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# Proton-induced lithium destruction cross-section and its astrophysical implications

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**Abstract.** Knowledge of the primordial nucleosynthesis offers a powerful tool to retrieve information on the baryon density of the Universe. In this context lithium isotopes play a crucial role and in particular we stress how important the bare nucleus cross-section for the $^7$Li(p, $\alpha$)$^4$He reaction is. Recent application of the Trojan Horse Method led to an indirect measurement of that cross-section. In the present paper its astrophysical implications are examined in the case of the Solar lithium problem and of the primordial nucleosynthesis.

**Key words.** nuclear reactions, nucleosynthesis, abundances – Sun: abundances – cosmology: cosmological parameters

## 1. Introduction

Proton-induced lithium destruction plays a role both in the evaluation of Big Bang nucleosynthesis and in the debated problem of atmospheric abundance of Li either in the Sun or in other MS stars making up of the various galactic populations. As it usually happens for charged-particle induced reactions, experimental measurements of this cross-section (Rolfs & Kavanagh 1986; Harmon 1989; Engstler 1992) face the main difficulty given by the presence of the Coulomb Barrier (whose height is $E_C$). This greatly reduces the cross-section $\sigma(E)$ at low energies ($E \ll E_C$), leading to a low-energy limit of experimental measurements, which is typically much larger than the energy relevant for astrophysical applications, $E_0$ (Rolfs & Rodney 1988). In such cases, an extrapolation of high energy data is usually performed via the definition of the astrophysical $S(E)$-factor

$$S(E) = \sigma(E) E \exp(2\pi\eta) \quad (1)$$

with $\eta = Z_1 Z_2 e^2/\hbar v$, the Sommerfeld parameter. Of course, this extrapolation "into the unknown" may introduce a large uncertainty in $\sigma(E_0)$.

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Moreover, measurements at ultra-low energies suffer from the complication due to the effects of electron screening (Assenbaum et al. 1987). This leads to an increase of $\sigma(E)$ (or equivalently of $S(E)$) with decreasing energy with respect to the case of bare nuclides. It should be pointed out that, in the astrophysical environments, the cross-section under plasma conditions $\sigma_{pl}(E)$ is related to the bare cross-section $\sigma(E)$ by a similar enhancement factor which depends on detailed properties of the plasma, such as the Debye-Hückel radius. So what is needed for astrophysical calculations is the bare nucleus cross-section, which must be inferred from the directly measured one by means of theoretical extrapolation. This has been done by the NACRE collaboration for the $^7$Li$(p, \alpha)^4$He reaction giving an extrapolated value $S(E = 0) = 59$ keV·b. In this paper we present the results of an alternative experimental approach, allowing the evaluation of the bare nucleus reactions cross-section without any extrapolation, overcoming the Coulomb Barrier and the electron screening effect

## 2. The method and experimental results

The Trojan Horse Method (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 (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 be 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 zone, thus by-passing the Coulomb barrier and the electron screening effect.

An improved theoretical formalism, based on a Distorted Wave Born Approximation (DWBA) (Typel & Wolter 2000) allows the extraction of the energy trend for the bare nucleus astrophysical factor whose absolute normalization must be performed via a comparison with direct data at energies above the Coulomb barrier, where the THM and the direct results should be equivalent.

This method has been applied to measure the bare nucleus astrophysical S(E)-factor of two important lithium-depleting reactions, the $^6$Li(d,$\alpha$)$^4$He (Spitaleri et al. 2001) and the $^7$Li(p, $\alpha$)$^4$He (Lattuada et al. 2001), and hence the electron screening potential for both reactions.

The reaction $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$ has been studied via the three-body reaction $^7$Li(d,$\alpha\alpha$)$^4$He at the Laboratori Nazionali del Sud, Catania. In this case the Trojan Horse particle was the deuteron, carring inside the "participant" proton. A first run of the experiment was performed at relative energies between $^7$Li and p higher than the relative Coulomb barrier (validity test). The results are taken from Zadro et al. (1989) and are shown in Fig. 1. A fair agreement is achieved and both resonances are correctly reproduced. The next step was to extract data at energies lower than the Coulomb Barrier. This was performed in the energy range $E_{\mathrm{cm}} = 0 \div 0.4$ MeV in two different experimental runs. A more complete description is reported in Calvi et al. (1997) and Lattuada et al. (2001).

