UNIVERSITETET I OSLO

EuNPC2025
Caen, France

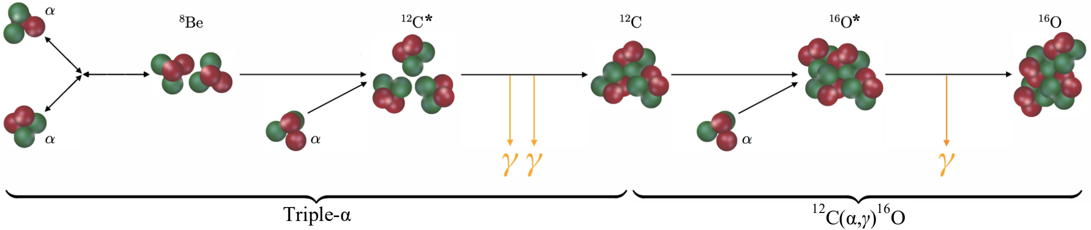
Helium burning and nuclear clustering: recent studies and constraints from direct reactions

Kevin C. W. Li

25 September 2025

NUKLEÆRSENTERET

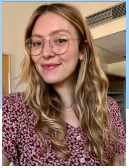
Helium burning in a nutshell



1. Resolving a discrepancy for the γ-decay branching ratio of the Hoyle state.
2. Other higher-lying resonances?
3. Comprehensive measurements at high energies.
4. Development of new indirect methods to constrain subthreshold contributions.
5. Establishing a more consistent framework for clustering studies.

A saga about the radiative width of the Hoyle state

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



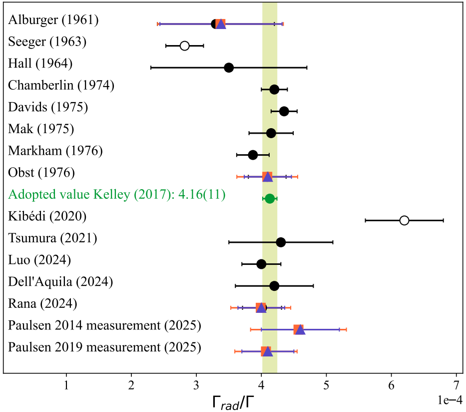
Dr. Wanja Paulsen

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]

- A discrepant measurement of the γ-decay branching ratio of the Hoyle state was reported by Kibédi *et al.* in 2020 as $\Gamma_{\text{rad}}/\Gamma = 6.2(6) \times 10^{-4}$.



A saga about the radiative width of the Hoyle state

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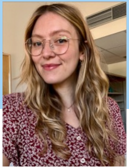

Dr. Wanja Paulsen

PHYSICAL REVIEW C **112**, 015803 (2025)

Remeasuring the γ-decay branching ratio of the Hoyle state

W. Paulsen,[1,2,*] K. C. W. Li,[1,2] S. Siem,[1,2] V. W. Ingeberg,[1,2] A. C. Larsen,[1,2] T. K. Eriksen,[1,2,3]
H. C. Berg,[1,†] F. L. B. Garrote,[1] D. Gjestvang,[1,2] A. Görgen,[1,2] M. Markova,[1,2] V. Modamio,[1,2]
E. Sahin,[1,2] G. M. Tveten,[1] and V. M. Valsdòttir[1,2]
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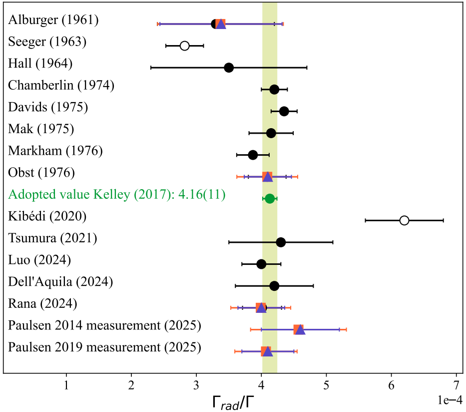
[3]*Department of Radiation Protection and Physics, Sector NUK Kjeller, Institute for Energy Technology, N-2007 Kjeller, Norway*

- New measurement in experiment with improved OSCAR array yielded $\frac{\Gamma_{\text{rad}}}{\Gamma} = 4.0(3) \times 10^{-4}$.
- A reanalysis of the previous data published by Kibédi *et al.* yielded $\Gamma_{\text{rad}}/\Gamma = 4.5(6) \times 10^{-4}$.



