

## **STATUS REPORT 2010-2012**

**Laboratory for Nuclear Science  
at Avery Point  
University of Connecticut  
<http://astro.uconn.edu>**



**USDOE Grant No: DE-FG02-94ER40870  
Principal Investigator: Moshe Gai**

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## 1.1 Abstract

Our research program encompasses several studies in Low Energy Nuclear Astrophysics covering stellar evolution and Big Bang Nucleosynthesis (BBN). During the last three years (FY10-FY12) we carried out an extensive research program at the HI $\gamma$ S at TUNL with our (upgraded) Optical Readout Time Projection Chamber (O-TPC) detector to study the formation of carbon and oxygen during stellar helium burning by studying the reactions:  $^{12}\text{C}(\gamma,3\alpha)$  and  $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$ , respectively. Data collected at the HI $\gamma$ S facility over the last two years were analyzed by UConn graduate student William R. Zimmerman who is now in residence and fully supported by TUNL at Duke University. UConn graduate student Aaron G. Swindell is developing a second TPC (OPAC2) for the study of the D( $\gamma$ ,p) reaction at HI $\gamma$ S of importance for Big Bang Nucleosynthesis. Mr. Swindell is also in residence at TUNL in North Carolina. Last summer (2012) Mr. Swindell was aided by UConn graduate student Susini DeSilva who considered joining our research group. The O-TPC detector project is a collaborative effort with colleagues at Duke and at Yale, at the Weizmann Institute of Science, Israel, at the PTB at Braunschweig, Germany, and at the Catholique University at Louvain-La-Neuve, Belgium.

We commenced an international collaboration with colleagues in the Soreq Nuclear center in Israel and the Paul Scherrer Institute in Switzerland for a measurement of neutron interactions with  $^7\text{Be}$  and the “primordial  $^7\text{Li}$  Problem”. We submitted a proposal to the US-Israel BSF and the US NSF for Catalyzing New International Collaboration (CNIC) to fund the international travel for this project.

We collaborate with colleagues at Yale University on developing the wire readout of a two phase (Liquid/Gas) Xenon TPC detector-- Particle Identification in Xenon at Yale (PIXeY). The same wire readout will be used in the OPAC2 detector at the HI $\gamma$ S facility to study the D( $\gamma$ ,p) reaction. The PIXeY prototype detector can be used in a number of applications including neutrino physics, double beta-decay experiments and Home Land Security. UConn graduate student Nicholas E. Destefano is working at Yale on the PIXeY prototype detector. This project is mainly funded by an ARI/DNDO grant from the department of Home Land Security (UConn a sub-award for Yale).

## 1.2 PERSONNEL AND FACILITIES:

<u>Faculty and Staff:</u>	Moshe Gai, Professor of Physics, <b>PI</b>
<u>Graduate Students:</u>	William R. Zimmerman (FY12: 100% TUNL), Nicholas E. Destefano, Aaron G. Swindell, Susini DeSilva (Summer 2012)
<u>Undergrad Student:</u>	Charlotte L. Kading, Emily E. Kading, Benjamin E. Cowley
<u>International Collaborators and Visitors:</u>	
<b>Yale University</b>	Professor Moshe Gai Professor Daniel N. McKinsey
<b>TUNL/Duke University</b>	Professor Henry R. Weller Professor Mohammad W. Ahmed
<b>Weizmann Institute, Israel</b>	Professor Amos Breskin Professor Micahel Hass Professor Harry J. Lipkin Dr. Leonid Weissman
<b>Soreq Nuclear Center, Israel</b>	Professor Michael Paul
<b>Hebrew University, Jerusalem, Israel</b>	Dr. Dorothea Schumann
<b>Paul Scherrer Institute, Switzerland</b>	Dr. Thierry Stora
<b>ISOLDE/CERN</b>	Dr. Volker Dangendorf
<b>PTB/Braunschweig, Germany</b>	Professor Thierry Delbar
<b>Louvain-La-Neuve, Belgium</b>	

### 1.3 Preamble:

The last three years (FY10 - FY12) were very pivotal for graduate student recruitment at the University of Connecticut. With UConn graduate student Mr. William R. Zimmerman in residence and funded by the TUNL at Duke University, we added last summer to our currently supported graduate students Mr. Nicholas E. Destefano and Mr. Aaron G. Swindell a third graduate student Ms. Susini DeSilva. Unfortunately

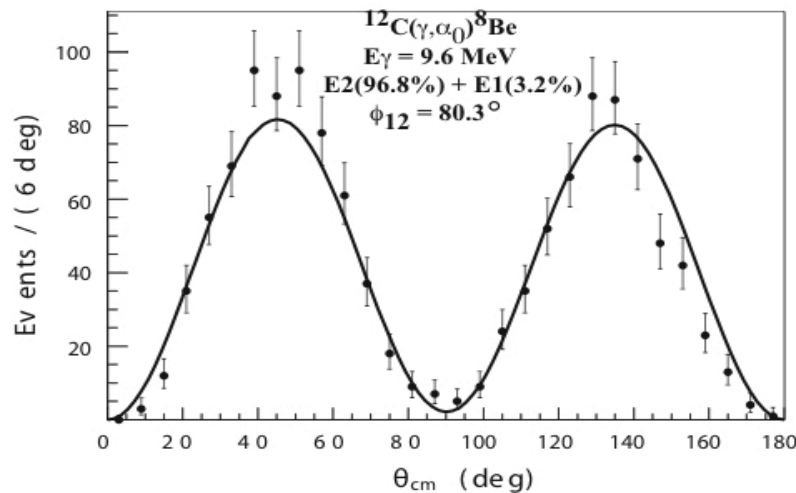


Fig. 1: Angular Distribution of the  $^{12}\text{C}(\gamma,\alpha_0)^8\text{Be}$  measured with the upgraded O-TPC detector; to be submitted for publication in the Physical Review, see [10] section 4.1.

at the HIγS facility. Almost two hundred hours of data taking were completed in January 2012 and the data are analyzed by UConn graduate student, William R. Zimmerman. We obtained results relevant for both carbon and oxygen formation during helium burning by studying the  $^{12}\text{C}(\gamma,3\alpha)$  and  $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$  reactions, respectively. Research and Development in search for appropriate gas (e.g. deuterated isobutane) to be used in the O-TPC at HIγS (OPAC2) for the study of the  $\text{D}(\gamma,\text{p})$  reaction was completed at the LNS by Mr. Aaron G. Swindell. This study is a pre-requisite for carrying out the experiment approved by PAC2009 relevant for Big Bang Nucleosynthesis. The second TPC detector (OPAC2) was delivered to TUNL for performing the  $\text{D}(\gamma,\text{p})$  measurement and is now being installed and tested at TUNL by Mr. Swindell.

We continue our collaboration with Professor McKinsey at Yale for developing a low background two phase (liquid/gas) xenon TPC-- Particle Identification in Xe at Yale (PIXeY). We are developing the wire readout for this detector. The same wire readout will be used in the OPAC2 detector that will be used at TUNL for the study of the  $\text{D}(\gamma,\text{p})$  reaction. Such a detector (PIXeY) promises to be useful for low counting experiments that will be located at the DUSEL in South Dakota, including neutrino detectors and liquid xenon double-beta decay detector, as well as Compton imaging gamma-camera for the detection of Special Nuclear Material (SNM). This study is carried out mainly by Mr. Nicholas E. Destefano and is mainly funded by the department of Home Land Security.

We engaged in a new study in Big Bang Nucleosynthesis in an attempt to solve the forty year old “Primordial  $^7\text{Li}$  Problem” by measuring the direct destruction of  $^7\text{Be}$  with neutrons. This study is planned at the new neutron beam from the LiLiT target at the Soreq Nuclear Center in Israel with a  $^7\text{Be}$  implanted target produced at ISOLDE/CERN from  $^7\text{Be}$  provided by the Paul Scherrer Institute in Switzerland. We applied for funds from the US-Israel BSF and the NSF/CNIC international program to cover the cost of the Interantional travel associated with this new project.

these students are only partially funded by this grant and supplement funding in the form of Teaching Assistanship and other grants are necessary. Data produced by the upgraded Optical Readout Time Projection Chamber (O-TPC) detector are being analyzed at TUNL, and a measured angular distribution is shown in Fig.1. The first instrumentation paper on the O-TPC detector was published in 2010 and the first Physics paper will be submitted to the Physical Review as we discuss below.

