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Key Reactions in Nuclear Astrophysics
ECT* 2025

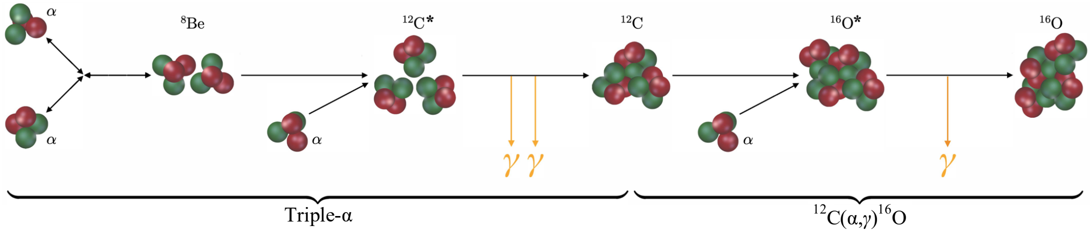
Clarifying key components within helium burning

Kevin C. W. Li

17 February 2025

NUKLEÆRSENTERET

Helium burning in a nutshell



1) Resolving a discrepancy for the γ-decay branching ratio of the Hoyle state.

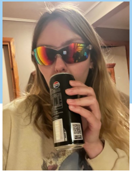
2) Discrepancy for the total width of the 3_1^- state in ^{12}C.

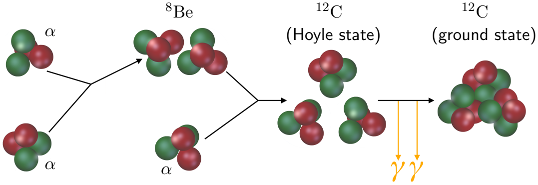
3) Comprehensive measurements at high energies.

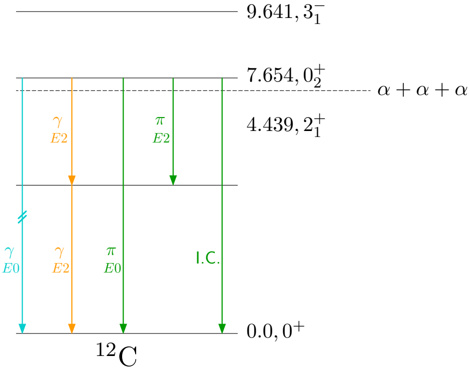
4) Development of new indirect methods to constrain subthreshold contributions.

A saga about the radiative width of the Hoyle state

saga (n.) 1709, "ancient Scandinavian legend of considerable length"







- At medium temperatures of 0.1–2.0 GK, the triple–α reaction is mediated by the 0_2^+ Hoyle state in ^{12}C.
- A discrepant measurement of the γ-decay branching ratio of the Hoyle state was reported by Kibédi *et al.* in 2020.

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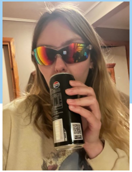


Wanja Paulsen

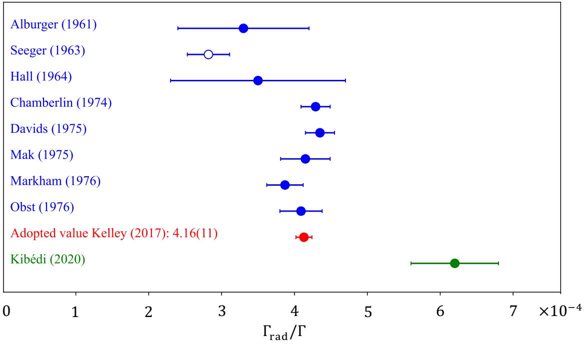
Official photo from PhD student

PHYSICAL REVIEW LETTERS **125,** 182701 (2020)

Radiative Width of the Hoyle State from γ-Ray Spectroscopy

T. Kibédi,[1,*] B. Alshahrani,[1,2,†] A. E. Stuchbery,[1] A. C. Larsen,[3] A. Görgen,[3] S. Siem,[3] M. Guttormsen,[3] F. Giacoppo,[3,‡] A. I. Morales,[4,§] E. Sahin,[3] G. M. Tveten,[3] F. L. Bello Garrote,[3] L. Crespo Campo,[3] T. K. Eriksen,[3] M. Klintefjord,[3] S. Maharramova,[3] H.-T. Nyhus,[3] T. G. Tornyi,[3,5,‖] T. Renstrøm,[3] and W. Paulsen[3]

- At medium temperatures of 0.1–2.0 GK, the triple–α reaction is mediated by the 0_2^+ Hoyle state in ^{12}C.
- A discrepant measurement of the γ-decay branching ratio of the Hoyle state was reported by Kibédi *et al.* in 2020.



