RADIATIVE REACTION RATES: FROM THE OBSERVATORY TO THE LABORATORY*

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The gamma ray telescopes launched in the recent years provide observations which in turn trigger a better thought of the nuclear physics involved in the gamma ray production in stars, novae and supernovae. Two examples are presented, with suggestions of experiments to run, either with stable or unstable beams.

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1. Introduction

Nuclear astrophysics is an interplay between nuclear physics and astrophysics where the need of nuclear physics data is determined by the evolution of stellar models and stellar observations triggering new questions. In this paper, we aim to present how observations of gamma ray lines by instruments flying on board of satellites, trigger nowadays nuclear physics experiments to enlighten the astrophysical models for the interpretation of the origin of observed gamma rays.

2. Observation of the 1.809 MeV line by the Comptel telescope

The observation of the 1.809 MeV gamma ray line, resulting from the de-excitation of ^{26}Mg produced by the ^{26}Al ground state β decay, leads to an estimate of the ^{26}Al amount in the galaxy of about 3 $M_\odot$ (HEAO-3) [1], (COMPTEL) [2, 3]. While the observed hot spot are expected to be produced by young objects (supernovae type II, Wolf Rayet stars...), the origin of the diffuse component is still under scrutiny, one assumption

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being that one source is nova explosion. The estimate of ^{26}Al released in nova explosions relies on estimate of reaction rates of all the nuclei of the chain leading to ^{26}Al during the hydrogen burning at typical temperature of 10^8 K. That chain is displayed in Fig. 1. In the context of explosive

Ne-Si region

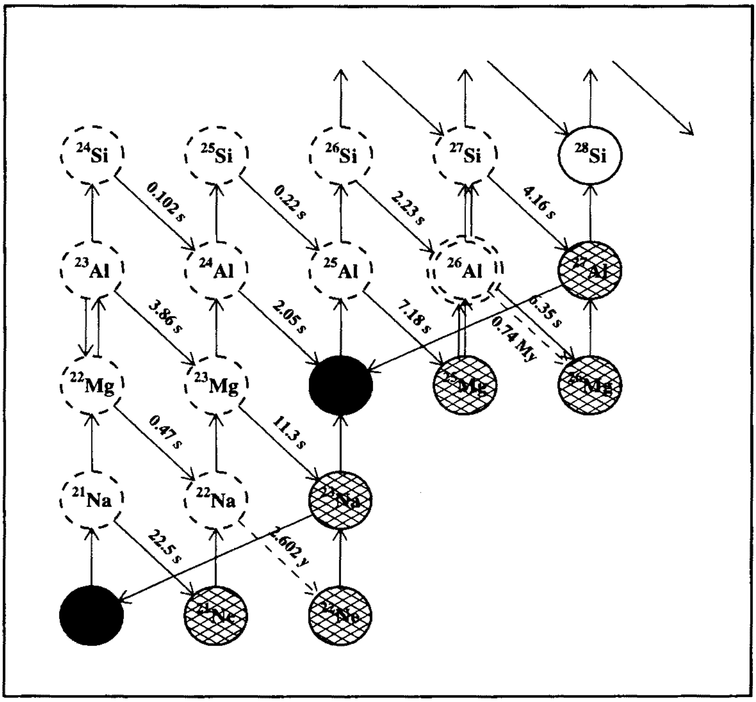

Fig. 1. Reaction chain leading to ^{26}Al in the explosive hydrogen burning. The stable isotopes are represented by full circles. ^{20}Ne and ^{24}Mg are the starting points of the burning chain in a Ne-Mg nova.

hydrogen burning, many radioactive species are involved and are represented by dashed circles in Fig. 1. Their destruction rates are in general poorly known.

In their nova model Coc *et al.* [4] consider the influence of uncertainties in the reaction rates for the ^{26}Al production. They check the nuclear data available and follow the flow leading to ^{26}Al during all the nova explosion time. They conclude to a need for a better determination of the rate of the reaction ^{25}Al$(p,\gamma)^{26}$Si and for a better accuracy for the ^{26}Al$(p,\gamma)^{27}$Si reaction [4].

