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The ^{6}Li(p,α)^{3}He bare nucleus astrophysical S(E)-factor and its astrophysical implications

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Abstract. The $^{6}Li(p,\alpha)^{3}He$ bare nucleus cross-section at astrophysical energies has been indirectly measured in the framework of the Trojan-Horse Method. This constitutes an important step to address the astrophysical problem of ^{6}Li (and more generally of light elements) surface abundance in stars. The agreement between results from direct and indirect methods is discussed in the context of the surface lithium abundances in stars.

Low-energy cross sections for reactions producing or destroying Lithium isotopes are a fundamental information for a number of still not completely solved astrophysical problems, e.g. the understanding of Big Bang nucleosynthesis and the so called "Lithium depletion" either 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 in the last few years has been extensively studied. Since ^{6}Li is more fragile than ^{7}Li its abundance can give hints on ^{7}Li depletion in stars. In order to do this both the production and destruction mechanisms must be studied and their cross sections should be measured in the astrophysically relevant energy window.

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 and Rebel (1994, 1996)) and ANC (Asymptotic Normalization Coefficients) (Ross et al. (1995); Gagliardi et al. (1999); Azhari et al. (1999); Gagliardi et al. (2002)) applied to transfer reactions, have been exploited. Among these methods, the so called Trojan-horse Method (THM) (Baur (1986); Spitaleri (1990); Spitaleri et al. (1999, 2000, 2001); Lattuada et al. (2001); Tumino et al. (2003)) appears to be particularly suited to investigate low-energy charged-particle two-

Send offprint requests to: C. Spitaleri body reactions by using appropriate three-body reactions, since it makes possible to suppress both Coulomb barrier and electron screening effects in the off-shell cross section of the two-body reactions.

Leaving the details of the method to the references (Spitaleri et al. (1999, 2001); Tumino et al. (2003); Pizzone et al. (2003)) we only stress that in order to get the two-body cross section for the process of interest from the three-body reaction, the Plain Wave Impulse approximation or the Modified Plane-Wave Born description can be adopted, as extensively treated in (Tumino et al. (2003); Spitaleri et al. (2004)).

Bare astrophysical S(E)-factor was thus measured for the ^{6}Li(p,α)^{3}He reaction as reported in (Tumino et al. (2004)). The polynomial fit to the THM data gives a S(0) value of S(0)=3.0±0.19 MeV·b.

In the following section we will discuss the astrophysical implication of these new THM results in the framework of ^{6}Li destruction in stellar environments. The reaction rate extracted from THM measurements is calculated in Pizzone et al. (2005), together with an estimate of the importance of astrophysical uncertainties with respect to the nuclear ones.

1. Astrophysical applications

As well known ^{6}Li burns at a lower temperature ($\approx 2 \cdot 10^6$) with respect to ^{7}Li ($\approx 2.5 \cdot 10^6$) in a way that it is almost completely destroyed when ^{7}Li burning is efficient. Thus detection of observable amounts of ^{6}Li in stellar atmospheres constrains the possible destruction of the less fragile ^{7}Li (Copi et al. (1997)). For a more detailed discussion please refer to Pizzone et al. (2005) and references within. 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. ^{6}Li was observed in two metal poor field disk stars: HD68284 and HD130551 (Nissen et al. (1999)); the ^{6}Li abundance is observed in relation with the ^{7}Li abundance with N(^{6}Li)/N(^{7}Li) $\approx$ 0.05±0.01. Our purpose is to discuss the quoted agreement for the $^6Li(p,\alpha)^3He$ 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 of the same quantity. It is thus interesting to check if other sources of uncertainty are of the same order of magnitude.

Present models were computed with an updated version of the FRANEC evolutionary code (see e.g. Chieffi & Straniero (1989)). The input physics adopted in our code have been described in details in (Cariulo et al. (2004)). Initial values for ^{6}Li and ^{7}Li in low metallicity disk stars are taken from the chemical galactic model calculations by (Valle et al. (2002)).

To calculate lithium burning for the selected stars we should precisely know masses and chemical compositions. Unluckily this is not the case for most of the observed stars; for these (Nissen et al. (1999); Bensby et al. (2003); Taylor (2003); Nordstrom et al. (2004)) available observational data includes absolute visual magnitude (M_V), effective temperature (T_e), surface gravity, [Fe/H] and α enhancement [α/Fe].

The comparison between the predicted and observed positions in the HR diagram, indicates that the selected stars should be evolved just after the 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% only due to microscopic diffusion (Pizzone et al. (2005)).

