In Memoriam, a Colleague and Beloved Friend

Sydney Benjamin Galès

November 1, 1943 – November 29, 2024

Corrine and Sydney Galès, Jaffa, Tel Aviv, April 27, 2019

Current Data on the $^{12}C(\alpha,\gamma)$ Reaction; a Critical Review and the Road Map Ahead*

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1. Oxygen Formation in Stellar Helium Burning/ the $^{12}C(\alpha,\gamma)$ Reaction
2. Status of World Best Data (Stuttgart's Heroic Effort + Plag *et al.*)
3. UConn Measurement, Optical Readout TPC (O-TPC @ HIγS)
4. The Warsaw electronic readout (eTPC @ HIγS)

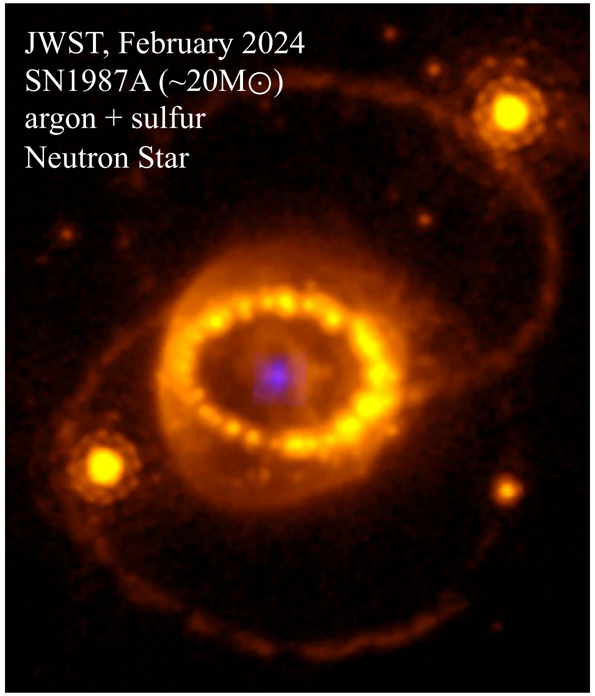
* Supported in part by the USDOE grant No. DE-FG02-94ER40870.

ECT*, Key Reactions in Nuclear Astrophysics, February 17, 2025

Laboratory for Nuclear Science At Avery Point

aka Laboratory for Astrophysics http://astro.uconn.edu

Nuclear Astrophysics in the Era of Windows on the Universe Multi-Messenger Astrophsyics (WoU-MMA)



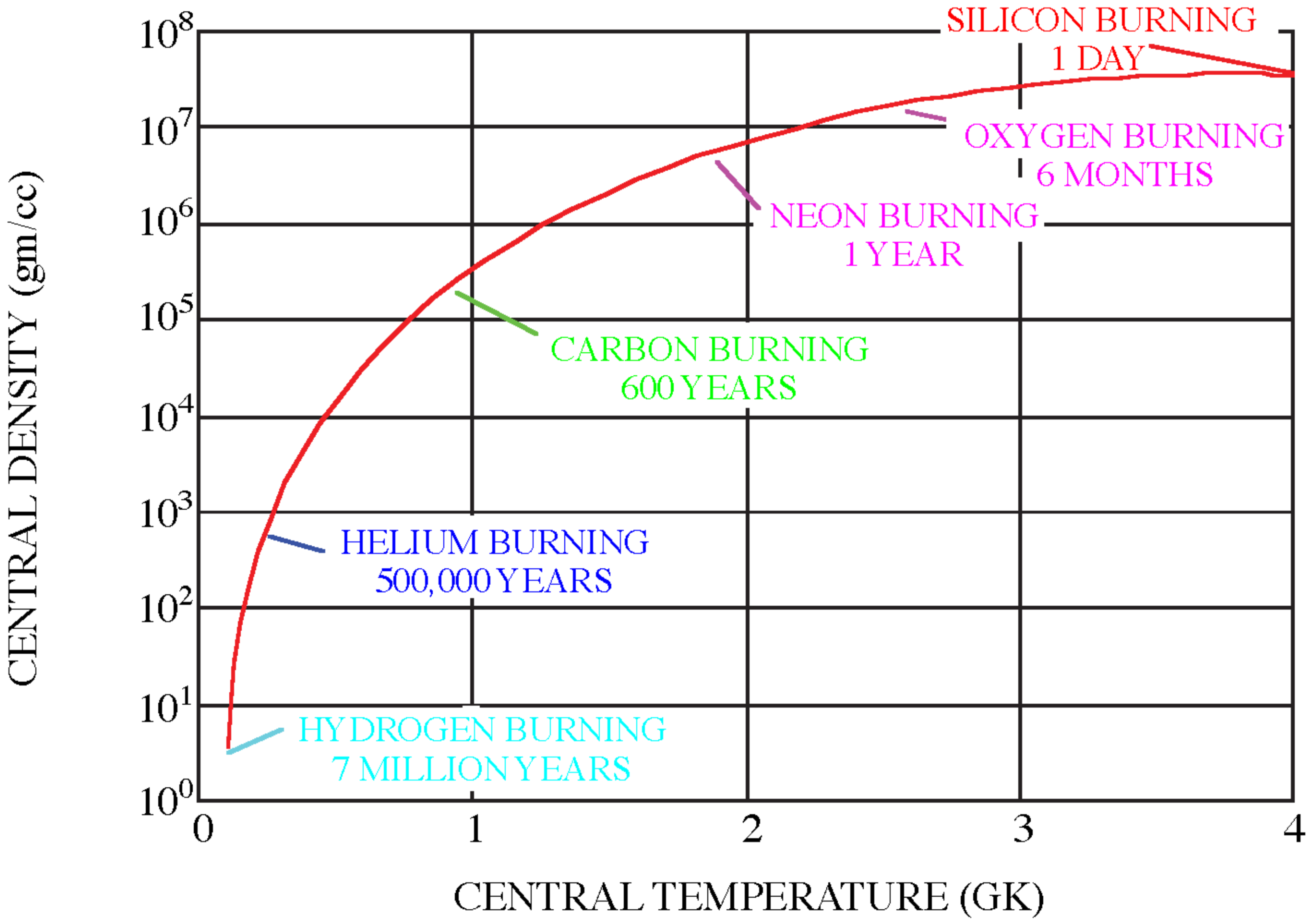
SN1987A: First MMA, Type II Supernova
Observed Neutrinos & 4 HR Later Light Curve (EM)/ MMA object
Progenitor: Sanduleak −69 202 (Sk -69 202) Blue Supergiant ~20M⊙
SN1987A (JWST 2024): Neutron Star, Not Black Hole
Type II SN: Neutron Star or Black Hole, Determined by C/O

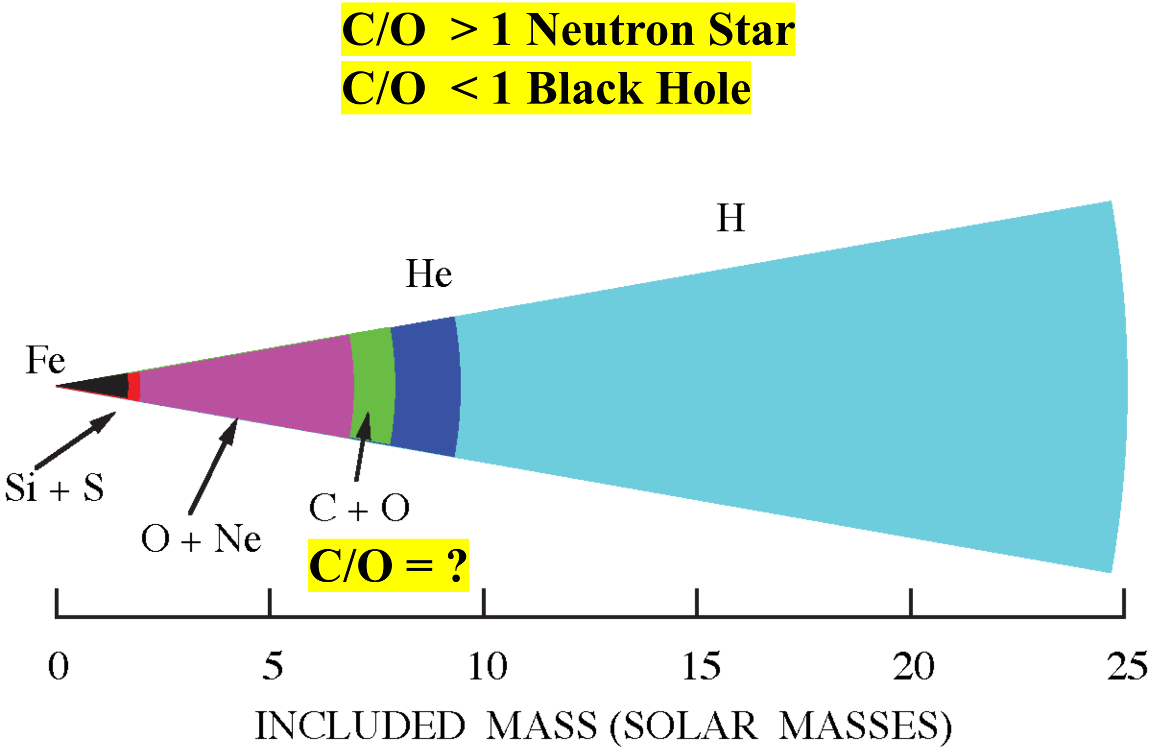
Helium Burning: $3\alpha \rightarrow {}^{12}C$ (~11%) "Hoyle State"
${}^{12}C(\alpha,\gamma){}^{16}O$ @300 keV ???
${}^{12}C(\alpha,\gamma) \rightarrow C/O = ?$

${}^{12}C(\alpha,\gamma)$ hence the C/O ratio, quite possibly the single Most important nuclear input to Stellar Evolution Theory

W.A. Fowler: Rev. Mod. Phys. 56, 149 (1984)
"The ${}^{12}C(\alpha,\gamma)$ reaction is of paramount importance"

Type II (Core Collapse) Supernova





Bethe & Brown, Scientific American 1985

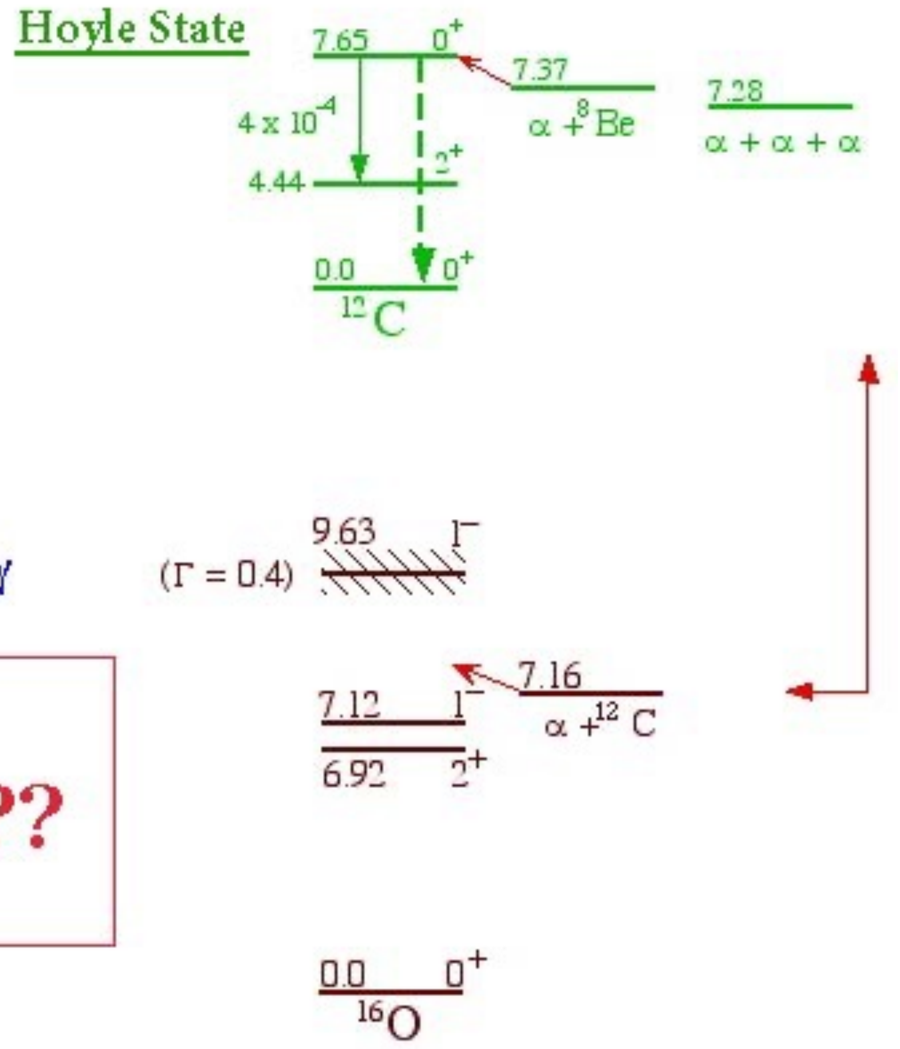
M. Gai, Nucl. Phys. A928, 313 (2014) (x10 Gai)

HELIUM BURNING IN (MASSIVE) STARS

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

(~11%)

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



C/O = ???

