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Light elements depletion in stellar atmospheres: the boron case

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Abstract. Due to the role played by the light elements lithium, beryllium and boron as "probe" of stellar mixing phenomena, the (p, α) channel for the boron destruction at astrophysically relevant energies was investigated. The reactions $^{11}B(p, \alpha)^{8}Be$ and $^{10}B(p, \alpha)^{7}Be$ are the main channels for its burning in stellar interior at about $T = 10^{6}$ Kelvin. By means of the indirect Trojan Horse Method the astrophysical S(E)-factor was then extracted for both reactions.

1. Introduction

In the last 30 years big efforts were made about the possibility to use LiBeB as probes of internal stellar structure and as messengers of mixing processes acting in the stellar interior. Different authors (Boesgard (2004a)) suggest that the study of LiBeB abundances in young F and G stars can give useful informations about different mixing processes presently not well known. In particular for such stars, standard stellar model does not take into account the possibility of "communication" between the convective zone and the nuclear destruction zone where the burning of such elements occurs mainly via (p,α) reactions induced at temperatures of some 10^6 Kelvin. This means that the residual LiBeB abundances in such stars would have to reflect the abundances of the original interstellar gas (Stephens et al. (1997)). The observational evidence suggests, in spite of the standard stellar models, that for F main sequence young stars there is a depletion of lithium and beryllium as the observations on Hyades, Praesepe (600 My) and on other young clusters reveal, while there is not evidence of this depletion in F pre-main sequence stars as the observations on Pleiades cluster (70 My) reveal (Boesgard (2004b)). The evidence of a Li-dip connected with a less pronounced Be-dip and the constancy of boron abundance as the stellar temperature varies together with the Li-Be and Be-B correlation are interpreted as a signature of non-standard mixing mechanisms acting inside these stars: in particular, mixing mechanisms induced by

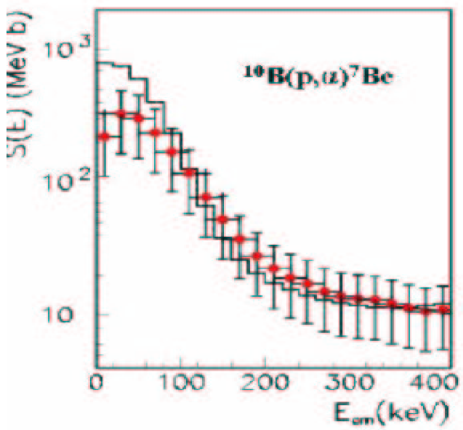

Fig. 1. S(E)-factor for the $^{10}B(p,\alpha)^7Be$ reaction. The indirect TH data are reported as red points while the direct data (Angulo et al. (1999)) are in form of histogram. Below 20 keV only an extrapolation is present on the direct data.

stellar rotation well describe the current observational status (Boesgard (2004b)). With the future aim to evaluate the impact of the still present nuclear uncertainties on the depleting rate for such light elements, the study of $^{11}B(p,\alpha)^8Be$ and $^{10}B(p,\alpha)^7Be$ was performed by means of the Trojan Horse Method (THM). After the selection of the quasi-free (QF) contribution on a suitable three-body reaction, this approach allows to extract the two-body "bare"-astrophysical S(E)-factor. Further, by using this indirect approach, the behavior of the bare astrophysical S-factor in the region around ultra-low energy values can be reached without extrapolations (Spitaleri et al. (1999)), usually made on the direct measurements. However, a normalization procedure of the TH data to the direct ones is needed, making the TH a complementary tool for the experimental nuclear astrophysics.

2. Study of the $^{10}B(p,\alpha)^7Be$ reaction

Aim of the experiment was to extract the astrophysical S(E)-factor for the reaction through the THM applied to the $^2H(^{10}B,\alpha^7Be)n$ reaction. "Hot-spot" for the study of this reaction is the presence of the Ex=8.701 MeV ^{11}C resonant level (J=5/2$^+$) at about E_{cm}(^{10}B-p)=10 keV. Because the Coulomb barrier penetration and electron screening effects, only an extrapolation on the bare S-factor is present on the available direct data (Angulo et al. (1999)). The application of the TH was then needed in order to get more information about the behavior of the excitation function in the energetic region around the resonant peak. The experiment was performed at the Pelletron-Linac laboratory (Departamento de Fisica Nuclear (DFN)) in Sa Paolo (Brazil). The Tandem Van de Graaf accelerator provided a 27 MeV 10B beam impinging on a deuterate polyethylene target (CD_2) of about 192 $\mu g/cm^2$ with a spot size on target of about 2 mm and intensities up 1 nA. Using the experimental setup described in (Lamia et al. (2007)), the presence of the QF-contribution on the three-body reaction $^2H(^{10}B,\alpha^7Be)n$ reaction was investigated by studying the experimental neutron momentum distribution and behavior of the coincidences yield as a function of neutron momentum "p_n" values. These studies confirmed that the neutron acted as "spectator" to the two-body reaction of interest. The data within $|p_n| \leq$30 MeV/c were further selected in order to get the bulk of the quasi-free contribution for the extraction of the bare-astrophysical S(E)-factor. Figure 1 shows the final result of this experiment. The indirect data are showed with red points while the direct data of (Angulo et al. (1999)) are reported in form of histogram. In particular below 20 keV only an extrapolation on the available direct data is present. A clear increase of the S(E)-factor down to 300 keV shows up, due to the contribution of the 8.701 MeV level of ^{11}C. The FWHM obtained in the present experiment for the resonance is about 110 keV, while independent measurements of such level report a value of about 16 keV. Due to the poor resolution, it was not possible to extract any information about the value of the astrophysical S(0)-factor or about the electron screening potential. However, this first approach to the study of the present reaction confirmed the power of the THM to reach the ultra-low energy values since its application allowed to study the resonant contribution

