Constraining the key reaction rates using indirect methods

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Outline

- ☑ Introduction: indirect techniques in nuclear astrophysics
- ☑ The ^{22}Ne(α,n) conundrum
- ☑ Hassle around the triple-alpha reaction
  - Radiative width of the Hoyle state
  - Neutrons assisted carbon nucleosynthesis

Indirect methods

- Indirect method: when the reaction of interest (1) for astrophysics is too difficult or impossible to measure directly, use a different ("easier") reaction (2) that informs the reaction of interest.
- Application of a model to go from (2) to (1) is often required.
- The less model-dependent the technique, the better.

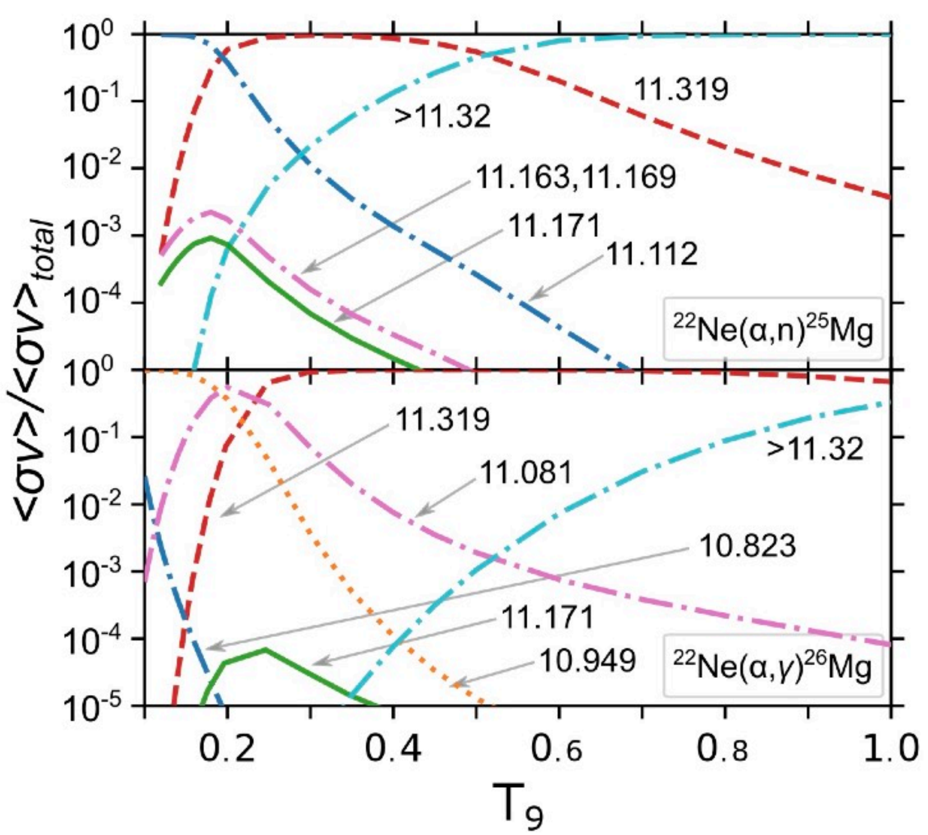
Indirect methods

- Constraints on (p,γ), (α,γ), (n,γ), pycnonuclear fusion, (α,p), and many others can be obtained indirectly
- Incomplete list of indirect methods
  - Transfer or inelastic scattering reactions
    - Spectroscopic factors / ANCs
    - Trojan Horse Method
    - surrogate
    - Oslo
    - Branching ratios
  - Coulomb dissociation
  - Time-reverse reactions
  - β-delayed charge particle spectroscopy / β-Oslo

The ^{22}Ne(α,n) conundrum

$^{22}Ne(\alpha,n)$ - neutron source for s-process

- $^{22}Ne(\alpha,n)$ is the neutron source for the weak branch of the s-process
- final abundances of some s-process elements depend on this reaction rate (NIC, Section 1.2 and 2)
- One ^{26}Mg resonance dominates the $^{22}Ne(\alpha,n)$ at $T_9 >$ 0.2, the 11.32 MeV



11.32 MeV resonance in ^{26}Mg

$$\omega\gamma_{(\alpha,\gamma)} = 37(4)\mu\text{eV}$$

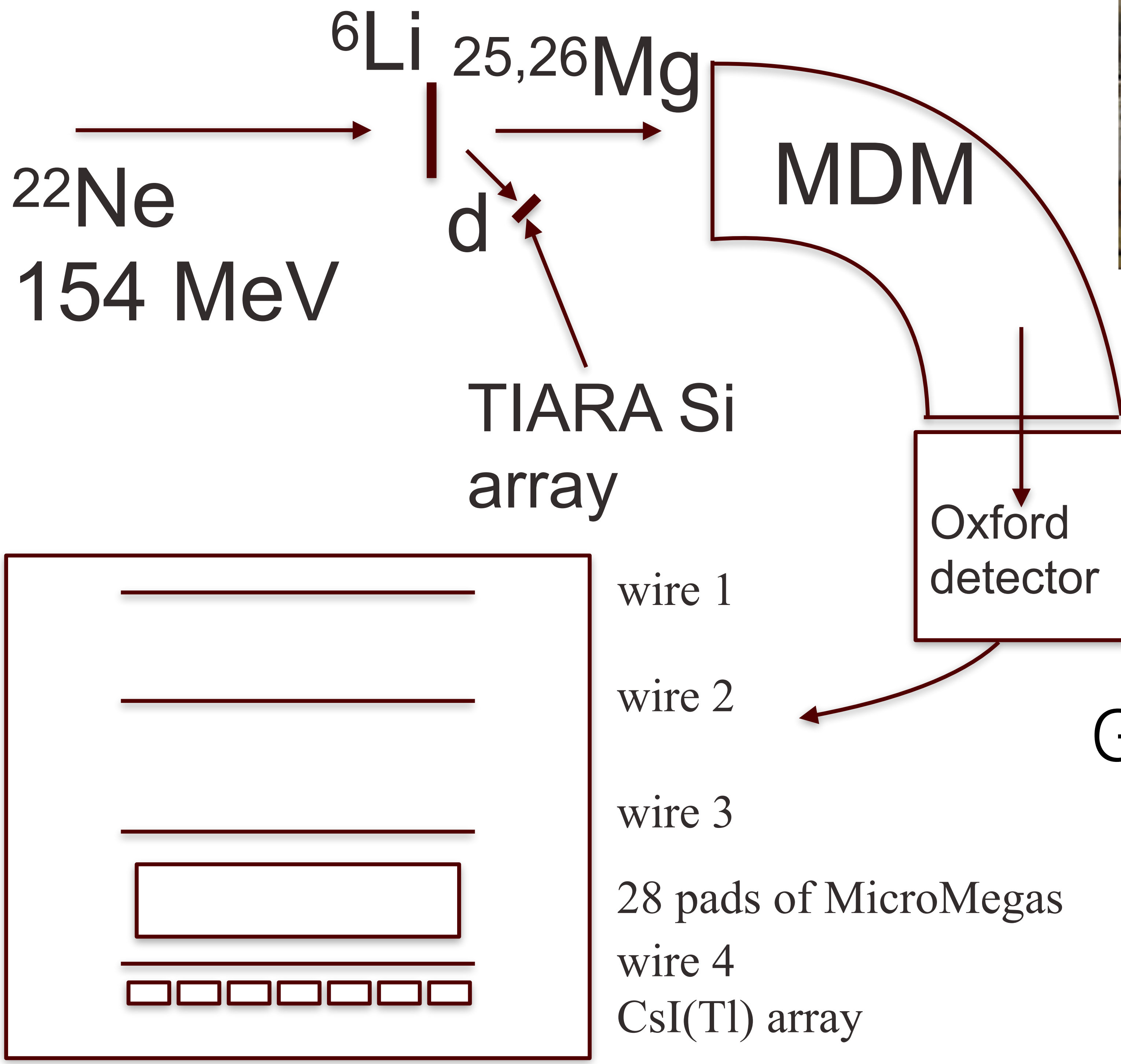
$$\omega\gamma_{(\alpha,\gamma)} \approx (2J+1)\frac{\Gamma_\alpha}{1+\Gamma_n/\Gamma_\gamma}$$

$$\omega\gamma_{(\alpha,n)} \approx (2J+1)\frac{\Gamma_\alpha}{1+\Gamma_\gamma/\Gamma_n}$$

$$\frac{\omega\gamma_{(\alpha,\gamma)}}{\omega\gamma_{(\alpha,n)}} = \frac{\Gamma_\gamma}{\Gamma_n}$$

