The Importance of Measuring Angular Distributions And Ambiguities of the $^{12}C(\alpha,\gamma)$ Reaction

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1. **Modern Data:**
   Stuttgart: GANDI/EUROGAM Arrays
   Karlsruhe BaF Array

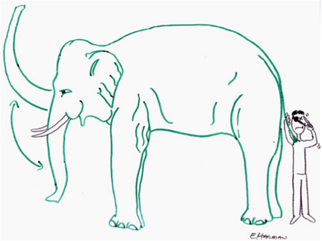
   What Have We Learned
   Where Do We Go From Here?

2. **Gamma Ray Detectors ($2M):**
   BaLa (BrilLance), CZT, Liquid Xenon

Starting-up the LUNA-MV Collaboration
LNGS, Assergi, Italy, February 7, 2013

W.A. Fowler; Rev. Mod. Phys. 56, 149 (1984)

$^{12}C(\alpha,\gamma)^{16}O$: "of Paramount Importance"



Eric T. Harman

Physics Today 55:12(2002)26

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

Integrated Luminosity: $\mathcal{L} \cong$ fb^{-1}
Implanted Pure ^{12}C target

PHYSICAL REVIEW C **86**, 015805 (2012)

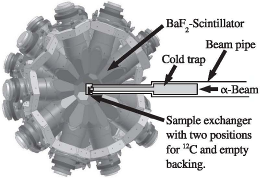


FIG. 1. The Karlsruhe 4π BaF_2 detector, consisting of 42 independent modules forming a spherical shell of BaF_2 that is 15 cm thick and has an inner radius of 10 cm.

516c J.W. Hammer et al. / Nuclear Physics A 752 (2005) 514c–521c

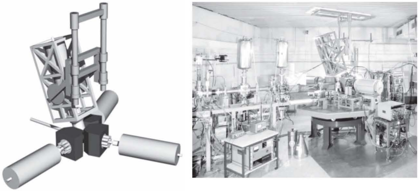


Figure 2. Sketch and photo of the GANDI detector array at the Stuttgart DYNAMITRON laboratory with four movable Ge(BGO) detectors in very close geometry. An angular distribution is obtained successively in three different positions of the lower three detectors.

PHYSICAL REVIEW C **73**, 055801 (2006)

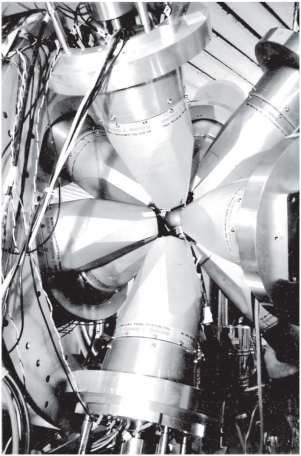
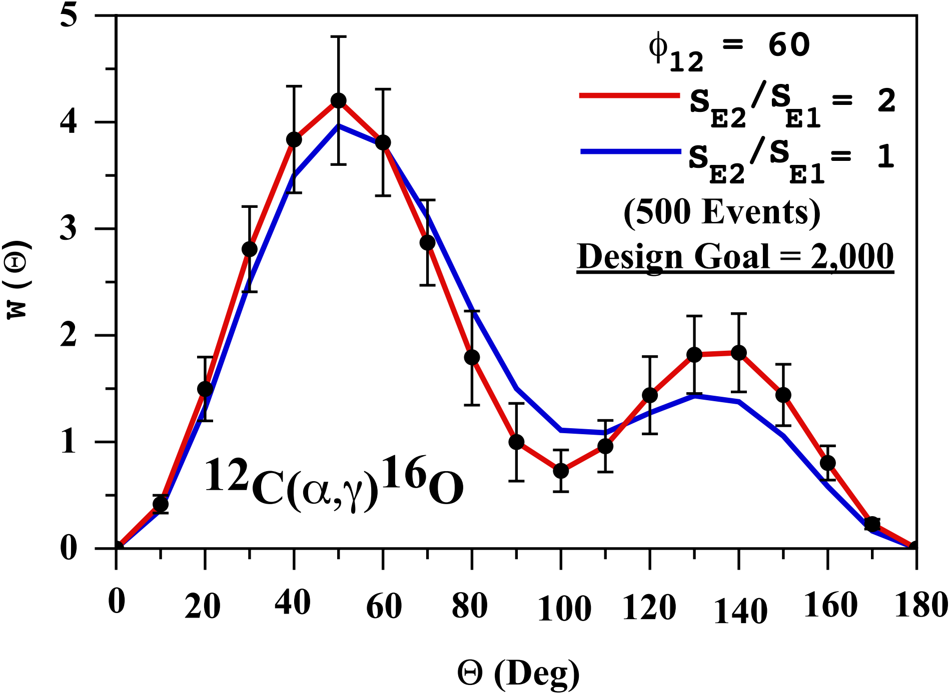
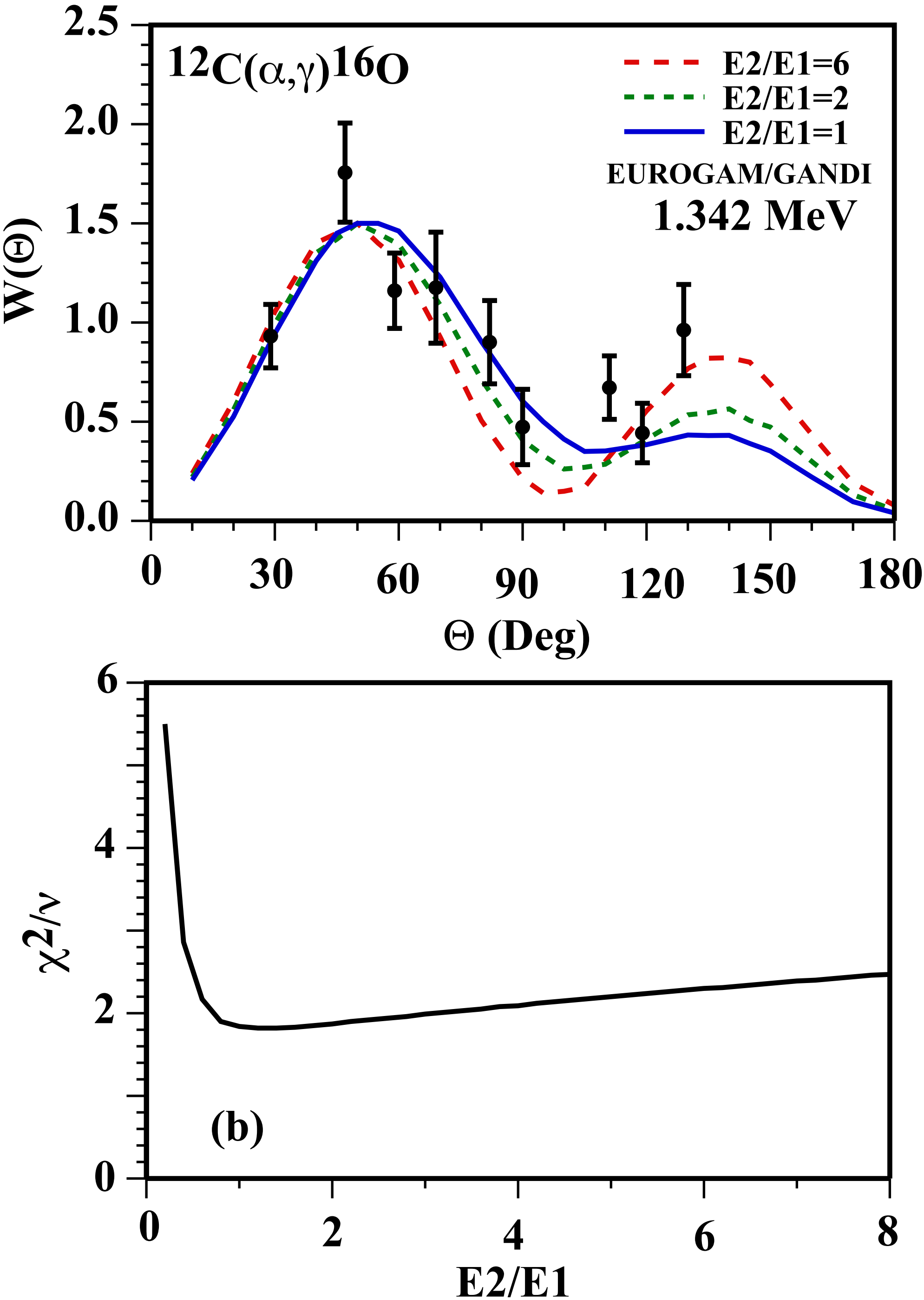


