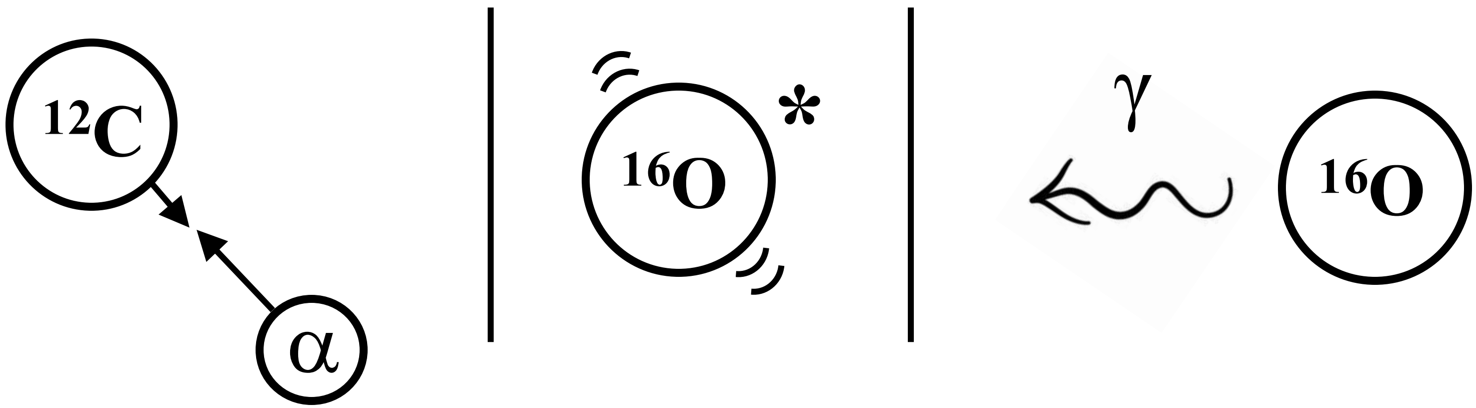
The $^{12}C(\alpha,\gamma)^{16}O$ reaction using TPC detectors and gamma beams



Robin Smith

Sheffield Hallam University

UCONN UNIVERSITY OF CONNECTICUT

HELIUM25, Helmholtz-Zentrum Dresden-Rossendorf – July 23rd 2025

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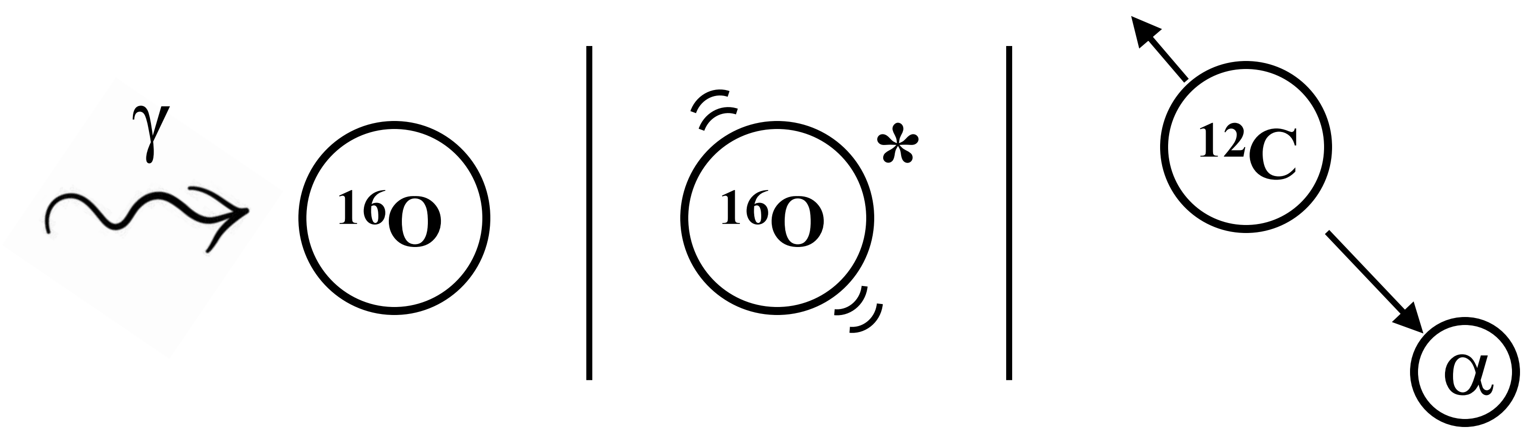

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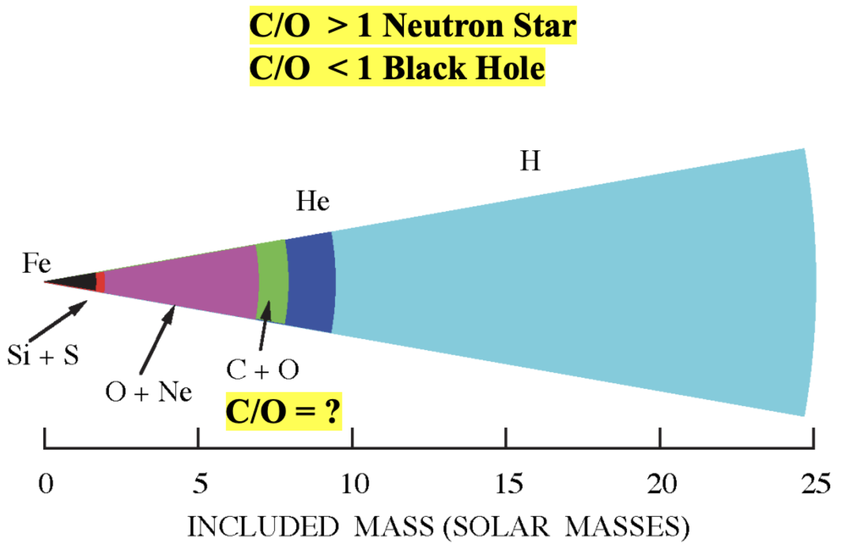
- Photo-dissociation with gamma beams at HIgS
- Warsaw TPC detector
- Data analysis and preliminary results



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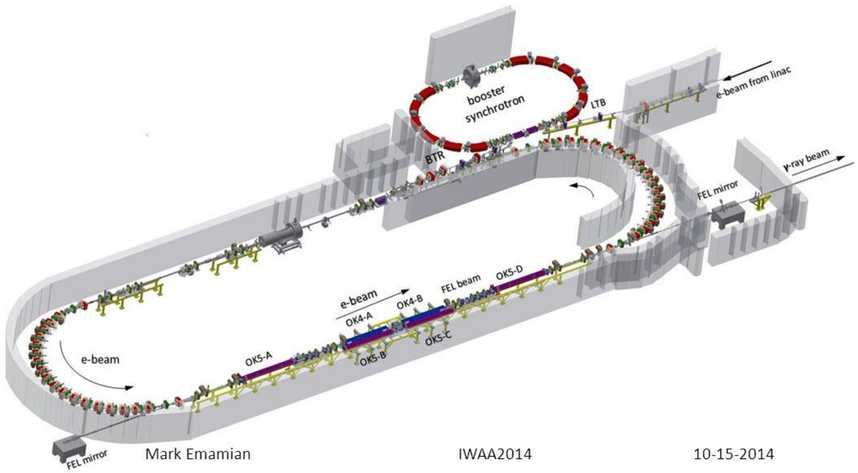

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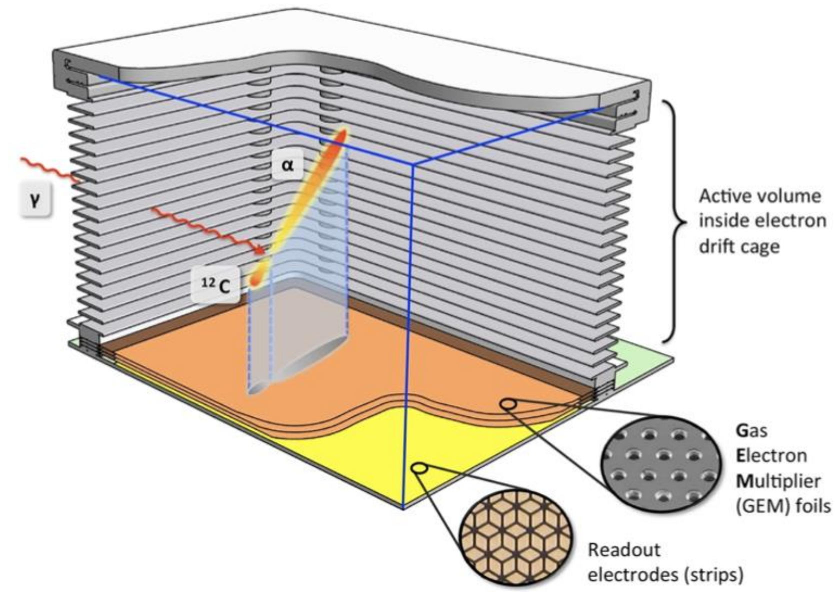

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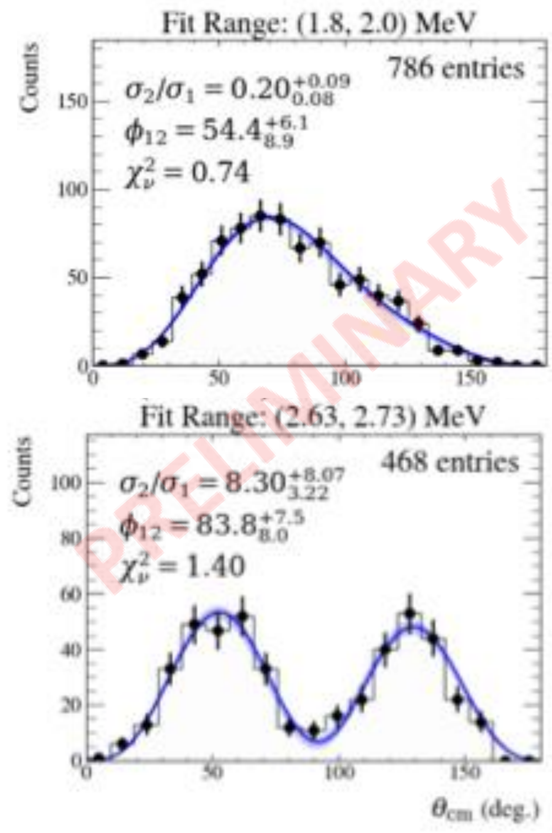

Stellar helium burning

- The ratio of carbon-to-oxygen C/O after helium burning is important

- Later aspects of stellar evolution and nucleosynthesis
  - Composition of White Dwarfs
  - Yield of intermediate-mass isotopes (C, Ne, O burning etc.)
  - Influence on explosive burning
    - Type Ia supernovae light curves
    - Final states of massive stars after SNeII

T. Rauscher, A. Heger, R. D. Hoffman, and S. E. Woosley, Astrophys. J. **576**, 323 (2002).
W.A. Fowler, Rev. Mod. Phys. **56** (1984) 149.

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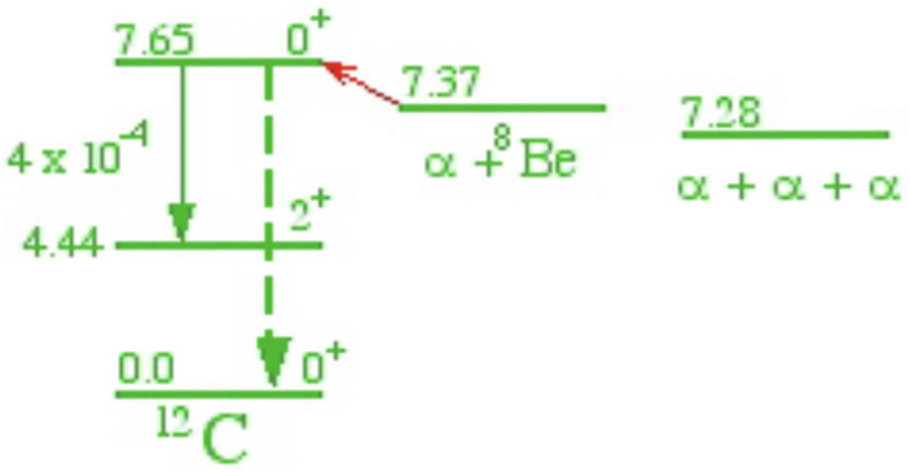
Triple-α reaction rate is well-constrained



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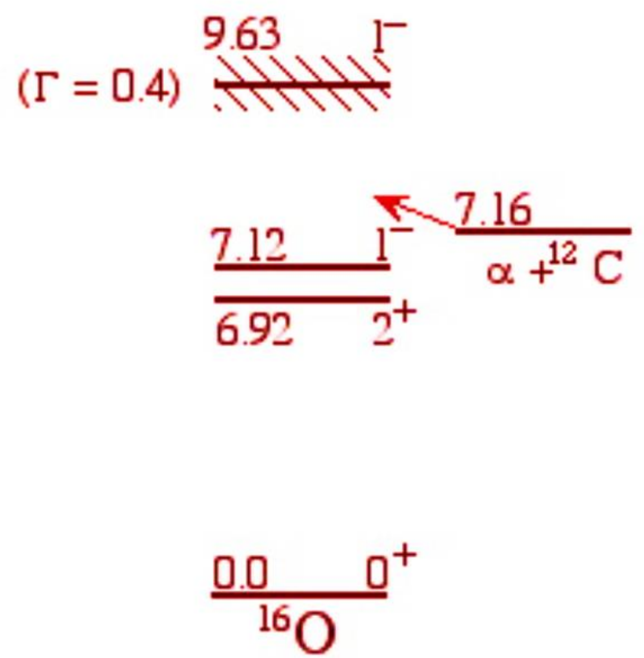
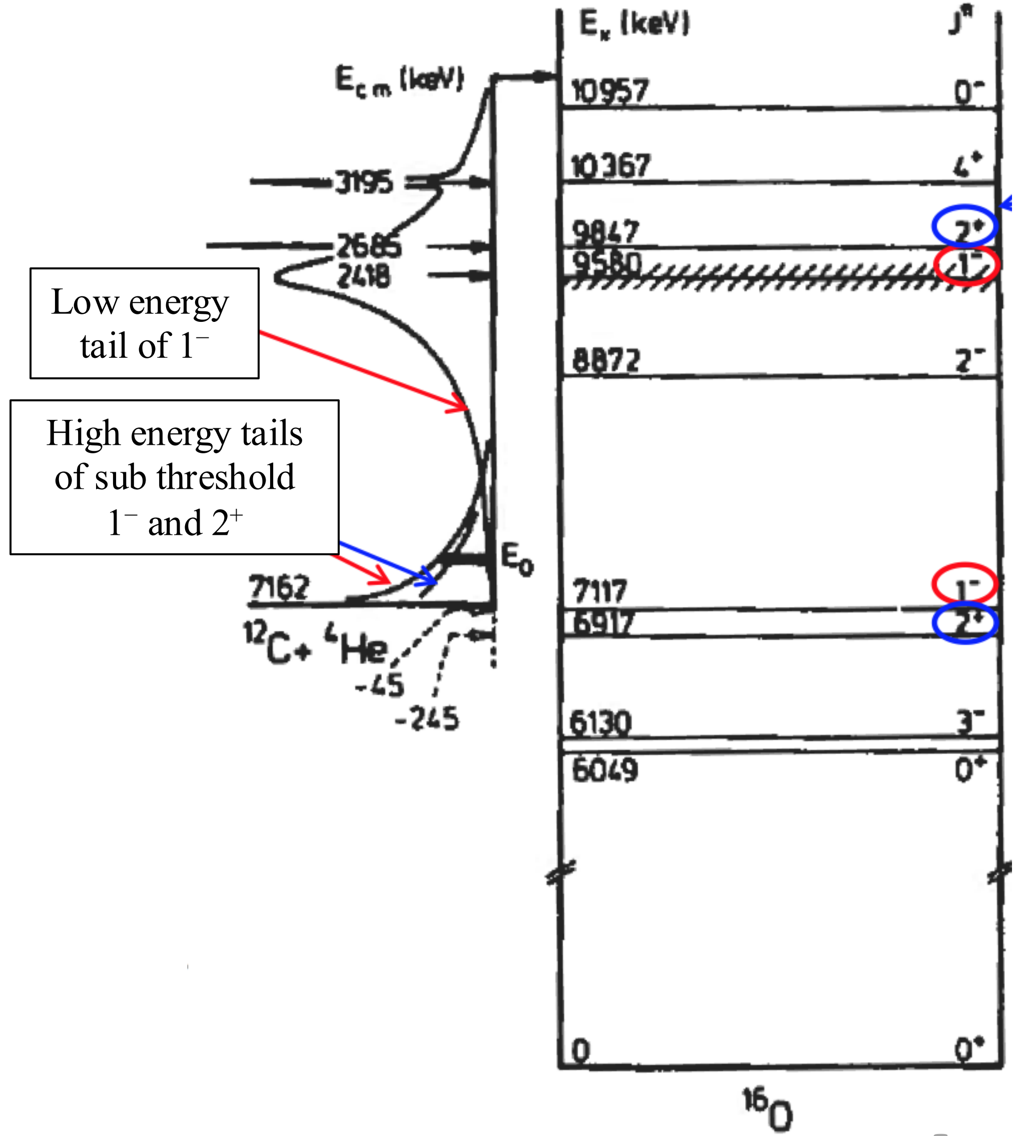
"The single most important nuclear physics uncertainty in astrophysics"



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

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

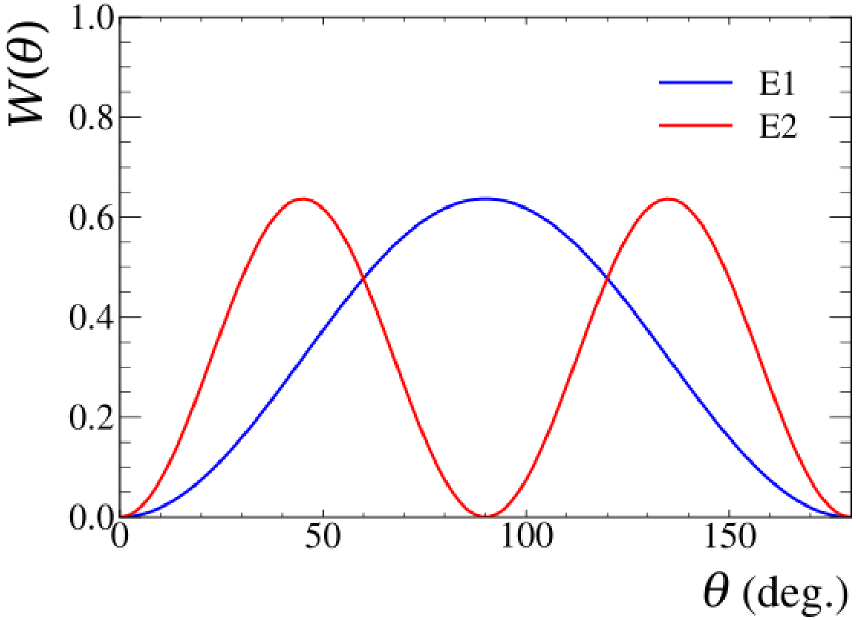
- Extrapolation to astrophysical energies relies on disentangling E1 and E2 partial cross sections
    - Precise angular distributions needed
    - Arguably existing datasets are subject to systematic uncertainties e.g. $^{13}C(\alpha,n)$ or high Q-value (n,γ) on nearby materials

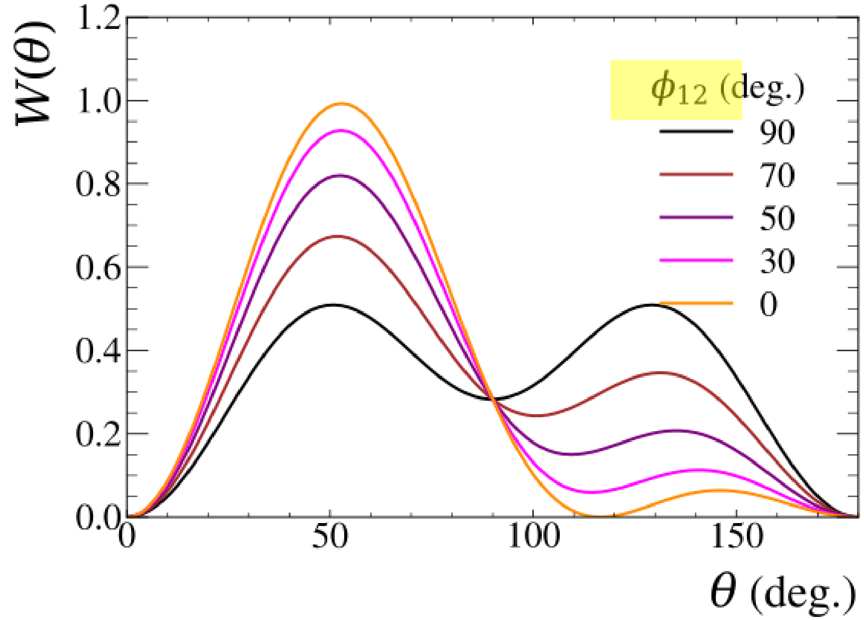


C. E. Rolfs, W. S. Rodney. *Cauldrons in the cosmos.* University of Chicago press, 1988.

Systematic uncertainties – ϕ_{12}

$$
\begin{aligned}
W(\theta) = &(3|A_{E1}|^2 + 5|A_{E2}|^2)P_0(\cos\,\theta) \\
&+ \left({}^{25}/_{7}|A_{E2}|^2 - 3|A_{E1}|^2\right) P_2(\cos\,\theta) \\
&- {}^{60}/_{7}|A_{E2}|^2 P_4(\cos\,\theta) \\
&+ 6\sqrt{3}|A_{E1}||A_{E2}|\cos\,\phi_{12}\,[P_1(\cos\,\theta) - P_3(\cos\,\theta)]
\end{aligned}
$$





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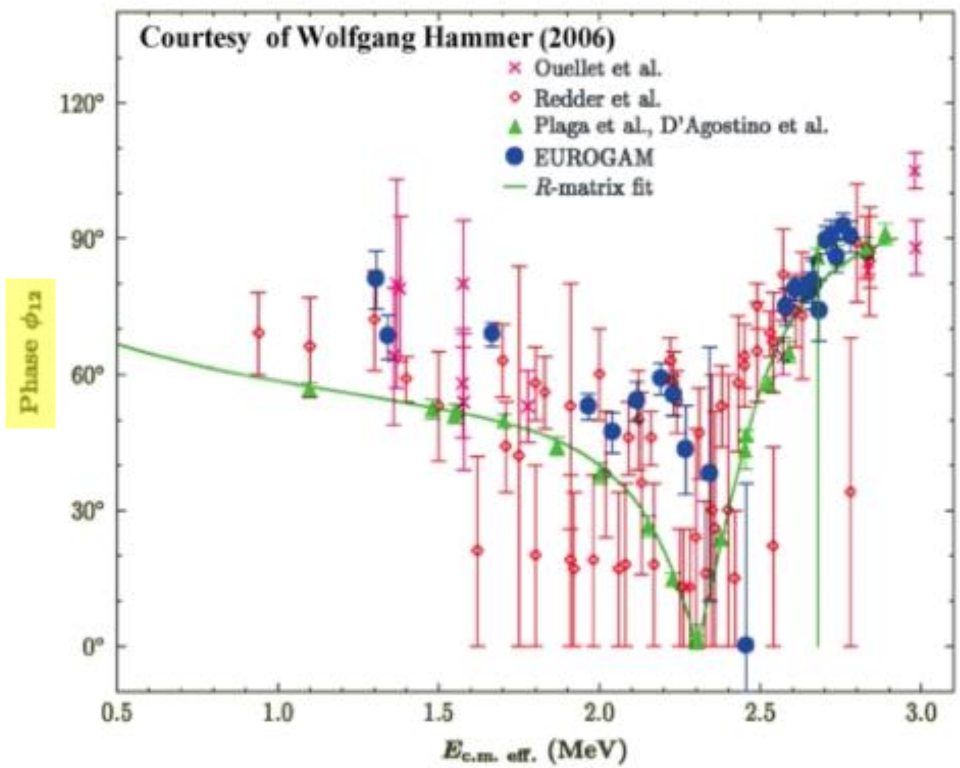

Figure prepared in 2006 by Professor Wolfgang Hammer, then senior leader of the Stuttgart group.

