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Astrophysical S-factors and reaction rates of (p,n)-reactions on ^{117}Sn, ^{118}Sn, ^{122}Sn, and ^{124}Sn

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Abstract. Astrophysical S-factors and reaction rates were derived from available cross sections of (p,n)-reactions on ^{117}Sn, ^{118}Sn, ^{122}Sn, and ^{124}Sn isotopes at incident proton energies up to 9 MeV. The statistical theory predictions of the observable quantities are ~2 times smaller at near threshold energies and have better agreement at higher energies.

A large number of nuclear data primarily concerning reactions induced by neutrons, photons, and charged particles at low energies is required for the modeling of stellar evolution and nucleosynthesis due to nuclear reactions in stars and long chains of radioactive decay. Although the majority of stable isotopes of elements heavier than iron were synthesized via slow and rapid neutron capture processes, charged particle induced reactions also play a significant role in explaining the existence of 32 stable, neutron deficient isotopes which cannot be formed by neutron capture. Many details of the nucleosynthesis process responsible for these so-called p-isotopes still remain elusive but the standard scenario (the so-called γ-process) produces the bulk of the p-isotopes by photodisintegration chains involving (γ,n), (γ,p), and (γ,α) reactions in explosive O/Ne-burning of core-collapse supernovae [1]. Temperatures of 2–3.5 GK are attained in such environments.

S-factors and reaction rates as quantities of astrophysical interest are derived from reaction cross sections not all of which can be measured in a laboratory experiment. The photodisintegration rates can be derived from the *stellar* capture rates by applying detailed balance. At present several databases of nuclear reactions for astrophysical application are being developed, compiling experimental cf. [2,3] and theoretical [4] reaction cross sections at the energies corresponding to stellar temperatures up to $T = 10^{10}$ K. Because of the scarce experimental data and the necessity of knowing reaction cross sections of unstable nuclei which cannot be measured under terrestrial conditions, theoretical predictions are required in many cases. These, in turn, can be tested by comparison with known experimental data. The statistical model of Hauser-Feshbach (H-F) [5] is usually applied for theoretical calculations of astrophysical nuclear reaction features.

In recent years some groups performed measurements of (p,γ)-reaction cross sections on series of middle-heavy nuclei at sub-Coulomb barrier proton energies relevant to stellar nucleosynthesis (see, e.g., [6–9] and references therein) and analyzed them using different computer codes [10–12] implementing H-F theory. (p,n)-reactions can also be analyzed in such a way since their cross sections are steeply increasing functions depending on incident proton energy above thresholds and their reaction rates quickly become comparable with (p,γ)-reaction ones. This is even more so for heavier nuclei since the Gamow peak is shifted towards higher energies as the charge of the nuclei involved increases and often covers the threshold energy. It is clear that the lower threshold (p,n)-reactions have to compete with the (p,γ)-reactions more effectively. Moreover, it was demonstrated recently that (p,n) reactions affect the abundances of light p-nuclei (up to Sn) in the γ-process [13] and thus the reactions studied here have a direct impact on γ-process studies.

In the present work we analyze the excitation functions of (p,n)-reactions on tin isotopes ^{117}Sn, ^{118}Sn, ^{122}Sn, and ^{124}Sn measured earlier by us [14] and other authors [15,16] and compare them with the predictions of the H-F statistical model code NON-SMOKER [10,11]. Our measurements were made using an activation technique with high resolution γ-spectrometry in the incident proton energy range 4–9 MeV. For the reactions ^{118}Sn(p,n)^{118m,g}Sb, ^{122}Sn(p,n)^{122m,g}Sb and ^{124}Sn(p,n)^{118m2,m1,g}Sb isomeric state excitation functions were measured separately but here we analyze the total (p,n)-reaction cross sections. Johnson et al. [15] carried out their measurements on all above nuclei for 2.6- to 7-MeV incident protons and Lovchikova et al. [16] on ^{117}Sn for 7-, 8-, and 9-MeV and ^{122}Sn for 6-, 7-, 8-, and 9-MeV incident protons by counting the emitted neutrons. All of the three teams used thin self-supporting targets of enriched tin isotopes.

