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Nuclear structure constrains on resonant energies: A solution of the cosmological ^{7}Li problem?

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Abstract

In this work, we study the cosmological ^{7}Li problem from a nuclear structure point of view, by including resonances in the reactions which populate beryllium. The calculation of primordial abundances is performed by solving the balance equations semi-analytically. It is found that the primordial abundance of lithium is indeed reduced, as a consequence of the presence of resonant channels in the relevant cross sections. We set limits on the resonant energy for each reaction relevant for the chain leading to ^{7}Li, by performing a statistical analysis of the available observational data.

Keywords: Primordial Nucleosynthesis; Lithium problem; Nuclear resonances

1. Introduction

Big Bang Nucleosynthesis (BBN) is the framework which describes the formation of light nuclei, such as deuterium, tritium, helium and lithium. The theory which describes this process relies upon nuclear reactions between these primordial elements, accompanied by electroweak decays. It has only one free parameter, the baryon density, which is related to the baryon-to-photon ratio. This parameter can be determined by the comparison between theoretical predictions of the primordial abundances and the observable data, or by the analysis of the data

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produced by the Wilkinson Microwave Anisotropy Probe (WMAP) satellite. The results obtained by the WMAP Collaboration [1] are consistent with the observed primordial abundances of deuterium and ^{4}He, but there exists a disagreement with the observed abundance of ^{7}Li. In the literature, this problem was analyzed using different theoretical approaches. Some authors have suggested that a better understanding of the turbulent transport in the radiative zones of stars is needed for a better determination of the abundance of primordial lithium [2], and others have explained that there exists a stellar lithium depletion that can depend on the mass of the star [3,4]. Recently, the nuclear aspect of the problem concerning the abundance of ^{7}Li have been revisited [5–7]. Under the conditions discussed in [5–7], nuclear-reaction and nuclear-structure mechanisms may reduce the abundance of lithium due to a depletion of the production of beryllium.

In this work, we analyze the effect upon the production of ^{7}Li due to the inclusion of isolated resonances in the reactions involving ^{7}Be, following the discussion advanced by Broggini et al. [5]. In order to perform the calculations of the primordial abundances we use the formalism developed by Esmailzadeh et al. [8], and to include the resonances we assume that the cross sections are described by the Breit–Wigner formula [9]. Naturally, because of the limitations possessed by the approximation (e.g.; its use is invalidated if one is dealing with very large widths), we shall take the results based on the Breit–Wigner formula as a rough evidence about the influence of resonances on the primordial abundances. We analyze the effects of the inclusion of these resonances separately, and, in particular, on the freeze-out temperature of beryllium, the ^{7}Be abundance and the lithium primordial abundance. We set constrains on the value of the resonant energy for each process using the available observable data. This paper is organized as follow. In Section 2 we describe the formalism which allows for the inclusion of resonances in the reaction rates relevant for BBN and the semi-analytical approach used to compute the lithium abundance. In Section 3 we present and discuss the results of the calculation of BBN abundances. Finally, the conclusions are drawn in Section 4.

2. Formalism

In this section we describe the formalism needed to compute primordial abundances in the context of BBN.

2.1. Nuclear reaction rates

The nuclear reactions which are relevant for the present study are the following:

$$^7\mathrm{Be} + d \to {}^4\mathrm{He} + {}^4\mathrm{He} + p, \qquad {}^7\mathrm{Be} + {}^4\mathrm{He} \to \gamma + {}^{11}\mathrm{C}, \qquad {}^7\mathrm{Be} + n \to p + {}^7\mathrm{Li}. \tag{1}$$

The reaction rate $[ij;kl]$ for the process $i + j \to k + l$[1] is written [8]

$$[ij;kl] = \rho_B N_A \langle \sigma v \rangle = 0.93 \times 10^{-3} \Omega_B h^2 T_9^3 N_A \langle \sigma v \rangle, \tag{2}$$

where σ is the cross section, v is the relative velocity, $\rho_B = 0.93 \times 10^{-3} \Omega_B h^2 T_9^3$ is the density of baryonic matter, N_A is the Avogadro number per gram, T_9 is the temperature in units of 10^9 K. The use of Maxwell–Boltzmann velocity-distribution leads to the estimate

[1] Hereafter, we denote the reactions rates as [Bed; $\alpha\alpha p$], [Beα; γC] and [Ben; p7], respectively, where p refers to proton, d to deuterium, α to ^{4}He, Be to ^{7}Be, γ to the photon, C to ^{11}C, n is the neutron and 7 stands for ^{7}Li.

$$\langle \sigma v \rangle = \left(\frac{\mu}{2\pi kT} \right)^{3/2} \int e^{-\frac{\mu v^2}{2kT}} v\sigma(E)\, d^3v, \tag{3}$$

where μ is the reduced mass.

