Constraining the key α-capture astrophysical reaction rates using the sub-Coulomb α-transfer reactions

Grigory Rogachev

TEXAS A&M UNIVERSITY

Acknowledgements

- ☑ ***Texas A&M University:*** E. Koshchiy, E. Uberseder, A. Mukhamedzhanov, A. Kock.
- ☑ ***Florida State University:*** A.N. Kuchera*, **M.L. Avila****, D. Santiago-Gonzales***, L.T. Baby, J. Belarge, K.W. Kemper.

* Present affiliation ***NSCL, Michigan State University***
** Present affiliation ***Argonne National Laboratory***
*** Present affiliation ***Louisiana State University***

Outline

- ANC from Sub-Coulomb α-transfer reaction
- Benchmark measurements
- Cascade transitions in $^{12}C(\alpha,\gamma)$
- The neutron source for s-process - $^{13}C(\alpha,n)$

M.L. Avila, GVR, E. Koshchiy, et al., Phys. Rev. C **90**, 042801(R) (2014).
M.L. Avila, GVR, E. Koshchiy, et al., Phys. Rev. Lett. **114**, 071101 (2015).
M.L. Avila, GVR, E. Koshchiy, et al., Phys. Rev. C **91**, 048801 (2015).

Background

- α capture reactions play important role in astrophysics.
- Direct measurements at Gamow energies are not possible because cross section is small due to Coulomb barrier.
- Extrapolations from direct measurements at higher energies often can poorly constrain the contribution from near α-threshold resonances
- Model independent indirect method to determine the contribution from near α-threshold resonances is highly desirable

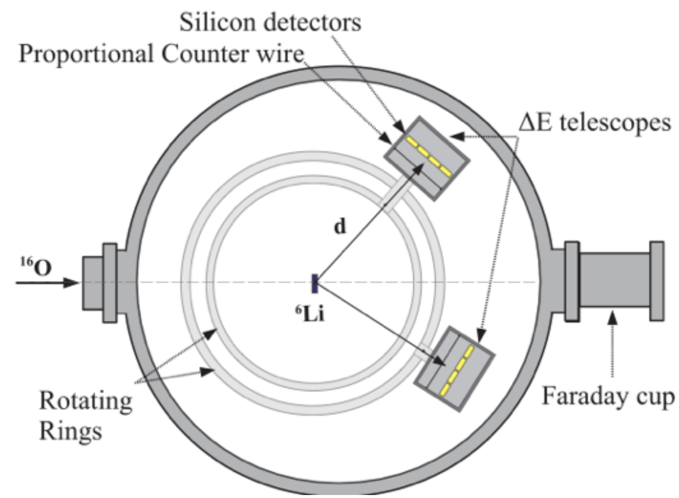
Method

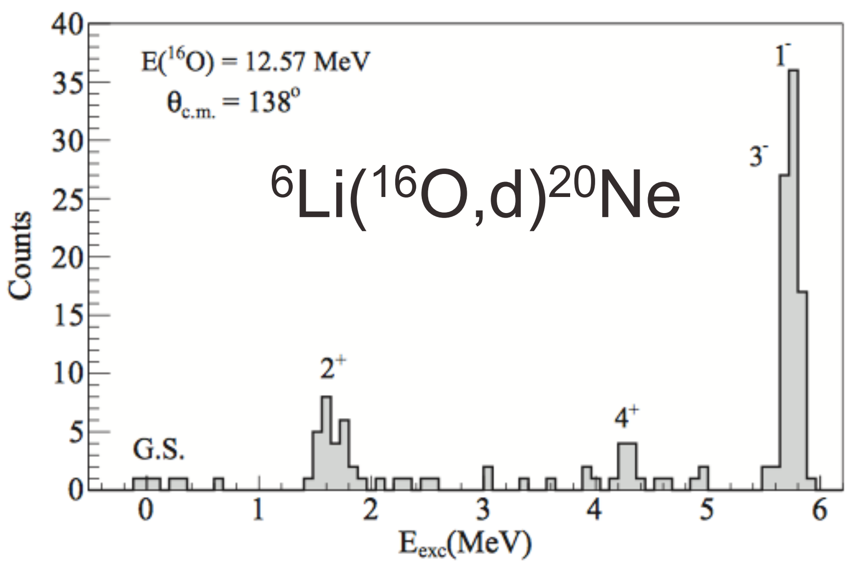
- Perform (^{6}Li,d) (or (^{7}Li,t)) α-transfer reaction at sub-Coulomb energy for both the exit and entrance channels.
- Extract Asymptotic Normalization Coefficients (ANC) instead of SF factors
- Sub-Coulomb energy eliminates dependance of the result on optical model parameters of the DWBA calculations
- ANC does not depend on the shape of the form- factors or the number of nodes in the cluster wave function
- There is a direct relation between contribution of the specific state to the α-capture reaction and its ANC

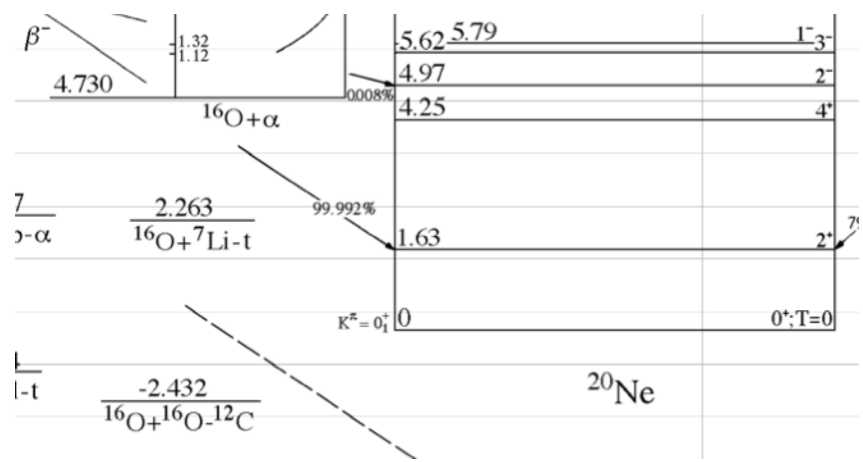
[C. Brune, et al., Phys. Rev. Lett. **83**, 4025 (1999)]

Benchmark experiment

- Test the sub-Coulomb α-transfer using the known widths of the 1^- state in ^{20}Ne.



