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Nuclear astrophysics: Recent results on CNO-cycle reactions and AGB nucleosynthesis

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Summary. — Nuclear astrophysics aims to measure nuclear-reaction cross sections of astrophysical interest to be included into models to study stellar evolution and nucleosynthesis. Low energies, $< 100\,\mathrm{keV}$, are requested for this is the window where these processes are more effective. Two effects have prevented to achieve a satisfactory knowledge of the relevant nuclear processes, namely the Coulomb barrier exponentially suppressing the cross section and the presence of atomic electrons. These difficulties have triggered theoretical and experimental investigations to extend our knowledge down to astrophysical energies. For instance, indirect techniques such as the Trojan Horse Method and new experimental facilities such as deep underground laboratories have been devised yielding new cutting-edge results.

PACS `26.20.-f` – Hydrostatic stellar nucleosynthesis.
PACS `25.70.Jj` – Fusion and fusion-fission reactions.

1. – Introduction

Nuclear astrophysics deals with the investigation of nuclear and particle physics phenomena that take place in astrophysical scenarios, such as stars in different evolutionary stages or the early universe. Limiting ourselves to low-energy phenomena, such as the ones occurring in quiescent stellar burning, the main input parameters for astrophysics are the cross sections $\sigma(E)$ of the reactions responsible for energy production and nucleosynthesis. The measurement of such cross sections at those energies of interest for astrophysics is not always possible because of the Coulomb repulsion between the interacting nuclei and the presence of atomic electrons. Indeed, the energy interval of interest usually ranges between few keV and few hundreds of keV in the case of charged-particle–induced reactions, thus nucleus-nucleus interaction takes place well below the Coulomb barrier (few MeV for p-induced reactions), at energies comparable with the electron binding energies in atoms. Therefore, cross sections can be as low as 10^{-15} barns or smaller, making the signal-to-noise ratio so poor to make the use of extrapolation from higher energies the only way to get a reliable estimate of cross sections at the energies of interest for astrophysics. This is usually performed by introducing the astrophysical factor: $S(E) = \sigma(E)\, E\, \exp(2\pi\eta)$, where $\eta = Z_1 Z_2 e^2/\hbar v$ is the Sommerfeld parameter, Z_1 and Z_2 the nuclear charges of the interacting ions and v their relative velocity. In the latest years, great improvements in the experimental approach used to measure low-energy cross sections have been implemented, allowing us to extend the measurements of some reactions involving light nuclei down to astrophysical energies ([1] and references therein). In these cases, the presence of atomic electrons have determined an enhancement of the astrophysical factor not related to the nuclear interaction but to the shielding of the nuclear charges by the surrounding negatively charged electronic clouds ([1] and references therein). Again, extrapolation has proved a valuable tool to access the $S(E)$ factor at astrophysical energies. Indirect techniques have then been developed to bypass such problems and measure the astrophysical factor at low energies. For instance, the Trojan-Horse Method (THM) [2,3] is a valid technique to get information on the $S(E)$ factor at astrophysical energies in the case of reactions having charged particles or neutrons in the exit channel, with no Coulomb suppression neither electron screening. In the case of radiative capture reactions, the Asymptotic Normalization Coefficient (ANC) [4] measurement has allowed us to obtain the zero-energy $S(E)$ factor with very high accuracy.

Recently, two reviews collecting and critically examining the latest measurements of nuclear reactions of interest for astrophysics have been released [5,6]. This is needed to arrange a set of recommended $S(E)$ factors to be used in astrophysical modeling. A key aspect that is worth to mention is the increasingly important role played by indirect methods in the evaluation of critical $S(E)$ factors. We will examine some relevant results concerning quiescent stellar nucleosynthesis, in particular CNO H-burning and extra-mixing in Asymptotic Giant Branch (AGB) stars, focusing on the results obtained through indirect methods.