The upgraded Optical Readout Time Projection Chamber (O-TPC) operating with  $\text{CO}_2$  gas, was used for data taking

## 2.1 Angular distribution of the $^{16}\text{O}(\gamma,\alpha)$ reaction (HIγS/TUNL/Duke)

W.R. Zimmerman, M.W. Ahmed, S.S. Henshaw, C.R. Howell, S.C. Stave, H.R. Weller, (TUNL), M. Gai (UConn)

Several new measurements of the  $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$  reaction using gamma-ray detectors have been reported [1,2] with energies in the vicinity of 1.0 MeV. However, the S-factors ( $S_{E1}$  and  $S_{E2}$ ) measured at these low energies (below  $E_{\text{cm}} = 1.5$  MeV) are with very low accuracy (40-80%) and most importantly one cannot rule out a low value (close to zero) of the E1 S-factor [3, 4]. These new experiments use some of the highest intensity alpha-particle beams (10 - 500  $\mu\text{A}$ ) with an impressive luminosity of  $10^{33}$  [1] and  $10^{31}$  [2]  $\text{cm}^{-2}\text{sec}^{-1}$ , and a  $4\pi$  array of HPGe and BaF, respectively. Yet the obtained accuracy of the S-factors is limited due to the limited accuracy of the measured angular distributions. A major disadvantage of measuring gamma rays is the large background and the low efficiency of the HPGe gamma-ray detectors. This large background is not observed in our experiment using a Time Projection Chamber (TPC) and in addition we measured detailed and complete angular distributions ( $0^\circ$  to  $180^\circ$  in  $6^\circ$  bins) and thus we have a large sensitivity to the E2/E1 ratio and the E1-E2 mixing phase ( $\phi_{12}$ ). One tantalizing new problem that was posed by the new gamma-ray data [1] 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:

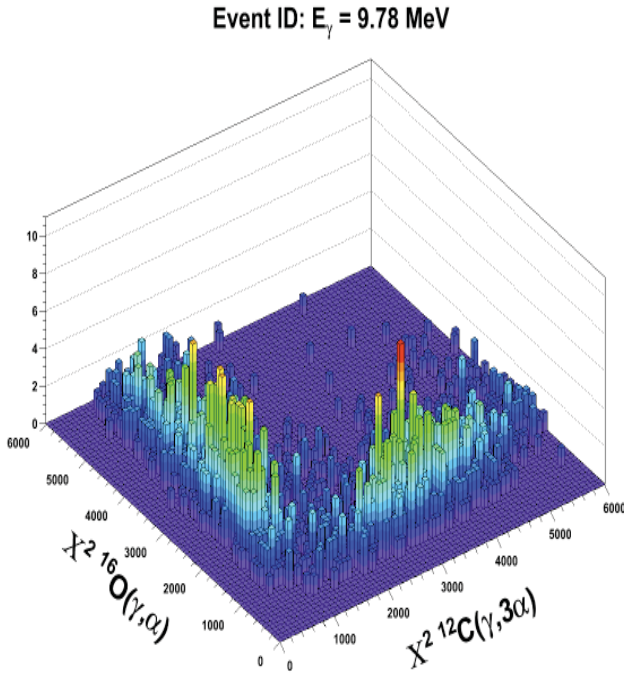
$$\phi_{12} = \delta_2 - \delta_1 + \arctan(\eta/2)$$

where  $\delta_1$  and  $\delta_2$  are the p and d wave elastic scattering phase shifts, respectively, and  $\eta$  is the Sommerfeld parameter. In Ref. [1] this 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 [5]. This disagreement is observed already at high energies, near the broad  $1^-$  resonance located at 9.585 MeV in  $^{16}\text{O}$  where the capture cross section is large, and it must be resolved. On the other hand ill-determined E1-E2 mixing phases ( $\phi_{12}$ ) also lead to ill determined  $S_{E2}/S_{E1}$  ratios. Thus measurements of complete angular distributions at relatively high energies (in the vicinity of the 9.585 MeV resonance) are also already relevant for Nuclear Astrophysics (in addition to resolving the conflict with unitarity).

We used our Optical-Readout Time Projection Chamber (O-TPC) [6] operating with  $\text{CO}_2(80\%) + \text{N}_2(20\%)$  gas mixture at 100 torr to measure complete angular distributions (binned in  $6^\circ$  from  $0^\circ$  to  $180^\circ$ ) with high sensitivity for extracting  $\phi_{12}$  and  $S_{E2}/S_{E1}$  ratios 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. Circularly polarized gamma-ray beams with average intensity of  $1.7 \times 10^8$  /s extracted from the HIγS facility [7] were used. Seven angular distributions were measured for  $E_\gamma = 9.1 - 10.7$  MeV ( $E_{\text{cm}} = 1.95 - 3.55$  MeV) covering the 9.585 MeV  $1^-$  resonance in  $^{16}\text{O}$ .

One major drawback of using  $\text{CO}_2$  gas is that the difference of Q-values for the dissociation of  $^{16}\text{O}$  and  $^{12}\text{C}$  (112 keV) is considerably smaller than the beam width of approximately 300 keV and comparable to the detector resolution of approximately 90 keV [6]. In addition the larger quenching factor for the low energy  $^{12}\text{C}$  projectiles leads to a smaller grid charge-signal from the dissociation of  $^{16}\text{O}$  with an energy very similar to that of the dissociation of  $^{12}\text{C}$ . Hence the total energy deposited in the O-TPC detector (grid charge signal) cannot be used to separate (and thus identify)  $^{12}\text{C}$  and  $^{16}\text{O}$  dissociation events.

To identify and distinguish  $^{16}\text{O}$  dissociation events from  $^{12}\text{C}$  dissociation events we relied on the line shape of the PMT signal which is very well determined by the calculated  $dE/dX$  along the track. In this



calculation we used the drift velocity of  $1.14$  cm/ $\mu$ s (at 100 torr) measured with a well collimated  $^{148}\text{Gd}$  source [6]. The measured line shape of the PMT signal is compared to 181 calculated functions of the out-of-plane angle (in  $\beta = 1^\circ$  increments) to determine the best fit. The calculated line shape has essentially only one free parameter, the out of plane angle ( $\beta$ ). A good  $\chi^2$  is found for the  $^{16}\text{O}$  dissociation events. The line shape of  $^{12}\text{C}$  dissociation events arise from a considerably more complicated  $dE/dx$  of the three body (non-colinear) decay pattern.

Fig. 1: Event identification  $\chi^2$  surface plot for all events as discussed in the text.

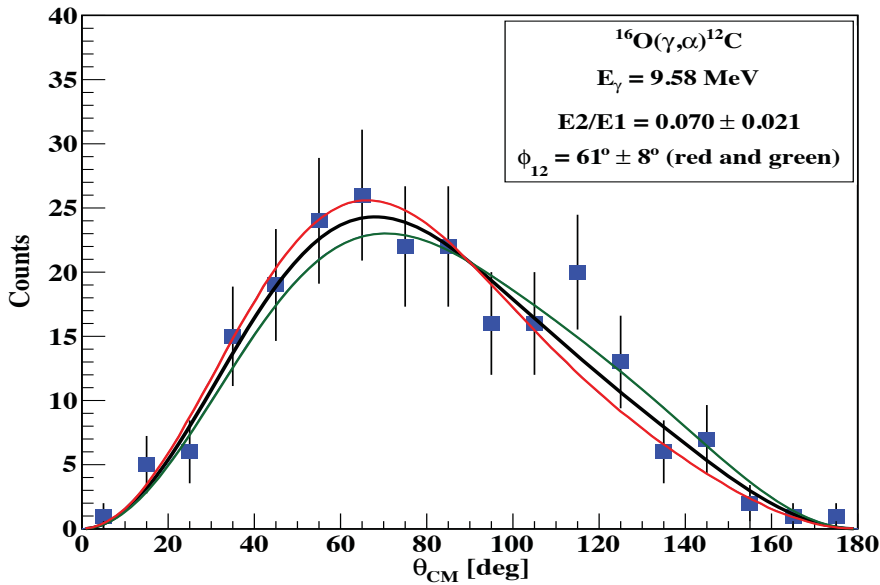


Fig. 2: Measured angular distribution for  $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$  events compared to the prediction for E1 + E2 interfering amplitudes. The interference phase angle ( $\phi_{12}$ ) and SE2/SE1 are indicated.

The line shape of  $^{12}\text{C}$  events requires  $181 \times 9 = 1,629$  functions that are calculated with sufficient angular bin size ( $\beta = 1^\circ$ ) as well as sufficient bin size ( $30^\circ$ ) for the  $\theta$  and  $\phi$  angles of the two alphas ( $\alpha'$

and  $\alpha''$ ) from the decay of  $^8\text{Be}$ . For ( $\alpha_1$ ) decay into the excited states we also considered the energy of the excited  $^8\text{Be}$ . A good  $\chi^2$  is found for the  $^{12}\text{C}$  dissociation events. The total  $\chi^2$  for each events fitted with the line shape expected for either  $^{16}\text{O}$  or  $^{12}\text{C}$  dissociation is shown in Fig. 1, demonstrating the satisfactory separation of  $^{16}\text{O}$  and  $^{12}\text{C}$  dissociation events.

