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Study of the neutron-induced reaction $^{17}\mathrm{O}(n,\alpha)^{14}\mathrm{C}$ at astrophysical energies via the Trojan Horse Method

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Summary. — Stellar nucleosynthesis processes are of vital importance for nuclear physics: all the heavy elements are created by neutron capture reactions that take place in stars. To correctly study such reactions the neutron abundance available in the environment must be known, which means that also the so-called "neutron poisons" must be considered. The present work will focus on the reaction $^{17}\mathrm{O}(n,\alpha)^{14}\mathrm{C}$ which removes neutrons from the stellar environment during the s-process. Even though the study of such reactions is of high interest, it still presents several technological problems regarding both the creation and characterization of the neutron beam and the radioprotection of the facility. Therefore, the Trojan Horse Method, an indirect method, has been chosen to study the $^{17}\mathrm{O}(n,\alpha)^{14}\mathrm{C}$ reaction in the energy region of astrophysical interest, from 300 keV in the center-of-mass frame down to zero. In the present work, after briefly recalling the main features of the method and reporting on the state of the art for the reaction cross-section measurements, the latest THM experiment will be presented.

1. – Introduction

Stellar nucleosynthesis processes are of vital importance for nuclear physics as they are the only ones responsible for the production of nuclei with mass number $A \geq 12$ [1]. In particular, the elements with $A \leq 52$ are produced by thermonuclear fusion processes, while heavier elements are produced mainly through neutron capture reactions. Among the latter, the most important reactions are essentially those that take part in the s-process (slow) and the r-process (rapid).

As the name suggests, the difference between those two processes lies in the time scale. In the first case (s-process) the neutron flux is such that the radiative capture (n,γ) is slower than the beta decay for the same nucleus. Therefore, if the nucleus is a beta-unstable isotope, it will have a high probability to decay before another neutron capture could take place. In the second case (r-process) the flow is so intense that the capture is considerably faster than the beta decay and the formed nucleus will have a low probability to decay before the next neutron capture.

The s-process is mainly responsible for the synthesis of heavy elements near the nuclear stability valley which account for about half of all heavy nuclei. It is possible to distinguish two different components of the process: 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 is present in massive stars ($M \geq 8M_{\odot}$). Only the latter will be considered in this work.

In order to study the reactions involved in those processes, the neutron abundance available in the stellar environment of interest should be known. The main neutron source for the weak component is the $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$, which is activated in two different contexts within the massive stars [3]: during the helium burning at $T_c \sim 1.6\times10^8$ K and during the carbon burning at $T_c \sim 1.1\times10^9$ K. However, in the same stellar environment other reactions, the so-called "neutron poisons", can take place.

The present work focuses on the $^{17}\mathrm{O}(n,\alpha)^{14}\mathrm{C}$ reaction, which is indeed a neutron poison since it removes one neutron from the environment but it does not take part in the s-process. Moreover, the $^{17}\mathrm{O}$ is formed by the $^{16}\mathrm{O}(n,\gamma)^{17}\mathrm{O}$ reaction which is also a neutron poison. Therefore, a total of two neutrons get removed each time the reaction chain takes place. However, the $^{17}\mathrm{O}$ has another open reaction channel: the $^{17}\mathrm{O}(\alpha,n)^{20}\mathrm{Ne}$ which recycles a neutron instead. Thus, it is clear that precisely knowing the cross-section of each of these reactions and the relative branching ratio between the $^{17}\mathrm{O}(n,\alpha)^{14}\mathrm{C}$ and the $^{17}\mathrm{O}(\alpha,n)^{20}\mathrm{Ne}$ is of fundamental importance for the correct evaluation of the neutron flux.

