Microscopic studies of clustering in light nuclei

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Clustering in light nuclei
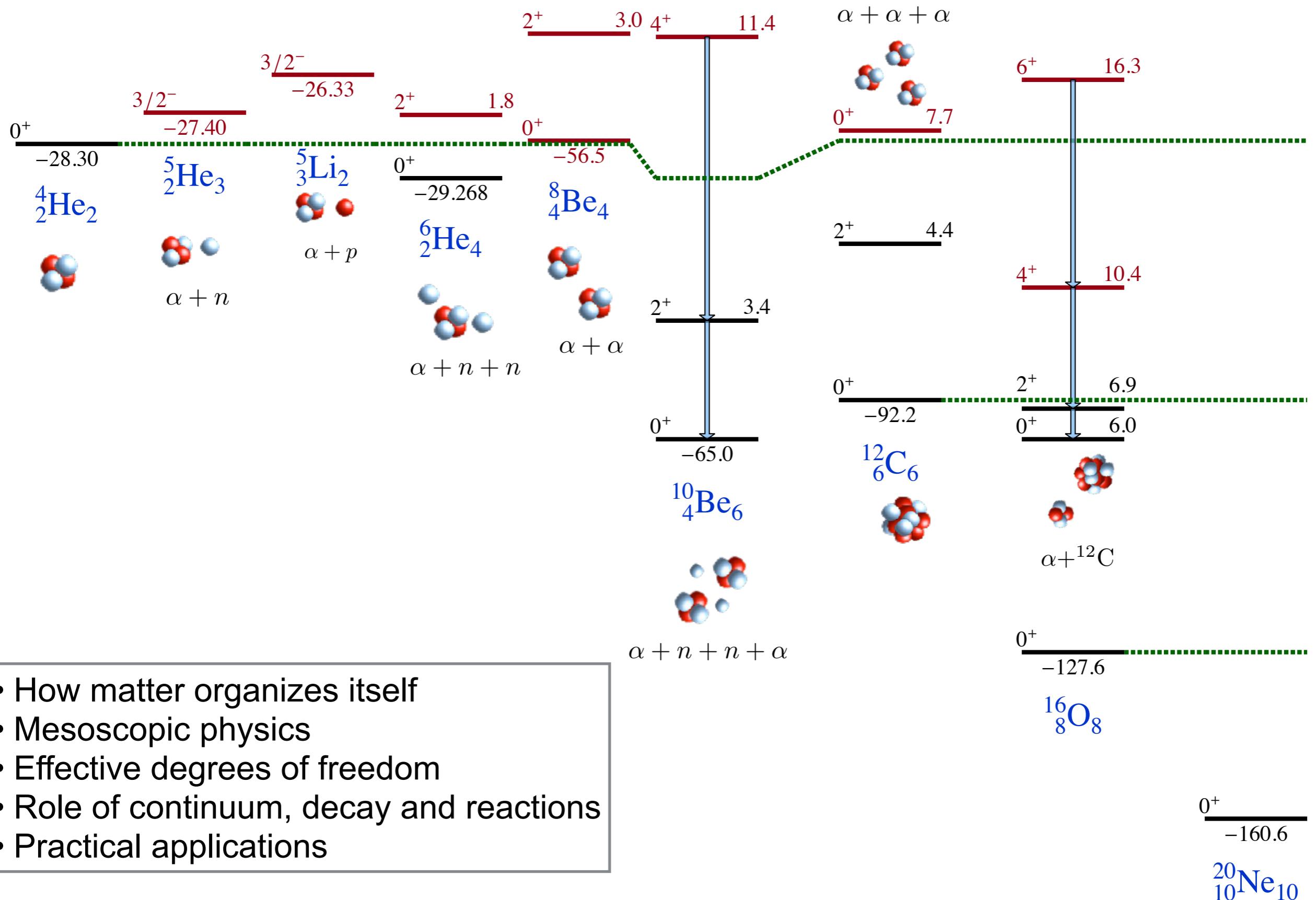
- How matter organizes itself
- Mesoscopic physics
- Effective degrees of freedom
- Role of continuum, decay and reactions
- Practical applications

The Nuclear Shell Model

The Hamiltonian

$$H = \sum_a \frac{\mathbf{p}_a^2}{2M} + \frac{1}{2} \sum_{a \neq b} U_{ab}$$

Translational invariance tells us

$$H = \frac{\mathbf{P}^2}{2MA} + H_{\text{int}} \quad \mathbf{P} = \sum_a \mathbf{p}_a$$

$$H_{\text{int}} = \frac{1}{2A} \sum_{a,b} \frac{(\mathbf{p}_a - \mathbf{p}_b)^2}{2M} + \frac{1}{2} \sum_{a \neq b} U_{ab}$$

$$\Psi = e^{i\mathbf{PR}} \Psi'$$
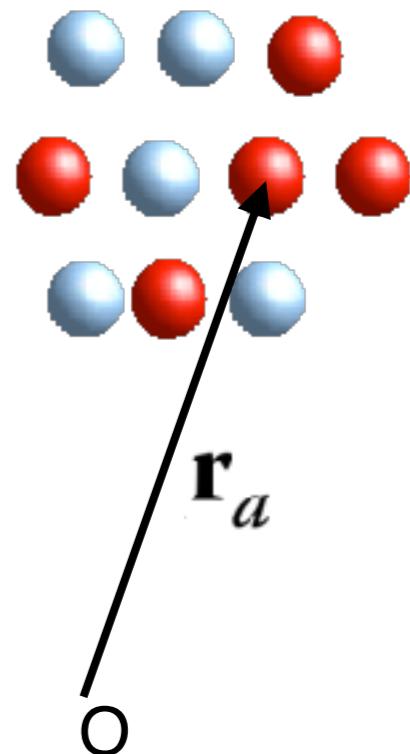
The Nuclear Shell Model

$$H = \frac{\mathbf{P}^2}{2MA} + H_{\text{int}} \quad H(\omega_0) = H + \frac{AM\omega_0^2}{2}\mathbf{R}^2 = H_{\text{cm}}(\omega_0) + H_{\text{int}}$$

$$H_{\text{cm}}(\omega_0) = \frac{\mathbf{P}^2}{2MA} + \frac{AM\omega_0^2}{2}\mathbf{R}^2 \qquad \Psi_{n\ell m} = \phi_{n\ell m}(\mathbf{R})\,\Psi'$$

$$E(\omega_0) = \hbar\omega_0(N_{\text{cm}} + 3/2) + E'$$

$$N_{\text{cm}} = 2n + \ell$$

1p,0f

1s,0d

0p

0s
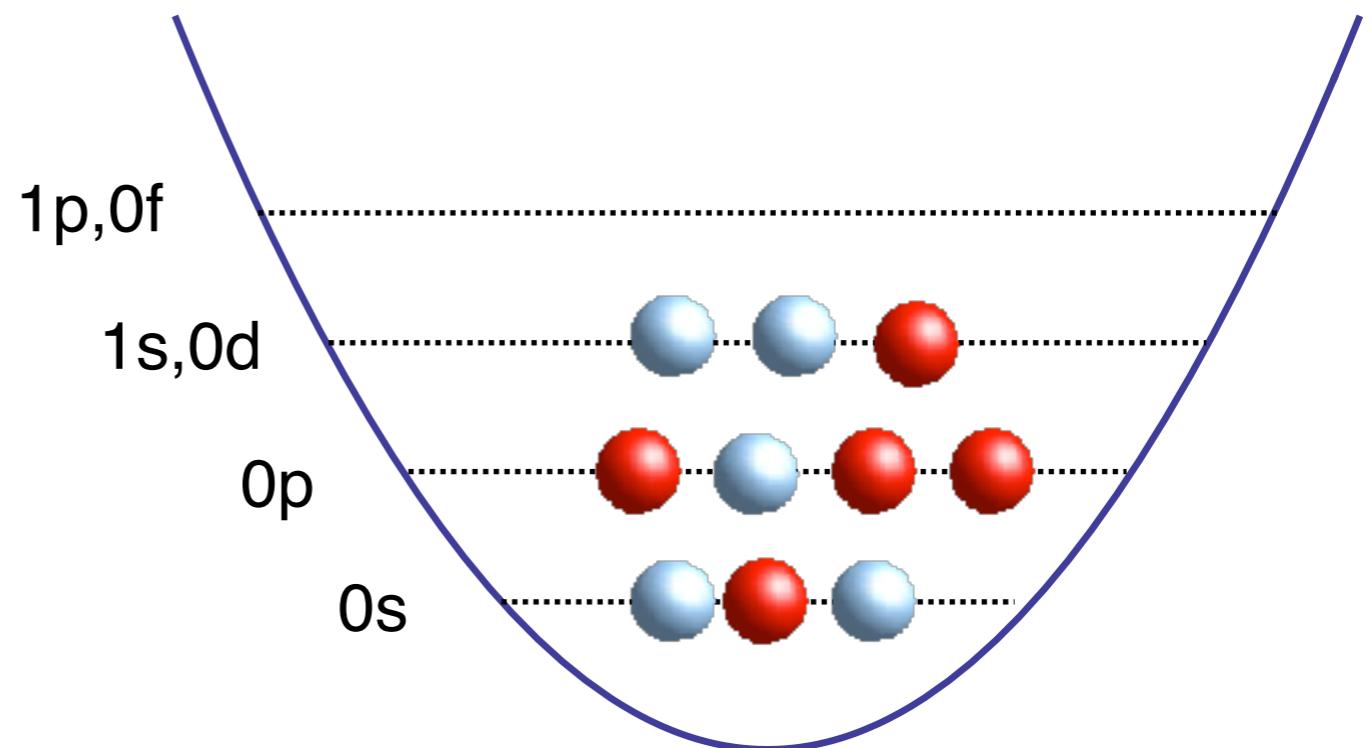
Configuration interactions (variational principle)

$$\Psi \; = \; C_1 \;\; \overset{\text{(harmonic oscillator)}}{\underset{}{}} \; + \; C_2 \;\; \overset{\text{(harmonic oscillator)}}{\underset{}{}} \; + \; C_3 \;\; \overset{\text{(harmonic oscillator)}}{\underset{}{}} \; + \ldots$$
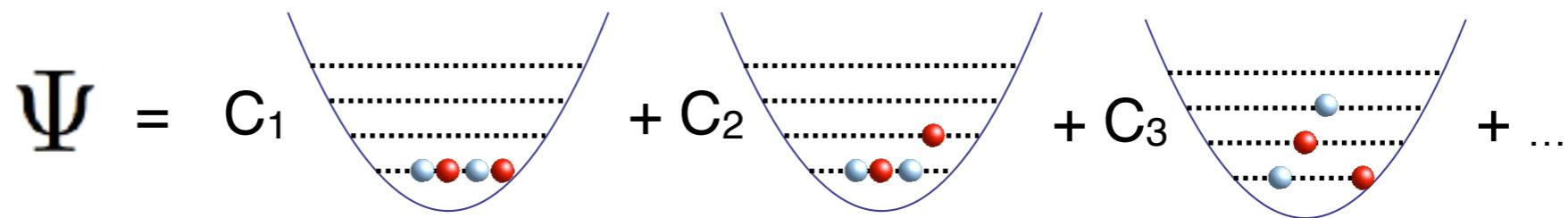
Alpha particle in no-core shell model
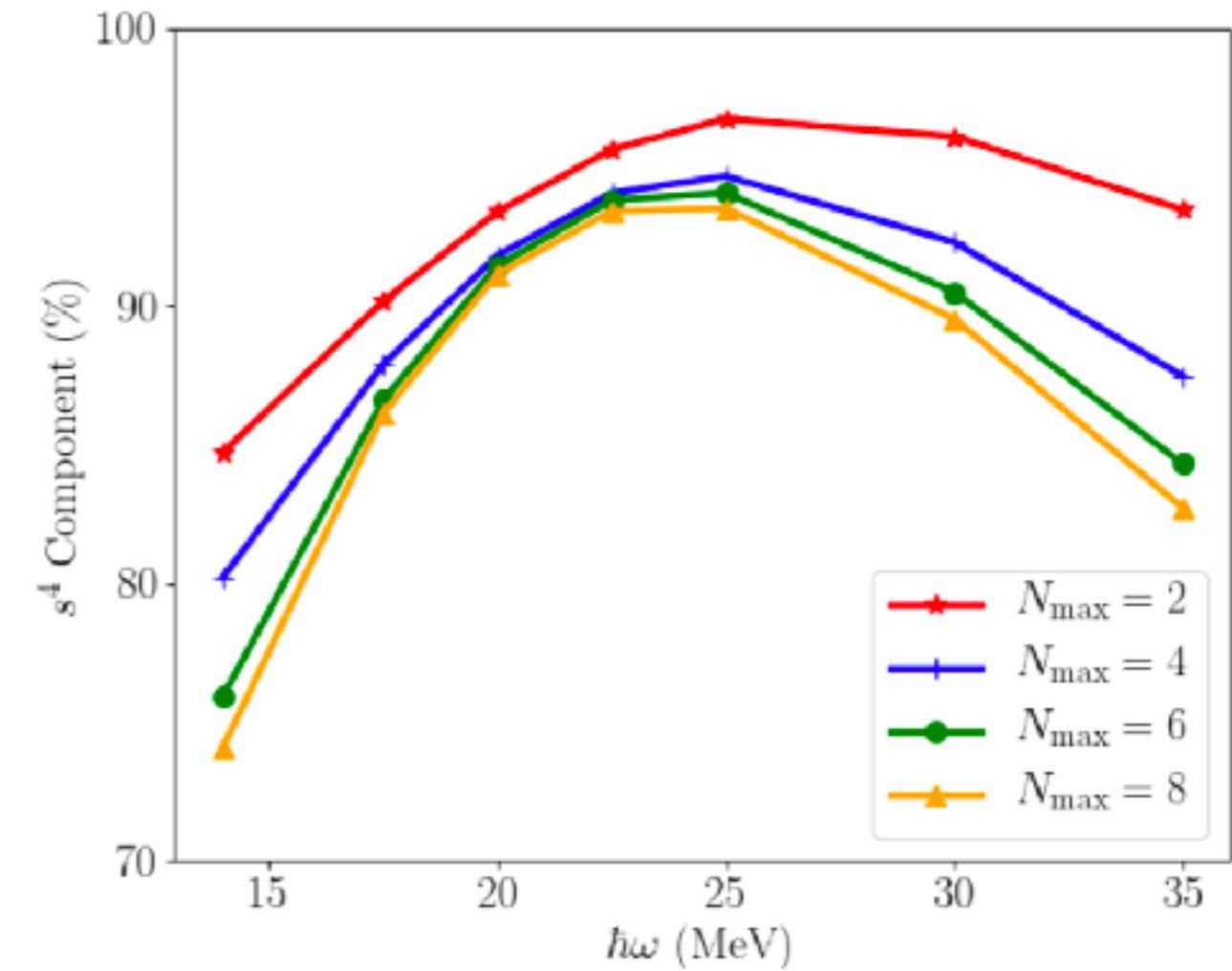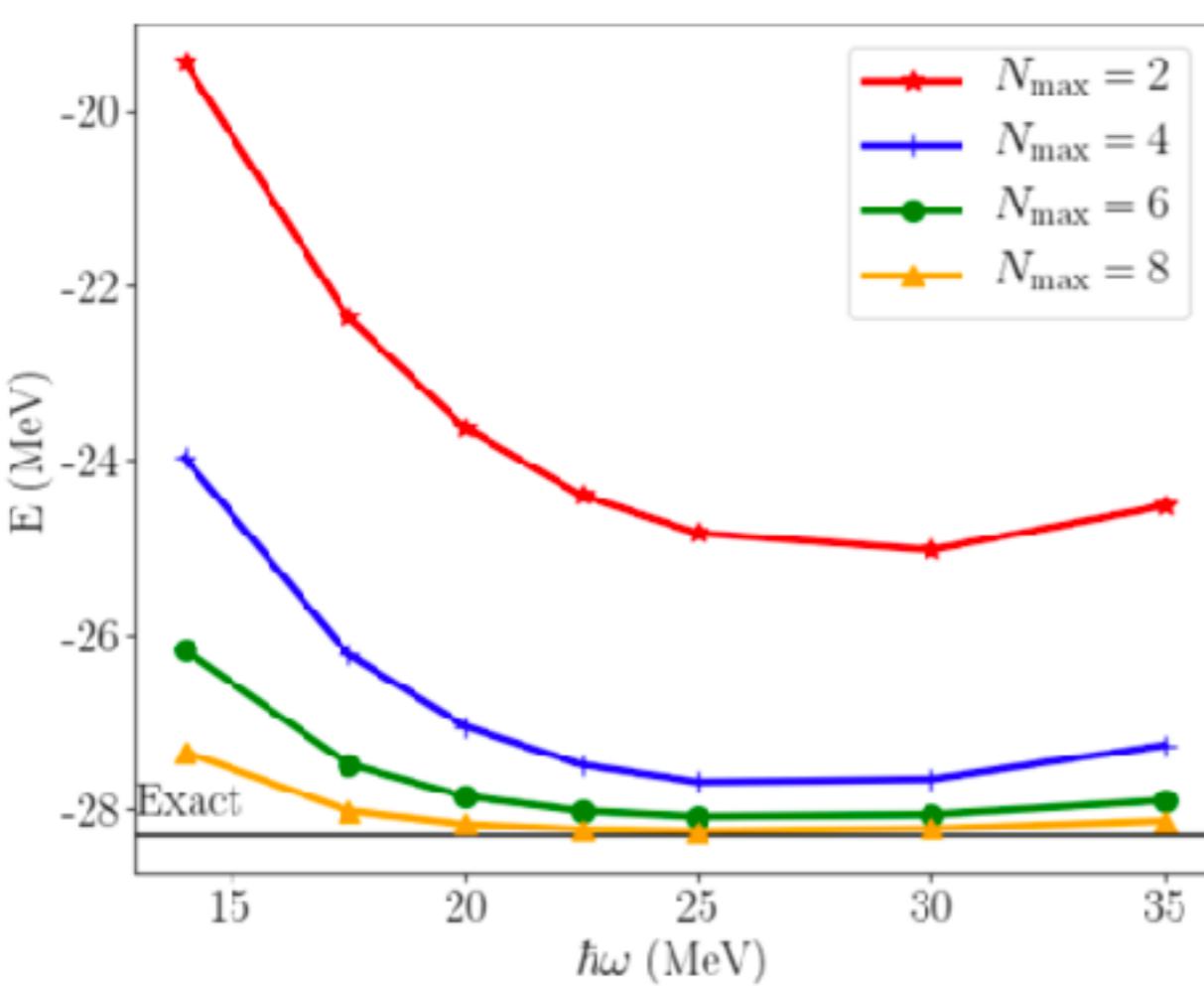
JISP-16 interaction