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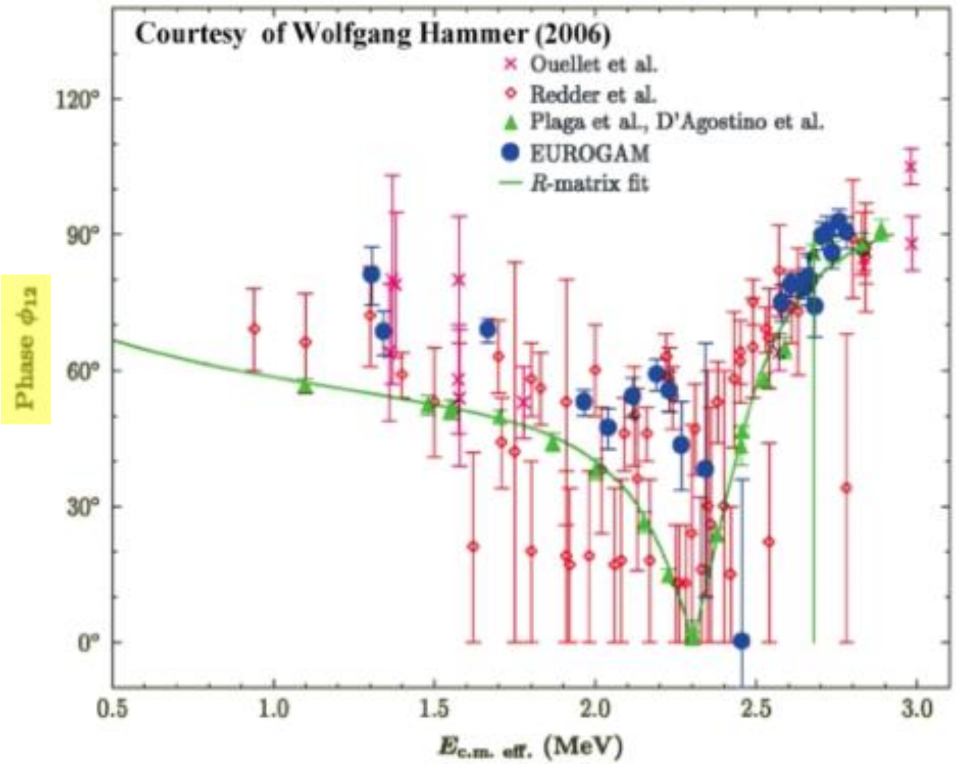
$$\phi_{12} = \delta_2 - \delta_1 + \tan^{-1}(\eta/2)$$



- The mixing phase angle can be calculated from elastic scattering phase shifts ▲
- Some past data sets show troubling disagreement with this fundamental prediction of quantum mechanics ●
- Fixing ϕ_{12} according to the elastic scattering data substantially changes the extracted E2/E1

M. Gai. Phys. Rev. C 88, 062801(R) (2013).732

Systematic uncertainties – ϕ_{12}

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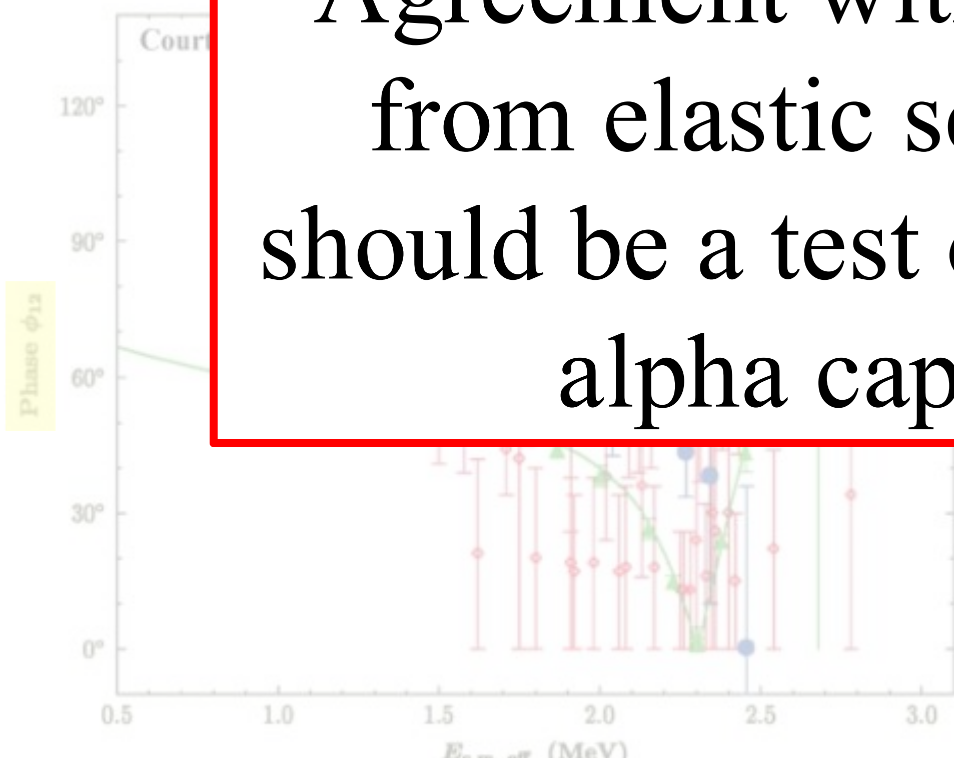

Agreement with ϕ_{12} extracted from elastic scattering data should be a test of the quality of alpha capture data

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quantum mechanics

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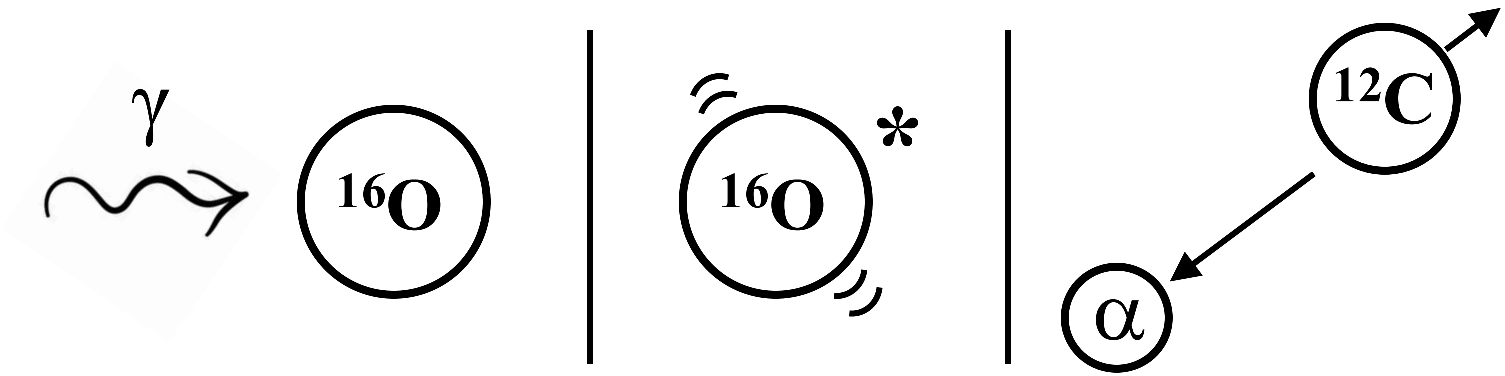
New Method – photo-dissociation

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



- Cross section is boosted by a detailed balance factor (×20 at Gamow window, ×60–80 in our energy region)
- Precisely measuring the final state particles elucidates detailed angular distributions and reaction energy
- **Require high intensity gamma beam and high-resolution charged particle detector (TPC)**

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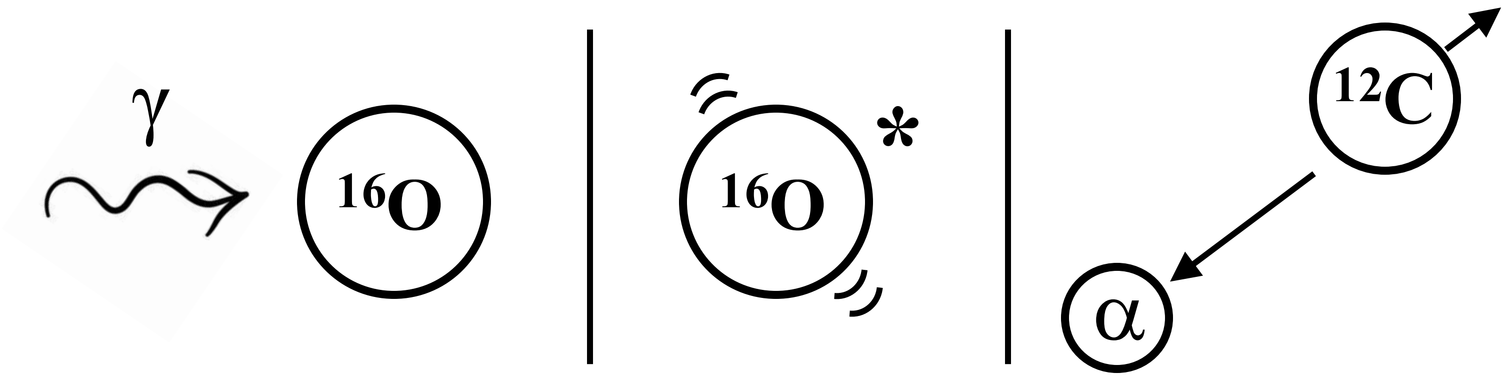

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Historical measurement

Volume 33B, number 4 PHYSICS LETTERS 26 October 1970

A TEST OF TIME REVERSAL INVARIANCE THROUGH DETAILED BALANCE OF THE REACTION $^{12}C(\alpha,\gamma)^{16}O$

U. Von WIMMERSPERG, G. KERNEL, B. W. ALLARDYCE, W. M. MASON and N. W. TANNER
Nuclear Physics Laboratory, Oxford, UK

Received 1 September 1970

The angular distributions of $^{12}C(\alpha,\gamma)^{16}O$ and its inverse $^{16}O(\gamma,\alpha)^{12}C$ have been measured at an excitation of 13.1 MeV where there is a strong asymmetry favouring the forward direction due to E1/E2 interference. The asymmetries for (α,γ) and (γ,α) were the same within one standard deviation, and reveal no evidence of a failure of time reversal invariance.

U. Von Wimmersperg, *et al.,* Physics Letters B 33, no. 4 (1970): 291-293.

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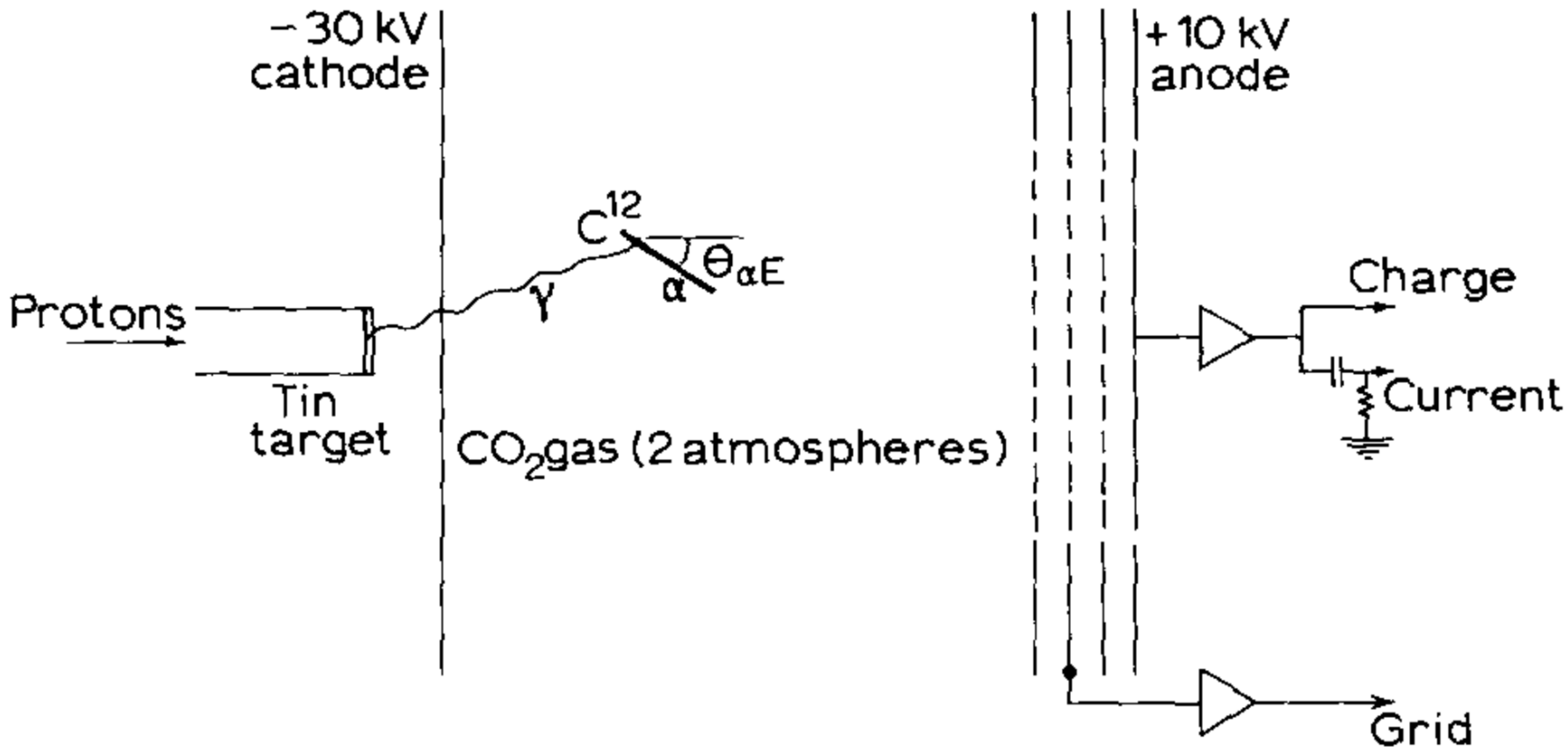

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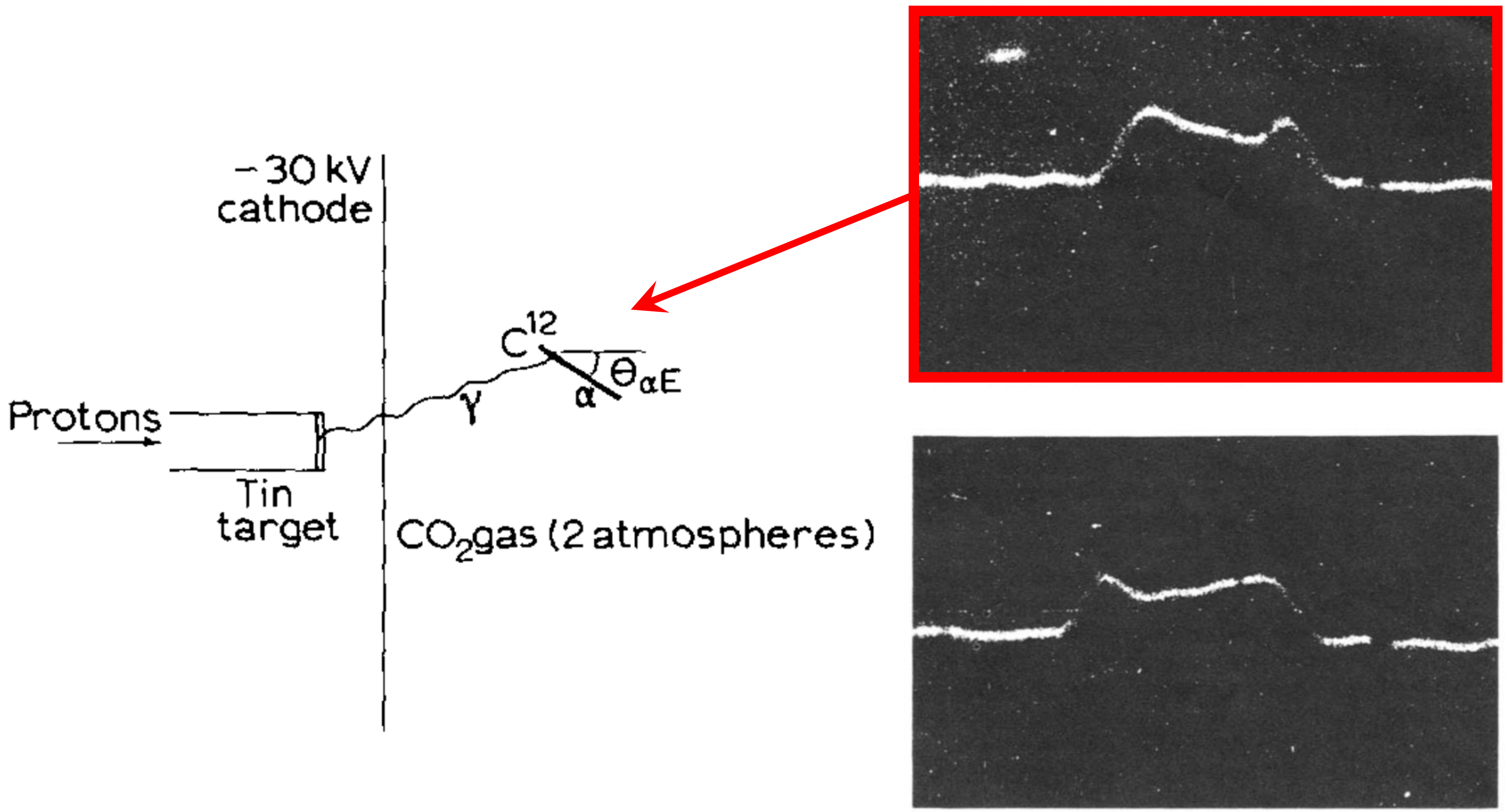

