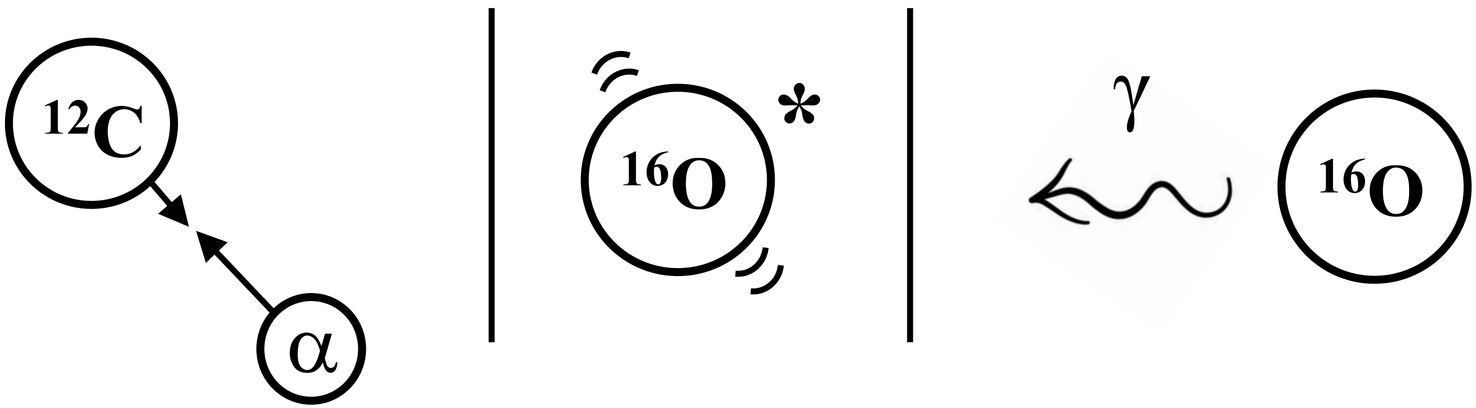
Exploring the key astrophysical reaction $^{12}C(\alpha,\gamma)$ with TPCs and γ beams



Robin Smith

Sheffield Hallam University

UCONN
UNIVERSITY OF CONNECTICUT

IOP Nuclear Physics Conference,
University of Brighton – April 15^{th} 2026

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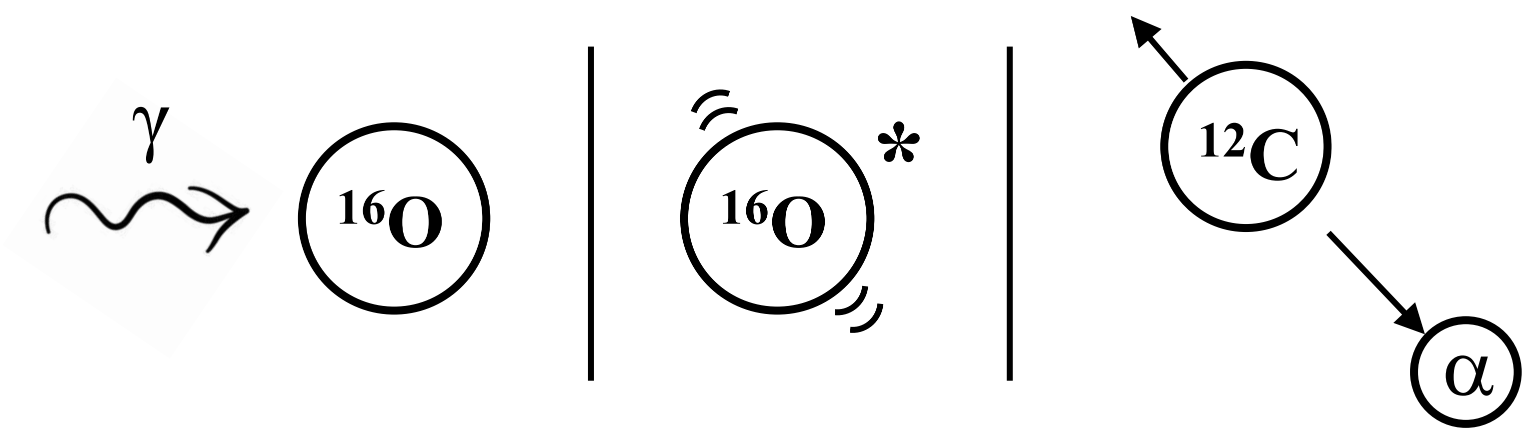

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IOP Nuclear Physics Conference,
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PhD thesis: 10.7190/shu-thesis-00759

Collaborators

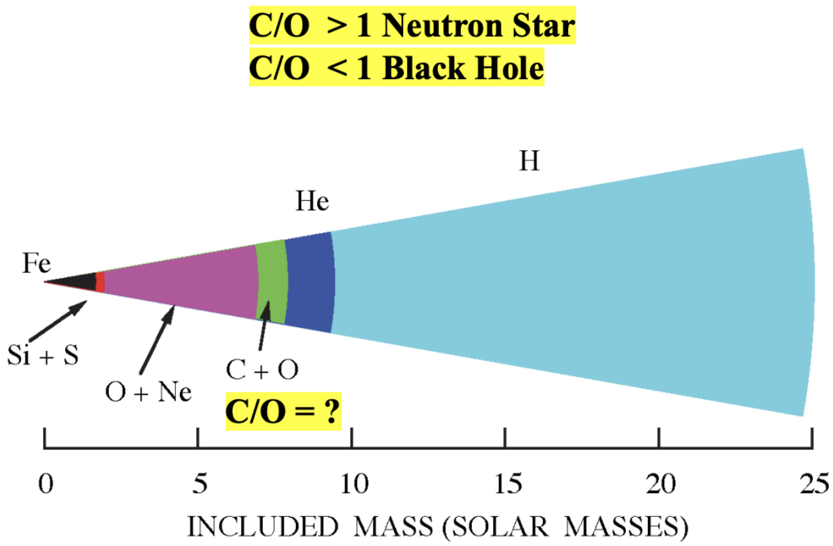
M. Cwiok[1], W. Dominik[1], A. Fijałkowska[1], M. Fila[1], Z. Janas[1], A. Kalinowski[1], K. Kierzkowski[1], M. Kuich[1], C. Mazzocchi[1], W. Oklinski[1], M. Zaremba[1], M. Gai[2], D. K. Schweitzer[2], S. R. Stern[2], M. Ahmed[4,5], S. Finch[3,4], U. Friman-Gayer[3,4], S. R. Johnson[5,4], T. M. Kowalewski[4,5], D. L. Balabanski[6], C. Matei[6], A. Rotaru[6], **K. C. Z. Haverson[7]**, R. Smith[7,2], 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] School of Engineering & Built Environment, Sheffield Hallam University, Sheffield, UK
[8] School of Physics and Astronomy, University of Birmingham, Birmingham, UK

Sheffield Hallam University UCONN UNIVERSITY OF CONNECTICUT UNIWERSYTET WARSZAWSKI TUNL NORTH CAROLINA CENTRAL UNIVERSITY FOUNDED 1910 UNIVERSITY OF BIRMINGHAM eli

Overview

- Importance of $^{12}C(\alpha,\gamma)^{16}O$ and issues with current data
- Photo-dissociation with gamma beams at HIγS
- Warsaw TPC detector
- Data analysis and preliminary results



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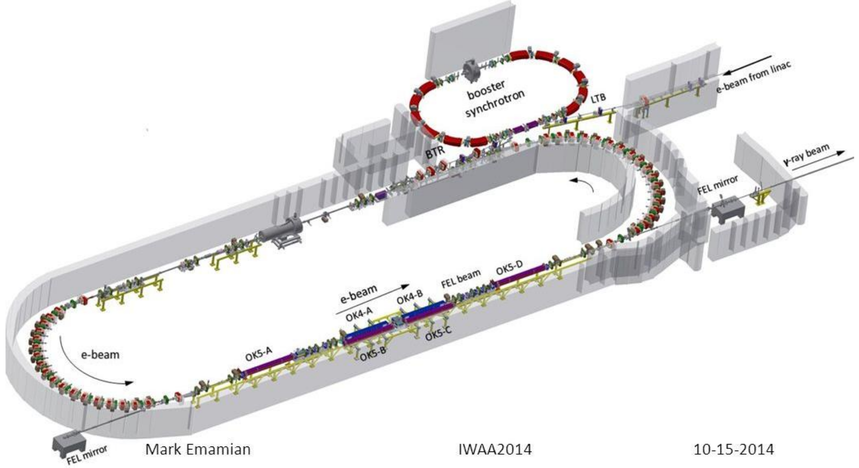

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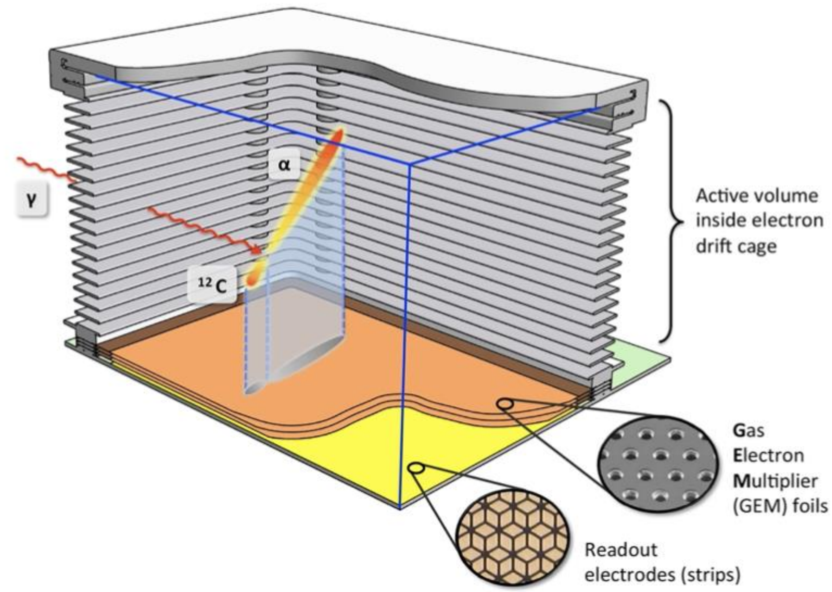

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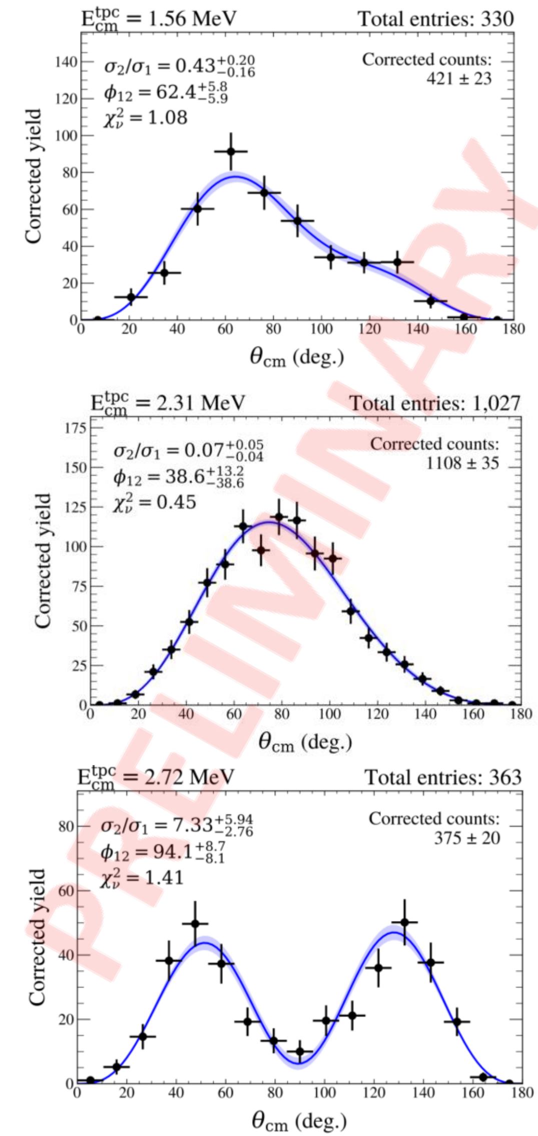

Stellar helium burning

- 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.

Stellar helium burning

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  - Cross sections for $3\alpha \rightarrow {}^{12}C$ and ${}^{12}C(\alpha,\gamma){}^{16}O$

Stellar helium burning

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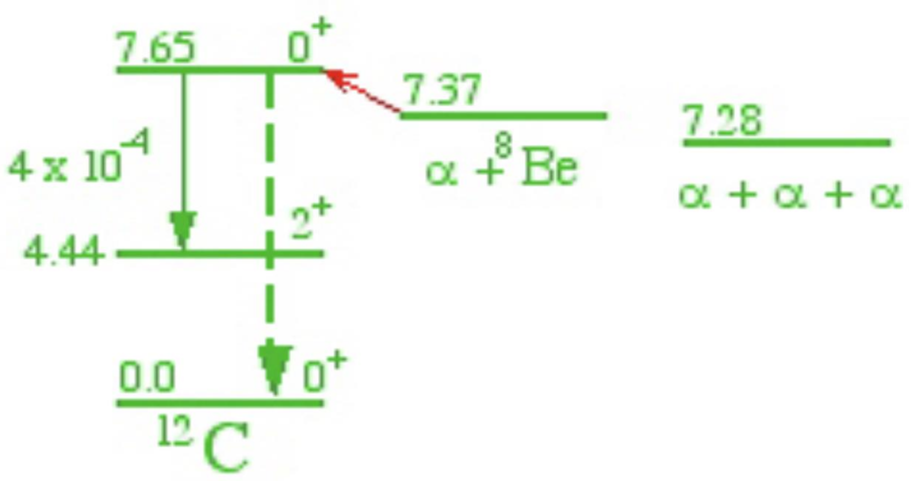
Triple-α reaction rate is well-constrained



W. Paulsen et al., Phys. Rev. C 112, 015803

Stellar helium burning

- The ratio of carbon-to-oxygen C/O after helium burning
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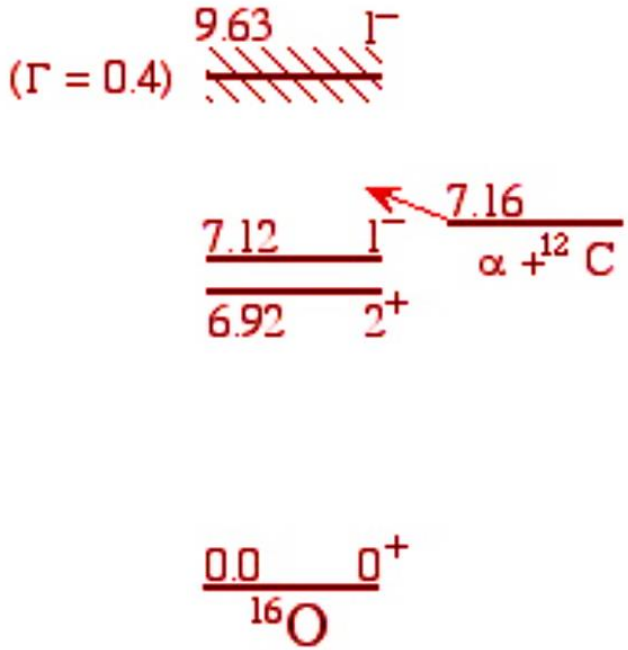
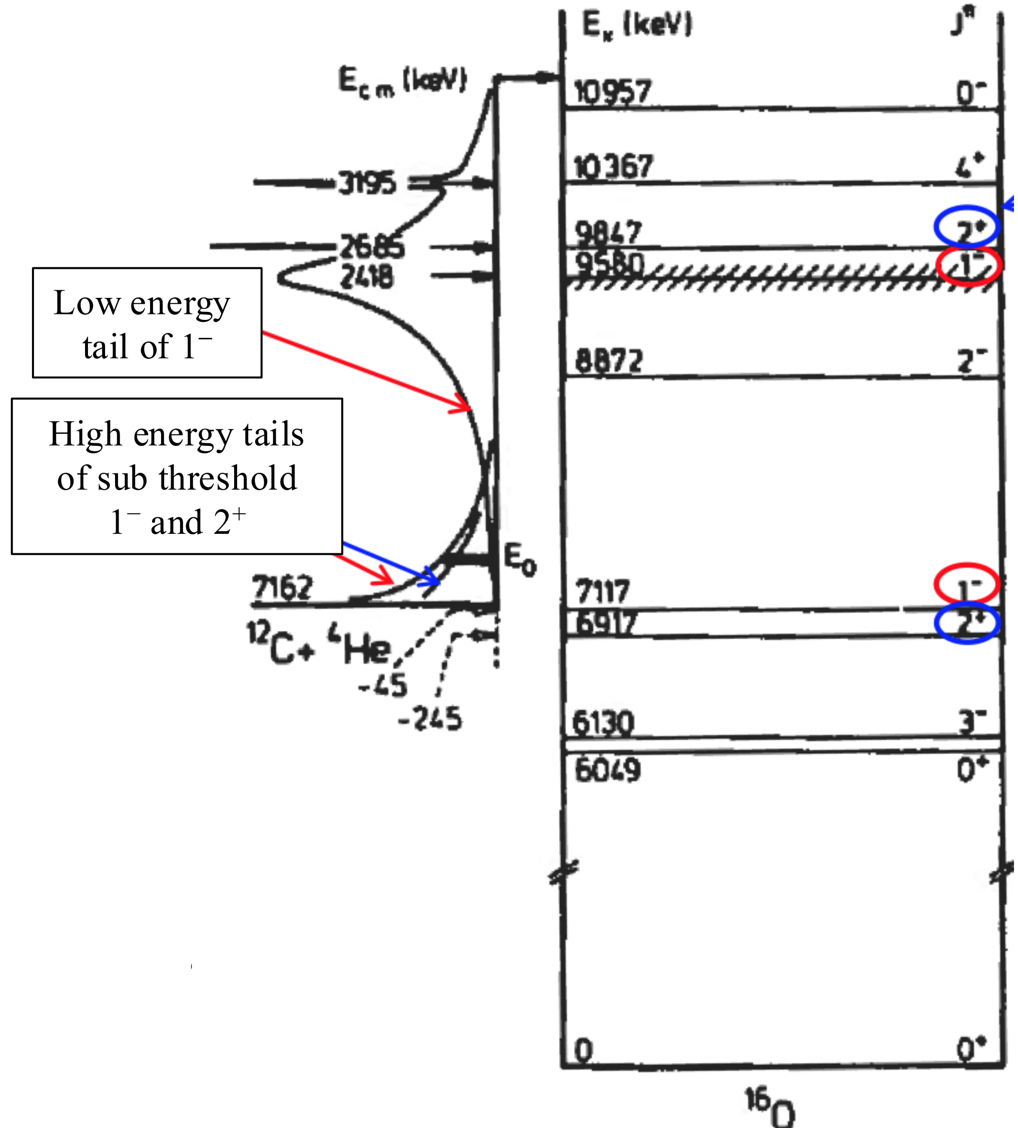
"The single most important nuclear physics uncertainty in astrophysics"



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

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

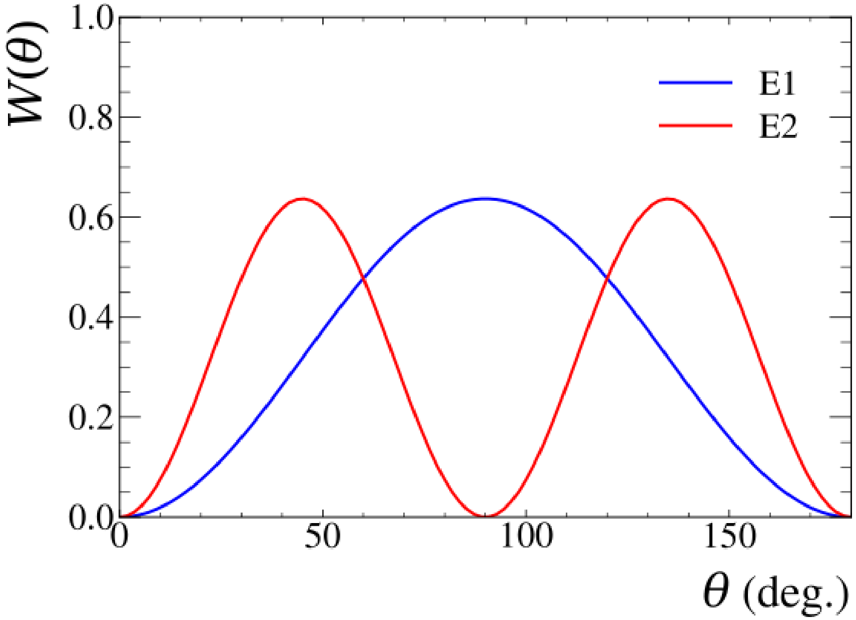
- Extrapolation to astrophysical energies relies on disentangling E1 and E2 partial cross sections
  - Precise angular distributions needed
  - Arguably existing datasets are subject to systematic uncertainties e.g. $^{13}C(\alpha,n)$ or high Q-value (n,γ) on nearby materials