Translational invariance and Center of Mass (CM)

Shell model, Glockner-Lawson procedure

$$\Psi_D = \phi_{000}(\mathbf{R}_D)\,\Psi'_D$$

SM state

Center-of-mass vibration

Intrinsic state
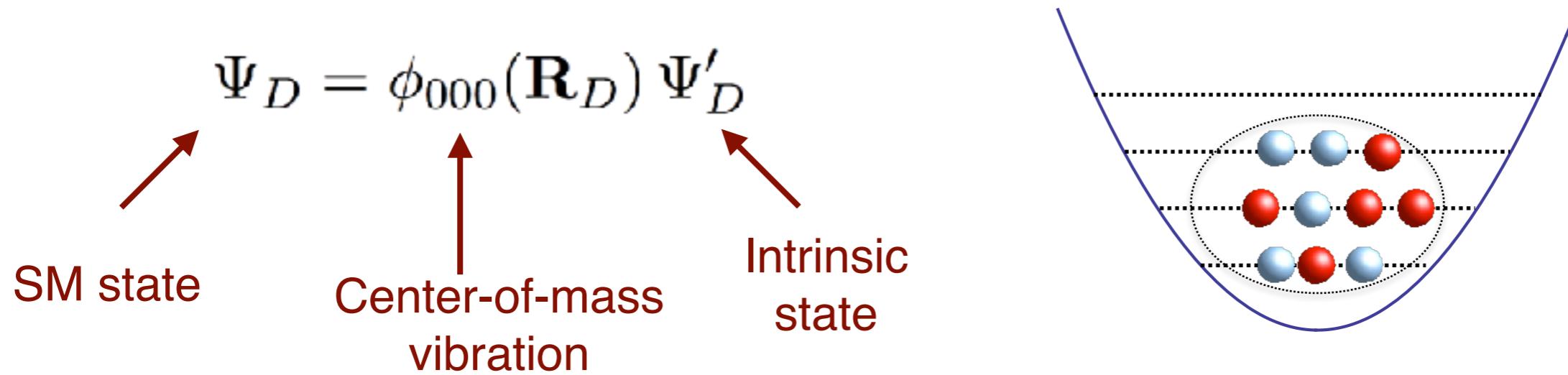
Controlling CM with operator $\mathbf{R}$

Control only CM quanta

$$D_\mu = \sqrt{\frac{4\pi}{3}}\,R_\mu \qquad R_\mu = \sqrt{\frac{\hbar}{2Am\omega}}(\mathcal{B}_\mu^\dagger + \mathcal{B}_\mu)$$

Center-of-Mass boosts

$$\Psi_{n\ell m} = \phi_{n\ell m}(\mathbf{R})\,\Psi'$$

$\mathcal{B}^\dagger$ and $\mathcal{B}$ CM quanta creation and annihilation (vectors)

$$\Psi_{n+1\,\ell m} \propto \mathcal{B}^\dagger \cdot \mathcal{B}^\dagger \,\Psi_{n\ell m}$$

$\mathcal{B}^\dagger \times \mathcal{B}$ CM angular momentum operator
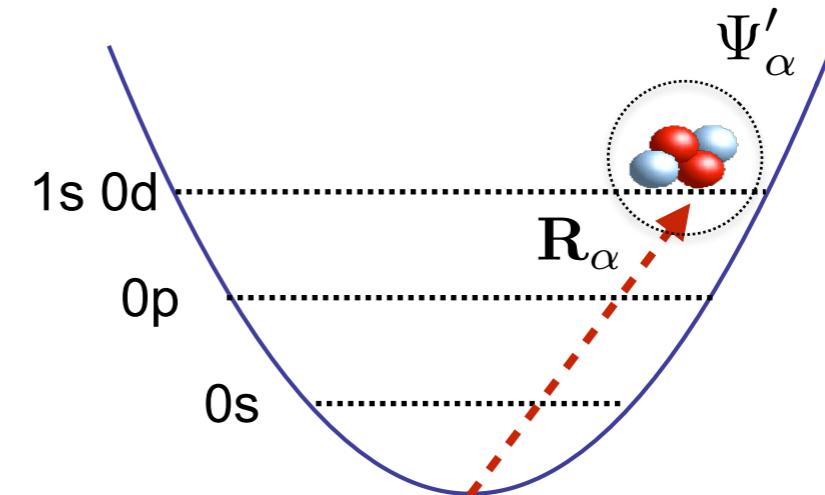
$$N = 2n + \ell$$

Select configuration content of NCSM wave functions for ^{4}He with hΩ = 20 MeV boosted by 8 quanta (L = 0).

Configuration	$N_{\text{max}} = 0$	$N_{\text{max}} = 4$
$(sd)^4$	0.038	0.035
$(p)(sd)^2(pf)$	0.308	0.282
$(p)^2(pf)^2$	0.103	0.094
$(p)^2(sd)(sdg)$	0.154	0.141
$(p)(sd)(sdg)(pfh)$	0.000	0.005
$(p)(sd)(pf)(sdg)$	0.000	0.009

K Kravvaris and A. Volya, Journal of Phys, Conf. Proc. 863, 012016 (2017)

CM-boosted configuration from shell model perspective
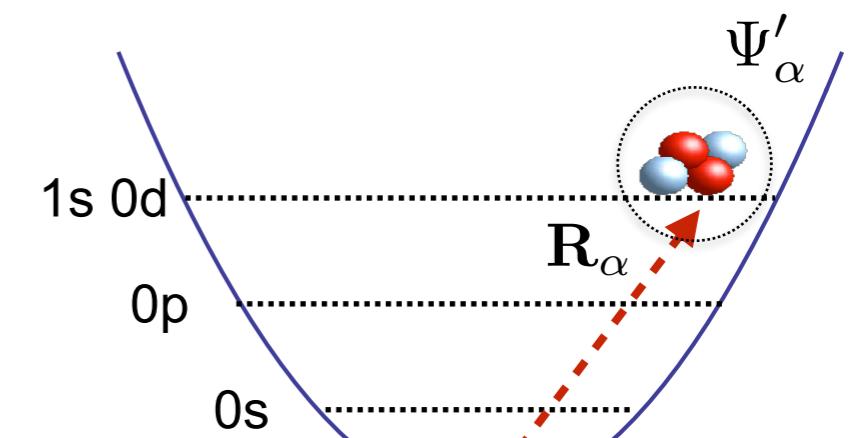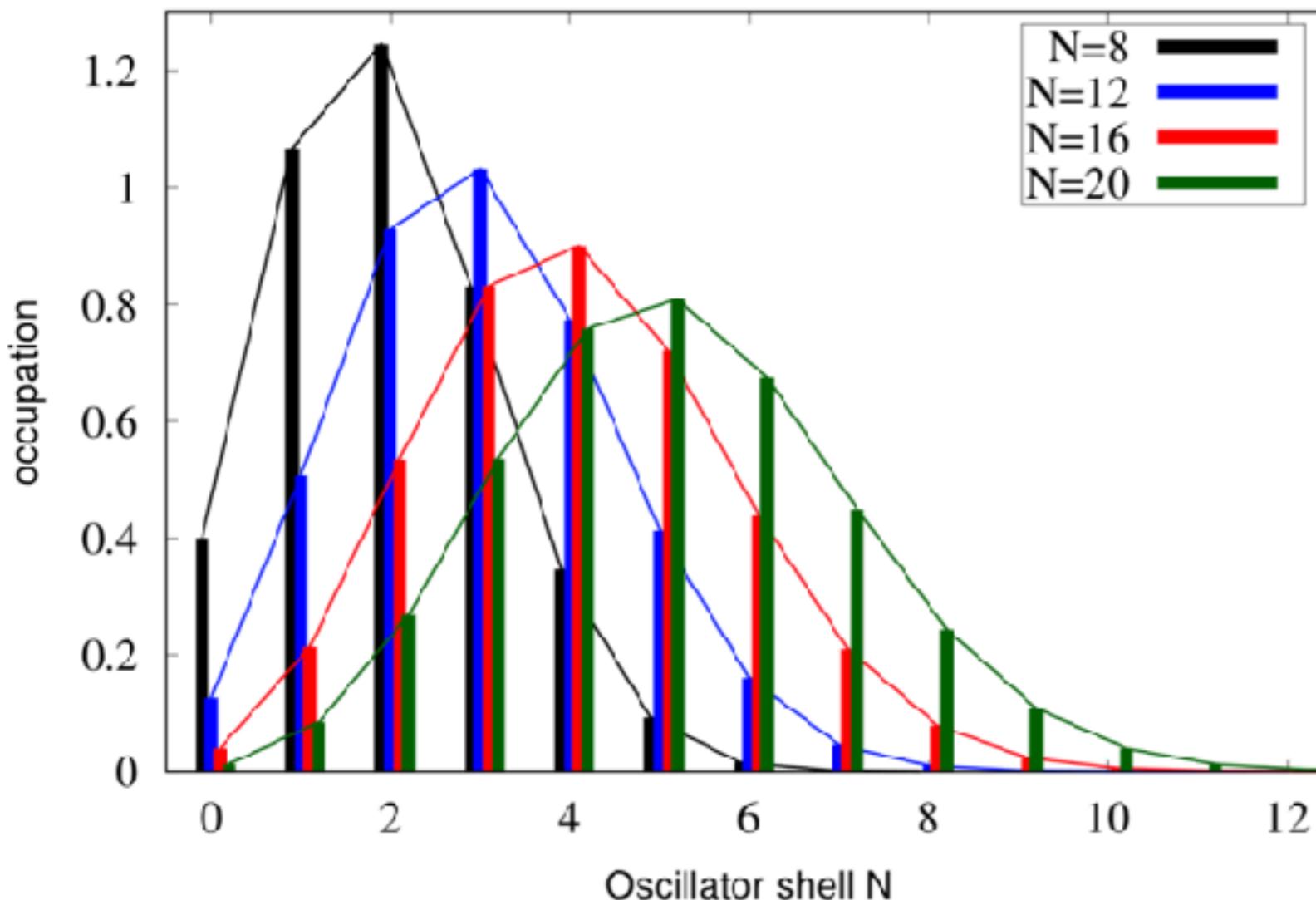
CM-boosted configuration from shell model perspective