The results of our analysis are given in the figures. Figure 1 shows the astrophysical S-factors derived from the experimental and theoretical cross sections $\sigma(E)$ through the expression $S = E\sigma(E)e^{2\pi\eta}$. Here, E is the center-of-mass energy, $\eta = Z_1Z_2e^2/h\upsilon$ is the Sommerfeld parameter with Z_1 and Z_2 as the charge numbers of interacting particles and υ their relative velocity. Figure 2 presents the laboratory reaction rates $N_A\langle\sigma\upsilon\rangle$ calculated for different stellar temperatures T from the experimental and theoretical cross sections using the well-known equation

$$N_A\langle\sigma\upsilon\rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{N_A}{(k_BT)^{3/2}} \int_{E_{th}}^{\infty} \sigma(E)\exp\left(-\frac{E}{k_BT}\right)dE,$$

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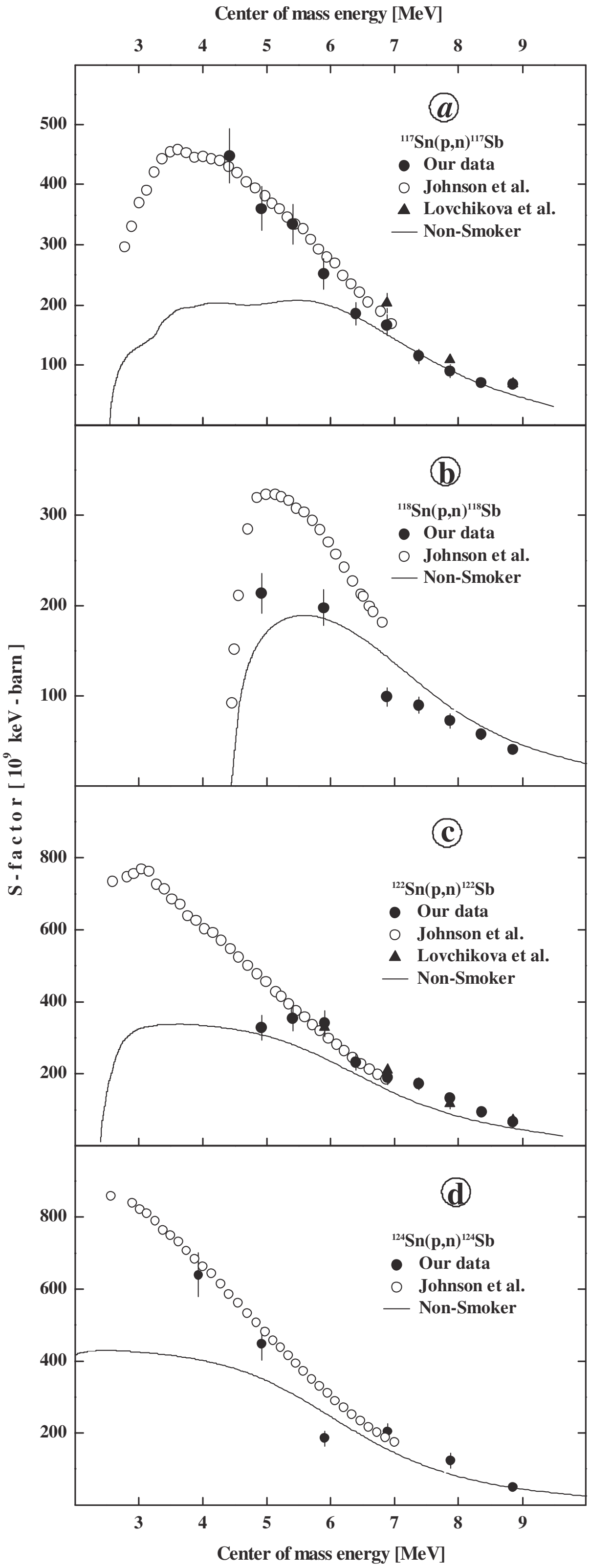

Fig. 1. Astrophysical S-factors of the reactions ^{117}Sn(p,n)^{117}Sb (*a*), ^{118}Sn(p,n)^{118}Sb (*b*), ^{122}Sn(p,n)^{122}Sb (*c*), and ^{124}Sn(p,n)^{124}Sb (*d*).

