Structure of light unstable nuclei studied with effective interactions

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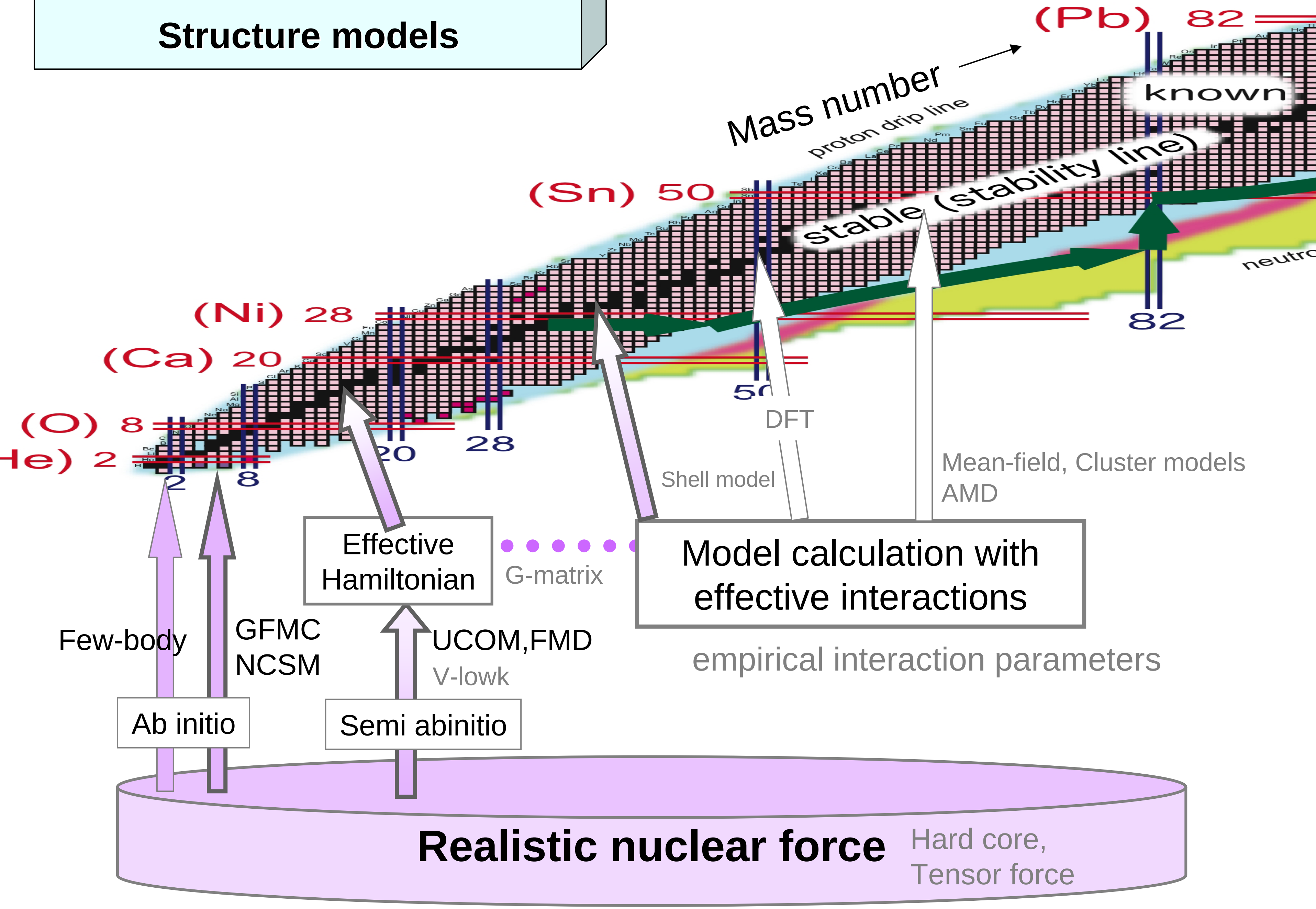
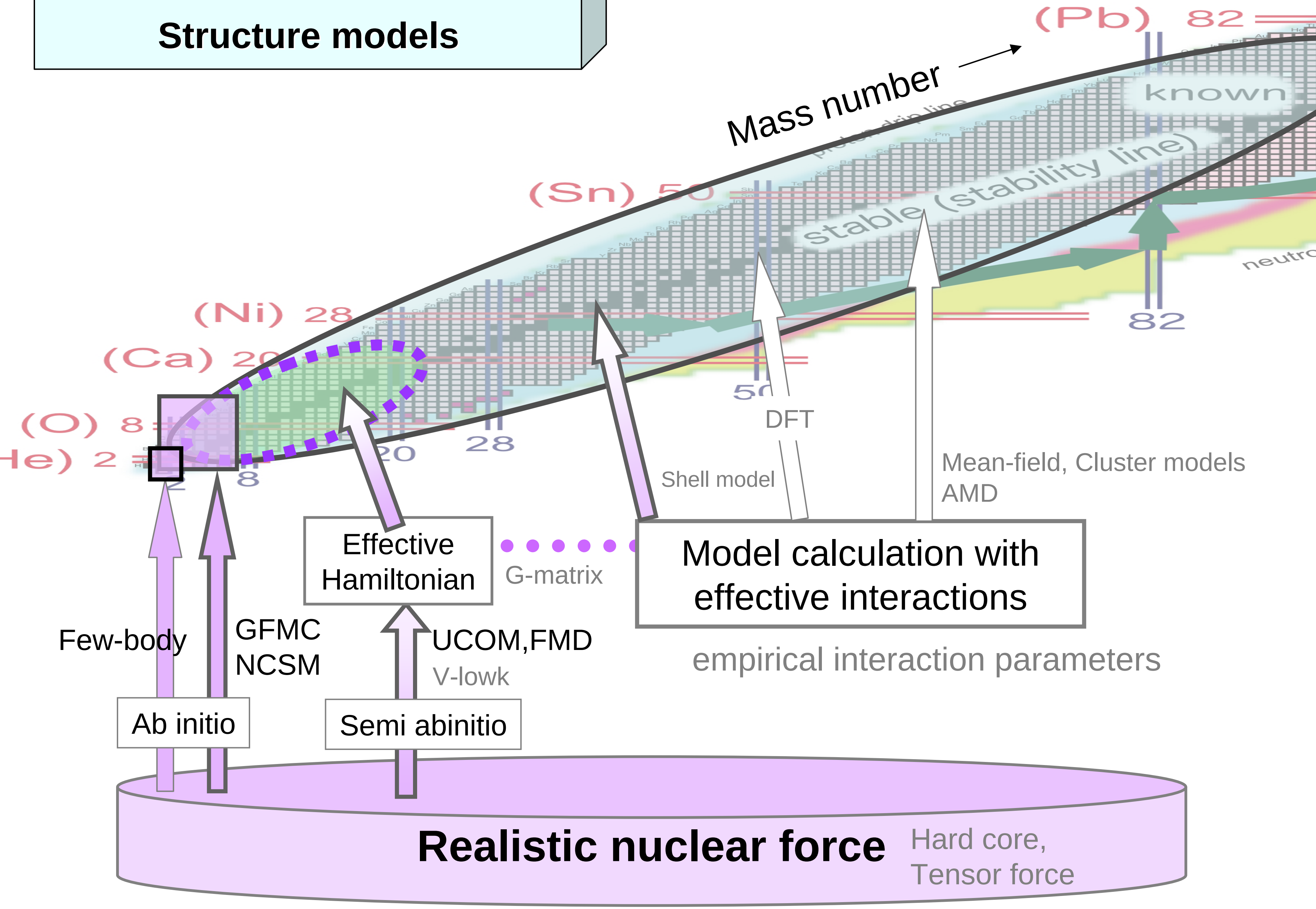
1. Introduction

Structure models



Structure models



phenomenological effective interactions

V_{ij}= central + ls force

2-body force

$$H=\sum_i t_i - T_G + \sum_{i<j} v(r_{ij})$$

Volkov, Minnesota (density independent)

$$v(r)=\sum_k (w_k + b_k P_\sigma - h_k P_\tau - m_k P_\sigma P_\tau)\exp\left(-\frac{r}{a_k^2}^2\right)$$

Gogny (density dependent)

$$v(r)=\sum_{k=1,2} (w_k + b_k P_\sigma - h_k P_\tau - m_k P_\sigma P_\tau)\exp\left(-\frac{r}{a_k^2}^2\right) + v_d(1+xP_\sigma)\rho^\sigma(r)\cdot\delta(r)$$

2-body+3-body force

$$H=\sum_i t_i - T_G + \sum_{i<j} v(r_{ij}) + \sum_{i<j<k} V_3$$

MV1 force $\quad V_3 = t_3 \delta(r_{12})\delta(r_{23})$

Enyo force $\quad V_3 = t_3 \exp\left[-\frac{r_{12}{}^2 + r_{23}{}^2 + r_{31}{}^2}{a^2}\right]$

1. Introduction

What are problems in present interactions ?

		N-N scattering	α-α pha-s	α radius/B.E.	p-shell radii/B.E	sd-shell radii/B.E	Matter saturation
Gauss 2-body	Minnesota	✓ S-wave	✓	✓ / ✓	✓ / ✓		
	Volkov		✓	✓ / ✓	✓ / ✓		
+density dependence	MV1			/ ✓	✓ / ✓	✓ /	✓
	Gogny, Skyrm			/ ✓	✓ / ✓	✓ / ✓	✓
+ finite-rang -3-body	Tohsaki's		✓	✓ / ✓	✓ / ✓	✓ / ✓	✓
	Enyo	←	✓	✓ / ✓	✓ / ✓	✓ / ✓	✓

Effective forces used in recent AMD calculations

- Volkov, Minnesota (density independent)

