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REVIEW
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Neutron-Driven Nucleosynthesis in Stellar Plasma

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A large uncertainty for the slow neutron capture nucleosynthesis (s-process) models is caused by the amount of neutrons available to the process itself. This quantity is strongly affected by the ^{13}C(α,n)^{16}O, and ^{22}Ne(α,n)^{25}Mg reaction cross sections, whose measurements at energies corresponding to the s-process thermal conditions (~ 10^2 keV) are mainly hampered by the Coulomb barrier. For this reason, indirect approaches could offer a complementary way of investigation and, among these, the Trojan Horse Method (THM) has been applied to determine these cross sections overcoming the Coulomb barrier. With this approach, a low-energy binary reaction cross section can be obtained selecting the quasi-free contribution from a suitable three-body reaction cross section, taking advantage of the cluster structure of proper nuclei.

Keywords: neutron induced reactions, stellar evolution, nucleosynthesis, indirect process, s-process

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1 INTRODUCTION

Neutron capture nucleosynthesis is the main responsible for the production of elements heavier than Fe. Such a process can be rapid (r-process) or slow (s-process), according with the comparison between the neutron capture reaction (n,γ) rates of the involved nuclei and their half-lives [1], but anyway they are a series of subsequent neutron captures, separated by $\beta-$ decays. Therefore, the rapidity of the process is determined by the intensity flux of neutron available in the stellar environment in which occurs.

In recent years, nuclear astrophysicists focused their attention to the s-process relevant cross sections, also considering that r-process abundances can be obtained by the s-process ones [2]. The s-process nucleosynthesis follows a path that wanders along the valley of β-stability close to the strongly bound isotopes of a given atomic weight (or mass number) A. The main site of the slow neutron captures is the final Asymptotic Giant Branch (hereafter AGB) phase of low- and intermediate-mass stars. Stars with mass up to 3 $M_\odot$ are actually responsible for the production of the main component of the s-process (i.e., nuclei from Sr to Bi) and the main neutron source is known to be the ^{13}C(α,n)^{16}O reaction [3]. It operates at typical energies of 8 keV in radiative conditions and provides a neutron density of about 10^6–10^7 n/cm^3 [4,5]. The ^{22}Ne(α,n)^{25}Mg reaction is the second neutron source in AGB stars and it is activated only marginally during the *thermal pulses* (periodic episodes of He-convective burning) in low mass stars. Only red giants more massive than 3 $M_\odot$ (the intermediate mass stars) burn ^{22}Ne efficiently, at maximum temperatures of 3–3.2 $\cdot$ 10^8 K. Even stars with larger masses, terminating their evolution as core-collapse Supernovae, are sites of s-process nucleosynthesis, and in particular they are responsible of the so-called weak component, namely that devoted to the production of nuclei with A $\leq$ 85 [6].

The s-process is considered as being a rather well-known nucleosynthesis mechanism because 1) its main component occurs in common astrophysical objects and 2) neutron capture reactions are not hampered by the Coulomb barrier. This fact makes the most of (n,γ) reactions relatively easy to be studied experimentally. However, there are still theoretical problems to be understood ([7]), as like as the ^{19}F abundance in AGB stars [8]. Thus, some nuclear reactions cross sections need to be measured with high precision in the energy range of AGB star nucleosynthesis, where objective experimental difficulties are present. Among them, we appoint:

1. Reactions delivering the neutrons for the s process, in particular ^{13}C(α,n)^{16}O (**Section 3**) and ^{22}Ne(α,n)^{25}Mg (**Section 4**), whose cross section determination is affected by the well-known problems in measuring the reactions between charged particles at low energy [9,10];
2. Neutron capture reactions on unstable nuclei, whose half-lives are characterised by time-scales close to those corresponding to neutron capture rates and thus might constitute branching points of the s-nucleosynthesis path;
3. Neutron capture reactions on the so-called poisons of the s-process, i.e. those relatively light nuclei that, having a very large neutron capture cross section, can absorb the neutrons delivered by the ^{13}C(α,n)^{16}O and the ^{22}Ne(α,n)^{25}Mg reactions, subtracting them to the s-nucleosynthesis. Among the poisons of the s-process we recall the ^{14}N, the $^{16-17}$O and the $^{25-26}$Mg. For reactions like ^{14}N (n,p)^{14}C or ^{17}O(n,α)^{14}C (**Section 5**), a precision study of these reactions is very hard to perform, owing to the non-existence of a pure-neutron target and to the current unavailability of a neutron beam facility with sufficient energy precision.
4. $\beta-$ decays of the nuclei involved in the s process in stellar plasma conditions are estimated only by theoretical calculations. A crucial contribution in this field will be provided by future experiments such as those planned at the PANDORA project [11,12], for which we refer to the specific paper in this volume.

