OPEN QUESTIONS IN STELLAR HELIUM BURNING
STUDIED WITH REAL PHOTONS *

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The outcome of helium burning is the formation of the two elements, carbon and oxygen. The ratio of carbon to oxygen at the end of helium burning is crucial for understanding the final fate of a progenitor star and the nucleosynthesis of heavy elements in Type II supernova, with oxygen rich star predicted to collapse to a black hole, and a carbon rich star to a neutron star. Type Ia supernovae (SNeIa) are used as standard candles for measuring cosmological distances with the use of an empirical light curve-luminosity stretching factor. It is essential to understand helium burning that yields the carbon/oxygen white dwarf and thus the initial stage of SNeIa. Since the triple alpha-particle capture reaction, $^\alpha Be(\alpha, \gamma)_{12}{^C}$, the first burning stage in helium burning, is well understood, one must extract the cross section of the $^{12}{^C}(\alpha, \gamma)_{16}{^O}$ reaction at the Gamow peak (300 keV) with high accuracy of approximately 10% or better. This goal has not been achieved despite repeated strong statements that appeared in the literature. Constraint from the beta-delayed alpha-particle emission of $^{16}{^N}$ were shown to not sufficiently restrict the p-wave cross section factor; e.g. a low value of $S_{E1}(300)$ can not be ruled out. Measurements at low energies, are thus mandatory for determining the elusive cross section factor for the $^{12}{^C}(\alpha, \gamma)_{16}{^O}$ reaction. We are constructing a Time Projection Chamber (TPC) for use with high intensity photon beams extracted from the H1yS/TUNL facility at Duke University to study the $^{16}{^O}(\gamma, \alpha)_{12}{^C}$ reaction, and thus the direct reaction at energies as low as 0.7 MeV. This work is in progress.

1. Introduction: Oxygen Formation in Helium Burning and
The $^{12}{^C}(\alpha, \gamma)_{16}{^O}$ Reaction

The outcome of helium burning is the formation of the two elements, carbon and oxygen $^{1,2,3}$. The ratio of carbon to oxygen at the end of helium burning is crucial for understanding the fate of Type II supernovae and the nucleosynthesis of heavy elements. While an oxygen rich star is predicted

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to end up as a black hole, a carbon rich star leads to a neutron star. At the same time helium burning is also very important for understanding Type Ia supernovae (SNeIa) that are now being used as a standard candle for cosmological distances. All thus far luminosity calibration curves and the stretching factor are based on empirical observations without fundamental understanding the relation between the time characteristics of the light curve and the maximum magnitude of Type Ia supernova. Since the first burning stage in helium burning, the triple alpha-particle capture reaction \((^8\text{Be}(\alpha,\gamma)^{12}\text{C})\), is well understood, one must extract the p-wave \([S_{E1}(300)]\) and d-wave \([S_{E2}(300)]\) cross section of the \(^{12}\text{C}(\alpha,\gamma)^{16}\text{O}\) reaction at the Gamow peak (300 keV) with high accuracy of approximately 10% or better to completely understand stellar helium burning, and better understand Type II and Type Ia supernova.

1.1. Beta-Delayed Alpha-Particle Emission of \(^{16}\text{N}\)

Early hopes for extracting the astrophysical E1 S-factor \([S_{E1}(300) = \sigma_{E1} \times E \times e^{2\pi\eta}]\) of the \(^{12}\text{C}(\alpha,\gamma)^{16}\text{O}\) reaction through constraints imposed by new data on the beta-delayed alpha-particle emission of \(^{16}\text{N}\) were examined in detail over the last few years and a few observations were made. The original Yale data were improved in a phase II experiment of the Yale-UConn group, and were found to be in disagreement with the TRIUMF data but consistent with the unpublished data of the Seattle group, see Fig. 1. In addition, an independent R-matrix analysis of the world data including the beta decay of \(^{16}\text{N}\) data was found to not rule out a small S-factor solution (10-20 keV-b). It is thus doubtful that one can extract the p-wave cross section factor with a reasonable accuracy as stated in Ref. \(^8\). The confusion in this field mandates a direct measurement of the cross section of the \(^{12}\text{C}(\alpha,\gamma)^{16}\text{O}\) reaction at low energies. A recent measurement at lower energies suggest a d-wave cross section factor that is at least twice larger than "the accepted value", and the their low energy data point(s) measured with low precision can not rule out a small p-wave cross section factor.
Fig. 1: The Yale-UConn data on the beta-delayed alpha-particle emission of $^{16}\text{N}$ compared to the TRIUMF and Seattle results. The TRIUMF and Seattle data are averaged over the energy resolution of the Yale-UConn experiment and are shown by continuous lines. The unpublished Seattle data are listed (by permission) in the appendix of Ref. 10.

