Università degli studi di Perugia

Facoltà di Scienze Matematiche, Fisiche e Naturali

Tesi di Laurea Magistrale in

Fisica

The ^{13}C(α,n)^{16}O reaction rate. Recent estimates, new measurements through the Trojan Horse Method and their astrophysical consequences.

Relatori

Prof. **Busso Maurizio Maria**

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Controrelatore

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...We are stardust, we are golden
We are billion year old carbon...

Woodstock - Crosby, Stills, Nash and Young

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CHAPTER ONE

INTRODUCTION.

Historically, stars have been part of religious practices and used for celestial navigation and orientation: there are examples of astronomical studies all around the world from Egypt to Greece, from the Maya population to the Chinese one. However, it was only due to European researchers during and after the XVIth century that astronomy assumed its modern role as a science. A special role was obviously played by the introduction of the telescope by Galileo Galilei in the XVIIth century; the subsequent search for physical explanations for the motion and appearance of stars founded astrophysics. This is the branch of astronomy that today studies the structure, evolution, chemical composition and physical properties of stars and galaxies. Important conceptual progresses on the physical behavior of stars occurred during the twentieth century because of new theoretical approaches, the application of modern physics and the advent of more accurate photometric and spectroscopic measurements. During the first decades of the XXth century, results from nuclear physics research, in particular the discovery of the enormous energy stored in the nuclei, led astrophysicists to guess that reactions among nuclear species were the source of the stellar power (Rolf & Rodney, 1988; Eddington et al., 1920). Since then, nuclear astrophysics has played a key role in providing the interpretation of astrophysical observations. In this sense, using the observational evidence coming from stellar atmospheres and the experimental evidence coming from nuclear experiments aimed at studying specific nuclear reactions, nuclear astrophysics can determine how the processes of nuclear fusion drives the structural changes and promotes stellar evolution.

This thesis is a particular example of the role played by nuclear astrophysics, as it covers the steps from the nuclear measurement of a reaction rate of astrophysical interest (the $^{13}C(\alpha,n)^{16}O$ reaction) up to the study of the stellar consequences implied by a reaction rate change. These consequences concern the release of neutrons and the ensuing n-capture nucleosynthesis in low mass stars. The above mentioned reaction is important because it is considered as the dominant neutron source active in stars with a mass included in the range 0.8 - 3 $M_{\odot}$, which actively contribute to the nucleosynthesis of heavy nuclei through neutron capture processes.

Roughly a half of all elements heavier than iron in the universe were produced in this way, in the so-called s (slow) process (Burbidge et al., 1957), which basically includes neutron-induced capture reactions and beta decays. The term slow, used to distinguish this mechanism from a rapid one (r-process, occurring in supernovae), refers to the fact that the neutron-capture timescale is in general longer than for the decay of unstable nuclei, which fact requires typical neutron densities of about $10^6 - 10^{10} n/cm^3$.

In order to set the stages for the nuclear astrophysics processes of interest, I shall first discuss the typical evolutionary phases for a star of one solar mass (assumed to represent a low mass star in general). A particular emphasis will be dedicated to the Asymptotic Giant Branch (AGB) stage when, after the exhaustion of helium at the center, the representative point in the H-R diagram ascends for a second time towards the red giant branch (RGB), asymptotically approaching it.

During this phase, and more specifically in the *Thermally Pulsing*-AGB, the C-O core is surrounded by two shells of helium and hydrogen burning alternatively. There is a helium rich intershell region between the two shells that becomes almost completely convective at intervals, while the temperature suddenly increases: it is the so-called thermal pulse (TP). The thermal pulse is repeated many times (from $\sim$ 5 to 50 cycles) before the envelope is completely eroded by mass loss, so nucleosynthesis products manufactured by He burning and the s-process at its bottom are carried to the surface. In the intershell region ^{12}C is abundant. The existence, now proven, of mixing episodes carrying protons downward from the envelope yields the formation of a p- and ^{12}C-rich layer after each thermal pulse. There, after the ignition of the H shell, p-captures generate the so-called ^{13}C pocket. In this context I shall discuss how neutrons are released thanks to the ^{13}C(α,n)^{16}O reaction and s-processing occurs in AGB stars, in the radiative inter-pulse phases. The typical stellar environment in which our reaction takes place corresponds to $T \sim 0.08 - 0.1 \times 10^9$ K. In such conditions, the other main neutron source, the ^{22}Ne(α,n)^{25}Mg reaction, is switched off, as it needs higher temperatures to be activated.