  Light nuclei A< 20

- MV1 force

  p-shell, sd-shell nuclei

Mass number dependent parameters

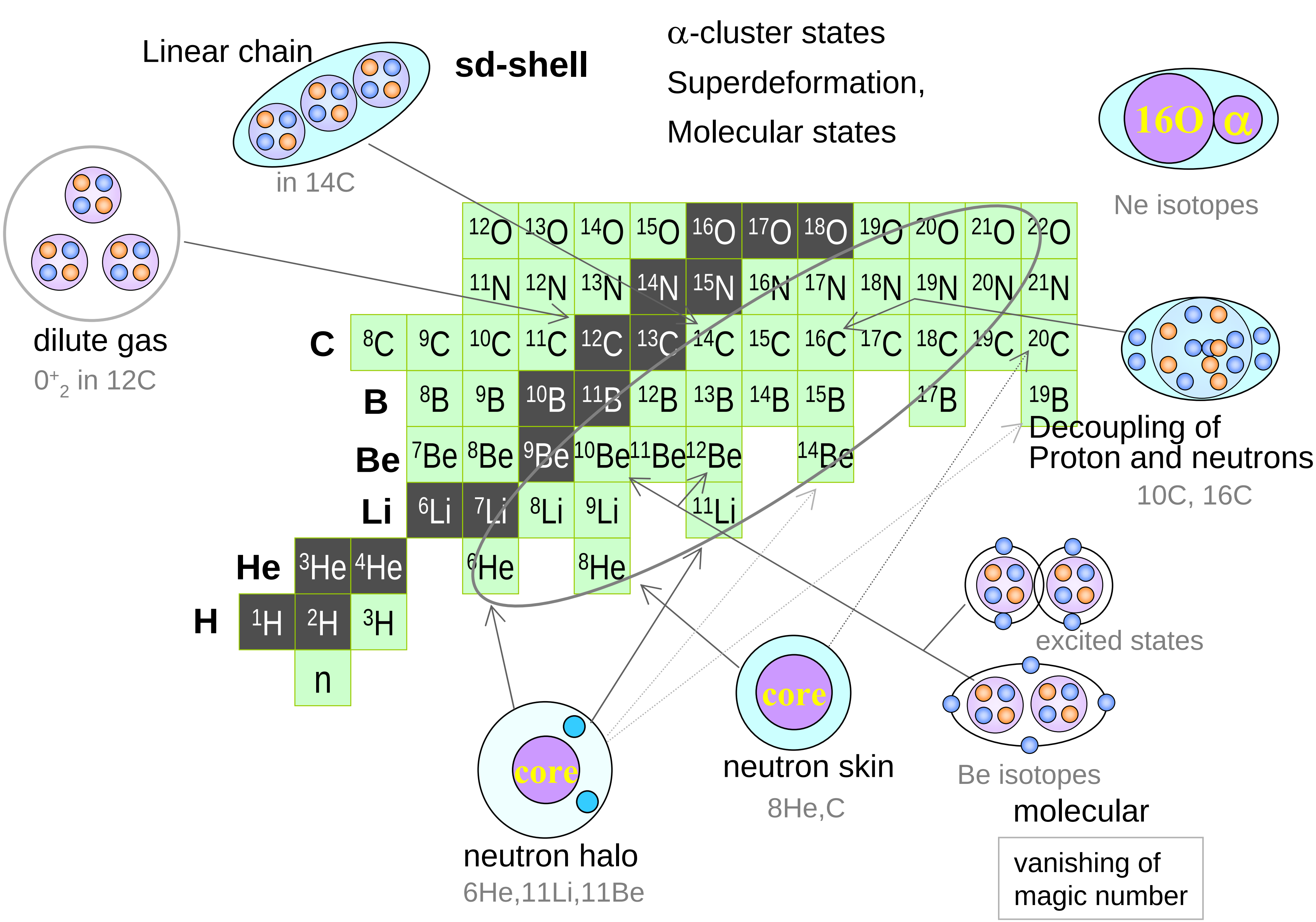
- Gogny and Skyrme (density dependent)

  sd-shell, fp-shell nuclei up to A=50

- Enyo force (3-body)

  sd-shell nuclei up to A=40

Exotic structure in light nuclei



2. Formulation of AMD

Formulation of AMD: wave function

Wave function

$$\Phi = c\Phi_{\mathrm{AMD}} + c'\Phi'_{\mathrm{AMD}} + c''\Phi''_{\mathrm{AMD}} + \cdots$$

$$\Phi_{\mathrm{AMD}} = \mathcal{A}\{\varphi_1, \varphi_2, \cdots, \varphi_A\}$$ Slater det.

spatial Gaussian

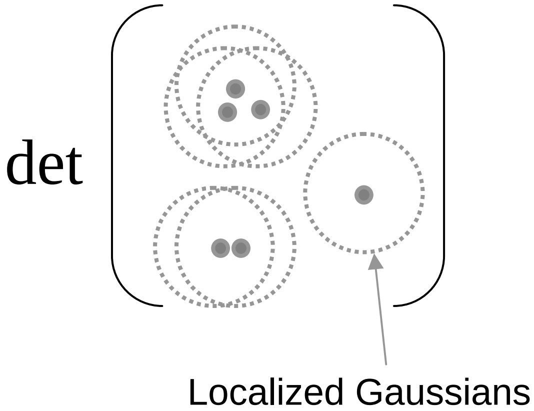
$$\varphi_{\mathbf{i}} = \phi_{\mathbf{Z_i}} \chi_{\mathbf{i}} \begin{cases} \phi_{\mathbf{Z_i}}(\mathbf{r_j}) \propto \exp\left[-\nu\left(\mathbf{r} - \frac{\mathbf{Z_i}}{\sqrt{\nu}}\right)^2\right] \\ \chi_{\mathbf{i}} = \begin{pmatrix} \frac{1}{2} + \xi_{\mathbf{i}} \\ \frac{1}{2} - \xi_{\mathbf{i}} \end{pmatrix} \times \quad p \text{ or } n \end{cases}$$

spin, isospin

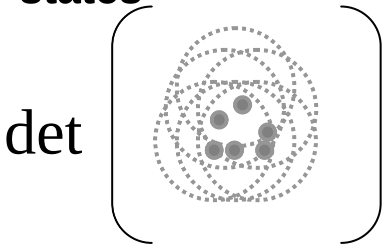
Complex parameter $\mathbf{Z} = \{\mathbf{Z}_1, \mathbf{Z}_2, \cdots, \mathbf{Z}_A, \quad \xi_1, \cdots, \xi_A\}$

Variational method $\delta \frac{\langle \Phi | H | \Phi \rangle}{\langle \Phi | \Phi \rangle} = 0$

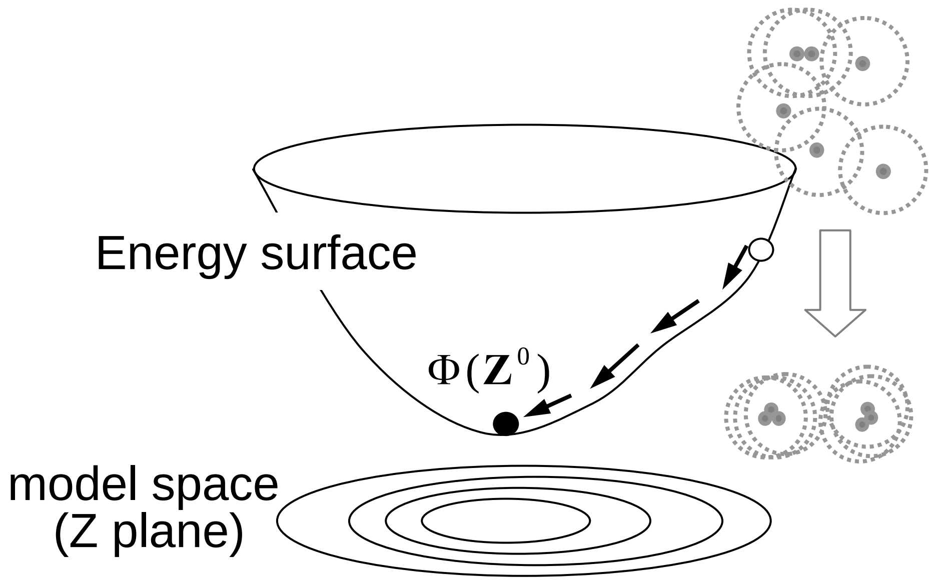
Cluster structure



Shell-model-like states



Formulation of AMD: energy variation



$$\delta \frac{\langle \Phi(\mathbf{Z}) | H | \Phi(\mathbf{Z}) \rangle}{\langle \Phi(\mathbf{Z}) | \Phi(\mathbf{Z}) \rangle} \equiv \delta E = 0$$

frictional cooling method

$$\frac{d\mathbf{Z}}{dt} = (\lambda + i\mu) \frac{1}{i\hbar} \frac{\partial E}{\partial \mathbf{Z}^*}$$

Simple AMD | Variation after parity projection before spin pro. (VBP)

VAP | Variation after spin-parity projection

$$\delta \frac{\langle P\Phi(\mathbf{Z}) | H | P\Phi(\mathbf{Z}) \rangle}{\langle P\Phi(\mathbf{Z}) | P\Phi(\mathbf{Z}) \rangle} \equiv \delta E = 0$$

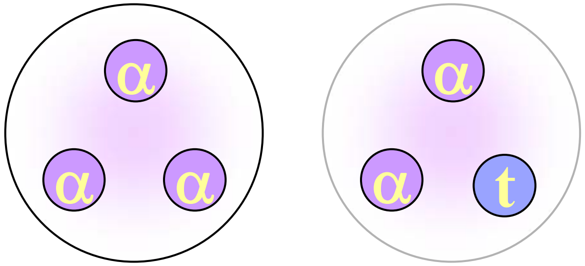
Constraint AMD & superposition $\approx$ AMD + GCM

Multi-configuration AMD

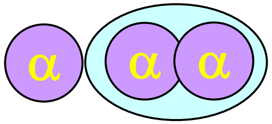
Variation with Constraints
Then superposition of basis wave functions.