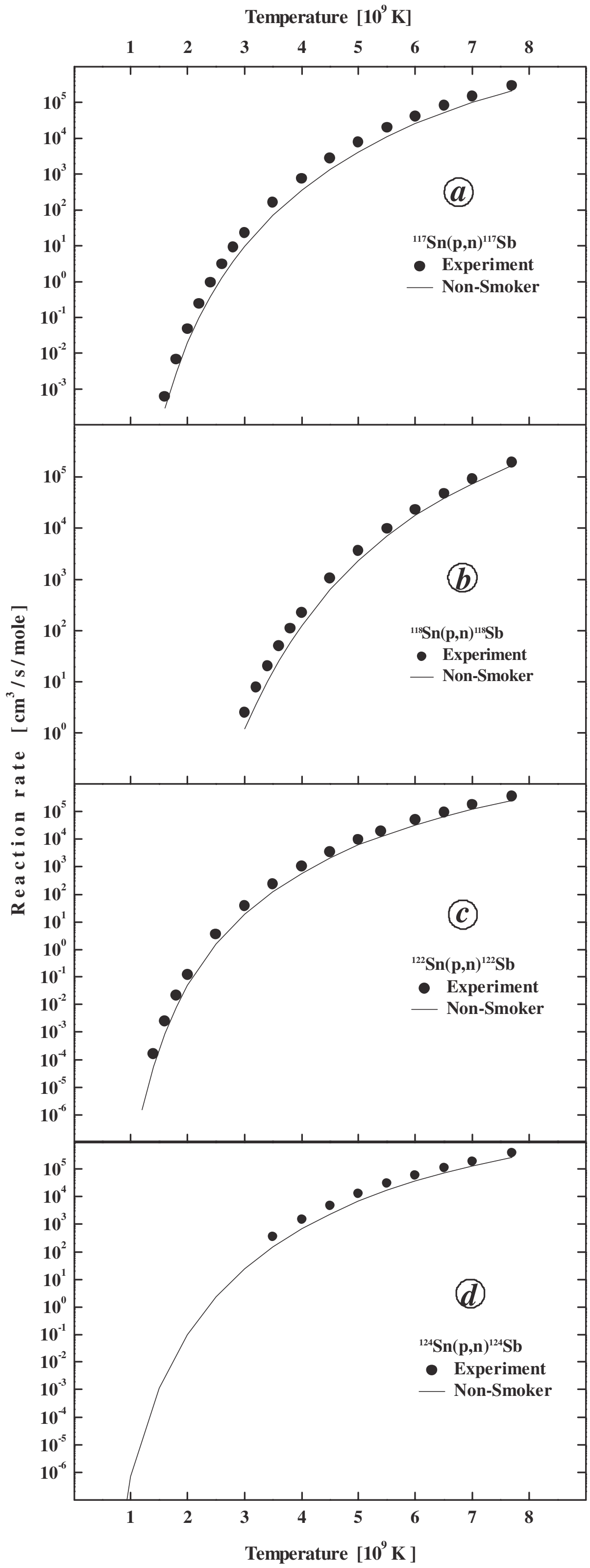

Fig. 2. Reaction rates of ^{117}Sn(p,n)^{117}Sb (*a*), ^{118}Sn(p,n)^{118}Sb (*b*), ^{122}Sn(p,n)^{122}Sb (*c*), and ^{124}Sn(p,n)^{124}Sb (*d*).

where N_A is the Avogadro number, μ the reduced mass of the system, k_BT the thermal energy with k_B being the Boltzmann constant. To perform the integration, our experimental data was interpolated polynomially unless otherwise specified below.

