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Indirect measurements of lithium isotopes destruction cross section in astrophysical environment

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Abstract. Obtaining information on low-energy cross sections is essential for understanding the Universe. Due to the presence of Coulomb barrier and the electron clouds this is usually done by means of theoretical extrapolations. Several indirect methods have been suggested to overcome these difficulties and among them the Trojan Horse Method has already been successful in several cases, which are briefly reviewed in this paper. Some astrophysical implications are also discussed.

1. Introduction

Understanding the Universe requires the knowledge of several nuclear reaction rates at energies typical of the different astrophysical sites. Both the stellar nucleosynthesis and energy production in stars are intimately connected to this. In the last decades, due to an improvement in the observational techniques, the elements' abundance has been widely studied. Specifically lithium isotope abundance were measured in different astrophysical sites. The large interest about lithium abundance is related to the role this element can play in modern Astrophysics. In fact lithium abundance can help to put strict constraints on the baryon density of the Universe [see Copi et al. (1995) and section 3 of this paper] as well as it can give precise hints on stellar structure and evolution (Michaud & Charbonneau (1991))

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In order to understand how lithium abundance has evolved with time, a precise knowledge of nuclear reaction cross sections for the production/destruction of lithium isotopes is needed. Among these reactions some of the most important lithium-destroying reactions are the $^7Li(p,\alpha)^4He$, $^6Li(d,\alpha)^4He$, $^6Li(p,\alpha)^3He$. These have been studied in the low energy range (0< E_{cm} < 400 keV) by means of the Trojan Horse Method.

It has been shown that at these energies the "electron screening" effect plays a major role in laboratory experiments (Assenbaum et al. (1987); Engstler et al. (1992)) being both target and projectile surrounded by atomic clouds. This gives rise to an enhancement factor, f_{lab}, in the low energy region of the S(E)-factor trend which can be parameterized as:

$$f_{lab}(E) = \frac{\sigma_s(E)}{\sigma_b(E)} = \exp\left(\frac{\pi Z_1 Z_2 e^2 U_e}{\hbar v E}\right), (1)$$

where U_e is the electron screening potential, $\sigma_s(E)$ and $\sigma_b(E)$ are respectively the screened and bare nucleus cross section.

Thus, in order to measure the astrophysically relevant bare nucleus S(E)-factor, extrapolations are usually carried out. A different possibility is given by indirect methods that are complementary to direct measurements. A succesful method for studying charged-particle induced reactions is the Trojan Horse Method (THM) which will be described in the following section.

2. The method and results

THM has been already extensively discussed in (Baur (1986)) and (Spitaleri et al. (1999)). Here we will briefly review its main features.

The THM is based on a quasi-free break-up process and allows to extract the cross section of a two-body reaction (e.g. of astrophysical interest)

$$a + x \to c + C$$

from a suitable three body one

$$a + A \to c + C + s\ .$$

In this notation the particle A, the "Trojan Horse", which can be either the projectile or the target nucleus, has a high probability of being clustered into x and s, i.e. $A = x \oplus s$. Particle x acts as a participant in the two body reaction, while s keeps the role of spectator. If the energy in the entrance channel is higher than the Coulomb barrier, then the interaction between x and a occurs directly in the nuclear interaction region, thus overcoming the Coulomb barrier and the electron screening effect.

This method has been applied to measure the bare nucleus astrophysical S(E)-factor of three important lithium-depleting reactions, the $^6Li(d,\alpha)^4He$ (Spitaleri et al. (2001)) and the $^7Li(p,\alpha)^4He$ (Lattuada et al. (2001)) and the $^6Li(p,\alpha)^3He$ (Tumino et al. (2003)).

We refer to (Spitaleri et al. (2001), Lattuada et al. (2001), Tumino et al. (2003), Typel & Wolter (2000)) for further details about experimental set-up and data-analysis. In figure 1 and 2 the bare nucleus S(E)-factors for the three reactions are plotted as a function of the energy; the comparison with direct data from Engstler et al. (1992) is also shown.

3. Astrophysical implications

Substantial amounts of the primordially synthesized elements (^2H, ^4He, ^7Li) should be found nowadays in appropriate astrophysical contexts. The Standard Big Bang model has the very powerful feature that prediction for production of light elements is essentially dependent on one free parameter, the baryon-to-photon ratio η (which is connected to the baryon density of the Universe, Ω_B). In this way a comparison between theoretically calculated yields and observed primordial abundances of such elements can be performed in order to test the Standard Big Bang Nucleosynthesis (SBBN). Moreover it is possible (Copi et al. (1995)) to infer hints

