Proc. 21st Winter Workshop on Nuclear Dynamics (2005) 000–000

21st Winter Workshop on Nuclear Dynamics
Breckenridge, Colorado, USA
February 5–12, 2005

Optical Readout Time Projection Chamber (O-TPC) for a Study of Oxygen Formation In Stellar Helium Burning [a]

Moshe Gai[1], Amos Breskin[2], Rachel Chechik[2], Volker Dangendorf[3], and Henry R. Weller[4].

[1] Dept. of Physics, Yale University, New Haven, CT 06520, USA.
[2] Dept. of Particle Physics, Weizmann Institute of Science, Rehovot, Israel.
[3] Physikalisch Technische Bundesanstalt, Braunschweig, Germany.
[4] Dept. of Physics, Duke University, Durham, NC 27708, USA.

Abstract. We are developing an Optical Readout Time Projection Chamber (O-TPC) detector for the study of the 12ag reaction that determines the ratio of carbon to oxygen in helium burning. This ratio is crucial for understanding the final fate of a progenitor star and the nucleosynthesis of elements prior to a Type II supernova; an oxygen rich star is 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. The O-TPC is intended for use with high intensity photon beams extracted from the HIγS/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. We are conducting a systematical study of the best oxygen containing gas with light emitting admixture(s) for use in such an O-TPC. Preliminary results with CO_2 + TEA mixture were obtained.

Keywords: TPC, Optical Readout, GEM, Stellar Evolution, Helium Burning, Oxygen Formation, S-factor
PACS: 25.20.-x, 26.50.+x, 29.40.Cs, 29.40.Gx,

[a]Work Supported by USDOE Grant No. DE-FG02-94ER40870 and the Yale-Weizmann Collaboration, American Committe on Weizmann Institute of Science.

1. Introduction: Oxygen Formation in Helium Burning and The ̧12ag Reaction

Carbon and oxygen are produced during helium burning in Red Giant stars before they undergo supernova explosions. These are some of the most important elements required to support life as we know it on earth, and as such, the understanding of the origin of carbon and oxygen was designated by Willie Fowler in his 1984 Nobel talk, the holy grail of Stellar Nuclear Physics [1]. Moreover, the ratio of carbon to oxygen (C/O) at the end of helium burning is one of the most important parameters for understanding stellar evolution. In a massive star (at least $8M_\odot$) it determines whether the star that undergoes Type II supernova, collapses to a black hole or a neutron star [2]. A sun-like star that ends up as a carbon plus oxygen white dwarf, is the progenitor star for a Type Ia supernova explosion (SNeIa), that are now used as a standard candle for measuring distances comparable to the size of the observed universe (13.7 Billion Light Years) [3]. These Hubble type measurements of cosmological distances (using SNeIa) allow us to conclude that the universe is composed for the most part of dark matter (approximately 23%), and dark energy (approximately 73%) with the latter giving rise to a recent (5 Billion years ago) accelerated expansion of the universe [4]. Thus the understanding of stellar evolution and the calibration of peak luminosity of SNeIa is essential for placing this conclusion on firm theoretical foundation. The C/O ratio of a white dwarf affects the peak luminosity and the shape of the light curve of SNeIa [5]. This ratio must be determined from laboratory measurements.

The outcome of helium burning is the formation of the two elements, carbon and oxygen [1, 2, 6]. The first stage in helium burning, the formation of ^{12}C via the triple alpha-particle capture reaction, is well understood [1] and is denoted, using standard Nuclear Physics notation, as the $^{8}Be(\alpha,\gamma)^{12}C$ reaction. Thus one must extract the cross section for forming oxygen via the fusion of carbon plus helium denoted by ̧12ag. This reaction is dominated by two partial waves and one must extract the p-wave (S_{E1}) and d-wave (S_{E2}) astrophysical cross section factors for the reaction as discussed in [6]. The cross section factors must be known at the Gamow peak (300 keV) relevant for stellar environment, with high accuracy of approximately 10% or better. Current data are measured at energies not lower than 1.2 MeV and the extrapolation to stellar burning energies of 0.3 MeV is particularly difficult due to substantial contributions from bound states of ^{16}O at very low energies.

