Clustering in light nuclei, Hoyle state, and Efimov effect

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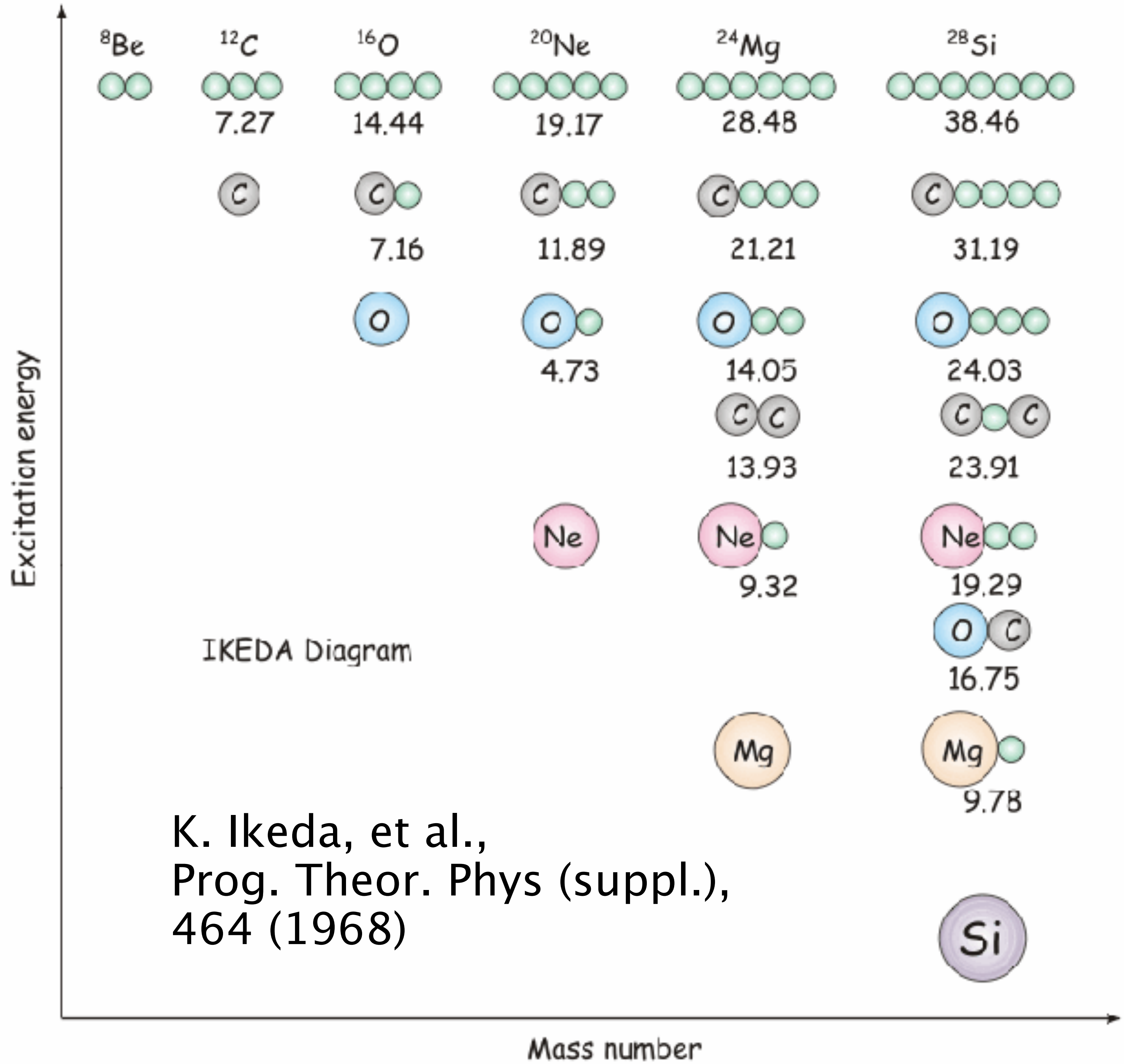
Outline

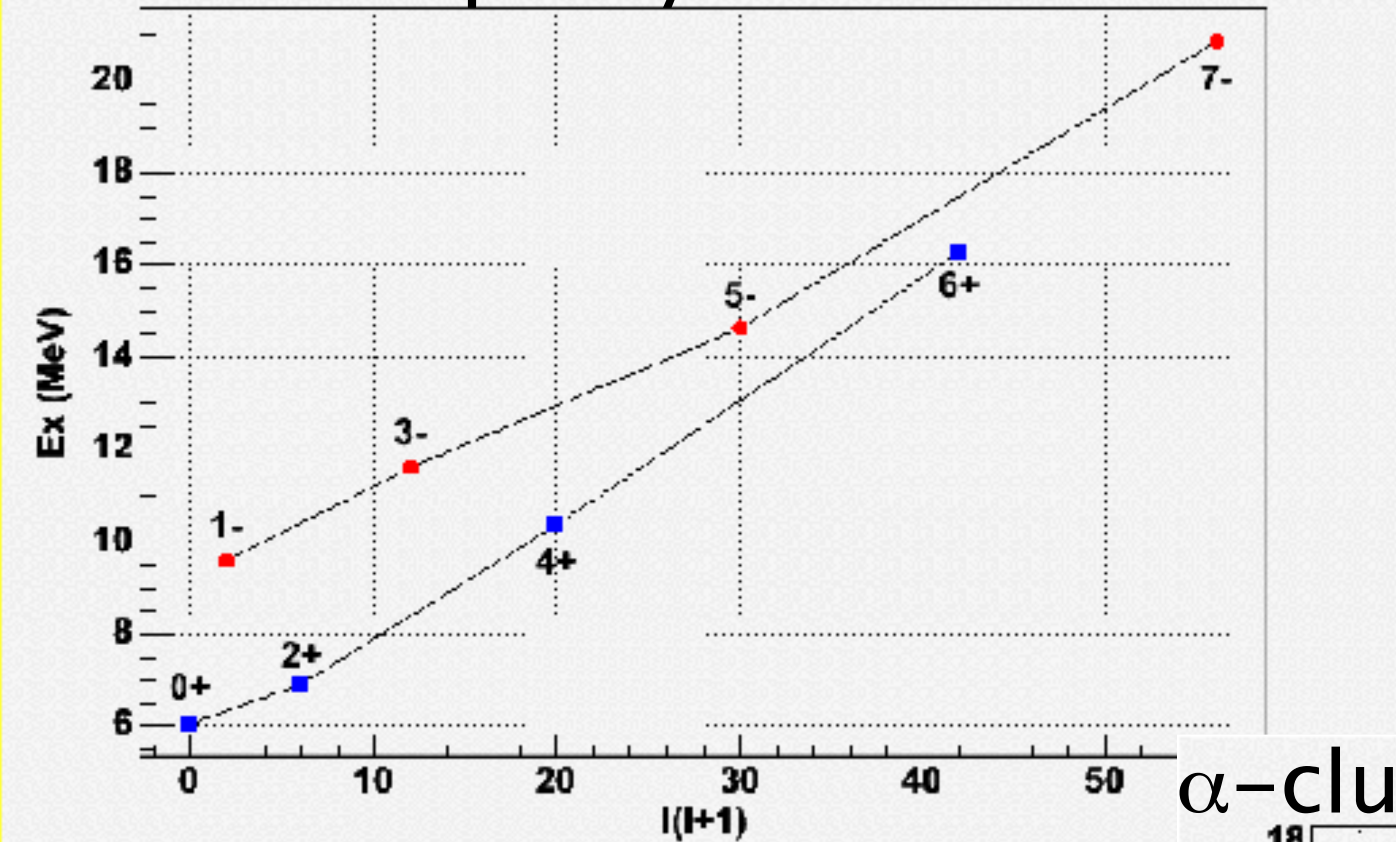
- Cluster structure in light nuclei
- New data on the properties of the Hoyle state
- Search for Efimov effect in ^{12}C



K. Ikeda, et al.,
Prog. Theor. Phys (suppl.),
464 (1968)

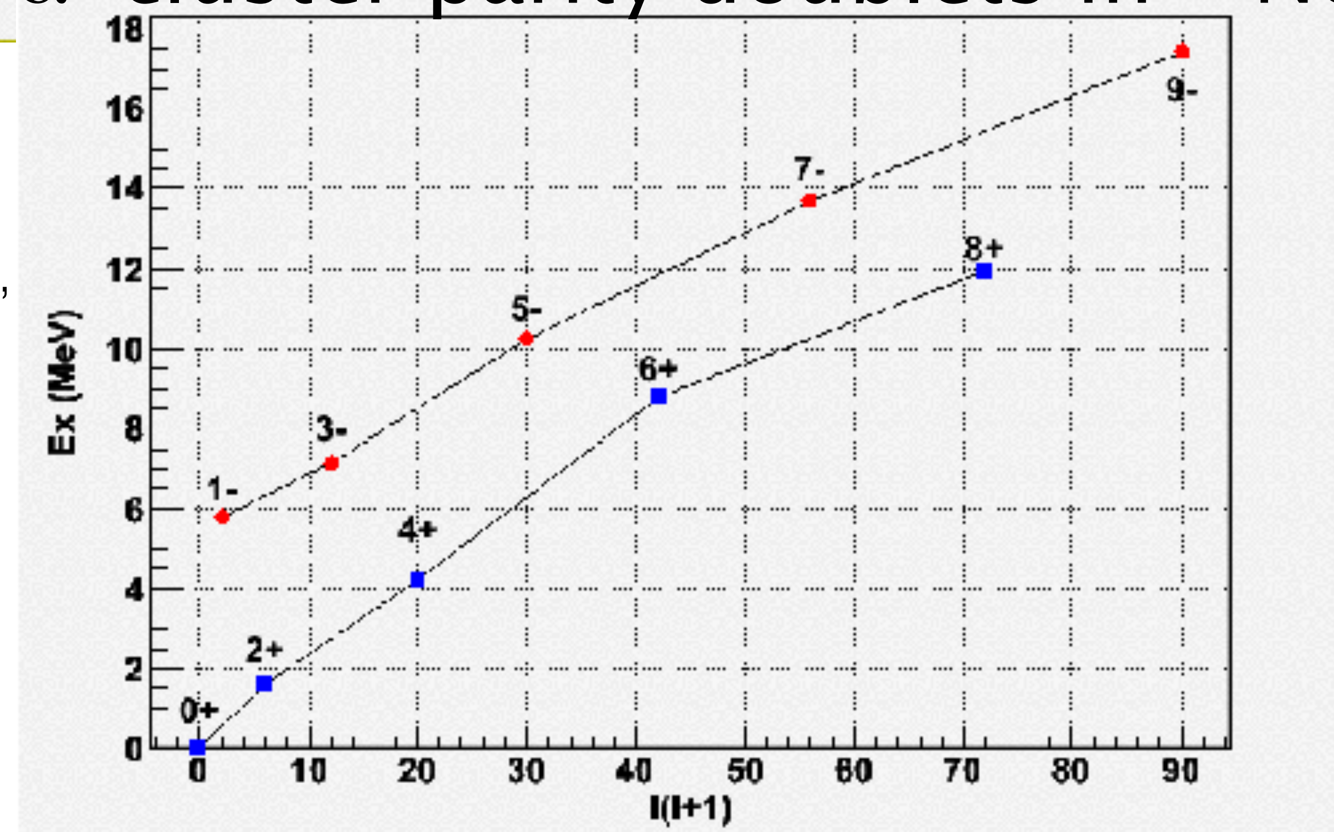
Parity doublets

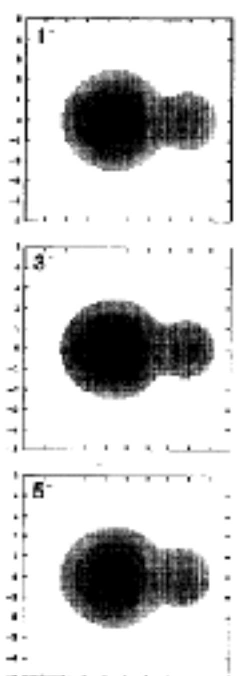
α–cluster parity doublets in ^{16}O



Sequence of states with pronounced α-cluster structure - large reduced alpha width

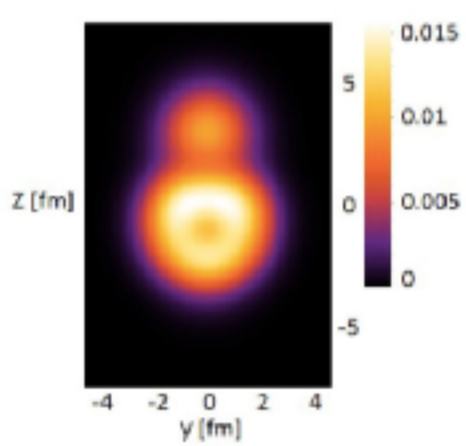
α–cluster parity doublets in ^{20}Ne



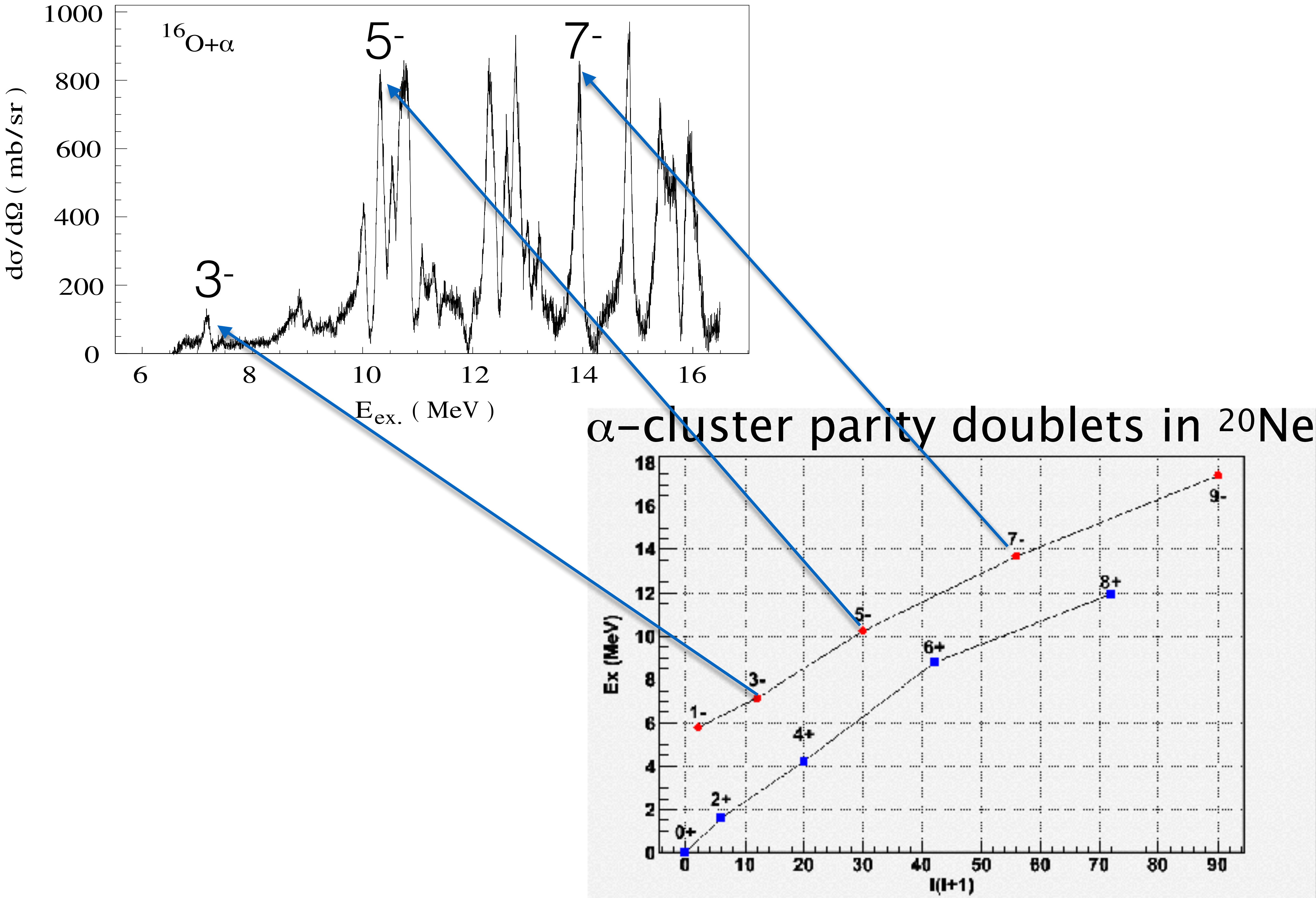


AMD: Y. Kanada-En'yo, H. Horiuchi; Prog.Th.Phys. 93 (1995), 115

THSR: Zhao, et al, PRC (2004)



