$^{12}C(\alpha,\gamma)^{16}O$: The Key Reaction in Stellar Nucleosynthesis

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The angular distributions of γ rays from the $^{12}C(\alpha,\gamma)^{16}O$ reaction have been measured at 20 energy points in the energy range $E_{cm} = 0.95$ to 2.8 MeV. The sensitivity of the present experiment compared to previous direct investigations was raised by 1–2 orders of magnitude, by using an array of highly efficient (100%) Ge detectors shielded actively with BGOs, as well as high beam currents of up to 500 μA that were provided by the Stuttgart DYNAMITRON accelerator. The S_{E1} and S_{E2} factors deduced from the γ angular distributions have been extrapolated to the range of helium burning temperatures applying the R-matrix method, which yielded $S_{E1}^{300} = (76 \pm 20)$ keV b and $S_{E2}^{300} = (85 \pm 30)$ keV b.

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The $^{12}C(\alpha,\gamma)^{16}O$ reaction is considered to be the key reaction in the helium burning of stars because it determines not only the C/O ratio but also the nucleosynthesis of all heavier elements [1,2]. Weaver and Woosley [3] investigated the influence of the $^{12}C(\alpha,\gamma)^{16}O$ rate on the production of a series of isotopes and found a better agreement between calculated and observed abundances for the case if the adopted value [4] of the $^{12}C(\alpha,\gamma)^{16}O$ rate is raised by a factor of 1.7. This reaction is dominated by the interplay of several resonances—two of them being below the particle threshold—and the nonresonant direct capture (DC) which gives rise to interferences within the excitation function. The cross section of the $^{12}C(\alpha,\gamma)^{16}O$ reaction at burning temperatures is of the order of 10^{-17} b which can neither be measured with present techniques nor be predicted by theory. Hence, the required information has to be obtained by experiments of high sensitivity at energies as low as possible and by extrapolation of the data to the energy region of stellar burning. The $^{12}C(\alpha,\gamma)^{16}O$ reaction has been the subject of extensive studies in order to obtain the astrophysical S-factors S_{E1} and S_{E2}. However, the resulting data sets deviate significantly from each other [5]. Now a new experiment making use of the progress in experimental techniques and facilities was undertaken which delivered for the first time γ-angular distributions with eight or nine data points in the entire energy range of this experiment, yielding more information and redundancy for the $E2$ part than the older experiments [6–9]. Information merely on the $E1$ part was also deduced from the detection of the ^{16}O recoils reported by [10], as well as from the β-delayed α decay of ^{16}N [11,12]. A comparison of the experimental characteristics of the recent direct experiments with the present one is given below:

Expt.	Beam curr. (μA)	Det. type, effic.	Backgr. suppr. factor	Ang. data points	Target (backing)	Meas. time (h)
Redder [6]	700	Ge, 14%–35%	no	3 (6)	^{12}C, Au	900
Ouellet [8]	20–35	Ge, 18%–30%	19	5 (6)	^{12}C, Au	1950
Roters [9]	20	BGO, 270%	11 (25)	2	^{4}He gas	5000
This expt.	450	Ge, 100%	40	8–9	^{12}C, Au	700

The setup of our new experiment is shown in Fig. 1.

It consisted of an array of three or four large Ge detectors ($\epsilon = 100\%$) in close geometry, actively shielded with BGO (Bismuth Germanate, $Bi_4Ge_3O_{12}$) crystals. The whole detector setup was placed on a heavy motor-driven revolving table. The absolute efficiency of the Ge detectors has been determined by using calibrated sources as well as the 992 keV resonance of the $^{27}Al(p,\gamma)^{28}Si$ reaction [13]. By making use of the BGO anti-Compton crystals, the background at the relevant γ energy around 9 MeV has been reduced by a factor of up to 40. Thus, the peak to background ratio of the present setup was considerably higher than those achieved in any previous direct experiment. The high beam currents available, together