Thanks to the indirect Trojan Horse Method (THM), described in the following section, one can extract the cross sections at the ultra-low energies of astrophysical interest for charged particle induced reactions, where this is made almost impossible by the Coulomb barrier presence. In more recent years, the method has been largely tested and applied with success to shed light on different problems, such as the different levels contributions to the cross sections [13,14], for neutron induced reactions [15–21] and for reactions induced by unstable beams [22,23], thus helping in solving the experimental difficulties of points 1 to 3.

2 THE TROJAN HORSE METHOD

The idea at the base of THM is to obtain the binary reaction cross section of interest for astrophysics $a + x \to c + C$, by measuring the reaction cross section of a given $A + a \to c + C + s$ quasi-free (QF) break-up reaction.

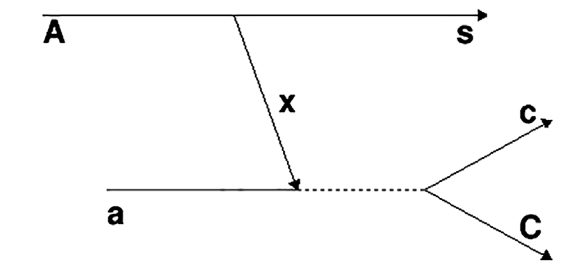

FIGURE 1 | Sketch of the polar diagram representing the TH process.

This is possible if we use a suitable nucleus A (called TH nucleus) that has a high probability to be found in a x-s cluster configuration, so that $A = x \oplus s$. The QF break-up of A occurs if, in the interaction between A and a, in the exit channel s keeps the same momentum distribution before its break-up. In this case s is the *spectator* to the virtual process $a + x \to c + C$ [24]. It has been experimentally demonstrated that changes in the Trojan Horse nucleus are not impacting the applicability of the THM, despite the change in the spectator cluster for example from a charged to a neutral particle [25,26]. **Figure 1** represents a sketch of the TH process, where it is possible to apply the polar approximation [27] only for small spectator momenta p_s respecting the relation in [28].

The possibility to reach ultra-low energies is given by the binding energy E_B of x inside A, which compensates for the beam energy [29–31]. One of the advantages of the THM is that, using only one beam energy, the variation of the spectator momentum values inside the limit in [28] makes it possible to scan almost the entire energy range of interest.

Once the QF break-up data have been selected from all other reaction mechanisms with the same final state, in the Plane Wave Impulse Approximation (PWIA) the three-body cross section can be factorized as:

$$\frac{d^3\sigma}{d\Omega_c d\Omega_C dE_C} \propto KF|\phi(p_s)|^2 \left(\frac{d\sigma}{d\Omega}\right)_{Cc}^{HOES} \quad (1)$$

where the phase space is taken into account by the kinematical factor KF and $|\phi(p_s)|^2$ is the squared Fourier transform of the radial wave function describing the intercluster motion inside the TH nucleus. The factor KF $\cdot|\phi(p_s)|^2$ is calculated by means of a Montecarlo simulation where the momentum distribution has a width fixed to the value measured experimentally, to account for the distortion effects arising at low transferred momenta [32,33].

The extracted $(d\sigma/d\Omega)^{HOES}$ obtained inverting **Eq. (1)** is denoted half-off-energy-shell (HOES), being x virtual and then the entrance channel off-shell, while the exit channel in on-shell (OES). This cross section has to be corrected for the penetration factor, that in case of n-induced reaction is only relative to the centrifugal barrier, and then it has to be normalized to direct data at energies higher than the Coulomb barrier, where the HOES and OES cross sections are proportional.

Details and reviews of the THM can be found in [34,35].