1.1. Beta-Delayed Alpha-Particle Emission of ^{16}N

The cross section of the fusion reaction is written in terms of an astrophysical cross section factor (the S-Factor) times a kinematical factor that is due to the small penetrability of the two interacting charged particles. During the 1990s it was suggested that one can measure the p-wave E1 S-factor using the beta-decay of ^{16}N [7, 8, 9, 10, 11, 12] followed by alpha decay of ^{16}O. This theoretical concept of using the beta-decay of ^{16}N was introduced to circumvent the fast drop of the cross section at lower energies due to penetration through the Coulomb barrier. Indeed some used the ^{16}N data to quote the S-factor with 25% uncertainty [10] and the problem was considered solved. But later it was shown by Hale [13] that the interpretation of the experimental data on the beta-decay of ^{16}N is inconclusive and the astrophysical cross section factor is ill determined by at least a factor of 4 and as much as 8. A recent measurement at lower energies [14] suggests 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.

We conclude that the astrophysical cross section factor must be measured directly at energies as low as possible and as close as possible to the Gamow window (300 keV) as it is in stellar helium burning. A unique opportunity [15, 16] presented itself with the newly constructed High Intensity Gamma Source (HIγS) now operating at Duke University, as we discuss below.

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

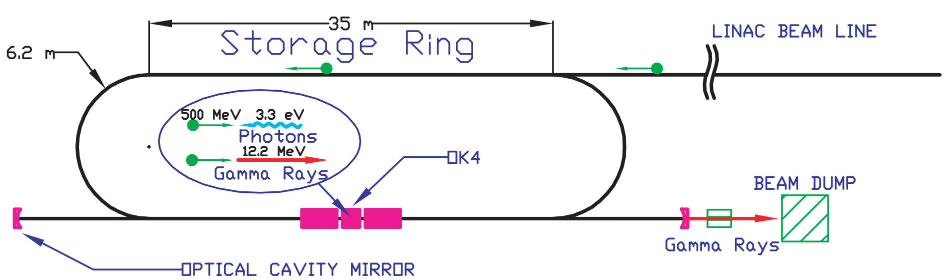

Fig. 1: A schematic diagram of the newly constructed HIγS facility of TUNL at Duke University [15].

In order to determine the cross section of the 12ag reaction at relative energies as low as 700 KeV, considerably lower than measured till now, it is useful to have an experimental setup with three conditions: enhanced cross section, high luminosity and low background. It turns out that the use of the inverse process, the $^{16}O(\gamma,\alpha)^{12}C$ reaction may indeed satisfy all three conditions. The cross section of the $^{16}O(\gamma,\alpha)^{12}C$ inverse reaction (with polarized photons) at the kinematical region of interest (photons approx 8-10 MeV) is larger by a factor of 80-160 than the cross section of the direct 12ag reaction. Note that the 100% linearly polarized gamma-ray beam (available at HIγS) yields an extra extra factor of two in the enhancement. It is evident that with similar luminosities and lower background (see below), the photodissociation cross section can be measured at center of mass energies as low as 700 keV, where the direct 12ag cross section can be estimated to be of the order of 10 pb (thus the corresponding photodissociation cross section is approximately 1nb). A very small contribution (less than 5%) from cascade gamma decay can not be measured in this experiment, but appears to be negligible and below the design goal accuracy of our measurement of ±10%.

The High Intensity Gamma Source (HIγS) [15], shown in Fig. 1, has already achieved many milestones and is approaching its design goals for 2-200 MeV gammas. This experiment will place a stringent demand of 8-10 MeV gammas at a resolution of 0.5% or better and intensity of order 10^9 /sec. The backscattered photons of the HIγS facility will be collimated and will enter the target/detector Optical Time Projection Chamber (O-TPC) setup as we propose below. With a Q value of -7.162 MeV, our experiment will utilize gammas of energies ranging from 7.9 to 10 MeV. Note that the emitted photons will be linearly polarized and the emitted particles will be primarily in a horizontal plane with a $sin^2\phi$ azimuthal angular dependence. This simplifies the tracking of particles in this experiment. The pulsed photon beam (0.1 nsec every 180 nsec with at most 500 gammas per pulse) provides a trigger for the track-recording image-intensified cooled CCD camera of the O-TPC; the scattering angle will be deduced from the reconstructed tracks relative to the beam direction with high accuracy using the (8 cm long) alpha tracks and (2 cm long) carbon tracks. The time projection information from the O-TPC will yield the azimuthal angle of the event of interest. Background events will be discriminated with time-of-flight techniques, and gating of the CCD camera. The image intensified CCD camera will be triggered by light detected in the PMT, see below. Background events (mainly) from oxygen isotopes, will be discriminated using the TPC as a calorimeter with a 5% 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 [17], proving that tracks from low energy light ions can be identified in the TPC with a manageable electron background resulting from the intense gamma beams. We also performed a test using silicon detectors in helium gas exposed to 25 MeV photons and measured the resulting electron background. We conclude that this background is manageable.