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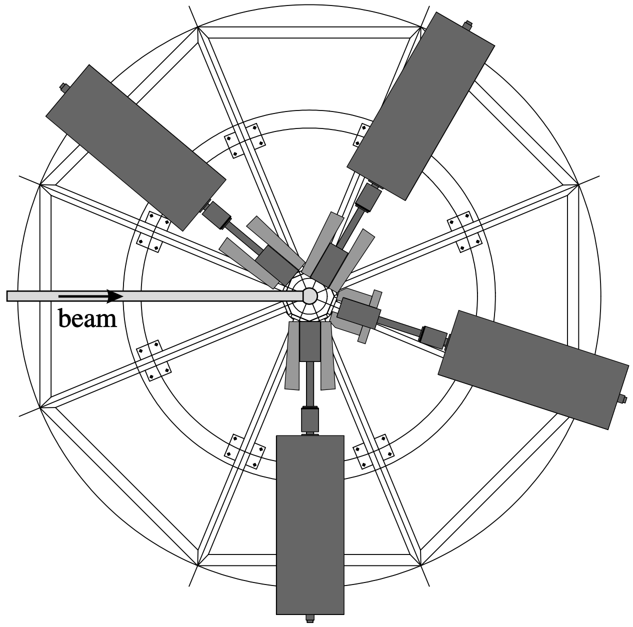

FIG. 1. Top view of the present experimental setup. The detector array used consisted of four high efficient ($\epsilon = 100\%$) HPGe detectors with active BGO shielding in close geometry around the target chamber. The array was placed on a motor driven revolving table.

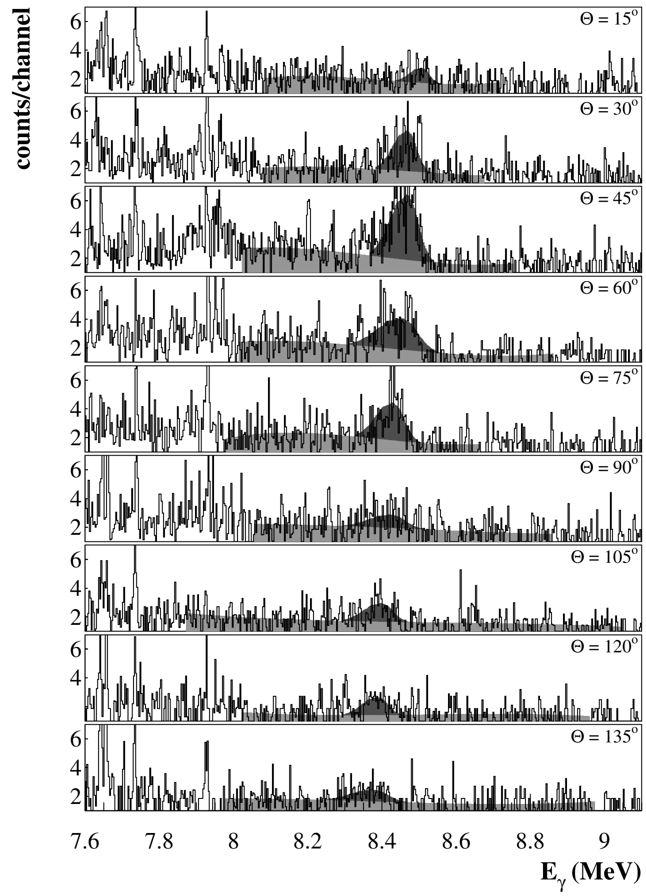

FIG. 2. High energy part of the γ spectra measured at $E_{\mathrm{cm}} = 1.254$ MeV and angular positions between $\Theta = 15°-135°$. The relevant peak (γ_0) is located at about 8.4 MeV and is marked by the dark area. The corresponding background is marked as grey area. The He^+ currents were about 400 μA and the measuring time was altogether 150 h.

with the high detection efficiency and the high background suppression factor of the present setup, have raised the sensitivity of the present measurements by about 1 to 2 orders of magnitude [14] compared to former experiments [6–9]. Some typical γ spectra measured in the present work at $E_{\mathrm{cm}} = 1.254$ MeV are shown in Fig. 2, exhibiting a clear signature of the lines and showing that the runs could well be extended below 1 MeV.

