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Abstract. An experiment was conducted at the High Intensity γ-ray Source (HIγS) facility at the Triangle Universities Nuclear Laboratory (TUNL) in Durham, NC, USA to measure the cross-section of the key astrophysical thermonuclear reaction ^{12}C(α,γ)^{16}O by means of its inverse photo-disintegration process. A high-intensity monochromatic γ-ray beam interacted with the CO_2 gas in the active volume of the Warsaw active target TPC detector. The reaction products were detected and their momenta reconstructed, so to also determine angular correlations. Data were collected at 15 beam energies ranging from 8.51 to 13.9 MeV. Preliminary results are presented.

1 Introduction

One of the fundamental questions in nuclear astrophysics is the creation of oxygen and carbon in the Universe. These two elements are not only the third and fourth most abundant elements in the Universe, respectively, but also the two most abundant elements in the human body. Our understanding of their formation mechanisms, and consequently of the stars' life cycle, is therefore important for understanding the origins of life on Earth.
Synthesis of carbon and oxygen happens in helium-burning thermonuclear reactions in the star's core, among which are the triple-alpha reaction and ^{12}C(α,γ)^{16}O. Star evolution models require, as input, details of the reaction rates as a function of the temperature/environmental conditions. The fundamental observable to determine the reaction rates is the cross-section,

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which has to be determined at the relevant energies (Gamow peak) [1]. Measuring the reaction probability at the Gamow peak is not possible, therefore extrapolations based on theoretical models, typically R-matrix, have to be employed. In order both to validate the models and constrain the extrapolations/R-matrix fits, hence reducing the uncertainties, accurate measurements at energies as-close-to the Gamow peak as-experimentally-achievable have to be carried on.
In this work, we focus on the measurement of the key helium-burning reaction ^{12}C(α,γ)^{16}O at low energies, i.e. below 2 MeV in the centre-of-mass (c.o.m.), which controls the carbon-to-oxygen ratio in the Universe. From the nuclear physics point of view, two reaction mechanisms are available in the Gamow window region (300 keV): non-resonant direct capture and capture into the tail of nearby 1^- or 2^+ resonances in ^{16}O (-0.045, -0.245, 2.42 and 2.68 MeV). In stellar environments, capture via ℓ=1 or ℓ=2 will dominate, hence not only the total E1+E2 cross section needs to be determined, but also its E1 and E2 components.

2 Methodology

Measuring the reaction cross-section for ^{12}C(α,γ)^{16}O at or close to the Gamow peak for helium-burning may still be too big a challenge from the experimental point of view; nevertheless, extrapolations with the help of R-matrix fits can help overcome this difficulty. The faster-than-exponential decrease of the cross section with decreasing c.o.m. energy (E_{cm}) makes such measurements particularly challenging, especially below 2 MeV.
The limitations in beam-intensity and target-thickness combinations, coupled with the large beam-induced γ background from contaminant reactions, such as ^{13}C(α,n)^{16}O, can be partially overcome thanks to the invariance of the strong and electro-magnetic interactions with respect to time-reversal. If, instead of the direct capture reaction ^{12}C(α,γ)^{16}O, its time-reversal photo-disintegration ^{16}O(γ,α)^{12}C is measured, a gain of a large factor in cross section can be achieved, thanks to the principle of detailed balance in nuclear reactions,

$$\sigma_{\alpha\gamma} \cdot \omega_{\alpha\gamma} \cdot p_{\alpha\gamma}^2 = \sigma_{\gamma\alpha} \cdot \omega_{\gamma\alpha} \cdot p_{\gamma\alpha}^2, \quad (1)$$

where $\sigma_{\alpha\gamma}, \omega_{\alpha\gamma}, p_{\alpha\gamma}$, $\sigma_{\gamma\alpha}, \omega_{\gamma\alpha}, p_{\gamma\alpha}$ are the cross section, spin factors, and momenta for the (α, γ) and (γ, α) reactions, respectively. At E_{cm}~1 MeV, the gain in cross section is of the order of 40. The advantages of such an approach, in addition to the gain in cross-section, are the inherent low-background, the negligible target deterioration, the different and negligible beam-induced background, the different definition of effective beam energy and, consequently, the different systematics.
In order to study the ^{16}O(γ,α) reaction, intense, monochromatic and well collimated γ-ray beams with energies in the range 8−15 MeV are needed in tandem with a detection set-up that allows reconstruction of the momenta of all the reaction products with close to 100% efficiency. It was shown [2] that a very good tool is an active-target time-projection chamber (active-target TPC), operated below atmospheric pressures (densities). The Warsaw active-target TPC was developed for studying nuclear photo-disintegration reactions where the products are charged particles, at astrophysically-relevant energies. It allows for full and unambiguous reconstruction of the momentum for multiple-particle events [3, 4], hence not only to determine the type of particles, and their energy, but also angular distributions to disentangle the contributions of the different multipolarities.
The Warsaw TPC has an active volume of 33 × 20 × 20 cm^3 and is immersed in a vacuum vessel equipped with a control system to maintain a constant gas pressure inside. The Warsaw TPC detector is composed of a cathode, a drift cage consisting of 12 aluminium electrodes, 2 mm-thick and 16 mm apart, for a total drift-length of 196 mm, an amplification structure