Recently accepted work by K. Sakanashi, T. Kawabata, *et al.*

K. Sakanashi *et al.*
https://doi.org/10.1016/j.physletb.2025.139893

Journal Pre-proof

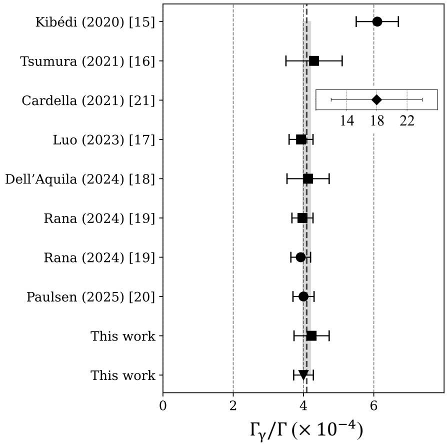
Precise measurement of the γ-decay probability of the Hoyle state with a new triple coincidence-detection method

K. Sakanashi[a,*], T. Kawabata[a,**], S. Adachi[b], H. Akimune[c], S. Aogaki[d], D.L. Balabanski[d], S. R. Ban[d], R. Borcea[e], Ș. Călinescu[e], C. Clisu[e], R. Corbu[d], C. Costache[e], A. Covali[d], M. Cuciuc[d], A. Dhal[d], I. Dinescu[e], N. Florea[e], T. Furuno[a,f], I. Gheorghe[e], A. Ionescu[e], M. Itoh[b], S. Kubono[g,h], A. Kuşoğlu[d,i], Y. Matsuda[c], C. Mihai[e], R. E. Mihai[e,m], C. Neacsu[e], D. Nichita[d], R. Niina[j], S. Okamoto[k], H. Pai[d], T. Petruse[d], M. Sferrazza[l], O. Sîrbu[d], P-A. Söderström[d], A. Spătaru[d], L. Stan[e], A. Tamii[j], D.A. Testov[d], A. Turturica[e], G. Turturică[d], S. Ujeniuc[e], V. Vasilca[d]

- Together, it seems reasonable that we have closed the book on this saga…

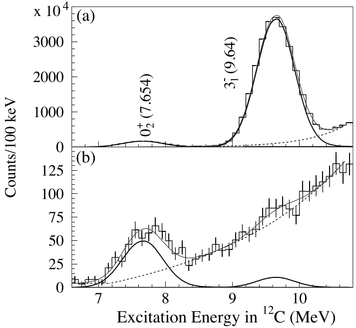
  However, at higher temperatures (2 GK), the triple-α proceeds through higher lying resonances, for which there is still significant uncertainty.

K. Sakanashi *et al.*
https://doi.org/10.1016/j.physletb.2025.139893

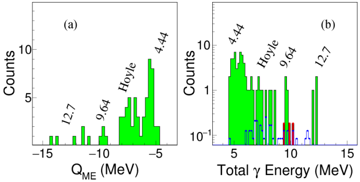


Explosive helium burning (T > 2 GK): 3_1^-

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



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



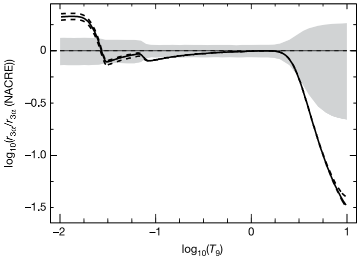
- For the 3_1^- state in ^{12}C, recent results suggest that the previous upper limit of $\Gamma_{rad}/\Gamma <$ 8.3×10^{-7} (95% C. L.) may be incorrect.
  D. Chamberlin *et al.*, Phys. Rev. C 10, 909 (1974)

- ^{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

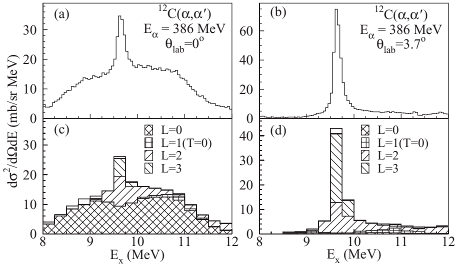
- ^{12}C(p, p') and ^{12}C(α, α')
  $\Gamma_{rad}/\Gamma < 6.4(51) \times 10^{-5}$
  G. Cardella *et al.*, Phys. Rev. C 104, 064315 (2021)

Explosive helium burning ($T > 2$ GK): 2_2^+, 0_3^+ and 0_4^+

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

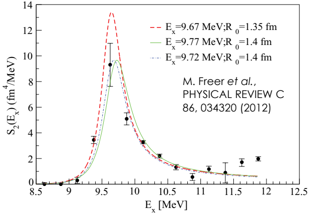


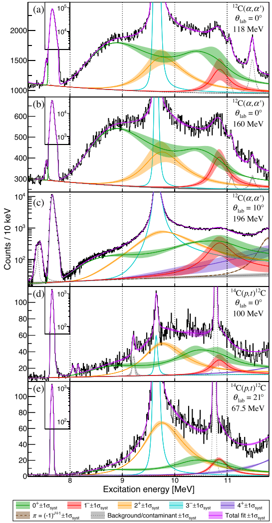
M. Itoh *et al.*, PHYSICAL REVIEW C 84, 054308 (2011)



Often conflicting observable parameters, for example, resonance energies and partial/total widths...

(we shall return back to this point further in this presentation.)





