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Precision measurements of the $^{12}C(\alpha,\gamma)$ reaction with gamma beams and TPC detector(s)

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Abstract. The cross section of the $^{12}C(\alpha,\gamma)^{16}O$ reaction, well-recognized as the most important nuclear input of stellar evolution theory, has eluded precise measurements over the last few decades, as evident in the lack of precise confirmation of an elementary prediction of quantum mechanics of the *E1-E2* mixing phase angle (ϕ_{12}). More troubling are modern data, measured with 4π array of HPGe detectors, that are in conflict with this prediction. A new method to measure this cross section with TPC detectors and gamma-beams, by measuring the time reverse $^{16}O(\gamma,\alpha)^{12}C$ reaction discussed here, shows great promise, for example the measured data do not disagree with the predicted ϕ_{12} and agree with the predicted trend.

1 Introduction

In stellar helium burning carbon and oxygen are formed and the C/O ratio is determined by the single process of the fusion of ^{12}C with an alpha-particle to form ^{16}O; the $^{12}C(\alpha,\gamma)$ reaction. This reaction needs to be extrapolated to stellar conditions of a stellar plasma with temperature of kT = 20 keV, and the most efficient burning energy of 300 keV (the Gamow peak). The reaction is dominated by the two partial waves of $l = 1$ and 2 that are denoted by the spectroscopic *E1* and *E2* amplitudes, respectively. The challenge in this field are precise measurements of angular distributions of the $^{12}C(\alpha,\gamma)$ reaction from which the *E1* and *E2* cross sections and amplitudes are extracted, for accurate extrapolation to stellar conditions.

The *E1* and *E2* amplitudes interfere with a mixing phase angle (ϕ_{12}) that require precisely measured angular distributions. The phase angle was calculated at first in the frame of R-Matrix theory [1], $\phi_{12} = \delta_2 - \delta_1 + \text{atan}(\eta/2)$, where δ_2 and δ_1 are the d- and p- waves phase shifts and η is the Sommerfeld parameter. However, more recently, Brune [2] and Gai [3] noted that the theoretical prediction of ϕ_{12} is a more general 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, that must be observed in all measured angular distributions.

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Fig. 1, prepared by Wolfgang Hammer for his retirement presentation of a review of the field (2006), demonstrates the state of affairs then and now. So far, no accurate measurement of ϕ_{12} was achieved over the resonance energy region, Ecm = 2.0 – 2.6 MeV, where the cross section is large and ϕ_{12} exhibit large variations. More troubling is the disagreement of the EUROGAM data [4], where all the 9 low energy data points that are measured with high precision, disagree with the ϕ_{12} value labeled as R-matrix fit, which in fact, is also predicted by unitarity [2,3]. We note that as shown in Table I of [4] the extracted *E1/E2* values vary by up to a factor of 5, depending whether they perform a three parameter free fit (*E1, E2* and ϕ_{12}), or fix ϕ_{12} for a two parameter fit. Indeed, such large variations of the *E1/E2* values were also noted by Gai [3] in his reanalysis of the EUROGAM data [4].