3 THE $^{13}C(\alpha,n)^{16}O$ NEUTRON SOURCE FOR THE MAIN COMPONENT

The main s-process neutron source has been singled out in AGB stars where, following the injection of protons from the outer layers into the carbon- and helium-rich shell, they are captured by carbon nuclei, leading to the formation of a ^{13}C pocket [36]. Then, at typical temperature range between 0.8×10^8 K and 1×10^8 K [3], ^{13}C is burnt through the $^{13}C(\alpha, n)^{16}O$ reaction producing neutrons. Such temperatures correspond to $^{13}C - \alpha$ center-of-mass energies of about $E_{13C-\alpha} \sim$ 140–230 keV. A recent review can be found in Xu et al. [37] and besides, theoretical evaluations are available, using microscopic cluster approach, leading to results in good agreement with the experimental data in [38] and in [39]. It is worth noting that the crucial role of the $\frac{1}{2}$+ subthreshold state was already foreseen in [38] despite of the absence of very low energy data at the time.

Owing to its astrophysical importance, the $^{13}C(\alpha, n)^{16}O$ reaction has been the subject of many direct and indirect studies. Indirect methods are mandatory since direct measurements could not span so far the energy window of astrophysical interest, which lies between 150 and 230 keV. For instance, the most recent direct measurement [40] could only reach about 230 keV in the center of mass system. Extrapolations to even lower energies are then necessary to establish the trend of the $^{13}C(\alpha, n)^{16}O$ astrophysical factor inside the Gamow window. However, the understanding of the astrophysical region of the S-factor is complicated by the interplay between the rise due to the ^{17}O 6.356 MeV $1/2^+$ level and the enhancement due to the electron screening effect (see e.g. La Cognata et al. [41] and references therein). The latter introduces a correction of about 20% at the lowest-energy data point of Drotleff et al. [42] at 279 keV, growing up exponentially approaching the energy region of astrophysical interest. Yet, larger uncertainties are introduced by the occurrence of the 6.356 MeV broad resonance in ^{17}O. Indeed, until 2015 [43], it was commonly assumed that the aforementioned $1/2^{+17}O$ state was lying −3 keV below the $^{17}O \rightarrow ^{13}C + \alpha$ dissociation threshold [44]. Precision spectroscopy studies [43] have shown that the location of such near-threshold resonance should be 4.7 keV above the $^{17}O \rightarrow ^{13}C + \alpha$ dissociation energy.

An additional challenge for direct measurements is the determination of the absolute value of the $^{13}C(\alpha, n)^{16}O$ astrophysical factor, since neutron detectors are often used to measure the cross section. Already in Heil et al. [45], the scatter of the absolute normalizations of existing data was evident and as large as a factor two. This spread was realistically attributed to systematic errors affecting neutron detection efficiency as a function of its energy. This is the reason that lead Heil et al. [45] to measure the experimental detection efficiency using a setup identical to the one used for the study of the $^{13}C(\alpha, n)^{16}O$ reaction and to cross check the results using a GEANT4 simulation. Then, the obtained astrophysical factor was used to scale existing $^{13}C(\alpha, n)^{16}O$ data sets. Earlier THM studies of this reaction used the Heil et al. [45] astrophysical factor for normalization.

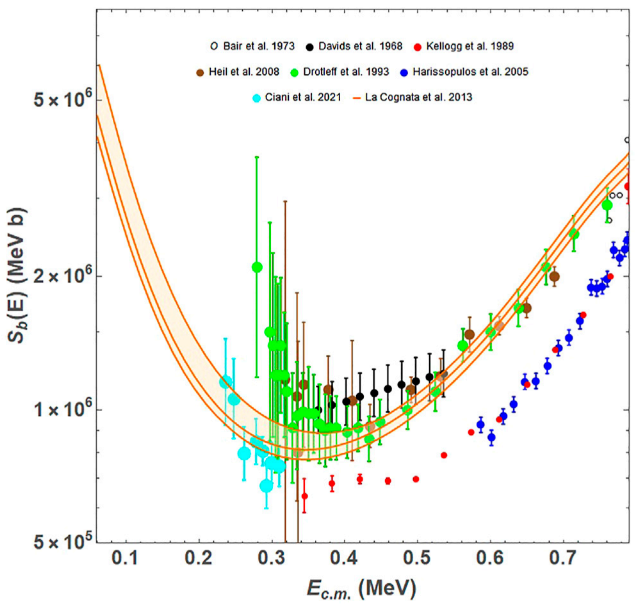

FIGURE 2 | Comparison of S(E)-factor obtained in Trippella and La Cognata [48] (orange band) with direct measurements: cyan solid circles are from Ciani et al. [40], black from Davids [58], open circles from Bair and Haas [59], red from Kellogg et al. [60], green from Drotleff et al. [42], blue from Harissopulos et al. [61], brown from Heil et al. [45].