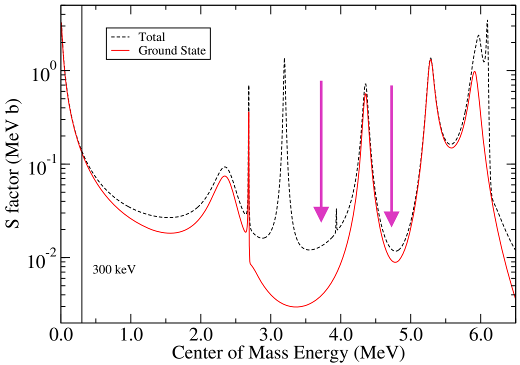
Physics Letters B 827 (2022) 136928

Constraining the $^{12}C(\alpha, \gamma)^{16}O$ uncertainty to ≈ 10%

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

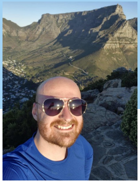
Phase 1:
Direct measurement in the off-resonance region at $E_{cm} \approx 4.7$ MeV, and up to $E_{cm} \approx 6.1$ MeV.

Phase 2:
Direct measurement in the off-resonance region at $E_{cm} \approx 3.5$ MeV.



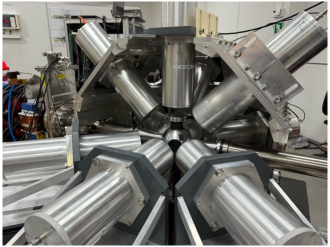
R. J. deBoer *et al.* (2017)
10.1103/RevModPhys.89.035007

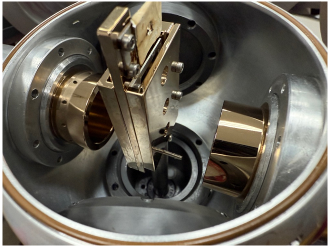
Phase 1: Off-resonance region at $E_{cm} \approx 4.7$ MeV to $E_{cm} \approx 6.1$ MeV.



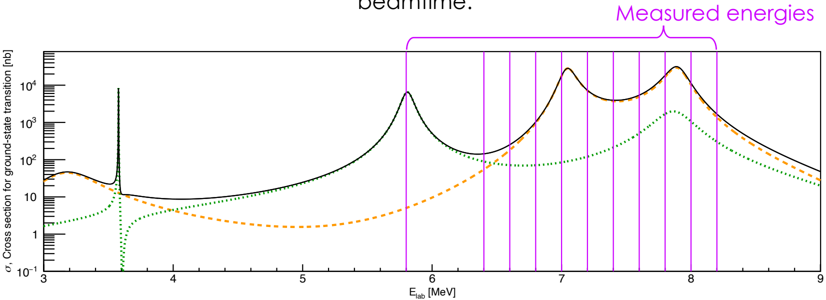
Jeppe Thingholm
PhD student

Info on H-line: https://tlabs.ac.za/2023/11/30/h-line/

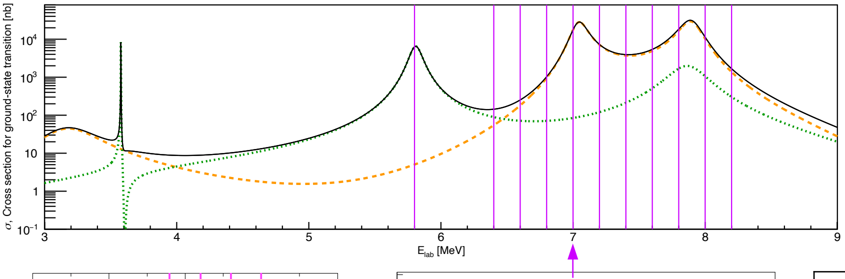


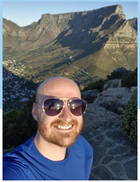


- 12 large-volume $LaBr_3$ detectors at the H-line of iThemba LABS.
- Enriched ^{12}C (99.9%) self-supporting foils, 24 $\mu g/cm^2$.
- Gold plated collimators and target sheath to mitigate $^{nat}Al(\alpha,n)$
- ~ 1.5 μA on target for approximately 3.5 continuous weeks of beamtime.

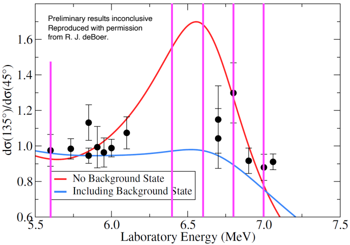


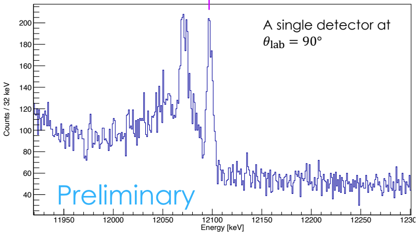
Phase 1: Off-resonance region at $E_{cm} \approx 4.7$ MeV to $E_{cm} \approx 6.1$ MeV.