So, one only needs to measure the γ/n BR

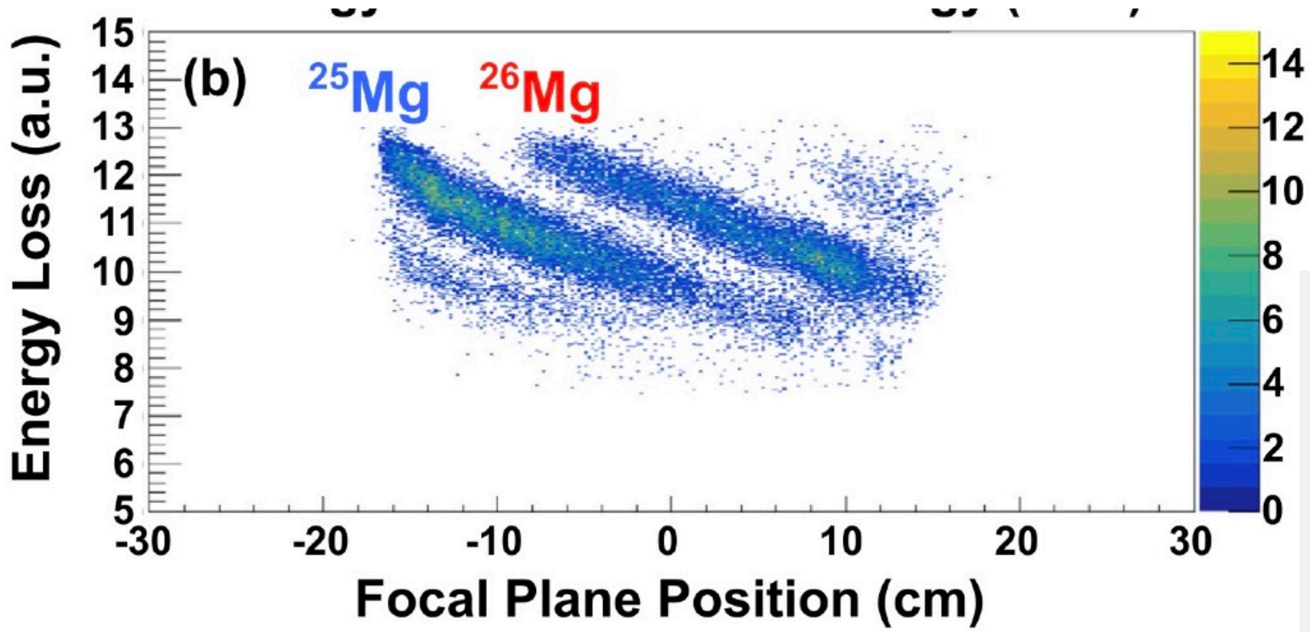
BR using $^{6}Li(^{22}Ne,d)$



G. Christian

S. Otta

11.32 MeV γ/n BR

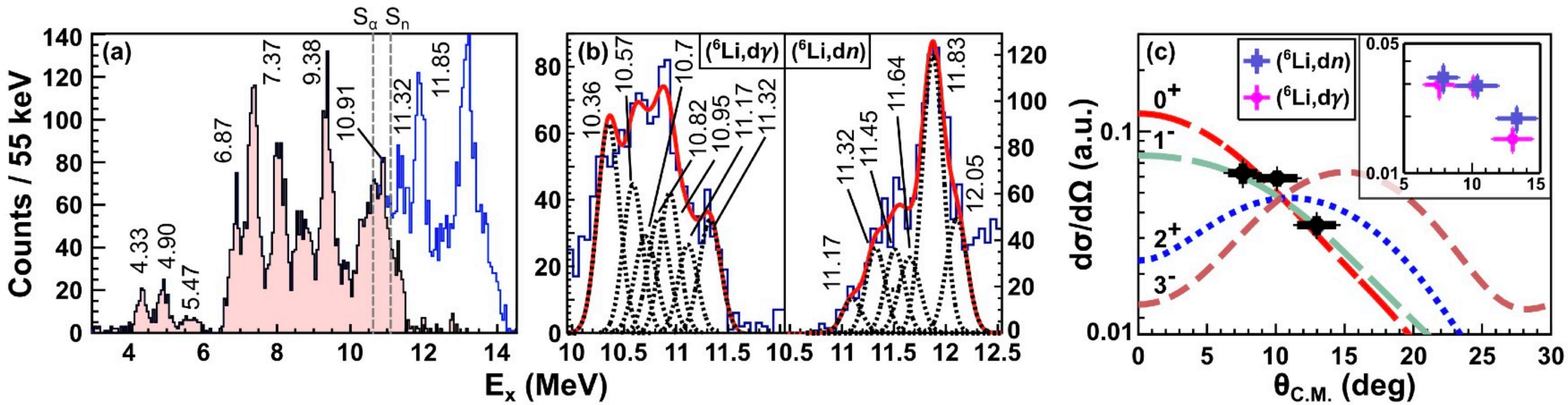


$\Gamma_n/\Gamma_\gamma = 1.14(26)$

$$\omega\gamma_{(\alpha,n)} = 42(11)\mu\text{eV}$$

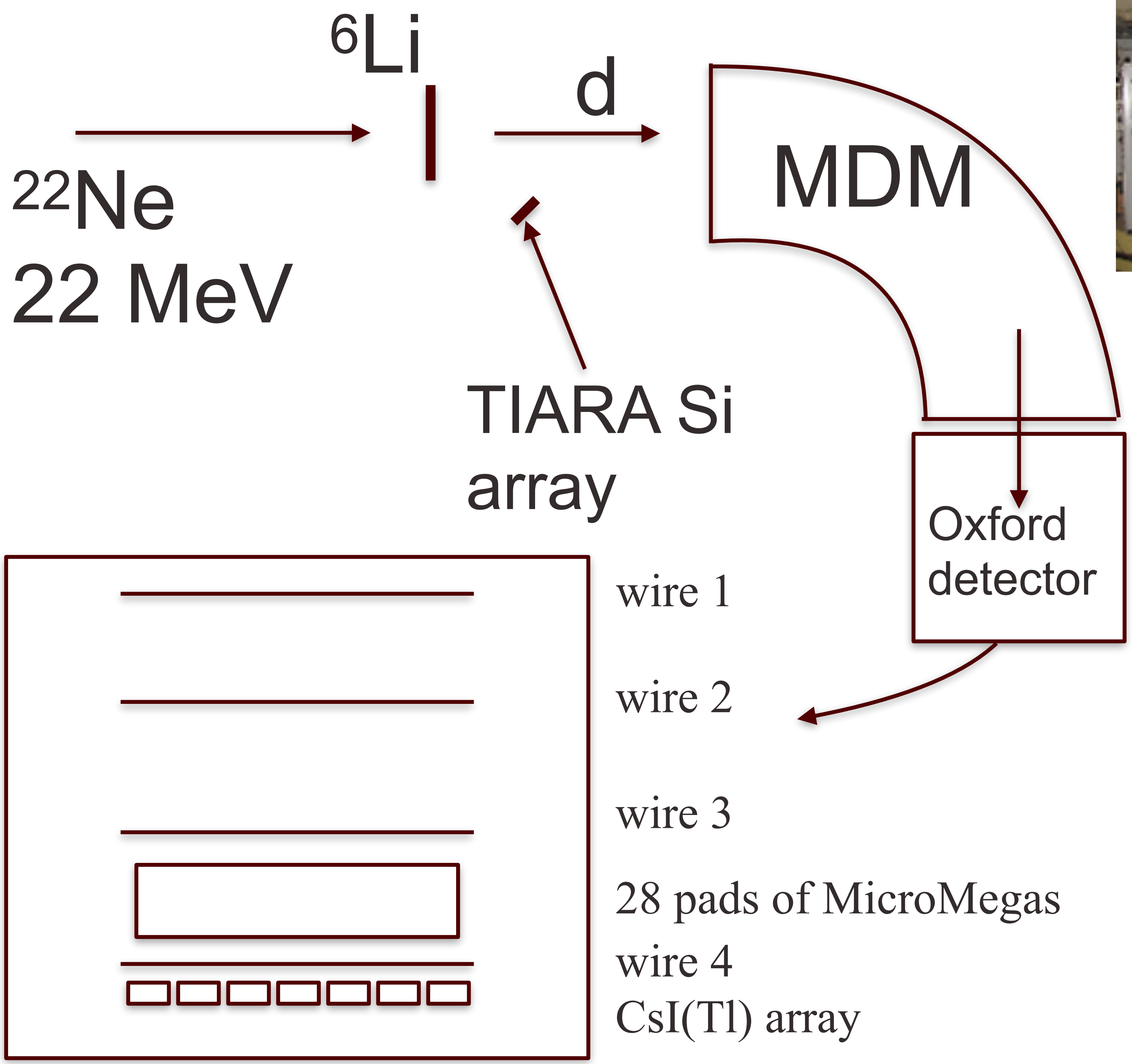
$$\Gamma_\alpha = 79(13)\mu\text{eV}$$

if 0^+



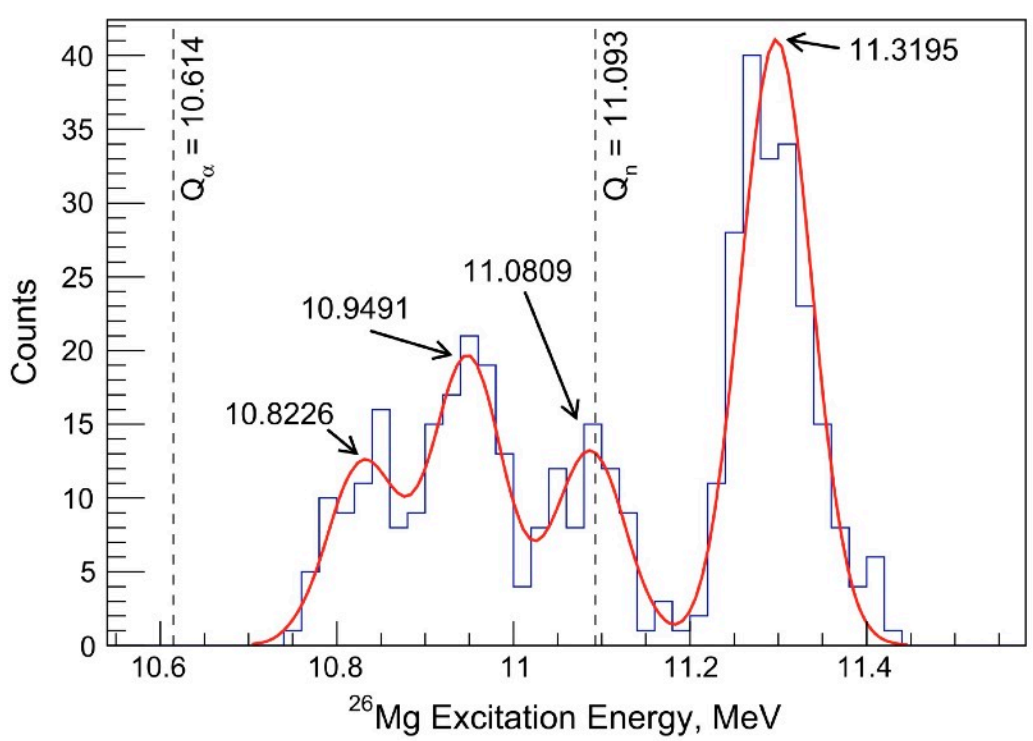
S. Ota, et al., PLB, 802 (2020)

sub-Coulomb ^{6}Li(^{22}Ne,d)



H. Jayatissa

- ☑ Perform (^{6}Li,d) α-transfer reaction at sub-Coulomb
- ☑ Extract ANC instead of SF factors
- ☑ Almost independent of the result on optical model parameters of the DWBA calculations, the number of nodes in the cluster wave function or the shape of the form factor
- ☑ The angular distribution is flat.



$$C^2 = \frac{2\mu R}{\hbar^2 W^2_{-\eta,l+1/2}(2kR)} \frac{\gamma^2}{1+\gamma^2 \frac{dS}{dE}}$$

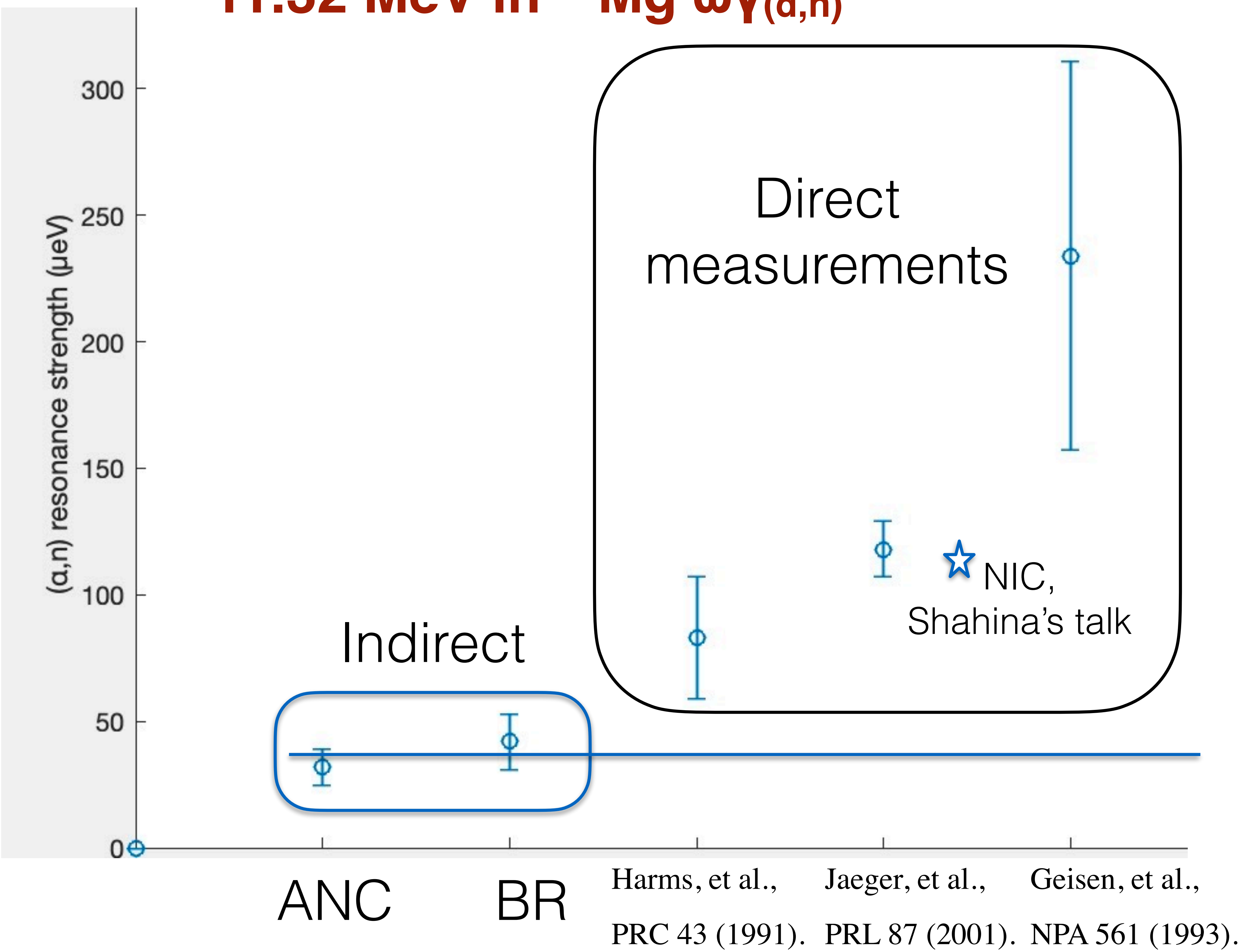
$$\Gamma_\alpha = \frac{2\gamma^2 P}{1+\gamma^2 \frac{dS}{dE}}$$

$$\Gamma_\alpha = 61(14)\mu\text{eV if } 0^+$$

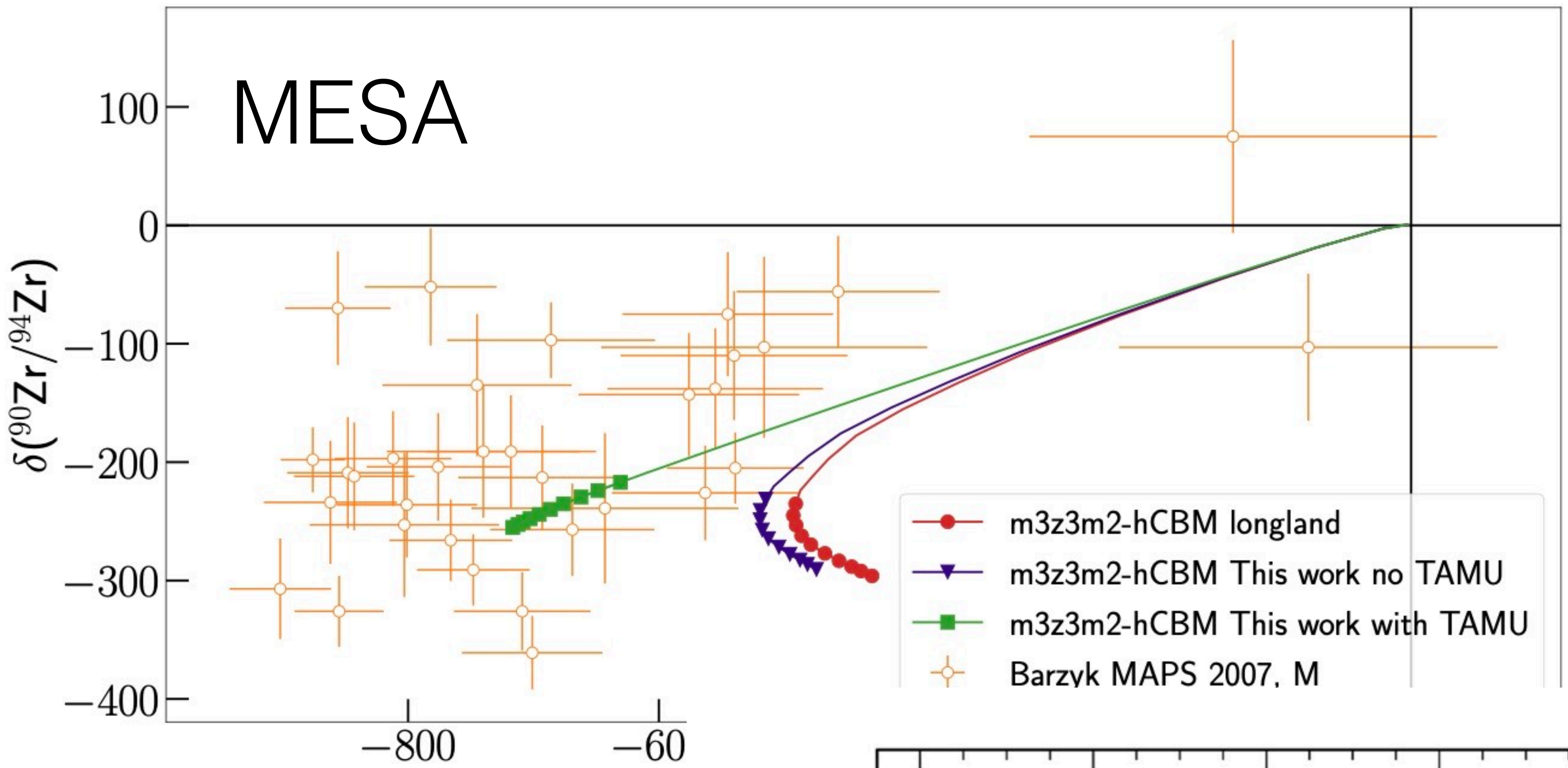
BR gives 79(13) μeV

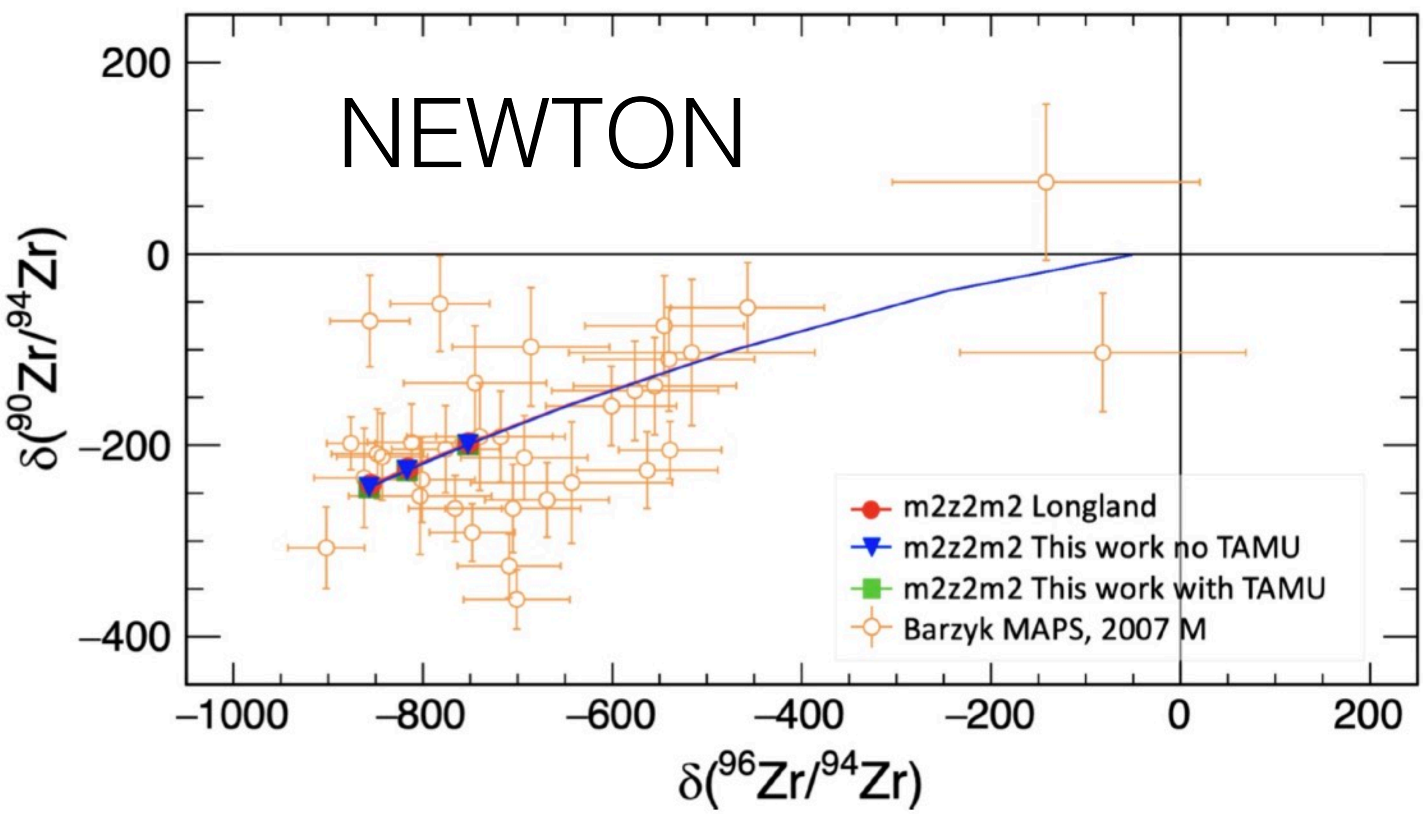
H. Jayatissa, et al., PLB, 802 (2020)

11.32 MeV in ^{26}Mg $\omega\gamma_{(\alpha,n)}$



Zr isotopic ratios from premolar SiC grains





P. Adsley, et al., PRC 103, 015805 (2021)

Radiative width of the Hoyle state

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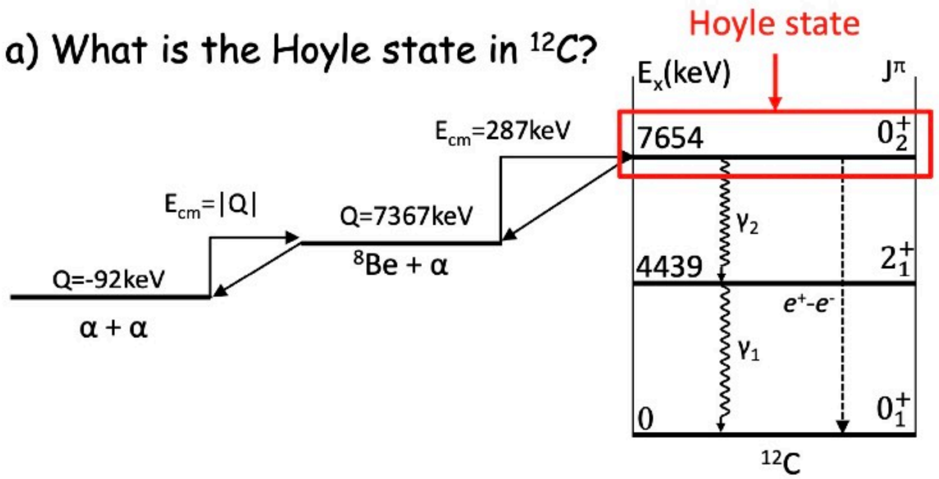
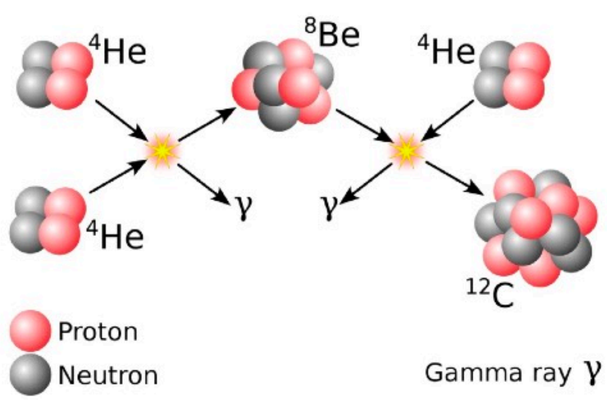
Radiative width of the Hoyle state

a) What is the Hoyle state in ^{12}C?