In the THM framework, the $^{13}C(\alpha, n)^{16}O$ S-factor was extracted from the $^{13}C(^6Li, n^{16}O)^2H$ QF cross section, measured at 8 MeV beam energy. With this method, neither Coulomb nor centrifugal barriers quell the cross section and electron screening does not shield the $^{13}C - ^4He$ interaction. However, astrophysical energies could be reached thanks to the energy spent to break ^6Li into to the $\alpha - d$ system as well as to their relative motion. Details on the THM measurement can be found in La Cognata et al. [46,47]. A drawback of the THM is the need of normalization to existing direct data. In those works, the $E_{13C-\alpha}$ energy region between ~ 0.6 – 1.2 MeV was selected, namely a region where the contribution of the threshold state is negligible.

While a THM S-factor in good agreement with the direct ones scaled to match the Heil et al. [45] absolute value was found, a Coulomb modified Asymptotic Normalization Coefficient (ANC) [47] for the $1/2^{+17}O$ threshold state equal to $7.7 \pm 0.3_{stat}{}^{+1.6}_{-1.5}{}_{norm}$ was determined, contradicting the existing independent assessments of the Coulomb modified ANCs, whose weighted average is 3.9 ± 0.5 fm^{-1}. This may be attributed to the systematic errors affecting direct data absolute normalization. This fact triggered further studies, which ended up in the work of Trippella and La Cognata [48]. Indeed, to unequivocally size the contribution of the ^{17}O threshold state to the reaction rate, many coherent measurements of its ANC were carried out [49–52].

The ANC method is another powerful indirect method meant to extract the direct radiative part of the cross section for reactions of importance for astrophysics: with this technique, in principle, it is in fact possible to study (p,γ), (n,γ) and (α, γ) reactions of astrophysical importance using p-, n- or α-transfer. Such transfer, at low energies, must show a mostly peripheral character, and such a condition must be verified experimentally. The difference between ANC and THM lies in which kind of reaction can be studied–direct and resonant capture, respectively–and in the reaction products: the ANC method, in fact, can be applied just for reactions that have γ-rays in the exit channel (see also [53] for a recent review on the ANC and, particularly [54], for proton [55], for neutron and [56] for alpha captures at low energies from suitable transfer reactions, also using mirror nuclei [57]).

Therefore, a change in the paradigm usually adopted in the THM application was implemented and the THM S-factor was normalized to the ANC of 6.356 MeV state. This approach lead to a concordance scenario for the $^{13}C\,(\alpha, n)^{16}O$ S-factor, where both direct (some data sets with a more appropriate normalization) and indirect data (both ANC and THM) accurately agree.

With the normalization of Trippella and La Cognata [48], the astrophysical factor in **Figure 2** (shown as an orange band upper, where middle and lower orange lines are used for recommended + 1σ, recommended and recommended − 1σ THM S-factor) was deduced. An ANC of 3.6 ± 0.7 fm^{-1} has been determined, in perfect agreement with the weighted average of the results in the literature. The corresponding THM S-factor at $E_{c.m.}$ = 140 keV was found to be $1.80^{+0.50}_{-0.17} \times 10^6$ MeVb, to be compared with the astrophysical factor in Heil et al. [45] $S(140\,\text{keV}) = 2.2^{+1.1}_{-0.8} \times 10^6$ MeVb. More details can be found in Trippella and La Cognata [48]; a recent direct measurement reported in Ciani et al. [40] has confirmed such results, as it is clearly demonstrated in **Figure 2**, where other direct measurements with their original normalizations are shown.

4 THE ^{22}NE(α,N)^{25}MG NEUTRON SOURCE FOR THE WEAK COMPONENT

A key role in the s-process is played by the $^{22}Ne(\alpha,n)^{25}Mg$ reaction, the major neutron producer for its weak component (60 < A < 0) in massive stars, influencing all the late evolution of stars, until their death. Despite of the importance of this reaction, in the energy region of astrophysical interest (E_{cm} = 600 ± 300 keV) three orders of magnitude discrepancies in the cross section of data available in literature are still present, making those data essentially not useful for astrophysical needs [62].