Parity doublets

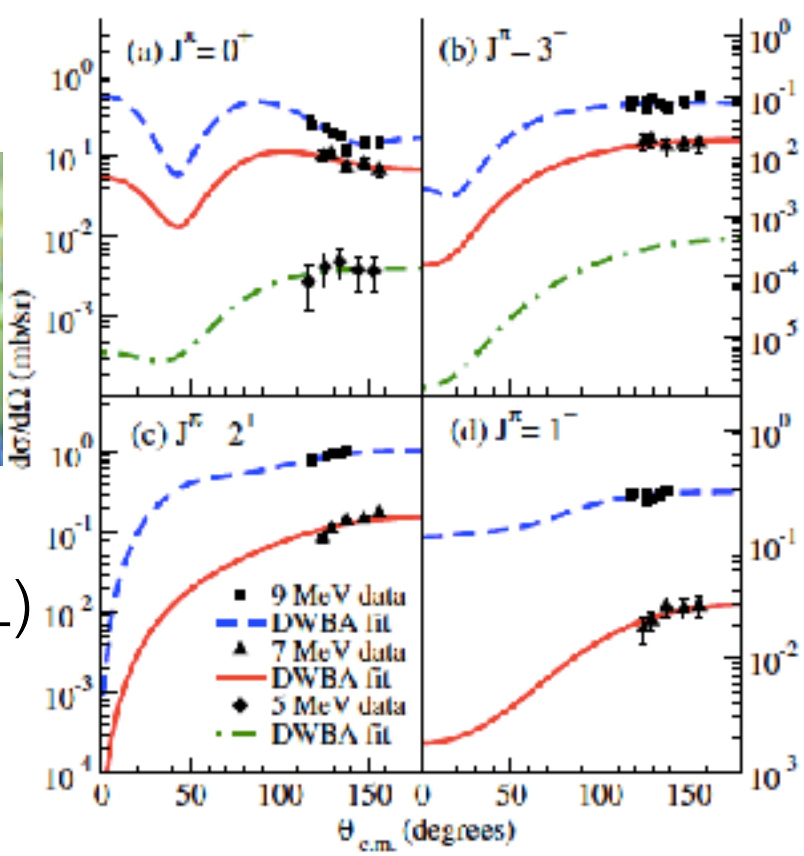


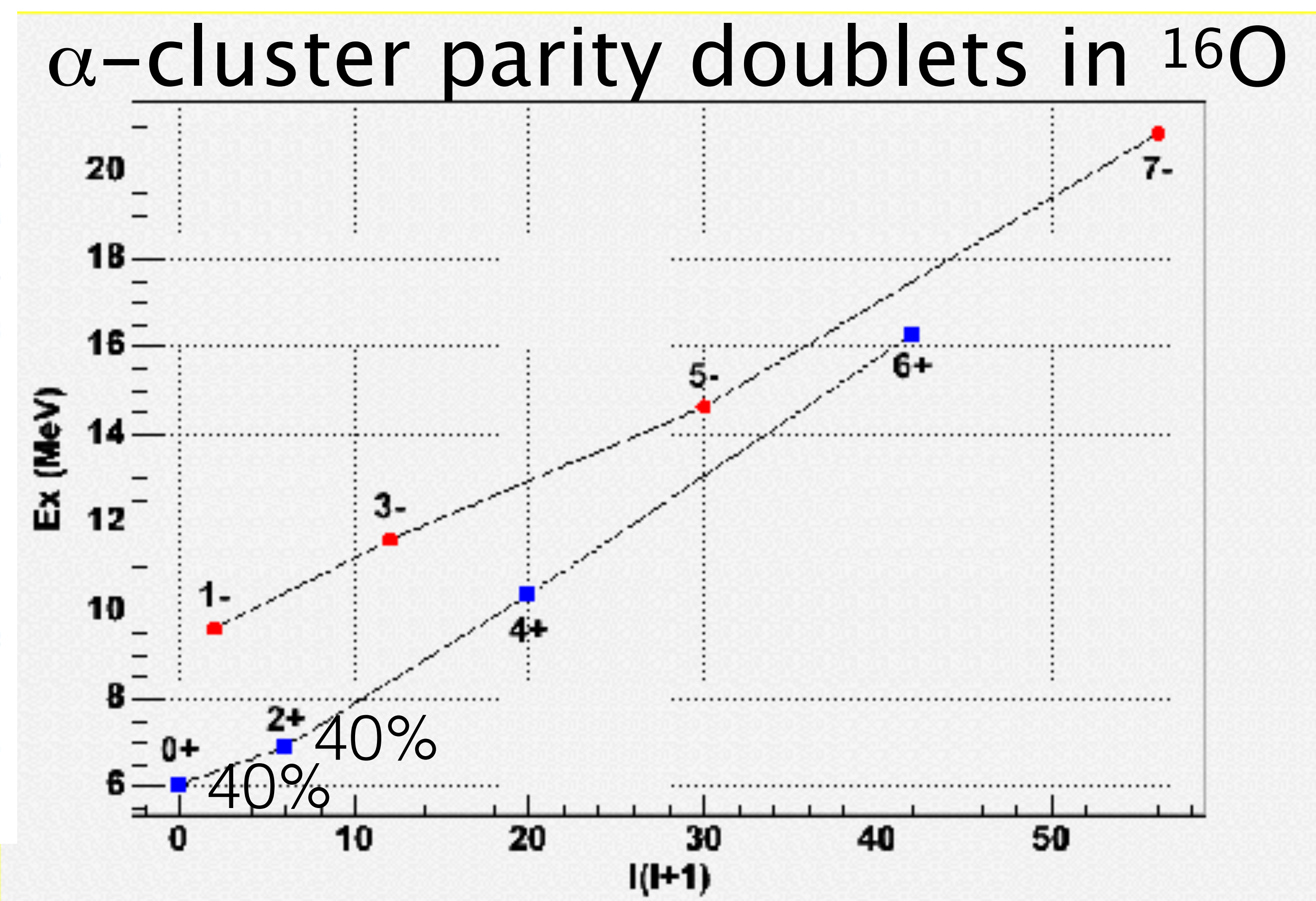
Parity doublets

- ☑ Clustering of bound states can be established model independently (almost) using sub-Coulomb α-transfer, e.q. (6Li,d) or (7Li,t)

$(C^{^{16}O(0^+)}_{\alpha-^{12}C})^2$ (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	[14]	N. Oulebsir, et al., PRC **85**, 035804 (2012).
...	...	$1.29 + 0.23$	$4.33 + 0.84$	[10]	C. Brune, et al., PRL. **83**, 4025 (1999).
...	...	$1.96^{+1.41}_{-1.27}$	$3.48 + 2.0$	[15]	A. Belhout, et al., NPA **793**, 178 (2007).
$2.43 + 0.30$	$1.93 + 0.25$	$1.48 + 0.16$	$4.39 + 0.59$	This work	M.L. Avila, GR, et al., PRL **114**, 071101 (2015).

