The Cosmic Lithium Abundances and Physics beyond the Standard Model

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The Big Bang Nucleosynthesis standard model

- General relativity
- Equilibrium initial conditions with baryon-to-photon ratio $6.2 \times 10^{-10}$
- Vanishing lepton number chemical potentials
- Radiation energy density given only by photons, electrons/positrons, neutrinos
- No decaying or annihilating relic particles
- No inhomogeneities in baryons
- No small antimatter domains
- No impurities like cosmic strings, primordial black holes

Karsten Jedamzik, IAU268, Light Elements in the Universe, November 9th ’09 – p. 2
SBBN: A one parameter model

Cyburt et al. 08

overconstrained $\rightarrow$ consistency checks possible
The $^7$Li Spite plateau

- (almost) no variation with metallicity and stellar temperature
- no measurable star-to-star scatter
- Interpretation - the Primordial $^7$Li Abundance

Spite & Spite 82, Bonifacio & Molaro 97, Ryan et al 99, Melendez Ramirez 04, Charbonnel & Primas 05, Asplund et al 06, ...

$^7$Li discrepancy $4.2 - 5.3\sigma$
Nuclear reactions/stellar atmospheres?

- Stellar temperature $\Delta T \sim 900$ K underestimated seems impossible

- Narrow nuclear resonance in

$$ ^7\text{Be} + ^2\text{H} \rightarrow ^9\text{B}^{*}_{5/2} \rightarrow ^4\text{He} + p $$

Cyburt & Pospelov 09, Angulo et al. 05

seems unlikely but not ruled out $\rightarrow$ need further measurement
Depletion of Lithium in PopII stars?

$^7\text{Li}$ is observed in the atmospheres of PopII stars. It may be destroyed via $^7\text{Li} + p \rightarrow ^4\text{He} + ^4\text{He}$ in the interior of the star. Atmospheric material transported into the star and $^7\text{Li}$-depleted gas returned to the atmosphere.

Spite plateau not primordial?

Depletion of $^7\text{Li}$ by factor 2 – 4 in halo stars is not understood and may currently only be explained with fine-tuned stellar conditions. Dispersion?
$^7$Li depletion by atomic diffusion in PopII stars?

Korn et al., Richards et al.

atomic diffusion

turbulent mixing

\[
D_T = 400 D_{AHe}^{gs} \left( \frac{\rho}{\rho(T_0)} \right)^{-3} \text{ at } \log(T_0) = 6.0 \pm 0.1 \rightarrow \pm 25\%
\]

\[\rightarrow \text{ factor 1.8 } ^7\text{Li depletion} \]

with depletion factor 1.8

SBBN + WMAP predicted Li/H

(2−σ -error bars)

observed Li/H by different groups

but stellar models ad hoc and tuned
$^6\text{Li}/H$ observations

A second Lithium plateau?

$^6\text{Li}/H \approx 6 \times 10^{-12}$ compare to standard BBN $^6\text{Li}/H \sim 10^{-14}$

$^6\text{Li}$ and $^7\text{Li}$ absorption features blend together

$^6\text{Li}$ from asymmetry of lines

asymmetry of lines from convective Doppler shifts?

non-LTE hydrodynamic simulations of two groups reach opposite conclusions
\textbf{\( ^6\text{Li} \) production by early cosmic rays: Energetics?}

\( ^6\text{Li} \) originates in galactic cosmic ray nucleosynthesis (along with \( ^{9}\text{Be} \), and B)

- via \( p + \alpha + \text{CNO} \rightarrow \text{LiBeB} \)
- and some \( \alpha + \alpha \rightarrow \text{Li} \)

need \textbf{100 eV/nucleon} to synthesize \( ^6\text{Li}/H \sim 5 \times 10^{-12} \)

standard cosmic rays may provide 5 eV/nucleon (up to \([Z] \sim -2.7\))

only very efficient accretion on central black hole, or large fraction of baryons in supermassive \( \sim 100 M_\odot \) stars may provide the required cosmic rays

Suzuki & Inoue 00 Rollinde \textit{et al.} 05, Prantzos \textit{et al.} 05 Nath \textit{et al.} 05
if $^6\text{Li}$ exists in these stars of the abundance as claimed $\rightarrow$

something important about the Universe has been learned
BBN with decaying and annihilating particles

- Injection of energetic nucleons and mesons
  - Charge exchange reactions
    \[ \pi^- + p \rightarrow \pi^0 + n \]
  - Elastic- and inelastic scatterings
    \[ p + p \rightarrow p(n) + (p)n + \pi's \]
  - Spallation reactions
    \[ p(n) + ^4\text{He} \rightarrow ^3\text{H}, ^3\text{He}, ^2\text{H} + \ldots \]
  - Coulomb stopping of charged nuclei
    \[ ^3\text{H} + e^\pm \rightarrow ^3\text{H}' + e^\pm \]

- Injection of energetic photons and electrons/positrons
  - Pair production on CMBR
    \[ \gamma + \gamma_{\text{CMBR}} \rightarrow e^- + e^+ \]
  - Inverse Compton scattering
    \[ e^\pm + \gamma_{\text{CMBR}} \rightarrow e^\pm + \gamma \]
  - Bethe-Heitler scattering
    \[ \gamma + p \rightarrow p + e^- + e^+ \]
  - Photodisintegration
    \[ \gamma + ^4\text{He} \rightarrow ^3\text{H} + p \]

including \(^3\text{He}/^\text{D} < 1.72; ^6\text{Li}/^7\text{Li} < 0.1875\)
Destruction of $^7\text{Li}$ during BBN by injection of neutrons