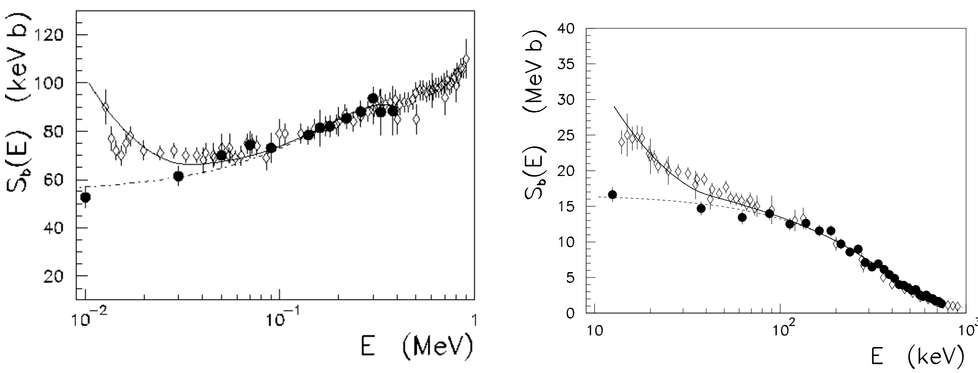


Fig. 1. Left panel: bare astrophysical S(E)-factor for the $^7Li(p,\alpha)^4He$ obtained via THM compared with direct data from Engstler et al. (1992). The dashed curve represents a polynomial fit while the solid one had been used for determining U_e. Right panel: The same for the $^6Li(d,\alpha)^4He$.

about the relevant cosmological parameter η and therefore Ω_B.

Among these "primordial" isotopes in the last decades, lithium has been studied both observationally and theoretically (Michaud & Charbonneau (1991)). In particular the key role of the reaction $^7Li(p,\alpha)^4He$ must be acknowledged for both the primordial nucleosynthesis and the lithium destruction in stellar environment. The indetermination of this cross section is one of the main sources of uncertainty in these fields (Vangioni-Flam et al. (2000), even if great efforts have been devoted to reducing it.

The bare nucleus cross section, measured via the THM in Lattuada et al., (2001), has been applied to the SBBN in order to investigate the sensitivity of the calculated lithium abundance with respect to the variation of the adopted cross section. As a simple approach we have used the code described in Fiorentini et al., (1998) and Lisi et al., (1999). In this calculation a number of neutrino species N_ν=3 is assumed.

In figure 2 (right) the predicted lithium number abundance after SBBN, is reported as a function of

$$x = log\eta + 10$$

for two different values of $^7Li(p,\alpha)^4He$ cross section. The solid line represents the calculation with the rate reported in NACRE (Angulo et al. (1999) while the dashed one adopts the cross section measured in Lattuada et al., (2001). At very low η the discrepancy between the two models is around 5 %, and progressively diminishes for higher η, as expected.

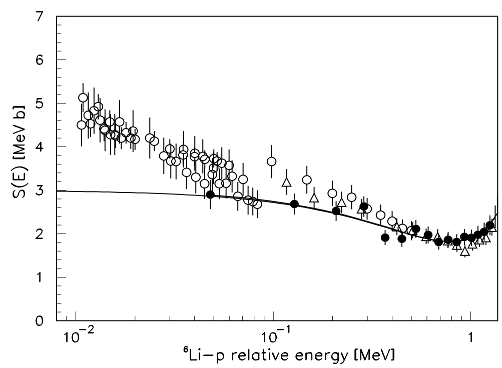
The comparison with observed primordial lithium abundance (for this value we adopted that of Ryan et al., (2000)) gives the following constraints on η (for the THM value of the $^7Li(p,\alpha)^4He$ cross section):

$$\mathbf{1}.82 < \eta_{10} < 4.07 \tag{2}$$

with $\eta_{10} = \eta \times 10^{-10}$.

These constraints on η can be expressed in terms of the baryonic adimensional density as:

$$0.016 < \Omega_B < 0.035 \tag{3}$$



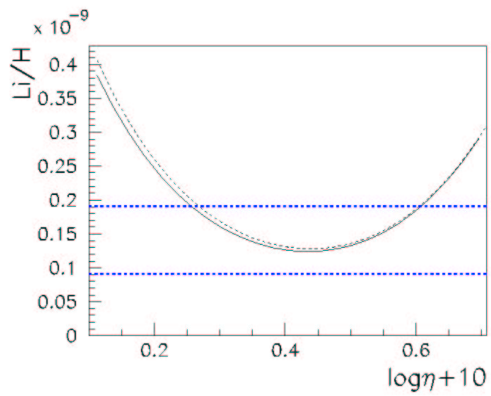


Fig. 2. Left: The same as figure 1 for the $^6Li(p,\alpha)^3He$; Right: Lithium primordial abundance as a function of the cosmological parameter η: solid line represents a calculation performed with the rate from NACRE and dashed line using data from Lattuada et al. (2001). Observational limits (thick dashed lines) are taken from Ryan et al. (2000).

assuming h=H/100=0.65, where H is the Hubble parameter. These results are in fair agreement with the recent and more detailed calculation performed by Coc et al., (2002).

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