The in-plane angle ( $\alpha$ ) measured by the track registered in the CCD image and the out-of-plane angle ( $\beta$ ) measured by the time projection signal of the PMTs allow us to deduce for each event the scattering angle ( $\theta$ ) and the azimuthal angle ( $\phi$ ) of the polar coordinate system used in scattering theory:  $\cos \theta = \cos \beta \times \cos \alpha$  and  $\tan \phi = \tan \beta / \sin \alpha$  [6]. The so obtained angular distribution measured at 9.6 MeV is shown in Fig. 2 together with that predicted for an E1 + E2 interfering amplitudes. The extracted E1-E2 interference phase angle:  $\phi_{12} = 61^\circ \pm 8^\circ$  is in agreement with the value predicted by unitarity.

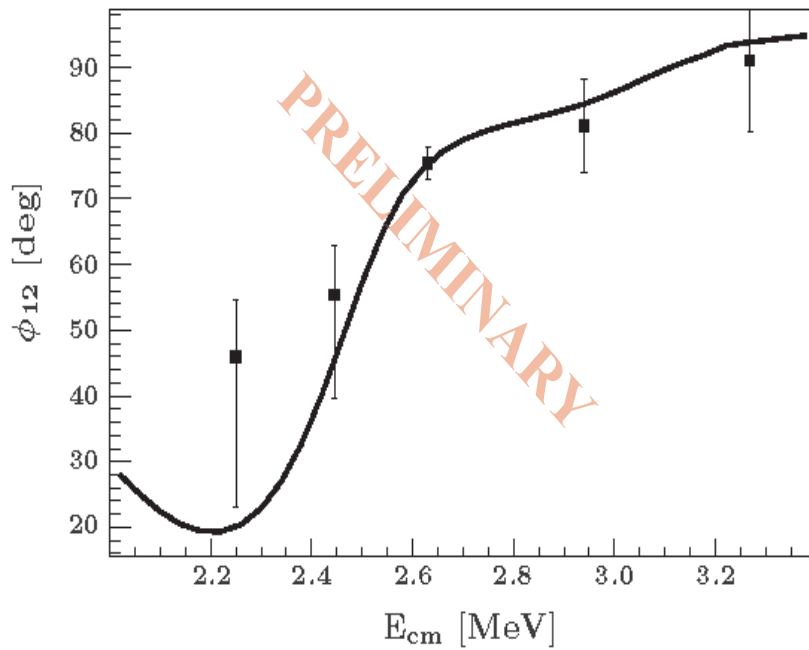


Fig. 3: Measured E1-E2 interference phase angle ( $\phi_{12}$ ) extracted from the measured angular distribution of the  $^{16}\text{O}(\gamma, \alpha)$  reaction compared to prediction as discussed in the text.

The measured angular distribution of the  $^{16}\text{O}(\gamma, \alpha)$  reaction ( $E_\gamma = 9.4 - 10.4$ ) were fitted with E1 + E2 interfering amplitudes and the interference phase angle ( $\phi_{12}$ ) was extracted, as shown in Fig. 3. In the same figure we show the predicted E1-E2 mixing phase angle ( $\phi_{12}$ ), discussed above, averaged over the energy resolution of the experiment, Beam FWHM = 300 keV.

- [1] M. Assuncao *et al.*; Phys. Rev. **C73**(2006)055801.
- [2] R. Plag *et al.*; Nucl. Phys. **A758**(2005)415c.
- [3] G.M. Hale; Nucl. Phys. **A621**(1997)177c.
- [4] L. Gialanella *et al.*; Eur. Phys. J. **A11**(2001)357.
- [5] C.R. Brune; Phys. Rev. C **64**, 055803 (2001).
- [6] M. Gai, M.W. Ahmed, S.C. Stave, W.R. Zimmerman, A. Breskin, B. Bromberger, R. Chechik, V. Dangendorf, Th. Delbar, R.H. France III, S.S. Henshaw, C.R. Howell, T.J. Kading, P.P. Martel, J.E.R. McDonald, P.-N. Seo, K. Tittelmeier, H.R. Weller and A.H. Young; JINST **5**(2010)12004.
- [7] H.R. Weller, M.W. Ahmed, H. Gao, W. Tornow, Y. Wu, M. Gai, R. Miskimen; Prog. Part. Nucl. Phys. **62**(2009)257.

## 2.2 Direct Evidence for the Second $2^+$ State in $^{12}\text{C}$ (HI $\gamma$ S/TUNL/Duke)

W.R. Zimmerman, M.W. Ahmed, C.R. Howell, J.M. Mueller, H.R. Weller (TUNL), M. Gai (UConn).

The scientific and historical significance of the search for the second  $2^+$  state in  $^{12}\text{C}$  has been discussed recently in a Physics Viewpoint [1].

We used our Optical-Readout Time Projection Chamber (O-TPC) [2] operating with  $\text{CO}_2$  gas and gamma beams extracted from the HI $\gamma$ S facility [3] to search for such a  $2^+$  state via the identification of triple alpha events from the  $^{12}\text{C}(\gamma,3\alpha)$  reaction. We have studied this reaction at  $E_\gamma = 9.08 - 10.78$  MeV. We used the event identification procedure discussed in section 2.1 to separate  $^{12}\text{C}(\gamma,3\alpha)$  events from  $^{16}\text{O}(\gamma,\alpha)$  events. The excitation curve that we measured for the direct  $^8\text{Be}(\alpha,\gamma)$  reaction is shown in Fig. 1 where we observe evidence for a wide [ $\Gamma = 800(130)$  keV] resonance at  $10.03(11)$  MeV.

The in plane angle ( $\alpha$ ) measured by the track registered in the CCD image and the out of plane angle ( $\beta$ ) measured by the Time projection signal of the PMT allow us to deduce for each event the scattering angle ( $\theta$ ) and the azimuthal angle ( $\phi$ ) of the polar coordinate system used in scattering theory:  $\text{Cos } \theta = \text{Cos } \beta \times \text{Cos } \alpha$  and  $\tan \phi = \tan \beta / \text{Sin } \alpha$  [2]. The so obtained angular distribution is shown in Fig. 2 together with the fitted E1 + E2 amplitudes (E1/E2 = 3%). The angular distribution shown in Fig. 2 includes only in plane ( $\beta < 20^\circ$ ) events for which the scattering angle ( $\theta$ ) is determined with high accuracy.

Our measurement provides unambiguous evidence for the second  $2^+$  state in  $^{12}\text{C}$  and it allows us to study the structure of the Hoyle state of  $^{12}\text{C}$  as discussed in our paper to be submitted to the Physical Review [4].

[1] H.O. Fynbo and M. Freer; Physics **4**(2011)94.

[2] M. Gai, M.W. Ahmed, S.C. Stave, W.R. Zimmerman, A. Breskin, B. Bromberger, R. Chechik, V. Dangendorf, Th. Delbar, R.H. France III, S.S. Henshaw, C.R. Howell, T.J. Kading, P.P. Martel, J.E.R. McDonald, P.-N. Seo, K. Tittelmeier, H.R. Weller and A. Young; JINST **5**(2010)12004.

[3] H.R. Weller, M.W. Ahmed, H. Gao, W. Tornow, Y. Wu, M. Gai, R. Miskimen; Prog. Part. Nucl. Phys. **62**(2009)257.

[4] W.R. Zimmerman, M.W. Ahmed, S.C. Stave, A. Breskin, V. Dangendorf, Th. Delbar, M. Gai, S.S. Henshaw, J.M. Mueller, C. Sun, K. Tittelmeier, H.R. Weller and Y. Wu, to be published.

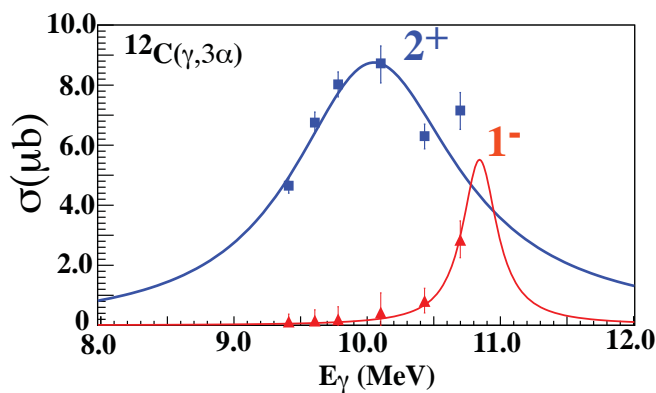


Fig. 1: The measured excitation curve of the  $^{12}\text{C}(\gamma,\alpha)$  reaction.

