Optical Readout TPC (O-TPC)
For a Study of
Stellar Helium Burning at HIγS

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1. The Collaboration
2. The Experiment (Briefly):
   Oxygen Formation in Stellar Helium Burning
   $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ Reaction With Real Photons
3. The Detector (O-TPC)
4. Performance of O-TPC
5. Future Developments

TUNL, Duke, 12 July 2007
The Laboratory for Nuclear Science
At Avery Point
The O-TPC at HIγS Collaboration:

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* Supported by US Department of Energy  

** Supported by the American Committee on Weizman Yale-Weizmann Collaboration  

*** In Kind Contribution, Optical Readout System
HELIUM BURNING IN (MASSIVE) STARS

I. \[ 3 \alpha \rightarrow ^{12} \text{C} \]

II. \[ \alpha + ^{12} \text{C} \rightarrow ^{16} \text{O} \]

1. Energy
2. \(^{12} \text{C} / ^{16} \text{O}\)
3. Heavier Elements

III. \[ \alpha + ^{16} \text{O} \rightarrow ^{20} \text{Ne} \] (NEGligible)
Explosion of a White Dwarfs (Defl., Delayed Det. & Merger)

Initial WD

Deflagration phase (2...3 sec)
preexpansion of the WD

Detonation phase (0.2...0.3 sec)
hardly any time for further expansion

Deflagration: Energy transport by heat conduction over the front, $v << v(\text{sound}) \Rightarrow$ ignition of unburned fuel (C/O)
Detonation: ignition of unburned fuel by compression, $v = v(\text{sound})$

Rem1: Pre-expansion depends on the amount of burning. The rate of burning hardly changes the final structure for DD-models (Dominguez et al. ApJ 528, 590)

Rem.2: HeDs (sub-MCh)
- disagree with LCs and spectra
  (Nugent et al. 96, Hoeflich et al. 96)
Peter Hoeflich (2002)

**INFLUENCE ON LIGHT CURVES (0-60 Days)**

DD21c: C/O = 1/1; Z = 0.02 (solar)
DD23c: C/O = 2/3; Z = 0.02 (solar)
DD24c: C/O = 1/1; Z = 0.0067 (solar/3)

**Bolometric Light Curves**

C/O Ratio of the WD
- Maxima ≈ 2-3 days later (i.e., 1-5 days)
- Peak to 'Tail' ratio changes by ≈ 0.3 m

Metallicity Z - negligible

OFF SET in M(dM15)
dM(V) ≈ 0.1 dt(rise)

**Change of Monochromatic Light Curves rel. DD21c**
The chlorine detector must be maintained in low-level operation until the chlorine and gallium detectors can be operated at full level simultaneously. Otherwise endless conjecture concerning time variations in the solar neutrino flux will ensue. Moreover, the results of the gallium observations may uncover information that has been overlooked in the past chlorine observations.

The CNO cycle operates at the higher temperatures which occur during hydrogen burning in main sequence stars somewhat more massive than the sun. This is the case because the CNO cycle reaction rates rise more rapidly with temperature than do those of the pp chain. The cycle is important because $^{12}$C, $^{14}$N, $^{15}$N, $^{17}$O, and $^{18}$O are produced from $^{12}$C and $^{14}$O as seeds. The role of these nuclei as sources of neutrons during helium burning is discussed in Sec. V.

V. THE SYNTHESIS OF $^{12}$C AND $^{18}$O AND NEUTRON PRODUCTION IN HELIUM BURNING

The human body is 65% oxygen by mass and 18% carbon, with the remainder mostly hydrogen. Oxygen (0.85%) and carbon (0.39%) are the most abundant elements heavier than helium in the sun and similar main sequence stars. It is little wonder that the determination of the ratio $^{12}$C/$^{16}$O produced in helium burning is a problem of paramount importance in Nuclear Astrophysics.

This ratio depends in a fairly complicated manner on the density, temperature, and duration of helium burning, but it depends directly on the relative rates of the $3\alpha\rightarrow^{12}$C process and the $^{12}$C($\alpha,\gamma$)$^{16}$O process. If $3\alpha\rightarrow^{12}$C is much faster than $^{12}$C($\alpha,\gamma$)$^{16}$O, then no $^{16}$O is produced in helium burning. If the reverse is true, then no $^{12}$C is produced. For the most part the subsequent reaction $^{16}$O($\alpha,\gamma$)$^{20}$Ne is slow enough to be neglected.