M. Avila
(now at ANL)

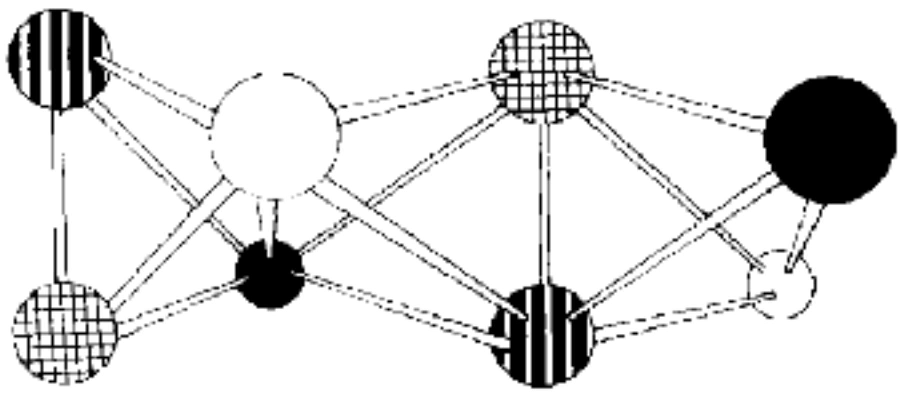




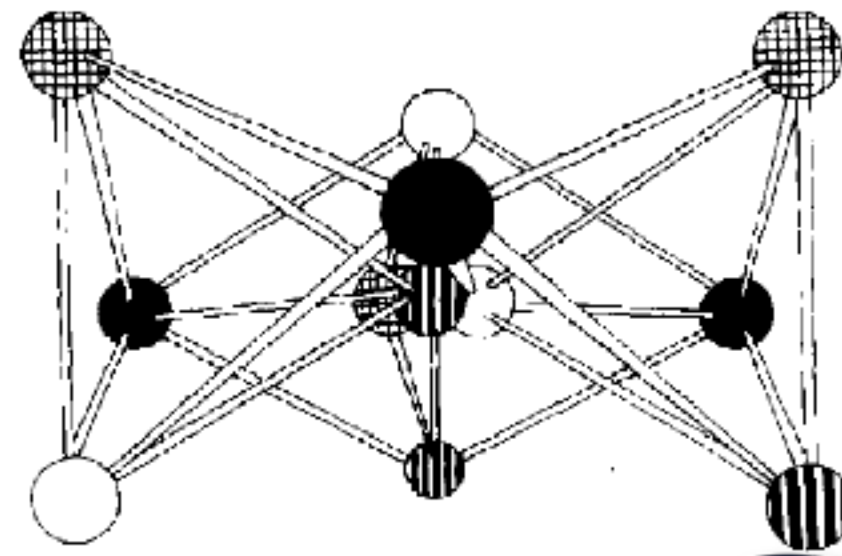
“Crystal” structure of nuclei

D. Robson, NPA 308 (1978) 381

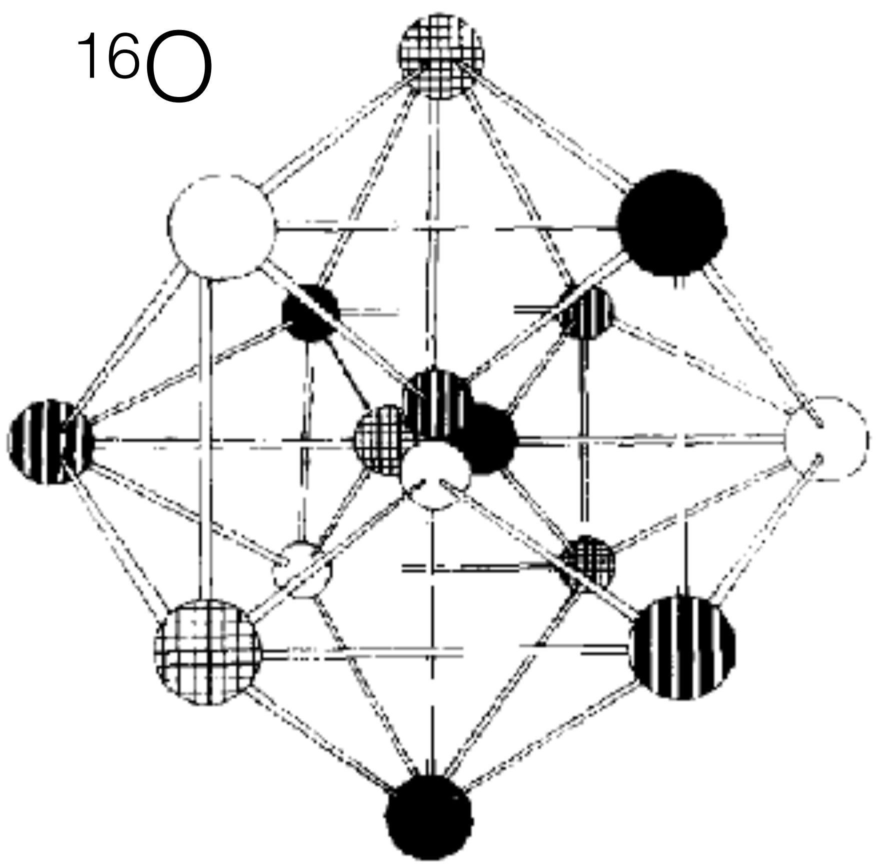
^{8}Be

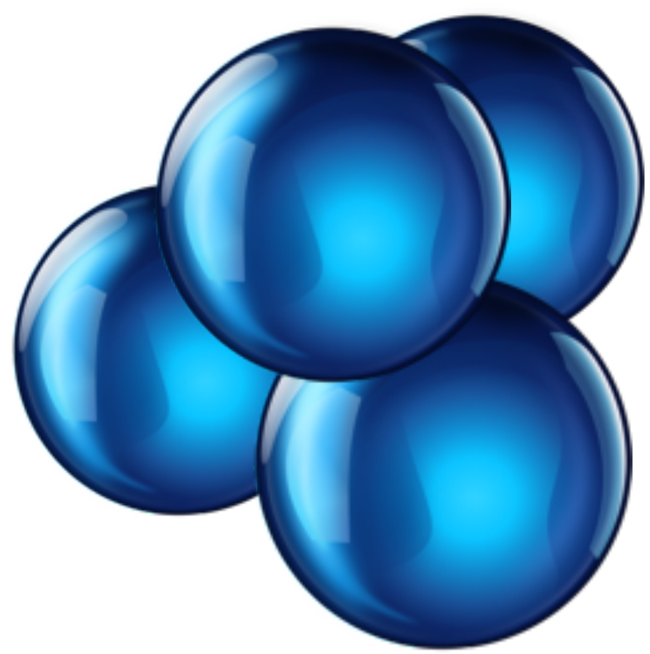


^{12}C



^{16}O





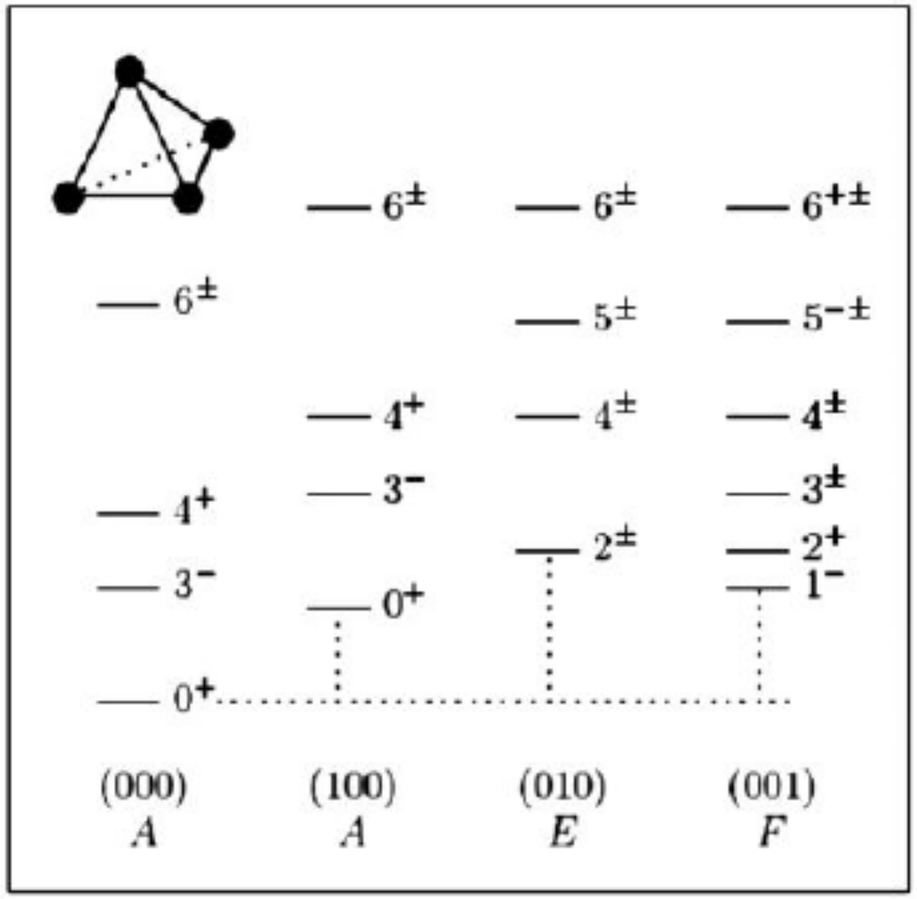
“Crystal” structure of nuclei

TABLE 3

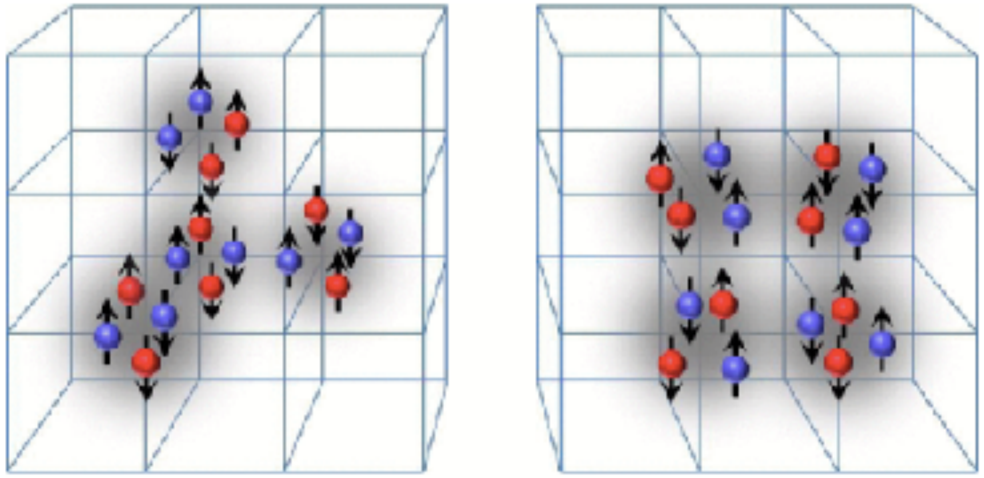
Energy levels of ^{16}O with $T = 0$, $E^* < 12.6$ MeV

Experiment [a]		Theory		
J^π	E^* (MeV)	E^* (MeV)	$n_2 n_3 n_E$	T_d representation
0^+	0.00	−0.15	0 0 0	A_1
0^+	6.05	7.15	2 0 0	A_1
3	6.13	6.21	0 0 0	A_1
2^+	6.92	6.68	1 0 0	E
1^-	7.12	6.08	0 1 1	F_2
2	8.87	(alpha-broken) [b]		
1^-	9.63	9.73 [c]	1 1 1	F_2
2^+	9.85	8.20	0 1 1	F_2
4^+	10.34	10.45	0 0 0	A_1
0^-	10.95	(alpha-broken)		
3^+	11.08	11.38	0 1 1	F_2
4^+	11.10	15.47 [d]	0 1 0	F_2
0^+	11.26	10.19	0 2 0	A_1
2^+	11.52	10.33	2 0 0	E
3^-	11.60	11.38	0 1 1	F_2
0^+	12.05	10.80 [c]	3 0 0	A_1
1^-	12.44	11.25	0 2 2	F_2
2	12.53	12.52	2 0 0	E

D. Robson, NPA 308 (1978) 381



R. Bijker, and F. Iachello, PRL (2014) 112 (15), 152501



E. Epelbaum, et al., PRL 112 (2014) 381

Missing components of Td - symmetry in ^{16}O

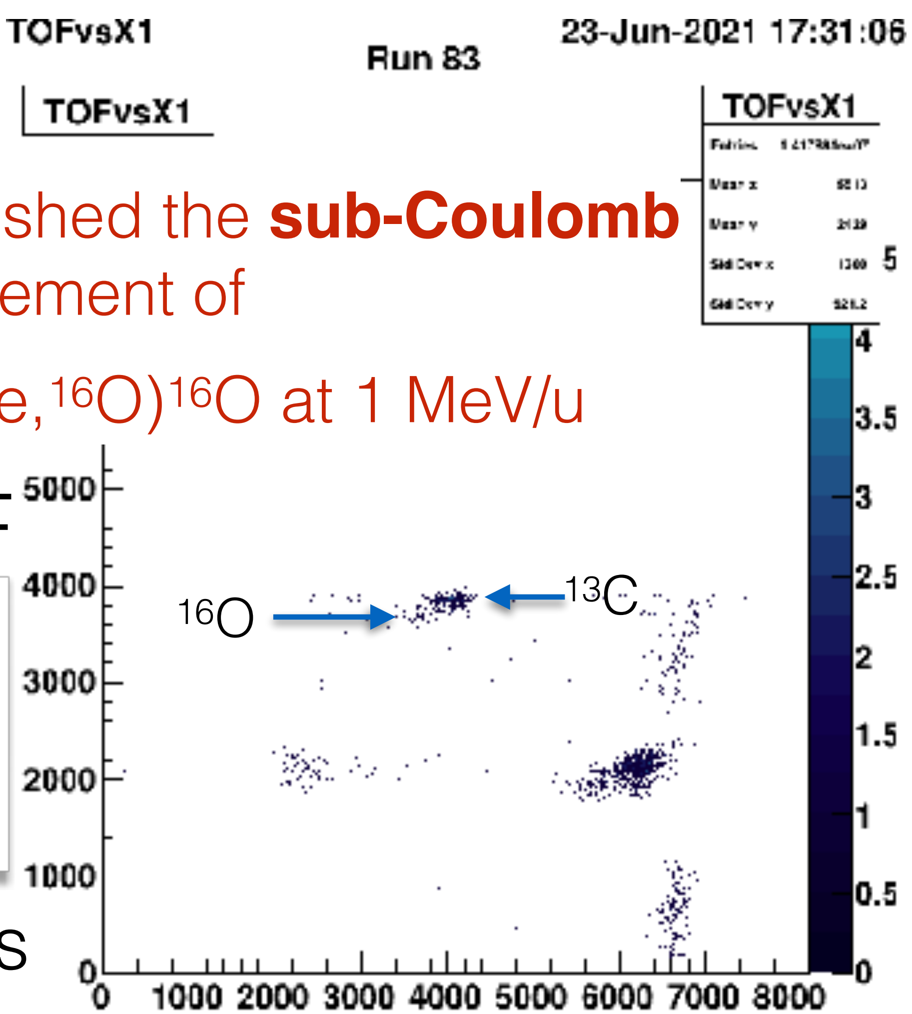
How cluster is the g.s. of ^{16}O?

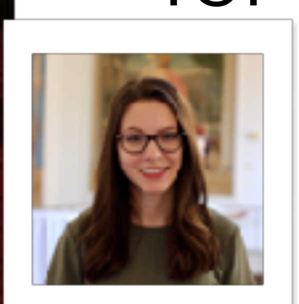
Experimental data is all over the place - from ANC of 14 to 4000 fm$^{-1/2}$!

Recent theor. SF~0.8
A. Volya, et al., PRC 91 (2015)

Just finished the **sub-Coulomb** measurement of

^{12}C(^{20}Ne,^{16}O)^{16}O at 1 MeV/u





E. Harris

Where is the 3$^-$?

TABLE I. Lowest order calculations of F_2-band energies.

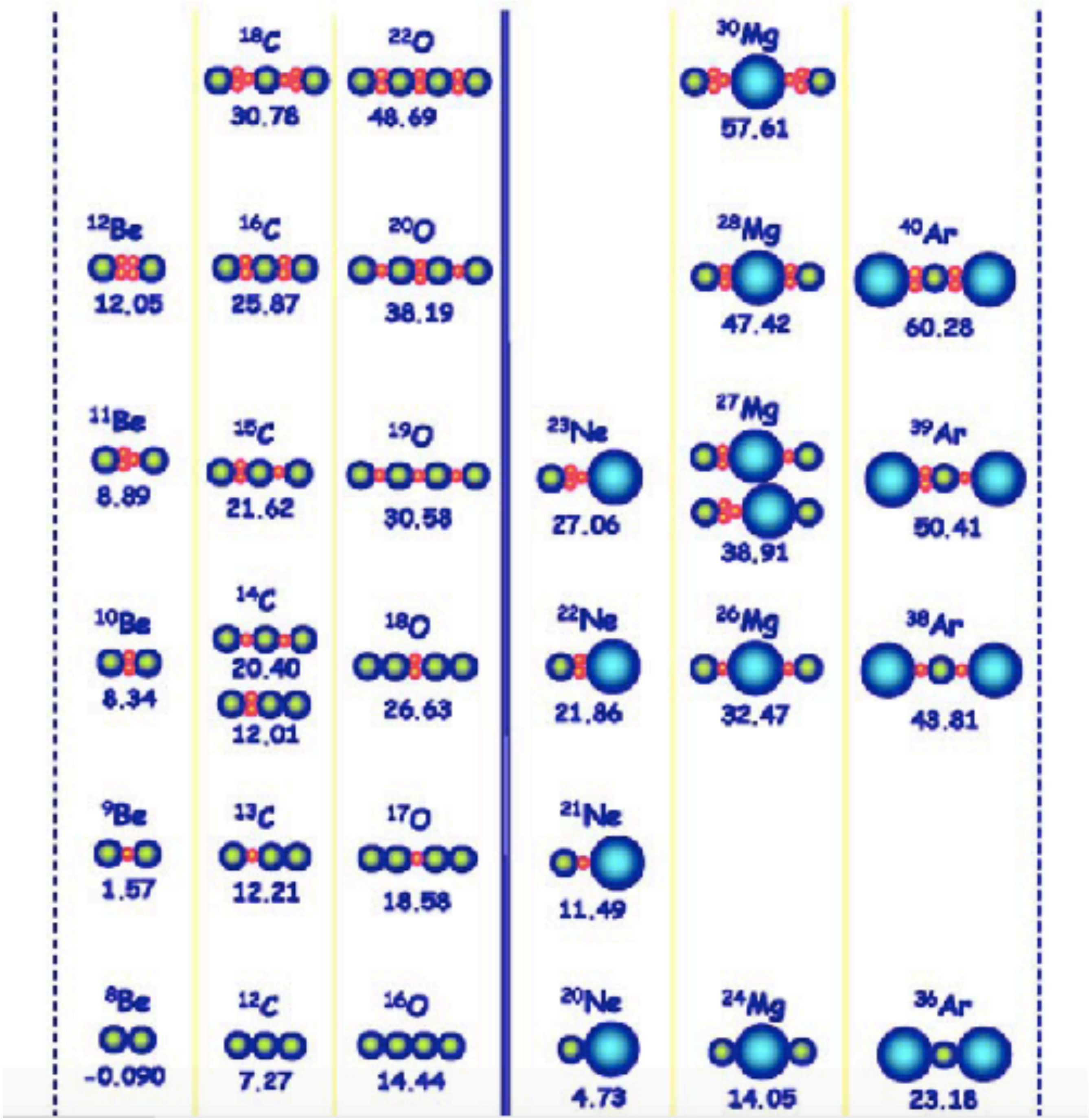
J_R^π	1_0^-	2_3^+	3_3^+	4_3^+	3$^-$	4_4^-	$5_6^\pm$	6_7^+
E (MeV)	7.12	7.01	11.16	16.35	9.9	14.35	14.75	20.99

D. Robson, PRC 25 (1982) 1108

					5, 16, ... 4, 30, 32, 33, 34, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82
6.0494 ± 1.0	$0^+;0$	0^+	$\tau_m = 96 \pm 7$ psec	π	5, 7, 11, 12, 13, 15, 17, 19, 21, 23, 30, 32, 33, 34, 38, 39, 43, 44, 47, 54, 55, 57, 66, 67, 70, 71, 73, 79, 81
6.129893 ± 0.04	$3^-;0$		$\tau_m = 26.6 \pm 0.7$ psec; $g = +0.556 \pm 0.004$	γ	1, 5, 7, 11, 12, 13, 15, 17, 18, 19, 21, 30, 31, 32, 33, 34, 37, 38, 39, 43, 44, 45, 46, 49, 50, 51, 53, 54, 66, 67, 68, 70, 71, 73, 79, 81
6.9171 ± 0.6	$2^+;0$	0^+	$\tau_m = 6.78 \pm 0.19$ fsec	γ	1, 5, 7, 11, 12, 13, 15, 17, 19, 30, 31, 32, 33, 34, 37, 38, 42, 43, 44, 45, 46, 47, 49, 50, 53, 54, 55, 67, 68, 70, 71, 73, 78, 80
7.11685 ± 0.14	$1^-;0$		$\tau_m = 12.0 \pm 0.7$ fsec	γ	1, 5, 7, 11, 12, 13, 17, 30, 31, 32, 33, 34, 37, 38, 39, 42, 43, 44, 46, 47, 50, 66, 67, 68, 70, 71, 73, 81
8.8719 ± 0.5	$2^-;0$		$\tau_m = 180 \pm 16$ fsec	γ, α	5, 7, 11, 12, 16, 19, 30, 31, 33, 37, 38, 39, 43, 45, 46, 47, 49, 50, 67, 68, 73, 81
9.585 ± 11	$1^-;0$	0^-	$\Gamma = 420 \pm 20$	γ, α	7, 9, 11, 12, 30, 38, 39, 45, 46, 47, 49, 50, 54, 55
9.8445 ± 0.5	$2^+;0$	$2^{+\,b}$	0.625 ± 0.100	γ, α	5, 7, 9, 11, 12, 19, 30, 31, 33, 37, 38, 39, 43, 46, 47, 49, 50, 54, 55, 66, 68, 70, 73, 78, 81
10.356 ± 3	$4^+;0$	0^+	26 ± 3	γ, α	5, 7, 9, 11, 12, 13, 14, 16, ...