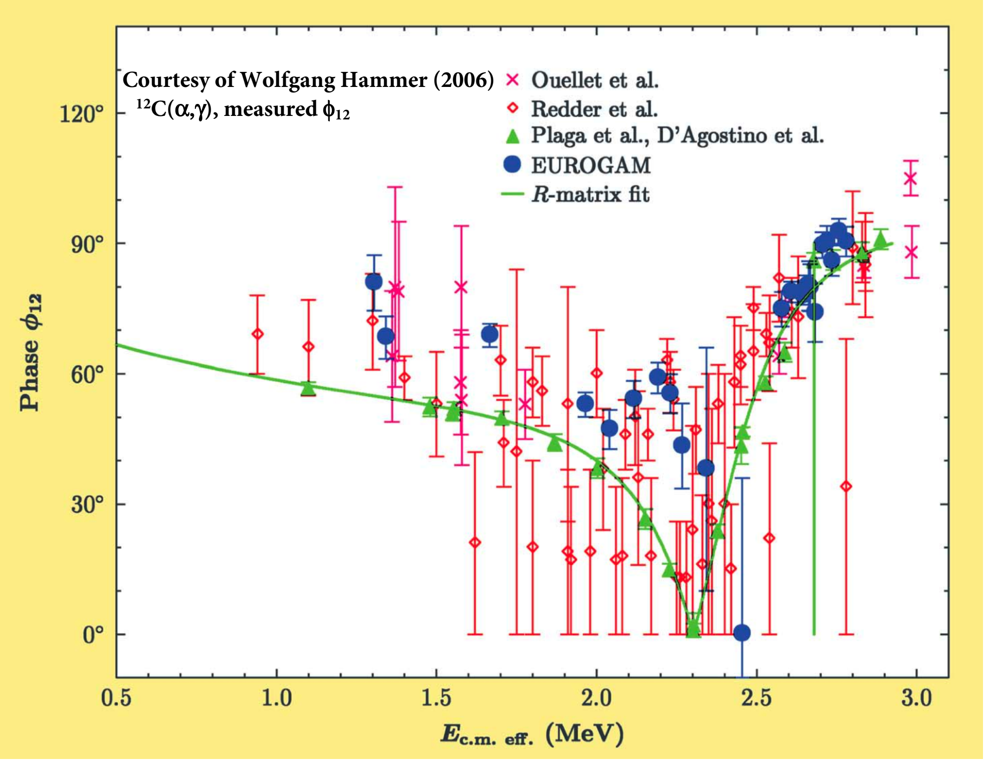
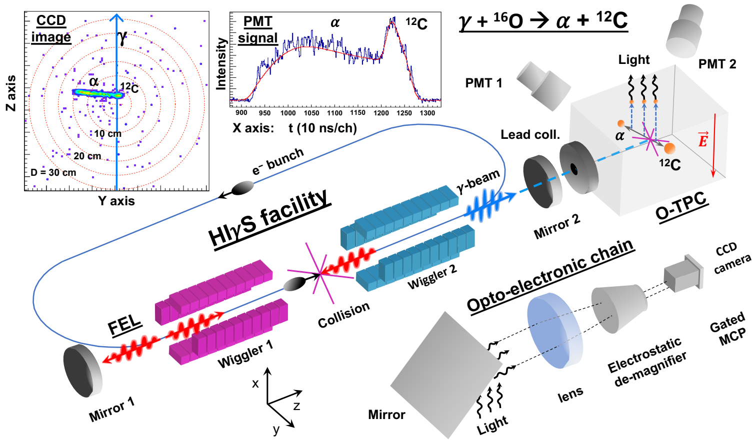


Fig 1: World data of measured ϕ_{12} compiled by Wolfgang Hammer (2006) [4]

2 The UConn-TUNL O-TPC Detector

The UConn-TUNL O-TPC was described in [5] and the analyses of the 2012 O-TPC data "on tape", that was performed during the COVID19 pandemic, are discussed in [6]. Briefly, we measure the ^{12}C(α,γ) reaction, by measuring the time reverse reaction of the photo-dissociation of ^{16}O in the ^{16}O(γ,α) reaction. As shown in Fig. 2 taken from [6], gamma-beams produced by backward scattering of free electron laser (FEL) photons from the GeV electrons in the ring, produce the HIγS quasi-monochromatic gamma-beam. The gamma-beam enters the O-TPC after a collimator 11 mm in diameter and 15 cm long. The O-TPC was operated with pure (grade 5) CO_2 (80%) + N_2 (20%) gas mixture at 100 torr. Tracks of alpha-particles and light nuclei emanating from the photo-dissociations of ^{16,17,18}O and ^{12}C were recorded in an array of PMT and a CCD camera, as shown in Fig.2.



<u>Fig. 2:</u> A schematic diagram of the HIγS gamma-beam system, the O-TPC detector and the opto-electronic readout chain, taken from [6]. A Typical track recorded by the CCD camera and the PMT signals, are shown together with the line shape analysis of the PMT time projection signal.

