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Light elements depletion in stellar environments

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Abstract. Big efforts have been devoted in the last years to the study of light elements abundances. Definitively their importance is strongly related to cosmology as well as to stellar structure and evolution. In fact hints on the primordial nucleosynthesis can be achieved from Li, Be and B primordial abundances. Moreover these studies can be a precious tool for testing and understanding the inner stellar structure, especially for what regards the mixing processes in stellar envelopes (Boesgard 2004).
In this framework the different nuclear processes which produce or destroy Li, Be and B must be studied in details and an accurate knowledge of the involved nuclear cross sections is necessary. In particular we will focus our attention on one of the main destruction channels for these elements in stellar environments, the (p, α) reactions. In particular this work will review the last results achieved by the Trojan Horse Method (THM) for the ^{6}Li(p,α)^{3}He, ^{6}Li(d,α)^{4}He, ^{7}Li(p,α)^{4}He, ^{10}B(p,α)^7Be, ^{9}Be(p,α)^{6}Li and ^{11}B(p,α)^{8}Be.

Key words. Stars: abundances – Stars: nucleosynthesis

1. Introduction

Low-energy cross sections for reactions producing or destroying light elements (Li, Be, B) are a fundamental information for a number of still not completely solved astrophysical problems, e.g. the understanding of Big Bang nucleosynthesis, the so called "Lithium depletion" either in the Sun or in other galactic stars as well as the study of non-standard mixing mechanisms in stars (Stephens et al. 1997; Boesgard 2004). In order to do this, both the production and destruction mechanisms of

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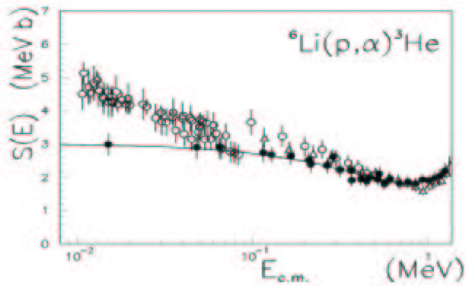

Fig. 1. Astrophysical S(E)-factor for the $^{6}Li(p,\alpha)^{3}He$ extracted by means of the THM (full circles) applied to the $^{2}H(^{6}Li,\alpha^{3}He)n$. Direct data (Engstler et al. 1988, 1992)are reported for comparison as empty symbols.

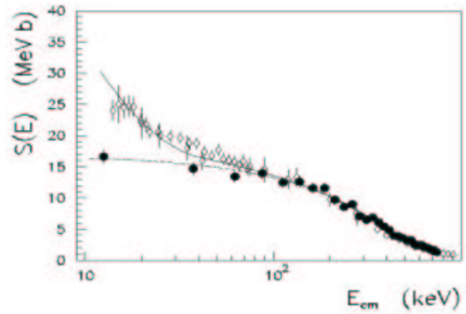

Fig. 2. Same as fig. 1 but for the ^{6}Li(d,α)^{4}He extracted from the ^{6}Li(^{6}Li,$\alpha\alpha$)^{4}He reaction compared with direct data (Engstler et al. 1988, 1992)

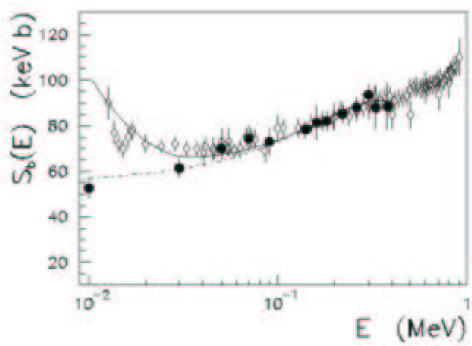

Fig. 3. Same as fig. 1 but for the ^{7}Li(p,α)^{4}He extracted from the ^{2}H(^{7}Li,$\alpha\alpha$)n reaction compared with direct data (Engstler et al. 1988, 1992)

these elements must be studied and their interaction 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 & Rebel 1994,and references therein) and ANC (Asymptotic Normalization Coefficients) (Azhari et al. 1999; Gagliardi et al. 1999, 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) appears to be particularly suited to investigate low-energy charged-particle two-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; Mukhamedzhanov et al. 2006) 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).

2. Experimental Results

The THM has been recently applied to several reactions whose cross section is crucial for the study of light element abundance in stellar environments. In particular the reactions ^{6}Li(p,α)^{3}He, ^{7}Li(p,α)^{4}He, ^{9}Be(p,α)^{6}Li and ^{11}B(p,α)^{8}Be were studied and the corresponding bare nucleus cross sections were measured. An exhaustive discussion of the experimental results is reported in references (Spitaleri et al. 1999, 2001; Musumarra et al. 2001; Spitaleri et al. 2004; Tumino et al. 2003; Lattuada et al. 2001; Romano et al. 2006) respectively.