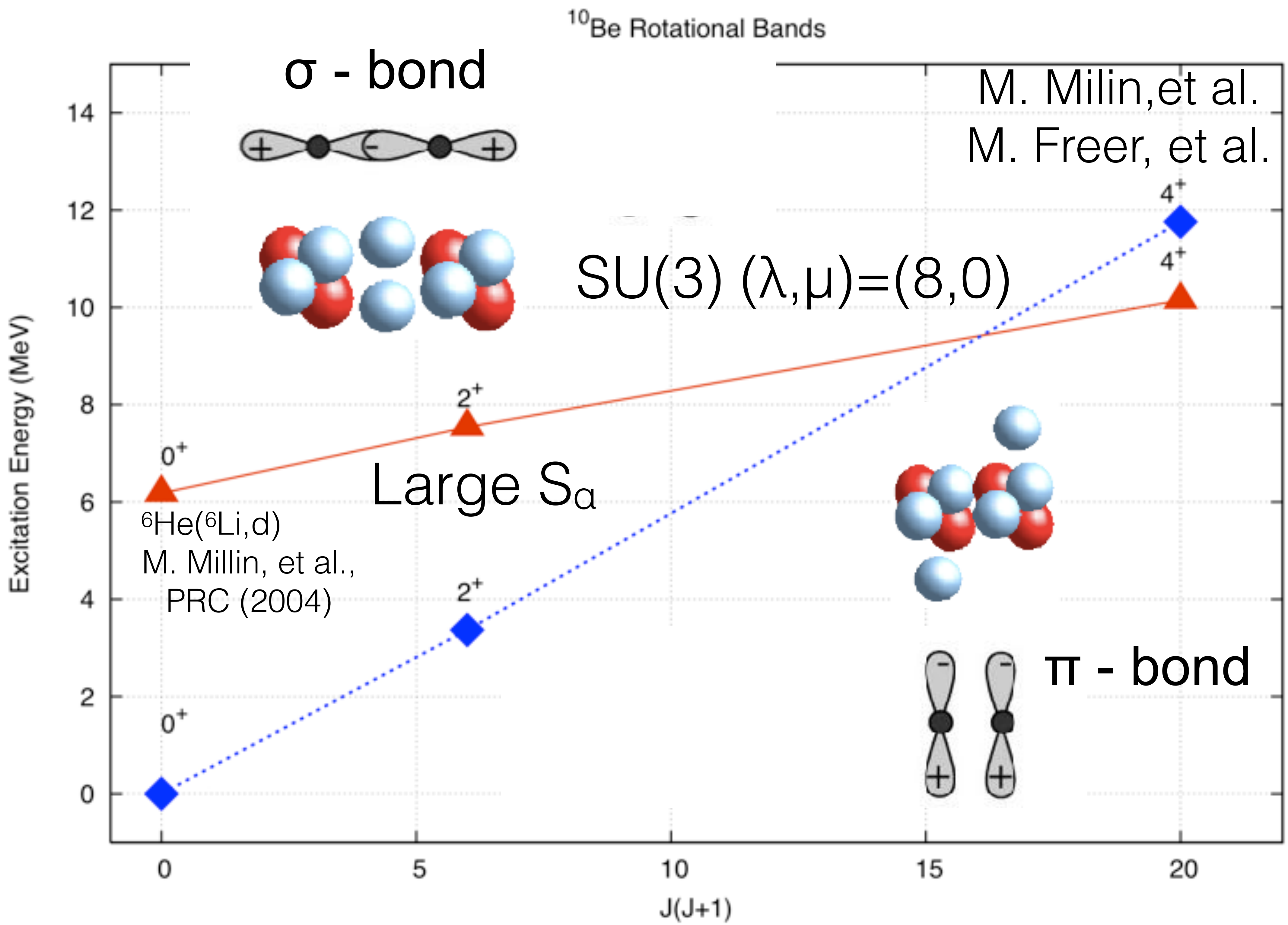
3$^-$???

Clustering in non self-conjugate nuclei

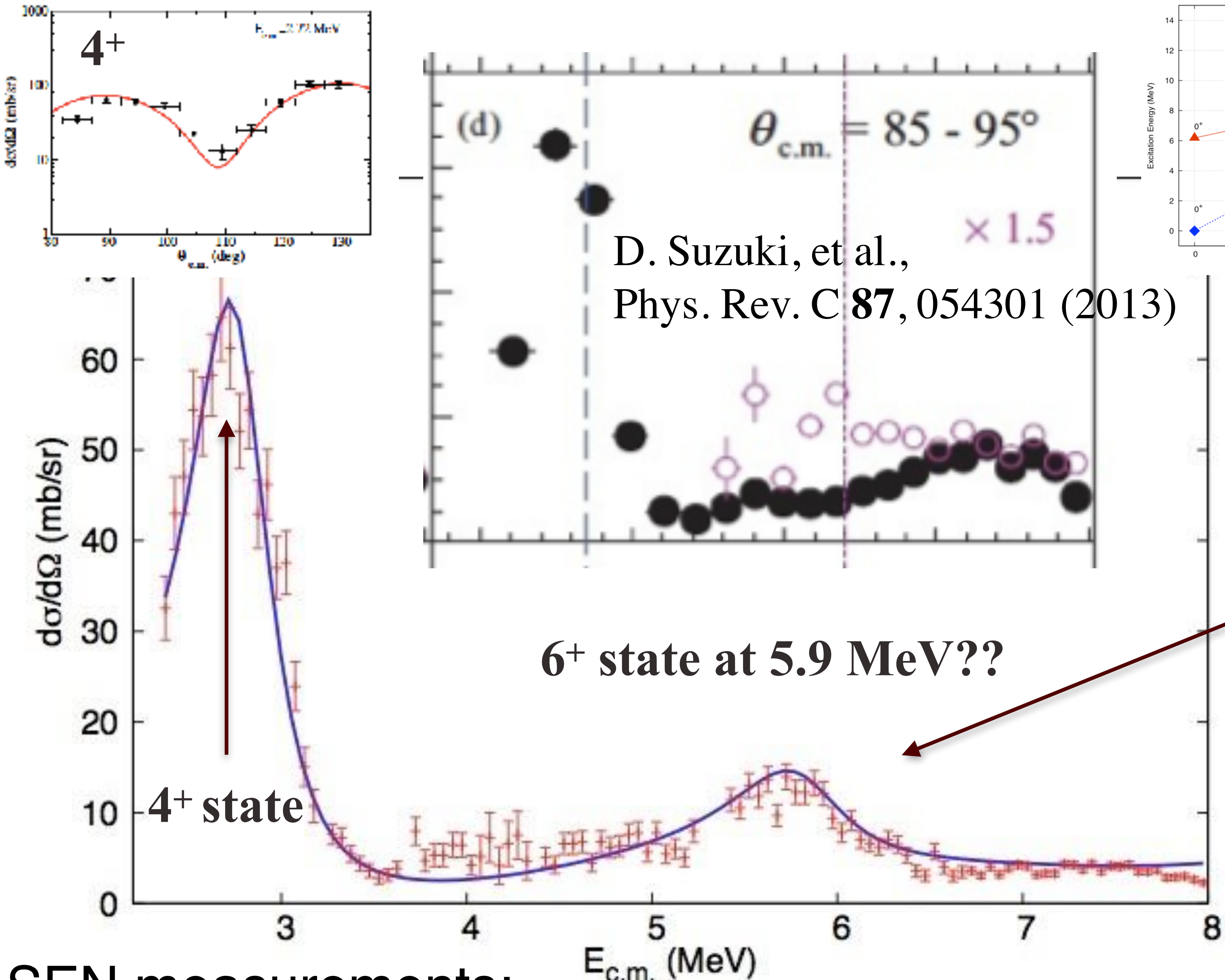


W. von Oertzen, et al., Phys. Rep. 432 (2006)

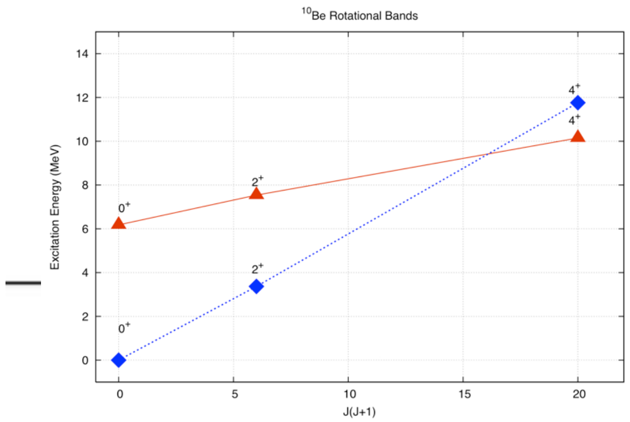
Molecular structures in ^{10}Be

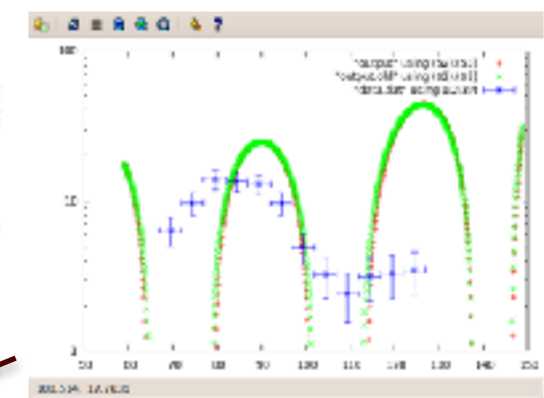


^{6}He+α excitation function at 90°



D. Suzuki, et al.,
Phys. Rev. C **87**, 054301 (2013)





6^{+} state at 5.9 MeV??

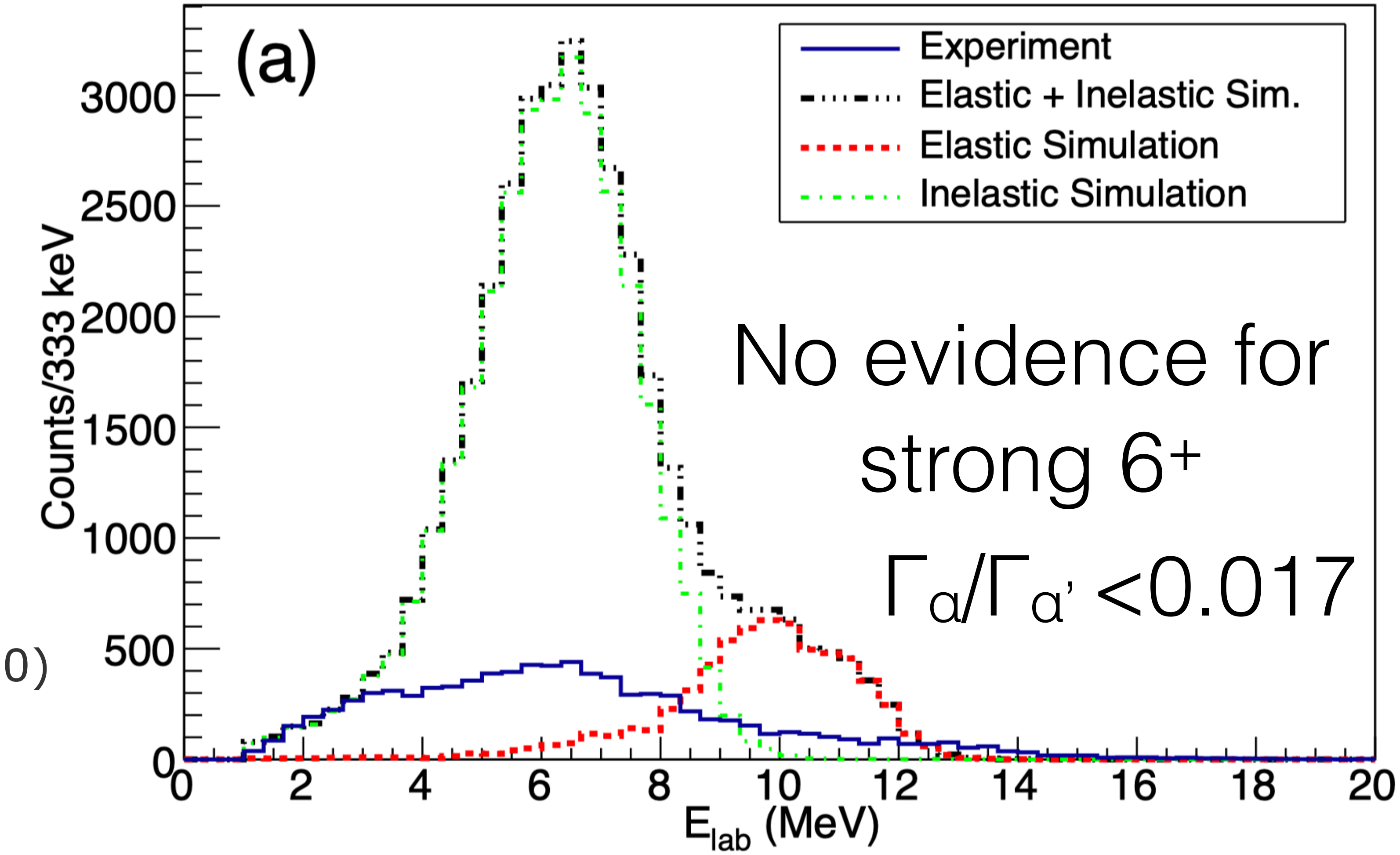
4^{+} state

ANASEN measurements:
E. Koshchiy, GR, et al., NIM A 870 (2017)

^{6}He+α excitation function at 160°-170°

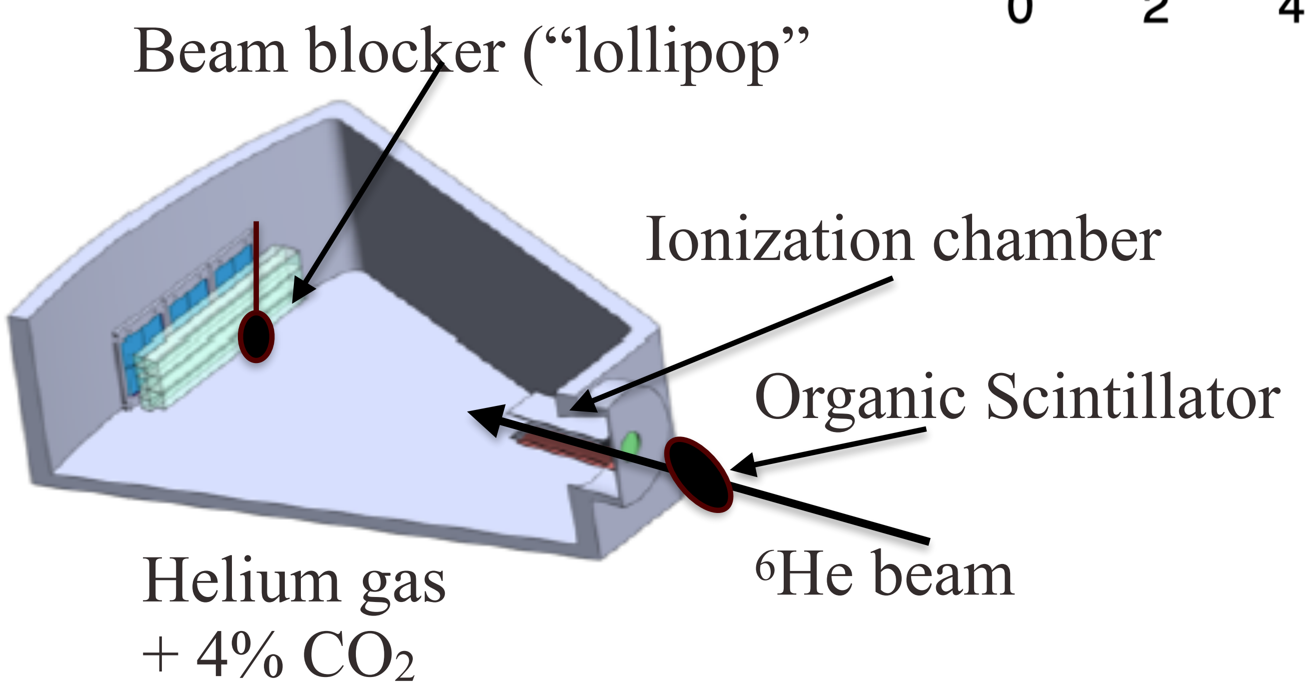
S. Upadhyayula
(now at TRIUMF)

