Experimental determination of the $^{17}$O($n_{th},\alpha$)$^{14}$C reaction cross section

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Abstract. The $^{17}$O($n_{th},\alpha$)$^{14}$C reaction cross section was determined at the high flux reactor of the ILL in Grenoble relative to the known $^{14}$N($n_{th},p$)$^{14}$C cross section. The $^{17}$O($n_{th},\alpha$)$^{14}$C measurements were performed with several highly enriched oxygen gas samples and the flux calibration was done with $^{14}$N$_2$ from the air. This resulted in a precise value of $(244 \pm 7)$ mb for the $^{17}$O($n_{th},\alpha$)$^{14}$C cross section.

1 Introduction

Inhomogeneous big bang models are able to reproduce the primordial light element abundances, but moreover lead to the production of potentially observable nuclides heavier than C. In addition, these models could solve conflicts that arise in the standard big bang model. At present it is thought that $^{14}$C may act as a bottleneck in the nucleosynthesis path to heavier elements. In this respect, Applegate et al. and Thielemann et al. demonstrated the dominant influence of the $^{17}$O($n,\alpha$)$^{14}$C reaction on the production of elements heavier than $A = 17$, which will be strongly hindered by this reaction since it recycles the mass flow back to $^{14}$C.

The $^{17}$O($n,\alpha$)$^{14}$C reaction could also help to explain anomalies in $^{18}$O/$^{16}$O and $^{17}$O/$^{16}$O ratios found in presolar grains. These grains are stellar condensates and their isotopic compositions reflect both the initial compositions of stars and the changes that arise as a result of nucleosynthesis and stellar evolution.

So far, only two direct measurements of the $^{17}$O($n,\alpha$)$^{14}$C reaction cross section are available at relevant neutron energies, which both completely rely on a value of 235 mb for the $^{17}$O($n_{th},\alpha$)$^{14}$C reaction cross section. This value definitely needs to be verified since it is based on only two old experimental cross section determinations: $(560 \pm 130)$ mb and $(235 \pm 5)$ mb.

2 Experimental method

2.1 Experimental setup

The measurements were performed at the end of the thermal neutron guide H22D of the high flux reactor of the ILL in Grenoble (France). The thermal flux at the sample position reached a value of about $5 \times 10^8$ n/cm$^2$s, the ratio of thermal neutrons to epithermal and fast neutrons was $10^6$ and the $\gamma$ ray flux from the reactor was reduced by a factor of $10^6$. The flux determination was done based on the known $^{14}$N($n_{th},p$)$^{14}$C cross section, which permits to perform these measurements with gaseous samples.

The reaction studied and the flux calibration should be performed in exactly the same detection geometry and in both cases the number of atoms should be well known.
To do this with gaseous samples, we rely on the basic principle that 1 mole (6.022 $\times 10^{23}$ atoms) of any gas at a pressure of 1 atm. fills a volume of 22.414 liter. When a volume of oxygen gas and afterwards the same volume of air (containing 77.8% $^{14}$N) is injected in the vacuum chamber, the gas resp. the air will be distributed homogeneously in the chamber. So the $^{17}$O resp. $^{14}$N density in the beam profile will be simply proportional to the resp. enrichment factors of both gasses.

Since the $^{17}$O($n_{th},\alpha$) and $^{14}$N($n_{th},p$) particles have low energies (1.4 MeV and 0.6 MeV resp.), special care had to be given to the detector choice. We used two (collimated) fully depleted surface barrier detectors (thicknesses 14.8 $\mu$m and 21.3 $\mu$m, resolution 55 keV and 31 keV) which have an excellent signal-to-noise ratio in the region of interest. Their energy calibration was done by means of the $^{14}$N($n_{th},p$)$^{14}$C, $^{10}$B($n_{th},\alpha$)$^7$Li and $^6$Li($n_{th},\alpha$) reactions. Both detectors were mounted in a vacuum chamber, parallel with and outside of the neutron beam.

