The Structure of the Hoyle State in ^{12}C and Stellar Helium Burning

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UConn and Yale

1. **Why 2^+_2 in ^{12}C? The Structure of the Hoyle State.**

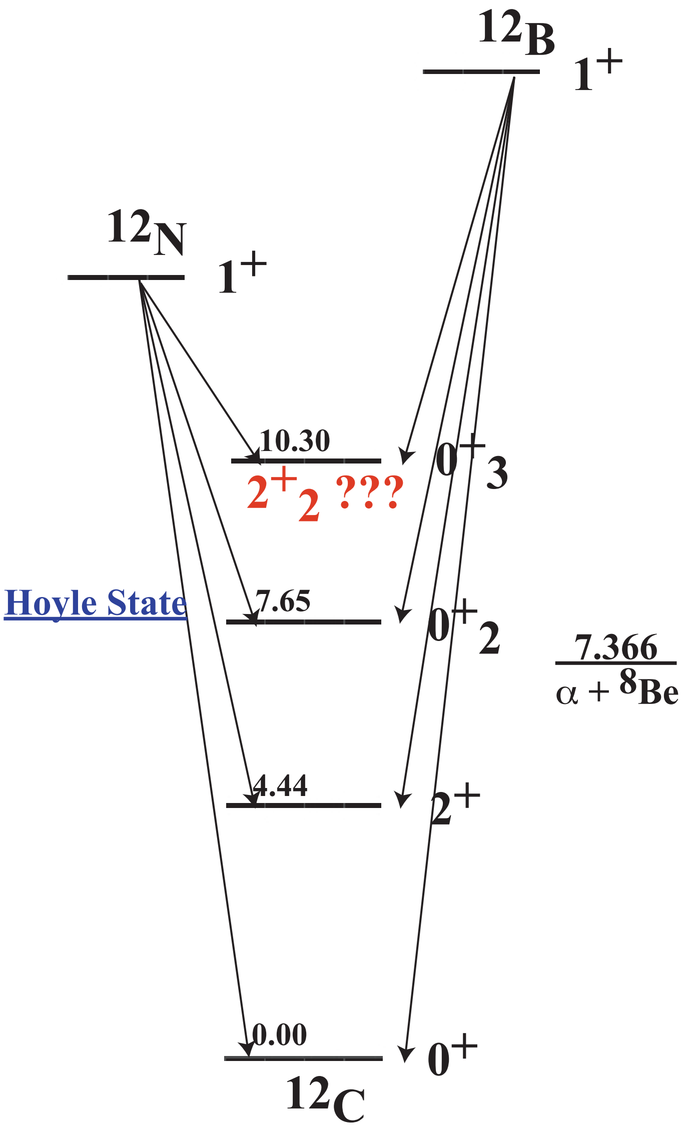
2. **The HIγS Facility: Real Photons $2 < E\gamma < 40$ MeV**
   $I\gamma \sim 3\text{x}10^8$ γ/sec
   $\Delta E \sim 2\%$

3. **The Detector: Optical Readout TPC (O-TPC)**

Advances in Nuclear Many-Body Theory
Peter Ring Fest
Primosten, Croatia, June 7, 2011

Above There is Heaven
and
Below There is Suzhou and Hangzhou

1983



Why Study the 2^{+}_{2} in ^{12}C ?

What is the Structure of the Hoyle State?

1. **Deformed three alpha state.**
   (Not linear chain, Brink 1966)
   (Is a rotational band built on it?)

2. **Low N limit of Bose Einstein Alpha Condensate.**

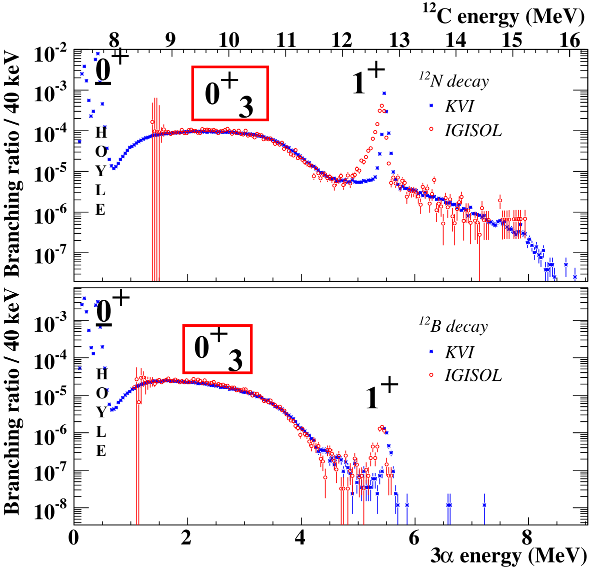
3. **Predicted e.g. Descouvemont & Baye at 9.11 MeV; B(E2: $2^+ \rightarrow$ gs) = 2.6 Wu.**

4. **Included in NACRE compliation.**
   x15 at T > 3 GK (Beyond Hoyle)

5. **Not Observed in beta-decay.**

6. **Observed in ^{12}C(p,p') and ^{12}C(α,α').**

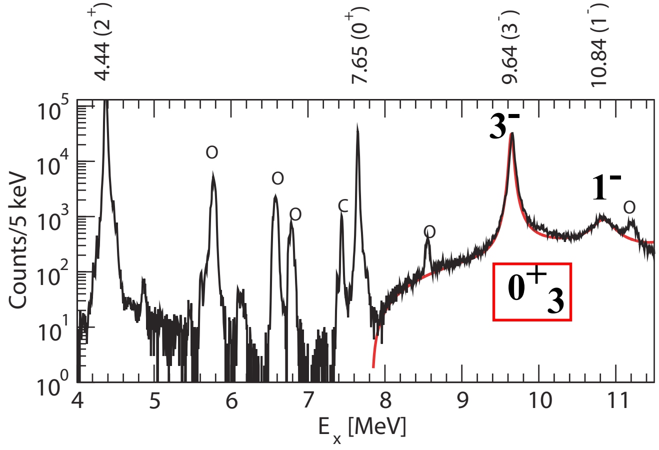
S. Hyldegaard *et al.;* Phys. Let B678(2009)459.



^{12}C(p,p')

PHYSICAL REVIEW C **80**, 041303(R) (2009)

M. Freer *et al*



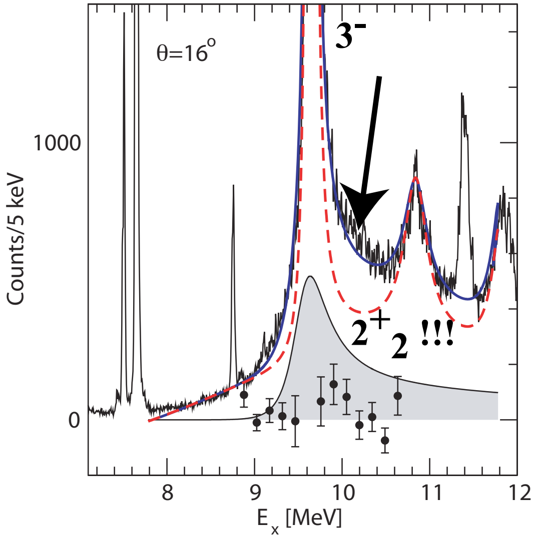


FIG. 2. (Color online) ^{12}C excitation energy spectrum measured at θ_{lab} = 28?. Contaminants from ^{16}O (O) and ^{13}C (C) are indi-

Further Evidence for the broad 2_2^+ at 9.6 MeV in ^{12}C.

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4. iThemba LABS, P.O. Box 722, Somerset West 7129, South Africa.

A recent measurement of the $^{12}C(p,p')$ reaction performed at the iThemba LABS [1] provided evidence for a broad ($\Gamma = 600$ keV) 2^+ state at 9.6 MeV in ^{12}C. The existence of this 2_2^+ state in ^{12}C has been the subject of much debate since it was observed in a $^{12}C(\alpha,\alpha')$ measurement [2] but it was not observed in the beta decays of ^{12}N and ^{12}B [3]. Such a 2^+ state at 9.11 MeV (a member of the rotational band built on top of the Hoyle state at 7.654 MeV in ^{12}C) was predicted [4] to significantly alter the rate of the formation of ^{12}C at high temperatures (T > 3GK) during stellar helium burning [5]. Such a rotational band was not predicted by the newly suggested low N limit of a BEC structure of the Hoyle state [6]. In this model the 2_2^+ was predicted to be an alpha-vibrational state.

We used a 25 MeV proton beam extracted from the Yale tandem to measure the $^{12}C(p,p')$ reaction at an energy lower than used in Ref. [1]. As we discuss below, at 25 MeV we observe small contributions from the broad ($\Gamma = 3.0$ MeV) 0_3^+ state at 10.3 MeV that dominated the iThemba LABS data [1]. But our experiment is plagued by another (most likely instrumental) background, hence we do not plan to continue this study (e.g. to achieve higher statistics). However, we present our data in this Brief Report since it gives credence to the findings of Ref [1] on the observation of the broad 2_2^+ state at 9.6 MeV in ^{12}C.

Measurements with a 25 MeV ($\sim$10 nA) proton beam and thin (40 $\mu g/cm^2$) natural ^{12}C and enriched (93%) ^{13}C targets were performed. The protons were detected in the Yale Enge Split Pole Spectrometer [7] with a solid angle of 2.8 msr and angular opening of $\Delta\theta \approx \pm 1°$, at lab angles of 20°, 35° and 45°. The energy resolution was measured using the narrow 0_2^+ Hoyle state at 7.654 MeV as well a the narrow 1^+ state at 12.710 MeV [8]. The large background observed in all three angles, see Fig. 1, cannot be associated with a state in ^{12}C. This background is larger at small angles and for lower energy scattered protons, hence we conclude that it arises (most likely) from plural scattering of protons (e.g. in the slits etc.).