There is general agreement about the rate of the $3\alpha\rightarrow^{12}$C process, as reviewed by Barnes (1982). However there is a lively controversy at the present time about the laboratory cross section for $^{12}$C($\alpha,\gamma$)$^{16}$O and about its theoretical extrapolation to the low energies at which the reaction effectively operates. The situation is depicted in Figs. 4, 5, and 6, taken with some modification from Langanke and Koozin (1983), Dyer and Barnes (1974), and Kettnem et al. (1982). The Caltech data obtained in the Kellogg Laboratory is shown as the experimental points in Fig. 4, taken from Dyer and Barnes (1974), who compared their results with theoretical calculations by Koozin, Tombrello, and Fox (1974). The Münster data are shown as the experimental points in Fig. 5, taken from
Helium Burning:

\[ 3\alpha \rightarrow 12C \text{ Known} \]

\[ \alpha + 12C \rightarrow 16O \quad ??? \]

\[ \frac{C}{O} = ? \]

\[ 12C(\alpha,\gamma)16O \ (E_{cm} = 300 \text{ keV}) \]

\[ \sigma(\alpha,\gamma) = S/E \times e^{-2\pi \eta} \]

\[ (\eta = e^{2Z_1Z_2/\hbar \nu} = Z_1Z_2\alpha/\beta) \]

 Astrophysical Cross Section Factor (P and D waves)

\[ SE1(300) \]
\[ SE2(300) \pm 15\% \]
$S_{E1}$ (MeV-b) vs. $E_{cm}$ (MeV)

- Solid line:
- Dashed line:
- Dotted line:
- Data points with error bars:

(b)
O-TPC at HI\(^\gamma\)S
(Detailed Balance)

\(^{16}\)O + \(\gamma\) \(\rightarrow\) \(\alpha + ^{12}\)C *

\[ E_\gamma = 8.0 - 10.0 \text{ MeV (±1%)} \]

* \(\sigma(\alpha, \gamma_{\text{cascade}}) \lesssim 4\% \text{ at 300 keV} \)

\[ \sigma(\gamma, \alpha) = \frac{(2S_1+1)(2S_2+1)}{2(S_4+1)} \times \frac{k_\alpha^2}{k_\gamma^2} \times \sigma(\alpha, \gamma) \]

\[ \sigma(\overline{\gamma}, \alpha) = \frac{(2S_1+1)(2S_2+1)}{1(2S_4+1)} \times \frac{k_\alpha^2}{k_\gamma^2} \times \sigma(\alpha, \overline{\gamma}_i) \]

but: \(\sigma(\alpha, \overline{\gamma}_i) = \frac{1}{2} \sigma(\alpha, \gamma)\)

\[ = \frac{(2S_1+1)(2S_2+1)}{2(S_4+1)} \times \frac{k_\alpha^2}{k_\gamma^2} \times \sigma(\alpha, \gamma) \]

\[ = \frac{1}{2} \times (80 - 160) \times \sigma(\alpha, \gamma) \]

\[ = (40 - 80) \times \sigma(\alpha, \gamma) \]

Luminosity = 1 nb\(^{-1}\) per Day

\(I_{\gamma} = 4.0 \times 10^7 \text{ /sec (phase 1)}, \ \Delta E = 2\%, \ \text{Collimator} = 1/2" \)

\(\sigma_{\alpha\gamma}(1.3\text{MeV}) = 0.6 \text{ nb}, \ \sigma_{\gamma\alpha}(8.5\text{MeV}) = 30 \text{ nb} \rightarrow 30\text{CPD} \)
Anticipated $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ Data

$S_{E1} \text{ (keV-b)}$

$E_{cm} \text{ (keV)}$

Hale(97)
TRIUMF(94)
$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ Data

$S_{E1} \text{ (keV-b)}$

$E_{cm} \text{ (keV)}$
Project Description

1. Introduction

The outcome of helium burning is the formation of the two elements carbon and oxygen [1]. The ratio of carbon to oxygen at the end of helium burning has been identified two decades ago as one of the key open questions in Nuclear Astrophysics [1] and is still today. To solve this problem one must extract the p-wave \([S_{E1}(300)]\) and d-wave \([S_{E2}(300)]\) cross section (factor) 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.