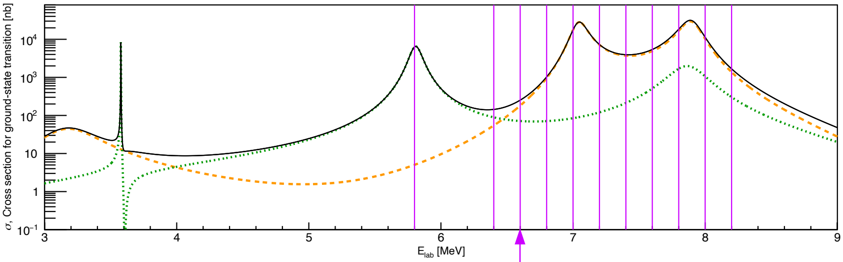
Jeppe Thingholm
PhD student

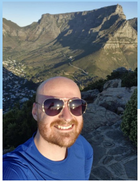




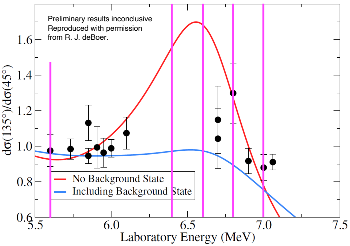
# $LaBr_3$	θ_{lab}
4	45°
5	90°
3	135°

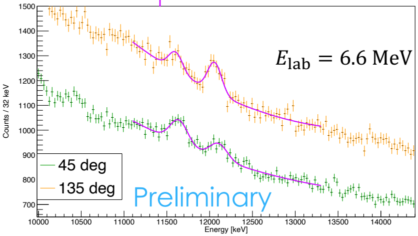
Phase 1: Off-resonance region at $E_{cm} \approx 4.7$ MeV to $E_{cm} \approx 6.1$ MeV.





Jeppe Thingholm
PhD student





Achieved sufficient signal-to-background for angular distributions (even in the off-resonance region).

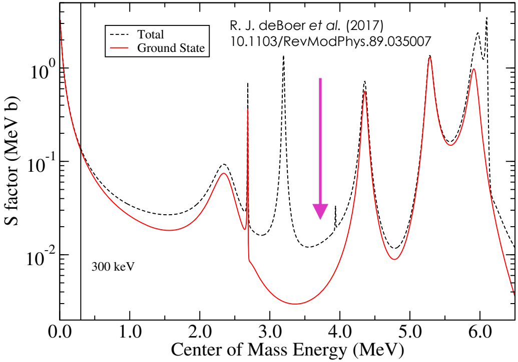
A precise time-dependent energy calibration is required!

Phase 2: Off-resonance region at $E_{cm} \approx 3.5$ MeV

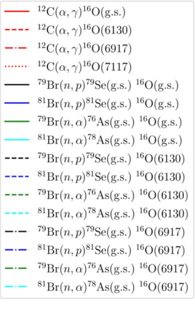
- The off-resonance region at $E_{cm} \approx 3.5$ MeV is particularly sensitive to the direct, external capture to the subthreshold states.
  [deBoer *et al.*,Rev. Mod. Phys., Vol. 89, No. 3]

- Aim to employ ~ 20 μA of current.

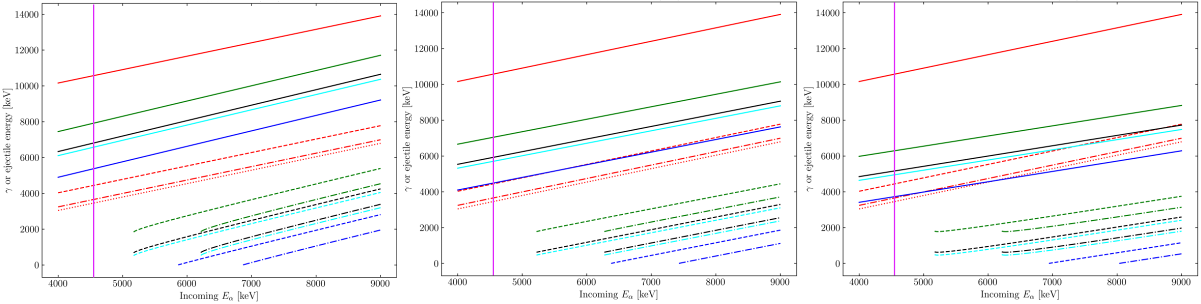
- Possibly a water-cooled, implanted target (perhaps improve enrichment).