Methodology

We can measure the γ-decay branching ratio through either

$$\frac{\Gamma_{\gamma}^{7.65}}{\Gamma^{7.65}} = \frac{N_{020}^{7.65}}{N_{\text{inclusive}}^{7.65} \times \epsilon_{3.21} \times \epsilon_{4.44} \times c_{\text{det}} \times W_{020}^{7.65}}$$

$$\frac{\Gamma_{\gamma}^{E2}}{\Gamma} = \frac{N_{020}^{7.65}}{N_{020}^{4.98}} \times \frac{N_{\text{singles}}^{4.98}}{N_{\text{singles}}^{7.65}} \times \frac{\epsilon_{\gamma}^{1.78}}{\epsilon_{\gamma}^{4.44}} \times \frac{\epsilon_{\gamma}^{3.20}}{\epsilon_{\gamma}^{3.21}} \times \frac{W_{020}^{4.98}}{W_{020}^{7.65}}$$

where

$N_{020}^{7.65}$ is the number of triple-coincidence events

$N_{020}^{7.65}$ is the number of inclusive events

ϵ's are the full-energy photopeak efficiencies

W's are the angular-correlation correction factors

The radiative width can then be determined as:

$$\frac{\Gamma_{\text{rad}}}{\Gamma} = \frac{\Gamma_{\gamma}^{E2}(1+\alpha_{\text{tot}}) + \Gamma_{\pi}^{E0}}{\Gamma}$$

$$\Gamma_{\text{rad}} = \left[\frac{\Gamma_{\text{rad}}}{\Gamma}\right] \times \left[\frac{\Gamma}{\Gamma_{\pi}^{\text{E0}}}\right] \times \left[\Gamma_{\pi}^{\text{E0}}\right]$$

Remeasuring the γ-decay branching ratio of the Hoyle state

2012

$^{12}\mathrm{C}(p,p')$ and $^{28}\mathrm{Si}(p,p')$ with $E_p = 16.0$ MeV

2014 PHYSICAL REVIEW LETTERS **125,** 182701 (2020)

$^{12}\mathrm{C}(p,p')$ and $^{28}\mathrm{Si}(p,p')$ with $E_p = 10.7$ MeV

2019

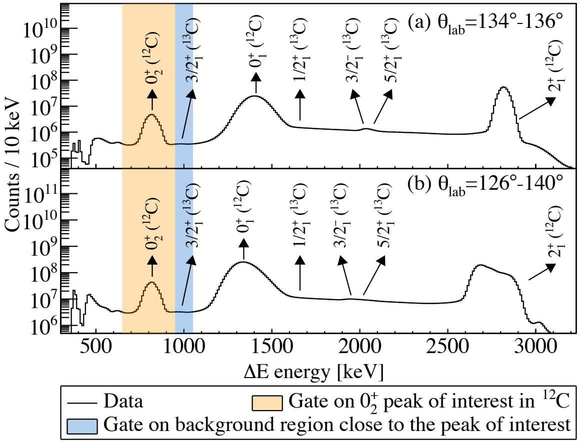
$^{12}\mathrm{C}(p,p')$ and $^{28}\mathrm{Si}(p,p')$ with $E_p = 10.8$ MeV

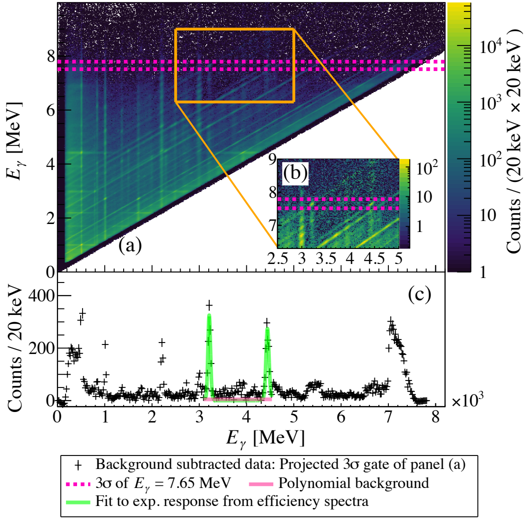
2020

$^{28}\mathrm{Si}(p,p')$ with $E_p = 16.0$ MeV

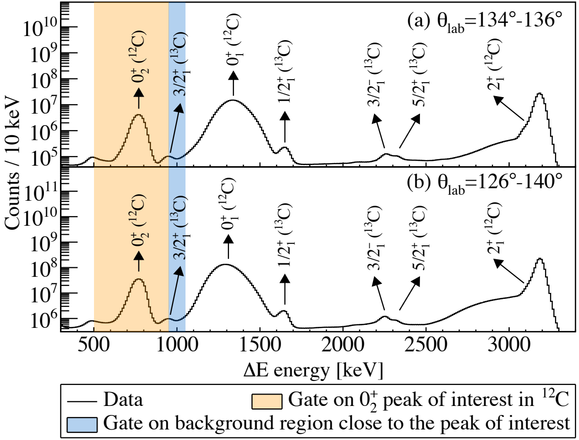
- To investigate this discrepancy, new measurements were performed in 2019 and 2020 with the $LaBr_3$:Ce detectors of the OSCAR array.
- An independent reanalysis was also performed on the 2014 experiment.
- First step was to recheck systematic issues with the data acquisition of all experiments—none were found.