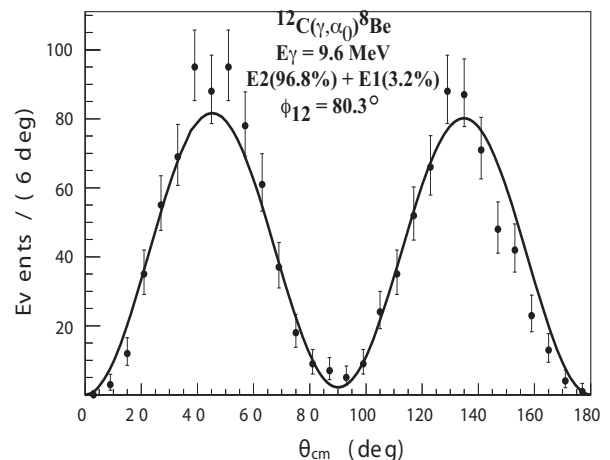


Fig. 2: Angular distribution for  $^{12}\text{C}(\gamma,\alpha)$  events measured with the shown E1 + E2 fitted amplitudes.



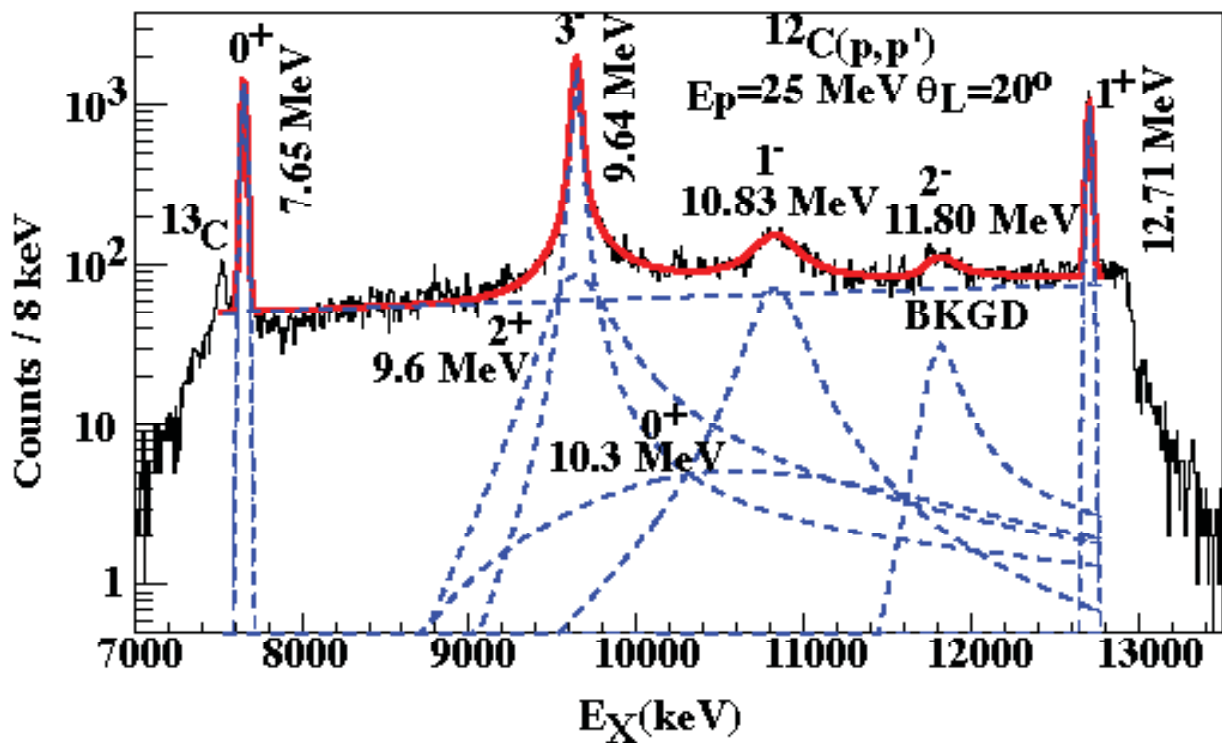
### 2.3 A Measurement of the $^{12}\text{C}(p,p')$ reaction at 25 MeV (Yale/WNSL)

W.R. Zimmerman, N.E. Destefano, M. Gai (UConn), P.D. parker (Yale), M. Freer (Birmingham), F. D. Smit (iThemba LABS)

A recent measurement of the  $^{12}\text{C}(p,p')$  carried out at the iThemba LABS provides evidence for a broad  $2^+$  state at 9.6 MeV in  $^{12}\text{C}$  [1], the same energy where a narrow  $3^-$  state (at 9.641 MeV) has been observed. Evidence for such a  $2^+$  state was also observed in our experiment at the HIγS facility as discussed in section 2.2. We have repeated the iThemba LABS measurements using 25 MeV proton beams from the Yale-ESTU tandem with a  $40\ \mu\text{g}/\text{cm}^2$  natural carbon target. The scattered protons were measured in the focal plane of the Enge Split Pole spectrometer at lab angles of  $20^\circ$ ,  $35^\circ$  and  $45^\circ$ . Measurements were also performed at each angle with the same setting using a  $^{13}\text{C}$  target. Evidence for the broad  $2^+$  state is observed in our experiment, much as in the iThemba LABS measurement, as skirts of the narrow  $3^-$  state, as shown in Fig. 1 and discussed in our Physical Review C publication [2].

[1] M. Freer *et al.*; Phys. Rev.C **80**(2009)041303(R).

[2] W.R. Zimmerman, N.E. Destefano, M. Freer, M. Gai and F.D. Smit;  
Phs. Rev. C **84**,027304 (2011).



## 2.4 The Destruction of ${}^7\text{Be}$ by Neutrons and the “Primordial ${}^7\text{Li}$ Problem” (SARAF/Soreq/Israel)

M. Gai (UConn), K.M. Nollett (ANL), L. Weissman (Soreq), M. Paul (Jerusalem), M. Hass (Weizmann), D. Schumann (PSI), Th. Stora (ISOLDE).

The disagreement of the predicted abundance of primordial  ${}^7\text{Li}$  with the observed abundance shown in Fig. 1 is a longstanding problem in Big Bang Nucleosynthesis (BBN) theory. While BBN theory correctly predicts the abundances of  ${}^2\text{H}$ ,  ${}^3\text{He}$  and  ${}^4\text{He}$  relative to hydrogen (that vary over four orders of magnitudes), it over predicts the abundance of primordial  ${}^7\text{Li}$  by a factor of approximately 3.5 (approximately 4-5 $\sigma$  discrepancy). Primordial  ${}^7\text{Li}$  is copiously produced directly (e.g. via the  ${}^6\text{Li}(n,\gamma)$  reaction etc.) but later during the first 4-15 minutes approximately 99% of the so produced  ${}^7\text{Li}$  is destroyed primarily via the  ${}^7\text{Li}(p,\alpha)$  reaction. Hence most of the predicted primordial  ${}^7\text{Li}$  is predicted to be produced via the (electron capture beta) decay of the primordial  ${}^7\text{Be}$  that is produced primarily in the  ${}^3\text{He}(\alpha,\gamma)$  reaction.

We commenced a research project to investigate the direct destruction of  ${}^7\text{Be}$  during (the first 10-15 minutes of) BBN via the  ${}^7\text{Be}(n,\alpha)$  and the  ${}^7\text{Be}(n,\gamma\alpha)$  reactions. If during that time the majority of the primordial  ${}^7\text{Be}$  is destroyed (before decaying to  ${}^7\text{Li}$ ) it will lead to a reduction of approximately 3 of the predicted abundance of the primordial  ${}^7\text{Li}$ , hence a resolution of the long standing disagreement. The rate of the  ${}^7\text{Be}(n,\alpha)$  reaction relies on a not well documented cross section of thermal neutron (only) measured in 1963 [1] and extrapolated from thermal neutron energies (25 meV) to higher BBN energies (25-100 keV) for the first and last time by Wagoneer in 1967 [2].

We are developing [3] a new measurement of the cross section of the  ${}^7\text{Be}(n,\alpha)$  reaction with neutron beams that mimic a quasi Maxwellian flux at 25 - 100 keV. The neutron beams will be provided by the newly constructed Soreq Applied Research Accelerator Facility (SARAF) at the Soreq Nuclear center in Israel and the  ${}^7\text{Be}$  target will be produced by implantation at the ISOLDE facility at CERN from a  ${}^7\text{Be}$  sample produced at the Paul Scherrer Institute (PSI) in Switzerland. A prototype measurement of the  ${}^{10}\text{B}(n,\alpha)$  reaction and the proposed  ${}^7\text{Be}(n,\alpha)$  experiment is planned in Phase I of SARAF using the Liquid Lithium (LILIT) target. The large area (450 mm<sup>2</sup>) thin (50  $\mu\text{m}$ ) silicon detector system that will be used to detect the two back to back alphas were delivered by the LNS at Avery Point to the Soreq Nuclear center in Israel. A measurement of the  ${}^{10}\text{B}(n,\alpha)$  reaction with thermal neutrons was already carried out by our group (in 1995) and the proposed prototype experiment relies upon this measurement.