<u>$^{12}C(\alpha,\gamma)$ Reaction:</u>

Two partial waves:

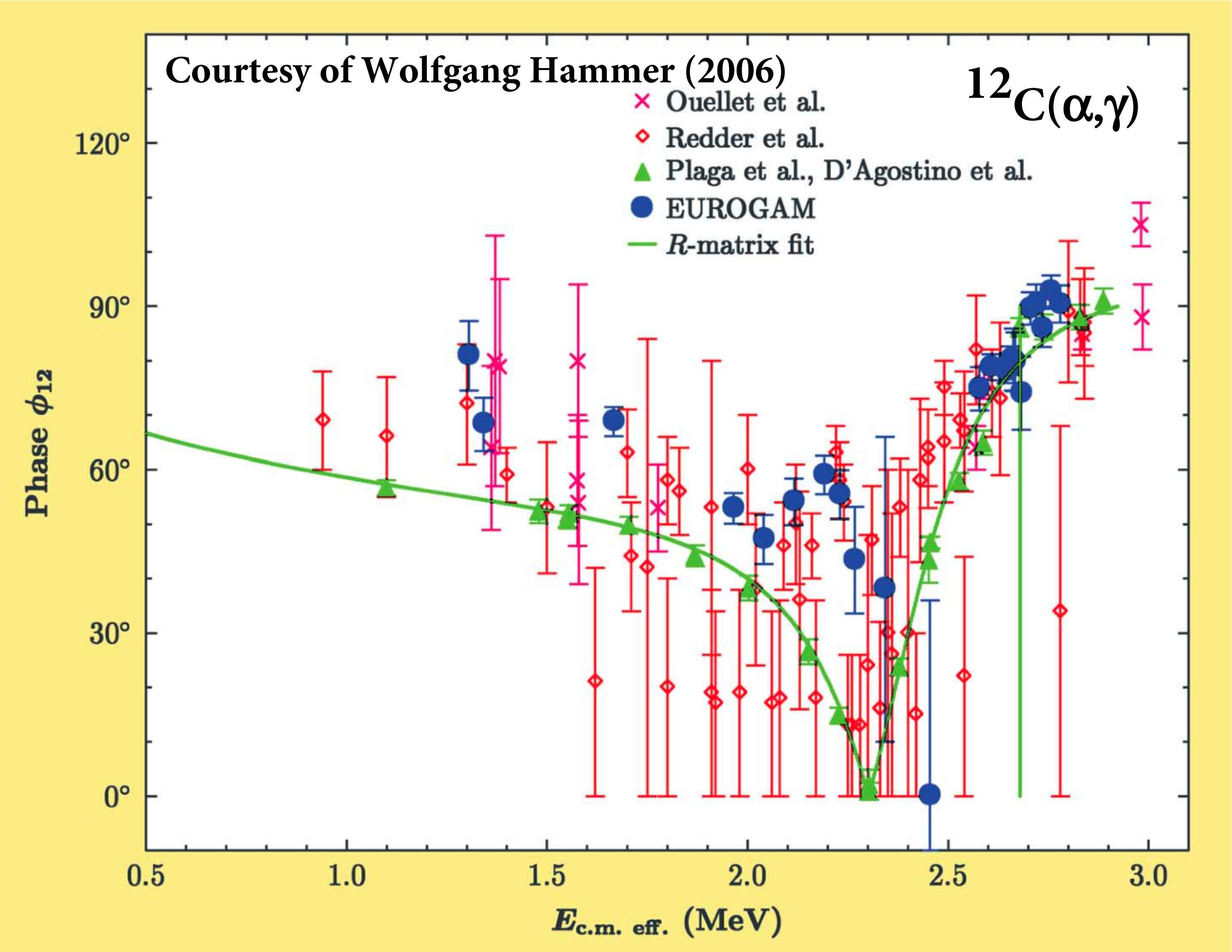
p-wave $S_{E1}(300)$

d-wave $S_{E2}(300)$

ϕ_{12} *E1-E2* Mixing Phase Angle

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

F.C. Barker and T. Kajino, Aust. J. Phys. 44, 369 (1991), R-Matrix Theory.



E1-E2 Mixing Phase Angle (ϕ_{12})

M. Gai, Phys. Rev. C 88, 062801(R) (2013).

C. R. Brune, Phys. Rev. C 64, 055803 (2001).

L.D. Knutson, Phys. Rev. C 59, 2152 (1999).

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

Required by Unitarity

EUROGAM

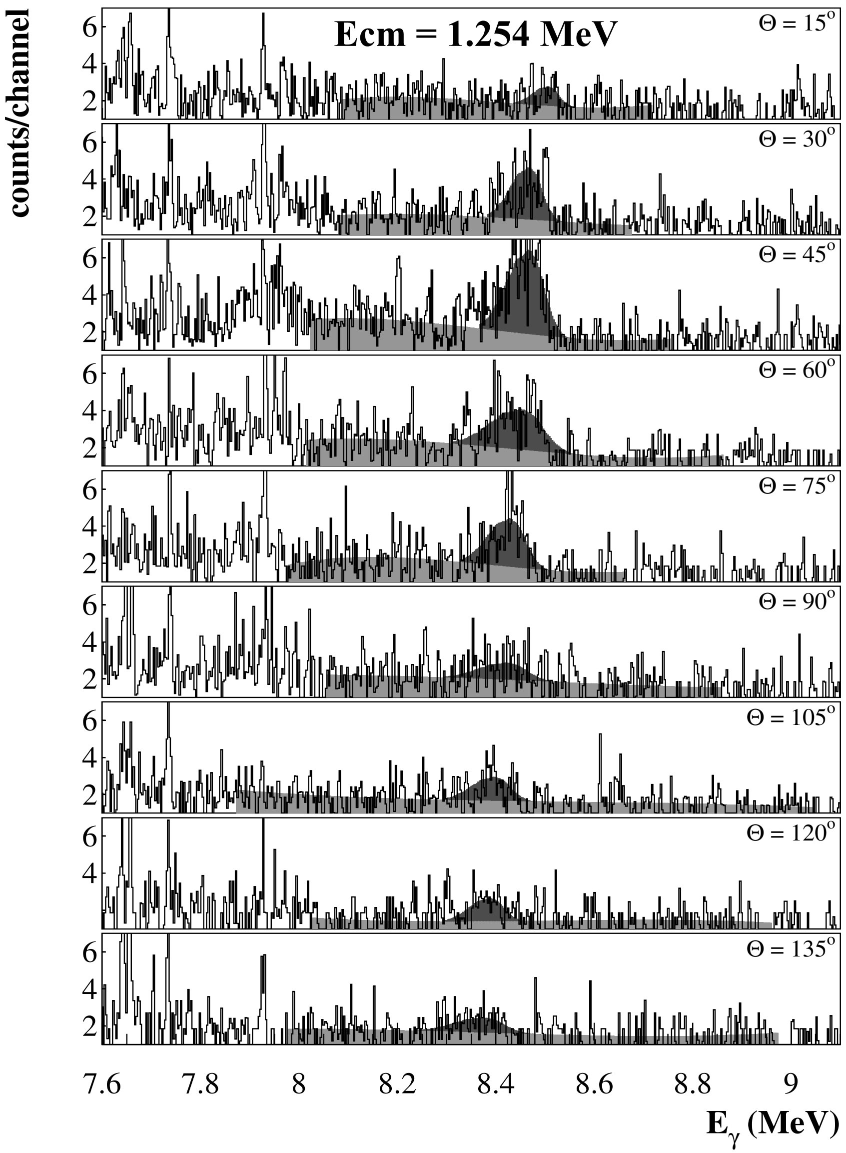
Assuncao *et al.*

TABLE I. Final results of the present $^{12}C(\alpha, \gamma)^{16}O$ experiment for the $E1$ and $E2$ capture γ-ray cross sections and their relative phase ϕ_{12}. $E_{\alpha,\mathrm{lab}}$ is the uncorrected α-particle energy; $E_{\mathrm{c.m.\,eff.}}$ is the effective c.m. energy calculated as explained in the text for the two considered cases: (I) using constant S factors for $E1$ and $E2$ contributions to calculate the tabulated value and constant cross sections to calculate a limiting value contribution to the uncertainty; (II) a limiting value of $E_{\mathrm{c.m.\,eff.}}$ calculated using a pure Breit-Wigner $E2$ resonance for the $E2$ contribution and a constant S factor for the $E1$. For the two-parameter fit, the phase ϕ_{12} was fixed according to Eq. (4.7) with the phases taken from elastic scattering [31,32]. The corresponding χ^2 values are reduced values for seven degrees of freedom (nine angles and two free parameters for the fit). For the three-parameter fit, the phase was determined according to Eq. (4.1) solely from the data of this experiment. The χ^2 is the reduced value for six degrees of freedom (nine angles and three free parameters for the fit).

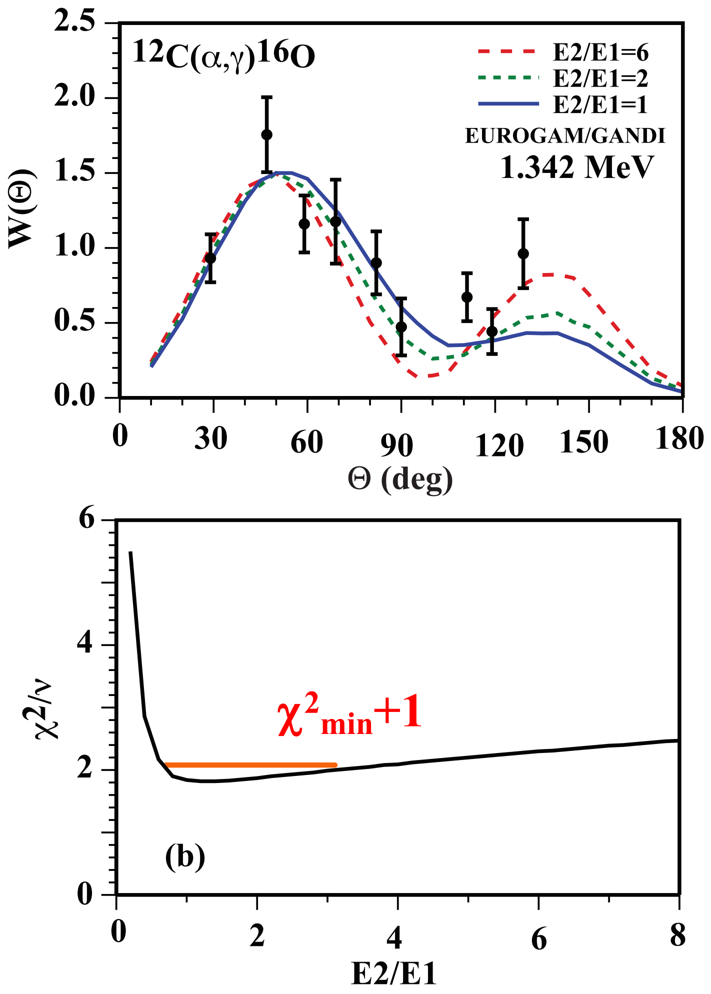
$E_{\alpha,\mathrm{lab}}$ (MeV)	$E_{\mathrm{c.m.\,eff.}}$ (MeV)		2-parameter fit, phase fixed **by Unitarity**				3-parameter fit, phase free				
	(I)	(II)	σ_{E1} (nb)	σ_{E2} (nb)	ϕ_{12} (deg)	χ^2	σ_{E1} (nb)	σ_{E2} (nb)		ϕ_{12} (deg)	χ^2
1.850 (2)	1.310(40)	**E1/E2 = 4.9**	0.19(5)	0.039(34)	54.4(20)	2.4	0.12(4)	0.14(4)	**= 0.9**	81(6)	1.1
1.900 (2)	1.340(40)	**1.1**	0.16(6)	0.15(6)	54.0(20)	2.0	0.16(4)	0.17(4)	**0.9**	68(5)	1.3
2.300 (2)	1.666(14)	**3.9**	1.39(22)	0.36(9)	49.9(20)	6.4	1.13(19)	0.73(14)	**1.5**	69(3)	3.2
2.700 (2)	1.965(9)	**6.6**	5.4(8)	0.80(14)	40.4(20)	2.8	5.0(7)	1.24(24)	**4.0**	53(3)	1.5
2.800 (2)	2.040(8)	**7.2**	7.8(11)	1.09(21)	35.9(20)	1.4	7.3(11)	1.6(4)	**4.6**	47(5)	1.1
2.900 (2)	2.116(7)	**14.9**	13.4(19)	0.90(18)	29.9(20)	2.3	12.3(18)	2.1(5)	**5.9**	54(4)	1.3
3.000 (2)	2.192(7)		22.7(33)	0.90(17)	20.5(20)	3.1	20.5(30)	3.1(8)		59(4)	1.4