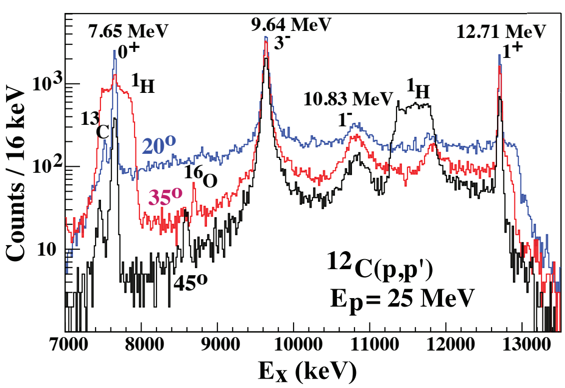


FIG. 1: (Color Online) The scattered proton spectra measured at lab angles of: 20° (top blue), 35° (middle red) and 45° (bottom black).

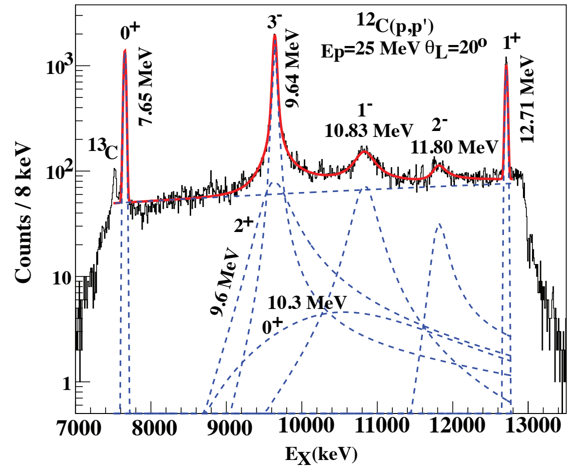


FIG. 2: (Color Online) Scattered proton spectrum measured at 20° compared to the sum (red line) of all contributions from all known states plus the broad 2_2^+ at 9.6 MeV and a linear background term (dashed blue lines).

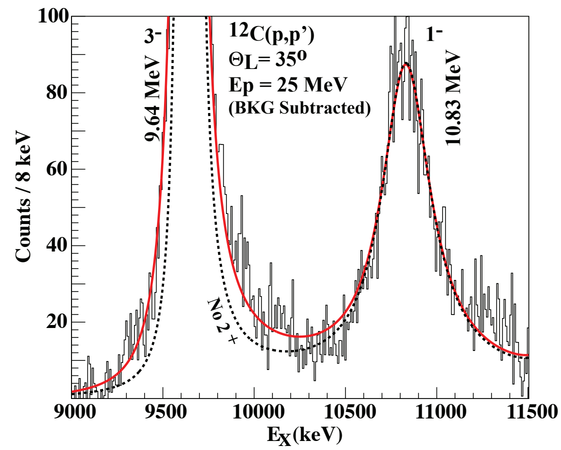
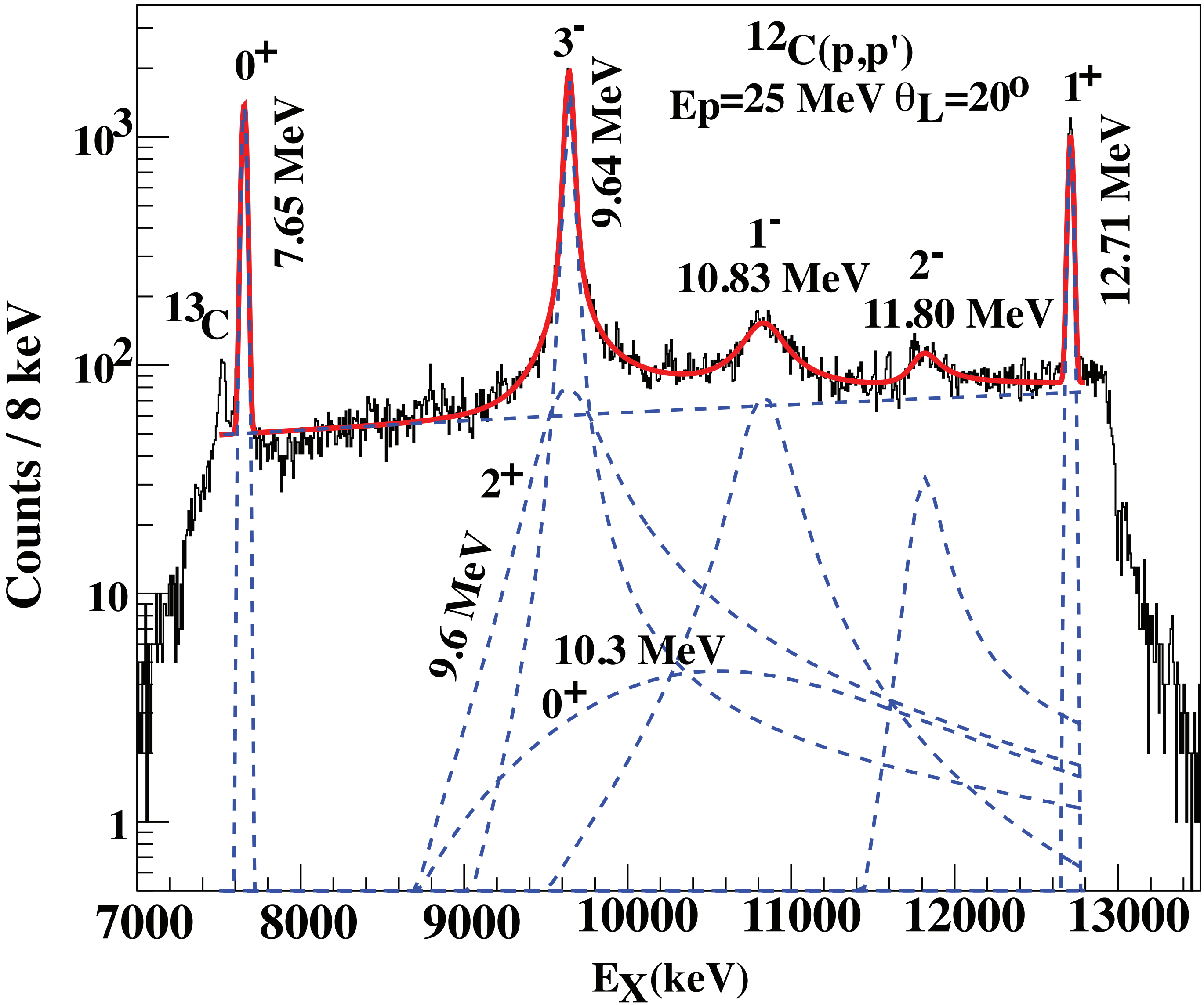
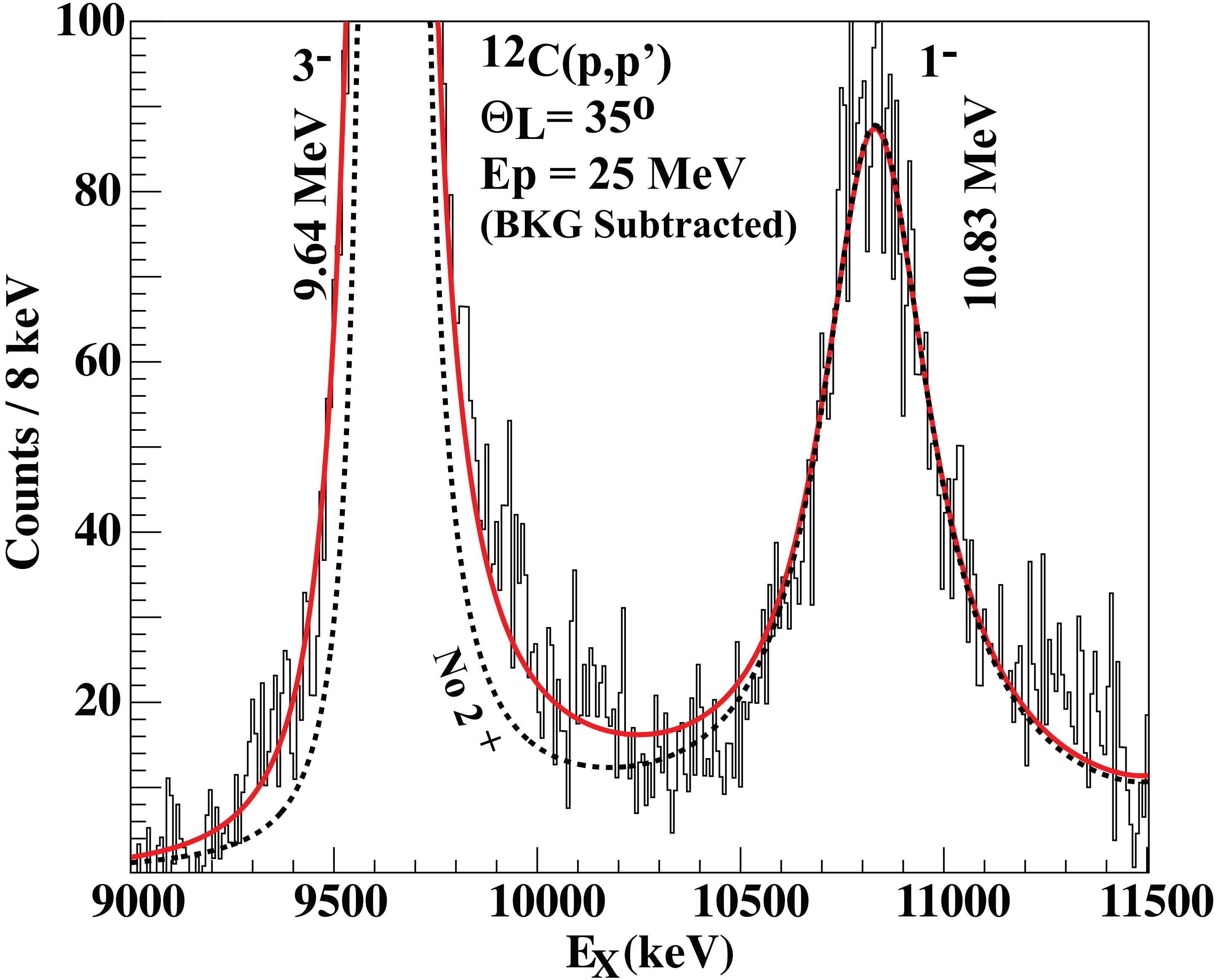


FIG. 3: (Color Online) The measured background-subtracted proton spectrum analyzed with (red line) and without (black dashed line) the contribution of the 2_2^+ state at 9.6 MeV.