Concerning the reaction ^{26}Al$(p,\gamma)^{27}$Si (^{26}A half life: 7.2 10^5 y) most of the uncertainty comes from the poor knowledge of a resonance strength at $E_p = 188$ keV. Contrary to an opinion commonly presented, the proton capture reaction rate on the isomeric state in ^{26}Al at 229 keV ($T_{1/2} = 6.35$ s) is not needed for the understanding of the 1.809 MeV line production problem in the galaxy. One should notice that in hydrostatic hydrogen burning (then far away from nova explosion conditions), large uncertainty of several orders of magnitude remains also on the ^{26}Al(p,γ) reaction rate at lower temperature (5×10^7 K) prevailing in AGB type stars, an other potential source of ^{26}Al.

Concerning the reaction ^{25}Al$(p,\gamma)^{26}$Si (^{25}Al half life: 7.18 s) three levels giving a resonant contribution to the reaction rate are expected in the Gamow peak range when looking at the mirror nucleus ^{26}Mg. Depending of the position of those unknown levels, the reaction rate at nova explosion temperature could be changed by several orders of magnitude.

The other reactions in the chain presented in Fig. 1 are of a less importance, either because they are known with an accuracy large enough because stable elements are involved, or because the flow pattern does not go through them.

3. Observation of the ^{12}C and ^{16}O lines

From the Comptel telescope two lines have been identified at about 4.4 MeV and 6.1 MeV [5]. They are coming form the Orion complex, and are non equivocal signature of ^{12}C and ^{16}O de-excitation. Several interpretations of those lines are existing. One of them is based upon the assumption of the acceleration of ^{12}C and ^{16}O up to energies large enough (higher than 1.5 MeV/u) to be excited by the stellar cloud, but low enough not to produce spallation elements unobserved by Comptel [7]. The acceleration mechanism is still debated, but it is probably linked to supernova explosion [6]. Carbon and oxygen could be accelerated from the supernova itself when exploding. They could also be present nearby the supernova, and accelerated by the shock-wave of the supernova explosion. The two schemes lead to two different energy distributions for the accelerated particles. Tatischeff *et al* [8] propose a fit of the Comptel data according to each acceleration scheme. The low energy cosmic rays composed of carbon and oxygen are excited in the interstellar medium composed mainly of hydrogen and helium. The nuclear physics provides the cross section of the excitation reaction ^{12}C(p,p'),^{12}C(α,α') (same reactions for ^{16}O), and an estimate of the cross sections being computed through coupled channels calculations when data are missing [8]. Two parameters are needed for each fit. One is attached to the acceleration process description, the other one is the ratio of the carbon to oxygen abundances in the beam. The best fit is obtained with $y_C/y_O \approx 0.7$.

It is tempting to compare that ratio with what one get from the end of a massive star burning, knowing that neither carbon nor oxygen abundances are affected by the explosion.

Fig. 2 shows that ratio in a pre-supernova stage for three different stellar masses, two models of convection, as a function of a coefficient multiplying the admitted [9] $^{12}C(\alpha,\gamma)^{16}O$ reaction rate. That ratio is deduced from the Weaver and Woosley computations [10]. To get the Tatischeff *et al.* result ($y_C/y_O \approx 0.7$), one should adopt the compiled $^{12}C(\alpha,\gamma)^{16}O$ reaction rate, when Weaver and Woosley proposed to increase it by 70% [10]. The major point of that section is to emphasize the need of a much more accurate determination for the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate, which is in any case strongly needed in the models of stellar evolution for massive stars [10].