3. Structure of unstable nuclei

3-1. cluster gas in $^{12}C^*$, $^{11}B^*(^{11}C^*)$, $^{8}He^*$



3-2. linear chain in C isotopes

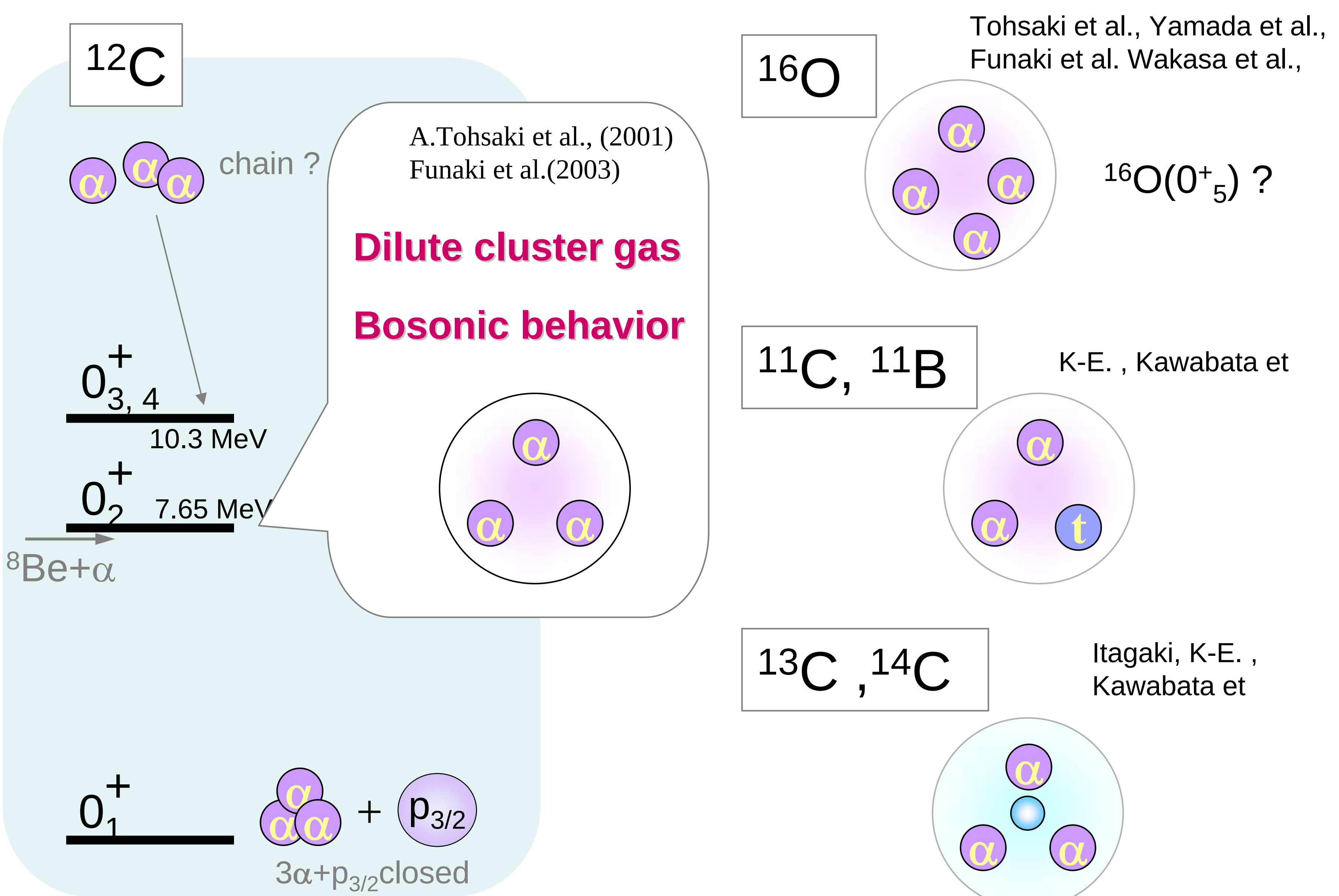


$\alpha+^{10}Be$

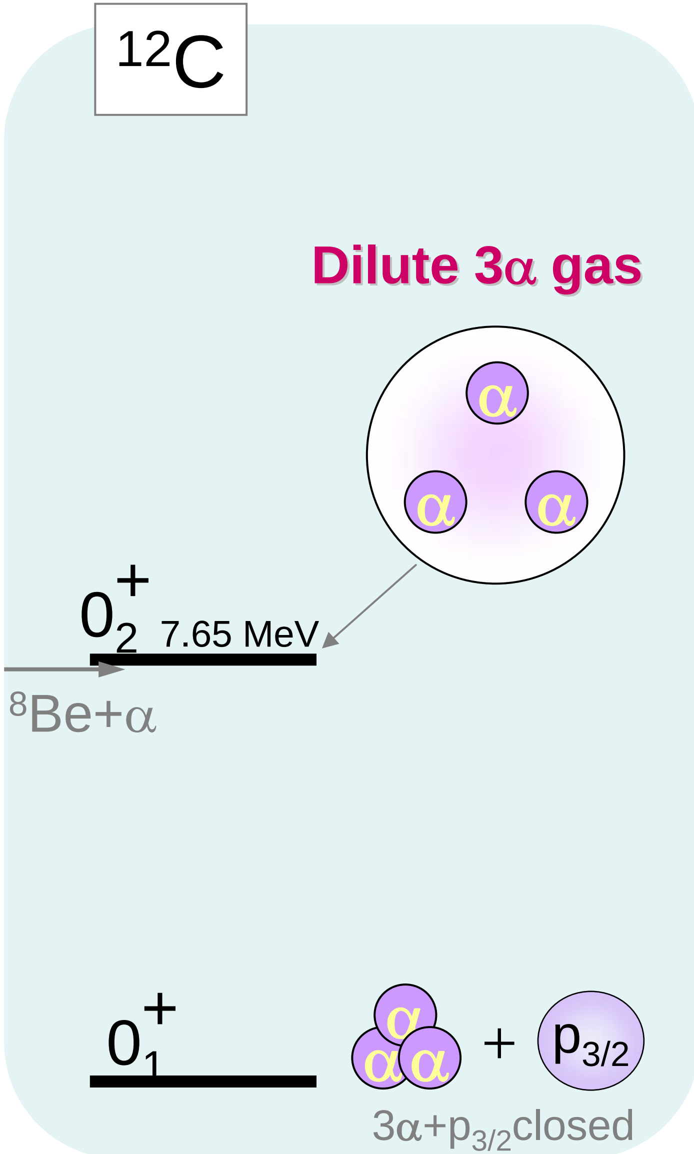
3-1. three-center cluster states:

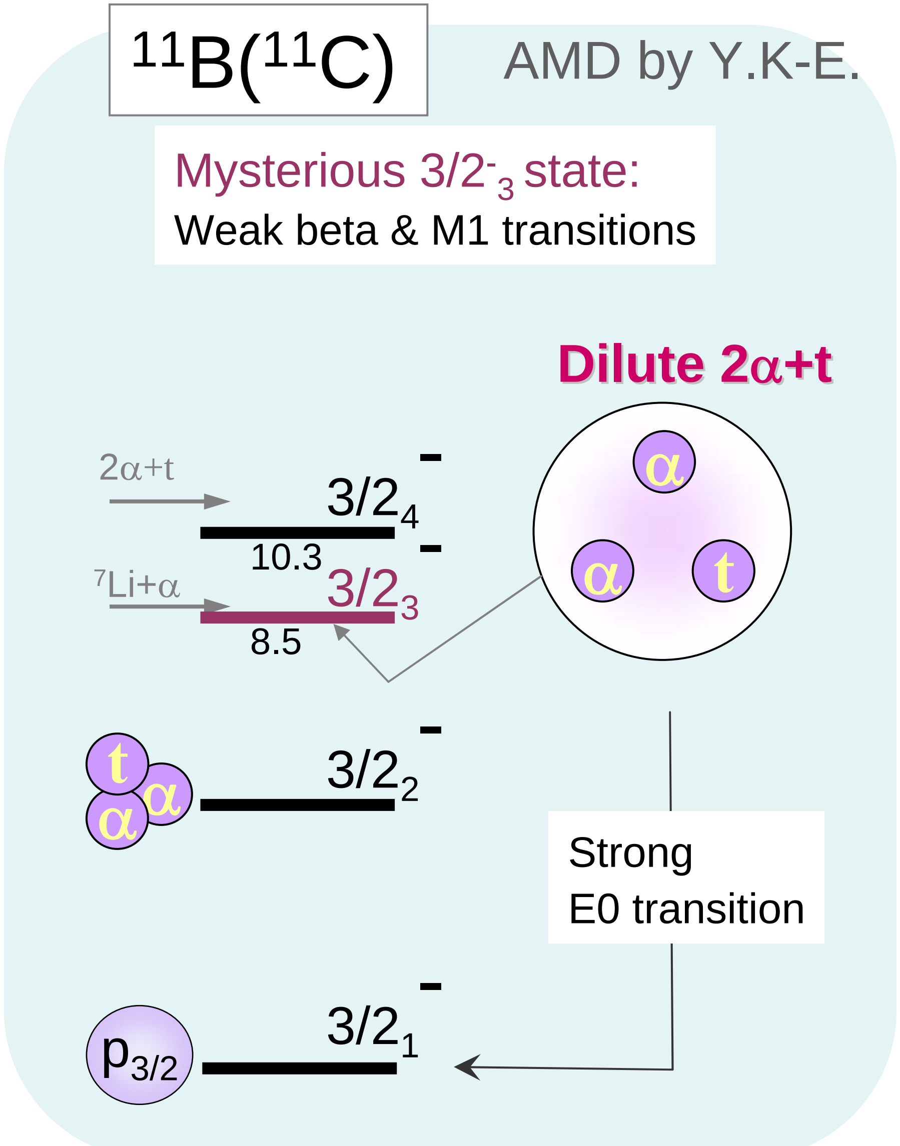
$^{12}C^*$, $^{11}B^*$($^{11}C^*$),

2-2. Cluster gas-like states



Three-center cluster states of ^{11}B and ^{11}C : analogy with $12C(0^+_2)$

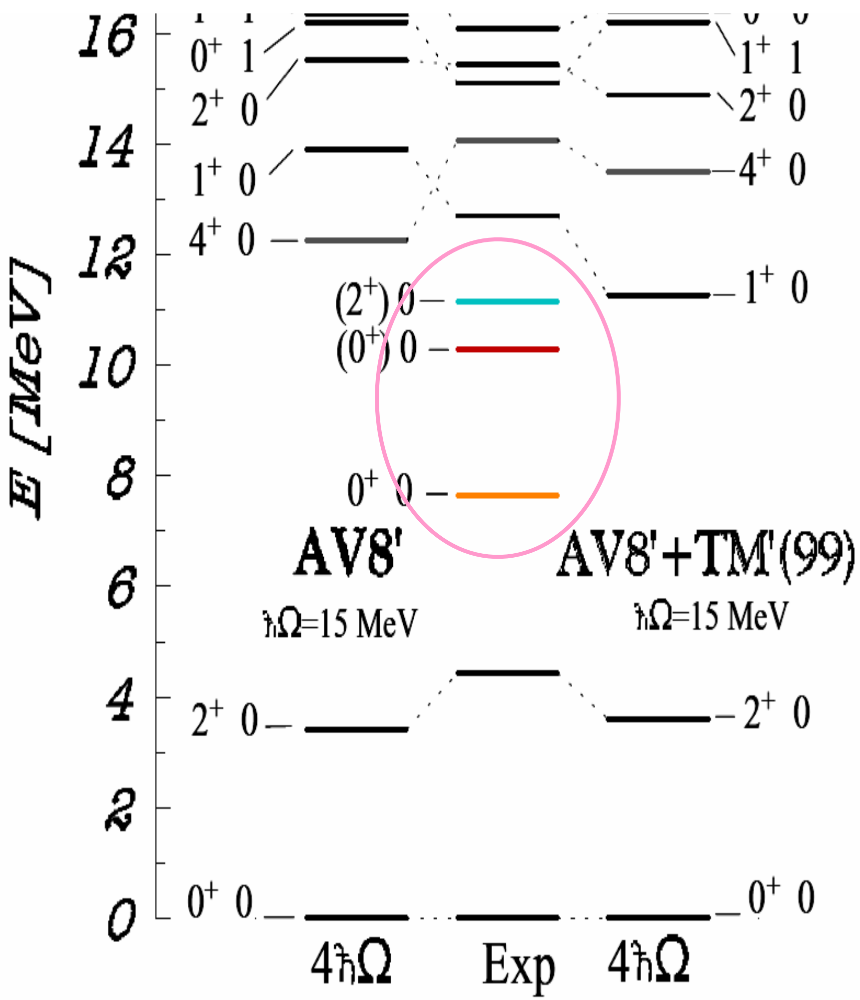




Missing in shell model calculations

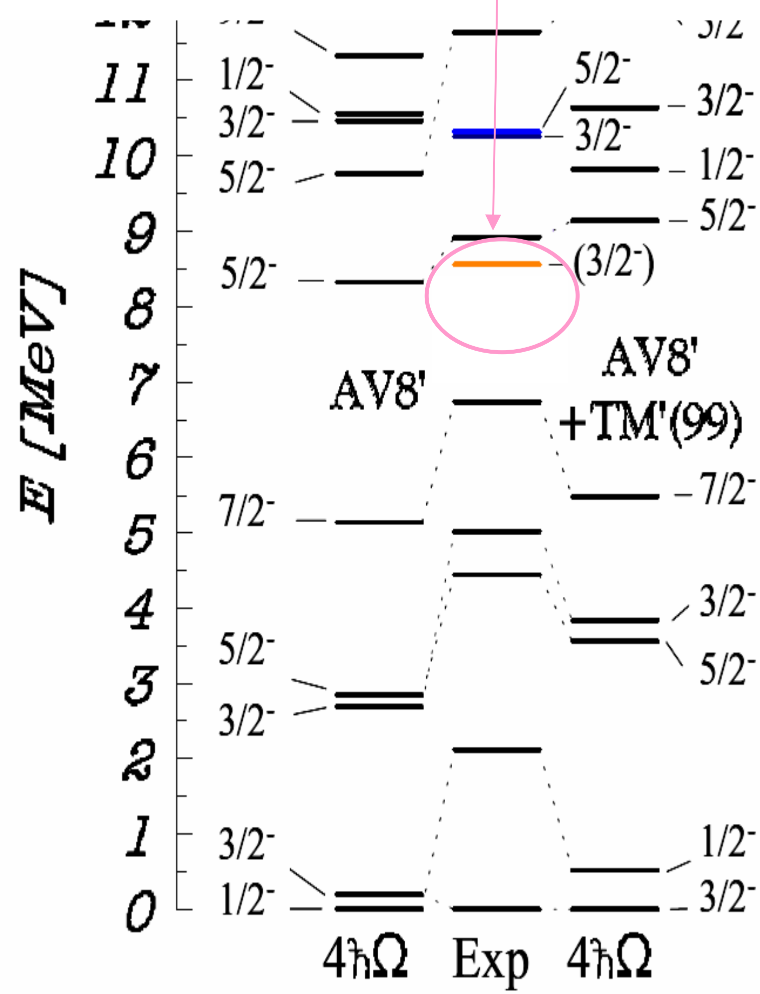
^{12}C

NCSM by Navratil et al. (2003)