2.1. Proposed Time Projection Chamber (TPC)

We are developing an Optical Readout Time Projection Chamber (TPC), based on the TPC constructed in the Physikalisch Technische Bundesanstalt, (PTB) in Braunschweig, Germany and the Weizmann Institute, Rehovot, Israel [18], 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 designed to be 40 cm wide and up to one meter long. We plan to 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 it allows for tracking of both alphas and carbons emitted back to back from the beam position in time correlation. The very different range of alphas and carbons (approximately a factor of 4), and differences in the lateral ionization density, will aid us in particle identification. The TPC will also allow us to measure angular distributions with respect to the photon beam thus separating the E1 and E2 components of the 1̧2ag reaction. The energy resolution of the TPC (5% or better) will allow us to exclude events from the photodissociation of nuclei other than ^{16}O, including isotopes of oxygen, that are present in the gas. In Fig. 2, based on Titt *et al.* [18], we show a schematic diagram of the proposed Optical Readout TPC.

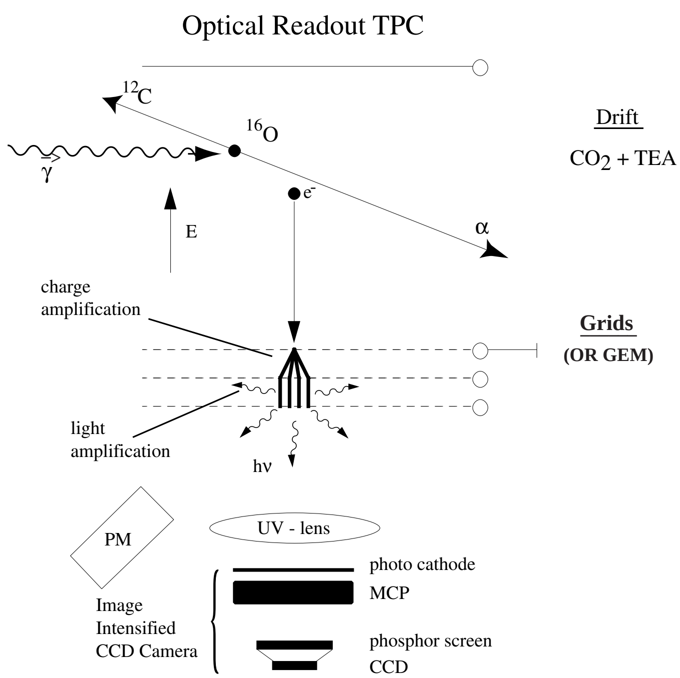

Fig. 2: A schematic diagram of the O-TPC that we propose to construct for this study. It is designed following the O-TPC used by the Weizmann-PTB collaboration [18].

The photon beam will enter 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 + TEA gas mixture, including ^{16}O. The charged particles resulting from the photodissociation process will induce secondary ionization electrons in the gas that drift along the electric field. The drift times are in the μsec range. The electrons that will reach electron-amplification element, e.g. cascaded parallel-grid avalanche multipliers [19] or the recently developed Gas Electron Multipliers (GEM) [20, 21], will be multiplied in an avalanche process by approximately a factor of 10^5, yielding charge signals. Scintillation processes induced by avalanche-electron excitations of selected gas molecules, e.g. triethylamine (TEA) [18] yield copious amount of UV photons. Optically imaged cascaded GEMs and the Thick GEM-like (T-GEM) multipliers recently developed at the Weizmann Institute [22], have higher multiplication factors and are expected to provide higher photon yields. A fraction of the avalanche light will be detected by the photomultiplier (PM) tube (Fig. 2). The PMT signal together with various grid signal(s), see Fig. 2, will be used in the trigger configuration of the Image Intensifier and the CCD camera, which takes a picture of the tracks. Dedicated pattern recognition algorithms will select the typical back-to-back Alpha-Carbon tracks. The background electrons lose approximately 100 keV in the entire TPC and and will be removed by appropriate thresholds. Events from the photodissociation of nuclei other than ^{16}O will be removed by measuring the total energy (Q-value) of the event with a resolution of approximately 5%.