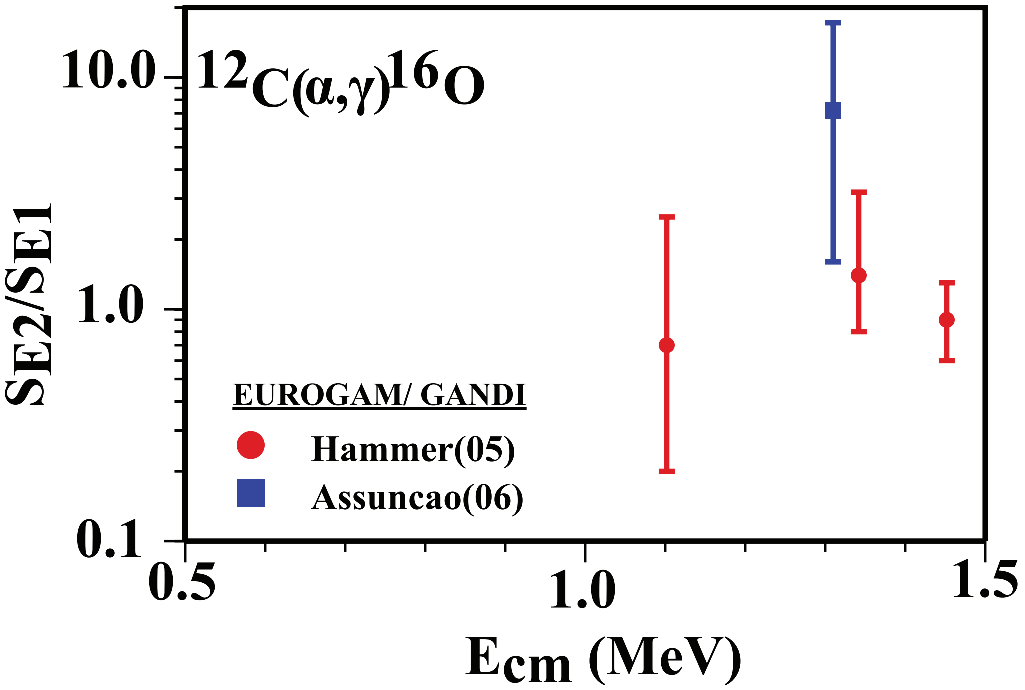
FIG. 2. View of the central part of the 4π-detector setup consisting of nine EUROGAM detectors in close geometry with the target in the center of the array in a small spherical vacuum chamber.