consisting of three 50 μm-thick Gas Electron Multiplier (GEM) foils, and a planar electrode (anode) segmented along 3 axes to obtain 3 independent linear sets of strips (U, V, W) with 1.5 mm pitch and oriented 60° with respect to each other for redundant readout. Such readout requires only about 1000 channels of electronics. The arrays of (U, V, W) strips enable dis-entangling the hit in 2 dimensions by generating virtual pixels. The time distribution of the charge collected at the electrode, combined with the drift velocity of the electrons in the given gas mixture and field in the drift cage, allows the determination of the third coordinate. The gas composition and density (pressure) are optimised for the reaction of interest. The data acquisition is based on the General Electronics for TPCs (GET) [5] complemented by a customised FPGA readout adaptation, which has been developed at the University of Warsaw. It allows to use sampling frequencies from 1 to 100 MHz (typically 12.5 or 25 MHz are used) and has adjustable gain and filtering for each channel. An external trigger can be used.

3 First measurements: ^{16}O photo-disintegration experiment

The first measurements were conducted in 2022 at the High Intensity γ-Ray Source (HIγS) facility at the Triangle University Nuclear Laboratory (TUNL) in Durham, NC, USA [6, 7]. Monochromatic γ-ray beams with energies ranging from 8.51 to 13.9 MeV were produced in Compton back-scattering of photons from a free-electron laser (FEL) with a relativistic electron beam. The beam energy was modulated by tuning the FEL wavelength and the electron beam. A collimator with diameter 10.5 mm was used to shape the beam spot on the target. The chamber was aligned with respect to the beam by means of a laser collinear with the beam trajectory as well as using attenuated beam and a γ camera for fine tuning of the alignment. Vertical alignment was such that the beam fit fully in between two consecutive electrodes of the TPC, hence avoiding generating background through the interaction of the γ beam with the electrodes.

The beam intensity and its variation in time was monitored throughout the experiment and determined through scintillation counters. Absolute calibration of the event rate determined by the scintillation detectors was obtained by means of (γ,n) activation measurements on ^{197}Au targets conducted synchronously with data taking with the chamber and with the auxiliary beam monitoring detectors. Preliminary analysis of the data yielded intensities well above $1.3{\cdot}10^8$ γ/s throughout the experiment, with a maximum of a few 10^8 γ/s at E_γ<10 MeV.

The beam energy, E_γ, was determined by impinging the attenuated γ beam into a calibrated HPGe detector, the spectrum was then deconvolved to determine the beam energy and energy spread, which was around 350 keV at E_γ=8.5 MeV. Such measurements were conducted every 8-12 hours to monitor the stability with time.

The data acquisition was triggered externally by using the integrated charge from the anode of the last GEM foil in the amplification stage.

The active gas in the chamber was pure CO_2, which allowed for the simultaneous measurement of ^{12}C photo-disintegration, with the pressure value chosen to optimise the length of the trajectories for the α and ^{12}C reaction products in the chamber. The CO_2 gas had natural isotopic composition, hence reactions on ^{12,13}C and ^{16,17,18}O isotopes are possible. ^{12}C and ^{16}O photo-disintegration reactions were the subject of the experiment, while ^{13}C and ^{17,18}O photo-disintegration would constitute beam-induced background. Photo-disintegration of ^{12}C and ^{16}O can be distinguished on the basis of the event topology, i.e. 3-particles vs. 2-particles disintegration, respectively. In the case of ^{13}C and ^{17,18}O, the (γ,α) reaction channels present very different Q-values with respect to ^{12}C and ^{16}O, respectively, and can be distinguished after analysis on the basis of the reconstructed momenta, see Section 4. The (γ,n) channel in ^{13}C and ^{17,18}O can be identified on the basis of the event topology, given the non-sensitivity of the detector to neutrons, while the (γ,p) channel in ^{16}O, which opens at E_γ = 12.1 MeV, can be distinguished thanks to the different Q-values combined with the different stopping power of protons and α particles.

