New Experimental Methods Determining Reaction Rates Stellar Evolution

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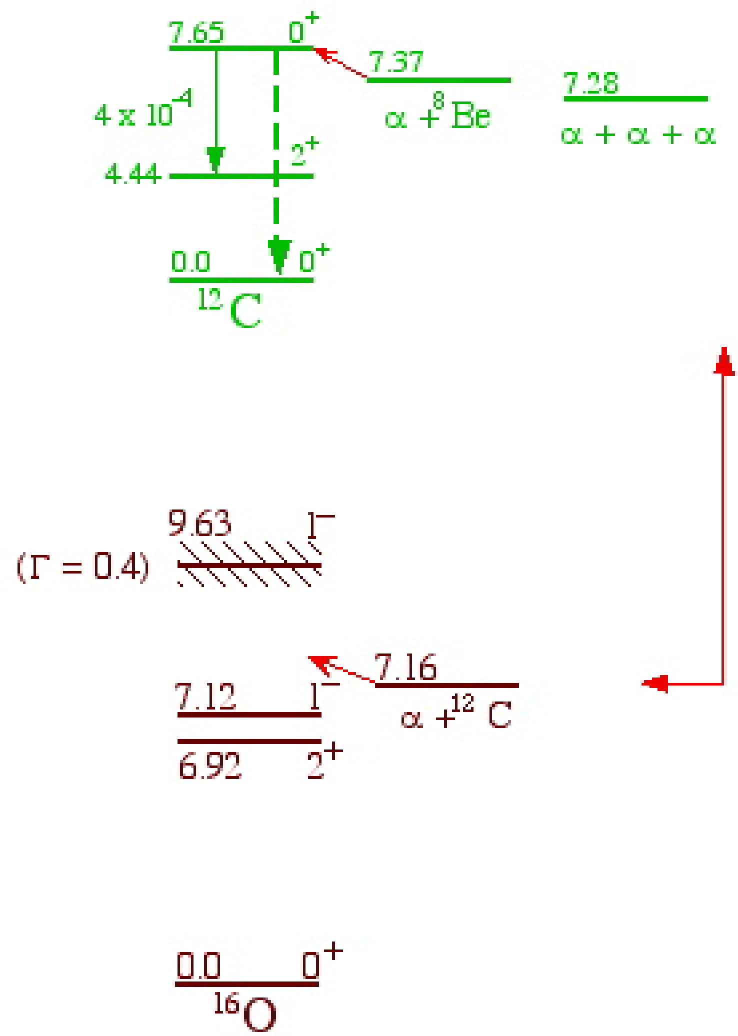
1. **The $^{12}C(\alpha,\gamma)^{16}O$ Reaction:**
   Cascade
   $S_{E1} = ?$ ^{16}N spectra } ⇒ **Confusion!**
   $S_{E2}/S_{E1} = ?$
   $^{12}C(\alpha,\gamma)^{16}O$ Conflict With Unitarity!
   $^{16}O(\gamma,\alpha)$ at HIγS With Optical TPC

2. **The $^{7}Be(p,\gamma)^{8}B$ Reaction:**
   The Coulomb Dissociation of ^{8}B
   (CD Viable Method)

Athens, November 24, 2011

HELIUM BURNING IN (MASSIVE) STARS

I. $3\alpha \rightarrow {}^{12}C$



II. $\alpha + {}^{12}C \rightarrow {}^{16}O$

1. Energy
2. ${}^{12}C/{}^{16}O$
3. Heavier Elements

III. $\alpha + {}^{16}O \rightarrow {}^{20}Ne$ (NEGLIGIBLE)

Helium Burning:

$3\alpha \rightarrow {}^{12}C$ Known

$\alpha + {}^{12}C \rightarrow {}^{16}O$???

C/O = ?

${}^{12}C(\alpha,\gamma){}^{16}O$ (E_{cm} = 300 keV)

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

$$(\eta = e^2 Z_1 Z_2/\hbar\upsilon = Z_1 Z_2 \alpha/\beta)$$

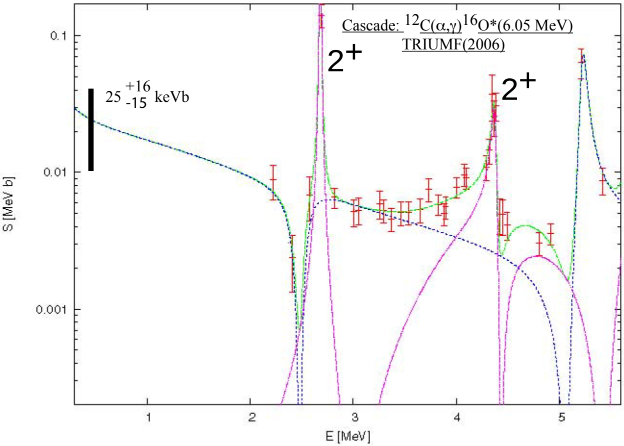
Astrophysical Cross Section Factor (P and D waves)

$S_{E1}(300)$
$S_{E2}(300)$
±15%

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

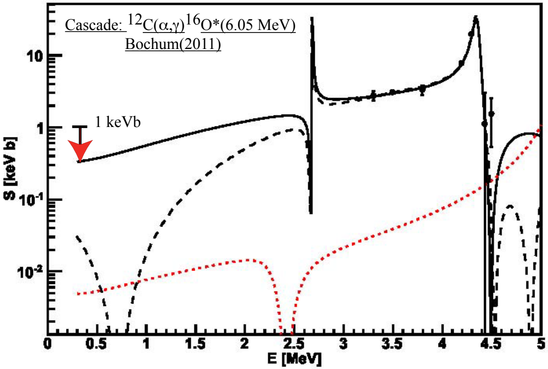
A Critical Review!

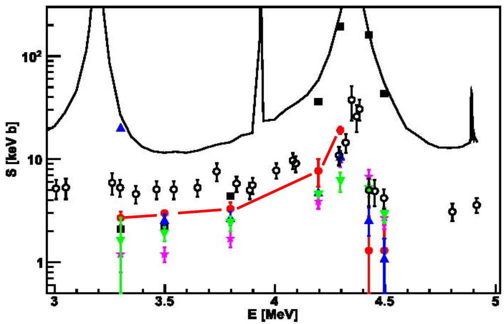
Opinions Confronted With (Conflicting) Data

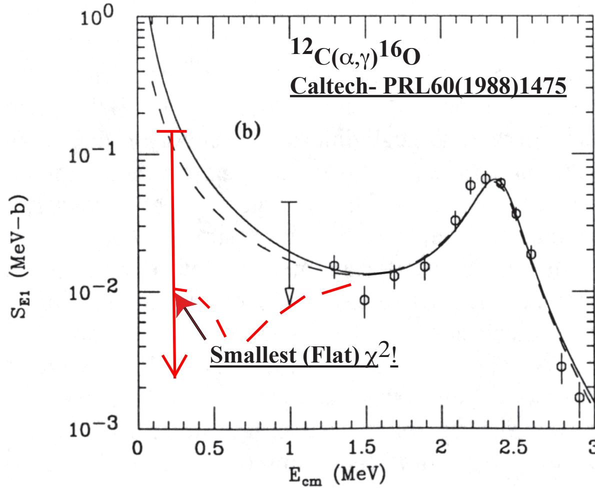


TRIUMF: C. Matei *et al.*; Phys. Rev. Lett. 97(2006)242503.

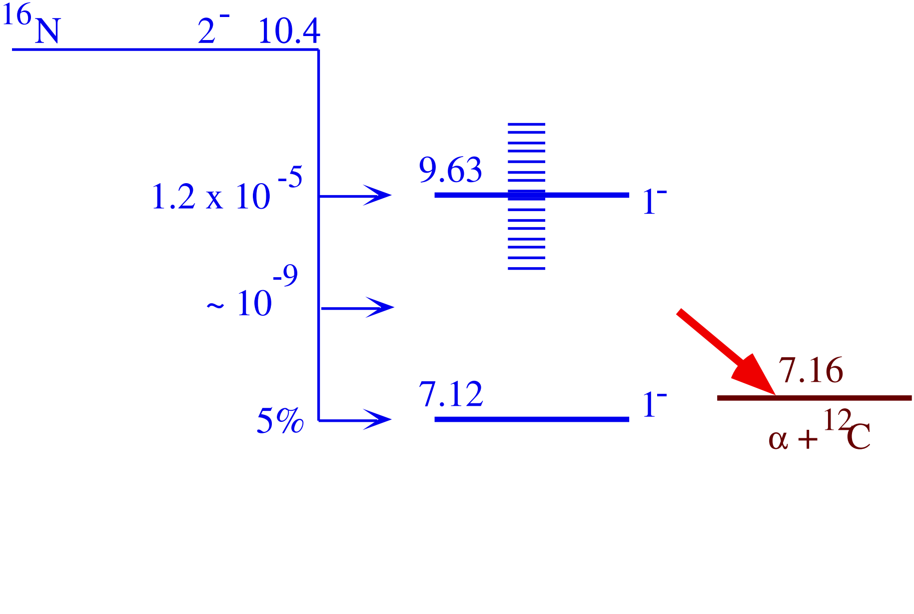
Bochum: D. Schurmann *et al.*; Phy. Lett. B703(2011)557.





