T_9 - .041T_9^{4/3} - .071T_9^{5/3})$

19. $d + d \rightarrow p + H_3(46.802)$
$4.17 \times 10^8 T_9^{-2/3} exp(-4.258/T_9^{1/3})$
$\times(1 + .098T_9^{1/3} + .518T_9^{2/3} + .355T_9 - .010T_9^{4/3} - .018T_9^{5/3})$

20. $H_3 + d \rightarrow n + He_4(204.13)$
$8.09 \times 10^{10} T_9^{-2/3} exp(-4.524/T_9^{1/3} - (T_9/.12)^2)$
$\times(1 + .092T_9^{1/3} + 1.80T_9^{2/3} + 1.16T_9 + 10.5T_9^{4/3} + 17.24T_9^{5/3})$

Properties of bound states

bound st.	$\lvert E_b^0 \rvert$	a_0	R_N^{sc}	$\lvert E_b(R_N^{sc}) \rvert$	R_{Nc}	$\lvert E_b(R_{Nc}) \rvert$	T_0
$^4HeX^-$	397	3.63	1.94	352	2.16	346	8.2
$^6LiX^-$	1343	1.61	2.22	930	3.29	780	19
$^7LiX^-$	1566	1.38	2.33	990	3.09	870	21
$^7BeX^-$	2787	1.03	2.33	1540	3	1350	32
$^8BeX^-$	3178	0.91	2.44	1600	3	1430	34
$^4HeX^{--}$	1589	1.81	1.94	1200	2.16	1150	28
DX^-	50	14	-	49	2.13	49	1.2
pX^-	25	29	-	25	0.85	25	0.6

Table 1: Properties of the bound states: Bohr a_0 and nuclear radii R_N in fm; binding energies E_b and "photo-dissociation decoupling" temperatures T_0 in KeV.

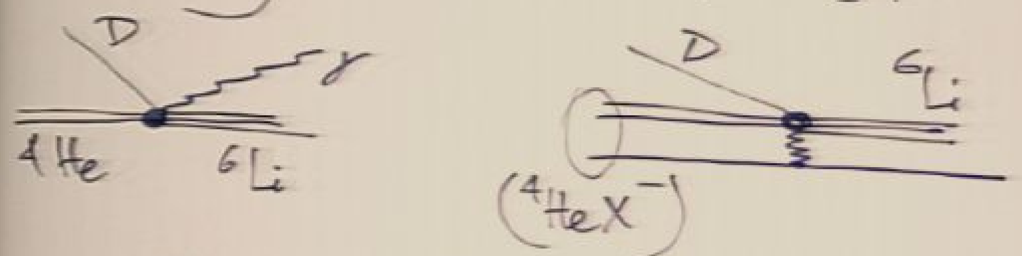
Technical slide

Number of bound states $({}^4He X^-)$

$$n_{BS}(T) = \frac{Y_X \cdot n_B(T) \cdot \exp(-T_*^2/T^2)}{1 + n_{He}^{-}(m_\alpha T)^{3/2}(2\pi)^{-3/2}\exp(-E_b/T)}$$

"Step function" $\sim \Theta\left(1 - \frac{T}{8.2\,\mathrm{keV}}\right)$

Relating reaction rates:



$$S_{CBBN} \simeq S_{SBBN} \times \frac{8}{3\pi^2}\frac{p_f a_0}{(\omega a_0)^5}\left(1 + \frac{m_D}{m_{He}}\right)^2.$$

$$S_{CBBN}(0) \simeq 0.3\ \mathrm{MeV \cdot bn}$$

Thermally averaged rate

$$\langle \sigma_{CBBN} v \rangle \simeq 1.8 \times 10^9 \times T_9^{-2/3}\exp(-5.37/T_9^{1/3})$$

Compare with

$$\langle \sigma_{SBBN} v \rangle \simeq 30\, T_9^{-2/3}\exp(-7.43/T_9^{1/3}).$$

${}^6Li$: Boltzmann equation

$$-H(T)\,T\,\frac{d\,{}^6Li}{dT} = D\,n_{BS}\langle\sigma_{CBBN}v\rangle - {}^6Li\,n_p\langle\sigma v\rangle$$

↑ main destruction channel.

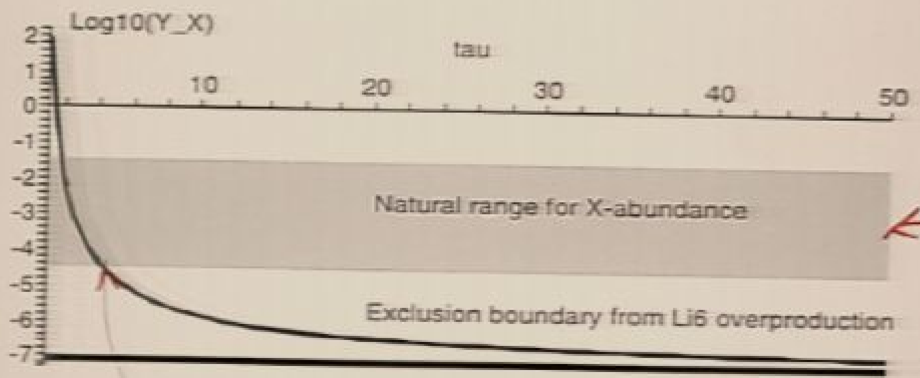
$$[{}^6Li] < 2\times10^{-11} \Rightarrow$$

$$\Rightarrow Y_x < 10^{-7} \Rightarrow \frac{n_{x^-}}{s} \lesssim 10^{-17}.$$

$O(10^{-5})$ abundance with lifetime ~ 1000 sec is capable of „curing" ${}^6Li$ problem.

Abundance vs. Lifetime

$$\log_{10}\left(\frac{n_X}{n_B}\right) \quad \text{vs} \quad \frac{\tau}{10^3\,\text{sec}}$$



$$\boxed{\tau < 4000\,\text{s}}$$

You get 1hr to figure this out when you switch LHC off

freeze-out range

$$\sigma_{ann} v = \frac{2\alpha_\pi^2}{m_X^2}(1-100)$$

$$100\,\text{GeV} < m_X < 1\,\text{TeV}$$

M.P., C. Bird and K. Koopmans, in preparation.

CBBN mechanisms of suppressing ^7Li abundance.

The key is to suppress ^7Be.

If (!) more than 50% of ^7Be is captured into (^7BeX), then the final outcome for ^7Be will be suppressed due to:

A. Factor of ~ 700 enhancement in $(^7BeX) + p \to (^8BX) + \gamma$ reaction

B. Recoil of ^7Be upon X^- decay $E_{Be} \gtrsim 1.6$ MeV would be enough to split ^7Be back to ^3He, ^4He.

C. In some models, interconversion of $(^7BeX^-) \to {^7Li} + X^0$, ^7Li is immediately destroyed by p.

Conclusions

1. Catalized BBN is a new twist to an old story of primordial nucleosynthesis

2. Long-lived X^- alter the abundance of ^6Li, ^7Li and other „heavier" elements produced in BBN

3. 8 orders of m. enhancement in CBBN channel for ^6Li production puts strong constraints on the abundance of X^- at $t \simeq 1000$ sec. $Y_{X^-} < 10^{-17}$ relative to entropy!

4. Whether or not CBBN provides a way of solving ^7Li problem depends on the efficiency of (^7_3eX) capture into bound states. 3-body nuclear calculations are on the way ....