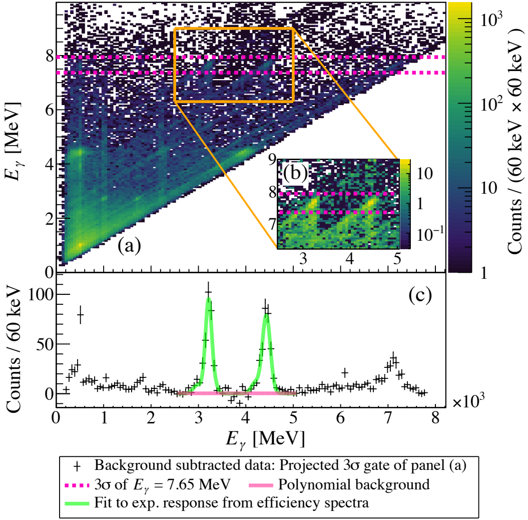
(2019, OSCAR) Inclusive and triple-coincidence events





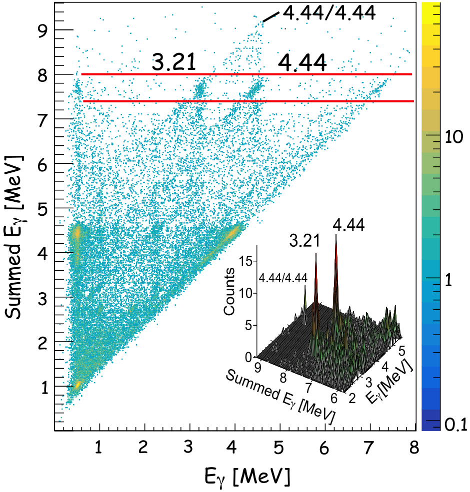
(2014, CACTUS) Inclusive and triple-coincidence events



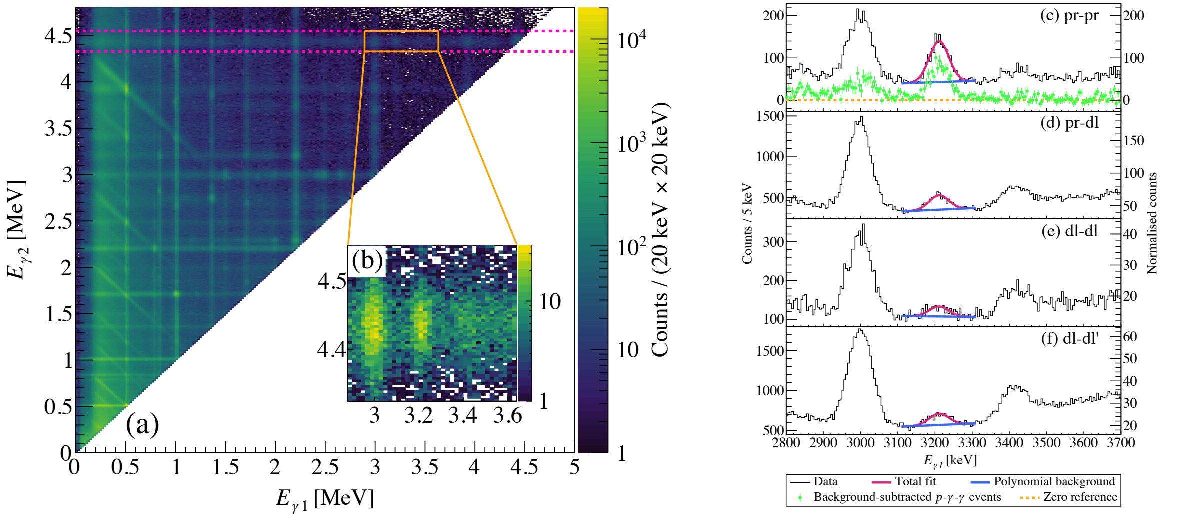


(2014, CACTUS) PRL (2017)

- The source is visible in this spectrum, although the binning obscures the feature somewhat.