b) Nuclear physics:

- ^{12}C is produced via 2α⇄^{8}Be(α,γ)^{12}C (3α-process) in star formation.
- ^{8}Be is known to be unbound to 2α-decay with a lifetime of about 10^{-16}s.
- α+^{8}Be⇄^{12}C equilibrium (Γ_α) is broken by the small leakage (1 in 2500 cases) to the ^{12}C ground state facilitated by the radiative branches; either two γ-decay (Γ_γ) or e^+e^- pair production (Γ_π).

c) Astrophysics:

- The reaction rate of 3α-process $\langle\sigma v\rangle \propto \omega\gamma \exp\left(-\frac{E_R}{hT}\right)$.
- The resonance strength $\omega\gamma = \frac{\Gamma_\alpha\Gamma_{\rm rad}}{\Gamma_\alpha+\Gamma_{\rm rad}} = \frac{\Gamma_{\rm rad}}{1+\Gamma_{\rm rad}/\Gamma_\alpha} \approx \Gamma_{\rm rad} = \Gamma_\gamma + \Gamma_\pi$ $(\Gamma_{\rm rad} \ll \Gamma_\alpha)$

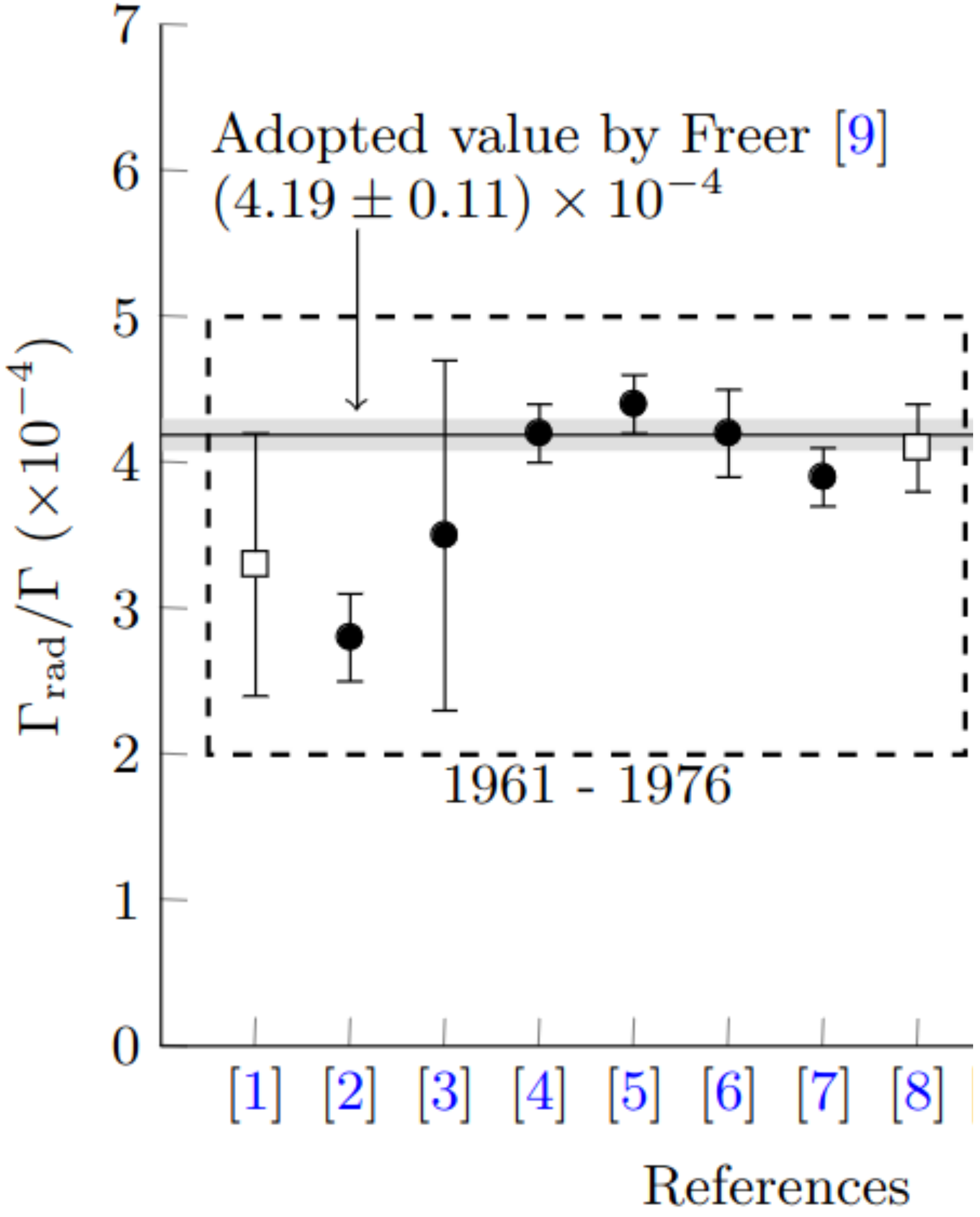
Experimental determination:

$$\Gamma_{\rm rad} = \frac{\Gamma_{\rm rad}}{\Gamma} \times \frac{\Gamma}{\Gamma_\pi(\mathrm{E0})} \times \Gamma_\pi(\mathrm{E0})$$

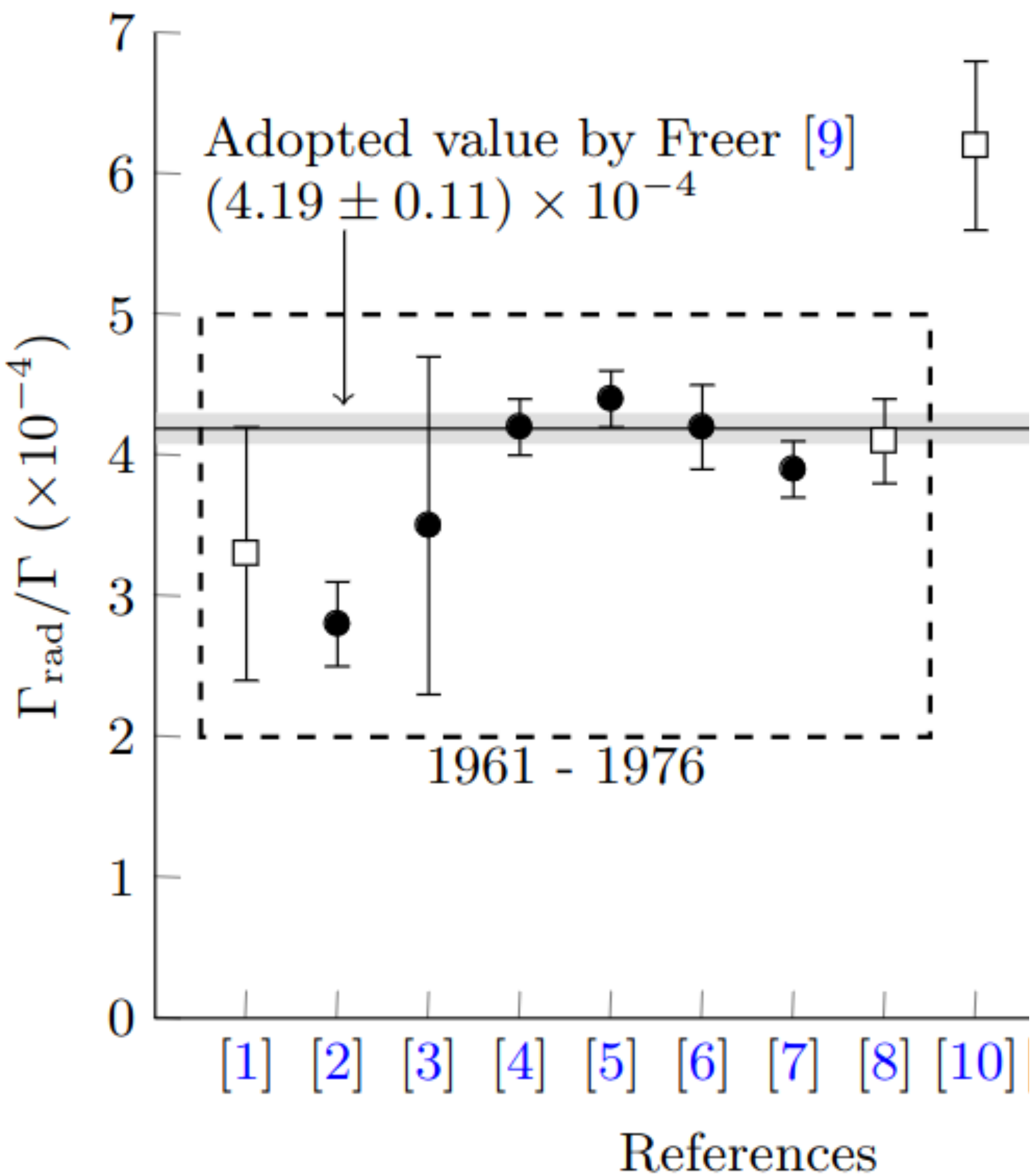
	Adopted [1]
$\Gamma_{\rm rad}/\Gamma$	$4.19(11) \times 10^{-4}$
$\Gamma_\pi(\mathrm{E0})/\Gamma$	$6.7(6) \times 10^{-6}$
$\Gamma_\pi(\mathrm{E0})$	62.3(2)μeV
$\Gamma_{\rm rad}$	3.8×10^{-3} eV

[1] M. Freer, et al., Prog. Part. Nucl. Phys. 78, 1 (2014).

Γ_{rad} / Γ branching ratio for the Hoyle



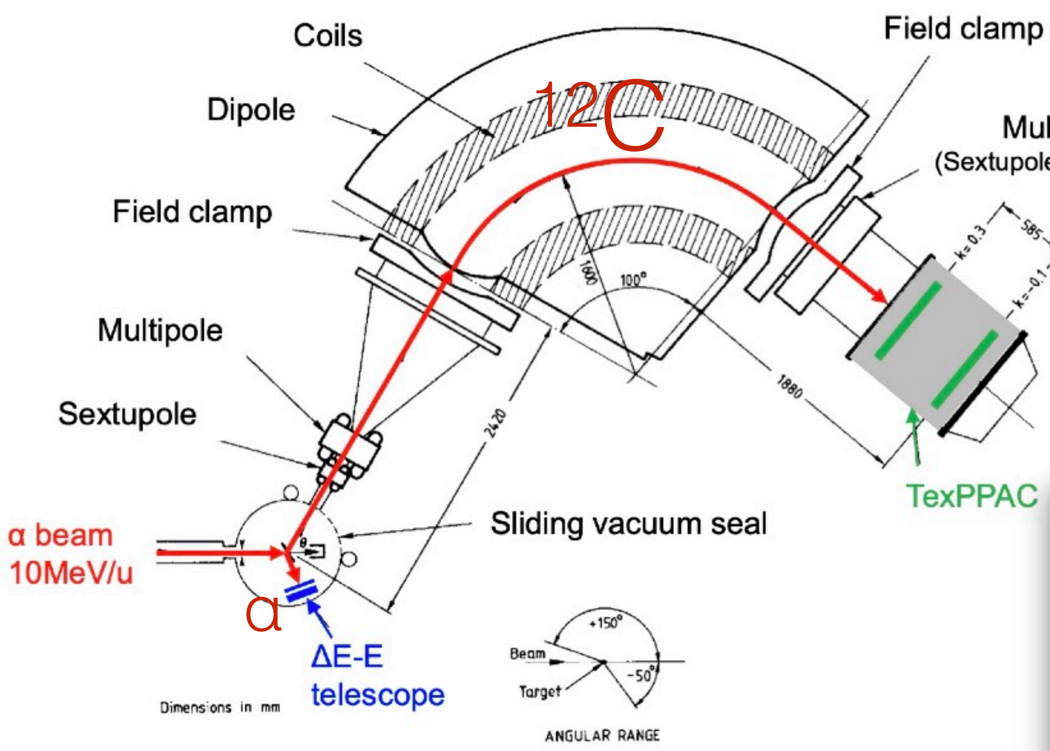
Γ_{rad} / Γ branching ratio for the Hoyle

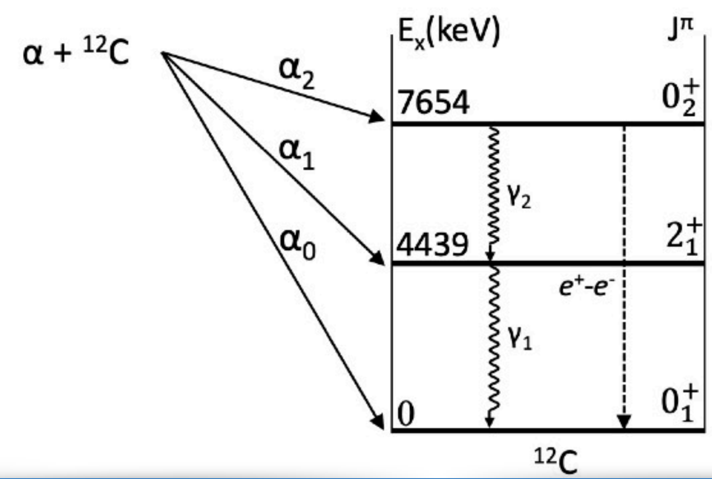


Kibedi, et al., PRL (2020)

Hoyle Γ_{rad} / Γ BR experiment

- Populate Hoyle using $^{12}C(\alpha,\alpha')^{12}C(Hoyle)$ reaction
- Use Si to count the Hoyles populated
- Use MDM spectrometer to count surviving ^{12}C

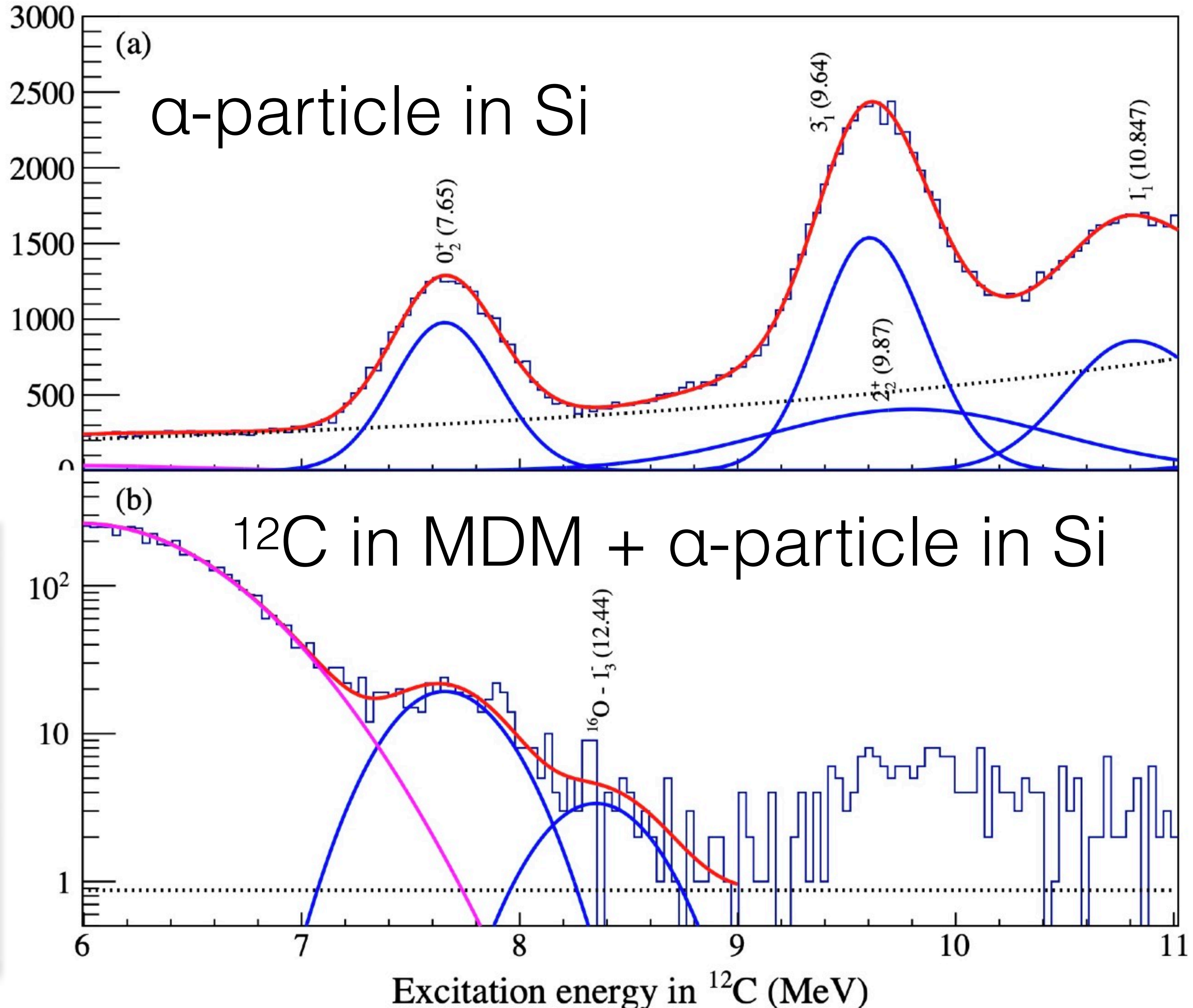




Used highly enriched ^{12}C target (<0.1% ^{13}C)