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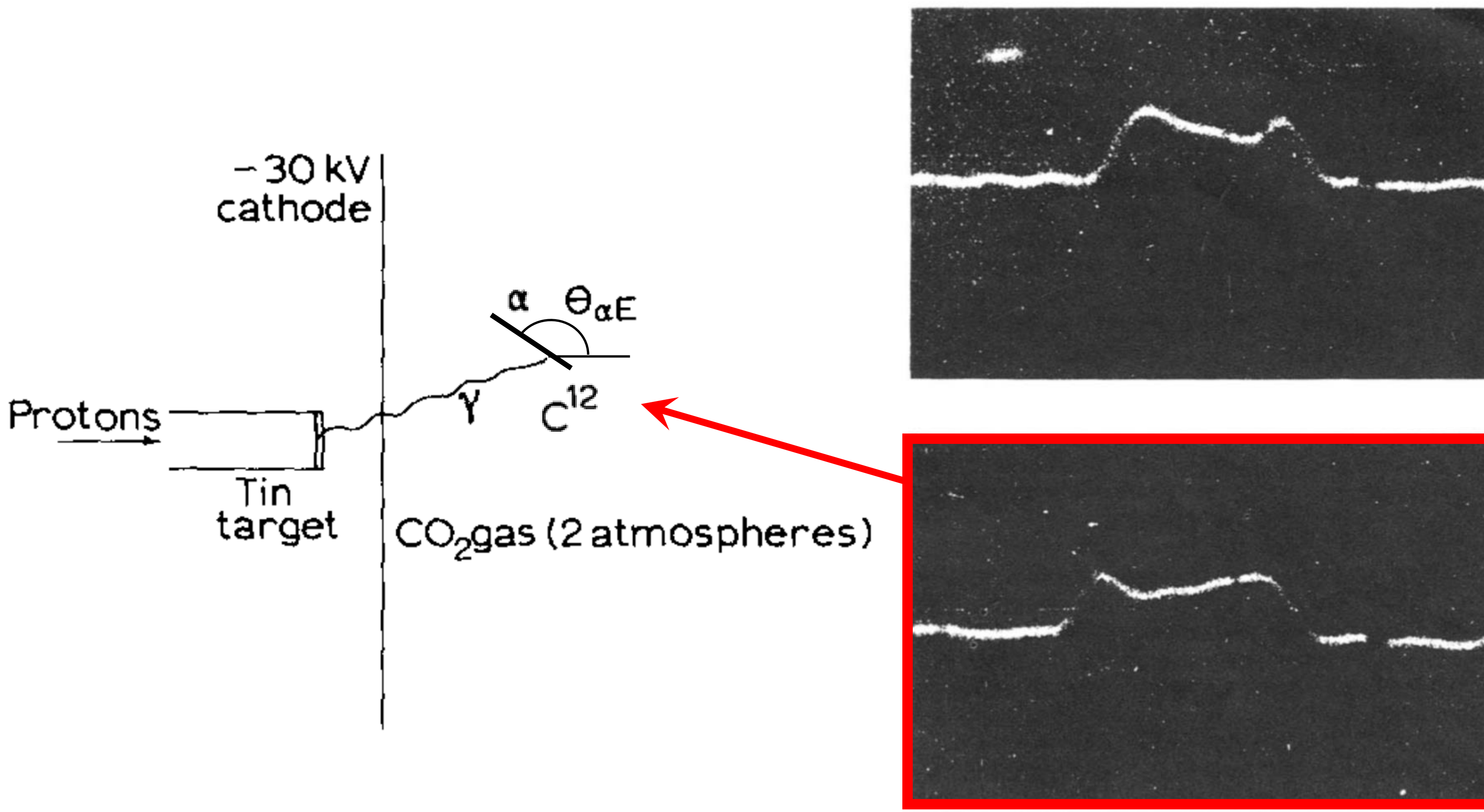

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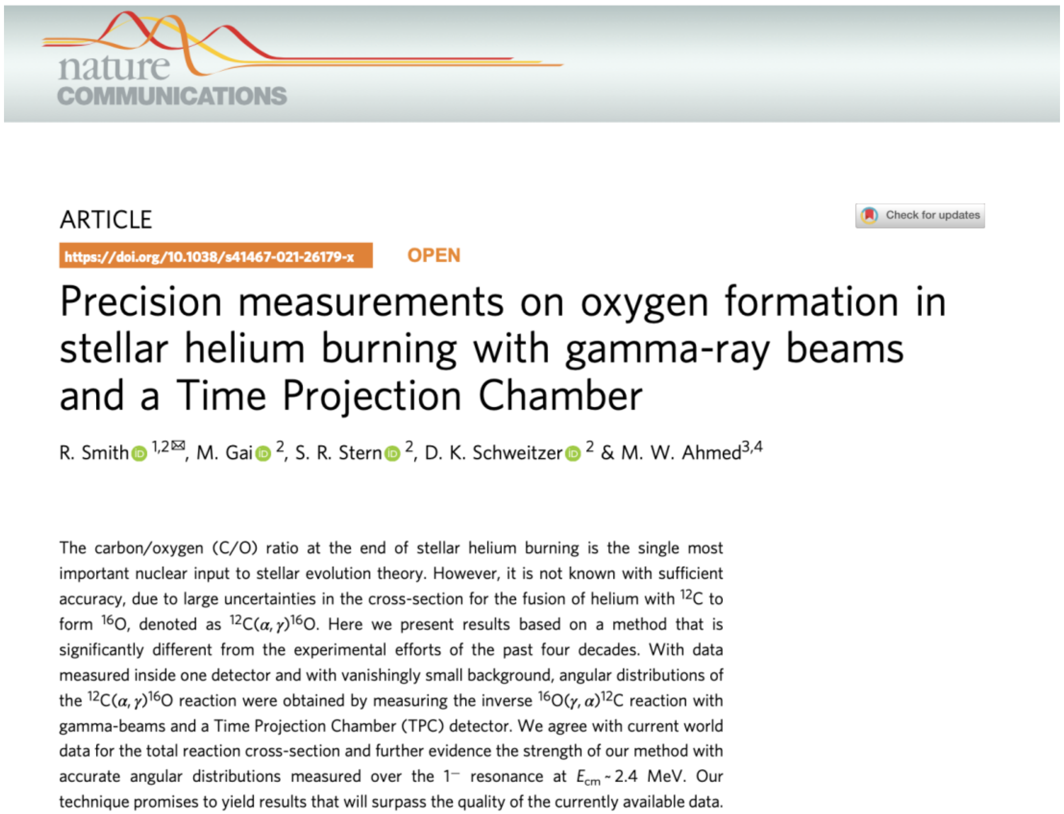
Optical TPC work

- Proof-of-principle TPC measurements were performed previously


nature COMMUNICATIONS

ARTICLE

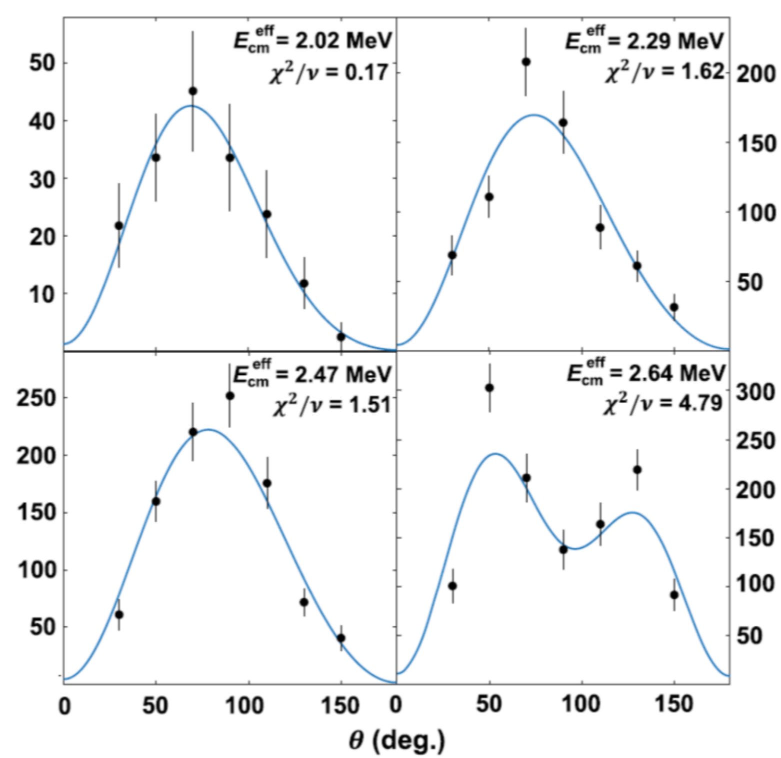
Check for updates

https://doi.org/10.1038/s41467-021-26179-x OPEN

Precision measurements on oxygen formation in stellar helium burning with gamma-ray beams and a Time Projection Chamber

R. Smith[1,2✉], M. Gai[2], S. R. Stern[2], D. K. Schweitzer[2] & M. W. Ahmed[3,4]

The carbon/oxygen (C/O) ratio at the end of stellar helium burning is the single most important nuclear input to stellar evolution theory. However, it is not known with sufficient accuracy, due to large uncertainties in the cross-section for the fusion of helium with ^{12}C to form ^{16}O, denoted as $^{12}C(\alpha,\gamma)^{16}O$. Here we present results based on a method that is significantly different from the experimental efforts of the past four decades. With data measured inside one detector and with vanishingly small background, angular distributions of the $^{12}C(\alpha,\gamma)^{16}O$ reaction were obtained by measuring the inverse $^{16}O(\gamma,\alpha)^{12}C$ reaction with gamma-beams and a Time Projection Chamber (TPC) detector. We agree with current world data for the total reaction cross-section and further evidence the strength of our method with accurate angular distributions measured over the 1^- resonance at E_{cm} ~ 2.4 MeV. Our technique promises to yield results that will surpass the quality of the currently available data.



R. Smith, M. Gai, *et al.*, *Nature Communications* 12.1 (2021): 5920.

K. C. Z. Haverson, R. Smith, M. Gai, *et al. Nature Communications Physics*, to be submitted July 2025

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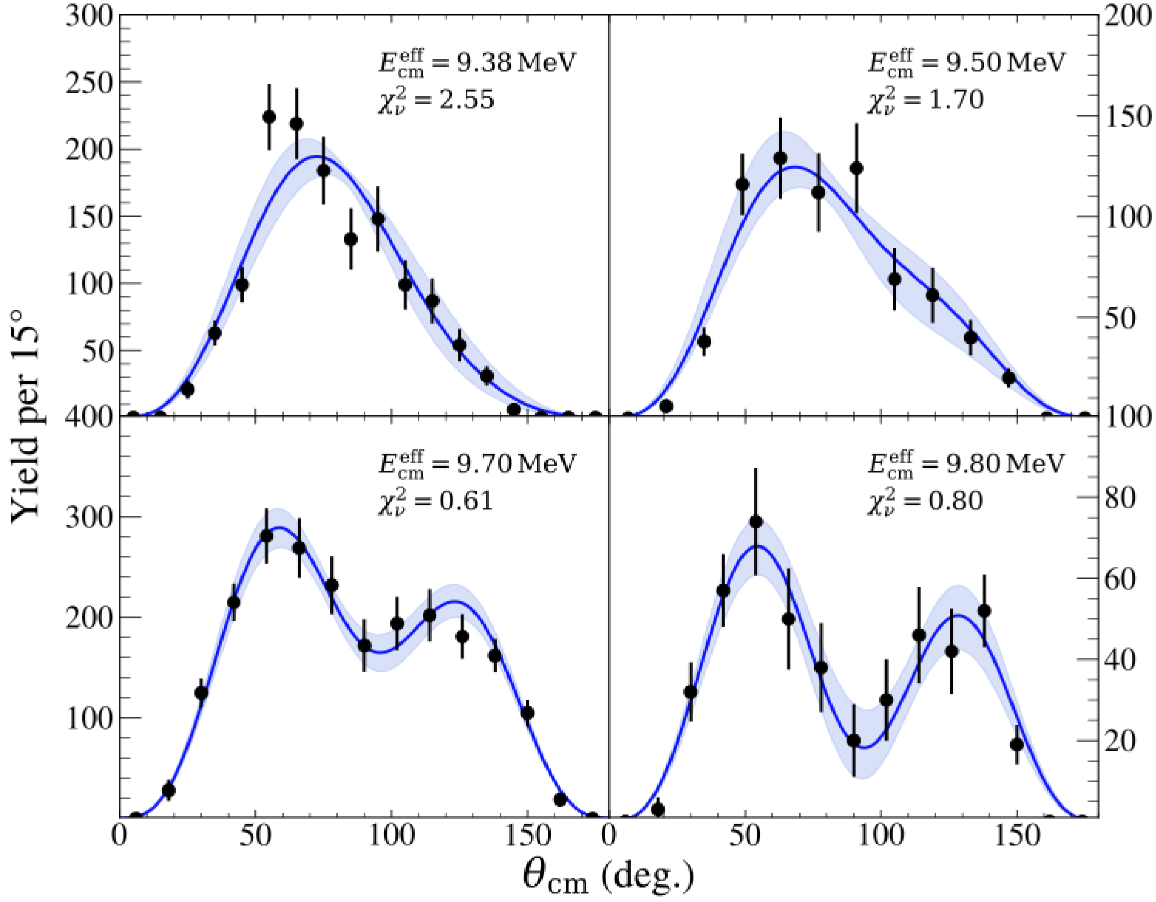

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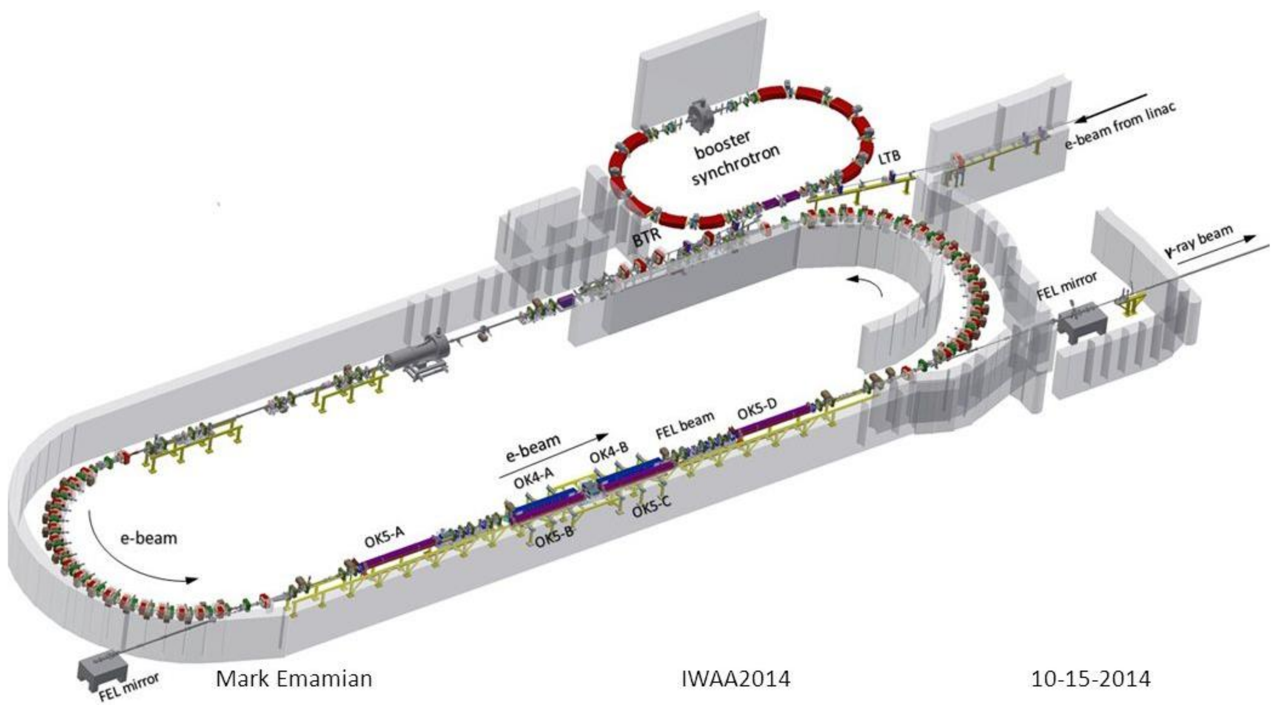
HIγS facility

- Free electron laser – λ = 190 – 1064 nm
- Compton backscattering increases the γ energy



H.R. Weller *et al.*, Progress in Particle and Nuclear Physics **62** (2009)

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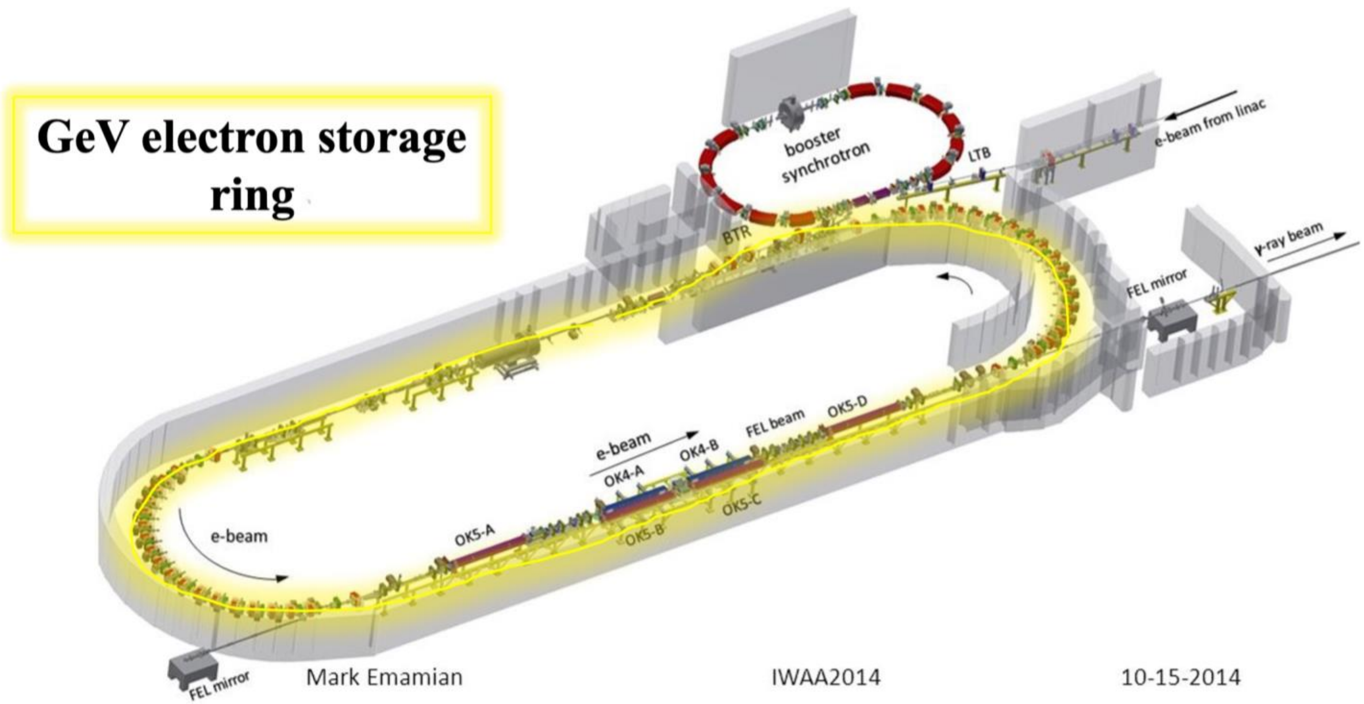

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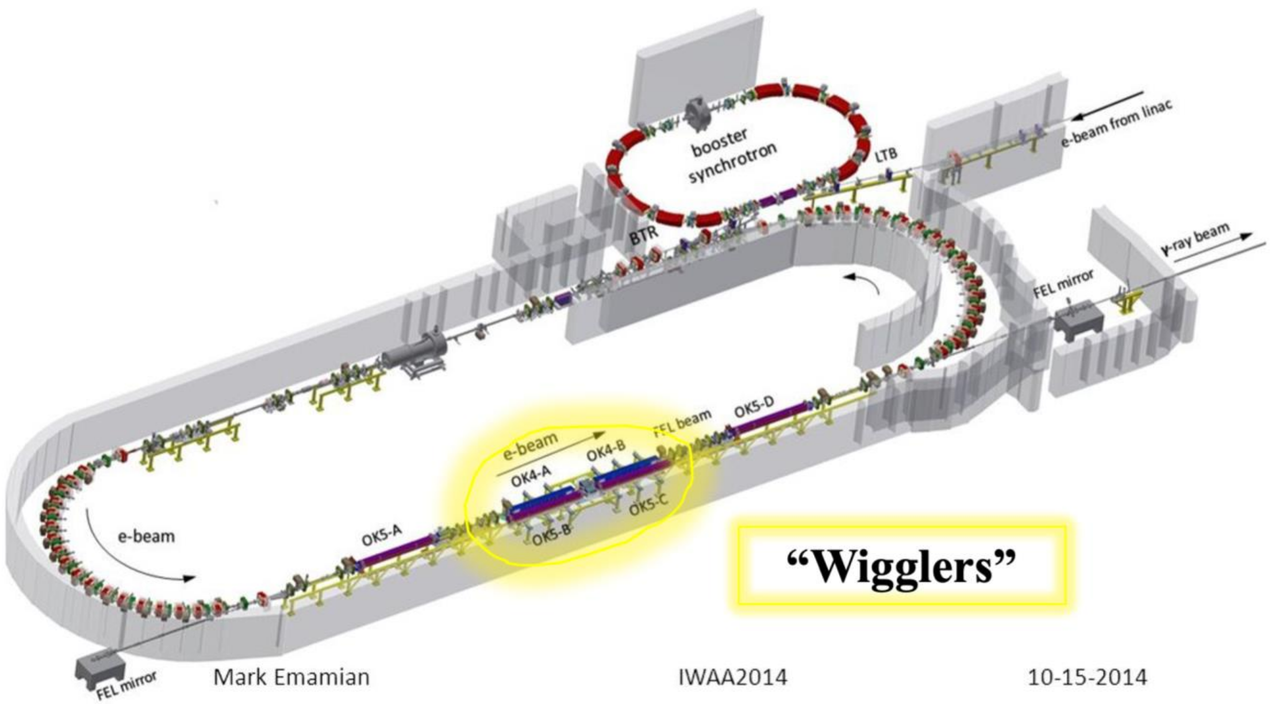