Even though neutrons-induced reactions clearly play a fundamental role in the nucleosynthesis of the elements in the universe, the study of such reactions presents several problems: creating and characterizing a neutron beam or, in the case of an inverse reaction, detecting neutrons requires considerable experimental and technological efforts,

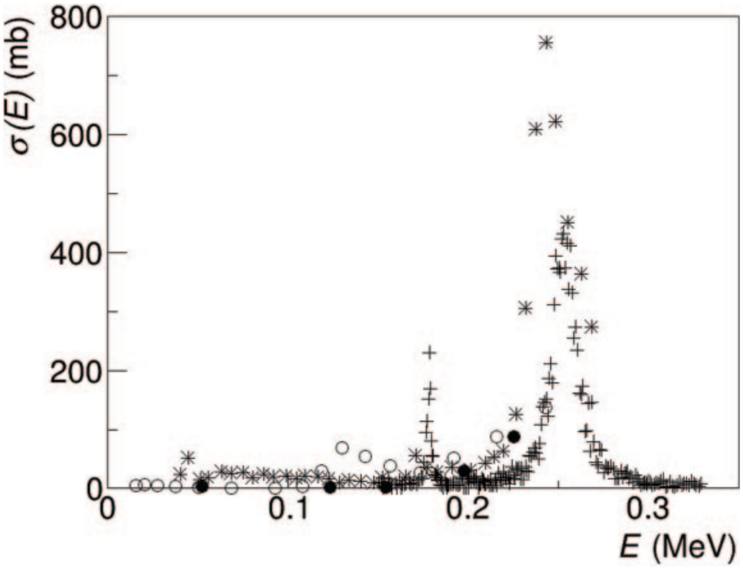

Fig. 1. – Directly measured cross-section data of the two-body ^{17}O$(n,\alpha)^{14}$C reaction as available in the literature. Asterisks are from the data of Sanders [6], circles are from Koehler *et al.* [7], full dots are from Shatz *et al.* [8], crosses are from Wagemans *et al.* [9].

even from a radioprotection point of view. Therefore, using an indirect method, that does not require to work directly with neutrons, could be a more feasible alternative. For that purpose, the Trojan Horse Method [4, 5], one of the most important indirect methods available today in the nuclear astrophysics field, was chosen.

The state of art for the ^{17}O$(n,\alpha)^{14}$C cross-section includes four different direct measurements [6-9] that however present some discrepancies between each other at astrophysical energies, as can be seen in fig. 1. As an alternative and complementary approach, the ^{17}O$(n,\alpha)^{14}$C cross-section has been already evaluated by means of the Trojan Horse Method (THM) by two previous experiments [10, 11]. In this article, after briefly recalling the main features of the chosen method and reporting on the main conclusions of the two previous THM measurements, the latest THM measurement for the ^{17}O$(n,\alpha)^{14}$C reaction will be presented.

2. – The Trojan Horse Method

The Trojan Horse Method (THM) was developed [12, 13] to address one of the main experimental problems that arises when trying to study nuclear reactions of astrophysical interest in the laboratory, due to the extreme difference between the two environments. Indeed, although most of the reactions among charged particles that occur in the stellar medium take place at an energy well below the Coulomb barrier, via the tunneling effect, the low probability for the penetration of the barrier is balanced out by the high number of particles present in the medium.

In a laboratory the number of hitting particles is instead considerably smaller, therefore the cross-section of the reactions is usually too small to be efficiently measured. Moreover, while for neutrons-induced reactions there is no Coulomb barrier, the centrifugal one, which arises from the nuclear potential, is still present and it can indeed suppress the cross-section for high angular momenta.

Although it is possible to address the first problem, working in reduced background conditions in an underground laboratory, this solution does not address the aforementioned problems related to working with neutrons: therefore, a more general approach is to use the so-called indirect methods. Among them the Trojan Horse Method was chosen to perform the present experiment. The theoretical foundations [4, 5, 14] of the method are inherited from the direct nuclear reactions theory, in particular from the so-called quasi-free knock-out reactions.

