Oxygen Formation in the Light of Gamma-Beams: [Precision Measurements of the ^{12}C(α,γ) Reaction with Gamma-Beams and a Time Projection Chamber]

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Abstract. The carbon/oxygen (C/O) ratio at the end of stellar helium burning is not known with sufficient accuracy due to the large uncertainty in the cross-section of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}O$ reaction. We developed a new method to measure this reaction that is significantly different from the experimental efforts of the past four decades. Data were measured with vanishingly small background, inside one detector, that also serves as an active target (AT-TPC). Angular distributions of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}O$ reaction were obtained by measuring the inverse $^{16}\mathrm{O}(\gamma,\alpha)^{12}C$ reaction with gamma-beams (from the HIγS facility) and an optical readout time projection chamber (O-TPC) detector. We agree with current world data on the measured total reaction cross-section. We further evidence the strength of our method with angular distributions measured over the 1^-resonance at $E_{cm} \sim 2.4$ MeV. We extract the *E1-E2* mixing phase angle (ϕ_{12}) over this resonance and obtained values that follow the trend of prediction based on unitarity of the scattering amplitude. Our technique promises to yield results that will surpass the quality of the currently available data. We continue these measurements to lower energies at the HIγS facility of TUNL at Duke University, and anticipate measurements down to $E_{cm} = 1.1$ MeV at the ELI-NP, the EU facility in Romania..

1 Introduction

The $^{12}\mathrm{C}(\alpha,\gamma)^{16}O$ reaction was measured in terrestrial laboratories at energies near or below 1.5 MeV. We refer the reader to [1] for a thorough review of all measurements performed over the last 47 years, including the most recent data measured by the Stuttgart group with the EUROGAM array [2]. These data were used extensively to extrapolate to stellar conditions [1].

In stellar conditions, two partial waves, $\ell = 1$ and 2, contribute. They are denoted by the spectroscopic *E1* and *E2* amplitudes. The challenges in this field are measurements of angular distributions of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}O$ reaction from which the *E1* and *E2* cross sections are extracted, for accurate extrapolations to stellar conditions.

The *E1-E2* interference phase angle (ϕ_{12}) was calculated at first in the frame of R-Matrix theory [3], in term of the elastic phase shifts: $\phi_{12} = \delta_2 - \delta_1 + atan(\eta/2)$ where η is the Sommerfeld parameter. However, more recently, Brune [4] and Gai [5]

*e-mail: moshe.gai@uconn.edu. Supported by USDOE grant No. DE-FG02-94ER40870.

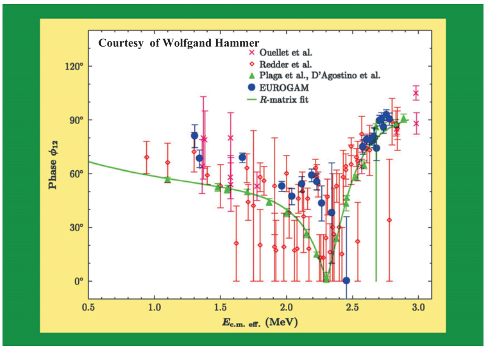

Figure 1. The world data on ϕ_{12} compiled by Professor Wolfgang Hammer. The Stuttgart EUROGAM data [2] are shown in blue. Figure courtesy of Professor Hammar.