- ^{12}C energy very low ~1.2 MeV/u
- TexPPACs - new focal plane det.
- Used 12C 5+ charge state
- ^{12}C charged state fractions were accurately measured

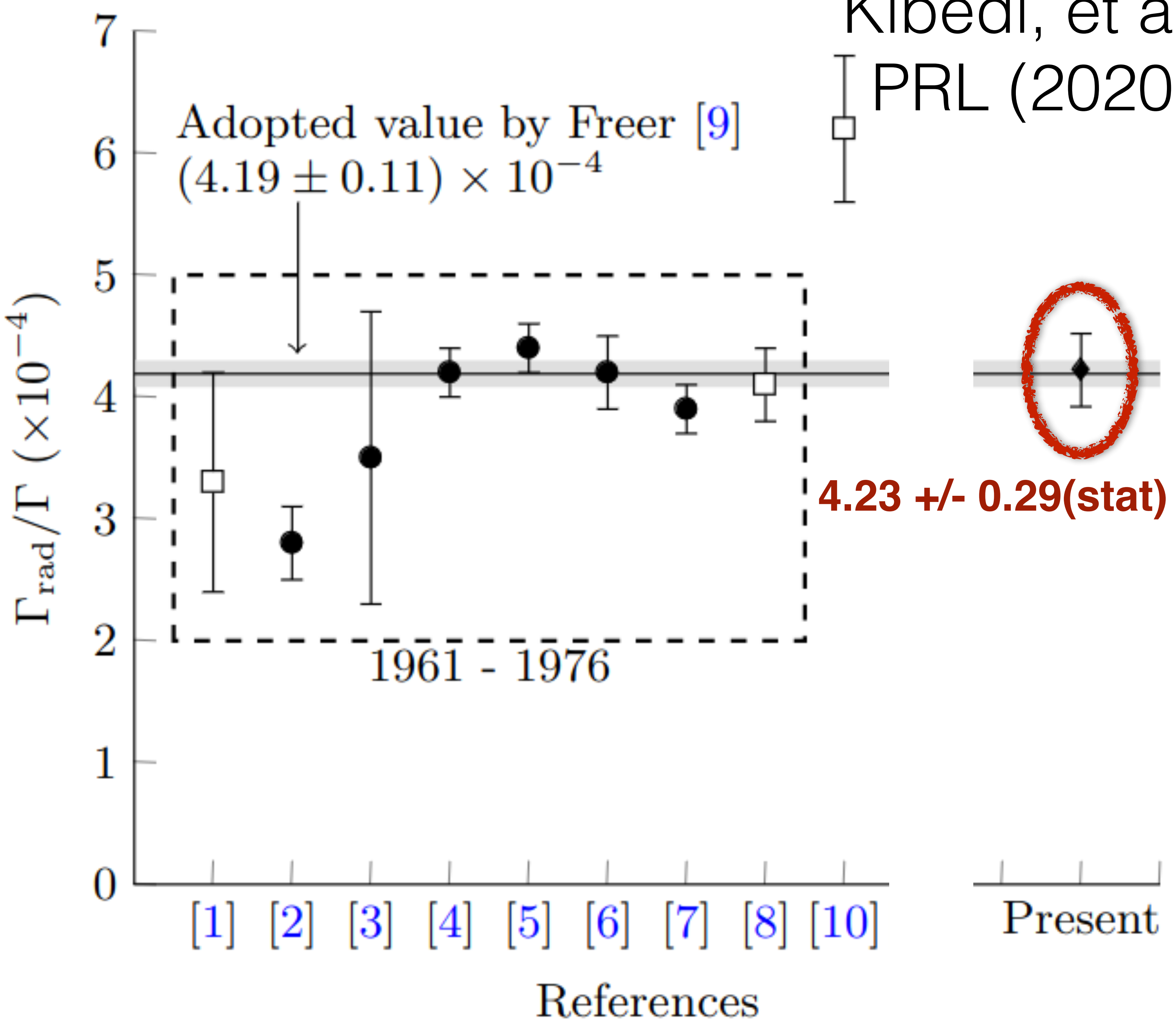
Hoyle Γ_{rad} / Γ BR results



Zifeng Luo
TAMU graduate student

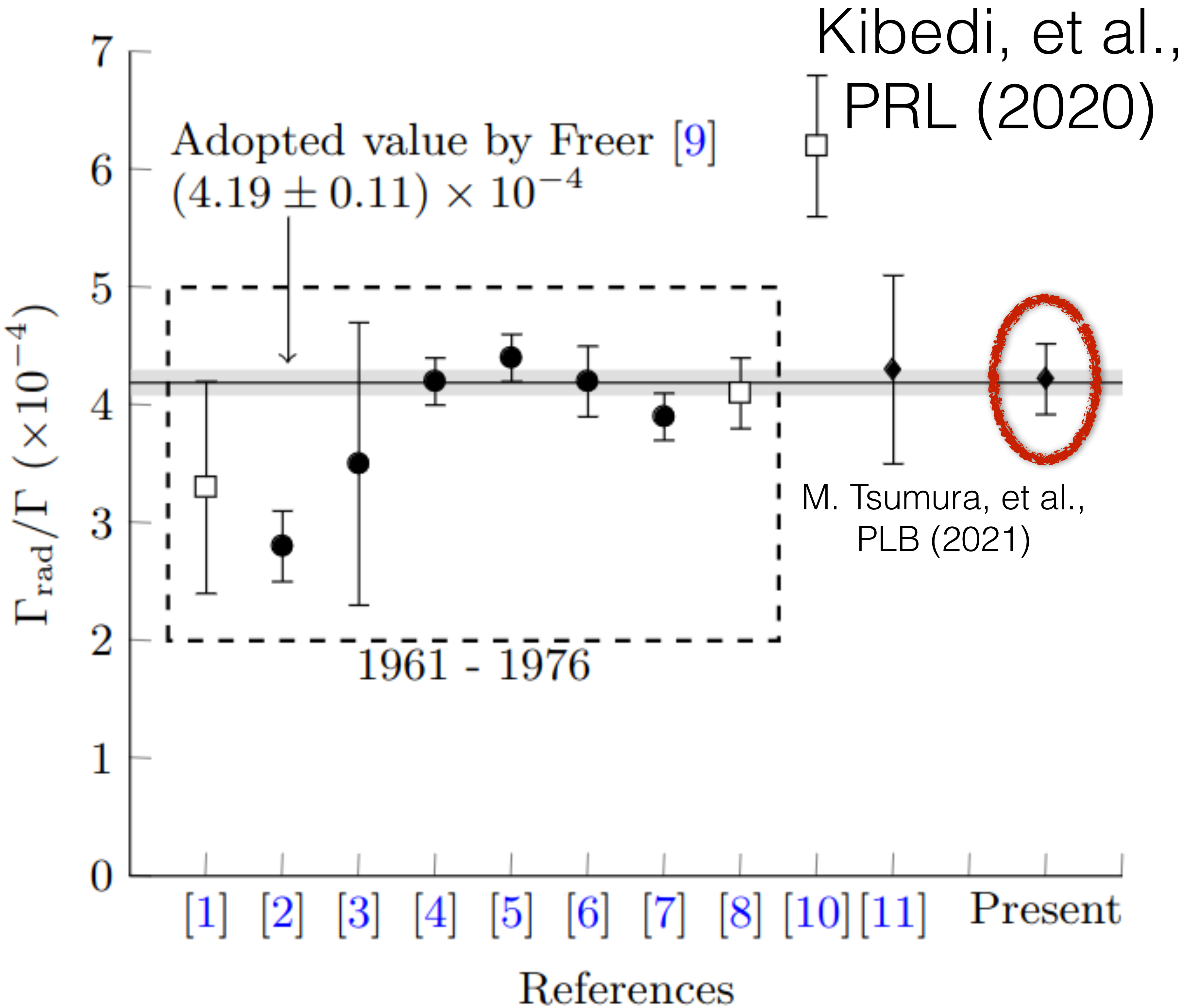
Γ_{rad} / Γ branching ratio for the Hoyle

Kibedi, et al., PRL (2020)



4.23 +/- 0.29(stat) +/- 0.18(sys) x10^{-4}

Γ_{rad} / Γ branching ratio for the Hoyle



The role of neutrons in carbon nucleosynthesis

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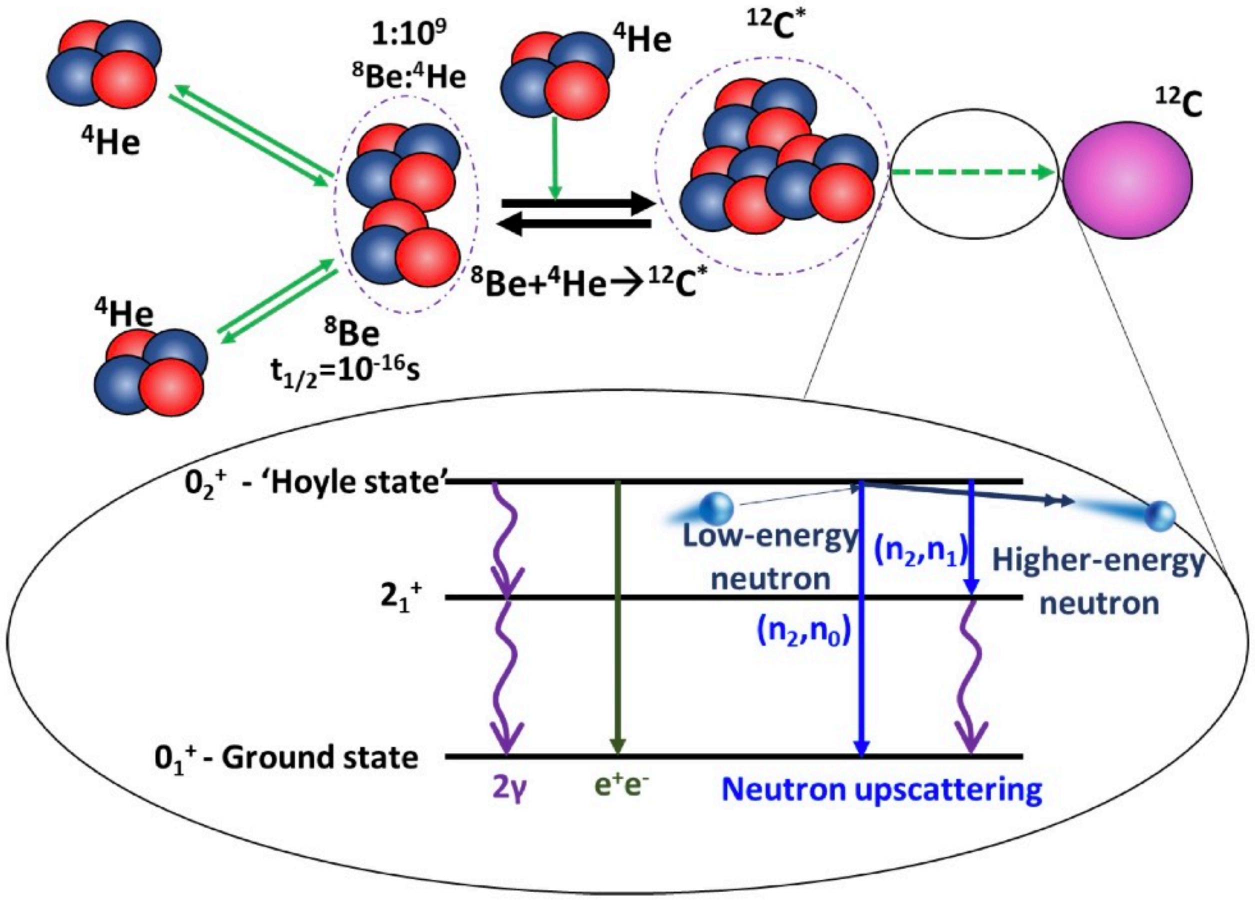
Triple-alpha reaction and neutron upscattering

- three alphas produce Hoyle state in ^{12}C (through ^{8}Be(g.s.))
- Hoyle state can be de-excited by:
  - gamma cascade
  - electron-positron pair
  - neutrons + Hoyle scattering
  - protons + Hoyle scattering OR **decay back to 3α**



PRL 119, 112701 (2017) PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2017

Enhancement of the Triple Alpha Rate in a Hot Dense Medium

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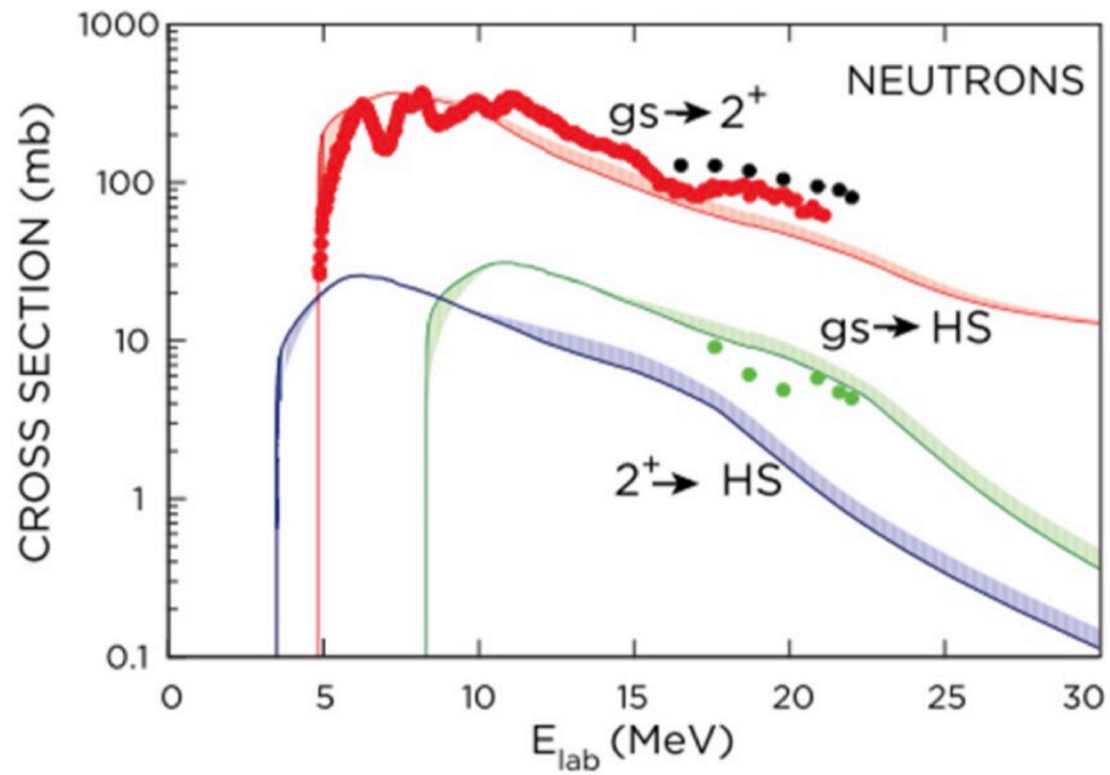
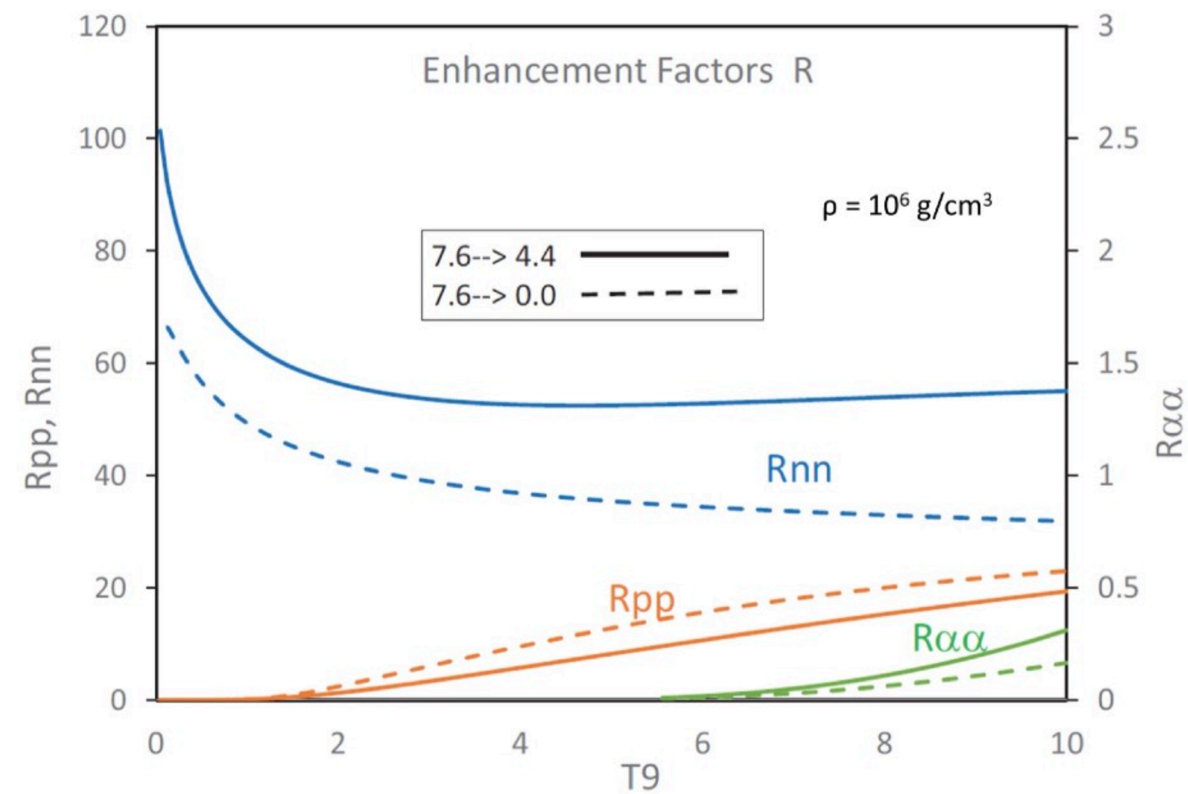
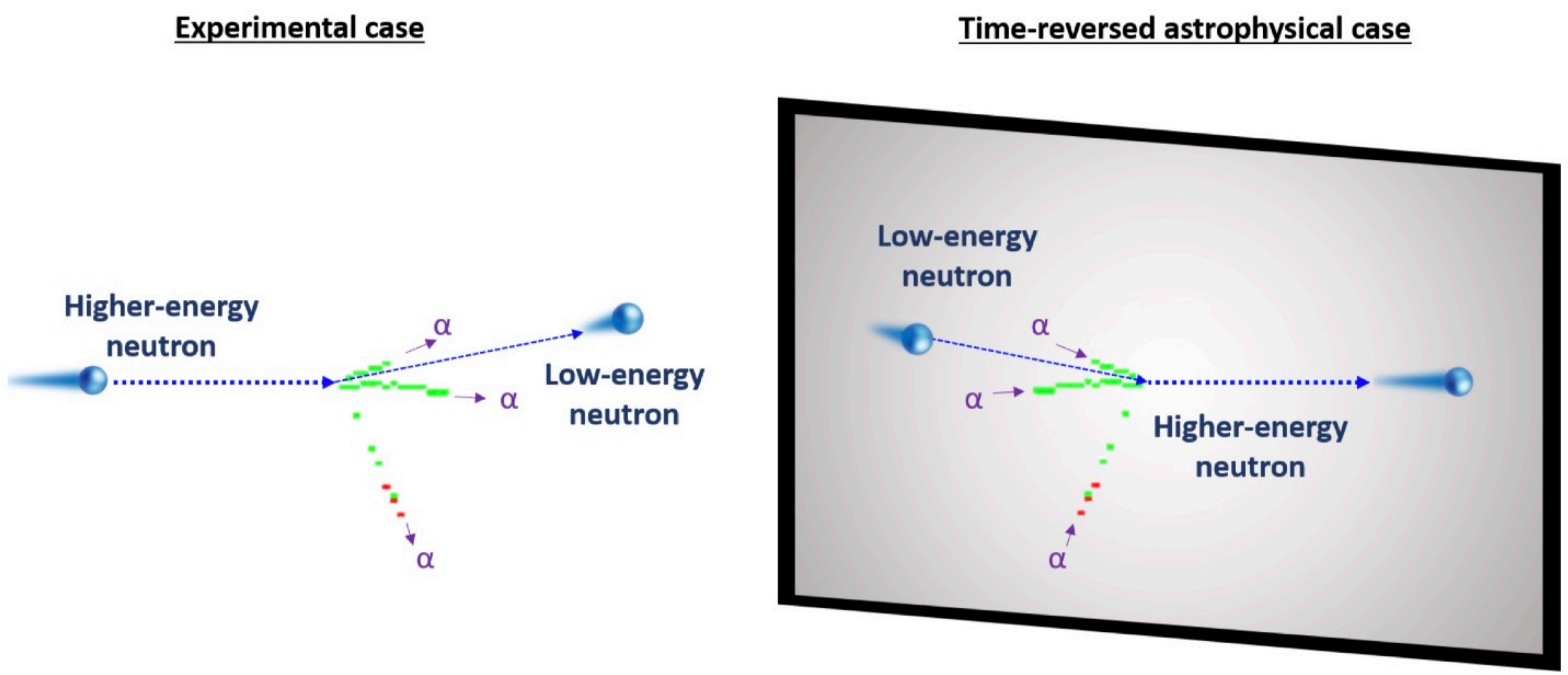
[M. Beard et al. Phys. Rev. Lett. 119, 112701]





