Primordial beryllium as a big bang calorimeter

Maxim Pospelov and Josef Pradler

1 Perimeter Institute for Theoretical Physics, Waterloo, ON, N2L 2Y5, Canada
2 Department of Physics and Astronomy, University of Victoria, Victoria, BC, V8P 1A1, Canada

Many models of new physics including variants of supersymmetry predict metastable long-lived particles that can decay during or after primordial nucleosynthesis, releasing significant amounts of non-thermal energy. The hadronic energy injection in these decays leads to the formation of Be via the chain of non-equilibrium transformations: Energy$_h \rightarrow$ T, $^3$He $\rightarrow$ $^6$He, $^6$Li $\rightarrow$ $^9$Be. We calculate the efficiency of this transformation and show that if the injection happens at cosmic times of a few hours, the release of $\mathcal{O}(10\text{ MeV})$ per baryon can be sufficient for obtaining a sizable $^9$Be abundance. The absence of a plateau-structure in the $^9$Be/H abundance down to a $\mathcal{O}(10^{-14})$ level allows one to use beryllium as a robust constraint on new physics models with decaying or annihilating particles.

The rare light elements lithium, beryllium, and boron play a pivotal role in observational cosmology. Their abundance pattern is key in our understanding of stellar structure and galactic evolution. It may also probe the very beginning of nuclear chemistry, known as big bang nucleosynthesis (BBN). Standard BBN (SBBN) theory has become what could be called a parameter-free theory. With the cosmic microwave background determination has become what could be called a parameter-free theory. However, there is a wealth of information that can still be extracted from BBN.

Standard BBN (SBBN) theory solely relies on Standard Model physics embedded in a Friedman-Robertson-Walker Universe. An overall concordance between the SBBN predictions and the observations inferred primordial abundances of D and $^4$He has put BBN on firm footing and made its framework an invaluable toolbox for testing models of new physics (see, e.g., [2]). Whereas Li, Be, and B are mainly produced in galactic cosmic rays [3, 4], the only stable isotope to reach out to a primordial fraction at the ppb level is $^7$Li. The SBBN yields of Be and B are negligible [3] and, to date, the only known scenarios which may produce Be in interesting amounts are inhomogeneous nucleosynthesis, see e.g. [5], and the catalysis of nuclear reactions by electromagnetically or strongly interacting relic particles [6–9].

The purpose of this paper is to show that non-equilibrium processes induced by the decay or annihilation of a relic particle species $X$ after BBN can lead to the production of primordial $^9$Be/H at the $\mathcal{O}(10^{-14})$ level and above, which makes these scenarios testable via atmospheric measurements of $^9$Be in extremely metal-deficient stars (MDSs). We identify the following prospective path to $^9$Be:

$$\text{Energy}_h \rightarrow \text{T, } ^3\text{He} \rightarrow ^6\text{He}, ^6\text{Li} \rightarrow ^9\text{Be},$$

where Energy$_h$ refers to the injection of energy via hadronic channels. The chain of transformations is initiated by the spallation of $^4$He due to “primary” nucleons and followed by repeated reactions on ambient $\alpha$-particles. It is well known that such non-thermal cascades—truncated at $A = 6$—can be an efficient source of “secondary” $^6$Li [10, 11], as it bypasses the extremely inefficient SBBN channel D($\alpha, \gamma$)6Li. Here we show that the exoergic reaction

$$^6\text{He} + ^4\text{He} \rightarrow ^9\text{Be} + n, \quad Q = 0.60 \text{ MeV}$$

is particularly capable of going one step further and bridging the $A = 8$ divide. As we shall argue, $^9$Be has the potential of becoming one of the “calorimeters” of choice in detecting non-thermal hadronic processes during this early epoch of our Universe. We also investigate a similar “tertiary” production of $^{10}\text{Be}$. Observations: The elements Li, Be, and B are detected via atomic resonance lines in the photospheres of MDSs. The constancy of $^7$Li/H at lowest metallicities [Fe/H] $< -1.5$ is known as the “Spite plateau” [12], and is interpreted as representing the primordial lithium component. Whereas numerous determinations exist—with $^7$Li/H in the range $(1 - 2.5) \times 10^{-10}$—the observational status of the isotopic ratio $^6$Li/$^7$Li remains doubtful. Though a plateau value of $^6$Li/$^7$Li $\simeq 0.05$ has been claimed from detections in a number of halo stars [13], this claim has also been challenged. Since the $^6$Li absorption line is not resolved spectroscopically from the one of $^7$Li, convective motions may well mimic its presence [14]. Indeed, a re-analysis [15] has diminished the number of such (3σ) detections to a mere number of two stars.