In order to take into account the resonances in the reaction rates, as suggested by Broggini et al. [5], we assume that the cross section for a generic process is describe by the Breit–Wigner formula [9]

$$\sigma(E) = \frac{\pi\hbar^2}{2\mu E} \frac{\omega_r \Gamma_1 \Gamma_2}{(E - E_r)^2 + \Gamma^2/4}, \tag{4}$$

where Γ_i is the partial width for the decay of the resonant state, Γ is the sum over all partial widths, $\omega_r = \frac{(1+\delta_{ab})g_r}{g_a g_b}$ and $g_r = 2J_r + 1$, J_r being the spin of the resonant state and E_r is the resonance energy in the center of momentum system. The average cross section $\langle \sigma v \rangle$ is

$$\langle \sigma v \rangle = \left(\frac{2\pi\hbar^2}{\mu kT} \right)^{3/2} \frac{(\omega\gamma)_r}{\hbar} e^{E_r/kT}, \tag{5}$$

where $\gamma_r = (\frac{\Gamma_1 \Gamma_2}{\Gamma})_r$ [9]. Finally, the reaction rate in presence of an isolated resonance is written

$$[ij; kl] = 9.69 \times 10^{-33} \Omega_B h^2 \left(\frac{T_9}{\mu} \right)^{3/2} (\omega\gamma)_r e^{-11.605 E_r/T_9}, \tag{6}$$

where T_9 is the temperature in units of 10^9 K. The use of the approximation (5) is limited by the value of the width of each of the resonances included in the calculation. Empirical values of the widths, both for entrance and decay channels, may be obtained from nuclear reactions. This is a sensitive aspect of the calculations, because the actual value of the resonances and their widths, extracted from experimental data, may restrict the range of values where the effect upon the abundance of ^{7}Li become noticeable. The exclusion of resonances and or the extent of their widths, for the case of the reaction [Bed; $\alpha\,\alpha\, p$], can be found in [10]. The other experimental element to take into account is the value of the threshold for particle emission in the considered reactions, since for energies below the threshold no particles are emitted and the emission of gamma rays from electromagnetic transitions is the only allowed decay channel, as it is the case of the reaction $^7\mathrm{Be} + {}^4\mathrm{He} \rightarrow \gamma + {}^{11}\mathrm{C}$ for resonances below 1.15 MeV. Having these limitations into account we shall explore the mechanism (that is the excitation and decay of resonances) for which the population of states leading to ^{7}Li may be depleted.

2.2. *Calculation of primordial abundances*

The equation that governs the primordial abundance Y_i of a given element i, is

$$\dot{Y}_i = J(t) - \Gamma(t) Y_i \tag{7}$$

where $J(t)$ and $\Gamma(t)$ are the time-dependent source and sink terms (these terms are functions of the other primordial abundances and of the reactions rates) and $\dot{Y}_i$ is the time derivative of the primordial abundance. The static solution of this equation is the quasi-static equilibrium (QSE) solution of Esmailzadeh et al. [8]

$$f_i = \frac{J(t)}{\Gamma(t)}. \tag{8}$$

In order to compute the primordial abundances, one must solve the system of differential equations, considering only the dominant reaction rates [8]. The semi-analytical approach consists in calculating the abundances between fixed points or stages. One solves the equations only for one element at each step and, for the other elements, one considers the quasi static equilibrium solution. To compute the final abundance of a given element, one must know the freeze-out temperature of that element. The freeze-out of the production of each element takes places when the dominant destruction reaction rate equals the expansion rate of the Universe, as explained by Bernstein et al. [11].

The differential equation that governs the primordial abundance of beryllium is

$$\begin{aligned}\dot{Y}_{\mathrm{Be}} &= Y_p Y_6[6\,p;\ \gamma\,\mathrm{Be}] + Y_3 Y_\alpha[3\,\alpha;\ \gamma\,\mathrm{Be}] - Y_\gamma Y_{\mathrm{Be}}[\mathrm{Be}\,\gamma;\ 3\,\alpha]\\ &\quad - Y_n Y_{\mathrm{Be}}[\mathrm{Be}\,n;\ p\,7] - Y_p Y_{\mathrm{Be}}[\mathrm{Be}\,p;\ \gamma\,8] - Y_d Y_{\mathrm{Be}}[\mathrm{Be}\,d;\ \alpha\,\alpha\,p]\\ &\quad - Y_\alpha Y_{\mathrm{Be}}[\mathrm{Be}\,\alpha;\ \gamma\,\mathrm{C}],\end{aligned} \tag{9}$$

where, inside the square bracket which denotes each reaction rate, the quantities 3, 6 and 8 read for ^{3}He, ^{6}Li and ^{8}B, respectively.