Using Hauser Feshbach XS predictions. High-density environment, large neutron enhancements at low temperature (≈ 0.2 GK (T9))

Measuring time-reversed reaction

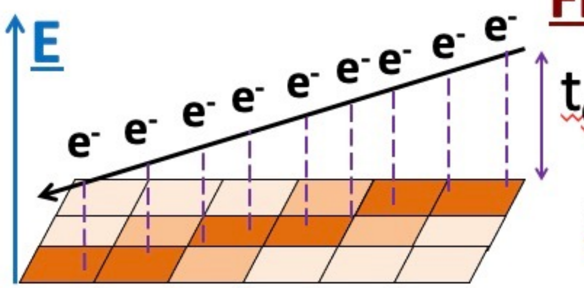


Time-reversal symmetry

Quantum mechanically we can relate a reaction and the time reverse of that reaction using "detailed balance"

TexAT TPC: Texas Active Target Time Projection Chamber

Field Cage

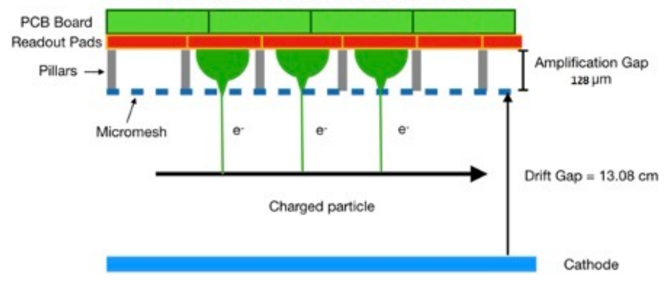


$t_{drift} \propto$ height

$t_{drift} \sim \mu s$

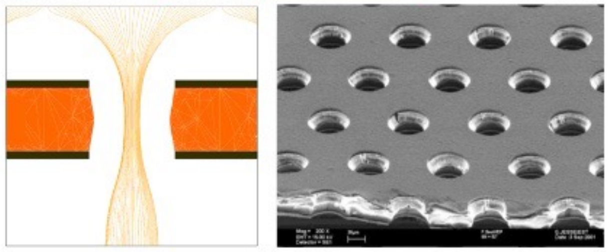
Provides electric field ~1 kV over 13 cm to drift electrons to the Micromegas. Drift time gives the height the electron was created at.

Micromegas



Micromegas (MM) provide gain factor of ~100 and segmented readout of 1024 channels.

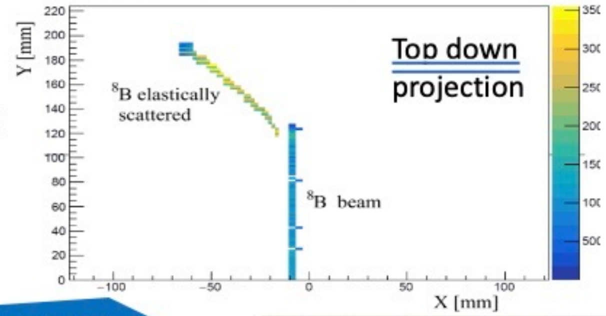
(TH)GEMs

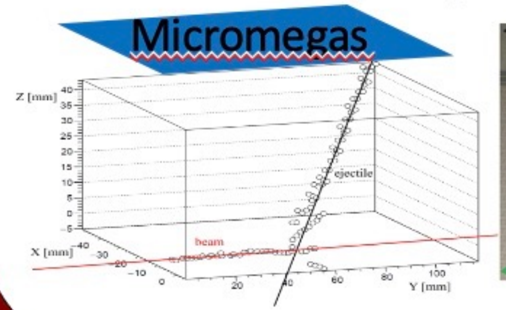


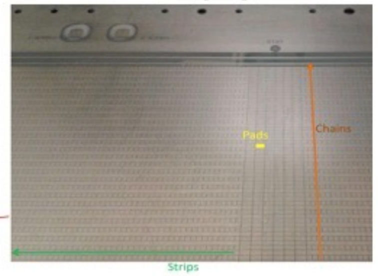
Choice between 50 µm (thin) and 1.5 mm thickness (thick). Provides additional gain factor of ~10-100.

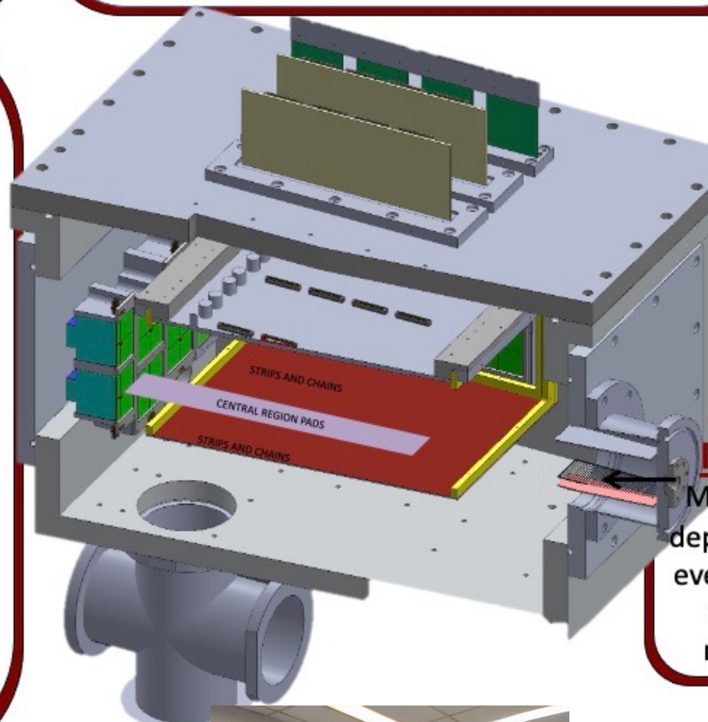
3D tracks

Readout segmentation of 1.75 x 3.5 mm (in central region) gives 3D track of the event.



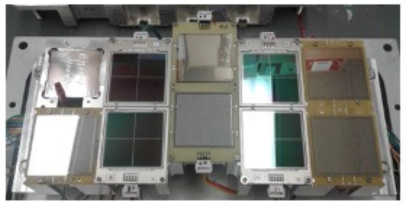






Si + CsI(Tl) wall

Good energy resolution measurement of light recoils that escape TPC. Telescope of 500,600 or 1000 µm Si + 40-mm-thick CsI.

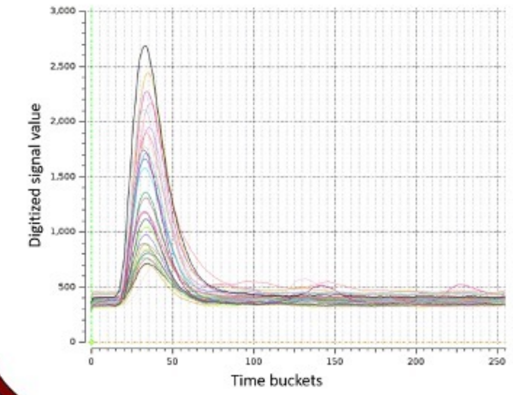


Ion Counter

Measures energy deposited in gas for every incoming ion for beam ID + normalization.

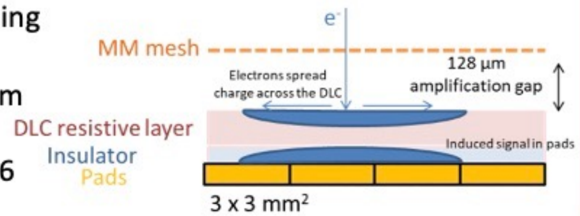
GET – General Electronics for TPCs

- 1024 TPC channels + 1024 for Si/CsI/spare
- 10-100 MHz waveform digitizer
- 512 time buckets
- On chip shaping + amplification
- Internal/external trigger schemes



Future upgrade: TeBAT

- ❑ New DLC charge-spreading MM technology
- ❑ Position resolution from 1.5 mm → 0.2 mm
- ❑ 1024 channels → 7056 channels



E. Koshchiy

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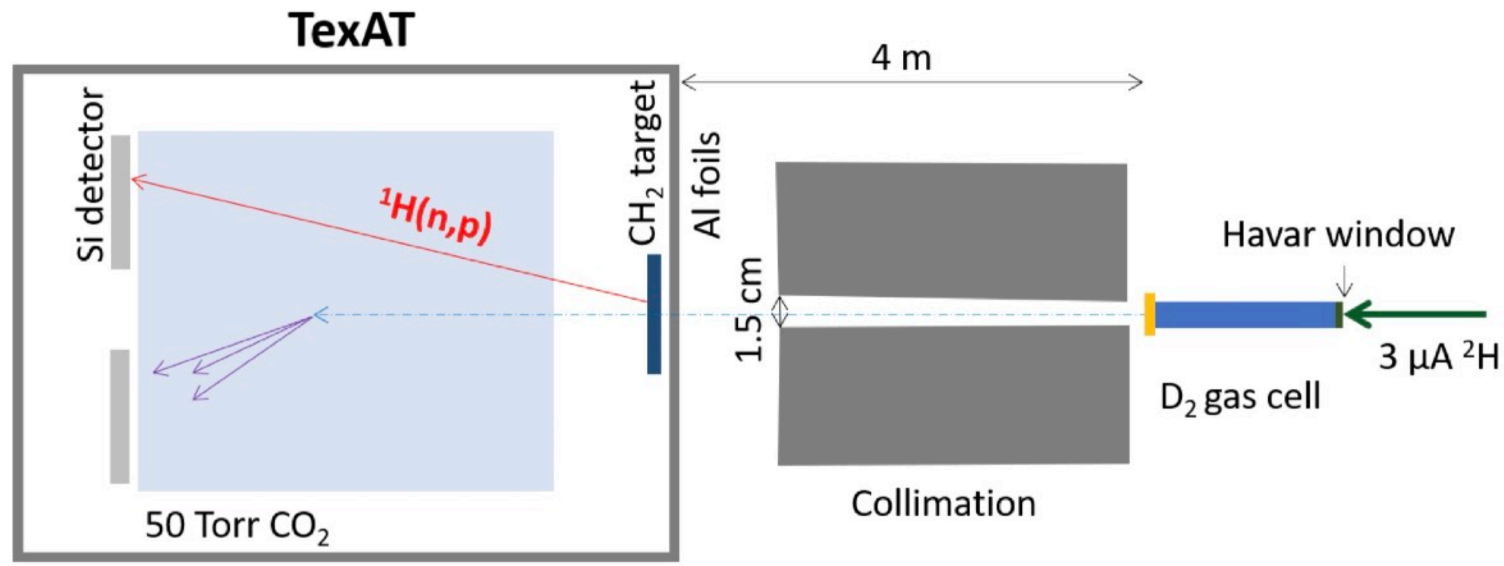
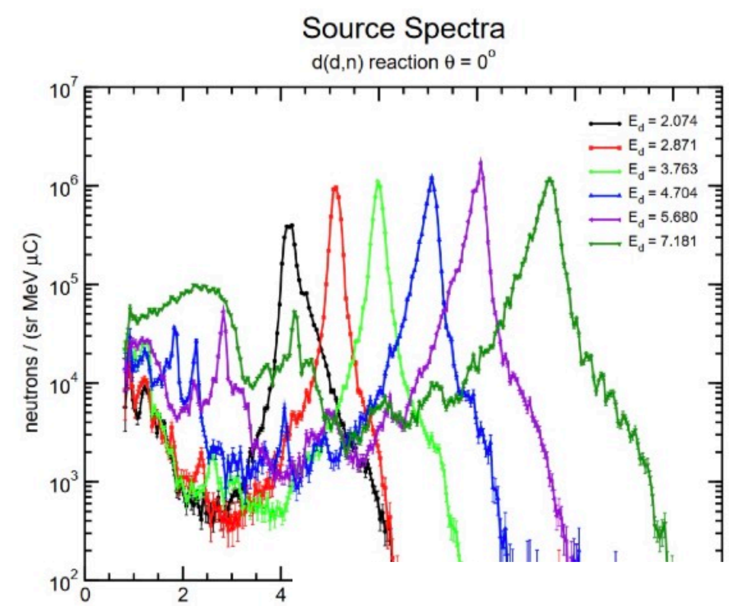
E. Koshchiy et al. NIM A 957, 163398 (2020)

U.S. DEPARTMENT OF ENERGY

TPCs and neutron beams

- Edwards Accelerator Lab - Ohio University
- Deuteron beam from accelerator: $\approx 10^{13}$ pps
- Neutron beam from $d(d,n)$ reaction - scanning from 7.2-10.0 MeV
- 5×10^3 neutrons/s: $\sigma(E_n) \approx 200$ keV
- Normalization is a big issue! Use $^1\mathrm{H}(n,p)$