In contrast to Li, Be and B show no indication of a plateau structure. Instead, they exhibit a scaling with metallicity, which points towards a pure cosmic ray origin. The lowest observationally inferred B abundance then sets a limit on its primordial value, $(B/H)_p \lesssim 5 \times 10^{-12}$ [16]. The determination of beryllium is especially robust since $^9$Be is the only stable isotope. Figure 11 shows a sample of $^9$Be detections (taken from [17]) as a function of metallicity. The lowest point in black corresponds to the upper limit obtained recently in [18] and which we are going to use as an indicative upper limit on primordial $^9$Be:

$$(^9\text{Be}/H)_p \lesssim 10^{-14}.$$  (3)

If instead only the detected values of $^9$Be are used, a nominal 3σ upper limit of $4.7 \times 10^{-14}$ can be deduced. In any case, $^9$Be is by far the rarest and the most constrained among the light elements.
In addition to being firmly detected, there lies another virtue of Be and B. 6Li is fragile and may well have been destroyed in MDSs. Such a destruction is indeed the essence of the “astrophysical solution” to the 7Li problem, which posits a uniform stellar depletion of 7Li by a factor 3 to 5 from its SBBN prediction 7Li/H ≈ 10^{-10} [19]. Any mechanism achieving this requires that the atmospheric material is transported deep enough into the hotter stellar interiors where 7Li is destroyed. If all three elements are subjected to the proton-burning reactions at the same temperature, one obtains

\[ ^7\text{Li}/^6\text{Li}_p = \left( \frac{^6\text{Li}}{^6\text{Li}_p} \right)^a = \left( \frac{^9\text{Be}}{^9\text{Be}_p} \right)^b \]

with the exponents given by \( a = (\sigma_{^7\text{Li}+p}^7\text{Li})/((\sigma_{^7\text{Li}_p}^7\text{Li})) \) and \( b = (\sigma_{^7\text{Li}_p}^7\text{Li})/((\sigma_{^9\text{Be}_p}^9\text{Be})) \) (which makes the estimate exponentially sensitive to temperature.) Evaluating the cross sections for 4He, 7Li, and 9Be as well as 9Be(p, D)8Be at a fiducial temperature of \( T = 10^6 \) K one finds \( a \approx 0.01 \) and \( b \approx 3 \times 10^{-6} \). Irrespective of a rather crude nature of [18], this estimate illustrates one point: had 7Li been depleted by an O(1)-factor, \(^{6}\text{Li} \) could have been suppressed substantially, while \(^{9}\text{Be} \) is to remain unaffected [20]. Therefore, if stellar depletion is indeed a prevalent factor in the reduction of 7Li, the use of 9Be over 6Li for constraining non-standard BBN scenarios may be preferred. Table I summarizes the observational status of the rare light elements 6Li, 9Be, and B = 10B + 11B, where we make a generous allowance for the possible stellar depletion of primordial 6Li.

**Conversion probability** The key quantity that determines the efficiency of [11] and ultimately the strength of \(^{9}\text{Be} \) constraints is \( P_{\text{Be}} \), that we define as the probability for an energetic \( A = 3 \) nucleus injected into the BBN plasma to produce \(^{9}\text{Be} \). Clearly, the chain [11] can be broken up into its sub-processes,

\[ P_{\text{Be}} = \langle P_{3\rightarrow 6} \rangle_{_{\text{E}_B}} \ast \langle P_{6\rightarrow 9} \rangle_{_{\text{E}_B}} \ast \langle P_{9\rightarrow 9} \rangle_{_{\text{E}_B}} \]  

where each individual probability \( P_{A_1\rightarrow A_2} \) is averaged over the distribution of \( A_1 \) injection energies \( E^\text{in}_{A_1} \). It is easy to see that \( P_{\text{Be}} \) has to be a functional of the initial energy distribution of the mass-3 element. The stars indicate that the quantities are not independent from each other but appear under integral signs.