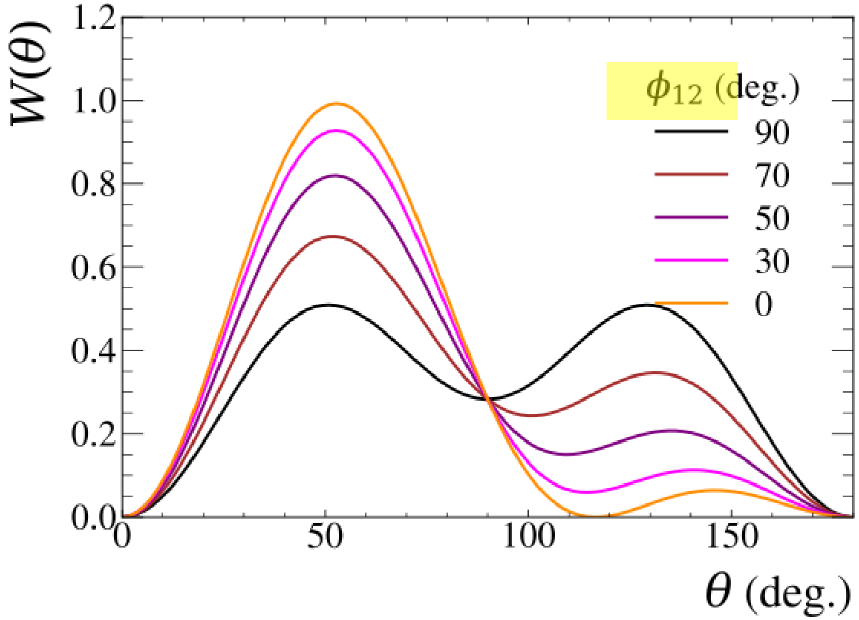


C. E. Rolfs, W. S. Rodney. *Cauldrons in the cosmos.* University of Chicago press, 1988.

Systematic uncertainties – ϕ_{12}

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





Systematic uncertainties – ϕ_{12}

$$W(\theta) = (3|A_{E1}|^2 + 5|A_{E2}|^2)P_0(\cos\theta) + \left({}^{25}/_7|A_{E2}|^2 - 3|A_{E1}|^2\right)P_2(\cos\theta) - {}^{60}/_7|A_{E2}|^2 P_4(\cos\theta) + 6\sqrt{3}|A_{E1}||A_{E2}|\cos\phi_{12}\,[P_1(\cos\theta) - P_3(\cos\theta)]$$

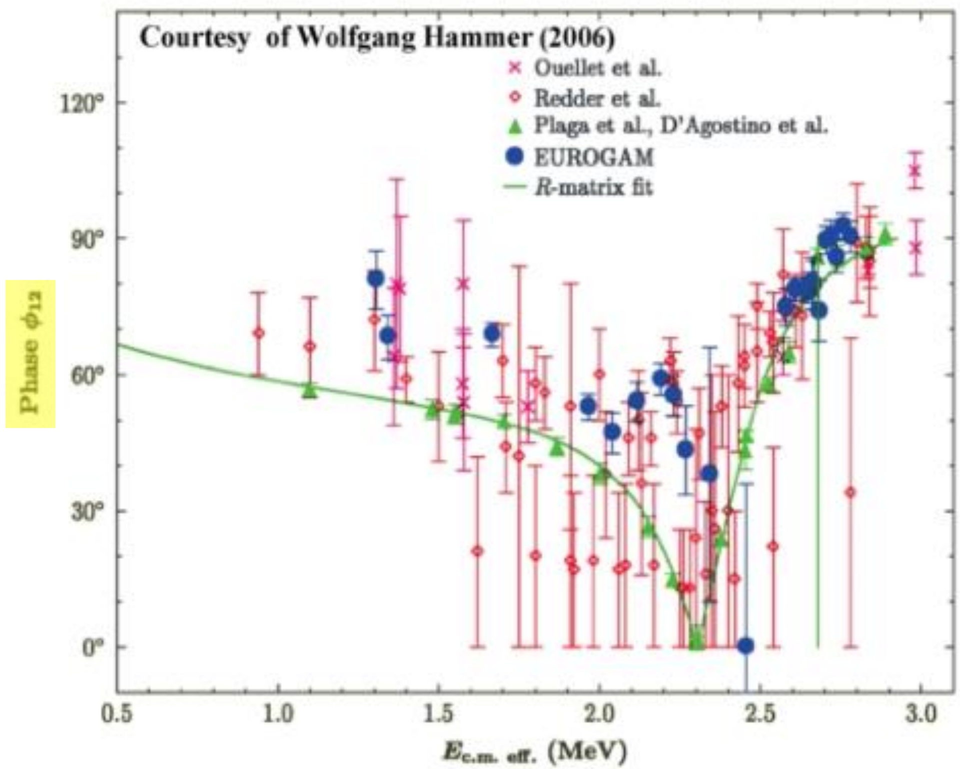


Figure prepared in 2006 by Professor Wolfgang Hammer, then senior leader of the Stuttgart group.

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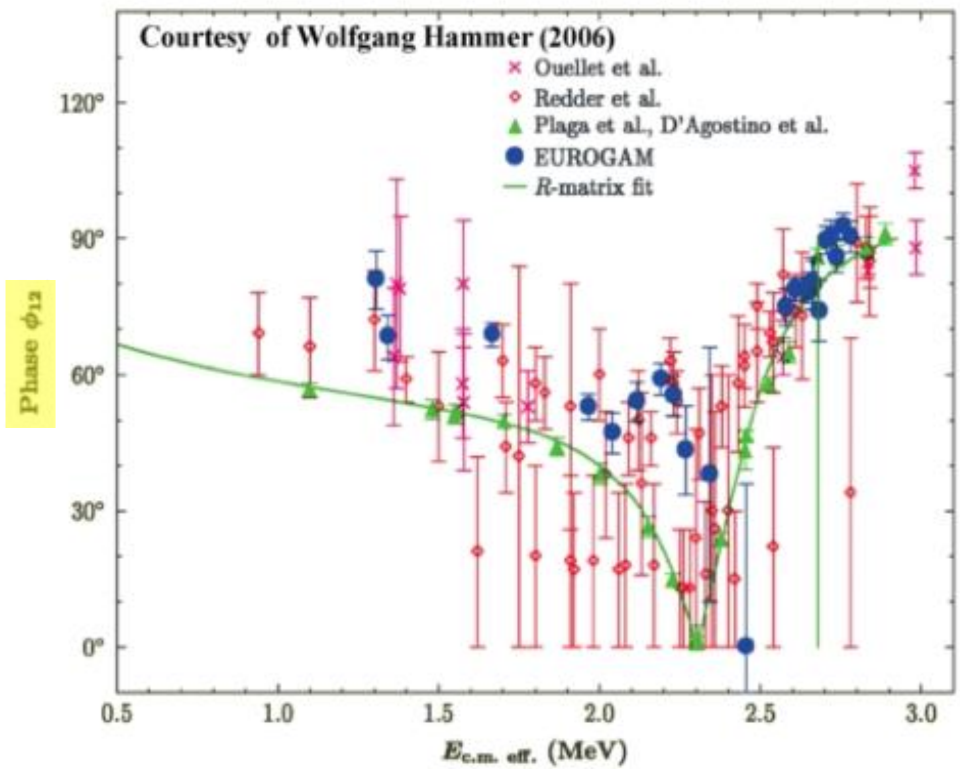
$$W(\theta) = (3|A_{E1}|^2 + 5|A_{E2}|^2)P_0(\cos\theta) + \left(25/7|A_{E2}|^2 - 3|A_{E1}|^2\right)P_2(\cos\theta) - 60/7|A_{E2}|^2 P_4(\cos\theta) + 6\sqrt{3}|A_{E1}||A_{E2}|\cos\phi_{12}[P_1(\cos\theta) - P_3(\cos\theta)]$$

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



- 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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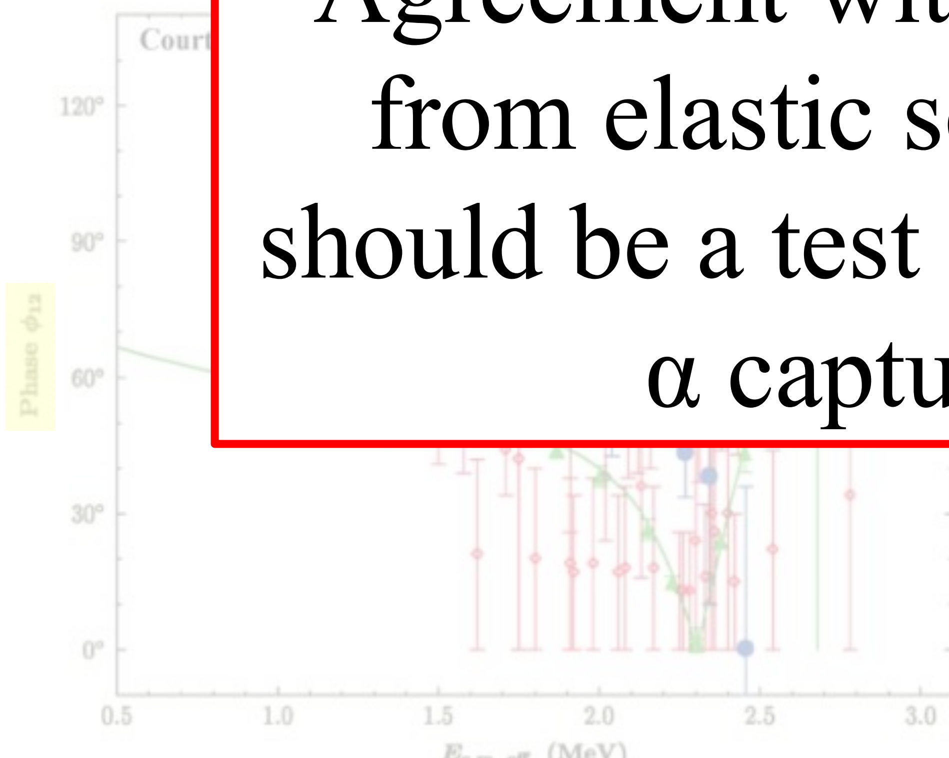

Agreement with ϕ_{12} extracted from elastic scattering data should be a test of the quality of α capture data

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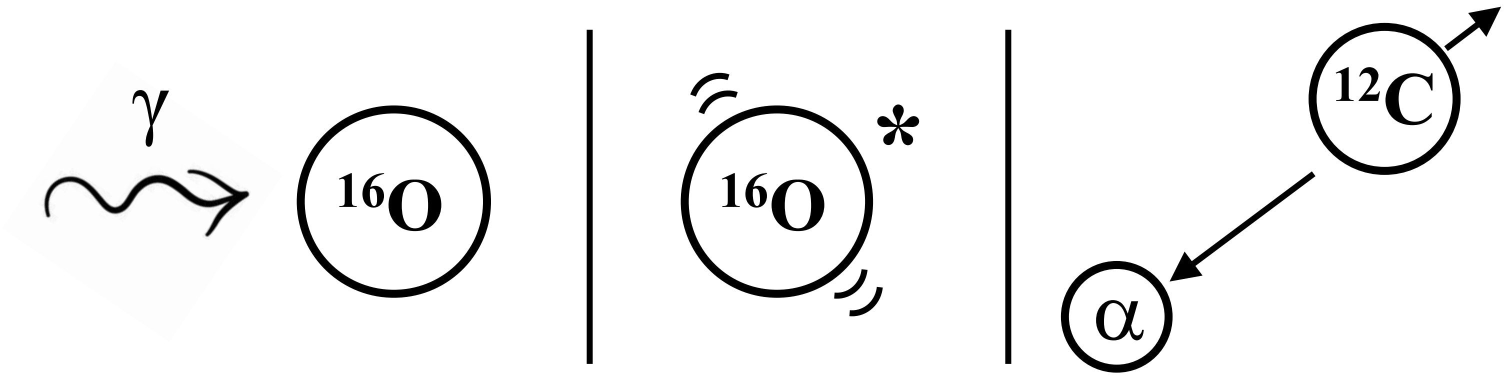
New Method – photo-dissociation

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



- 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)**

"New" Method – photo-dissociation

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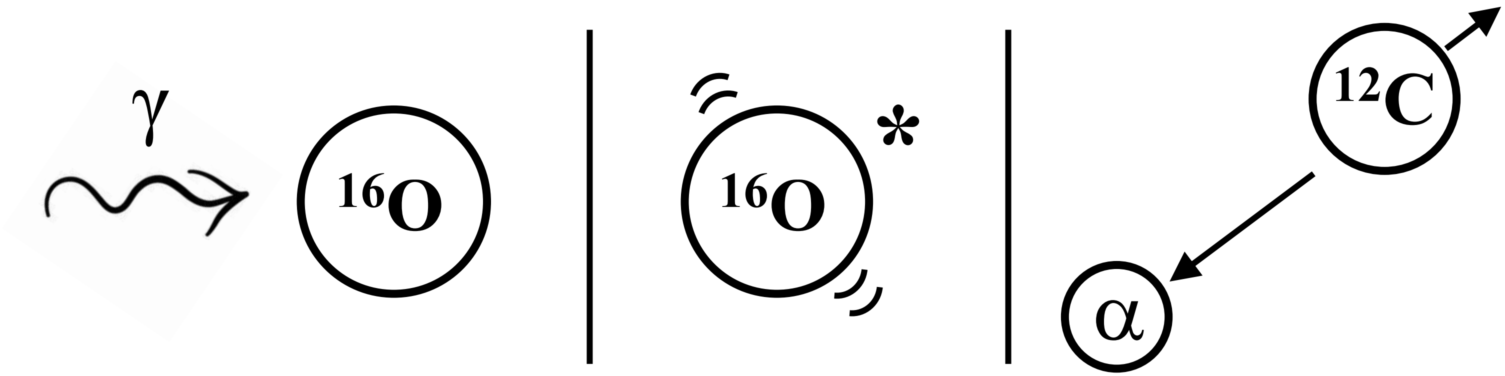

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Historical measurement

Volume 33B, number 4 PHYSICS LETTERS 26 October 1970

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

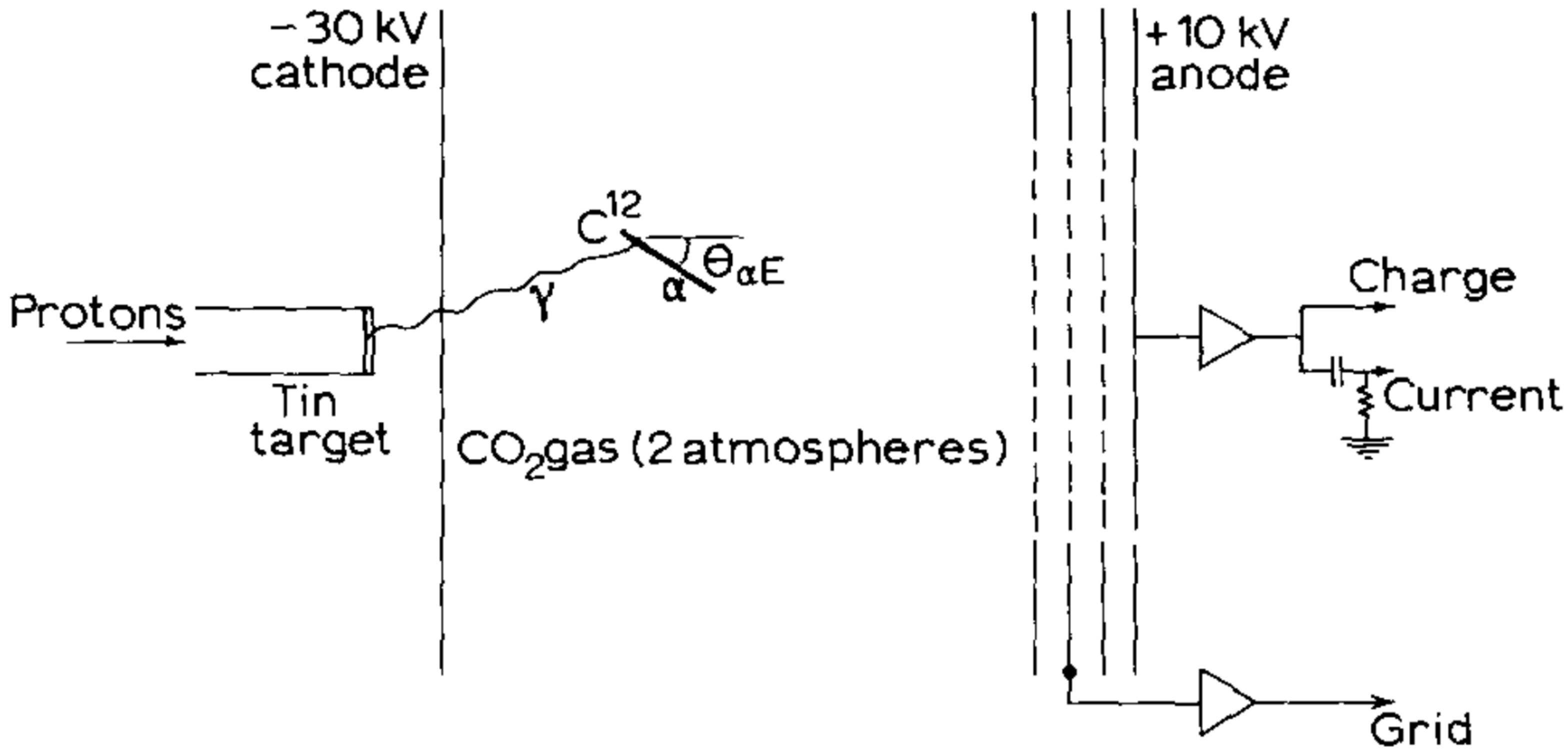
U. Von WIMMERSPERG, G. KERNEL, B. W. ALLARDYCE, W. M. MASON and N. W. TANNER
Nuclear Physics Laboratory, Oxford, UK

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.

Historical measurement



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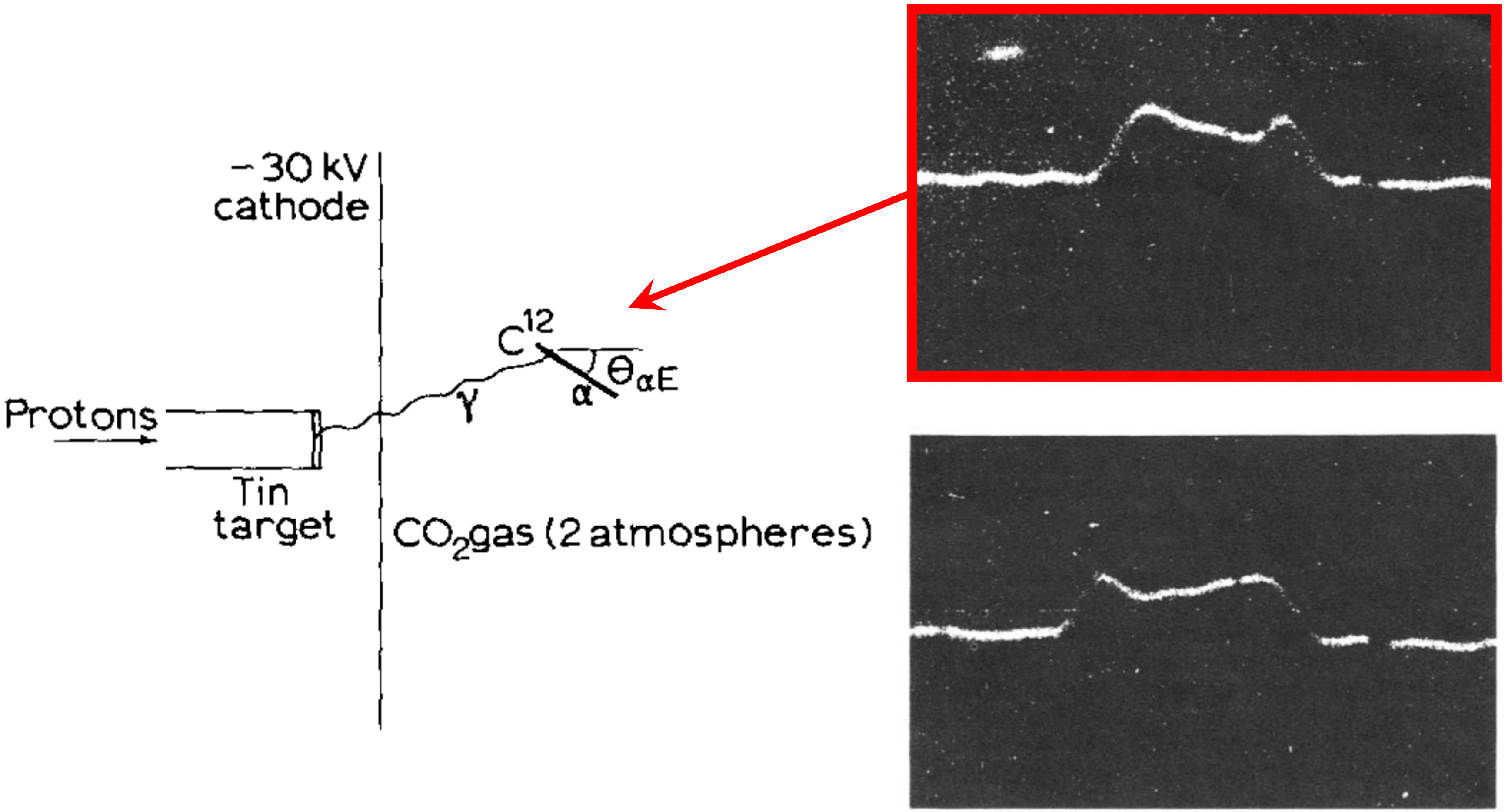