According to Esmailzadeh et al. [8], the predominant destruction reaction rate is $[\mathrm{Be}\,n;\ p\,7]$ and the predominant source term is $Y_3 Y_\alpha[3\,\alpha;\ \gamma\,\mathrm{Be}]$. However, since we are considering that either $^7\mathrm{Be} + d \to {}^4\mathrm{He} + {}^4\mathrm{He} + p$ or $^7\mathrm{Be} + {}^4\mathrm{He} \to \gamma + {}^{11}\mathrm{C}$ have an isolated resonance, the predominant sink terms are, not only $[\mathrm{Be}\,n;\ p\,7]$ but also $[\mathrm{Be}\,d;\ \alpha\,\alpha\,p]$ or $[\mathrm{Be}\,\alpha;\ \gamma\,\mathrm{C}]$.

The freeze-out temperature of ^{7}Be (T_9^{Be}) is calculated by equating the expansion rate of the Universe ($H = \frac{1}{356} T_9^2$) with the dominant reaction (destruction) rate

$$H = Y_n[\mathrm{Be}\,n;\ p\,7] + f(E_r, T_9), \tag{10}$$

where $f(E_r, T_9)$ stands for $Y_d[\mathrm{Be}\,d;\ \alpha\,\alpha\,p]$, and $Y_\alpha[\mathrm{Be}\,\alpha;\ \gamma\,\mathrm{C}]$. The neutron abundance can be determined by solving the quasi-static equation $\dot{Y}_n = 0$. The solution to this equation can be written as

$$Y_n = Y_d \frac{Y_d[d\,d;\ n\,3] + Y_t[d\,t;\ n\,\alpha]}{Y_p[n\,p;\ \gamma\,d] + Y_3[3\,n;\ p\,t] + [n]}. \tag{11}$$

In the last equation, t stands for tritium. Considering $\dot{Y}_t = 0$, we re-write the previous expression as

$$Y_n = Y_d^2 \frac{[d\,d;\ n\,3] + [d\,d;\ p\,t]}{Y_p[n\,p;\ \gamma\,d] + Y_3[3\,n;\ p\,t] + [n]}. \tag{12}$$

Then, considering the quasi-static equation for ^{7}Be, we can compute the beryllium primordial abundance at the freeze-out temperature [8]

$$Y_{\mathrm{Be}} = \frac{Y_3 Y_\alpha[3\,\alpha;\ \gamma\,\mathrm{Be}]}{Y_n[\mathrm{Be}\,n;\ p\,7] + f(E_r, T_9^{\mathrm{Be}})}. \tag{13}$$

Next, with the calculated abundance of beryllium and its freeze-out temperature, one can determine the primordial abundance of ^{7}Li. The differential equation which governs the primordial abundance of lithium is

$$\dot{Y}_7 = Y_n Y_6[6\,n;\ \gamma\,7] + Y_n Y_{\mathrm{Be}}[\mathrm{Be}\,n;\ p\,7] + Y_t Y_\alpha[t\,\alpha;\ \gamma\,7] - Y_p Y_7[7\,p;\ \alpha\,\alpha].$$

The quasi-static equation $\dot{Y}_7 = 0$ is solved by considering the dominant production and destruction terms as follows

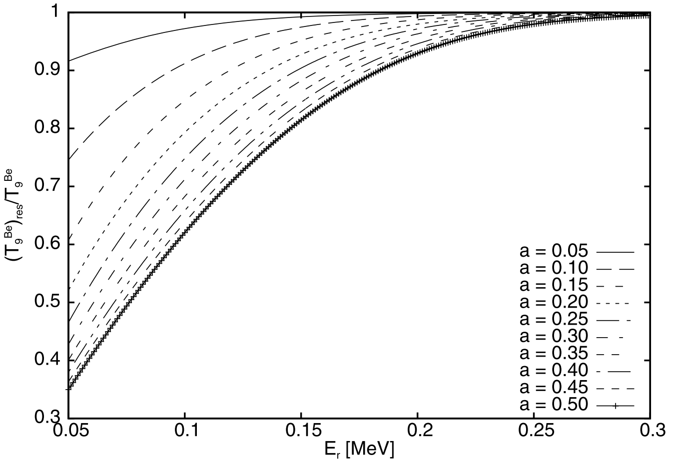

Fig. 1. Ratio $(T_9^{\rm Be})_{res}/T_9^{\rm Be}$ of the freeze-out temperature of beryllium as a function of the resonant energy E_r, for different values of the parameter a, considering an isolated resonance in the reaction $^7{\rm Be}+d\to{}^4{\rm He}+{}^4{\rm He}+p$.

$$Y_7=\frac{Y_nY_{\rm Be}[{\rm Be}\,n;\ p\,7]+Y_tY_\alpha[t\,\alpha;\ \gamma\,7]}{Y_p[t\,p;\ \alpha\,\alpha]}, \tag{14}$$

where $Y_{\rm Be}$ is the value obtained by evaluating Eq. (13) at the freeze-out temperature of beryllium. The abundance of tritium is determined by solving the equation $\dot{Y}_t=0$, and the expression for Y_n is given in Eq. (12). In order to calculate the final lithium abundance, we evaluate this expression at the freeze-out temperature of lithium ($T_9^{\rm Li}$) which is the solution of

$$Y_p[7\,p;\ \alpha\,\alpha]=H. \tag{15}$$

As one can see, the inclusion of an isolated resonance in either $[{\rm Be}\,d;\ \alpha\,\alpha\,p]$, $[{\rm Be}\,\alpha;\ \gamma\,{\rm C}]$ or $[{\rm Be}\,n;\ p\,7]$ does not affect the freeze-out temperature of lithium. However, its abundance is reduced due to the change in the beryllium primordial abundance resulting from the change in the freeze-out temperature of it.