\[ P_{A_1\rightarrow A_2} = \int_{E^\text{th}_{A_2}}^{E^\text{th}_{A_1}} \frac{dE_{A_1} n_{\text{He}} \sigma_{A_1\rightarrow A_2}(E_{A_1})}{dE_{A_1}/dx}. \]  

Here, \( n_{\text{He}} \) is the number density of ambient alpha particles and \( \sigma_{A_1\rightarrow A_2} \) is the cross section for the A2 formation via \( A_1(\alpha, N)A_2 \) with \( N = n \) or \( p \). The energy loss rate \( dE_{A_1}/dx \) of \( A_1 \) is of great importance as it regulates the overall efficiency of the \(^{9}\text{Be} \) producing chain; \( E^\text{th}_{A_2} \) is the energy of \( A_2 \) once it is thermalized. For the temperatures that are of most interest to us, \( T \leq 20 \) keV, the thermalization rate is dominated by Coulomb stopping on electrons and positrons in the plasma.

Equation [11] is to be averaged over the \( A_1 \) energy distribution \( f_{A_1}(E_{A_1}) = \sigma_{A_1} d\sigma_{A_1}/dE_{A_1} \); \( \sigma_{A_1} \) is the cross section for producing \( A_1 \) secondaries from 4He. In general, \( f_{A_1} \) also depends on the energy of the primary which gives rise to \( A_1 \). For the spallation products T and 4He produced in N(\( \alpha, X \))4He reactions, \( f_3 \) is largely independent of the incident nucleon energy, and we shall use the fit to \( f_3(E) \) as the sum of exponential factors [21]; see also [22]. When it comes to \( A_1 = 6 \), i.e. 6Li and 9He, we assume a flat distribution of the differential cross section with respect to the CM scattering angle.

When computing \( \langle P_{6\rightarrow 9} \rangle_{_{\text{E}_B}} \) one should also account for the fact that 6He may eventually decay (\( \tau_{\text{He}} \approx 0.8 \) s) before interacting hadronically. This, however, has almost no influence on [5]. We find that even for temperatures \( T \) as low as 1 keV more than 90% of 6He survives the initial degradation from \( E^\text{th}_6 \) to a kinetic energy of \( \sim 1 \) MeV below which the cross section for [2] becomes too small. Turning to the last factor in [5], the probability that a newly created \(^{9}\text{Be} \) nucleus actually survives, we remark that in our BBN code the proton burning of thermalized \(^{9}\text{Be} \) (as well as of \(^{6}\text{Li} \) and \(^{9}\text{He} \)) are already accounted for. Therefore, we identify \( \langle P_{9\rightarrow 9} \rangle \) in [5] with

![FIG. 1. Beryllium detections (squares) and fit of their Be-Fe trend taken from [17]. The triangle shows the upper limit from [15]: A(X) ≡ log_{10}(X/H) + 12.](image)

| element | SBBN | primordial limit | \( T_i/\text{keV} \) |
|---------|------|-----------------|----------------|
| \(^6\text{Li}/\text{H}\) | \( \sim 10^{-14} \) | \( \lesssim \text{few } \times 10^{-10} \) | 8 |
| \(^9\text{Be}/\text{H}\) | \( < 10^{-18} \) | \( \lesssim 10^{-14} \) | 10 |
| B/\text{H} | \( < 10^{-15} \) | \( \lesssim 5 \times 10^{-12} \) | 20 |
the “in-flight” destruction probability prior to thermalization. Finding \( \langle P_{3\rightarrow 9} \rangle \) in an obvious modification of \( T \)
we conclude that the survival probability is always well above 90% so that this factor is of no importance. On similar grounds, we can neglect any potential “in-flight” p-destruction of \( A = 6 \) secondaries.

Figure 2 shows \( P_{3\rightarrow 9} \) for the various channels as labeled. The exponential drop in the number of electron-positron pairs leads to the sharp rise of \( P_{3\rightarrow 9} \) with temperature, with the peak at \( T \approx 20 \) keV, followed by a slow decline caused by the logarithmic growth of the stopping power at lower temperatures.