The trend of the excitation function measured so far shows a steep drop in the yield which makes it possible to provide only upper limits to the cross section already at center-of-mass energies of the order of 800 keV, that is at the edge of the region of interest. A clear picture of the status of the art can be found in [63]. Indeed, direct measurements at such low energies are very challenging due to the exponential Coulomb damping (Coulomb barrier is located at 3.5 MeV) of the cross section to values less than 1 μb, pushing the signal-to-noise ratio essentially to zero.

Indirect measurements, such as capture and transfer reactions [63], at low energy are thus needed to supply resonance parameters, such as spectroscopic factors, to be used in the calculation of the reaction rate. In this regard, a recent paper [10] recalculated the reaction rates of $^{22}Ne(\alpha,n)^{25}Mg$ and its competitor $^{22}Ne(\alpha,\gamma)^{26}Mg$, updating energies and spin-parities of all the ^{26}Mg levels, particularly focusing on the results in [64], obtained with $^{22}Ne(^{6}Li,d)^{26}Mg$, and $^{22}Ne\,(^{7}Li,t)^{26}Mg$ transfer reactions. The authors find that, excluding the results in [64], s-process nucleosynthesis will not substantially change, but including them leads to a better agreement of Ba and Zr isotopic ratios with the data from presolar SiC grains. However, the results reported in [10,64] suggest the need for further measurements, particularly focusing on the excitation function trend, to include also levels interference in the reaction rate evaluation.

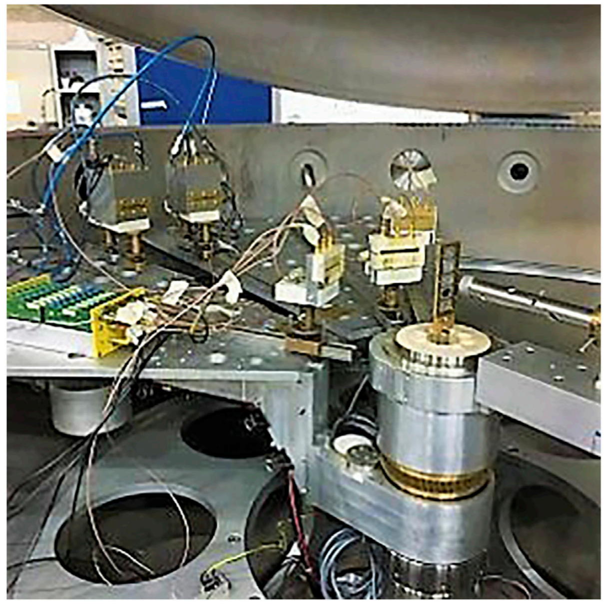

FIGURE 3 | Setup of one of the experimental runs of the Magn-a experiment in Catania, at LNS, aimed to perform the $^{2}H(^{25}Mg,\alpha p)^{22}Ne$ reaction to extract the $^{22}Ne(\alpha,n)^{25}Mg$ cross section with the THM and the detailed balance principle.

To try to deal with this issue, a new measurement was performed at INFN-LNS of Catania (Italy), aimed at bypassing the challenges that prevented to obtain the result until now. To avoid problems related to the poor efficiency in neutron detection, the idea was to obtain the desired cross section applying the detailed balance principle to the inverse reaction: $^{25}Mg(n,\alpha)^{22}Ne$. Then, to avoid the use of neutron beam (and the consequent worsening of the energy resolution) the THM was used, exploiting the well-known p-n structure of the deuteron, used as neutron virtual source. The experiment to measure the 3-body $^{2}H(^{25}Mg,\alpha p)^{22}Ne$ cross section was performed in the Camera2000 scattering chamber, because of its 1 m radius that allowed to put detectors as far as it was needed to keep a good angular resolution to apply the THM. In **Figure 3** is evident how the use of THM also helped to bypass complex setups. Moreover, THM allowed the use of thin CD_2 targets, to minimize the beam energy spread on the target. The first ^{25}Mg beam of LNS was accelerated with the Tandem accelerator for this experiment.

This measurement was performed with two different experimental approaches, and thus setups. At first, coincidences between α particles and the spectator proton, using Position Sensitive Detectors (PSD), were detected, reconstructing the ^{22}Ne kinematics offline, identifying the desired ions with ΔE-E technique using thin PSD (35 μm thickness) as ΔE stage. Dealing with the very low energy of the spectator proton below 1 MeV, forced to reduce the acquisition system threshold to its minimum. The second approach tried was to detect ^{22}Ne and α particles in coincidence, reconstructing the proton kinematics offline. This has implied to change beam energy to stay focused on the region where QF kinematics is most probable, as required by THM, from $^{(7+)25}$Mg at 74 MeV to $^{(6+)25}$Mg at 50 MeV. The ΔE stage PSDs were substituted with two Ionization Chambers (5 cm deep), filled with isobutane (p = 65 mb) to detect and separate ^{22}Ne. The analysis of these data is still ongoing and additional validity tests are mandatory in order to safely apply THM to this specific case.