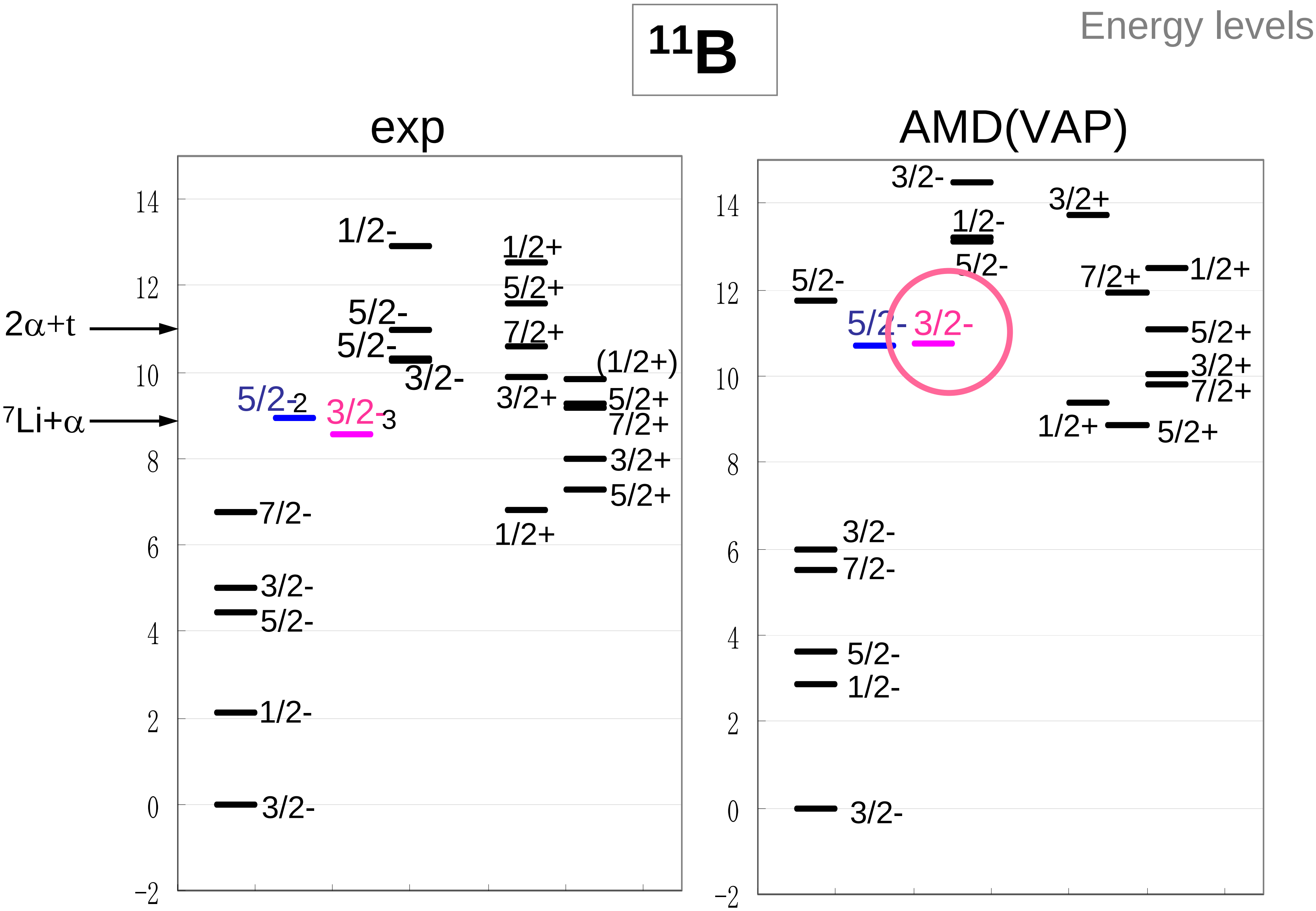
^{11}B

$3/2^-_3$ state is missing



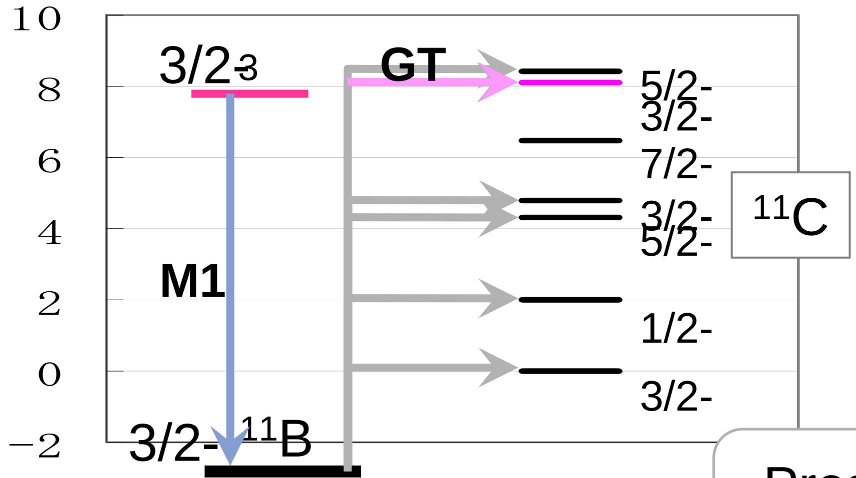
Present results by AMD

Energy levels

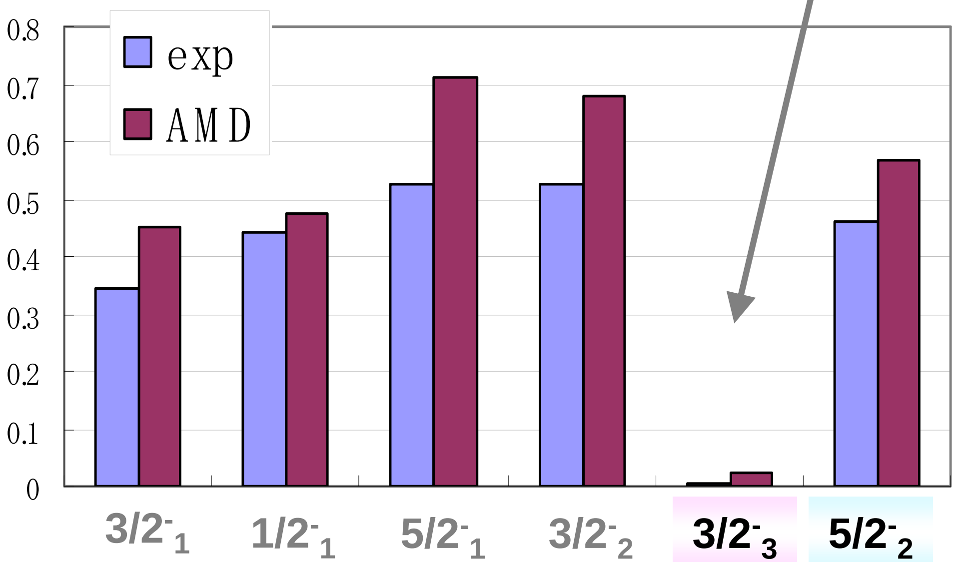


$^{11}B \rightarrow {}^{11}C^*$ GT-transition strength

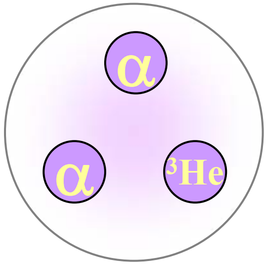
$^{11}B \rightarrow {}^{11}C^*$



B(GT)



Present calc. reproduces weak GT and M1 transitions



$2\alpha+{}^3He$
loosely bound 3 clusters

Dilute $2\alpha+{}^3He(t)$

exp: Y. Fujita, et al. PRC 70, 011306(R)(2004).
AMD:

Isoscalar E0 and radius of $^{11}B(3/2^-_3)$ state

Large $B(E0;IS) \equiv |M_p + M_n|^2$ (fm⁴)

Inelastic scattering data (d,d')
Kawabata et al. nucl-ex/051204(2005)

	Exp.	AMD
$^{11}B_{g.s.} \rightarrow {}^{11}B(3/2^-_3)$	94 ± 16	94
$^{12}C_{g.s.} \rightarrow {}^{12}C(0+_2)$	121 ± 9	137