Here we report only the final results and we refer to those papers for an exhaustive discussion about the experiments and data analysis; the astrophysical $S(E)$-factor is plotted in Fig. 2 and it is compared with the direct data obtained in Engstler et al. (1992). A second-order polynomial fit to the indirect data (Lattuada et al. 2001) gives $S(E = 0) = 55 \pm 3$ keV·b, in agreement with theoretical predictions (Aliotta et al. 2000) and only slightly smaller than the value obtained in the direct measurements (Engstler et al. 1992).

## 3. Astrophysical applications

As one can easily predict, the small variation in the cross-section is not expected to produce important variations in the current astrophysical scenarios. However, it seems worthwhile to investigate the effect of the new value on the solar lithium problem and primordial nucleosynthesis.

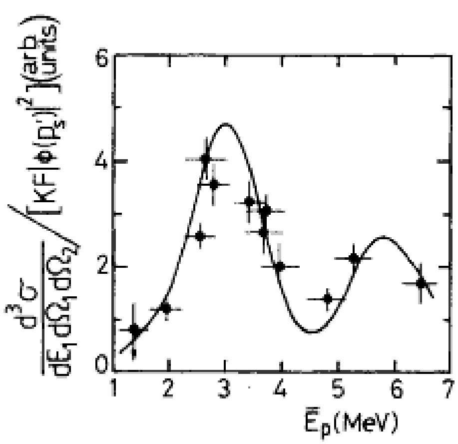


**Fig. 1.** Comparison between the two body differential cross-section extracted from indirect data (full dots) and direct data (solid line) for the $^7$Li(p, $\alpha$)$^4$He reaction (Zadro et al. 1989) at energies above the Coulomb Barrier.

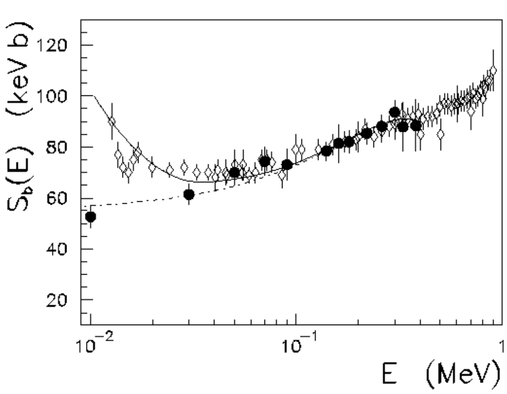


**Fig. 2.** The bare astrophysical $S(E)$-factor for the $^7$Li(p, $\alpha$)$^4$He compared with direct data. The fit performed to obtain the electron screening contribution is also shown as a solid line (taken from Lattuada et al. 2001).

As for the first issue, the present lithium abundance on the solar surface corresponds to a mass fraction of $\approx 7.0 \times 10^{-11}$ (Grevesse & Sauval 1998); this value has to be compared with the meteoritic value of $\approx 9.9 \times 10^{-9}$ (Anders & Grevesse 1989). Since the proto-solar nebula is assumed to be homogeneous at the beginning of the solar system, the Sun has clearly depleted lithium by a factor 140.

We have investigated the impact of our measurement of the bare nucleus cross-section for the $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$ reaction on the lithium abundance on the solar surface. This has been done by using the FRANEC code, which is extensively discussed in Ciacio et al. (1997). It was applied to calculate a solar model that includes the light elements' diffusion; in particular the lithium surface abundance at the present time ($t_\odot = 4.6 \times 10^9$ years) was calculated taking into account both Pre-Main Sequence and Main Sequence lithium depletion. Our Standard Solar Model (SSM) reproduces at the solar age the observed luminosity, radius and $Z/X$ ratio and the helioseismic observables (Ciacio et al. 1997) (see e.g. Bahcall et al. 2001 for more details on SSMs). We adopted the OPAL

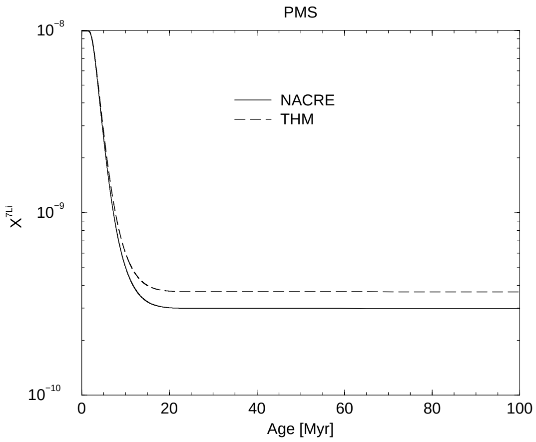


**Fig. 3.** Time-evolution of the lithium surface abundance (mass fraction) during the PMS phase for the Sun. The solid line represents a calculation performed using the FRANEC code with the rate for the $^7$Li(p, $\alpha$)$^4$He taken from Angulo et al. (1999). The dashed line represents the same model calculation with the cross-section extracted in Lattuada et al. (2001).

