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Trojan Horse estimate of bare nucleus astrophysical S(E)-factor for the ^{6}Li(p,α)^{3}He reaction and its astrophysical implications

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Abstract. The ^{6}Li(p, α)^{3}He bare nucleus cross-section at astrophysical energies has been indirectly measured in the framework of the Trojan-Horse Method, finding an agreement within the experimental errors with the results of data extrapolations from direct methods. This result is thus an independent check of the extrapolation method used until now. The method of measure is recalled and the results are shown with particular attention to the bare cross section value at the Gamow energy. The quoted agreement between direct and indirect methods is discussed in the context of the surface lithium abundances in stars. It is shown that the problem of stellar lithium abundances is not at the nuclear physics level but it is an astrophysics problem that requires improvements in our knowledge of the mixing mechanisms, the reduction of the uncertainties on the other (non-nuclear) physical inputs, and more precise observational data.

Key words. nuclear reactions, nucleosynthesis, abundances

1. Introduction

Low-energy cross sections for reactions producing or destroying lithium isotopes are fundamental for a number of still not completely solved astrophysical problems, e.g. understanding Big Bang nucleosynthesis and the "Lithium depletion" in the Sun or in other galactic stars. In particular, not only the more abundant ^{7}Li has a relevant astrophysical importance but also ^{6}Li whose abundance has been extensively studied only recently. Since ^{6}Li is more fragile than ^{7}Li its abundance can give hints of the ^{7}Li depletion mechanism. Both production and destruction mechanisms must be studied and their cross sections should be measured in the astrophysically relevant energy window. In the recent decades, destruction mechanisms for lithium have been studied; in particular, great effort has been devoted to the study of relevant reactions such as ^{7}Li(p,α)^{4}He, ^{6}Li(d,α)^{4}He, ^{6}Li(p,α)^{3}He, at astrophysically important energies (Engstler et al. 1992). Due to the difficulties encountered in charged-particle experimental studies at sub-Coulomb energies (e.g. electron screening effect), indirect methods, e.g. Coulomb dissociation (Baur & Rebel 1994, 1996) and ANC (Asymptotic Normalization Coefficients) (Ross et al. 1995; Gagliardi et al. 1999; Azhari et al. 1999; Gagliardi et al. 2002) have been applied to transfer reactions. Among these methods, the Trojan-Horse Method (THM) (Baur 1986; Spitaleri 1990; Spitaleri et al. 1999, 2000, 2001; Lattuada et al. 2001; Tumino et al. 2003) is particularly well suited for investigating low-energy charged-particle two-body reactions using appropriate three-body processes. This method overcomes both Coulomb barrier and electron screening effects in the off-shell cross section of the two-body reactions. An experimental program is presently underway applying the THM to the study of relevant reactions destroying lithium in cosmic environments. The ^{7}Li(p,α)^{4}He and the ^{6}Li(d,α)^{4}He reactions have been studied through the d(^{7}Li,α α)n and the ^{6}Li(^{6}Li,α α)^{4}He three-body reactions respectively (Spitaleri et al. 1999; Musumarra et al. 2001; Lattuada et al. 2001; Spitaleri et al. 2001; Pizzone et al. 2003). The extracted astrophysical S(E) factors were compared with those from direct measurements and showed in fair agreement in the energy range in which screening effects are negligible. Since the THM provides the bare S(E) factor, i.e. free of screening effects, improved information on the screening potential U_e was obtained from comparison with shielded direct data. The extracted values confirmed the isotopic independence of U_e, although they were found to be much larger than the adiabatic limit (176 eV). In the case of the ^{7}Li(p,α)^{4}He reaction, the implications of the THM bare S(E) measure for the problem of the solar surface ^{7}Li abundance and on primordial nucleosynthesis has been discussed (Pizzone et al. 2003). In both cases, the change for lithium abundances due to the new cross section with respect to the NACRE compilation Angulo et al. (1999) is around 5%.

In the present paper we discuss the THM results for the ^{6}Li(p,α)^{3}He reaction in the context of surface light element abundances in stars. The THM bare cross section has been extracted from the d(^{6}Li,α^3He)n three body reaction performed at 14 MeV of beam energy. The Proton-induced reaction on ^{6}Li is the main contribution leading to ^{6}Li destruction in stars. In particular the Gamow window corresponding to lithium stellar burning from 0 to 20 keV, i.e. within the energy region where electron screening effect in laboratory measurements cannot be neglected.