5
4
3
2
1
0
w (Θ)
0
20
40
60
80
100
120
140
160
180
Θ (Deg)
φ12 = 60
SE2/SE1 = 2
SE2/SE1 = 1
(500 Events)
Design Goal = 2,000
12C(α,γ)16O



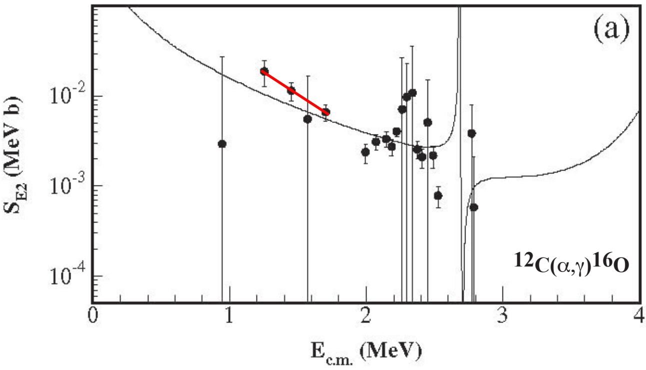
12C(α,γ)16O
E2/E1=6
E2/E1=2
E2/E1=1
EUROGAM/GANDI
1.342 MeV
W(Θ)
Θ (Deg)
0.0
0.5
1.0
1.5
2.0
2.5
0
30
60
90
120
150
180
(b)
χ2/ν
E2/E1
0
2
4
6
8

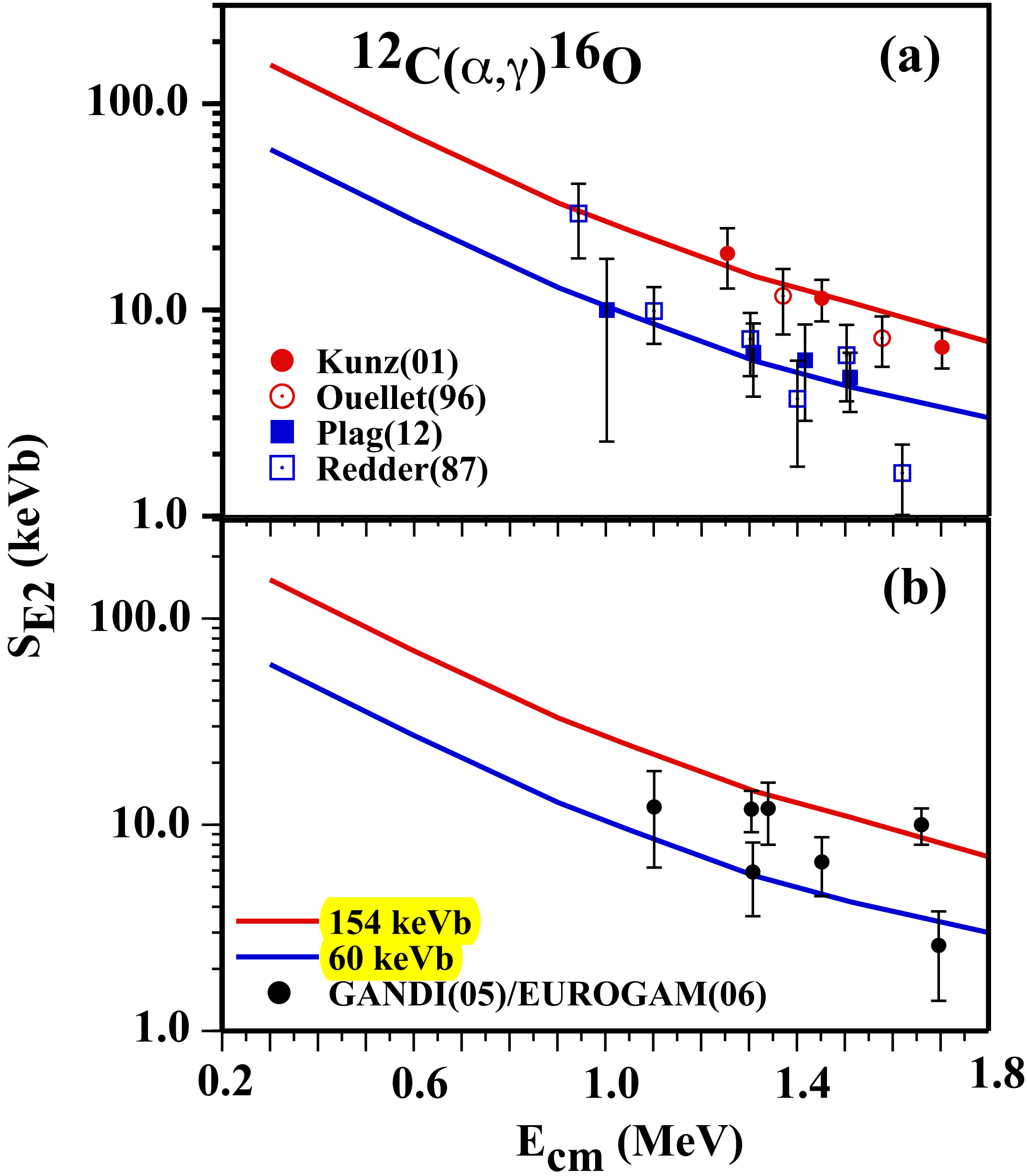


$^{12}C(\alpha,\gamma)^{16}O$
10.0
1.0
0.1
S_{E2}/S_{E1}
EUROGAM/ GANDI
Hammer(05)
Assuncao(06)
0.5
1.0
1.5
Ecm (MeV)