The data shown in Fig. 1 allow us to discriminate inelastic scattering from contaminants in the target (e.g. hydrogen, oxygen or ^{13}C), since the contaminant lines appear at each angle at a different computed "excitation energy" in ^{12}C. The contaminant lines were also directly



$^{12}C(p,p')$
Ep=25 MeV $\theta_L=20^o$
0^+
7.65 MeV
3^-
9.64 MeV
1^+
12.71 MeV
1^-
10.83 MeV
2^-
11.80 MeV
^{13}C
2^+
9.6 MeV
10.3 MeV
0^+
Counts / 8 keV
10^3
10^2
10
1
7000
8000
9000
10000
11000
12000
13000
E_X(keV)



100
80
60
40
20
Counts / 8 keV
3⁻
9.64 MeV
$^{12}C(p,p')$
$\Theta_L = 35^o$
Ep = 25 MeV
(BKG Subtracted)
1⁻
10.83 MeV
No 2+
9000
9500
10000
10500
11000
11500
E_X(keV)

Hoyle State (7.654 MeV): Low N Limit of Alpha-Condensate in ^{12}C

arXiv.org > nucl-th > arXiv:1103.3940v1

P. Ring, and P. Schuck, The Nuclear Many-Body Problem (Springer-Verlag, Berlin, 1980).

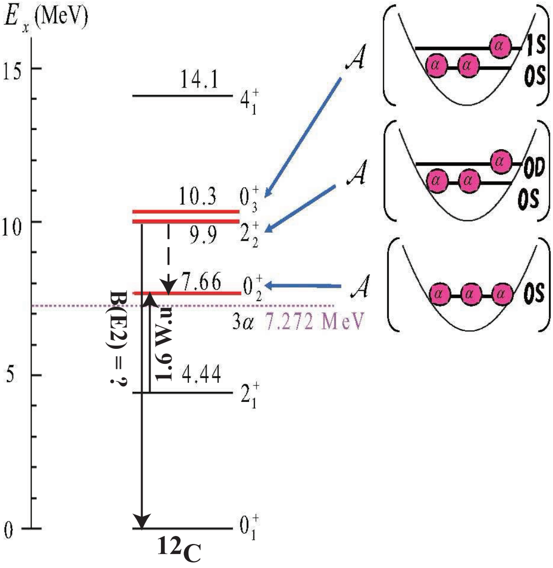


Fig. 15 (Color online) Theoretical interpretation of the 0_2^+, 2_2^+ and 0_3^+ states.

Descouvemont and Baye; PRC36(1987)54

Deforemed 2^+_2 at 9.11 MeV in ^{12}C

B(E2: $2^+_2 \rightarrow$ gs) = 0.5 - 2.6 W.u.

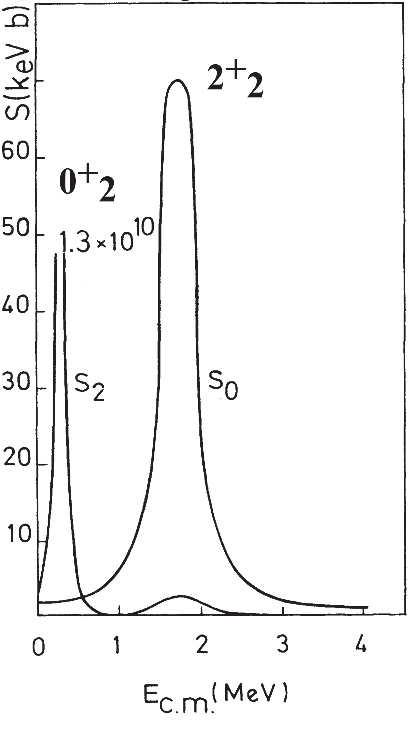
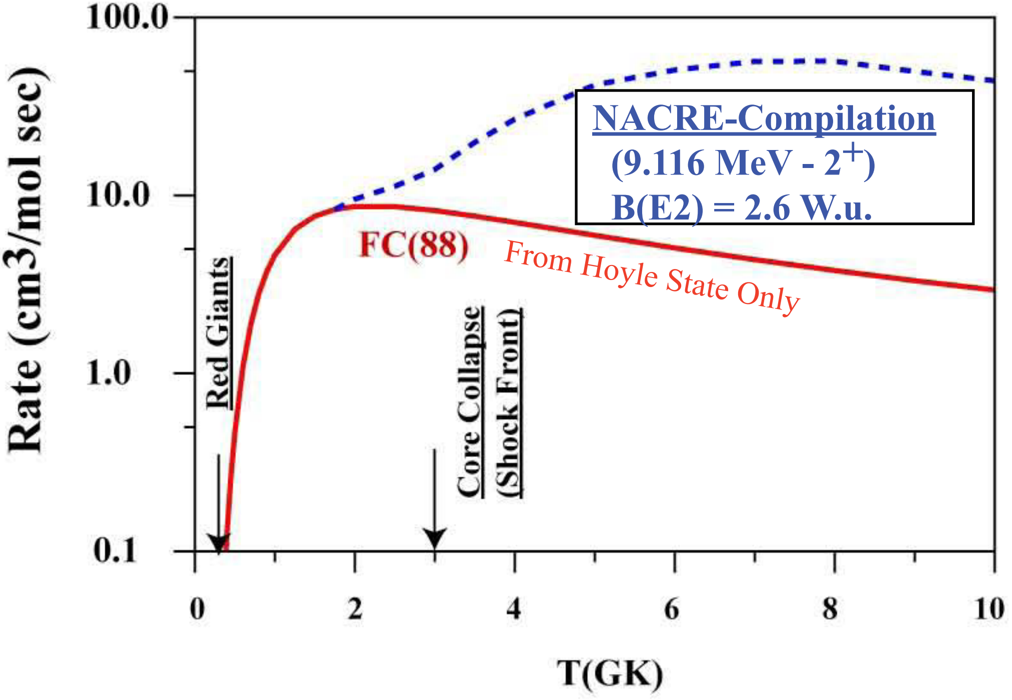
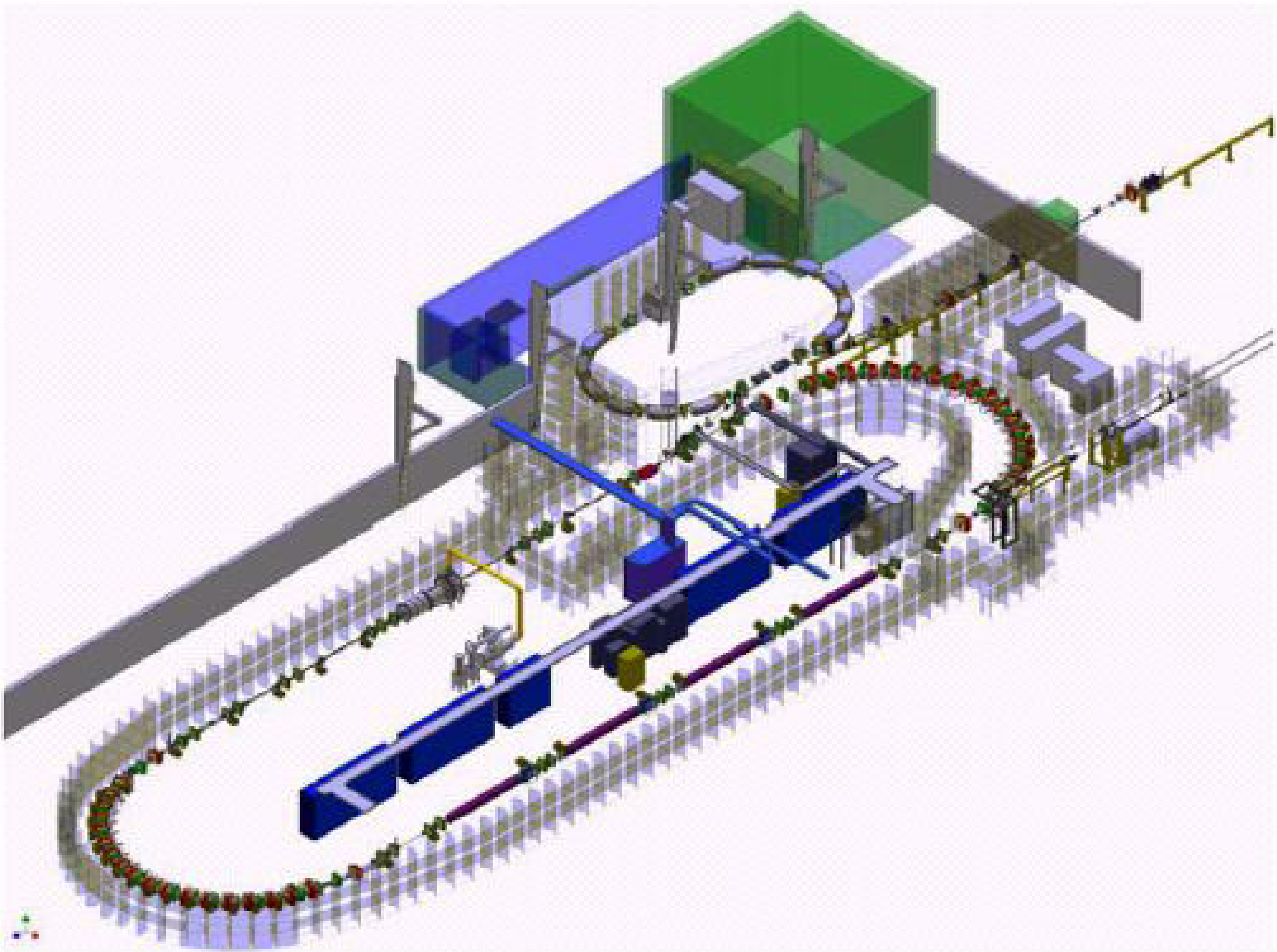


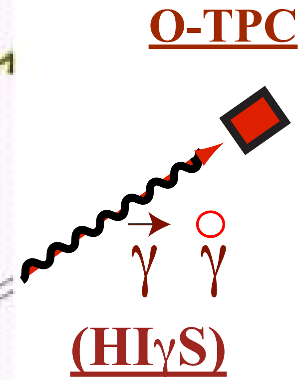
FIG. 2. $^8Be(\alpha,\gamma)^{12}C$ astrophysical S factors for transitions towards the 0_1^+ and 2_1^+ states of ^{12}C.