3 Results

One of the many achievements of the analyses of the O-TPC data, is the automated line shape analyses that allowed separating the ^{12}C and ^{16}O dissociation events. In our automated analysis that is described in great length in our Nature paper [6], the measured time projection PMT signals are compared to a table of calculated line shapes, 180 line shapes for the ^{16}O dissociation events and 1,000 line shapes for the ^{12}C dissociation events. The resulting so-defined "reduced χ^2/ν values" are shown in Fig. 3. The ^{12}C and ^{16}O dissociation events are very well separated from each other and are measured with a large signal to background ratio, as high as 20:1, as shown in Fig. 3.

A major advantage of using the O-TPC is that all data points are measured in one detector, with very low background, if any. Hence the relative efficiencies of data points are very simple to simulate using standard Monte Carlo techniques. The accurate angular distributions measured with the O-TPC, allowed us to measure the *E1* and *E2* amplitudes and perform "phase shift like" analyses of the *E1-E2* interference angle (ϕ_{12}). We measure ϕ_{12} with an accuracy of $\pm 6°$, or better.

In contrast to the data shown in Fig. 1 our recently extracted $\phi_{12,}$ measured with low statistics [6], *is not in disagreement with the predicted ϕ_{12}, and it follows the predicted trend*, as shown in Fig. **4**. The low statistics measurement of the O-TPC "data on tape" [6] was repeated in our measurements at HIγS in August 2022 with considerably higher statistics [7], using the Warsaw eTPC detector. The analyses of these data are in progress and initial results were shown in this conference [7].

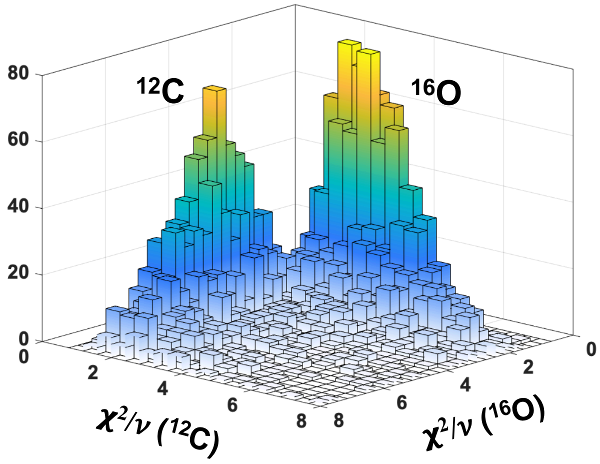


Fig. 3: Two-dimensional Lego plot of the lowest value of the so-defined "reduced χ^2/ν values" when fitting the measured PMT line-shape with the predicted line shapes of ^{16}O and ^{12}C dissociation events, taken from [6].

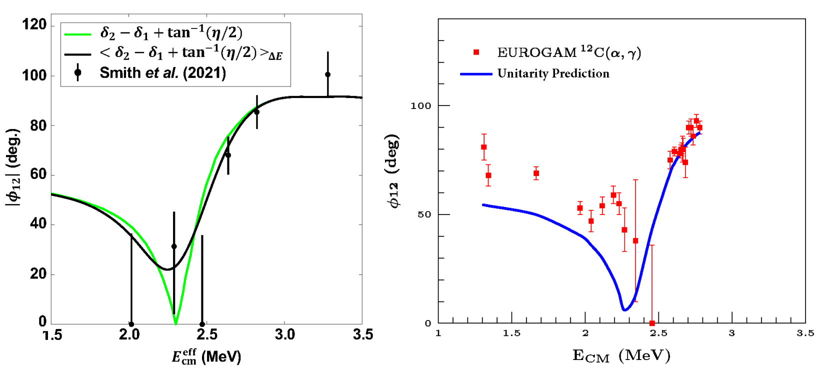


Fig. 4: The *E1-E2* mixing phase angle (ϕ_{12}) measured by the EUROGAM collaboration [4], and our low statistics O-TPC results [6]. New higher statistics data were measured in August 2022, with the Warsaw eTPC [7]. Analysis of the new data is in progress.

4 Conclusions

Our newly developed method for measuring the cross section of the ^{12}C(α,γ) reaction with TPC(s) and gamma-beams shows great promise for progress in the field. New data measured with Warsaw eTPC have been extended down to Eγ = 8.51 MeV [7]. We plan to continue to measure further down with lower gamma-beam energies.

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