(2019, OSCAR) Triple-coincidence events with γ–γ



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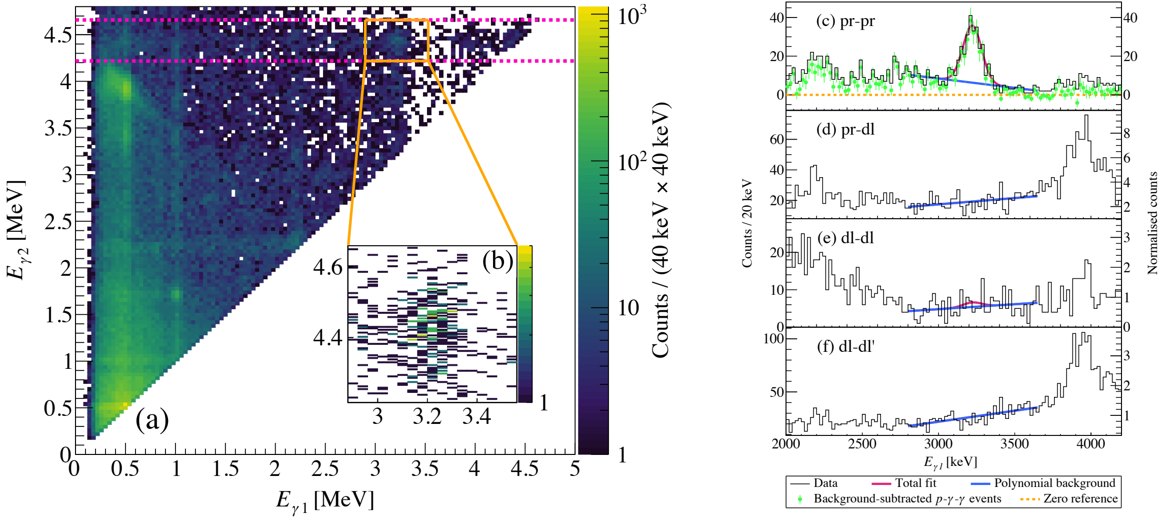
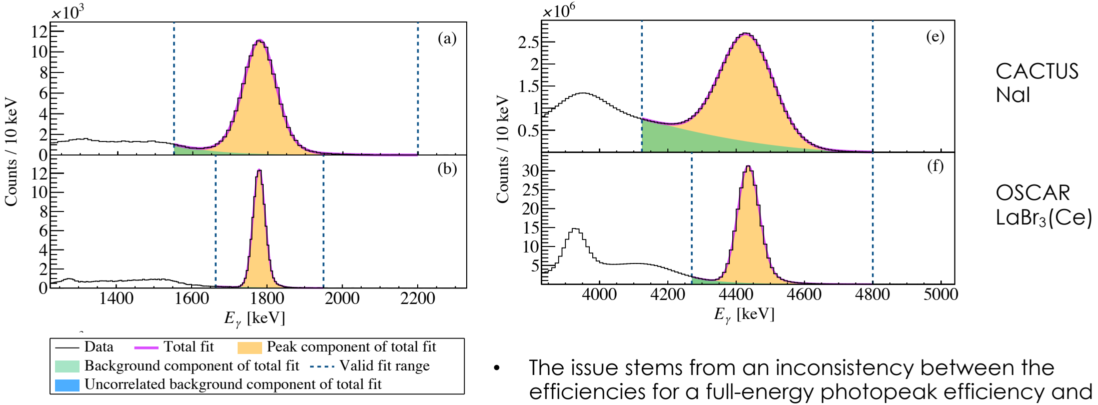


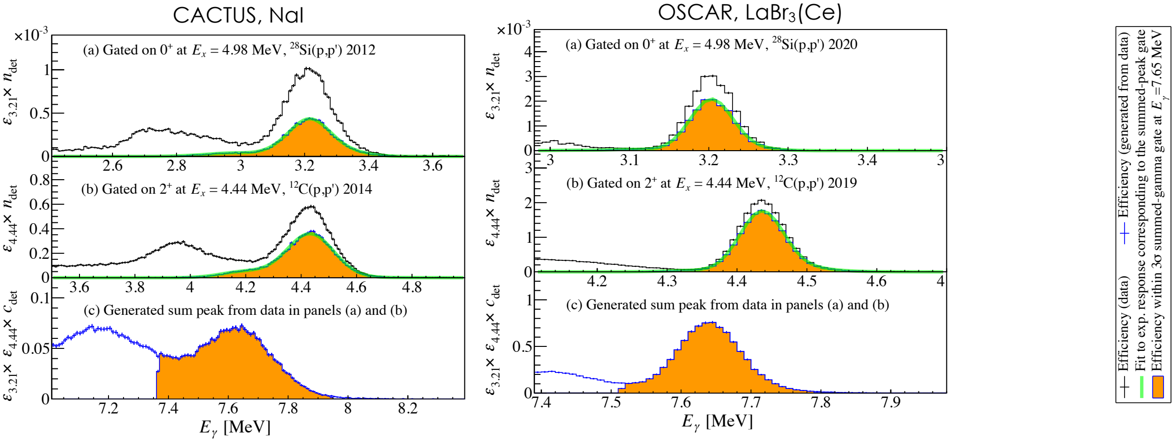
Gates on γ–γ matrices and the detector response



$$\frac{\Gamma_\gamma^{7.65}}{\Gamma^{7.65}} = \frac{N_{020}^{7.65}}{N_{\text{inclusive}}^{7.65} \times \epsilon_{3.21} \times \epsilon_{4.44} \times c_{\text{det}} \times W_{020}^{7.65}}$$

- The issue stems from an inconsistency between the efficiencies for a full-energy photopeak efficiency and a gated efficiency.
- For a gate on a γ–γ matrix, one of the “fitted” efficiencies should be exchanged for a gated efficiency.