$$\langle \mathbf{R}^2 \rangle = \frac{\hbar}{M\omega_0}(N_{\mathrm{cm}} + 3/2) \qquad |\phi_{n\ell}(r)|^2 \sim \frac{1}{\sqrt{\langle \mathbf{R}^2 \rangle - r^2}}$$
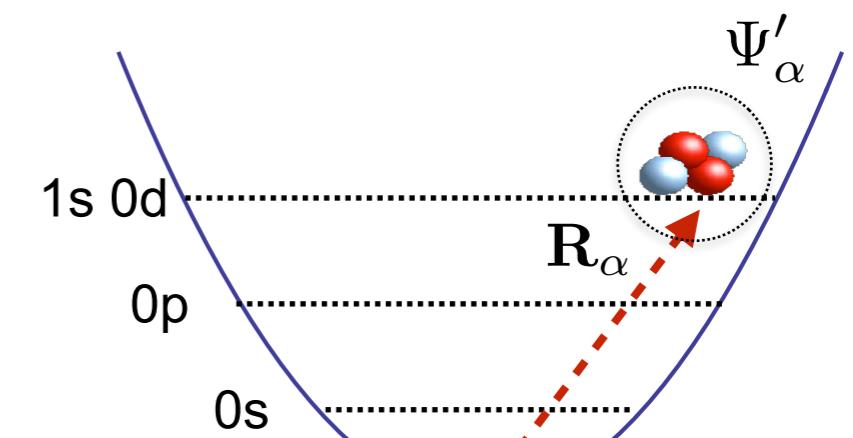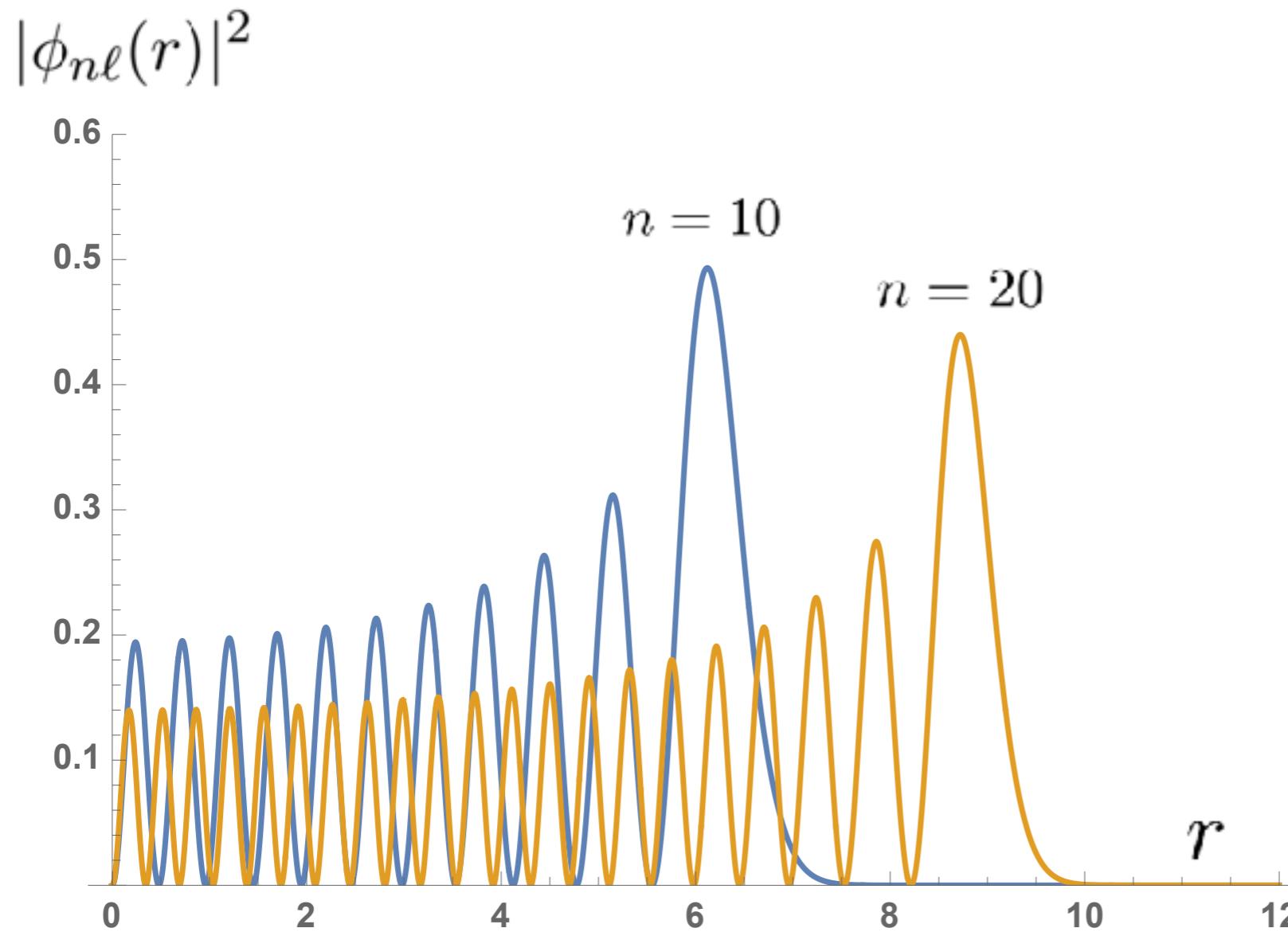
Configuration Interaction

State, equivalent to operator (polymorphism)

$$|\Psi\rangle \equiv \hat{\Psi}^\dagger|0\rangle = \sum_{\{1,2,3,\ldots A\}} \langle 1,2\ldots A|\Psi\rangle \, \hat{a}_1^\dagger \hat{a}_2^\dagger \ldots \hat{a}_A^\dagger|0\rangle$$

$$|\Psi_\alpha\rangle = \Psi_\alpha^\dagger|\rangle = \sum_{\{m\}} X_m^\alpha a_{m_1}^\dagger a_{m_2}^\dagger a_{m_3}^\dagger a_{m_4}^\dagger|\rangle$$

$$|\Psi_{\mathrm{D}}\rangle = \Psi_{\mathrm{D}}^\dagger|\rangle = \sum_{\{m\}} X_m^{\mathrm{D}} a_{m_1}^\dagger a_{m_2}^\dagger \ldots a_{m_{A_{\mathrm{D}}}}^\dagger|\rangle$$

Anti-symmetrized channel wave function components are generated by acting with state creation operator and forward ordering.

$$|\Psi_{\mathrm{C}}\rangle = \Psi_\alpha^\dagger \Psi_{\mathrm{D}}^\dagger|\rangle$$

Code at http://www.volya.net [cosmo]

Configuration interaction approach and clustering

Traditional shell model configuration m-scheme
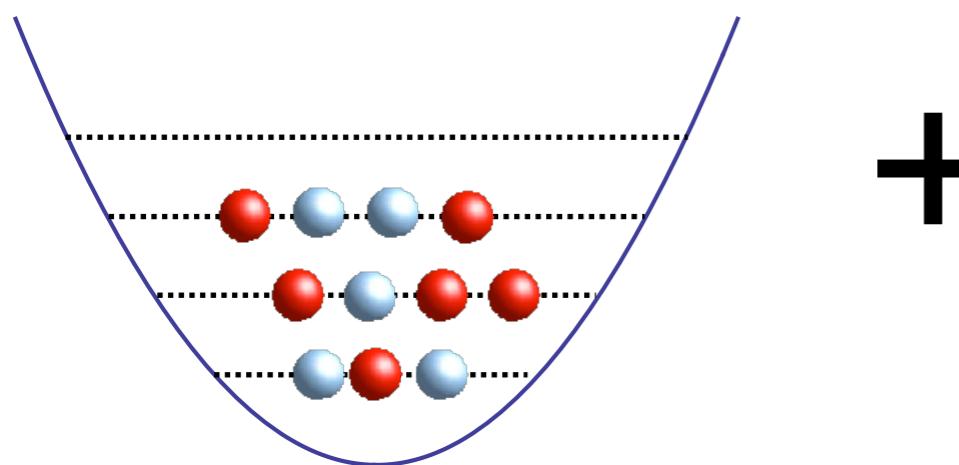
Cluster configuration

$$|\text{channel}\rangle \sim |\Phi \Psi_D\rangle \equiv \Phi^\dagger \Psi_D^\dagger |0\rangle$$

$$|\Psi\rangle = \Psi^\dagger |0\rangle \sim a_1^\dagger a_2^\dagger \dots a_A^\dagger |0\rangle$$

Φ

Ψ_D

$+$
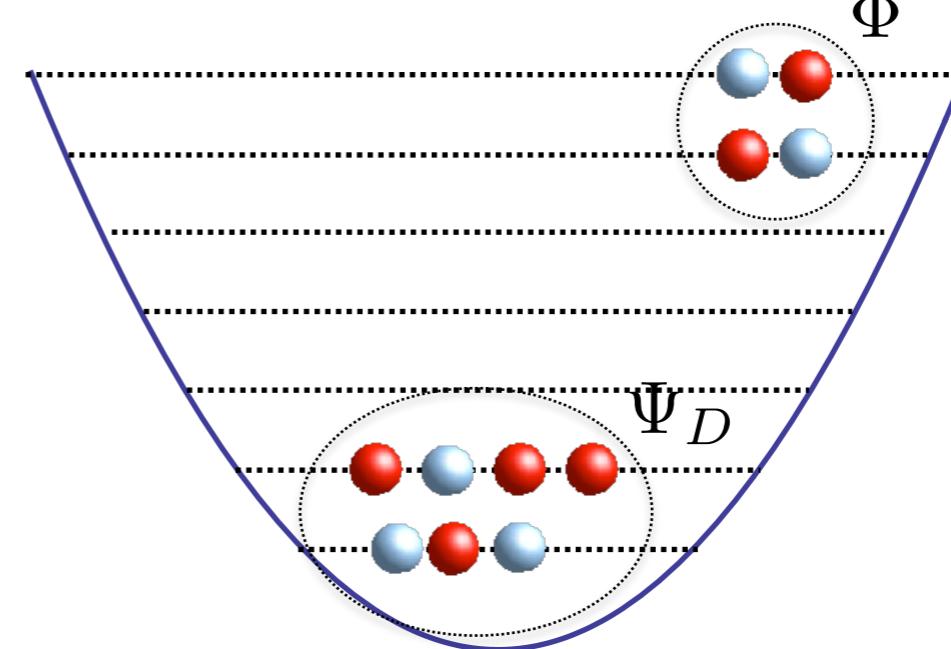
$|\Psi\rangle$ $+$ $\Phi^\dagger |\Psi_D\rangle$

Recoil Recoupling
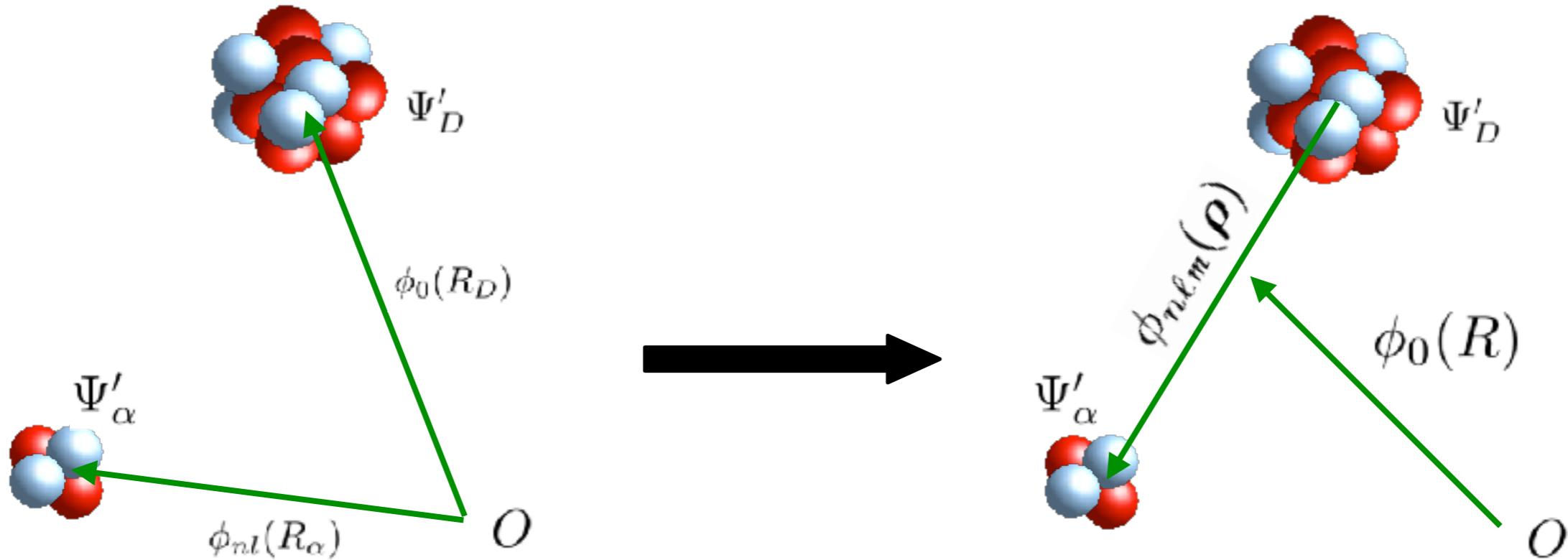
- Recoupling is done with Talmi-Moshinsky brackets

$$\Phi_{n\ell m} = \mathcal{A}\left\{\phi_{000}(\mathbf{R})\phi_{n\ell m}(\boldsymbol{\rho})\Psi'^{(1)}\Psi'^{(2)}\right\}$$

Clustering reaction basis channel
(basis states for clustering)

$$\Psi = \phi_{000}(\mathbf{R})\Psi'$$

Boost

$$\Psi_{n\ell m} = \phi_{n\ell m}(\mathbf{R})\,\Psi'$$

CM-Recouple

$$\Phi_{n\ell m} = \mathcal{A}\left\{\phi_{000}(\mathbf{R})\phi_{n\ell m}(\boldsymbol{\rho})\Psi'^{(1)}\Psi'^{(2)}\right\}$$
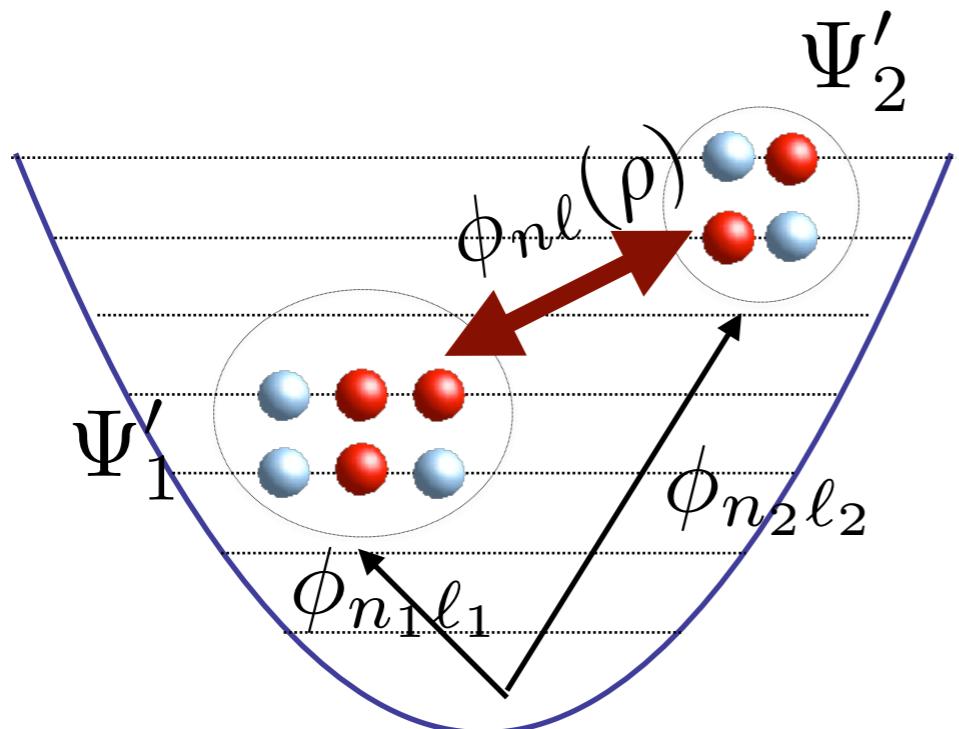
$$\Phi^\dagger_{n\ell} = \sum_{\substack{n_1\ell_1 \\ n_2\ell_2}} \mathcal{M}^{n\ell 00;\ell}_{n_1\ell_1 n_2\ell_2} \left[\Psi^\dagger_{n_1\ell_1 m_1} \times \Psi^\dagger_{n_2\ell_2 m_2}\right]_\ell$$