Triple Alpha Burning Rate: $^{8}Be(\alpha,\gamma)^{12}C$



DFELL & HIGS





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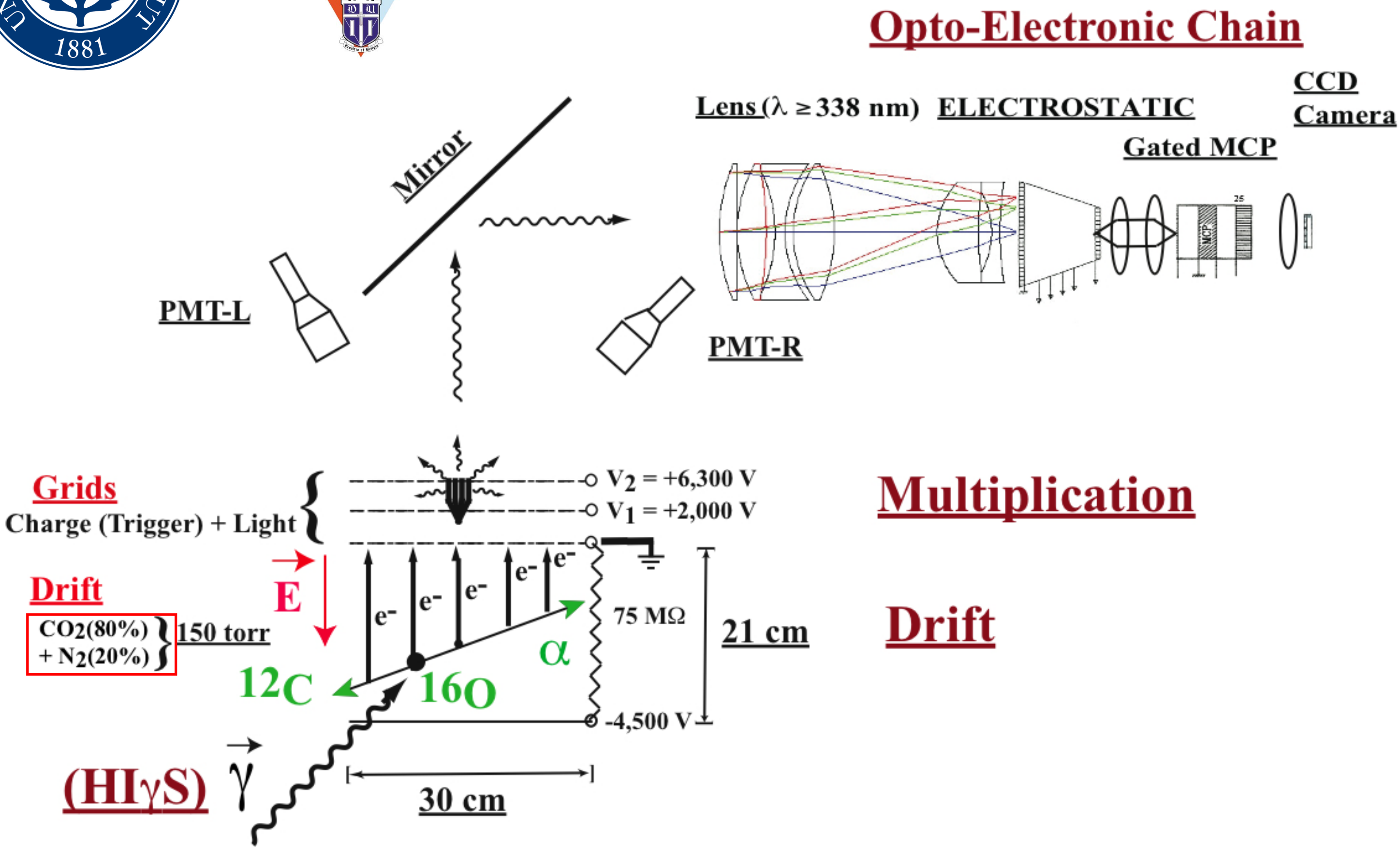
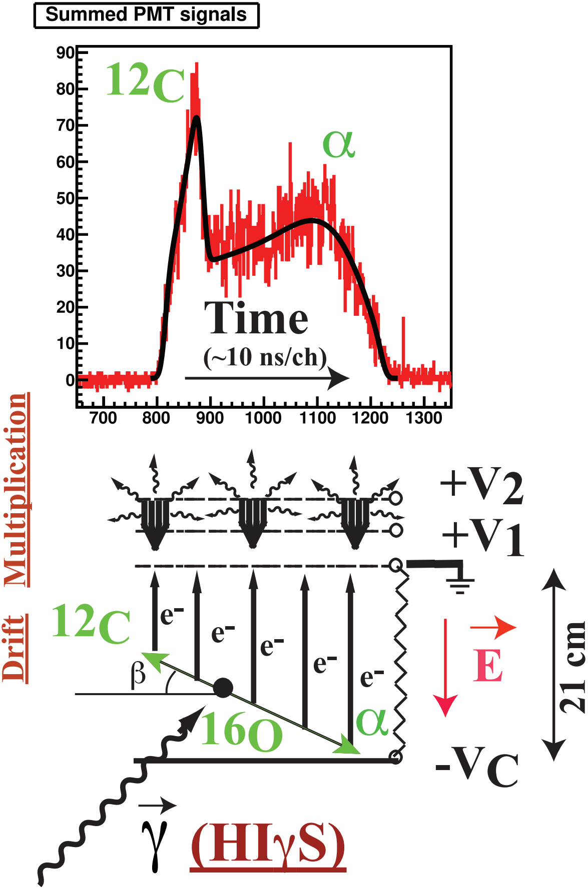
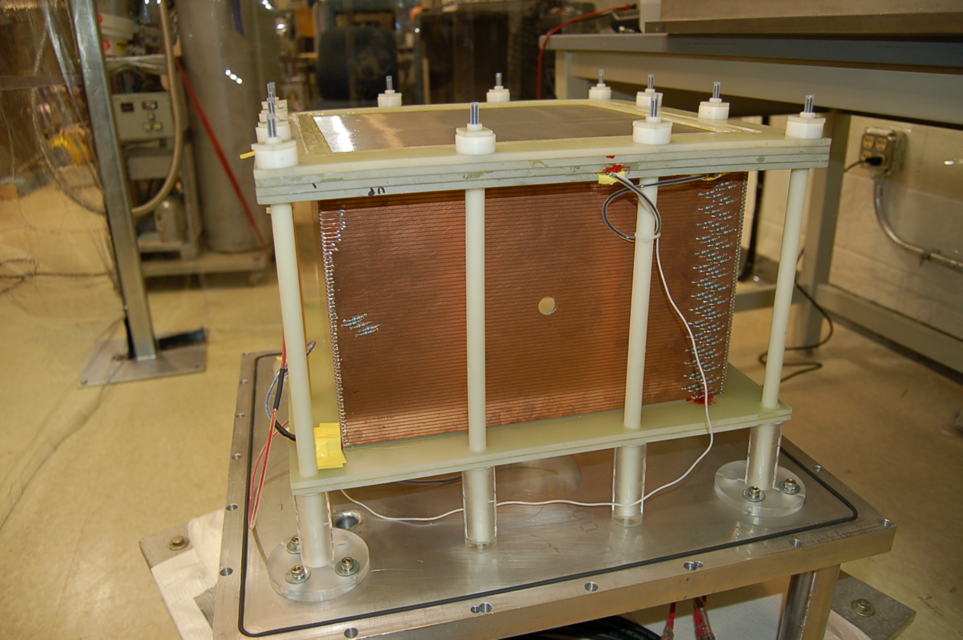
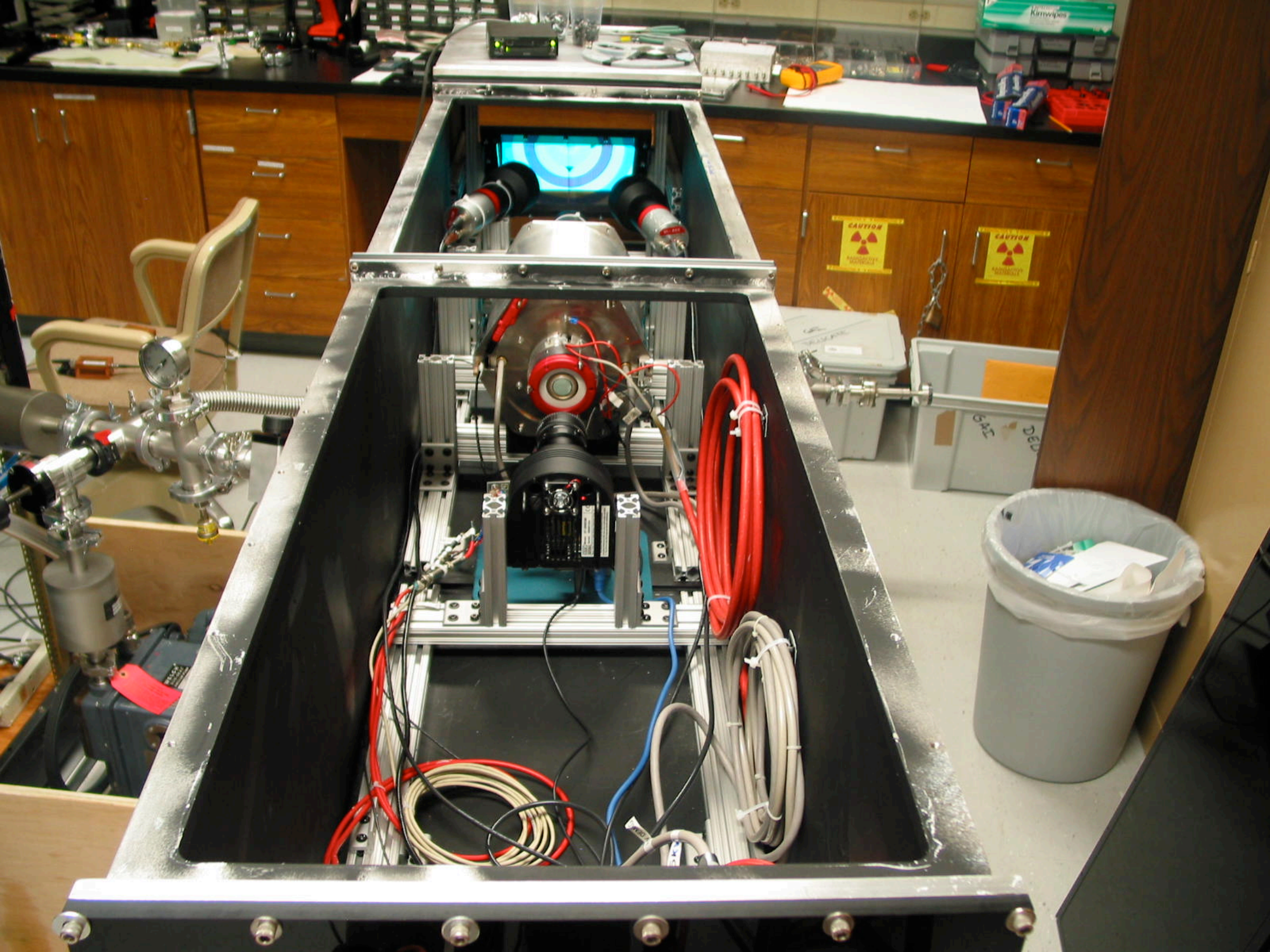