3. Results

In order to perform the calculation of each of the reactions listed in (1) we have assumed a relationship between the resonant energy, E_r, and the width of the resonance, Γ, such that $\Gamma=aE_r$, and vary the parameter a. To compute the light nuclei abundances we have adopted the WMAP value of the baryon density $(\Omega_Bh^2)_{WMAP}=0.0224\pm0.0008$ [1,12,13], the primordial abundances of proton, deuterium, ^{3}He and ^{4}He are

$$Y_p=0.749,\qquad Y_d=2.36\times10^{-5},\qquad Y_3=6.76\times10^{-6},\qquad Y_\alpha=0.24915, \tag{16}$$

respectively. Thus, the freeze-out temperature of lithium (see Eq. (15)) is estimated at the value

$$T_9^{\rm Li}=0.1849. \tag{17}$$

3.1. The reaction $^7{\rm Be}+d\to{}^4{\rm He}+{}^4{\rm He}+p$

In Fig. 1 we show the normalized freeze-out temperature of beryllium ($(T_9^{\rm Be})_{res}/T_9^{\rm Be}$) as a function of the resonant energy, for different values of the parameter a. The freeze-out

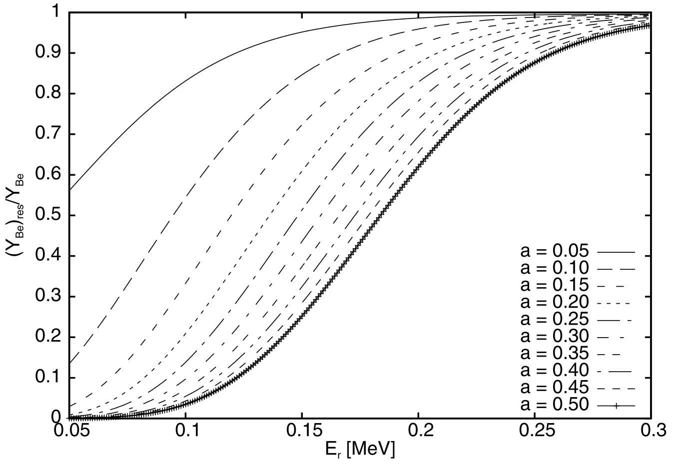

Fig. 2. Ratio between the abundance of beryllium with ($(Y_{\mathrm{Be}})_{res}$) and without (Y_{Be}) including a resonant state in the beryllium spectrum, as a function of the resonant energy E_r, for different values of the parameter a, considering an isolated resonance in the reaction $^7\mathrm{Be} + d \to {}^4\mathrm{He} + {}^4\mathrm{He} + p$.

temperatures have been calculated with, $(T_9^{\mathrm{Be}})_{res}$, and without, T_9^{Be}, including a resonance in the spectrum of ^{7}Be. The temperature is lower than the standard one for resonant energies lower than 0.25 MeV, for all the values of the parameter a. The effect of the variation of a is noticeable. The freeze-out temperature decreases if a increases. It means that a resonant state with a large width, in the entrance channel of the reaction, will cause a significant reduction of the freeze-out temperature and the effect will be dominant at lower energies. The changes in the freeze-out temperature of beryllium modify the primordial abundance of this element. The freeze-out of ^{7}Be occurs earlier than in the standard model, and as a consequence, the primordial abundance of this element must be lower than value predicted by the standard calculation.

In Fig. 2 we show the results for the normalized abundance of beryllium as a function of the resonant energy, for different values of the parameter a. The primordial abundance have been calculated with, $(Y_{\mathrm{Be}})_{res}$, and without, Y_{Be}, including a resonance in the spectrum of ^{7}Be. The effect of the inclusion of a resonance in the reaction is quite important. The primordial abundance of ^{7}Be decreases for all values of the resonant energy considered, and this effect is more important for large values of a.

The results for the primordial abundance of lithium with, $(Y_7)_{res}$, and without, Y_7, including a resonance in the spectrum of ^{7}Be are shown in Fig. 3, as a function of the resonant energy, and for different values of the parameter a. The effect is quite noticeable. It is seen that the value of Y_7 can be reduced almost to one half of the standard value depending on the values of E_r and a.