Resonating group method ⁸Be

$$\mathcal{F}_\ell(\rho) = \sum_n \chi_n \Phi_{n\ell}$$

$$\sum_n \mathcal{H}^{(\ell)}_{nn'} \chi_{n'} = E \sum_n \mathcal{N}^{(\ell)}_{nn'} \chi_{n'}$$

$$\mathcal{H}^{(\ell)}_{nn'} = \langle \Phi_{n\ell} | H | \Phi_{n'\ell} \rangle \qquad \mathcal{N}^{(\ell)}_{nn'} = \langle \Phi_{n\ell} | \Phi_{n'\ell} \rangle$$
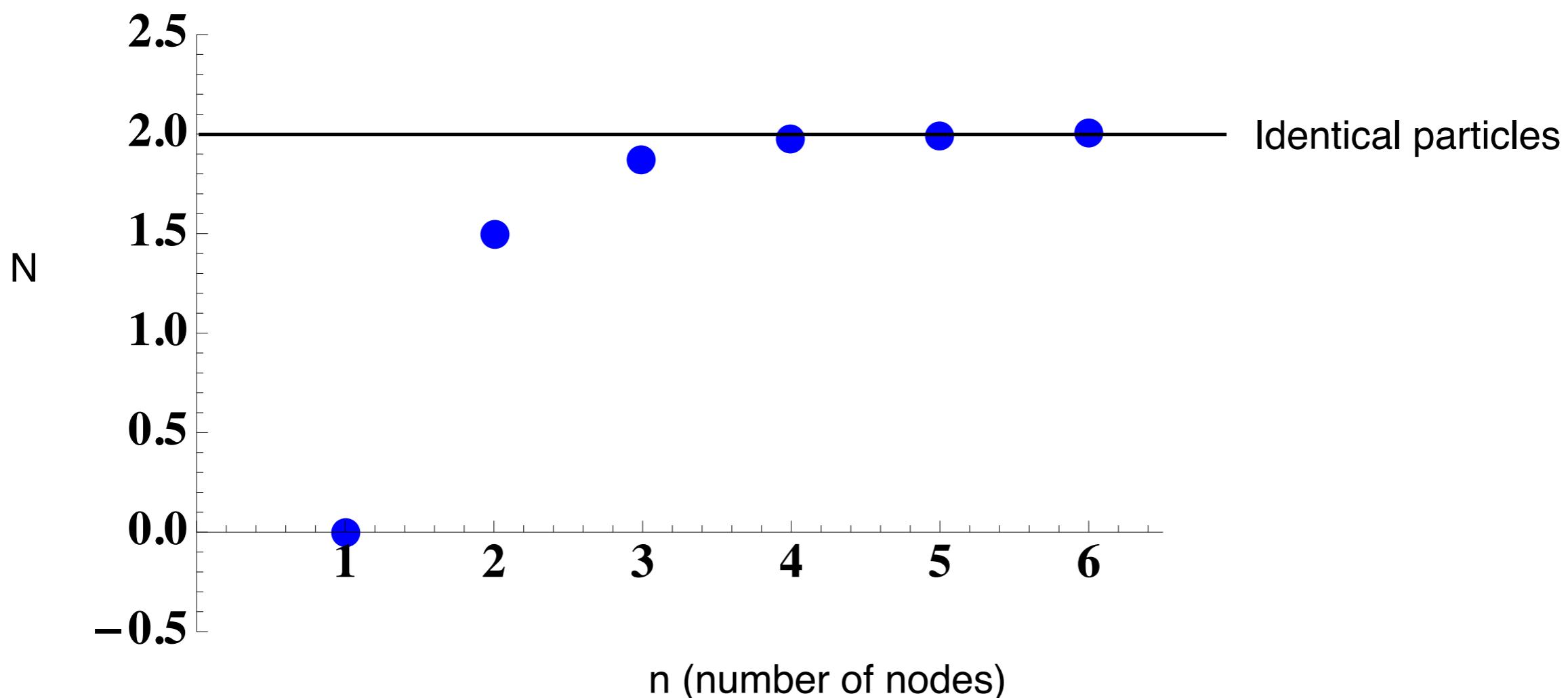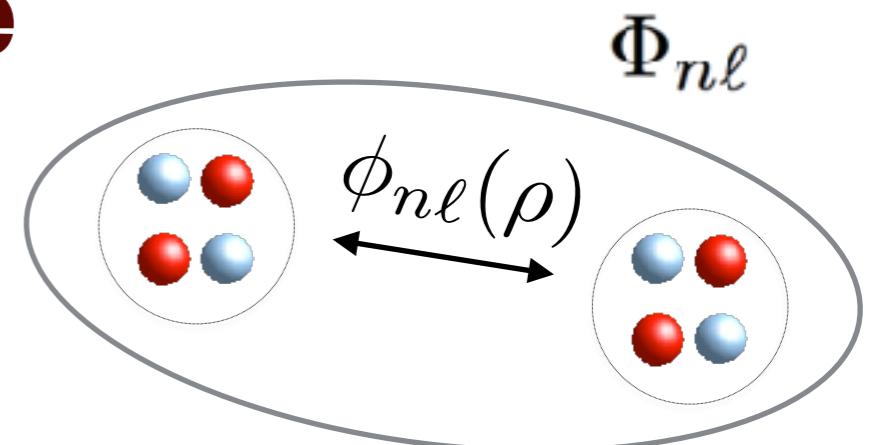
Resonating group method and reactions

$$\sum_n \mathcal{H}_{nn'}^{(\ell)} \chi_{n'} = E \sum_n \mathcal{N}_{nn'}^{(\ell)} \chi_{n'}$$

$$\begin{pmatrix} \mathcal{H}_{00} & \ldots & \mathcal{H}_{0n} & 0 & 0 & 0 \\ \vdots & \ddots & \vdots & 0 & \vdots & \vdots \\ \mathcal{H}_{n0} & \ldots & \mathcal{H}_{nn} & T_{nn+1} & 0 & \vdots \\ 0 & 0 & T_{n+1n} & T_{n+1n+1} & T_{n+1n+2} & 0 \\ 0 & \ldots & 0 & T_{n+2n+1} & T_{n+2n+2} & \ddots \\ 0 & \ldots & \ldots & 0 & \ddots & \ddots \end{pmatrix} \begin{pmatrix} \chi_0 \\ \vdots \\ \chi_n \\ x_{n+1} \\ x_{n+2} \\ \vdots \end{pmatrix} = E \begin{pmatrix} \mathcal{N}_{00} & \ldots & \mathcal{N}_{0n} & 0 & 0 & 0 \\ \vdots & \ddots & \vdots & 0 & \vdots & \vdots \\ \mathcal{N}_{n0} & \ldots & \mathcal{N}_{nn} & 0 & 0 & \vdots \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & \ldots & 0 & 0 & 1 & 0 \\ 0 & \ldots & \ldots & 0 & 0 & \ddots \end{pmatrix} \begin{pmatrix} \chi_0 \\ \vdots \\ \chi_n \\ x_{n+1} \\ x_{n+2} \\ \vdots \end{pmatrix}$$
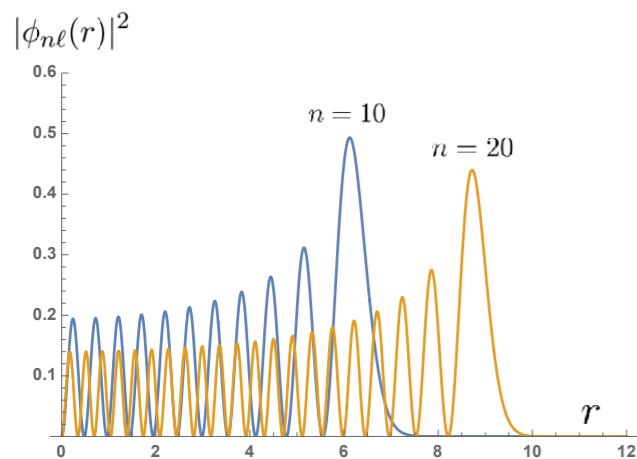
Asymptotic solution with phase shift

$|\phi_{n\ell}(r)|^2$

$\mathcal{N}_{nn}$

$\alpha + \alpha$
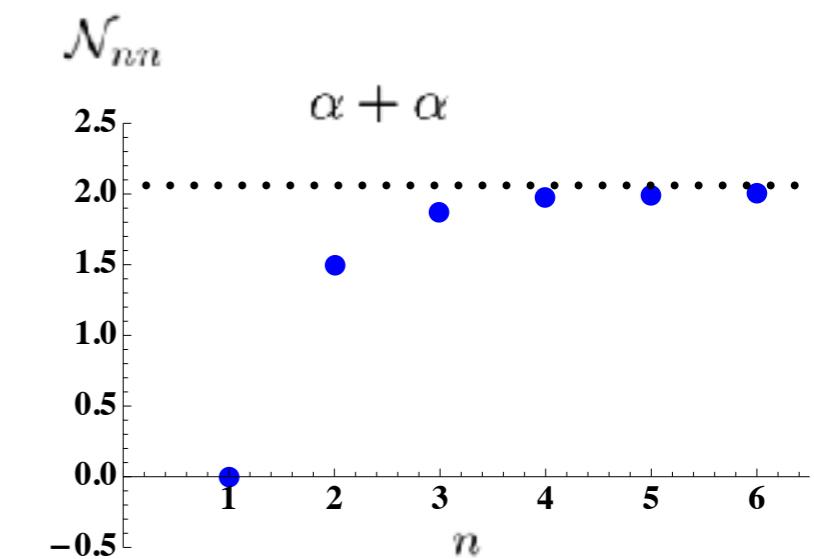
J-matrix (or HORSE) method: J. M. Bang, Annals of Physics **280**, 299 (2000)
Experimental data: Phys. Rev. 168, 1114 (1968); Nucl. Phys. **A287**, 317 (1977)

alpha+alpha scattering phase shifts

L=2

— N=12
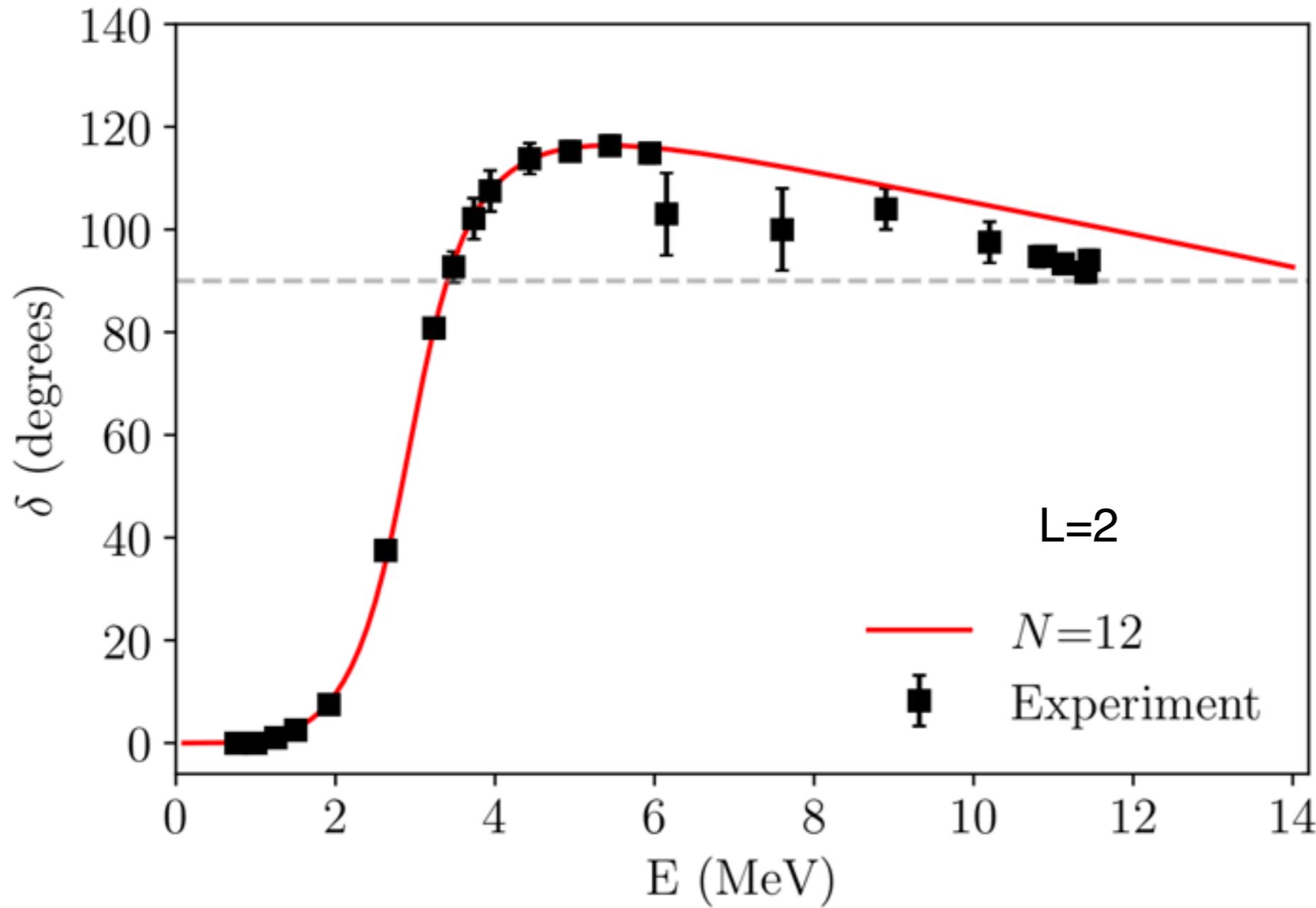
■ Experiment

Experimental data from S. A. Afzal, A. A. Z. Ahmad, and S. Ali, Rev. Mod. Phys. 41, 247 (1969).