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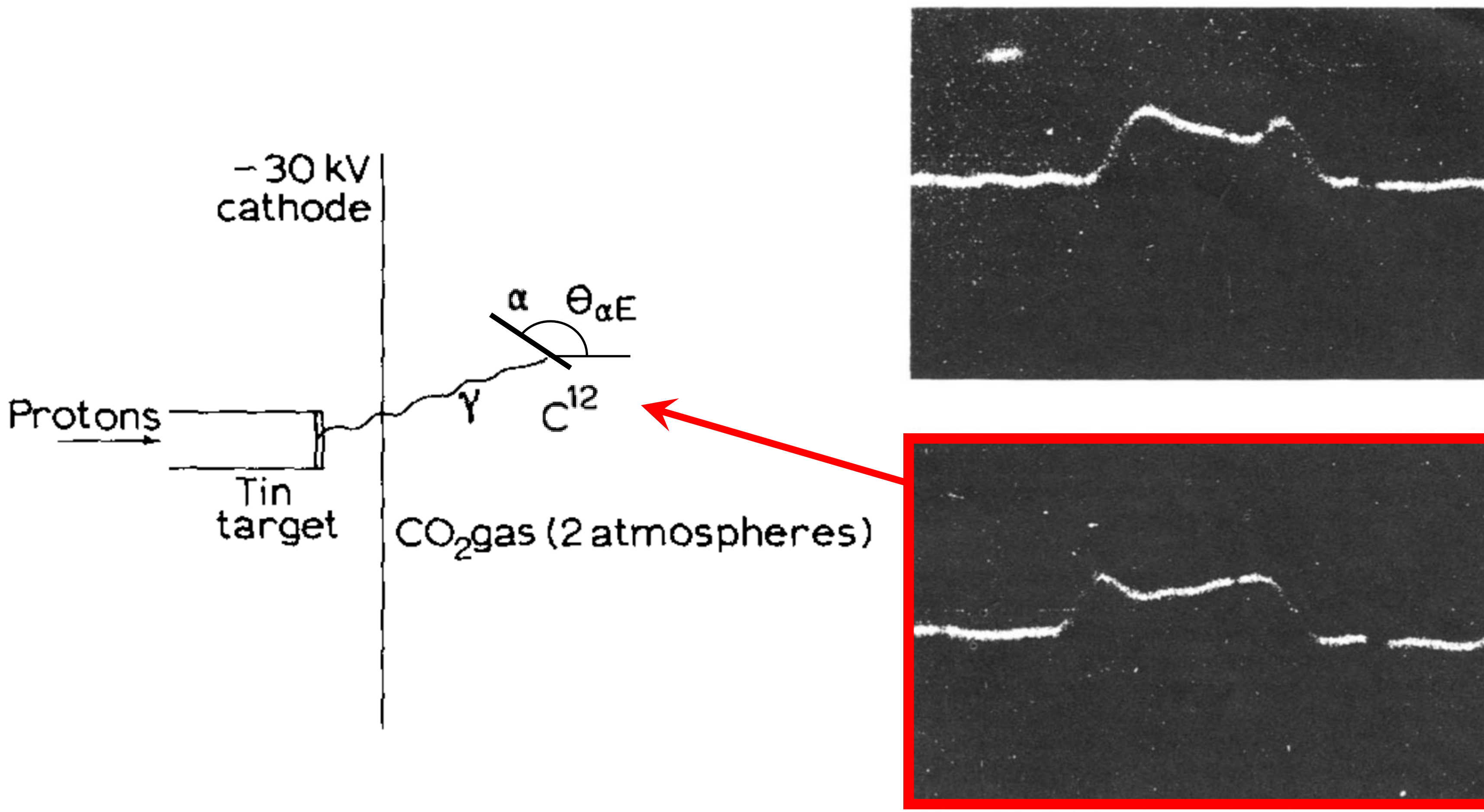

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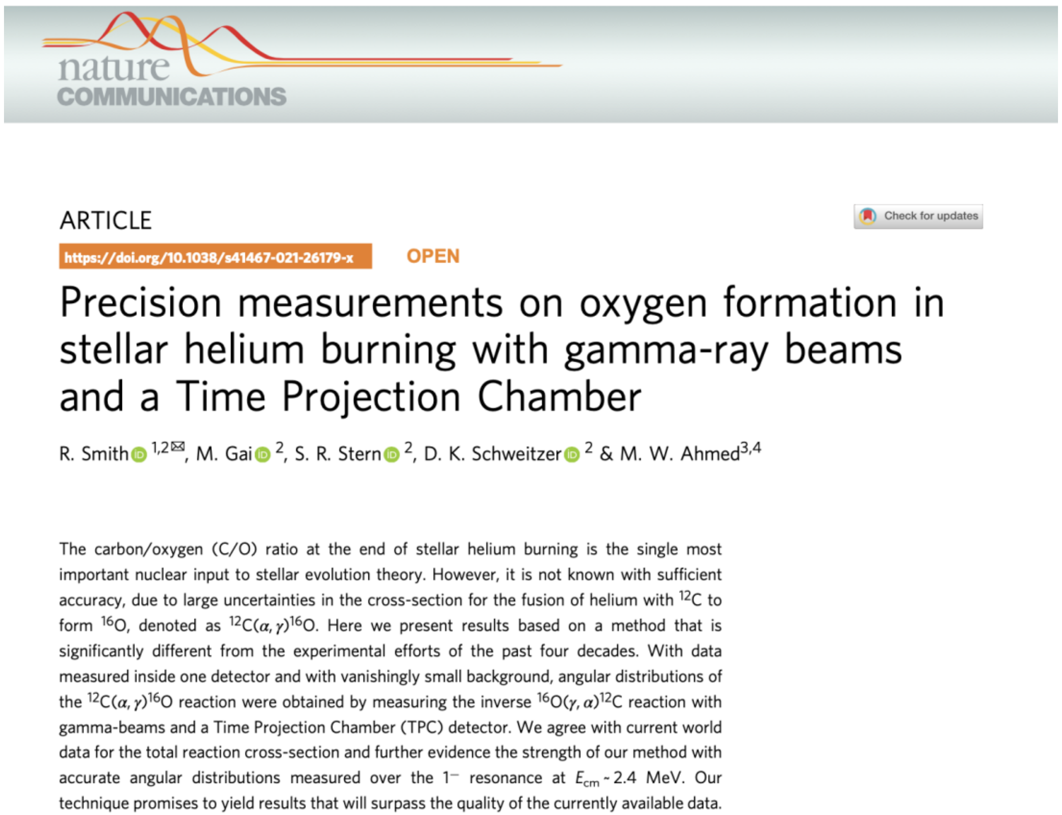
Optical TPC work

- Proof-of-principle TPC measurements were performed previously


nature COMMUNICATIONS

ARTICLE

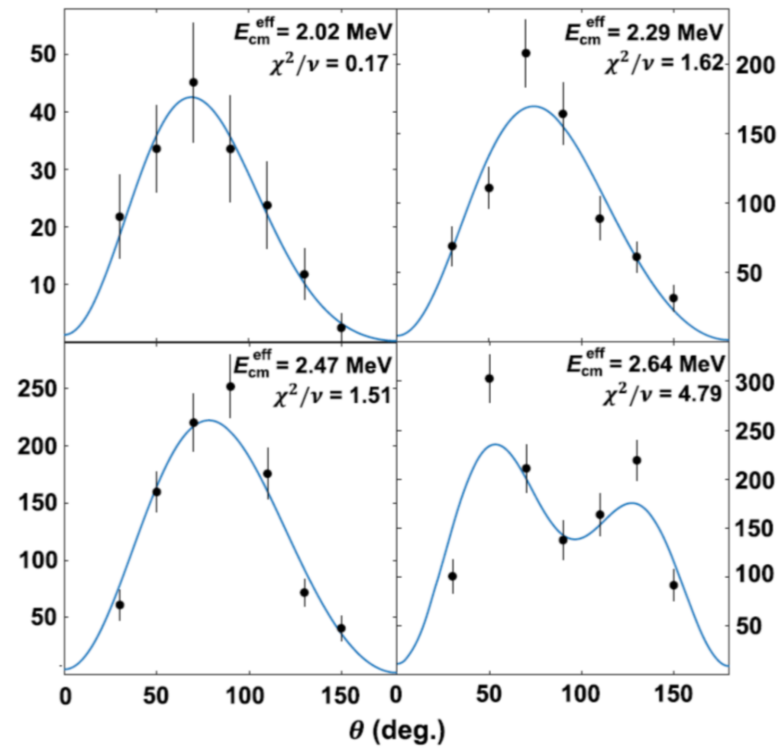
Check for updates

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 $E_{cm} \sim 2.4$ 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)

K. C. Z. Haverson, R. Smith, M. Gai, *et al. Nature Communications Physics* 9, 27 (2026)

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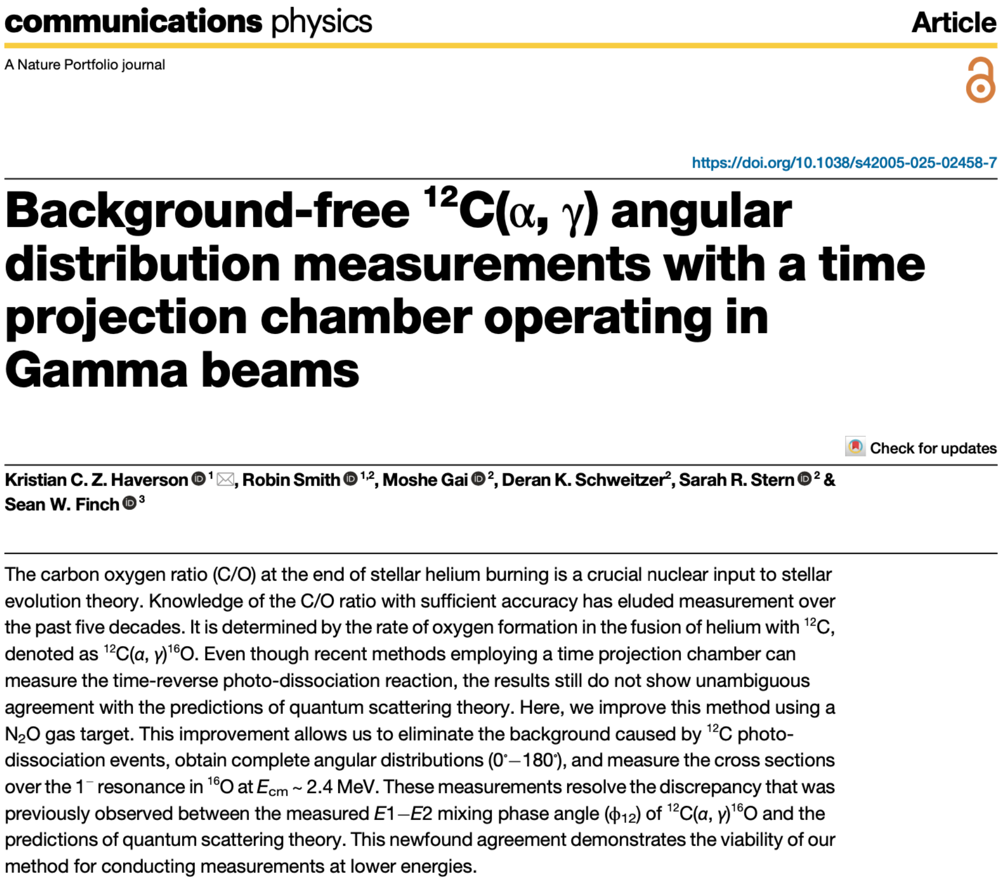
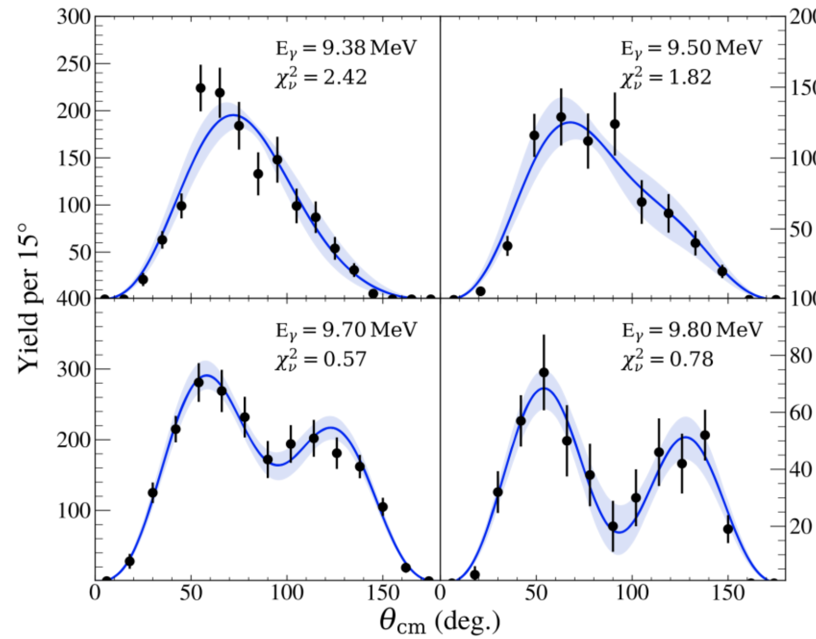

communications physics **Article**
A Nature Portfolio journal
https://doi.org/10.1038/s42005-025-02458-7

Background-free $^{12}C(\alpha, \gamma)$ angular distribution measurements with a time projection chamber operating in Gamma beams

Check for updates

Kristian C. Z. Haverson[1], Robin Smith[1,2], Moshe Gai[2], Deran K. Schweitzer[2], Sarah R. Stern[2] & Sean W. Finch[3]

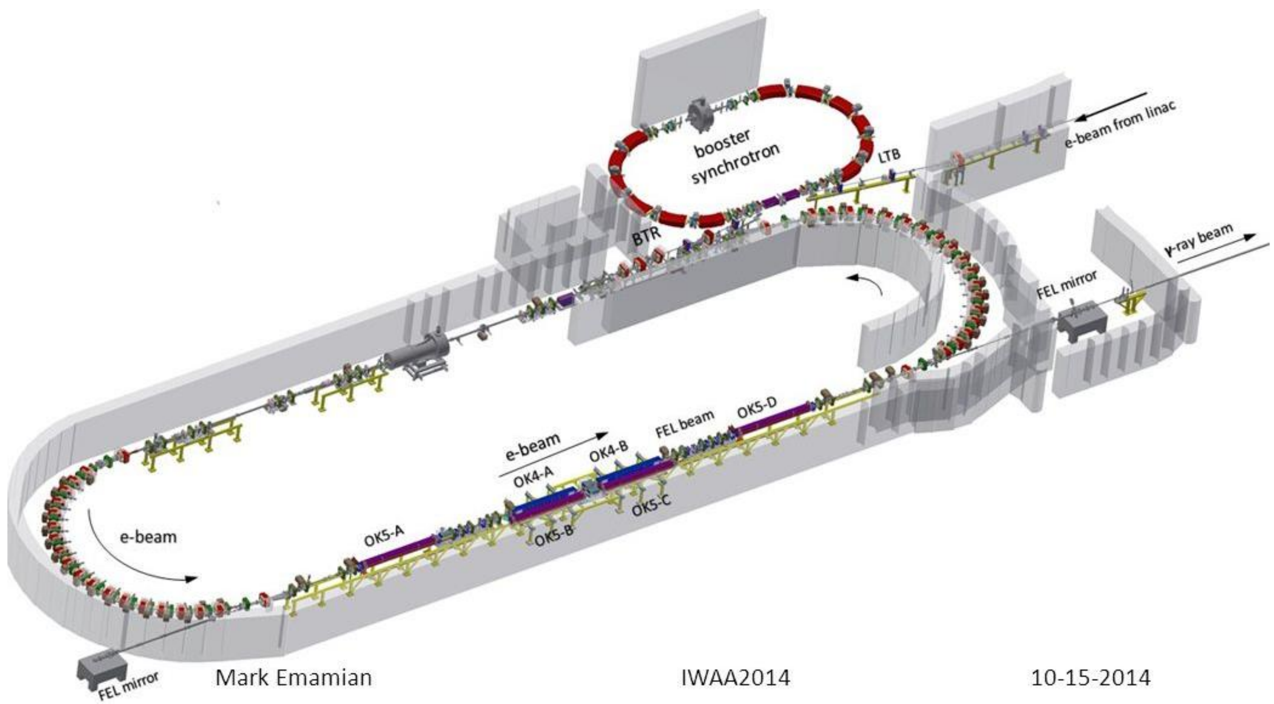
The carbon oxygen ratio (C/O) at the end of stellar helium burning is a crucial nuclear input to stellar evolution theory. Knowledge of the C/O ratio with sufficient accuracy has eluded measurement over the past five decades. It is determined by the rate of oxygen formation in the fusion of helium with ^{12}C, denoted as $^{12}C(\alpha, \gamma)^{16}O$. Even though recent methods employing a time projection chamber can measure the time-reverse photo-dissociation reaction, the results still do not show unambiguous agreement with the predictions of quantum scattering theory. Here, we improve this method using a N_2O gas target. This improvement allows us to eliminate the background caused by ^{12}C photo-dissociation events, obtain complete angular distributions (0°−180°), and measure the cross sections over the 1^- resonance in ^{16}O at $E_{cm} \sim 2.4$ MeV. These measurements resolve the discrepancy that was previously observed between the measured $E1-E2$ mixing phase angle (ϕ_{12}) of $^{12}C(\alpha, \gamma)^{16}O$ and the predictions of quantum scattering theory. This newfound agreement demonstrates the viability of our method for conducting measurements at lower energies.



R. Smith, M. Gai, *et al.*, *Nature Communications* 12.1 (2021)
K. C. Z. Haverson, R. Smith, M. Gai, *et al. Nature Communications Physics* 9, 27 (2026)

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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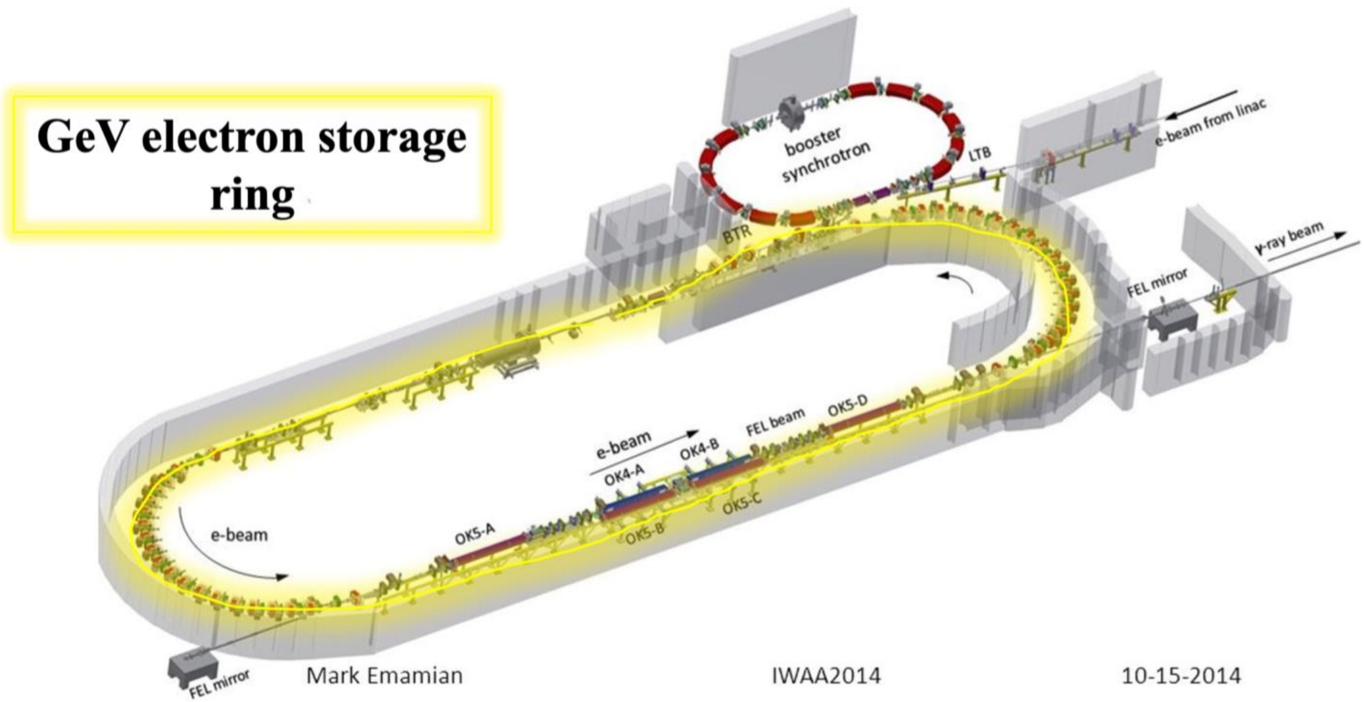