2. – The ^{15}N$(p,\alpha)^{12}$C reaction

The ^{15}N$(p,\alpha)^{12}$C reaction is a key reaction in the CNO cycle and plays a crucial role in the production chain of the key isotope ^{19}F in AGB stars [7,8]. Because of its astrophysical relevance it has been subject to both direct and indirect (via the THM) investigations to extend our knowledge down to the energies of interest for astrophysics, below 70 keV. A summary of the low-energy measurements of the ^{15}N$(p,\alpha)^{12}$C astrophysical factor is given in fig. 1. It clearly demonstrates the advantage of indirect techniques in extracting the low-energy ^{15}N$(p,\alpha)^{12}$C $S(E)$ factor (red circles), as a full coverage of the energy range relevant for astrophysics has been possible. It is worth noting, anyway, that such methods can introduce systematic effects, due to the nuclear-reaction model adopted in data reduction [9,10], so validity tests are mandatory to evaluate and possibly correct any additional sources of uncertainty. In the present case, the indirect measurement confirmed the results of extrapolation from higher-energy direct data.

3. – The ^{15}N$(p,\gamma)^{16}$O reaction

The ^{15}N$(p,\gamma)^{16}$O reaction provides the path to form ^{16}O in stellar hydrogen burning, thus transforming the CN cycle into the CNO bi-cycle and CNO tri-cycle. In stellar environments the ^{15}N$(p,\gamma)^{16}$O reaction proceeds at very low energies, lower than 70 keV. This range is not covered by experimental data, as is shown in fig. 2, even the recent high-quality data set in [11] could only measure down to about 120 keV. Extrapolation

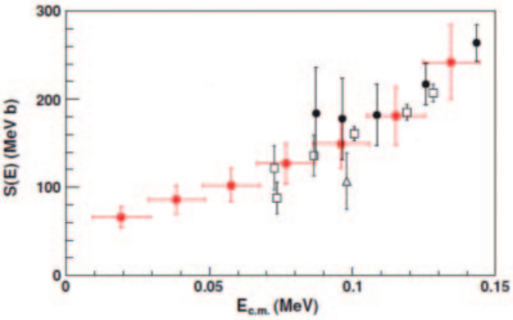

Fig. 1. – (Colour on-line) Low-energy ^{15}N$(p,\alpha)^{12}$C astrophysical factor. Red circles are the THM data from [7,8]. Black symbols are direct data (check [8] for more details).

is therefore crucial to estimate the reaction rate at astrophysical temperatures, and this has been performed by applying the R-matrix theory [11,12]. By means of the ANC approach, the contribution of direct capture has been pinned down with high accuracy (dashed line in fig. 2), turning out to be much lower than what previously estimated, yielding a zero-energy astrophysical factor 9 times smaller than the one in the literature (compare [4] and references therein). The R-matrix fitting is shown in fig. 2 as a full line. A clear disagreement shows up at low energies (black squares), which is probably linked to some systematic error in the experimental data. This result has been confirmed by the new data set in [11] and by the R-matrix fit in [12].

4. – The ^{17}O$(p,\alpha)^{14}$N reaction

The ^{17}O abundance plays a key role both in novae nucleosynthesis and in γ-ray astronomy. This rare isotope is processed in the CNO cycle, and it is important for the subsequent formation of the short-lived ^{18}F radioisotope, of special interest in novae observations. The ^{17}O$(p,\alpha)^{14}$N reaction is its main destruction channel, for this

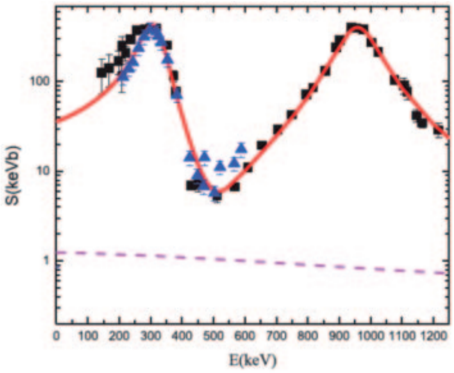

Fig. 2. – ^{15}N$(p,\gamma)^{16}$O astrophysical factor. The symbols are for the direct data, while the dashed and full line are for the direct reaction contribution estimated through the ANC and the R-matrix parameterization of $S(E)$, respectively. See [4,12] for a more detailed description.