The targets used were produced by implanting ^{12}C atoms into gold. The gold layered backing used for this purpose was especially developed for long term experiments and high beam power of up to 10 kW/cm^2 [15]. The target implantation was carried out at a facility of the DTL, Bochum. Hereby, the depletion in respect to the detrimental ^{13}C was improved by a factor of 1000. The optimal target thickness was $(2-3) \times 10^{18}$ atoms/cm^2. In order to avoid any carbon buildup on the target surface, three cryotraps and a turbomolecular pump were installed near the target position. In this way a very clean vacuum of about $(2-5) \times 10^{-8}$ mbar could be achieved. The target composition and purity was checked by looking for the $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ as well as for the $^{12}\mathrm{C}(p, \gamma)^{13}\mathrm{N}$ reactions, the latter serving also for the daily target thickness controls. The target was replaced when a deterioration of about 20% was found.

The collected beam charge was measured by means of a calibrated electronic beam integrator. The angular distributions with 9(8) data points were obtained by using 3(4) detectors in 3(2) table positions. It has to be emphasized that the table position was changed every 1–2 h in order to equalize target effects. In addition, the targets were frequently turned to 180° to perform also yield contribution measurements from the backings. To measure the γ-angular distributions 420 h and 220 h for the background runs have been spent; 60 h were necessary to check the target deterioration. In our analysis, the γ_0- as well as any other possible cascade transitions arising in the spectra have been carefully evaluated by using the appropriate fitting procedures for line shapes and background. Figure 3 shows the angular distribution of γ_0 for $E_{\mathrm{cm}} = 1.254$ MeV as an example. The data have been properly corrected for target deterioration due to sputtering and for any effects due to finite geometry. The extension of the target spot with a diameter of about 10 mm and the size and position of the Ge detectors was taken into account by simulating the setup with the Monte Carlo code GEANT. The numerical results are presented in Table I. The large error bar at $E_{\mathrm{cm}} = 945$ keV is due to shorter measuring time at this energy.

The values for σ_{E1}, σ_{E2}/σ_{E1}, and σ_{E2} have been obtained by using the formula for the interference of $E1$ and

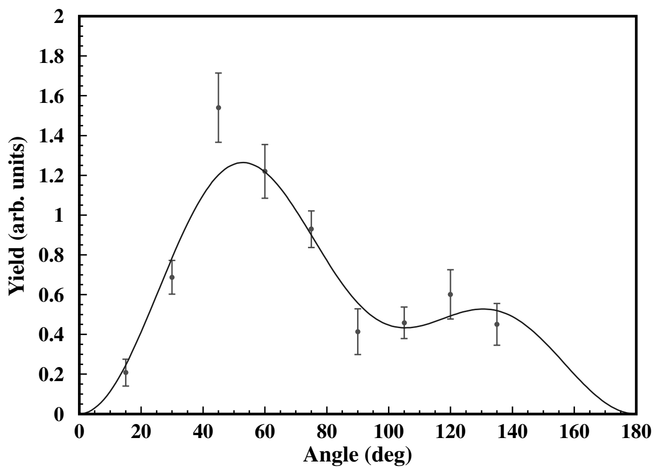

FIG. 3. Angular distribution of the γ_0 line of $^{12}C(\alpha,\gamma)^{16}O$ at $E_{\mathrm{cm}} = 1.254$ MeV. The curve represents a Legendre polynomial fit to the data points from which one obtains the σ_{E2}/σ_{E1} ratio and σ_{E1}; the phase Φ was fixed by using the elastic scattering data of [17,18].

$E2$ transitions in angular distributions, given in the paper of Dyer and Barnes [16]. The parameter Φ (phase) of this formula was not kept open, but determined by using the elastic α-scattering data of Plaga *et al.* [17] and D'Agostino Bruno *et al.* [18]. This treatment has already been proposed by Barker [19].