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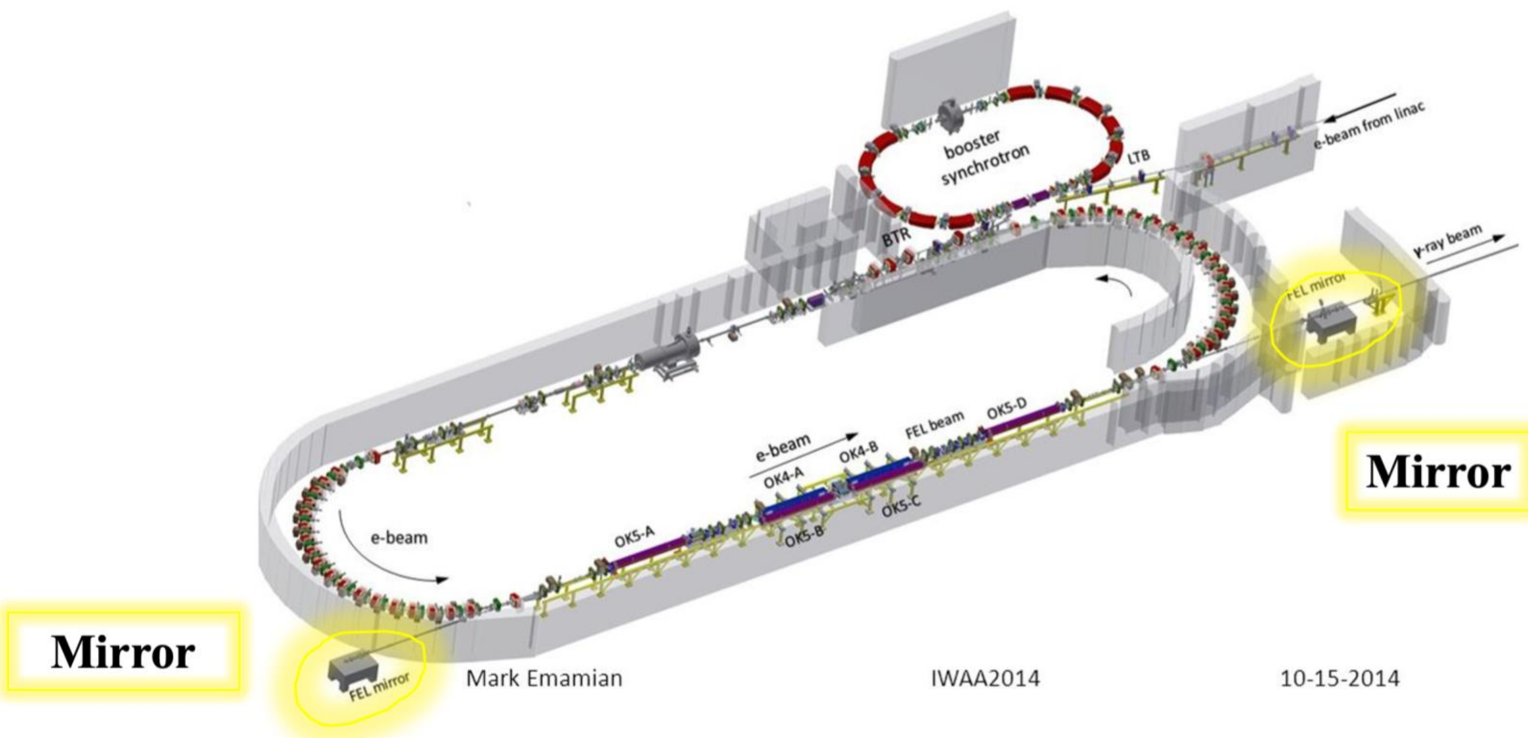

H.R. Weller *et al.*, Progress in Particle and Nuclear Physics **62** (2009)

HIγS facility + TPC

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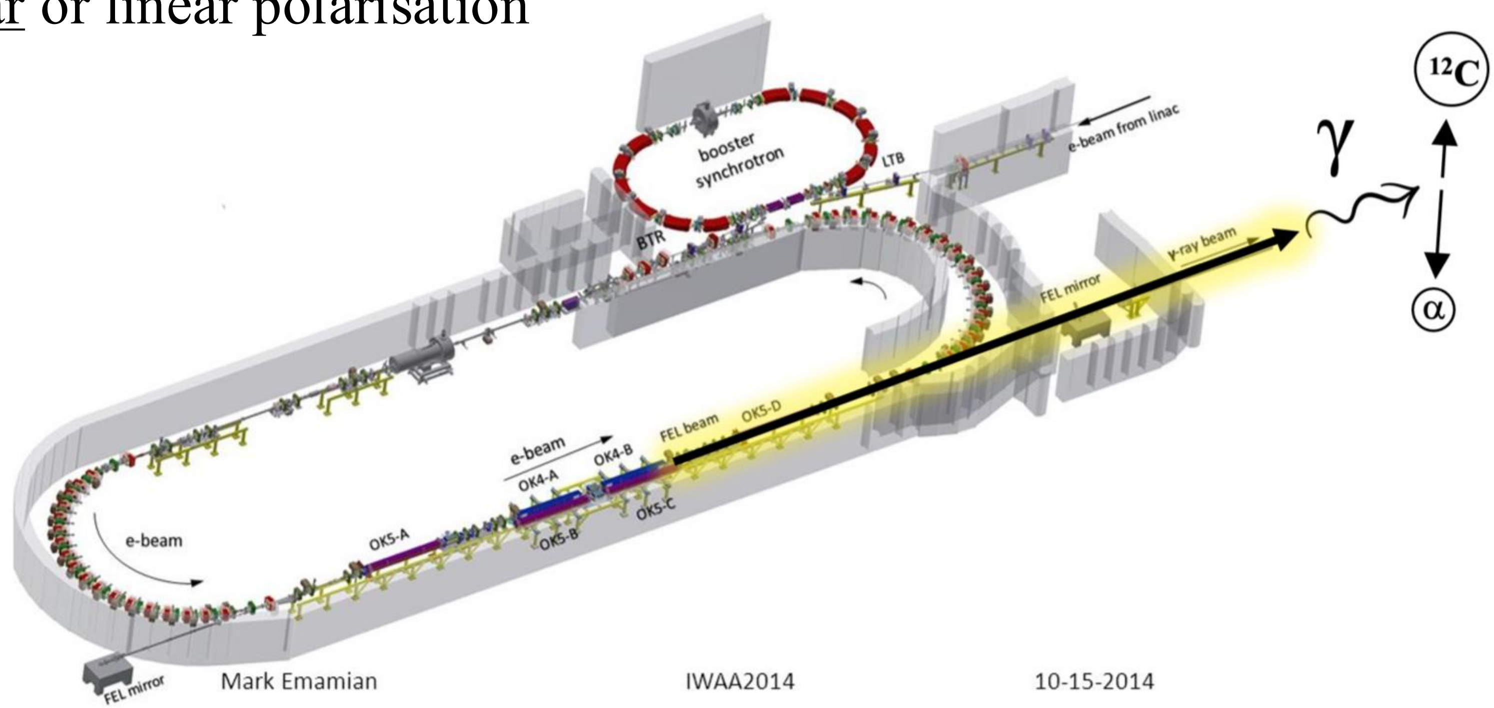
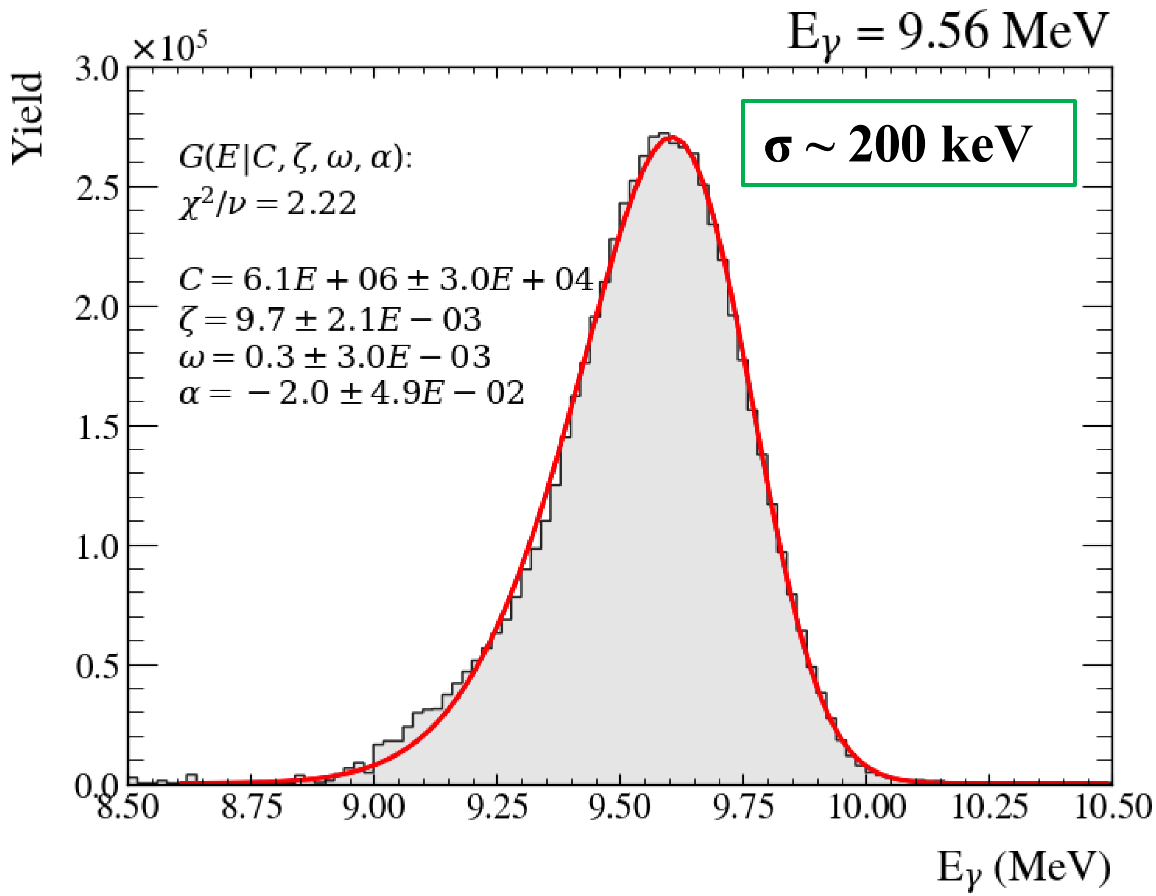
- *Active Target* TPC operating with CO_2 gas
- <u>Circular</u> or linear polarisation



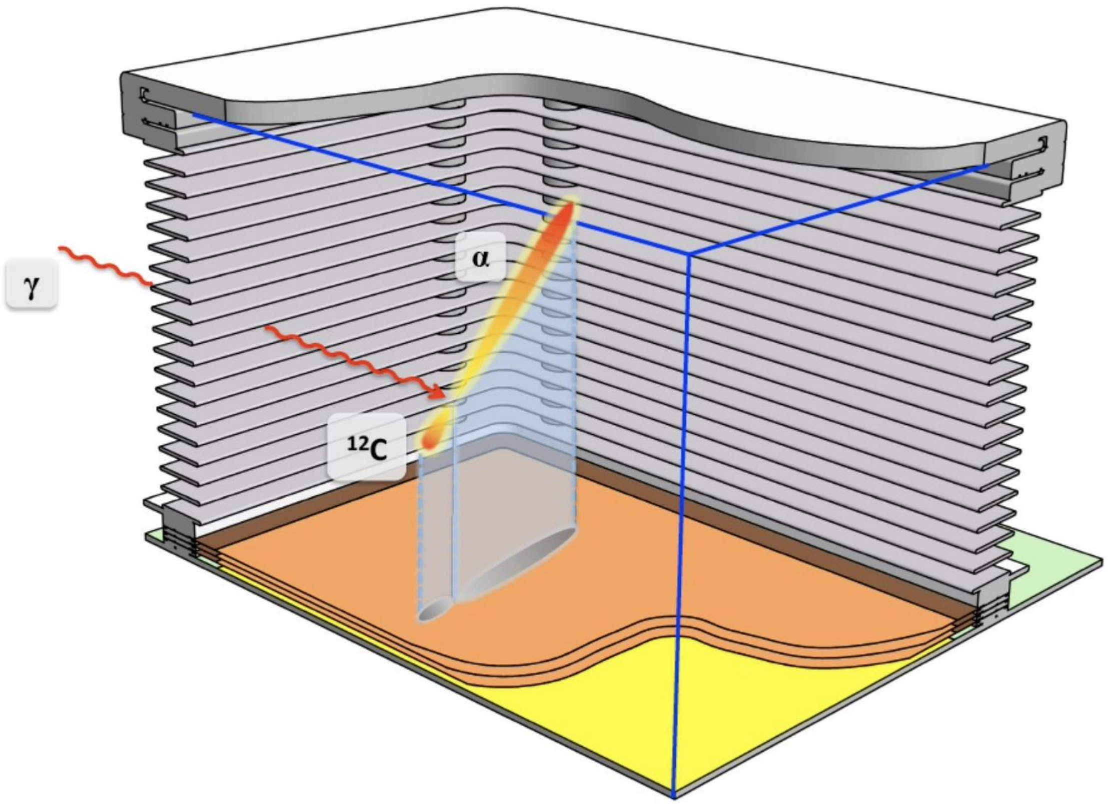
H.R. Weller *et al.*, Progress in Particle and Nuclear Physics **62** (2009)

γ-beam characterisation

- Energy spectrum of attenuated beam measured in HPGe detector
- Measured spectrum unfolded (Geant4-based response matrix)
- Total beam intensity monitored using foil activation



Detector – Warsaw TPC



Active volume
33 x 20 cm^2 (readout) x 20 cm (drift)

Charge amplification
Gas Electron Multiplier (GEM) structures

Readout
Planar, 3-coordinate, redundant strip arrays, ~1000 channels
GET electronics
100 Hz triggering

M. Ćwiok *et al.* Acta Phys.Pol. B, 49:509, 2018.
Gai, M., *et al.* (2020). *Nuclear Instruments and Methods in Physics Research Section A*, *954*, 161779.
M. Kuich et al., Acta Phys. Pol. B Proc. Suppl. 16 (2023) 4-A17.
M. Ćwiok et al., EPJ Web Conf. 290 (2023) 01004

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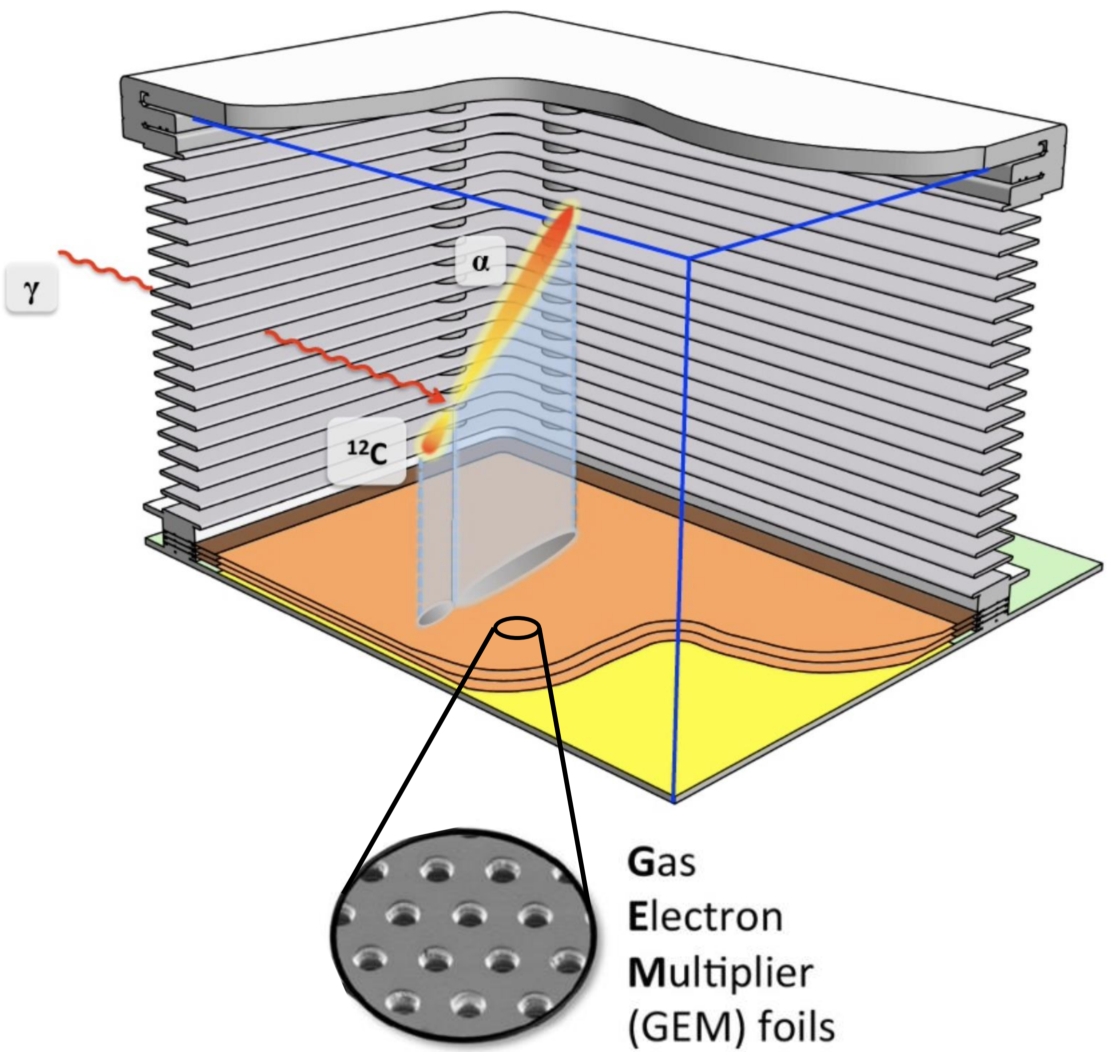

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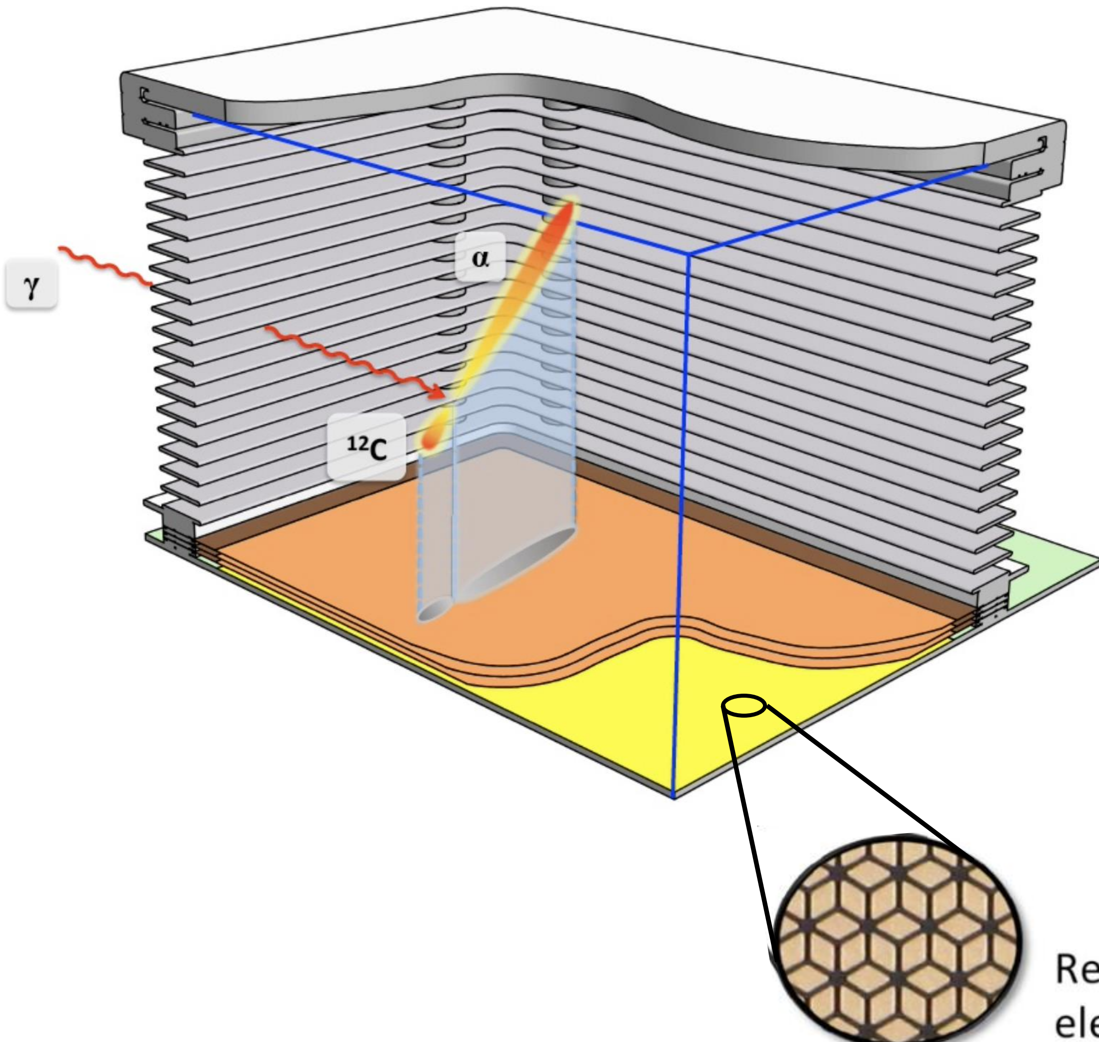