The LiLiT target for producing the neutron beams was constructed by the group of Professor Michael Paul at the Hebrew University of Jerusalem. We submitted a proposal to the US-Israel BSF and the NSF/CNIC International division to fund the international travel of this program.

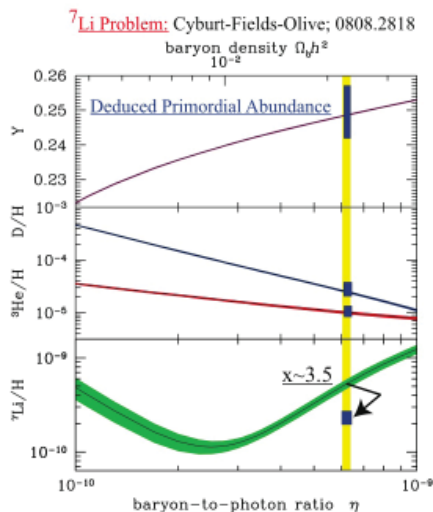


Fig. 1: BBN Prediction and observed primordial abundances of light elements.

[1] P. Bassi *et al.*; Il Nuovo Cimento **28**(1963)1049.  
[2] R.V. Wagoner, W.A. Fowler, and F. Hoyle; ApJ **148**(1967)3. R.V. Wagoner *et al.*; ApJ **148**(1967)3, R.V. Wagoner ApJSupp.**18**(1967)247, R.V. Wagoner, ApJ **179**(1973)343.

[3] M. Gai and L. Weissman; Letter of Intent Submitted to the SARAF facility, May 5, 2011.

### 3.1 Upgrade of the Optical Readout System of the O-TPC ([HIγS/TUNL/Duke](#))

M.W. Ahmed, S.C. Stave, H.R. Weller (TUNL), W.R. Zimmerman, M. Gai (UConn).

The original lens designed specifically for the O-TPC by the optical engineer Dr. Oded Arnon, Tel Aviv, Israel, with diameter of 142 mm was purchased from OptiMAX, NY, and it was installed in the Optical Readout chain of the O-TPC. This lens replaces the 60 mm diameter lens that was on loan from PTB and it improves the light collection by up to a factor of 15. The much improved quality of the track images (with approximately 1000 photo-electron) allowed us to perform the measurements discussed in this progress report.

A new camera was installed in the optical chain of the O-TPC-- an ORCA-R2 model manufactured by Hamamatsu Photonics. The new camera contains a 1.3 Megapixel cooled interlined CCD sensor. The quantum efficiency of the CCD peaks near 500 nm at 70%. The CCD pixel size is 6.45  $\mu\text{m}$ . The exposure times can be adjusted between 10  $\mu\text{s}$  to 70 minutes. The pixels can be binned up to a factor of 8 to increase readout speed. At no binning and full frame readout, the image transfer speed is 8 frames per second (fps). In maximally binned full frame readout, the image transfer rate can be as high as 40 fps. During the experiment, the image transfer rate was typically 6 to 8 fps with over 90% livetime.

The new camera has three advantageous: 1) low noise due to advanced cooling (the camera was cooled by Peltier thermoelectric device and air cooling). The operating temperature during the experiment was  $-35^{\circ}\text{C}$ . This provided an order of magnitude better signal to noise ratio as compared to the previously used camera from SBIG. This improved signal to noise ratio is critical in event pattern recognition. 2) The new camera provides a faster readout via IEEE 1394 interface. As compared to the previously used camera with 0.3 fps maximum readout speed, the new camera provided a factor of 25 faster image transfer rate during the experiment. This improvement reduced the DAQ deadtime and allowed us to

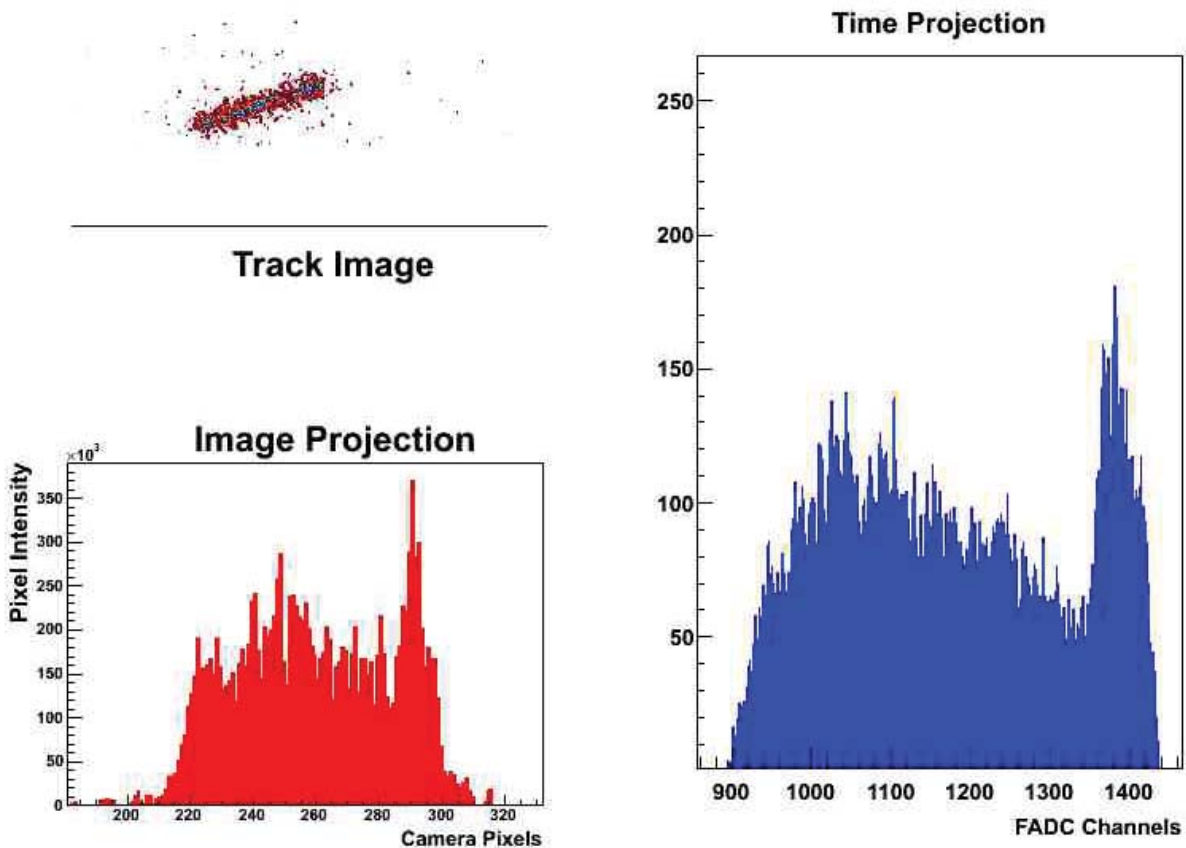


Fig. 1: Track image and projection obtained with the new CCD camera compared to the PMT signal.

run at a lower energy threshold which was critical in obtaining  $^{16}\text{O}$  breakup data at as low as gamma ray energy of 9.08 MeV. 3) The new camera interface allowed us to provide a fast trigger for the image capture and readout based upon the OTPC grid signal. The camera capture start, duration, and readout were triggered by a logic signal from the constant fraction discriminator (CFD) of the OTPC grid pulse height signal. The camera also provided a fast busy signal to inhibit the DAQ system during an image capture or the readout. This fast interface enabled us to reduce the amount of electronics required with the previously used camera to allow us a hand-shake between the computer taking image data and the computer taking digitizer data. The new fast camera triggering interface reduced the overall dead time of the system. During most of the data taking in 2010, the DAQ system livetime was over 90% up to a rate of 10 Hz.

The OTPC has been upgraded with a total of six (6) PMTs as compared to three PMTs used in the previous setups. The new 3-inch diameter PMTs are R10133 type manufactured by Hamamatsu Photonics. The voltage dividers are P-1408N type, custom made by Saint-Gobain Crystals. These added PMTs improved the time projection signal and hence improved the out-of-plane angle determination of the tracks. Signals from all six PMTs are now added to provide a sum signal for analysis. The power supplies for the PMTs were also upgraded for stable operation. A new set of NHQ203M type power supplies with a maximum voltage of 3 kV and limiting current of 4 mA were installed.