The $^{12}C(\alpha,\gamma)^{16}O$ reaction rate determination is a complicate puzzle. The problem arises from the existence of interferences between a subthreshold 2^+ resonant capture and direct E2 capture, between 1^- levels located higher and below the reaction threshold for E1 capture. Several recent

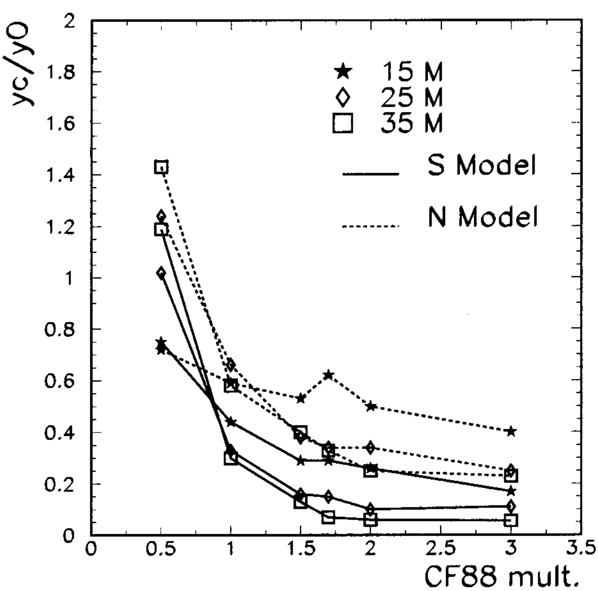

Fig. 2. The molar abundances ratio between carbon and oxygen at the end of carbon burning in massive star, as a function of the $^{12}C + \alpha$ reaction rate (see text). The S and N model refer to two different modes for the convection (see Ref. [10]).

measurements have tried to disentangle that puzzle. As an example, the E1 component of the $^{12}C(\alpha, \gamma)^{16}O$ reaction has been extracted from the decay of ^{16}N to ^{16}O followed by the decay of ^{16}O into the open channel $^{12}C + \alpha$ [11–13].

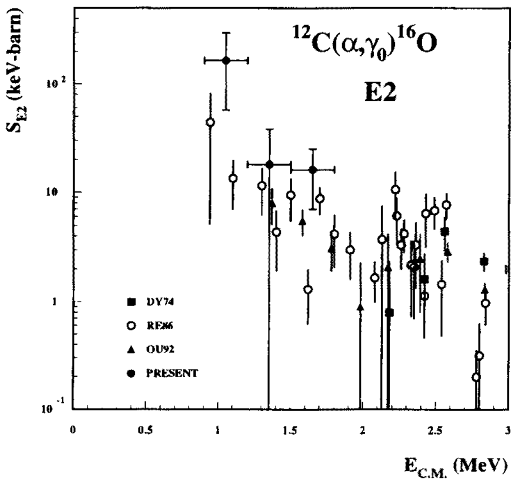

Fig. 3. Results from the break up experiment compared with a compilation of available data for the astrophysical S-factor S_{E2} of the $^{12}C(\alpha, \gamma)^{16}O$ reaction. Only the statistical error of the present measurement is given. The direct measurement data are from [15–17].

A first attempt to determine the E2 component has be achieved recently, using the break up method [14]: a large Z target infer the breakup of a ^{16}O beam into two fragments ^{12}C and α. The $^{12}C(\alpha, \gamma)^{16}O$ reaction cross section is deduced from the inverse cross section $^{16}O(\gamma, \alpha)^{12}C$. The obtained results are displayed in Fig. 3, and compared with direct experiment ones. The breakup results do not present yet the required accuracy, but look encouraging. That same experiment should be repeated with a larger statistic, at higher relative ^{12}C-α energies to demonstrate the reliability of the method.

4. Conclusion

The recent observation by the Comptel telescope of some gamma lines has triggered further thought to be given to the nuclear physic involved. It appears once again that some reaction rates such as $^{12}C + \alpha$ are still not determined with enough accuracy. Reaction rates involving radioactive species are still needed when dealing with explosive scenarios, but only few well identified reactions are of concern. It is expected that the new generation of observatories to be launched in the next years will keep alive that need of accurate reaction rate determinations as an input for stellar evolution models.

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