We believe that our calculation of \( P_{3\rightarrow 9} \) is accurate to
within a factor of two or three as it is largely based on experimental data. When available, we made use of the (inverse) cross section data collected in \[10\]. For the two nuclear reactions of most interest, \( ^{4}\text{He}(\alpha,n)^{7}\text{Be} \) and \( T(\alpha,p)^{6}\text{He} \), we used the measurements of \[24\] and \[27\], respectively. The former reaction shows a large cross section above 100 mmb over a wide range of energies, reaching a peak of 400 mmb at \( E_{\alpha} \approx 5 \) MeV. The latter yields a maximum of 9 mb at \( E_{\alpha} \approx 20 \) MeV and was approximated by a constant S-factor of \( S \approx 520 \text{mb/MeV} \) for its inverse reaction \( ^{6}\text{He}(p,\alpha)\text{T} \). Previous investigations of secondary \( ^{6}\text{Li} \) production have not accounted for the \( ^{6}\text{He} \) channel. This is well justified, because the rate for \( T(\alpha,p)^{6}\text{He} \) reaction is considerably less than that of \( T(\alpha,n)^{6}\text{Li} \); the cross section for the latter as well as for \( ^{4}\text{He}(\alpha,p)^{6}\text{Li} \) we take from \[27\].

Constraints Having obtained \( P_{3\rightarrow 9} \), we now compute the actual output of \( ^{9}\text{Be} \) in the spirit of previous works on non-equilibrium BBN. The induced non-thermal contribution to the Boltzmann equation is of the form
\[
dn_{3\rightarrow 9}/dt|_{\text{nth}} = n_{4\text{He}}\Gamma_{4\rightarrow 3} \cdot P_{3\rightarrow 9},
\]
where \( \Gamma_{4\rightarrow 3} \) is the destruction rate of \( ^{4}\text{He} \) to \( A = 3 \) final states. Let \( X \) decay with some hadronic branching fraction \( B_{h} \) and denote by \( N_{i}(\epsilon) \) the number of energetic nucleons per \( X \)-decay with kinetic energy \( \epsilon \). Then, the spallation rate is given by
\[
\Gamma_{4\rightarrow 3} = n_{X} \sum_{i=n,p} \int_{E_{\text{thr}}}^{\epsilon_{\text{had}}/2} d\epsilon \; N_{i}(\epsilon) \sigma_{4\rightarrow 3}^{(i)}(\epsilon)\epsilon v_{i}(\epsilon)
\]
where \( \epsilon_{\text{had}} \) is the injected hadronic energy per \( X \)-decay and \( E_{\text{thr}} \sim 20 \text{ MeV} \) is the threshold energy in the \( A = 3 \) producing reaction \( p/n + ^{4}\text{He} \) with cross section \( \sigma_{4\rightarrow 3} \). We do not need to account for other hadronic shower products such as long-lived mesons \( \pi^{\pm}, K^{\pm} \) or \( K_{L} \). For cosmic times \( t \gtrsim 100 \text{ s} \), they decay before interacting hadronically—unless the \( X \)-abundance is in excess of baryons \[28\]. We also find that photodissociation channels such as \( ^{4}\text{He}(\gamma,N)^{3}\text{He} \) and \( ^{7}\text{Li}(\gamma,N)^{6}\text{He}/^{6}\text{Li} \) are not important for the production of \( ^{9}\text{Be} \).

The time evolution of \( N_{i} \) is governed by the propagation equation \[22\]
\[
\partial_{t} N_{i} = J_{i} - \Gamma_{i,\text{sc}} N_{i} - \partial_{t} (\epsilon \Gamma_{i,\text{stop}} N_{i}),
\]
where \( \Gamma_{i,\text{stop}} = -\epsilon^{-1}dE_{i}/dt \) is the continuous stopping rate, \( \Gamma_{i,\text{sc}} \) is the total hadronic scattering rate and \( J_{i} \) is the sum of all source terms. Up to secondary contributions from elastic and inelastic down-scattering processes, \( J_{i} \) is given by \( J_{i} \approx B_{h} Q_{i}(\epsilon)/\tau_{X} \), where \( Q_{i}(\epsilon) \) is the primary nucleon spectrum in the decay of \( X \) and \( \tau_{X} \) is the \( X \)-lifetime. Annihilating \( X \) are treated in complete analogy with the replacement \( \tau_{X}^{-1} \rightarrow n_{X}(\sigma_{\text{ann}}v) \) where \( \langle \sigma_{\text{ann}}v \rangle \) is the annihilation cross section to hadrons. Following \[29,30\] we simulate a generic hadronic \( X \)-decay (and obtain \( Q_{i} \)) by using the PYTHIA \[31\] model for \( e^{+}e^{-} \) annihilations to hadrons.