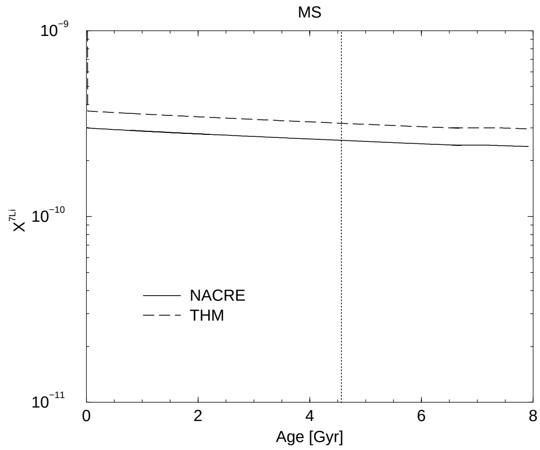


**Fig. 4.** Time-evolution of the lithium surface abundance during the MS phase for the Sun. The solid line represents a calculation performed with the rate for the $^7$Li(p, $\alpha$)$^4$He taken from (Angulo et al. 1999). The dashed line represents the same model calculation with the cross-section extracted in (Lattuada et al. 2001). The vertical dotted line marks the present age of the Sun.

opacity (Rogers & Iglesias 1995) and equation of state (Rogers & Iglesias 1996), and the mixing length parameter $\alpha = 1.9$; the initial helium abundance is $Y = 0.269$ and the metallicity $Z = 0.0198$.

Since the evolution of lithium abundance will be described from the PMS phase, we took as the initial value of lithium abundance the meteoritic value, $9.9 \times 10^{-9}$.

Two different calculations have been performed using the FRANEC code: in the first case, we adopted the cross-section of the $^7$Li($p, \alpha$)$^4$He given by the NACRE (Angulo et al. 1999) compilation. The second calculation was performed by assuming as the cross-section the THM one reported in Lattuada et al. (2001). As it was expected the difference is quite small and is around 5%. In Fig. 3 we report the trend of lithium abundance versus stellar age (expressed in units of $10^6$ years) for the Sun during the PMS phase. The solid line represents the calculation performed using the rate of the $^7\mathrm{Li} + \mathrm{p} \rightarrow \alpha + \alpha$ extracted from the NACRE compilation while the dashed one represents the result for the THM measurement of the cross-section.

In the MS phase the lithium abundance decreases, mainly due to microscopic diffusion, as sketched in Fig. 4; again the solid line represents the calculation performed using the rate reported in the NACRE compilation (Angulo et al. 1999) while the dashed one represents that obtained by using the THM cross-section. The same $\alpha$, metallicity, primordial helium and physical inputs were assumed for both phases.

Thus the present measurement of the $^7$Li(p, $\alpha$)$^4$He $S(0)$-factor does not significatively change the superficial lithium abundance for the present Sun, with respect to the NACRE compilation as expected because of the small discrepancy between the two rates. As expected, the "Lithium problem" for the Sun as well as for the population I and II (and hence the time evolution of the lithium abundance) is not solved even applying the THM and the observed lithium surface abundance is not reproduced by the model. Incidentally, we notice that our results for the solar lithium abundance are in agreement with the ones of Piau & Turck-Chieze (2002), who adopt similar physical inputs with time steps in the PMS adjusted to the $^7$Li burning time at the bottom of the external convective zone. Other mechanisms and uncertainties should be taken into account in order to solve the "Lithium problem" such as the efficiency of convection in the external envelope of stars, non-standard mixings, rotation, uncertaintes on opacity and the equation of state (see e.g. Swenson et al. 1994; Morel et al. 1997; Brun et al. 1999; Imperio et al. 2001). A better evaluation of the role and relative weight of each one of these mechanisms will provide more reliable bases to the astrophysical models.

As for the second issue, Big Bang nucleosynthesis has emerged as one of the pillars of the Big Bang Model and probes the Universe to the earliest times, from a fraction of a second to hundreds of seconds.

According to the Standard Big Bang model (Malaney & Mathews 1993) for $T \leq 10^9$ K the formation of light nuclei (up to $A \leq 7$) from protons and neutrons is possible. Consistent amounts of these primordially synthesized elements 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 ($^2$H, $^4$He, $^7$Li) is primarily dependent only on one free parameter, the baryon-to-photon ratio $\eta$ (which is connected to the baryon density of the Universe). Starting from this, the measured primordial abundances can be fitted up to 10 orders of magnitudes (Schramm & Turner 1998).