By means of the THM, it is therefore possible to obtain the half-off-energy-shell (HOES) [4] cross-section of a certain two-body reaction $x + A \to b + B$ by studying an appropriate three-body reaction $a + A \to b + B + s$, usually called the Trojan Horse (TH) reaction, where the nucleus a has a high probability to have a clustered state $x + s$. Under the *quasi-free* [4] kinematical conditions, the x cluster acts like a "participant" to the two-body reaction, meanwhile the s cluster acts like a "spectator". Moreover, under these conditions, the cross-section of the QF reaction will have a maximum for a certain couple of values for the angles of emission of the b and B particles in the final state, the so-called "quasi-free angles" [4]. Calculating those angles and subsequently placing the detectors at such positions is crucial to maximize the efficiency of the experimental setup.

Moreover, using the Plane Wave Impulse Approximation, it is possible to define the relation between the triple-differential cross-section of the TH reaction $\mathrm{d}^3\sigma_{TH}/\mathrm{d}\Omega_b\mathrm{d}\Omega_B\mathrm{d}E_b$ and the half-off-the-energy-shell cross-section of the two-body reaction for the bare nuclei $(\mathrm{d}\sigma^{b.n.}_{xA}/\mathrm{d}\Omega)_{HOES}$:

$$\frac{\mathrm{d}^3\sigma_{TH}}{\mathrm{d}\Omega_b\mathrm{d}\Omega_B\mathrm{d}E_b} \propto K.F.\,|\Phi(p_s)|^2 \left(\frac{\mathrm{d}\sigma^{b.n.}_{xA}}{\mathrm{d}\Omega}\right)_{HOES}. \tag{1}$$

The so-called *kinematic factor* has been indicated with $K.F.$, which includes various factors related, as the name suggests, exclusively to the kinematics of the reaction; meanwhile $|\Phi(p_s)|^2$ indicates instead the square module of the radial wave function of the spectator inside the nucleus a expressed in the momentum space. Other details of the adopted experimental approach can be found in refs. [4, 5, 14] and references therein. The THM has been historically applied to many charged-particles–induced reactions of interest for both stellar nucleosynthesis [15-23] and primordial nucleosynthesis [24-26]. The extension to neutrons-induced reactions has been recently developed to study the ^{6}Li(n, α) reaction [27, 28] and since then it has been applied to multiple other reactions [29, 30], meanwhile the extension of the method to the study of reactions induced by radioactive beams has been recently performed in refs. [31-33].

3. – Past THM applications to the ^{17}O$(n, \alpha)^{14}$C reaction

The previously mentioned direct measurements of the ^{17}O$(n, \alpha)^{14}$C reaction's cross-section have been recently corroborated by the indirect investigations performed via the THM [10, 11]. These THM studies cover the energy region of interest for astrophysics and assess the contribution of the two already known resonant levels detected by Wagemans *et al.* [9]. In addition, these THM measurements clearly showed the presence of two more resonances.

The first one of these is centered at about 75 keV and corresponds to the 8.121 MeV level of the ^{18}O, which, due to its J^π assignment, is populated with $\ell = 3$ in the ^{17}O $+ n$

system and is, therefore, usually hindered in direct measurements. The second one, which corresponds to the 8.039 MeV level of ^{18}O, is a sub-threshold resonance centered at -7 keV in the center-of-mass frame, thus influencing the $^{17}O(n,\alpha)^{14}C$ reaction rate at very low energy.

The reaction's angular distribution was studied, for each of the four resonances mentioned above, by Guardo *et al.* [11], and it was found that the resonance corresponding to the 8.213 MeV level is better reproduced by adopting $\ell = 2$ instead of $\ell = 0$, as is usually assumed.

However, the analyses of Gulino *et al.* [10] and Guardo *et al.* [11] were limited in a narrow center-of-mass angular range, with a significant statistical uncertainty that needs to be further improved. Thus, a new experiment with an improved detection setup was needed for a precise evaluation of the $^{17}O(n,\alpha)^{14}C$ reaction rate and to have detailed information on the influence of the sub-threshold state.

4. – The new experiment

The $^{17}O(n,\alpha)^{14}C$ reaction has been investigated in the energy region of astrophysical interest, between 0 and 300 keV in the center-of-mass frame, applying the THM to the three-body reaction $^2H(^{17}O,\alpha^{14}C)^1H$.