Resonating group method ⁸Be results
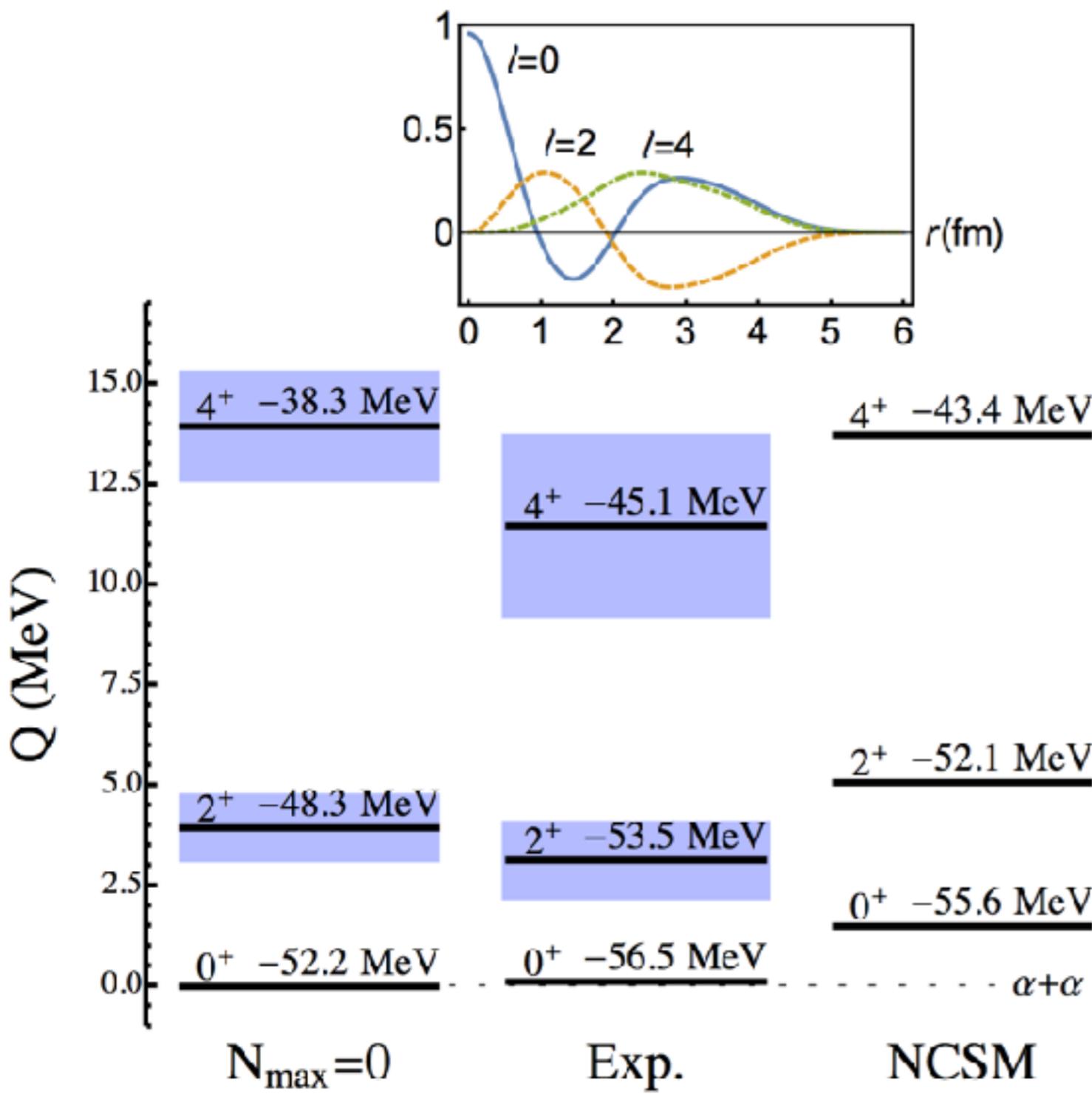
		Theory	Exp.
l=0	ev	8.7	5.6
l=2	MeV	1.3	1.5
l=4	MeV	2.1	3.5

Spectroscopic amplitudes
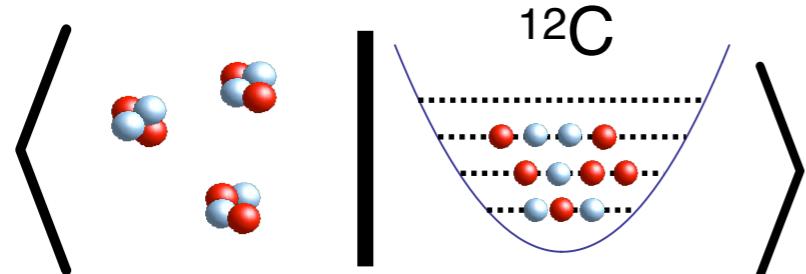
parent	J^π	channel	$|\langle\Psi|\mathcal{F}_\ell\rangle|$
^{8}Be[4]	0^+	$\alpha[0]+\alpha[0]$	0.905
^{8}Be[4]	2^+	$\alpha[0]+\alpha[0]$	0.898
^{8}Be[4]	4^+	$\alpha[0]+\alpha[0]$	0.874
^{8}Be[4]	0^+	$\alpha[2]+\alpha[2]$	0.961
^{8}Be[4]	2^+	$\alpha[2]+\alpha[2]$	0.957
^{8}Be[4]	4^+	$\alpha[2]+\alpha[2]$	0.943
^{10}Be[4]	0^+	^{6}He[0]$+\alpha[0]$	0.844
^{10}Be[4]	0^+	^{6}He[4]$+\alpha[0]$	0.820
^{10}Be[4]	2^+	^{6}He[0]$+\alpha[0]$	0.834
^{10}Be[4]	2^+	^{6}He[4]$+\alpha[0]$	0.796
^{12}C[4]	0_1^+	$\alpha[0]+\alpha[0]+\alpha[0]$	0.841
^{12}C[4]	0_2^+	$\alpha[0]+\alpha[0]+\alpha[0]$	0.229

Spectroscopic amplitudes.

Ttriple-alpha RGM

$N_{max}(rel)=12$

$$\left\langle \; \middle| \; ^{12}C \; \right\rangle$$
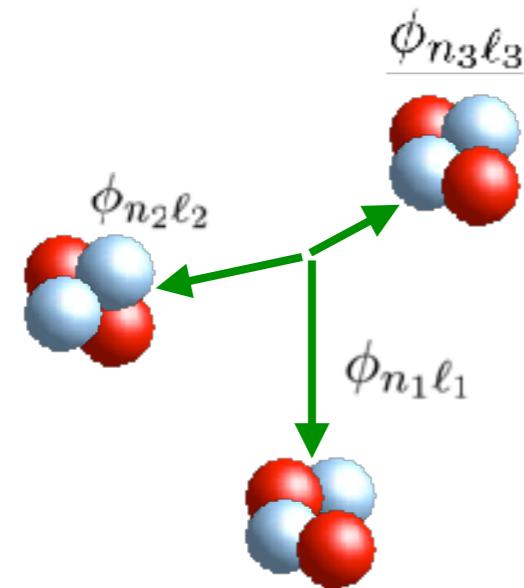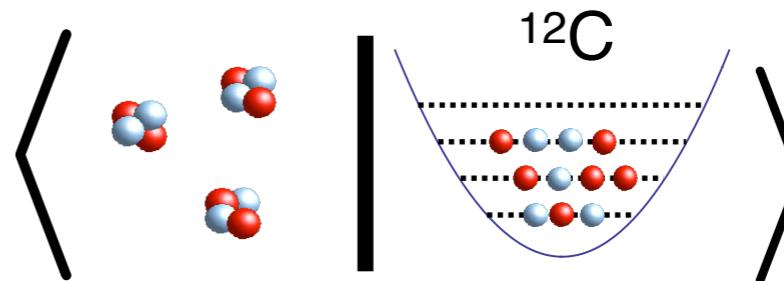
parent	channel	overlap
$^{12}C[4](0_1^+)$	$\alpha[0] + \alpha[0] + \alpha[0]$	0.841
$^{12}C[4](0_2^+)$	$\alpha[0] + \alpha[0] + \alpha[0]$	0.229

$$\left| \left\langle \; ^{8}Be+\alpha \; \middle| \; \alpha+\alpha+\alpha \; \right\rangle \right|^2 = 0.89$$

Molecular orbits ²¹Ne

(^{16}O+α)+n

$\mathcal{H}_{nn}$

E (MeV)

Basis	RGM	USDB	Experiment
$5/2^+$(L=2) 3.63	$5/2^+$ 3.858	$5/2^+$ 3.7185	$5/2^+$ 3.735
$9/2^+$(L=2) 3.50			
$3/2^+$(L=4) 3.30			
$5/2^+$(L=4) 2.89	$9/2^+$ 2.921	$1/2^+$ 2.859	$9/2^+$ 2.866
	$1/2^+$ 2.754	$9/2^+$ 2.831	$1/2^+$ 2.794
$1/2^+$(L=2) 2.57			
$7/2^+$(L=2) 1.87		$7/2^+$ 1.757	$7/2^+$ 1.745
	$7/2^+$ 1.523		
$5/2^+$(L=0) 1.04			
	$5/2^+$ 0.449		$5/2^+$ 0.35
		$5/2^+$ 0.266	
$3/2^+$(L=2) −43.5	$3/2^+$ −43.7	$3/2^+$ −47.2	$3/2^+$ −47.2
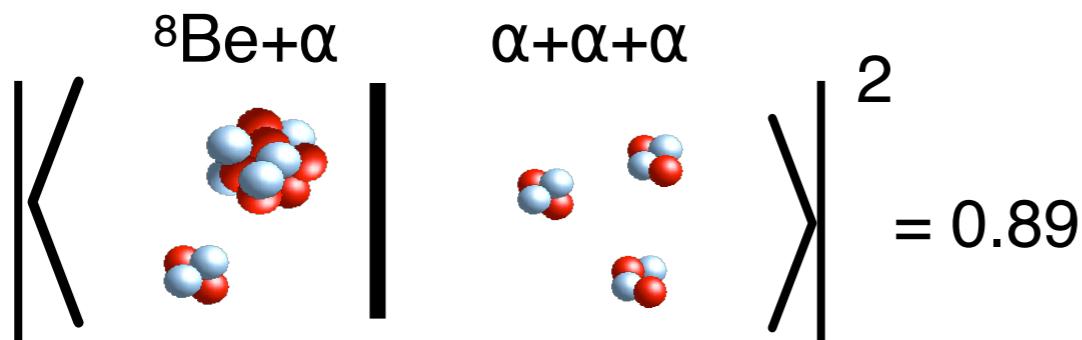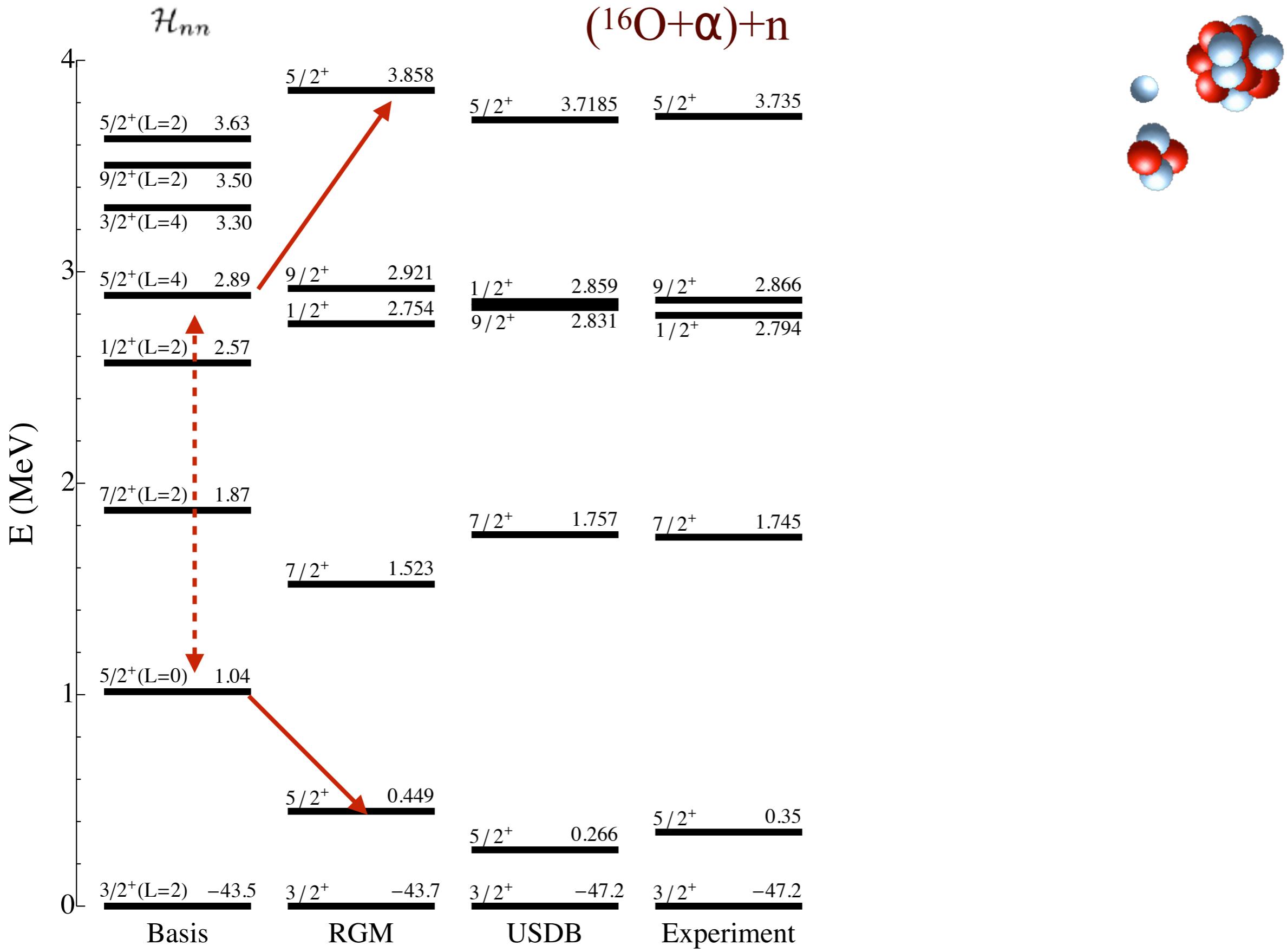
Weak-Coupling Behavior

J^π	$\mathcal{S}^{(new)}$			$\mathcal{S}^{(exp)}$		
	$\ell = 0$	$\ell = 2$	$\ell = 4$	$\ell = 0$	$\ell = 2$	$\ell = 4$
3/2+		1.0	0.18		1.0 ± 0.05	0.42 ± 0.04
5/2+	0.78	0.02	0.44	1.04 ± 0.41	...	0.32 ± 0.18
7/2+		0.9	0.14		0.91 ± 0.08	0.23 ± 0.04
9/2+,1/2+		0.81	0.33		0.9 ± 0.05	0.29 ± 0.03

N. Anantaraman, J. P. Draayer, H. E. Gove, J. Tˉoke, and H. T. Fortune. Alpha-particle stripping to ^{21}Ne. Phys.Rev. C18, 815 (1978); Phys.Lett. 74B, 199 (1978)