Figure 4(a) shows how the $E1$-excitation function with the new capture data has been described by a three-level–R-matrix fit ($E_R = -45.1$ and 2400 keV + "background" level) assuming a radius $R_0 = 6.5$ fm for the inner space with the nuclear interaction which was also used by Barker and Kajino [20] and Angulo and Descouvemont [21]. In a consistent manner also elastic α-scattering data [17,18] for $l = 1$ and 3 and the β-delayed α decay of ^{16}N [22] have been included in our R-matrix fit. The R-matrix fit for these three data sets is shown in Fig. 4 in three graphs. The boundary parameter was chosen in a way to obtain physically relevant parameters for the subthreshold levels; so γ widths and energies from literature [23] could be used. A five-level fit could not improve the description of S_{E1} because of the lack of data at energies above 4 MeV. The $E2$ data have been described with a five-level–R-matrix fit (−245, 2680, 4320, 5650 keV and the background level) using again the elastic scattering data from literature for $l = 2$ [17,18], γ widths [23], and the resonance parameters for

TABLE I. Numerical results from this experiment.

E_{cm} (keV)	σ_{E2}/σ_{E1} (uncert.)	Phase Φ (deg)	S_{E1} (keV b)	ΔE_{E1}	S_{E2} (keV b)	ΔS_{E2}
945	1.097(4515)	59	2.7	16.5	2.9	21.8
1254	1.277(324)	55	14.7	3	18.8	6.1
1451	0.790(137)	53	14.4	2.1	11.4	2.6
1572	0.468(862)	52	11.9	10.6	5.6	11.4
1702	0.355(55)	49	18.6	2.4	6.6	1.4
1997	0.095(21)	40	25.0	3.1	2.4	0.6
2072	0.105(17)	35	29.5	3.6	3.1	0.7
2147	0.081(12)	28	40.8	4.9	3.3	0.7
2184	0.055(9)	24	49.7	6	2.7	0.6
2223	0.068(6)	17	58.9	4.9	4.0	0.5
2259	0.132(355)	10	53.6	34.8	7.1	19.6
2299	0.202(246)	1	47.8	15.3	9.8	12.9
2335	0.174(392)	9	62.9	33.4	10.9	25.4
2374	0.039(7)	21	64.9	7.7	2.6	0.6
2407	0.034(8)	32	62.5	7.5	2.1	0.6
2449	0.152(279)	44	30.8	11.8	5.1	10.2
2486	0.061(16)	53	36.0	4.4	2.2	0.7
2526	0.031(8)	61	25.2	3	0.8	0.3
2771	0.630(597)	87(9)	6.1	3	3.8	4.1
2787	0.078(203)	67(37)	7.5	2.4	0.6	1.6