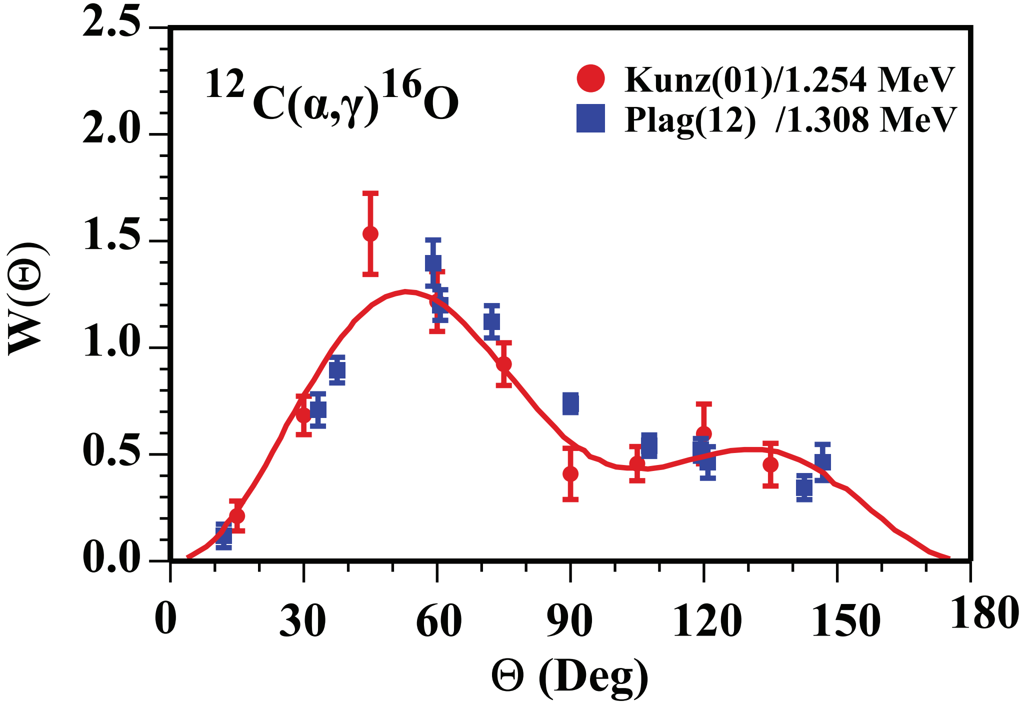
R. Kunz *et al.*; PRL 86(2001)3244

SE2 = 86 ±30 keVb

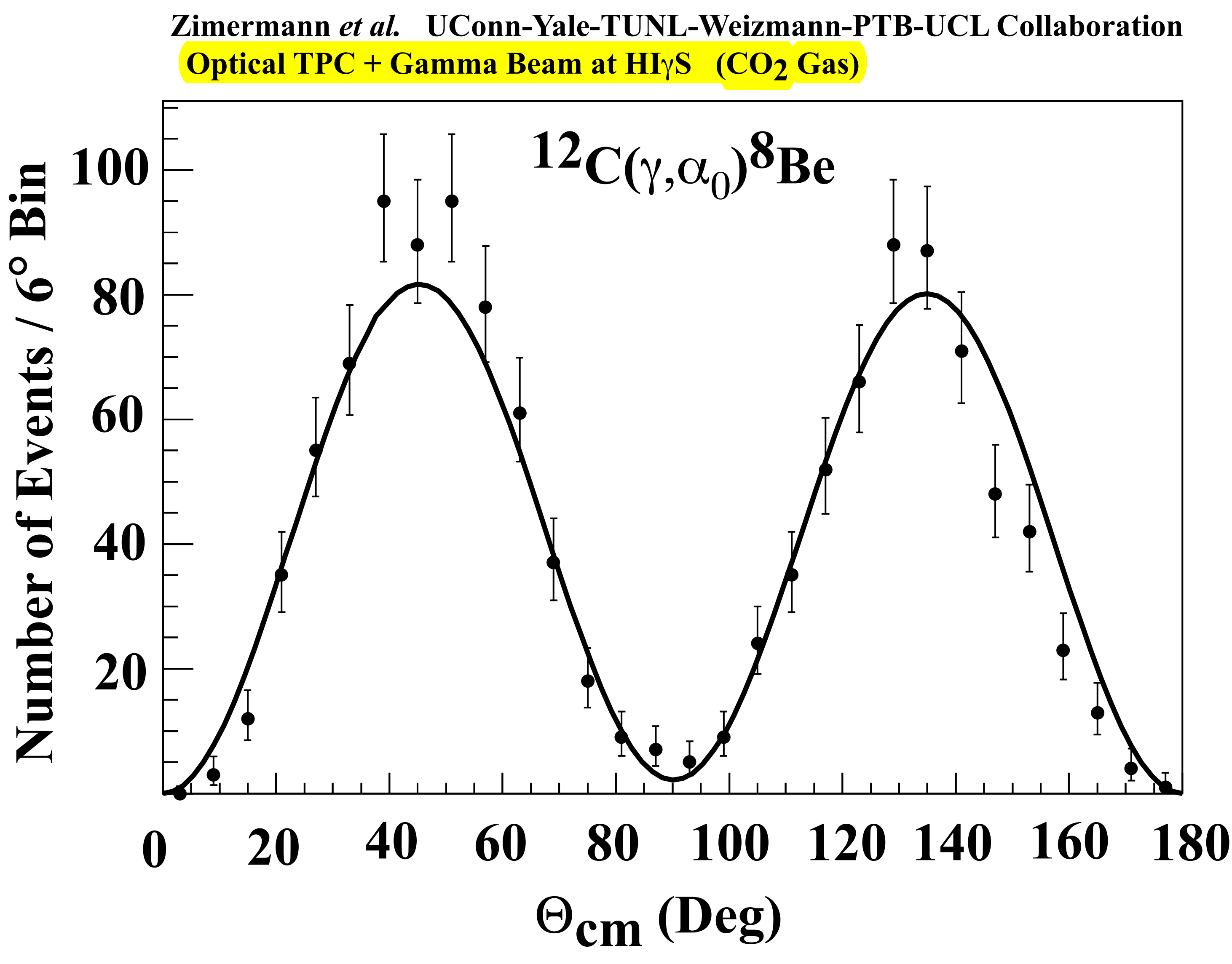




$^{12}C(\alpha,\gamma)^{16}O$
(a)
Kunz(01)
Ouellet(96)
Plag(12)
Redder(87)
(b)
154 keVb
60 keVb
GANDI(05)/EUROGAM(06)
S_{E2} (keVb)
E_{cm} (MeV)
100.0
10.0
1.0
0.2
0.6
1.0
1.4
1.8



2.5
2.0
1.5
1.0
0.5
0.0
W(Θ)
$^{12}C(\alpha,\gamma)^{16}O$
Kunz(01)/1.254 MeV
Plag(12) /1.308 MeV
0
30
60
90
120
150
180
Θ (Deg)



Zimermann et al. UConn-Yale-TUNL-Weizmann-PTB-UCL Collaboration
Optical TPC + Gamma Beam at HIγS (CO2 Gas)
12C(γ,α0)8Be
Number of Events / 6° Bin
100
80
60
40
20
0
20
40
60
80
100
120
140
160
180
Θcm (Deg)