S. Upadhyayula, GR, et al.,
Phys.Rev. C 101, 034604 (2020)



No evidence for strong 6^{+}

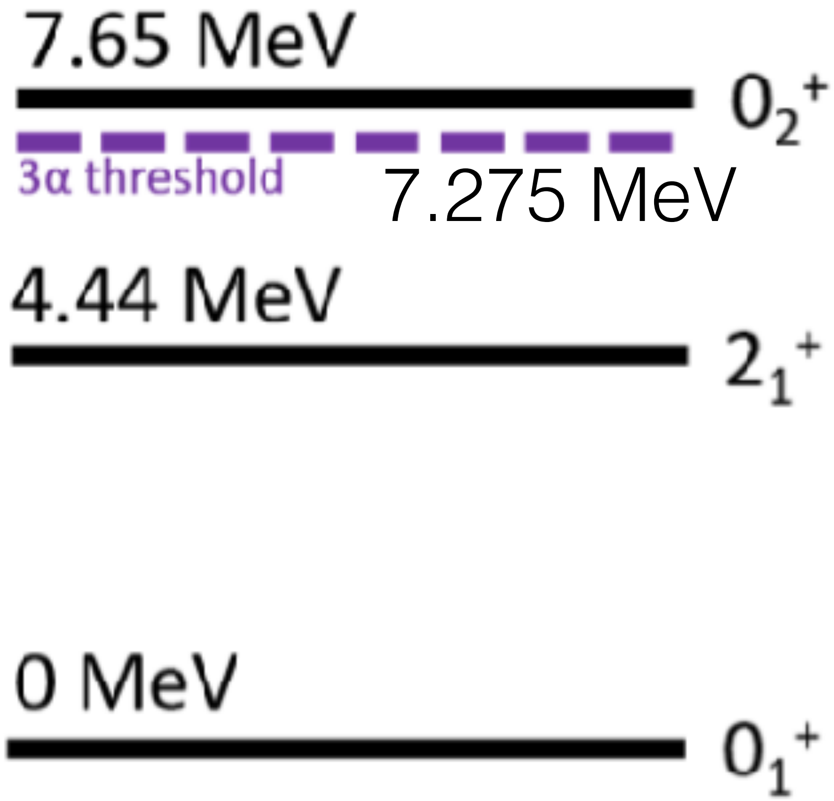
$\Gamma_{\alpha}/\Gamma_{\alpha'} < 0.017$



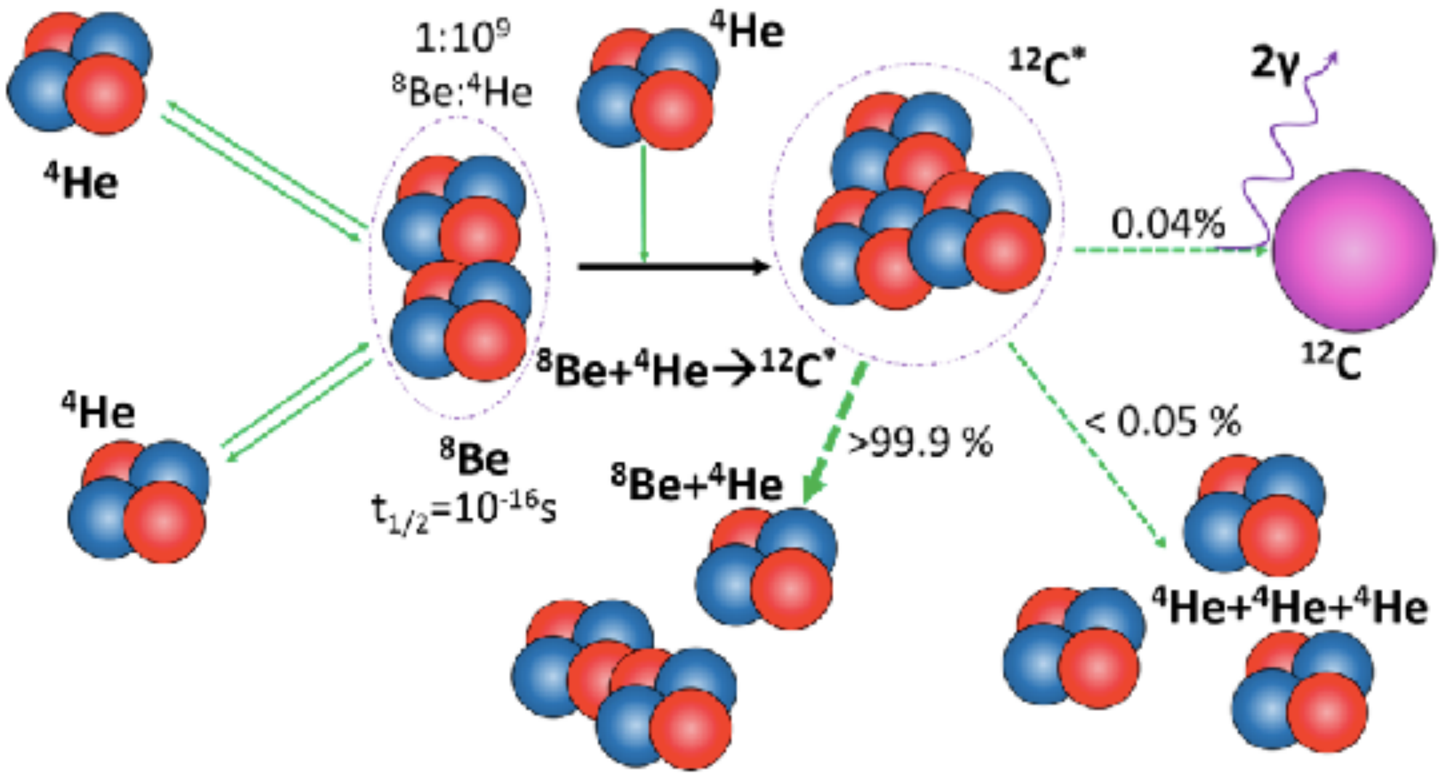
JISP16 calculations:
The lowest 6^{+} has SF = 0.1 for ^{6}He(g.s.)+α and SF=0.6 for ^{6}He(2^{+})+α

K. Kravvaris, A. Volya, AIP Conf Proc **2038**, 020026 (2018)

Hoyle state

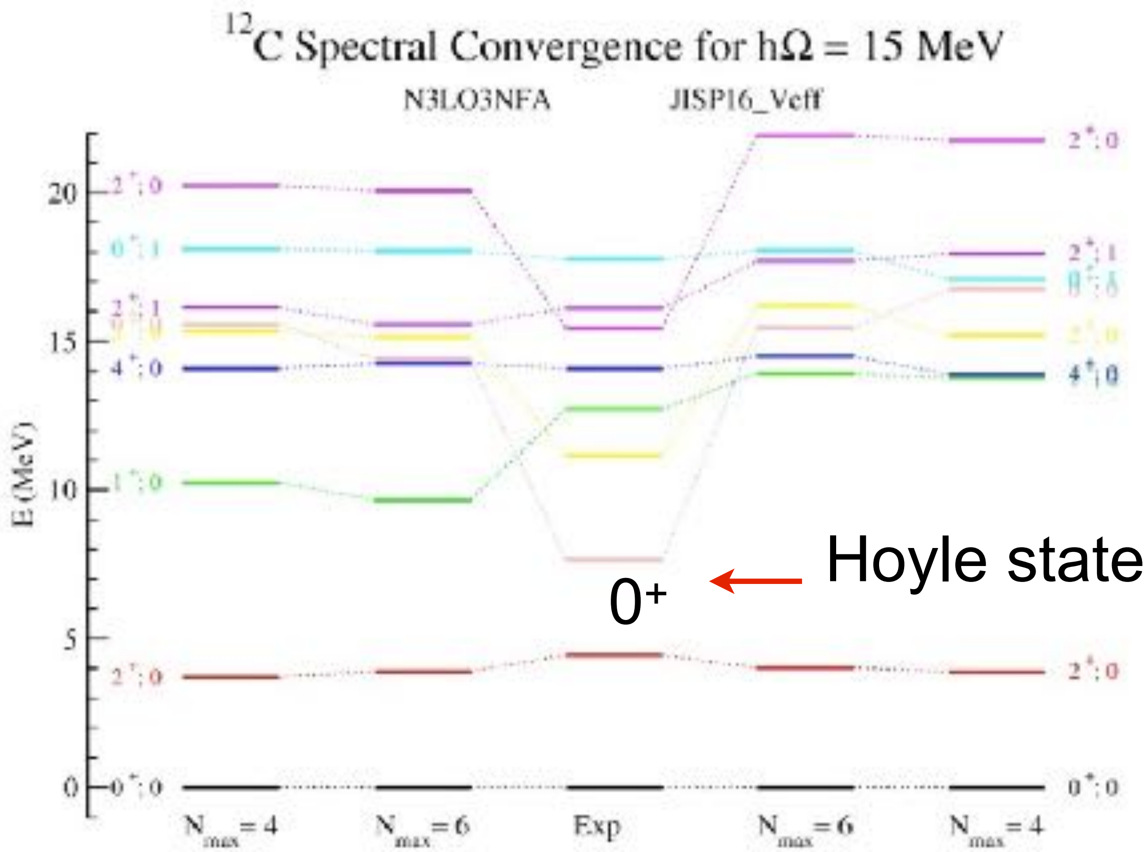


7.65 MeV
0_2^+
3α threshold
7.275 MeV
4.44 MeV
2_1^+
0 MeV
0_1^+



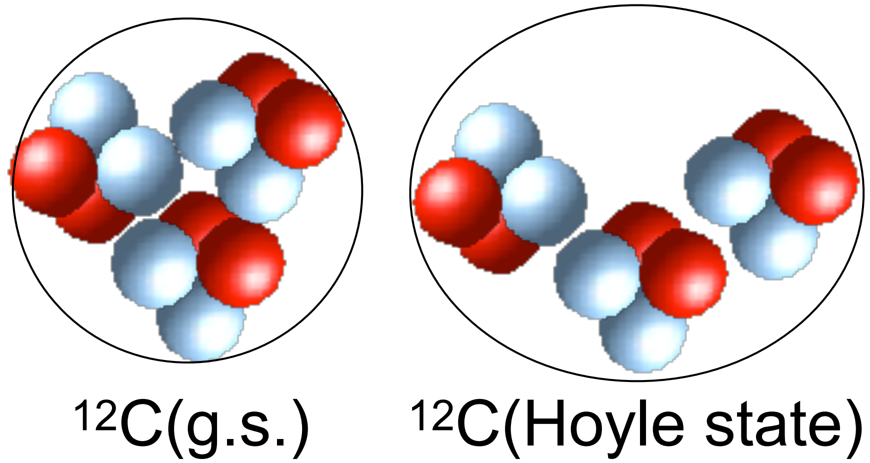
^{4}He
^{4}He
1:10^9
^{8}Be:^{4}He
^{4}He
^{12}C*
2γ
0.04%
^{12}C
^{8}Be
$t_{1/2}$=10^{-16}s
^{8}Be+^{4}He→^{12}C*
>99.9 %
< 0.05 %
^{8}Be+^{4}He
^{4}He+^{4}He+^{4}He
^{4}He

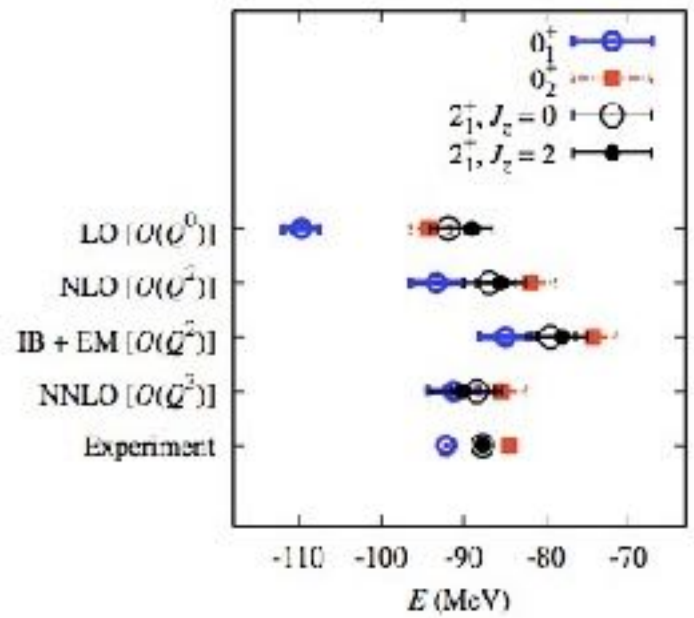
Recent theoretical advances



A.M. Shirokov, et al., PRC 79, 014308 (2009)

Hoyle state is underbound in NCSM with JISP16 by 8 MeV!



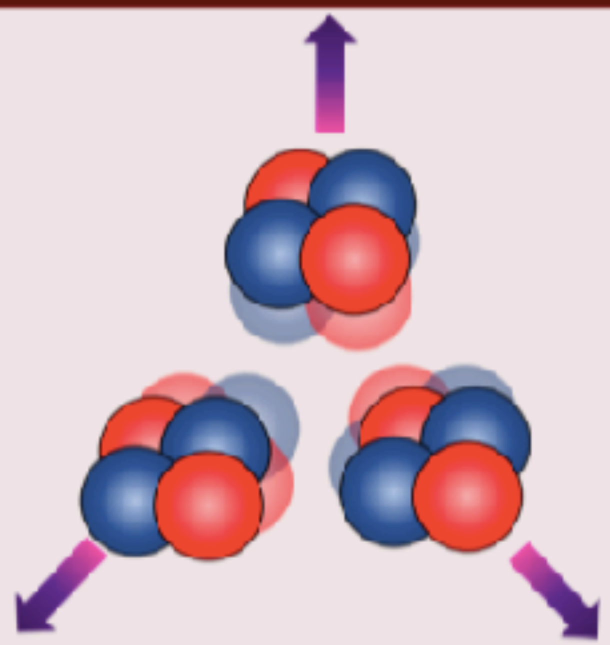


Lattice EFT reproduces α-cluster like structures for the Hoyle and g.s. state of ^{12}C

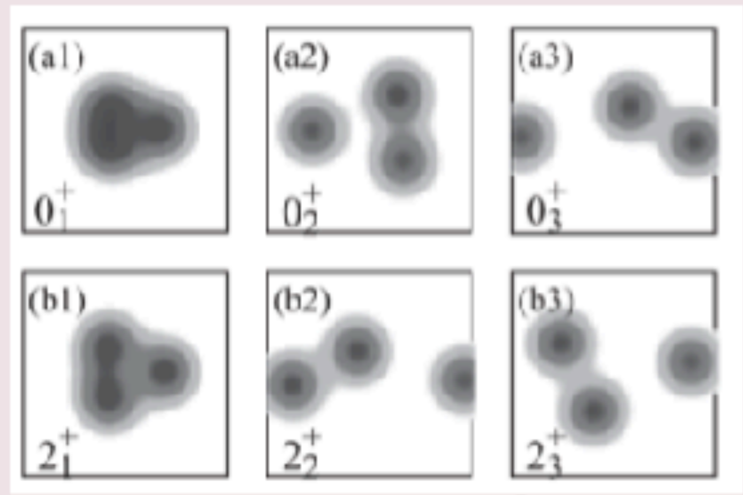
E. Epelbaum, et al., PRL 106, 192501 (2011)

^{12}C - Hoyle state decays

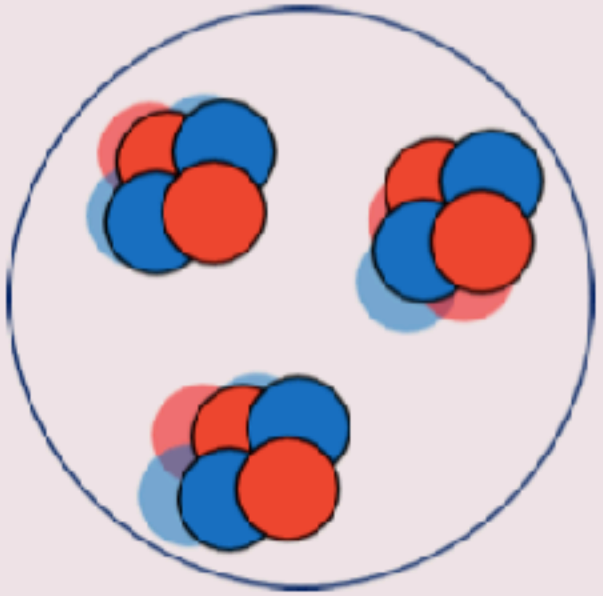
Internal structure of the Hoyle state has an impact on this branching ratio → How do we think about the structure of the Hoyle state? Highly 3α clustered - yes, but how so?