We have conducted light output tests with CO_2 + TEA gas mixture and find promising results for electron amplification and light output in this gas mixture. This work is in progress at the Weizmann Institute.

3. Design Goal

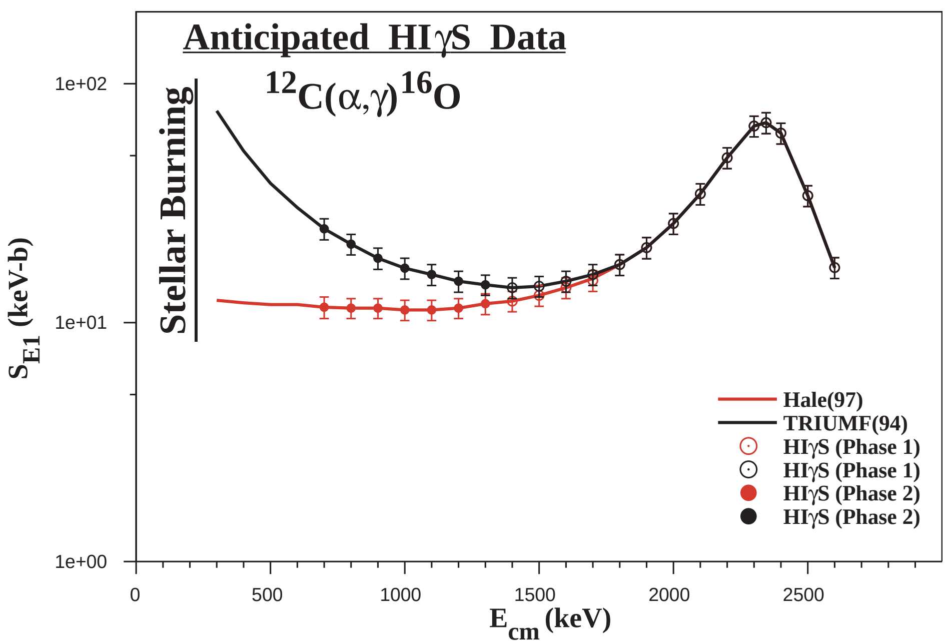

Fig. 3: Anticipated results for the p-wave astrophysical cross section factor compared with predictions.

The time projection of the drift electrons will allow us to measure the inclination angle ϕ of the plane of the byproducts, and the tracks themselves will allow for measurement of the scattering angle θ, both with an accuracy of better than two degrees. The so obtained angular distributions will be fitted with Legendre polynomials to provide the contributions of the p- and d- partial waves, from which the cross section factors will be deduced. The results of our simulation showing the anticipated astrophysical S-factors for p-waves (SE1) and d-waves (SE2) are shown in Figs. 3 and 4, respectively

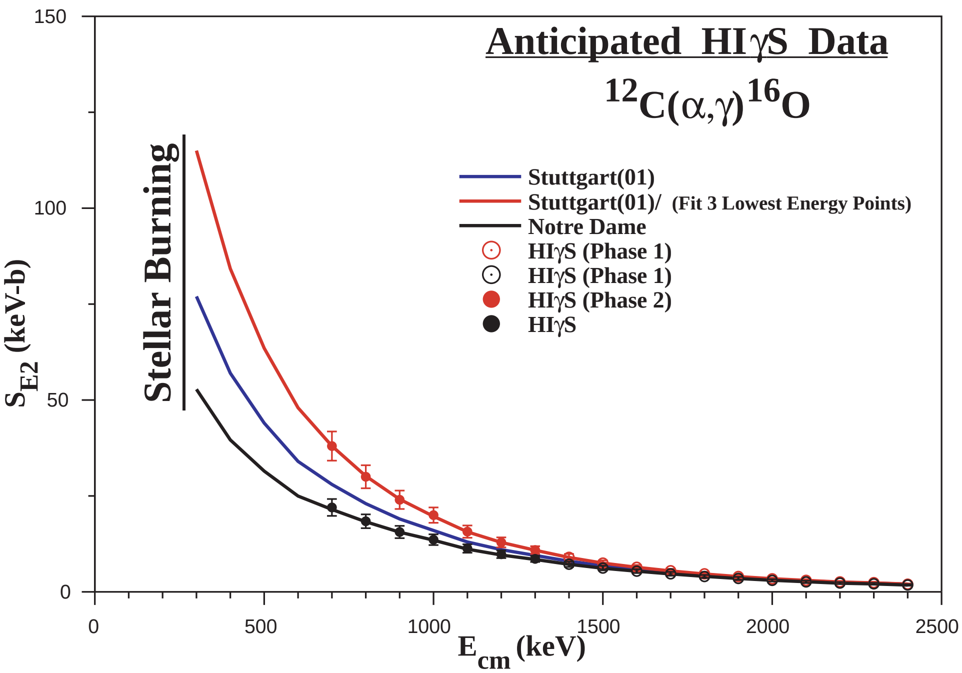

Fig. 4: Anticipated results for the d-wave astrophysical cross section factor compared with predictions.

