Shedding light on ^{17}O(n,α)^{14}C reaction at astrophysical energies with Trojan Horse Method and Asymptotic Normalization Coefficient

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Abstract. The ^{17}O(n,α)^{14}C reaction plays a critical role in astrophysical nucleosynthesis, particularly influencing the s-process in stellar environments. Due to the limitations of direct measurement techniques, indirect methods such as the Trojan Horse Method (THM) and Asymptotic Normalization Coefficient (ANC) analysis are employed to study this reaction at astrophysical energies. This paper discusses the application of THM and ANC to derive the reaction cross sections and explore the contributions of various resonant states of ^{18}O. The results obtained from these indirect methods are consistent and provide new insights into the reaction mechanisms, enhancing our understanding of neutron capture processes and neutron poisons in stars. The findings also demonstrate the effectiveness of combining THM and ANC for studying neutron-induced reactions, potentially facilitating future research using Radioactive Ion Beams (RIBs). This work underscores the importance of indirect measurement techniques in advancing nuclear astrophysics, particularly where direct measurements are challenging.

1 The Astrophysical Scenario

Stellar nucleosynthesis processes are fundamental in nuclear physics, serving as the primary mechanisms for the production of nuclei with mass numbers $A \geq 12$ [1]. While elements with $A \leq 52$ are mainly obtained through thermonuclear fusion processes, heavier elements are produced via neutron capture reactions, such as those involved in the s-process and the r-process.

The s-process is mainly responsible for the synthesis of those heavy elements that can be found near the nuclear stability valley, which represents nearly half of all heavy nuclei. In the context of the s-process, it is possible to distinguish two different components: the so-called main component, which occurs mainly in AGB stars ($1.3M_\odot \leq M \leq 8M_\odot$)[2, 3], and the weak component, which usually occurs in massive stars ($M \geq 8M_\odot$).

The main neutron source for the weak component of the s-process is the ^{22}Ne$(\alpha, n)^{25}Mg$ nuclear reaction, which ignites in two different scenarios in massive stars [2]: during the helium burning at $T_c \sim 1.6 \times 10^8 K$ and during the carbon burning at $T_c \sim 1.1 \times 10^9 K$. However, in the same environment other reactions, the so-called "neutron poisons", can occur.

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Therefore, to study the reactions involved in those processes, the neutron abundance available in the stellar environment of interest should be precisely known. Specifically for the weak component of the s-process, one of the main neutron poisons is the radiative capture reaction $^{16}O(n,\gamma)^{17}O$. However, once formed, the ^{17}O nucleus can follow various competing pathways, among which there is the $^{17}O(\alpha, n)^{20}Ne$ reaction, which recycles a neutron, and the $^{17}O(n,\alpha)^{14}C$ reaction, that is once again a neutron poison. Accurate knowledge of the relative occurrence of these two reactions is thus crucial for correctly assessing the neutron abundance.

2 Direct methods: status of art and limits

Presently, there are three direct measurements available in the literature [4–6] of the $^{17}O(n,\alpha)^{14}C$ reaction and two direct measurements [7, 8] of the reverse reaction $^{14}C(\alpha,n)^{17}O$. In the data from Wagemans et al. [6] and Bair et al. [8] two resonant structures are clearly present, which are also vaguely represented in the data of Sanders et al. [7], however, below approximately 150 keV in the center-of-mass frame, the absolute scale of the available data is not consistent. Moreover below 1 keV, an increase in the cross section can be observed both in the data of Koehler and Graff [4] and Wagemans et al. [6] that, as already proposed by the authors, can be linked to the presence of a subthreshold resonance, that can not be easily studied via direct measurements.

These measurements show how, despite the enormous technological and scientific developments in the field, direct measurements of neutron induced reactions still present numerous experimental challenges. Since pure neutron targets do not exist, the only possible choices are to either work with a neutrons beam or to detect neutrons in the exit channel of the reaction. Accelerating neutrons is undoubtedly challenging still today and requires dedicated facilities, which in turn push for the study of inverse reactions. While many techniques are available for measuring the energy of neutrons, the resolution may not always be ideal for the purpose.

3 Indirect Methods

In the field of nuclear astrophysics, where reactions must be studied under challenging experimental conditions not easily reproducible in a laboratory settings, indirect methods offer a viable alternative and complementary approach, that can circumvent the complexities associated with direct measurements. This approach not only broadens the scope of research but also enhances the precision of direct data already available. In this work we will discuss about and use two of the most used indirect methods for nuclear astrophysics: the Trojan Horse Method and the Asymptotic Normalization Coefficient.

3.1 Trojan Horse Method

The Trojan Horse Method (THM) is based upon the theoretical framework of Quasi-Free (QF) break-up reactions. It studies the cross-section of a specific three-body reaction, $a+A \rightarrow b + B + s$, to evaluate the cross-section of the target two-body reaction, $x + A \rightarrow b + B$, at sub-Coulomb energies. In THM, the Trojan Horse (TH) nucleus a is assumed to exhibit a well-clustered state with a $x + s$ configuration. Notably, this method offers the advantage of the two-body reaction occurring without encountering Coulombian and centrifugal barriers, as well as avoiding electron screening effects. Additionally, under Quasi-Free conditions with a fixed beam energy, the THM allows for the exploration of a broad energy range by leveraging intercluster motion, even extending to the sub-threshold region. The method has been largely applied to study reactions of interest for nuclear astrophysics induced both by charged particles[9, 10] and neutrons [11, 12]. For a comprehensive understanding of the method and its underlying physics, readers are directed to Ref. [13, 14] and the references therein. The Trojan Horse Method (THM) has been applied to the ^{17}O(n,α)^{14}C reaction, as discussed in Ref. [15, 16]. These measurements confirms the contribution of the 8213 keV and 8282 keV resonant levels of the intermediate ^{18}O system, already shown in direct measurements. Moreover, they also clearly show the contribution of the 8125 keV resonant level, which is usually suppressed in the direct measurements due to the large (ℓ=3) angular momentum required for its population in the entrance channel, and the sub-threshold 8038 keV resonant level. For both these states, information about the corresponding neutron Γ_n and alpha partial widths Γ_α are now available. Building on this, a novel experiment using the Asymptotic Normalization Coefficient and aimed at examining these ^{18}O resonant states has been carried out.

