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# INVESTIGATION OF NEUTRON PRODUCING ($\alpha,n$)- REACTIONS RELEVANT FOR THE ASTROPHYSICAL s-PROCESS

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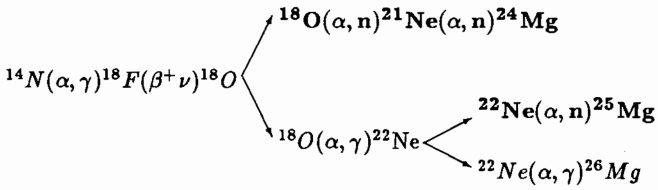
## Introduction

In the astrophysical s–process the elements with A $\geq$56 are produced by neutron capture and successive $\beta$-decays in "slow" time scale [1]. According to standard stellar models, neutron production and neutron capture occurs during the helium burning stage of the stars and therefore only ($\alpha$,n)-reactions are considered as possible neutron sources. Some reaction chains are conceivable:




Nitrogen-14 is a remnant from the CNO-cycles and will be transformed to oxygen-18 which exhibits a temperature dependant branching between the ($\alpha$,n)- and ($\alpha,\gamma$)- reaction [2]. Lower stellar temperatures<0.6 $T_9$ favour the ($\alpha,\gamma$)-reaction of oxygen-18, leading to one of the presumed neutron sources $^{22}Ne(\alpha,n)^{25}Mg$. On the other hand according to some other stellar models some mixing of material of the hydrogen burning phase with material of the helium burning phase becomes possible due to instabilities, convection or rotation, leading to the reaction chain:

$$3\alpha \rightarrow ^{12}C(p,\gamma)^{13}N(\beta^+\nu)^{13}C(\alpha,n)^{16}O$$

Our knowledge of ($\alpha$,n)-reactions especially at low energies is incomplete, thus giving rise to further investigations.

## $^{13}C(\alpha,n)^{16}O$

This reaction has been investigated with thick targets (about 200 keV) by Davids [3] in the energy range 475-700 keV and by Ramström and Wiedling [4] from 600 - 1150 keV, in the latter case without spectroscopic information. The cross section of this reaction is decreasing by nearly an order of magnitude every 100 keV, therefore a reinvestigation using improved methods is worthwile. In $^{17}O$ there are states at 6.972, 6.862 and 6.356 MeV, of which the two higher ones may lead to resonances in the neutron channel at about 660 and 800 keV. The state at 6.356 MeV is lying near the $\alpha$-threshold and thus the high energy tail of a possible resonance may influence the cross section in the energy range of interest. According to a microscopic calculation of Descouvemont [5] an increasing S-factor towards low energies will result from this behaviour.
The experiment makes use of the high $\alpha$-currents of the Stuttgart Dynamitron-accelerator using enriched and watercooled solid state targets with thickness of about 20

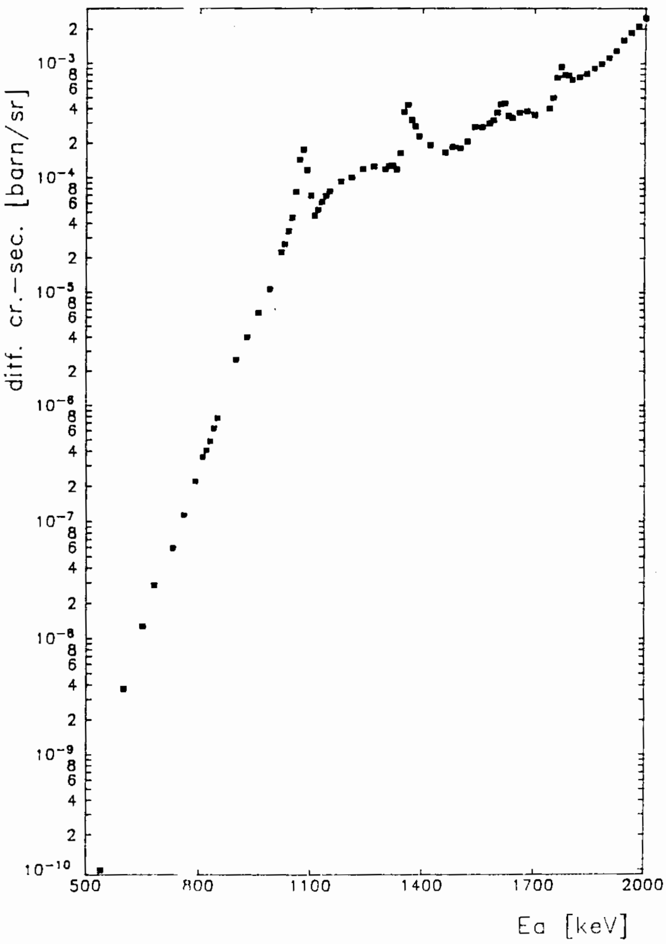



**Fig. 1** *Differential cross section of $^{13}C(\alpha,n)^{16}O$ measured with a 4"Øx 2" NE213 detector under 30° in close geometry. The target thickness was about 20 keV, the $He^+$-currents ranged from 50-120 $\mu A$. $E_\alpha$ is given in the laboratory system.*

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keV [6]. To begin with, scintillation detectors of the NE213 type have been used for reasons of high efficiency and immediate availability. After unfolding of the proton recoil spectra an energy information with moderate resolution can be obtained. Detectors for higher resolution - using $^3$He - are being developed. The cross section was measured between 450 and 2000 keV, covering nearly 8 orders of magnitude. A first result assuming isotropic angular distribution of the neutrons as a first approach is shown in Fig. 1. There was no indication for resonances at $E_\alpha$ = 660 and 800 keV.