OTPC uses a hybrid DAQ system comprising a VME based digitizer readout system and a windows based camera readout system. The VME readout system is based upon CODA data acquisition system. The hardware includes a 4-volt 12 bit Analog-to-Digital Converter (ADC, CAEN V785) for pulse height measurement, an 8-channel 12 bit transient digitizer (FADC, Struck SIS3301) for time projection measurement, and a 32-channel scaler (Struck SIS3800). The trigger supervisor is a Struck module (SIS3610). The real-time operating system on the VME Single Board Computer (SBC) is VxWork. The SBC is a Motorola MVME-5100 with PowerPC chip. The windows OS is Windows7 Enterprise Edition. A custom application based upon Software Development Kit (SDK) from Hamamatsu Photonics for the ORCA-R2 was developed for the OTPC. The windows application communicates with the CODA system via TCP/IP to obtain the run information. The application runs as a client of CODA system. The application is started and waits for a trigger from the CODA system to capture image. The CODA system directs this application to takes a dark image on start of a run. After a dark image completion, the system is ready to take beam data. Any event which satisfies the OTPC grid pulse height threshold will create a trigger to read the digitizers and scalers as well as trigger the camera. At this point, the windows application will service this camera trigger and capture, transfer, and store the image in the system memory. Each image is time stamped with the run number and the event number. In order to save the images faster, the images are stored on the RAM disk of the system. The images are transferred every 5 minutes from the RAM to the hard disk for storage.

In Fig. 1 we show a track image captured by the new Hamamatsu CCD camera together with a longitudinal projection (pixel content) of the track. The pixel content shows the expected structure of an  $\alpha + ^{12}\text{C}$  track. The observed structure is very similar to the one observed in the PMT light signal. We already developed line shape analyses for the PMT signal as discussed in [1].

- [1] M. Gai, M.W. Ahmed, S.C. Stave, W.R. Zimmerman, A. Breskin, B. Bromberger, R. Chechik, V. Dangendorf, Th. Delbar, R.H. France III, S.S. Henshaw, C.R. Howell, T.J. Kading, P.P. Martel, J.E.R. McDonald, P.-N. Seo, K. Tittelmeier, H.R. Weller and A.H. Young; JINST **5**(2010)12004.

### 3.2 Construction and Test of the OPAC2 TPC for a Measurement of $D(\gamma,p)$ at HI $\gamma$ S (UConn)

A.G. Swindell, M. Gai (UConn), M.W. Ahmed, C.R. Howell, H.R. Weller (TUNL)

The cross section of the  $p(n,\gamma)$  reaction to form deuterium is not known with sufficient accuracy. Indeed the theoretical accuracy is considerably better than measurements. But this reaction rate is essential for Big Bang Nucleosynthesis. HI $\gamma$ S PAC09 approved 60 hours of beam time for measuring the  $d(\gamma,p)$  reaction. We constructed at the LNS at Avery Point a new TPC detector (OPAC2) shown in Fig. 1, that will be dedicated to this measurement. For performing this experiment a deuterated isobutane and nitrogen gas mixture will be used and we tested at Avery Point the operation of OPAC2 with pure isobutane gas. Good charge signals were obtained as shown in Fig. 2.

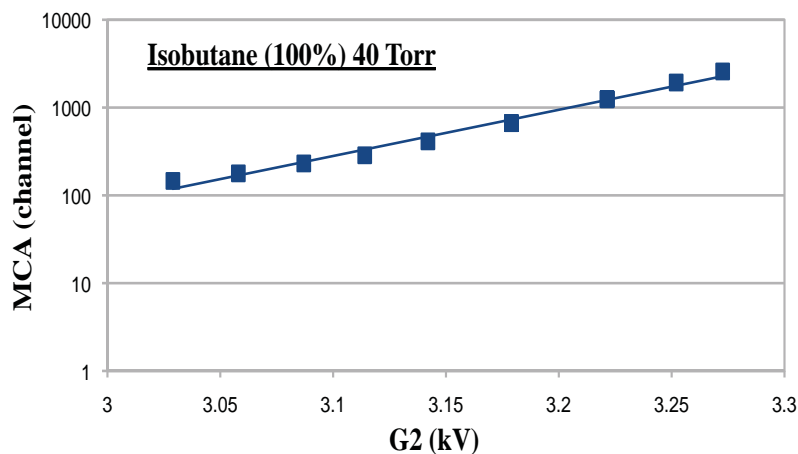
For the track reconstruction in the OPAC2 TPC detector we intend to use an x-y wire readout system instead of the optical readout used in the O-TPC detector that we constructed for experiments at the HI $\gamma$ S facility. Such a wire readout system is now under development by us in a collaborative effort with the McKinsey group at Yale

as discussed in section 3.3. The R&D effort that we perform in collaboration with the McKinsey group at Yale university (which is funded by the Department of Home Land Security) will be of great benefit for this project.



**Fig. 1:** The drift volume and multiplication grids of the OPAC2 detector together with a test alpha-source and trigger silicon detector.

The operation of a TPC detector with isobutane turned out to be non trivial. We found that the o-ring used in the Mass Flow Controller (MFC) absorbed the isobutane gas and expanded as well as lost its structural integrity. Hence a dedicated MFC for flowing isobutane in the gas handling system was installed. The OPAC2 detector that was constructed and tested at the LNS at Avery Point was delivered to HI $\gamma$ S and the gas handling system that we originally constructed at the HI $\gamma$ S facility was altered to allow the operation with isobutane. Test of OPAC2 are being conducted at the HI $\gamma$ S facility and we anticipate in-beam measurements at the HI $\gamma$ S after tests of the OPAC2 detector at the TUNL.



**Fig. 2:** Gain curve measured with pure iso-butane gas at 40 torr in OPAC2 (Anode Voltage = +800 V).

### 3.3 Development of TPC wire grids and wire readout (Yale)

N.E. Destefano, M. Gai (UConn) E.P. Bernard, Ch.G. Wahl, N.A. Larsen, D.N. McKinsey (Yale)

We are involved in a collaborative effort with the McKinsey group at Yale University for developing gamma-camera that will be used to detect Special Nuclear Materials (SNM) in cargo containers. This project is funded for the most part by the Department of Home Land Security, but applications of the detector technology and especially of the x-y wire readout scheme that we are developing at Yale are of importance for our research program at HI $\gamma$ S, as described in section 3.2. Other applications of the liquid xenon detector technology include neutrino physics and double beta decay measurements that can be carried out at an underground laboratory.

The work at Yale University is primarily intended for Applications of a Two-Phase (Liquid/Gas) Xenon Gamma Cameras for the Detection of Special Nuclear Material (SNM). For this gamma-camera we are developing the PIXeY prototype detector (Particle Identification in Xenon at Yale). In this collaboration the UConn group is in charge of developing wire grids and x-y wire readout. For the production of wire grids we are using the technology we imported from the Weizmann Institute in Israel for the preparation of grids for the O-TPC detector that we use at the HI $\gamma$ S facility. We constructed a special loom for wire stretching at the WNSL at Yale University as shown in Fig. 1, where we fabricated and tested the wire grids.



Fig. 1: Nick Destefano and Ethan Bernard preparing a wire grid at our detector lab at WNSL at Yale.

For the x-y wire readout we designed [1] the JFET amplifier shown in Fig. 2. This wire readout is similar to the one developed by the GERDA collaboration for measuring the double beta decay of  $^{76}\text{Ge}$  in the Gran Sasso Underground laboratory. We visited the Radeka group in the Instrumentation Division of Brookhaven National Lab for consultation on the design of this preamplifier. A test of the JFET showed the expected characteristic performance and computer simulations of the electronics did not reveal any design flaws. Tests of the amplifier are currently in progress and tests of the x-y wire readout will follow. For this test we are using an existing detector test chamber at the WNSL at Yale.

[1] N.E. Destefano *et al.*;  
Bull. Amer. Phys. Soc. **55#14, 85** (2010).

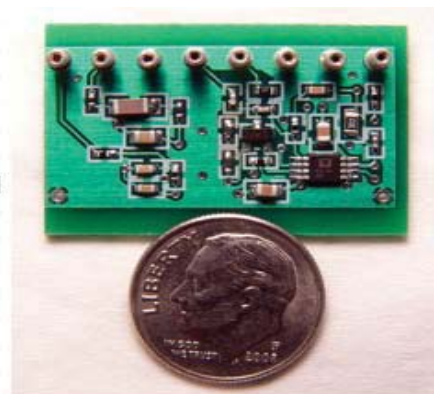
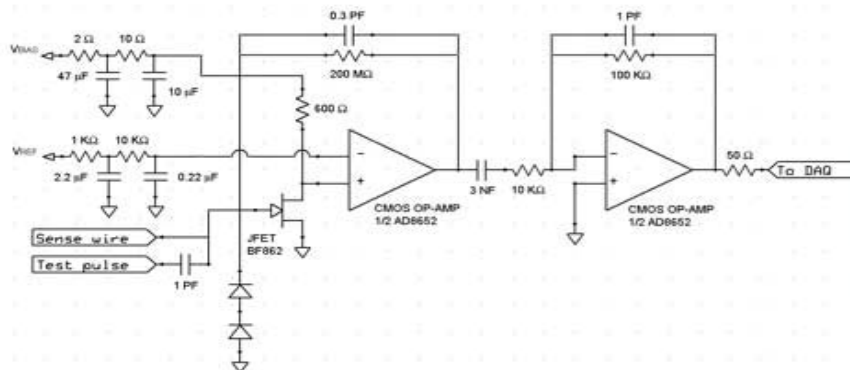


Fig. 2: The JFET amplifier designed and constructed by UConn graduate student N.E. Destefano in collaboration with E.P. Bernad and Ch.G. Wahl of the McKinsey group at Yale.