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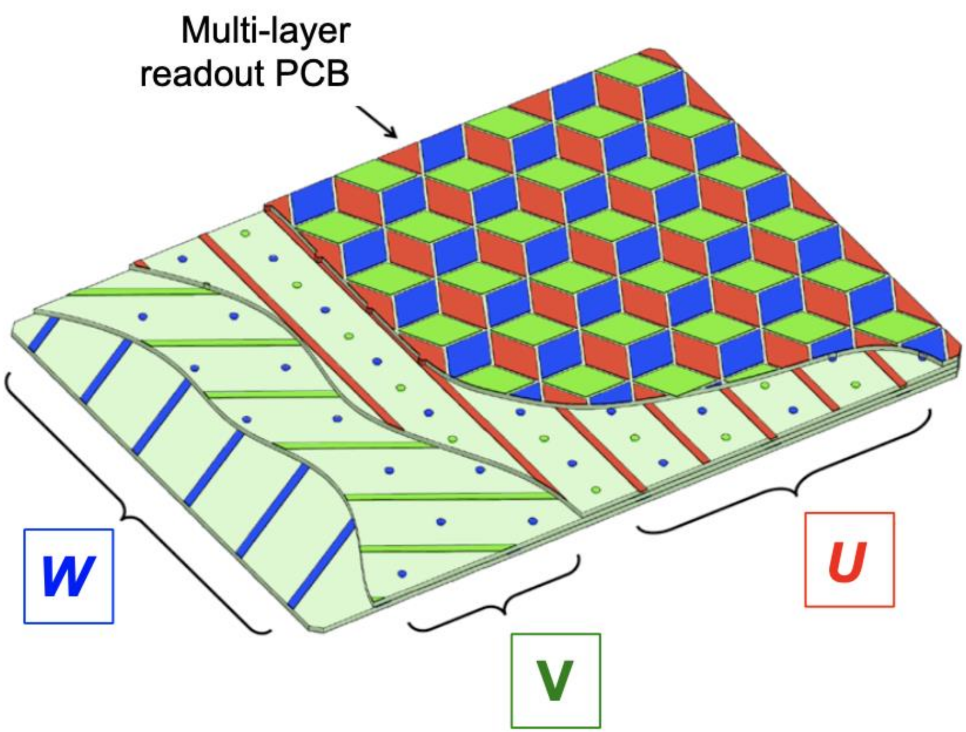

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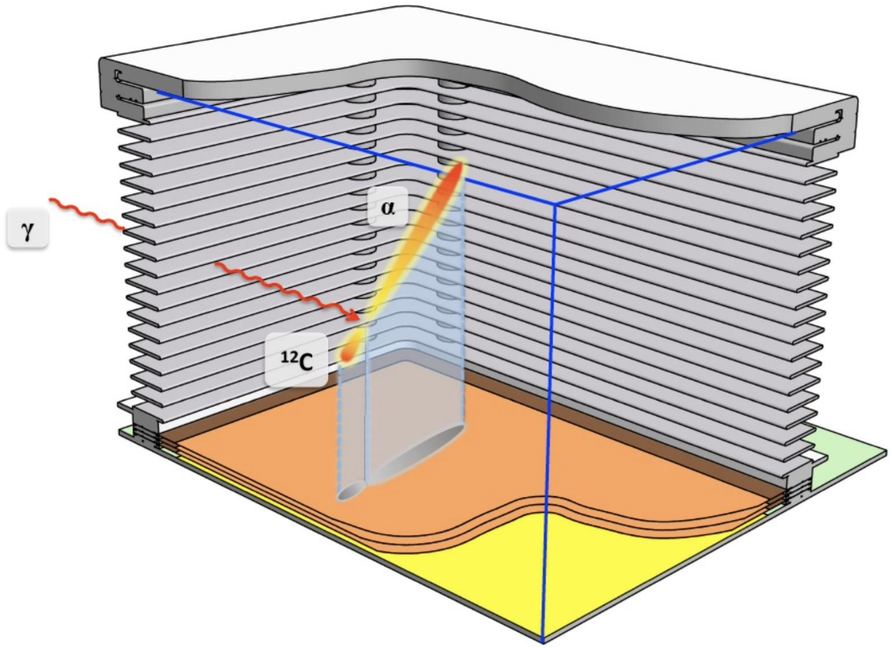
HIgS campaign – 2022



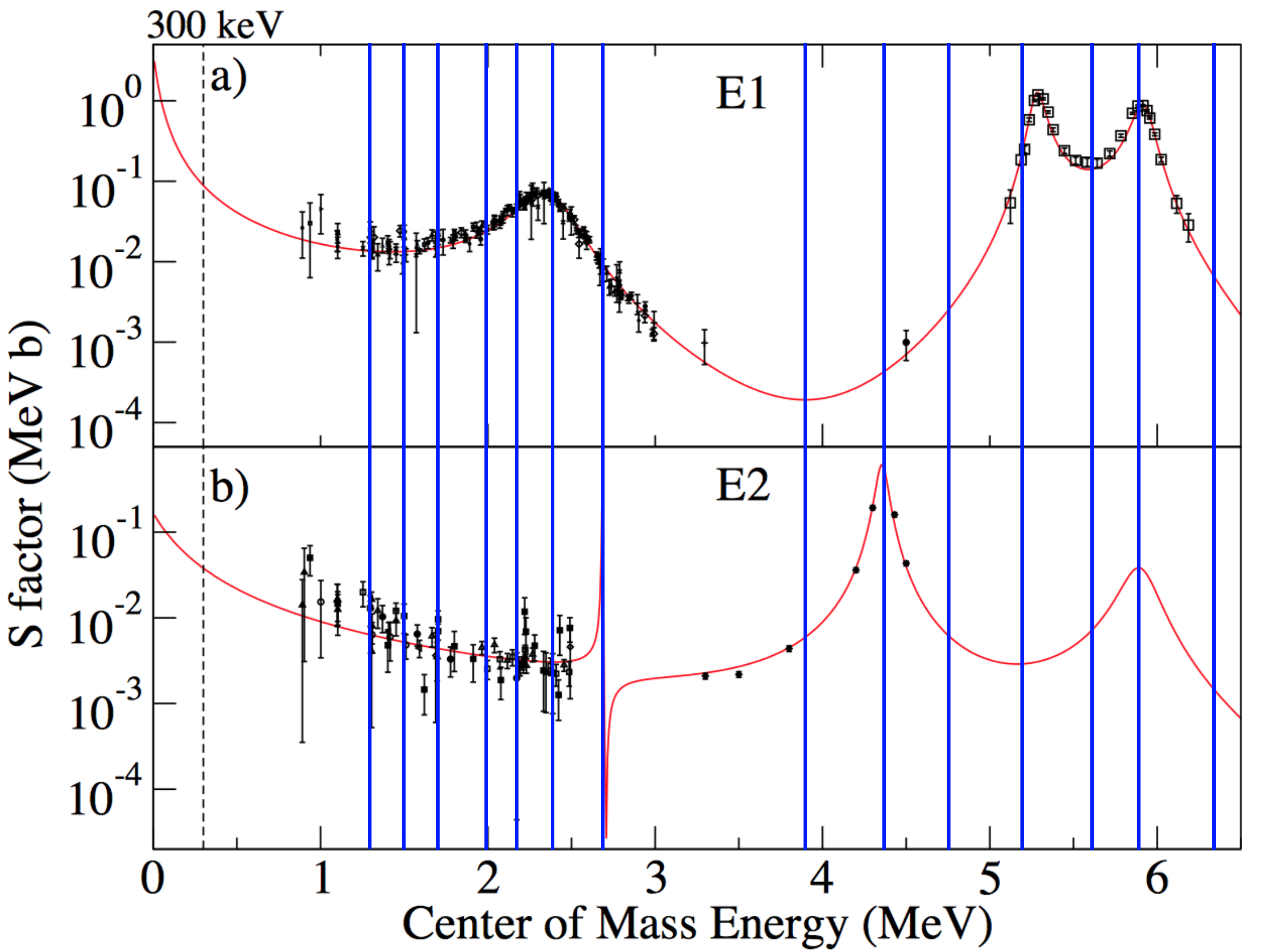
130–250 mbar pure CO_2 gas

γ-beams between 8.5 and 13.9 MeV

$\sim 4 \times 10^8$ γ/s and ΔE ~ 2%

M. Ćwiok et al., EPJ Web Conf. 279 (2023) 04002.

HIgS campaign – 2022



R. J. deBoer *et al.*, The $^{12}C(\alpha,\gamma)^{16}O$ reaction and its implications for stellar helium burning, Rev. Mod. Phys. **89** (2017)

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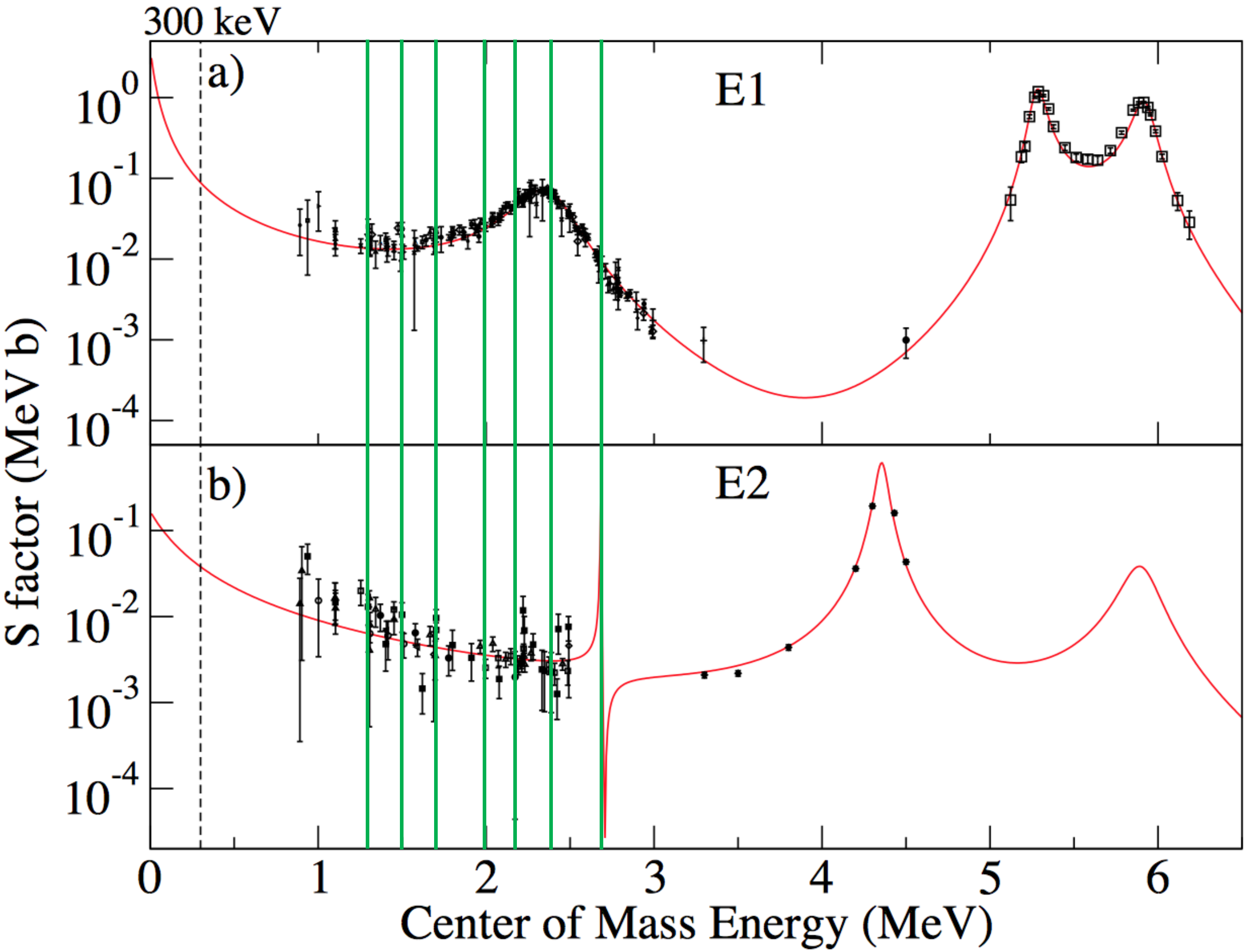

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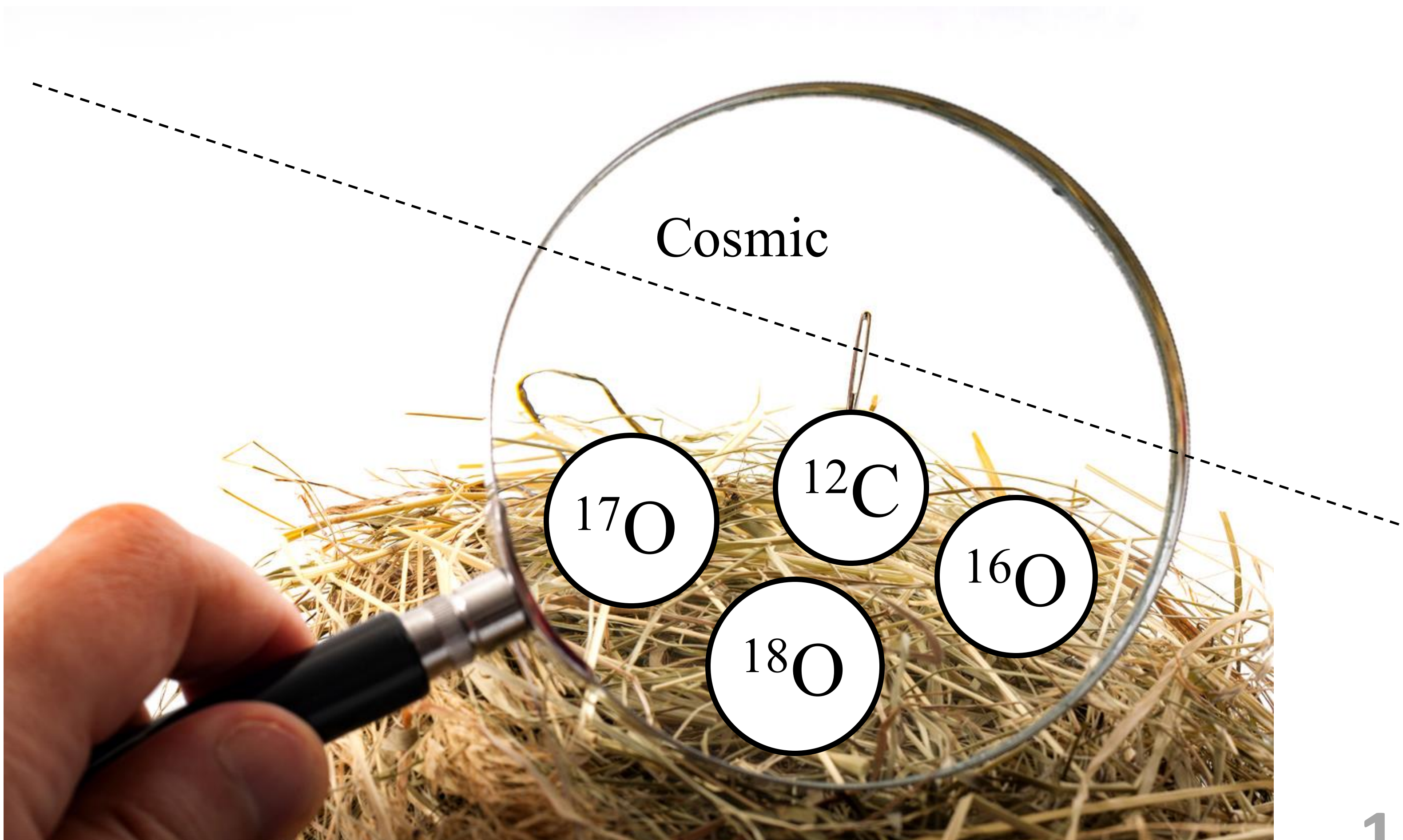
Analysis:
Finding an ^{16}O needle in a haystack



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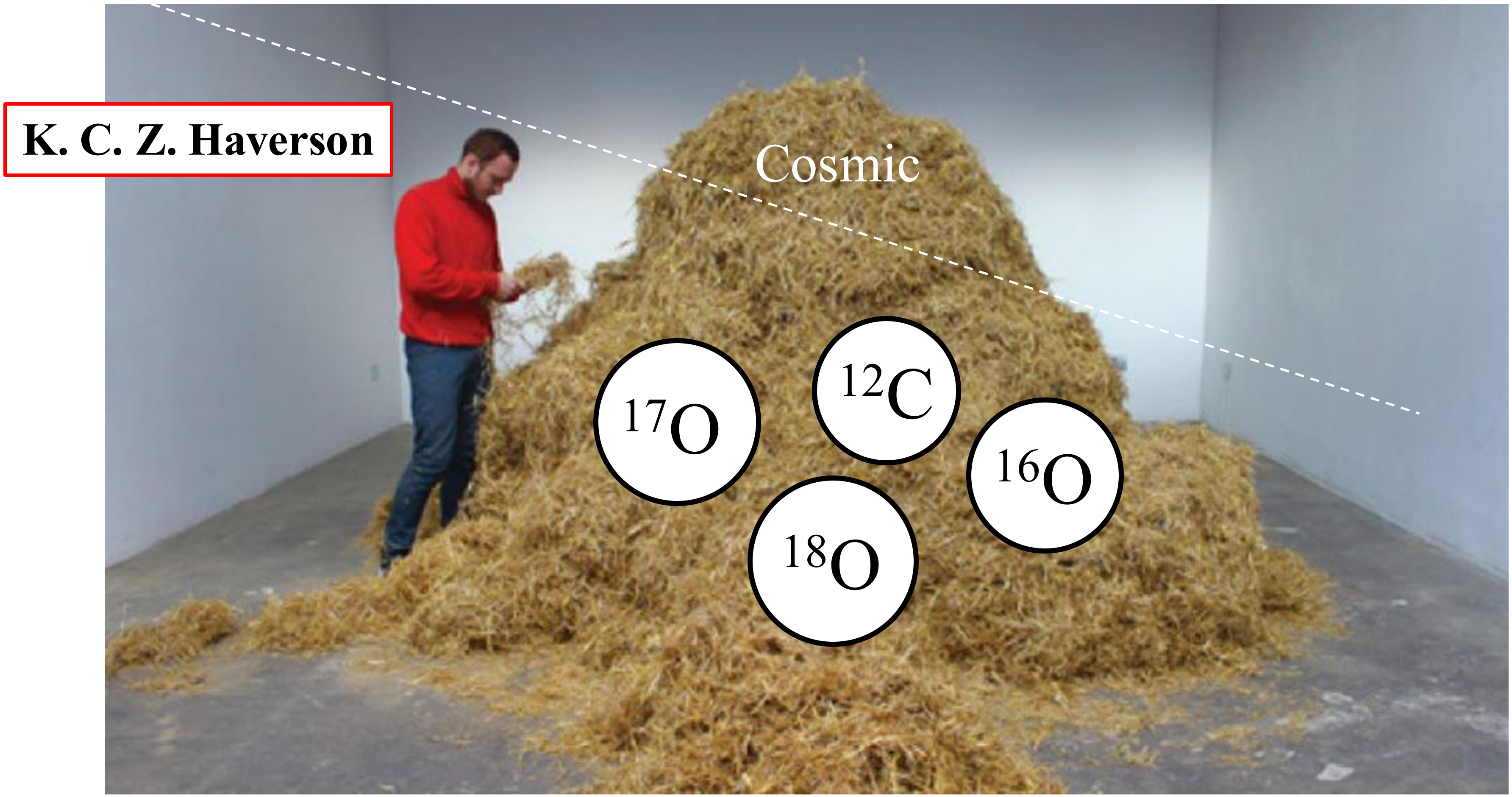