Time Projection

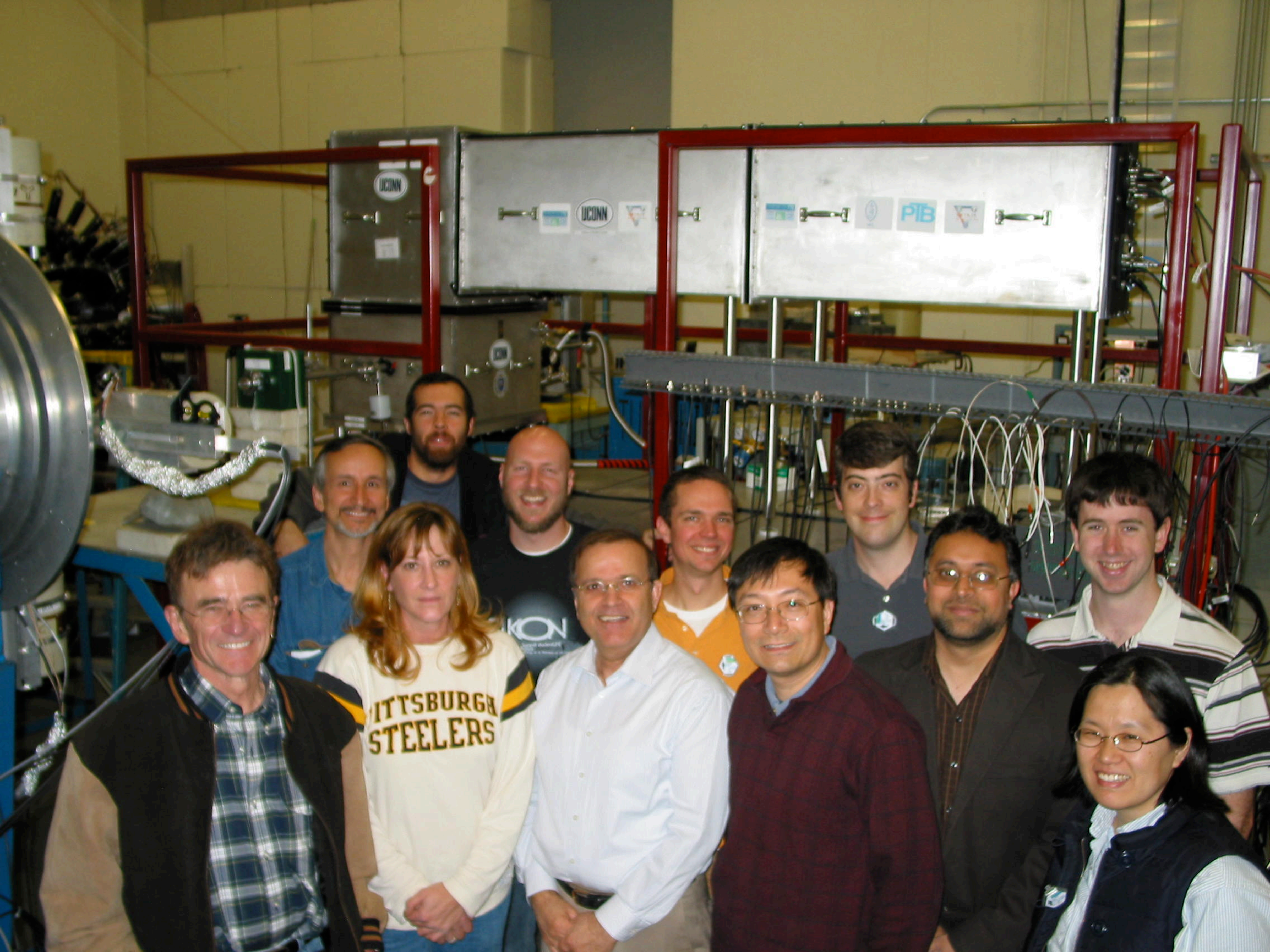


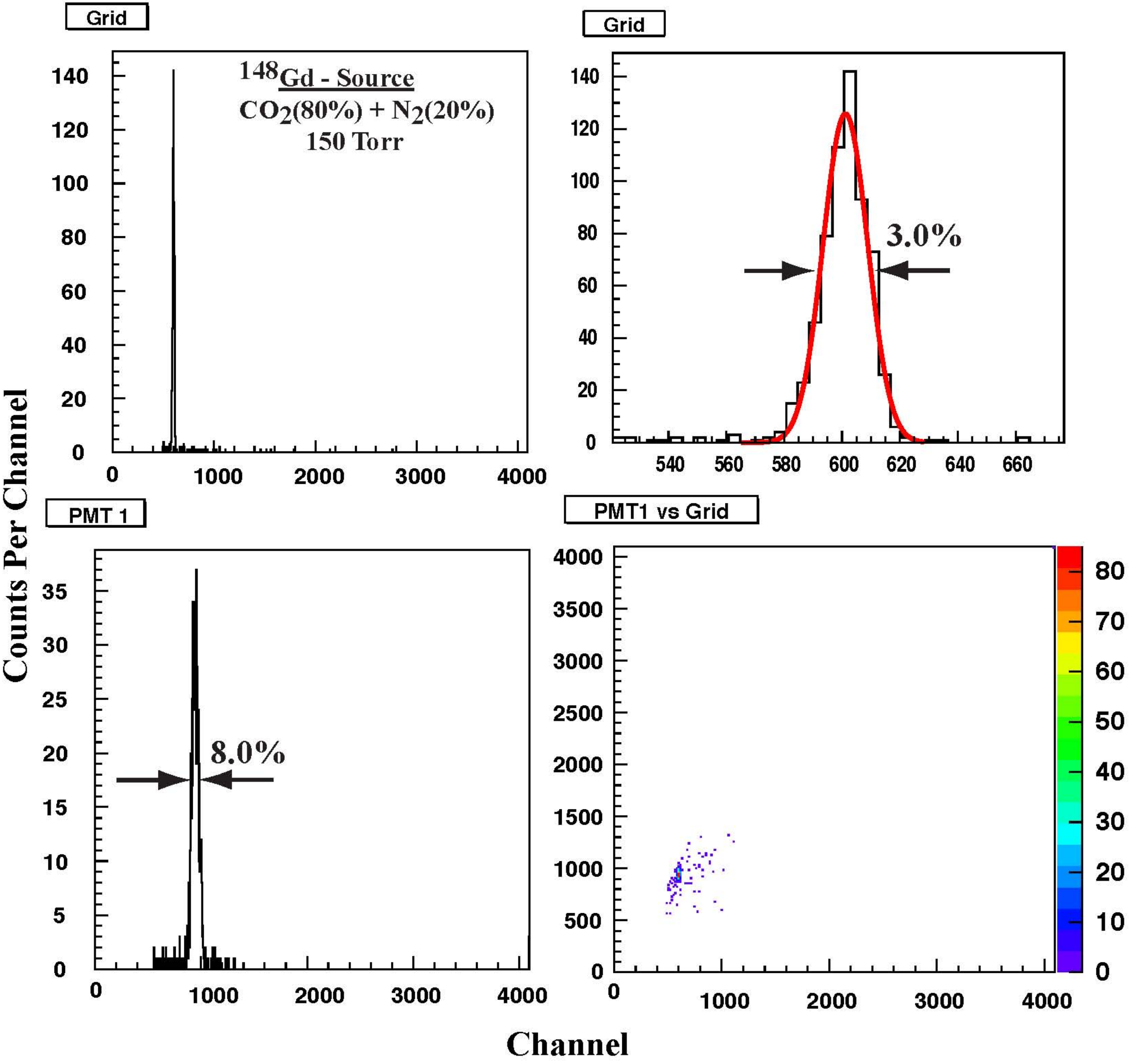



UCONN
Ziploc
Reynolds Wrap
MANUALS
Kimberly Clark

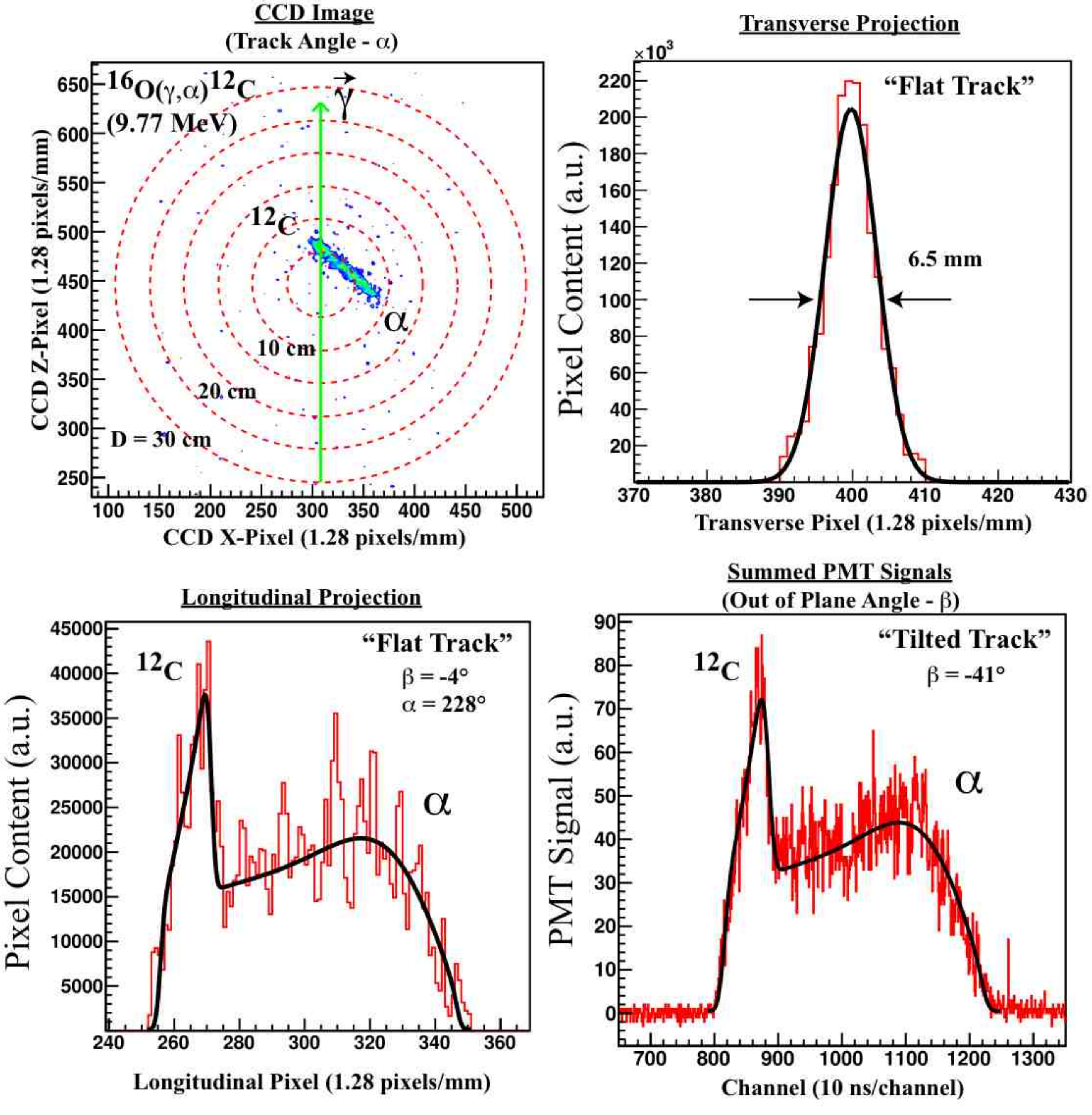

Kimwipes
CAUTION
CAUTION


PTB
UCONN