In the above conditions big problems affecting our knowledge of reaction rates are related to the effects of the Coulomb barrier for the charged-particle-induced reactions and to electron screening. The presence of the barrier implies an exponential suppression for the cross section and does not allow a direct measurement at the energies of astrophysical interest. Cross section measurements at such low energies must also cope with a low signal-to-noise ratio, which can be improved only in underground experimental facilities, such as LUNA at the Laboratorio Nazionale del Gran Sasso.

At present, existing direct measurements for the reaction ^{13}C(α,n)^{16}O, collected in the NACRE compilation by Angulo et al. (1999), stop at the minimum value of 280 keV, whereas the region of astrophysical interest, the so-called "Gamow window", corresponds to (190 $\pm$ 90) keV at a temperature of 0.1×10^9 K. Below the limit reached be measurements only a theoretical extrapolation is possible. Various types of approaches have been tried over the years to extend the measurement of the cross section into the region of astrophysical interest. The main aim of these efforts is to improve the accuracy of the measurement, reducing the uncertainty, which sometimes exceeds 300%. The major source of error is the presence of a subthreshold resonance corresponding to the excited state of ^{17}O ($E_{res} = 6.356$ Mev or $E_{c.m.} = -3$ keV). The most recent works in the literature are oriented towards a substantial lowering of the reaction rate, because it is believed that the role of the resonance mentioned above was overestimated in the past.

In this context I participated to a new experiment at the Florida State University, made by the ASFIN2 collaboration (centered at Laboratorio Nazionale del Sud) applying an indirect technique called "Trojan Horse Method" (hereafter THM). The THM is based on a quasi-free break-up process and allows to extract the cross section of the two-body reaction (of astrophysical interest):

$$x + a \rightarrow c + C \qquad (.1)$$

from a suitable three-body one:

$$A + a \rightarrow c + C + s \qquad (1.2)$$

Here A acts as the Trojan Horse nucleus, being a cluster $x \oplus s$ structure. In the hypothesis of the TH-nucleus quasi-free break-up, s represents the spectator of the virtual 2-body reaction of interest for astrophysics.

Our experiment was performed by measuring the sub-Coulomb ^{13}C(α,n) ^{16}O scattering within the interaction region via the THM, applied to the ^{13}C(^{6}Li,n^{16}O)d reaction in the quasi-free kinematics regime. However, the final result deriving by the Trojan Horse method is not complete yet, because data analysis is still under development and will be finalized in the next months.

Since the result derived from the THM is not yet applicable, it was decided to check what would be the consequences for n-capture nucleosynthesis if the presently-accepted rate were to change by some substantial factor. Presently, the rate most commonly used is that suggested by Drotleff et al. (1993). A decrease of its values by roughly a factor of 3 would correspond approximately to the alternative indications by Kubono et al. (2003). I shall show that a result in this direction would imply substantial changes in the operation of the crucial s-process branching at ^{85}Kr with respect to what is assumed today. Elements far from this region would be essentially unchanged.

I also analyzed the effects of an increase in the rate by Drotleff et al. (1993) by the same factor of 3, noting that the changes would be more widespread over the s-process path and would introduce remarkable changes in our ideas on the solar abundance distribution. These results encourage a deeper study of the $^{13}C(\alpha,n)^{16}O$ reaction.

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