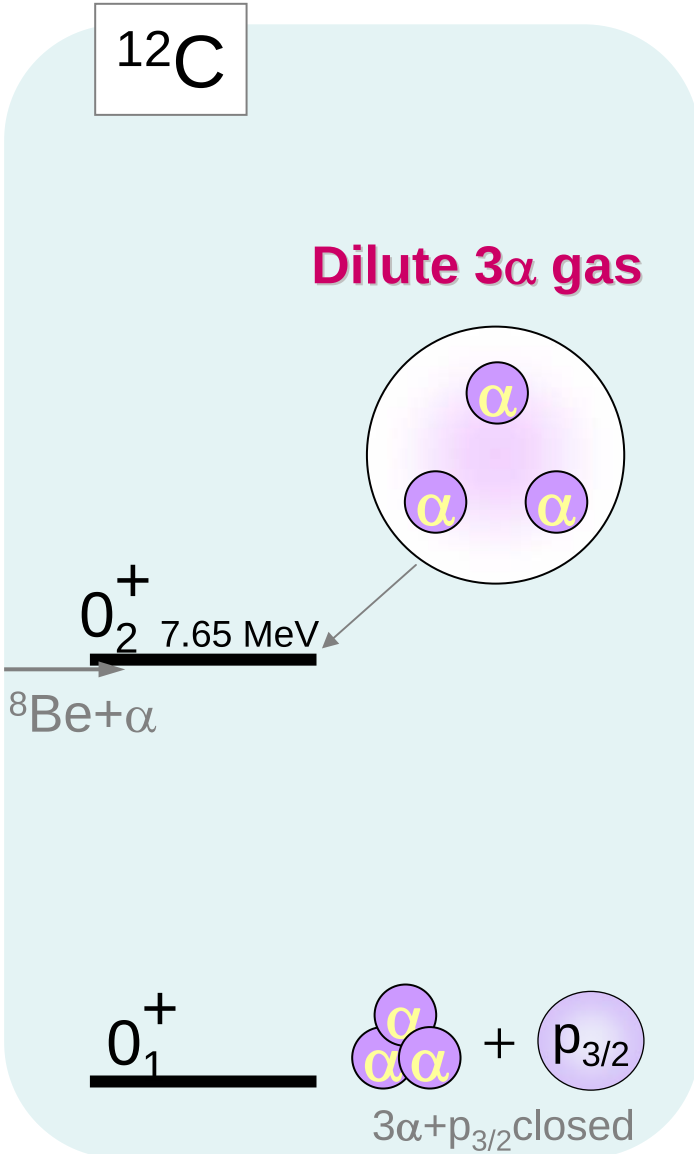
Dilute
Cluster states

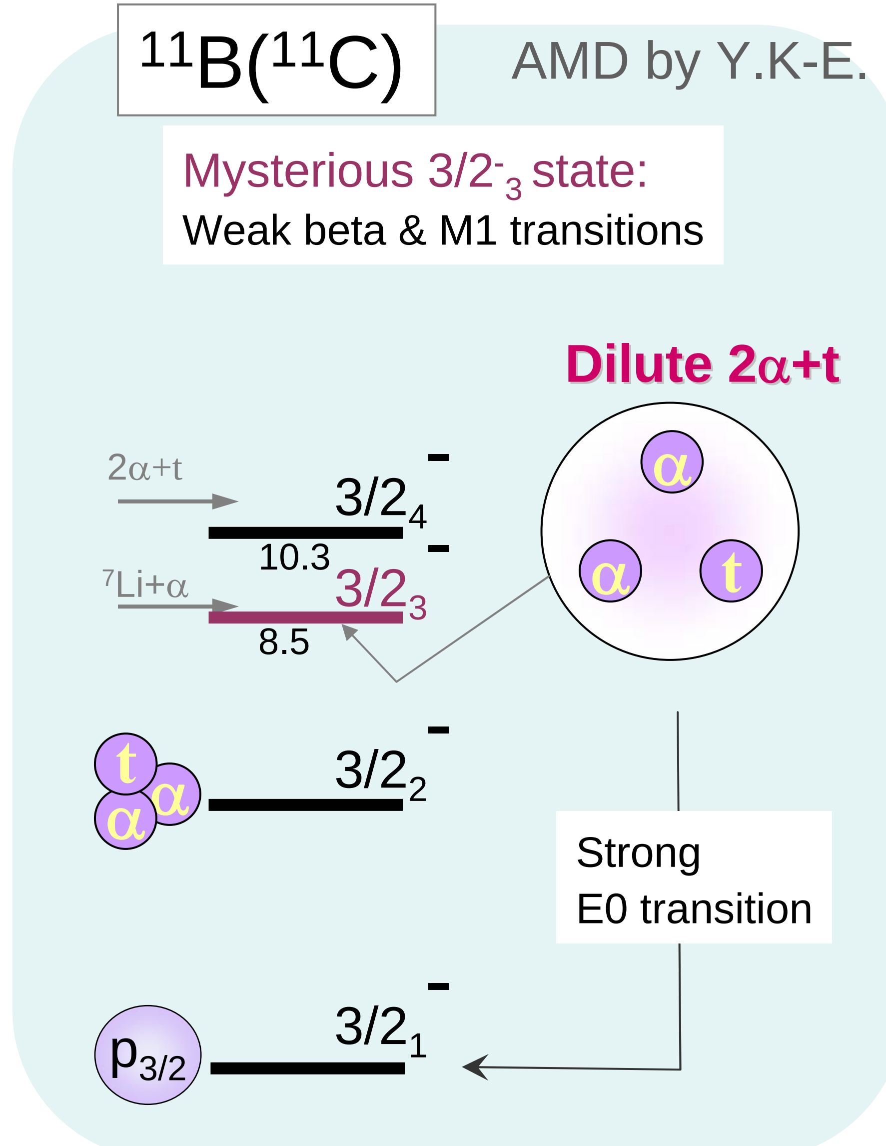
Large radius (AMD)

^{11}B	r.m.s.r (fm)	
$3/2^-_1$	2.5	
$3/2^-_2$	2.7	
$3/2^-_3$	3.1	2α+t

	^{12}C	r.m.s.r (fm)	
	0^+_1	2.5	
3α	0^+_2	3.3	3.5 (RGM) 3.8 (ACW)

Three-center cluster states of ^{11}B and ^{11}C : analogy with $12C(0^+_2)$

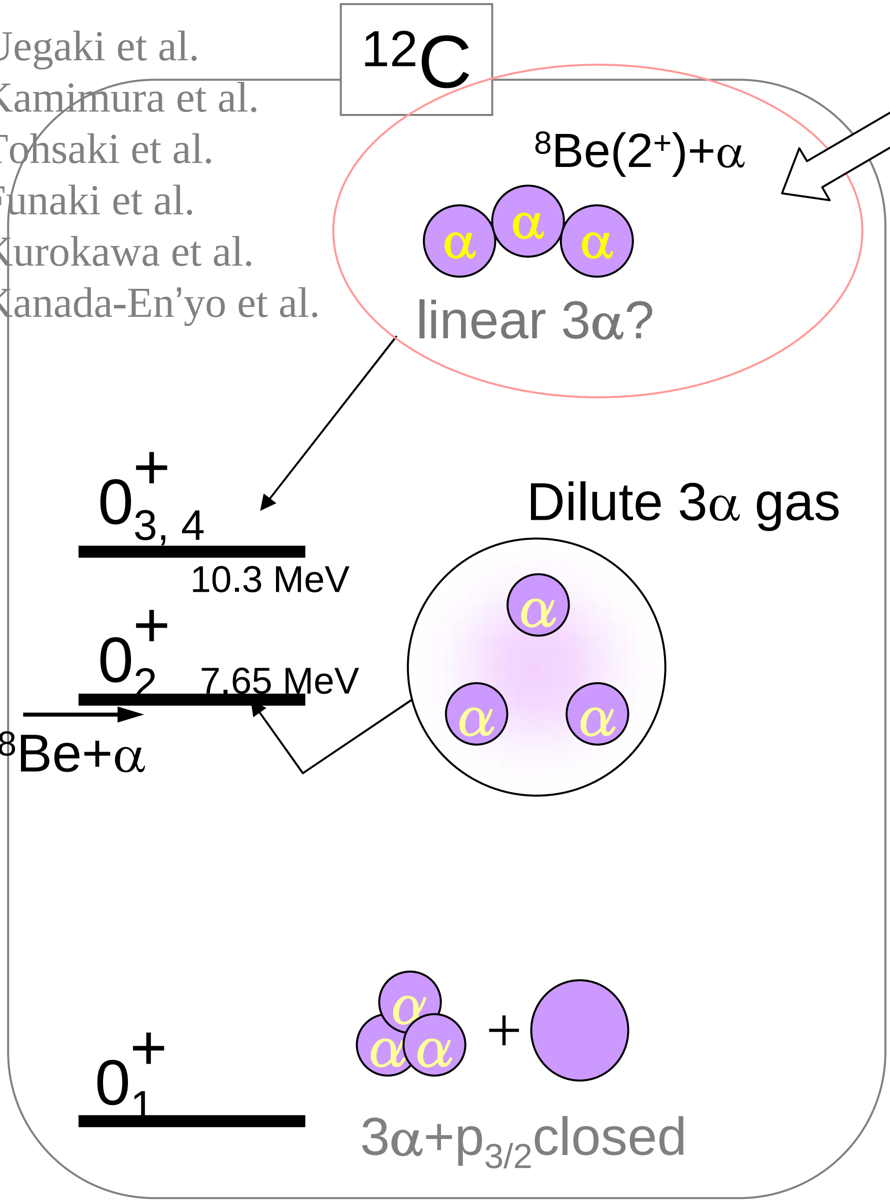




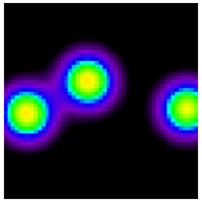
3-2. Linear chain structure in C isotopes

Linear chain-like structure

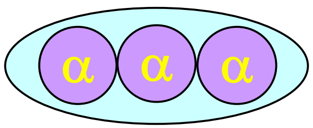
Uegaki et al.
Kamimura et al.
Tohsaki et al.
Funaki et al.
Kurokawa et al.
Kanada-En'yo et al.



theoretically suggested in 3αGCM, AMD, FMD and 3αOCM calc.



In neutron-rich C

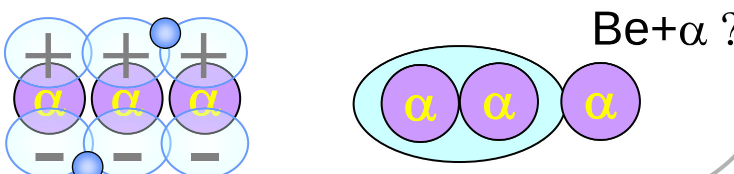


^{14}C ?