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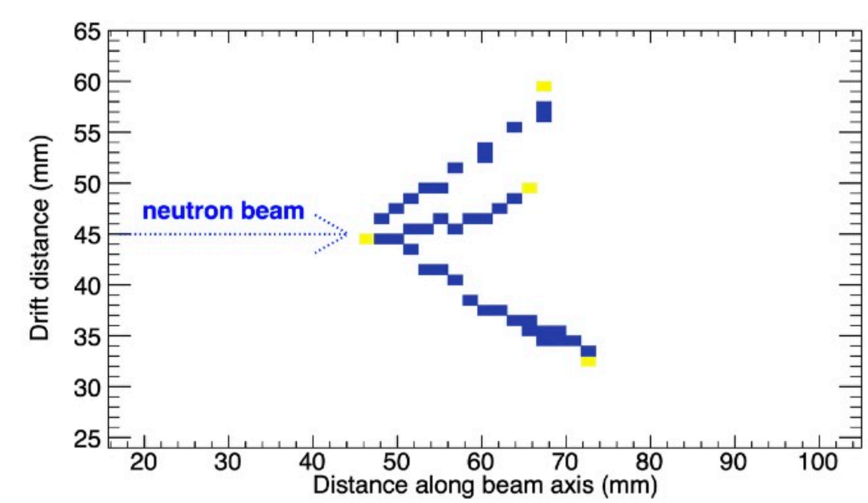
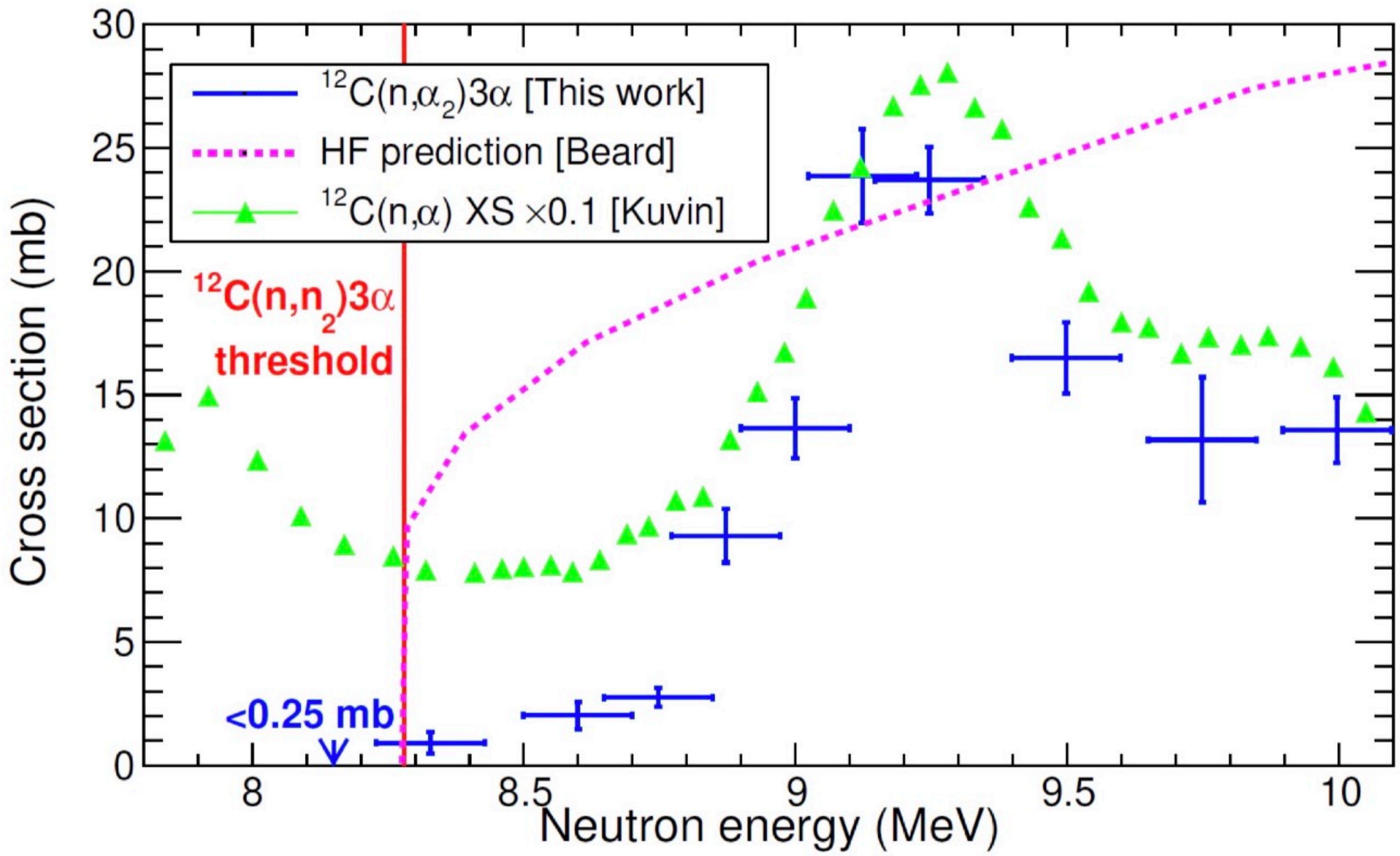
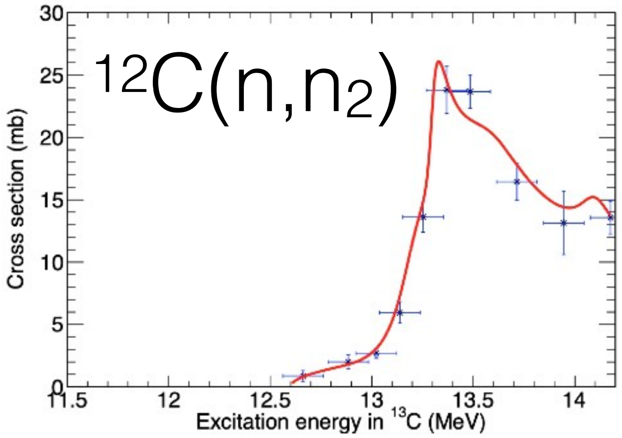


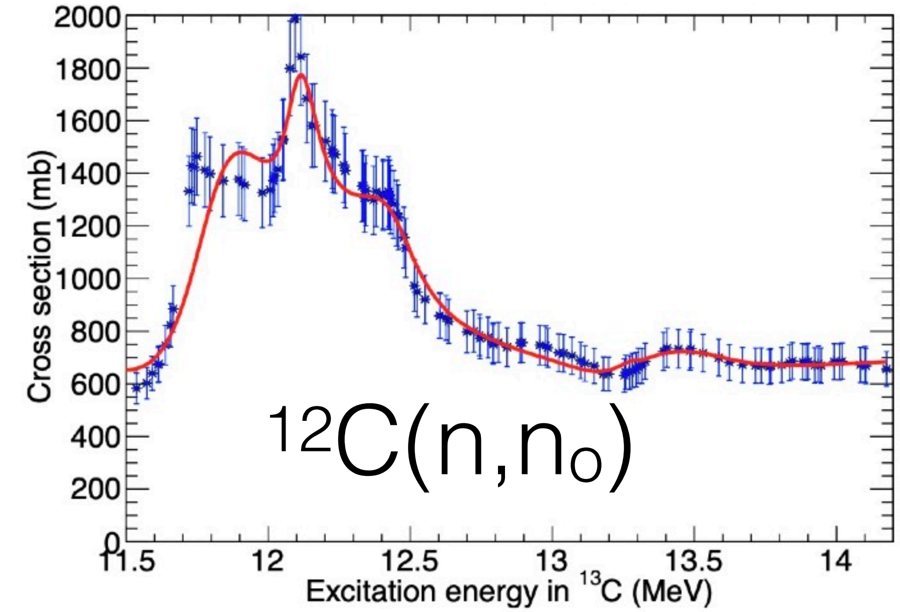
$^{12}C(n,n_2)$Hoyle reaction XS

Reconstruct three α-particles to make Hoyle state, count the events and neutrons!
$^{12}C(n, \alpha_{1,2})^9Be^\star$ contribution is removed



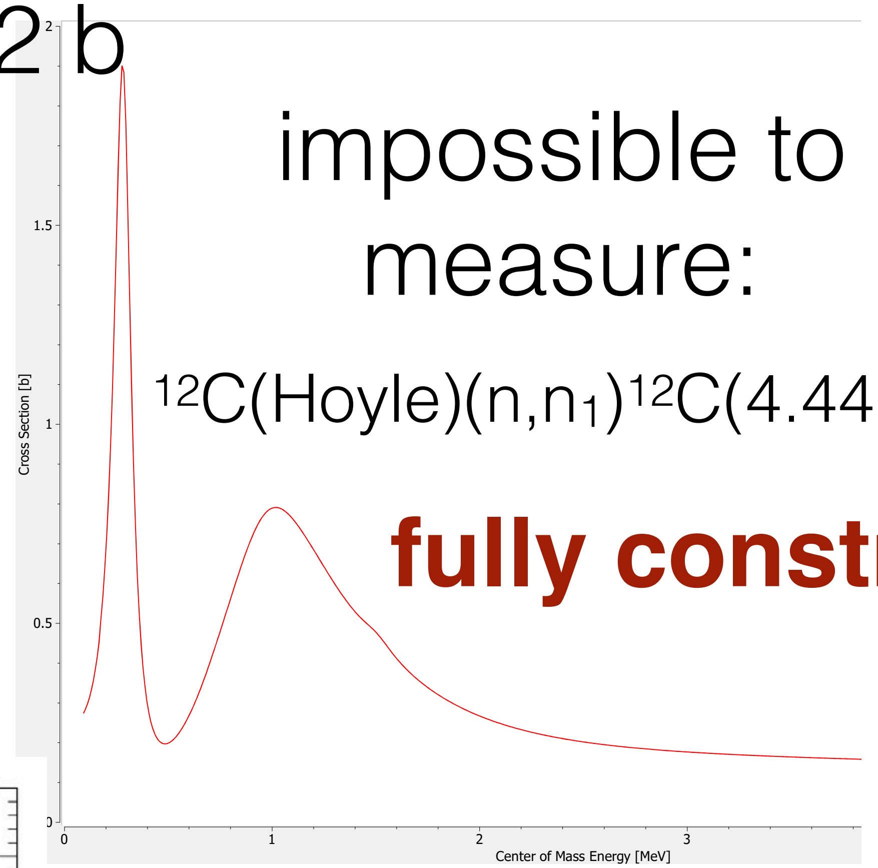
R-matrix analysis





2 b

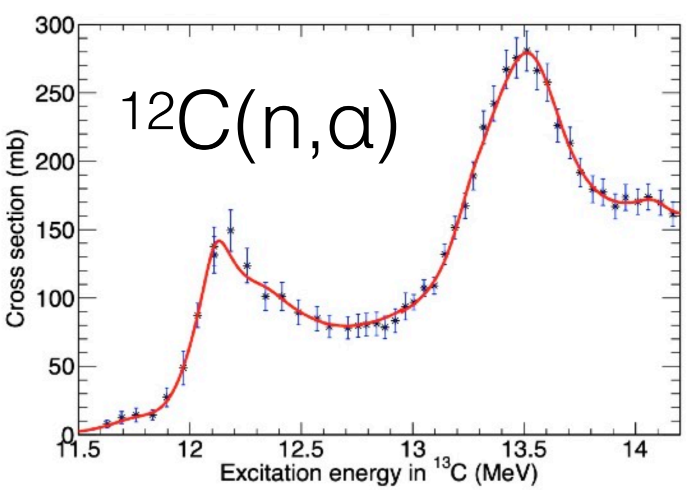
1 b

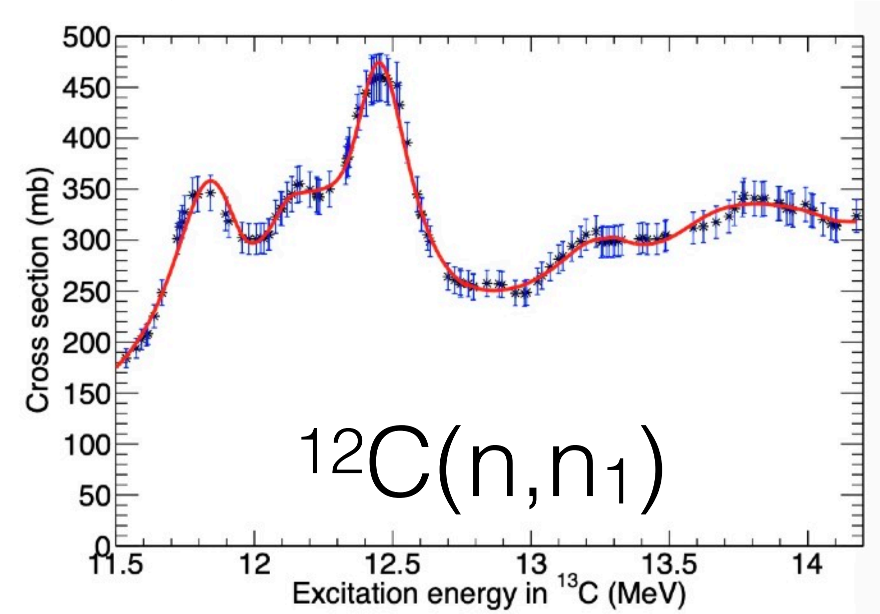


impossible to measure:

$^{12}C(Hoyle)(n,n_1)^{12}C(4.44\ MeV)$

fully constrained





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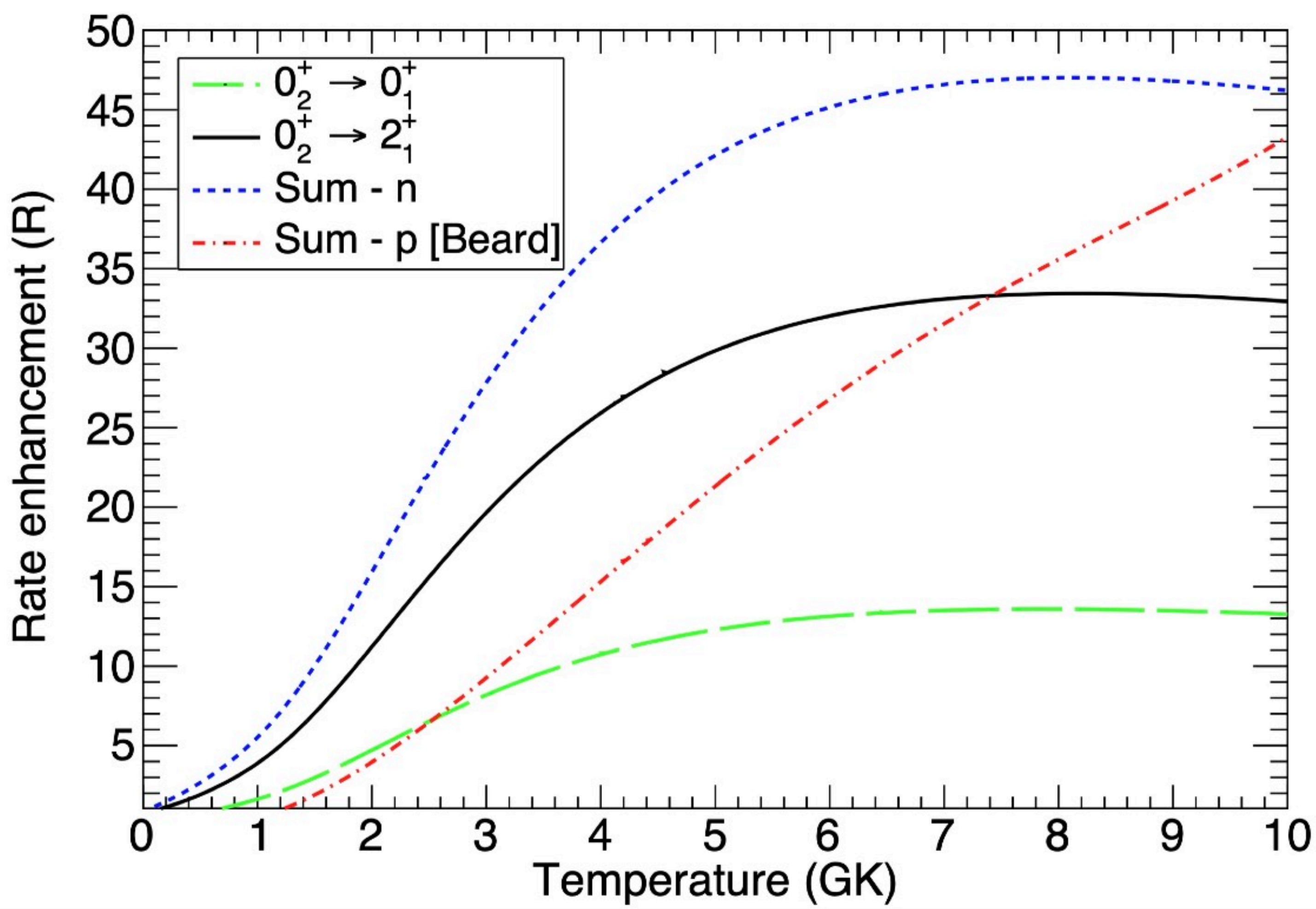
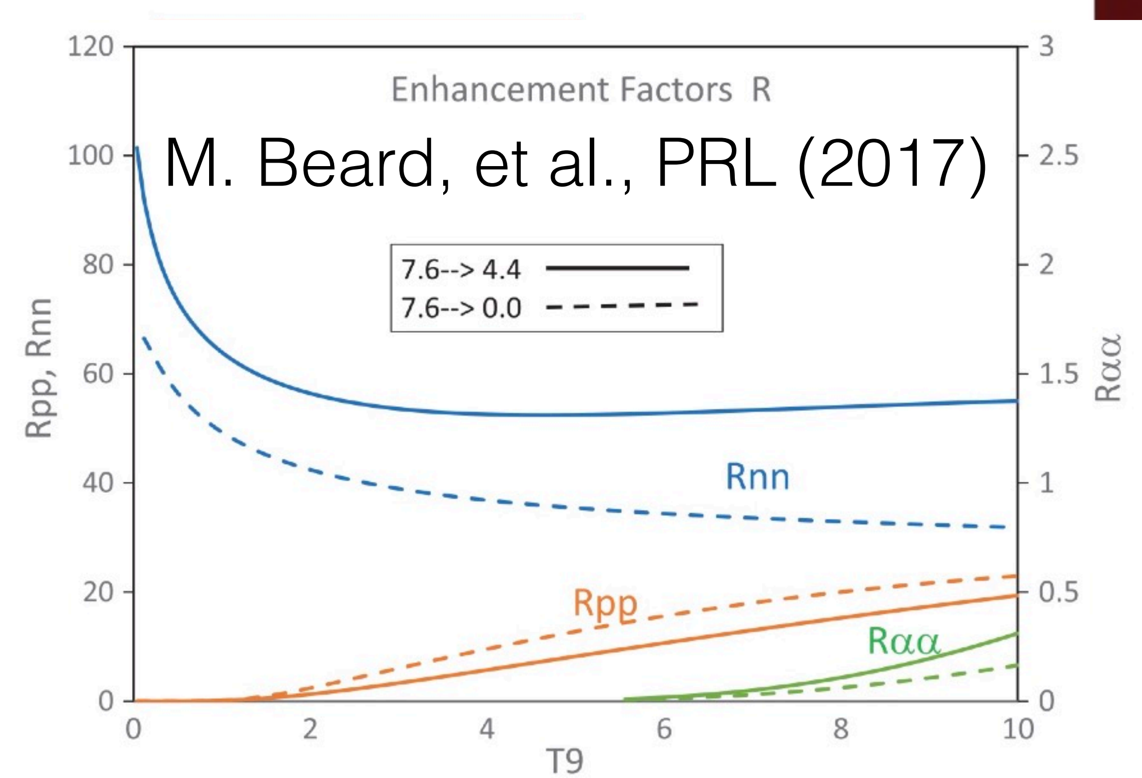
Neutron-upscattering enhancement of the triple-alpha process