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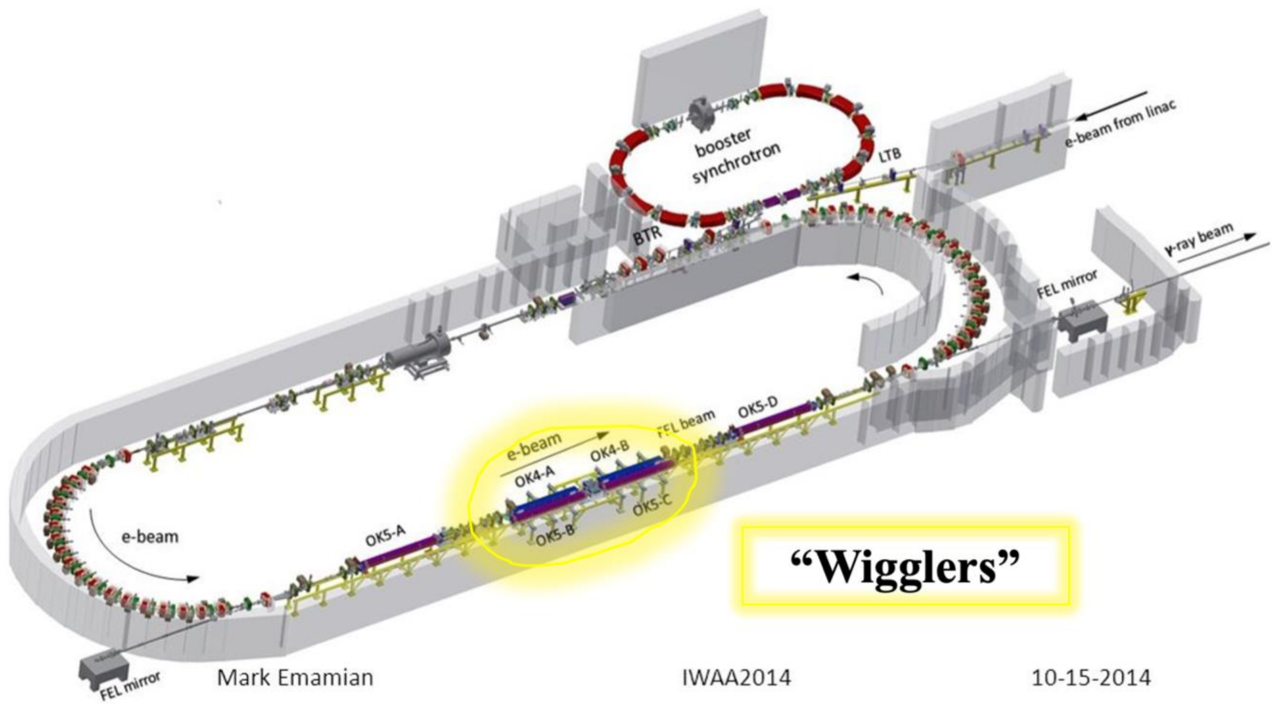

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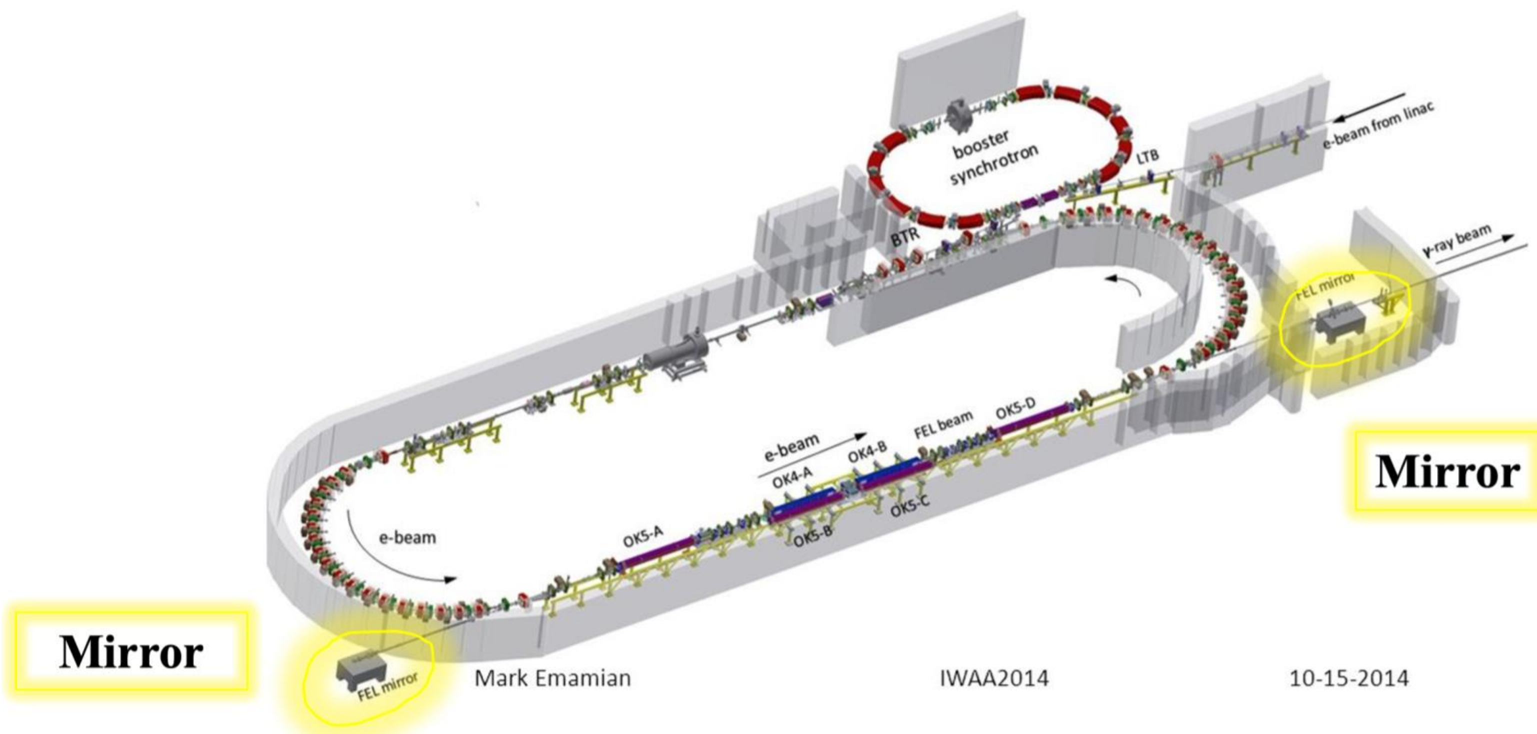
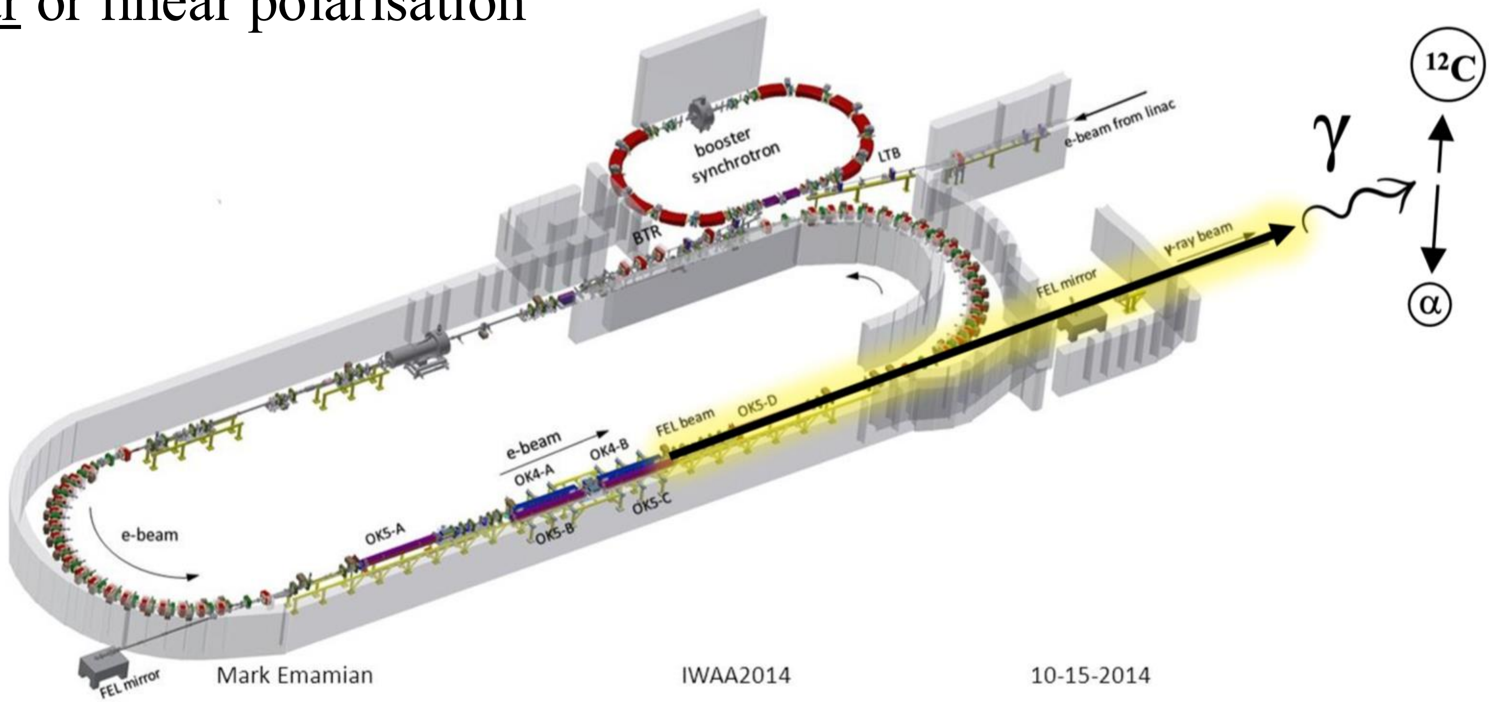


H.R. Weller *et al.*, Progress in Particle and Nuclear Physics **62** (2009)

HIγS facility + TPC

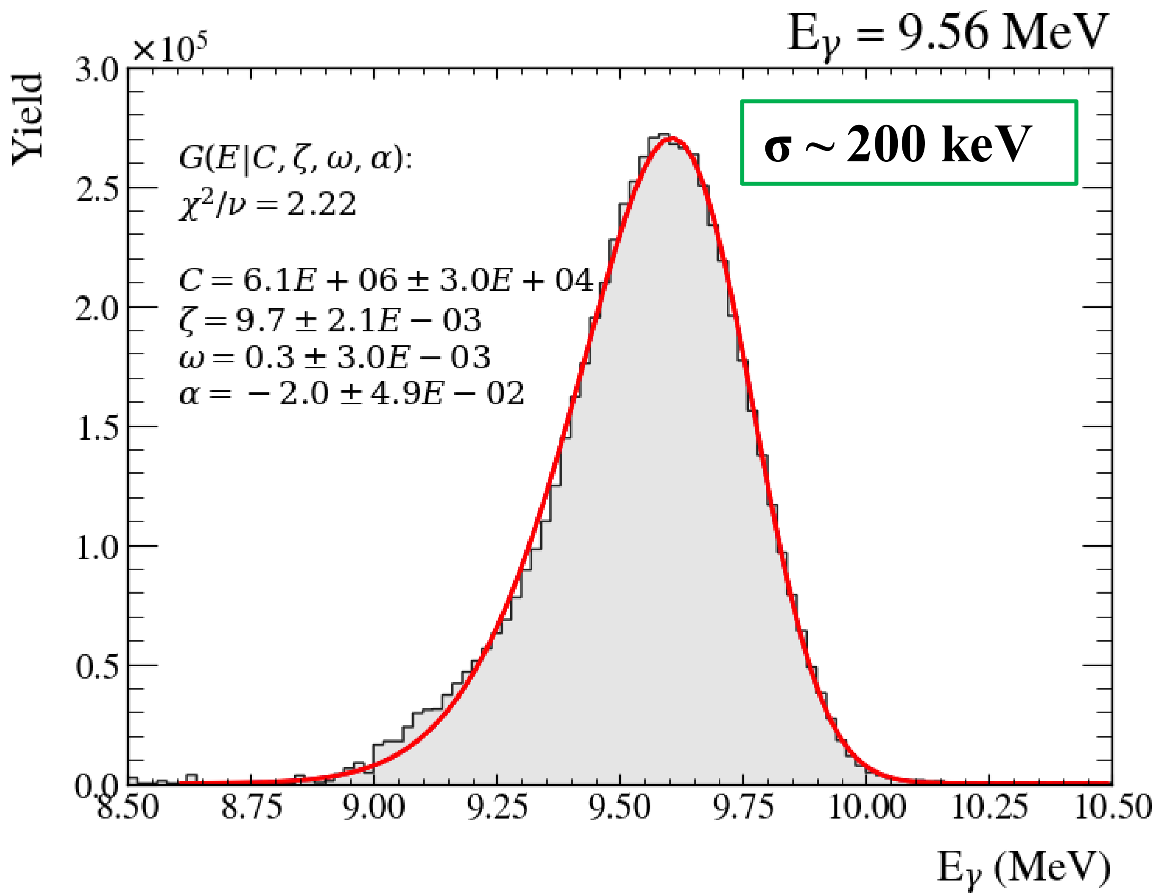
- Free electron laser – λ = 190 – 1064 nm
- Compton backscattering increases the γ energy
- *Active Target* TPC operating with CO_2 gas
- <u>Circular</u> or linear polarisation



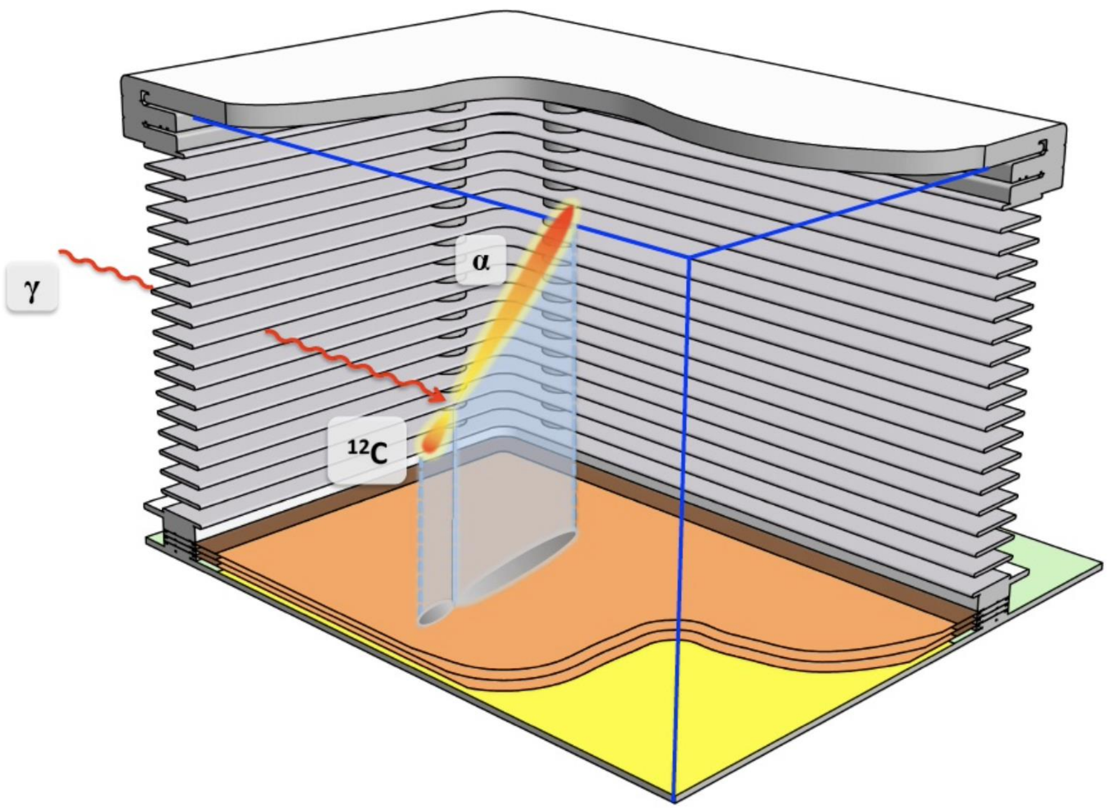
H.R. Weller *et al.*, Progress in Particle and Nuclear Physics **62** (2009)

γ-beam characterisation

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



Detector – Warsaw TPC



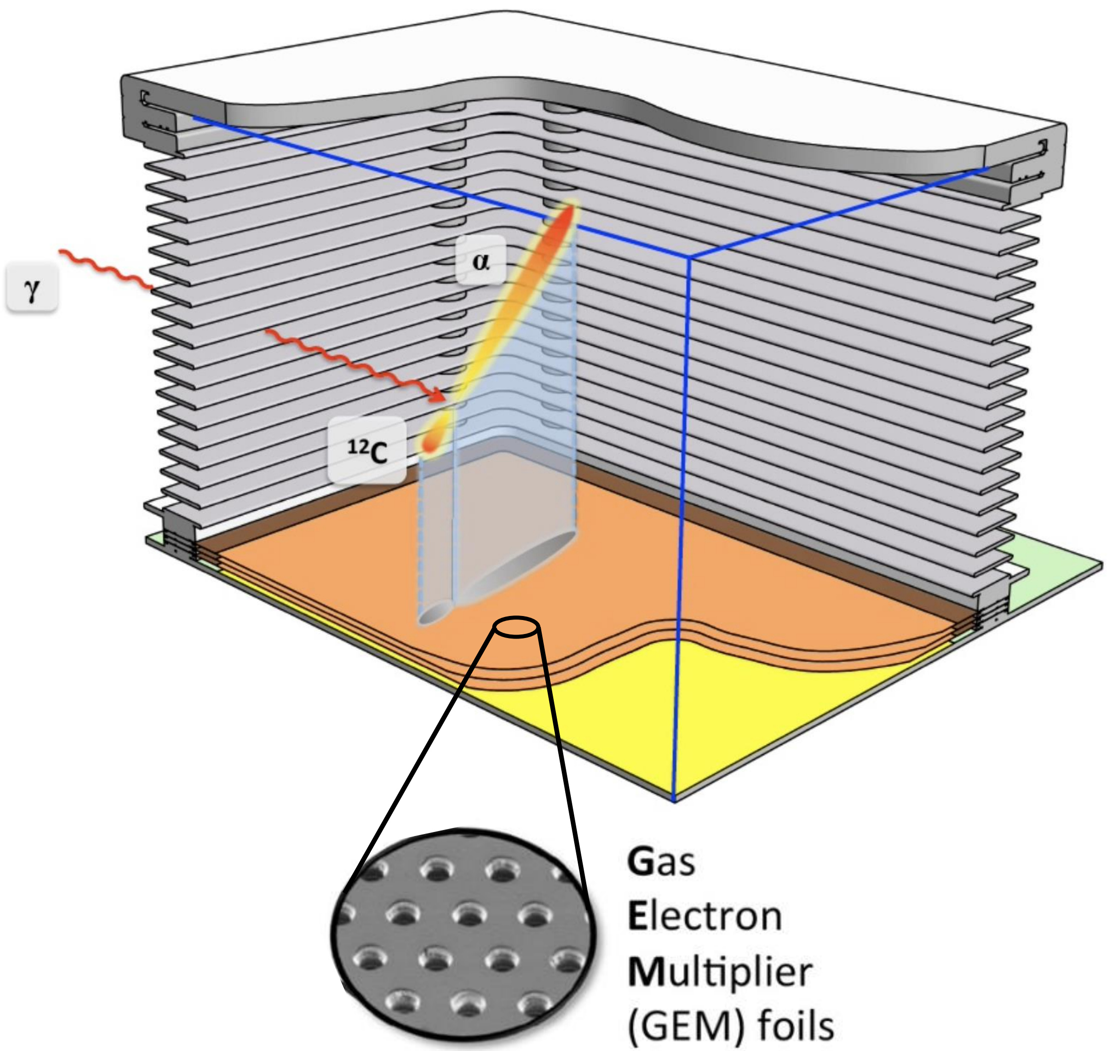
Active volume
33 x 20 cm^2 (readout) x 20 cm (drift)