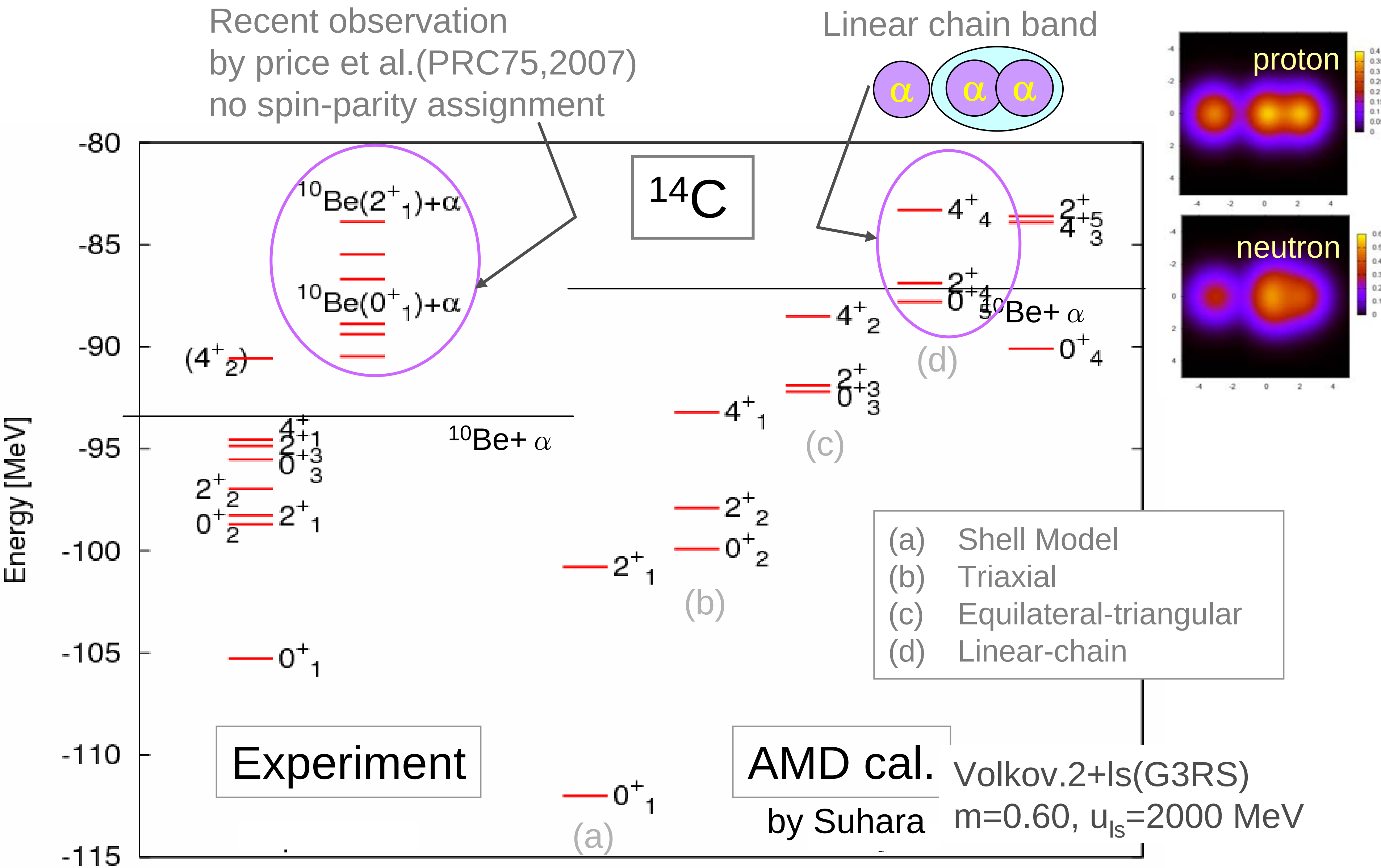
can be stabilized by additional neutrons ?

^{15}C K-E. et al,

^{16}C Itagaki et al., von Oertzen et al.,



Linear chain-like state in 14C



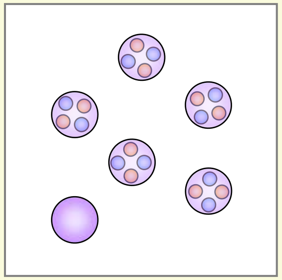
preliminary

3-3. dineutron cluster in $^{8}He^{*}$

Y. K-E., arXiv:0707.2120

Dineutron gas ?

α-condensation

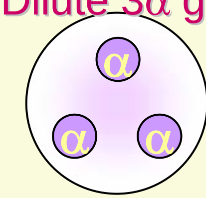


Roepche et al.(1998)

$^{12}C(0_2^+)$

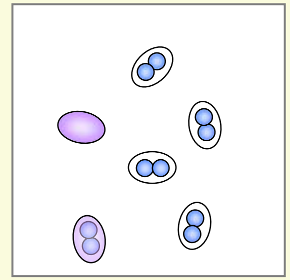
$^{16}O^*$

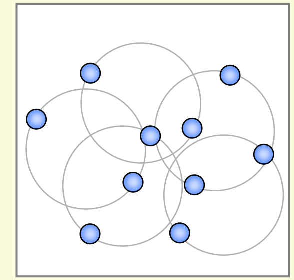
Dilute 3α gas



Tohsaki et al., Yamada et al., Funaki et al.

di-neutron in dilute neutron matter

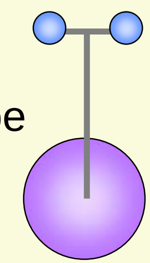




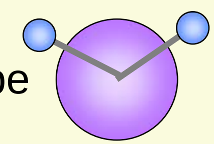
Matsuo et al.(2006)

di-neutrons in halo nuclei (^{6}He, ^{11}Li)

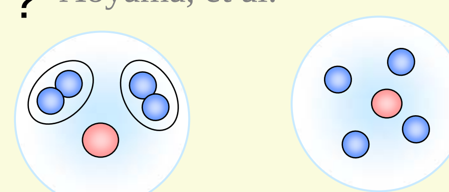
T-type



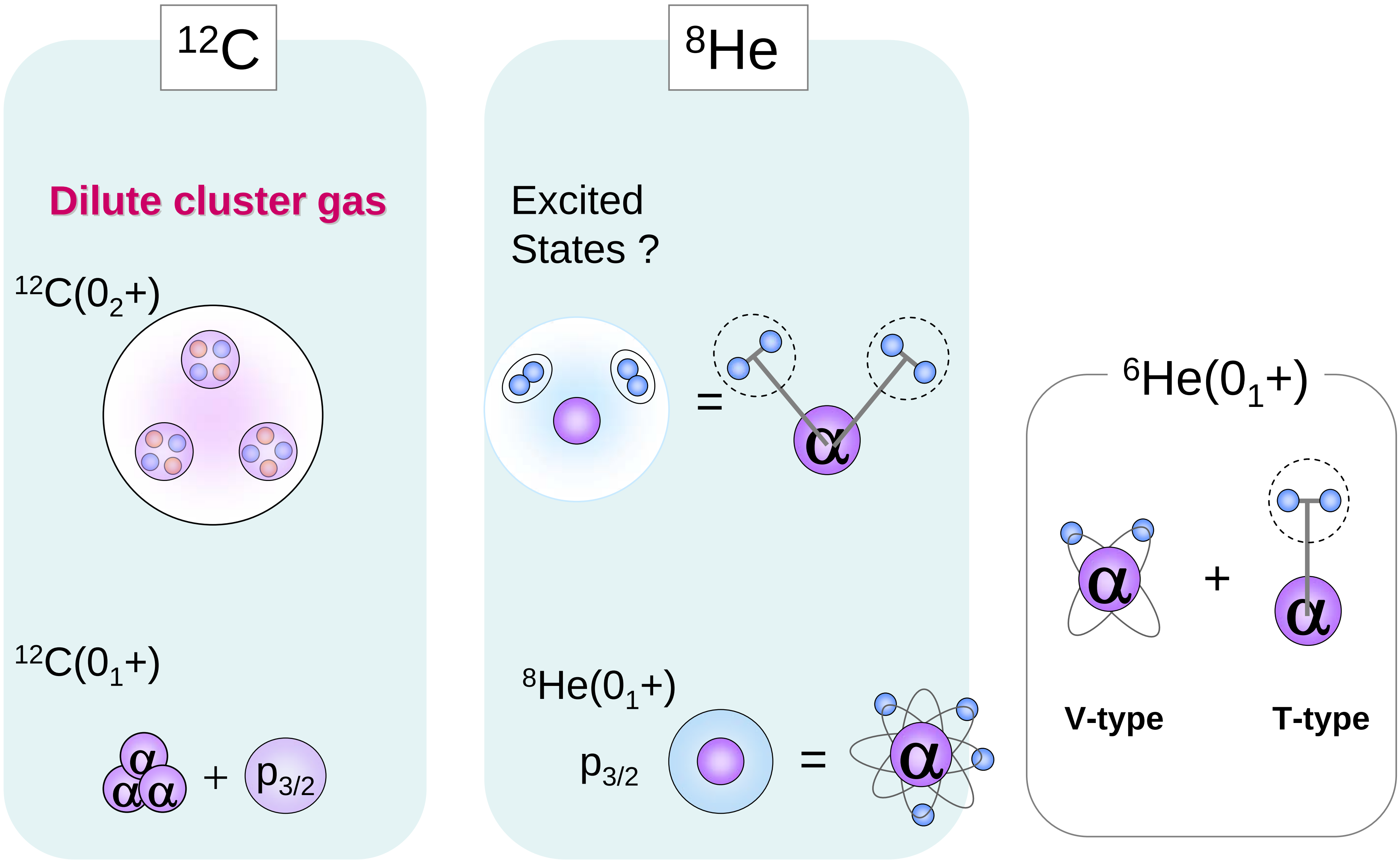
V-type



$^{5,\,7}H^*$? Aoyama, et al.

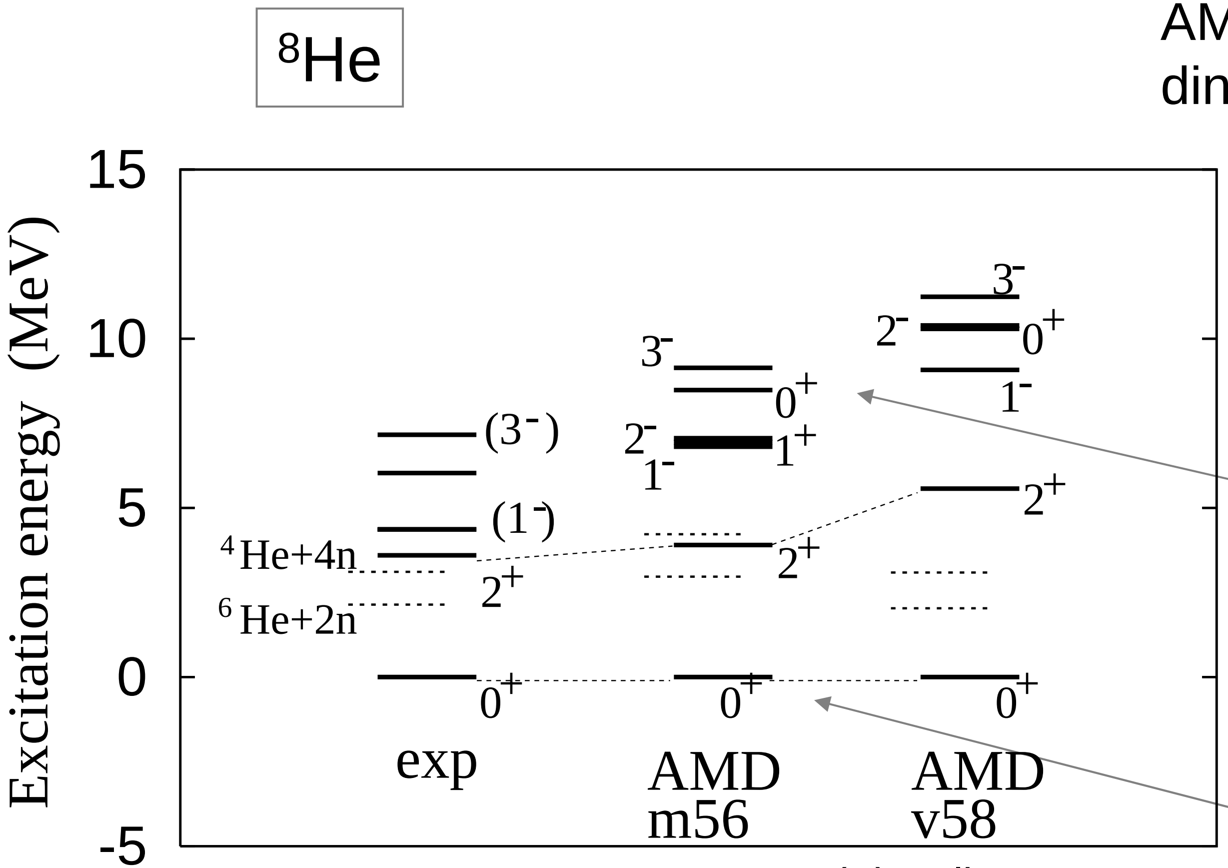


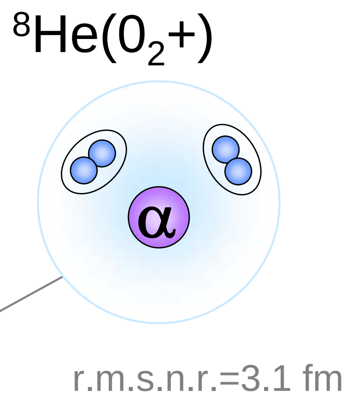
Two dineutrons in ^8He

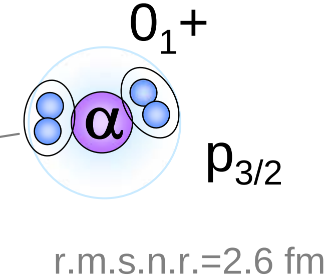


Possible dineutron gas-like state of ^{8}He

AMD+GCM calc. suggests dineutron gas-like state







(C) MV1
m=0.56
b=h=0.15

(A) Volkov No.2
m=0.58
b=h=0

AMD+GCM
with effective N-N interactions(MV1, Volkov)