2. Basic features of the THM

The THM selects the quasi free contribution of a given reaction between a particle A and a nucleus a, whose associated wave function has a large amplitude for an $x \oplus b$ cluster configuration (Trojan-Horse). Under appropriate kinematical conditions, particle A interacts only with the cluster x, leaving b as a spectator to the process $A + x(+b) \rightarrow c + d(+b)$. The main feature of the THM is that although the $a + A$ reaction proceeds at an energy above the Coulomb barrier, the $x - b$ binding energy compensates for their relative motion, providing a quasi free channel $A + x$ even at very low sub-Coulomb energies. In this way Coulomb suppression and electron screening effects are overcome.

Leaving the details of the method to the references (Spitaleri et al. 1999, 2001; Tumino et al. 2003), we stress that in order to get the two-body cross section from the three-body reaction for the process of interest, the Plain Wave Impulse approximation or the Modified Plane-Wave Born (MPWBA) description are adopted, as extensively treated in Tumino et al. (2003), Spitaleri et al. (2004). The MPWBA fully accounts for both Coulomb and off-energy-shell effects in the two-body cross section, making use of plane waves only in the entrance and exit channels of the three-body reaction. As long as the energies involved are high enough and the spectator is a neutron, as in the present case, the plane-wave approach affects only the absolute magnitude of the two-body cross section, but not its energy dependence. The relation between the triple differential cross section and the two body cross section of interest is given by:

$$\frac{d^3\sigma}{dE_C d\Omega_C d\Omega_c} \propto KF \; |W(\boldsymbol{Q}_{Bb})|^2 \, \frac{v_{Cc}}{v_{Ax}} \sum_l P_l \frac{d\sigma_l}{d\Omega_{Ax}} \quad (1)$$

where KF is a kinematic factor, $W(\boldsymbol{Q})$ the spectator momentum distribution and $\frac{d\sigma_l}{d\Omega_{Ax}}$ represents the on-shell two-body cross section for the $C + c \rightarrow A + x$ reaction in partial wave l, whose Coulomb suppression at low energies is compensated for by the penetrability factor

$$P_l(k_{Ax}R) = G_l^2(k_{Ax}R) + F_l^2(k_{Ax}R). \quad (2)$$

Equation (1), where we neglect the interference from different partial waves l, strongly resembles the factorization resulting from a Plane Wave Impulse Approximation (PWIA) (Chant & Roos 1977) further corrected for the Coulomb penetration. The a priori inclusion of Coulomb and off-shell effects is indeed the main feature of the present approach. Absolute cross sections are obtained through normalization to direct data that are available for most reactions of astrophysical interest at energies equal to or above the Coulomb barrier.

3. Experimental results on the ^{6}Li(p,α)^{3}He

The direct ^{6}Li(p,α)^{3}He reaction was performed using a proton beam and a ^{6}Li solid target, as well as a ^{6}Li beam and a H_2 gas target (Engstler et al. 1988; Kwon et al. 1989; Engstler et al. 1992). Although the absolute cross section was measured at very low energy (Engstler et al. 1988; Kwon et al. 1989; Engstler et al. 1992), experimental data below 100 keV could not be used to determine the bare nucleus S(E) dependence for a center-of-mass energy approaching zero, since it is affected by the electron screening. Thus a polynomial expansion $S_b = a+bE+cE^2+dE^3$ was used to fit the data for both atomic and molecular targets above 100 keV in order to extrapolate the behavior of the bare nucleus S_b(E) factor to the lower energy region. The extrapolated S(0) value is 2.86 ± 0.80 MeV·b (Engstler et al. 1992).

The first investigation of the ^{6}Li(p,α)^{3}He reaction in the framework of the THM was performed via the d(^{6}Li,α^3He)n three-body reaction at a beam energy of 25 MeV (Tumino et al. 2003). The experiment clearly revealed the presence of the quasi-free mechanism proceeding through a virtual two-body reaction between the incident ^{6}Li and the proton in ^{2}H. The quasi-free two-body cross section was compared with the direct data, showing a very good overall agreement in the ^{6}Li-p relative energy range 0.12−2.4 MeV, with a distinct resonant contribution from the 7.2 MeV ($5/2^-$) state of ^{7}Be. The result is the first unified validity test for the THM below and above the Coulomb barrier. A second run of the d(^{6}Li,α^3He)n three-body experiment was then performed at a beam energy of 14 MeV (Tumino et al. 2004), in order to populate the very low energy part of the ^{6}Li-p bare nucleus S(E)-factor spectrum, down to the Gamow peak. The experimental set-up and data-analysis are extensively discussed elsewhere (Tumino et al. 2004) and we refer to that paper for more details.