2. The Proposed $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ Experiments

For determining the cross section of the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ at very low energies, as low as $E_{\text{cm}} = 700$ KeV, considerably lower than measured till now, it is advantageous to have an experimental setup with larger (amplified) cross section, high luminosity and low background. It turns out that the use of the inverse process, the $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ reaction may indeed satisfy all three conditions. The cross section of $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ reaction (with polarized photons) at the kinematical region of interest (photons approx. 8-8.5 MeV) is larger by a factor of approximately 100 than the cross section of the direct
$^{12}$C($\alpha, \gamma$$^{16}$O reaction. Note that the linear polarization of the photons yields an extra factor of two in the enhancement due to detailed balance. Thus for the lowest thus far measured data point at 0.9 MeV with the direct cross section of approx. 60 pb, the photodissociation cross section is 6 nb. It is evident that with similar luminosities and lower background, see below, the photodissociation cross section can be measured to yet lower center of mass energies, as low as 0.7 MeV, where the direct $^{12}$C($\alpha, \gamma$$^{16}$O reaction cross section is of the order of 1 pb. A very small contribution (less than 5%) from cascade gamma decay can not be measured in this method, but appears to be negligible and below the design goal accuracy of our measurement of $\pm$10%.

Fig. 2: Schematic diagram of the HI$\gamma$S facility for the production of intense MeV gamma beams.

The High Intensity Gamma Source (HI$\gamma$S), shown in Fig. 2, has already achieved many of its design milestones and is rapidly approaching its design goal for 2-200 MeV gammas. For 9 MeV gammas we expect an energy resolution of 0.1% and intensity of order $10^3$/sec. Currently achieved intensities are of the order of $10^8$/sec with energy resolution of approx. 0.5%. The backscattered photons of the HI$\gamma$S facility are collimated (3 mm diameter) and enter the target/detector TPC setup as we discuss below. With a Q value of -7.162, our experiment will utilize gammas of energies approximately 8 to 10 MeV. Note that the emitted photons are linearly polarized and the emitted particles are primarily in a horizontal plane (parallel to target room floor) with a $\sin^2\phi$ azimuthal angular dependence, thus simplifying the tracking of particles in this experiment. The pulsed photon beam (0.1 ns every 180 nsec with at most 500 gammas per pulse) provides additional trigger for removing background. The image intensified CCD camera is triggered by light detected in the PMT, see be-
low, and the time projection information from the drift chamber yields the azimuthal angle of the event of interest. The scattering angle is measured with high accuracy using the (8 cm long) alpha tracks and (2 cm long) carbon tracks. Background events from contaminants carbon, oxygen and fluorine isotopes, are discriminated using the TPC as a calorimeter with a 2% energy resolution. Time of flight techniques, and flushing of the CCD between two events will also be used. To reduce noise, the CCD will be cooled. We note that similar research program with high intensity photon beams and a TPC already exists at the RCNP at Osaka, Japan, proving that tracks from low energy light ions can be identified in the TPC with a manageable electron background. An \(^{16}O(e,e'\alpha)^{12}C\) experiment with virtual photons proposed at the MIT-Bates accelerator is useful to extract only the \(d\)-wave astrophysical cross section factor and thus it complements our experiment proposed for the HI\(\gamma\)S-TUNL facility.