The S-factor curve is given in Fig. 2 (preliminary) and one can recognize that it is dominated by a broad resonance at about 1100 keV, which was not taken into account in the former analysis. At present the data don't permit a decision with regard to an increasing S-factor towards lower energies. More disclosure is expected from the evaluation of the angular distribution measurement of the neutrons and from possible interference effects.

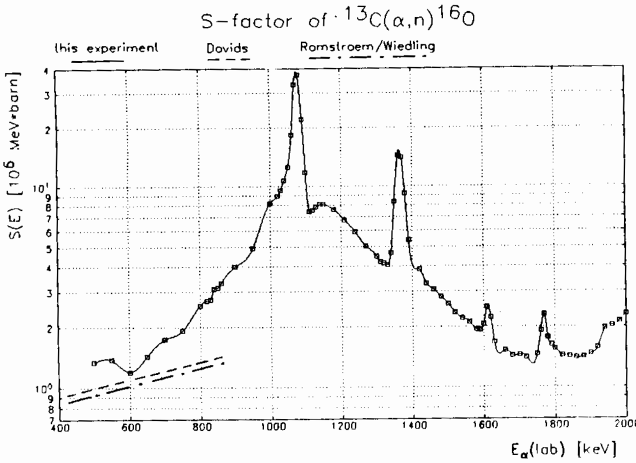


**Fig. 2** *S-factor of $^{13}C(\alpha,n)^{16}O$ (preliminary) in comparison with the evaluation of Davids [3] and Ramström and Wiedling [4]*

## $^{22}$Ne($\alpha$,n)$^{25}$Mg and $^{22}$Ne($\alpha,\gamma$)$^{26}$Mg

Both concurring $^{22}$Ne-reactions have been investigated in the energy range 600 - 2200 keV using the Stuttgart windowless gastarget RHINOCEROS and the high $\alpha$-currents from the Dynamitron accelerator. For the case of the ($\alpha$,n)-reaction three neutron groups $n_0$, $n_1$ and $n_2$ could be observed by using $^3$He-detectors with good energy resolution but low efficiency (about $10^{-4}$) and by using a germanium detector to detect the subsequent gammas of $n_1$ and $n_2$. In consequence of the low efficiencies only data in the $\alpha$-energy range 1350-2200 keV could be obtained, leaving the interesting low energy region still open. But in the $\gamma$-branch several new resonances have been observed, the lowest at 830 keV, leading to a drastic increase of the reaction rate compared to the topical evaluation of Fowler, Caughlin and Zimmermann [7] as shown in Fig. 3. This increase in favour of the ($\alpha,\gamma$)-channel will reduce the importance of the $^{22}$Ne($\alpha$,n)$^{25}$Mg-reaction if the ($\alpha$,n)-channel will not change too at low energies.

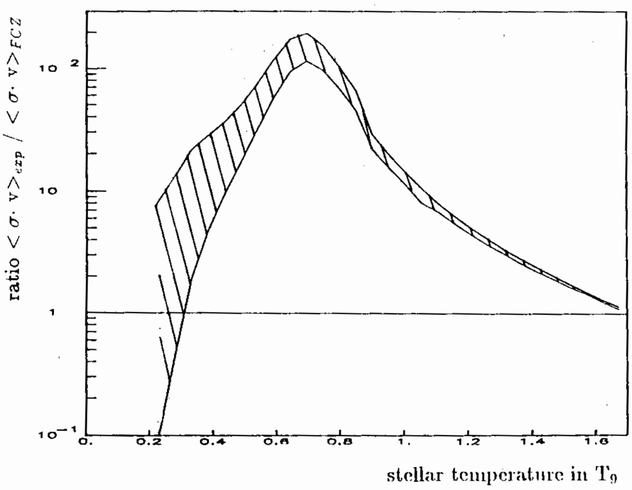


**Fig. 3** *Ratio of the reaction rates of $^{22}Ne(\alpha,\gamma)^{26}Mg$ $N<\sigma{\cdot}v>_{exp}/N<\sigma{\cdot}v>_{FCZ}$ plotted as function of the stellar temperature in $10^9$ K. exp = this experiment ; FCZ = evaluation of Fowler, Caughlan and Zimmermann [7].*