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

Detector – Warsaw TPC



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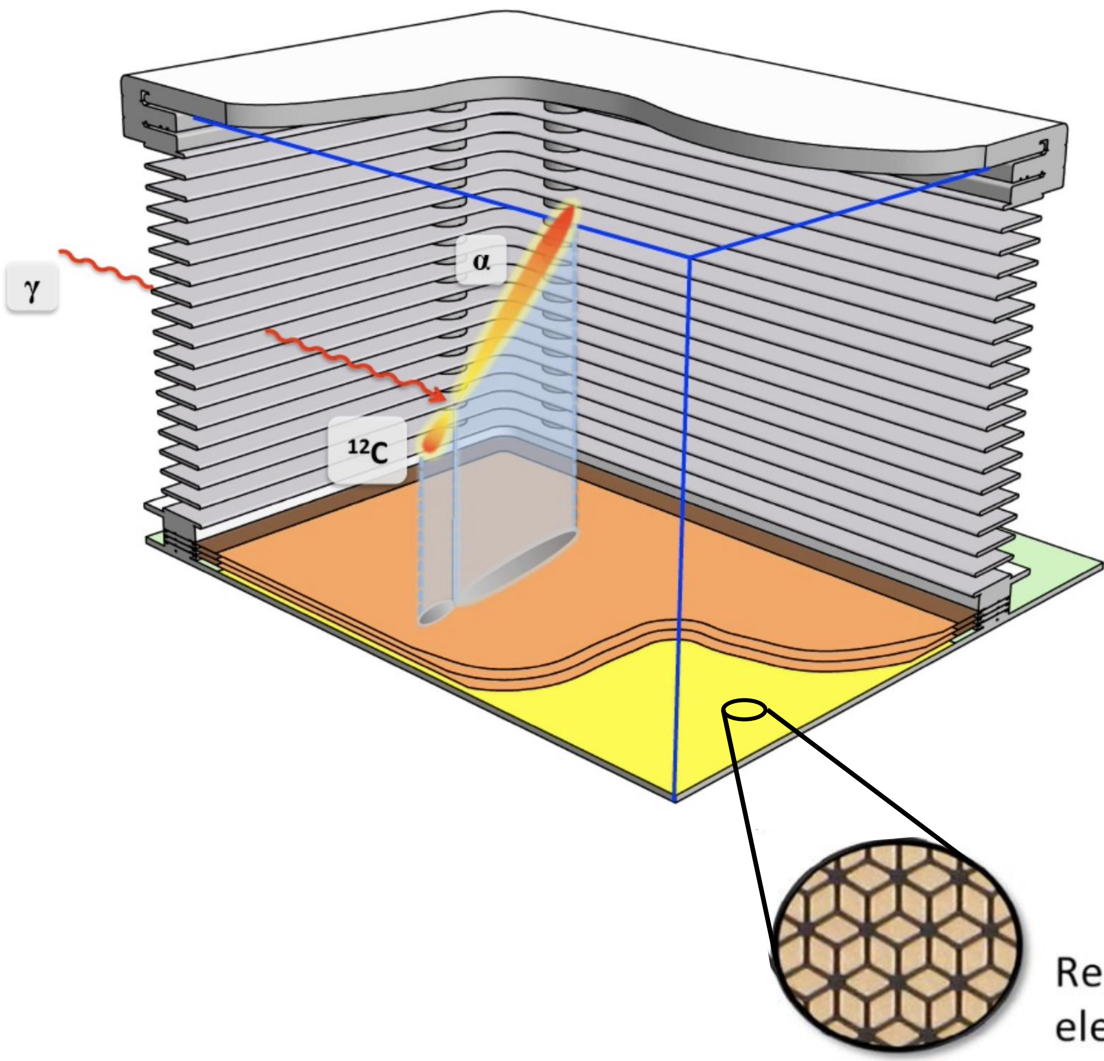

Readout electrodes (strips)

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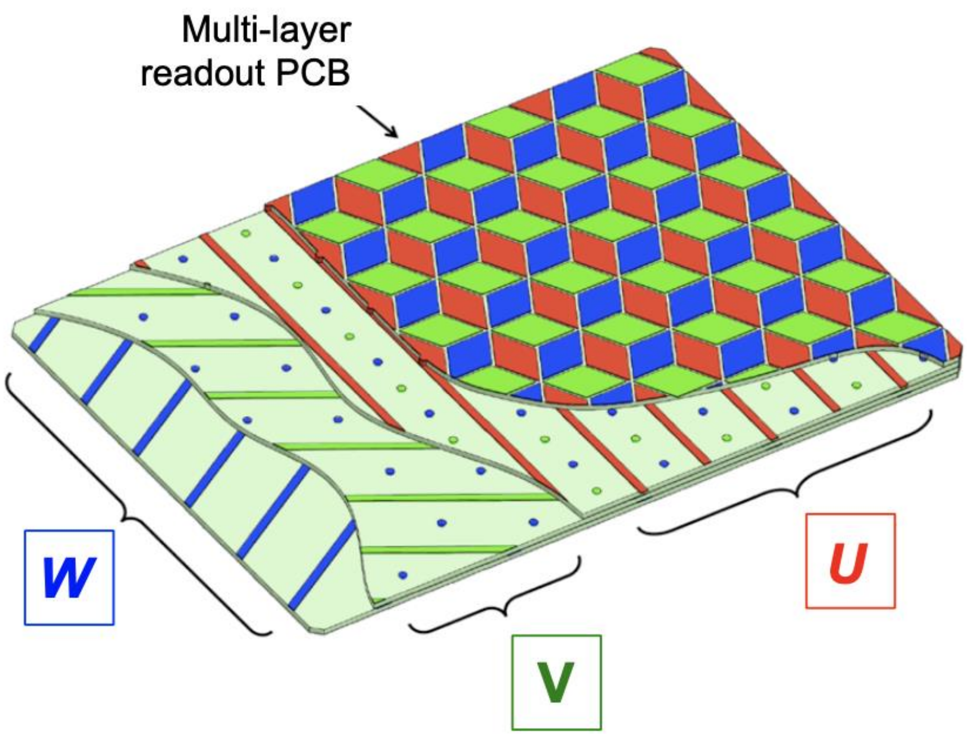

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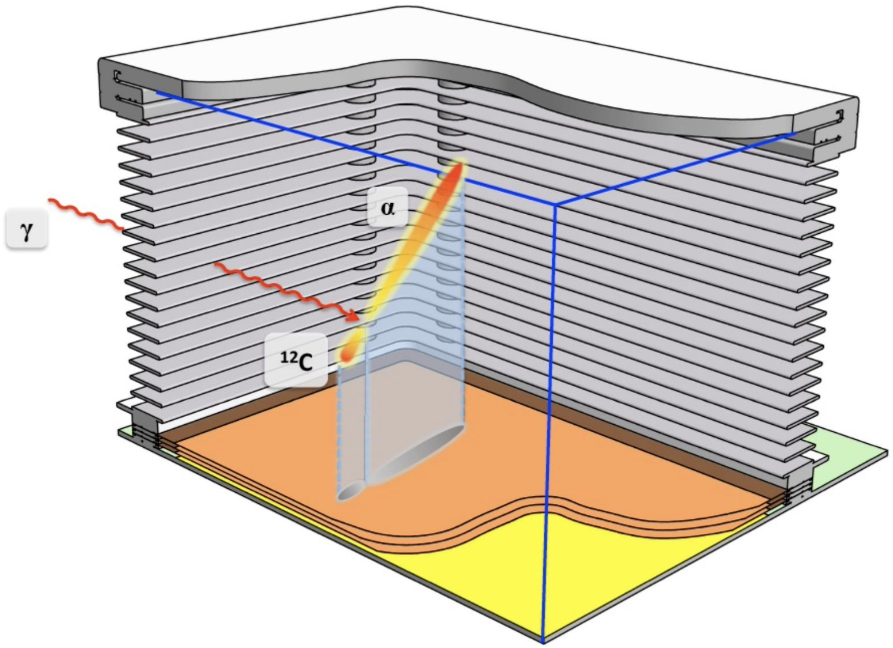
HIγS campaign – 2022



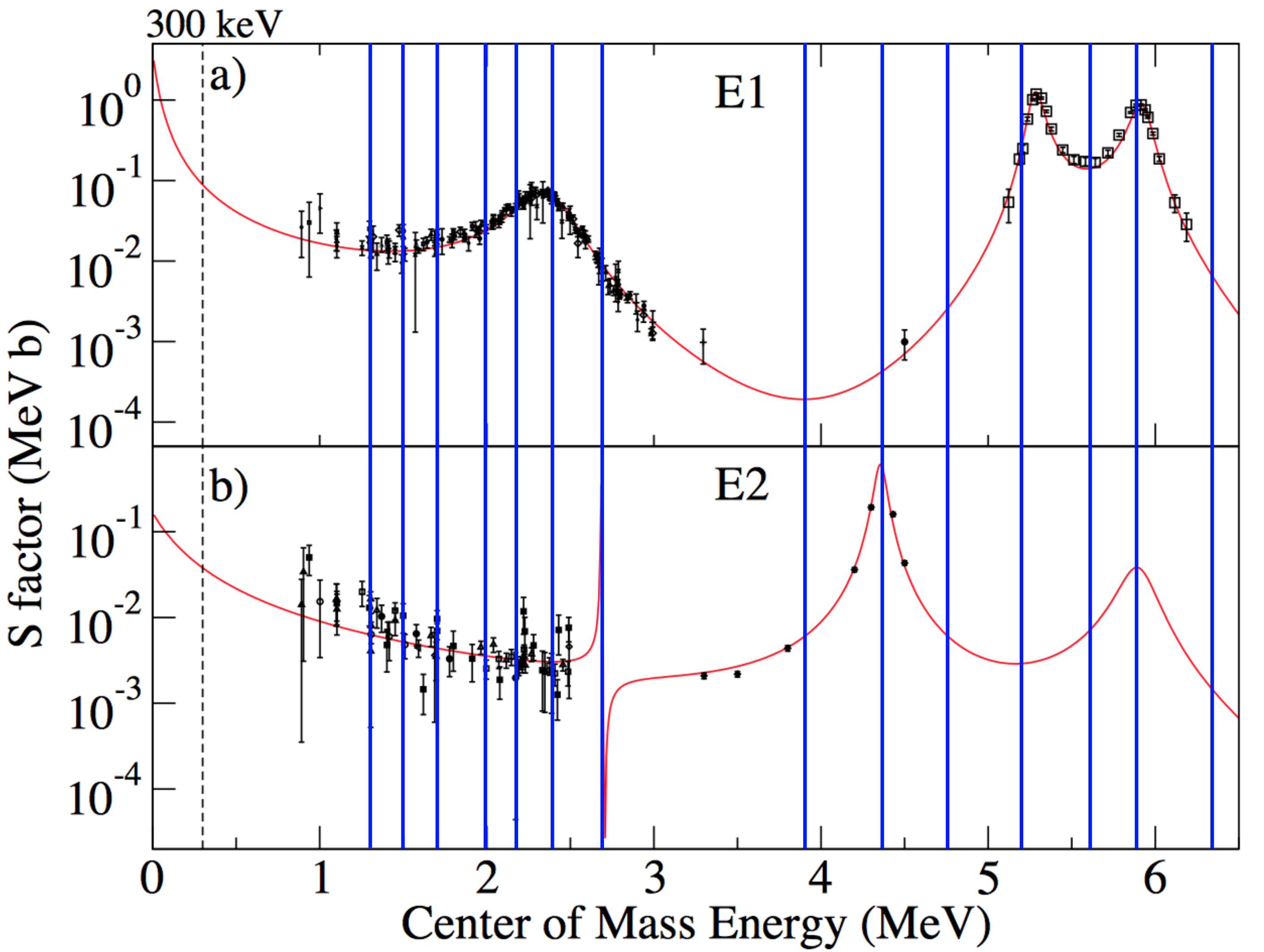
130–250 mbar pure CO_2 gas

γ-beams between 8.5 and 13.9 MeV

~ 4 × 10^8 γ/s and ΔE ~ 2%

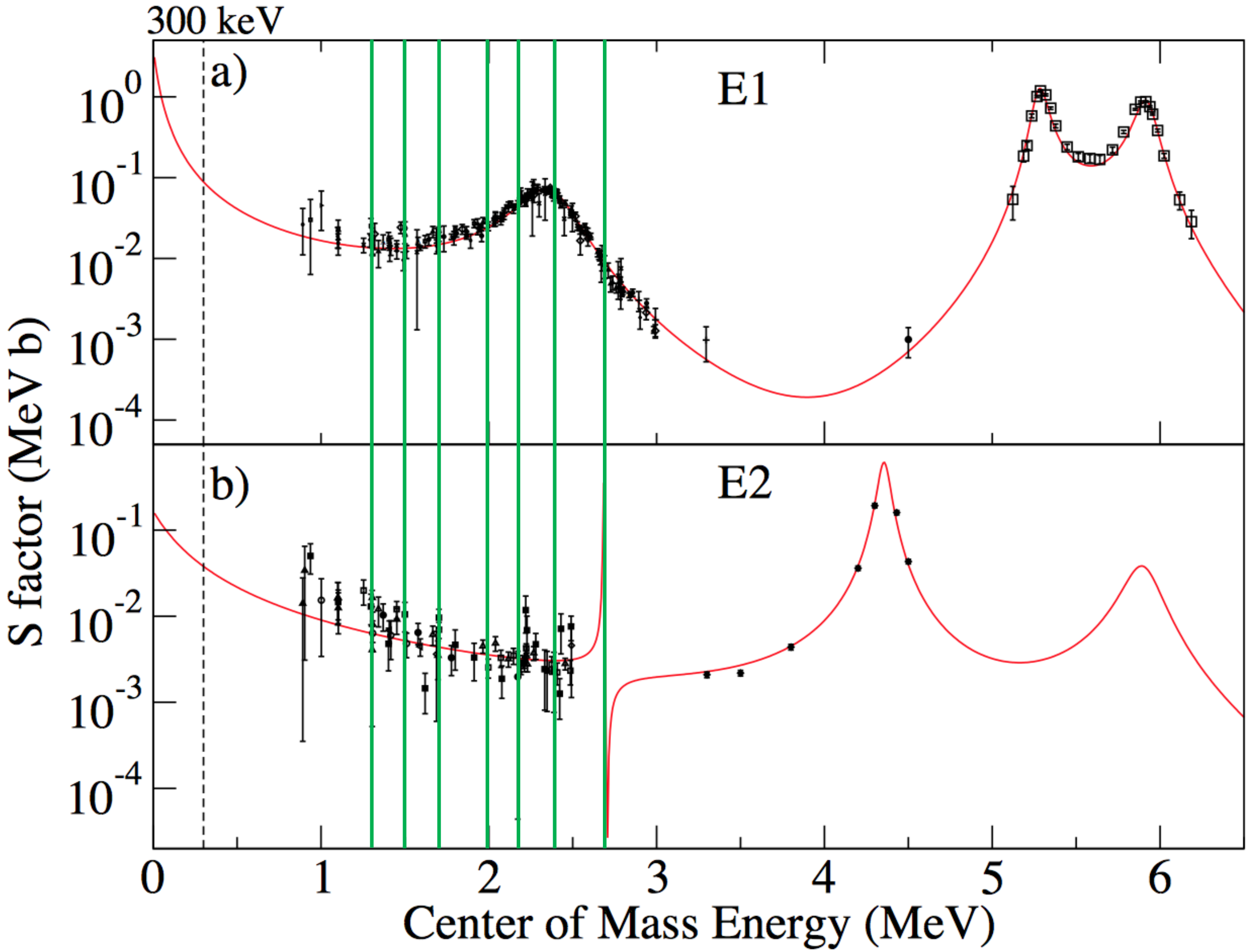
M. Ćwiok et al., EPJ Web Conf. 279 (2023) 04002.

HIγS 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)

HIγS campaign – 2022



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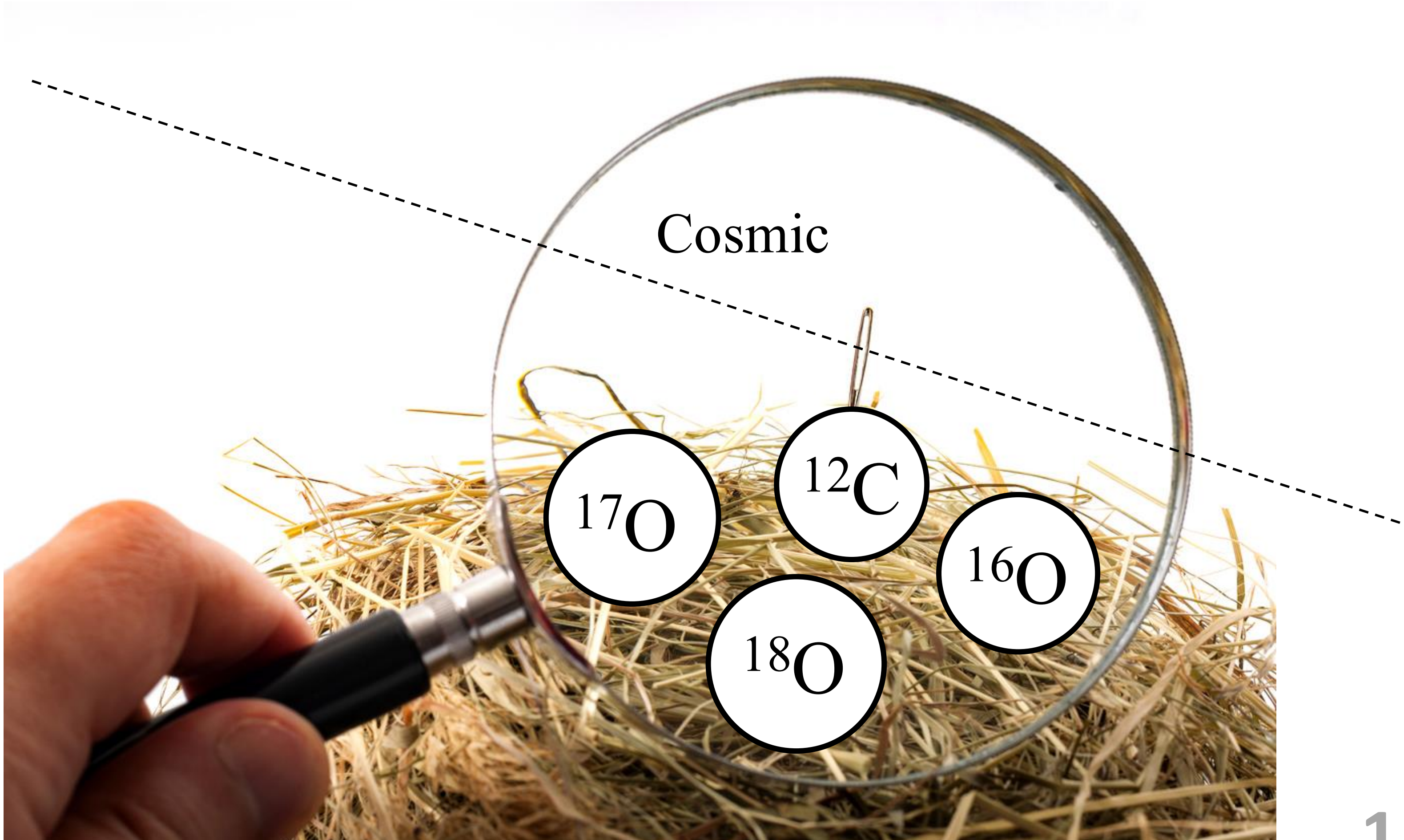
Analysis:
Finding an ^{16}O needle in a haystack



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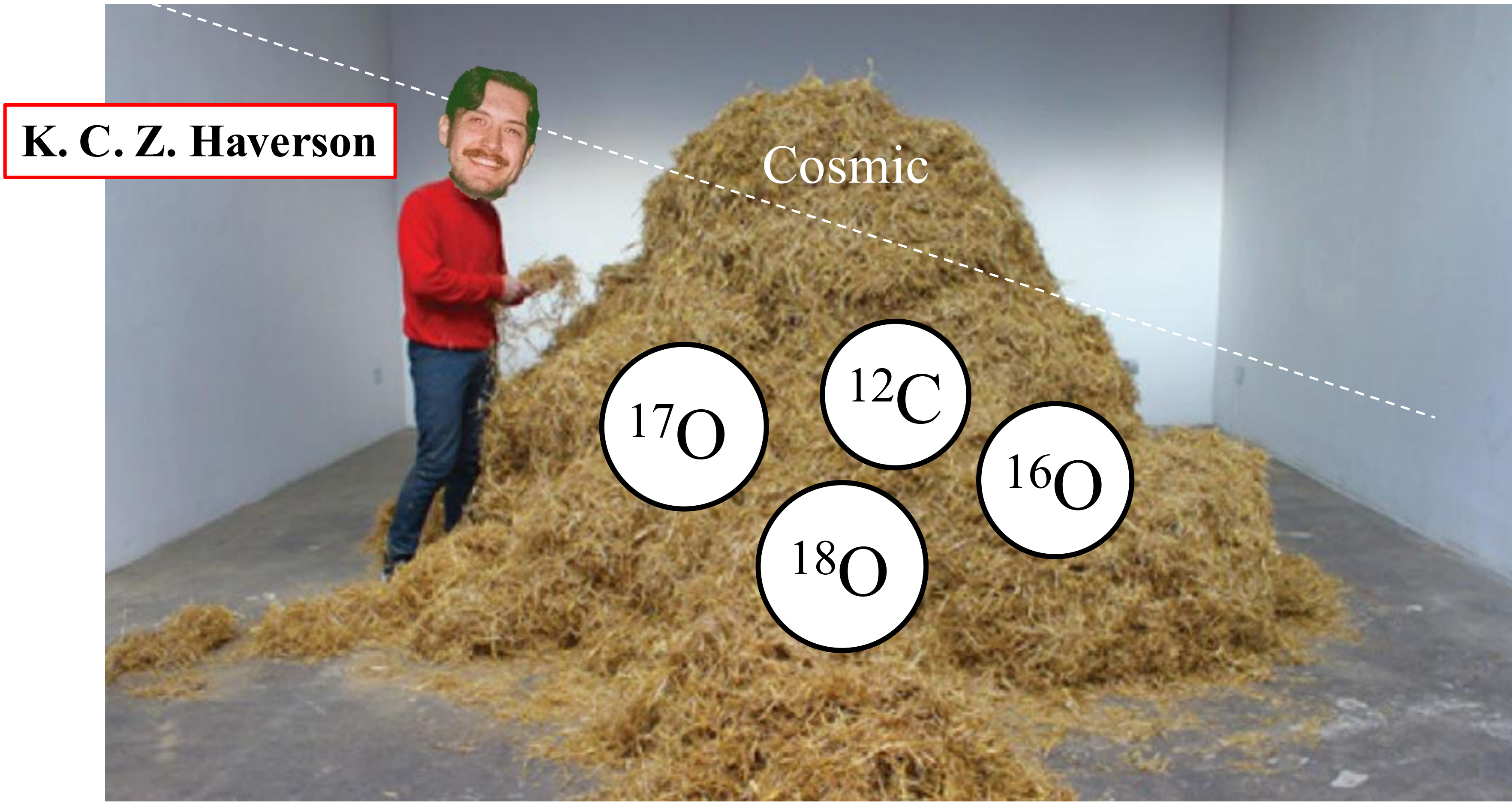