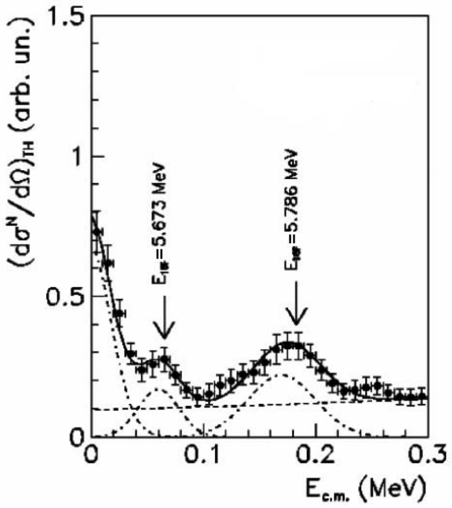

Fig. 3. – Low-energy Trojan-Horse (TH) ^{2}H(^{17}O$, \alpha^{14}$N)n cross section, namely the "nuclear" cross section (N). From the fitting of the experimental data the resonance strength of the 65 keV peak is obtained [13, 14].

reason it has been subject to several experimental investigations (see [13, 14] and references therein). Anyway, the ^{17}O$(p, \alpha)^{14}$N astrophysical factor has not yet achieved the requested degree of accuracy in the center-of-mass energy range 0.017–0.370 MeV, by means of direct studies only. In particular, the 65 keV resonance dominating the low-energy $S(E)$ factor deserved a more precise investigation. This has been addressed by applying the THM, by measuring the ^{2}H(^{17}O$, \alpha^{14}$N)n reaction to deduce the 65 keV

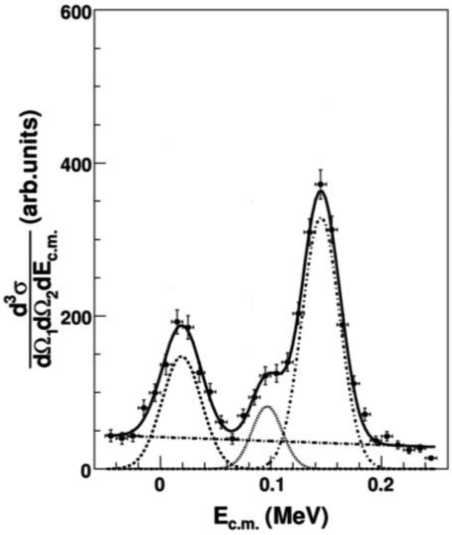

Fig. 4. – Low-energy ^{2}H(^{18}O$, \alpha^{15}$N)n TH cross section. As in fig. 3, it yields the strengths of the low-energy resonances [17, 18, 20].

resonance strength from the coincidence yield (fig. 3). The resulting strength $\omega\gamma = 3.66^{+0.76}_{-0.64} \times 10^{-9}$ eV is in fair agreement with the one in the literature, though possibly suggesting a non-negligible contribution of electron screening affecting the direct measurement [13, 14]. Additional investigations are currently ongoing.

5. – The ^{18}O$(p,\alpha)^{15}$N reaction

The ^{18}O$(p,\alpha)^{15}$N reaction influences both the ^{19}F production in AGB and post-AGB stars and the oxygen isotopic pattern. Its astrophysical factor has to be measured with good accuracy over a wide range of energies, from 0 to 1 MeV, as the ^{18}O$(p,\alpha)^{15}$N reaction intervenes in a number of astrophysical scenarios such as extra-mixing at the bottom of the convective envelope (where $T < 0.04 \times 10^9$ K [15, 16]) and nucleosynthesis in R-Coronae Borealis stars (where $T \sim 0.2 \times 10^9$ K [17]). The lower-energy resonance parameters [18, 19] and the higher-energy astrophysical factor [17, 20] have been deduced through the THM. In particular, the strength of the 20 keV resonance has been ascertained, turning out to be about 35% larger than what given in the literature. The THM cross section is displayed in fig. 4. From the comparison of the yield of the 20 keV and 144 keV resonances the strength of the former has been deduced. In a similar way, the determination of the resonance parameters of the 656 keV resonance produced a reaction rate up to a factor of 2 larger than the one in the literature at temperatures $T > 0.5 \times 10^9$ K.

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