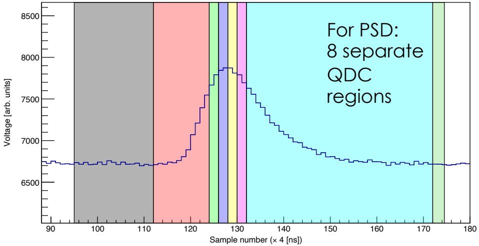
Phase 2: At $E_{lab} \approx 4.7$ MeV, PSD/TOF crucial



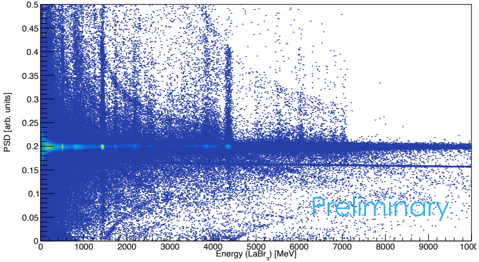
- Neutron-induced reactions (in the $LaBr_3$ crystals) can contaminate the cascade photopeaks of interest.
- Neutron-induced gamma-ray emission (upstream) may be mitigated a high-Z material such as using tantalum.
- Detecting both gamma rays in the cascade (not necessarily both events in the full-energy photopeak) will be the approach.

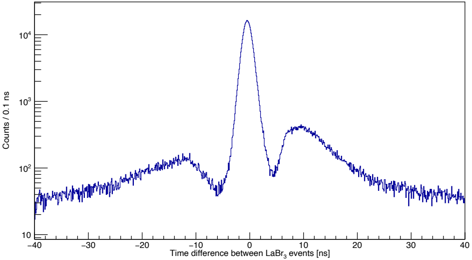


Phase 2: Off-resonance region at $E_{cm} \approx 3.5$ MeV



- Will attempt to measure the full cascade in the off-resonance region.
- Pulse-shape discrimination (PSD) being developed for the large-volume 3.5" x 8" $LaBr_3(Ce)$ detectors.
- Time difference (i.e. time of flight) between events may be an important gate!





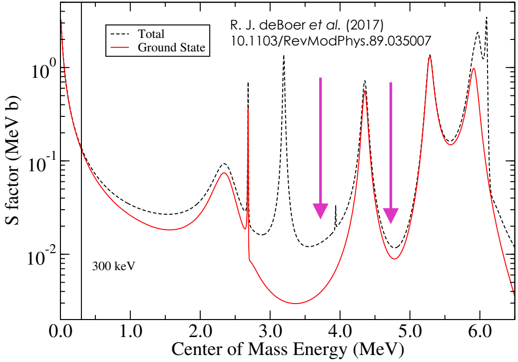
A massive team effort!
A special thank you to local staff and students!

New indirect approach for $^{12}C(\alpha, \gamma)^{16}O$

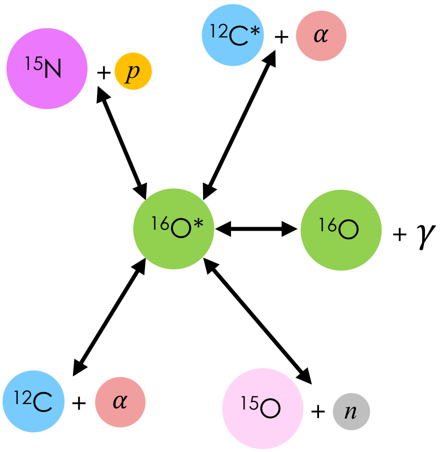
ANCs are often employed to constrain subthreshold (sub-Coulomb transfer often understood to be most reliable)

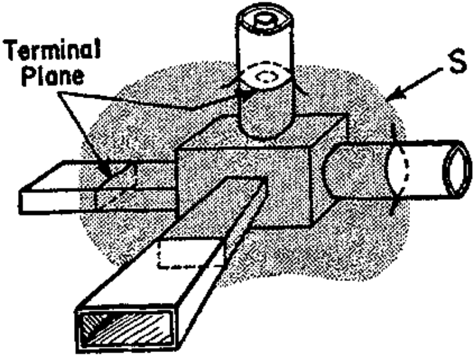
Addressing the call for new indirect methods to verify current indirect methods.

- 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.