Gates on summed-γ matrices and detector response

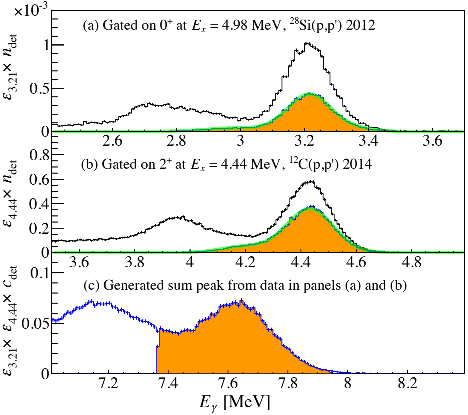


$$\frac{\Gamma_{\gamma}^{7.65}}{\Gamma^{7.65}} = \frac{N_{020}^{7.65}}{N_{\text{inclusive}}^{7.65} \times \epsilon_{3.21} \times \epsilon_{4.44} \times c_{\text{det}} \times W_{020}^{7.65}}$$

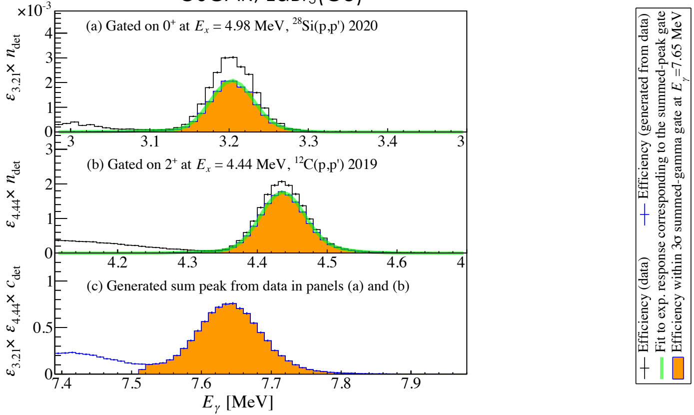
- For a projection of a summed–γ matrix, the total efficiency ($\epsilon_{3.21}\epsilon_{4.44}c_{\text{det}}$) should be exchanged for a gated efficiency.

Gates on summed-γ matrices and detector response

CACTUS, NaI



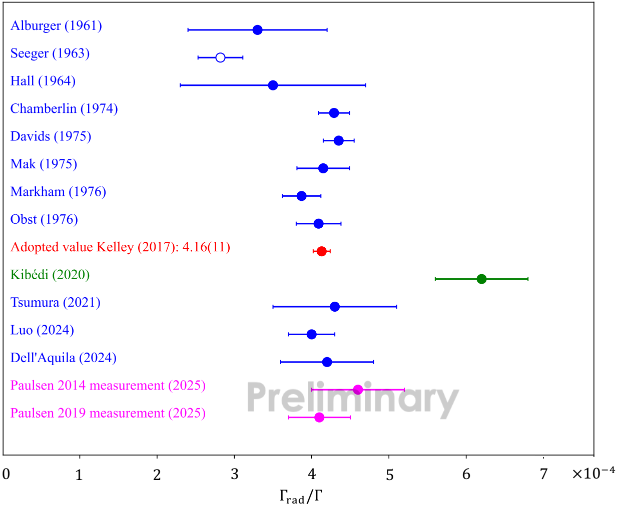
OSCAR, $LaBr_3$(Ce)



$$\frac{\Gamma_\gamma^{E2}}{\Gamma} = \frac{N_{020}^{7.65}}{N_{020}^{4.98}} \times \frac{N_{\rm singles}^{4.98}}{N_{\rm singles}^{7.65}} \times \frac{\epsilon_\gamma^{1.78}}{\epsilon_\gamma^{4.44}} \times \frac{\epsilon_\gamma^{3.20}}{\epsilon_\gamma^{3.21}} \times \frac{W_{020}^{4.98}}{W_{020}^{7.65}}$$

- For a projection of a summed–γ matrix, the total efficiency ($\epsilon_{3.21}\epsilon_{4.44}c_{\rm det}$) should be exchanged for a gated efficiency.