## $^{21}$Ne($\alpha$,n)$^{24}$Mg

Neon-21 will be produced besides the generation from oxygen-18 via the reaction chain :

$$^{16}O(\alpha,\gamma)^{20}Ne(p,\gamma)^{21}Na(\beta^+,\nu)^{21}Ne(\alpha,n)^{24}Mg.$$

The$^{21}$Ne($\alpha$,n)$^{24}$Mg-reaction has been investigated using the windowless gastarget RHINOCEROS and scintillation detectors (NE213) for the neutron detection and a germanium detector for the $\gamma$-detection. Two neutron groups could be detected in the energy range 900 to 2350 keV leading to the observation of 5 new resonances in this range, but without changing the astrophysical relevant reaction rate considerably. Fig. 4 is showing the excitation function for the neutron groups $n_0$ (lower curve) and $n_1$ (upper curve).

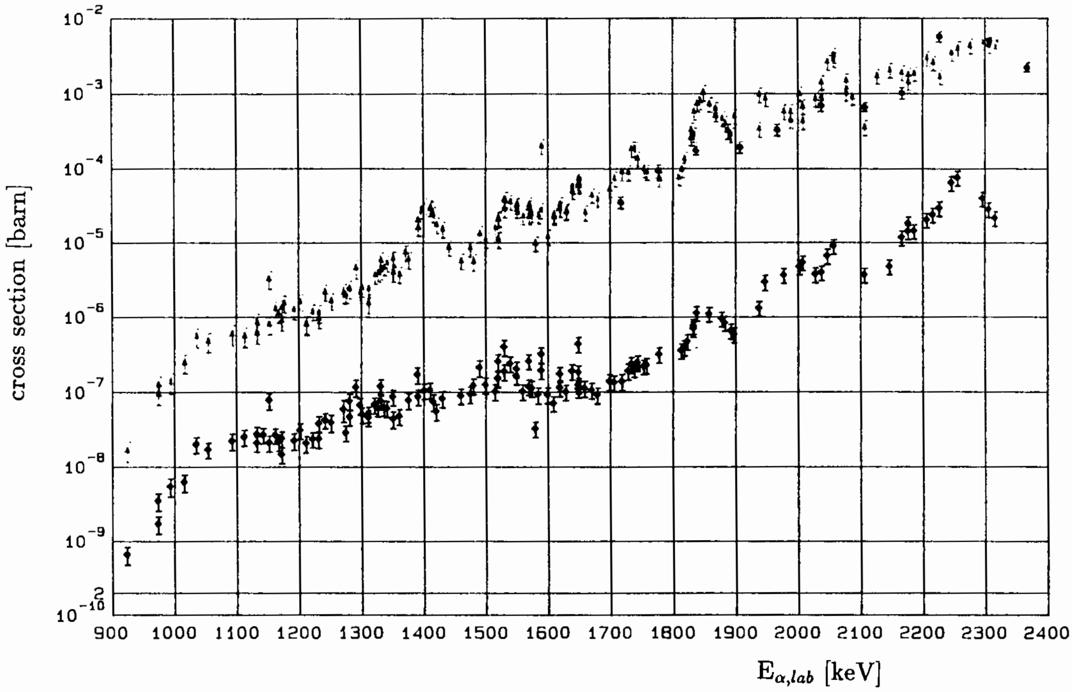


**Fig. 4** *Excitation function of* $^{21}Ne(\alpha,n_{0,1})^{24}Mg$

## $^{18}O(\alpha,n)^{21}Ne$

A new measurement of $^{18}O(\alpha,n)^{21}Ne$ has been made very recently by using enriched solid state targets and proton recoil spectroscopy of the neutrons in the $\alpha$-energy range 1000 to 2600 keV, the lowest point being 150 keV above threshold. Fig. 5 is showing the excitation function in a logarithmic scale, the data points being not yet response-corrected.

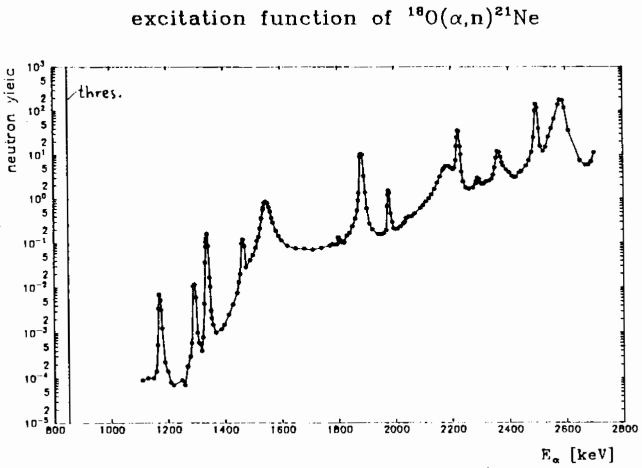


**Fig. 5** *Excitation function of* $^{18}O(\alpha,n)^{21}Ne$ *in logarithmic scale. The points are cleared up for background, but not response-corrected.*

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