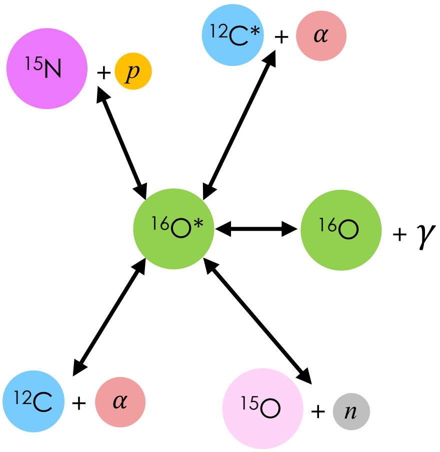
Resonant scattering in a nutshell

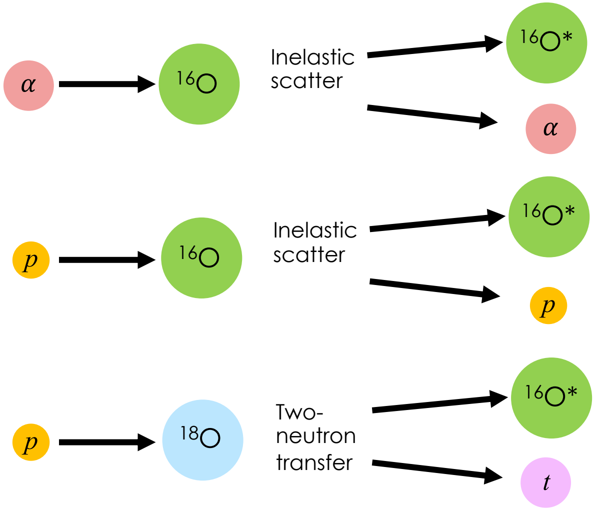




"A transmission line (waveguide) junction"
E.P. Wigner, Nuclear Reactions and Level Widths, American Journal of Physics 17, 99-109 (1949)

Resonant scattering vs "direct" reaction





In short: can one predict these excitation spectra?
More conservatively: a consistent framework for analysis?

Current status quo:

1. Conflicting results for observables such a resonance energies and widths.

2. Simple fits with Lorentzians vs. multi-level, multi-channel formalism.

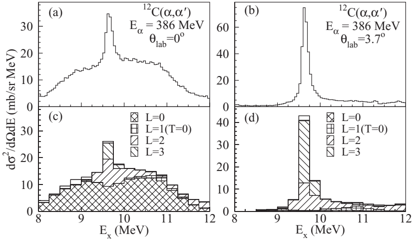
3. Wigner-Eisenbud vs Brune parametrisation?

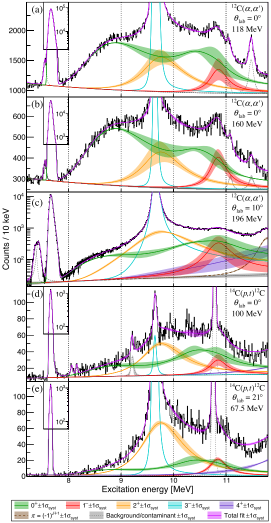
- In the former case: for each Jpi block, what resonance is the natural boundary condition satisfied? Often not published.

  A key practical advantage of the Brune parametrisation is its reduced dependence on arbitrary choices by the analyst.

- If the transformation required is not feasible, then <u>functionally</u>, the results may likely become relegated to being rough guides for global analyses

M. Itoh *et al.*, PHYSICAL REVIEW C 84, 054308 (2011)





Physics Letters B 827 (2022) 136928

A unified framework is needed to integrate the efforts of independent studies and to provide a coherent description.

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

$G_{\lambda ab}^{1/2}$: feeding amplitude, should be related to the scattering amplitude

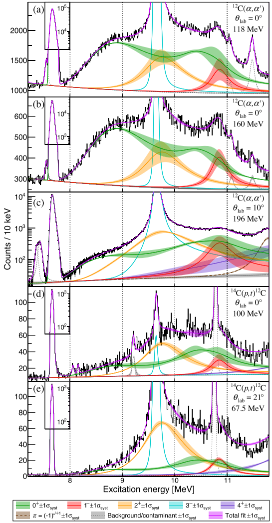
For 1 level:

$$N_{ab,c}(E) = \frac{G_{ab}\,\Gamma_c}{(E - E_r - \Delta)^2 + \frac{1}{4}\Gamma^2},$$

Some open questions:

What lineshape for inclusive spectra, $N_{ab,c}(E)$, appears to have the appropriate degrees of freedom, and yields results which are quite consistent.

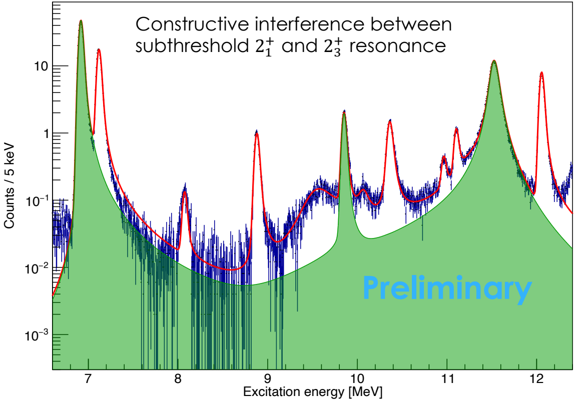
How to treat γ-ray channels on the same (or compensated) footing, such that subthreshold states can be described in a single framework?