These results are in agreement with the results obtained by Broggini et al. [5] and by Cyburt and Pospelov [7].

The available data of lithium may be used to obtain the best-value of the resonant energy for different values of the parameter a, by implementing a χ^2-test. The observable data was extracted from Bonifacio et al. [14,15], Bonifacio and Molaro [16], Molaro et al. [17], Ryan et al. [18], Boesgaard et al. [19], Hosford et al. [20], Asplund et al. [21], Monaco et al. [22], Meléndez et al. [3], Sbordone et al. [23]. Regarding the consistency of the data, we have followed the treatment of Beringer et al. [24] and increased the errors by a fixed factor $\Theta_{^7\mathrm{Li}} = 1.41$.

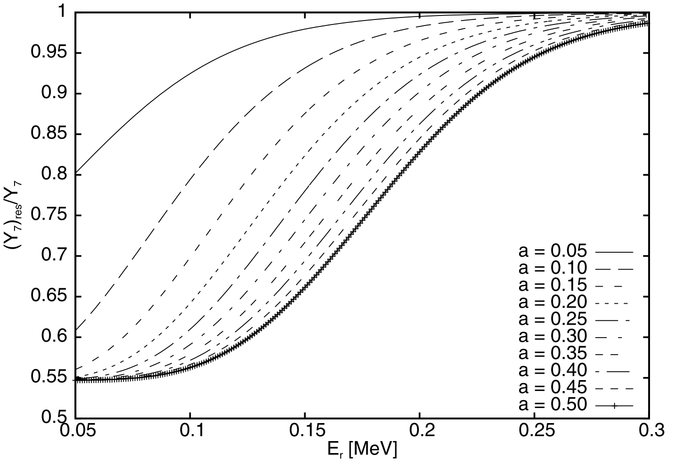

Fig. 3. Ratio between the abundance of lithium with $((Y_7)_{res})$ and without including a resonant state (Y_7) in the beryllium spectrum, as a function of the resonant energy E_r, for different values of the parameter a, in the reaction $^7\text{Be} + d \to {}^4\text{He} + {}^4\text{He} + p$.

Table 1
Best-fit and 1σ errors of the resonant energy of an isolated resonance in reaction $^7\text{Be} + d \to {}^4\text{He} + {}^4\text{He} + p$, for different values of the parameter a (the parameter remains fixed in the statistical test).

a	$E_r \pm \sigma$ [MeV]	$\chi^2/(N-1)$
0.15	$0.066^{+0.014}_{-0.040}$	1.00
0.20	$0.080^{+0.016}_{-0.040}$	1.00
0.25	$0.091^{+0.016}_{-0.040}$	1.00
0.30	$0.099^{+0.017}_{-0.043}$	1.00
0.35	$0.105^{+0.018}_{-0.044}$	1.00
0.40	$0.111^{+0.018}_{-0.046}$	1.00
0.45	$0.116^{+0.018}_{-0.048}$	1.00
0.50	$0.120^{+0.019}_{-0.049}$	1.00

The results of the analysis are presented in Table 1. There is a good fit for all values of the parameter a considered, since $\chi^2/(N-1) = 1$ (N is the number of observational data, $N = 11$). The best-fit value of the resonant energy increases its value for larger values of the parameter a. These results for the resonant energy are dependent on the observable data set used in the statistical analysis, however, the favored value of the resonant energy is lower than 0.2 MeV. Our results are of the same order of magnitude of those presented by Broggini et al. [5].

In Fig. 4 we present the one-dimensional likelihood for the resonant energy, for different values of the parameter a.

As said in the previous section, the value of the total width, for this channel, is further constrained experimentally [10].

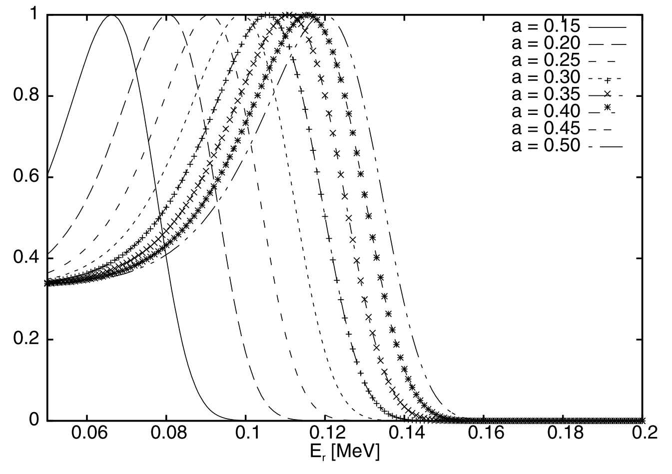

Fig. 4. 1-Dimensional likelihood for the resonant energy E_r, for different values of the parameter a the parameter, which remains fixed in the statistical test, in the reaction $^7\mathrm{Be} + d \to {}^4\mathrm{He} + {}^4\mathrm{He} + p$.