Updated results



- New 2019 measurement yields

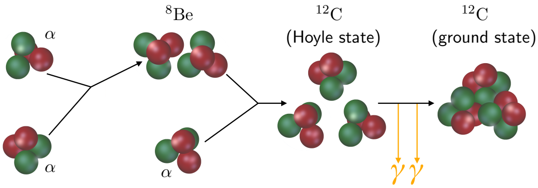
$$\frac{\Gamma_{rad}}{\Gamma} = 4.1(1)\times 10^{-4}$$

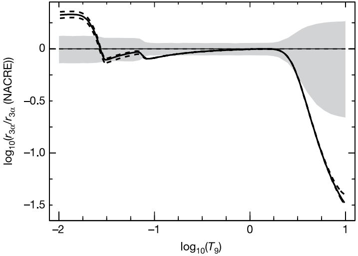
- Corrected reanalysis of 2014 measurement yields:

$$\frac{\Gamma_{rad}}{\Gamma} = 4.5(6)\times 10^{-4}$$

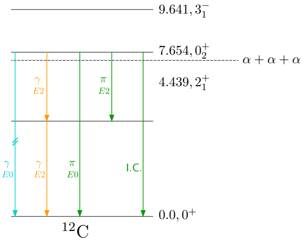
- Also in agreement with several recently published charged-particle measurements.

Explosive helium burning and the 3_1^- state in ^{12}C





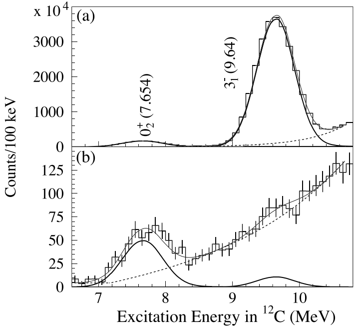
H. O. U. Fynbo, C. A. Diget et al., Nature (London) 433, 136 (2005)



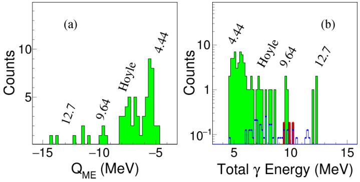
- At high temperatures of above 2.0 GK, the triple–α reaction is mediated by resonances above the Hoyle state in ^{12}C.
- A pioneering study by Tsumura *et al.* (2021) indicated that the 3_1^- resonance, which has often been neglected, may be significant.

Explosive helium burning and the 3_1^- state in ^{12}C

M. Tsumura et al., Physics Letters B 817 (2021) 136283



G. Cardella et al., Phys. Rev. C 104, 064315 (2021)



- For the 3_1^- state in ^{12}C, recent results suggest that the previous upper limit of $\Gamma_{rad}/\Gamma < 8.3 \times 10^{-7}$ (95% C. L.) may be incorrect.
  D. Chamberlin *et al.*, Phys. Rev. C 10, 909 (1974)

- ^{1}H(^{12}C,^{12}Cp) measurement:
  $\Gamma_{rad}/\Gamma < 1.3^{+1.2}_{-1.1} \times 10^{-6}$
  M. Tsumura *et al.*, Physics Letters B 817 (2021) 136283

- ^{12}C(p, p') and ^{12}C(α, α')
  $\Gamma_{rad}/\Gamma < 6.4(51) \times 10^{-5}$
  G. Cardella *et al.*, Phys. Rev. C 104, 064315 (2021)

The total width of the 3_1^- state in ^{12}C

PHYSICAL REVIEW C **109**, 015806 (2024)

Understanding the total width of the 3_1^- state in ^{12}C

K. C. W. Li,[1,*] R. Neveling,[2] P. Adsley,[3,4] H. Fujita,[5] P. Papka,[2,6] F. D. Smit,[2] J. W. Brümmer,[2,6]
L. M. Donaldson,[2,7] M. N. Harakeh,[8] Tz. Kokalova,[9] E. Nikolskii,[10]
W. Paulsen,[1] L. Pellegri,[2,7] S. Siem,[1] and M. Wiedeking[2,7]
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[3]*Department of Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA*
[4]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*
[5]*Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan*
[6]*Department of Physics, University of Stellenbosch, Private Bag X1, 7602 Matieland, South Africa*
[7]*School of Physics, University of the Witwatersrand, Johannesburg 2050, South Africa*
[8]*Nuclear Energy Group, ESRIG, University of Groningen, 9747 AA Groningen, The Netherlands*
[9]*School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, B15 2TT, United Kingdom*
[10]*NRC Kurchatov Institute, Ru-123182 Moscow, Russia*

Ref.	Resolution[a] (keV)	$\Gamma(E_r)$ (keV)	$\Gamma_{obs}(E_r)$ (keV)	Γ_{FWHM} (keV)
Douglas *et al.*	–	–	–	30(8)
Browne *et al.*	≈40	–	–	36(6)[b]
Alcorta *et al.*	60–120	–	–	43(4)
	55–85			
Kokalova *et al.*	54(2)[c]	48(2)	–	–

- Constraining the radiative width of the 3_1^- state requires knowledge of the total width, Γ.
- A significantly larger total width was reported by Kokalova *et al.* in 2013, which raised the ENSDF for the total width to $\Gamma = 46(3)$ keV (and there it still remains).