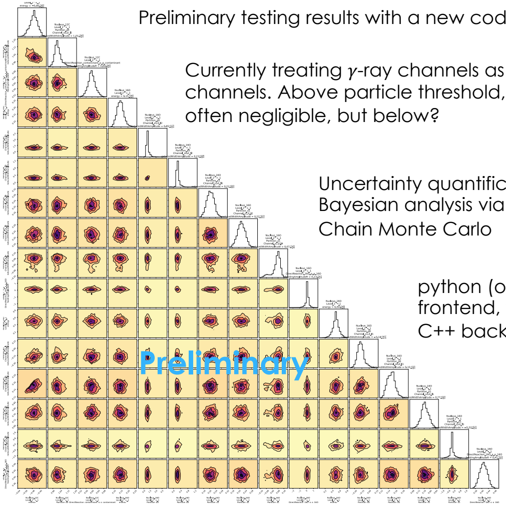


Physics Letters B 827 (2022) 136928

$^{16}O(p,p')^{16}O$ with a self-supporting ice target

A. Tamii, H. Matsubara *et al.*
https://www.rcnp.osaka-u.ac.jp/Divisions/np1-a/thesis/Matsubara_PhD2010.pdf





Preliminary testing results with a new code: **DIPR**

Currently treating γ-ray channels as particle channels. Above particle threshold, this is often negligible, but below?

Uncertainty quantification: Bayesian analysis via Markov Chain Monte Carlo

python (or C++) frontend, with a C++ backend

$^{16}O(p,p')^{16}O$ with a self-supporting ice target

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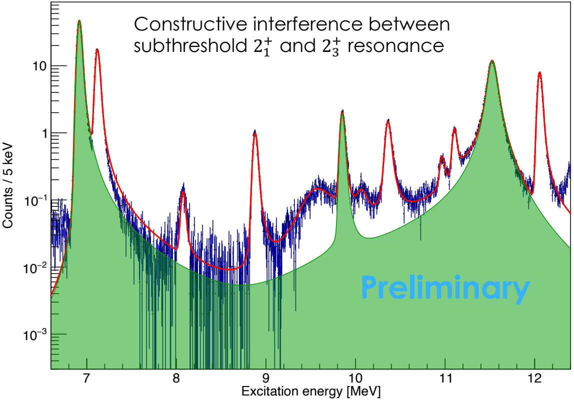
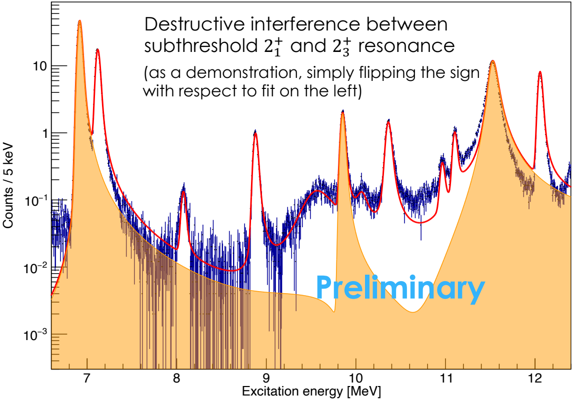
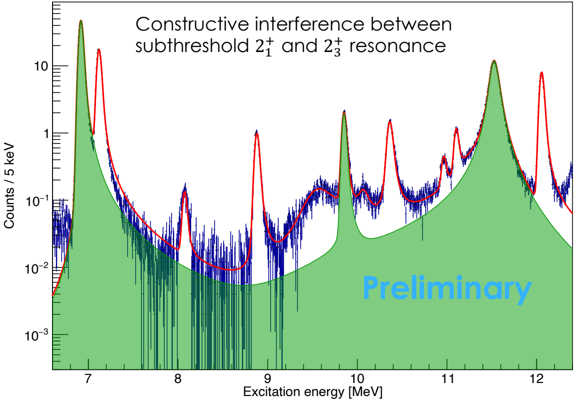


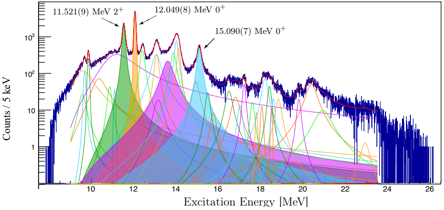


Global analysis with other data sets

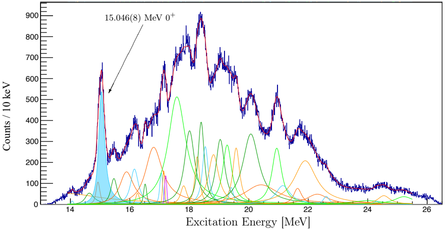
A. Tamii, H. Matsubara *et al.*
https://www.rcnp.osaka-u.ac.jp/Divisions/np1-a/thesis/Matsubara_PhD2010.pdf



$^{16}O(\alpha, \alpha')^{16}O$, gated on α_0 decay mode



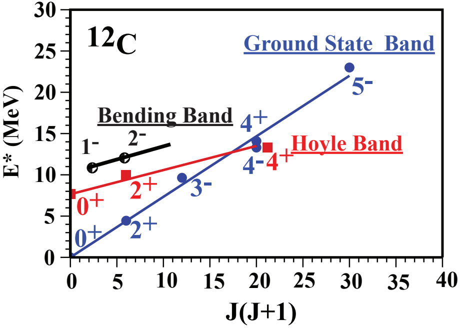
$^{16}O(\alpha, \alpha')^{16}O$, gated on α_1 decay mode