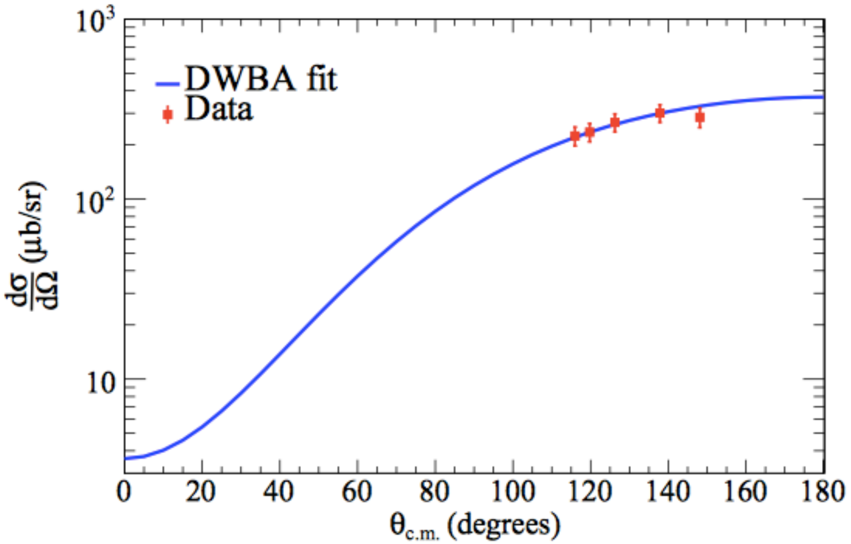


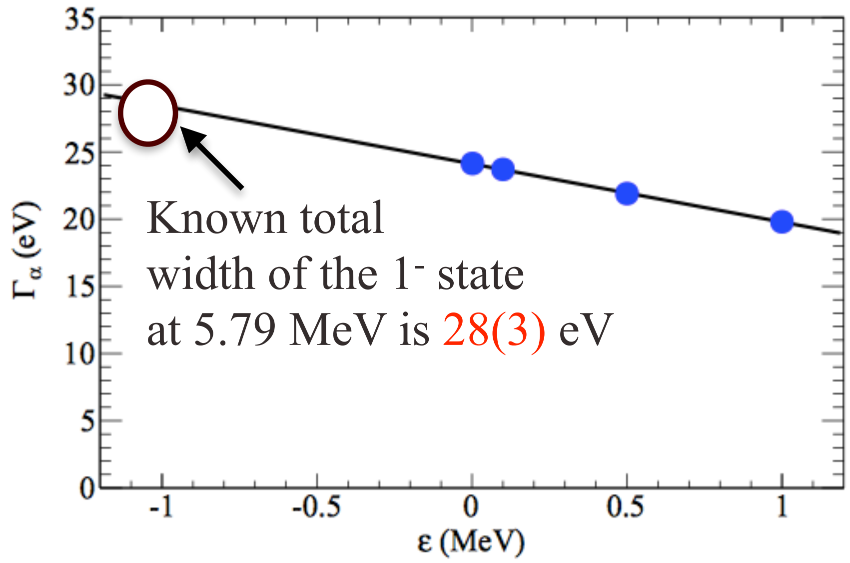


M.L. Avila, GVR, E. Koshchiy, et al., Phys. Rev. C **90**, 042801(R) (2014).

Benchmark experiment

- ☑ Use DWBA to extract the ANC for the 1⁻
- ☑ Calculate its known width from measured ANC.



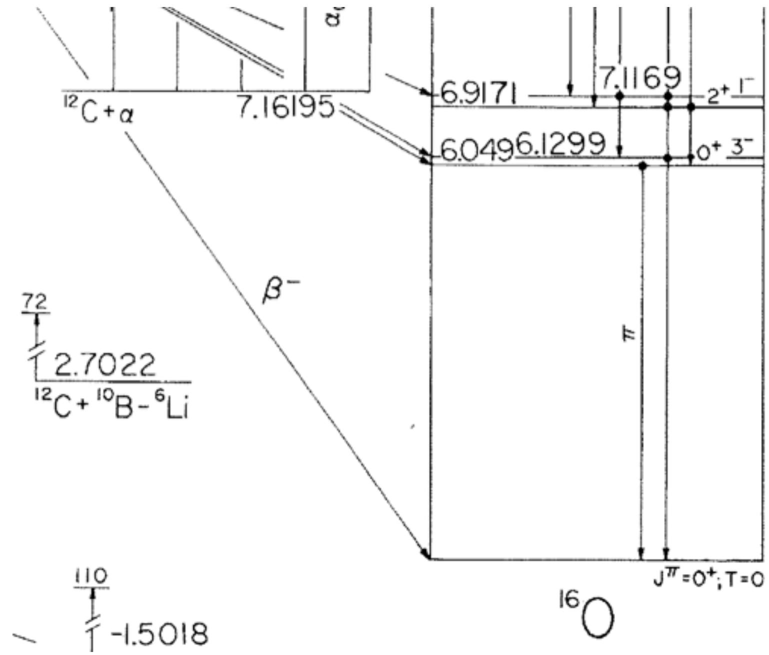


$$\Gamma_\alpha = P_l(kR)\frac{W^2_{-\eta,l+1/2}(2kR)}{\mu R}\left(C^{^{16}O}_{\alpha\,^{12}C}\right)^2,$$

Partial α width of the 1⁻ state determined from ANC is 29(6) eV.