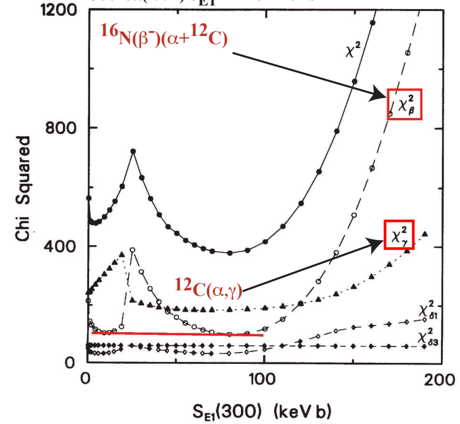
TRIUMF- R.E. Azuma *et al.*; PRC50(1994)1194

$^{12}C(\alpha,\gamma)$ Data:

Redder(1987) $S_{E1}(300)$ = 9 - 450 keVb

Kremer(1988) Flat χ^2 with minimum at 10 keVb.

Ouellett(1992) S_{E1} = 1 +6-1 keVb

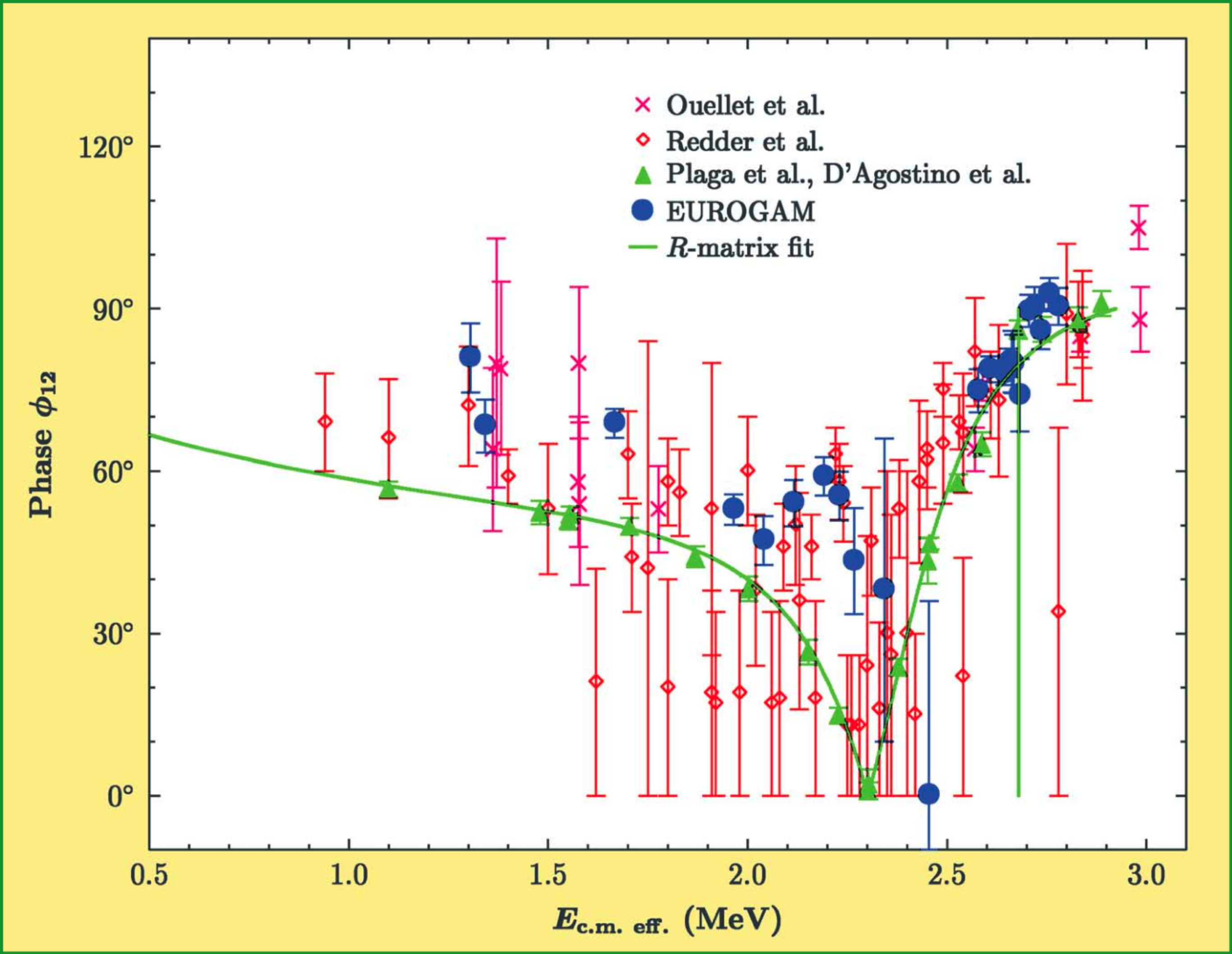


Aps President, Burt Richter, April, 1994
Zhiping Zhao, Ph.D.'93, Yale University
"DNP/ 1994 Best Ph.D. Thesis Award"

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

(Unitarity!)

K. M. Watson; Phys. Rev. 95(1954)228
L. D. Knutson; Phys. Rev. C59(1999)2152
C. R. Brune; Phys. Rev. C64(2001)055803



Conclusions

A. Ambiguities:

1. $S_{E2}(300) \approx 60$ or 154 keVb

2. $S_{E1}(300) \approx 10$ or 80 keVb

B. Conflict:

$\phi_{12} \Leftrightarrow$ Unitarity

Need Precise Detailed $W(\Theta)$
Binning $< 10°$
$E_{cm} < 1.0$ MeV

High Efficiency Segmented Gamma-Detector
BrilLance (BaLa), CZT, Xenon?
$2M

Ambiguities in the Rate of Oxygen Formation During Stellar Helium Burning; the $^{12}C(\alpha,\gamma)^{16}O$ Reaction.

