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Determination of the $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ and $^6\mathrm{Li}(p,\gamma)^7\mathrm{Be}$ astrophysical factors down to zero energy using the asymptotic normalization coefficients.

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Abstract. The $p-p$-chain reaction $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ can sensitively influence the prediction of the $^7\mathrm{Be}$ and $^8\mathrm{B}$ neutrino fluxes. Despite its importance, the knowledge of its reaction cross section at energies of the core of the Sun (15 keV - 30 keV) is limited and the accuracy far from the desired $\sim$ 3% level. In the present paper the indirect measurement of the external capture contribution using the asymptotic normalization coefficient (ANC) technique is reported. The angular distributions of deuterons emitted in the $^6\mathrm{Li}(^3\mathrm{He},d)^7\mathrm{Be}$ α-transfer reactions were measured and the ANCs extracted from the scaling of distorted-wave Born approximation (DWBA) and coupled-channel (CC) calculations. Then, the astrophysical S-factor for the $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ reaction was calculated assuming $E1$ direct capture and the zero energy value turned out to be 0.534 ± 0.025 keVb. Both our experimental and theoretical approaches were benchmarked through the analysis of the $^6\mathrm{Li}(p,\gamma)^7\mathrm{Be}$ astrophysical factor, with interesting astrophysical applications to the understanding of the primordial lithium problem. In particular, the present work disfavors the occurrence of a claimed 200 keV resonance in the astrophysical factor.

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1 The astrophysical background

The ^{3}He(α,γ)^{7}Be reaction is among the key ones in nuclear astrophysics. It is the first reaction of the 2^{nd} and 3^{rd} $p-p$ chain branch and therefore the uncertainty of its rate strongly influences the precision of the predicted flux of the ^{7}Be and ^{8}B neutrinos. While the detection of the neutrinos coming directly from the core of the Sun became more and more precise after the construction of larger and more efficient neutrino detectors, sensitive to a wider neutrino energy range, the ^{3}He(α,γ)^{7}Be reaction remained critical after decades, despite the large number of experimental and theoretical studies devoted to it.

In particular, the flux of the $p-p$ neutrinos was measured with a precision of about 3.4% by the BOREXINO, SNO and Super-Kamiokande collaborations [1–3]. The precise neutrino flux measurements are used to constrain the Standard Solar Model (SSM) and provide information on the core temperature of the Sun; however, the relevant nuclear reaction cross sections are to be known with matching accuracy. At present, the uncertainties of these input parameters are far too high, typically of the order of 5-8% [4] contrary to the 3% precision required [5, 6]. Therefore, an improvement on the knowledge of the low-energy cross section of the ^{3}He(α,γ)^{7}Be reaction would result in a substantial reduction of the uncertainties and might have important consequences for the SSM.

The main reason behind such uncertainties is the fact that the astrophysically relevant energy region lies between about 15 keV and 30 keV for a temperature of 15 MK, characterizing the core of the Sun, and at these temperatures the ^{3}He(α, γ)^{7}Be reaction cross section is far too small to be measured directly. Theory-based extrapolations are therefore necessary to obtain the reaction rate [7–9]. Regarding the experimental methods recently adopted they can be sorted into three groups: the detection of prompt γ rays [10–13], the measurement of the ^{7}Be activity [14–18], and the counting of the ^{7}Be recoils with a recoil mass separator [19].

Regarding the theoretical description, several different models - including external capture models (e.g. [20]), potential models (e.g. [21, 22]), modified two-body potential approach [23], resonating group calculation (e.g. [24]), *ab initio* models (e.g. [25, 26]) and R-matrix theory [27, 28] - were used to describe the reaction. While the precision of the extrapolations are of the order of 6-7%, the difference between the zero-energy ^{3}He(α,γ)^{7}Be astrophysical factor $S_{34}(0)$ values exceeds 10%. The predicted $S_{34}(0)$ factors are shown in fig. 1. The figure shows that the calculated $S_{34}(0)$ factors depend strongly on the model used in the extrapolations and high precision experimental data is needed to constrain the theoretical models.