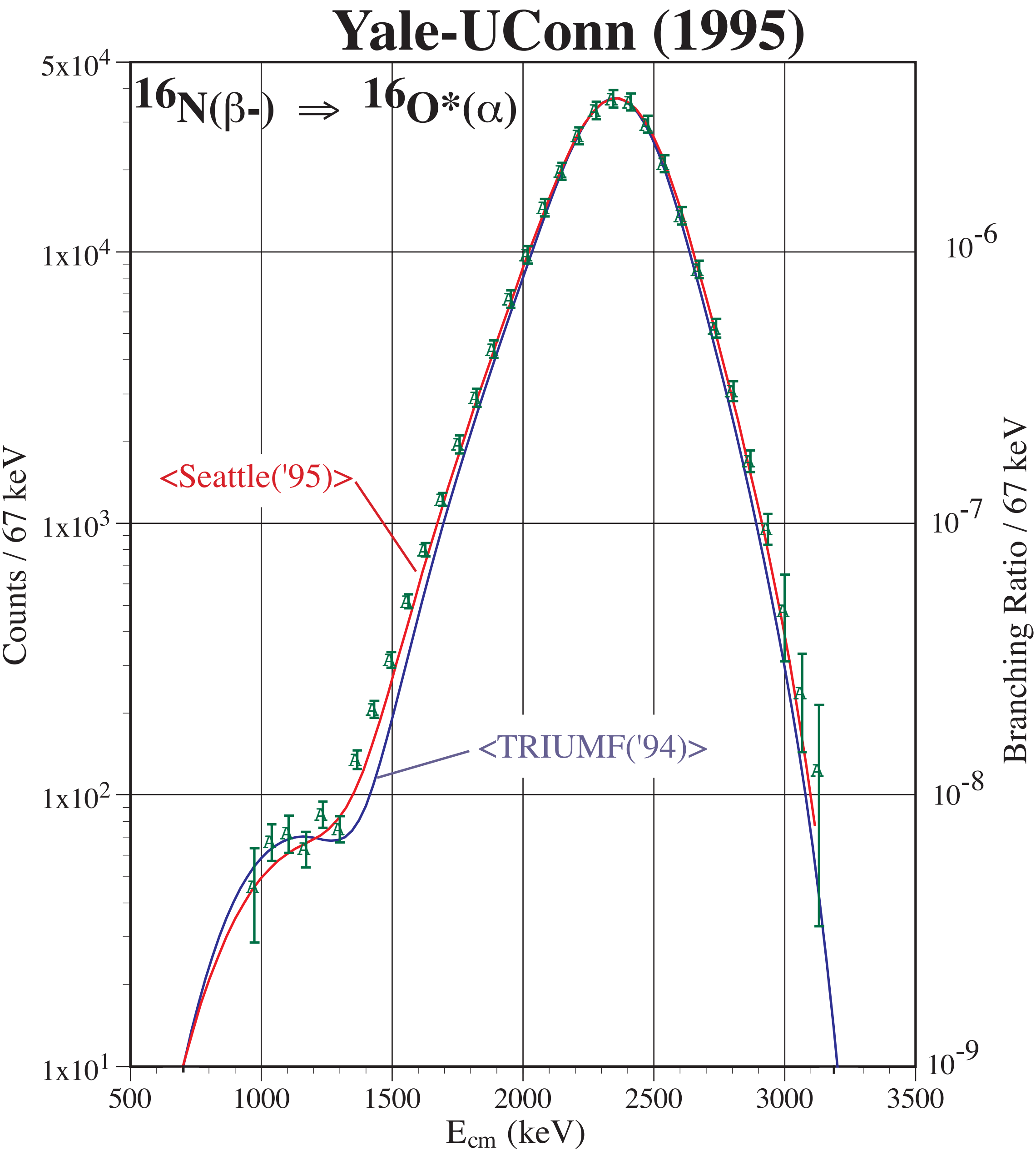


$^{12}C(\alpha,\gamma)^{16}O$
Caltech- PRL60(1988)1475
(b)
Smallest (Flat) χ^2!
S_{E1} (MeV−b)
E_{cm} (MeV)



Enhancement: (I) W_0^5

(II) Matrix Elements


Yale-UConn (1995)
16N(β-) ⇒ 16O*(α)
<Seattle('95)>
<TRIUMF('94)>
5x10^4
1x10^4
1x10^3
1x10^2
1x10^1
10^-6
10^-7
10^-8
10^-9
Counts / 67 keV
Branching Ratio / 67 keV
500
1000
1500
2000
2500
3000
3500
E_cm (keV)

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

"The low-energy part of the spectrum was found to be in better agreement with earlier data measured at Mainz [16] and Yale [14] than with the data from the TRIUMF [5] group".

X.D. Tang *et al.*; Phys. Rev. Lett. 99(2007)

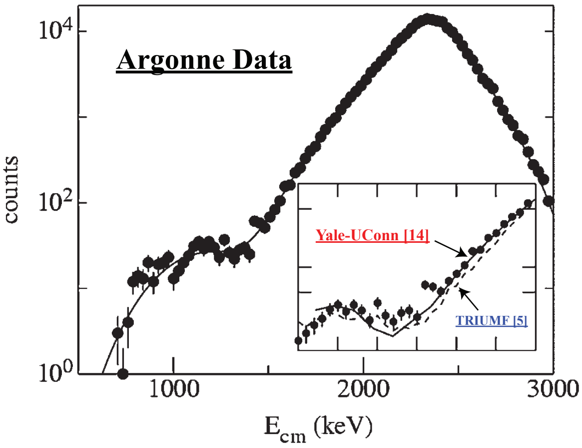


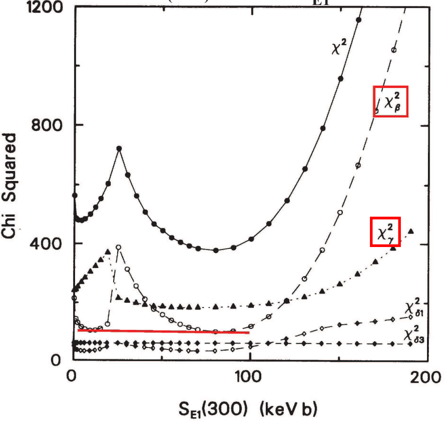
FIG. 4. Summed α spectrum obtained in this experiment in comparison with an R-matrix fit. The insert shows the low-energy part of spectrum together with the previous results (solid [14] and dashed lines [5]). See text for details.

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

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

Same as Caltech(1988) with minimum χ^2 = 10 keVb

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



Ouellet *et al.;* PRL 13(1992)1896

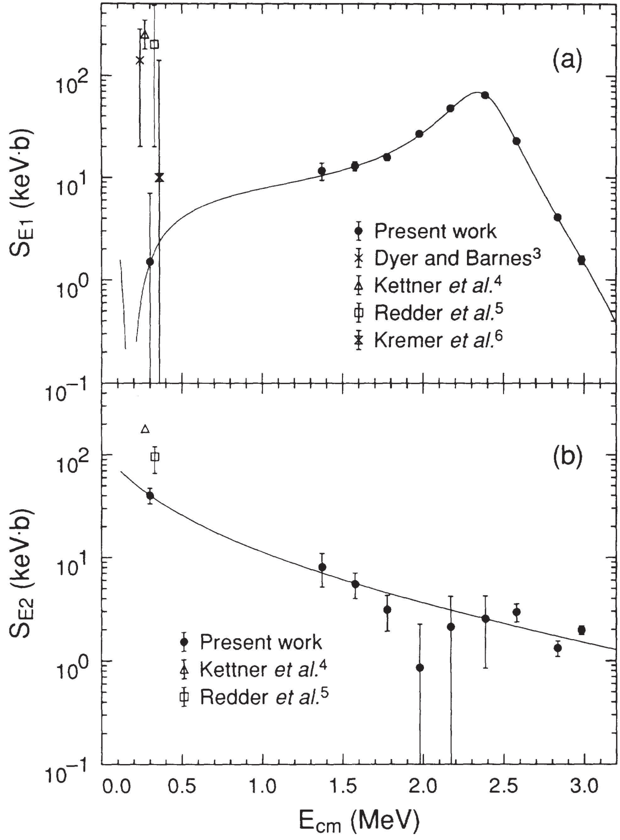
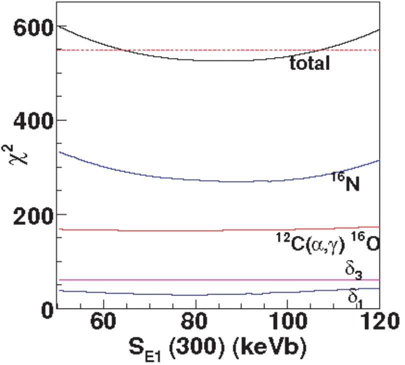
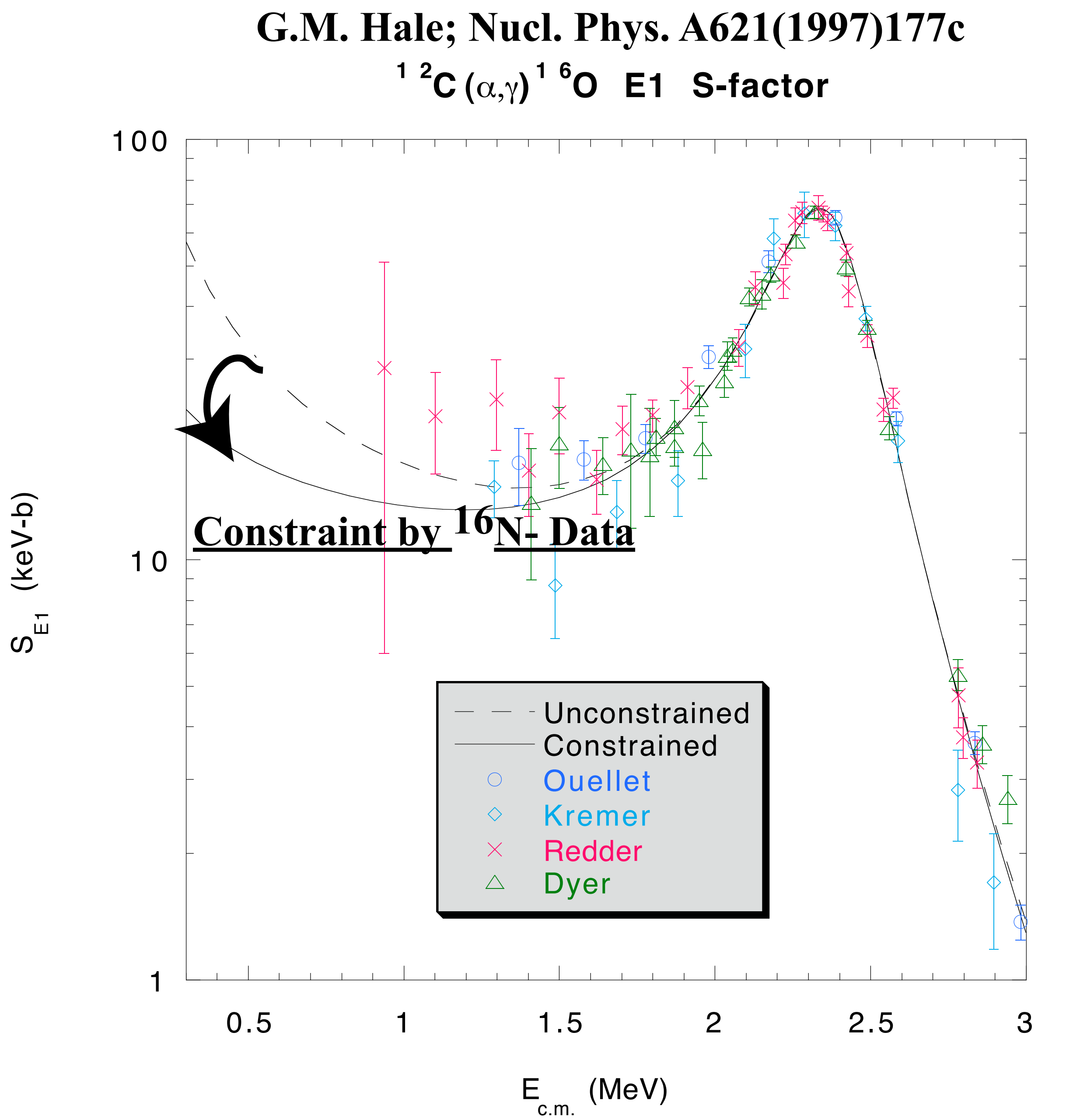


FIG. 3. (a) $E1$ and (b) $E2$ S factors for the ground-state transition of $^{12}C(\alpha,\gamma)^{16}O$. The solid circles on the right and the curves show the present data and the lines of best fit. The points on the left indicate the results of extrapolations for $S(0.3$ MeV); the $E1$ values of Refs. [3], [5], and [6], come from a three-level R-matrix analysis.