2.1. Proposed Time Projection Chamber (TPC)

![Fig. 3: Schematic diagram of the Optical Readout TPC](image)

We are constructing an Optical Readout Time Projection Chamber (TPC), similar to the TPC constructed in the Physikalisch Technische Bundesanstalt, (PTB) in Braunschweig, Germany and the Weizmann Institute, Rehovot, Israel, for the detection of alphas and carbon, the byproduct of...
the photodissociation of $^{16}O$. Since the range of available alphas is approximately 8 cm (at 100 mbars) the TPC is 40 cm wide and up to one meter long. We first construct a 40 cm long TPC for initial use at the HIγS beam line at TUNL/Duke. The TPC is largely insensitive to single Compton electrons, and the large compton electron flux, if a problem, can be blocked using a standard beam blocker placed between the drift chamber volume and the Multi Wire Proportional Counter of the TPC. The TPC allows for tracking of both alphas and carbons emitted almost back to back from the beam position in time correlation. The very different range of alphas and carbons (aprox. a factor of 4), and differences in the lateral ionization density, will aid us in particle identification. The TPC also allow us to measure angular distributions with respect to the photon beam thus separating the E1 and E2 components of the $^{12}C(\alpha, \gamma)^{16}O$ reaction. The excellent energy resolution of the TPC (aprox. 2%) allows us to exclude events from the photodissociation of nuclei other than $^{16}O$, including isotopes of carbon, oxygen and fluorine, that are present in the gas. In Fig. 3, taken from Titt et al. 20, we show a schematic diagram of the Optical Readout TPC.

The photon beam enters the TPC through an entrance window in the drift chamber part of the TPC and mainly produce background $e^+e^-$ pairs and a smaller amount of Compton electrons, as well as the photodissociation of various nuclei present in the $CO_2 + Ar$ gas mixture, including $^{16}O$. The charged particle byproducts of the photodissociation create delta electrons that create secondary electrons that drift in the chamber electric field with a total time of the order of 1 µs per 5 cm. The time projection of the drift electrons allows us to measure the inclination angle ($\phi$) of the plane of the byproducts, and the tracks themselves allow for measurement of the scattering angle ($\theta$), both with an angular resolution better than two degrees. The electrons that reach the multi-wire chamber are multiplied (by aprox. a factor of $10^5$) and interact with a small (3%) admixture of triethylamine (TEA) 20 or $CF_4$ 21 gas to produce UV or visible photons, respectively. The light detected in the photomultiplier tube, see Fig. 3, triggers the Image Intensifier and CCD camera which takes a picture of the visible tracks. The picture is downloaded to a PC and analyzed for recognition of the two back-to-back alpha-carbon tracks originating from the beam position. The background electrons lose aprox. 0.5 KeV/cm in the TPC and are removed by an appropriate threshold in the trigger Photo Multiplier Tube (PMT). Events from the photodissociation of nuclei other than $^{16}O$ are removed by measuring the total energy (Q-value) of the event with a resolution of 2%. 
2.2. Design Goals

The luminosity of our proposed $^{16}$O($\gamma$, $\alpha$)$^{12}$C experiment can be very large. For example, with a 30 cm long fiducial length target with 30% CO$_2$ at a pressure of 76 torr (100 mbar) and a photon beam of $2 \times 10^9$ /sec, we obtain a luminosity of $10^{29}$ sec$^{-1}$cm$^{-2}$, or a day long integrated luminosity of 10 nb$^{-1}$. Thus a measurement of the photodissociation of $^{16}$O with cross section of 1 nb, yields 10 count per day, leading to a sensitivity for measuring the direct $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction with a cross section as low as 10 pb, corresponding to energies as low as 700 keV. The construction and tests of the TPC is in progress at the University of Connecticut, at the PTB in Braunschweig and the Weizmann Institute. A mark I experiment to measure coincidences between $\alpha$-particles and $^{12}$C is in progress at the TUNL/Hi$\gamma$S facility.

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