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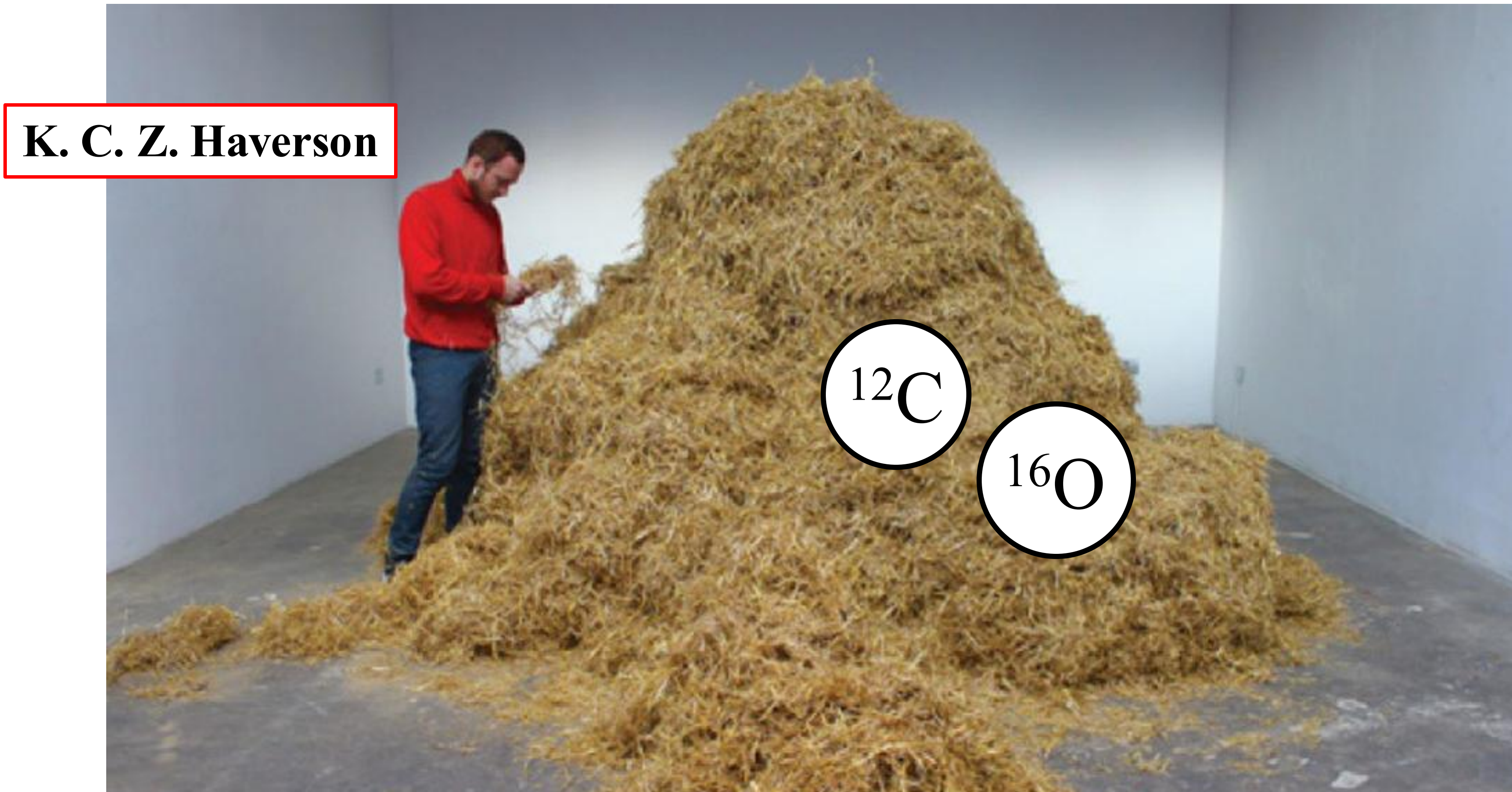
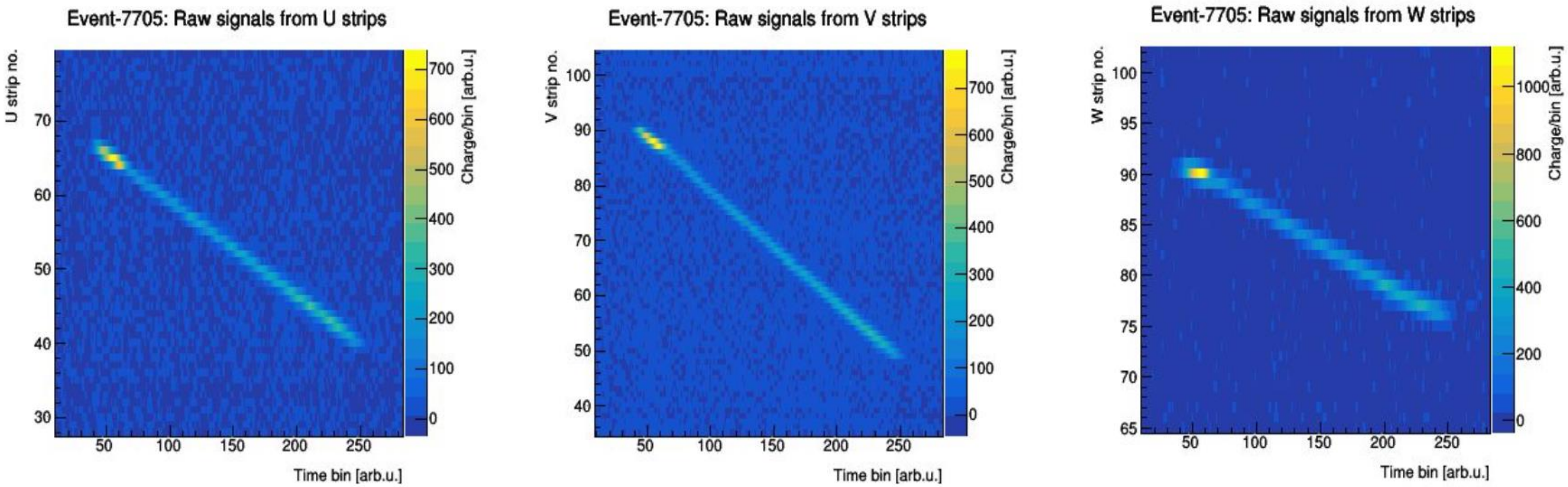
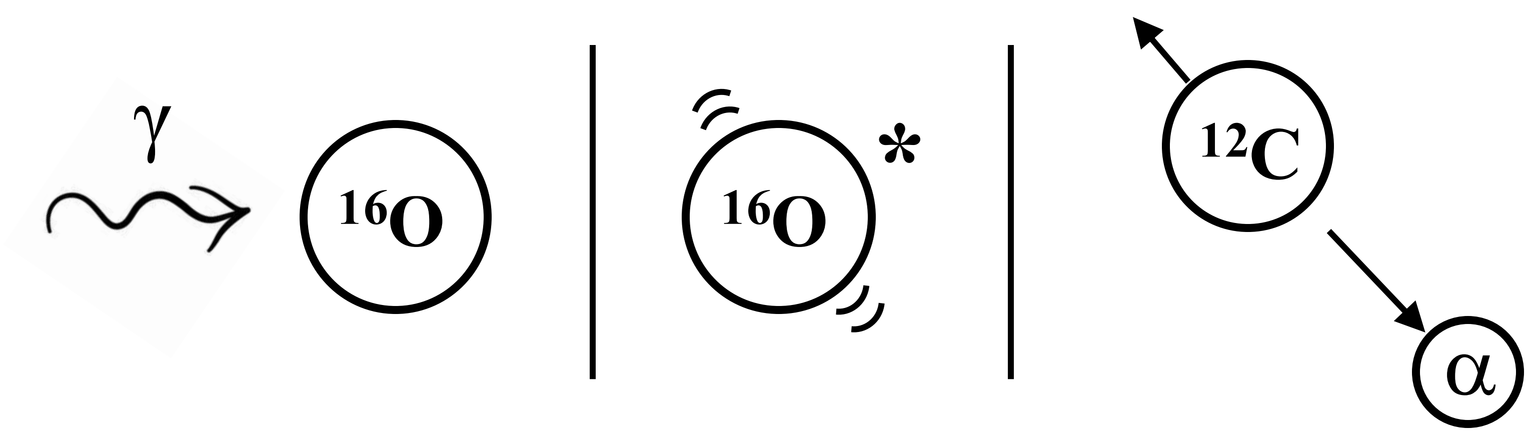
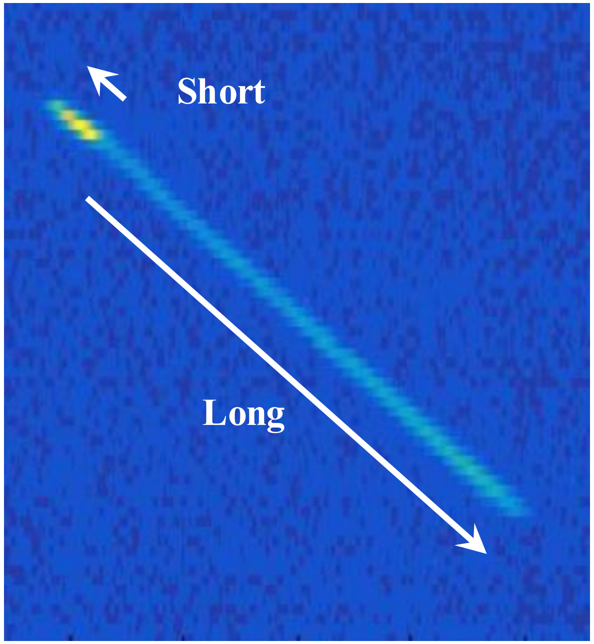


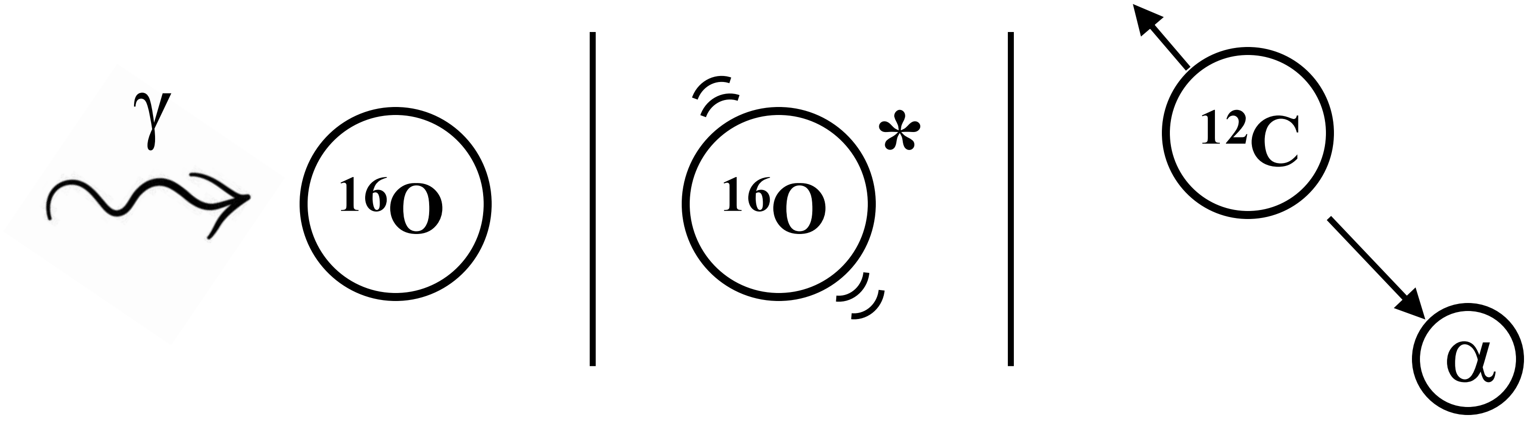
Example events – $^{16}O(\gamma,\alpha)^{12}C$



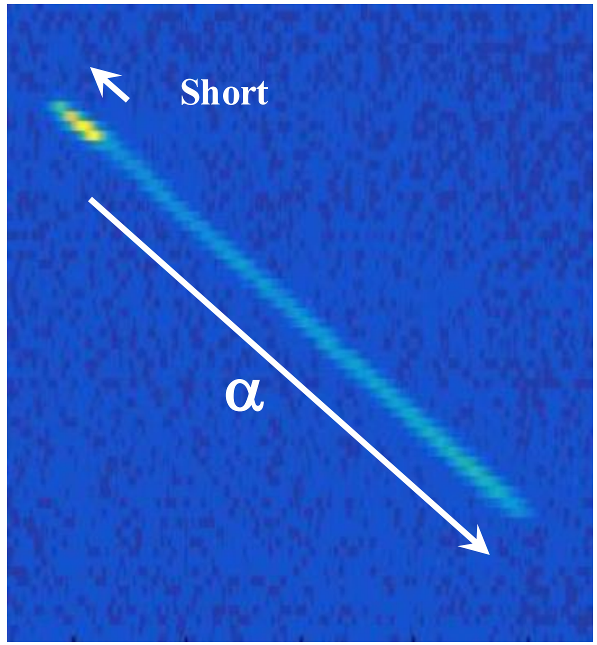


Example events – $^{16}O(\gamma,\alpha)^{12}C$





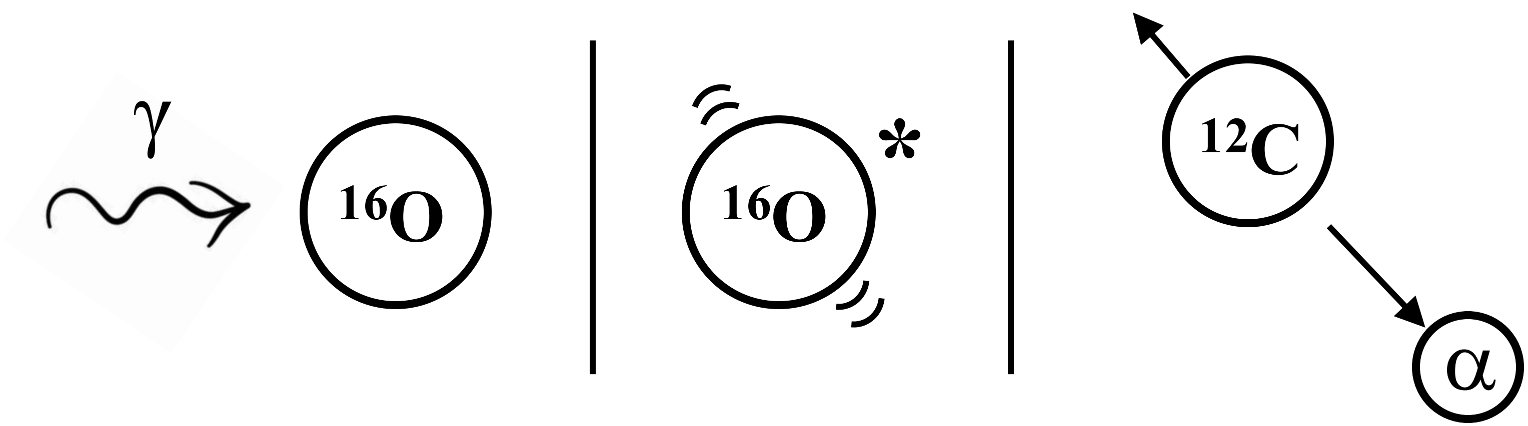
Example events – $^{16}O(\gamma,\alpha)^{12}C$



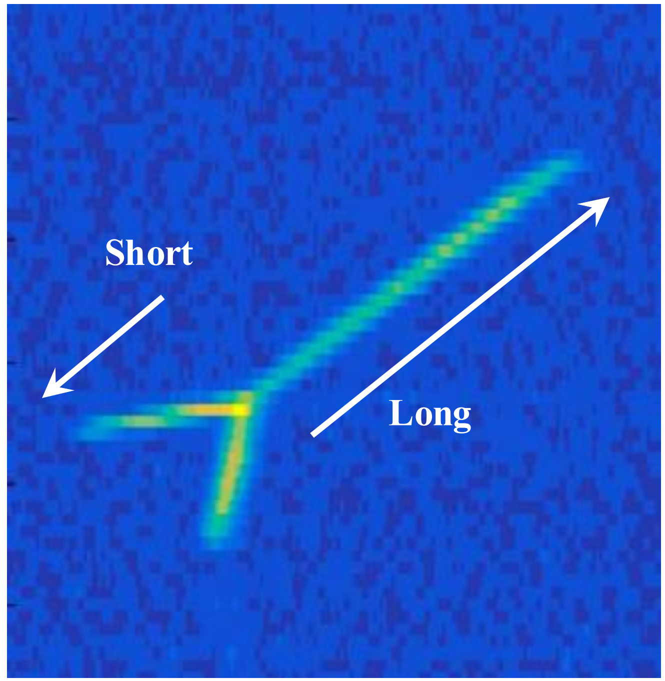
α Track length converted to energy using SRIM

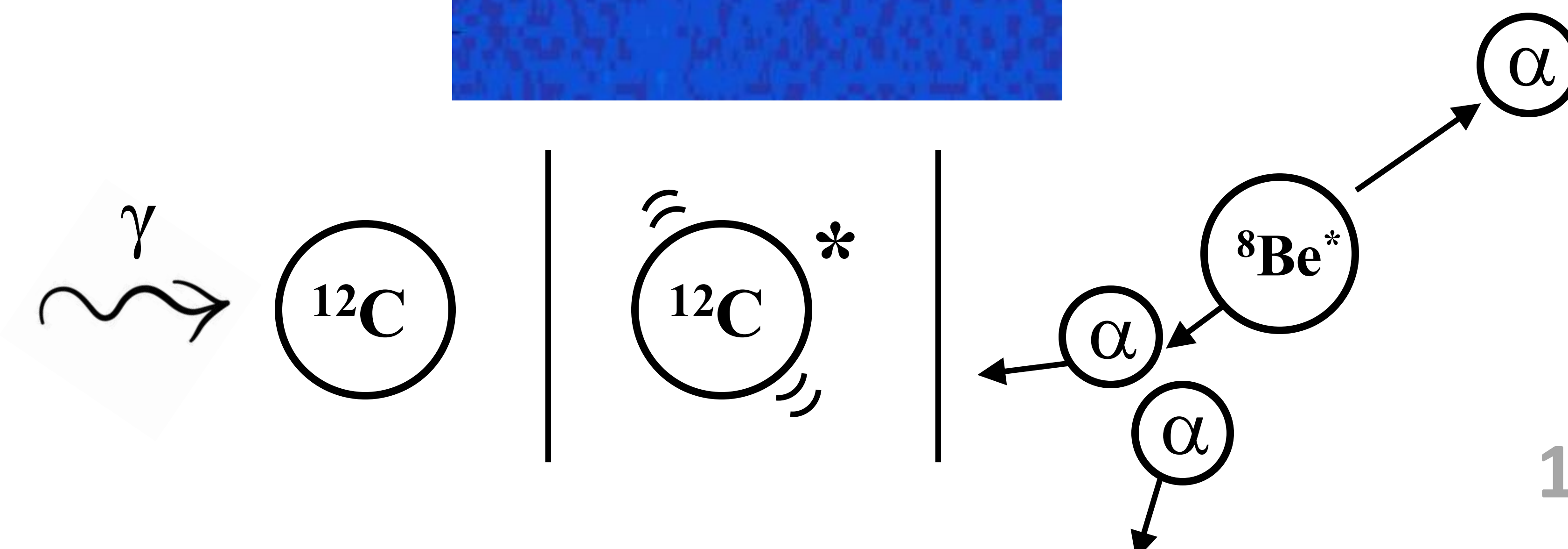
Can be boosted into CoM frame to give total E_{CoM}

Minor calibration to known ^{16}O resonances due to stopping power uncertainties

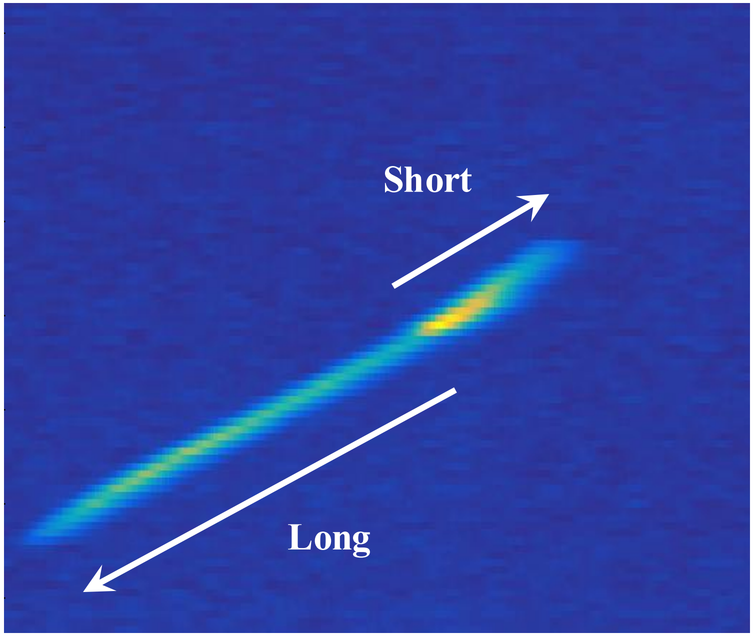


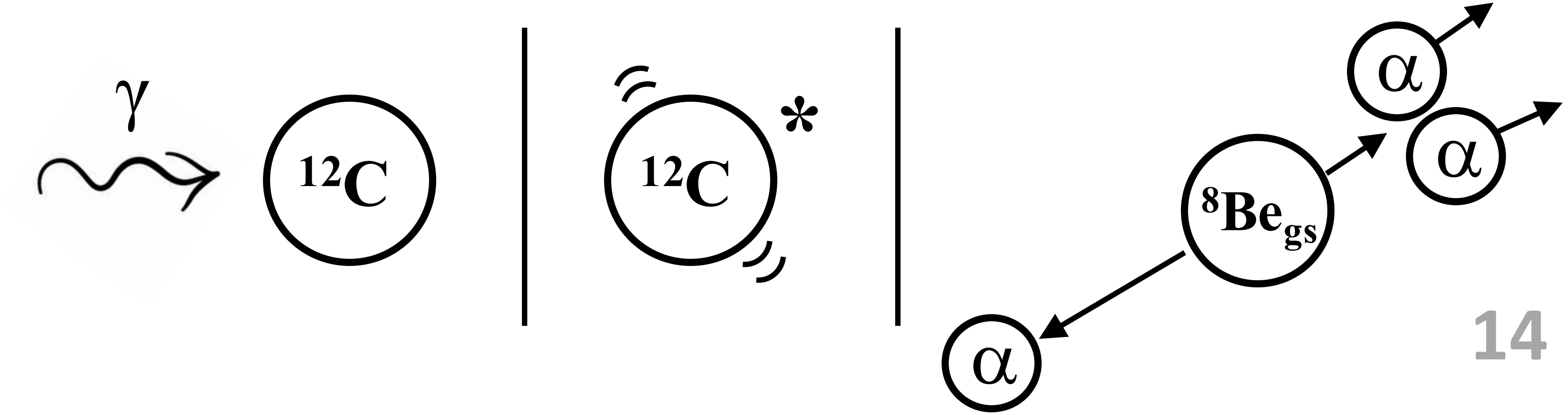
Example events – $^{12}C(\gamma,\alpha_1)$