After the standard THM analysis, the bare nucleus S(E)-factor was extracted in the energy range $E_{\rm cm}$ = 10−1200 keV and normalized to direct data taken from Engstler et al. (1992) in the energy range $E_{\rm cm}$ = 800÷1200 keV. The normalized THM data are shown in Fig. 1 as full circles, and compared with the direct behaviour (open circles) in the ^{6}Li-p energy range from 0 to 1 MeV. The solid line in the figure represents a second order polynomial fit to the THM data giving a bare nucleus S(0) value of S(0) = 3.0±0.3 MeV·b, including systematic errors arising from normalization (Table 1). The derived electron screening potential is $U_{\rm e}$ = 450 ± 100 eV, in agreement with direct determination by Engstler et al. (1992); thus the systematic discrepancy between the experimental data and the adiabatic approximation (which represents a theoretical upper limit for $U_{\rm e}$) is evident. Moreover the isotopic independence of the electron screening effect is confirmed as seen from the comparison with the $U_{\rm e}$ estimates from the ^{7}Li(p,α)^{4}He and the ^{6}Li(d,α)^{4}He reactions (see Engstler et al. 1992; Lattuada et al. 2001). The bare nucleus S(E)-factor is the relevant quantity for astrophysical application and that the THM allows its measurement without any extrapolation.

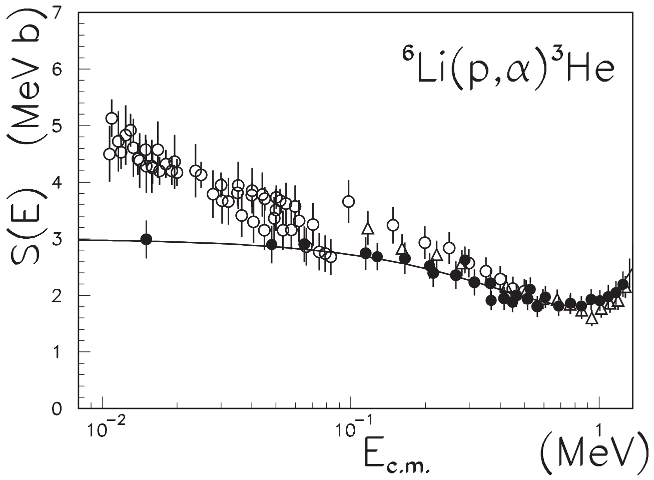

Fig. 1. Bare nucleus astrophysical S(E)-factor extracted according to the THM prescriptions (full dots). The direct data from Engstler et al. (1992) and Elwyn et al. (1979) are shown as open circles and open triangles respectively. The solid line represents the polynomial fit to the THM data.

Table 1. Bare nucleus S(0) and screening potential estimates for the direct (Engstler et al. 1992) and indirect ^{6}Li(p,α)^{3}He and ^{7}Li(p,α)^{4}He measurements.

Reaction	Method	S(0) MeV·b	U_e^{exp} eV
^{6}Li(p,α)^{3}He	THM	3.00 ± 0.3	450 ± 100
	Direct	2.86 ± 0.80	470 ± 150
^{7}Li(p,α)^{4}He	THM	55 ± 3	330 ± 30
	Direct	58	300 ± 160

The reaction rates for the ^{6}Li(p,α)^{3}He and ^{7}Li(p,α)^{4}He processes were therefore calculated assuming the bare nucleus cross section from the THM measurement. The reaction rate $R = N_A\langle\sigma v\rangle$ (measured in cm^3 s^{-1} mol^{-1}) can be written following Fowler et al. (1967) as:

$$R = (7.83\times 10^9 (Z_1Z_2/\mu)^{1/3} S_{\rm eff}) T_9^{-2/3} \exp(-\tau) \quad (3)$$

where $S_{\rm eff} = S(0)[1 + a_1T_9^{1/3} + a_2T_9^{2/3} + a_3T_9 + a_4T_9^{4/3} + a_5T_9^{5/3}]$, $\tau = 4.25(Z_1^2Z_2^2/\mu T_9)^{1/3}$, T_9 is the temperature in billions of K, Z_1 and Z_2 charges of the interacting particles and μ the reduced mass. The a_i coefficients are reported in Table 2 for both reactions.