It is worth noting that many other possibilities of indirect measurements can be considered. The possible extension of the THM to p-wave intercluster motion nuclei could open the doors to the use of ^{23}Ne as TH nucleus for its ^{22}Ne + p configuration, and another good candidate TH nucleus can be the ^{26}Mg as ^{22}Ne+α in s-wave. In any case, the possibility of new highly ^{4}He-enriched solid targets obtained with NESTOR [65], the new ECR ion source at LNS, will be pivotal for these measurements.

5 NEUTRON POISONS REACTIONS

The presence of certain nuclei lighter than Fe produced in the previous stages of stellar evolution, causes the capture of a large fraction of the neutrons produced by the ^{13}C(α,n)^{16}O and ^{22}Ne(α,n)^{25}Mg reactions. These neutron poisons reactions significantly constrain the *s*-process efficiency [1]. As an example, due to the large abundances of ^{12}C and ^{16}O, the ^{12}C(n,γ)^{13}C and ^{16}O(n,γ)^{17}O reactions are serious neutrons consumer, removing a non-negligible fraction of the produced neutrons [5].

5.1 The ^{17}O(n,α)^{14}C

In massive stars (with initial mass $M > M_{\odot}$), due to the high abundance of oxygen from CNO cycle, one of the most important neutron poison reaction is the ^{16}O(n,γ)^{17}O [66]. The ^{17}O produced by the ignition of this reaction can undergo the ^{17}O(α,n)^{20}Ne reaction, that represents a recycling channel for neutrons, or the ^{17}O(n,α)^{14}C reaction that is another neutron-absorbing reaction [67]. Thus, in order to establish the total neutron flux available for the so-called weak s-process pathway, it is of fundamental importance to ascertain the ratio between the cross sections of the aformentioned reactions. For this reason, the ^{17}O(n,α)^{14}C reaction has triggered several measurements with direct experiments and by applying the detailed balance principle to the inverse reaction [68–72]. The population of two excited

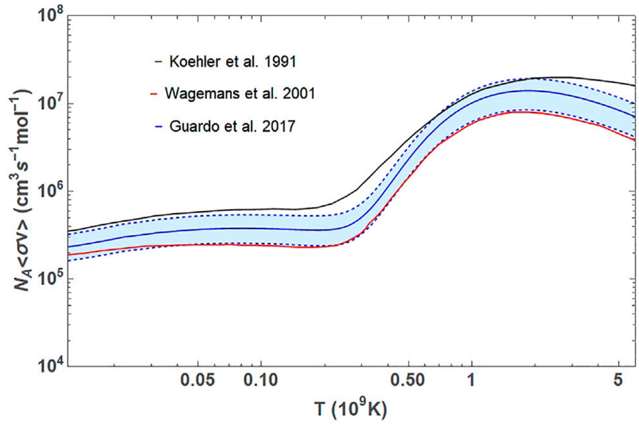

FIGURE 4 | THM reaction rate for the ^{17}O (n,α)^{14}C reaction (blue line) in comparison with the ones available in literature (see text for details).

states at 8,213 keV and 8,282 keV and the contribution of a sub-threshold level at 8,038 keV are present in the available data, while no evidence for the 8,125 keV level is shown [73]. Indeed, the contribution of this resonance is suppressed by the centrifugal barrier, since this resonance is populated in *f*-wave. In addiction, in the astrophysically relevant temperature region, the reaction rate calculated from measurements available in literature, is affected by a difference of about a factor of 2.5–3, due to disagreement present in the different data sets [71].

For such a reason, two THM measurements were performed at different laboratories, namely at LNS-INFN in Catania (Italy) and at ISNAP (Institute for Structure and Nuclear Astrophysics) in Notre Dame (IN—United States). The experiments were devoted to the measurement of the cross section of the ^{2}H (^{17}O,α^{14}C)p three-body reaction to cover the energy range from zero up to a few hundred keV in the binary reaction center-of-mass energy [74,75]. A ^{17}O beam of 41 (43.5) MeV was delivered onto a CD_2 target in the LNS (ISNAP) experiment.