4 Preliminary results

A preliminary analysis of the data was conducted on a portion of the statistics collected. All data were collected and analysed with dedicated software developed at the University of Warsaw. Events were visually inspected in order to assign them to categories according to their respective topology (1-, 2-, 3-particle events, background and noise). Background consisted of alpha particles from radon in the environment and of recoils following (γ,n) reactions on the CO_2 atoms. Such events are easily separated from the rest.
Those events classified as two- or three-particles were analysed further to determine the momenta of the particles. Two example events are presented in Fig. 1. The 2-particle case shown in Fig. 1 (left) is identified as a ^{16}O(γ,α)^{12}C reaction, while the 3-particle case in Fig. 1 (right) corresponds to a ^{12}C(γ,3α) event, both at E_γ = 8.66 MeV. Assignment of the two-particle event to ^{16}O(γ,α)^{12}C or to ^{17,18}O(γ,α)^{13,14}C is done by comparing the track length for two-particle events. In Fig. 2 the histogram of the sum of the α and ^{12}C track length is shown for E_γ = 8.66 and 11.5 MeV.
Momentum reconstruction of the particles emitted in the reaction also allows a reconstruction of the angular distribution of the events. In Fig. 3 (left), the polar angular distribution is shown for events identified as ^{16}O(γ,α) at 11.5 MeV beam energy. A distribution characteristic for E2 multipolarity is observed, as expected for the 11.5 MeV 2^+ resonance in ^{16}O.
The γ beam delivered to the measuring station was circularly polarised to a degree well above 90%, as determined by measurements of the polarisation of the laser beam [8]. The reconstruction of the momenta of the reaction products for 2-particle events allowed for confirmation of the degree of circular polarisation of the γ beam, see Fig. 3 (right). Preliminary evaluation gives a degree of circular polarisation in good agreement with expectations [8].

5 Summary and outlook

An active-target time-projection chamber operating at pressures below atmospheric was developed at the University of Warsaw for studying photo-disintegration reactions of astrophysical interest at or close-to the relevant energies. The methodology exploits the principle of

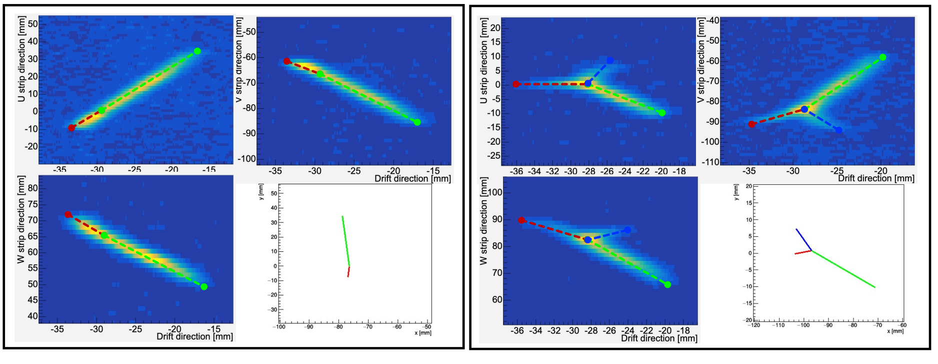

Figure 1. Event reconstruction example for an ^{16}O (left) and a ^{12}C (right) photo-disintegration event at E_γ=8.66 MeV. The raw data for the charge collected by each strip (U, V, W) strip is plotted as a function of strip position and time (both rescaled to mm), while the bottom-right plot shows the projection of the reconstructed tracks on the anode plane.

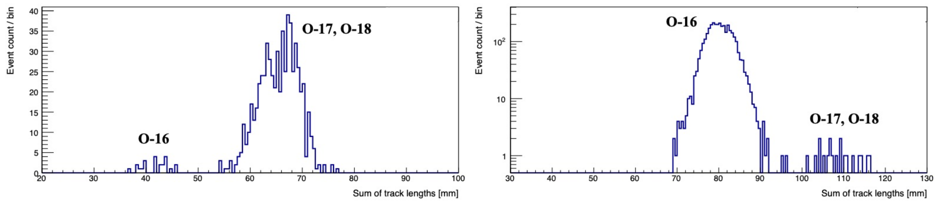

Figure 2. Identification plot, based on the sum of the α and ^{12,13,14}C track lengths for two-particle events at E_γ = 8.66 MeV (left) and 11.5 MeV (right). Partial statistics and laboratory reference frame.

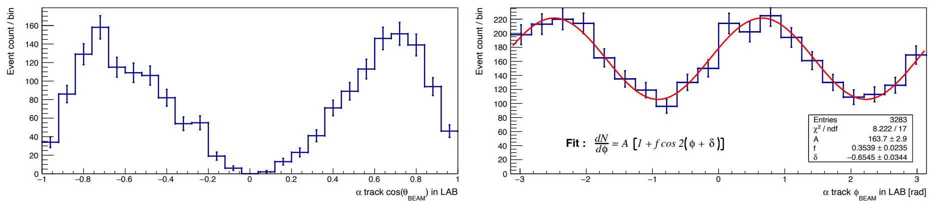

Figure 3. Polar (θ) and azimuthal (ϕ) angle distributions (left and right panels, respectively) in the laboratory reference frame for ^{16}O(γ,α) events at E_γ=11.5 MeV. Partial statistics. See text.

detailed balance in nuclear reactions to determine the cross section of ^{12}C(α,γ)^{16}O by measuring that of the inverse reaction. The first experiments were conducted in 2022 at the HIγS facility at TUNL, where intense, monochromatic γ-ray beams were made to impinge on the active gas target inside the TPC and the reaction products were detected. Data were collected for beam energies ranging from 8.51 to 13.9 MeV. Preliminary analysis shows that the complete evaluation will provide the cross sections as well as angular distributions, to determine the E1 and E2 contributions. Future experiments are being planned to increase the statistics and reach lower energies.

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