4. Astrophysical implications

To study the origin and evolution of the light element abundances in the Galaxy one should take into account several competing processes: the Big Bang, cosmic rays production, stellar depletion and nucleosynthesis, all of which are linked to the cosmic and chemical evolution (see e.g. Michaud & Charbonneau 1991; Hobbs 2000; Boesgard 2004, for reviews).

In general, theoretical analyses of light element abundances in stars are still limited by the lack of precise information on the efficiency of envelope convection, microscopic diffusion,

Table 2. Coefficients for the reaction rate expansion for the ^{6}Li(p,α)^{3}He and ^{7}Li(p,α)^{4}He reactions obtained from THM measurements.

Coefficient	^{7}Li(p,α)^{4}He	^{6}Li(p,α)^{3}He
a_1	0.0493	0.0496
a_2	0.927	−0.243
a_3	0.320	−0.084
a_4	–0.332	0.037
a_5	–0.292	0.033

radiative acceleration and on the possible presence of additional mixing mechanisms (e.g. induced by the stellar rotation, see Ventura et al. 1998; Talon & Charbonnel 1998; Brun et al. 1999; Cayrel et al. 1999a,b; Pinsonneault et al. 1999; Montalban & Schatzman 2000). Moreover, the predicted light element depletion strongly depends on the adopted physical inputs, such as the nuclear reaction rates, the equation of state, the opacity of the stellar matter, still affected by relevant uncertainties (see e.g. D'Antona & Mazzitelli 1997; Pinsonneault 1997; Turcotte et al. 1998; Palla 2000; Jeffries 2005, for some results of evolutionary models). It is therefore not surprising that discrepancies persist between the predicted and observed light element abundances e.g. solar ^{7}Li abundance (see e.g. the discussion in Xiong & Deng 2002; Piau & Turck-Chieze 2002; Schlattl & Weiss 1999; Blocker et al. 1998) or light element abundance in open clusters and disk stars (see e.g. Santos et al. 2004; Boesgardet al. 2004; Boesgard et al. 2004; Piau et al. 2003; Sestito et al. 2003; Sills & Deliyannis 2000).

For ^{6}Li the most relevant mechanisms of production of this isotope are spallation and fusion processes normally due to the interaction of galactic cosmic rays with the interstellar medium (see e.g. Vangioni-Flam 1999; Ramaty et al. 2000, for a review). Many studies have followed the evolution of ^{6}Li in our Galaxy (see e.g. Yoshii et al. 1997; Fields & Olive 1999; Vangioni-Flam 1999; Valle et al. 2002). The original abundance of Galactic ^{6}Li is still an open question (see e.g. Rollinde et al. 2004; Lambert 2004).

Detection of ^{6}Li in stellar atmospheres constrains the possible destruction of the less fragile ^{7}Li (Copi et al. 1997). Since the depth of the convective zone increases with metallicity or with decreasing mass, ^{6}Li is almost completely depleted in high metallicity disk stars, as it is in the Sun (Asplund et al. 2004) and it is below the detection level in all but the hottest main sequence thick disk and halo stars.

The detection of ^{6}Li in stellar spectra is very difficult since high resolution, high signal to noise spectra are required (see e.g. Smith et al. 1998). Recent measurements of halo stars (Smith et al. 1998; Cayrel et al. 1999a; Hobbs 2000; Nissen et al. 1999, 2000; Asplund et al. 2001, 2004; Aoki et al. 2004) frequently have yielded only upper limits to the ^{6}Li abundance; for halo stars in which ^{6}Li has been observed, the abundances show a "plateau" as a function of [Fe/H] (e.g. Lambert 2004) and whether in these stars ^{6}Li is burned or not is uncertain. ^{6}Li was observed in two metal-poor field disk stars: HD 68284 and HD 130551 (Nissen et al. 1999) with an abundance ratio $N(^6\mathrm{Li})/N(^7\mathrm{Li}) \approx 0.05\pm0.01$.

We are interested in stars in which ^{6}Li burning has already started but where depletion is not complete, that is, metal-poor disk stars.

Our purpose is to discuss the reported agreement of the ^{6}Li(p,α)^{3}He bare nucleus cross-section between direct and indirect methods in the context of the ^{6}Li abundances in stars. After the THM measurement the ^{6}Li burning cross section extrapolation performed in the direct method is validated to a 5−10% level of accuracy and the corresponding uncertainty of the surface lithium abundance is expected to be similar. It is thus interesting to check if other sources of uncertainty are of the same order of magnitude.