Constraining cascade transitions in $^{12}C(\alpha,\gamma)$ reaction

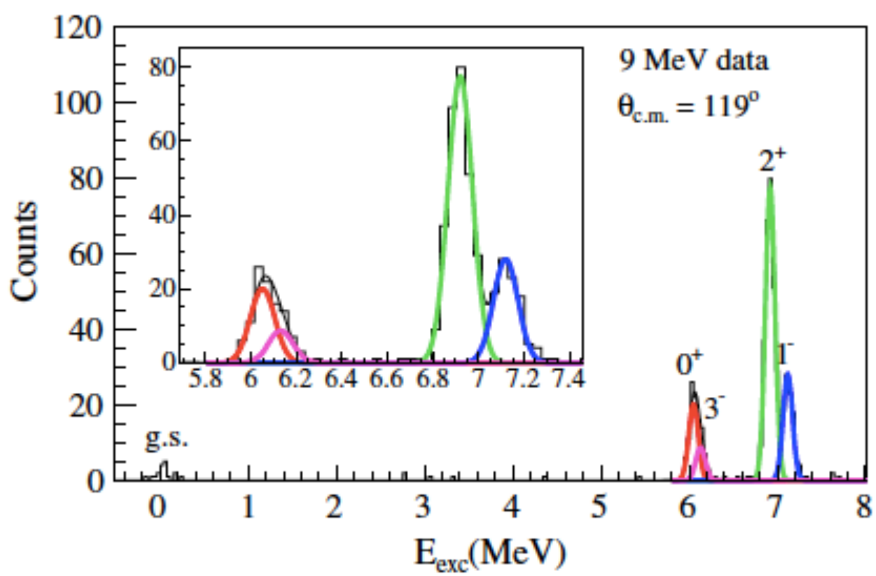
- E2 and E1 transition to the ground state dominate.
- The cascade transitions may contribute as well.
- The contribution of the 0^+ 6.05 MeV transition is uncertain:
  - 25+/-15 keV b (15% of the total) [1]
  - <1 keV b (negligible) [2]



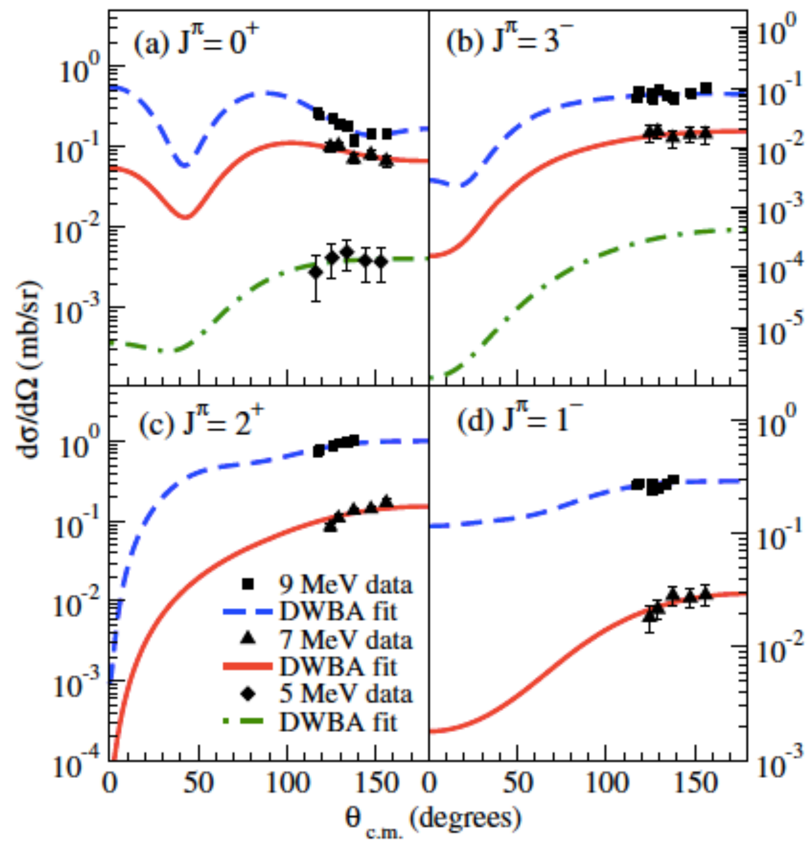
[1] C. Matei, L. Buchmann, W.R. Hannes, et al., Phys. Rev. Lett **97**, 242503 (2006).
[2] D. Schurmann, A.D. Leva, L. Gialanella, et al., Phys. Lett. B **703**, 557 (2011).

Constraining cascade transitions in $^{12}C(\alpha,\gamma)$ reaction

- Spectrum of deuterons from $^{6}Li(^{12}C,d)$ reaction. 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).

Constraining cascade transitions in $^{12}C(\alpha,\gamma)$ reaction

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

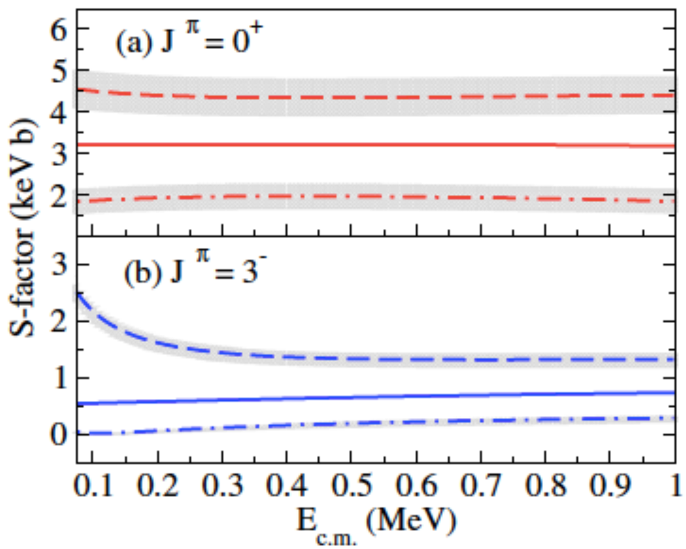
$(C^{^{16}O(0^+)}_{\alpha-^{12}C})^2$ (10^6 fm^{-1})	$(C^{^{16}O(3^-)}_{\alpha-^{12}C})^2$ (10^4 fm^{-1})	$(C^{^{16}O(2^+)}_{\alpha-^{12}C})^2$ (10^{10} fm^{-1})	$(C^{^{16}O(1^-)}_{\alpha-^{12}C})^2$ (10^{28} fm^{-1})	Ref.
...	...	2.07 ± 0.80	4.00 ± 1.38	[1]
...	...	1.29 ± 0.23	4.33 ± 0.84	[2]
...	...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