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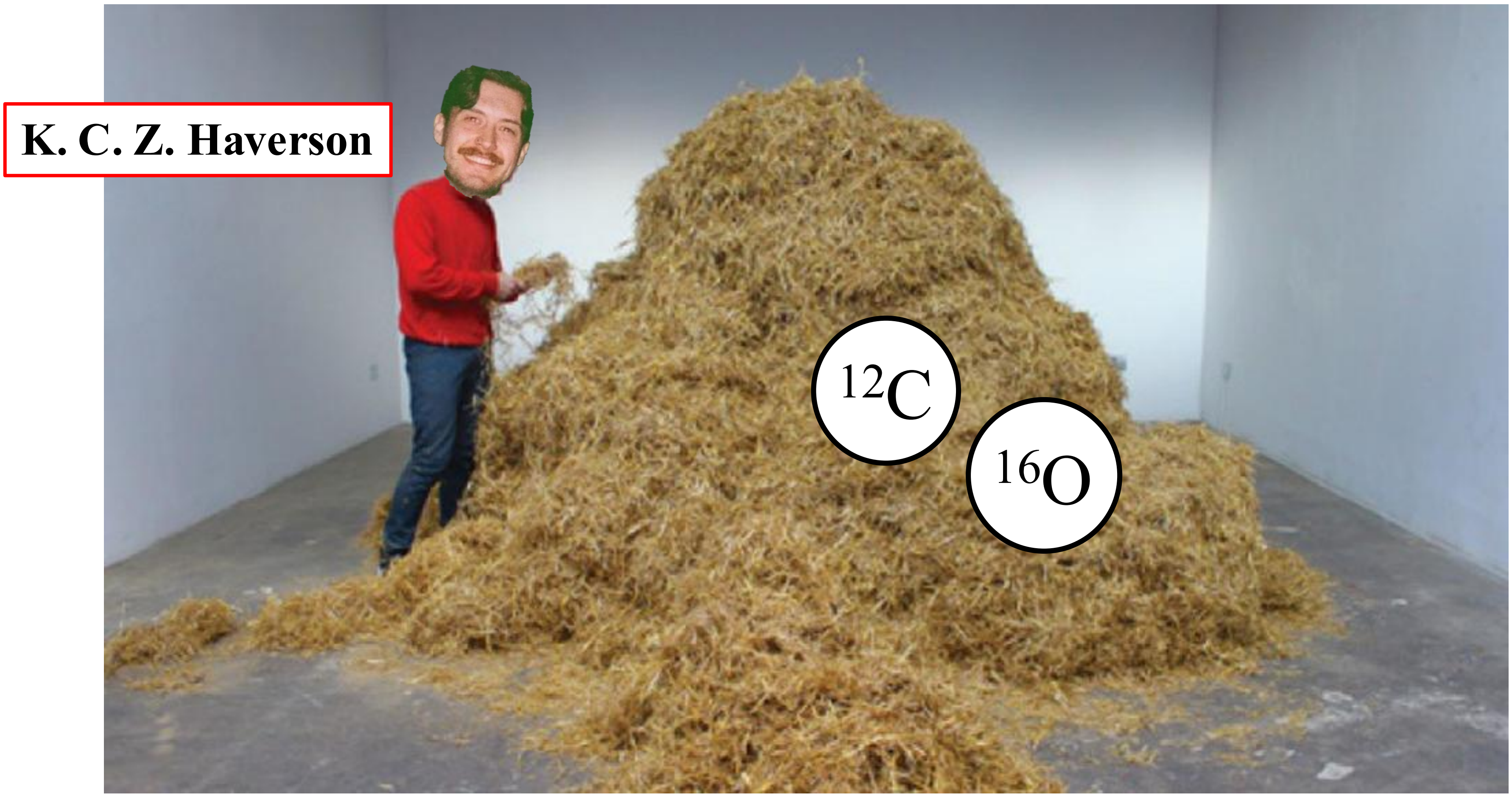
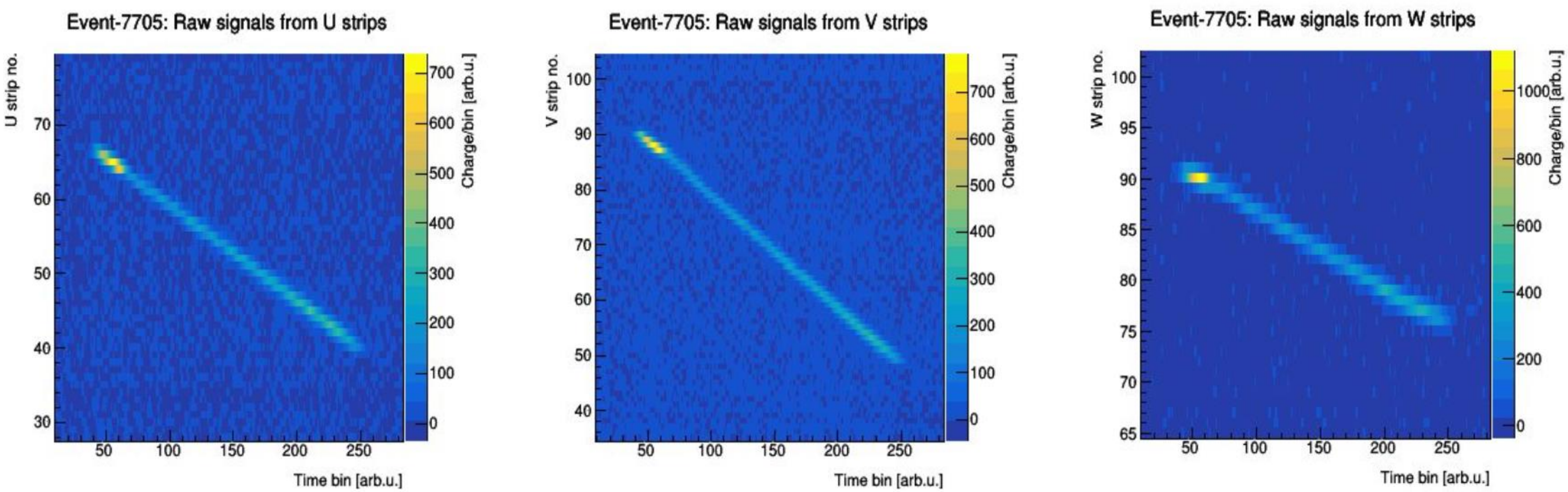
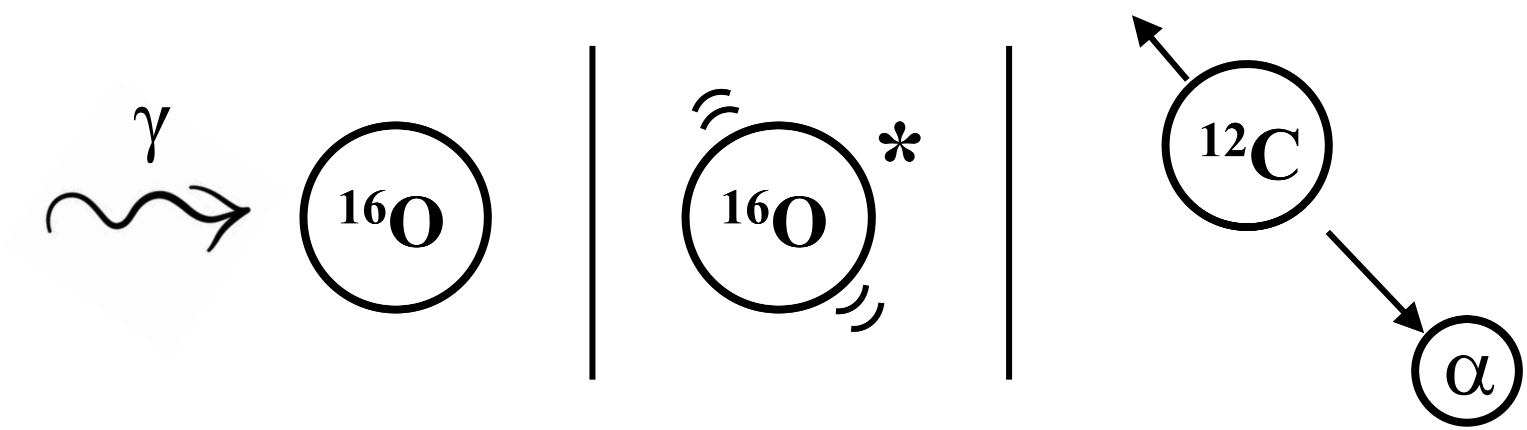


Example events – $^{16}O(\gamma,\alpha)^{12}C$





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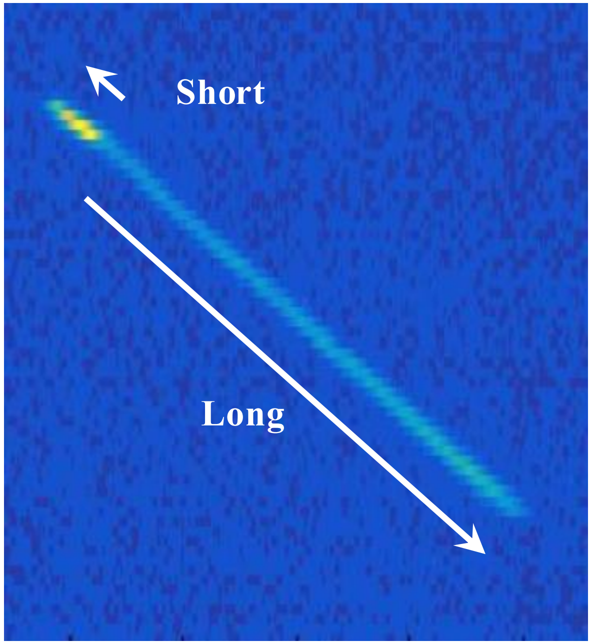
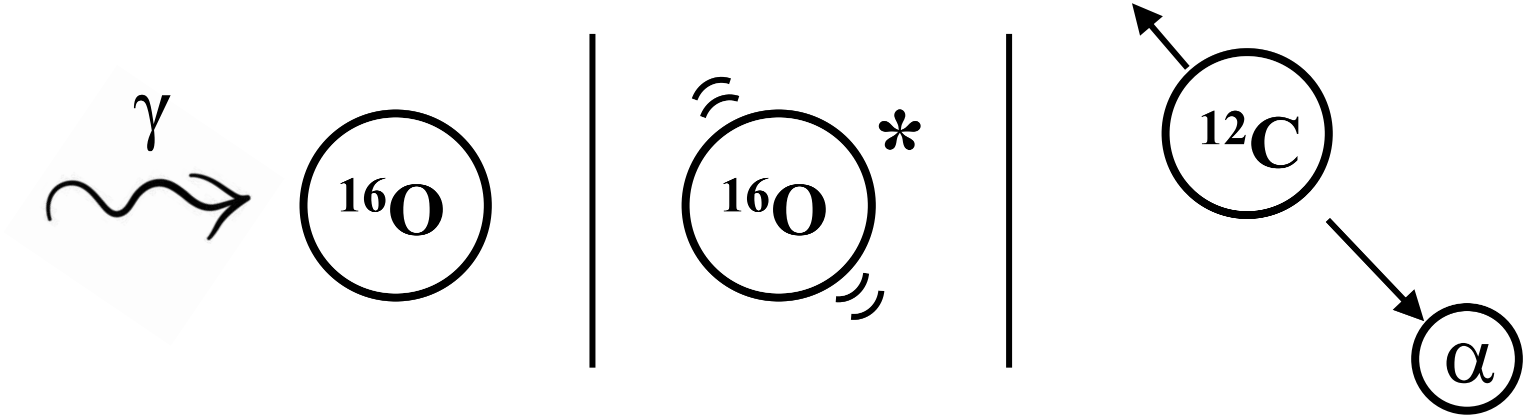
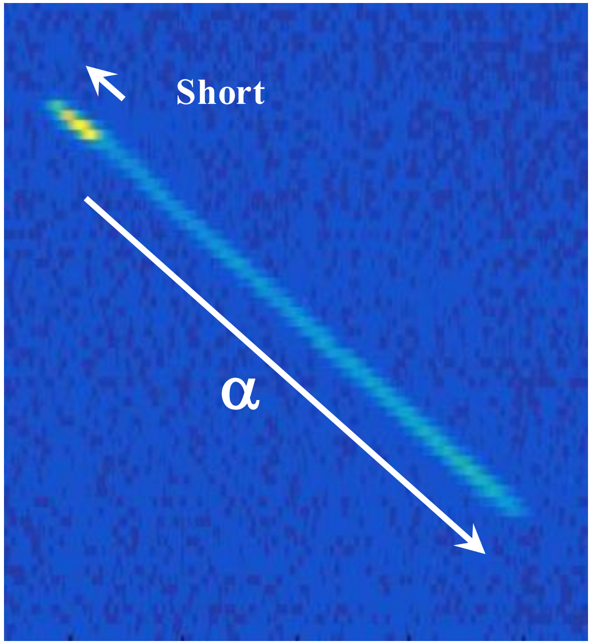




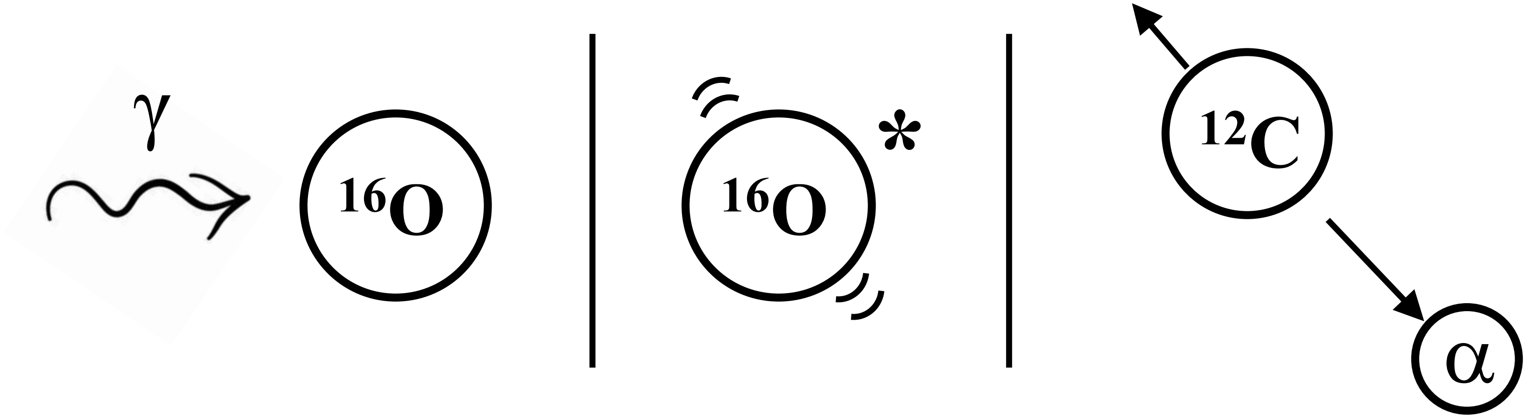
Example events – $^{16}O(\gamma,\alpha)^{12}C$



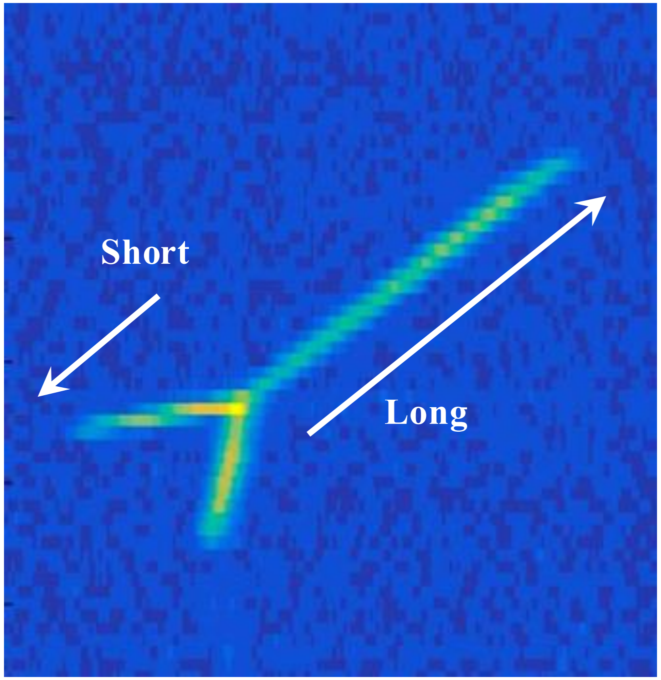
α Track length converted to energy using SRIM

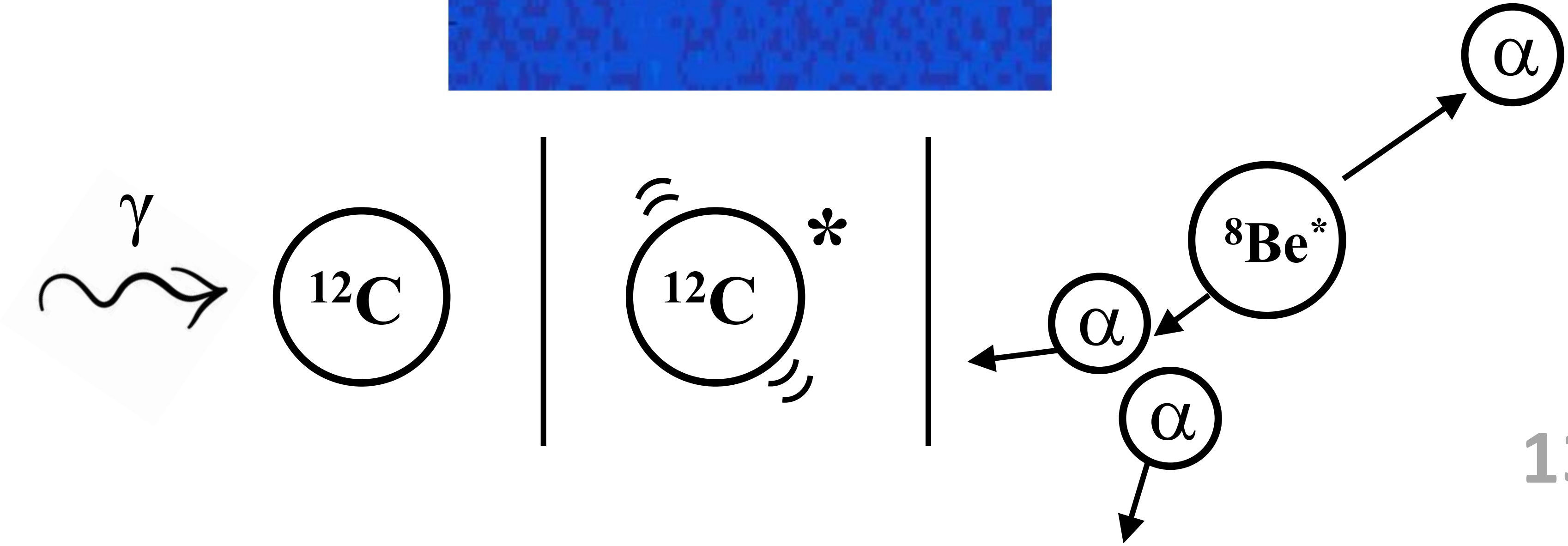
Can be boosted into CoM frame to give total E_{CoM}