In order to probe the presence of the QF reaction process, the procedure described in [74,75] was followed, finally extracting the HOES cross section of the ^{17}O (n,α)^{14}C reaction.

The experimental data of the two data sets, weighted over the respective errors and summed in order to improve the statistical precision, were then normalized to the available direct measurements [71], integrated to the angular distribution and fitted following the modified R-matrix approach [76] in order to calculate the reduced γ-widths of the excited levels. Thus, the calculated reaction rate is shown in **Figure 4** with a blue line, while the blue band highlights the region allowed by uncertainties (statistical and normalization). In comparison, reaction rates from [69] (black line) and [71] (red line) are reported.

In this measurement, it was possible to excite the sub-threshold level centered at −7 keV in the center-of-mass system corresponding to the 8.039 MeV level of ^{18}O, which is important to determine the ^{17}O(n,α)^{14}C reaction rate. In addiction, it was found that the resonance corresponding to the 8.213 MeV level is better reproduced by adopting an angular momentum l = 2 instead of l = 0, as assumed in the past [68]. This result triggered the need of a new experiment with an improved detection setup and a wider angular coverage, whose analysis is still ongoing [77]. Finally, the use of deuteron as source of virtual neutrons allows us to populate the level centered at 75 keV in the ^{17}O-n center-of-mass system, corresponding to the 8.121 MeV level of ^{18}O. Due to its 5^- J^π assignment, the population of such level is suppressed in direct measurements because of its $l = 3$ angular momentum. The application of the modified R-matrix approach made it possible to measure the neutron and α partial widths that are in agreement with the ones available in the literature, while these partial widths were extracted for the first time in the case of the 8.125 MeV level. Therefore, extensive calculations are ongoing in order to understand the precise impact of the present results on astrophysics.

5.2 The ^{14}N(n,p)^{14}C

^{14}N is very abundant in stars, due to its production during the stage prior to the *s*-process, namely the hydrogen-burning in the CNO cycle. Thus, with its relatively high cross section, this reaction represents a strong neutron poison, especially in low-mass AGB stars [78]—thus for the main component elements production. Moreover, ^{14}N is of crucial importance in the nucleosynthetic origin of fluorine and the He-burning shell in AGB stars is thought to be the most likely site for this synthesis, mainly through the nuclear chain ^{14}N(α,γ)^{18}F(β^+) ^{18}O(p,α) ^{15}N(α, γ)^{19}F. In this sense, the ^{14}N(n,p)^{14}C reaction plays a key role because of its double effect of removing neutrons and producing protons. In addition, the protons can trigger the ^{18}O(p,α)^{15}N or the ^{13}C(p,γ)^{14}N reactions, being the last one in competition with the ^{13}C(α,n)^{16}O reaction [5].

The first direct measurement of the stellar ^{14}N (n,p)^{14}C cross section was done by [79]. Their result for the reaction rate was about a factor three smaller than the rate used in most of the previous s-process calculations, but it was also 2–3 times smaller than rates estimated from the inverse reaction and extrapolations from the thermal cross section, for which an evaluated value of 1.83 b was adopted. Indeed, measurements performed from thermal neutron energy up to 35 keV [80,81] found clear evidence for a 1/v behavior of the ^{14}N(n,p)^{14}C reaction cross section up to approximately 30 keV and also their results for the stellar reaction rate at kT = 525 keV are about a factor of 3 higher than reported by [79]. Measurements with quasimonoenergetic neutrons at 25 keV from [82] are in fair agreement with the results from [80,81] and with the estimates from the inverse reaction, since again the same thermal value was used for the normalization. Another direct measurement of the ^{14}N (n,p)^{14}C stellar cross section at kT = 525 keV was done by [83]. The authors found a value approximately a factor of 2 higher than [79] and a rather good agreement with the other results. In 1999 a new measurement at neutron energies of 35.8 and 67.1 keV by [84] supports the previous measurements but have rather large (20 and 12%, respectively) uncertainties. In 2000 [85] determined at the high flux reactor of the ILL in Grenoble an accurate value of (1.93 ± 0.05) b for the ^{14}N(n$_{thermal}$,p)^{14}C cross section, that is in good agreement with some results present in literature but differs by 10% with the lower extreme value.