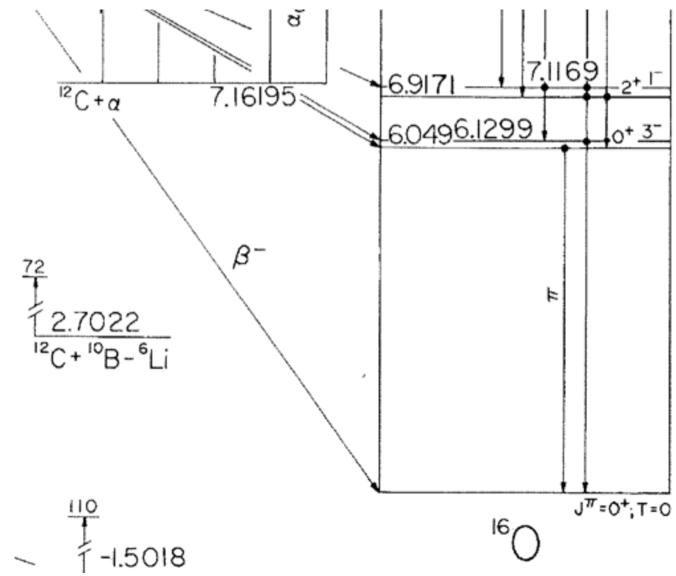
[1] N. Oulebsir, F. Hammache, P. Roussel, et al., Phys. Rev. C **85**, 035804 (2012).
[2] C. Brune, W.H. Geist, R.W. Kavanagh, et al., Phys. Rev. Lett. **83**, 4025 (1999).
[3] A. Belhout, S. Ouichaoui, H. Beaumevieille, et al., Nucl. Phys. A **793**, 178 (2007).

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

Constraining cascade transitions in $^{12}C(\alpha,\gamma)$ reaction

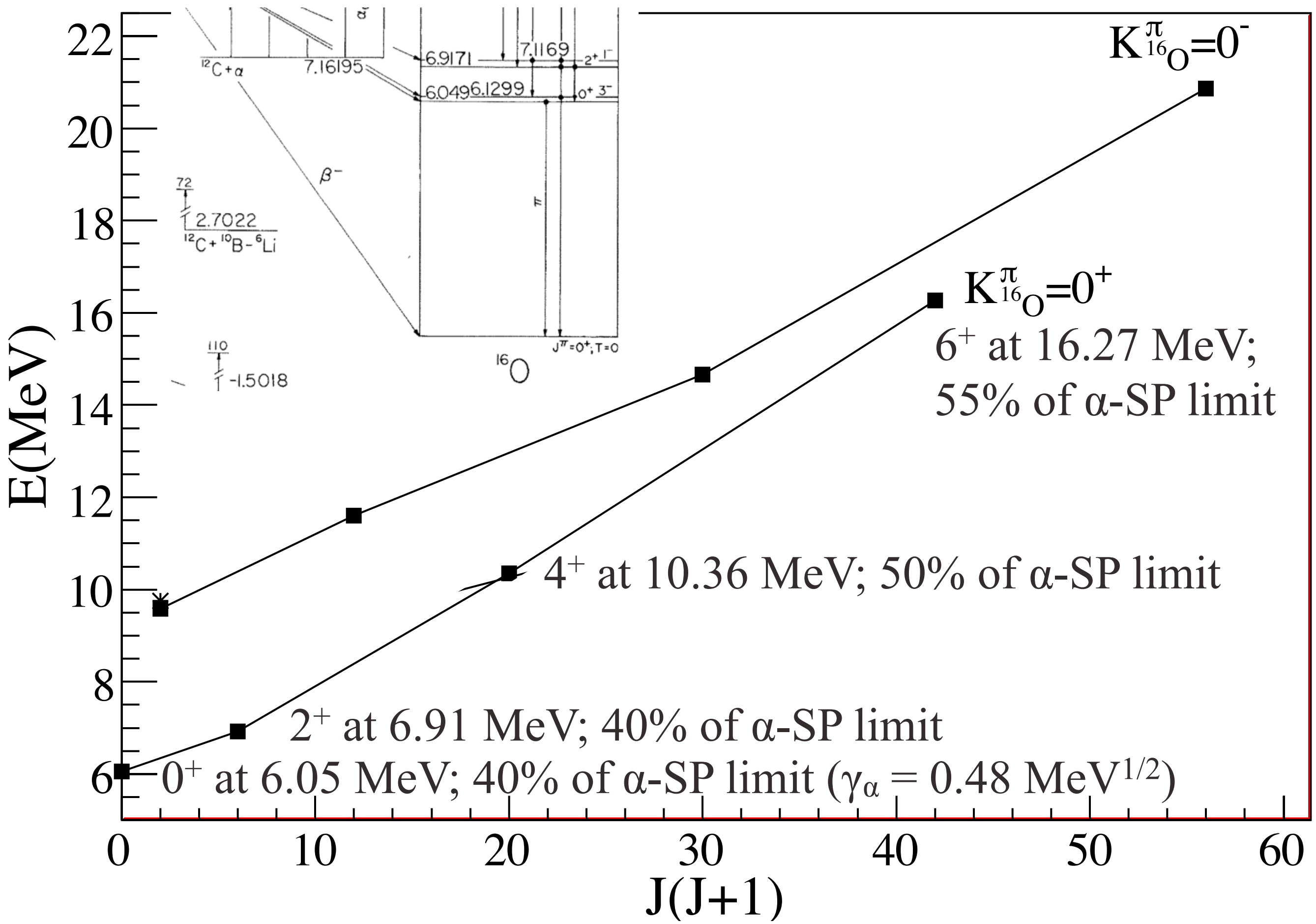
- Direct capture is completely determined by the ANC of the state the α-particle is captured into





- Interference of direct capture with the resonance capture through the tails of the higher lying states is important