A. K. Nurmukhanbetova, V. Z. Goldberg, D. K. Nauruzbayev, M. S. Golovkov, A. Volya, Phys. Rev. C 100 (2019) 062802.

Clustering in ²⁰Ne
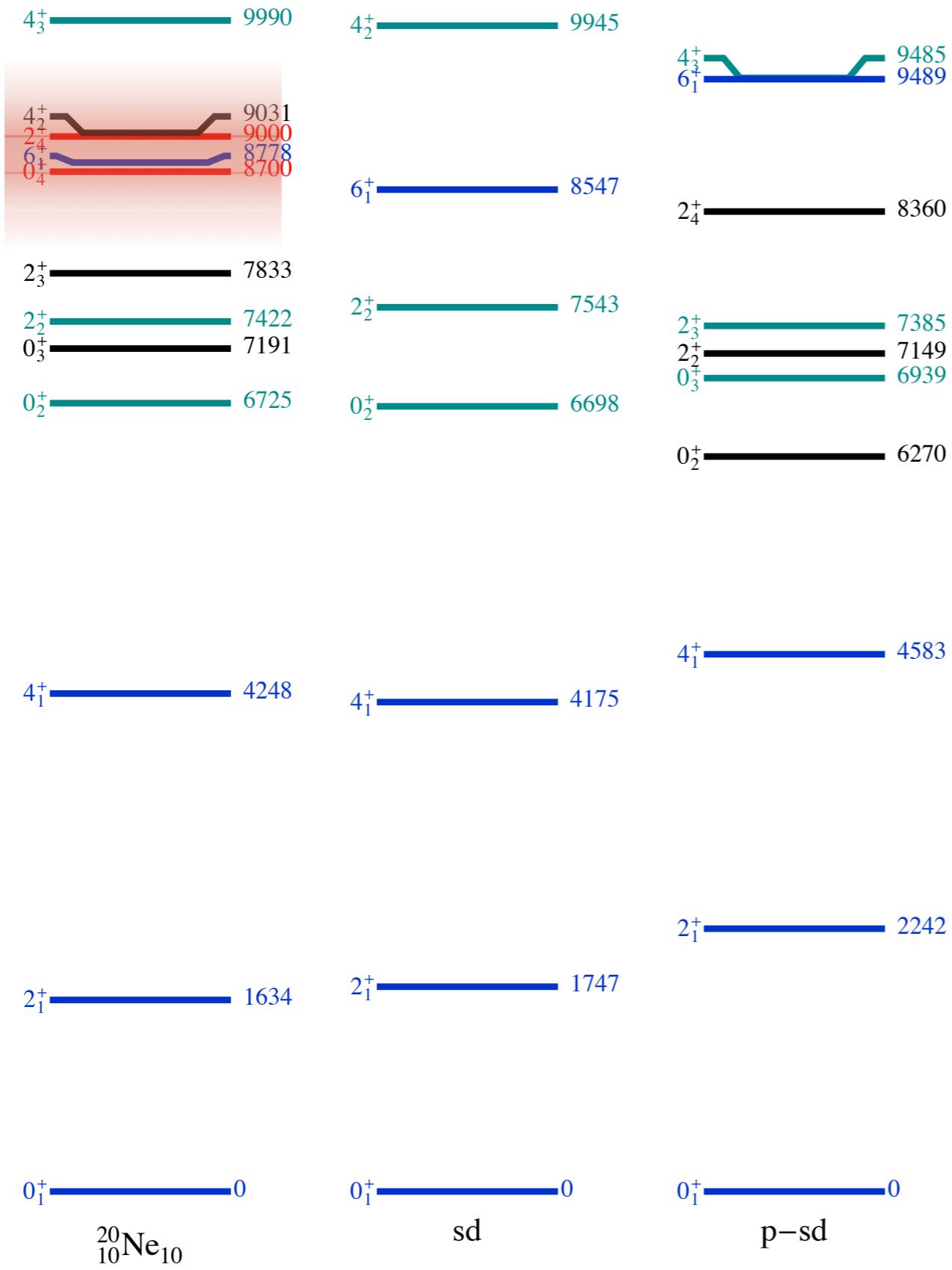
J	E MeV	Γ width	SF ex	SF th.
0+	0	0		0.73
2+	1.63	0		0.67
4+	4.25	0		0.62
0+	6.73	19	0.47	0.46
0+	7.19	3.4	0.02	0.10
2+	7.42	15	0.19	0.12
2+	7.83	2	0.01	0.09
0+	8.7	800	0.3	
6+	8.78	0.11	0.5	0.51
2+	9.00	800	0.86	

D.K. Nauruzbayev et al., Phys. Rev. C **96**, 014322 (2017)

Clustering and continuum
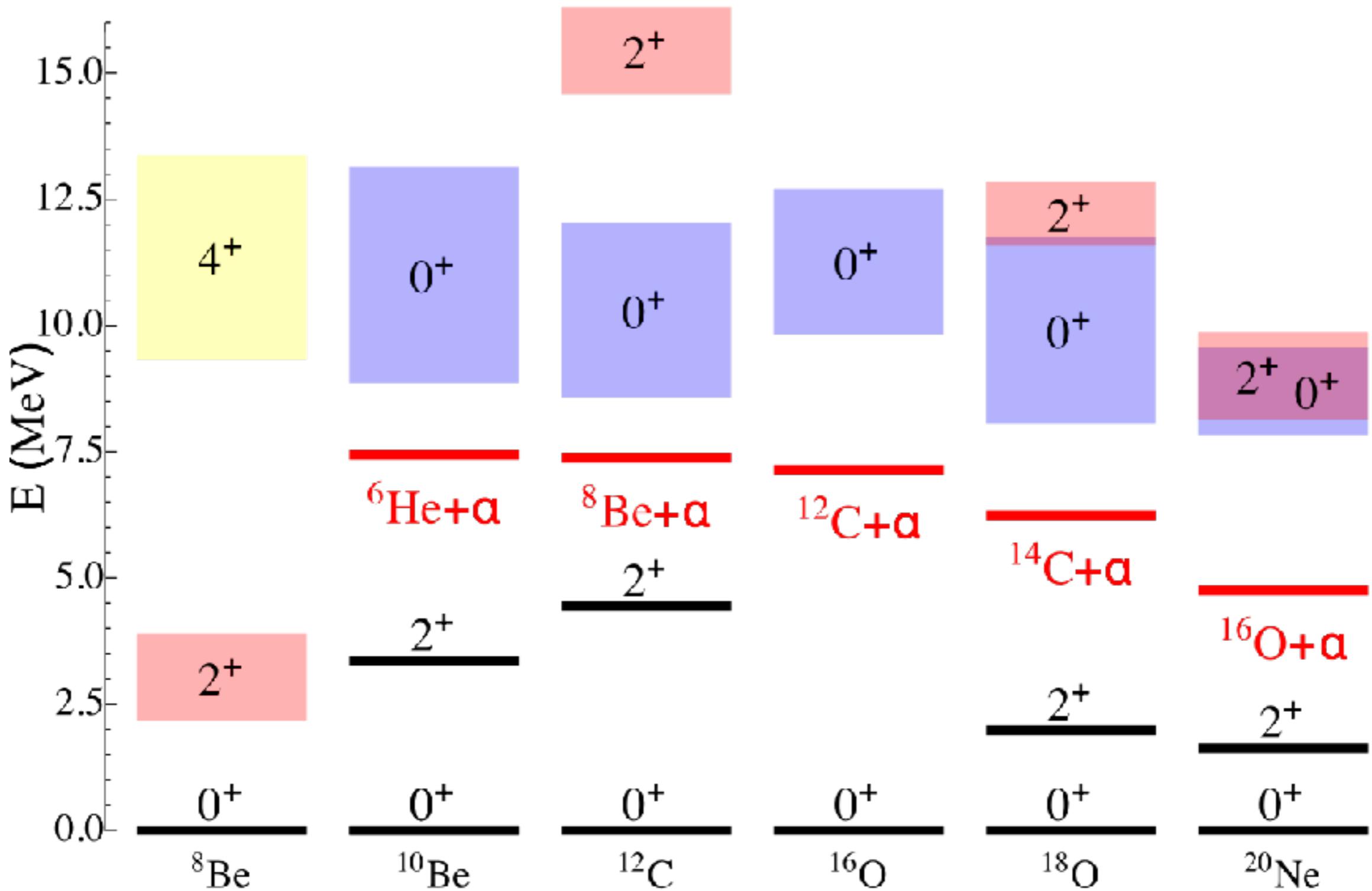
Clustering in light nuclei
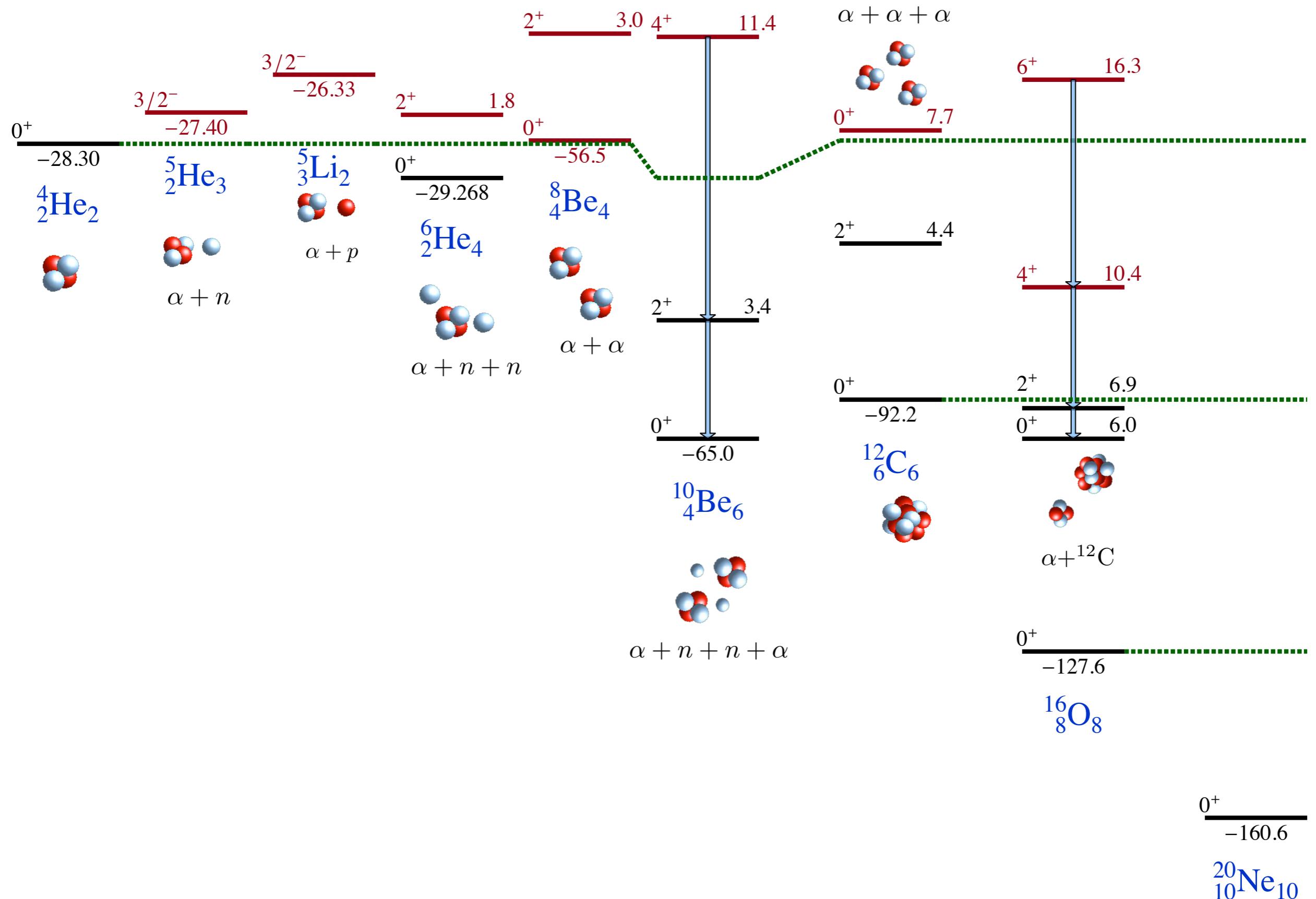
Searching for clustering strength
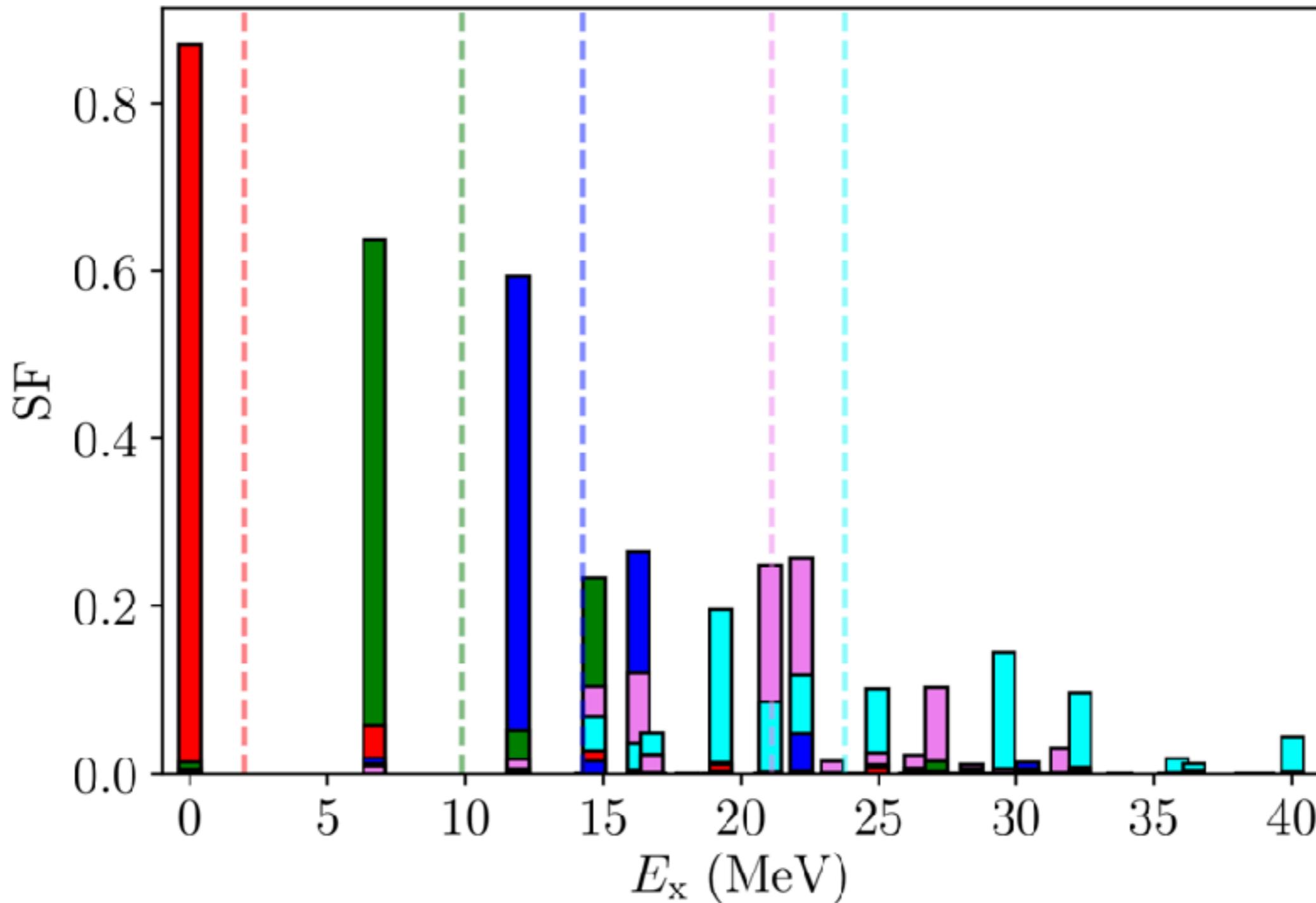
Distribution of dynamic spectroscopic factors for ^{20}Ne $\rightarrow$ ^{16}O(g.s.) + α. The dashed lines correspond to the RGM energies for each decay channel.