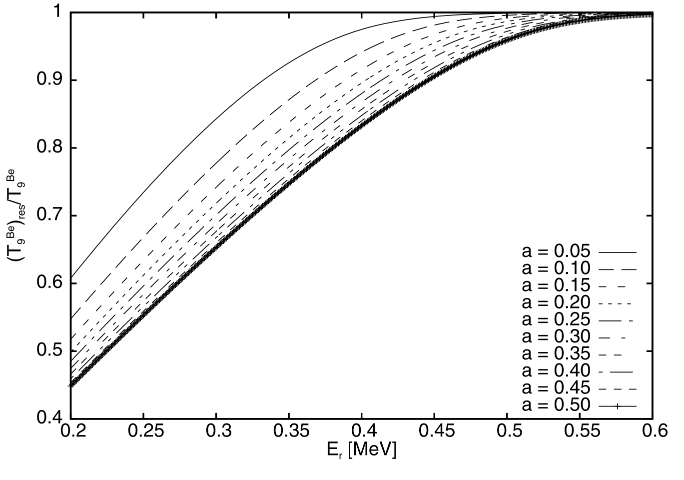

Fig. 5. Ratio $(T_9^{\mathrm{Be}})_{res}/T_9^{\mathrm{Be}}$ of the freeze-out temperature of beryllium as a function of E_r, and a, in the reaction $^7\mathrm{Be} + {}^4\mathrm{He} \to \gamma + {}^{11}\mathrm{C}$.

3.2. The reaction $^7\mathrm{Be} + {}^4\mathrm{He} \to \gamma + {}^{11}\mathrm{C}$

In Fig. 5 the freeze-out temperature of beryllium is presented as a function of the resonant energy and width. This temperature is again lower than the standard one, like in the previous case. However, the effect due to the resonance on the reaction rate, for the present case, is larger than in the previous one (see Fig. 1). As before, the results show that the freeze-out temperature of beryllium is reduced if the resonance is a broad resonance.

The changes on T_9^{Be} reflect upon the primordial abundance of beryllium. These variations from the standard value are presented in Fig. 6. They are considerably larger than for the case of the reaction of the previous subsection. The primordial abundance of ^{7}Be decreases faster as a function of the width of the resonance.

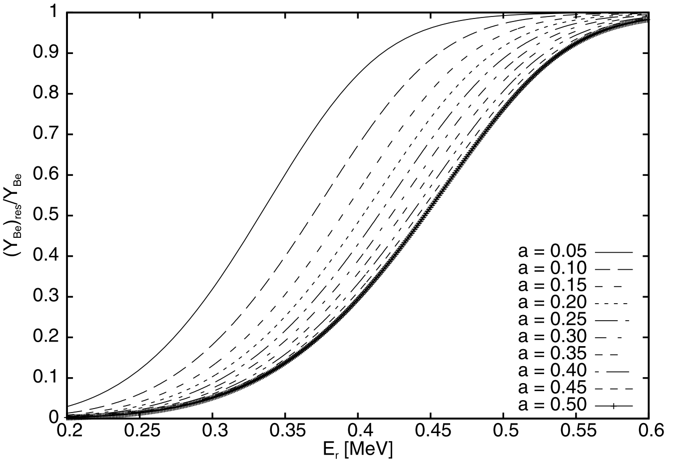

Fig. 6. Ratio between the abundance of beryllium with $((Y_{\mathrm{Be}})_{res})$ and without (Y_{Be}) including a resonant state in the beryllium spectrum, as a function of E_r and a, in the reaction ${}^7\mathrm{Be} + {}^4\mathrm{He} \to \gamma + {}^{11}\mathrm{C}$.

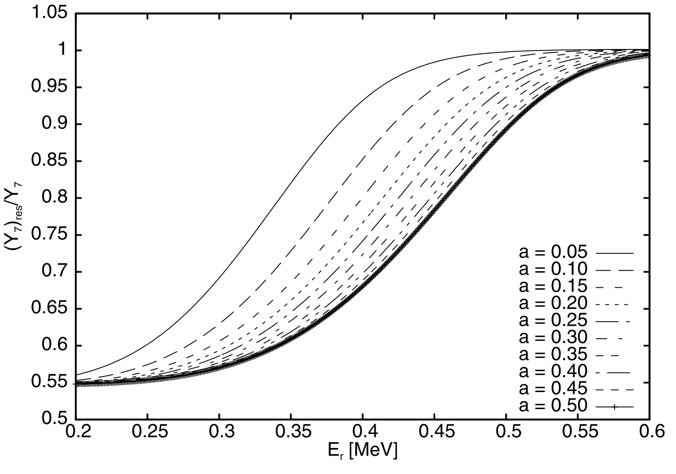

Fig. 7. Ratio between the abundance of lithium with $((Y_7)_{res})$ and without (Y_7) including a resonant state in the beryllium spectrum, as a function of E_r and a, in the reaction ${}^7\mathrm{Be} + {}^4\mathrm{He} \to \gamma + {}^{11}\mathrm{C}$.