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

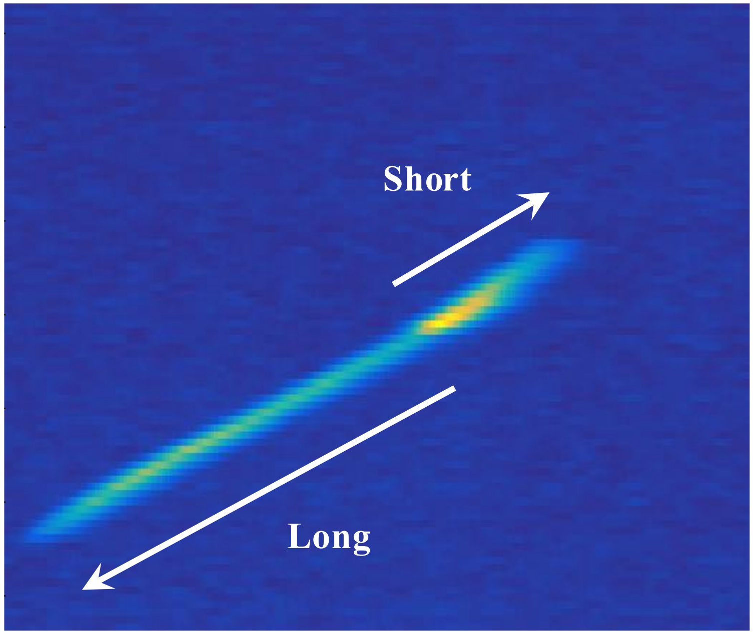


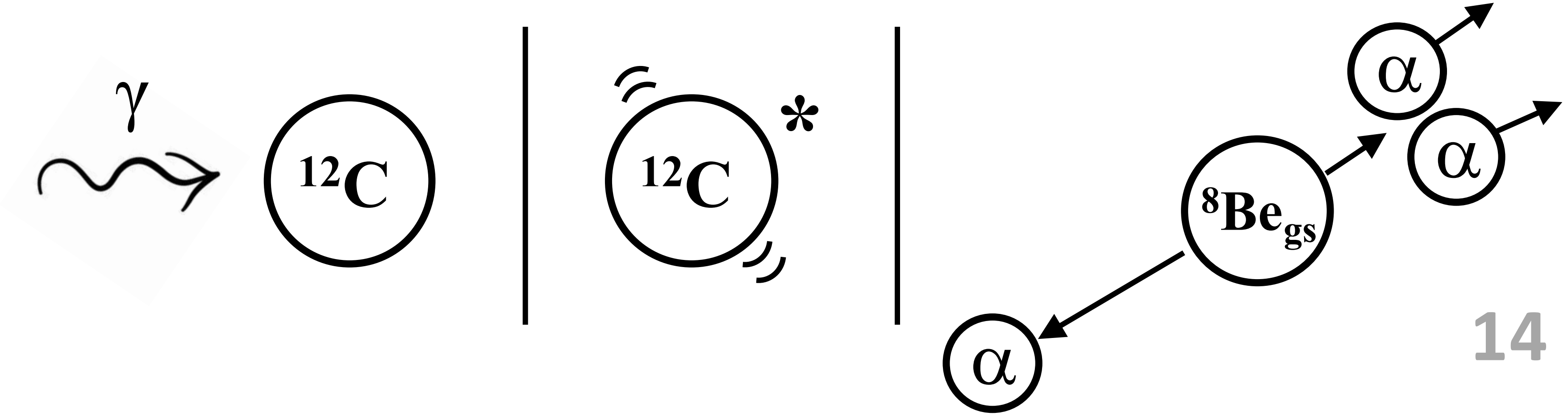
Example events – $^{12}C(\gamma,\alpha_1)$



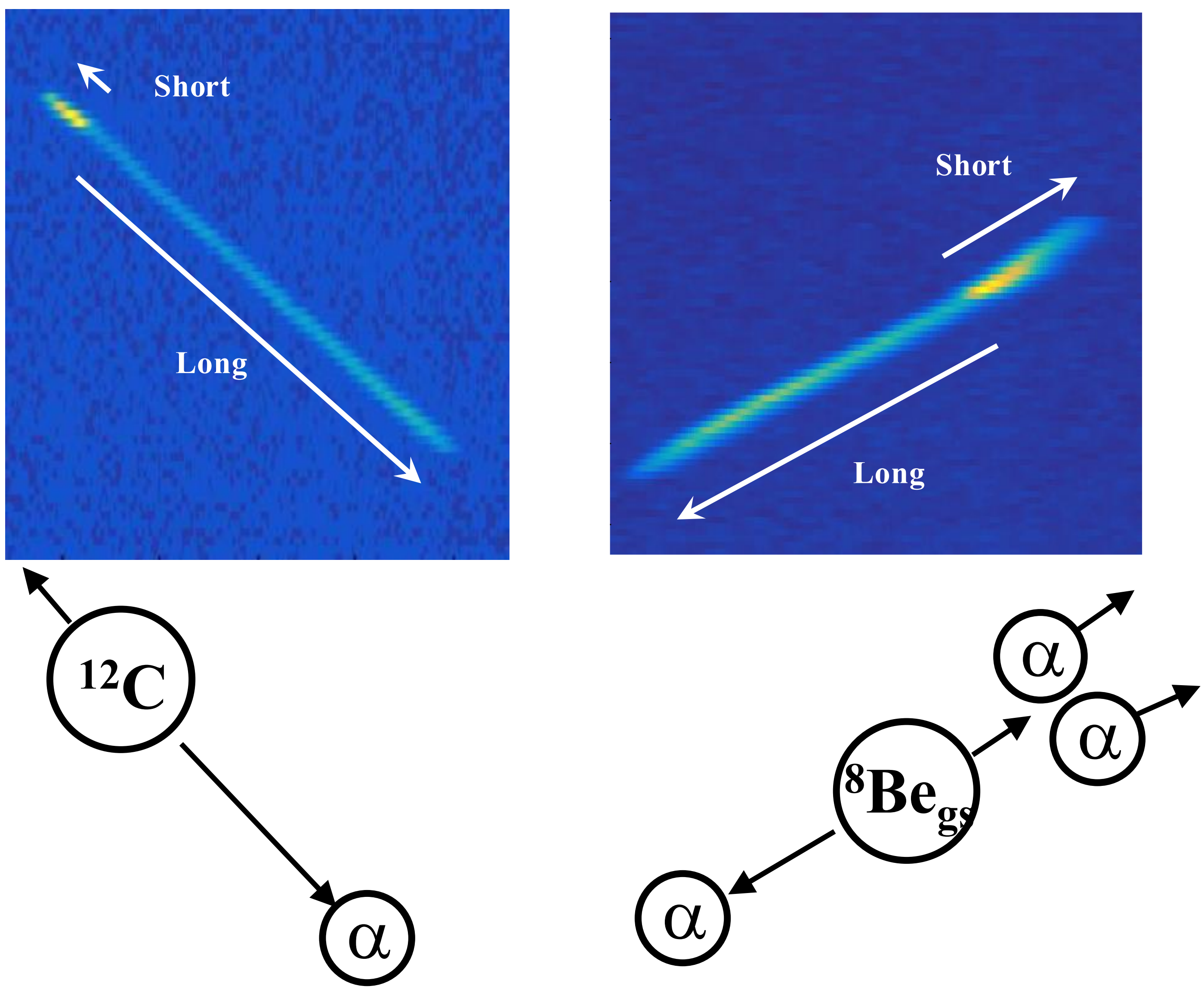


Example events – $^{12}C(\gamma,\alpha)^{8}Be_{gs}$

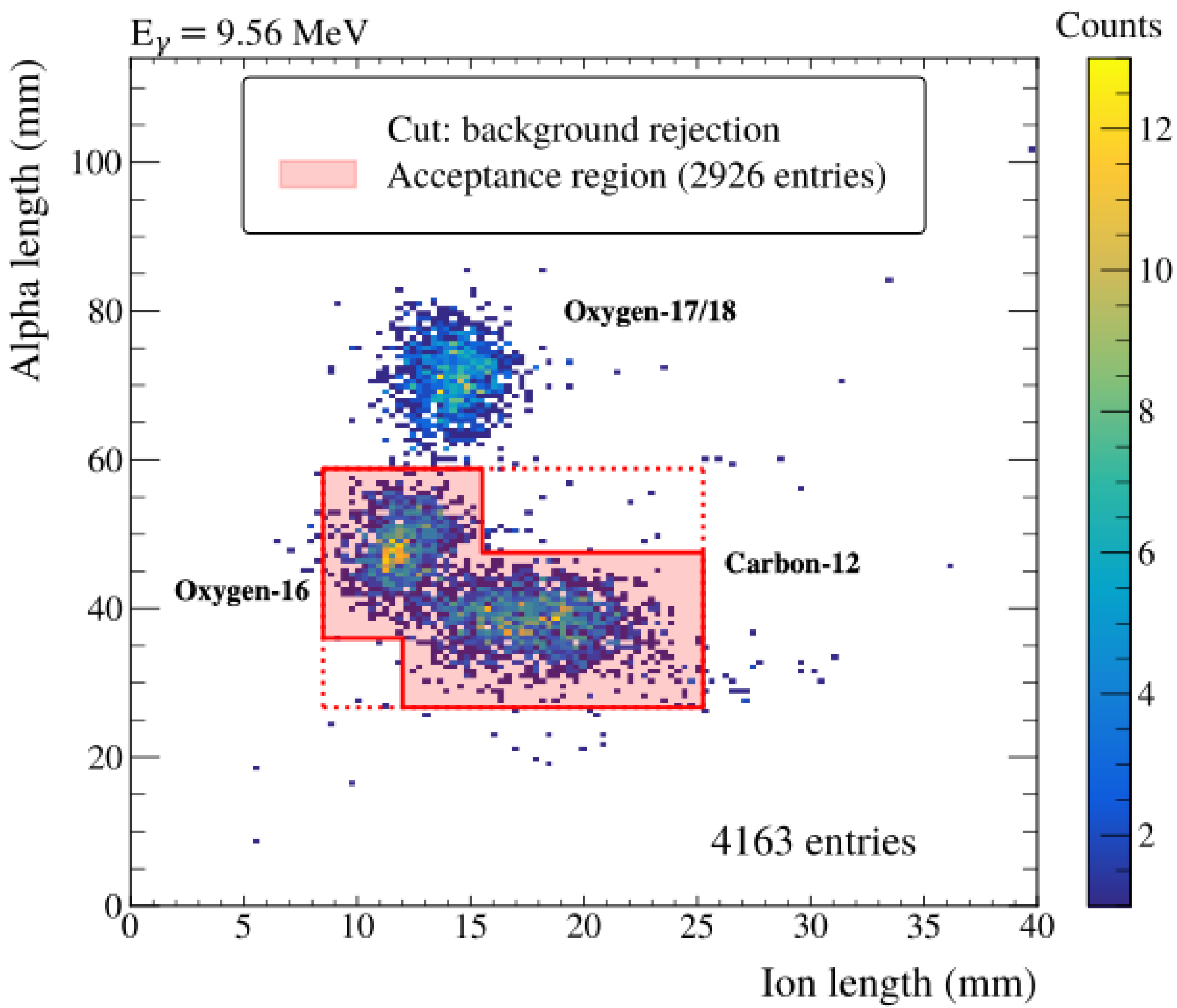




$^{16}O(\gamma,\alpha)^{12}C$ vs. $^{12}C(\gamma,\alpha)^{8}Be_{gs}$

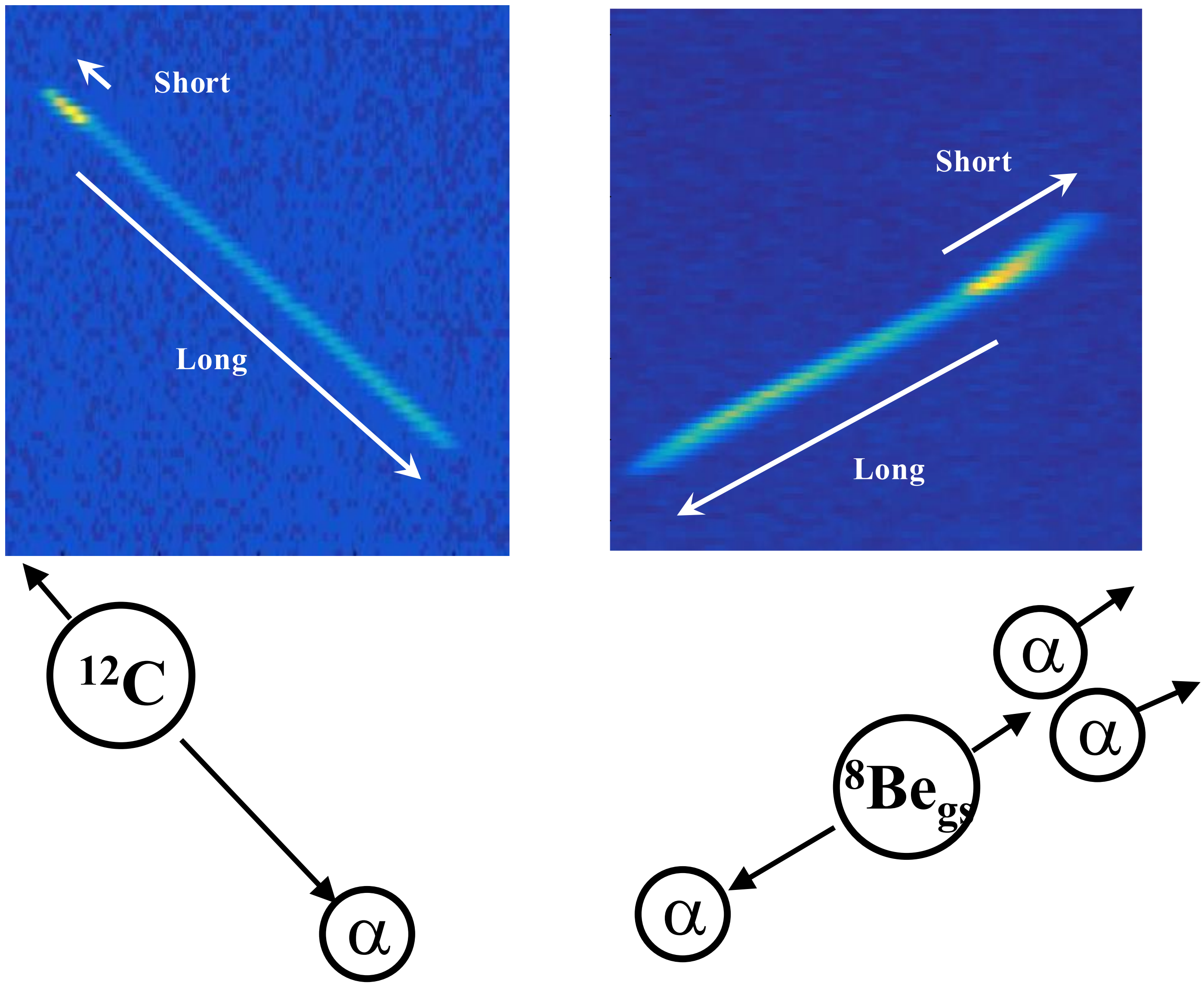


Channel selection

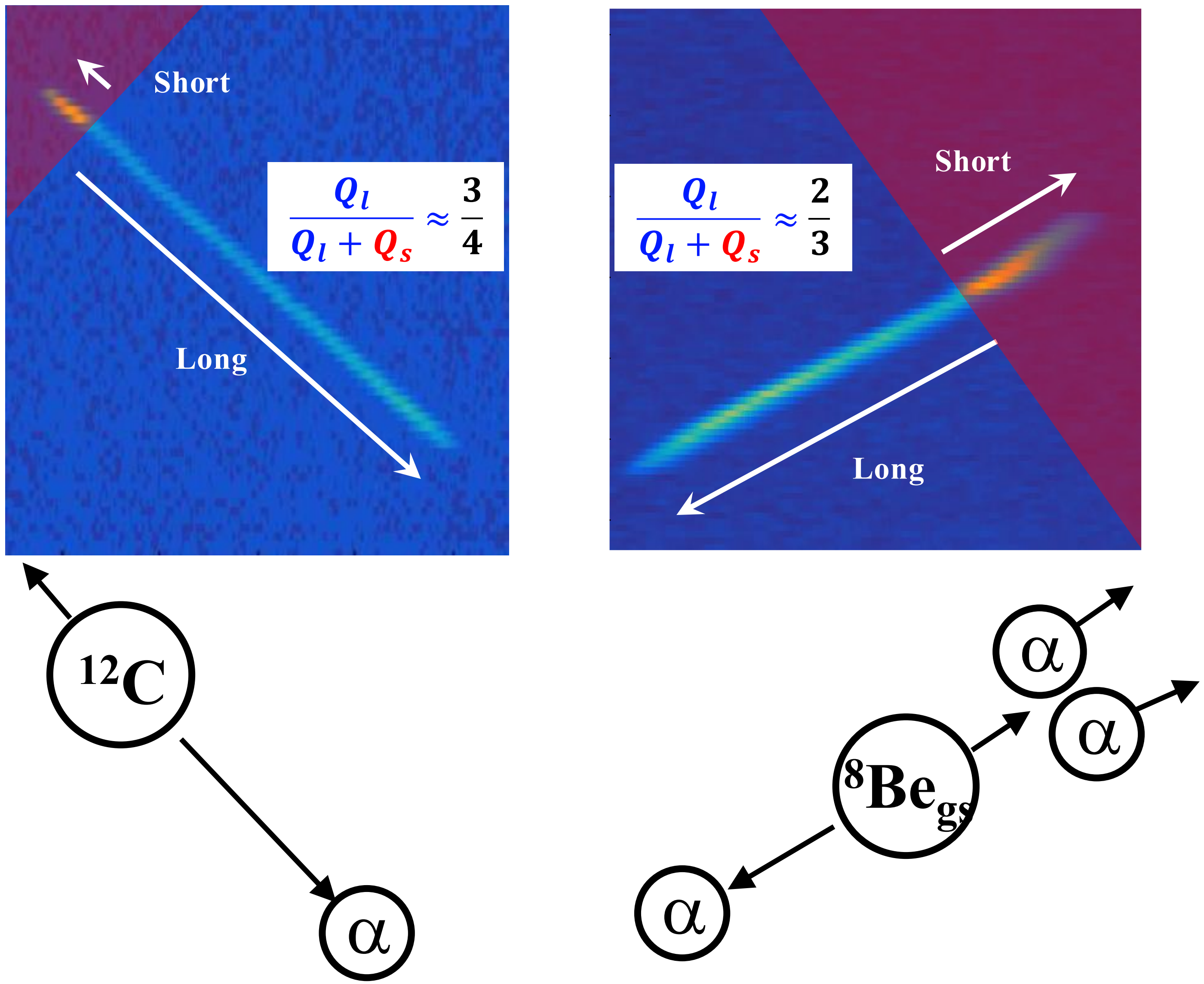


Work of K. C. Z. Haverson

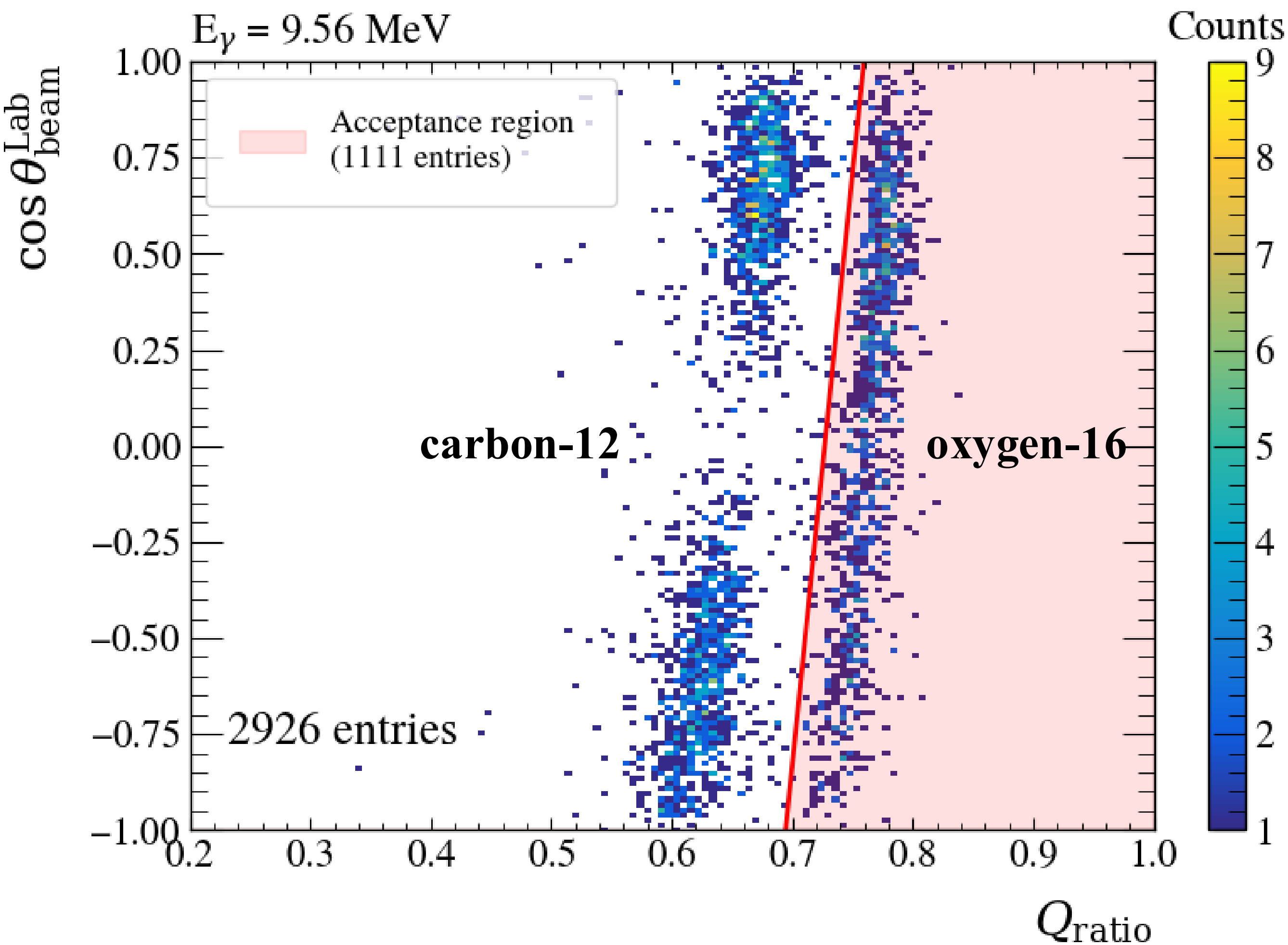
$^{16}O(\gamma,\alpha)^{12}C$ vs. $^{12}C(\gamma,\alpha)^{8}Be_{gs}$