The observational quantities for these two stars, within the relative uncertainties, can be fitted by several combinations of the adopted values for masses, chemical compositions, efficiency of the external convection (values of the mixing length parameter) which lead to different lithium depletion.

We will show that the change in the lithium abundance due to the uncertainty on this quantities highly overcomes the variation of ^{6}Li and ^{7}Li values due to the change of burning cross sections from NACRE to THM (Pizzone et

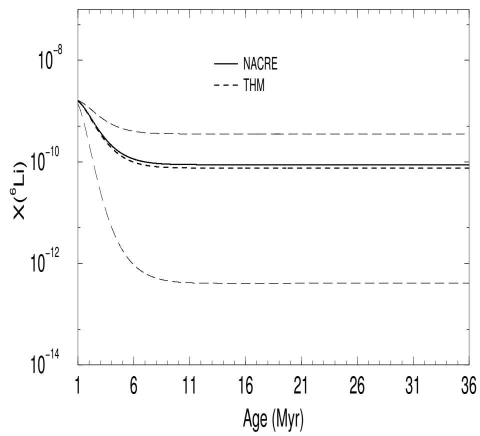

Fig. 1. The behaviour of ^{6}Li abundance during the PMS phase. Continuous line indicates a model (M=0.97 Z=0.004 Y=0.24 α=1.76) calculated with the NACRE cross sections for ^{6}Li burning while the dashed line refers to the same model with the THM bare nucleus cross section. The region contained between the long dashed lines represents the range of variation allowed by different choices about the stellar masses, chemical compositions and efficiency of the external convection for the selected stars (see text).

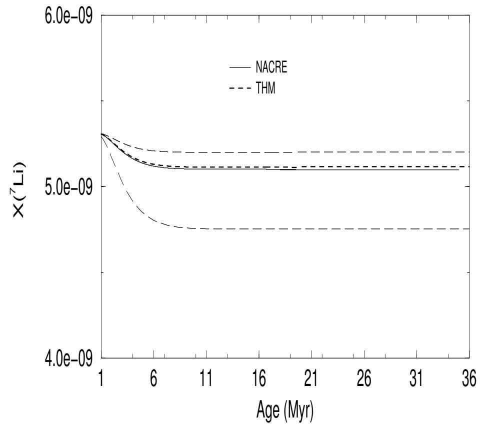

Fig. 2. As in Fig.2 but for the ^{7}Li abundance

al. (2005)). We examined a range of masses from 0.89 $M_\odot$ to 0.99 $M_\odot$, of metallicity from Z=0.004 to 0.006, of original helium abundance from Y=0.24 to 0.27 and of mixing length values from 1.5 to 2.2. The variation of the lithium abundances due to the present uncertainties on the physical inputs different from nuclear cross sections are not taken into account because not relevant for the present analysis.

Figures 1 and 2 shows the behaviour as a function of time of ^{6}Li and ^{7}Li abundances during the PMS phase. The continuous line represents the results for the NACRE extrapolated ^{6}Li(p,α)^{3}He and ^{7}Li(p,α)^{4}He cross sections,respectively, for a given combination of stellar parameters (M=0.97 $M_\odot$ Z=0.004 Y=0.24 α=1.76) compared with the results for the same model and THM cross sections. The region contained between the long dashed lines represents the range of variation allowed by the selected different choices about the stellar parameters. Figure 2 shows the ^{7}Li behaviour; as expected, it is quite undepleted as indicated by the survival of a detectable amount of ^{6}Li.

It's evident that the range of lithium abundances due to different stellar parameters is very much wider than the differences in the abundances due to the cross sections changes. This means that now the problem of the surface lithium abundances is not at the nuclear physics level but it is an astrophysics problem to be likely solved with the improvements of our knowledge of the mixing mechanisms, the reduction of the uncertainties on the other physical inputs, the availability of more precise observational data. Cross section measurements, at least for lithium burning reactions at stellar energies, are on the contrary a well fixed point to start the analysis.

2. Conclusions

Measurements of the ^{6}Li(p,α)^{3}He and ^{7}Li(p,α)^{4}He bare nucleus cross section at astrophysical energies by means of the indirect Trojan Horse Method lead to a difference of $\approx$5% for the S(E=0)-factor with the results of the extrapolations of the data taken with the direct methods. The systematic discrepancy between experimental data and the adiabatic approximation for screening calculations, already found, in direct experiments is confirmed. The implications of these new THM results for the problem of ^{6}Li abundance in stellar surfaces have been discussed showing that the cross section measurement for the ^{6}Li burning reaction is now a well fixed value, a point from one should start to try to solve the still open problem of light elements destruction in stars.

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