Breathing mode of triangular arrangement of α-particles (D_{3h} symmetry [1])?



More general 'bent-arm' ^{8}Be + α structure (from AMD calculations [2])?



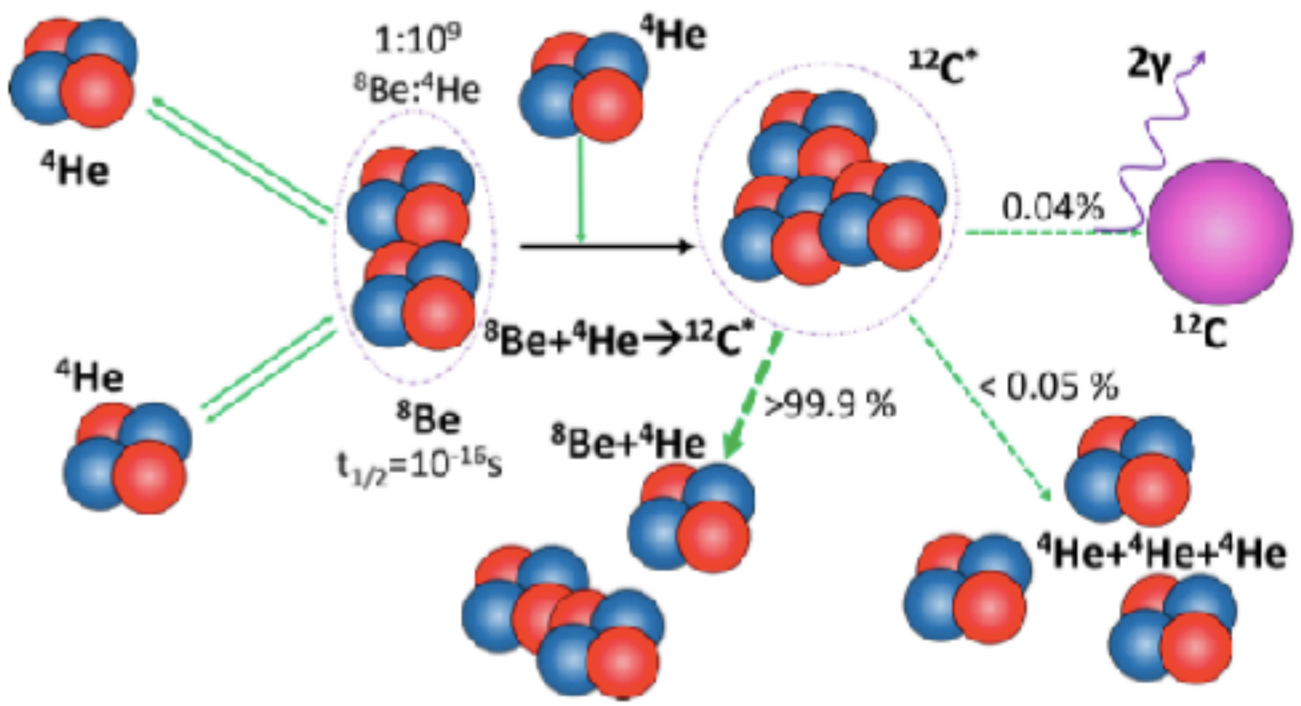
Dilute gas of α-particles [3]?

[1] D. J. Marín-Lambárri et al. Phys. Rev. Lett. 113, 012502 (2014)
[2] Y. Kanada-En'yo Prog. Theor. Phys. 117, 4 (2007)
[3] Tohsaki, Horiuchi, Schuck and Röpke, Phys. Rev. Lett. 87, 192501 (2001)

“democratic” decay mode of the Hoyle state may be a key to understanding its structure

^{12}C - Hoyle state decays

Aim of this measurement to measure Hoyle decay branching ratio directly to 3α rather than via $^{8}\mathrm{Be}(g.s)$



Current limits <0.019% 95% C.L. [1-3].

Factor of 10 or more improvement needed for model rejection [4], i.e. 1 in 40,000.

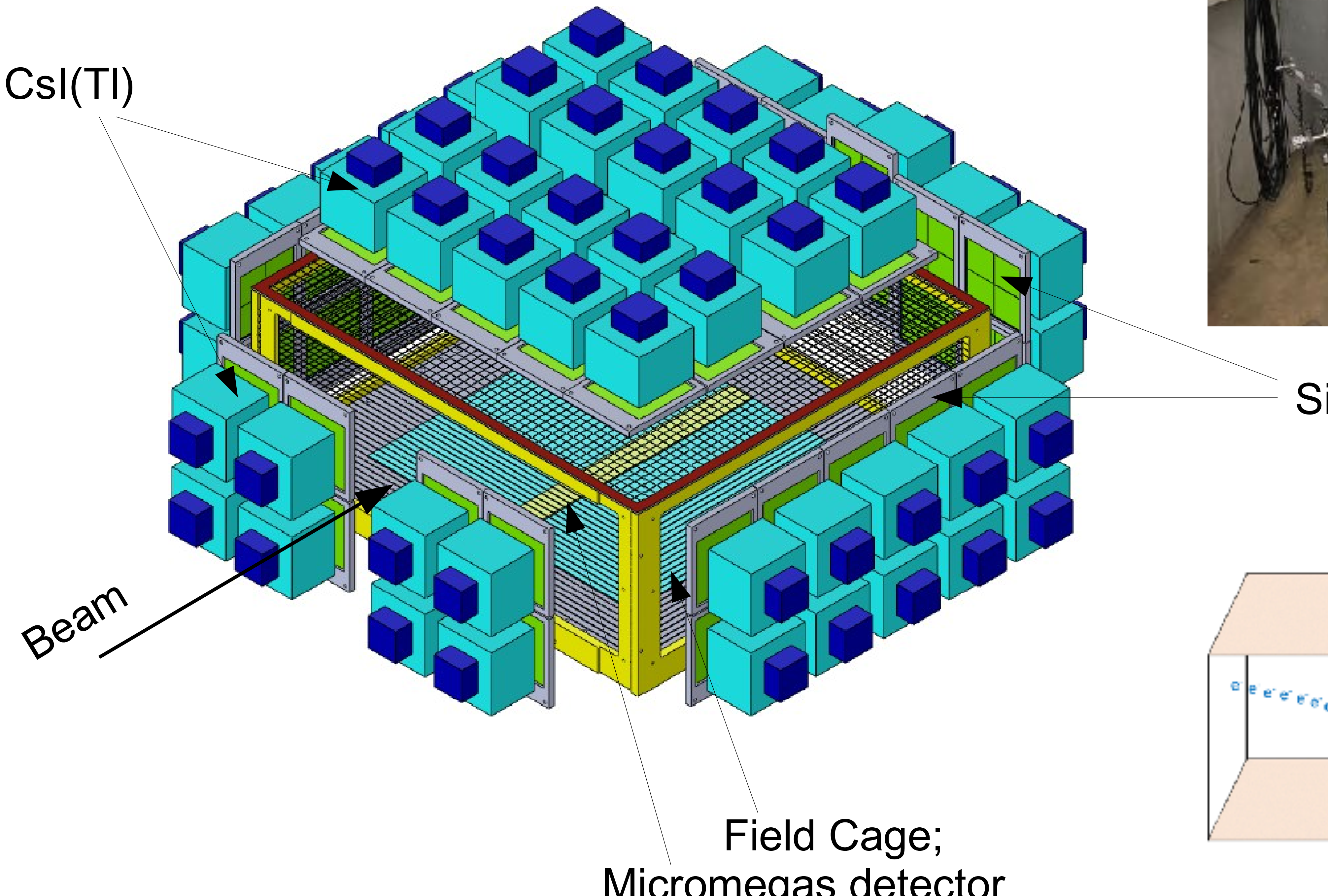
[1] R. Smith et al., PRL **119**, 132502 (2017)
[2] D. Dell'Aquila et al., PRL **119**, 132501 (2017)
[3] T.K. Rana et al., Phys. Lett. B, **793** 130-133 (2019)
[4] H. Zheng et al., PLB **779** 460-3 (2018)

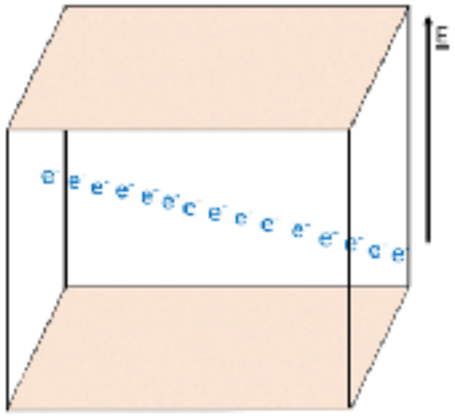
Active Target is a convenient tool to look for rare decays