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 CO_2 at a pressure of 76 torr (100 mbar) and a photon beam of 1×10^9 /sec, we obtain a luminosity of $1.5 \times 10^{29}\ sec^{-1}cm^{-2}$ (15 nb^{-1}/day). Thus a measurement of the photodissociation of ^{16}O with a cross section of 1 nb, yields 15 counts per day, leading to a design goal sensitivity for measuring the direct 1̧2ag reaction with a cross section as low as 10 pb, corresponding to energies as low as 700 keV. A mark I experiment to measure coincidences between α-particles and ^{12}C is in progress at the TUNL/HIγS facility.

References

1. W.A. Fowler, Rev. Mod. Phys. **56**(1984)149.
2. T.A. Weaver, and.E. Woosley; Physics Report, **227**(1993)65.
3. M. Phillips, Astrophys. J. Lett. **413**(1993)105. M. Hamuy et al., Astron. J. **106**(1993)2392; ibid **109**(1995)1. A. Riess, W. Press, R. Kirshner, Astrophys. J. **473**(1996)88.
4. S. Perlmutter; Physics Today **56:4**(2003)53, and reference therein.
5. P. Hoeflich, Ch. Gerardy, E. Linder, and H. Marion; astr-ph/0301334.
6. M. Gai; From the Sun to the Great Attractor, Lecture Notes in Physics, Springer, 2000, p. 49.
7. Zhiping Zhao; Ph.D. thesis, Yale University, 1993.
8. Z. Zhao, R.H. France III, K.S. Lai, S.L. Rugari, M. Gai, and E.L. Wilds; Phys. Rev. Lett. **70**(1993)2066, ER **70**(1993)3524.
9. L. Buchmann; *et al.*; Phys. Rev. Lett. **70**(1993)726.
10. R.E. Azuma, *et al.*; Phys. Rev. **C50**(1994)1194.
11. Ralph H. France III; Ph.D. thesis, Yale University, 1996, http://www.phys.uconn.edu/∼france/thesis.html.
12. R.H. France III, E.L. Wilds, N.B. Jevtic, J.E. McDonald, and M. Gai; Nucl. Phys. **A621**(1997)165c.
13. G.M. Hale; Nucl. Phys. **A621**(1997)177c.
14. R. Kunz *et al.*; Phys. Rev. Lett. **86**(2001)3244.
15. A Proposal: "A FREE-ELECTRON LASER GENERATED GAMMA-RAY BEAM FOR NUCLEAR PHYSICS", W. Tornow, R. Walter, H.R. Weller, V. Litvinenko, B. Mueller, P. Kibrough, Duke/TUNL, 1997.
16. Toni Feder, Physics Today, Volume 55, No. 12, p. 26, 2002.
17. T. Shima, Y. Nagai, T. Kii, T. Baba, T. Takahashi, and H. Ohgaki; Nucl. Phys. **A629**(1998)475c.
18. U. Titt, A. Breskin, R. Chechik, V. Dangendorf, H. Schmidt-Bocking, H. Schuhmacher; Nucl. Instr. Meth. **A416**(1998)85. U. Titt, V. Dangendorf, H. Schuhmacher; Nucl. Phys. **B Supp. 78**(1999)444. U. Titt, Dissertation zur Erlangung des Doktorgrades. (Ph.D. thesis), J.W. Goethe Universitat Frankfurt, 1999.
19. A. Breskin, R. Chechik and D. Sauvage; Nucl. Instrum. Meth. **A286**(1990)251.
20. F.Sauli; Nucl. Instrum. Meth. **A386**(1997) 531.
21. A. Breskin, M. Balcerzyk, R. Chechik, G. P. Guedes, J. Maia and D. Mormann; Nucl. Instr. Meth. **A513**(2003)250.
22. R.Chechik, A.Breskin, D.Moermann and C.Shalem; Nucl. Instrum. and Meth. **A535**(2004)303.