HUSKY
TOPCO

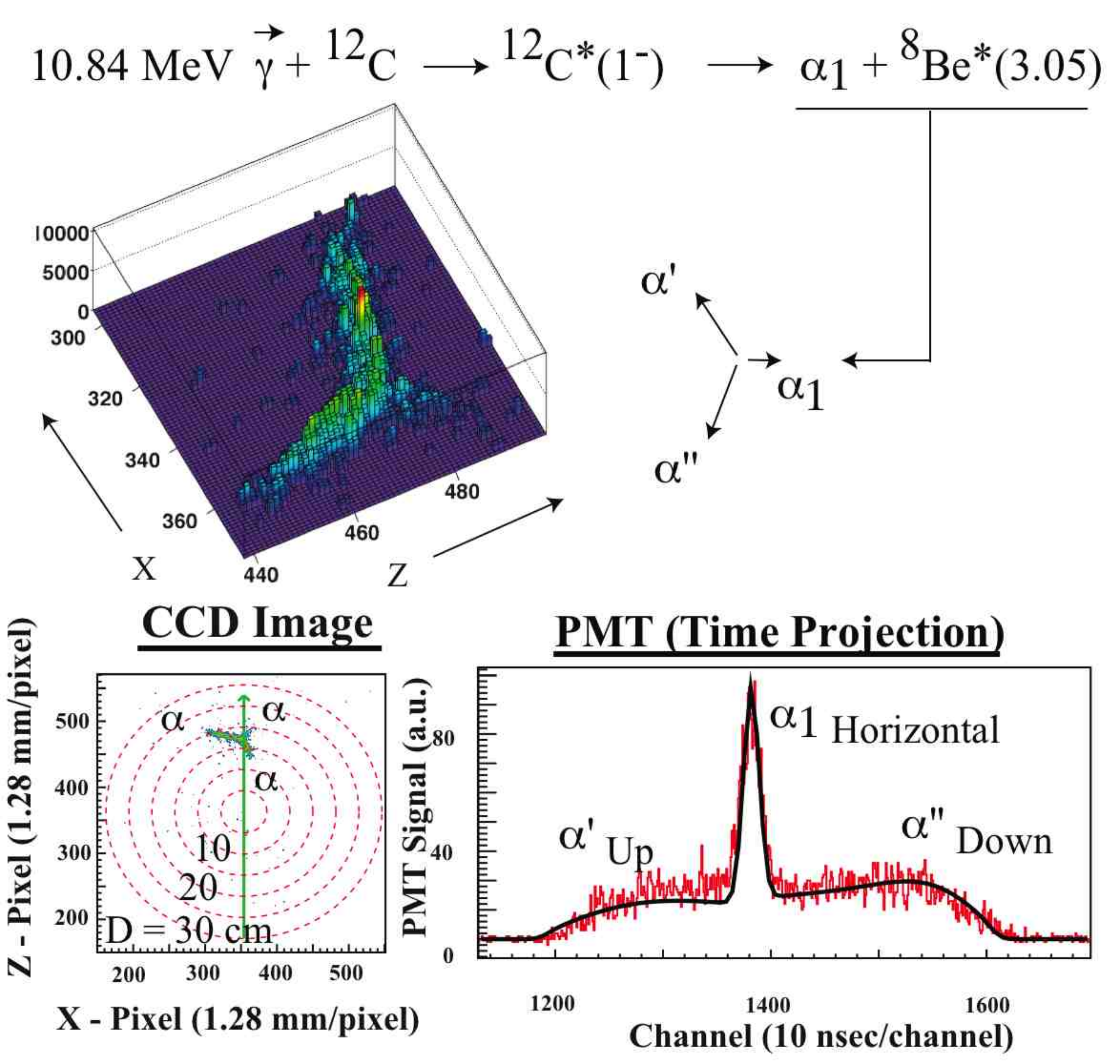

UCONN
UCONN
PTB
STEELERS



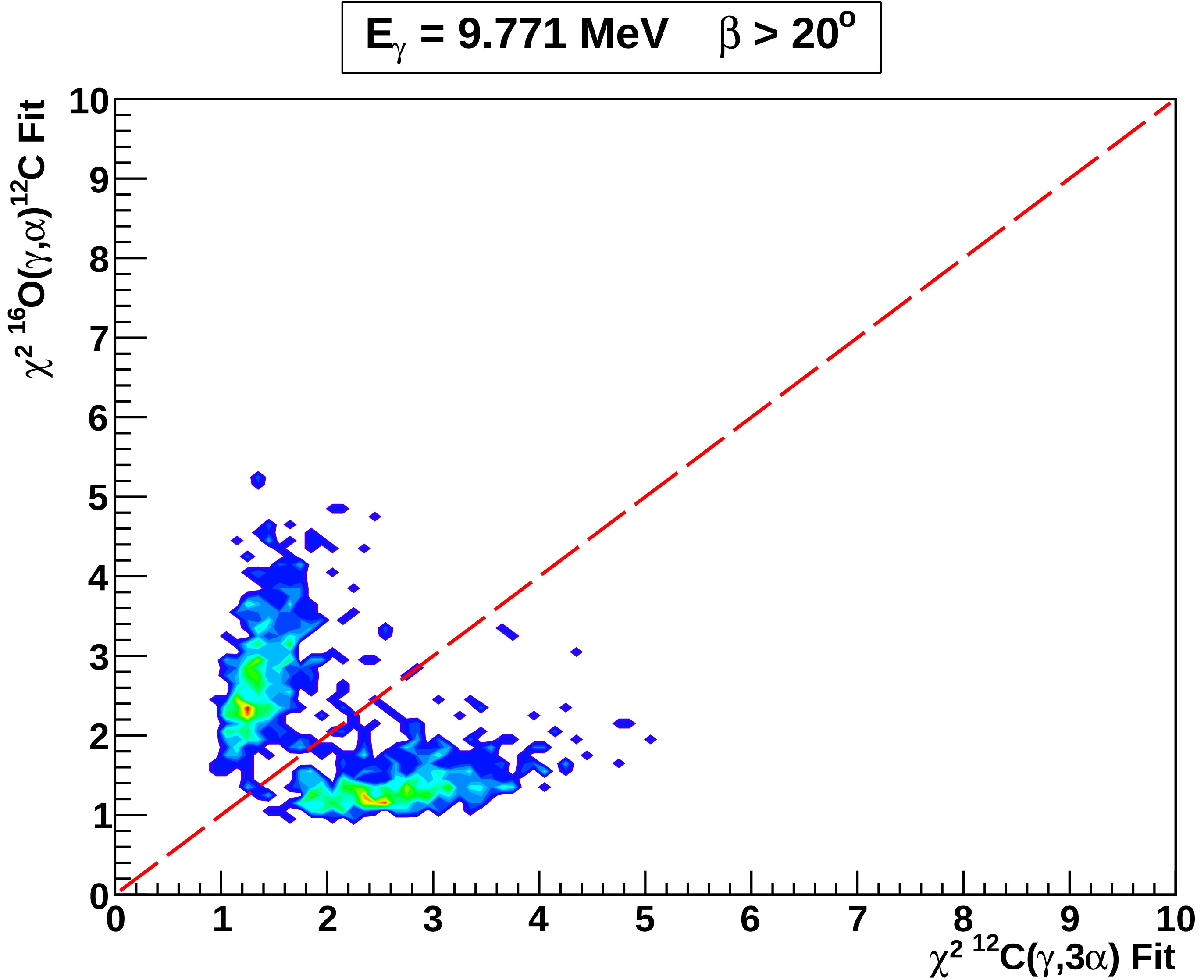
Grid
148Gd - Source
CO2(80%) + N2(20%)
150 Torr
Grid
3.0%
PMT 1
8.0%
PMT1 vs Grid
Counts Per Channel
Channel