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 about the relevant cosmological parameter $\eta$ and therefore $\Omega_{\mathrm{B}}$.

This procedure has some uncertainties; although many of them have been reduced thanks to recent improvements (for instance the uncertainty on $\tau_n$, neutron decay period), some still remain important:

- errors on observed primordial abundances;
- uncertainty on the Hubble parameter;
- errors on reaction cross-section at astrophysical energies.

Up to now, a lot has been done in all these fields, but a definitive solution is still far from being found.

Among these "primordial" isotopes, lithium has been studied both observationally and theoretically in the last decades (Michaud & Charbonneau 1991). In particular the key role of the reaction $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$ must be acknowledged for both the primordial nucleosynthesis and the lithium destruction in the 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 $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$ reaction is one of the main channels of lithium destruction also in the Big Bang nucleosynthesis (BBN) network (Schramm & Turner 1998); its rate influences the calculated abundance of primordial nucleosynthesis. The bare nucleus cross-section, measured via the THM in Lattuada et al. (2001), has been applied to the BBN 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 program described in Fiorentini et al. (1998) and in Lisi et al. (1999). In this calculation we assumed a number of neutrino species $N_\nu = 3$.

In Fig. 5 the predicted lithium abundance, by number, after BBN is reported as a function of

$$x = \log\eta + 10$$

for two different choices of $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$ 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 $\eta$ the discrepancy between the two models is around 5%, and progressively diminishes for higher $\eta$, 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 $\eta$ (for the THM value of the $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$ cross-section):

$$1.82 < \eta_{10} < 4.07 \qquad (2)$$

with $\eta_{10} = \eta \times 10^{-10}$ and considering only the mean value of the calculated abundance. This is in agreement with recent and more accurate calculations (Vangioni-Flam et al. 2000).

These constraints on the $\eta$ parameter can be expressed in terms of the baryonic adimensional density according to the relation:

$$\Omega_\mathrm{B} = \frac{\rho_\mathrm{B}}{\rho_\mathrm{c}} = 0.00366 \cdot \eta_{10} \cdot h^{-2} \qquad (3)$$

where $\rho_\mathrm{B}$ is the baryonic density, $\rho_\mathrm{c}$ is the critical density, $h = H_0/100$ with $H_0$ the Hubble parameter. Our constraints on $\eta$ the following limits on the baryon density are

$$0.016 < \Omega_\mathrm{B} < 0.035 \qquad (4)$$

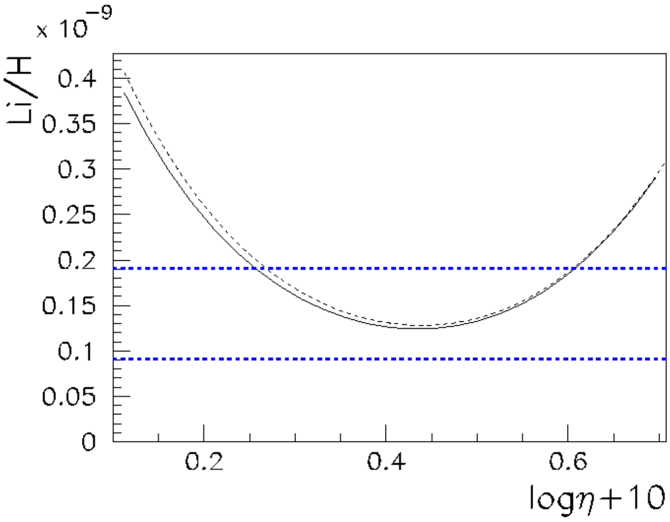


**Fig. 5.** Theoretical prediction of the Li abundance vs. the baryon to photon ratio, $\eta$. Solid line represents the model with $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$ reaction rate adopted Angulo et al. (1999) while dashed line the rate obtained from Lattuada et al. (2001). Thick dashed lines represent the observed "primordial abundance" according to Ryan et al. (2000).

assuming $h = 0.65$. These results are in fair agreement with the recent calculation performed by Coc et al (2002).

## 4. Conclusions

The application of the recent determination of the $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$ bare nucleus cross-section, via the Trojan Horse Method, has produced results in the field of the Solar lithium problem and primordial nucleosynthesis which agree within 5% with the ones based on present compilations of nuclear reaction rates. Our aim is to study other reactions of astrophysical interest via the same method, such as the $^6\mathrm{Li(p,}\ \alpha)^3\mathrm{He}$, whose anlysis is in progress.

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