Argonne- X.D. Tang *et al.*; PRC 81(2010)045809



(b)


G.M. Hale; Nucl. Phys. A621(1997)177c
12C (α,γ) 16O E1 S-factor
Constraint by 16N- Data
Unconstrained
Constrained
Ouellet
Kremer
Redder
Dyer
100
10
1
0.5
1
1.5
2
2.5
3
S E1 (keV-b)
E c.m. (MeV)

Eur. Phys. J. A **11**, 357–370 (2001)

THE EUROPEAN PHYSICAL JOURNAL A

The E1 capture amplitude in $^{12}C(\alpha, \gamma_0)^{16}O$

L. Gialanella[1], D. Rogalla[1], F. Strieder[1], S. Theis[1], G. Gyürki[5], C. Agodi[4], R. Alba[4], M. Aliotta[1,a], L. Campajola[2], A. Del Zoppo[4], A. D'Onofrio[3], P. Figuera[4], U. Greife[1], G. Imbriani[2], A. Ordine[2], V. Roca[2], C. Rolfs[1,b], M. Romano[2], C. Sabbarese[3], P. Sapienza[4], F. Schümann[1], E. Somorjai[4], F. Terrasi[3], and H.P. Trautvetter[1]

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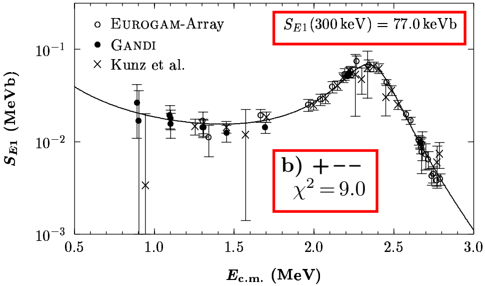
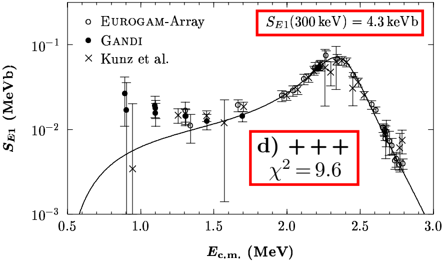
Abstract. An excitation function of the ground-state γ_0-ray capture transition in $^{12}C(\alpha, \gamma)^{16}O$ at $\theta_\gamma = 90^\circ$ was obtained in far geometry using six Ge detectors, where the study of the reaction was initiated in inverse kinematics involving a windowless gas target. The detectors observed predominantly the $E1$ capture amplitude. The data at $E = 1.32$ to 2.99 MeV lead to an extrapolated astrophysical S factor $S_{E1}(E_0) = 90 \pm 15$ keV b at $E_0 = 0.3$ MeV (for the case of constructive interference between the two lowest $E1$ sources), in good agreement with previous works. However, a novel Monte Carlo approach in the data extrapolation reveals systematic differences between the various data sets such that a combined analysis of all available data sets could produce a biased estimate of the $S_{E1}(E_0)$ value. As a consequence, the case of destructive interference between the two lowest $E1$ sources with $S_{E1}(E_0) = 8 \pm 3$ keV b cannot be ruled out rigorously.

J.W. Hammer et al.



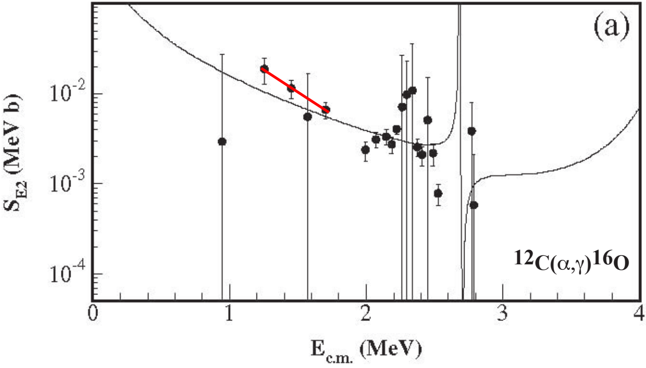


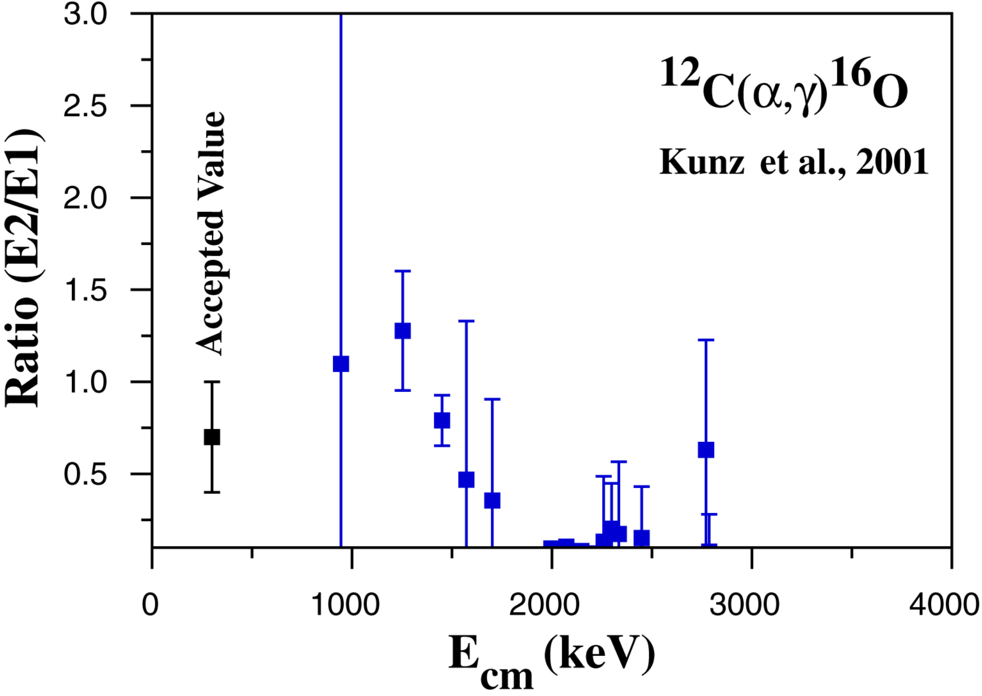
The $^{12}C(\alpha,\gamma)^{16}O$ Reaction:

$S_{E2}/S_{E1} = ?$

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

SE2 = 86 ±30 keVb





3.0
2.5
2.0
1.5
1.0
0.5
Ratio (E2/E1)
Accepted Value
12C(α,γ)16O
Kunz et al., 2001
0
1000
2000
3000
4000
Ecm (keV)

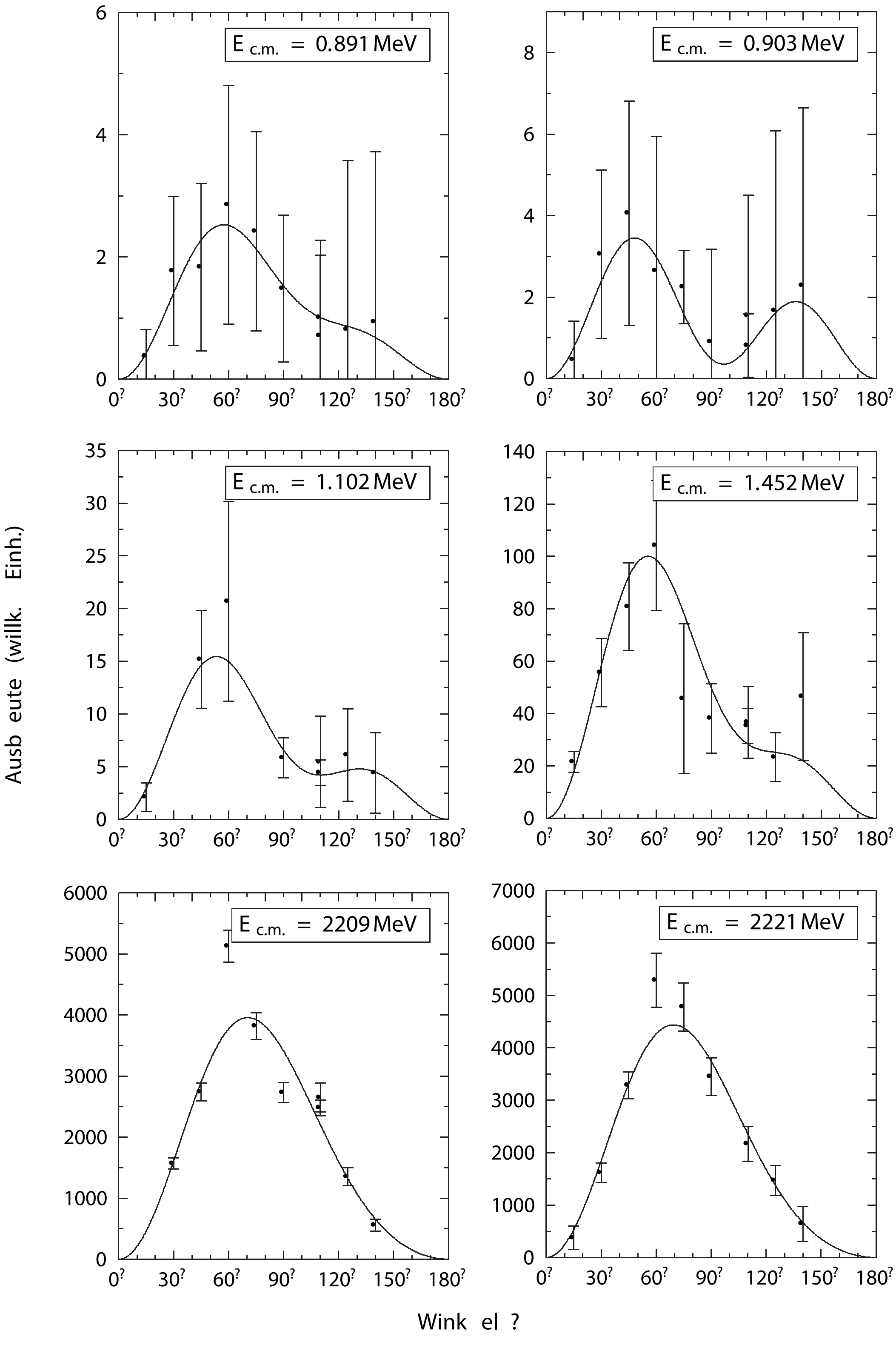


Abbildung 4.11: Beispiele für Wink elverteilungen, die während des Drehtisch-Exp eriments gemessen wurden.