The (heroic) Stuttgart Effort: 1) 450 μA 2) 700 HRs 3) Four x 100% HPGe
4) EUROGAM 5) 0.01% ^{13}C [x100 Reduced $^{13}C(\alpha,n)$]

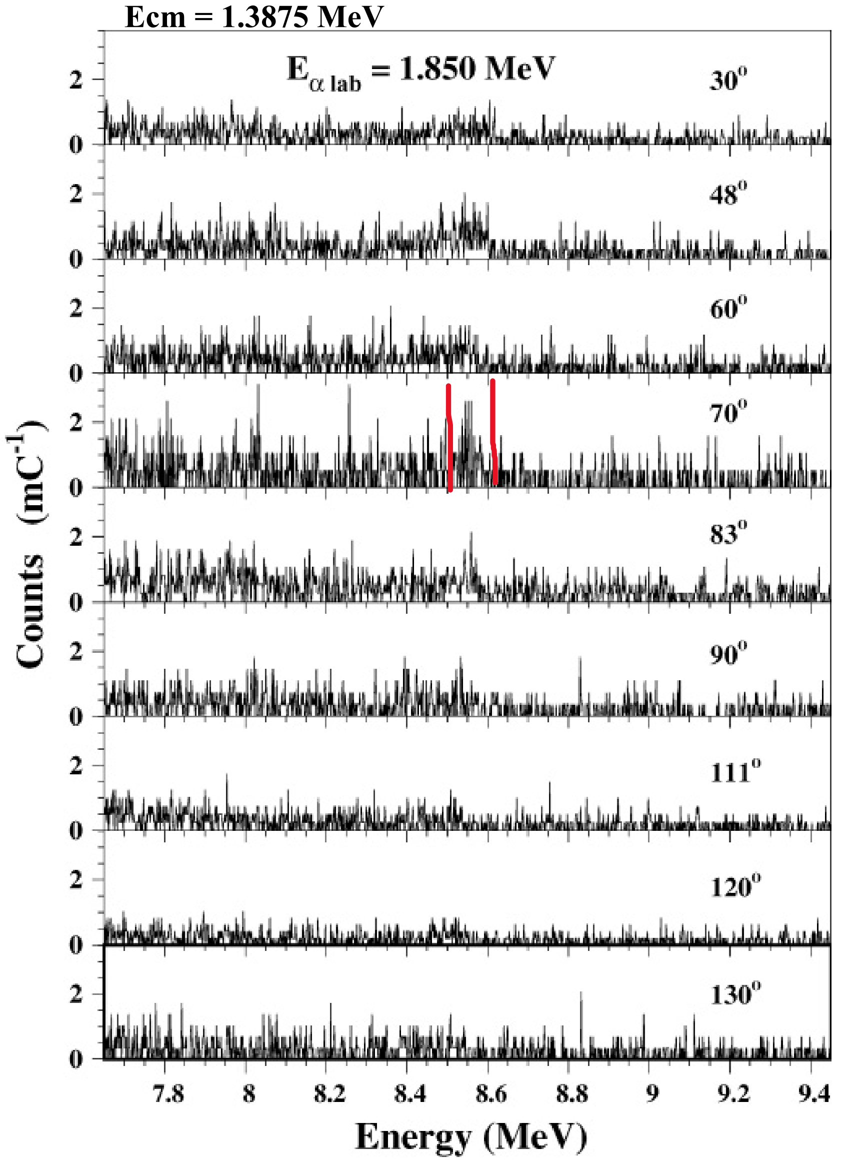
R. Kunz *et al.*, PRL, 86, 3244 (2002)



M. Gai, PRC, 88, 062801(R) (2013)



M. Assuncao *et al.*. PRC 73, 055801 (2006)



Ph.D. Thesis, Michael Fey, Stuttgart March 2004, Unpublished, $^{12}C(\alpha,\gamma)$

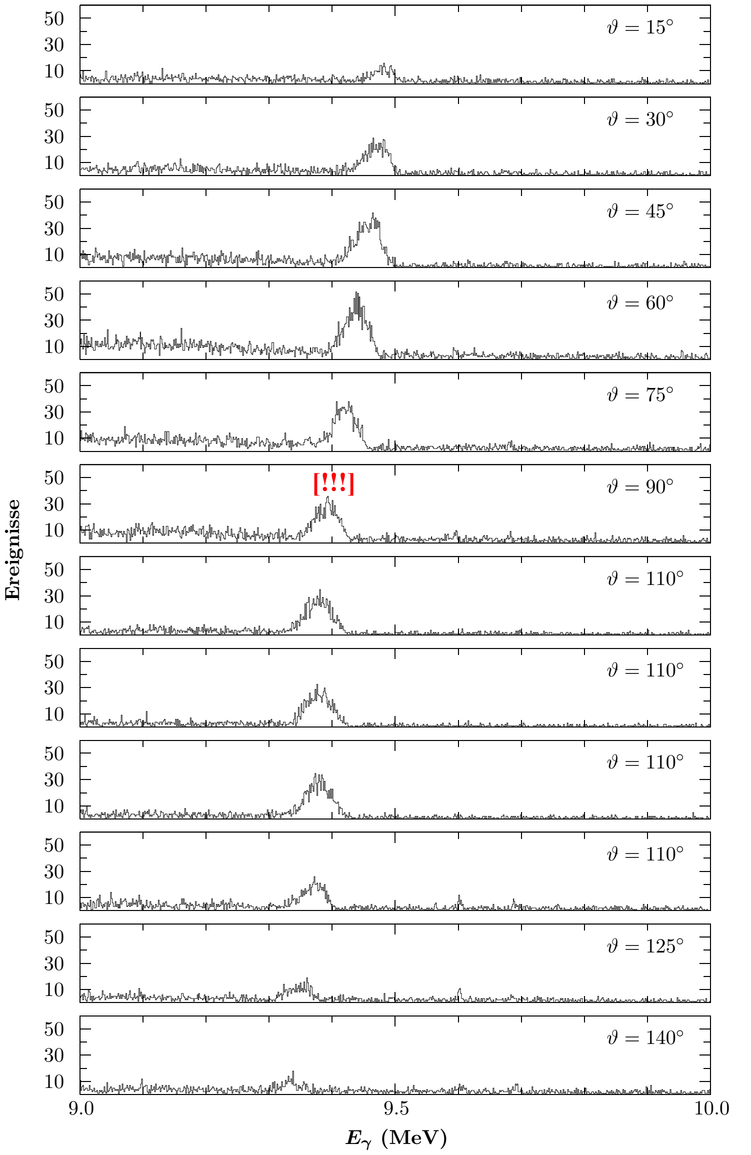


Abbildung C.35: Im Rahmen des Drehtisch-Experiments gemessene γ-Roh-Spektren bei $E_{\mathrm{c.m.}} = 2.209$ MeV. E_L=2.945 MeV

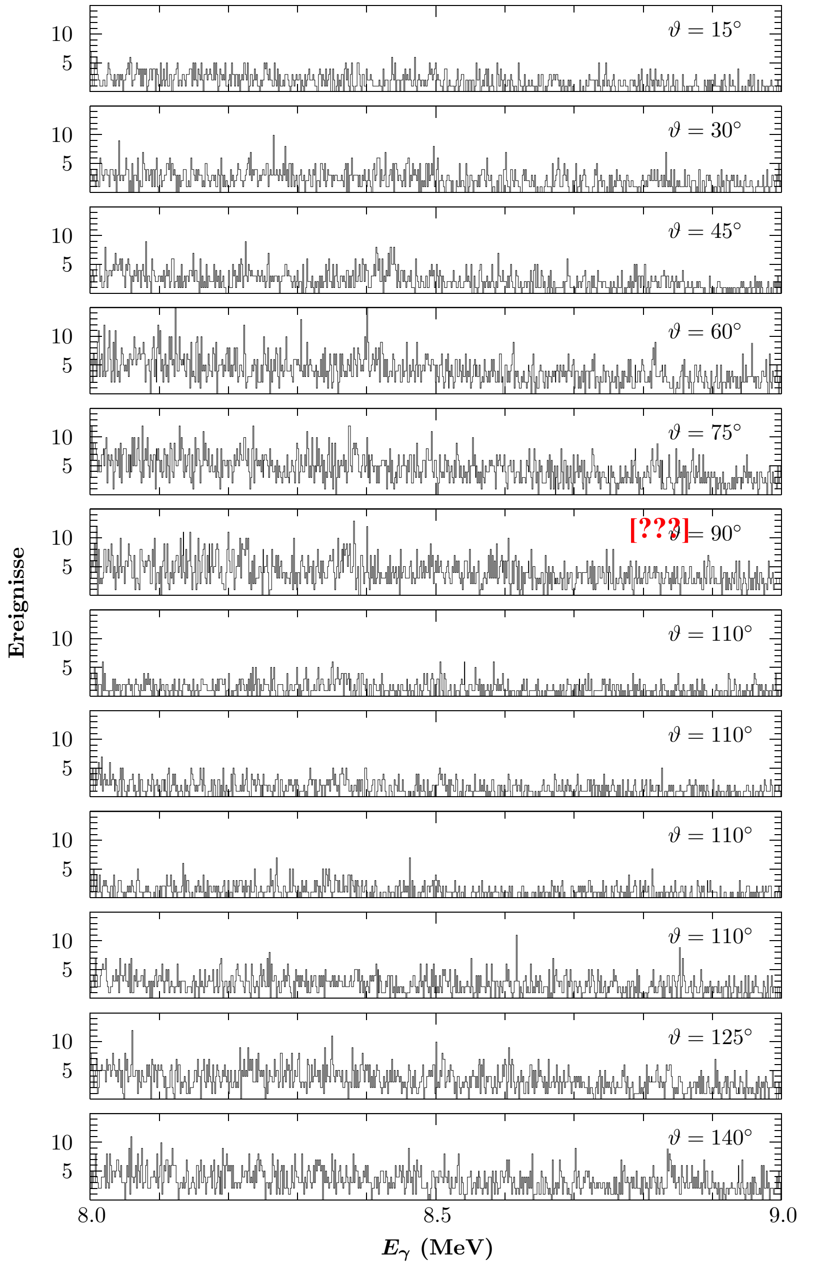


Abbildung C.34: Im Rahmen des Drehtisch-Experiments gemessene γ-Roh-Spektren bei $E_{\mathrm{c.m.}} = 1.696$ MeV. E_L=2.261 MeV