Investigation on parameterisations & backgrounds

- A multi-level multi-channel R-matrix derived fit of the spectra

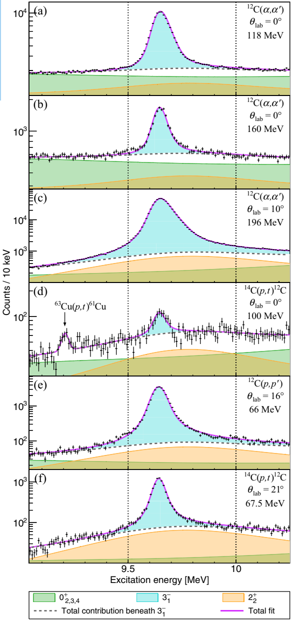
$$N_{ab,c}(E) = P_c \left| \sum_{\lambda,\mu}^{N} G_{\lambda ab}^{\frac{1}{2}} \gamma_{\mu c} A_{\lambda\mu} \right|^2$$

- The one-level approximation for the 3_1^- state is given by

$$N_{ab,c}(E) = \frac{G_{ab}\,\Gamma_c}{(E - E_r - \Delta)^2 + \frac{1}{4}\Gamma^2}, \qquad \Delta_{\lambda\mu} = \sum_{c'} -(S_{c'} - B_{c'})\gamma_{\lambda c'}\gamma_{\mu c'},$$

- Many different approximations are used... some quantities are strictly R-matrix parameters, as opposed to physical quantities.

- Distinction between formal and observed parameters is particularly important for clustered states near theshold!



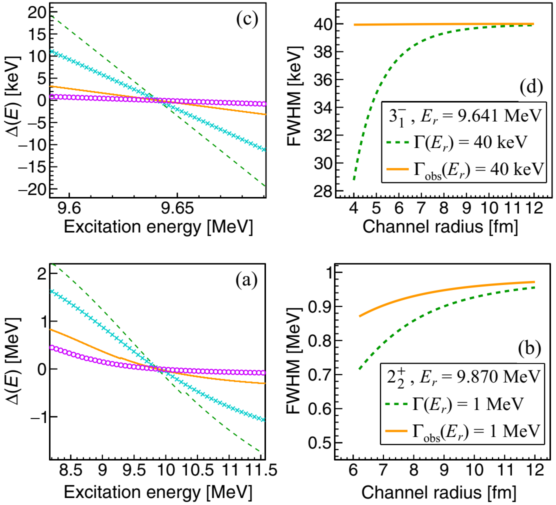
Channel-radius dependence

- For levels just above particle threshold, beware of channel radius effects. Here, the formal R-matrix width and the observed width may differ significantly.

$$\Gamma_{\mathrm{obs},\mu}(E) = \frac{\sum_{c'} 2\gamma^2_{\mu c'} P_{c'}(\ell, E)}{1 + \sum_{c'} \gamma^2_{\mu c'} \frac{dS_{c'}}{dE}\Big|_{E=E_r}}$$

- ENSDF stores the physical total width (FWHM) of states/resonances.

- When comparing widths, consistency of either physical (observed) widths or formal widths must be maintained.



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$$\Gamma_{\mathrm{obs},\mu}(E) = \frac{\sum_{c'} 2\gamma_{\mu c'}^2 P_{c'}(\ell, E)}{1 + \sum_{c'} \gamma_{\mu c'}^2 \frac{dS_{c'}}{dE}\Big|_{E=E_r}}$$

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Ref.	a_c (fm)	$\Gamma(E_r)$ (keV)	$\Gamma_{\mathrm{obs}}(E_r)$ (keV)	Γ_{FWHM} (keV)
Browne *et al.* [19]	–	–	–	36(11)
Alcorta *et al.* [20]	–	–	–	43(8)
Kokalova *et al.* [21]	4.7[a]	48(2)	39(4)[b]	39(4)[b]
This work	4.8	46(2)	38(2)	38(2)

- For the 3_1^- state in ^{12}C, we recommend a physical total width (FWHM) of

$$\Gamma_{\mathrm{obs}}(E_r) = 38(2)\ \mathrm{keV},$$

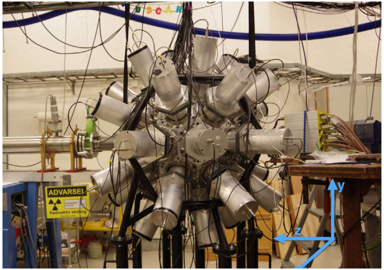
which is in contrast to the current ENSDF value of 46(3) keV.

Future approaches: triple-α

Addressing the γ-decay branches of resonances in ^{12}C:

1. $^{12}C(p,p')^{12}C$ measurement at Oslo Cyclotron laboratory (scheduled for 2025) using the OSCAR array of 30 $LaBr_3(Ce)$ detectors (3.5"× 8").

The Oslo Cyclotron Laboratory (OCL)



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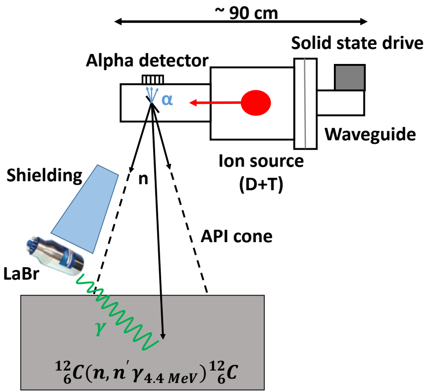
2. Plans for $^{12}C(n,n')^{12}C$ using D-T generators with Associated Particle Imaging (API).