J. Bishop ✉, C. E. Parker, G. V. Rogachev, S. Ahn, E. Koshchiy, K. Brandenburg, C. R. Brune, R. J. Charity, J. Derkin, N. Dronchi, G. Hamad, Y. Jones-Alberty, Tz. Kokalova, T. N. Massey, Z. Meisel, E. V. Ohstrom, S. N. Paneru, E. C. Pollacco, M. Saxena, N. Singh, R. Smith, L. G. Sobotka, D. Soltesz, S. K. Subedi, A. V. Voinov, J. Warren & C. Wheldon — Show fewer authors





21/22

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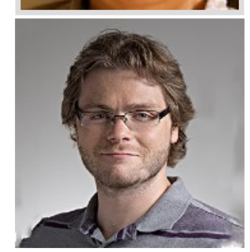
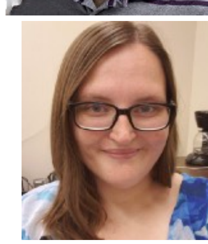







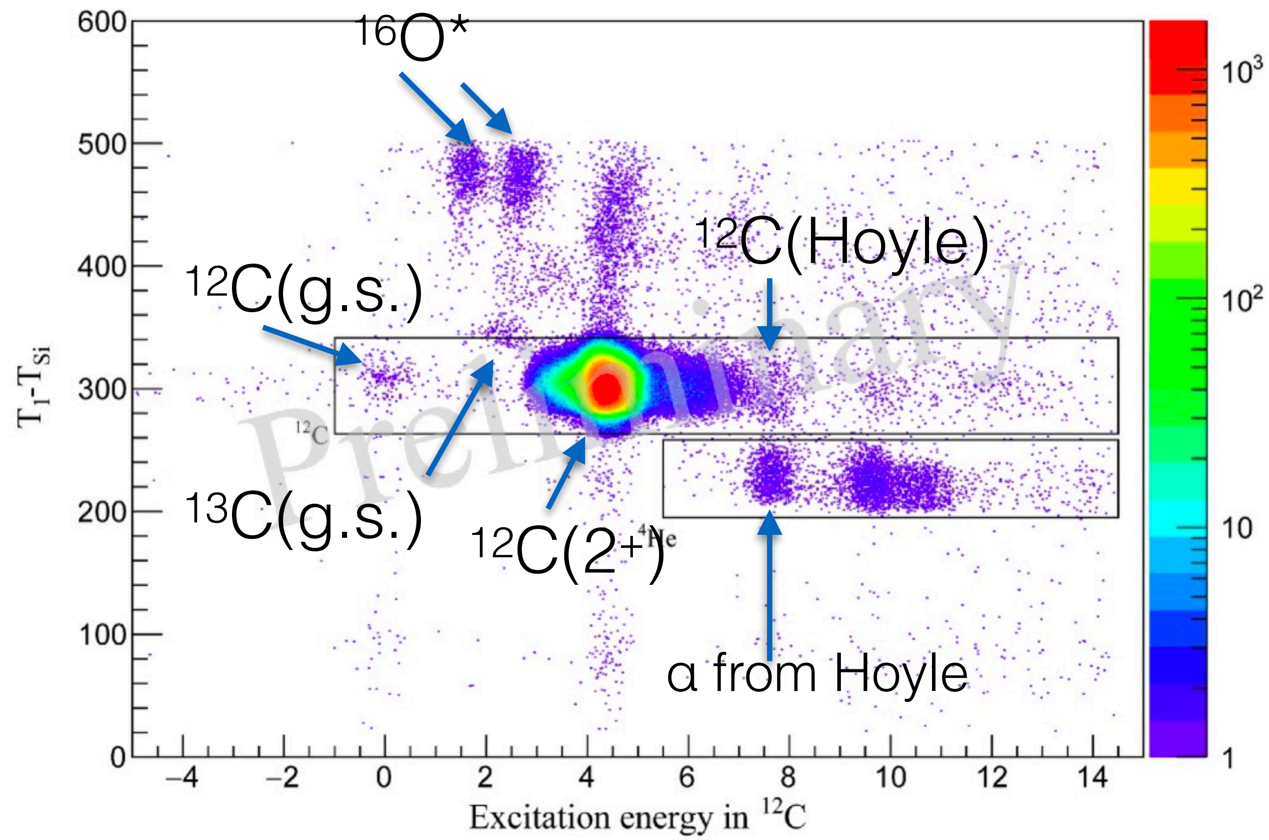


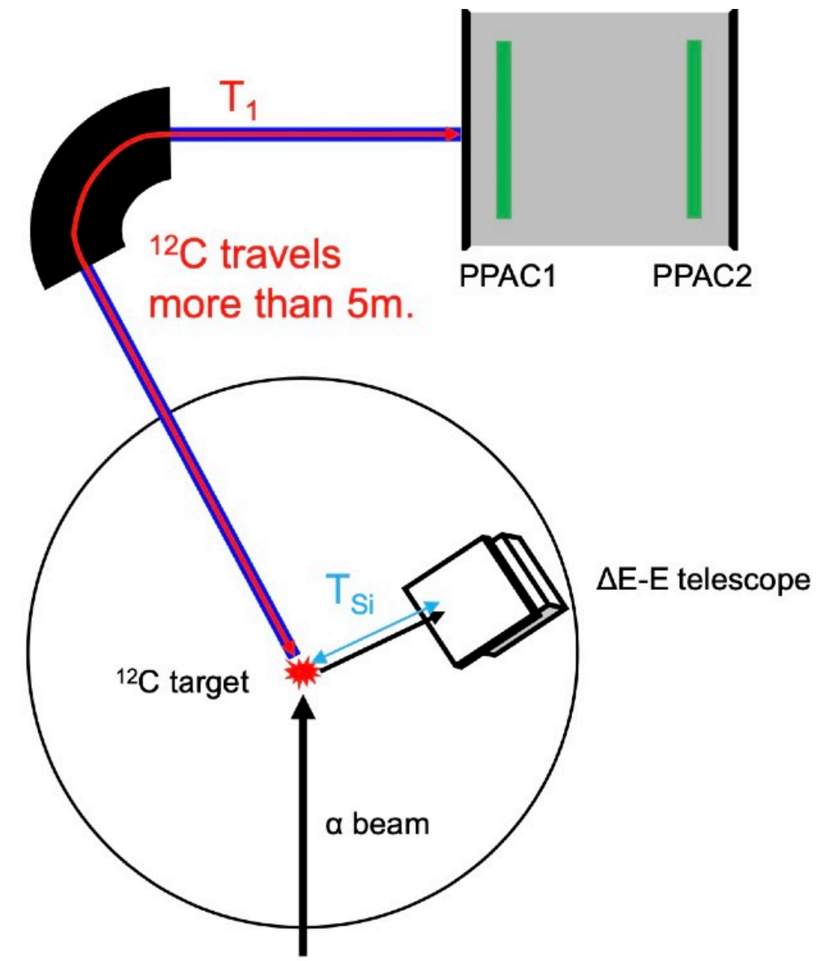
Summary

- Indirect methods are essential in nuclear astrophysics
- Major discrepancy between direct and indirect methods for the $^{22}Ne(\alpha,n)$ reaction
- The radiative width of the Hoyle state is well constrained - no problem there.
- Neutron upscattering on Hoyle is well-constrained now and is not as important in carbon nucleosynthesis as was suggested previously.


GIG EM
AGGIES

Hoyle Γ_{rad} / Γ BR experiment





Zifeng Luo
TAMU graduate student

Recommended paper on the topic:

nature

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Article | Published: 02 December 2020

Enhanced triple-α reaction reduces proton-rich nucleosynthesis in supernovae

Shilun Jin, Luke F. Roberts, Sam M. Austin & Hendrik Schatz

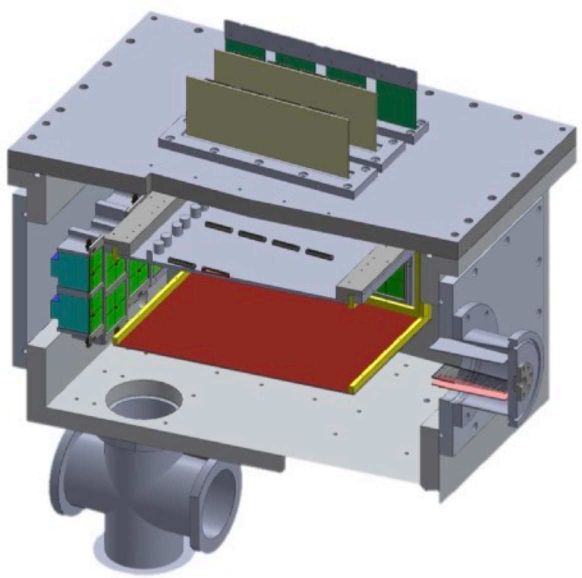
Nature **588**, 57–60 (2020) | Cite this article

TPCs and neutron beams

TPCs can be well-suited to many different types of neutron-induced measurements

Active-target (gas IS the target and readout medium) TPC filled with CO_2 looking to measure:

- $^{12}\mathrm{C}(n, n_2)3\alpha$ - inelastic neutron scattering to the Hoyle state
- $^{12/16}\mathrm{C}/\mathrm{O}(n, \alpha)$ - hugely important reactions for nuclear data measured parasitically



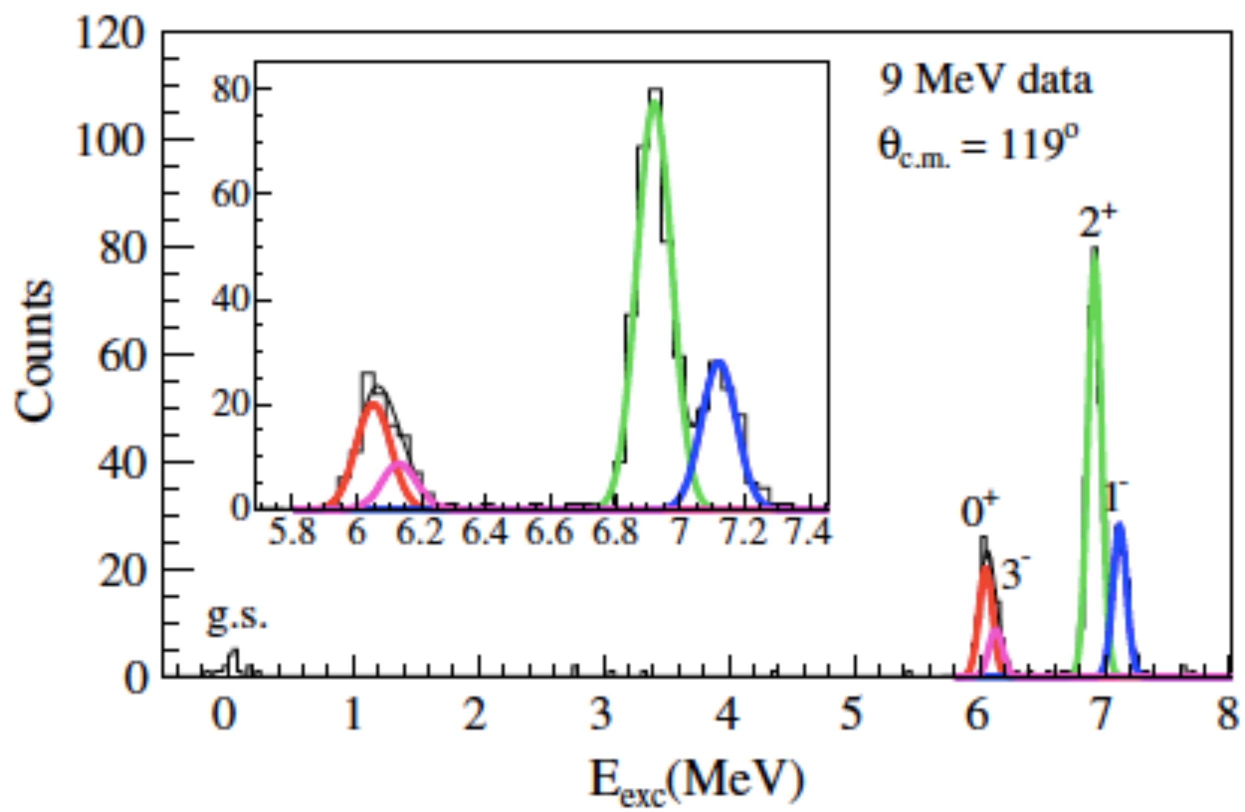
Can be measured with the TexAT with 50 Torr CO_2 gas. Represents a great opportunity for future measurements with low-energy recoil products - can be well resolved using low pressure TPC.