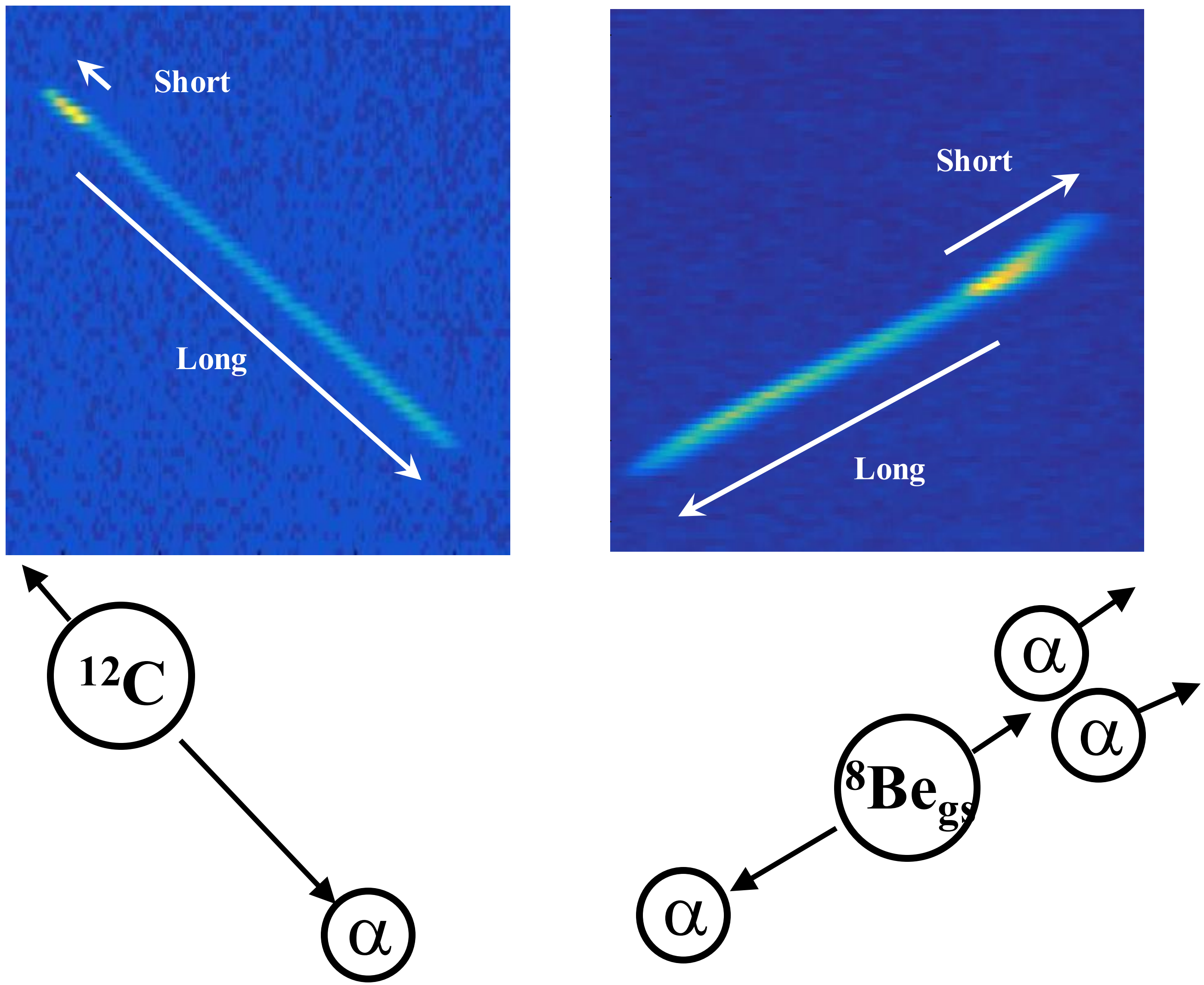


Example events – $^{12}C(\gamma,\alpha)^{8}Be_{gs}$

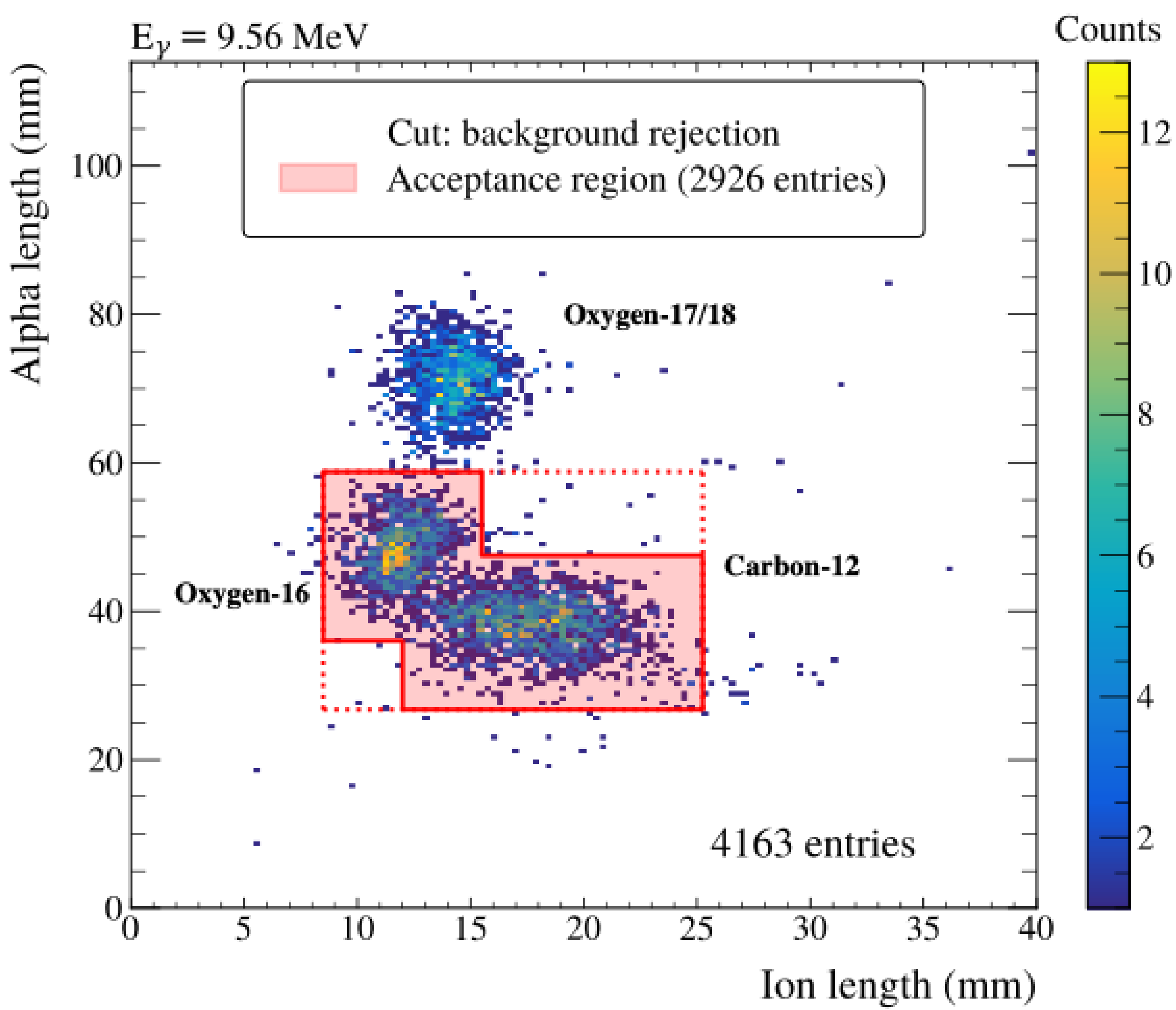




$^{16}O(\gamma,\alpha)^{12}C$ vs. $^{12}C(\gamma,\alpha)^{8}Be_{gs}$

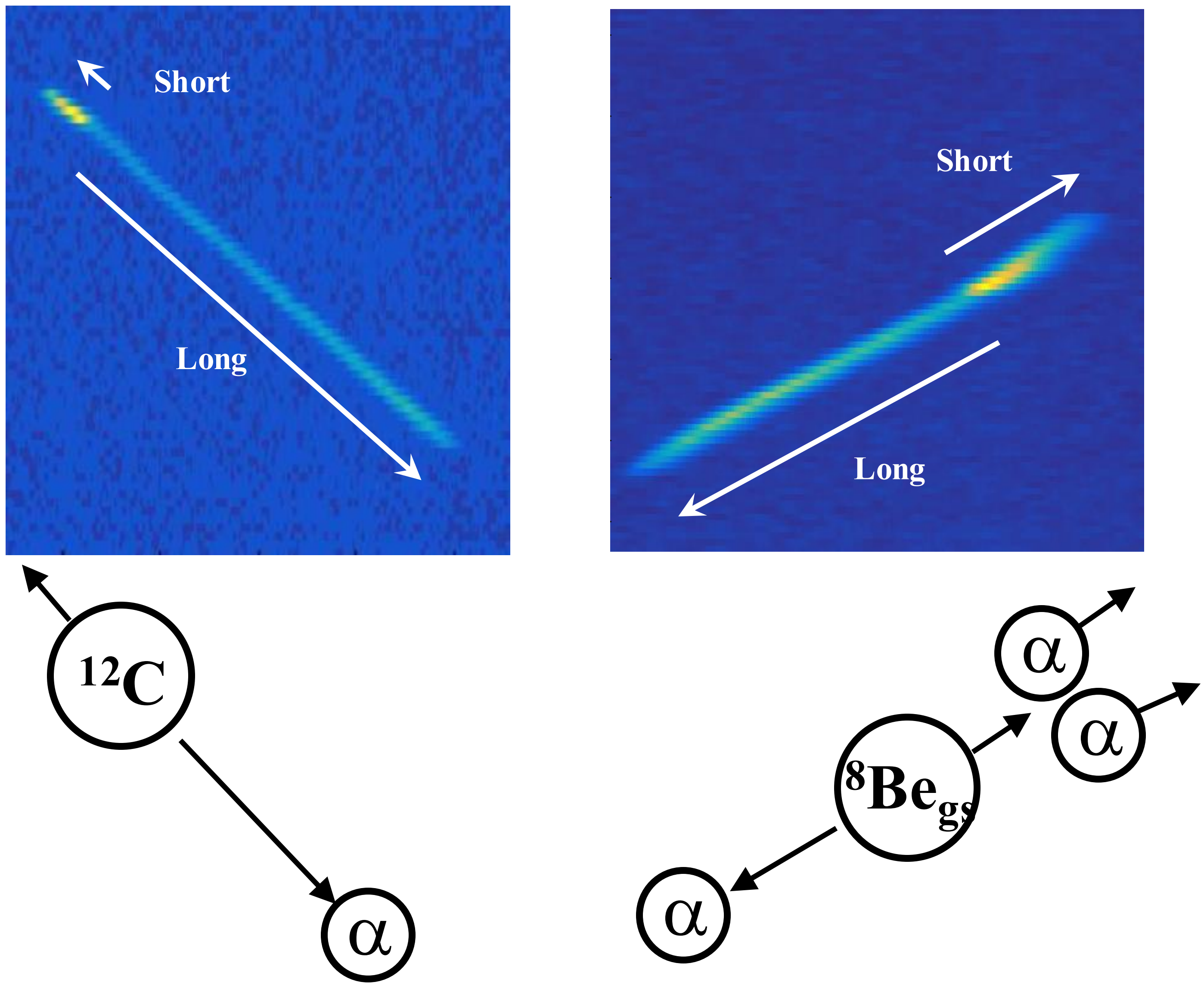


Channel selection

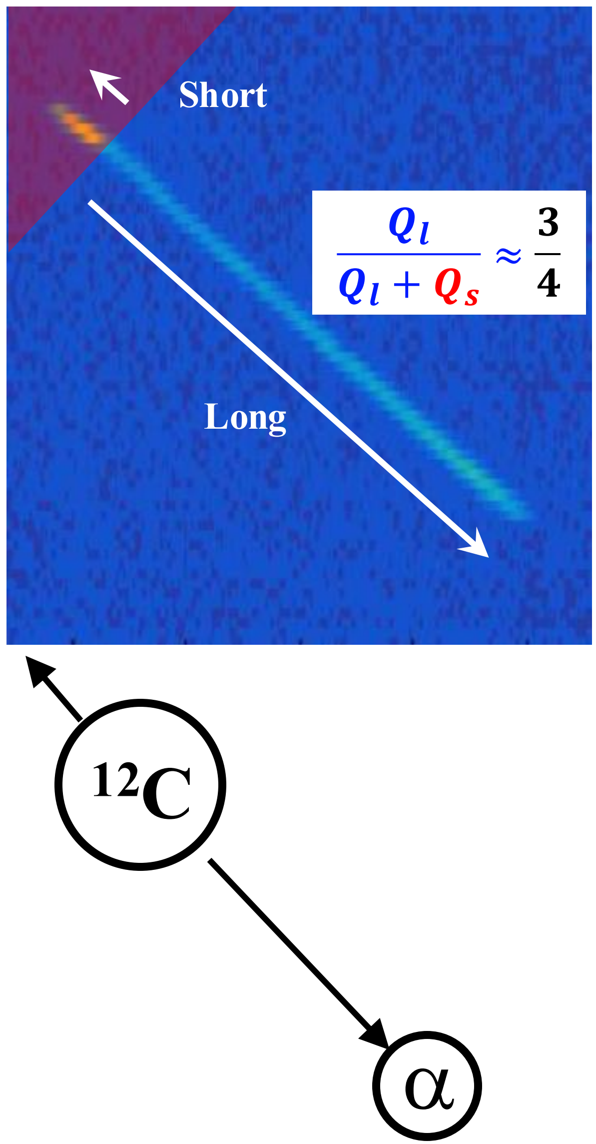


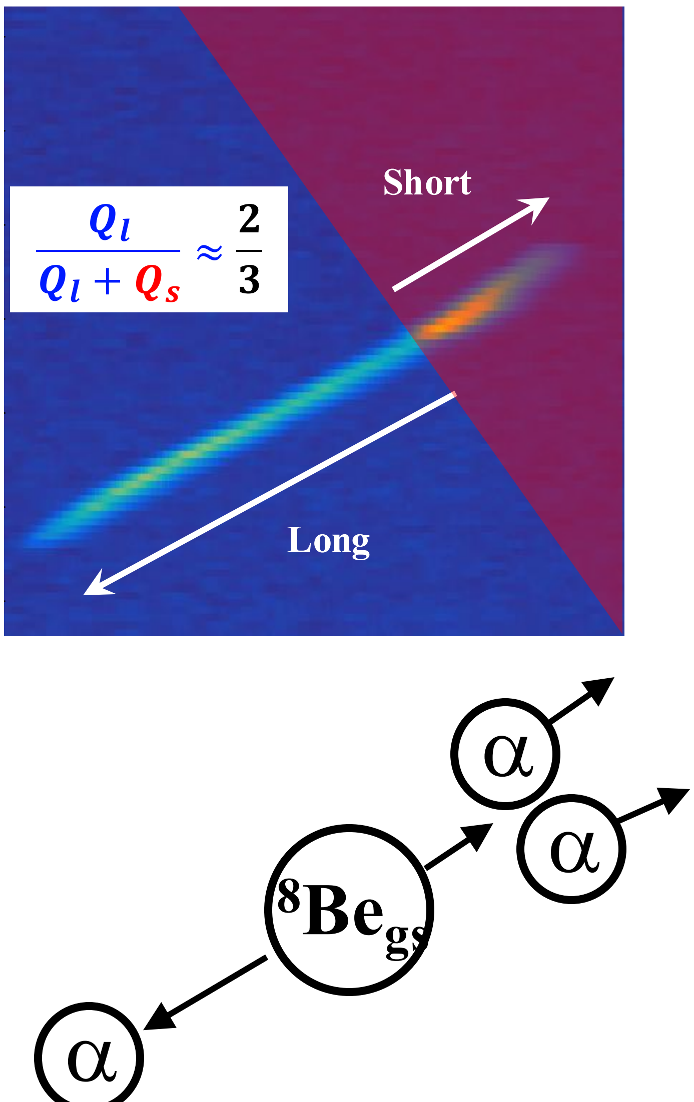
Work of K. C. Z. Haverson

$^{16}O(\gamma,\alpha)^{12}C$ vs. $^{12}C(\gamma,\alpha)^{8}Be_{gs}$

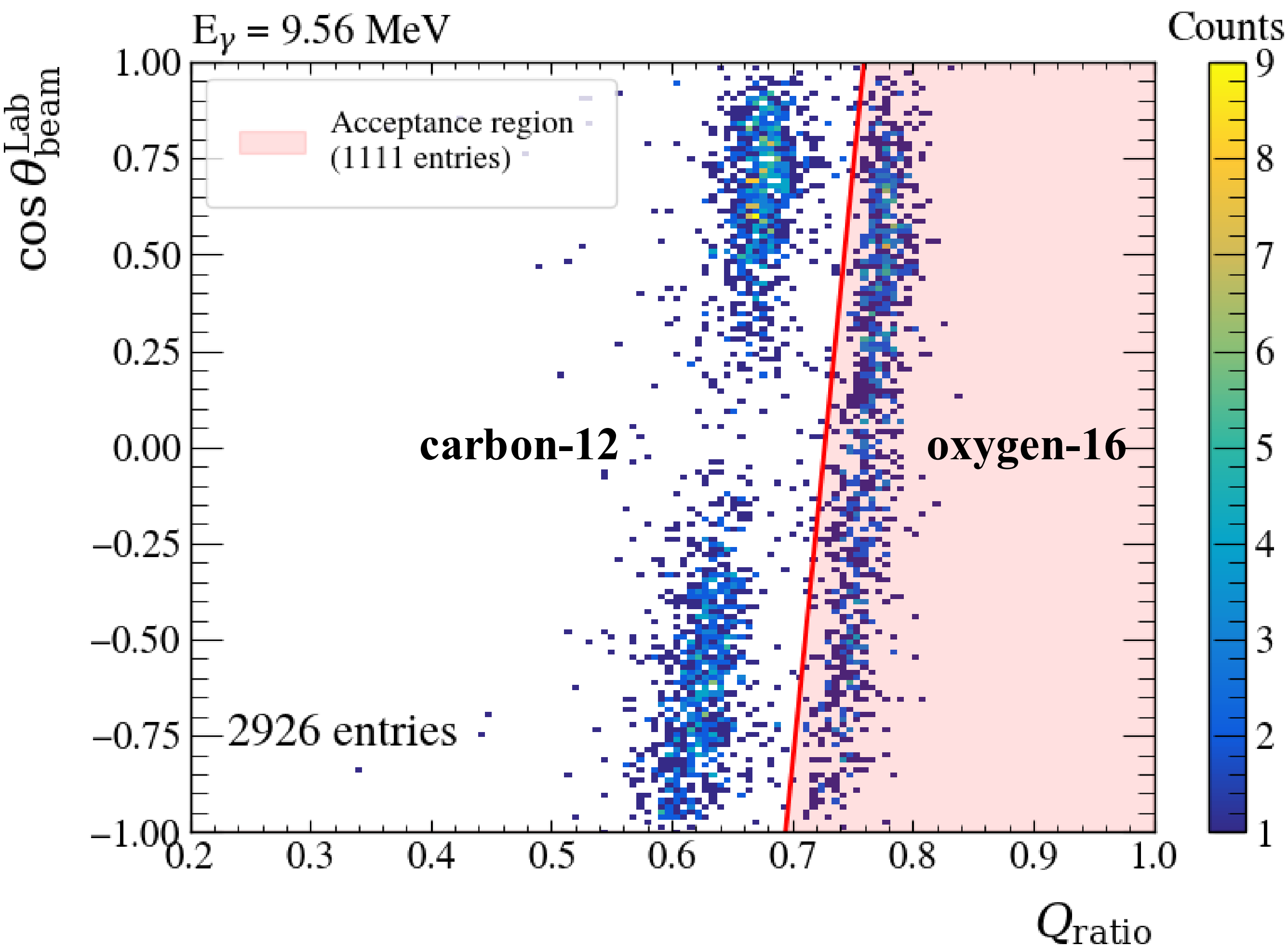


$^{16}O(\gamma,\alpha)^{12}C$ vs. $^{12}C(\gamma,\alpha)^{8}Be_{gs}$



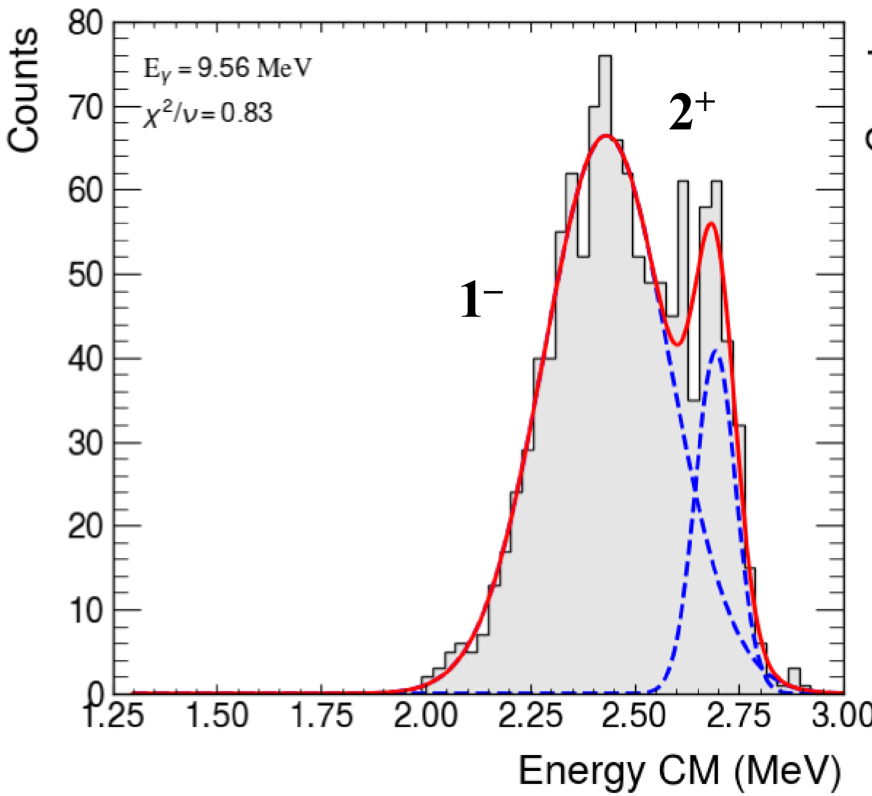


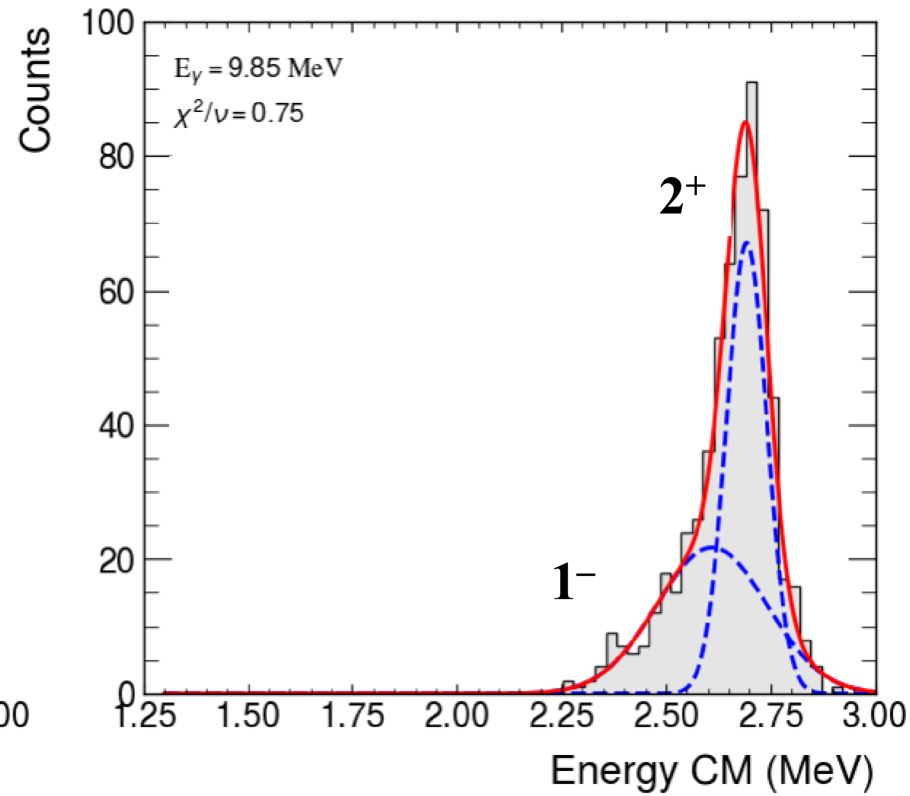
Channel selection



Work of K. C. Z. Haverson

CoM energy resolution

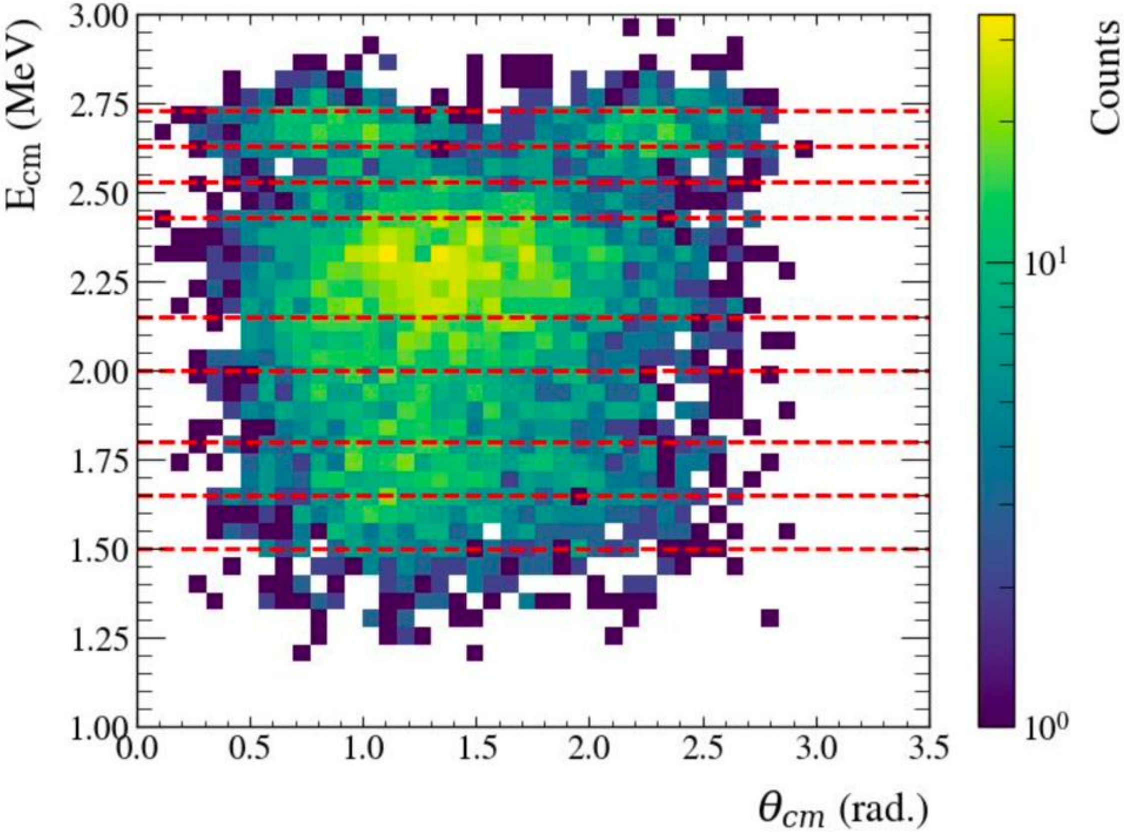




σ = 50 keV
Factor of 4 better than gamma beam

Work of K. C. Z. Haverson

Energy windows

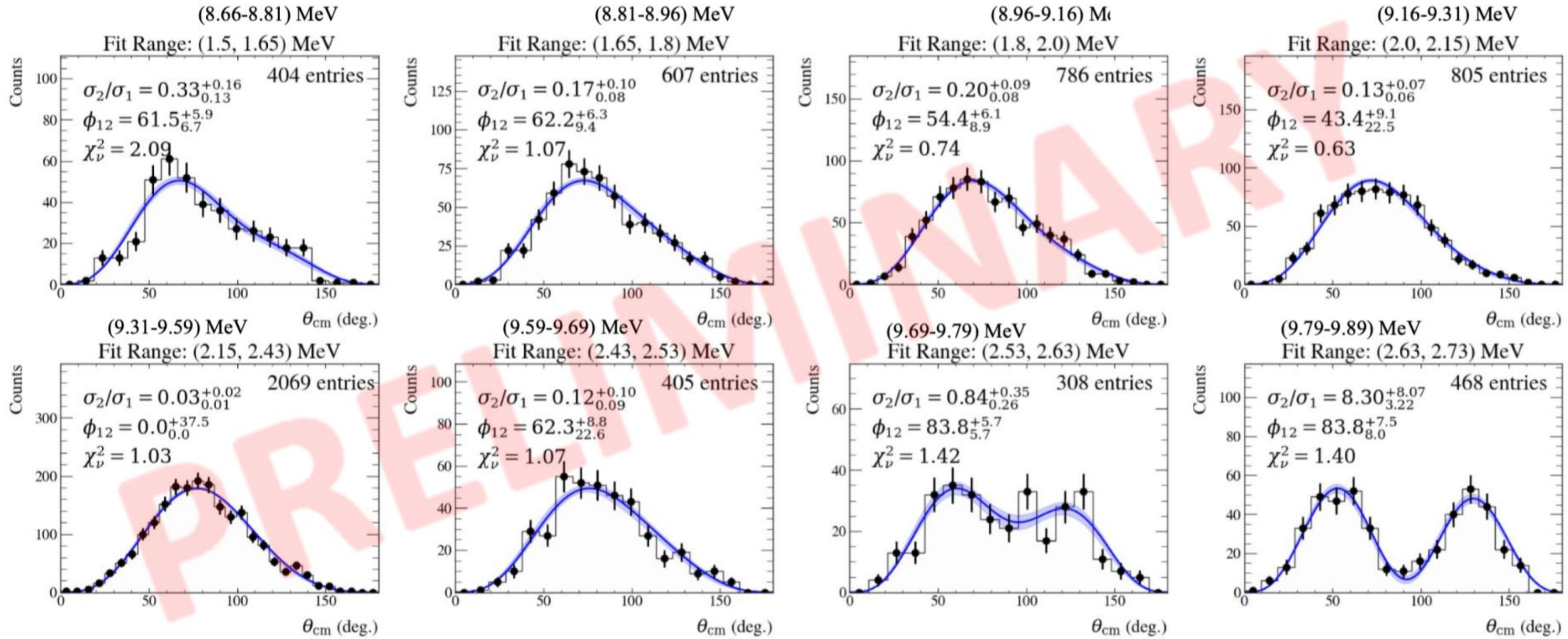


The bins of the measured W(θ)

Ecm (MeV)	Eγ (MeV)	ΔE (keV)	^{16}O (Counts)
1) 2.63-2.73	9.79-9.89	100	468
2) 2.53-2.63	9.69-9.79	100	308
3) 2.43-2.53	9.59-9.69	100	405
4) 2.15-2.43	9.31-9.59	180	2069
5) 2.0-2.15	9.96-9.31	150	805
6) 1.8-2.0	8.96-9.96	200	786
7) 1.65-1.8	8.81-8.96	150	607
8) 1.5-1.65	8.66-8.81	100	404
		Total	5,852

Work of K. C. Z. Haverson

Angular distributions



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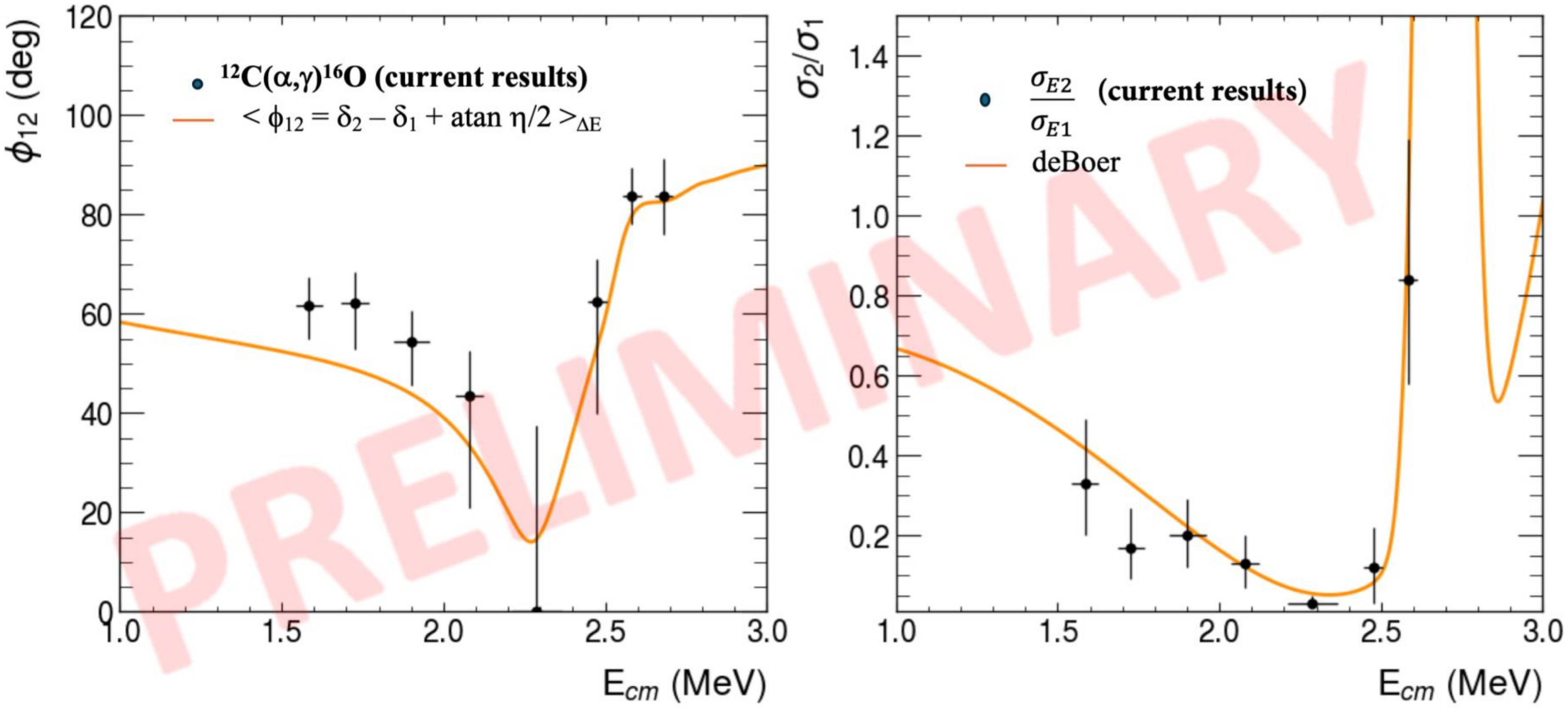
Extracted parameters



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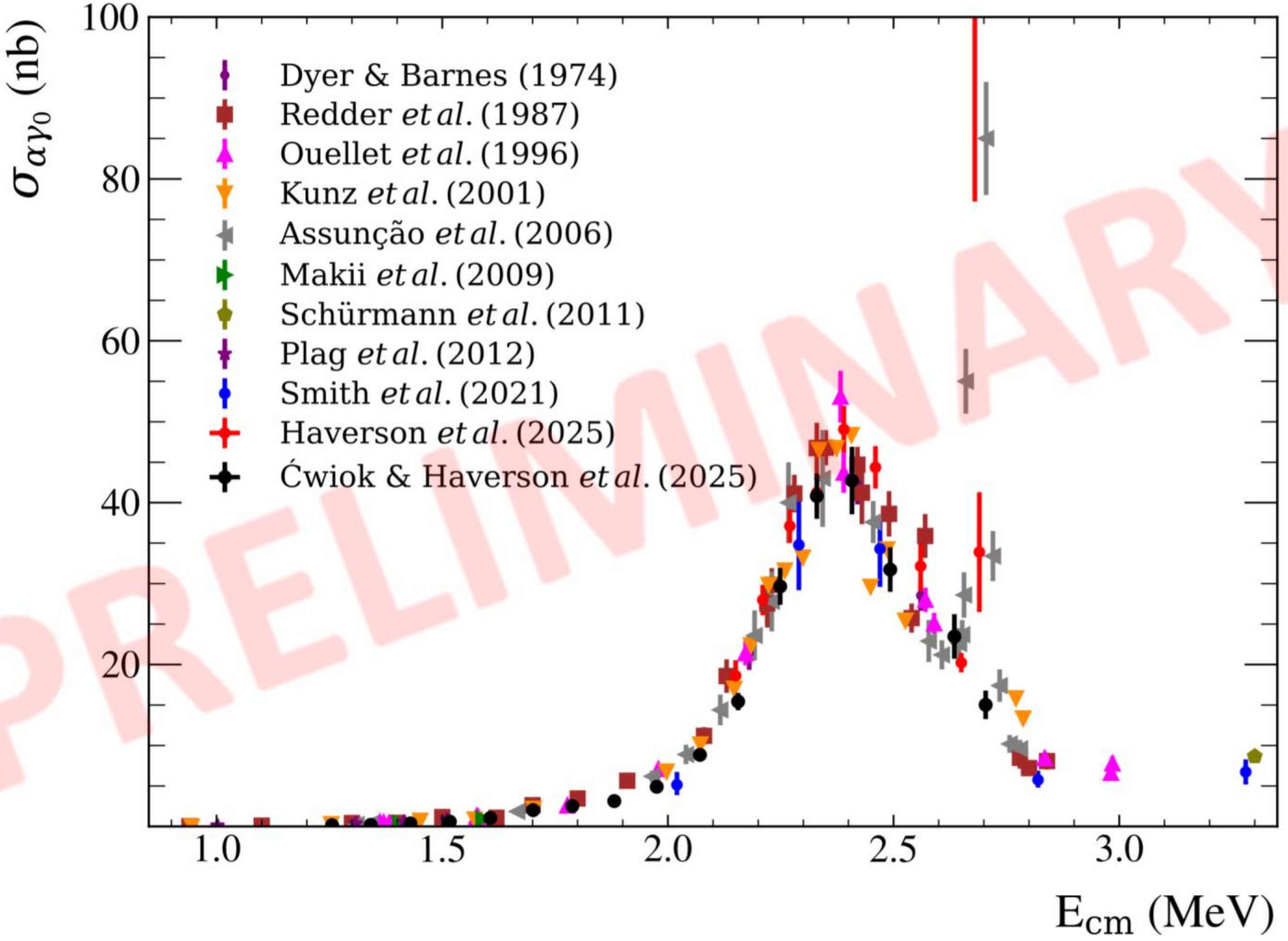
Total ground state cross section



Work of K. C. Z. Haverson

Summary

- Gamma beams + TPC offer low backgrounds, high selectivity, ~2^{o} angular resolution

- Detailed balance factor boosts the cross section