We adopt the two observed disk stars as representative examples to study the surface ^{6}Li abundance and we assume as an estimate of the uncertainty on the ^{6}Li(p,α)^{3}He cross section the 10% error arising from THM data obtained by the present work.

Thus we are not interested in reproducing particular observational results for lithium abundances, rather we aim to evaluate the relative effects on this quantity of the nuclear parameters with respect to other physical parameters. We will therefore perform a sensitivity test by adopting a single set of models with given physical inputs.

The present models are computed with an updated version of the FRANEC evolutionary code (see e.g. Chieffi & Straniero 1989). The input physics adopted in our code has been described in detail in Cariulo et al. (2004). Our models account for atomic diffusion, including the effects of gravitational settling and thermal diffusion, with diffusion coefficients given by Thoul et al. (1994). We adopt the Schwarzschild criterion to define convective regions where convection is treated using the mixing length formalism (see the description in Brocato & Castellani 1993). Rotation is not included in our models. With respect to Cariulo et al. (2004) we updated the equation of state (the OPAL EOS_{2001} tables at the URL: `http://www-phys.llnl.gov/Research/OPAL`, see also Iglesias & Rogers 1996), the conductive opacity (Potekhin 1999) and the heavy element mixture (Asplund et al. 2004) adopted for the model abundances and the opacity tables. Initial values for ^{6}Li and ^{7}Li in low metallicity disk stars which, as discussed before, are not observationally known, are taken from the chemical galactic model calculations by Valle et al. (2002).

Table 3 summarizes recent observational physical parameters for the two selected stars (Nissen et al. 1999; Bensby et al. 2003; Taylor 2003; Nordstrom et al. 2004). The T_e evaluation by different authors can vary by $\pm\approx100$ K and that absolute visual magnitudes are calculated from the observed visual ones. The parallaxes are taken from the Hipparcos calalogue (ESA 1997) and thus are affected by both photometric and parallax errors. The estimated [α/Fe] is about 0.15. An observational evaluation of the Helium abundance is not possible for these stars, and the primordial helium abundance as well as the ratio between metal and helium enrichment of the galactic medium ($\mathrm{d}Y/\mathrm{d}Z$) are not precisely defined yet (see e.g. Olive & Skillman 2004; Luridiana et al. 2003; Castellani et al. 1999; Pagel & Portinari 1998). The observational quantities reported in Table 3 with their uncertainties can be fitted by several plausible combinations of the adopted values for masses, chemical compositions, efficiency of the envelope convection (different values of the mixing length parameter), which lead to different lithium depletions. We note that the fit of the absolute visual magnitude requires the adoption of a bolometric correction value whose uncertainty is as about 0.05 mag. (Bensby et al. 2003).

Table 3. Observational physical parameters for HD 68284 and HD 130551 are from Nissen et al. (1999), Bensby et al. (2003), Taylor (2003), Nordstrom et al. (2004). The table shows: star identification, absolute visual magnitude, effective temperature (in Kelvin degrees), logarithm of surface gravity (cgs units), [Fe/H], see text. The mean uncertainty on the selected parameters is also shown.

Star	M_V	T_eff	log g	[Fe/H]
HD 68284	3.42 ± 0.19	5883 ± 100	3.96 ± 0.1	-0.59 ± 0.06
HD 130551	3.76 ± 0.09	6237 ± 100	4.18 ± 0.1	-0.62 ± 0.06

We find that the change in the lithium abundance due to the uncertainty on stellar physical parameters largely dominates over the variation of ^{6}Li and ^{7}Li values due to the uncertainties of the burning cross sections measured via THM. We are interested in exploring a relatively broad range of plausible physical parameters so that we can better analyze the sensitivity of the lithium isotopes depletions. We selected a mass range from 0.89 $M_\odot$ to 0.99 $M_\odot$, metallicity from $Z = 0.004$ to 0.006, original helium abundance from $Y = 0.24$ to 0.27 and mixing length values from 1.5 to 2.2 and we accepted as representative of the two observed stars only the models that reproduce all the observational quantities shown in Table 3 within the quoted errors. The physical parameters adopted for these models are shown in Table 4. It is worth noting that our selected fits do not exhaust the possibilities to reproduce the data in Table 3 with different stellar parameters, however these suffice for our purposes.