The $K^\pi = 0^+$ cluster band in ^{16}O

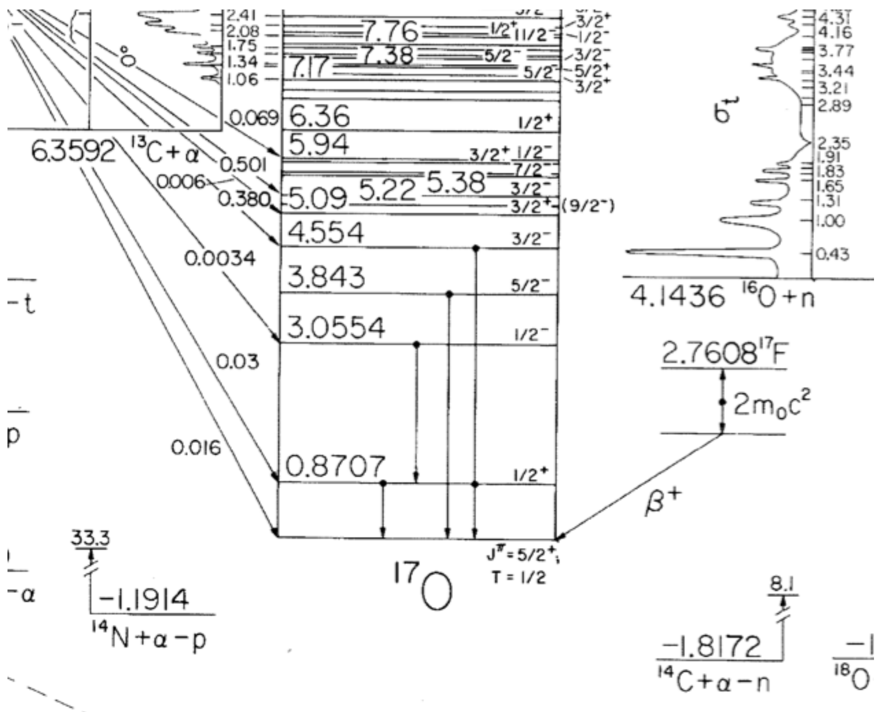


- reduced width is calculated directly from ANC and compared to the α-SP limit
- the γ_α used in [1] for the 0^+ at 6.05 MeV was 0.01 MeV$^{1/2}$

[1] D. Schurmann, A.D. Leva, L. Gialanella, et al., Phys. Lett. B **703**, 557 (2011).

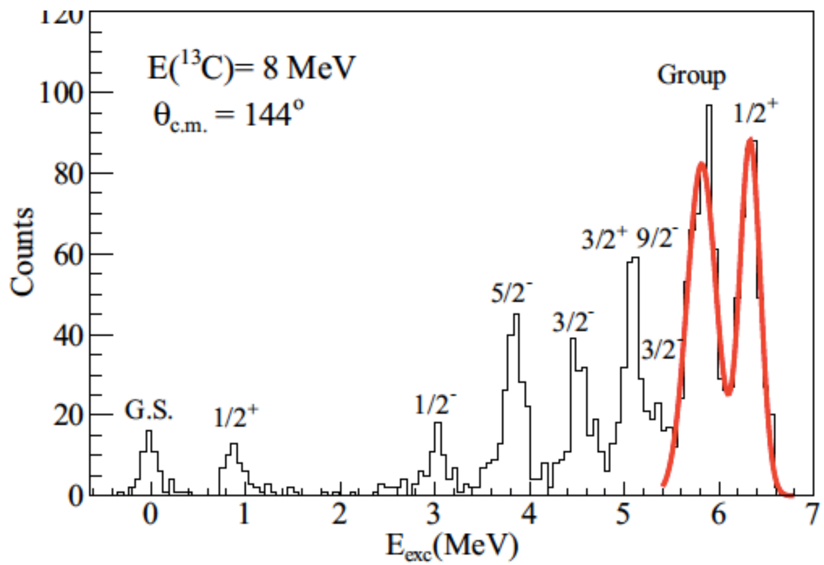
The main neutron source for s-process in AGB stars - $^{13}C(\alpha,n)$ reaction

- $^{13}C(\alpha,n)$ reaction rate has direct influence on final abundances of some s-process isotopes and in some models determines if the ^{60}Fe is produced [S. Cristallo, et al., arXiv:0902.0243v2 (2009)].
- The $^{13}C(\alpha,n)$ cross section at Gamow window is dominated by tails of near α threshold states.