2.2 Measurements

The measuring sequence consists of three gas injections. Before each injection a vacuum of $10^{-3}$ torr (see figure 1) is established in the system. First, the volume of air between the glass seal S and valve 2 is injected in the vacuum chamber and the $^{14}$N($n_{th},p$) particles counted. Then, the glass seal is broken by means of the steel rod A, the oxygen is injected and the $^{17}$O($n_{th},\alpha$) particles are counted. Finally, the second part of the flux measurement is executed: air contained in the volume from valve 2 and the bottle (since the glass seal is broken!) is injected in the chamber and again the $^{14}$N($n_{th},p$) particles are counted. When subtracting the first measurement from the third one, the $^{14}$N($n_{th},p$) counting rate corresponding to the air in the sealed part of the bottle is obtained. This sequence was repeated with several bottles containing 100 ml of oxygen gas (1 atm.) with $^{17}$O enrichments of 58.2 at.% and 85.5 at.%. Typical results are shown in figure 2. On the left side we see the pulse height spectrum for the $^{17}$O($n_{th},\alpha$) reaction obtained 15 hours after the injection of 85.5 at.% enriched

![Figure 1: Schematic picture of the setup (not on scale!) showing the gas injection system.](image-url)
17O gas. The right side of the figure shows the 14N(nth,p) flux measurement. Both spectra are corrected for (small) background contributions.

Figure 2: Energy distribution for the 17O(nth,α)14C reaction and for the flux determination 14N(nth,p)14C.

3 Results and discussion

The 17O(nth,α)14C reaction cross section is determined relative to the 14N(nth,p)14C reaction, using the relation

$$\sigma_{\alpha}^{(17)O} = \sigma_{p}^{(14)N} \frac{Y_{\alpha}^{(17)O} \cdot N^{(11)N}}{Y_{p}^{(14)N} \cdot N^{(17)O}}$$

in which $\sigma$ is the thermal cross section value, $Y$ the counting rate after background subtraction and $N$ the number of atoms per cm$^3$.

As mentioned earlier, the $N^{(14)N}/N^{(17)O}$ density ratio will be equal to the isotopic enrichment ratio $I^{(14)N}/I^{(17)O}$ of the gasses used. The $I^{(14)N}$ value still needs to be multiplied by a factor $f(p,h)$ to correct for the meteorological conditions during the measurements, because the filling of the glass bottle with atmospheric air is sensitive to the atmospheric pressure ($p$) and the humidity of the air ($h$) at that moment. For the 14N(nth,p) cross section, we adopted the evaluated value of $(1.83 \pm 0.03)$ b, so relation (1) becomes:

$$\sigma_{\alpha}^{(17)O} = 1.83 \frac{Y_{\alpha}^{(17)O} \cdot I^{(14)N}}{Y_{p}^{(14)N} \cdot I^{(17)O}} f(p,h) b$$

Two experiments were performed with oxygen gas with an enrichment of 58.2 at.% in 17O and with only one detector mounted and three with gas enriched to 85.5 at.% and two detectors mounted. Hence eight values for the 17O(nth,α) cross section could be calculated using relation (2). The corresponding results are displayed in figure 3, which demonstrates the reproducibility of our method.
The uncertainty on the results is composed of three contributions: (i) a statistical error varying between 0.4 % and 1.4 %; (ii) the uncertainty on the meteorological correction factor, for which a conservative value of 1 % was adopted; (iii) a systematic normalisation uncertainty of 1.6 % due to the uncertainty on the $^{14}$N(n$_{th}$,p) cross section. A weighted average of the eight runs was calculated using the statistical errors, resulting in a value of (244 ± 7) mb for the $^{17}$O(n$_{th}$,α) cross section.

This result agrees within the experimental uncertainties with the value of Hanna et al. They used CO$_2$ gas with an isotopic enrichment in $^{17}$O of ≈ 0.3 % and 2 % and determined the $^{17}$O(n$_{th}$,α) cross section relative to the activation cross section of gold. They performed six measurements resulting in an average value of (235 ± 5) mb.

4 Conclusions

The present result combined with the value of Hanna et al. converges to a value of about 240 mb for the $^{17}$O(n$_{th}$,α) cross section. This confirms the correctness of the normalisation of the $^{17}$O(n,α) measurements at higher neutron energies, which relied on a thermal value of 235 mb. This in turn increases the confidence in the astrophysical reaction rates calculated from these higher energy data.

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