K.J. 04

$^7\text{Li}$ destruction: $^7\text{Be} + n \rightarrow ^7\text{Li} + p$; $^7\text{Li} + p \rightarrow ^4\text{He} + ^4\text{He}$

at $T \approx 30$ keV

need only $10^{-5}$ extra neutrons per baryon

some extra $^2\text{H}$ will be also synthesized

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production of $^6\text{Li}$ in SBBN by $\text{D} + ^4\text{He} \rightarrow ^6\text{Li} + \gamma$ which is quadrupole suppressed $\rightarrow ^6\text{Li}/\text{H} \sim 10^{-14}$
Production of $^6\text{Li}$ in cascade nucleosynthesis

$^6\text{Li}$ is very easily produced by small "perturbations" of the standard model Dimopoulos et al. 88, K.J. 00

Electromagnetic:

\[ \gamma + ^4\text{He} \rightarrow ^3\text{H} + p \]

\[ ^3\text{H} + ^4\text{He} \rightarrow ^6\text{Li} + n \]

at $T \lesssim 0.1 \text{ keV}$

Hadronic:

\[ n + ^4\text{He} \rightarrow ^3\text{H} + p + n \]

\[ ^3\text{H} + ^4\text{He} \rightarrow ^6\text{Li} + n \]

at $T \lesssim 10 \text{ keV}$
Production of $^6\text{Li}$ in catalytic nucleosynthesis

negatively charged weak mass scale particles $X^-$ during BBN → formation of bound states with nuclei

$^7\text{Be} + X^- \rightarrow (^7\text{Be}X^-) + \gamma$ at $\approx 30$ keV

$^4\text{He} + X^- \rightarrow (^4\text{He}X^-) + \gamma$, at $\approx 10$ keV

$X^-$ acts as catalysator for reactions

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

$(^4\text{He}X^-) + ^4\text{He} \rightarrow (^8\text{Be}X^-) + \gamma$;

$(^8\text{Be}X^-) + n \rightarrow ^9\text{Be} + X^-$

important when $B_h \lesssim 10^{-2}$ as with supersymmetric stau!
Catalysis and $^6\text{Li, }^7\text{Li, and }^7\text{Be}$

Catalysis:

- main production mechanism for $^6\text{Li}$ if $B_h \lesssim 10^{-2}$
- may only solve the $^7\text{Li}$ problem, if $B_h \lesssim 10^{-5}$ rather small and $\Omega_X \gtrsim 10$ rather large
- not clear if may lead to some $^9\text{Be}$ production
The lithium friendly parameter space

K.J. 04

D/H
3e-05

7Li/H
1e-10

6Li/7Li 1
0.1
1e-02

τ (sec)

Bailly, K.J., Moulhaka 08

ΩXh²Bh

Yp>0.258

D/H>4x10⁻⁵
Signatures at the LHC!

A metastable particle $X$ with life time between $100 - 1000$ sec, if not too massive, could be potentially produced at the LHC (since having at least some hadronic interactions), and ...., if electromagnetically or strongly interacting stopped in the detector $\rightarrow$ smoking gun for non-standard BBN $\rightarrow$ possible connection to the dark matter.

Examples:
- supersymmetric gravitino
- supersymmetric stau Next-to-LSP with gravitino LSP
- gluino in split supersymmetry
Example: Gravitino dark matter in the CMSSM

K.J., Choi, Roszkowski, Ruiz de Austri 06

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Production of cosmic $^6\text{Li}$ by neutralino annihilation

K.J. 04ab, Pospelov & K.J. 09

uu-quark, $^6\text{Li}/^7\text{Li} = 0.01-0.09,0.024-0.68$; $\text{D}/\text{H}=3.5,4.4,5.3\times10^{-5}$; $^7\text{Li}/\text{H} = 1.5,2.3,4\times10^{-10}$
Signatures at the LHC!

If the LHC discovers a light stable neutralino of mass 
\( m \approx 20 - 90 \text{ GeV} \) and of hadronic annihilation cross section 
\( 3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1} \) as required to explain origin of the dark 
matter by annihilation freeze-out \( \rightarrow \) explanation of all the \( ^6\text{Li} \) 
as claimed to exist in HD84937.
Varying fundamental constants and $^7\text{Li}$

Dmitriev, Flambaum, & Webb 04, Dent, Stern, & Wetterich 07, Berengut, Flambaum, & Dmitriev 09

$^7\text{Li}$ depends strongly on $B_d$ and $B_{^7\text{Be}}$

$\Delta B_d/B_d \approx -0.019 \pm 0.005 \rightarrow$ reduce $^7\text{Li}$ (and $^4\text{He}$)

$\Delta m_q/m_q \approx 0.013 \pm 0.002 \rightarrow$ reduce $^7\text{Li}$
Conclusions

- the by standard BBN at $\eta_{\text{WMAP}}$ predicted D (and $^4\text{He}$) are in good agreement with those observed
- in contrast, there is a factor 3-4 discrepancy between SBBN predicted and observationally inferred $^7\text{Li}$
- this discrepancy could possibly be removed if $^7\text{Li}$ is destroyed in Pop II stars, though how this is done exactly is not understood
- alternatively BBN could have been non-standard, e.g. including the decay of a relic particle $\rightarrow$ potentially testable at the LHC
- accelerators ultimately may teach us that the apparent anomalies in the cosmic $^7\text{Li}$ (and $^6\text{Li}$) abundance are ultimately connected to the dark matter
D/H from Quasar Absorption Systems

Tytler, Fan, & Burles 96

significant dispersion → underestimated systematic errors?

D/H = 2.98$^{+0.29}_{-0.23}$ × 10$^{-5}$