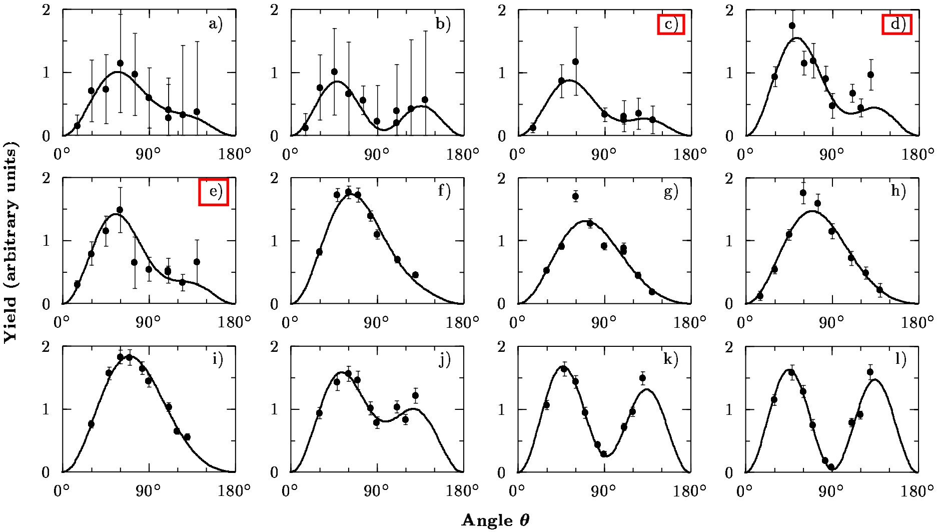
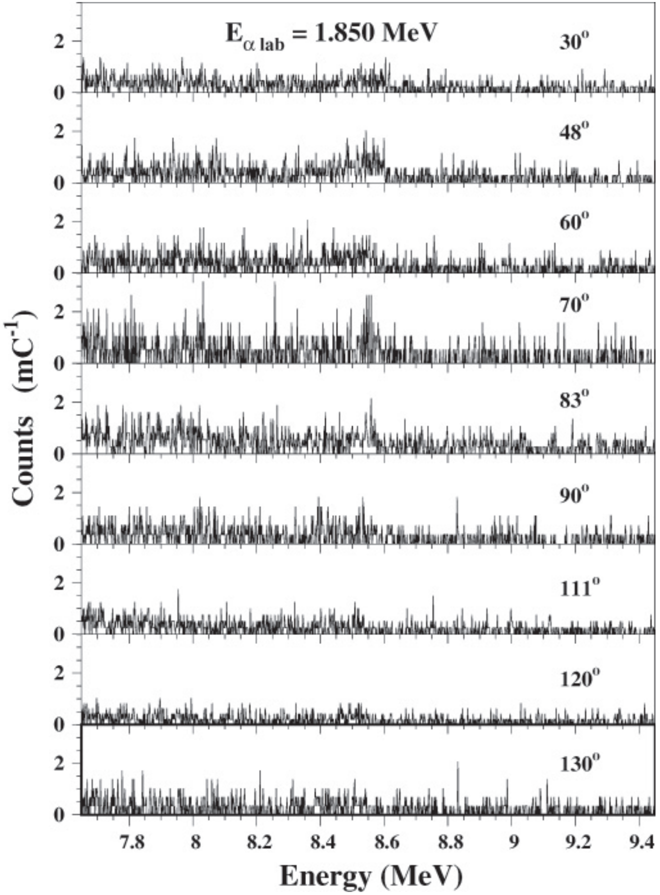
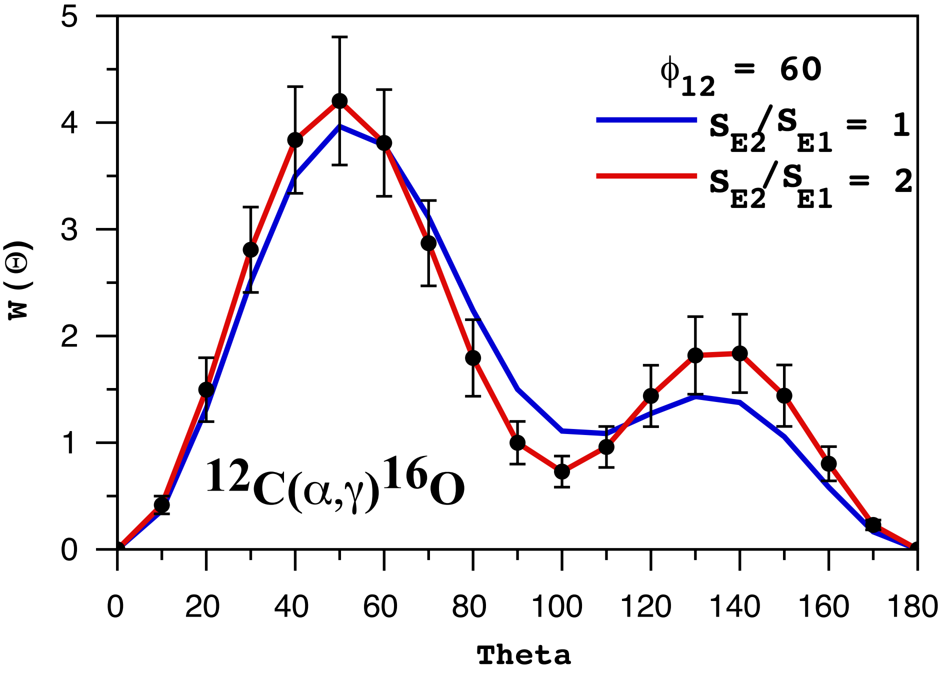


Figure 4. Typical γ angular distributions measured at the following effective c.m. energies: a) 891 keV, b) 903 keV, c) 1102 keV, d) 1342 keV, e) 1452 keV, f) 1965 keV, g) 2209 keV, h) 2221 keV, i) 2267 keV, j) 2645 keV, k) 2660 keV, l) 2667 keV. The solid curves represent the relevant Legendre fits. The error bars shown here include also systematic uncertainties. The $E1$, $E2$ characteristics and interferent mixing of both can be seen clearly. From these angular distributions σ_{E1} and σ_{E2} were separated and deduced.

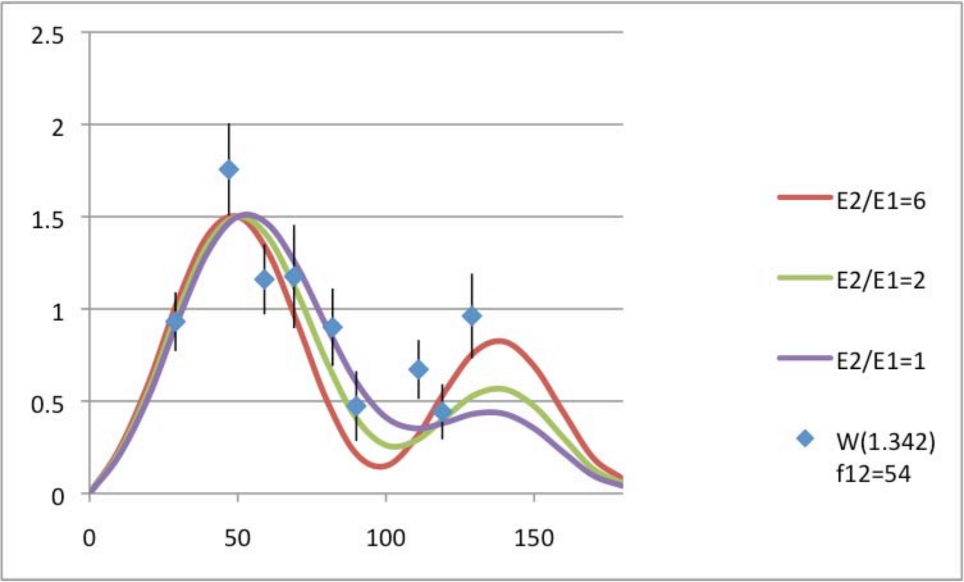
EUROGAM: PHYSICAL REVIEW C **73**, 055801 (2006)