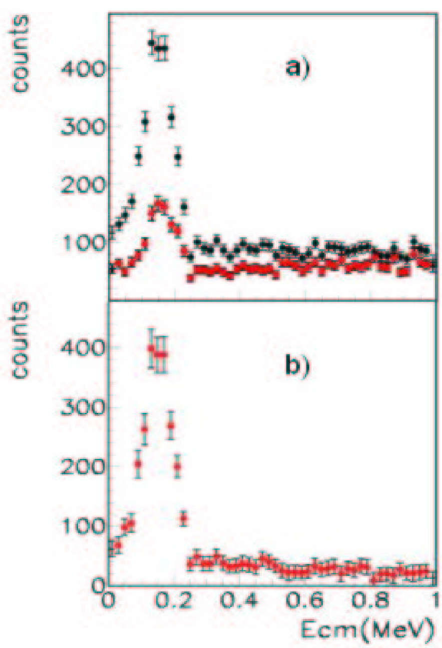

Fig. 2. : Panel a) Comparison between 3-body coincidence yield (black points) and the selected background (red points). Panel b) Three-body coincidence yield after background subtraction.

even in the energy region reached through the extrapolations.

3. Study of the $^{11}B(p,\alpha)^8Be$ reaction

Aim of the experiment was to extract the astrophysical S(E)-factor for the $^{11}B(p,\alpha)^8Be$ reaction through the THM applied to the $^2H(^{11}B,\alpha^8Be)n$ three-body reaction. "Hot-spot" for the study of this reaction is the presence of the Ex=16.106 MeV 12C resonant level (J=2^+) at about $E_cm(^{11}$B-p)=150 keV. The experiment was performed at the LNS of Catania. The SMP Tandem Van de Graaf accelerator provided a 27 MeV 11B beam impinging on a deuterated polyethylene target (CD_2) of about 170 $\mu g/cm^2$ with spot size on target of about 2 mm and intensities of about 2 nA. Due to its instability against alfa-decay, the detection of ^{8}Be was performed with a DPSD (Dual Position Sensitive Detector) centered at 20, while the alfa particles were detected by using three usual PSD centered at 17(PSD1), 37(PSD2) and 57(PSD3) on opposite side with respect to the beam. The trigger for the acquisition was made by selecting the coincidences between the DPSD and one of the three PSD's. Further details about experimental setup and selection of the data are deeply discussed in (Spitaleri et al. (2004)). Recently the data were further analyzed in order to evaluate the different energy resolution on the three different angular pairs of detectors. In particular an estimation of the energy resolution leads at about 50 keV for DPSD-PSD1 pair, at about 40 keV for DPSD-PSD2 pair and finally at about 80 keV for DPSD-PSD3. In order to extract the behavior of the astrophysical S(E)-factor, we have recently re-studied only the DPSD-PSD2 pair, having the lowest energy resolution estimated at about 40 keV in E_{cm}. However, due to the present resolution on the variable E_{cm} of our interest, the FWHM of the mentioned resonant contribution is quite larger ($\Gamma \approx$120 keV) if compared to that of about 5 keV reported by the direct measurements (Becker et al. (1987)). Moreover, the presence of sequential mechanisms on the selected data was further checked. In more details, the selected particles in the exit channel of interest for the TH investigation could come from formation and subsequent decay of an intermediate compound nucleus. Obviously these processes are quite different from the quasi-free ones and a detailed investigation on their contribution in the selected data is needed. In particular, as deeply discussed in more articles, these kind of mechanisms represent an "expected"-background to subtract on our data. The contribution of the levels of ^{9}Be on the E_{cm} spectrum was then established and the situation is reported in figure 2. The upper part of the figure shows how the selected background affects the selected data in the momentum region of $|p_n| \leq$40 MeV/c. The black points represent the coincidence yield within $|p_n| \leq$40 MeV/c, while the red ones represent the contribution of the selected levels of the intermediate ^{9}Be compound nucleus. In the lower part, the three-body coincidence yield is reported (red points) after the correction for the selected background.

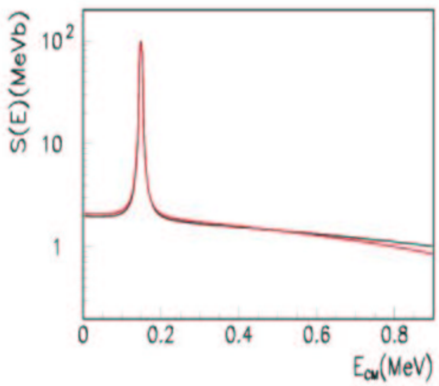

Fig. 3. :Comparison between the fit on the TH S(E)-factor (black line) and direct S(E)-factor (red line) as reported in (Becker et al. (1987)).

Following the usual description of the method, the MPWIA was then applied in order to extract the astrophysical S(E)-factor (Typel et al. (2000). The experimental three-body coincidence yield was fitted with a second order polynomial plus a Breit-Wigner function. Knowing the contribution coming form both resonant (l=1) and non-resonant (l=0), it was possible to calculate the astrophysical S(E)-factor. Moreover, because the energy resolution of about 40 keV on the present TH data, a folding of these fits was then needed in order to make the normalization and then the comparison with the direct ones. Because the presence of two different contributions in excitation function, two constants of normalization were needed in order to compare the TH data with the direct ones. The preliminary results of this very recent analysis is reported in figure 3 and now under analysis. The full black line represents the behavior of the S(E)-factor as extracted by means of THM while the full red line represents the fit on the direct data as reported in (Becker et al. (1987)). The two set of data are however in agreement within the experimental error and more details about the analysis are at moment under study.

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