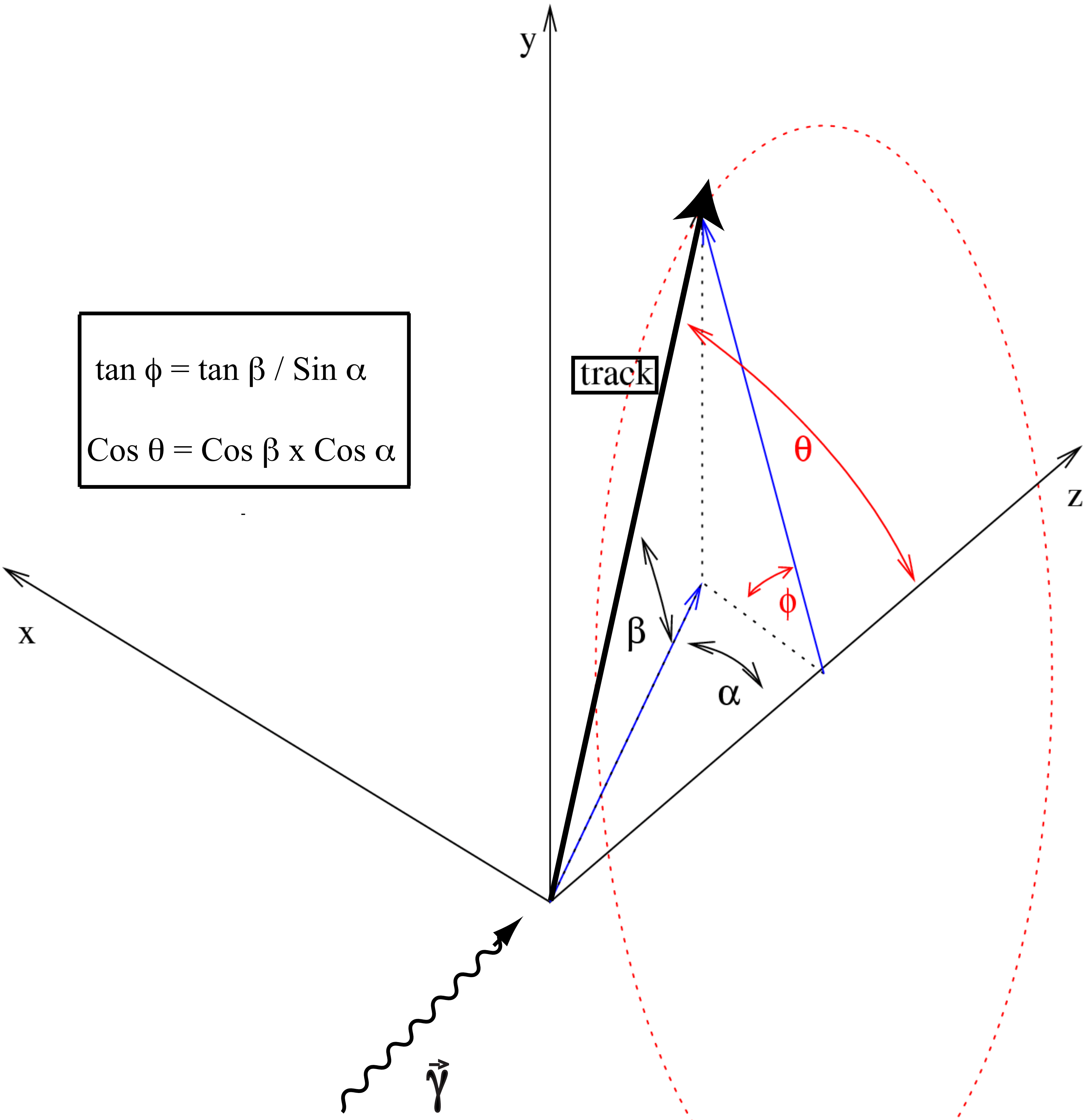
CCD Image
(Track Angle - α)
¹⁶O(γ,α)¹²C
(9.77 MeV)
γ
¹²C
α
10 cm
20 cm
D = 30 cm
CCD Z-Pixel (1.28 pixels/mm)
CCD X-Pixel (1.28 pixels/mm)
Transverse Projection
×10³
"Flat Track"
6.5 mm
Pixel Content (a.u.)
Transverse Pixel (1.28 pixels/mm)
Longitudinal Projection
¹²C
"Flat Track"
β = -4°
α = 228°
α
Pixel Content (a.u.)
Longitudinal Pixel (1.28 pixels/mm)
Summed PMT Signals
(Out of Plane Angle - β)
¹²C
"Tilted Track"
β = -41°
α
PMT Signal (a.u.)
Channel (10 ns/channel)



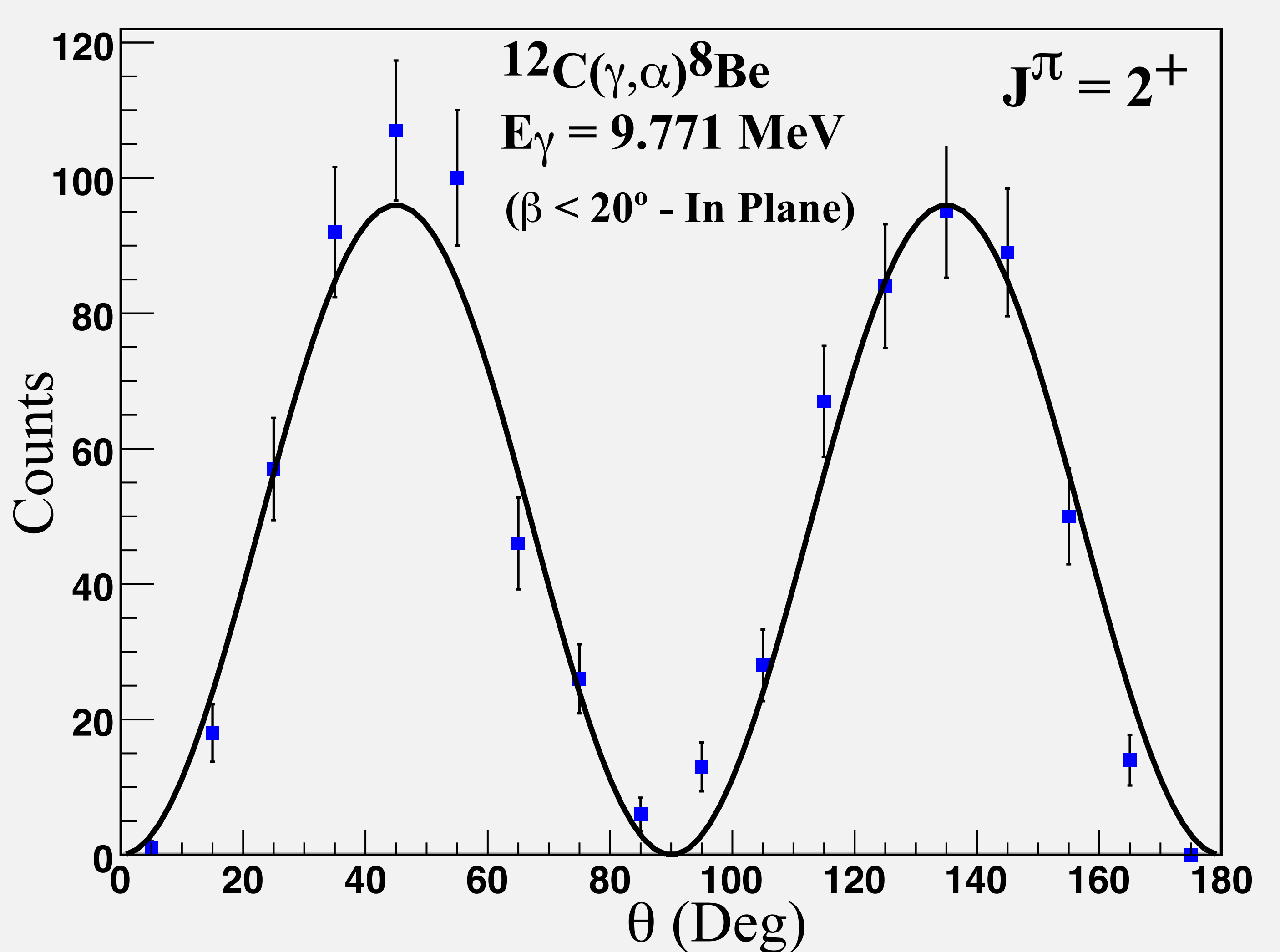
10.84 MeV $\vec{\gamma}$ + ^{12}C → ^{12}C*(1$^-$) → α_1 + ^{8}Be*(3.05)
10000
5000
0
300
320
340
360
440
460
480
X
Z
α'
α$_1$
α''
CCD Image
Z - Pixel (1.28 mm/pixel)
X - Pixel (1.28 mm/pixel)
500
400
300
200
α
α
α
10
20
D = 30 cm
PMT (Time Projection)
PMT Signal (a.u.)
Channel (10 nsec/channel)
α$_1$ Horizontal
α' Up
α'' Down
80
40
0
1200
1400
1600