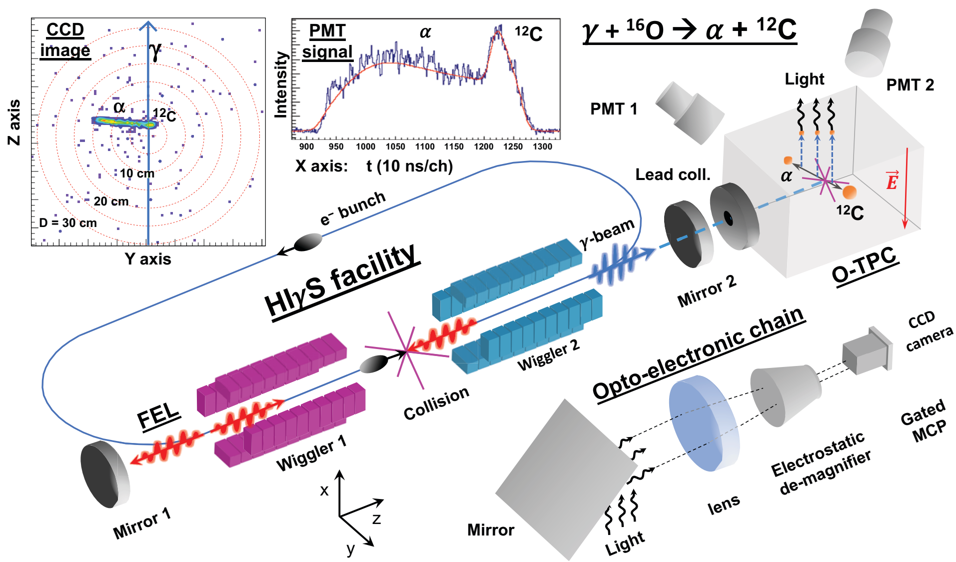

Figure 2. Schematic diagram of the HIγS beam and O-TPC. CCD image and PMT signal are shown on top left. Figure reproduction from [6] with permission from Springer Nature. Open Access Creative Commons license, creativecommons.org/ licenses/by/4.0/

noted that the theoretical prediction for ϕ_{12} is a consequence of the Watson theorem, which is derived assuming the unitarity of the scattering matrix. Hence the predicted ϕ_{12} is an elementary consequence of quantum mechanics. It must be observed in all measured angular distributions.

But as seen in Fig. 1, so far, no available measurement of ϕ_{12} over the broad 1^- resonance of ^{16}O (at E_{cm} = 2.4 MeV) show agreement with this fundamental prediction of quantum theory, even though at these energies the cross sections are large. Most disturbing is the disagreement of the modern measurements of the Stuttgart group [2], since these data were used for extrapolation [1]. As we show in Fig. 1, all 9 low energy data points at 1.3 - 2.3 MeV, that were measured with small error bars, disagree with the predicted ϕ_{12}, suggesting an ill understood systematic error(s), that were already noted before [5].

2 Measurement of the $^{16}O(\gamma, \alpha)$ at HIγS

We chose to measure the $^{12}C(\alpha, \gamma)^{16}O$ reaction by measuring the time reversed $^{16}O(\gamma, \alpha)^{12}C$ reaction, from which the direct reaction can be deduced using detailed

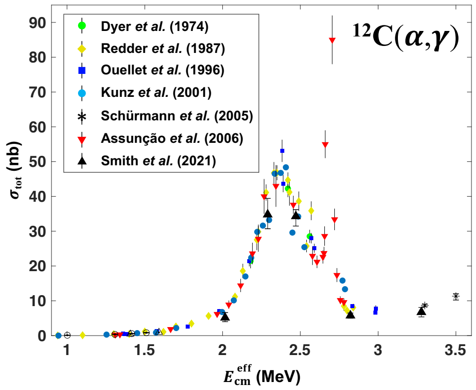

Figure 3. The world data on the total reaction cross section compared to our result [6]. Figure reproduction from [6] with permission from Springer Nature. Open Access Creative Commons license, creativecommons.org/ licenses/by/4.0/

balance. The setup of our measurement, data analyses, reduction and results are described in great details in our recently published Nature Communications paper [6]. But this discussion is beyond the scope of the current short contribution.