The new experiment [16] was performed at the Laboratori Nazionali del Sud (LNS-INFN) in Catania using the VdG tandem to accelerate a ^{17}O beam at 43.5 MeV on a CD_2 target. The deuteron was chosen as Trojan Horse nucleus since it has a high probability of being in a p-n clustered state. In this state, the inter-cluster s-wave motion has a well-known radial wave function which is the so-called Hulthén wave function.

The experimental setup, which is sketched in fig. 2, is composed of two groups of detectors placed at the so-called "quasi-free angles" and for each group there was a position-sensitive detector (PSD) for the detection of the α particles and a ΔE-E telescope, made up by an ionization chamber as the first stage and another PSD as the second stage, for the detection and the identification of carbon nuclei. Indeed, by plotting the energy loss for the first stage of the telescope ΔE *vs.* the total energy loss in the telescope E, it is possible to distinguish in Z the nuclei detected. As can be seen in fig. 3, it is possible to identify the events coming from the scattering of the beam

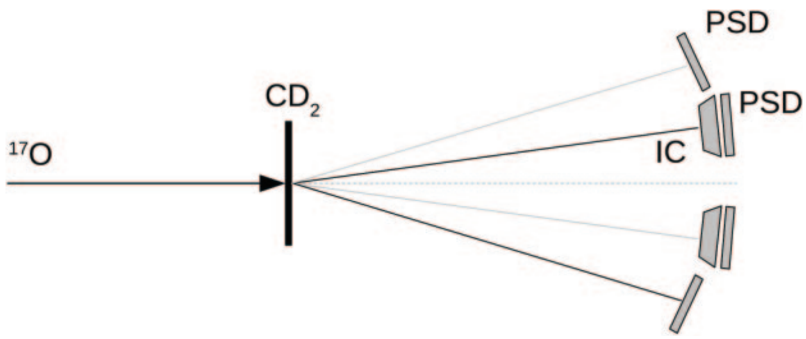

Fig. 2. – Sketch of the experimental setup, not in scale. The ^{17}O beam was impinging on a CD_2 target. The emitted particles were detected by two groups of detectors composed of one position sensitive device (PSD) for the α particles and a ΔE-E telescope, made up by an ionization chamber (IC) and another PSD, for the C nuclei.

which correspond to the two typical bulges indicated by the arrows in fig. 3. The left one refers to the scattering on the C nuclei present in the target, while the right one refers to the scattering on ^{2}H nuclei. All the events with a carbon in the final state are therefore selected and it is assumed that an alpha particle is detected by the coupled PSD, while the proton spectator is emitted but not detected. This assumption can be verified by reconstructing the energy and the momentum of the proton and subsequently evaluating the three-body Q value. In fig. 4 it is possible to see, compared to the theoretical value ($-0.407\,\mathrm{MeV}$) represented by a vertical line, the experimental spectrum obtained for this observable. As is noticeable in the figure, the Q value has a clear peak ($Q = -0.5 \pm 0.2\,\mathrm{MeV}$) in accordance with the aforementioned theoretical value. This is an evidence of the correct selection of the events and the correct reconstruction of the energy and momentum of the spectator. These primary results have been also published in ref. [34].

Moreover, by plotting the Q value against the $\theta_{c.m.}$, *i.e.*, the angle in the center-of-mass frame between ^{14}C nuclei and α particles in the final state, it is possible to check if the selected events correctly populate the desired angular range. As can be seen in fig. 5, one of the goals of the experiment, *i.e.*, getting a broader center-of-mass angular range, was achieved and the events indeed cover a range between nearly 40 and 120 degrees. Many other tests have been performed to assure the validity of the events selection, however they cannot be all shown in the present work for the sake of brevity.