Texas Active Target

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

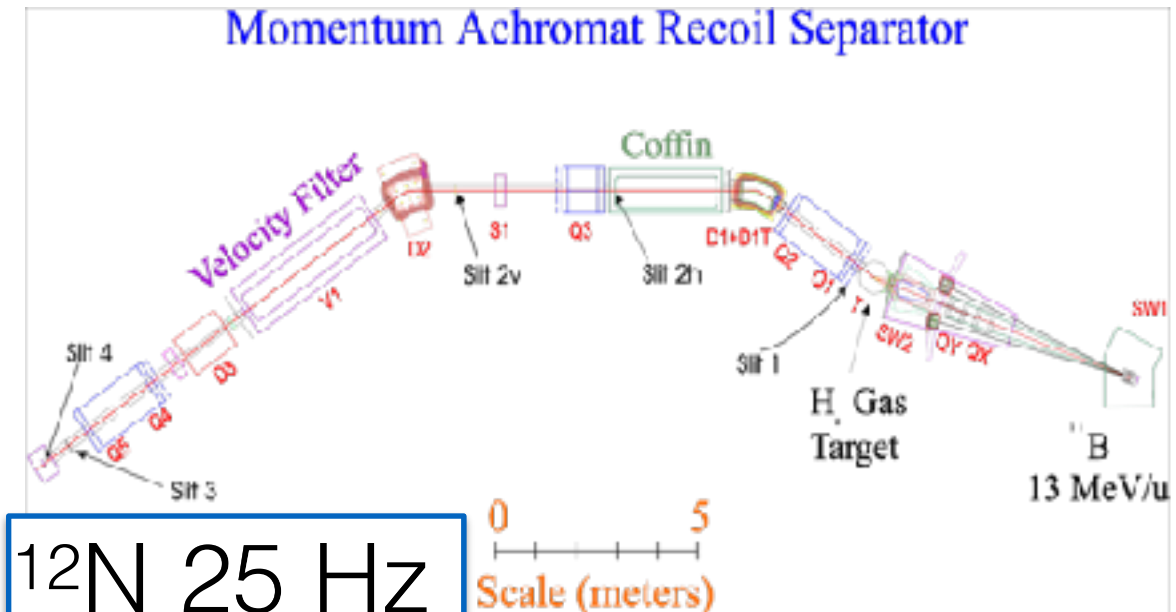
Detectors: Si
CsI(Tl)
Micromegas: 1024





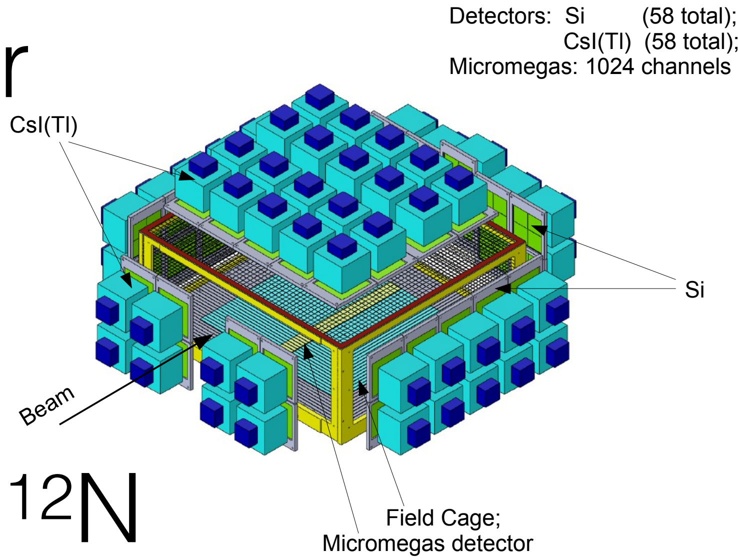
β delayed charged particle emission

^{12}C - Hoyle state decays

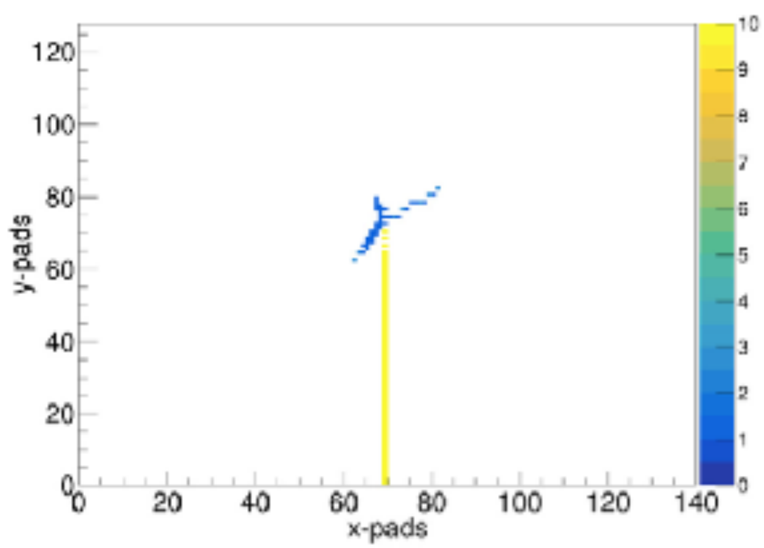


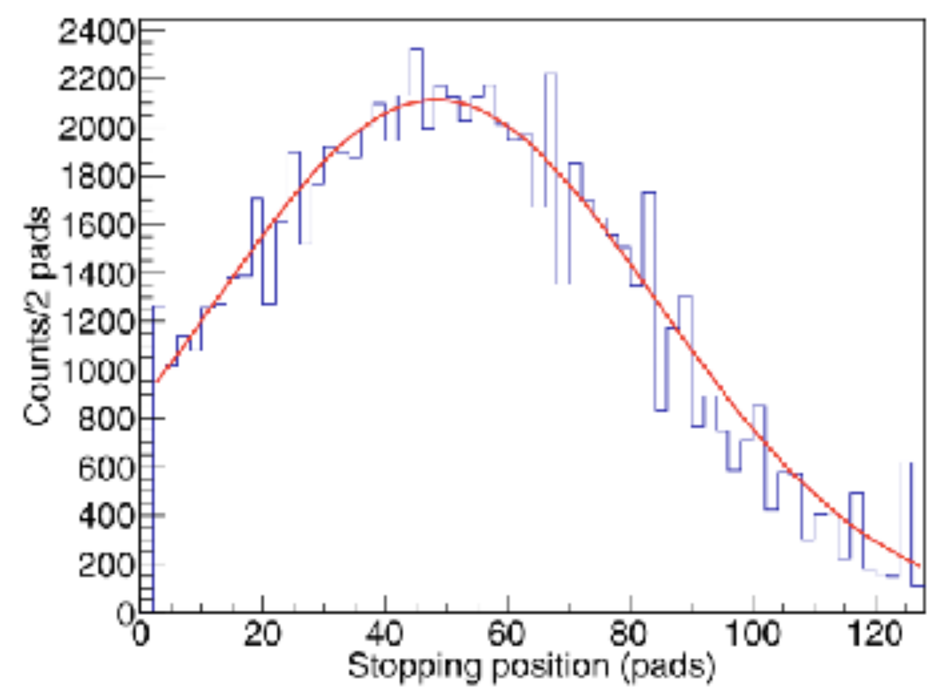
^{12}N 25 Hz

25 Torr CO_2



^{12}N

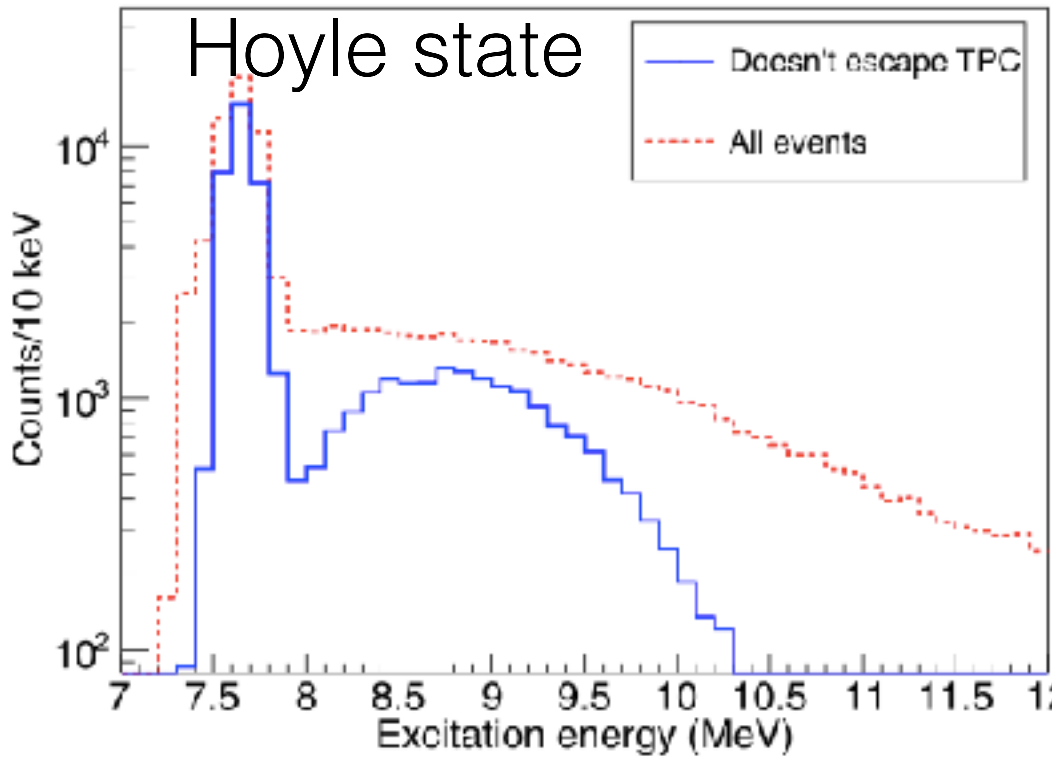


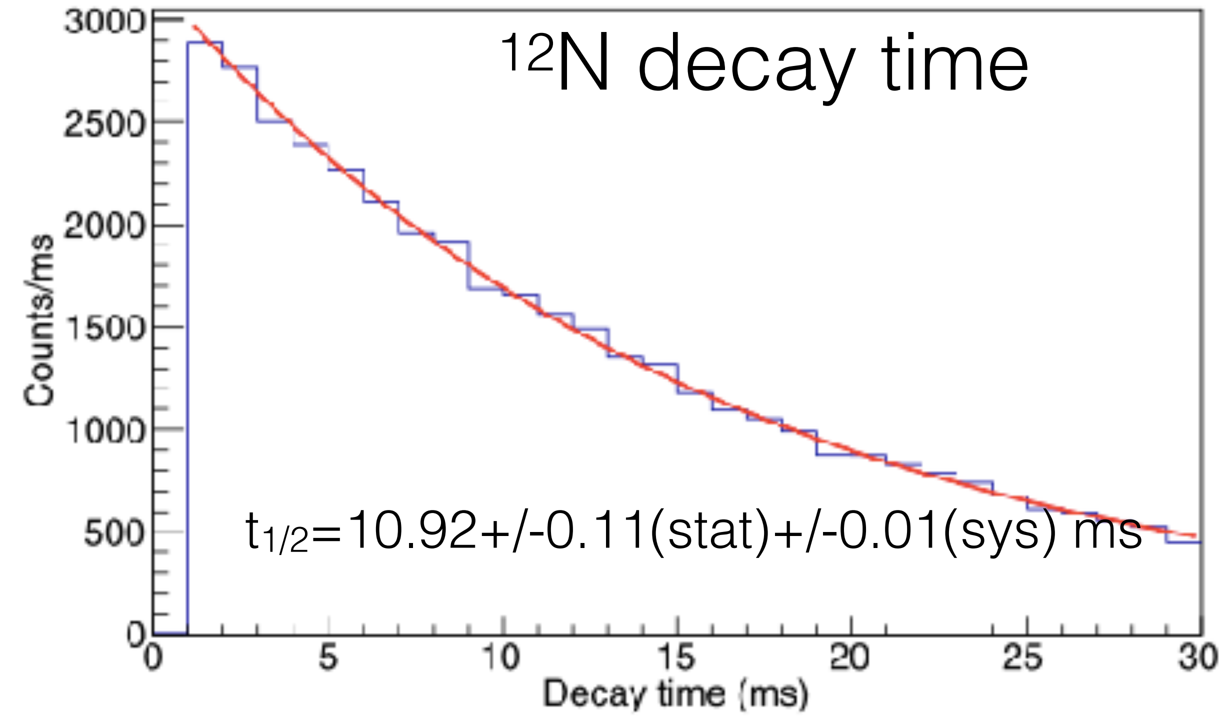


L1B trigger: ^{12}C decay

L1A trigger: ^{12}N beam

^{12}C - Hoyle state decays





The most precise ^{12}N $t_{1/2}$=11.00+/-0.016 ms

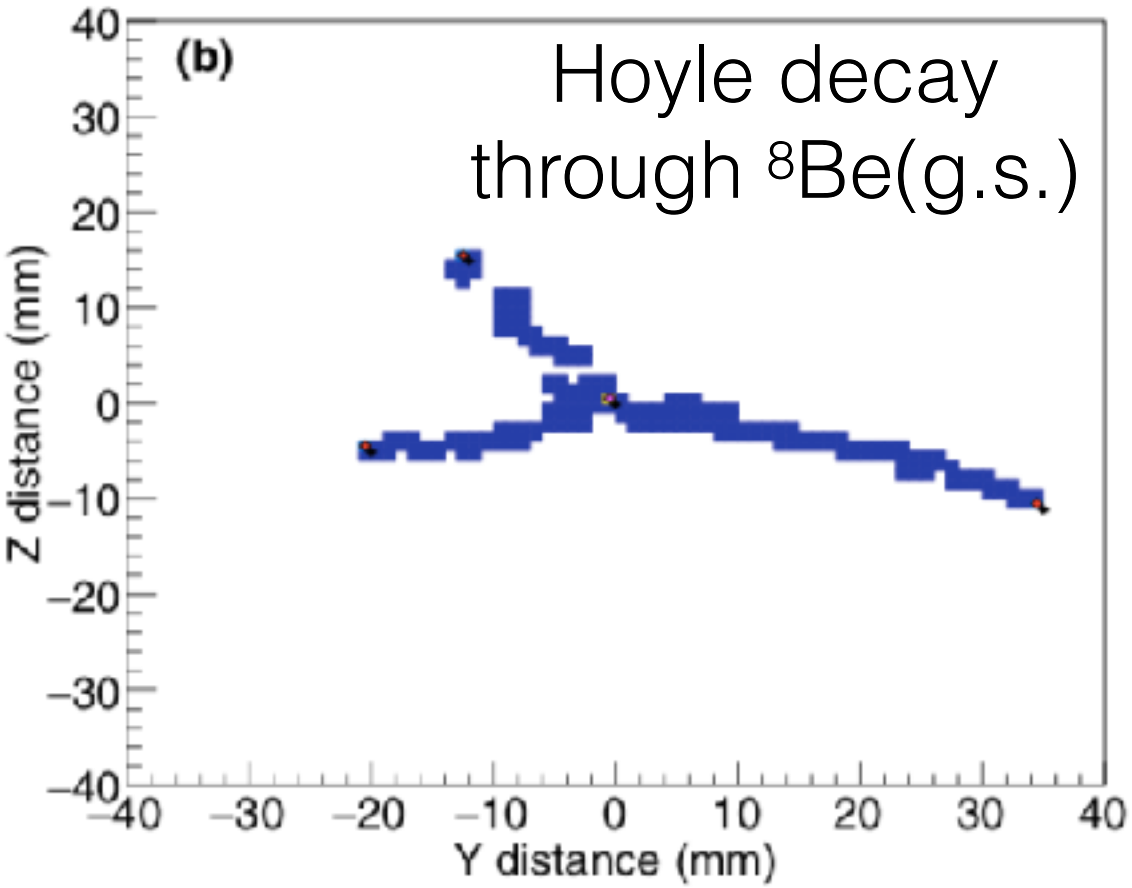
Table 1
Branching ratios for ^{12}C states populated in ^{12}N β^+-decay from the present work and from KVI [3,32].

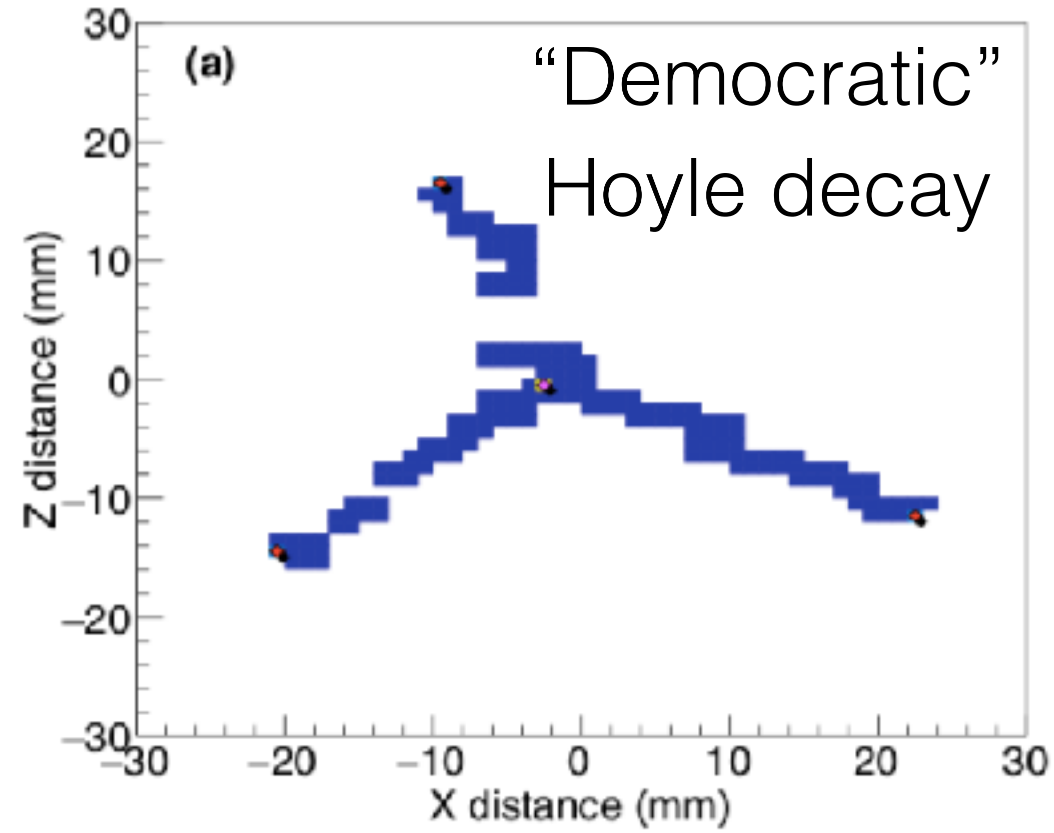
State	KVI(%)	Current work(%)
g.s	96.17 ± 0.05	–
4.44 MeV - 2_1^+	1.90 ± 0.04	–
7.65 MeV - 0_2^+	1.44 ± 0.03	1.58 ± 0.01 (stat.) ± 0.11 (sys.)
7.3–16.3 MeV - 3α	2.11 ± 0.03	2.54 ± 0.01 (stat.) ± 0.18 (sys.)
$0_2^+/3\alpha$	68 ± 2	62.1 ± 0.4 (stat.) ± 0.2 (sys.)