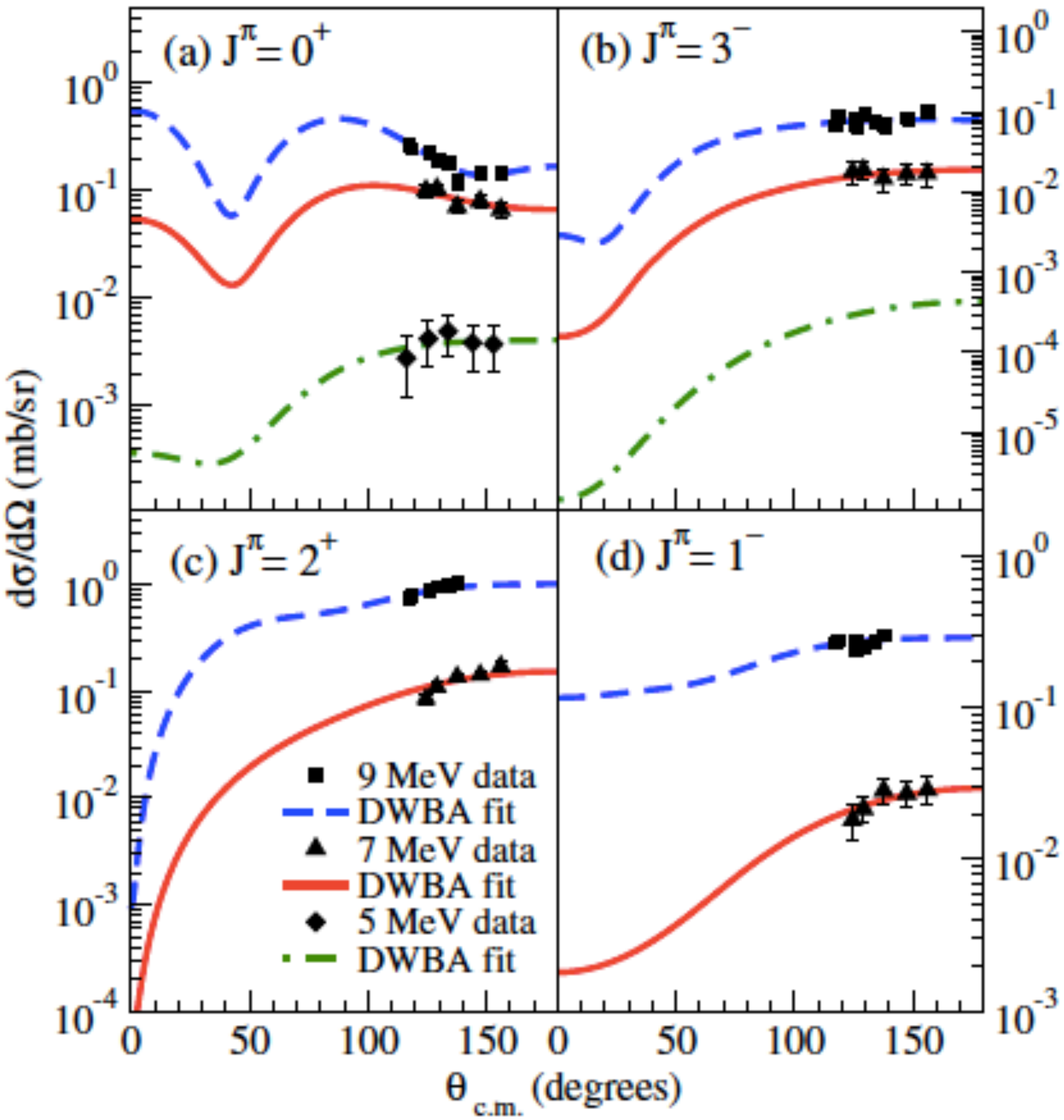
TexAT "Hoyle" Publications

- J. Bishop, et al., NIM A964 (2020) 163773.
- J. Bishop, et al., PRC 102 (2020) 041303.
- J. Bishop, et al., PRC Letter 103 (2021) L051303.
- J. Bishop, et al., Nature Communication 13 (2022) 2151

ANCs for $^{12}C(\alpha,\gamma)$ reaction

- ☑ Spectrum of deuterons from sub-Coulomb $^{6}Li(^{12}C,d)$ reaction. The total energy of the ^{12}C beam is 9 MeV.
- ☑ Angular distributions





M.L. Avila, GVR, E. Koshchiy, et al., Phys. Rev. Lett. **114**, 071101 (2015).

ANCs for $^{12}C(\alpha,\gamma)$ reaction

- ANC of all sub-threshold states in ^{16}O

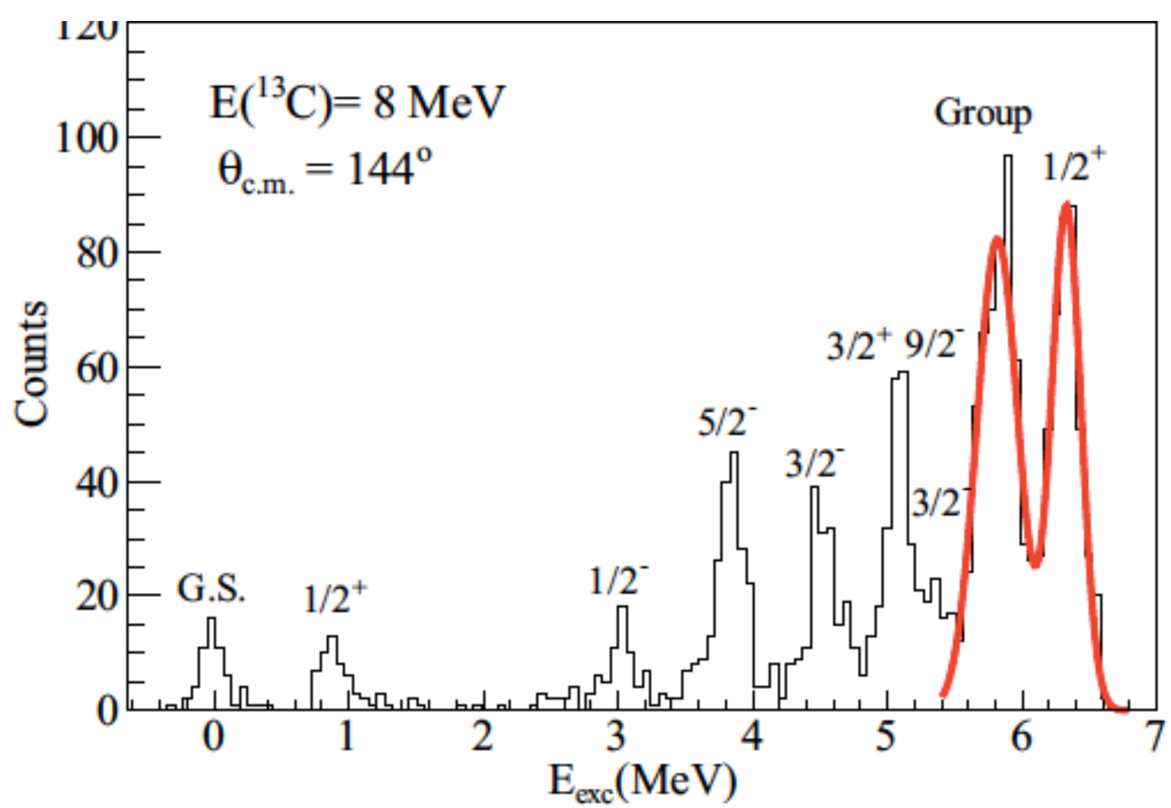
$(C^{^{16}O(0^+)}_{\alpha-^{12}C})^2$ (10^6 fm^{-1})	$(C^{^{16}O(3^-)}_{\alpha-^{12}C})^2$ (10^4 fm^{-1})	$(C^{^{16}O(2^+)}_{\alpha-^{12}C})^2$ (10^{10} fm^{-1})	$(C^{^{16}O(1^-)}_{\alpha-^{12}C})^2$ (10^{28} fm^{-1})	Ref.
...	...	2.07 ± 0.80	4.00 ± 1.38	[1]
...	...	1.29 ± 0.23	4.33 ± 0.84	[2]
...	...	$1.96^{+1.41}_{-1.27}$	3.48 ± 2.0	[3]
2.43 ± 0.30	1.93 ± 0.25	1.48 ± 0.16	4.39 ± 0.59	This work

[1] N. Oulebsir, F. Hammache, P. Roussel, et al., Phys. Rev. C **85**, 035804 (2012).
[2] C. Brune, W.H. Geist, R.W. Kavanagh, et al., Phys. Rev. Lett. **83**, 4025 (1999).
[3] A. Belhout, S. Ouichaoui, H. Beaumevieille, et al., Nucl. Phys. A **793**, 178 (2007).

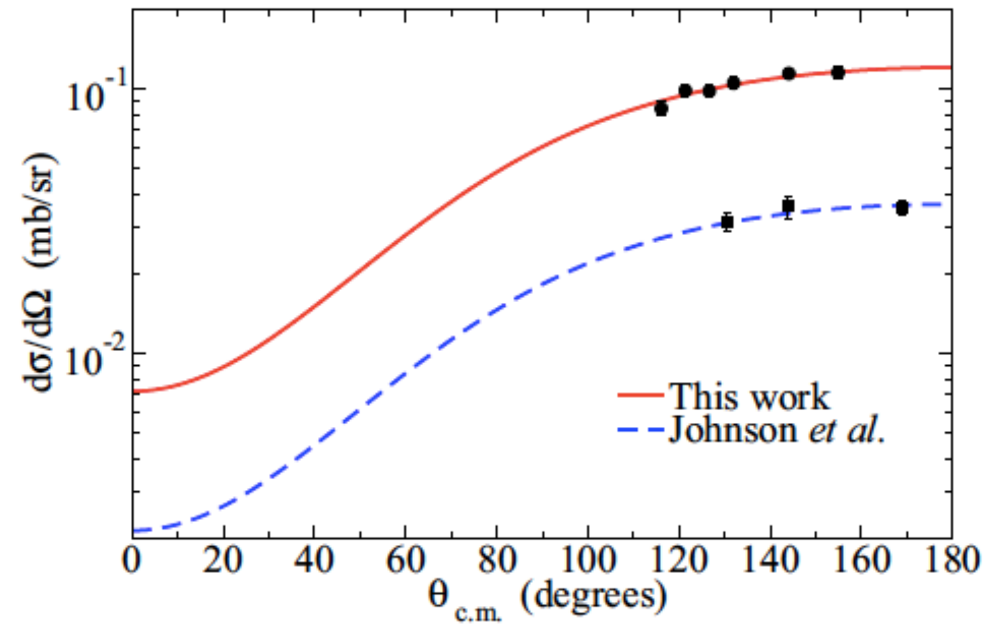
This work: M.L. Avila, GVR, E. Koshchiy, et al., Phys. Rev. Lett. **114**, 071101 (2015).

The ^{6}Li(^{13}C,d) reaction at sub-Coulomb energy

- Spectrum of deuterons from ^{6}Li(^{13}C,d) reaction. Total energy of the ^{13}C beam is 8 MeV.

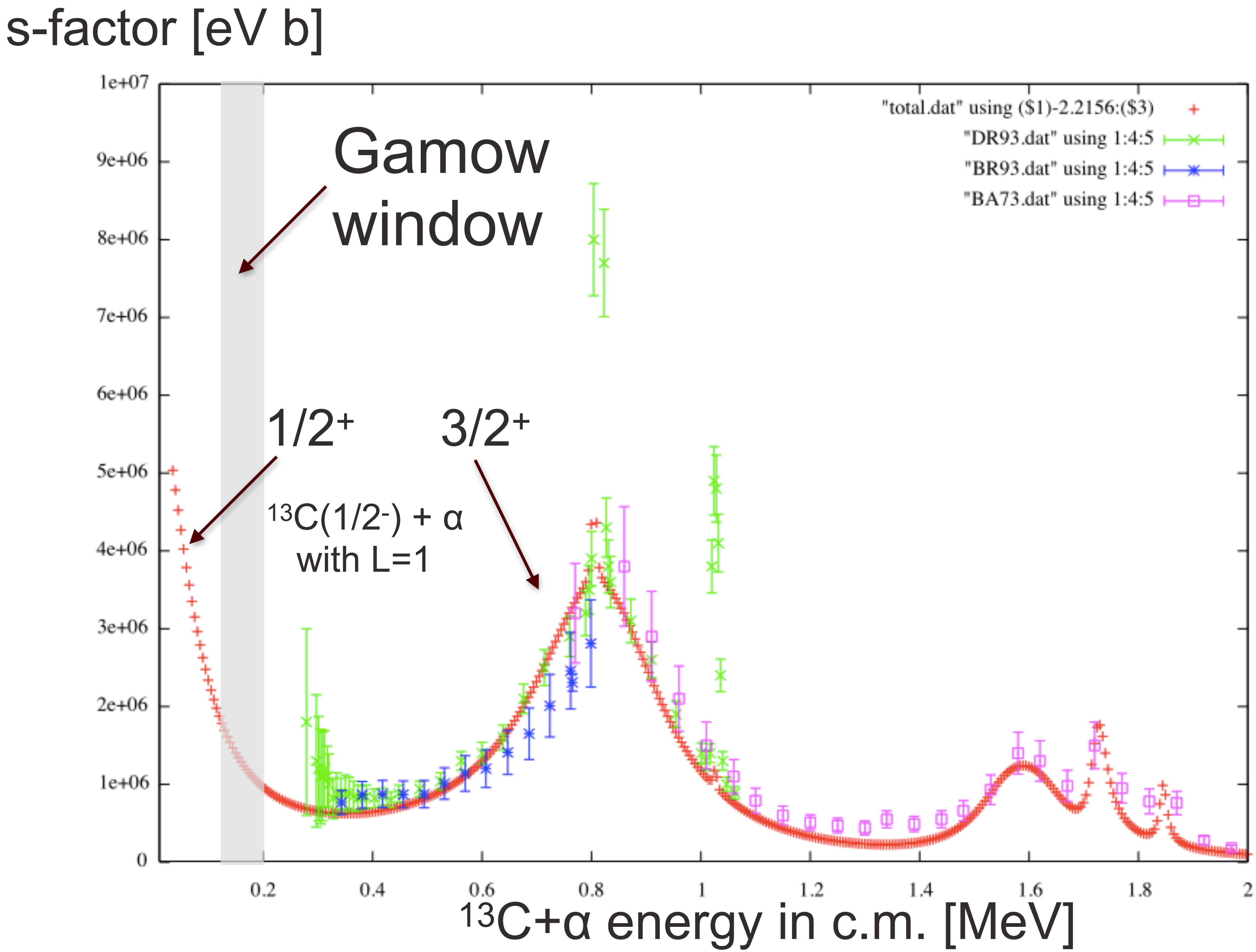


- Angular distribution

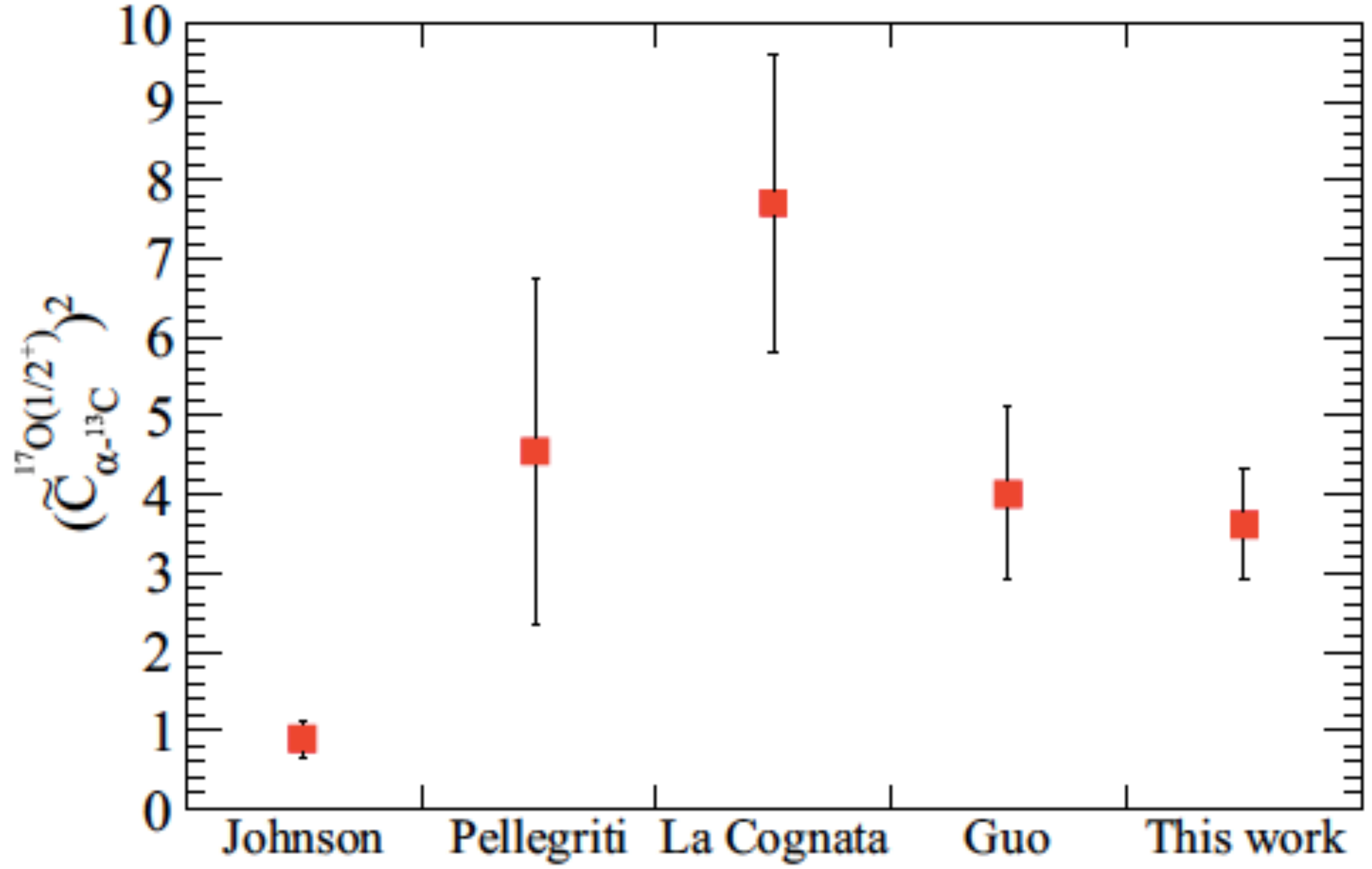


M.L. Avila, GVR, E. Koshchiy, et al., Phys. Rev. C **91**, 048801 (2015).

The s-factor for the $^{13}C(\alpha,n)$



α - ANC for the 1/2$^+$ state at 6.356 MeV in ^{17}O.



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M.G. Pellegriti, F. Hammache, P. Roussel, et al., Phys. Rev. C 77, 042801 (2008).
M. LaGognata, C. Spitaleri, O. Trippella, et al., Phys. Rev. Lett. 109, 232701 (2012).
B. Guo, Z.H. Li, M. Lugaro, et al., Astrophys. J 756, 193 (2012).