3.2 Asymptotic Normalization Coefficient

The Asymptotic Normalization Coefficient (ANC) is a crucial nuclear property in the context of nuclear reactions. It quantifies the extent of the overlap between the bound-state wave function of the initial and final nuclei. Specifically, the ANC method enables us to determine the cross section for a peripheral direct capture reaction, denoted as (A(a,γ)B), by evaluating the radial overlap integral involving the (X) and (B) nuclei from the (A(X,Y)B) transfer reaction. In this framework, we treat the nuclei (X) and (A) as (X = Y + a) and (B = A + a), respectively. Over the past two decades, this method has found widespread application in studying proton, neutron, and α direct captures within stellar environments, see as an example [17]. For more details about the method and its application to nuclear astrophysics we direct the readers to Ref. [18] and references therein. To determine the ANC for the resonant states of the intermediate system ^{18}O, the ^{17}O(d,p)^{18}O reaction and the ^{17}O+d elastic scattering have been studied, choosing the deuteron due its simple p+n structure. The results [19] show a reasonably strong concordance between the ANC calculations and the direct data for energies over 150 keV in the center-of-mass frame. Below this threshold, as already said, direct data are not consistent with each other and the ANC calculations show a marked decrease in the cross section, linked to the lack of an accurate assessment of the subthreshold level. Moreover, it is possible to also compare these results with those obtained from the application of the THM. In particular, in Table 1 it is possible to see the comparison between the total width (Γ_{tot}) values for the ^{18}O level states obtained from the THM measurement [15] and those obtained from the ANC measurement [19]. Meanwhile in Fig. 1 it is possible to see the plot of the corresponding R-matrix calculation for both the THM and ANC analysis. Once again, the comparison show a good agreement between the two method, further highlighting the possibility to use independent ANC studies to validate the results obtained via the THM, and vice versa.

4 Conclusion

In this contribution we have reported the application of two indirect methods to the study of the ^{17}O(n,α)^{14}C reaction. The results of both indirect methods are consistent, within the limits given by the data uncertainty. This paves the way for opening new frontiers for experiments, particularly in the realm of neutron-induced reactions with Radioactive Ion Beams (RIBs) which is still experiencing a scarcity of direct experimental data, primarily due to the technical challenges associated with the concurrent generation of neutron and radioactive beams.

Table 1. Comparison between the total width (Γ_{tot}) values for the ^{18}O level states obtained from the THM measurement [15] and those obtained from the ANC measurement [19]

$E_{c.m.}$ (keV)	-6	75	178	244
Γ_{tot} THM [15] (MeV)	2400±300	36±5	2200±300	13000±3400
Γ_{tot} ANC [19] (MeV)	N.A.	33±6	2150±420	16670±3350

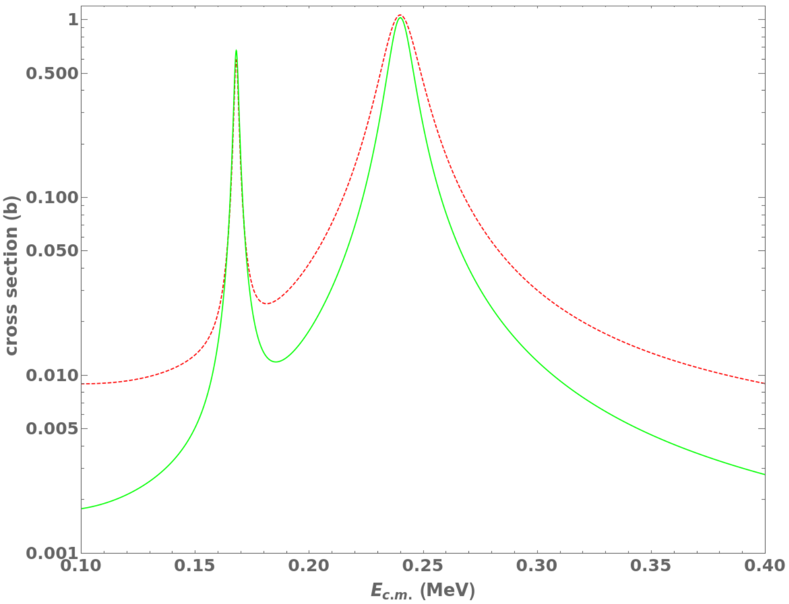

Figure 1. Plot of the R-matrix calucation using the resonance parameters coming from the THM data analysis (green continuous line) and ANC data analysis (red dashed line).

Thus, the consistency of ANC and THM results not only provides a robust cross-verification mechanism but also could be a key factor in the expansion of research capabilities in nuclear astrophysics studies, where direct measurements have been historically difficult.

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