Channel coupling in ¹⁸O
I=1 channel

Channel coupling in ¹⁸O
l=1 channel

1^- 7.40
1^- 6.66

$n = 3$

1^- 4.49

$3\hbar\omega$

10.4
9.47
$n = 4$

$5\hbar\omega$

$n = 5$

0^+ 0

$1\hbar\omega$

14.3

10.8
9.76
9.19

1^- 6.2

1^- 4.45

0^+

Exp

Channel coupling in ¹⁸O
l=1 channel

$n = 5$

$5\hbar\omega$

10.4

$n = 4$

9.47

$3\hbar\omega$

14.3

10.8

9.76

9.19

1⁻ 7.40

1⁻ 6.66

$n = 3$

1⁻ 4.49

1⁻ 6.2

1⁻ 4.45

Coupling to channels leads to structural changes
• Reduction of particle-hole mixing
• Redistribution of alpha strength (superradiance)

0⁺ ——————— 0

$1\hbar\omega$

0⁺ —————

Exp
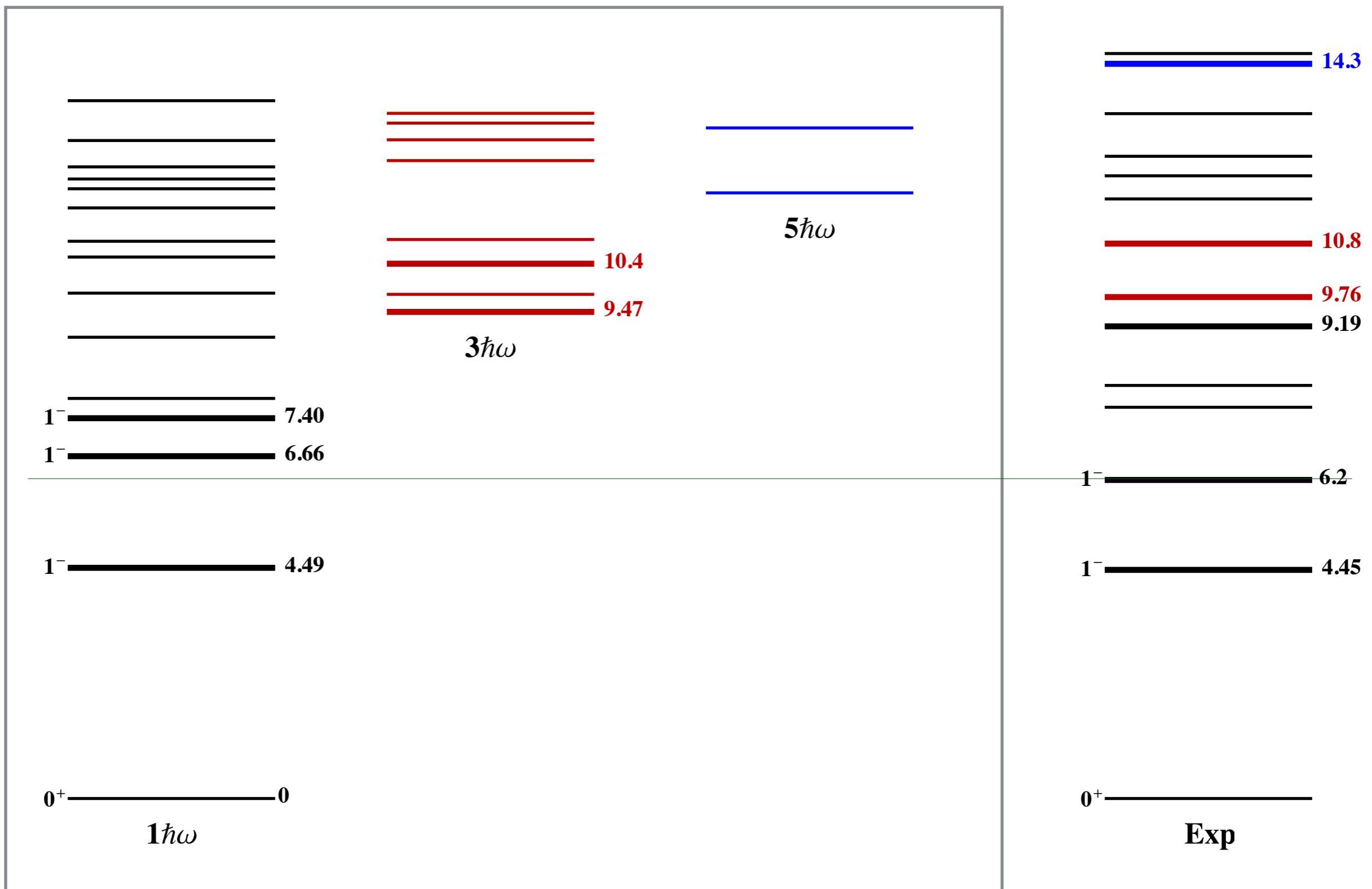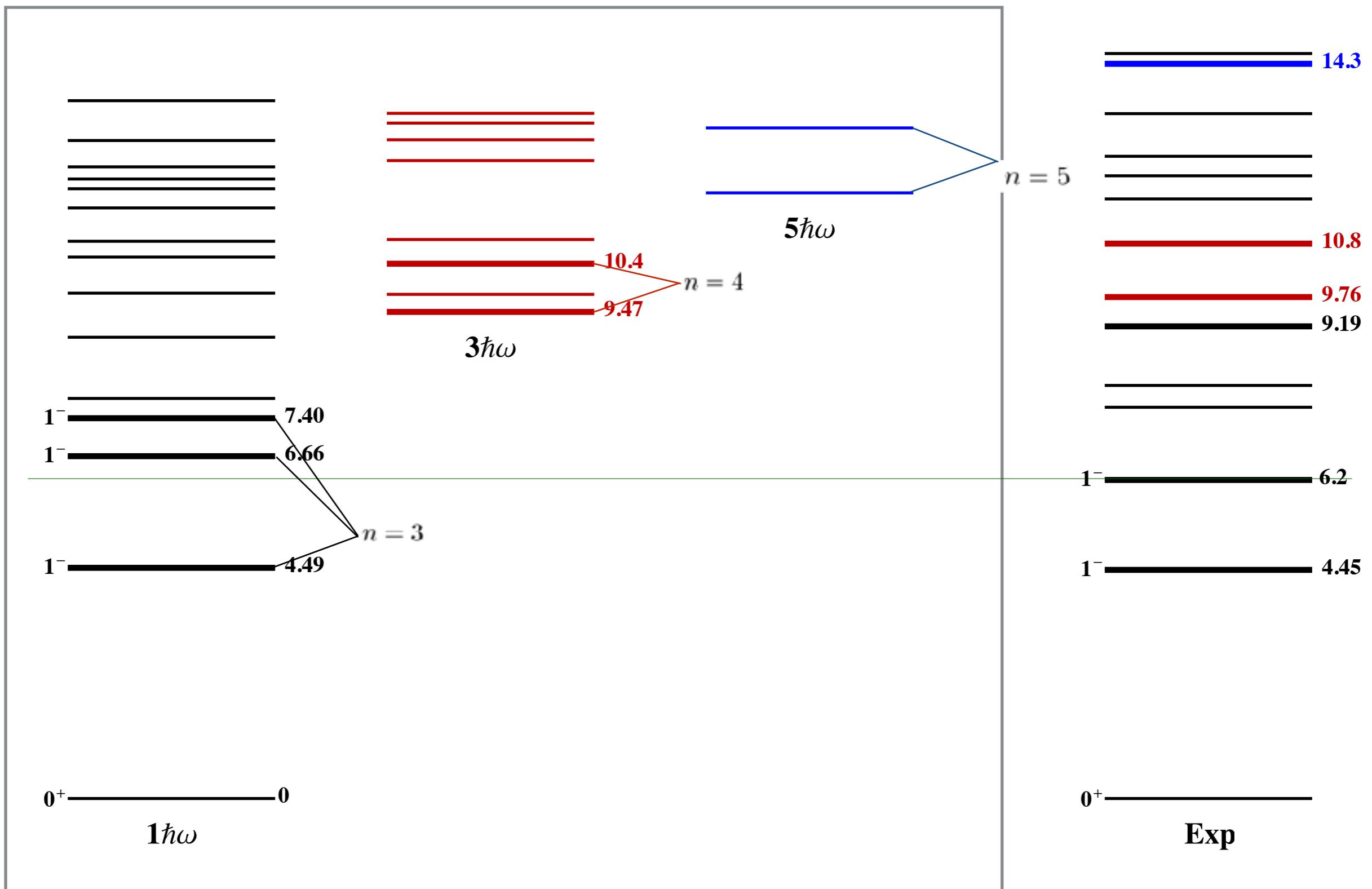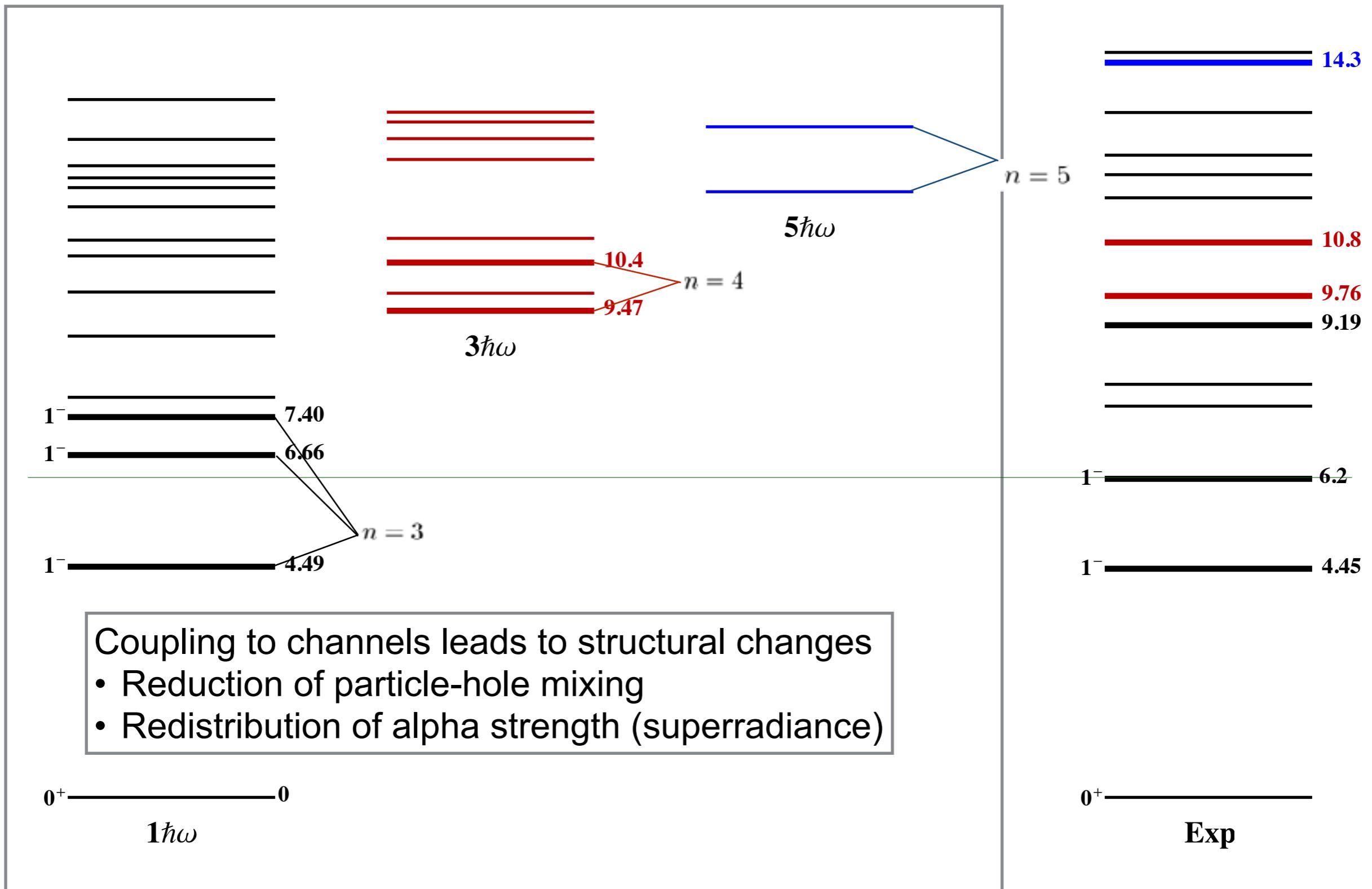
Wave function realignment
Superradiance

$$H = \begin{pmatrix} \epsilon - \frac{i}{2}\Gamma & v \\ v & 0 \end{pmatrix} = H_0 - \frac{i\Gamma}{2}A^\dagger A \qquad A = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

Stationary system $\Gamma = 0$

Energies
$$E_{1,2} = \frac{1}{2}\left(\epsilon \pm \sqrt{\epsilon^2 + 4v^2}\right)$$

Spectroscopic Factors
$$\mathrm{SF}_{1,2} = \frac{1}{2}\left(1 \pm \frac{\epsilon}{\sqrt{\epsilon^2 + 4v^2}}\right)$$

Observing superradiance

$$H = \begin{pmatrix} \epsilon - \frac{i}{2}\Gamma & v \\ v & 0 \end{pmatrix} = H_0 - \frac{i\Gamma}{2}A^\dagger A \qquad A = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

Energies
$$\mathcal{E}_{1,2} = \frac{1}{2}\left(\epsilon - \frac{i}{2}\Gamma \pm \sqrt{\left(\epsilon - \frac{i}{2}\Gamma\right)^2 + 4v^2} \right)$$

