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$E1$ and $E2$ capture cross section and astrophysical reaction rate of the key reaction $^{12}C(\alpha,\gamma)^{16}O$

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The key reaction $^{12}C(\alpha,\gamma)^{16}O$ has been investigated in three different experiments at the Stuttgart DYNAMITRON in the course of international collaborations. In the energy range $E_{\mathrm{c.m.}} = 0.89-2.8\,\mathrm{MeV}$ He^+ beams of several hundred microamperes were directed on isotopically enriched carbon targets of high purity and with high beam power capabilities. To obtain γ angular distributions three different arrays of actively shielded HPGe detectors have been used to separate the $E1$ and $E2$ capture cross section which is necessary to describe and extrapolate the reaction in the energy range of stellar burning. The sensitivity of these experiments could be raised by a factor of 10–100 compared to previous investigations. The S-factor functions were fitted by an R-matrix analysis considering different data sets of capture data, elastic scattering data and the decay of ^{16}N. The astrophysical reaction rate has been determined with $\pm 25\,\%$ accuracy in the temperature range $0.001 \leq T_9 \leq 10$.

The outstanding importance of the reaction $^{12}C(\alpha,\gamma)^{16}O$ is well known from literature [1]. Equally the complicated level structure of the daughter nucleus ^{16}O leading to nonpredictable interferences in the excitation functions of $E1$ and $E2$ capture has been discussed many times [2]. More than 30 experiments have been performed in the past three decades to determine the cross section, the extrapolated S-factor values S_{E1}^{300}, S_{E2}^{300}, and S_{tot}^{300} and the reaction rate. The published values and their uncertainties contradict

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each other strongly: e.g. $S_{E1}^{300} = 1$–$288\,\mathrm{keVb}$, $S_{E2}^{300} = 7$–$120\,\mathrm{keVb}$, and $S_{\mathrm{tot}}^{300} = 40$–$430\,\mathrm{keVb}$ (see references in [3]). The reaction rate has been reported recently to have an uncertainty of $\pm 31\,\%$ [4], $\pm 41\,\%$ [5], $+85\,\% -43\,\%$ [6]. At present an accuracy of $10\,\%$ is requested [7], stimulating new efforts for the experimental determination of this rate.

Therefore two new experiments, characterized by high primary intensity ($0.5\,\mathrm{mA}$ He^+), a 4π-like detector setup, and sophisticated target technique have been undertaken to determine the $E1$ and $E2$ parts of the capture cross section in a wide energy range and thus to better constrain the astrophysical reaction rate. Two different 4π HPGe detector setups were constructed and optimized for the measurement of γ angular distributions: the special EUROGAM detector array and the GANDI array (**G**amma **AN**gular **DI**stribution Exp.), shown in Fig. 1.

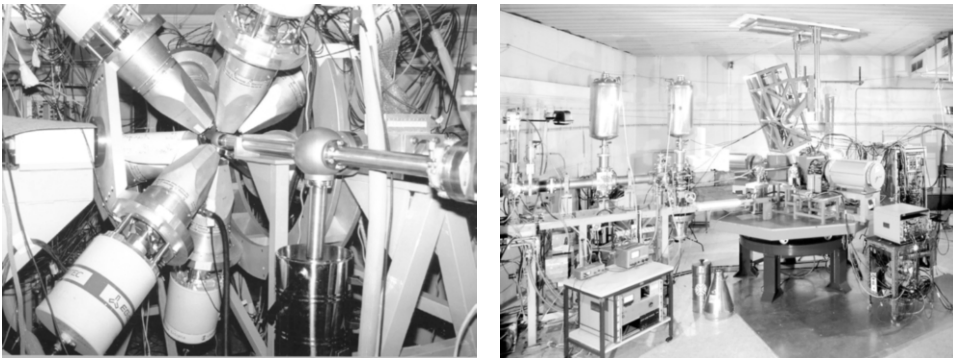

Figure 1. Two 4π-like γ detector arrays: Special EUROGAM (left) and GANDI array (right) at the Stuttgart DYNAMITRON laboratory.

With the 4π EUROGAM array a total of 25 γ angular distributions were measured. For each distribution a beam charge of typically 10–30 C was collected. Details with figures and tables are given in [8]. In the second experiment using the GANDI array 12 γ angular distributions were measured in the low energy range with $500\,\mu\mathrm{A}$ beam current. For the lowest point, at $E_{\mathrm{c.m.}} = 891\,\mathrm{keV}$, a beam charge of 164 C was collected, yielding a cross section in the range of a few picobarns. The results of the GANDI experiment are given in detail in [3]. The angular distributions were used to separate the cross sections for $E1$ and $E2$ capture, fixing the relative phase ϕ_{12} between these contributions by means of phases from elastic α-scattering [9–11].

The R-matrix calculations were performed using the code ERMA of Kunz [4,12]. They are based on the Stuttgart capture data for $E1$ and $E2$, the scattering phases of [9,10], and the data of the β-delayed α-decay of $^{16}\mathrm{N}$ [13,14]. For $E1$ a three level fit and for $E2$ a five level fit were performed. Details are given in [3] and in a paper which is in preparation. The experimental data together with the calculated S-factor functions are shown in Fig. 2.