2 The ANC experiment

Here we present the results of a new approach that has made it possible to deduce the $S_{34}(0)$ factor of the ^{3}He(α,γ)^{7}Be reaction with no need of extrapolation, using the asymptotic normalization coefficient (ANC) technique [35]. Indeed, present-day direct measurements cannot reach down to astrophysical energies due to the vanishing cross sections, and have to rely on extrapolations, often based on theoretical models. The large scatter in the calculated $S_{34}(0)$ (see fig.1) suggests the presence of unaccounted systematic errors. Instead, the ANC indirect method makes it possible to directly access $S_{34}(0)$, leading to an improved accuracy provided that sources of systematic errors such as the model dependence and the occurrence of unwanted competitive reaction mechanisms are tested. This is done using a variety of

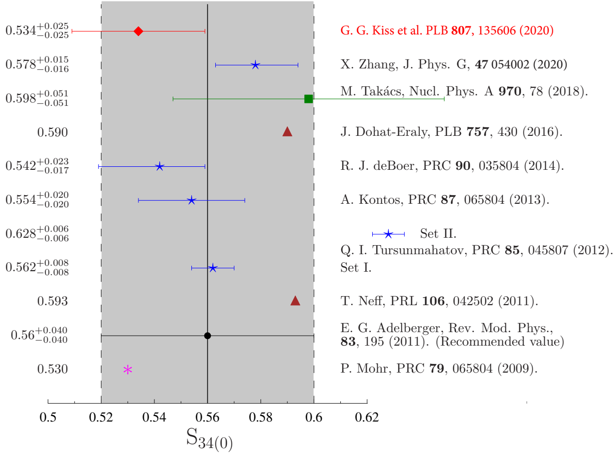

Figure 1. Summary of the most recent ^{3}He(α,γ)^{7}Be $S_{34}(0)$ factor results (fig.1 of [32]): derived from the analysis of elastic scattering angular distributions [22] (pink star), theoretical calculations [25, 30] (dark red triangle), extrapolations of experimental data sets [13, 23, 28, 29] (blue star), prediction based on neutrino yield measurement [31] (green box) and derived using the ANC technique [32] (red diamond). The solid central line represents the recommended value of [8], with its uncertainty indicated with the shaded area. For Tursunmahatov et al. [23], the $S_{34}(0)$ value obtained by fitting [10, 12, 14, 15] is shown.

methods, e.g., testing multiple potential models and parameters, and benchmarking the deduced cross sections against known ones (see ref.[36] for a detailed discussion). The ANC approach is especially suitable since the ^{3}He(α,γ)^{7}Be reaction at stellar energies is a pure external direct capture process [8], so it essentially proceeds through the tail of the nuclear overlap function, with no sensitivity to nuclear structure details. The shape of the overlap function in the tail region is solely determined by the Coulomb interaction and, in turn, the amplitude of the overlap function determines the rate of the capture reaction [37, 38]. Since the direct capture cross sections are proportional to the squares of the ANCs - which are found from transfer reactions - with the study of the near barrier ^{6}Li(^{3}He,d)^{7}Be α particle transfer reaction the ANCs for the ^{3}He(α,γ)^{7}Be reaction can be obtained.

The transfer reaction was measured using the ^{3}He beams provided by the 3.5 MV singletron accelerator of the Department of Physics and Astronomy (DFA) of the University of Catania (Italy) and the FN tandem accelerator at the John D. Fox Superconducting Accelerator Laboratory at the Florida State University (FSU), Tallahassee (FL), USA. More details about the experiment and the theoretical analysis can be found in [32, 33]. To deduce the ANCs, deuteron angular distributions were measured at two energies ($E_{lab.}$ = 3 MeV and $E_{lab.}$ = 5 MeV) over a broad angular range using silicon ΔE-E telescopes mounted on a turntable. Monitor detectors were placed at fixed angles with respect to the beam axis for absolute normalization. ^{6}LiF (enriched in ^{6}Li by 95%) and pure ^{6}Li targets (enriched in ^{6}Li by 98%) were used. Thanks to the ΔE-E particle identification technique [34] and to the high-resolution achieved, clear evidence of d_0 and d_1 groups, corresponding to ^{7}Be ground and first excited states, was obtained. At the backward hemisphere the differential cross section (DCS) increases with increasing angles and this confirms the presence of a dominant