E_{cm} = 1.310(40) MeV

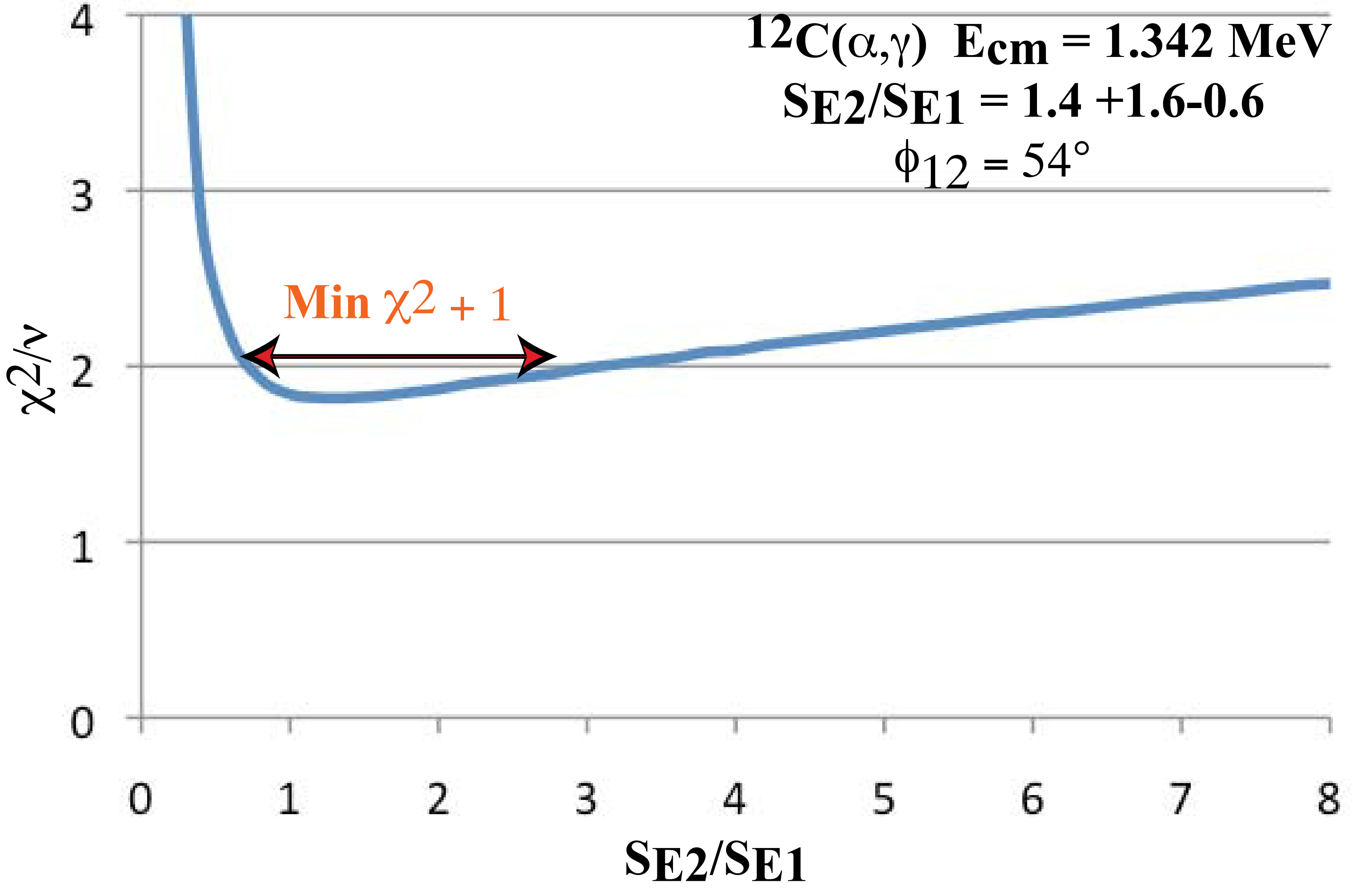




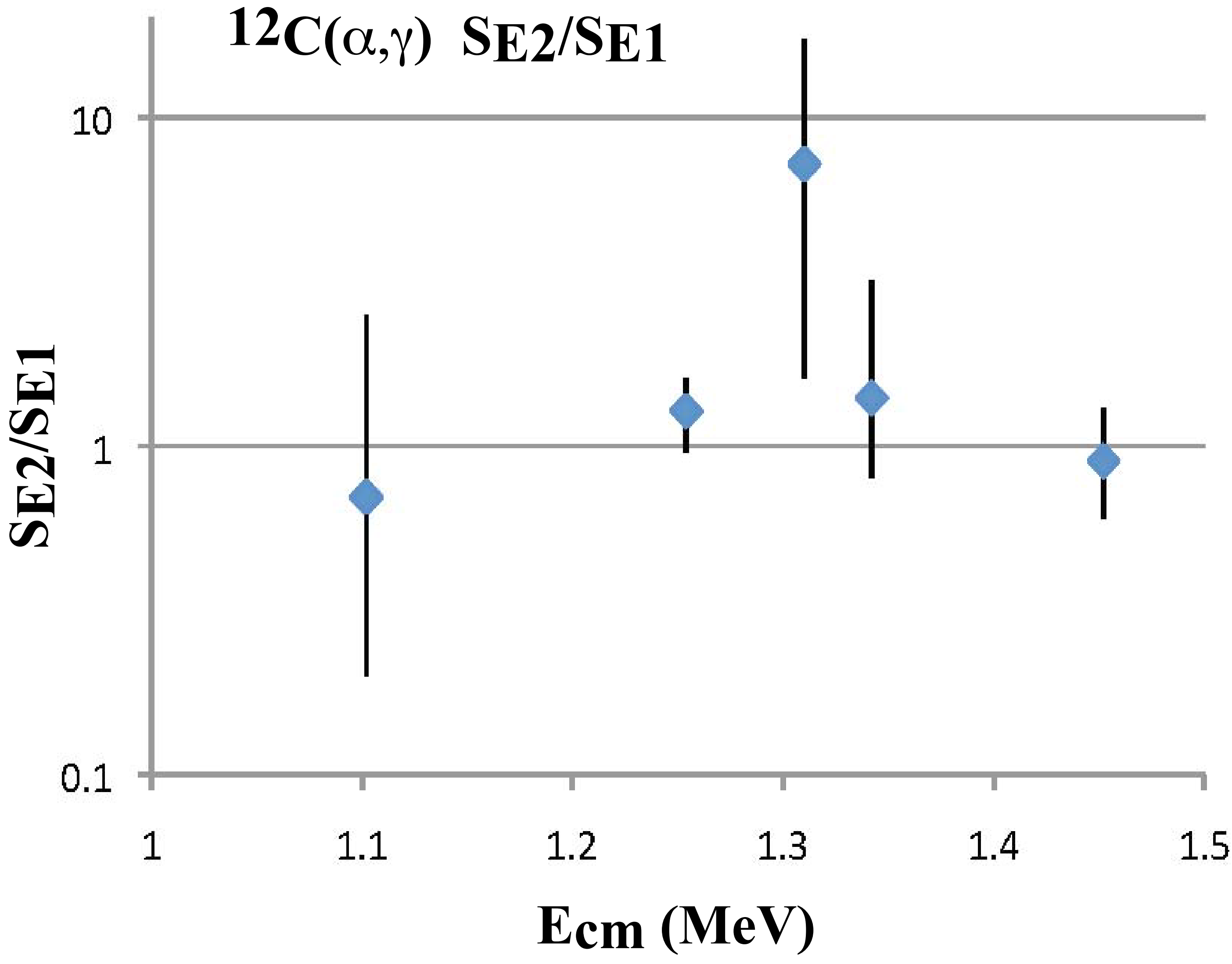
ϕ_{12} = 60
S_{E2}/S_{E1} = 1
S_{E2}/S_{E1} = 2
$^{12}C(\alpha,\gamma)^{16}O$
W(Θ)
Theta
0
1
2
3
4
5
0
20
40
60
80
100
120
140
160
180



2.5
2
1.5
1
0.5
0
0
50
100
150
E2/E1=6
E2/E1=2
E2/E1=1
W(1.342)
f12=54



12C(α,γ) Ecm = 1.342 MeV
SE2/SE1 = 1.4 +1.6-0.6
φ12 = 54°
Min χ2 + 1
χ2/ν
4
3
2
1
0
0
1
2
3
4
5
6
7
8
SE2/SE1



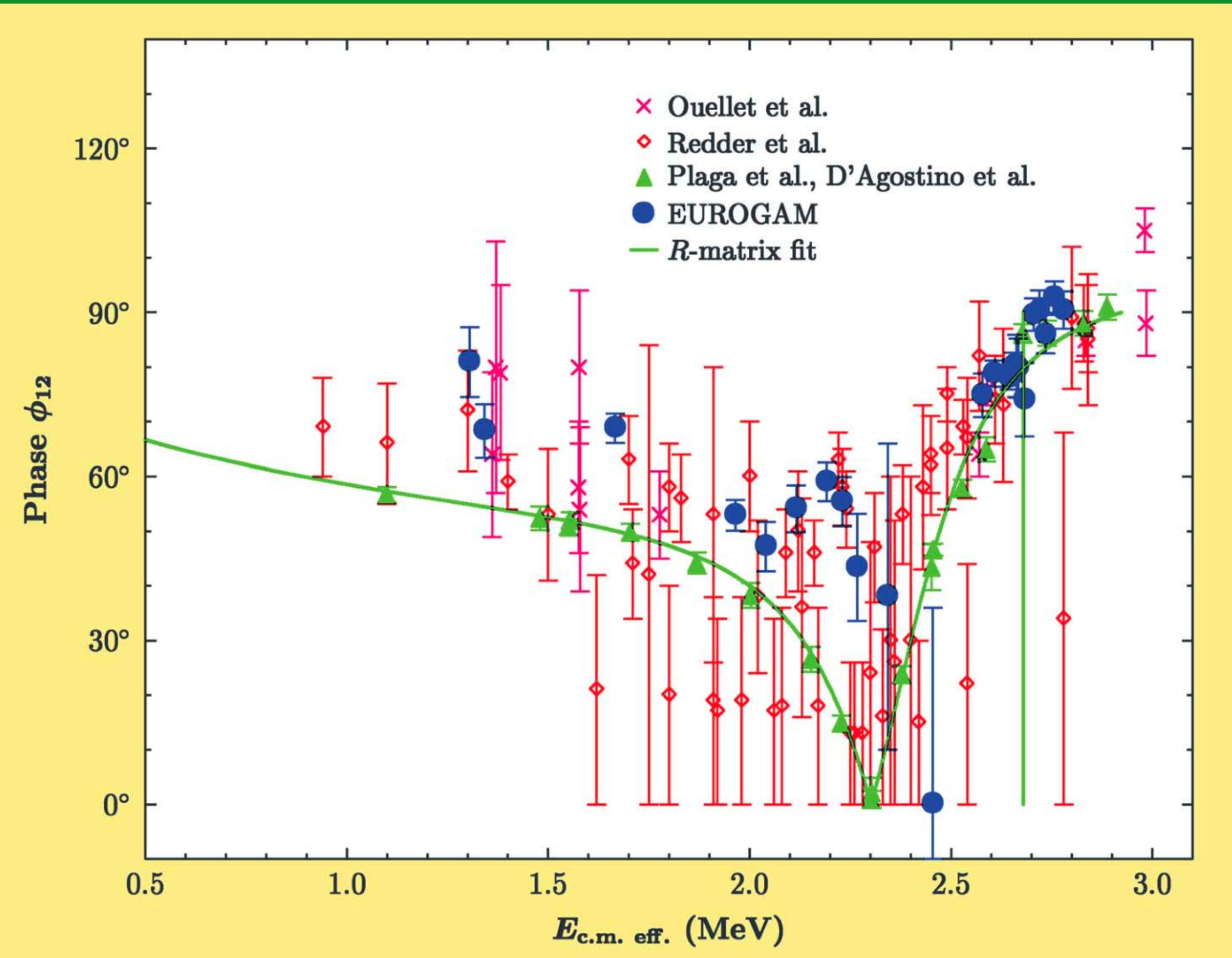
$^{12}C(\alpha,\gamma)$ S_{E2}/S_{E1}
10
1
0.1
1
1.1
1.2
1.3
1.4
1.5
S_{E2}/S_{E1}
Ecm (MeV)