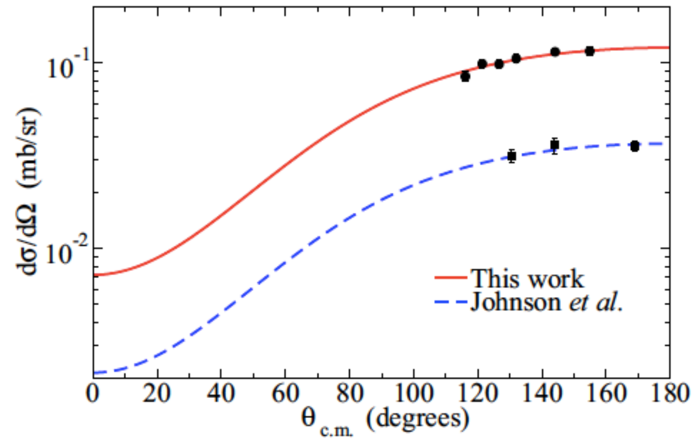


The $^6Li(^{13}C,d)$ reaction at sub-Coulomb energy

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

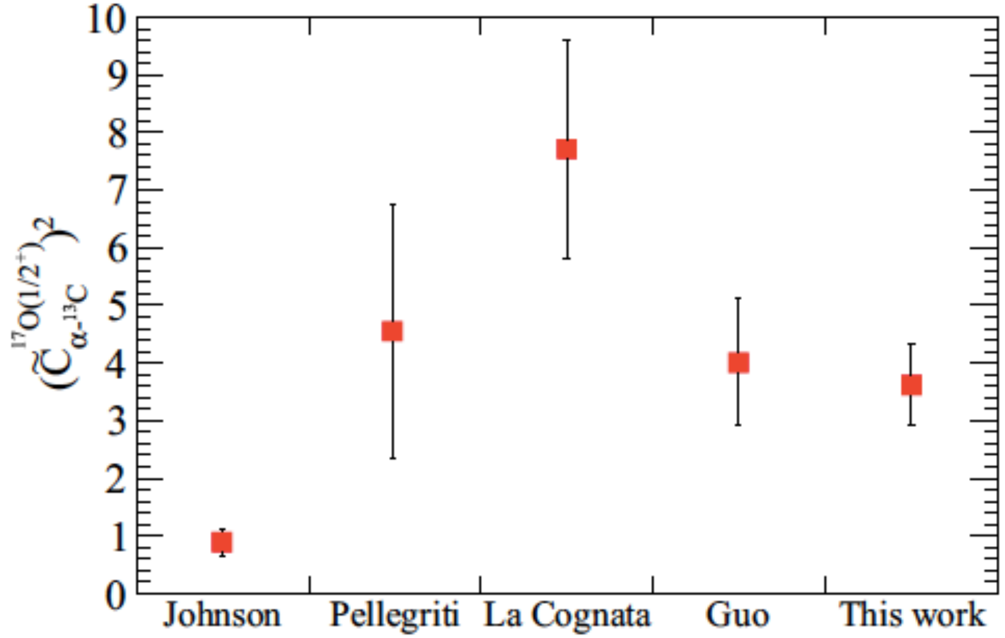


- Angular distribution



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

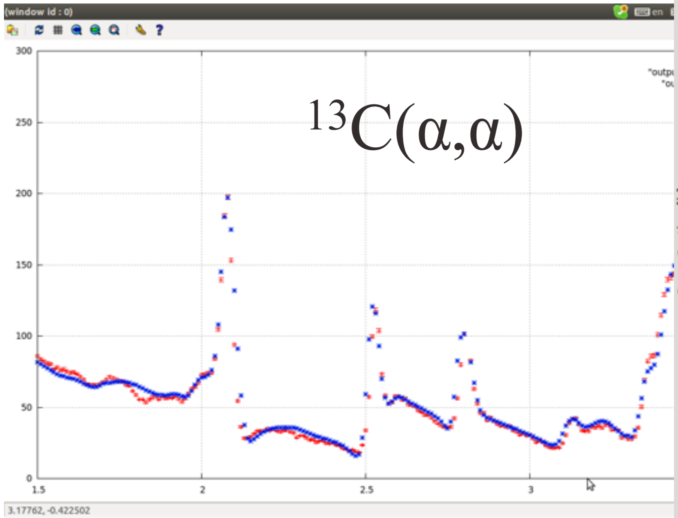
α - ANC for the 1/2$^+$ state at 6.356 MeV in ^{17}O.

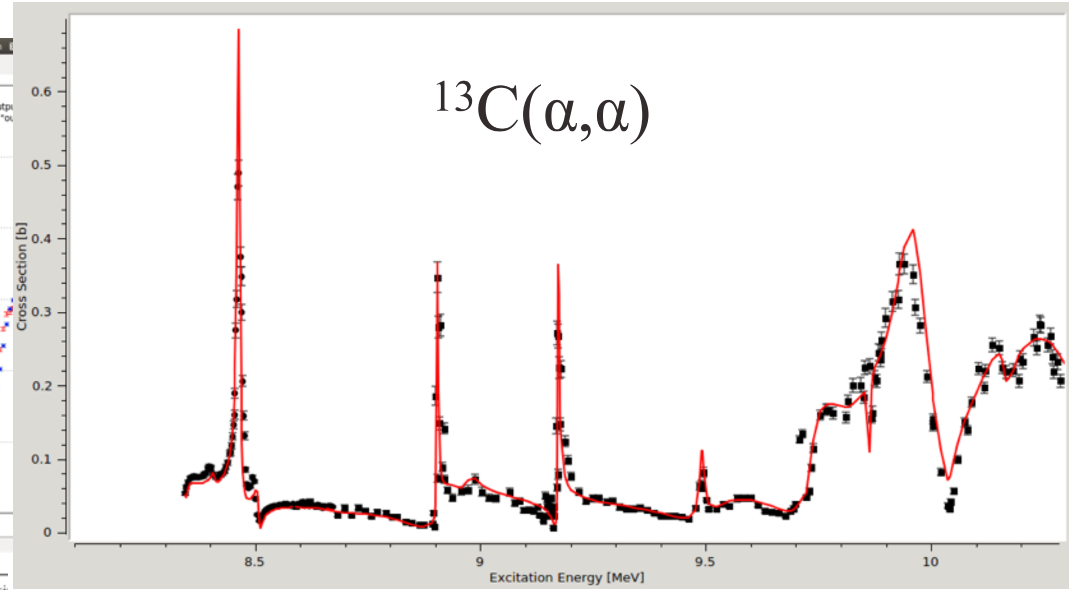


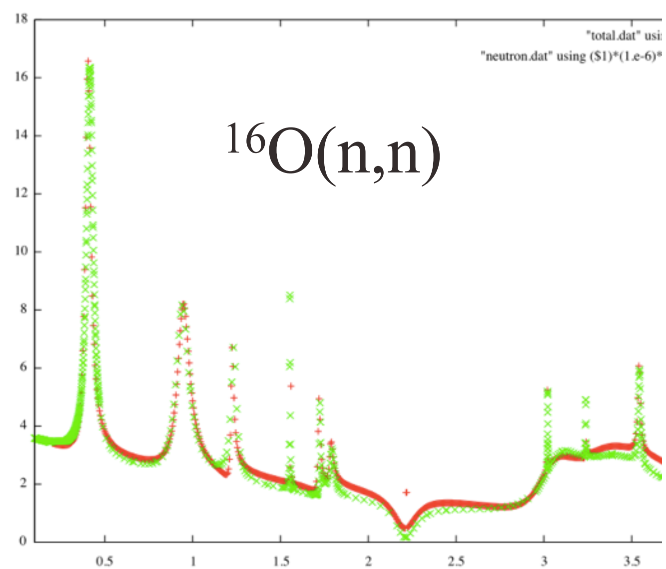
E.D. Johnson, GVR, A.M. Mukhamedzhanov, et al., Phys. Rev. Lett. 97, 192701 (2006).
M.G. Pellegriti, F. Hammache, P. Roussel, et al., Phys. Rev. C 77, 042801 (2008).
M. LaGognata, C. Spitaleri, O. Trippella, et al., Phys. Rev. Lett. 109, 232701 (2012).
B. Guo, Z.H. Li, M. Lugaro, et al., Astrophys. J 756, 193 (2012).