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DRAFT #1, DRAFT #1, DRAFT #1 (January 27, 2013)
PLEASE DO NOT CIRCULATE!!!

The rate of oxygen formation determines the C/O ratio during stellar helium burning. It is the most important nuclear input of stellar evolution theory including the evolution to Type II and Type Ia supernova. Yet the low energy cross section of the fusion of ^{4}He + ^{12}C denoted as the ^{12}C$(\alpha,\gamma)^{16}$O reaction still remains uncertain after forty years of extensive work. We analyze and critically review the most recent measurements with unprecedent characteristics at very low energies ($E_{cm} \geq 1.0$ MeV) of complete angular distributions of the outgoing gamma-rays from which we extract the $\ell = 2$ (E2) and $\ell = 1$ (E1) astrophysical cross section factors. We show that the measured E2 cross section factors lead to two distinct extrapolations of $S_{E2}(300) \approx 60$ or ≈ 154 keVb. Our analysis of the angular distribution measured with the EUROGAM/GANDI arrays lead us to conclude considerably larger error bars than published. We conclude that the modern data, just the same as previous data including the spectrum of the beta decay of ^{16}N, do not rule out the solution of small E1 cross section factor [$S_{E1}(300) \approx 10$ keVb] in favor of the large solution [$S_{E1}(300) \approx 80$ keVb]. We point to a much neglected discrepancy between the measured E1-E2 phase difference (ϕ_{12}) and unitarity as required by the Watson theorem, suggesting a systematic difficulty of some of the measured gamma-ray angular distributions. These ambiguities must be resolved by future measurements of complete and detailed angular distributions of the ^{12}C(α,γ) reaction at very low energies ($E_{cm} \leq 1.0$ MeV).

PACS numbers:

Stellar Helium burning that follows Hydrogen burning in stars is an important burning stage in the evolution of stars. During this stage the elements carbon and oxygen are formed and as such it is one of the most vivid examples of the anthropic principle [1]. During this stage carbon is synthesized by the so called "triple alpha process" but in the same time carbon is also destroyed by fusing with an additional alpha-particle to form ^{16}O in the ^{12}C$(\alpha,\gamma)^{16}$O reaction. Hence the formation of oxygen in stellar helium burning determines the C/O ratio; an essential parameter in stellar evolution theory [1].

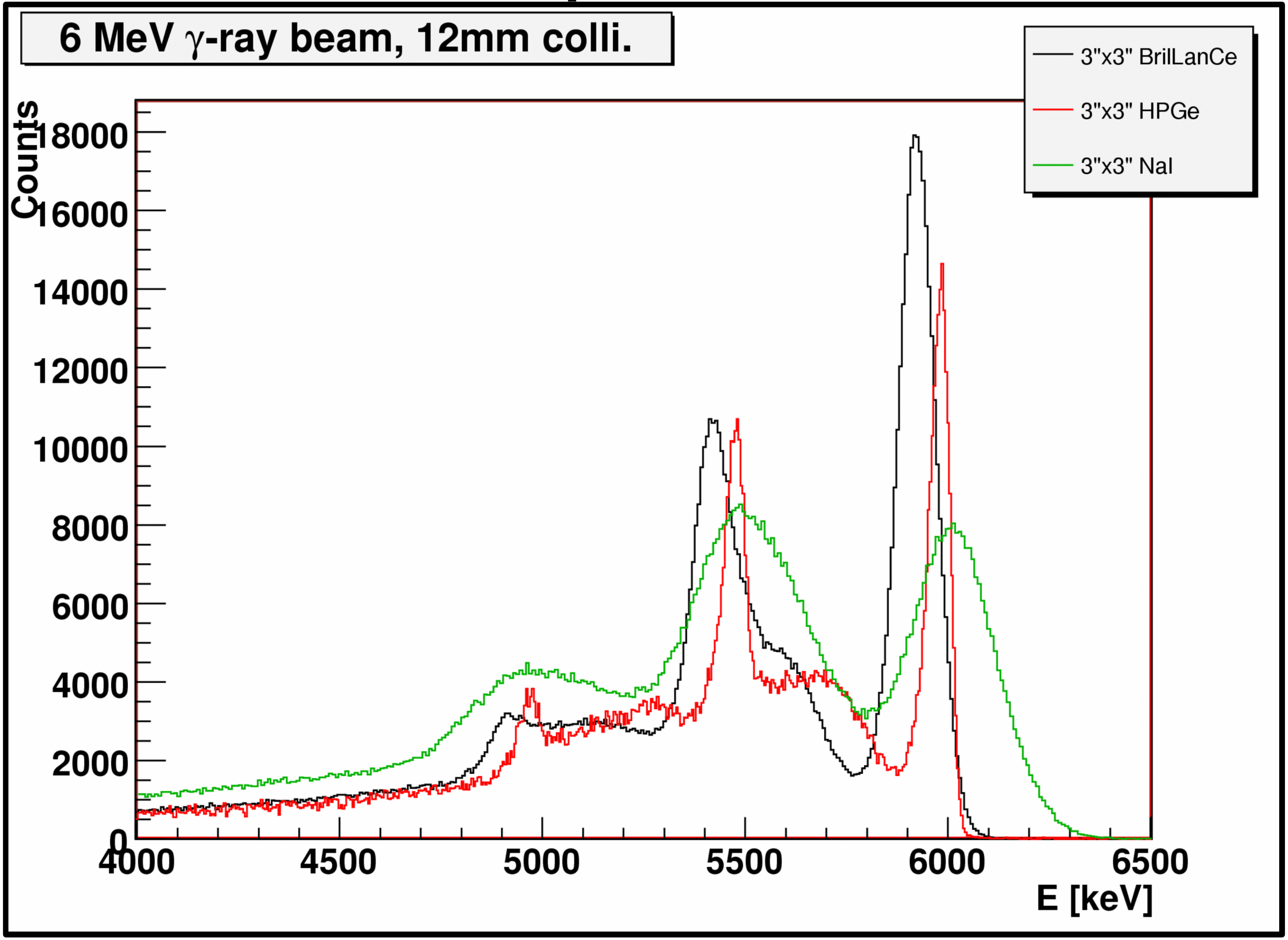
The importance of the C/O ratio for the evolution of heavy stars ($M > 8M_\odot$) that evolve to core collapse (type II) supernova has been discussed extensively [2] but more recently it was shown that the C/O ratio is also important for understanding the ^{56}Ni mass fraction produced by lower mass stars ($M \approx 1.4M_\odot$) that evolve into Type Ia supernova (SNeIa) [3] and thus the C/O ratio is also important for understanding the light curve of SNeIa. Such SNeIa are used as cosmological "standard candles" with which the accelerated expansion of the universe and dark energy were recently discovered [4].