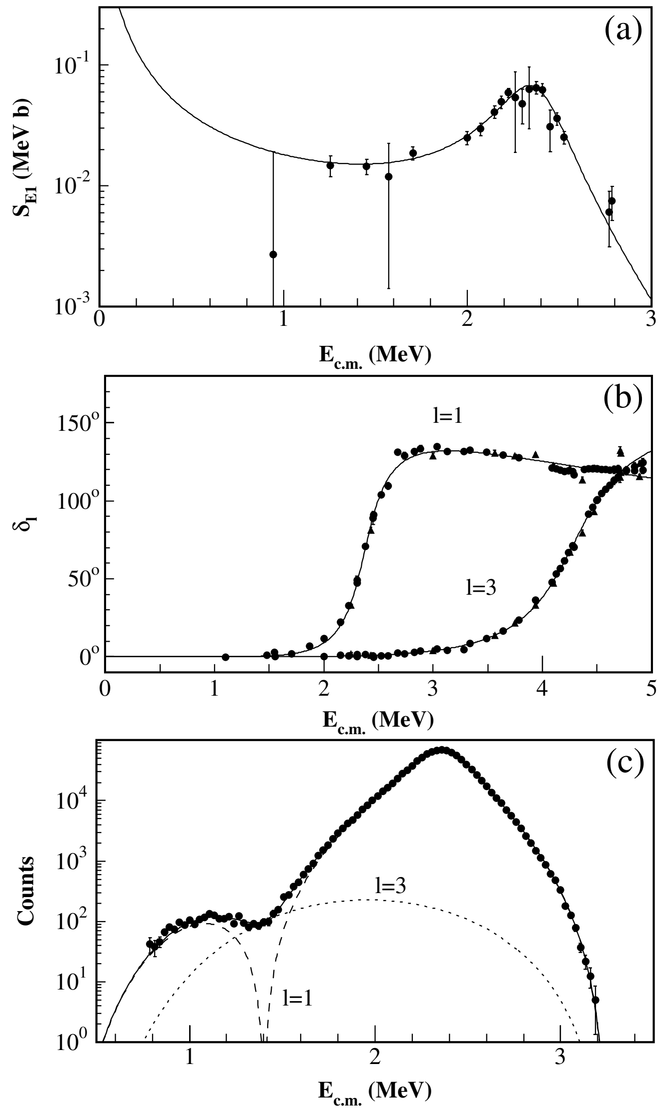

FIG. 4. Consistent three-level–R-matrix fit to the S_{E1} capture data of this work (a), the α-elastic scattering data ($l = 1, 3$) of Plaga *et al.* [17] and D'Agostino Bruno *et al.* [18] (b), and the decay spectrum of ^{16}N [22] (c).

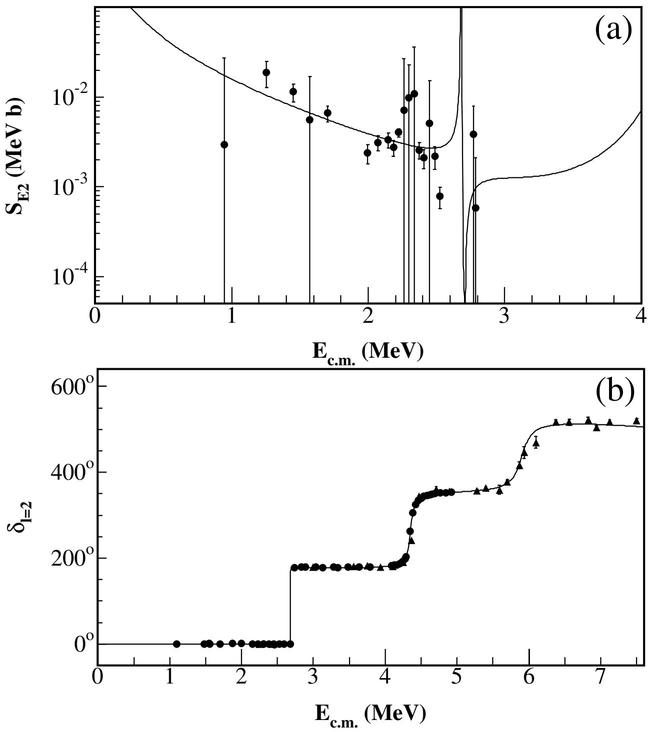

FIG. 5. Five-level–R-matrix fit to the S_{E2} capture data of this work (a) and to the α-elastic scattering data ($l = 2$) of Plaga *et al.* [17] and D'Agostino Bruno *et al.* [18] (b).

the 2^+ resonance [23]. The result is shown in Fig. 5. This fit is consistent with the recent data of Tischhauser [24].

The S-factor curves are extrapolated into the range of burning temperature. The following values for the $E1$, the $E2$ part of the S factor, the contribution due to γ cascades, and the total S factor at 300 keV have been extracted:

$$S_{E1}^{300} = (76 \pm 20)\ \mathrm{keV\,b}, \qquad S_{E2}^{300} = (85 \pm 30)\ \mathrm{keV\,b},$$

$$S_{\mathrm{casc}}^{300} = (4 \pm 4)\ \mathrm{keV\,b}, \qquad S_{\mathrm{tot}}^{300} = (165 \pm 50)\ \mathrm{keV\,b}.$$

Although the present experiment has been performed with a tenfold better sensitivity than all previous ones [7–9], this is not reflected in the quoted uncertainties which include both statistical and systematic errors induced by R-matrix analysis and fitting procedures. Our quoted errors are therefore of the same order for the S_{E1} and higher for the S_{E2} than the corresponding values of Ouellet *et al.* [7,8]. We believe that the errors quoted by Ouellet *et al.* are strongly underestimated. The S_{E1} value is in agreement with the determination via the ^{16}N decay [22], with the revised value of Ouellet *et al.* [8] of (79 ± 16) keV b and with the value of Roters *et al.* of (95 ± 44) keV b [9]. The S_{E2} value differs from the determination of Ouellet (36 ± 6) keV b, while Roters *et al.* specify no S_{E2} extrapolation value.

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