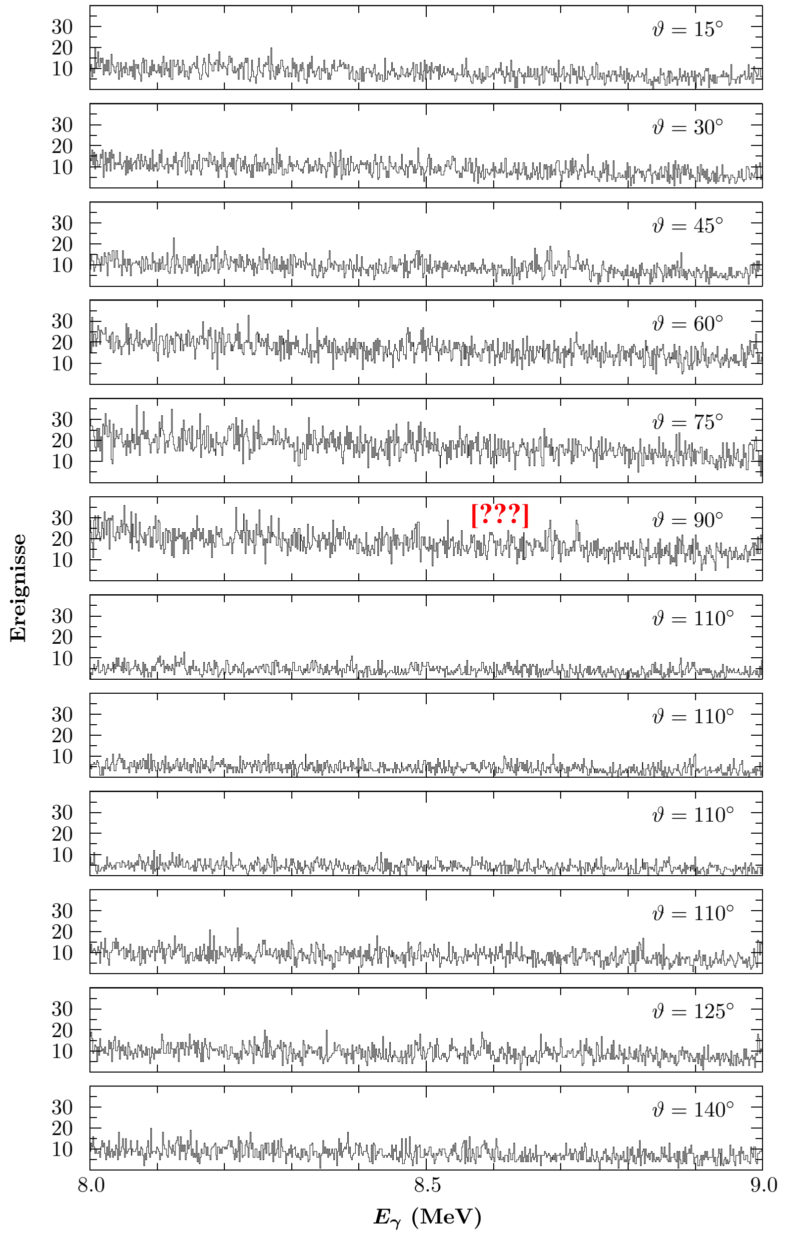


Abbildung C.33: Im Rahmen des Drehtisch-Experiments gemessene γ-Roh-Spektren bei $E_{\mathrm{c.m.}} = 1.452$ MeV. E_L=1.936 MeV

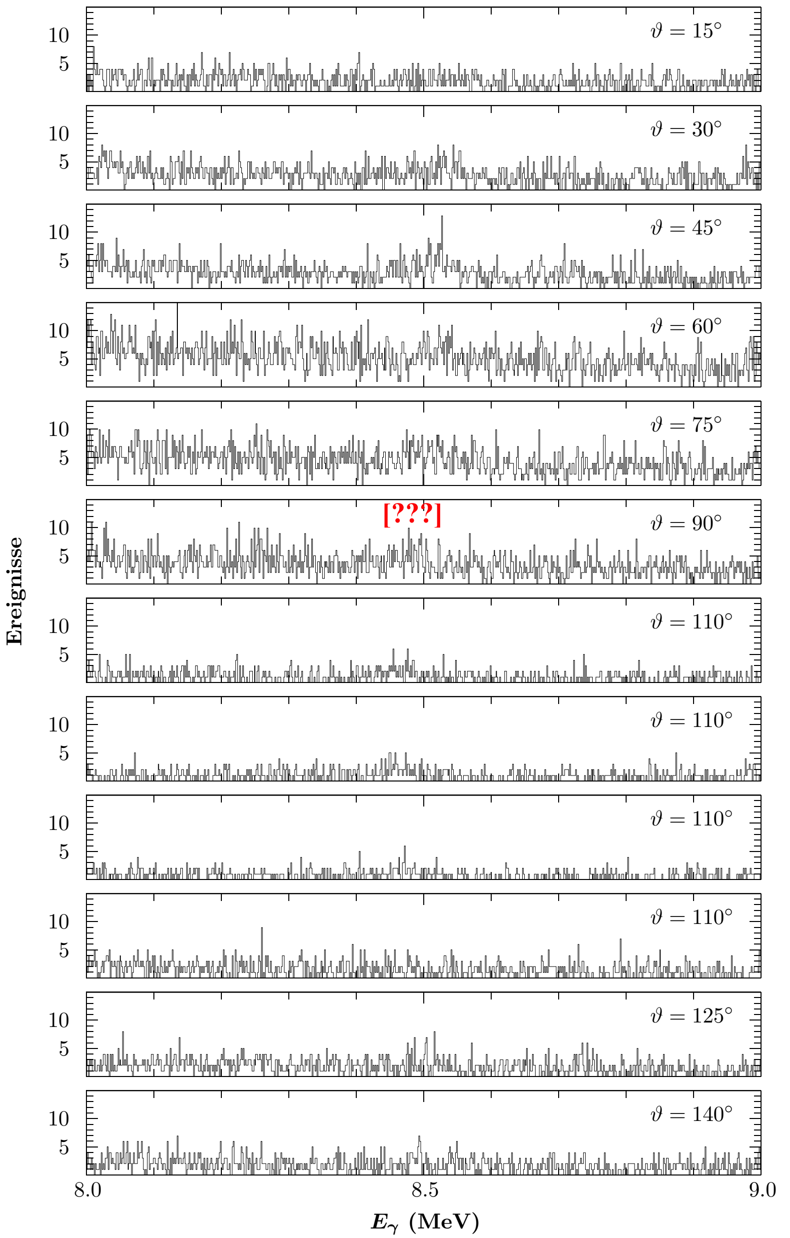


Abbildung C.32: Im Rahmen des Drehtisch-Experiments gemessene γ-Roh-Spektren bei $E_{\mathrm{c.m.}} = 1.308$ MeV. E_L=1.744 MeV

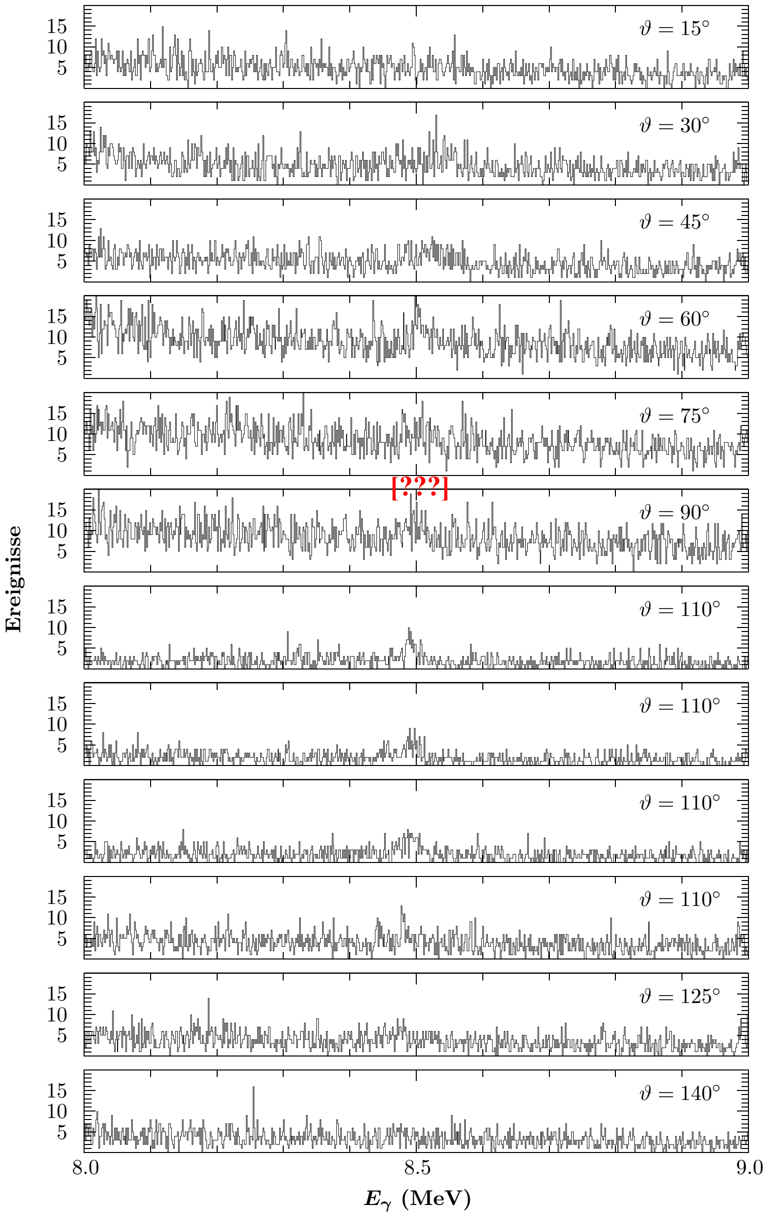


Abbildung C.31: Im Rahmen des Drehtisch-Experiments gemessene γ-Roh-Spektren bei $E_{\mathrm{c.m.}} = 1.305$ MeV. E_L=1.740 MeV

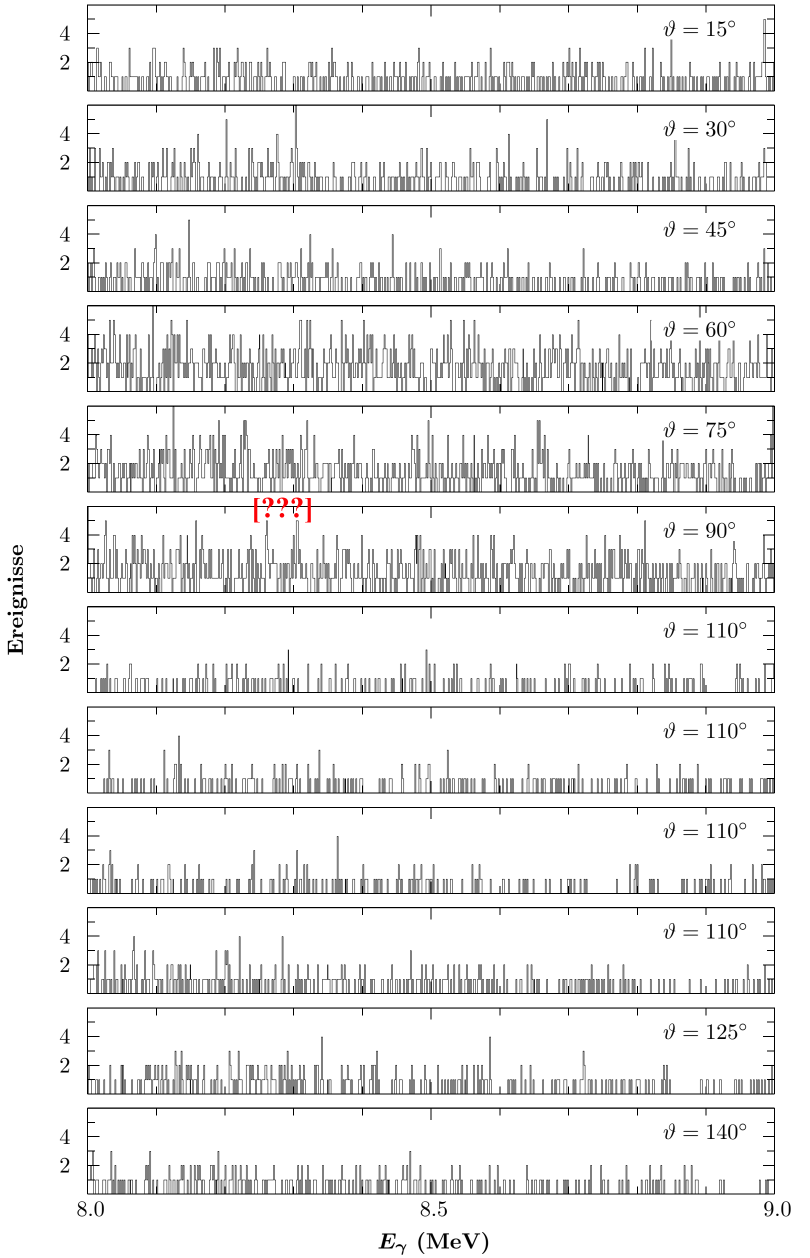


Abbildung C.30: Im Rahmen des Drehtisch-Experiments gemessene γ-Roh-Spektren bei $E_{\mathrm{c.m.}} = 1.103$ MeV. E_L=1.470 MeV