Fine tuning of effective N-N interaction

Central (MV1 or Volkov)+LS (G3RS with $u_I = -u_{II} = 2000$ MeV)

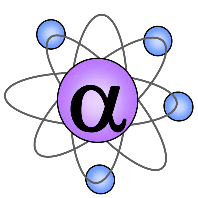
$$v(r) = \left((1-m) + bP_\sigma - hP_\tau - mP_\sigma P_\tau\right) \sum_{k=1,2} V_k \exp\left(-\frac{r^2}{a_k^2}\right)$$

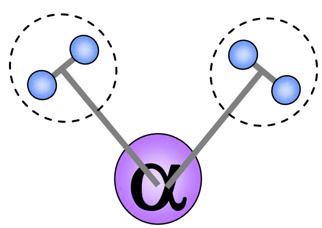
N-N properties

	(A) Volkov 2	(B) MV1	(C) MV1	(D) V2	exp.
	m=0.58	m=0.62	m=0.56	m=0.51,	
	b=h=0	b=h=0	b=h=0.15	b=h=0.15	
n-n	bound	bound	almost unbound	unbound	unbound
S(1E) fm	9.7	6.4	>100	-24	-18
S(3E) fm	9.7	6.4	4.2	5.4	5.4

$^8He(0_1+)$

$p_{3/2}$





n-n

α-n:^5He

α-2n   2n-2n   α-α ?

Effective N-N interaction

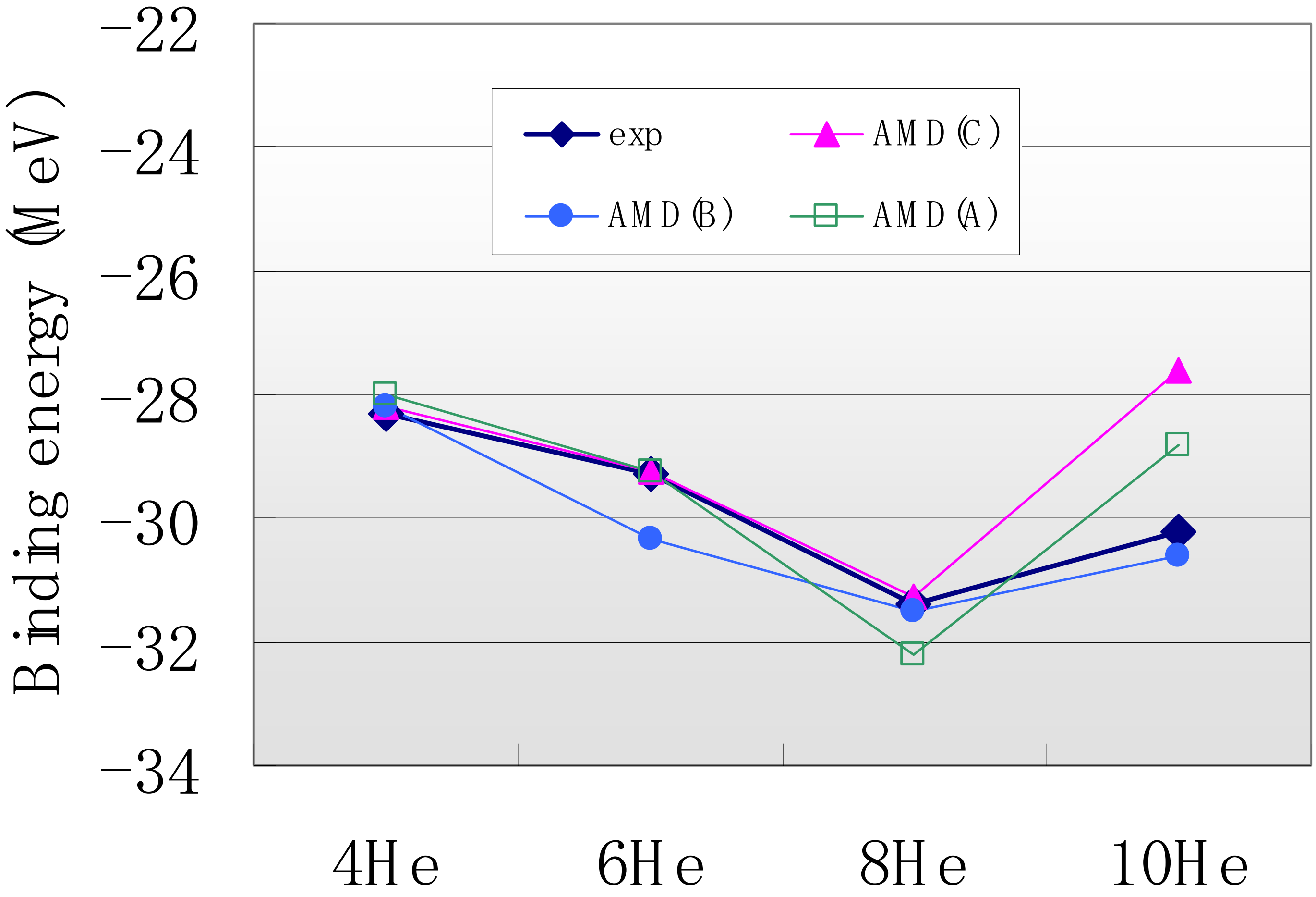
Effective N-N Interaction

Central (MV1 or Volkov)

+LS (G3RS with $u_I = -u_{II} = 2000$ MeV)

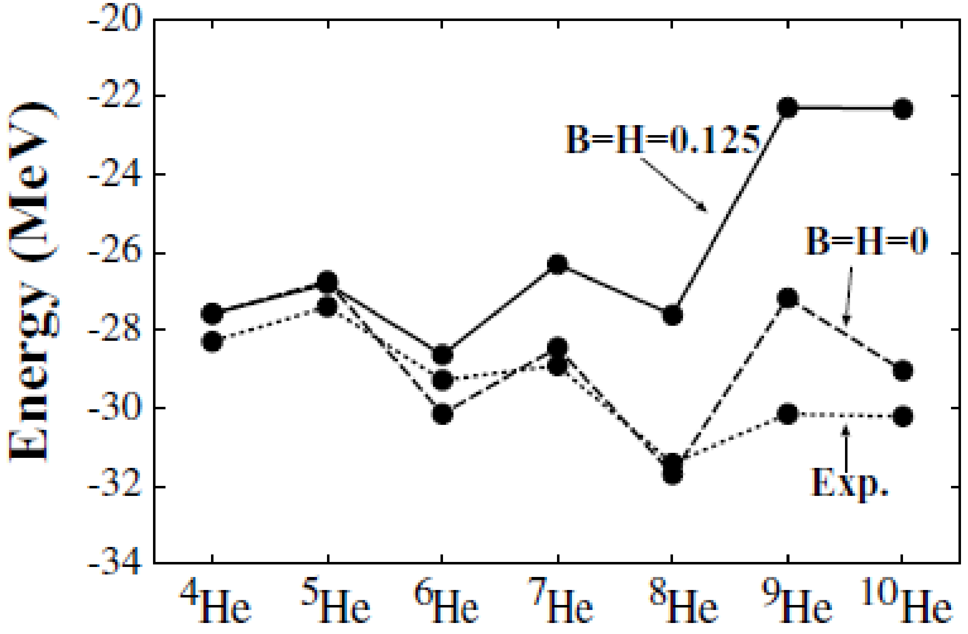
	(A) Volkov 2	(B) MV1	(C) MV1	(D) V2
	m=0.58,	m=0.62,	m=0.56,	m=0.51,
	b=h=0	b=h=0	b=h=0.15	b=h=0.15
n-n	too strong	too strong	slightly strong	good
α-n:^{5}He	good	good	slightly strong	too strong
α-2n:^{6}He	good	strong	good	weak
α-α	good	too weak	slightly weak	too strong

Binding energy



Other works with effective nuclear forces

S.Aoyama et al. ,PRC 74, 017307(2006)
Volkov No.2 (m=0.60)



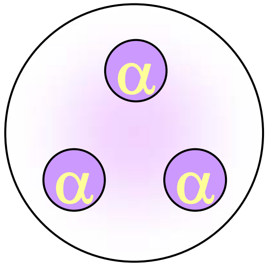
nn(T=1) force is too strong

FIG. 2. Systematics of the calculated binding energies of the He isotopes compared with experimental data. The solid line corresponds to the case of $B = H = 0.125$, whereas the dashed line to the case of $B = H = 0$. The experimental values are shown as the dotted line.

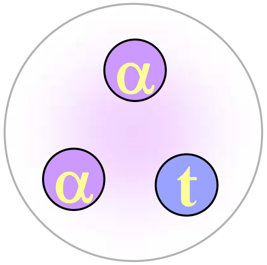
4. Summary

Various cluster states appear in excited states.

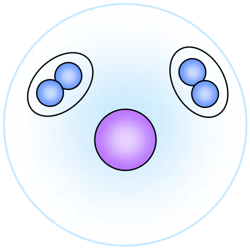
1. Cluster gas states similar to 12C*



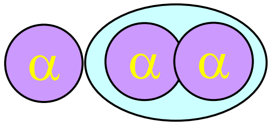
$^{11}B^*$($^{11}C^*$) with 2α+t(^{3}He)



$^{8}He^*$: α+2n+2n



2. linear chain in $^{14}C^*$



α+^{10}Be

Problems in effective interactions

Effective interactions with a simple form (central and LS Forces) were used.