The comparison between the predicted and observed positions in the HR diagram indicates that the selected stars have evolved just after central H exhaustion (Turn-Off, TO). Theoretical models indicate that for these stars lithium burning seems to be active only in the Pre-Main Sequence (PMS) phase, while in the MS the surface lithium abundance should decrease by about 10% due to microscopic diffusion. After central H exhaustion, the H burning continues in a shell surrounding the He core and the stars move to lower temperatures. In this phase the convective envelope extends into regions in which lithium has accumulated due to the effect of diffusion and the external lithium abundance temporarily increases and then decreases below the level of detectability when the external convection reaches regions in which lithium has been completely burned (dilution effect). The presence of an observable amount of lithium indicates that the stars are still in the phase before this deep extension of convection. However, since the burning occurs in the PMS we will take only this phase into account.

Table 4. Physical parameters of selected evolutionary models that reproduce the observational values for HD 68284 and HD 130551 reported in Table 3. α indicates the adopted mixing length value.

M ($M_\odot$)	Z	Y	α
0.89	0.004	0.27	2.2
0.92	0.004	0.27	1.8
0.97	0.004	0.24	1.8
0.99	0.004	0.27	1.5
0.99	0.006	0.24	1.9

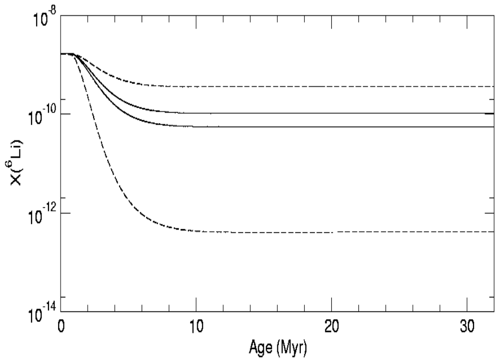

Fig. 2. The behaviour of ^{6}Li abundance during the PMS phase. Solid lines refer to the same model (M = 0.97 Z = 0.004 Y = 0.24 α = 1.76) calculated with the THM upper and lower limits on ^{6}Li burning cross sections respectively. The region between the long-dashed lines represents the range of variation allowed by different choices of stellar masses, chemical compositions and efficiency of the external convection for the selected stars shown in Table 4 (see text).

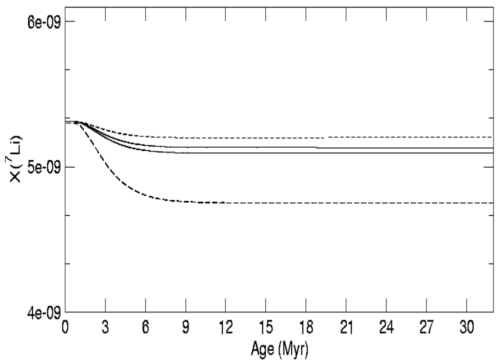

Fig. 3. ^{7}Li abundance during the PMS phase. Same description as in Fig. 2.

We can thus calculate the variation of ^{6}Li and ^{7}Li abundances in PMS for the models with different physical parameters, reported in Table 4 with respect to the uncertainty on these abundances due to the errors on THM measurement.

The variation of lithium abundances due to the present uncertainties in the physical inputs other than nuclear cross sections are not taken into account because they are not relevant for the present analysis.

Figures 2 and 3 shows the behaviour of ^{6}Li and ^{7}Li abundances as a function of time during the PMS phase. The solid lines represent the results for the upper and lower limit of THM cross section (error from normalization is included)

for a given combination of stellar parameters (M = 0.97 $M_\odot$ Z = 0.004 Y = 0.24 α = 1.76). The region between the long-dashed lines represents the range of variation allowed by the different choices of the stellar parameters shown in Table 4. Figure 3 shows the ^{7}Li behaviour with the same meaning for the represented lines. As expected, ^{7}Li is quite undepleted as indicated by the survival of a detectable amount of ^{6}Li.

It is evident that the variability range of ^{6}Li and ^{7}Li abundances due to different stellar parameters is very much wider than that due to the cross section uncertainties. This means that the problem of the surface lithium abundances is not at the nuclear physics level but is an astrophysical problem that requires improvements in our knowledge of the mixing mechanisms, the reduction of the uncertainties on the other (non-nuclear) physical inputs, and more precise observational data. The bare nucleus cross section, at least for lithium burning reactions at stellar energies, are now well determined.