Figures 1–3 report the energy trend of the astrophysical S(E)-factor for the main lithium destroying reactions studied via THM: ^{6}Li(p,α)^{3}He, ^{6}Li(d,α)^{4}He, ^{7}Li(p,α)^{4}He, respectively. The obtained results clearly show a good agreement with direct data after normalization at higher energies. Only at very small energies, just below 100 keV, a discrepancy related to the presence of electron screening effect in direct data (Engstler et al. 1988, 1992) shows up for each reaction.

These results have led to astrophysical implications which are extensively reported in (Pizzone et al. 2003, 2005). For completeness sake we would like to highlight that the reaction rate obtained from THM measurement is strongly coherent with NACRE (Angulo et al. 1999) extrapolation. This leads substantially to unchanged astrophysical implications. Moreover it was pointed out that with present nuclear cross sections uncertainties the main error source for lithium problem arises from astrophysical uncertainties.

Other processes, involved in light elements destruction were also studied by means of THM. In particular the two boron depleting reactions, ^{11}B(p,α_0)^{8}Be and ^{10}B(p,α)^{7}Be, were studied at astrophysical energies. These measurements, as in other cases with the THM application, were performed in two steps. The first one consists in a validity test, whose task is to understand whether it is possible to apply the THM to retrieve information on low-energy cross section. The second step, once the first has been accomplished is to measure the S(E)-factor at astrophysical energies.

Results for the ^{11}B(p,α)^{8}Be are reported in details in (Spitaleri et al. 2004).

The first analysis step, i.e. the validity test, has been already performed for the ^{9}Be(p,α)^{6}Li after studying the ^{2}H(^{9}Be,α^{6}Li)n, ^{10}B(p,α^{7}Be)n after studying the ^{2}H(^{10}B,α^{7}Be)n and ^{11}B(p,α_0)^{8}Be after the ^{2}H(^{11}B,α_0^{8}Be)n. For these reactions the excitation function was studied below the coulomb barrier and, in particular, the expected resonances were properly populated in spite of the lower energy resolution arising from THM with respect to direct measurements.

Figures 4–5 show the energy trend of the astrophysical S(E)-factor for ^{9}Be(p,α)^{6}Li and ^{10}B(p,α)^{7}Be, respectively. The obtained results clearly show in both cases a good agreement with direct data (Zahnow et al. 1997) after normalization at higher energies. The resonances are well reproduced in the two cases even if direct data resolution was worsened to the same level of the indirect one. We stress that the reproduction of sub Coulomb resonances is an important validity test for THM application to these reaction. This will open the path to the measurement at astrophysical energies (below 200 keV) as already performed for reactions involving lithium isotopes. In Figure 5 the S(E)-factor for the ^{10}B(p,α)^{7}Be is reported (Lamia et al. 2007). The histogram represents the worsened direct data (Angulo et al. 1993) for the whole energy range but below 20 keV, since no direct measurements are present only an extrapolation is reported. THM data are plotted as full circles. The experimental result confirms that with THM one can reach the ultra-low energies usually reached through extrapolation. Since this reaction should be studied around 10 keV it is worthwhile a more precise investigation at these energies in order to understand the reliability of the extrapolation.

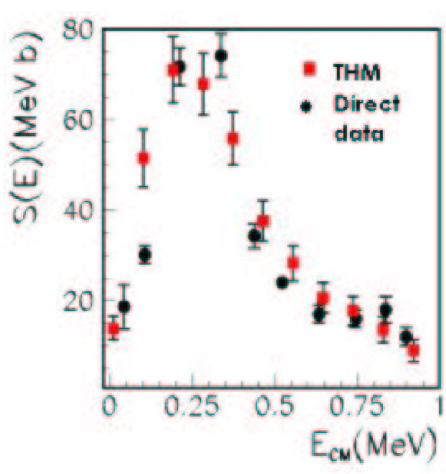

Fig. 4. Astrophysical S(E)-factor for the $^{9}Be(p,\alpha)^{6}Li$ extracted by means of the THM applied to the $^{9}Be(d,\alpha^{6}Li)n$. Direct data (Zahnow et al. 1997) are reported for comparison.