^{117}Sn(p,n)^{117}Sb. The experimental S-factor values of all teams agree each with other in the intersecting energy range while the theoretical results are in good agreement with the experiment at the higher energies where the ^{117}Sn(p,γ) S-factor is much smaller than the (p,n) one but smaller by factor ~2 at the lower energies (panel *a* of fig. 1) where (p,γ) is dominating. This indicates that the H-F calculation may not yield the proper flux distribution between the two possible exit channels. The Q-value of the ^{117}Sn(p,n)^{117}Sb reaction is –2.54 MeV. This means that the Gamow window $\Delta E_0 = 4(E_0kT/3)^{1/2}$ with $E_0 = [2\pi^2e^2Z_1Z_2kT(\mu c^2/2)^{1/2}/hc]^{2/3}$ [17] opens at the stellar temperature $T = 1.3$ GK for the reaction in question. The Gamow window at a temperature of 3.3 GK corresponding to the upper edge of the γ-process is 3.7 ± 1.2 MeV. Thus, the Johnson data cover the γ-process region completely for this threshold reaction. To be able to calculate the reaction rate up to 10^{10} K (as required by the rate compilations) experimental data for the reaction cross sections up to 11 MeV are needed. Since our data only reach 9 MeV we were able to obtain the reaction rates up to $T = 7.7$ GK. They are displayed by the points in panel *a* of figure 2. The NON-SMOKER result (the solid curve) underestimates the reaction rate by 51% for $T = 1.6$ GK and 29% for $T = 7.7$ GK.

^{118}Sn(p,n)^{118}Sb. The experimental values of S-factors of the ^{118}Sn(p,n)^{118}Sb reaction (panel *b* in fig. 1) obtained by the different groups are in some disagreement and the theoretical prediction (the full line) is closer to our data (the black points). Since this reaction has a Q-value of –4.44 MeV, the Gamow peak covers the reaction threshold beginning from $T = 3$ GK, i.e. practically beyond the bounds of the γ-process. Only this temperature range is shown in panel *b* of figure 2.

The experimental reaction rates were calculated combining our data with the Johnson data at energies less than 5 MeV. With this approach, the NON-SMOKER code underestimates the reaction rates by 52% for $T = 3$ GK and by 12% at 7.7 GK

^{122}Sn(p,n)^{122}Sb. The experimental and theoretical S-factors and rates of this reaction are presented in the panels *c* of figures 1 and 2, respectively. The experimental results of the three groups agree with each other, with the exception of our data point at the lowest energy. The theoretical values are smaller especially in the low energy region. The Gamow window for this reaction opens at $T = 1.2$ GK since its Q-value is −2.40 MeV but the availability of the experimental data allows to calculate the reaction rates for $T = 1.4$ GK and more. The reaction rates are underestimated by statistical theory by 65% for $T = 1.4$ GK and by 30% for $T = 7.7$ GK.

^{124}Sn(p,n)^{124}Sb. The reaction data are shown in the panels *d* of figures 1 and 2. The experimental S-factors of the different groups are in satisfactory agreement but the theory calculations yield smaller values. The Q-value of this reaction is –1.40 MeV but the experimental cross sections are available at energies of 2.6 MeV and above. The lack of experimental data in the 1.4-2.6 MeV region allows to calculate the reaction rates only beginning at 3.6 GK for which the low energy edge of the Gamow window reaches down to 2.6 MeV. This underlines the need to measure the cross sections at the near threshold energies corresponding to the lower stellar temperatures. The disagreement between experimental and theoretical values of the reaction rate amounts to 56% at $T = 3.6$ GK and 30% at $T = 7.7$ GK.

Summarizing, the analysis of the (p,n) excitation functions for ^{117}Sn, ^{122}Sn, and ^{124}Sn in the energy range up to 9 MeV shows that the statistical model underestimates the S-factors and reaction rates by approximately a factor of two at the lower energies and has good agreement with the experiment at the higher energies. It is impossible to arrive at an unambiguous conclusion for the ^{118}Sn(p,n)^{118}Sb reaction because of the disagreement between experiments but the theoretical prediction is close to our data.

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