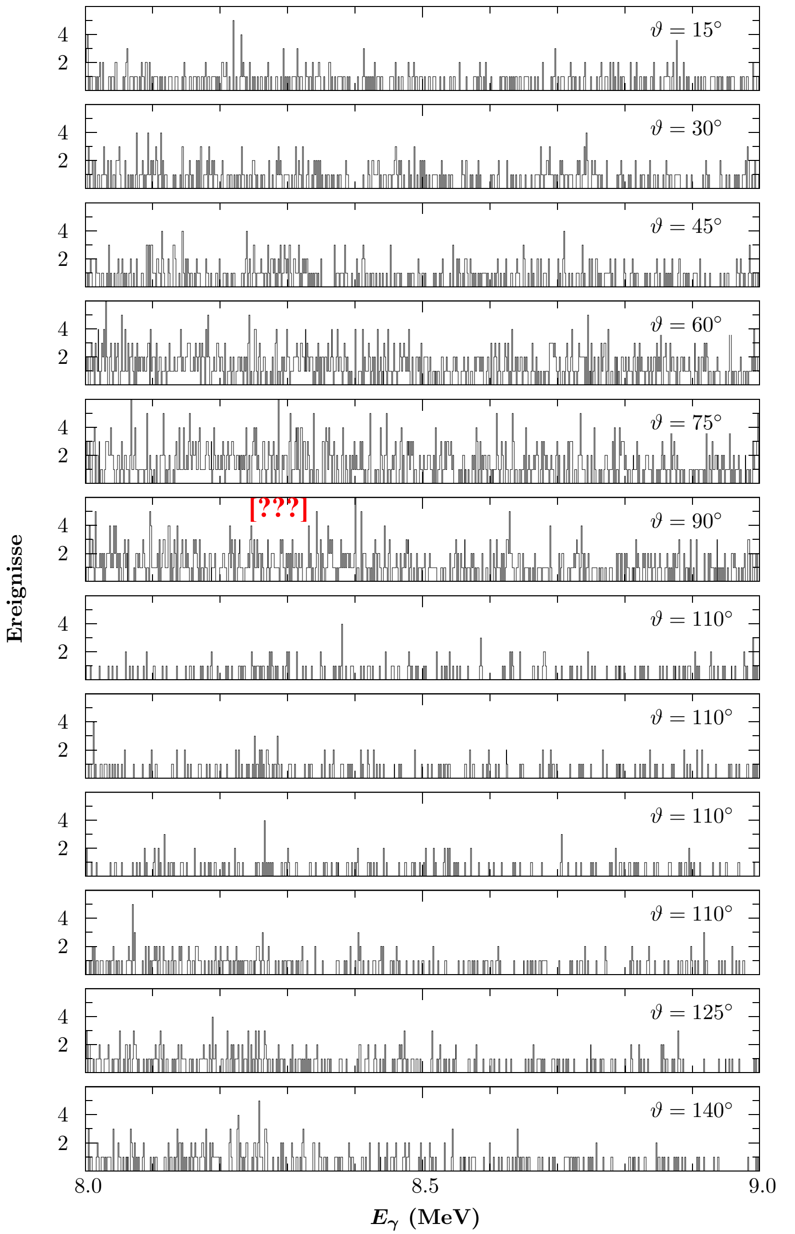


Abbildung C.29: Im Rahmen des Drehtisch-Experiments gemessene γ-Roh-Spektren bei $E_{\mathrm{c.m.}} = 1.102$ MeV. **E_L=1.469 MeV**

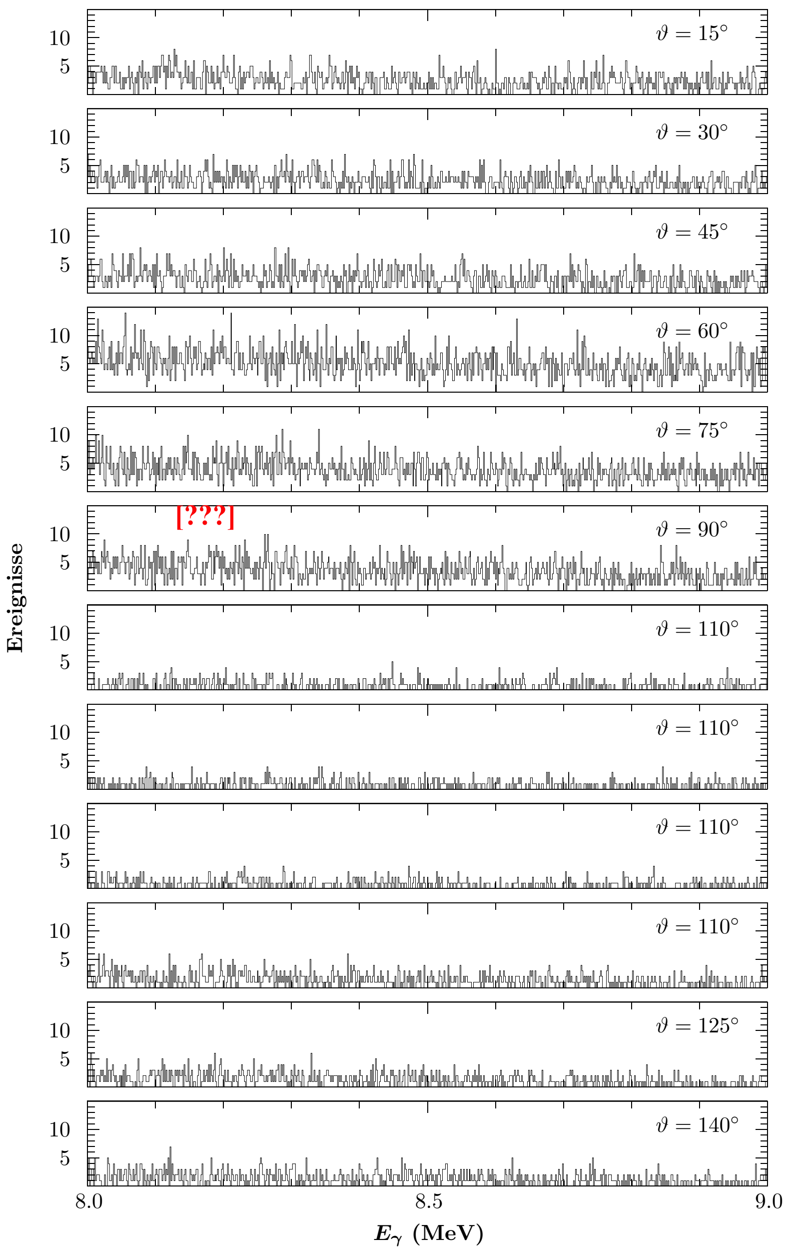


Abbildung C.28: Im Rahmen des Drehtisch-Experiments gemessene γ-Roh-Spektren bei $E_{\mathrm{c.m.}} = 1.099$ MeV. **E_L=1.465 MeV**

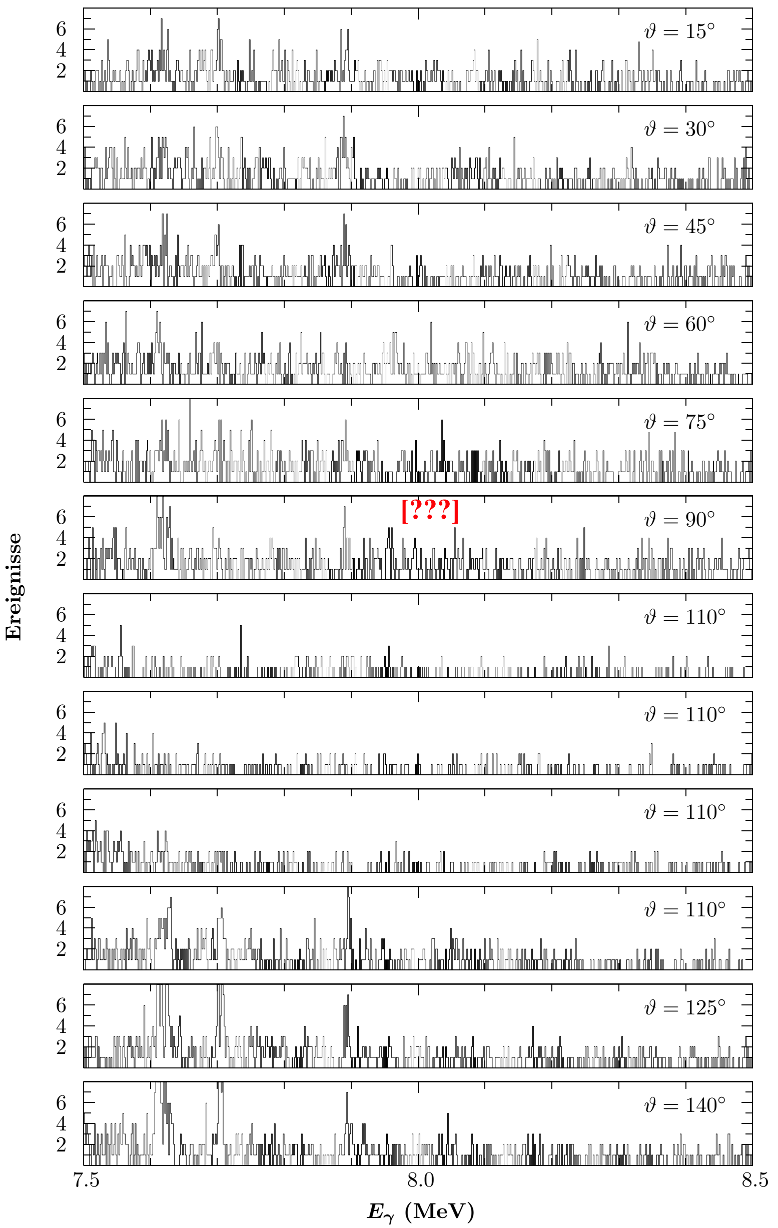


Abbildung C.27: Im Rahmen des Drehtisch-Experiments gemessene γ-Roh-Spektren bei $E_{\mathrm{c.m.}} = 0.903$ MeV. **E_L=1.204 MeV**

Ph.D. Thesis, Michael Fey, Stuttgart, March 2004, Unpublished

$^{12}C(\alpha,\gamma)$ Reaction Measured With EUROGAM - Array

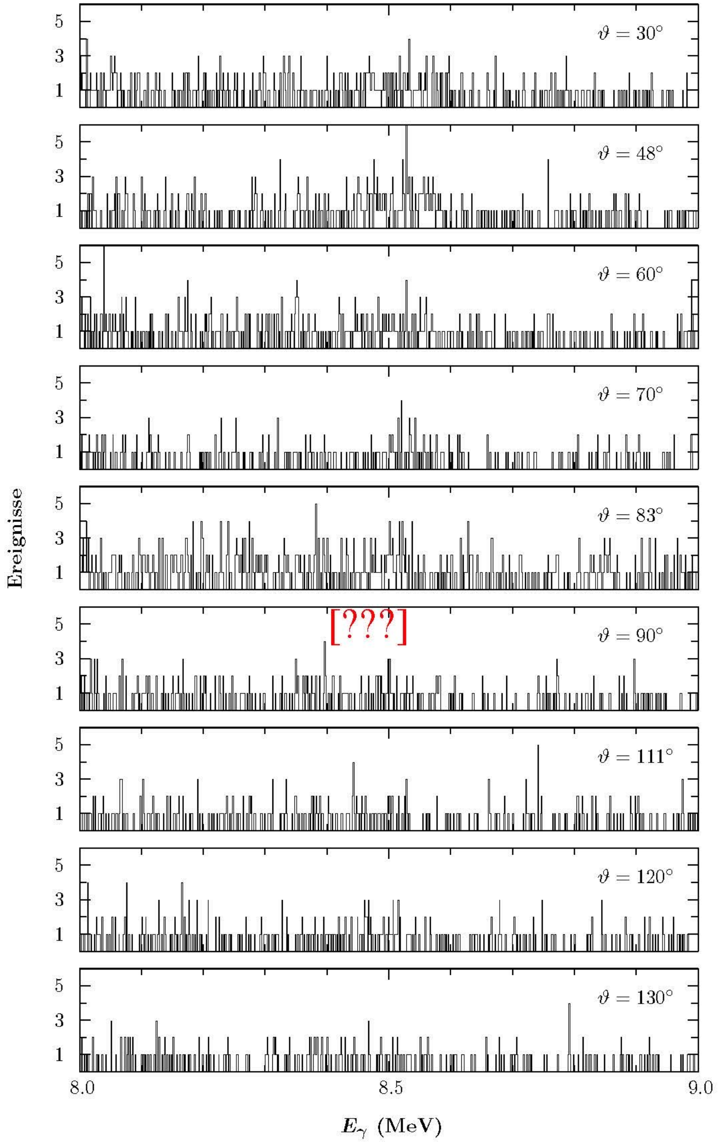


Abbildung C.1: Im Rahmen des EUROGAM-Array-Experiments gemessene γ-Roh-Spektren bei $E_{\mathrm{c.m.}} = 1.305$ MeV. 1.740