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

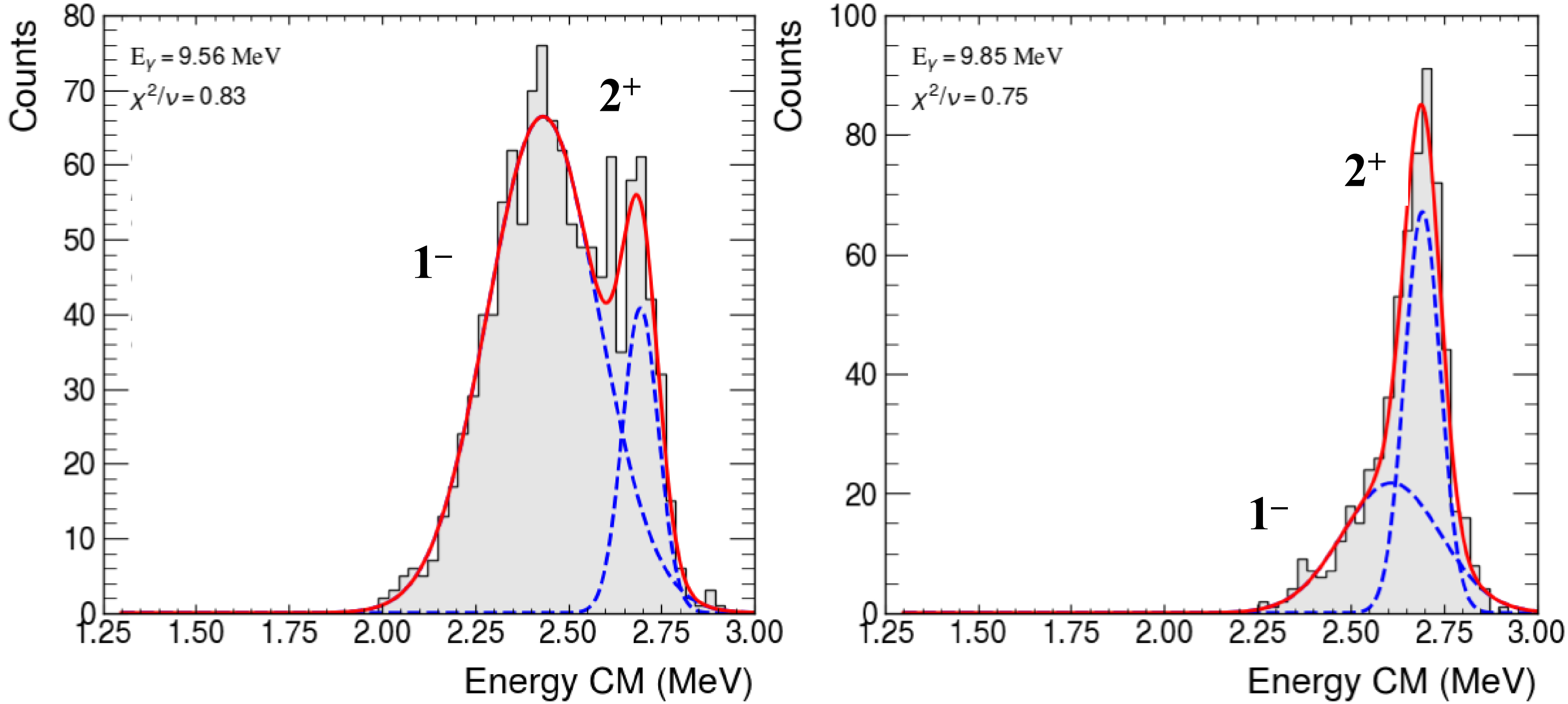


Channel selection



Work of K. C. Z. Haverson

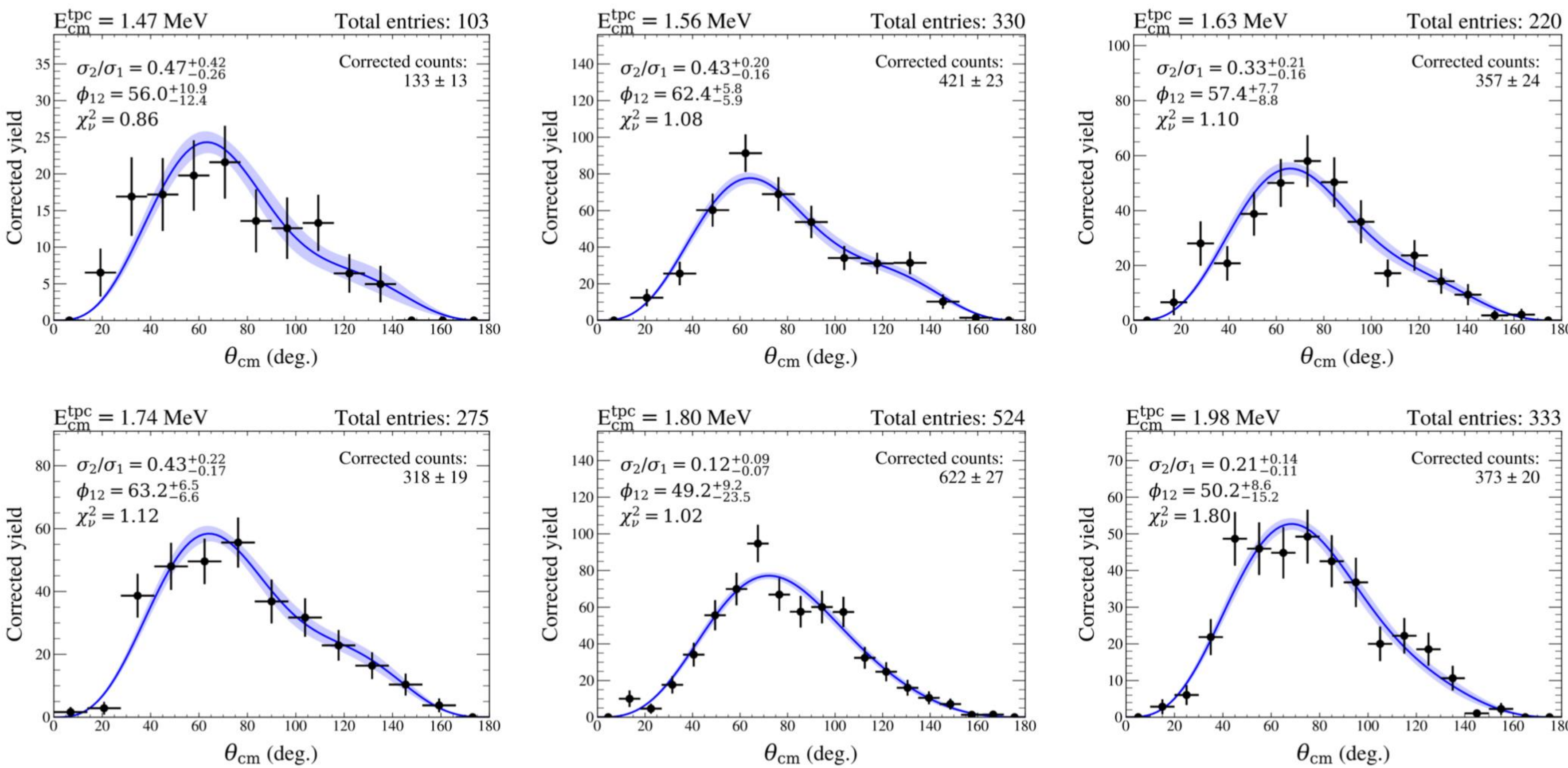
CoM energy resolution



σ = 50 keV
Factor of 4 better than gamma beam

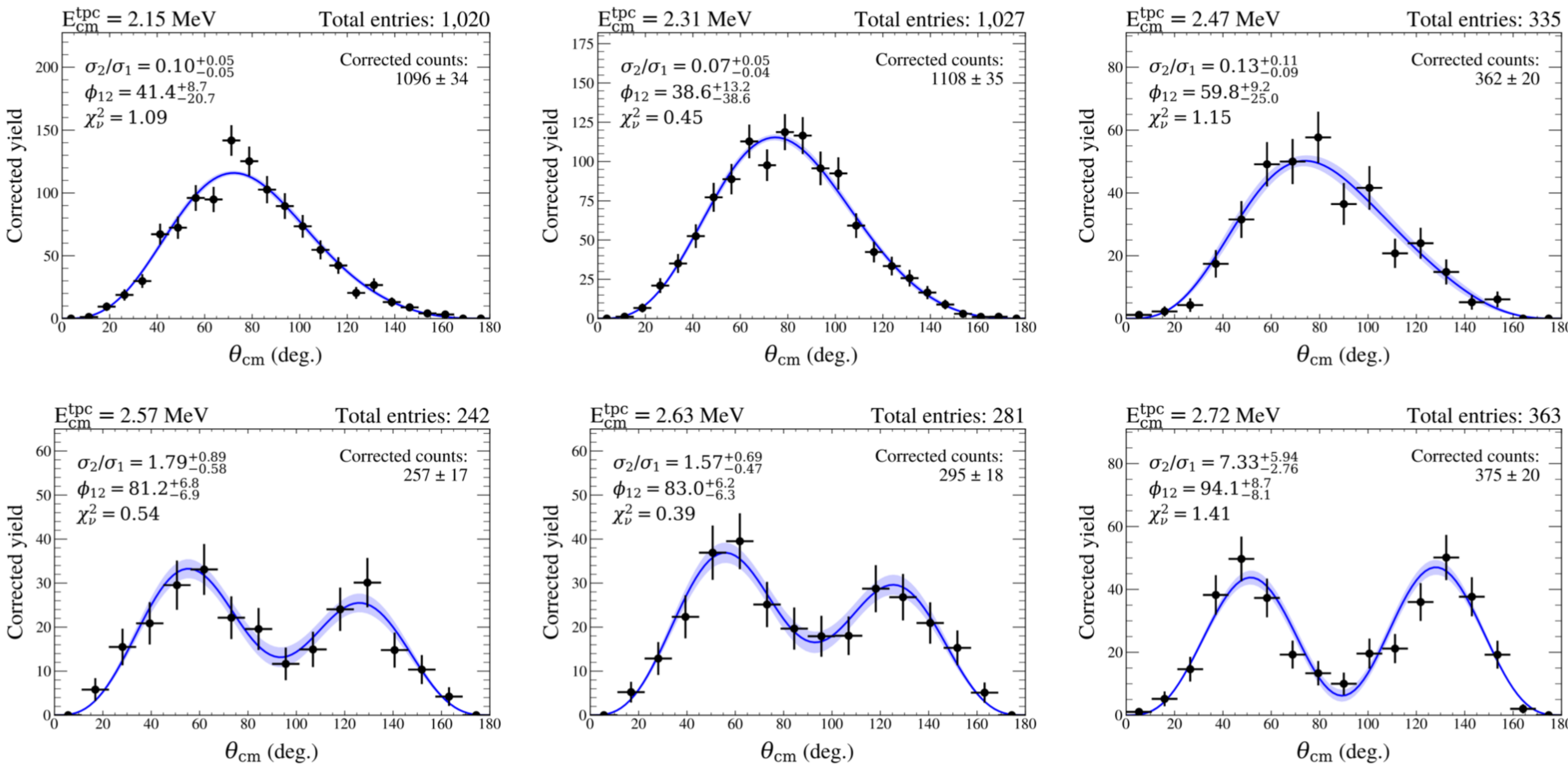
Work of K. C. Z. Haverson

Angular distributions



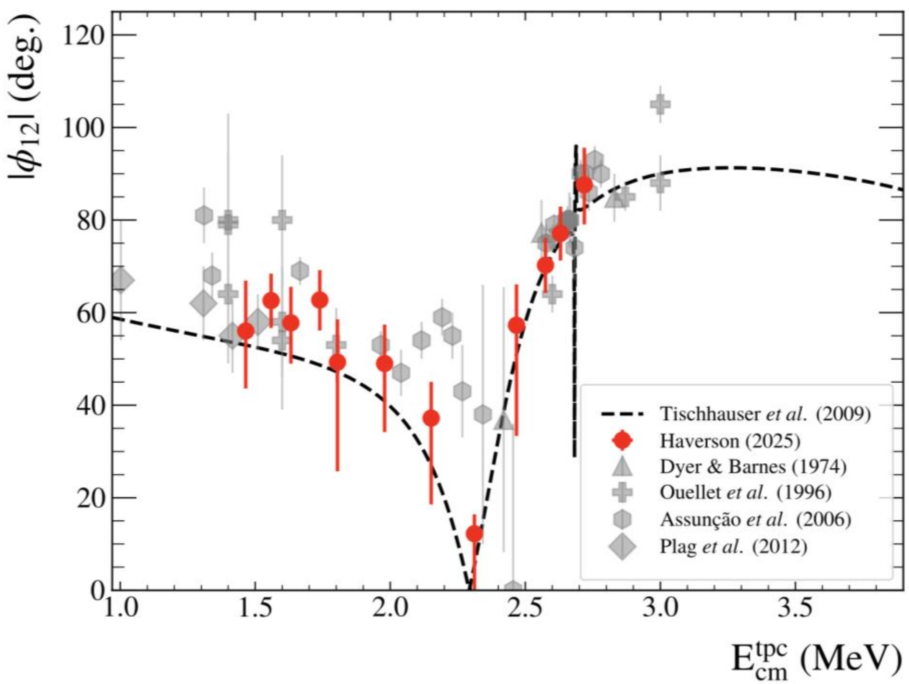
K. C. Z. Haverson, PhD thesis: 10.7190/shu-thesis-00759

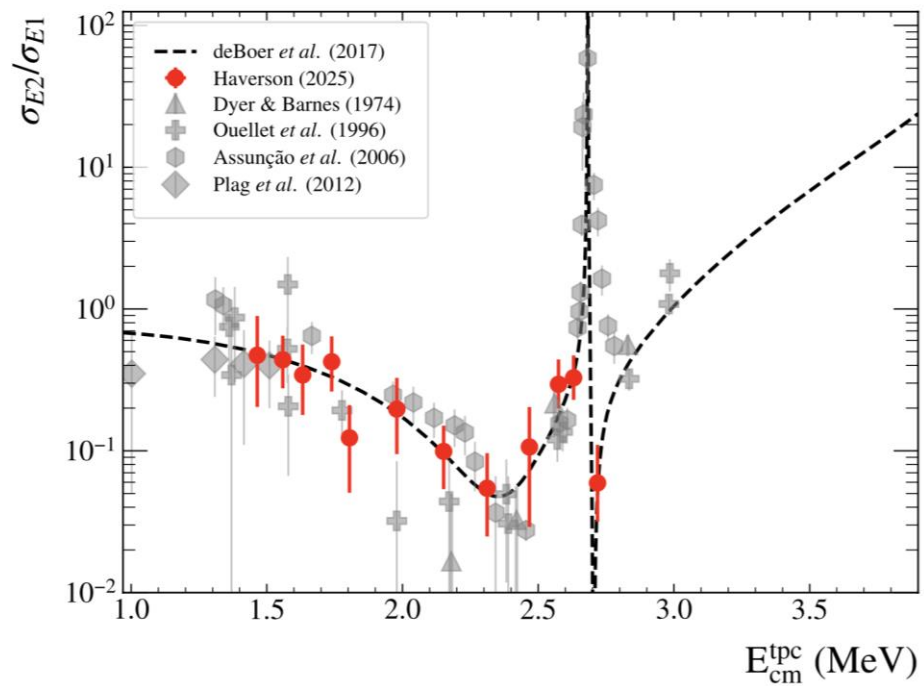
Angular distributions



K. C. Z. Haverson, PhD thesis: 10.7190/shu-thesis-00759

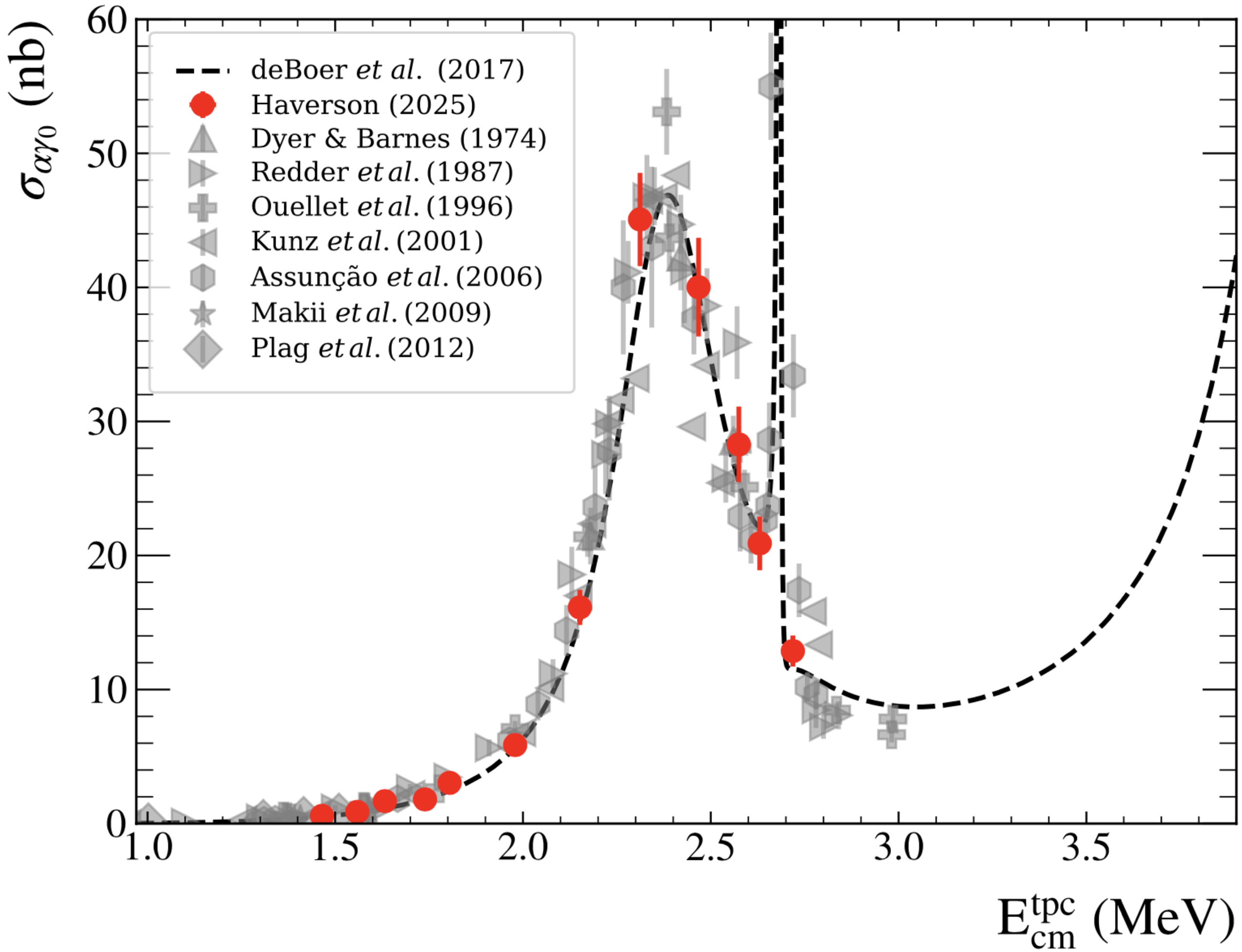
Extracted parameters





K. C. Z. Haverson, PhD thesis: 10.7190/shu-thesis-00759

Ground state integrated cross section



K. C. Z. Haverson, PhD thesis: 10.7190/shu-thesis-00759

Summary

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

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

- Detailed balance factor boosts the cross section

- Angular distribution results follow expected trends – φ_{12} agreement with elastic scattering (paper in preparation)

- As was previously shown with Optical TPC

Outlook

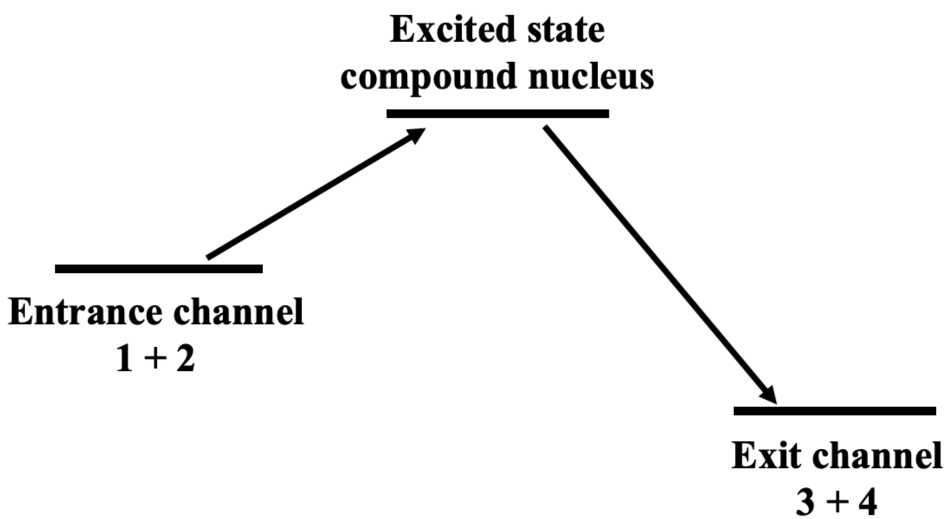
- Further measurements scheduled at HIγS over ~1 month of beam time July/August 2026

- Increase in beam intensity to $\sim 10^9$ γ/s

- Same set-up as used in 2022

- Plans to measure as low as $E_{cm} = 1$ MeV

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



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