5. Conclusions

Measurements of the ^{6}Li(p,α)^{3}He bare nucleus cross section at astrophysical energies using the indirect Trojan Horse Method lead to an agreement at the 10% level with the results of data extrapolations from direct methods, which are thus confirmed. The systematic discrepancy between experimental data and the adiabatic approximation for screening calculations, already found in direct experiments, is confirmed too. The implications of these new THM results for the problem of ^{6}Li abundance in stellar surfaces have been discussed showing that the bare nucleus cross sections for lithium burning reactions are now well determined and that the solution of the problem of light elements destruction in stars lies elsewhere.

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References

Angulo, C., Arnould, M., Rayet, M., et al. 1999, Nucl. Phys. A, 656, 3
Aoki, W., Inoue, S., Kawanomoto, S., et al. 2004, A&A, 428, 579
Asplund, M., Lambert, D. L., Nissen, P. E., Primas, F., & Smith, V. V. 2001, in Cosmic Evolution, ed. E. Vangioni-Flam, R. Ferlet, & M. Lemoine, World Scientific, 95
Asplund, M., Grevesse, N., & Sauval, A. 2004 [arXiv:astro-ph/0410214]
Azhari, A., Burjan, V., Carstoiu, F., et al. 1999, Phys. Rev. C, 82, 3960
Baur, G. 1986, Phys. Lett. B, 178, 135
Baur, G., & Rebel, H. 1994, J. Phys. G 20, 1, and references therein
Baur, G., & Rebel, H. 1996, Annu. Rev. Nucl. Part. Sci. 46, 321
Bensby, T., Feltzing, S., & Lundstrom, I. 2003, A&A, 410, 527
Blöcker, T., Holweger, H., Freytag, B., et al. 1998, Space Sc. Rev., 85, 105B
Boesgaard, A. M. 2004 [arXiv:astro-ph/0412198]