Several new measurements of the \(^{12}\text{C}(\alpha,\gamma)^{16}\text{O}\) reaction using gamma-ray detectors have been reported [2, 3] with energies in the vicinity of 1.0 MeV. However, the S-factors are measured with very low accuracy (40-80%) and most importantly one cannot rule out a low value of the E1 S-factor [4, 5]. These new experiments use some of the highest intensity alpha-particle beams (10 - 500 µAmp) with an impressive luminosity of \(10^{33}\) [2] and \(10^{31}\) [3] cm\(^{-2}\)sec\(^{-1}\), and a 4\(\pi\) array of HPGe and BaF, respectively, gamma-detectors with an obtained large counting statistics. Yet the obtained accuracy of the S-factors is limited due to the limited accuracy of the measured angular distribution. A major disadvantage of measuring gamma rays is the large background. This large background is not expected in our proposed experiment using a Time Projection Chamber (TPC) and in addition we will measure detailed angular distributions and thus large sensitivity to the E2/E1 ratio.

One tantalizing new problem that was posed by the new gamma-ray data [2] is the disagreement between E1/E2 mixing phases \((\phi_{12})\) extracted from the measured gamma-ray angular distributions and the mixing phase predicted by theory:

\[
\phi_{12} = \delta_2 - \delta_1 + \arctan(\eta/2)
\]

where \(\delta_1\) and \(\delta_2\) are the p and d wave elastic phase shifts and \(\eta\) is the Sommerfeld parameter. In Ref. [2] the disagreement is considered as a simple disagreement between data and the prediction of R-Matrix theory. But in fact the above relationship is rooted in the Watson theorem and unitarity. This disagreement is observed already at high energies, on the broad 1\(^{\text{st}}\) resonance located at 9.58 MeV where the capture cross-section is large, and it must be resolved.

Our experiment with O-TPC will measure complete angular distributions with high sensitivity for extracting \(\phi_{12}\) due to the fact that we can measure over a large angular range including angles close to the beam position where gamma ray data cannot be obtained. Thus we propose to resolve this issue.

2. Status of the O-TPC Detector

A study with a prototype (8 cm diameter) Optical Readout Time Projection Chamber (O-TPC) operating with a gas mixture of \(\text{CO}_2(90\%) + \text{N}_2(10\%)\) at 75 torr has been completed and published by this collaboration [6]. Tracks from 1 MeV energy deposited by alpha-particles have
\( E = 2.0 \text{ MeV} \)

\( S_{E2}/S_{E1} = 1.0 \)

- \( \phi_{12} = 45 \)
- \( \theta = 90 \)
- \( \theta = 45 \)
- \( \theta = 0 \)

\( W(\theta) \) vs \( \theta \) (Deg)
$3^\text{He}$, $t$, $P$, $4^\text{He} + \gamma$ (25 MeV), $e^-$
Optical Readout TPC (O-TPC)

Drift
- CO₂ (90%)
- N₂ (10%)

Grids
Charge (Trigger) + Light

150 torr

γ

(HIγS)
80 hPa N$_2$ + CO$_2$ (75\%) (4.5 MeV alphas)
**CO₂+TEA (18%)**

**CO₂+N₂ (10%)**
Quantum Efficiency of CHORUS BV55 Optical Chain/ PTB. March 2006.
Contrast Transfer Function Mask, PTB, June 2006.
**Fig.56:** ROI full vertical binning of the 3 mm mask (a = white value; b = black value; c = pixel contents)
Benjamin Bromberger - PTB (University of Braunschweig)
Triggered Readout of OTPC System

Q Comp

LabJack

Data RDY

Read Trig

TCP/IP

VME

USB

SBC

ADC

BUSY OR

CCD

Anal CFD

Veto
Lens Fiducial Circle (D ~ 15cm) at 85 cm Distance
O-TPC: CO₂(90%) + N₂(10%) at 100 Torr

148Gd (3.183 MeV)

6.0%

Light

(≈270 photo e⁻)

14.3%

Charge

Light

500

0

1000

0

500

1000

Channel

Charge

Counts/Channel
$^{148}\text{Gd (3.183 MeV)}$
(150 Torr)
Drift Field

Output (Channel)

Voltage (kV)

Drift Field
Tracks From $^{148}$Gd (3.181 MeV)
TRI-OTPC

Mirrors?  
Fiber Optics?

Lens

TOP VIEW
Laser power, low emittance, low bandwidth puts T-REX at the forefront of high brightness

We estimate T-REX peak brilliance at 1 MeV exceeds synchrotrons by 15 orders of magnitude
August, 2007: O-TPC moves to TUNL (We need a clean room)

September, 2007: O-TPC calibrated at TUNL DAQ system tested

Fall, 2007: One shift test
Phase 1:
First week of data
Break
Second week of data

Supplementary Request
(DOE ~$40K)

January 21, 2008: End of my sabbatical leave!!!

Summer 2008: Please Consider an upgrade of HIγS ala T-REX (LLNL)