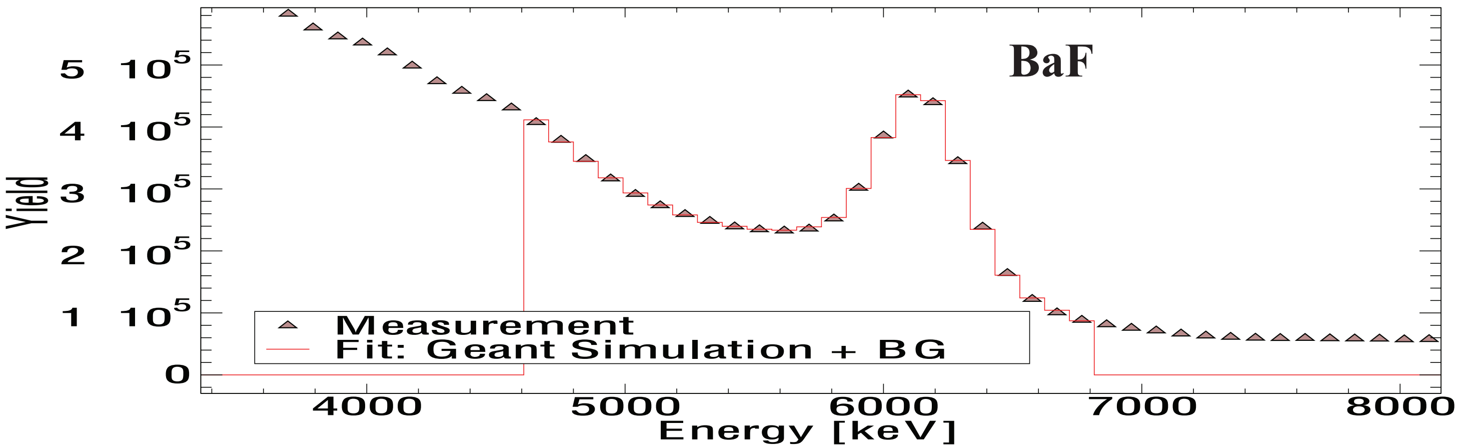
Stellar evolution theory requires the knowledge of the C/O ratio with an uncertainty of 10% or better. This requires accurate measurements at low energies and extrapolation of the measured astrophysical cross section factors to the Gammow window at 300 keV [1]. Since mainly two ($\ell = 1$ and 2) partial waves contribute to the reaction, accurate angular distribution data are needed at low energies to determine with high accuracy the astrophysical cross section factors $S_{E1}(300)$ and $S_{E2}(300)$ defined in [1]. This goal has not been achieved as yet.

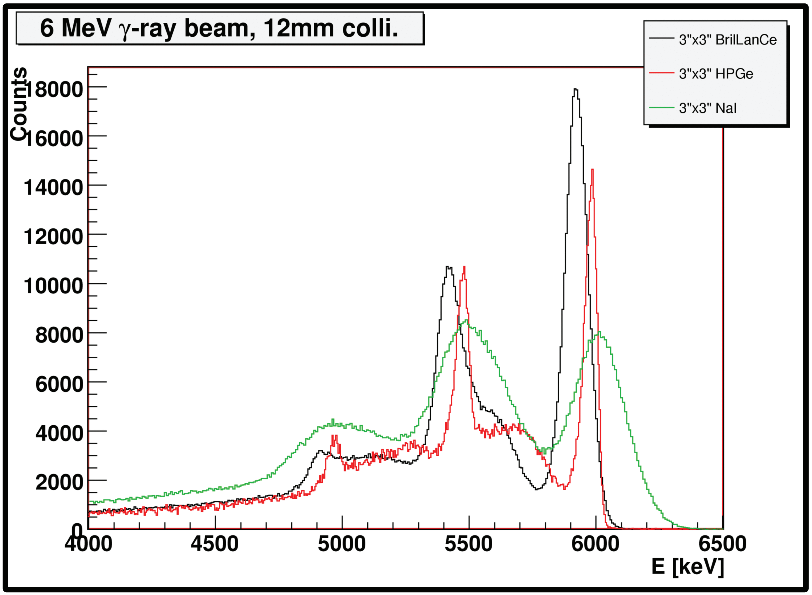
Recently some of the most impressive gamma-ray measurements of the ^{12}C$(\alpha,\gamma)^{16}$O reaction were published [5–9] including measurements of complete angular distribution at center of mass energies approaching 1.0 MeV. These measurements use large luminosities of the order of of 10^{35} $cm^{-2}sec^{-1}$ with integrated luminosities close to one inverse fb. [6–9], and a large (so called 4π) array of gamma-ray detectors. These unprecedented performance characteristics that were not available before led to an expectation of a resolution of the long (now forty years old) debate on the value of the low energy cross section of the ^{12}C(α,γ) reaction. These measurements provide the first possible detailed study of the cross section of the ^{12}C(α,γ) reaction at low energies approaching 1.0 MeV.