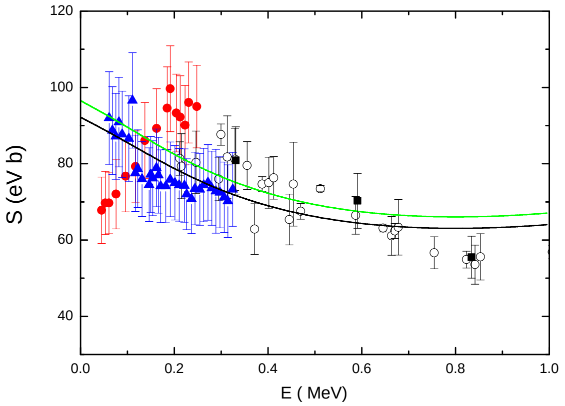

Figure 2. The experimental and calculated astrophysical S-factor for the radiative-capture ^{6}Li(p,γ)^{7}Be reaction (fig.7 of ref.[33]). The solid green line is the direct component of the astrophysical S factor, obtained using the weighted average ANC values from the near-barrier proton transfer ^{6}Li(^{3}He,d)^{7}Be reaction at $E_{^3\mathrm{He}}$=3 and 5 MeV. The black line is the S factor obtained from the ANCs deduced from the analysis of ^{6}Li(p,γ)^{7}Be directly measured reaction [44]. Blue solid triangles represent the bare-nucleus astrophysical factor from ref.[44] (including systematic error), red filled circles are the experimental astrophysical factor published in [45], empty circles are taken from [46] and black solid squares from [47].

one-step α-particle exchange mechanism. Similarly, one-step proton transfer mechanism is found to be dominant in the forwards hemisphere, with negligible interference.

The ANCs for the ^{3}He + $\alpha \to$ ^{7}Be channel was deduced in the framework of the modified Distorted Wave Born Approximation (DWBA) [39] assuming one step proton and α particle transfer [40]. By normalizing the calculated DCSs to the experimental ones for each experimental point ($\theta = \theta^{\mathrm{exp}}$) for the backward angle regions, the ANCs for ^{3}He + $\alpha \to$ ^{7}Be$_{\mathrm{g.s}}$ and ^{3}He + $\alpha \to$ ^{7}Be(0.429 MeV) (namely, ^{7}Be first excited state) channels were deduced. The channels coupling effects (CCE) were derived for each experimental point of θ^{exp} using the FRESCO code [41] by taking into account only one step processes with proton stripping ^{6}Li(^{3}He, d)^{7}Be and exchange mechanism with the α-particle cluster transfer ^{6}Li(^{3}He, ^{7}Be)d.

The weighed mean values of the square of the ANCs for the ^{3}He + $\alpha \to$ ^{7}Be(g.s.) and ^{3}He + $\alpha \to$ ^{7}Be(0.429 MeV) are equal to C^2= 20.84 ± 1.12 [0.82; 0.77] fm^{-1} and C^2= 12.86 ± 0.50 [0.35; 0.36] fm^{-1}, respectively, which are in an excellent agreement with those of [23] derived from the analysis of the experimental S-factor data of [10, 12, 14, 15]. The uncertainties given here includes both experimental errors in the $d\sigma^{\mathrm{exp}}/d\Omega$ (first term in square parentheses), as well as the model uncertainties (second term in square parentheses). Then, the direct capture contribution to the ^{3}He(^{4}He,γ)^{7}Be astrophysical factor at energies corresponding to the core temperature of the Sun was derived within the modified two-body potential model (MTBPM) framework [42, 43], and the resulting S_{34}(0) and S_{34}(23 keV) factors were found to be S_{34}(0) = 0.534 ± 0.025 [0.015; 0.019] keVb and S_{34}(23 keV) = 0.525 ± 0.022 [0.016; 0.016] keVb. The comparison with the values in the literature is performed in fig.1, and shows an improved accuracy with respect to the to-date recommended value in ref.[8] but an uncertainty still higher than the target value, calling for more work to further reduce it.