E_γ = 9.771 MeV $\beta > 20^o$
χ^2 $^{16}O(\gamma,\alpha)^{12}C$ Fit
χ^2 $^{12}C(\gamma,3\alpha)$ Fit
0
1
2
3
4
5
6
7
8
9
10

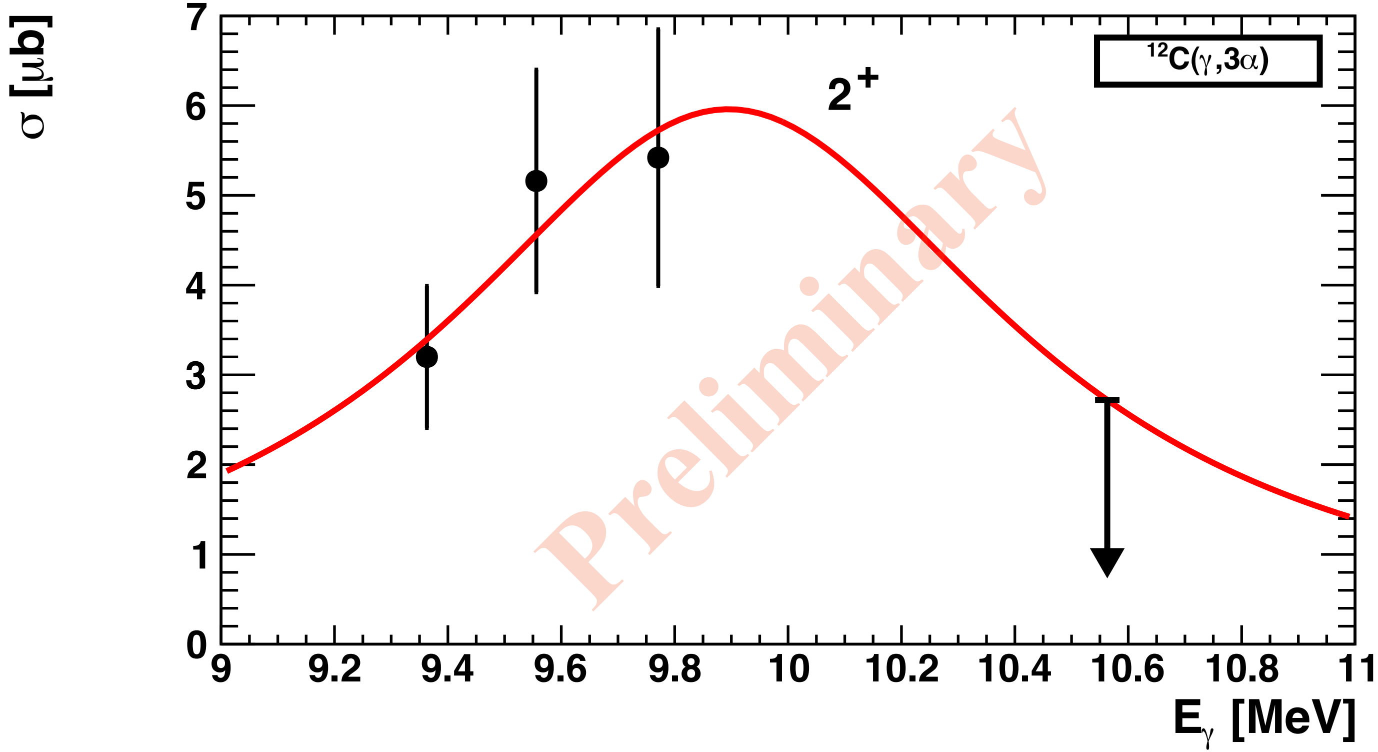


tan ϕ = tan β / Sin α
Cos θ = Cos β x Cos α
y
x
z
track
θ
ϕ
β
α
γ

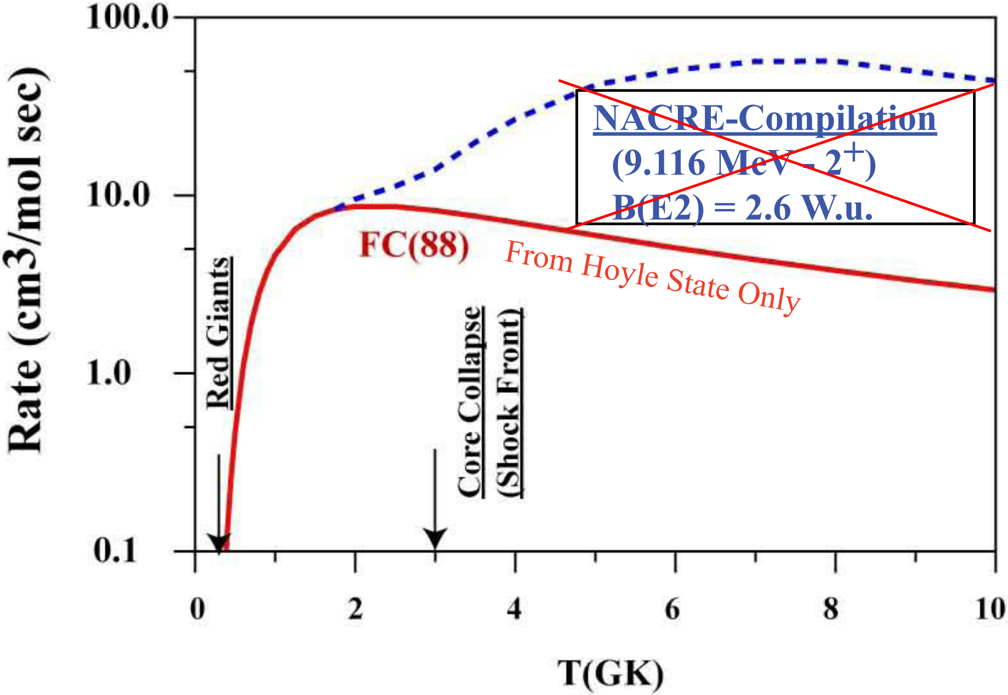


12C(γ,α)8Be
Eγ = 9.771 MeV
(β < 20º - In Plane)
Jπ = 2+
Counts
θ (Deg)
0
20
40
60
80
100
120
0
20
40
60
80
100
120
140
160
180

B(E2: $2^{+}_{2} \rightarrow$ gs) $\approx$ 0.3 W.u.

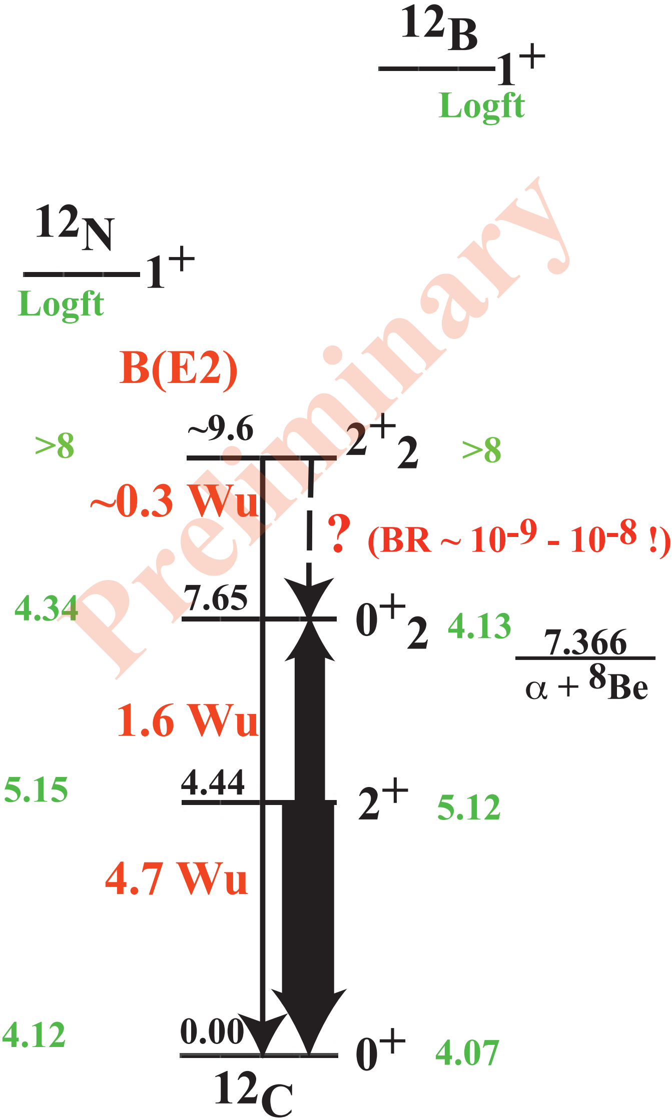


Triple Alpha Burning Rate: $^{8}Be(\alpha,\gamma)^{12}C$



Conclusions

B(E2: $2^+_2 \rightarrow 0^+_2$) = ?



The O-TPC at HIγS Collaboration:

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NGCSU:*
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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