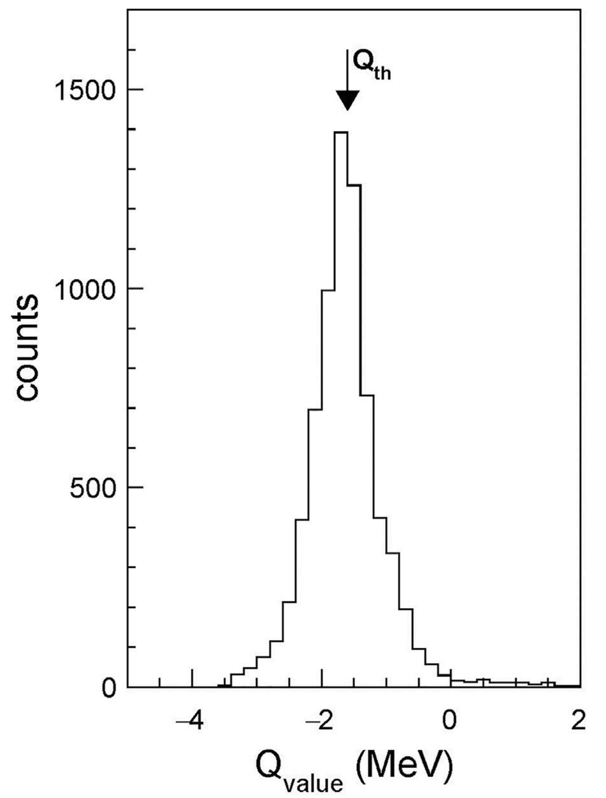

FIGURE 5 | The experimental Q-value for the selected ^{2}H(^{14}N,p ^{14}C)p events. The black arrow correspond to the theoretical Q value, Q_{th} = -1.6 MeV.

For this reason, a careful new evaluation is needed and the THM was applied to determine the cross section of the ^{14}N (n,p) ^{14}C reaction by selecting the QF contribution to the ^{2}H(^{14}N,p ^{14}C)p reaction. The experiment was performed at INFN-LNS where the SMP Tandem accelerator provided a 40 MeV ^{14}N beam on deuterated polyethylene target (CD_2) of about 150 μg/cm^2 was placed at 90°with respect to the beam axis. The reaction channel selection has been performed *via* the prior selection of the Z = 6 locus in the ΔE-E telescope and the full kinematic reconstruction of the selected events with the hypothesis of an unitary mass for the third undetected particle.

The experimental Q-value spectrum has been reconstructed and the result is shown in **Figure 5**. The spectrum is centered at −1.61 MeV, showing a FWHM of about 130 keV, reflecting the energy loss of the incoming beam in the 150 μg/cm^2 CD_2 thick target. The experimental value nicely overlaps the expected one of −1.599 MeV, thus showing the correct selection of the reaction channel. Further studies on these data, presently under way and beyond the scope of this article, will be published in near future.

6 CONCLUSION

The use of THM is helping in achieving neutron producers and poisons reaction cross sections at energies relevant for the s-process in stars, where they are otherwise unreachable, because of the Coulomb barrier presence or the struggling with the neutron detection.

For $^{13}C(\alpha,n)^{16}O$ the results obtained with THM has already moved forward our knowledge in this sense, as it summarized in Trippella and La Cognata [48]. On the contrary, much work remains to be done for $^{22}Ne(\alpha,n)^{25}Mg$, where the results of an ongoing analysis of a TH measurement can boost our knowledge on its reaction rate. This has not been found out yet, despite of recent indirect measurements clarifying the role of crucial levels in ^{26}Mg. The same holds for the neutron poisons reactions, which affect the neutron flux available for the s-process nucleosynthesis, mainly $^{17}O(n,\alpha)^{14}C$ and $^{14}N(n,p)^{14}C$. Also in these cases, ongoing analysis on TH measurements will help in completing the picture of our understanding of the neutron involving reactions in the stellar plasma.

Thus, the overall s-process nucleosynthesis understanding can be strongly constrained by the results of these reaction rates, jointly with the measurements of half-lives of radioactive nuclei at the s-process path branching points.

AUTHOR CONTRIBUTIONS

RS, MLC, GLG, SP, and MLS wrote the paper. All the coauthors participated to the experiments described in the paper and revised the paper itself. Experimental data were analyzed by MLC, RS, GLG, and MLS for $^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,n)^{25}Mg$, $^{17}O(n,\alpha)^{14}C$ and $^{14}N(n,p)^{14}C$, respectively.

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