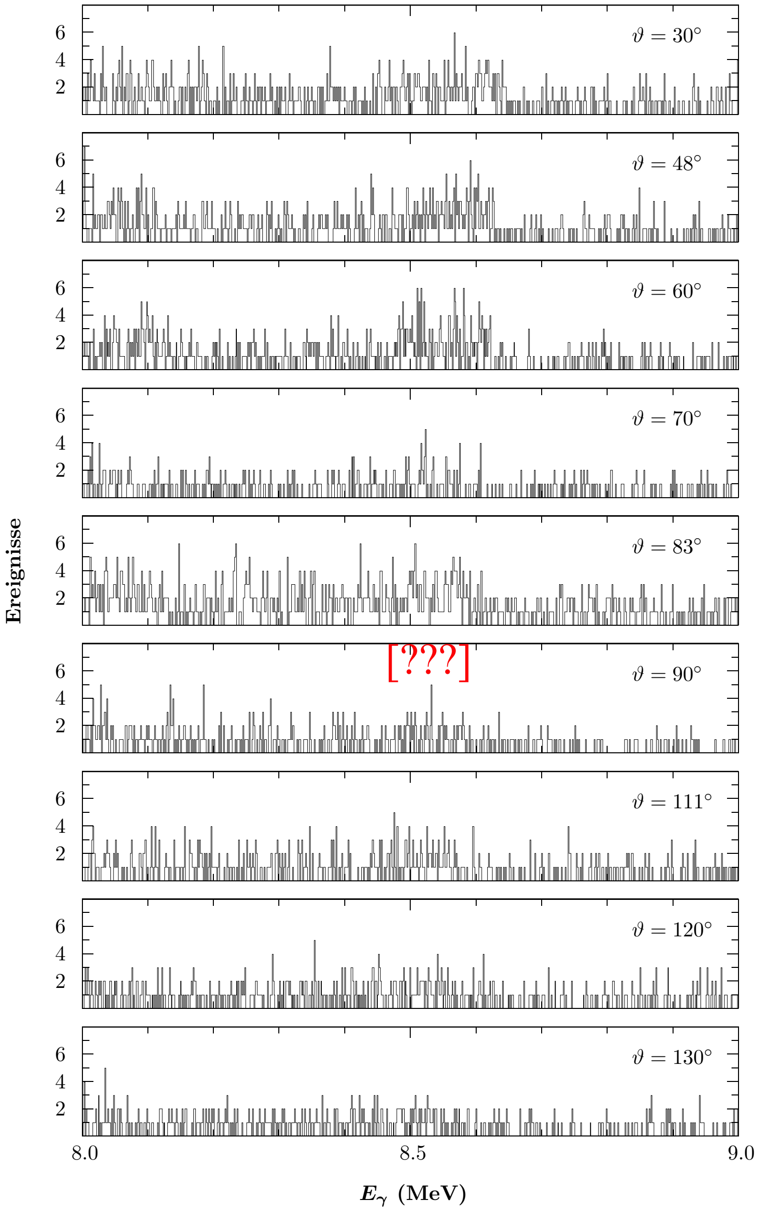


Abbildung C.2: Im Rahmen des EUROGAM-Array-Experiments gemessene γ-Roh-Spektren bei $E_{\mathrm{c.m.}} = 1.342$ MeV. 1.790

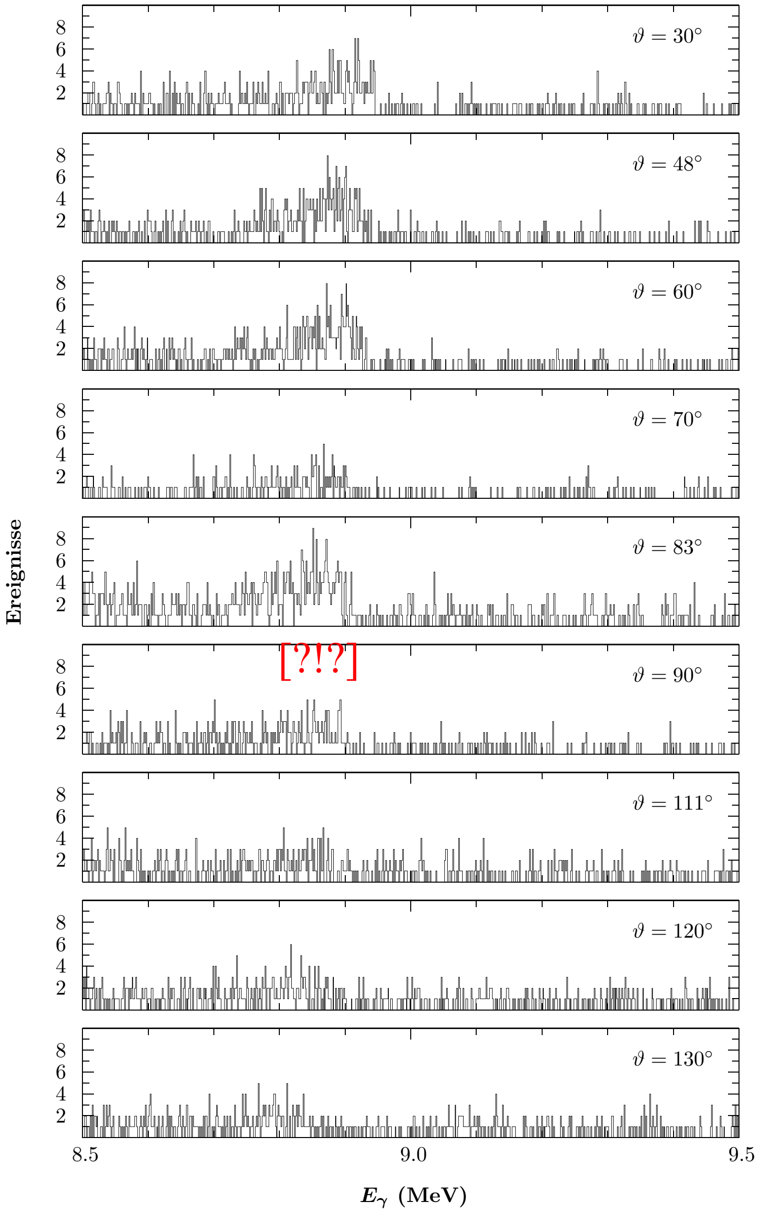
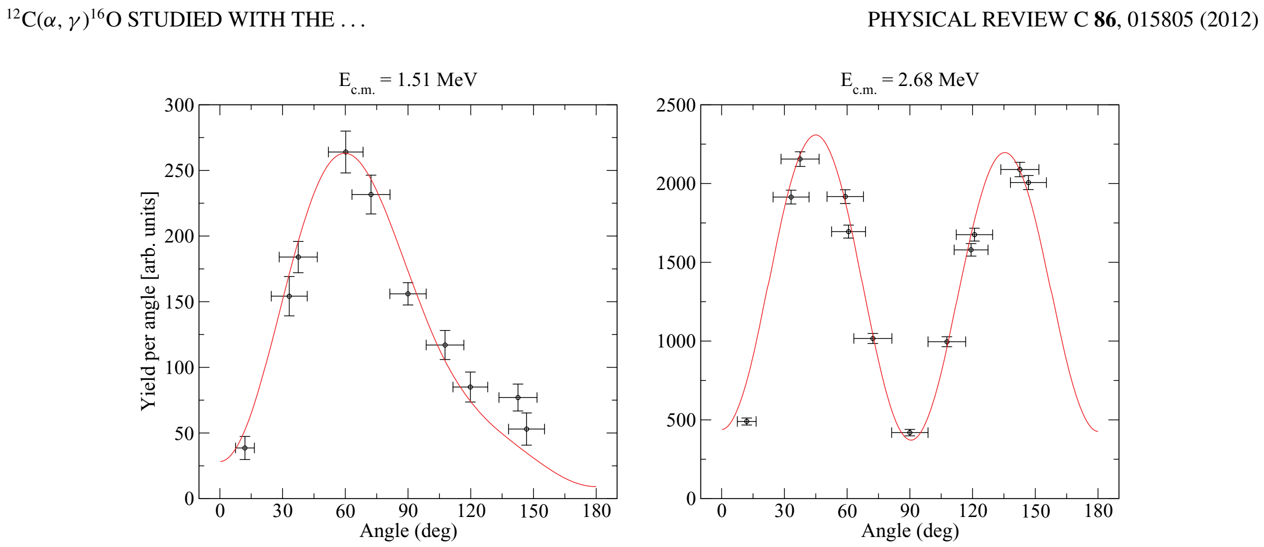
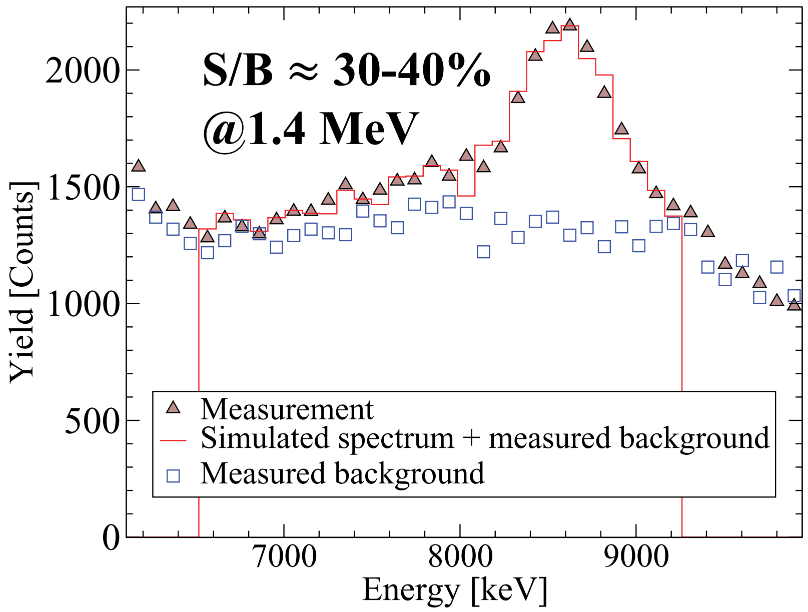
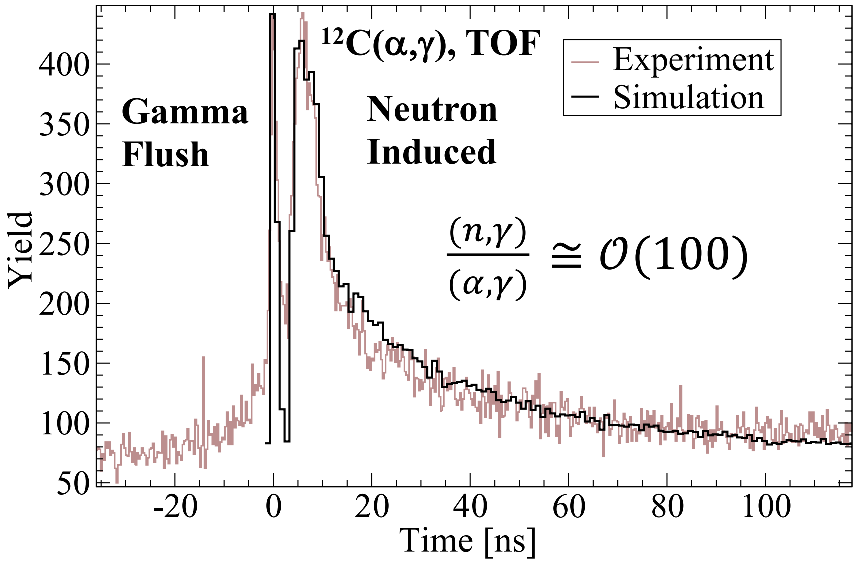


Abbildung C.3: Im Rahmen des EUROGAM-Array-Experiments gemessene γ-Roh-Spektren bei $E_{\mathrm{c.m.}} = 1.666$ MeV. 2.221