In Fig. 7 we show how the primordial abundance of lithium is modified as a function of the resonant energy and of the parameter a. Our results are indeed comparable to those of Broggini et al. [5] and Cyburt and Pospelov [7].

Repeating the procedure described before, we have used the observable data of lithium in order to perform a χ^2 test to obtain the best-value of the resonant energy for different values of the parameter a (these values are fixed during the statistical test, as described in Section 3.1). The results are presented in Table 2. There is a good fit for all values of the parameter a considered. The best-fit value of the resonant energy increases for larger values of the parameter a. Although the values are lower than those presented by Broggini et al. [5], they are of the same order of magnitude.

Table 2
Best-fit and 1σ errors of the resonant energy of an isolated resonance in reaction $^7\text{Be} + {}^4\text{He} \to \gamma + {}^{11}\text{C}$.

a	$E_r \pm \sigma$ [MeV]	$\chi^2/(N-1)$
0.10	$0.267^{+0.033}_{-0.067}$	1.00
0.15	$0.283^{+0.034}_{-0.083}$	1.00
0.20	$0.294^{+0.036}_{-0.094}$	1.00
0.25	$0.302^{+0.037}_{-0.102}$	1.00
0.30	$0.309^{+0.038}_{-0.110}$	1.00
0.35	$0.315^{+0.038}_{-0.112}$	1.00
0.40	$0.320^{+0.038}_{-0.114}$	1.00
0.45	$0.324^{+0.040}_{-0.115}$	1.00
0.50	$0.327^{+0.040}_{-0.116}$	1.00

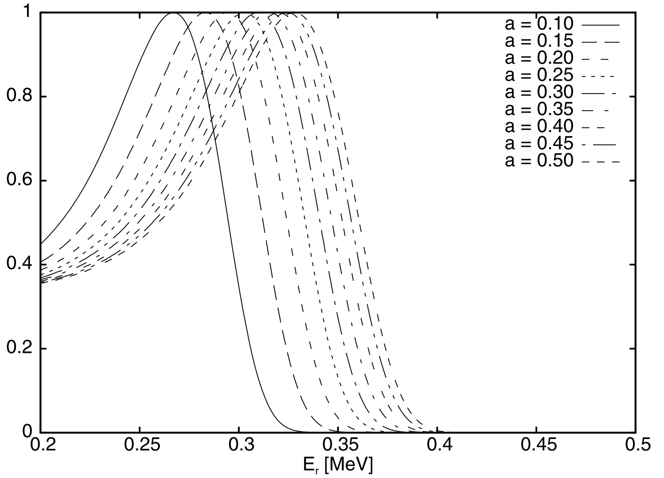

Fig. 8. 1-Dimensional likelihood for the resonant energy, for different values of the parameter a, in the reaction $^7\text{Be} + {}^4\text{He} \to \gamma + {}^{11}\text{C}$.

In Fig. 8 we show the 1-dimensional likelihood for the resonant energy, for different values of a. Since for this reaction the available decay channels at low energies are electromagnetic transitions, one may think of an upper value of the width of the order of few hundreds of eV. This is an additional constraint to the results presented in Fig. 8.

3.3. The reaction $^7\text{Be} + n \to {}^7\text{Li} + p$

In Fig. 9 we show the normalized freeze-out temperature of beryllium as a function of the resonant energy, for different values of the parameter a. The modification in the temperature is lower than 1% for all the values of the parameter a. The effect induced by the variation of a is negligible. In Fig. 10 we present the normalized abundance of beryllium as a function of E_r

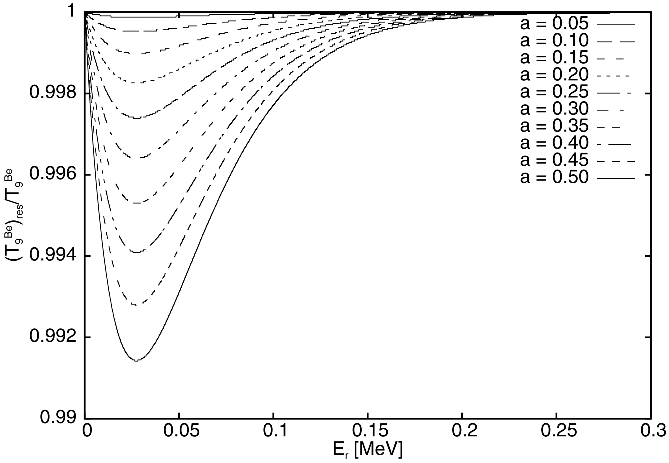

Fig. 9. Ratio $(T_9^{\mathrm{Be}})_{res}/T_9^{\mathrm{Be}}$ of the freeze-out temperature of beryllium as a function of E_r and a, in the reaction $^7\mathrm{Be} + n \to p + {}^7\mathrm{Li}$.