Width
$$\Gamma_{1,2} = -2\operatorname{Im}\left(\mathcal{E}_{1,2}\right)$$

Spectroscopic Factors
$$\mathrm{SF}_{1,2} = \Gamma_{1,2}/\Gamma$$

Observing superradiance
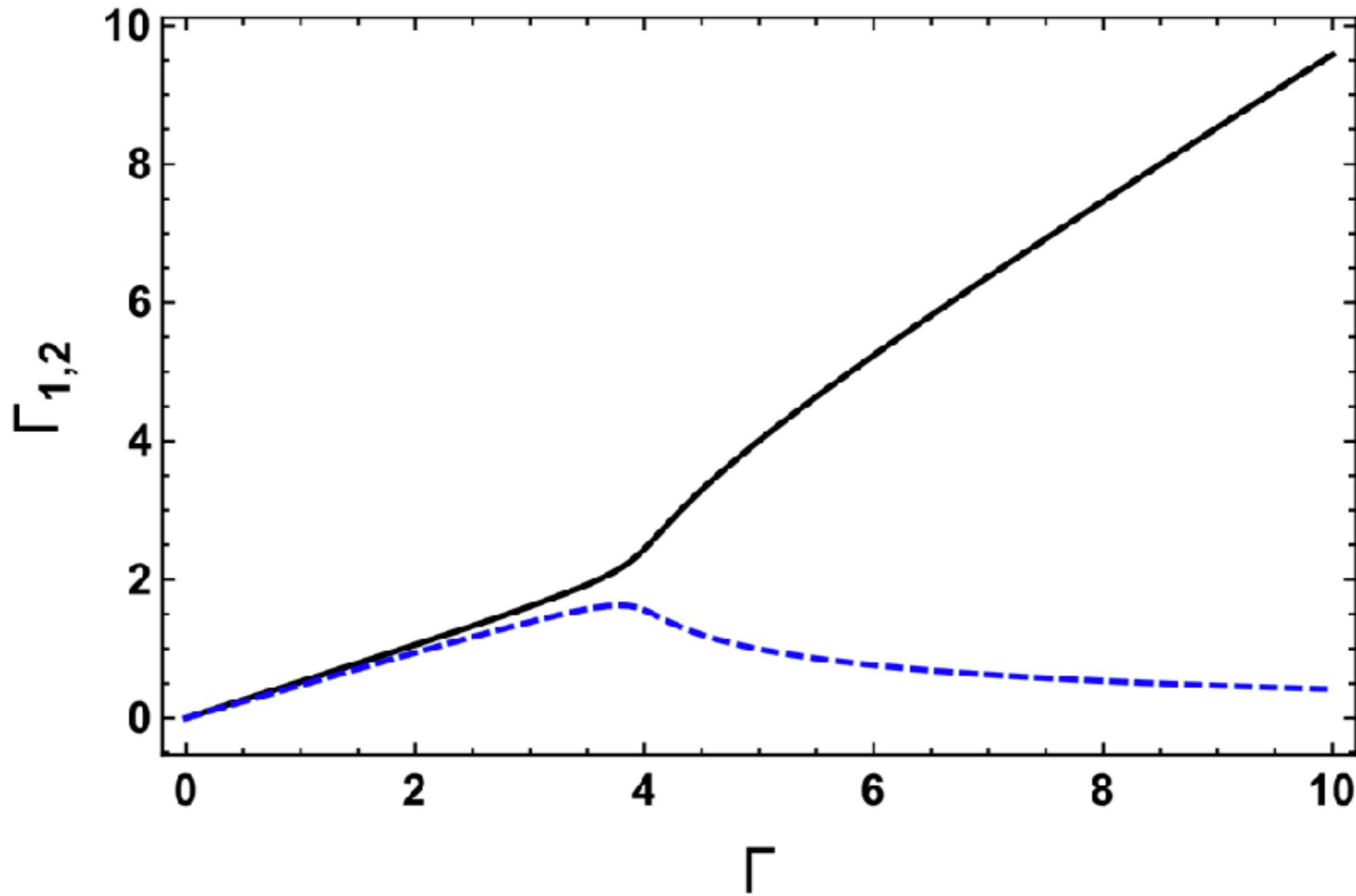
Spectroscopic factor for superradiant state
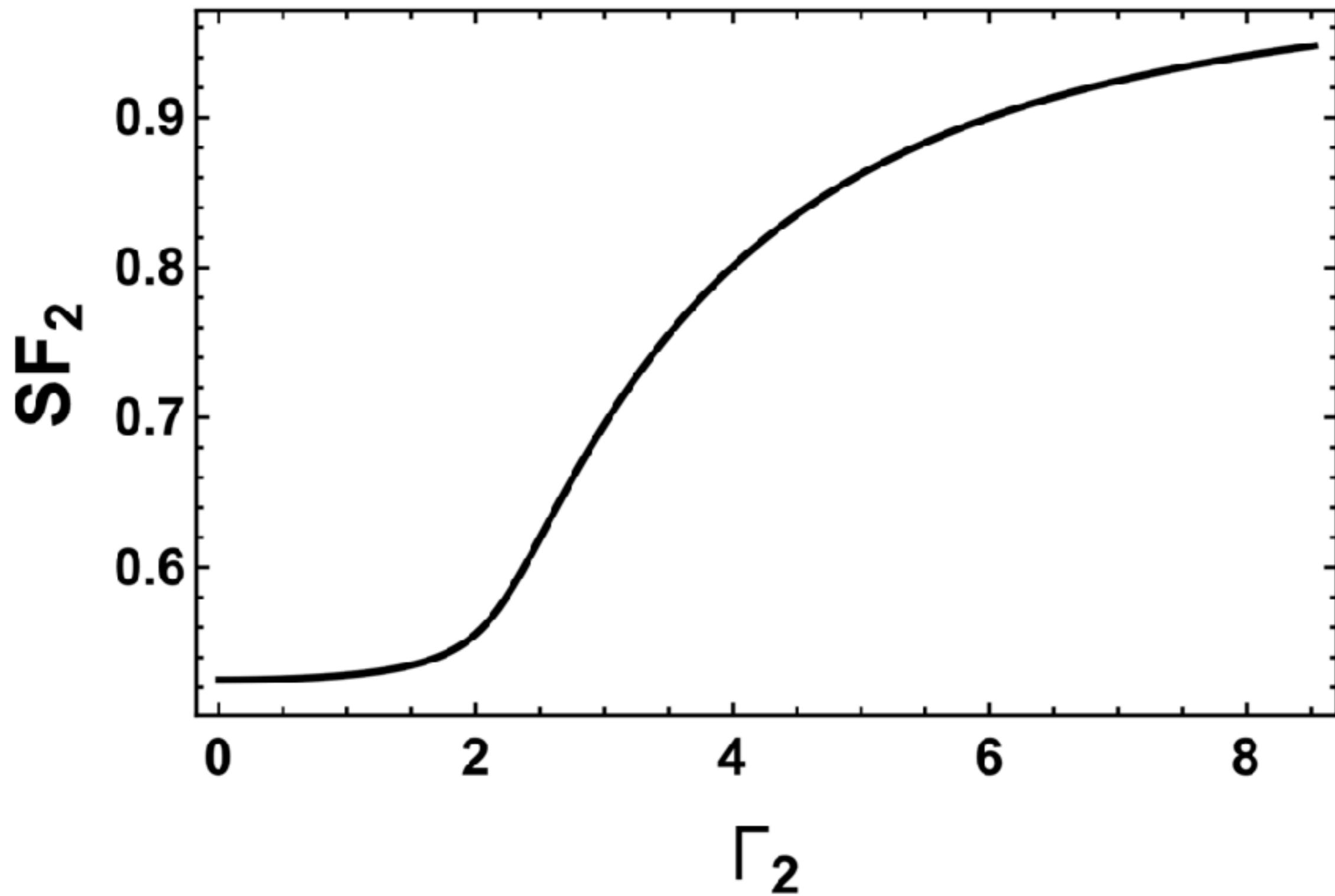
Clustering in A=18 mirror systems
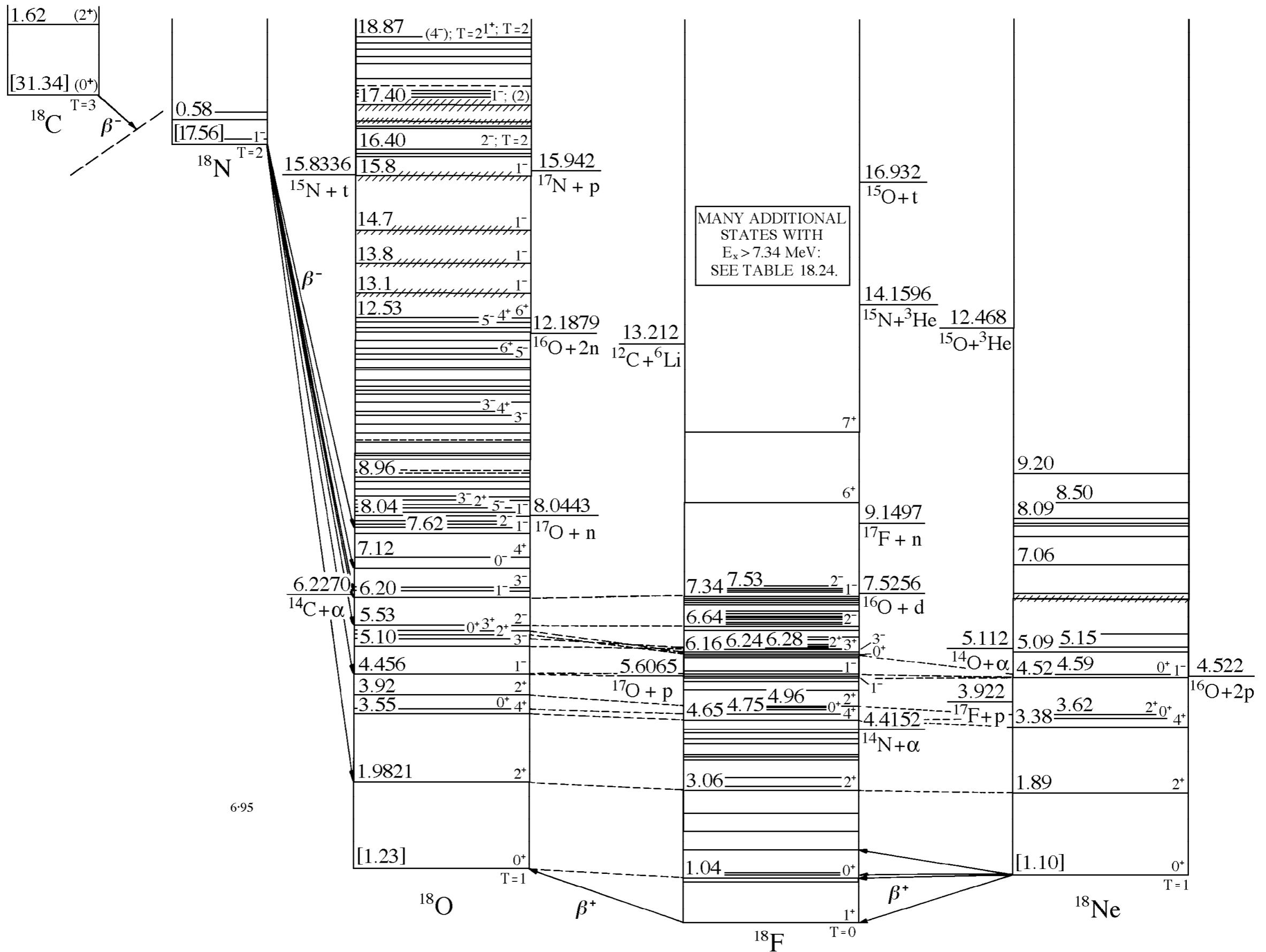
Clustering in A=18 mirror systems

Isospin symmetry

^{18}C T=3

1.62   (2$^+$)

[31.34]   (0$^+$)

β^-

^{18}N T=2

0.58

[17.56]   1$^-$

β^-

^{18}O T=1

18.87   (4$^-$); T=2   1$^+$; T=2

17.40   1$^-$; (2)

16.40   2$^-$; T=2

15.8   1$^-$

14.7   1$^-$

13.8   1$^-$

13.1   1$^-$

12.53   5$^-$ 4$^+$ 6$^+$

  6$^+$ 5$^-$

  3$^-$ 4$^+$ 3$^-$

8.96

8.04   3$^-$ 2$^+$ 5$^-$ 1$^-$

7.62   2$^-$ 1$^-$

7.12   0$^-$ 4$^+$

6.20   1$^-$ 3$^-$

5.53   2$^-$

5.10   0$^+$ 3$^+$ 2$^+$ 3$^-$

4.456   1$^-$

3.92   2$^+$

3.55   0$^+$ 4$^+$

1.9821   2$^+$

6·95

[1.23]   0$^+$

15.8336
$^{15}N + t$

12.1879
$^{16}O + 2n$

8.0443
$^{17}O + n$

6.2270
$^{14}C + \alpha$

15.942
$^{17}N + p$

13.212
$^{12}C + ^6Li$

^{18}F T=0

MANY ADDITIONAL STATES WITH $E_x > 7.34$ MeV: SEE TABLE 18.24.

7$^+$

6$^+$

7.53   2$^-$ 1$^-$

6.64   2$^-$

6.16 6.24 6.28   2$^+$ 3$^+$

5.6065   1$^-$

4.65 4.75 4.96   0$^+$ 2$^+$ 4$^+$

3.06   2$^+$

1.04   0$^+$

1$^+$

β^+

7.34

16.932
$^{15}O + t$

14.1596
$^{15}N + ^3He$

9.1497
$^{17}F + n$

7.5256
$^{16}O + d$

5.112
$^{14}O + \alpha$

3.922
$^{17}F + p$

4.4152
$^{14}N + \alpha$

^{18}Ne T=1

9.20

8.50

8.09

7.06

5.09 5.15

4.52 4.59   0$^+$ 1$^-$

3.38 3.62   2$^+$ 0$^+$ 4$^+$

1.89   2$^+$

[1.10]   0$^+$

β^+

12.468
$^{15}O + ^3He$

3$^-$ 0$^+$

1$^-$

4.522
$^{16}O + 2p$

17O + p

5.112

3.922
$^{17}F+p$

J	E (MeV)	Γ (keV)	SF	E (MeV)	Γ (keV)	SF
		^{18}Ne			^{18}O	
1-	9.08(1)	357	**0.21(1)**	9.19(2)	200	**0.20(1)**
1-	9.57(1)	1062	**0.51(5)**	9.76(2)	630	**0.46(4)**
1-	10.58(4)	416	**0.15(5)**	10.8(3)	630	**0.29(4)**
1-	13.730(2)	780	**0.2(1)**	14.3(3)	400	**0.10(4)**
2+	9.19(3)	265	**0.21(2)**	9.79(6)	90	**0.10(3)**
2+	10.94(6)	1302	**0.52(3)**	12.21(8)	1000	**0.37(9)**
2+	13.4 (2)	1755	**0.45(8)**	12.8(3)	4800	**1.56(13)**
2+	16.9(2)	1515	**0.3(2)**			
3-				8.29(6)	2.9	**0.18(1)**
3-	8.77(8)	419	**1.0(4)**	9.35(2)	110	**0.48(13)**
3-	11.0(1)	497	**0.28(7)**	11.95(1)	300	**0.17(2)**
3-	12.7(2)	2025	**0.7(2)**	12.98(4)	770	**0.32(5)**
3-	14.8(2)	3967	**1.0(2)**	14.0(2)	2100	**0.7(1)**
4+	8.16	31	**0.8(3)**	7.11*		
4+	13.3(3)	845	**0.37(4)**	13.46(2)	210	**0.12(1)**
4+	14.15(21)	375	**0.14(10)**	14.77(5)	680	**0.28(2)**
5-	11.31(4)	15	0.03(2)	11.63(1)	30	**0.13(1)**
5-	12.9(2)	532	**0.48(12)**	13.08(1)	120	**0.17(1)**
5-	13.79(8)	219	**0.14(10)**	14.1(1)	260	**0.23(2)**
5-	14.6(7)	521	**0.27(20)**	14.7(1)	230	**0.16(6)**

M. Barbui *et al.*, "α-cluster structure of ^{18}Ne," *Phys. Rev. C*, vol. 106, no. 5, p. 054310, Nov. 2022, doi: 10.1103/PhysRevC.106.054310.

J	^{18}Ne			^{18}O		
	E (MeV)	Γ (keV)	SF	E (MeV)	Γ (keV)	SF
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1-	9.57(1)	1062	**0.51(5)**	9.76(2)	630	**0.46(4)**
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A. Volya, M. Barbui, V. Z. Goldberg, and G. V. Rogachev, "Superradiance in alpha clustered mirror nuclei," *Commun Phys*, vol. 5, no. 1, Art no. 1, Dec. 2022, doi: 10.1038/s42005-022-01105-9.

Channel coupling in ¹⁸O
l=1 channel

$5\hbar\omega$

$n = 5$

10.4
$n = 4$
9.47

$3\hbar\omega$

14.3

10.8

9.76

9.19

1^- —— 7.40

1^- —— 6.66

$n = 3$

1^- —— 4.49

1^- —— 6.2

1^- —— 4.45

Coupling to channels leads to structural changes
• Reduction of particle-hole mixing
• Redistribution of alpha strength (superradiance)

0^+ —— 0

$1\hbar\omega$

0^+ ——

Exp

Thanks to all collaborators:

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Resources: https://www.volya.net/ (see research, clustering)