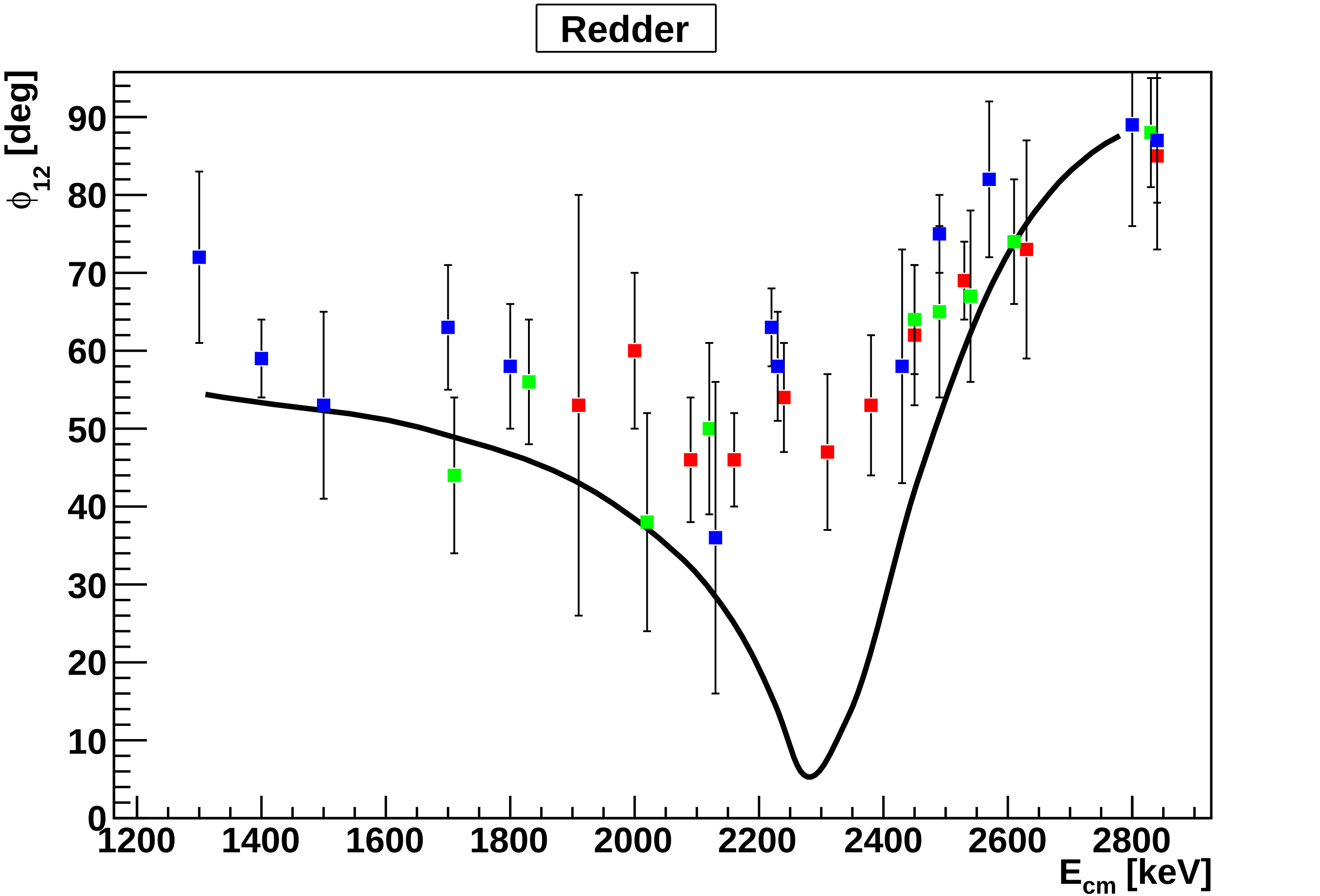
$$\varphi_{12} = \delta_2 - \delta_1 + \arctan(\eta/2)$$

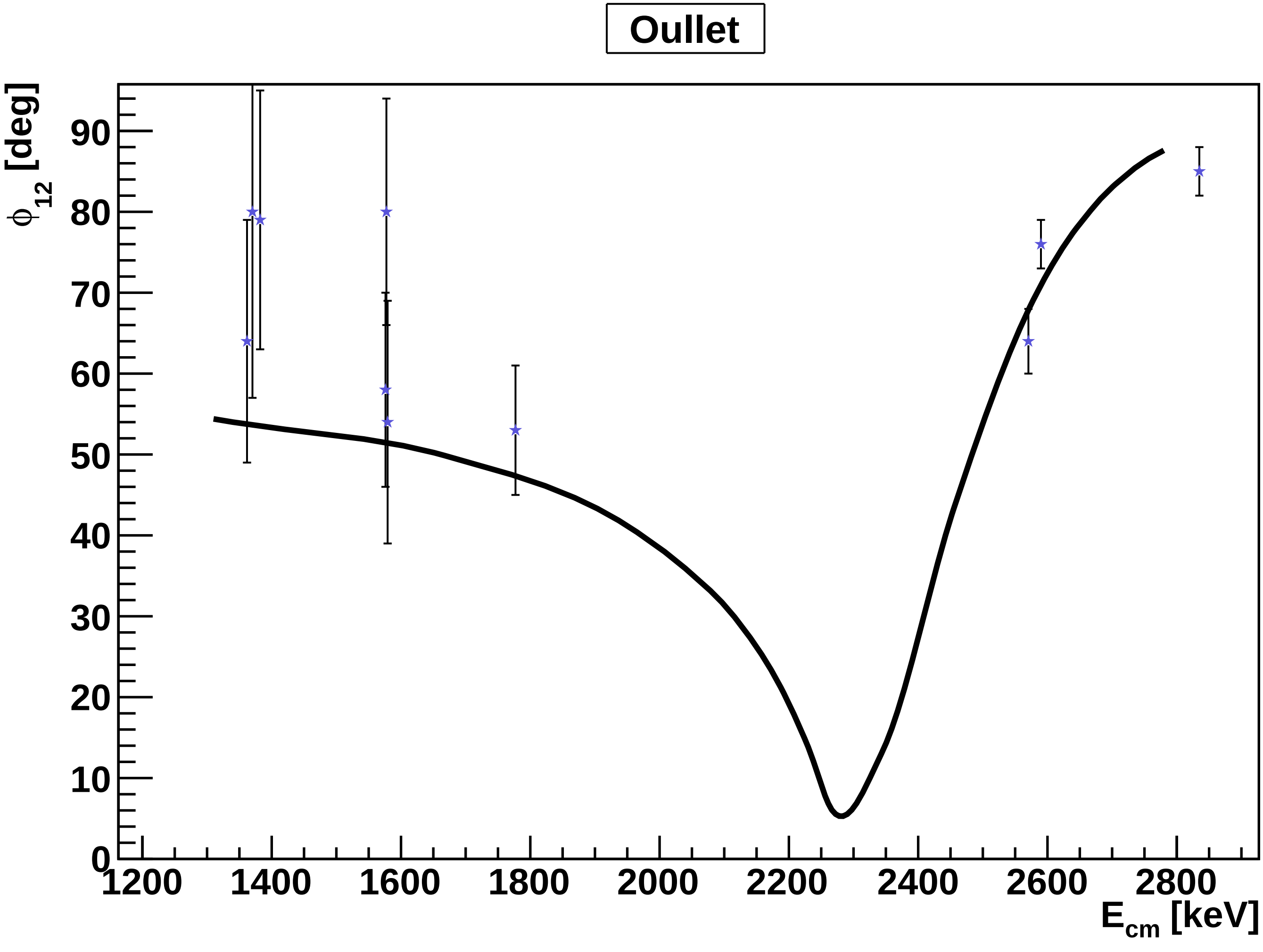
(Unitarity!)

K. M. Watson; Phys. Rev. 95(1954)228

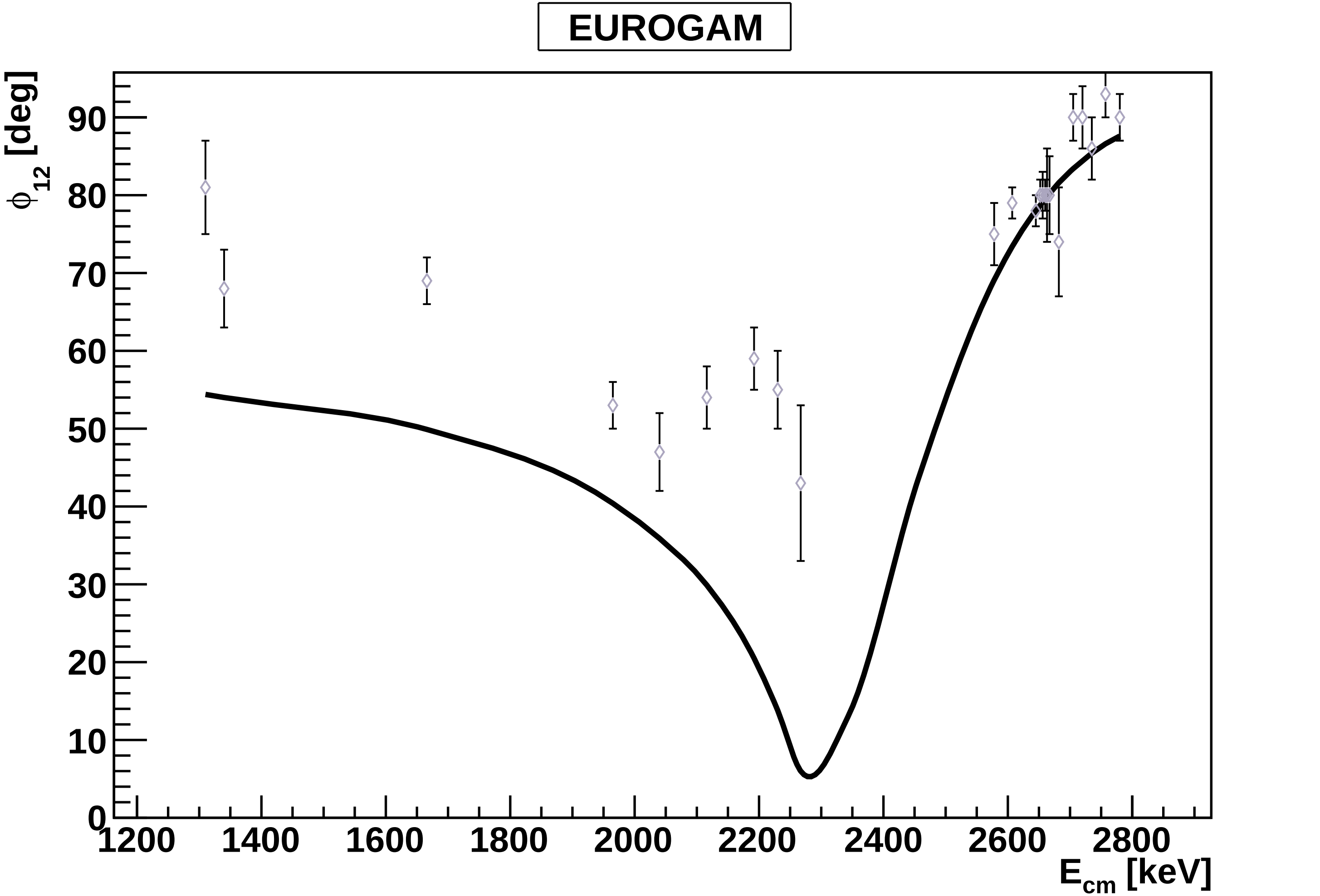
L. D. Knutson; Phys. Rev. C59(1999)2152




Redder
ϕ_{12} [deg]
0
10
20
30
40
50
60
70
80
90
1200
1400
1600
1800
2000
2200
2400
2600
2800
E_{cm} [keV]



Oullet
ϕ_{12} [deg]
0
10
20
30
40
50
60
70
80
90
1200
1400
1600
1800
2000
2200
2400
2600
2800
E_{cm} [keV]


EUROGAM
ϕ_{12} [deg]
0
10
20
30
40
50
60
70
80
90
1200
1400
1600
1800
2000
2200
2400
2600
2800
E_{cm} [keV]