In this paper we analyze and critically review the recently published angular distributions. The angular distributions provide a direct measurement of the E2 and E1 cross section factors and should be given the highest priority. We study the E2 cross section factors (S_{E2}) measured at low energies (E_{cm}) below 1.7 MeV in order to avoid the energy region where higher lying states are dominant and to be most sensitive to the the bound 2^+ state at 6.917 MeV in ^{16}O. We show that the measured S_{E2} are ill determined by an average factor of 2.57 and consequently the extrapolated E2 cross section factors lead to two distinct solutions of $S_{E2}(300) \approx 60$ or ≈ 154 keVb. We show that the small value solution of the E1 cross section factor [$S_{E1}(300) \approx$ 10keV] that

6 MeV γ-rays detector comparison

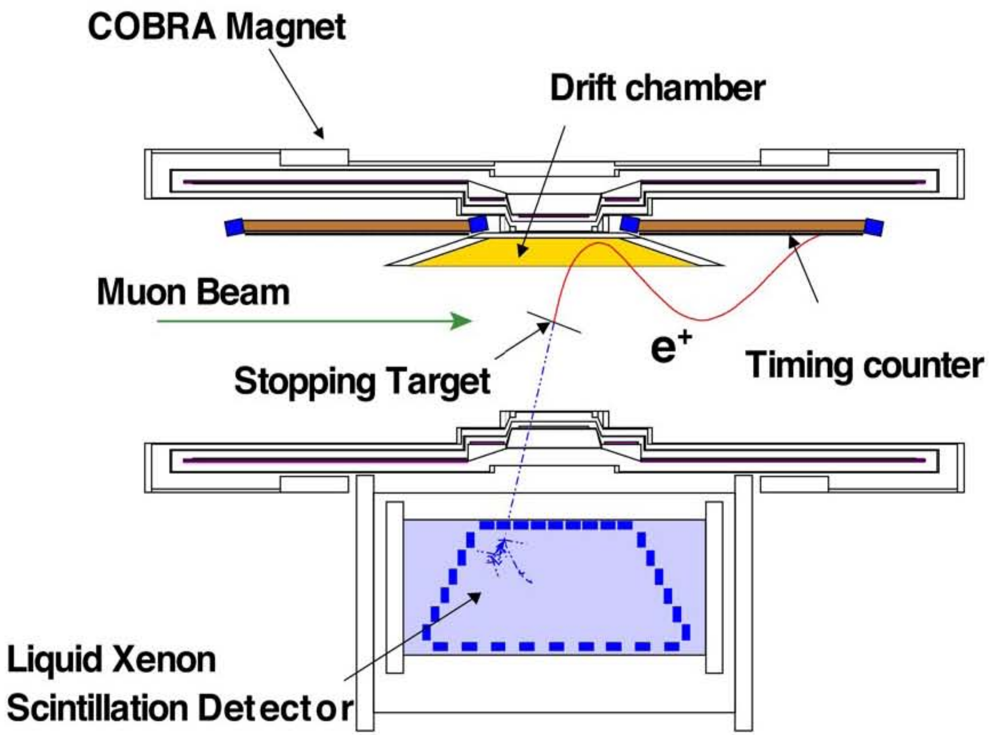


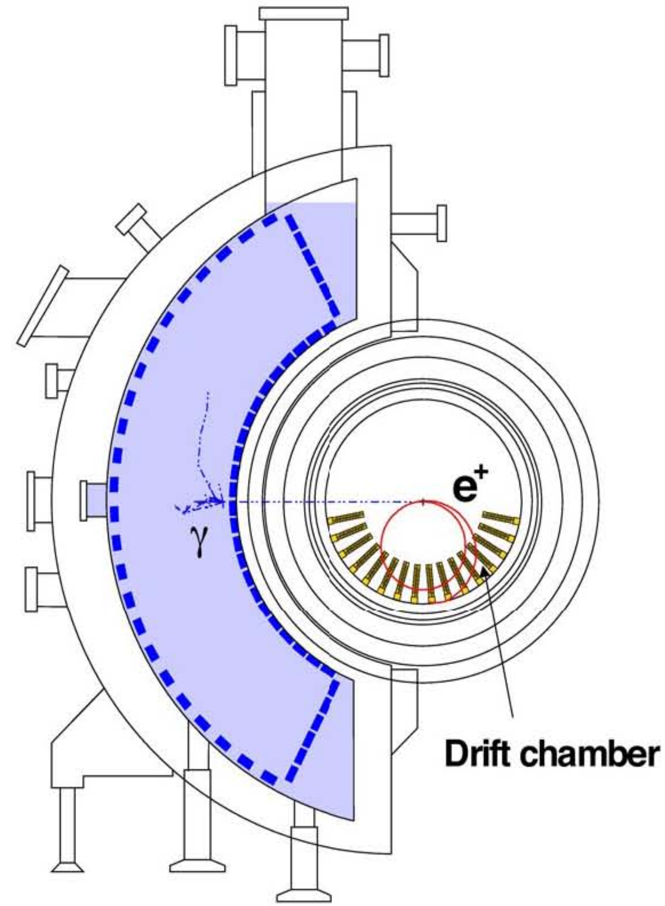

BaF
Measurement
Fit: Geant Simulation + BG
Yield
Energy [keV]
0
1 10^5
2 10^5
3 10^5
4 10^5
5 10^5
4000
5000
6000
7000
8000


6 MeV γ-ray beam, 12mm colli.
3"x3" BrilLanCe
3"x3" HPGe
3"x3" NaI
Counts
E [keV]
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
4000
4500
5000
5500
6000
6500

1m

MEG detector





- Positron spectrometer
  - **Special gradient magnetic field(COBRA)**
    - Sweeps out high rate e+ quickly
    - Constant bending radius of e+
  - **Drift chamber**
    - Made of ultra thin material
    - Precise e+ tracking
  - **Timing counter**
    - Precise e+ timing
    - Plastic scintillator + PMTs
- LXe gamma detector
  - 2.7 ton of liquid xenon
  - Homogeneous detector
  - Good time, position, energy resolution
- Waveform digitizer for all detectors (pileup ID)

The PIXeY Detector
Yale-UConn Collaboration