What has been done so far is limited to selecting only the exit channel of the reaction, which means to just select the three-body reaction $^{2}\mathrm{H}(^{17}\mathrm{O}, \alpha^{14}\mathrm{C})p$ among all the possible others with a carbon nucleus in the final state. However, even though the initial and final state are fixed, the latter can still be reached through various reaction mechanisms. Therefore, another necessary condition for applying the THM is the selection of the events coming from the QF break-up reaction mechanism [4,5] where the proton, the "spectator"

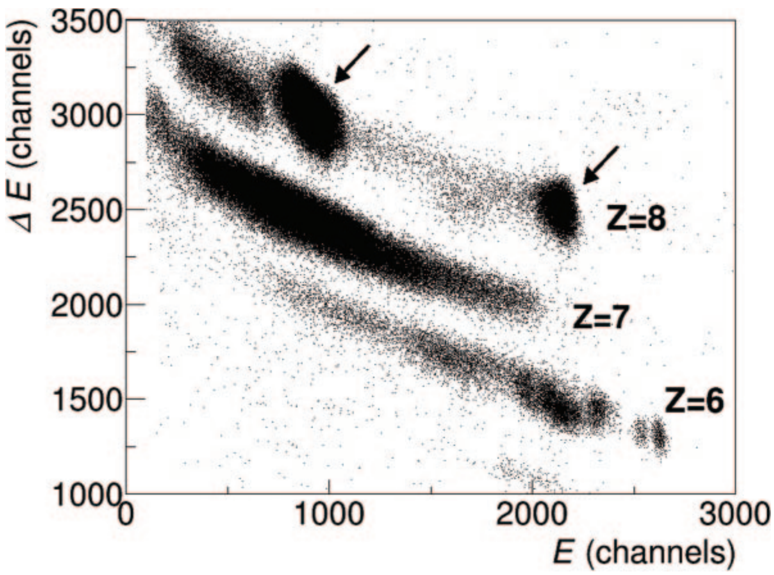

Fig. 3. – Energy loss ΔE in the first stage of the telescope plotted against the energy loss E in the second stage. The black arrows point to the bulges coming from the scattering of the beam on both ^{12}C (left arrow) and ^{2}H (right arrow) nuclei in the CD_2 target. Adapted from ref. [34].

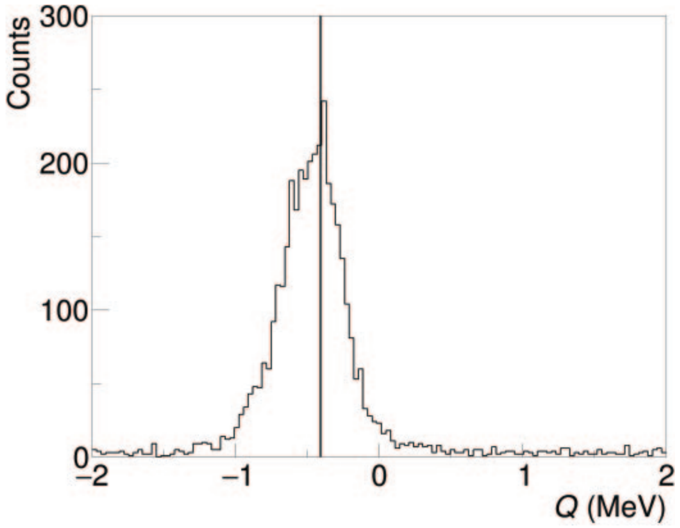

Fig. 4. – Experimental Q spectrum for the $^2H(^{17}O,\alpha^{14}C)H$ reaction, the vertical line marks the theoretical value of $-0.407\,\mathrm{MeV}$. Adapted from ref. [34].

in this formalism, preserves, after the reaction, the same momentum distribution that it had inside the deuteron, before the break-up took place.