In Table 1 the results for the bare nucleus S(E)-factor at E=0 after an appropriate fit

Table 1. Bare nucleus astrophysical S(E)-factor at zero energy for the reactions discussed in the text.

reaction	S(E=0) MeV·b (THM)	S(E=0) MeV·b (direct)	ref
$^{6}Li(p,\alpha)^{3}He$	3.00± 0.19	2.97	(Tumino et al. 2003)
$^{7}Li(p,\alpha)^{4}He$	0.055 ± 0.003	0.058	(Lattuada et al. 2001)
$^{6}Li(d,\alpha)^{4}He$	16.9±0.5	17.4	(Spitaleri et al. 2001)
$^{11}B(p,\alpha_0)^{8}Be$	0.41 ± 0.09	2.1	(Spitaleri et al. 2004)

Table 2. Electron screening potential obtained through the application of THM for lithium depleting reactions.

reaction	U_e^{THM} eV	U_e^{Dir} eV	Adiabatic U_e eV
$^{6}Li(p,\alpha)^{3}He$	450±100	440±150	180
$^{7}Li(p,\alpha)^{4}He$	330±40	300±160	180
$^{6}Li(d,\alpha)^{4}He$	320±50	330±120	180

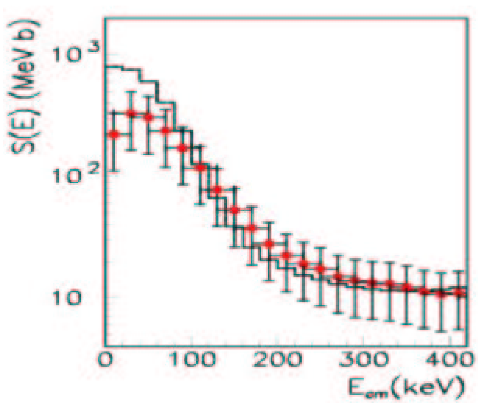

Fig. 5. Same as fig. 4 but for the ^{10}B(p,α)^{7}Be extracted from the ^{10}B(d,α)^{7}Be)n reaction. See discussion in the text.

are reported together with the results obtained from the direct measurements. The agreement between the two data-sets is good for each case and only for the $^{11}B(p,\alpha)^{8}Be$ a discrepancy between THM and direct data, not yet fully understood, shows up.

The electron screening potential, U_e, was extracted as well for the reactions cited above. A big discrepancy shows up with respect to the adiabatic approximation and the results are reported in Table 2. However results are in a clear agreement with other experimental data like the ones obtained from direct experiments (Engstler et al. 1992). The isotopic independence is also verified.

3. Conclusions

As already said in the ^{6}Li(p,α)^{3}He and ^{7}Li(p,α)^{4}He cases, THM results lead to unchanged astrophysical implications Pizzone et al. (2005) with respect to the most commonly adopted reactions rate compilation (e.g. NACRE). Moreover, for an improved investigation of boron destruction the ^{11}B(p,α_1)^{8}Be cross section will be studied in the next future. New measurements are also required for the ^{9}Be(p,α)^{6}Li and ^{10}B(p,α)^{7}Be and they will be devoted to the study of low energy behavior.

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References

Angulo, C., et al. 1993, Z. Phys., A345, 231
Angulo, C., Arnould, M., Rayet, M., et al. 1999, Nucl. Phys. A, 656, 3
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
Boesgaard, A.M. 2004, The Light Elements: Lithium, Beryllium and Boron, Carnegie Observatories Astrophysics Series, Vol.4
Engstler, S., et al. 1988, Phys Lett. B, 202, 179
Engstler, S., et al. 1992, Z.Phys. A, 342, 471
Gagliardi, C.A., Tribble, R. E., Azhari, A., et al. 1999, Phys. Rev. C, 59, 1149
Gagliardi, C.A., Azhari, A., Burjan, V., et al. 2002, Eur. Phys. J A, 13, 227
Lamia, L., et al. 2007, Nucl. Ph. A, 787,309
Lattuada, M., Pizzone, R.G., Typel, S., et al. 2001, ApJ, 562, 1076
Mukhadzhanov, A., et al. 2006, EPJ A, 27S, 205
Musumarra, A., Pizzone, R.G., Blagus, S. et al. 2001, Phys. Rev., 64, 068801
Pizzone, R.G., et al. 2003, A&A, 398, 423
Pizzone, R.G., et al. 2005, A&A, 438, 799
Romano, S., et al. 2006, EPJ A, 27S, 221
Spitaleri, C. 1990, Problems of fundamental Physics, II, World Scientific, ed. by R. Cherubini, P. Dal Piaz, B. Minetti
Spitaleri, C., Aliotta, M., Cherubini, S., et al. 1999, Phys. Rev.C, 60, 5802
Spitaleri, C., Aliotta, M., Figuera, P., et al. 2000, EPJA, 7, 181
Spitaleri, C., Typel, S., Pizzone, R.G., et al. 2001, Phys. Rev.C, 63, 5801
Spitaleri, C., Lamia, L., Tumino, A., et al. 2004, Phys. Rev.C, 69, 5806
Stephens, A., Boesgaard, A.M., et al. 1997, ApJ, 491, 339
Tumino, A., et al. 2003, Phys. Rev.C, 67, 065803
Zahnow, D., et al. 1997, Z. Phys. A 359, 211