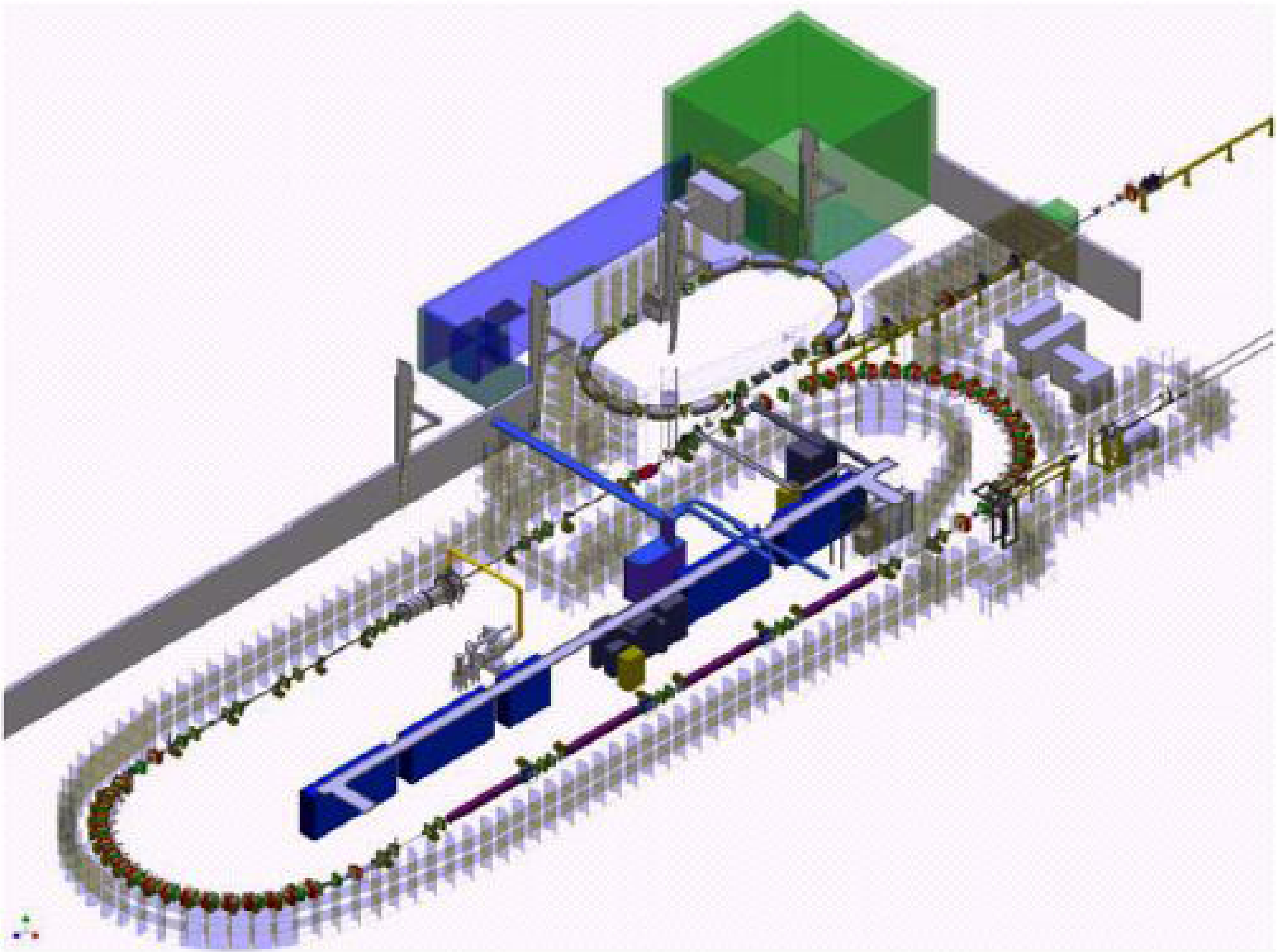
The $^{12}C(\alpha,\gamma)^{16}O$ Reaction:

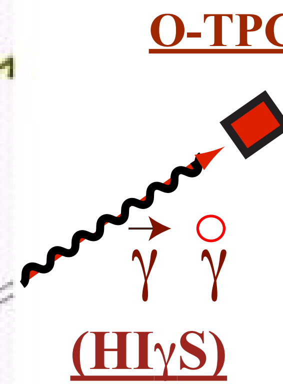
1. **Data:**
   Cascade
   ^{16}N spectra } ⇒ **Confusion!**
   Need Good $W(\theta)$ for $E < 1.5$ MeV
   $S_{E2}/S_{E1} = ?$

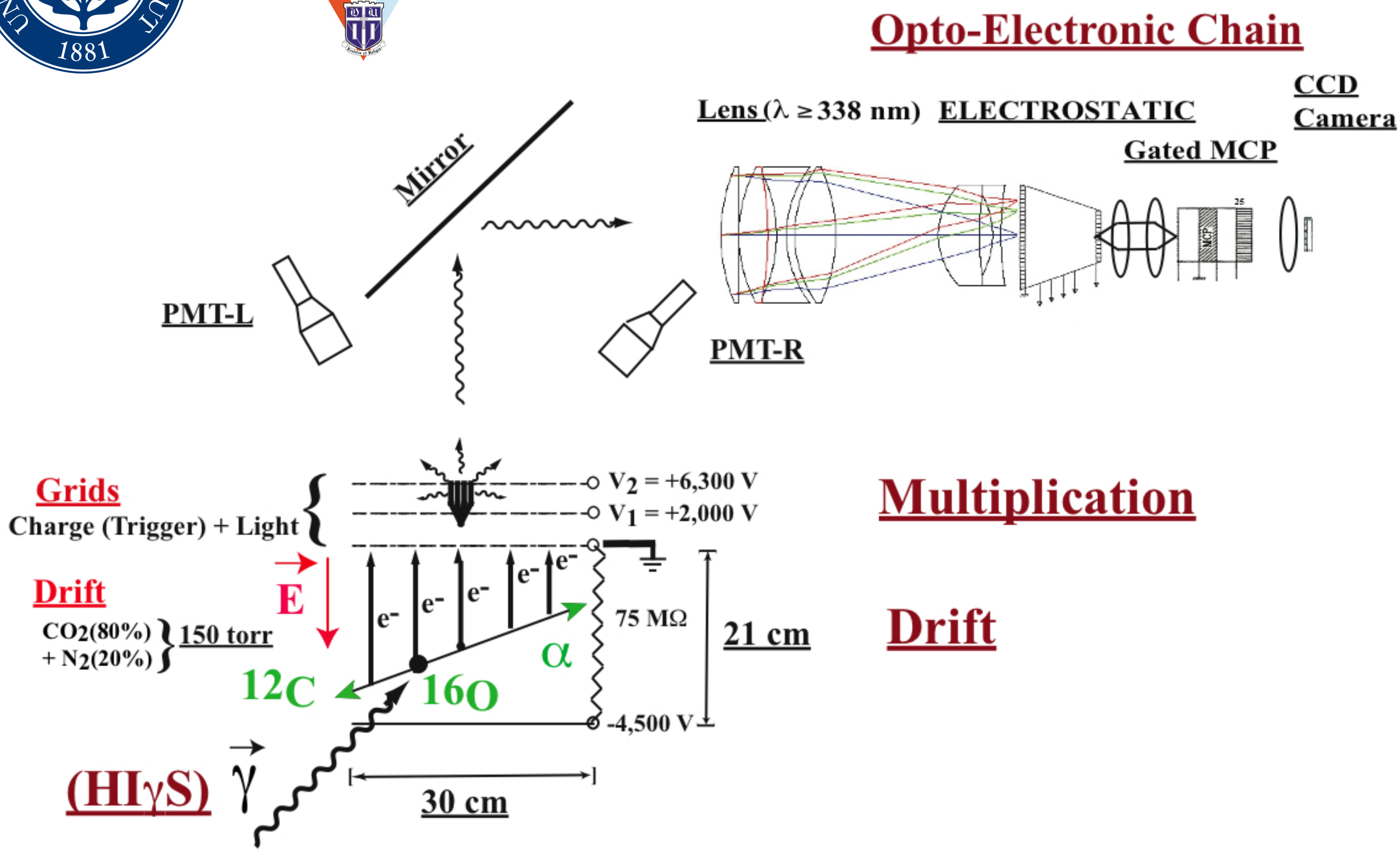
2. **Cannot Rule Out Small $S_{E1}(300)$**
   $^{12}C(\alpha,\gamma)$ NOT
   $^{16}N\ \chi^2$ NOT
   ^{16}N In Principle NOT
   ^{16}N R-Matrix NOT

3. **Conflict With Unitarity!**
   ($\phi_{12} \Leftrightarrow S_{E2}/S_{E1}$)