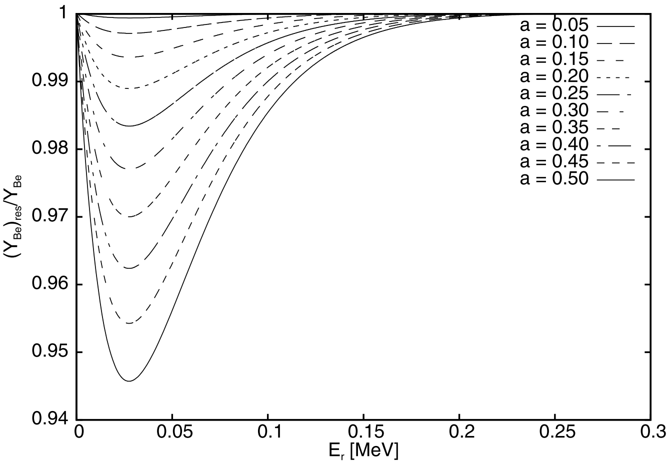

Fig. 10. Ratio between the abundance of beryllium with $((Y_{\mathrm{Be}})_{res})$ and without (Y_{Be}) including a resonant state in the beryllium spectrum, in the reaction $^7\mathrm{Be} + n \to p + {}^7\mathrm{Li}$.

and a. The effect of the inclusion of a resonance in this reaction amounts to approximately 5%, for the considered values of the resonant energy.

Finally, we have computed the primordial abundance of lithium. The results are shown in Fig. 11. The effect induced by the inclusion of a resonance, for this case, is smaller than 2%.

4. Conclusion

In this work we have computed the primordial abundances of light elements using a semi-analytical approach and considering the inclusion of an isolated resonance in the reactions leading to beryllium. The results seems to confirm the claims of Broggini et al. [5], since

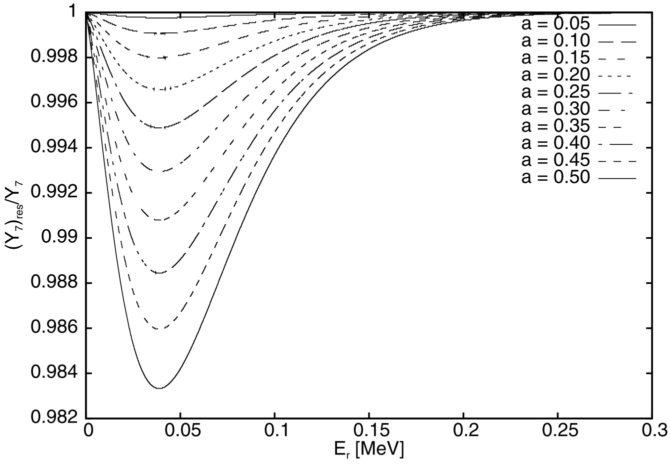

Fig. 11. Ratio between the abundance of lithium with $((Y_7)_{res})$ and without (Y_7) including a resonant state in the beryllium spectrum, with the parameters of the previous figures, in the reaction $^7\mathrm{Be} + n \to p + {}^7\mathrm{Li}$.

we found that there exists a reduction of the primordial abundance of lithium due to a depletion of the beryllium abundance, produced by resonances in the reactions, particularly in $^7\mathrm{Be} + d \to {}^4\mathrm{He} + {}^4\mathrm{He} + p$ and $^7\mathrm{Be} + {}^4\mathrm{He} \to \gamma + {}^{11}\mathrm{C}$. However, if the resonance is present in the reaction $^7\mathrm{Be} + n \to p + {}^7\mathrm{Li}$, the amount of primordial lithium is not modified substantially, a result which is also in agreement with the results of Refs. [5,7].

We also found that the value of the parameter a, in the relationship between the partial width and the resonant energy $\Gamma = aE_r$, is crucial to determine the level of depletion of the primordial abundance of $^7\mathrm{Li}$. We have performed a statistical analysis in order to obtain the best-fit value of the resonant energy for a fixed value of a, and found that, for the reaction $^7\mathrm{Be} + d \to {}^4\mathrm{He} + {}^4\mathrm{He} + p$, the best-fit value of E_r lies between 50 and 150 keV (given a partial width in the range of 10 and 60 keV). The resonant energy for $^7\mathrm{Be} + {}^4\mathrm{He} \to \gamma + {}^{11}\mathrm{C}$ is higher, between 250 and 350 keV (given partial width in the range of 30 and 164 keV). It would be very interesting to see if these results are supported by nuclear structure calculations of the participant light elements, to further restrict the position and width of the resonances.

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