   Neutron-by-neutron precision

   Thick targets (limited by TOF resolution)

M. A. Unzueta *et al.*
Rev. Sci. Instrum. 92, 063305 (2021)



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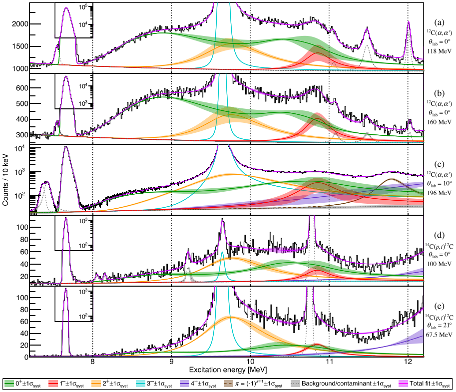
https://doi.org/10.1103/PhysRevC.105.024308



Is there another 0^+ state at $E \sim 9$ MeV?

Together with broad 0^+ states... how reasonable is it to assume the Hoyle-state γ-ray reduced width?

Rotational band: $2_2^+ \rightarrow 0_2^+$ transition?

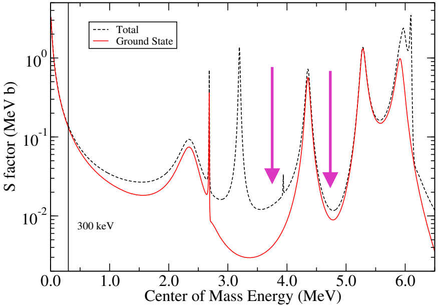
Future approaches: $^{12}C(\alpha, \gamma)^{16}O$

Addressing the call for comprehensive measurements at higher energies over a wide range:

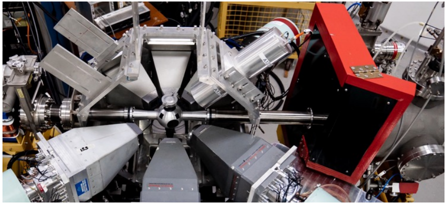
1. Measurement at the new tandetron facility of iThemba LABS (scheduled for August 2025).

   Builds upon previous effort by J. deBoer *et al.* at Notre Dame.

2. Constrain not only background levels… but by measuring in off-resonance regions where external capture is more dominant, may be able to constrain subthreshold ANCs.



- $E_{cm} \approx 3$ to 6.7 MeV
- Enriched ^{12}C targets (~20 ug/cm^2



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

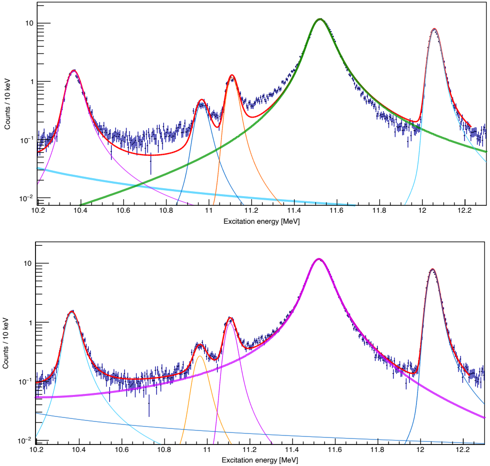
ANCs are often employed to constrain subthreshold (sub-Coulomb transfer often understood to be most reliable)

Addressing the call for new indirect methods to verify current indirect methods.

- Extension of R-matrix theory to direct reactions

- There must be correspondence between resonance scattering and direct reactions. Interference form cannot be constrained... but the same reduced widths.

$^{16}O(p,p')^{16}O$ on ice target, 295 MeV (RCNP)



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Addressing the call for new indirect methods to verify current indirect methods.

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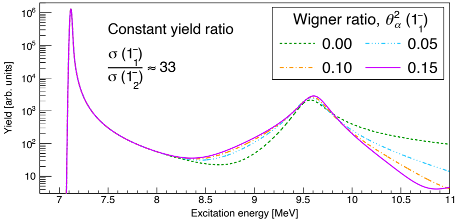
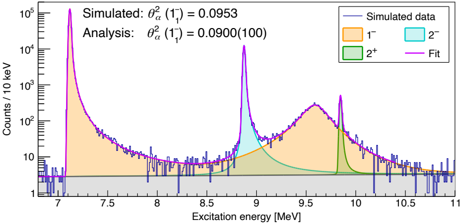
- There must be correspondence between resonance scattering and direct reactions. Interference form cannot be constrained... but the same reduced widths.

Approved at IJCLab: $^{15}N(^{3}He, d)^{16}O$ at 25 MeV





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