### 3.4 First energy measurements with the xenon PIXeY detector (Yale)

N.E. Destefano, M. Gai (UConn), D.N. McKinsey, E.P. Bernard, S.B. Cahn, A. Curioni, B. Edwards, Ch.J. Kachulis, N.A. Larsen, A. Lyashenko, J.A. Nikkel, Y. Shin, Ch.G. Wahl, A.H. Young (Yale)

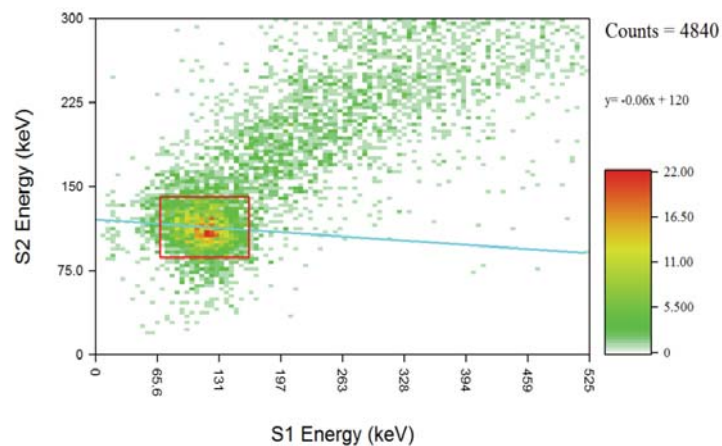
One of the major goals of the UConn group in the collaboration with the McKinsey lab at Yale is to improve the energy resolution of the two phase (liquid/gas) xenon detector (PIXeY). Good energy resolution is essential for extending and improving the search for neutrinoless double beta decay that is currently under way by the EXO-200 [1] collaboration (and the KamLAND-Zen [2] collaboration).

The graduate student Nicholas Destefano performed extensive simulations of the field geometry in the PIXeY detector and produced the high quality grids required for improving the energy resolution to be close to 1% ( $\sigma$ ) at 2.61 MeV. First results [3] with low energy (122.1 keV)  $^{57}\text{Co}$  source as well as higher energy (511 and 1,274 keV)  $^{22}\text{Na}$  source were performed. In Fig. 1 we show first results of total (S1 and S2 signals) energy measurements with the  $^{57}\text{Co}$  source. Further work is in progress of improving the energy resolution of the PIXeY detector.

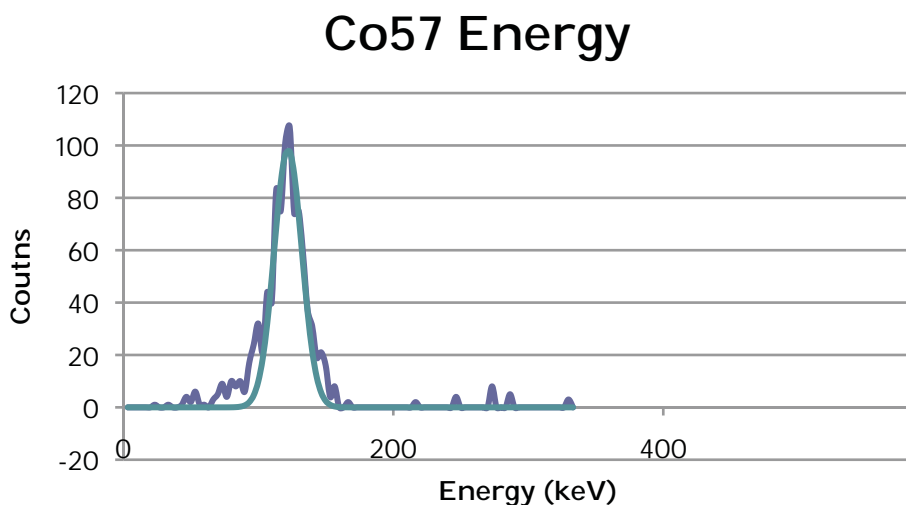
[1] M. Auger *et al.*; Phys. Rev. Lett. **109**, 032505 (2012).

[2] A. Gando *et al.*; Phys. Rev. C **85**, 045504 (2012).

[3] N. Destefano *et al.*; Bull. Amer. Phys. Soc. **57**,#9, 91(2012).



**Fig. 1:** First measurements of total energy (S1 signal from prompt light and S2 signal from amplified drifting electrons) in PIXeY with  $^{57}\text{Co}$  source.



## 4 Publications

### 4.1 Publications in Refereed Journals:

- (1) STELLAR HELIUM BURNING: CARBON AND OXYGEN FORMATION (STUDIED WITH OPTICAL-TPC AT  $HI\gamma S$ ).  
Moshe Gai  
J. Phys. **CS202**(2010)012016.
- (2) AN OPTICAL READOUT TPC (O-TPC) FOR STUDIES IN STELLAR EVOLUTION WITH GAMMA BEAMS AT  $HI\gamma S$ .  
M. Gai, M.W. Ahmed, S.C. Stave, W.R. Zimmerman, A. Breskin, B. Bromberger, R. Chechik, V. Dangendorf, Th. Delbar, R.H. France III, S.S. Henshaw, T.J. Kading, P.P. Martel, J.E.R. McDonald, P.-N. Seo, K. Tittelmeier, H.R. Weller, and A.H. Young.  
JINST **5**(2010)12004.
- (3) SOLAR FUSION.  
E. G. Adelberger, A. Garcia, R. G. Hamish Robertson, K. A. Snover, A. B. Balantekin, K. Heeger, M. J. Ramsey-Musolf, D. Bemmerer, C. A. Bertulani, J.-W. Chen, H. Costantini, P. Prati, M. Couder, E. Uberseder, M. Wiescher, R. Cyburt, B. Davids, S. J. Freedman, M. Gai, D. Gazit, L. Gialanella, G. Imbriani, U. Greife, M. Hass, W. C. Haxton, T. Itahashi, A. Junghans, K. Kubodera, K. Langanke, D. Leitner, M. Leitner, P. Vetter, L. Winslow, L. E. Marcucci, T. Motobayashi, A. Mukhamedzhanov R. E. Tribble, Kenneth M. Nollett, F. M. Nunes, T.-S. Park, P. D. Parker, R. Schiavilla, E. Simpson, C. Spitaleri, F. Strieder and H.-P. Trautvetter, K. Suemmerer and S. Typel.  
Rev. Mod. Phys. **83**(2011)195.
- (4) THE STRUCTURE OF  $^{12}C$  AND STELLAR HELIUM BURNING.  
Moshe Gai for the UConn-Yale-Duke-Weizmann-PTB-UCL Collaboration  
J. Phys. **CS267**(2011)012046.
- (5) THE STRUCTURE OF  $^{12}C$  AND STELLAR HELIUM BURNING.  
Moshe Gai for the UConn-Yale-Duke-Weizmann-PTB-UCL Collaboration  
APH Pol B **42**(2011)775.
- (6) FURTHER EVIDENCE FOR THE BROAD  $2^+_2$  AT 9.6 MEV IN  $^{12}C$ .  
W.R. Zimmerman, N.E. Destefano, M. Freer, M. Gai and F. D. Smit.  
Phys. Rev. C **84**(2011)027304.
- (7) STELLAR HELIUM BURNING STUDIED WITH AN OPTICAL READOUT TPC (O-TPC) AT  $HI\gamma S$ .  
Moshe Gai for the UConn-Yale-Duke-Weizmann-PTB-UCL Collaboration  
J. Phys. **CS316**(2011)012033.
- (8) STUDIES IN NUCLEAR ASTROPHYSICS WITH AN OPTICAL READOUT TPC (O-TPC) AT  $HI\gamma S$ .  
Moshe Gai for the UConn-Yale-Duke-Weizmann-PTB-UCL Collaboration  
J. Phys. **CS337**(2012)012054.
- (9) THE U(7) STRUCTURE OF  $^{12}C$  AND THE HOYLE  $2^+$  STATE.  
Moshe Gai  
Amer. Inst. Phys. **CP1488**, 95 (2012).



- (10) UNAMBIGUOUS IDENTIFICATION OF THE SECOND  $2^+$  STATE IN  $^{12}\text{C}$  AND THE STRUCTURE OF THE HOYLE STATE.  
W.R. Zimmerman, M.W. Ahmed, S.C. Stave, A. Breskin, V. Dangendorf, Th. Delbar, M. Gai, S.S. Henshaw, J.M. Mueller, C. Sun, K. Tittelmeier, H.R. Weller and Y. Wu.  
To be submitted, Phys. Rev., 2012.