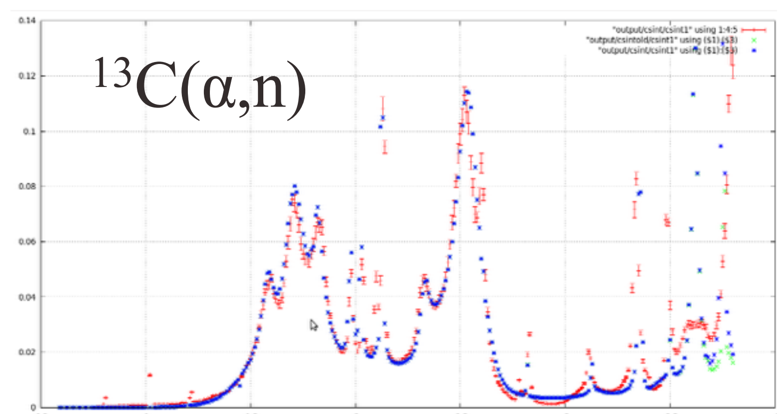
Complete R-matrix fit for ^{17}O

Previous attempt: M. Heil, et al., PRC 78 (2008).

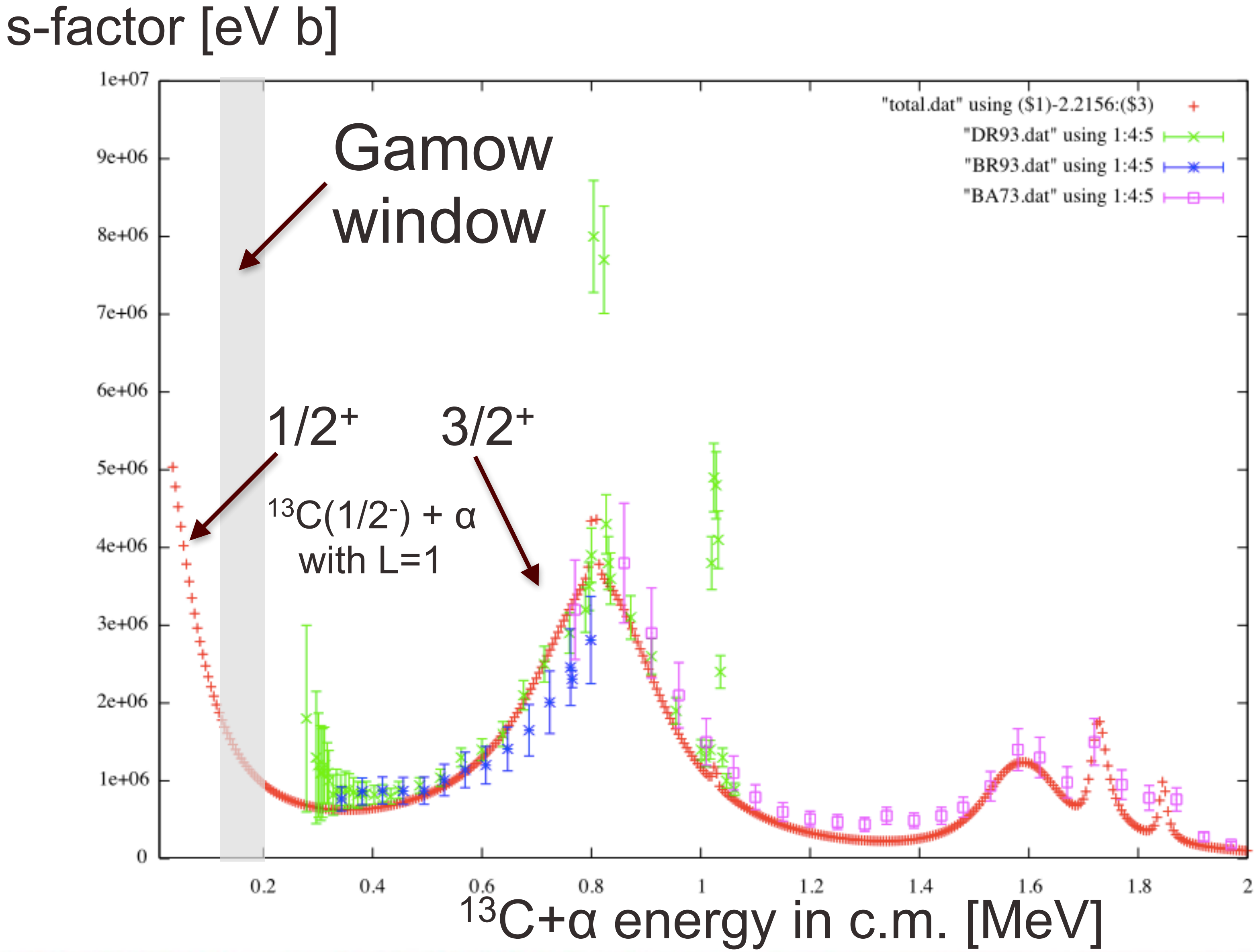




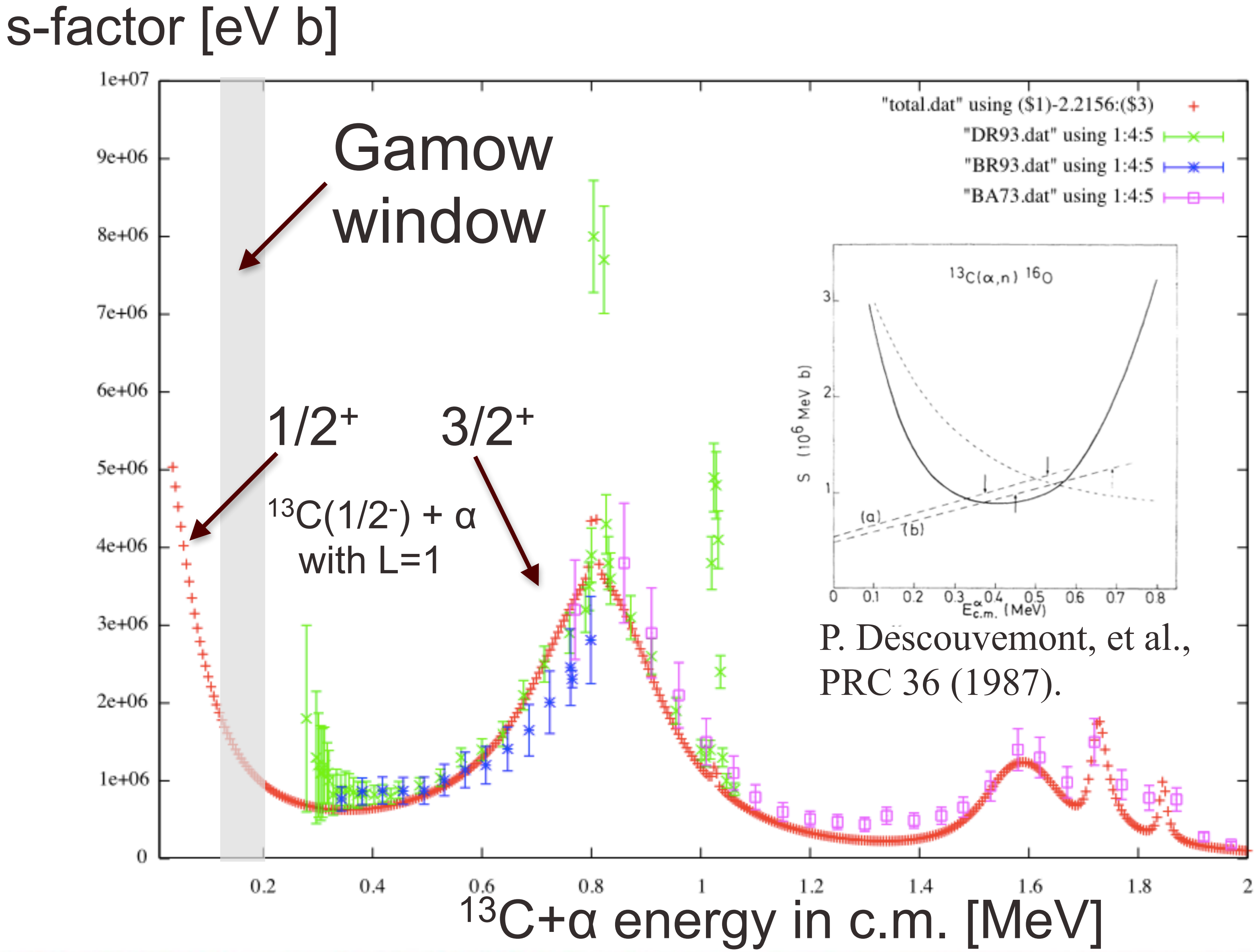




The s-factor for the $^{13}C(\alpha,n)$



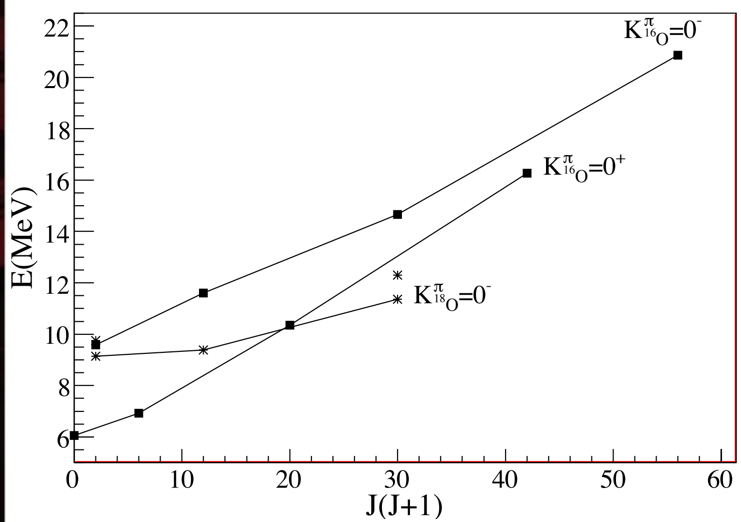
The s-factor for the $^{13}C(\alpha,n)$



P. Descouvemont, et al., PRC 36 (1987).

The $K^{\pi} = 1/2^{+}$ and $1/2^{-}$ cluster band in ^{17}O

- The $K^{\pi}=0^{+}$ and 0^{-} bands in ^{16}O have their analogous $1/2^{-}$ and $1/2^{+}$ bands in ^{17}O.



^{16}O	^{17}O
0^{+} at 6.05 MeV (40%)	$1/2^{-}$ at 3.06 MeV (30%)
	SF from: [M.G. Pellegriti, et al., Phys. Rev. C 77, 042801 (2008).]

^{16}O	^{17}O
1^{-} at 9.5 MeV (100%)	**$1/2^{+}$ at 6.36 MeV (50%)** **$3/2^{+}$ at 7.20 MeV (50%)**
3^{-} at 11.6 MeV (100%)	$5/2^{+}$ at 7.40 MeV (50%) $7/2^{+}$ at 9.70 MeV ???

Summary

- Sub-Coulomb α-transfer reaction provides a model independent way to constrain the astrophysical reaction rates.
- The method was benchmarked against known width of 1^- state at 5.79 MeV in ^{20}Ne.
- **Cascade transitions** (CT) s-factor for **^{12}C(α,γ)** reaction have been constrained. The combined CT contribution **does not exceed 4%** of the total cross section.
- **Uncertainties** of the neutron source for the s-process reaction **^{13}C(α,n)** have been **dramatically reduced**.
- The first three members of the highly clustered rotational band **$K^{\pi}=1/2^+$ are firmly established in ^{17}O**.

THANK YOU!

TEXAS A&M UNIVERSITY

ATM