Briefly, the quasi mono-energetic gamma-beam ($\Delta E/E \sim 3\%$) was produced by the back-angle scattering of FEL photons with approximately 1 GeV electron beams, as discussed in [7]. The gamma beams incident on the Optical readout Time Projection Chamber (O-TPC) constructed at the University of Connecticut [8]. The photo-dissociation of oxygen in the CO_2 gas produces the α+^{12}C ions. These ions travel through the gas-filled chamber and the ionization tracks are amplified and recorded by the CCD camera through an optical readout system. A time projection of tracks is also recorded by using a set of Photo Multiplier Tubes. Again, we refer the reader to [6] for a complete review of our measurement.

The in plane angle (α) is measured ($\pm 2°$) from the CCD image, and the out of plane angle (β) is measured with the time projection signal recorded by the PMTs. The scattering and azimuthal angles (θ and ϕ) are deduced: $\tan\phi = \tan\beta/\sin\alpha$ and $\cos\theta = \cos\beta$ x $\cos\alpha$. Complete ($0°$ - $180°$) angular distributions were measured at nominal beam energies of $E_\gamma = 9.08, 9.38, 9.48, 9.58, 9.78, 10.1$ and 10.4 MeV.

The measured angular distributions were fitted with the standard $E1 + E2$ amplitude [9] :

$$W(\theta) = (3|A_{E1}|^2 + 5|A_{E2}|^2)P_0(\cos\,\theta) + \left(\frac{25}{7}|A_{E2}|^2 - 3|A_{E1}|^2\right) P_2(\cos\,\theta)$$
$$- \frac{60}{7}|A_{E2}|^2 P_4(\cos\,\theta) + 6\sqrt{3}|A_{E1}||A_{E2}|\cos\,\phi_{12}\,[P_1(\cos\,\theta) - P_3(\cos\,\theta)]$$

2.1 Results

The total reaction cross section measured in our HIγS experiment is shown in Fig. 3 taken from [6]. The agreement with the world data on the total reaction cross section serves as "proof of principle" of our new method. The extracted $E1 - E2$ mixing phase angle (ϕ_{12}) is shown in Fig. 4. The current results are from "data on tape" taken in 2012 (and analyzed during the COVID-19 pandemic). These data are with low statistics and we intend to remeasure it with higher statistics. Never-the-less the $E1 - E2$ mixing phase angle (ϕ_{12}) extracted by us is in agreement with the trend of the theoretical prediction. It serves as an impetus to repeat this measurement with higher statistics and continue to low energies.

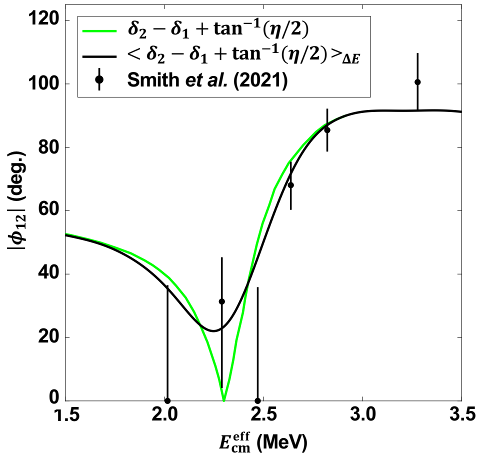

Figure 4. The measured $E1 - E2$ mixing phase angle (ϕ_{12}). Figure reproduction from [6] with permission from Springer Nature. Open Access Creative Commons license, creativecommons.org/ licenses/by/4.0/

3 Future Prospects at the HIγS and the ELI-NP

The current results were obtained with an optical readout TPC (O-TPC). A considerably better electronic readout TPC [10, 11] was constructed at the University of Warsaw (the ELITPC) with considerably better performance characteristics. We intend to repeat the measurement reported here with the O-TPC at the HIγS using the ELITPC, and continue to lower energies approaching ~1.7 MeV. After completing the measurements at the HIγS we plan to continue these measurements down to 1.1 MeV at the newly constructed ELI-NP facility in Romania [12] using the VEGA beam.

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