In order to obtain a better assessment of the relevance of the different capture data sets, the R-matrix calculations were carried out for six cases: the EUROGAM (A) and

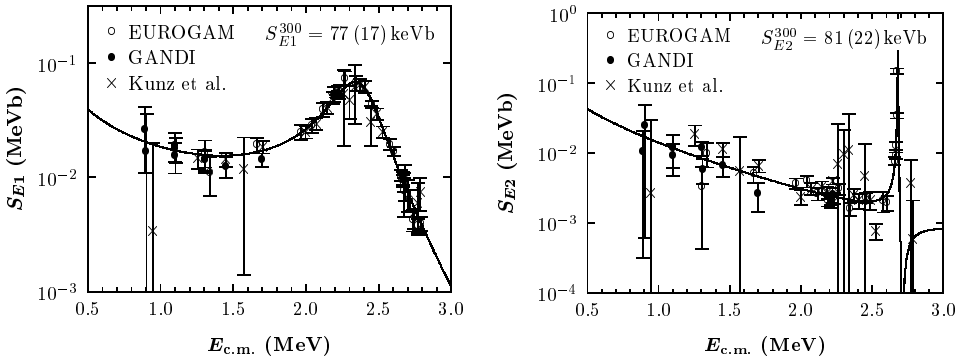

Figure 2. S-factors for $E1$ and $E2$ capture in ^{12}C(α,γ)^{16}O. The solid curves represent the best R-matrix fit which is used for the reaction rate.

the GANDI (B) experiment alone, and additionally the 20 data points (C) of Kunz *et al.* [12] were included; further for the combinations of data sets (A + B), (B + C), and (A + B + C). Table 1 shows the 300 keV extrapolated values for the different data sets and their combinations. The agreement between the fits is very good, the combination of the three data sets from the recent DYNAMITRON experiments (A+B+C) gives the lowest uncertainty and is our final result.

Table 1
Extrapolation values S_{E1}^{300} and S_{E2}^{300} for the different combination of data sets A, B, and C (A = EUROGAM, B = GANDI, C = Kunz *et al.*). For all cases also data of elastic scattering [9–11] and ^{16}N decay [13,14] were considered. The result of case A + B + C yields the lowest uncertainty and is used for the calculation of the reaction rate.

Data from:	A	B	C	A + B	B + C	A + B + C
S_{E1}^{300} (keV b)	81 (20)	77 (19)	76 (20)	77 (19)	76 (18)	77 (17)
S_{E2}^{300} (keV b)	80 (27)	78 (26)	85 (30)	80 (25)	81 (23)	81 (22)
S_{tot}^{300} (keV b)	—	—	165 (50)	—	—	162 (39)

The capture data of the present experiments (EUROGAM, GANDI) cover the energy range $E_{\rm c.m.} = 0.89 - 2.8$ MeV. Because of the lack of experimental data at higher energies the resonance parameters for the R-matrix description have been taken from Tilley *et al.* [15]. The S-factor for contributions by cascade transitions $S_{casc}^{300} = 4\,(4)$ keVb has been taken from Kunz *et al.* [12]. The contributions of resonances with other multipolarities were calculated using data from Tilley *et al.* [15] and assuming Breit-Wigner curves with energy dependent widths but without making assumptions on their unknown interference terms.

The astrophysical reaction rate was obtained by the convolution of the excitation functions (Fig. 2) with corresponding Maxwell-Boltzmann distributions of α-particles by numerical integration. This new rate has a maximum total uncertainty of $\pm 25\,\%$. For the

reaction rate the usual analytical form has been given by the following equations [6]:

$$N_A\langle\sigma v\rangle = r_1 + r_2 + r_3 + r_4 \qquad [\mathrm{cm}^3(\mathrm{s}\cdot\mathrm{mol})^{-1}]$$

$$r_1 = \frac{a_0}{T_9^2\left(1+a_1\,T_9^{-2/3}\right)^2}\,\exp\left(-\frac{a_2}{T_9^{1/3}}-\left(\frac{T_9}{a_3}\right)^2\right) \qquad r_2 = \frac{a_4}{T_9^2\left(1+a_5\,T_9^{-2/3}\right)^2}\,\exp\left(-\frac{a_6}{T_9^{1/3}}\right)$$

$$r_3 = \frac{a_7}{T_9^{3/2}}\,\exp\left(-\frac{a_8}{T_9}\right) \qquad r_4 = \frac{a_9}{T_9^{2/3}}\left(1+a_{10}\,T_9^{1/3}\right)\exp\left(-\frac{a_{11}}{T_9^{1/3}}\right).$$

The fit parameters for the analytical expression of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction rate are:

$a_0 = 1.51\times10^8$; $a_1 = 0.0666$; $a_2 = 32.12$; $a_3 = 1.03$; $a_4 = 1.11\times10^9$; $a_5 = 0.735$; $a_6 = 32.12$; $a_7 = 0.0$; $a_8 = 0.0$; $a_9 = 16200$; $a_{10} = 2.19\times10^6$; $a_{11} = 38.814$.

The analytical expression is valid in the full temperature range of $0.001 \le T_9 \le 10$ reproducing the reaction rate with a maximum uncertainty of 8 %. In the most interesting temperature range of $T_9 = 0.1-0.3$ this uncertainty is only 1 %.

At burning temperature $T_9 = 0.2$ this new reaction rate is about 8 % higher than the rate given by Buchmann [6], about 20 % lower than the rate given by the NACRE collaboration [5], and it agrees well with the rate of Kunz *et al.* [4]. The temperature dependence of this rate differs from those of Buchmann and NACRE, especially at higher temperatures.

We have measured 37 new γ angular distributions each consisting of 8–10 data points to deduce new reaction rates for $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$. We emphasize that the angular distribution at the lowest energy (891 keV) has been measured with the highest sensitivity reached by any experiment of this kind. We claim that our results put strong constraints on the reaction rate since the data of three independent experiments are in very good agreement (see Table 1) and contribute to the final result.

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