Jack Bishop

Bishop, GR, S. Ahn, et al., NIM A 964 (2020) 163773

^{12}C - Hoyle state decays



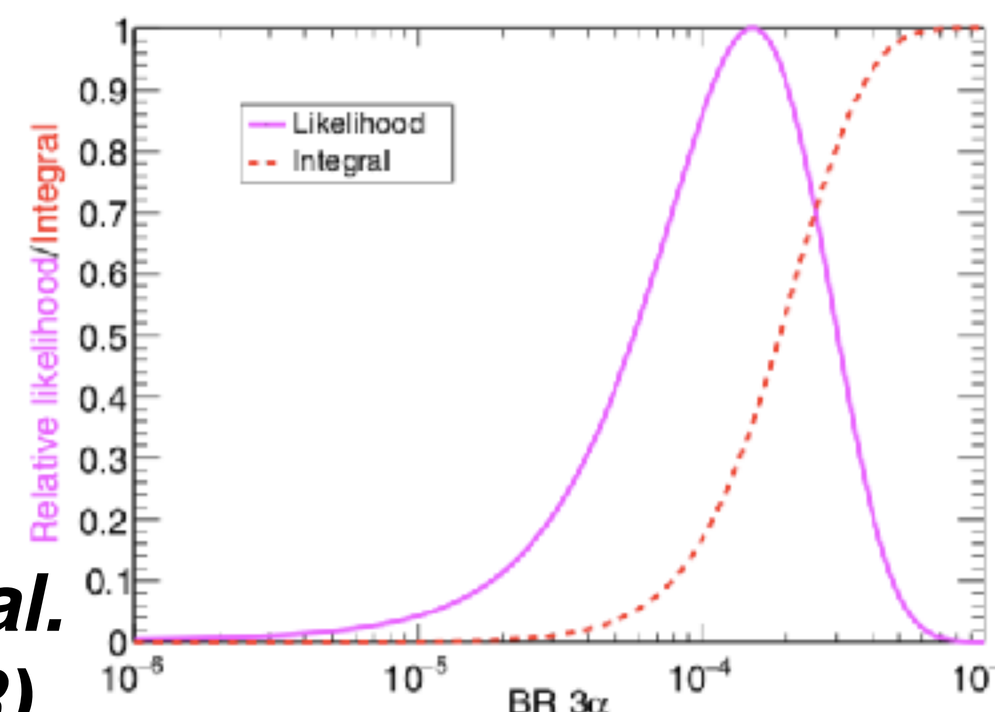


Jack Bishop

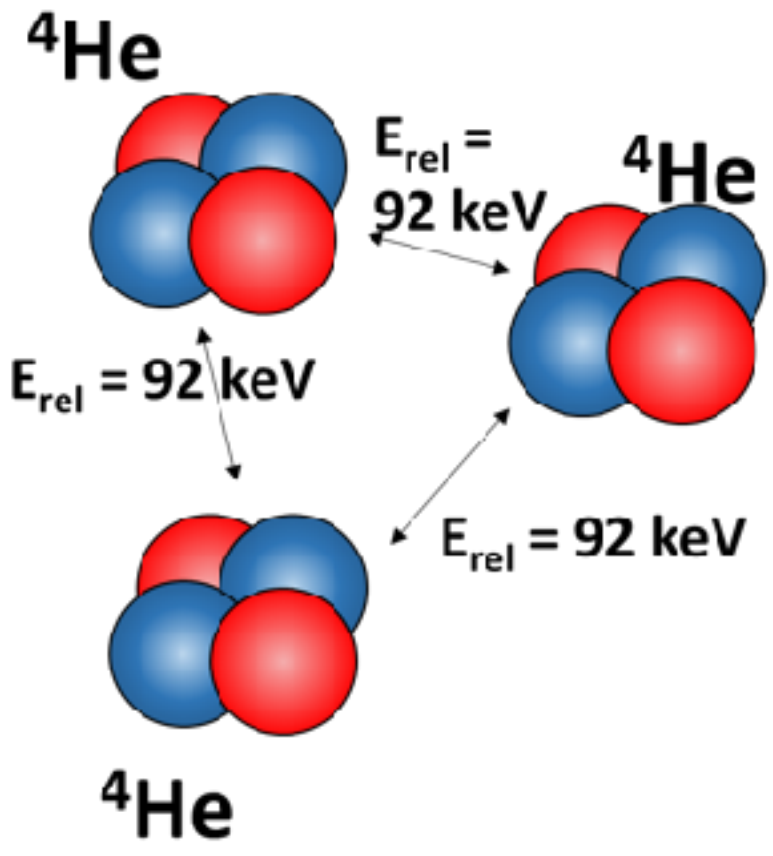
Hoyle "democratic" branching ratio:

- most likely **0.01%**
- **minimum 0.0058%**
- **maximum 0.043%**

J. Bishop, GR, S. Ahn, et al. PRC 102 (2020) 041303(R)



Search for Efimov effect



- Efimov predicted [PRL 1970] infinite series of states in three boson systems, scaling as $(22.7)^n$
- Originally, Hoyle state was considered
- Observed in ultracold Cs atoms
- It appears that Hoyle is not a Efimov state [H. Suno, et al., PRC 91, 014004 (2015)]
- Some evidence for 7.458 MeV state with alphas in mutual 92 keV resonance (Efimov?) [S. Zhang, et al., PRC 99, 044605 (2019)]

Search for Efimov effect

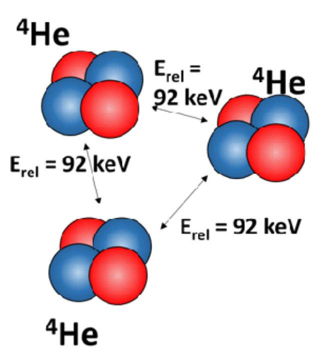
Q: Does the Efimov effect survive the Coulomb force in ^{12}C?

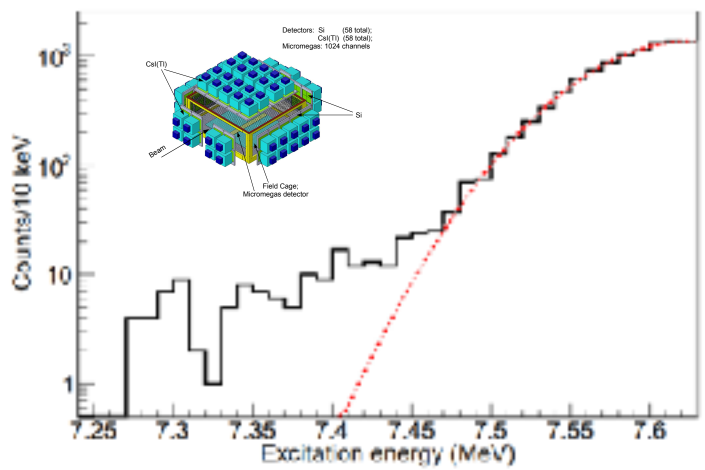
Q: Is there an additional low-lying state in 0^+ at, or around, 7.458 MeV?

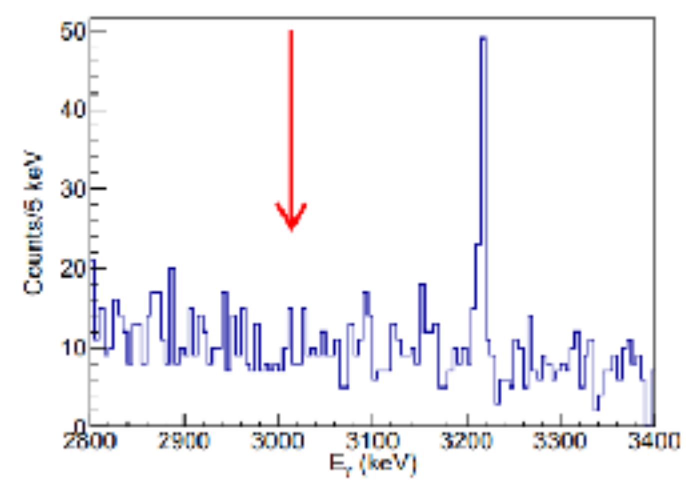
A: Populate state with β-decay and observe decay

Observe low-E decays with TexAT using beta-delayed charged-particle spectroscopy technique

Observe gamma decays from decay of ^{12}B from Gammasphere data [M. Munch, PRC 93, 065803 (2016)]

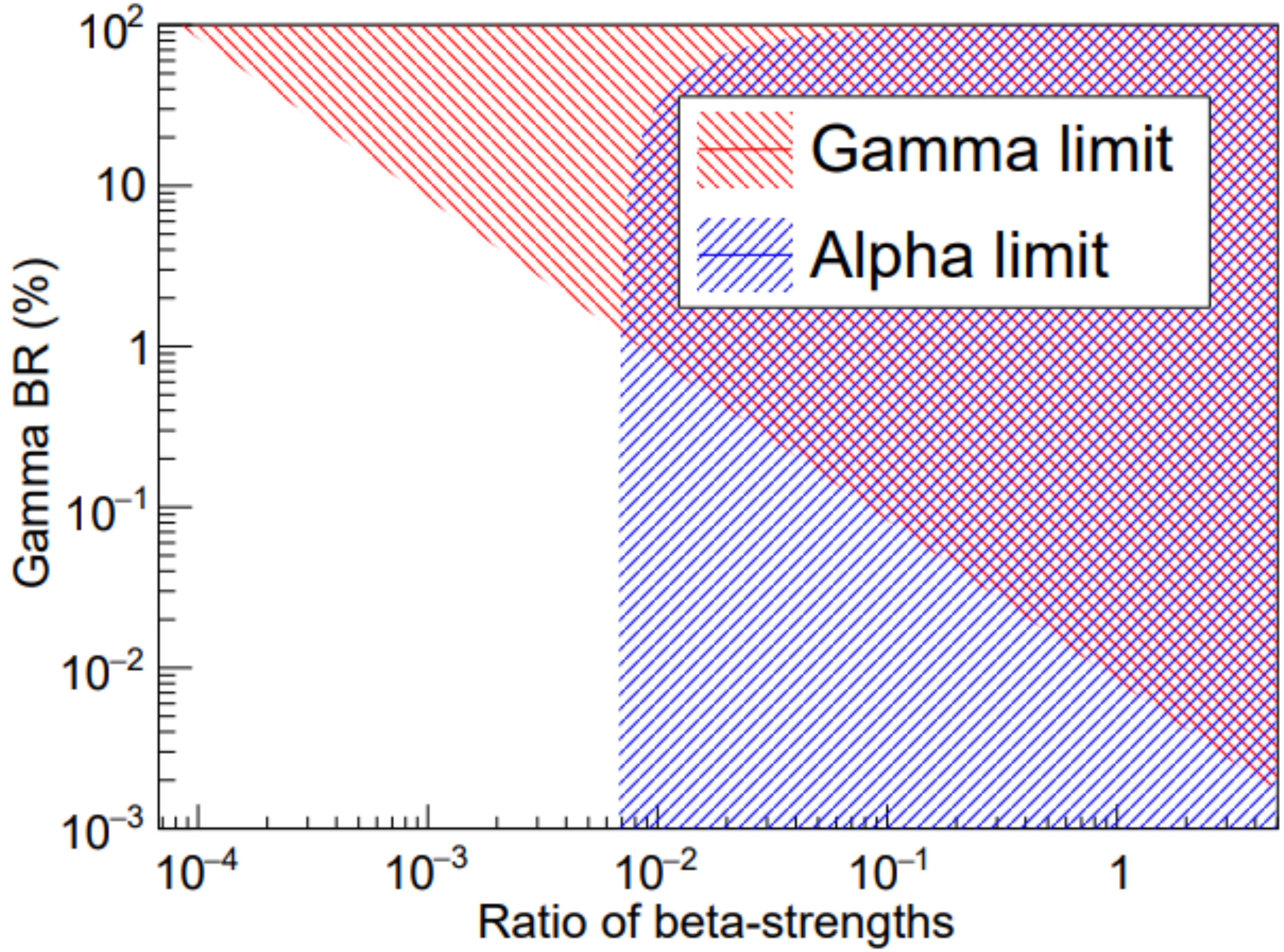






From combined alpha/gamma spectroscopy, Efimov state cannot exist unless feeding strength relative to Hoyle is <0.7% Hoyle (for all BR) or <0.01% for $BR_\gamma \approx 1$

Efimov effect: universal scale-invariant 3-body interaction

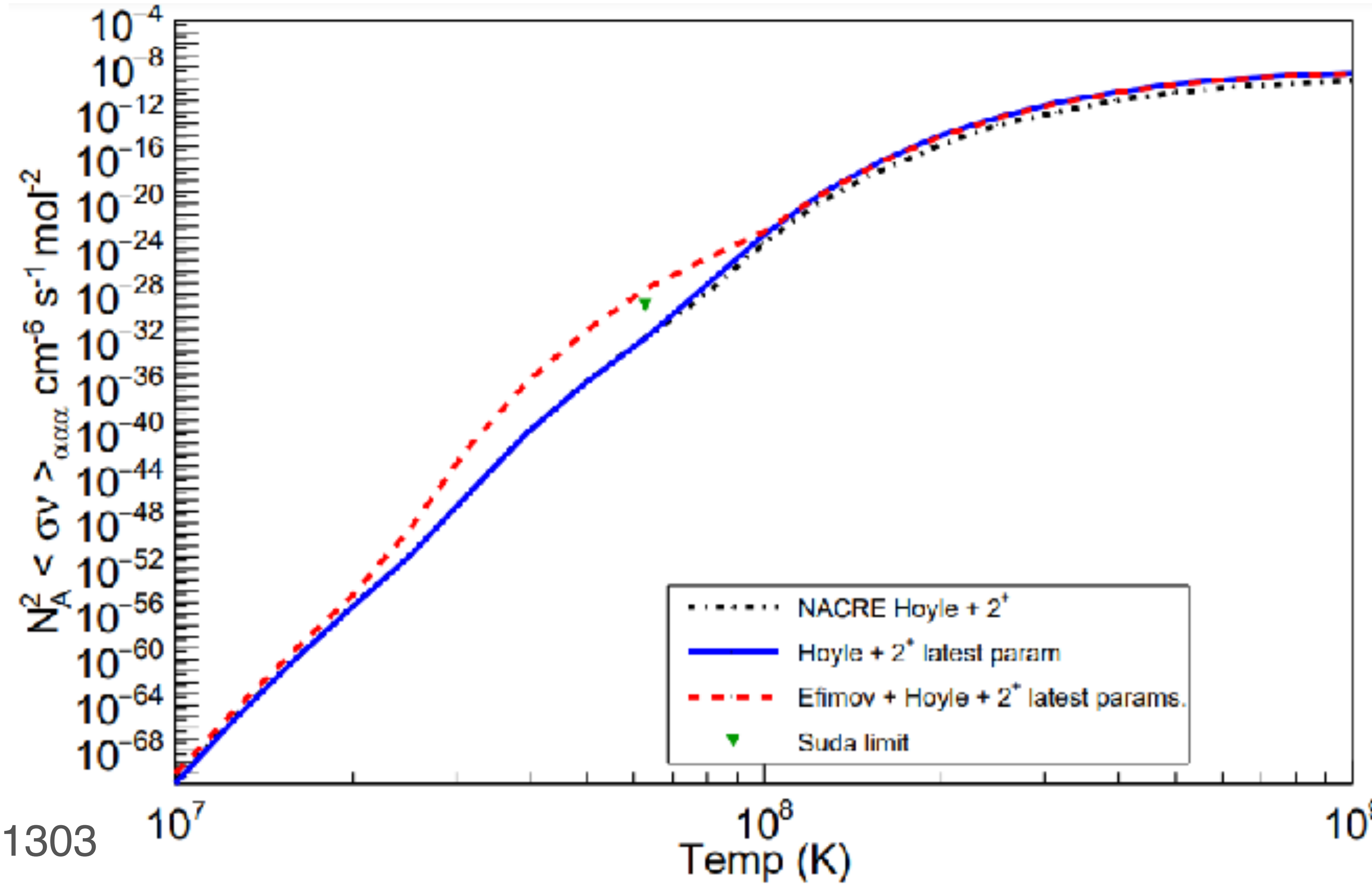


with respect to the Hoyle state

Efimov effect: universal scale-invariant 3-body interaction

Jack Bishop

J. Bishop, GR, et al.,
Phys. Rev. C **103**, (2021) L051303



Additional low-lying 0^+ greatly enhances triple-alpha reaction rate at $10^{7.8}$ K such that red giant phase is no longer possible – T. Suda et al. ApJ 741, 61 (2011)

Summary

- Clustering plays an important role in structure of light nuclei. Model independent data on clustering in g.s. are needed.
- Democratic decay of the Hoyle state was observed.
- No evidence for Efimov effect in ^{12}c.

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