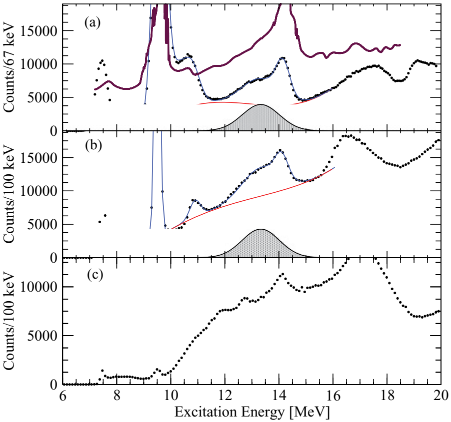
Very old results, will be incorporated into a more global analysis

Future cluster studies with a unified framework

D. J. Marín-Lámbarri *et al.*, PRL 113, 012502 (2014)



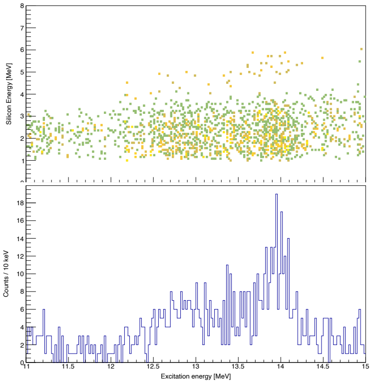
M. Freer *et al.*, PRC 83, 034314 (2011)



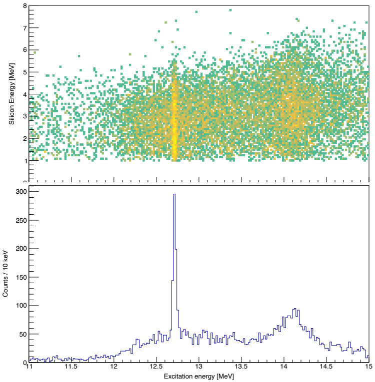
- Algebraic Cluster Model (ACM) predicts rotation-vibration structure in ^{12}C.
- Currently, the broad 4^+ (rotational excitation?) at ~13 MeV has only been observed at Notre Dame tandem

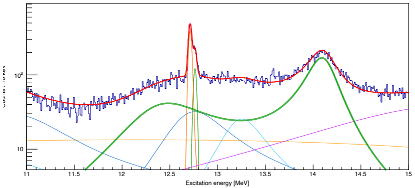
4^{+} rotational excitation of the Hoyle state

$^{12}C \rightarrow {}^{8}Be(0_1^+) + \alpha$



$^{12}C \rightarrow {}^{8}Be(2_1^+) + \alpha$





The 4^{+} nature of the broad resonance at $E_x \approx 13$ MeV with $\Gamma = 1.7(2)$ MeV has been questioned due to a supposed lack of interference with narrower 4^{+} level at $E_x \approx 14.1$ MeV with $\Gamma = 272(6)$ MeV.

A preliminary multi-level fit shows no such consistency. The interference depends on the decay channels of the levels!

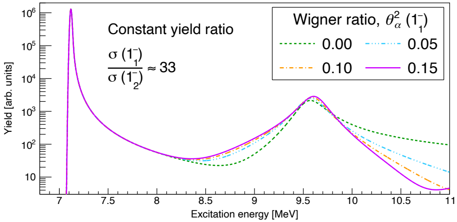
Future approach at IJCLab focused on $E1$: $^{15}\mathrm{N}(^{3}\mathrm{He}, \mathrm{d})^{16}\mathrm{O}$

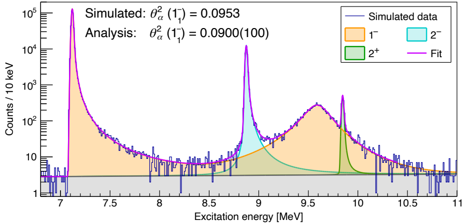
ANCs are often employed to constrain subthreshold (sub-Coulomb transfer often understood to be most reliable)

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.

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





Merci de votre attention!

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J. Thingholm, V. W. Ingeberg, L. M. Donaldson, R. Neveling, A. Inoue, K. Malatji, P. Adsley, L Pellegri, R. J. deBoer, T. B. Bokhutlo, J. W. Brümmer, J. C. N. Ondze, S. Courtin, B. Dennison, R. M. Gesue, S. Hart, K. Haverson, L. J. Jafta, S. Jongile, P. Jones, T. Khumalo, L. Maqungo, T. G. Modise, R. E. Molaeng, A. Netshiya, E. C. Vyfers, B. Singh, R. Smith, S. Courtin, B. Dennison

W. Paulsen, S. Siem, V. W. Ingeberg, A. C. Larsen, T. K. Eriksen, H. C. Berg, F. L. B. Garrote, D. Gjestvang, A. Görgen, M. Markova, V. Modamio, E. Sahin, G. M. Tveten, V. M. Valsdòttir