Boesgaard, A. M., McGrath, E. J., Lambert, D. L., & Cunha, K. 2004, ApJ, 606, 306
Boesgaard, A. M., Armengaud, E., & King, J. R. 2004, ApJ, 605, 864
Brocato, E., & Castellani, V. 1993, ApJ, 410, 99
Brun, A. S., Turck-Chieze, S., & Zahn, J.-P. 1999, ApJ, 525, 1032
Calvi, G., Cherubini, S., Lattuada, M., et al. 1997, Nucl. Phys. A, 621, 139
Cariulo, P., Degl'Innocenti, S., & Castellani, V. 2004, A&A, 424, 927
Castellani, V., Degl'Innocenti, S., & Marconi, M. 1999, A&A, 349, 834
Cayrel, R., Spite, M., Spite, F., et al. 1999a, A&A, 343, 923
Cayrel, R. Y., & Lebreton, P. 1999b, Morel Astrophysics and Space Science, 265, 87
Chaboyer, B. 1994, ApJ, 432, L47
Chant, N. S., & Roos, P. 1977, Phys. Rev., C15, 57
Chieffi, A., & Straniero, O. 1989, ApJS, 71, 47
Copi, C. J, Schramm, D. N., & Turner, M. S. 1997, Phys. Rev. D, 55, 3397
D'Antona, F., & Mazzitelli, I. 1997, Mem. SAIT, 68, 807
Elwyn, A. J., Holland, R. E., Davids, C. N., et al. 1979, Phys. Rev. C, 20, 1984
Engstler, S., Krauss, A., Neldner, K., et al. 1988, Phys. Lett. B, 202, 179
Engstler, S. G., Raimann, C., Angulo, C., et al. 1992, Z. Phys. A, 342, 471
Fields, B. D., & Olive, K. A. 1999, New. Astron., 4, 255
Fowler, W. A., Caughlan, G. R., & Zimmermann, B. A. 1967, ARA&A, 5
Gagliardi, C., Tribble, R. A, Azhari, A., et al. 2002, Phys. Rev. C, 59, 1149
Gagliardi, C., Azhari, A., Burjan, V., et al. 2002, Eur. Phys. J. A, 13, 227
Hobbs, L. M. 2000, Phys. Rep., 333-334, 449
Iglesias, C. A., & Rogers, F. J. 1996, ApJ, 464, 943
Jeffries, R. D. 2005, in Chemical abundances and mixing in stars in the Milky Way and its satellites, ed. L. Pasquini, & S. Randich, ESO Astrophys. Symp. (Springer-Verlag), in press [arXiv:astro-ph/0411111]
Kwon, J. U., Kim, J., & Sung, B. N. 1989, Nucl. Phys. A, 493, 112
Lambert, D. L. 2004 [arXiv:astro-ph/0410418]
Lattuada, M., Pizzone, R. G., Typel, S., et al. 2001, ApJ, 562, 1076
Luridiana, V., Peimbert, A., Peimbert, M., & Cervino, M. 2003, ApJ, 592, 846
Montalban, J., & Schatzman, A. 2000, A&A, 354, 943
Michaud, G., & Charbonneau, P. 1991, Space Sci. Rev., 57, 1
Musumarra, A., Pizzone, R. G., Blagus, S., et al. 2001, Phys. Rev., C64, 068801
Nissen, P. E., Lambert, D. L., Primas, F., & Smith, V. V. 1999, A&A, 348, 211
Nissen, P. E., Asplund, M., Hill, V., & D Odorico, S. 2000, A&A, 357, L49
Nordström, B., Mayor, M., Andersen, J., et al. 2004, A&A, 418, 989
Olive, K. A., & Skillman, E. D. 2004, ApJ, 617, 29
Palla, F. 2002, Proceedings of Star Formation and the Physics of Young Stars, Aussois, France, EAS Publ. Ser., ed. J. Bouvier, & J.-P. Zahn (EDP Sciences), 3, 111
Piau, L., & Turck-Chièze, S. 2002, ApJ, 566, 419
Piau, L., Randich, S., & Palla, F. 2003, A&A, 408, 1037
Pinsonneault, M. H. 1997, ARA&A, 35, 557
Pinsonneault, M. H., Walker, T. P., Steigman, G., & Narayanan, V. K. 1999, ApJ, 527, 180
Pizzone, R. G., Spitaleri, C., Lattuada, M., et al. 2003, A&A, 398, 423
Potekhin, A. Y. 1999, A&A, 351, 787
The Observatory 2000, 120, 269
Rollinde, E., Vangioni-Flam, E., & Olive, K. A. 2004 [arXiv:astro-ph/0412426]
Ross, J. C., Görres, C., Iliadis, G., et al. 1995, Phys. Rev. C, 52, 1681
Schlattl, H., & Weiss, A. 1999, A&A, 347, 272
Santos, N. C., Israelian, G., Randich, S., Garcia Lopez, R. J., & Rebolo, R. 2004, A&A, 425, 1013
Sestito, P., Randich, S., Mermilliod, J.-C., & Pallavicini, R. 2003, A&A, 407, 289
Sills, A., & Deliyannis, C. P. 2000, ApJ, 544, 944
Smith, V. V., Lambert, D. L., & Nissen, P. E. 1993, ApJ, 408, 262
Smith, V. V., Lambert, D. L., & Nissen, P. E. 1998, ApJ, 506, 405
Spitaleri, C. 1990, Problems of fundamental Physics, II, World Scientific, ed. R. Cherubini, P. Dal Piaz, & B. Minetti
Spitaleri, C., Aliotta, M., Cherubini, S., et al. 1999, Phys. Rev. C, 60, 055802
Spitaleri, C., Aliotta, M., Figuera, P., et al. 2000, Eur. Phys. J. A, 7, 181
Spitaleri, C., Typel, S., Pizzone, R. G., et al. 2001, Phys. Rev. C, 63, 005801
Spitaleri, C., Lamia, L., Tumino, A., et al. 2004, Phys. Rev. C, 69, 055806
Talon, S., & Charbonnel, C. 1998, A&A, 335, 959
Taylor, B. J. 2003, A&A, 398, 731
Thoul, A., Bahcall, J., & Loeb, A. 1994, ApJ, 421, 828
Turcotte, S., & Christensen-Dalsgaard, J. 1998, Space Sci. Rev., 85, 133
Tumino, A., Spitaleri, C., di Pietro, A., et al. 2003, Phys. Rev. C, 67, 065803
Tumino, A., Spitaleri, C., Pappalardo, L., et al. 2004, Progr. Theor. Phys. Suppl., 154, 341
Vangioni-Flam, E., Cassé, M., & Cayrel, R. 2000, New Astron., 4, 245
Valle, G., Ferrini, F., Galli, D., & Shore, S. N. 2002, ApJ, 566, 252
Ventura, P., Zeppieri, A., Mazzitelli, I., & D'Antona, F. 1998, A&A, 331, 1011
Xiong, D. R., & Deng, L. 2002, MNRAS, 336, 511
Yoshii, Y., Kajino, T., & Ryan, S. 1997, ApJ, 485, 605