From inspection of Table II we expect a \( O(1) \)-surviving fraction of non-thermally fused \( ^{6}\text{Li} \) or \( ^{9}\text{Be} \) only for \( T \lesssim 20 \text{ keV} \). For these temperatures, neutrons are not stopped before interacting hadronically. On the other hand, for protons with \( \epsilon \lesssim 1 \text{ GeV} \) it is a reasonable approximation to assume that the energy degradation term
in (8) dominates. Then, employing a quasi-static equilibrium condition \( \partial_t N_i \approx 0 \) to (8) (a good approximation for \( \Gamma_{\text{in}} \ll \Gamma_{\text{sc}}, \Gamma_{\text{stop}} \)) one finds \[^2\]

\[
\frac{\epsilon N_p(e)}{\Gamma_{\text{p,in}}} \simeq \frac{1}{\Gamma_{\text{p,stop}}} \int_e^\infty d\epsilon' \frac{Q_p(e')}{\Gamma_{\text{n,in}}} \simeq \frac{\epsilon Q_n(e)}{\Gamma_{\text{n,sc}}}. \tag{9}
\]

Using (9) to obtain \( \Gamma_{\alpha-3} \) in (1), we solve the BBN network of Boltzmann equations for various combinations of \( \tau_X \) and \( X \)-abundance \( Y_X \). The latter is normalized on the number density of baryons, \( Y_X \equiv n_X/n_b \).

Figure 3 shows contour lines of constant \(^9\)Be/H and \(^6\)Li/H as a function of \( \tau_X \) and \( \epsilon_{\text{had}} Y_X \). We have assumed \( B_h = 1 \) so that \( \epsilon_{\text{had}} = m_X = 1 \) TeV. The (solid) \(^9\)Be contours, when compared with the ones for \(^6\)Li (dashed), illustrate that \(^9\)Be is more sensitive to energy injection at earlier times, reaching its maximal abundance for \( \tau_X \simeq 1.5 \times 10^4 \) s. For larger lifetimes, as the primordial gas keeps rarefying, it becomes increasingly difficult to produce \(^9\)Be from \( A = 6 \). For \( \tau_X \gtrsim 10^6 \) s the hadronic process looses further ground as neutrons decay before interacting strongly. At optimal \( \tau_X \), the current limits on primordial \(^9\)Be probe the energy injection at a level of \( 10 \) MeV per nucleon, or \( 10^{-12} \) GeV per entropy. More elaborate treatments along the lines of \[^{22,29,30}\] will certainly help to improve on the estimate of produced \(^9\)Be per unit injected energy. It is important to note, however, that the ratio \(^9\)Be/\(^6\)Li, and thus their relative importance as constraints will not be affected by that.

Another (competitive) constraint on hadronic energy injection is due to overproduction of \(^7\)Be from \( \epsilon_{\text{had}} = 1 \) TeV. The (solid) \(^7\)Be contours, when compared with the ones for \(^6\)Li (dashed), illustrate that \(^7\)Be is more sensitive to energy injection at earlier times, reaching its maximal abundance for \( \tau_X \simeq 5 \times 10^3 \) s. For larger lifetimes, as the primordial gas keeps rarefying, it becomes increasingly difficult to produce \(^7\)Be from \( A = 6 \). For \( \tau_X \gtrsim 10^6 \) s the hadronic process looses further ground as neutrons decay before interacting strongly. At optimal \( \tau_X \), the current limits on primordial \(^7\)Be probe the energy injection at a level of \( 10 \) MeV per nucleon, or \( 10^{-12} \) GeV per entropy. More elaborate treatments along the lines of \[^{22,29,30}\] will certainly help to improve on the estimate of produced \(^7\)Be per unit injected energy. It is important to note, however, that the ratio \(^7\)Be/\(^6\)Li, and thus their relative importance as constraints will not be affected by that.

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