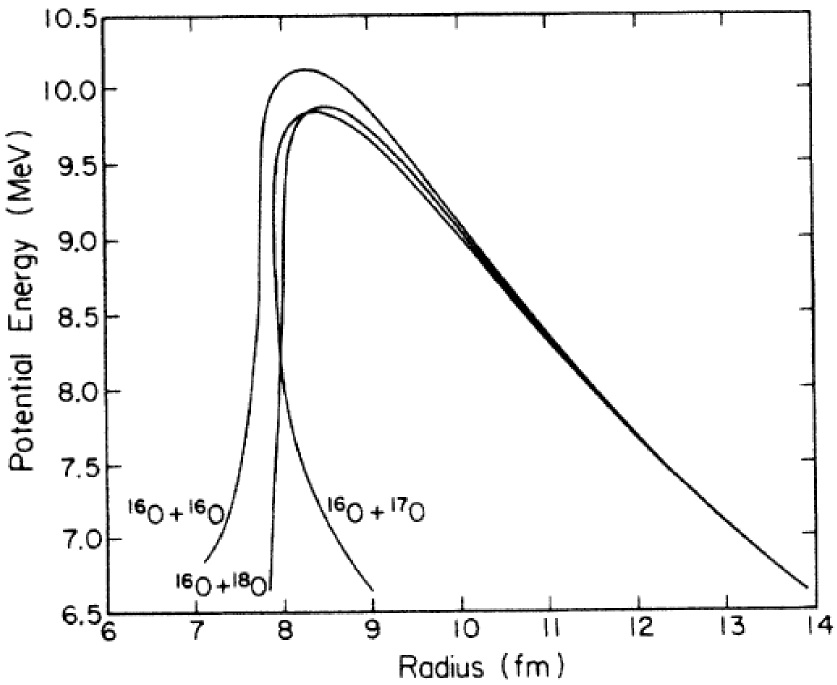
Global fit of experimental data with one parameter set is difficult.
Fine tuning of interaction parameters was done.
System depending parameters.

For more quantitative reproduction of energy levels and for more predictive power, we need to overcome problems of the present effective interactions.

Future plan: Model calculations based on realistic force
- Structure dependence: explicit treatment of tensor force
- Less structure dependent part:
  - Hard core of central force with UCOM-like treatment
  - density-dependent ls force, other operator terms ?
- Link of effective interactions with realistic interactions: GCM

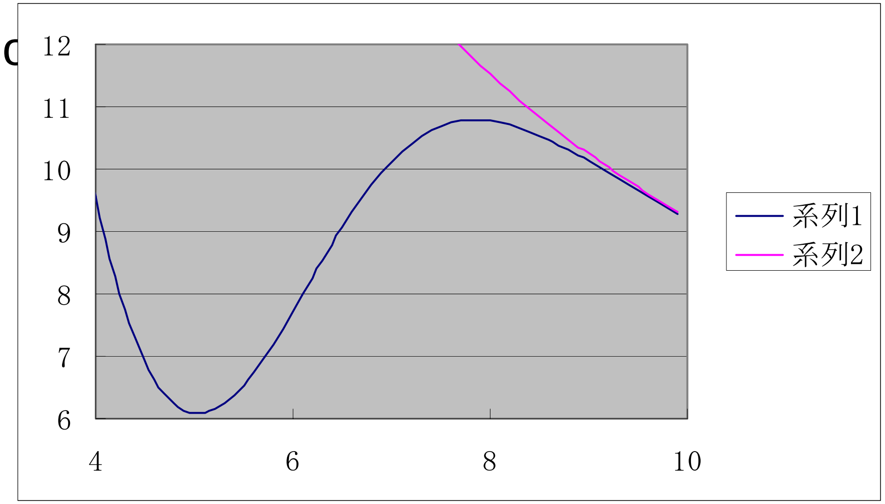
J.Thomas, Phys.Rev.C 33, 1679 (1986)

16O-16O potential reduced from fusic

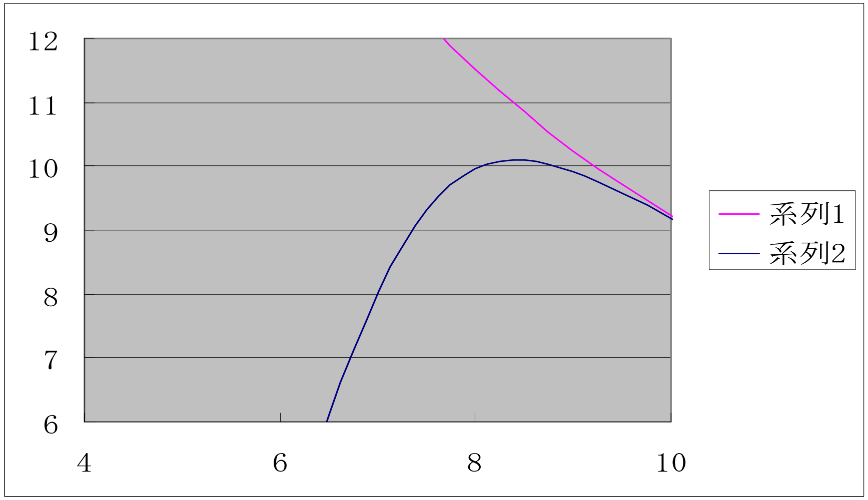


Barrier 10 MeV high
at 8 fm

Gogny(D1S) V(d)



MV1(m=0.60)



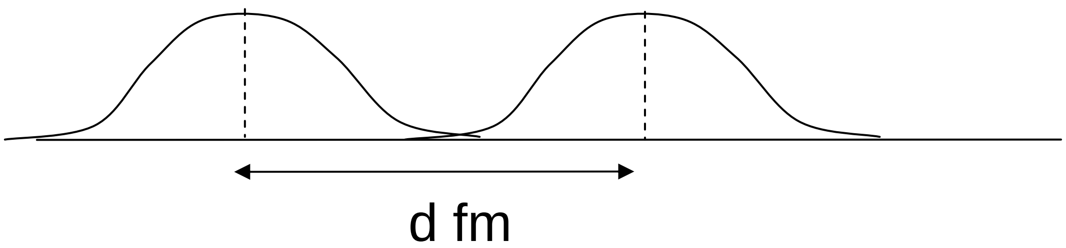
d (fm)

16O-16O

Barrier height：0.5～1 MeV larger、 Fusion cross：2-3 times smaller

Treatment of relative motion（coordinate）

$$\Phi_{^{16}\mathrm{O}\text{-}^{16}\mathrm{O}}(d)$$

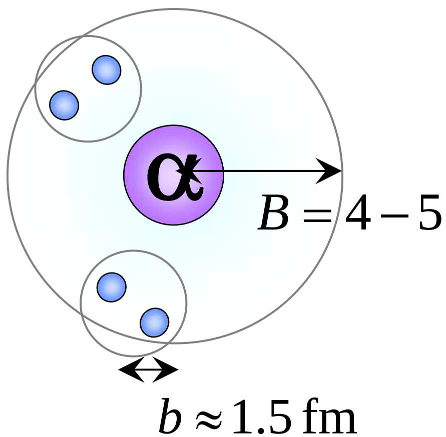


$$E(d)=\frac{\left\langle \Phi_{^{16}\mathrm{O}\text{-}^{16}\mathrm{O}}(d)\middle| H \middle| \Phi_{^{16}\mathrm{O}\text{-}^{16}\mathrm{O}}(d)\right\rangle}{\left\langle \Phi_{^{16}\mathrm{O}\text{-}^{16}\mathrm{O}}(d)\middle| \Phi_{^{16}\mathrm{O}\text{-}^{16}\mathrm{O}}(d)\right\rangle}$$

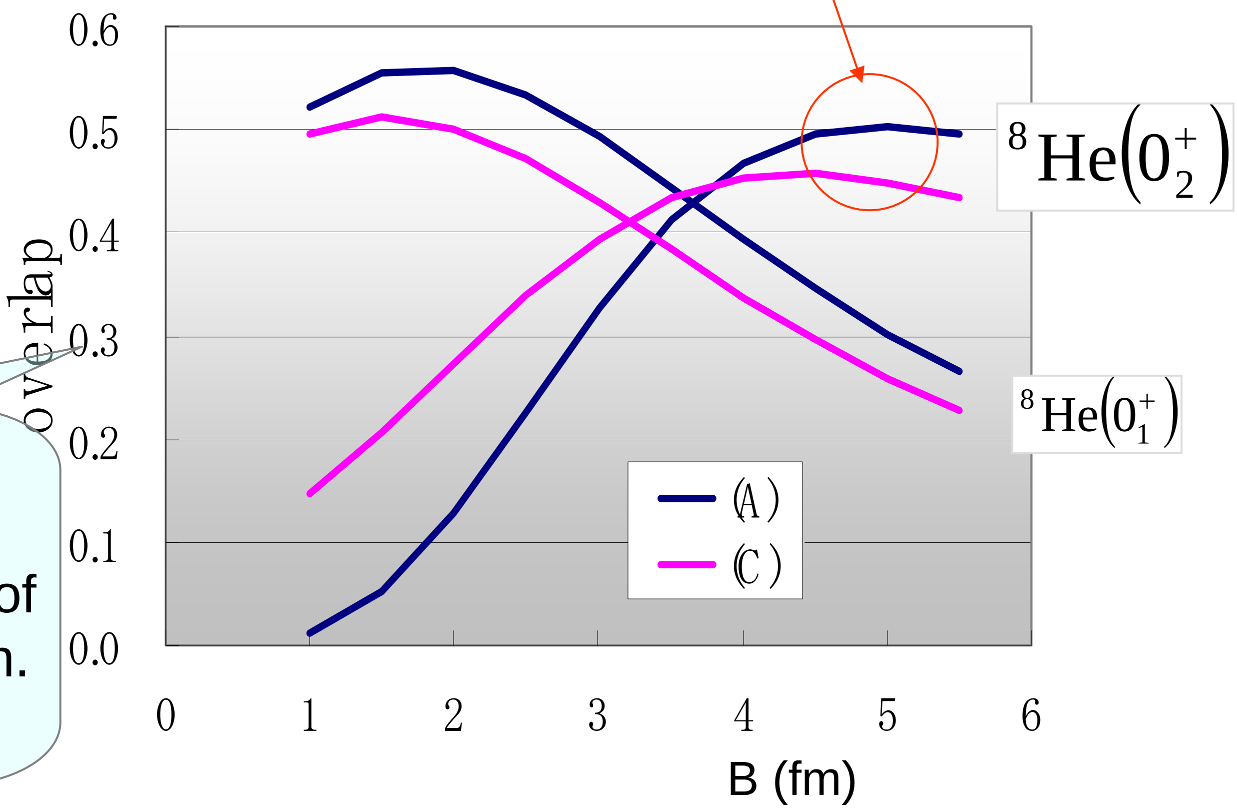
$$V(d)\approx E(d)-T_{rel}(\infty)$$

^{2}n condensate wave function

$$\Phi_{Cond}(B) = \int d^3\mathbf{R}_1 d^3\mathbf{R}_2 \exp\left(-\frac{(\mathbf{R}_1-\mathbf{R}_\alpha)^2}{B^2}\right)\exp\left(-\frac{(\mathbf{R}_2-\mathbf{R}_\alpha)^2}{B^2}\right) A[\phi_{2n}(\mathbf{R}_1)\phi_{2n}(\mathbf{R}_2)\phi_\alpha(\mathbf{R}_\alpha)]$$



$$\left|\left\langle {}^8\mathrm{He}(0_2^+) \middle| \Phi_{Cond}(B=4-5\,\mathrm{fm}) \right\rangle\right|^2 \approx 0.5$$



^{8}He(0^+_2)

has 50 % component of
^{2}n condensate wave fn.
$\Phi_{Cond}(B=4-5\,\mathrm{fm})$