- Demonstrated essentially background-free measurement of $^{16}O(\gamma,\alpha)^{12}C$

- Preliminary analysis indicates that data follow expected trends

- Simulation work still underway to assess if data reduction cuts bias the angular distributions

Collaborators

M. Cwiok[1], W. Dominik[1], A. Fijałkowska[1], M. Fila[1], Z. Janas[1], A. Kalinowski[1], K. Kierzkowski[1], M. Kuich[1], C. Mazzocchi[1], W. Oklinski[1], M. Zaremba[1], M. Gai[2], D. K. Schweitzer[2], S. R. Stern[2], M. Ahmed[4,5], S. Finch[3,4], U. Friman-Gayer[3,4], S. R. Johnson[5,4], T. M. Kowalewski[4,5], D. L. Balabanski[6], C. Matei[6], A. Rotaru[6], K. C. Z. Haverson[7], R. Smith[7], C. Wheldon[8], Tz. Kokalova[8], R. A.M. Allen[8], M. R. Griffiths[8], S. Pirrie[8], and P. Santa Rita Alcibia[8]

[1] Faculty of Physics, University of Warsaw, Warsaw, Poland
[2] University of Connecticut, CT, USA
[3] Physics Department, Duke University, Durham, NC, USA
[4] Triangle Universities Nuclear Laboratory, Durham, NC, USA
[5] Dept of Physics & Astronomy, University of North Carolina, Chapel Hill, NC, USA
[6] IFIN-HH / ELI-NP, Bucharest-Magurele, Romania
[7] Dept of Engineering and Mathematics, Sheffield Hallam University, Sheffield, UK
[8] School of Physics and Astronomy, University of Birmingham, Birmingham, UK

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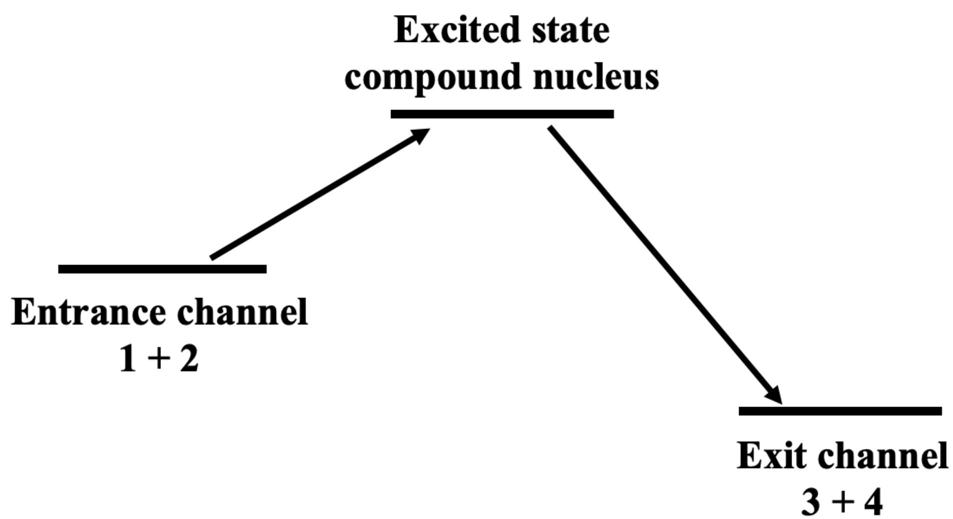
Detailed balance:
$^{16}O(\gamma,\alpha)^{12}C \leftrightarrow {}^{12}C(\alpha,\gamma)^{16}O$



$$\frac{\sigma_{12}}{\sigma_{34}} = \frac{m_3 m_4}{m_1 m_2}\frac{E_{34}}{E_{12}} \times \frac{(2J_3+1)(2J_4+1)}{(2J_1+1)(2J_2+1)} \times \frac{(1+\delta_{12})}{(1+\delta_{34})}$$