R. Plag and R. Reifarth, M. Heil, F. Kaeppeler, G. Rupp, F. Voss, and K. Wisshak, Phys. Rev. C 86, 015805 (2012)



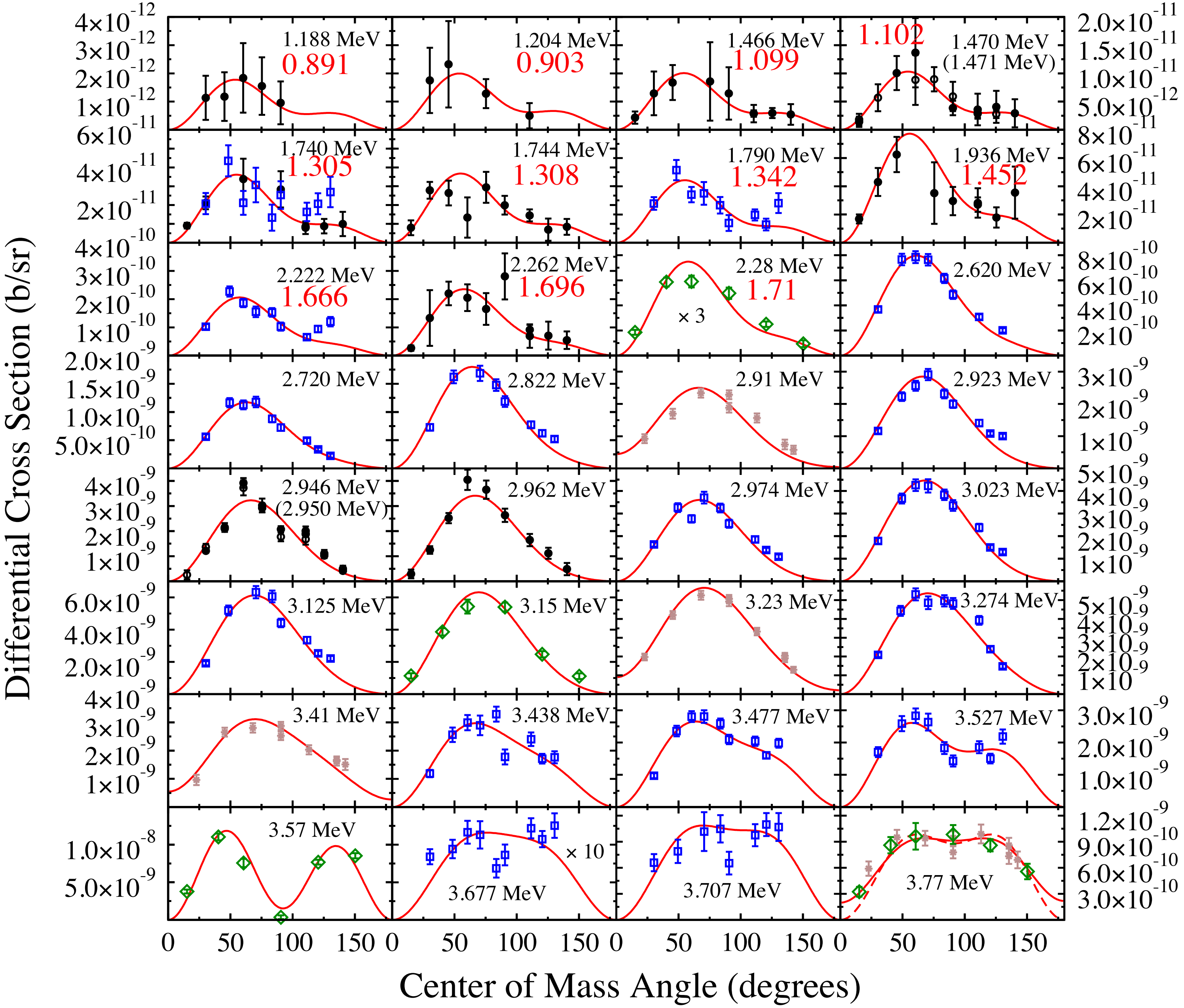




<u>BaF_2/ 4π Array</u> (~10 Angles)
^{13}C depleted x 10^4 👍
TOF Remove $^{13}C(n,\alpha)$ 👍
Pulsed Beam ~ 6 μA
Ecm = 1.51, 1.416, 1.308, 1.002 MeV
ϕ_{12} = 58°, 55°, 62°, 67° (±10% → 19%) 👍

No data between 2.68 and 1.51 ☹

Richard deBoer et al., RMP 89, 03500742 (2017)



1) **deBoer did not use Plag's data**
2) **They rely on the ANC**
3) **The S-factor is derived from Alpha-transfer, e.g. (^{7}Li,t)**
Not from capture gamma-ray
Indirect Method ala 1980's

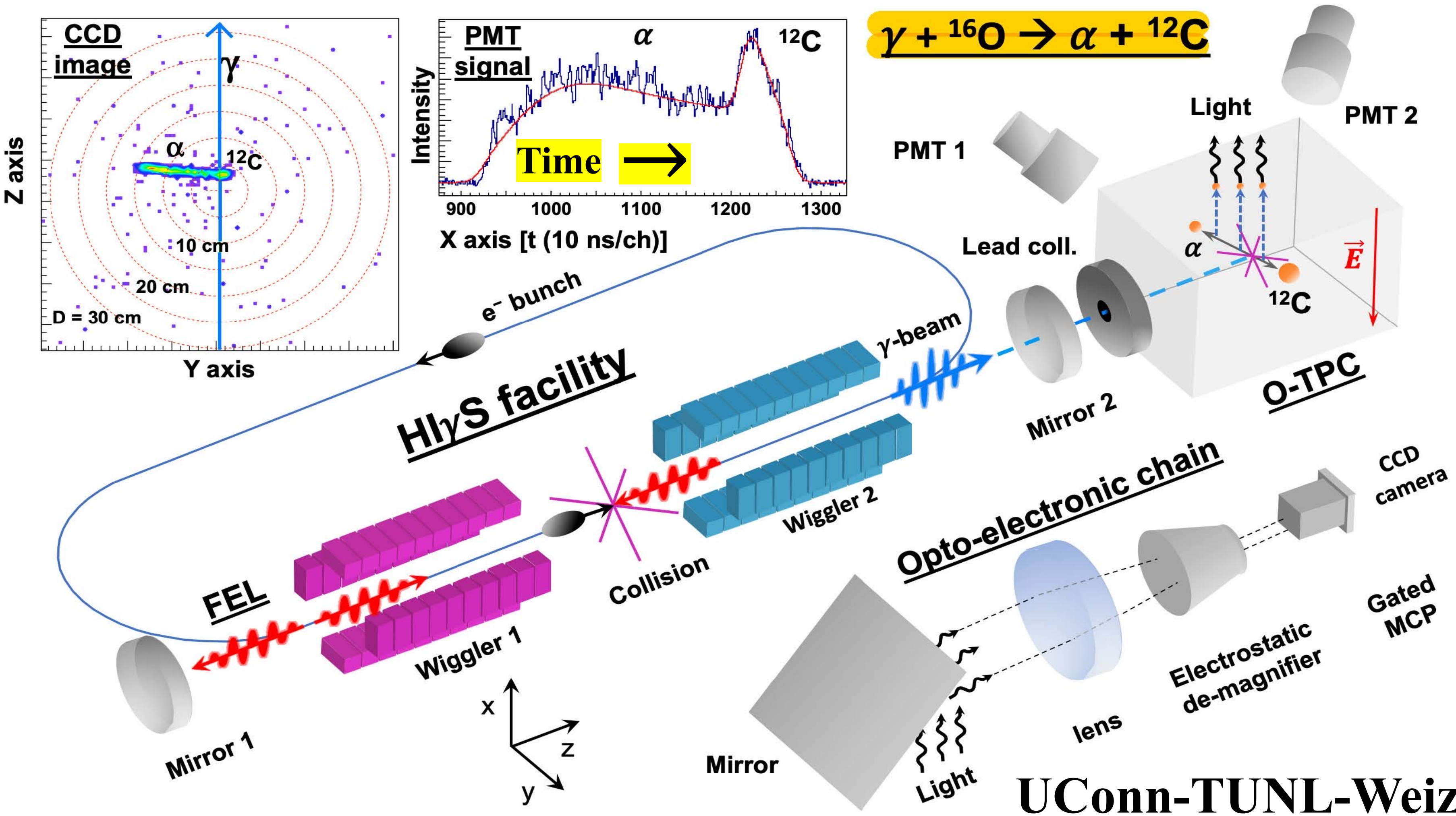
51 years after Dyer & Barnes

This is the status of our field

Detailed Balance: $^{12}C + \alpha \rightarrow {}^{16}O + \gamma$ **(in Stars)**

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

(O-TPC: CO_2)



Active Target TPC

$CO_2(80\%) + N_2(20\%)$

M. Gai *et al*,

JINST 5, 12004 (2010)

UConn-TUNL-Weizmann-PTB (2012)

SHU-UConn-TUNL (2021)

R. Smith, M. Gai, D.K. Schweitzer, S.R. Stern and M.W. Ahmed,
Nature Communications, 12, 5920 (2021).
https://www.nature.com/articles/s41467-021-26179-x

Detailed Balance:

(Inverse, Time Reversed Reaction)

$$\sigma[^{12}C(\alpha,\gamma)^{16}O] = \frac{2\,k_\gamma{}^2}{k_\alpha{}^2}\,\sigma[^{16}O(\gamma,\alpha)^{12}C] \,*$$

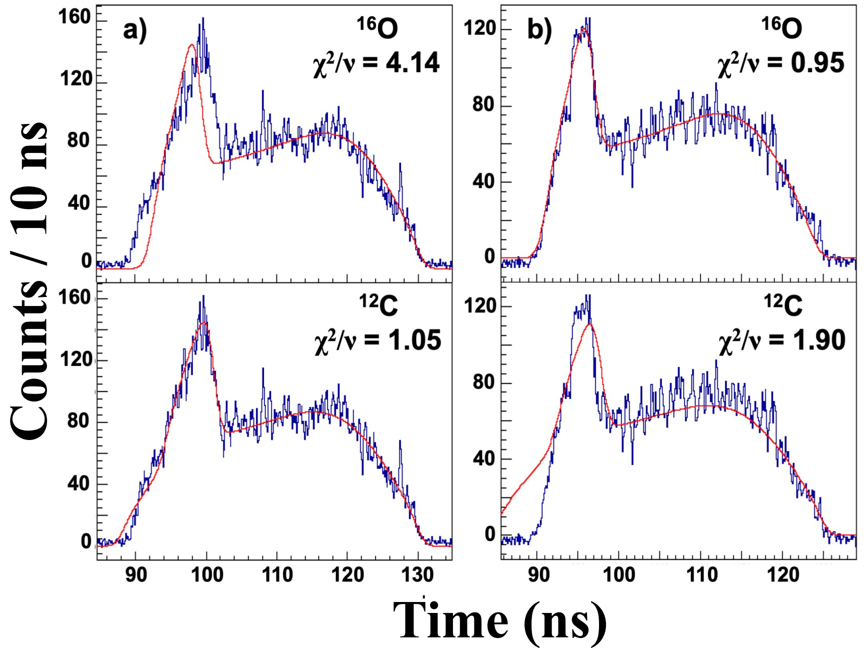
$$\sigma[^{16}O(\gamma,\alpha)^{12}C] \;\approx \sim 50 \text{ x } \sigma[^{12}C(\alpha,\gamma)^{16}O]$$