In this regard the relative energies between two of the three products in the exit channel, taken in pairs such as ^{14}C-α, ^{14}C-p and α-p, have been reconstructed. By plotting one of those energies against each of the others, it is possible to seek for the presence or absence of regions with a higher density of events, that forms a distinct structure parallel to the vertical or horizontal axis. In fig. 6 the presence of the first indicates the formation of a resonance in the relative energy of the pair ^{14}C-α, *i.e.*, the formation of

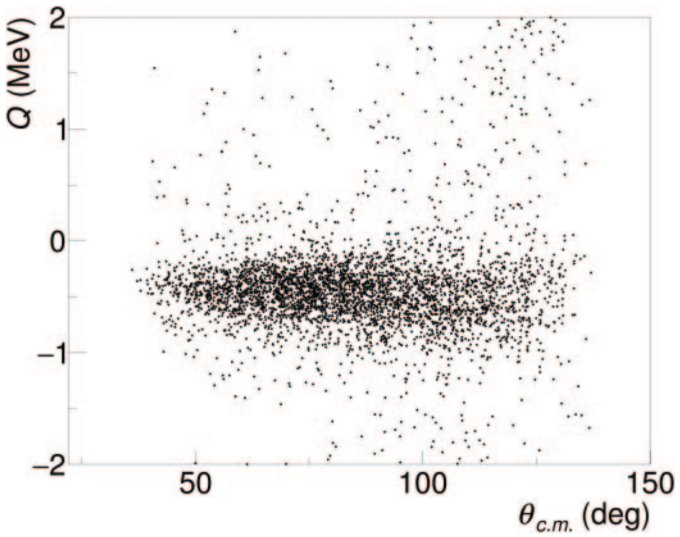

Fig. 5. – Scatter plot of the Q value *vs.* the $\theta_{c.m.}$ angle.

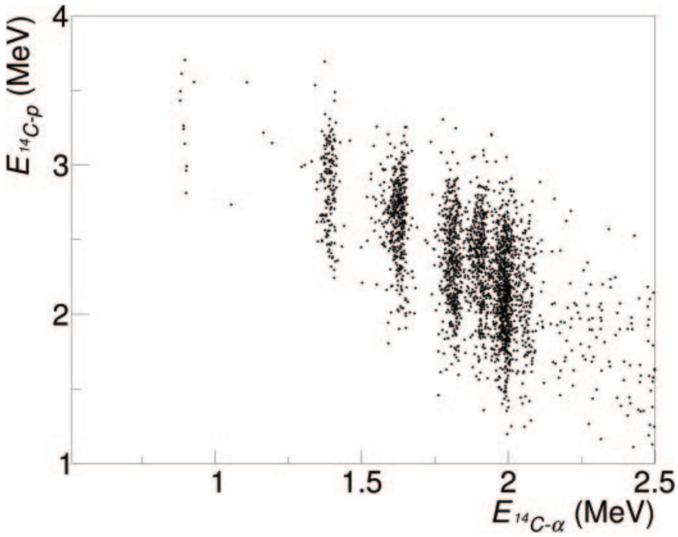

Fig. 6. – Scatter plot of the relative energy between ^{14}C nuclei and protons ($E_{^{14}\text{C-}p}$) against the relative energy between ^{14}C nuclei and α particles ($E_{^{14}\text{C-}\alpha}$).

resonant state in the ^{18}O* system, meanwhile the absence of the latter ensures the lack of contributions from alternative reaction channels, namely the formation of resonant states of the ^{15}N, aside the one of interest. Therefore, since we are confident of the absence of such events, it will be possible to continue with the data analysis by selecting only those coming from the quasi-free contribution by following the standard procedure described in refs. [4, 5, 14]. After these mandatory steps, the 2-body HOES cross-section will be derived and compared to the previous one.

5. – Conclusions

The data analysis is still ongoing, however, thanks to the results obtained so far, it is possible to conclude that the experiment was quite successful in its execution. The preliminary results show the correct selection of events for the ^{2}H(^{17}O, α^{14}C)^{1}H reaction channel and the proper population of the desired range of interest for both $\theta_{c.m.}$ and $E_{c.m.}$. Therefore, a more in-depth analysis of the data coming from this last THM experiment could finally give definite answers to the open questions regarding the cross-section of the ^{17}O$(n,\alpha)^{14}$C reaction.

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