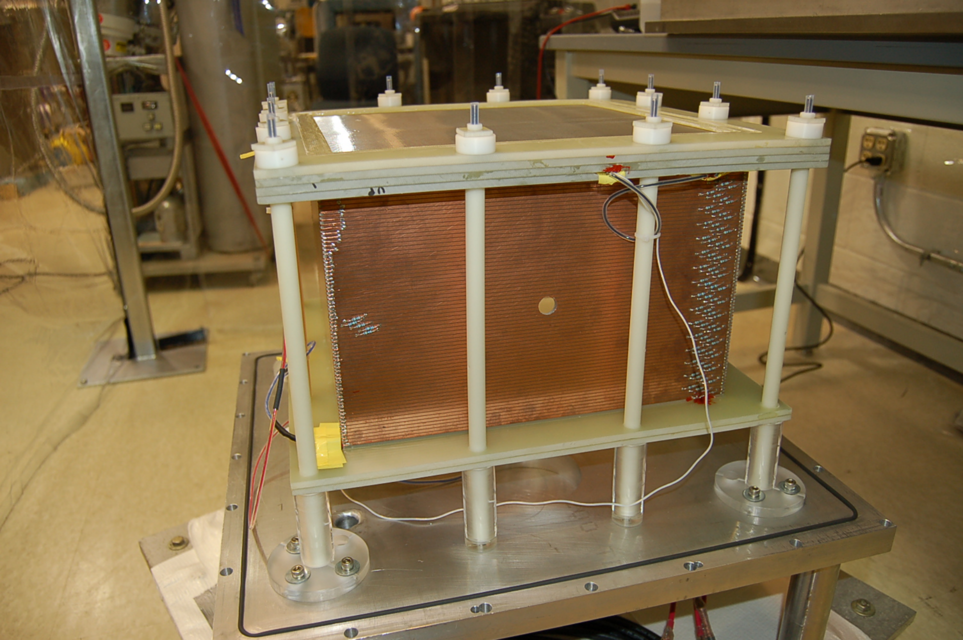
DFELL & HIGS



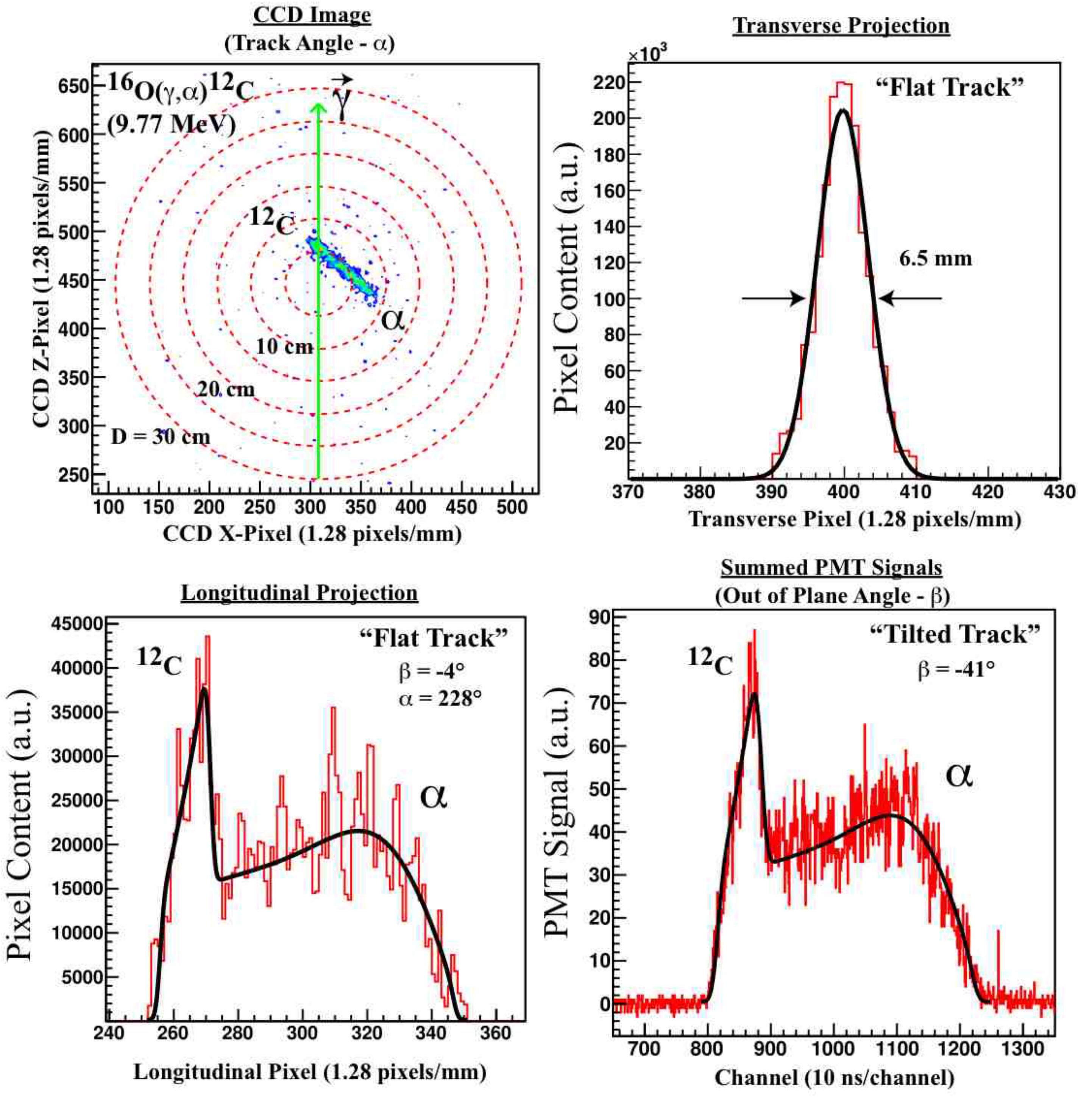


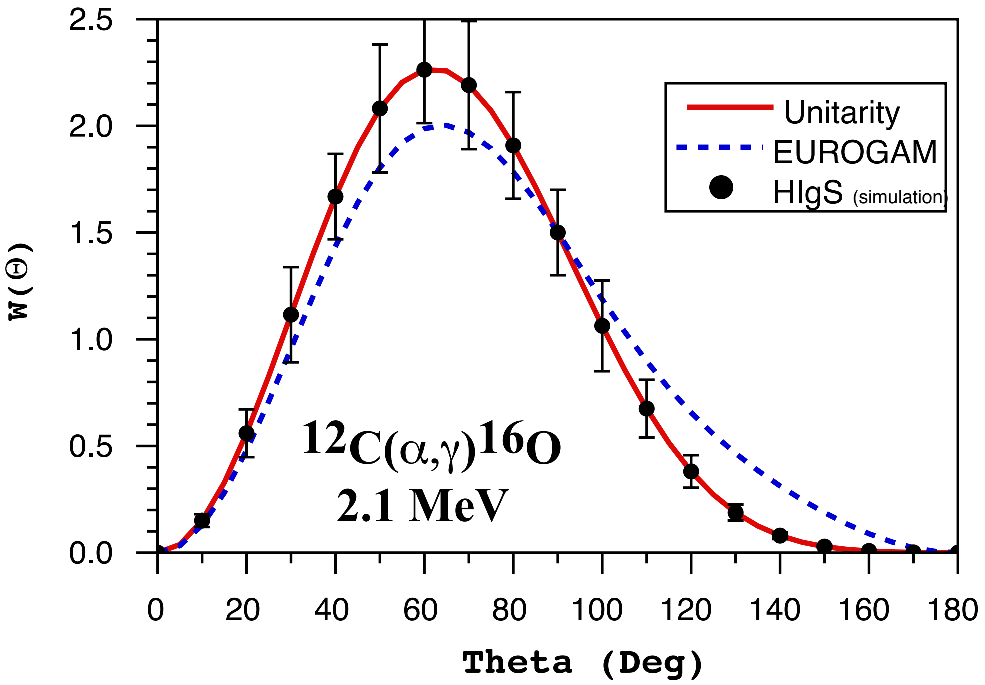


Opto-Electronic Chain
Lens (λ ≥ 338 nm)
ELECTROSTATIC
Gated MCP
CCD Camera
Mirror
PMT-L
PMT-R
Grids
Charge (Trigger) + Light
V2 = +6,300 V
V1 = +2,000 V
Multiplication
Drift
E
CO2(80%) + N2(20%)
150 torr
e-
75 MΩ
21 cm
Drift
α
12C
16O
-4,500 V
(HIγS)
γ
30 cm

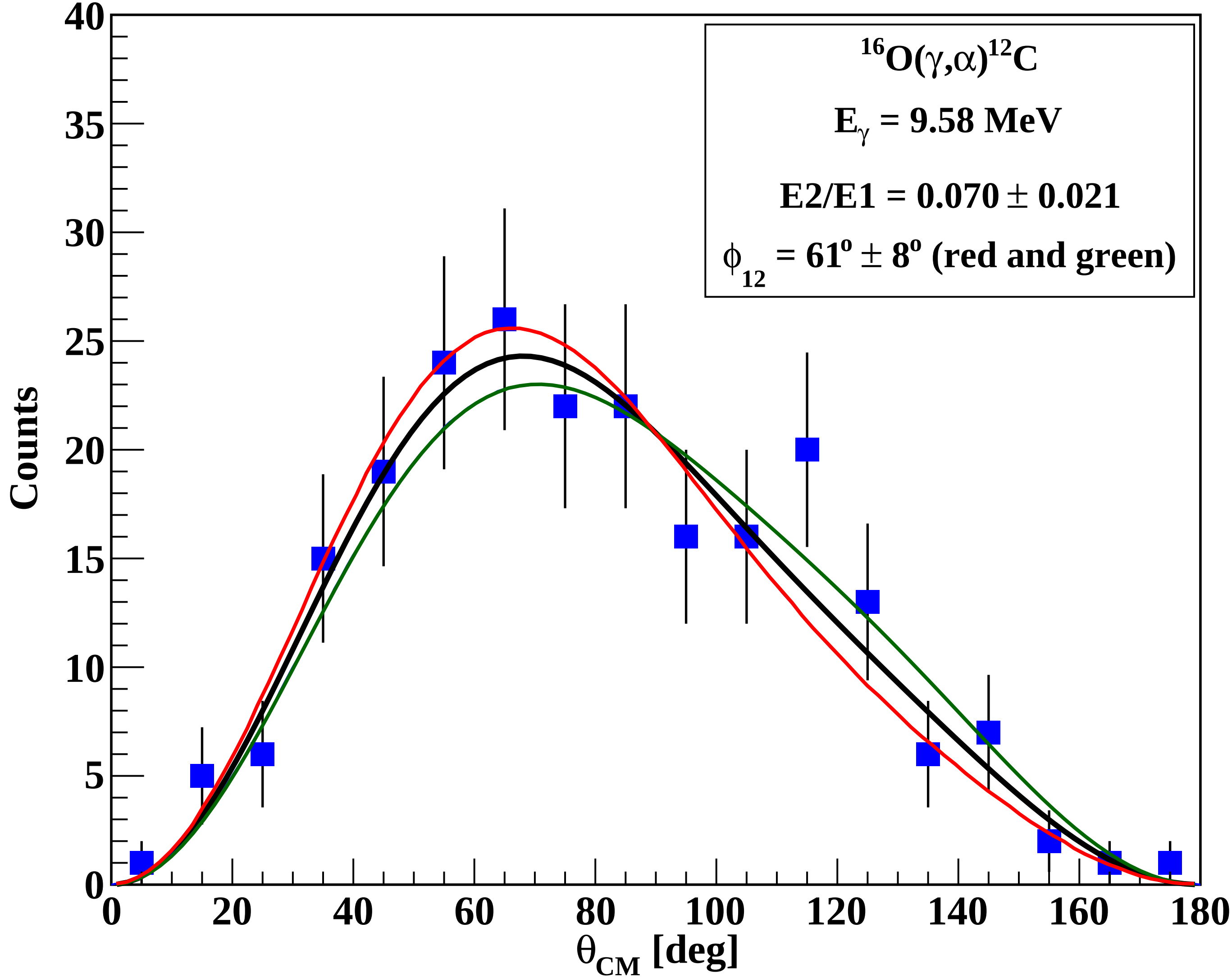


M. Gai *et al.*; JINST 5(2010)12004





Unitarity
EUROGAM
HIgS (simulation)
$^{12}C(\alpha,\gamma)^{16}O$
2.1 MeV
W(Θ)
Theta (Deg)
0.0
0.5
1.0
1.5
2.0
2.5
0
20
40
60
80
100
120
140
160
180



$^{16}O(\gamma,\alpha)^{12}C$
E_γ = 9.58 MeV
E2/E1 = 0.070 ± 0.021
ϕ_{12} = 61° ± 8° (red and green)
Counts
θ_{CM} [deg]
0
5
10
15
20
25
30
35
40
0
20
40
60
80
100
120
140
160
180

The $^{12}C(\alpha,\gamma)^{16}O$ Reaction 40 Years Later:

1. **Data:**
   $^{12}C(\alpha,\gamma)$
   Cascade
   ^{16}N spectra
   } $\Rightarrow$ **Conflicting!**
   Need Good $W(\theta)$ for $E < 1.5$ MeV

2. **Cannot Rule Out Small $S_{E1}(300)$**
   $^{12}C(\alpha,\gamma)$ **NOT**
   ^{16}N χ^2 **NOT**
   ^{16}N In Principle **NOT**
   ^{16}N R-Matrix **NOT**

3. **Cannot Rule Out E2 Dominance**
   $S_{E2}/S_{E1} = ?$

4. **Conflict With Unitarity!**
   $(\phi_{12} \Leftrightarrow S_{E2}/S_{E1})$