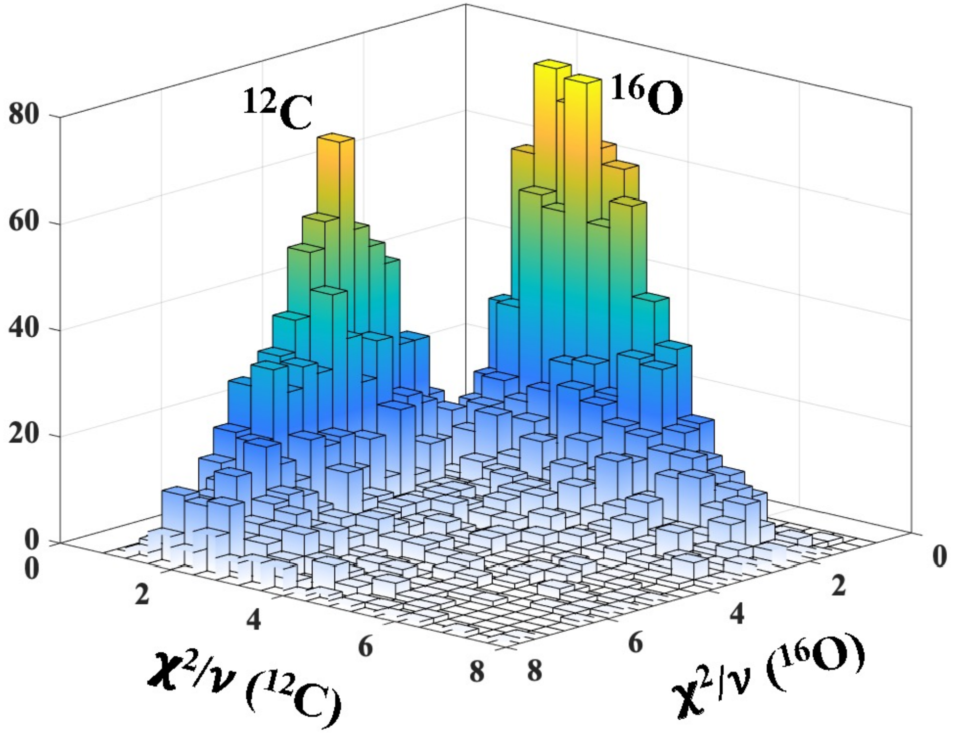
* For Real Photons 2S+1 = 2 (not 3)

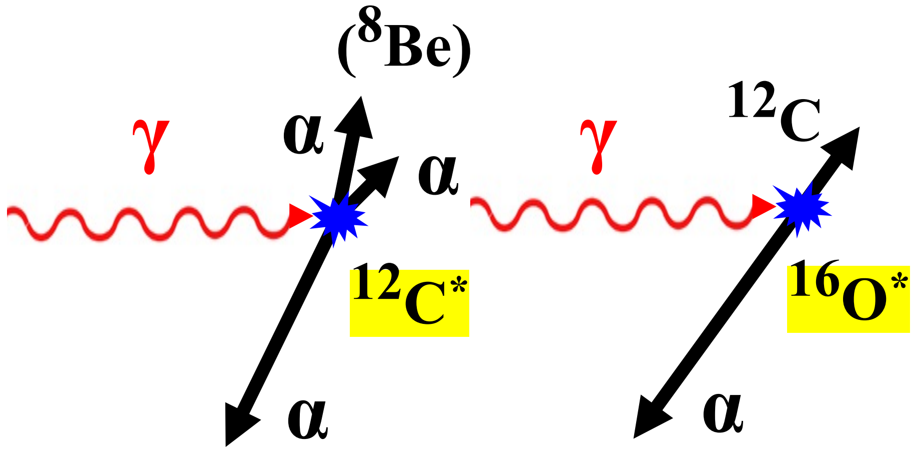
Not a "Surrogate Reaction"

Not an Indirect Measurement

Line Shape Analysis (CO_2 Gas)







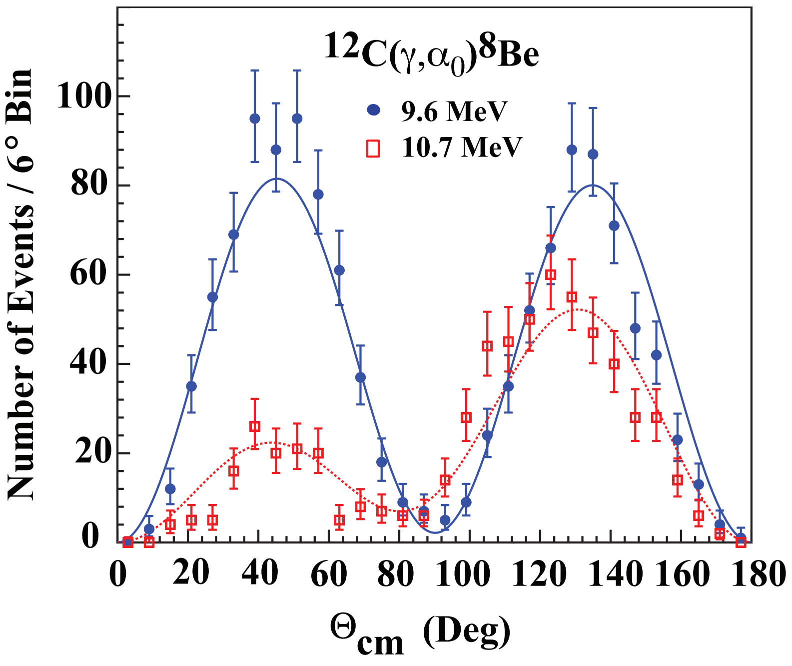
Machine Learning

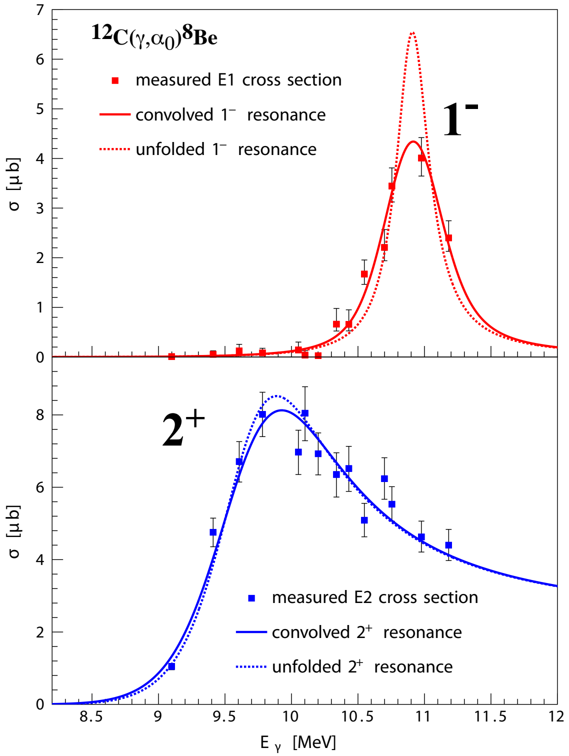
$Q(^{16}O^*) - Q(^{12}C^*) = 112$ keV

UConn-TUNL Optical Readout TPC (O-TPC)

$^{12}C(\gamma,3\alpha)$

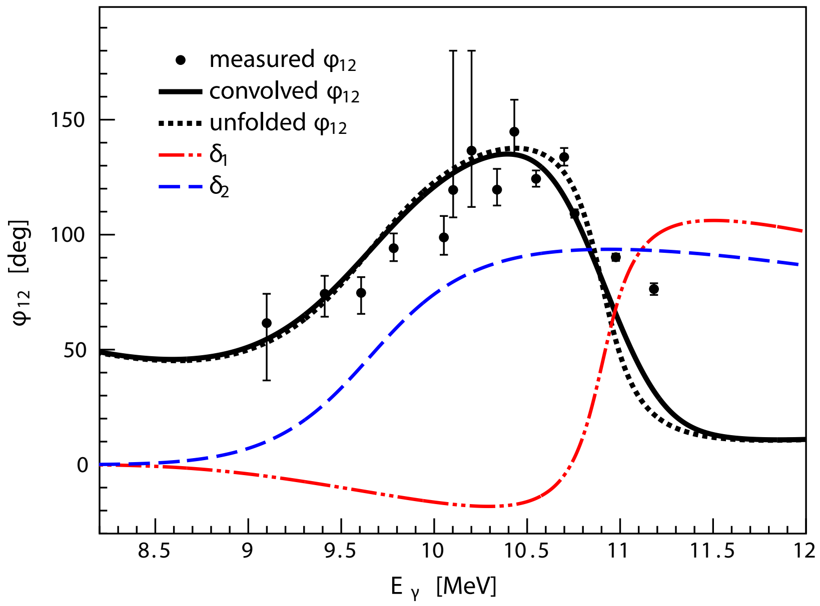
	9.6 MeV	10.7 MeV
E2/(E1+E2) =	0.97 ± 0.02	0.71 ± 0.05
ϕ_{12} =	80 ± 6°	132 ± 5°





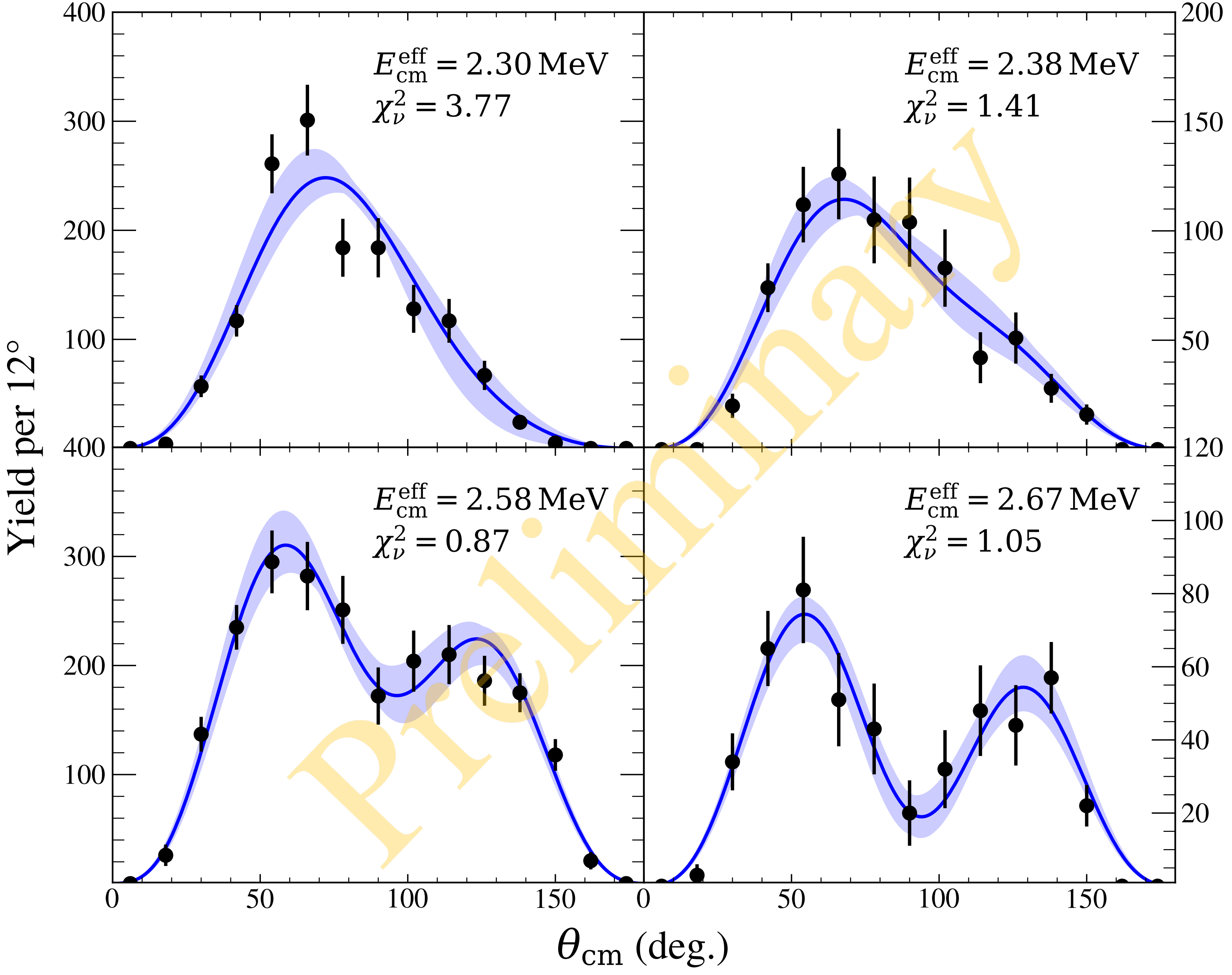
W.R. Zimmerman *et al.*; Phys. Rev. Lett. 110(2013)152502

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



<u>R-Matrix Fit:</u> $\Gamma\gamma(1^-) = 29 \pm 2.1$ meV $B(E1) = 6.5\times10^{-5}$ W.u.

$\Gamma\gamma(2^+) = 182\ ^{+43}_{-53}$ meV $B(E2) = 1.2$ W.u.



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

O-TPC Data N_2O gas
Angular distributions measured at 17 angles

Kristian C.Z. Haverson
@ SHU, UConn-SHU (2024)

O-TPC (Nature + N_2O) Data Benchmarked against World Data
First Agreement of data on ϕ_{12} with Quantum Mechanics