3 Independent validation of the approach: the $^{6}\mathrm{Li}(p,\gamma)^{7}\mathrm{Be}$ reaction

Since the one-step proton transfer is dominant in the forward hemisphere, the ANCs for the $^{6}\mathrm{Li} + p \rightarrow {}^{7}\mathrm{Be}$ channel was deduced as well, using a similar approach as discussed above. The $^{6}\mathrm{Li}(p,\gamma)^{7}\mathrm{Be}$ astrophysical factor influences a variety of astrophysical scenarios, including big bang and stellar nucleosynthesis [33]. Moreover, conflicting results of direct measurements have been published [44, 45], reporting contradictory low-energy trends. The weighted mean values of the square of the ANCs for $^{6}\mathrm{Li} + p \rightarrow {}^{7}\mathrm{Be}$ were found to be 4.81 ± 0.38 fm^{-1} and 4.29 ± 0.27 fm^{-1} for the ground and first excited states of ^{7}Be, respectively. The overall uncertainties correspond to the averaged squared errors, including both experimental errors in the $d\sigma^{\mathrm{exp}}/d\Omega$ and the theoretical uncertainty from the DWBA analysis. Finally, as discussed in ref.[33], the $^{6}\mathrm{Li}(p,\gamma)^{7}\mathrm{Be}$ astrophysical S-factor was calculated assuming $E1$ direct capture (DC) (green line in fig.2). At E=0, the indirect $S_{61}^{(\mathrm{DC})}(E)$ equals $65.781 \pm 5.227[3.380; 1.040; 3.859]$ eV·b and $30.675 \pm 1.957[0.464; 0.514; 1.828]$ eV·b for the ground and the first excited states of ^{7}Be, respectively, leading to a total S-factor of 96.5 ± 5.7 eV·b. This value is in excellent agreement with the extrapolated S-factor to zero energy (S(0) = 95 ± 9 eV·b) of [44], with an uncertainty 1.6 times lower. While this result does not support the occurrence of the 200 keV resonance claimed in [45], such agreement is a validation of the method used for deducing the $^{3}\mathrm{He}(^{4}\mathrm{He},\gamma)^{7}\mathrm{Be}$ S-factor.

A further validation of the adopted theoretical approach is given by the re-analysis of the $^{6}\mathrm{Li}(\mathrm{p},\gamma)^{7}\mathrm{Be}$ directly-measured astrophysical factor [44]. The ANCs for the $^{6}\mathrm{Li} + p \rightarrow {}^{7}\mathrm{Be}(\mathrm{g.s.})$ and $^{6}\mathrm{Li} + p \rightarrow {}^{7}\mathrm{Be}(0.429\,\mathrm{MeV})$ channels were derived from the experimental total astrophysical S-factor and the branching ratios of ref. [44], within the MTBPM [43]. The values of the weighted means for the ANC values for ^{7}Be ground and first excited states obtained from all the experimental data in [44] are equal to $(C^{exp}_{1\,1/2+1\,3/2})^2 = 4.345 \pm 0.576\,[0.033;\ 0.041;\ 0.574]\,\mathrm{fm}^{-1}$ and $(C^{exp}_{1\,1/2+1\,3/2})^2 = 4.571 \pm 0.595\,[0.027;\ 0.033;\ 0.594]\,\mathrm{fm}^{-1}$, respectively. These ANCs are in excellent agreement with the values of 4.81 ± 0.38 fm^{-1} for the ground and 4.29 ± 0.27 fm^{-1} for the first excited state of ^{7}Be extracted from the analysis of the $^{6}\mathrm{Li}(^{3}\mathrm{He},d)^{7}\mathrm{Be}$ transfer reaction. Furthermore, the corresponding $^{6}\mathrm{Li}(\mathrm{p},\gamma)^{7}\mathrm{Be}$ was calculated assuming $E1$ DC leading to the black line in fig.2. The excellent agreement with the astrophysical factor reported by ref.[44] is a further validation of the adopted method.

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