## **4.2 Talks, Contributions, Conference Proceedings:**

- (1) NUCLEAR ASTROPHYSICS WITH AN OPTICAL READOUT TPC (O-TPC) AND GAMMA BEAMS FROM HIGS AT DUKE.  
Moshe Gai for the Yale-UConn-TUNL-Weizmann-PTB-UCL Collaboration.  
Nuclear Physics in Astrophysics V, April 3 - 8, 2011, Eilat, Israel.
- (2) LOW-POWER, LOW-NOISE CHARGE PRE-AMPLIFIER FOR APPLICATIONS IN COLD GASEOUS XENON.  
Nicholas E. Destefano, Moshe Gai, Ethan P. Bernad, Nicols A. Larsen, Daniel N. McKinsey.  
Fourth Annual Academic Research Intitiative (ARI), April 26 - 28, 2011, Alexandria, VA.
- (3) THE DESIGN OF LIQUID XENON COMPTON GAMMA RAY IMAGER.  
Ethan P. Bernad, Sidney B. Cahn, Alessandro Curioni, Christopher J. Kachulis, Nicols A. Larsen, Daniel N. McKinsey, Nicholas E. Destefano, Moshe Gai.  
Fourth Annual Academic Research Intitiative (ARI), April 26 - 28, 2011, Alexandria, VA.
- (4) CRYOGENICS IN PIXeY: A XENON-BASED GAMMA RAY IMAGER.  
Nicols A. Larsen, Ethan P. Bernad, Sidney B. Cahn, Alessandro Curioni, Alexey Lyashenko, James Nikkel, Yunchang Shin, Alex Young, Daniel N. McKinsey, Nicholas E. Destefano, Moshe Gai.  
Fourth Annual Academic Research Intitiative (ARI), April 26 - 28, 2011, Alexandria, VA.
- (5) THE NUCLEAR PHYSICS OF HYDROGEN BURNING IN STARS.  
Moshe Gai  
American Astronomical Society, May 23, 2011, Boston, MA.
- (6) THE STRUCTURE OF THE  $2+$  STATE IN  $^{12}\text{C}$  AND STELLAR HELIUM BURNING.  
Moshe Gai for the Yale-UConn-TUNL-Weizmann-PTB-UCL Collaboration.  
Advances in Nuclear Many Body-Theory, June 7 - 10, 2011, Primosten, Croatia.
- (7) MEASUREMENT OF THE CROSS SECTION OF THE  $^7\text{Be}(n,\alpha)$  REACTION AND THE PROBLEM OF THE PRIMORDIAL  $^7\text{Li}$ .  
M. Gai, M. Hass, K.M. Nollett, M. Paul, D. Schumann, Th. Stora, L. Weissman.  
Second Workshop on Radionuclides From Accelerator Waste, Aug 19 - Sept 2, 2011, PSI, Switzerland.
- (8) APPLICATION OF TWO-PHASE (LIQUID/GAS) XENON GAMMA CAMERA.  
Nicholas E. Destefano, Moshe Gai, Aaron G. Swindell, Alexander H. Young, Daniel N. McKinsey, Ethan P. Bernard, Sidney B. Cahn, Blair Edwards, Christopher J. Kachulis, Nicole A. Larsen, Alexey Lyashenko, James A. Nikkel, Christopher G. Wahl  
Applications of Nuclear Physics in Science and Technology (ANS&T), Aug 22, 2011, Washington, DC.
- (9) FURTHER MEASUREMENT(S) OF NEUTRON INTERACTION WITH  $^7\text{Be}$ .  
M. Gai  
MicroWorkshop for Research at the SARAF, Soreq Nuclear Center, Israel.
- (10) NEW EXPERIMENTAL METHODS FOR DETERMINING REACTION RATES IN STELLAR EVOLUTION.  
Moshe Gai  
Workshop on Thermonuclear Reaction Rates, November 24 - 25, 2011, Athens, Greece.

- (11) THE SCIENCE OF HOMELAND SECURITY.  
Moshe Gai  
Workshop on Nuclear Dynamics 2012; Dorado del Mar, Puerto Rico, April 9-14, 2012.
- (12) DESIGN AND OPTIMIZATION OF THE YALE PIXeY TWO PHASE XENON DETECTOR.  
N.E. Destefano, M. Gai, E.P. Bernard, B. Edwards, N. Larsen, A. Lyashenko, C. Wahl, D.N. McKinsey.  
IEEE 2012 Symposium on Radiation and Applications. Sorma West 2012, May 13 - 15, 2012.
- (13) THE STRUCTURE OF THE HOYLE STATE AND ITS 2+ PARTNER STATE IN 12C.  
Moshe Gai for the Yale-UConn-TUNL-Weizmann-PTB-UCL Collaboration.  
Beauty in Physics; Cocoyoc, Morelos, Mexico, May 14 - 18, 2012.
- (14) THE STRUCTURE OF THE HOYLE STATE AND ITS 2+ PARTNER STATE IN 12C.  
Moshe Gai for the Yale-UConn-TUNL-Weizmann-PTB-UCL Collaboration.  
Nuclear Structure and Related Topics, Dubna, Russia, July 3-7, 2012.
- (15) DESIGN, TECHNICAL DEVELOPMENT, AND PROJECTED PERFORMANCE OF THE PIXeY LIQUID XENON COMPTON IMAGING DETECTOR.  
E.P. Bernad, S.B. Cahn, A. Curioni, B. Edwards, Ch.J. Kachulis, N.A. Larsen, A. Lyashenko, J.A. Nikkel, Y. Shin, B.P. Tennyson, Ch.G. Wahl, A.H. Young, D.N. McKinsey, M.S. DeSilva, N.E. Destefano, M. Gai. 5th Annual ARI Grantees Conference, Leesburg, VA, July 23 - 25, 2012.
- (16) PROSPECTS FOR GAMMA-RAY IMAGING WITH LIQUID XENON.  
N.A. Larsen, E.P. Bernad, S.B. Cahn, B. Edwards, Ch.J. Kachulis, A. Lyashenko, D.N. McKinsey, J.A. Nikkel, Y. Shin, B.P. Tennyson, Ch.G. Wahl, N.E. Destefano, M.S. DeSilva, M. Gai.  
5th Annual ARI Grantees Conference, Leesburg, VA, July 23 - 25, 2012.
- (17) CHARACTERIZATION OF THE TWO-PHASE XENON DETECTOR FOR R&D ON COMPTON IMAGING.  
N.E. Destefano, M.S. DeSilva, M.Gai, D.N. McKinsey, E.P. Bernad, S.B. Cahn, A. Curioni, B. Edwards, Ch.J. Kachulis, N.A. Larsen, A. Lyashenko, J.A. Nikkel, Y. Shin, B.P. Tennyson, Ch.G. Wahl, A.H. Young. 5th Annual ARI Grantees Conference, Leesburg, VA, July 23 - 25, 2012.
- (18) STATUS OF MEASUREMENTS OF THE 12C(a,g) REACTION AT LOW ENERGIES.  
Moshe Gai  
VIII TOURS 2012 Symposium, Black Forest, Lenzkirch-Saig, German, September 2-7, 2012.
- (19) THE STRUCTURE OF THE HOYLE STATE VIA A MEASUREMENT OF THE “HOYLE BAND” IN 12C.  
Moshe Gai for the Yale-UConn-TUNL-Weizmann-PTB-UCL Collaboration.  
10th Inter. Conf. on Clustering, Debrecen, September 24-28, 2012.
- (20) DESIGN OF TWO-PHASE LIQUID-XENON COMPTON IMAGING DETECTOR.  
Ch.G. Wahl, E.P. Bernad, Ch.J. Kachulis, N.A. Larsen, B.P. Tennyson, S.B. Cahn, D.N. McKinsey, M.S. DeSilva, N.E. Destefano, M. Gai. Bull. Amer. Phys. Soc. **57**,#9, 91 (2012).
- (21) PROGRESS ON THE CHARACTERIZATION OF THE YALE PIXeY TWO-PHASE DETECTOR.  
N.E. Destefano, M. Gai, D.N. McKinsey, E.P. Bernad, S.B. Cahn, A. Curioni, B. Edwards, C.J. Kachulis, N.A. Larsen, A. Lyashenko, J.A. Nikkel, Y. Shin, C.G. Wahl, A.H. Young.  
Bull. Amer. Phys. Soc. **57**,#9, 92 (2012).

- (22) STATUS AND DESIGN OF TWO-PHASE LIQUID -XENON COMPTON-IMAGING DETECTOR.  
C. G. Wahl, E. P. Bernard, C. Kachulis, B. Edwards, N. A. Larsen, B. Tennyson, S. B. Cahn, D. N.  
McKinsey, N. E. Destefano, M. Gai.  
2012 IEEE Nuclear Science Symposium Conference Record, Anaheim, CA, Oct. 27 - Nov. 3, 2012.