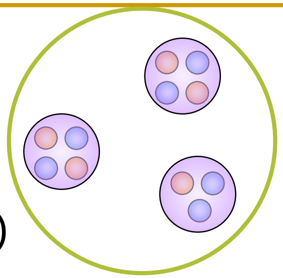
Linear-chain and gas-like structures in nuclei near ^{12}C

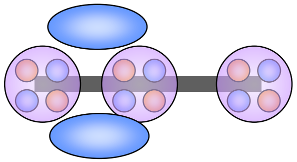
Tadahiro Suhara (Matsue Coll. of Tech.)

Outline

Background



Gas-like state (^{11}B)



Linear-chain state (^{14}C)

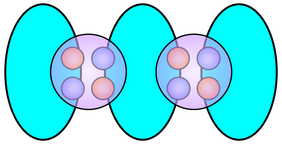
In nuclei near ^{12}C, gas-like and linear-chain structures seem to exist universally.

Gas-like structure

2α+dineutron(^{10}Be), 2α+t(^{11}B), 3α(^{12}C), 3α+n(^{13}C)

Linear-chain structure

$2\alpha+2n(\sigma_{1/2})^2$(^{10}Be), $2\alpha+2n+p(\sigma_{1/2})^3$(^{11}B), 3α(^{12}C), 3α+Xn(^{13}C, ^{14}C, ^{16}C)



$2\alpha+2n(\sigma_{1/2})^2$(^{10}Be)

Aim

We want to find the proton-neutron dependence of gas-like and linear chain structures.

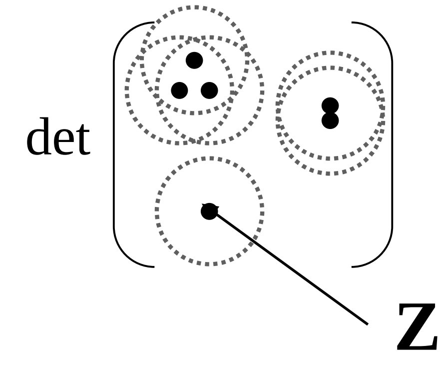
Method

β-γ constraint AMD+GCM

β-γ constraint AMD+GCM

AMD（Antisymmetrized Molecular Dynamics）

A wave function of A-body system



$$\Phi_{\mathrm{AMD}} = \det[\varphi_1, \varphi_2, \ldots, \varphi_{\mathrm{A}}]$$

$$\varphi_i = \phi(\mathbf{Z}_i)\chi(\boldsymbol{\xi}_i)$$

spatial

$$\phi(\mathbf{Z}_i) \propto \exp[-\nu(\mathbf{r} - \frac{\mathbf{Z}_i}{\sqrt{\nu}})^2]$$

spin and isospin

$$\chi(\boldsymbol{\xi}_i) = \begin{pmatrix} \xi_{i\uparrow} \\ \xi_{i\downarrow} \end{pmatrix} \times (\mathrm{p}\ _{\mathrm{or}}\ \mathrm{n})$$

Set of variational parameters

$$Z = \{\mathbf{Z}_i, \boldsymbol{\xi}_i\}$$

$$\begin{cases} \mathbf{Z}_i : \text{center of Gaussian w ave packets} \\ \boldsymbol{\xi}_i : \text{spin direction} \end{cases}$$

β-γ constraint AMD+GCM

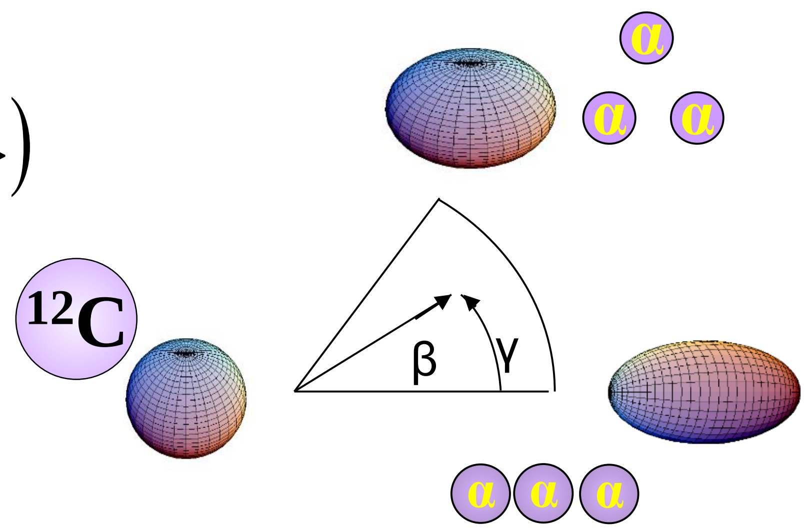
Constraints

The quadrupole deformation (β, γ)

$$\beta\cos\gamma = \frac{\sqrt{5\pi}}{3}\frac{2<z^2>-<x^2>-<y^2>}{R^2}$$

$$\beta\sin\gamma = \sqrt{\frac{5\pi}{3}}\frac{<x^2>-<y^2>}{R^2}$$

$$R^2 = \frac{5}{3}\left(<x^2>+<y^2>+<z^2>\right)$$



β-γ constrained AMD+GCM

GCM (Generator Coordinate Method)

Wave function for the $J^{\pm}n$ state

$$\left|\Phi_n^{J\pm}\right\rangle = \sum_K \sum_i f_n(\beta_i, \gamma_i, K) P_{MK}^J \left|\Phi^{\pm}(\beta_i, \gamma_i)\right\rangle$$

Hamiltonian

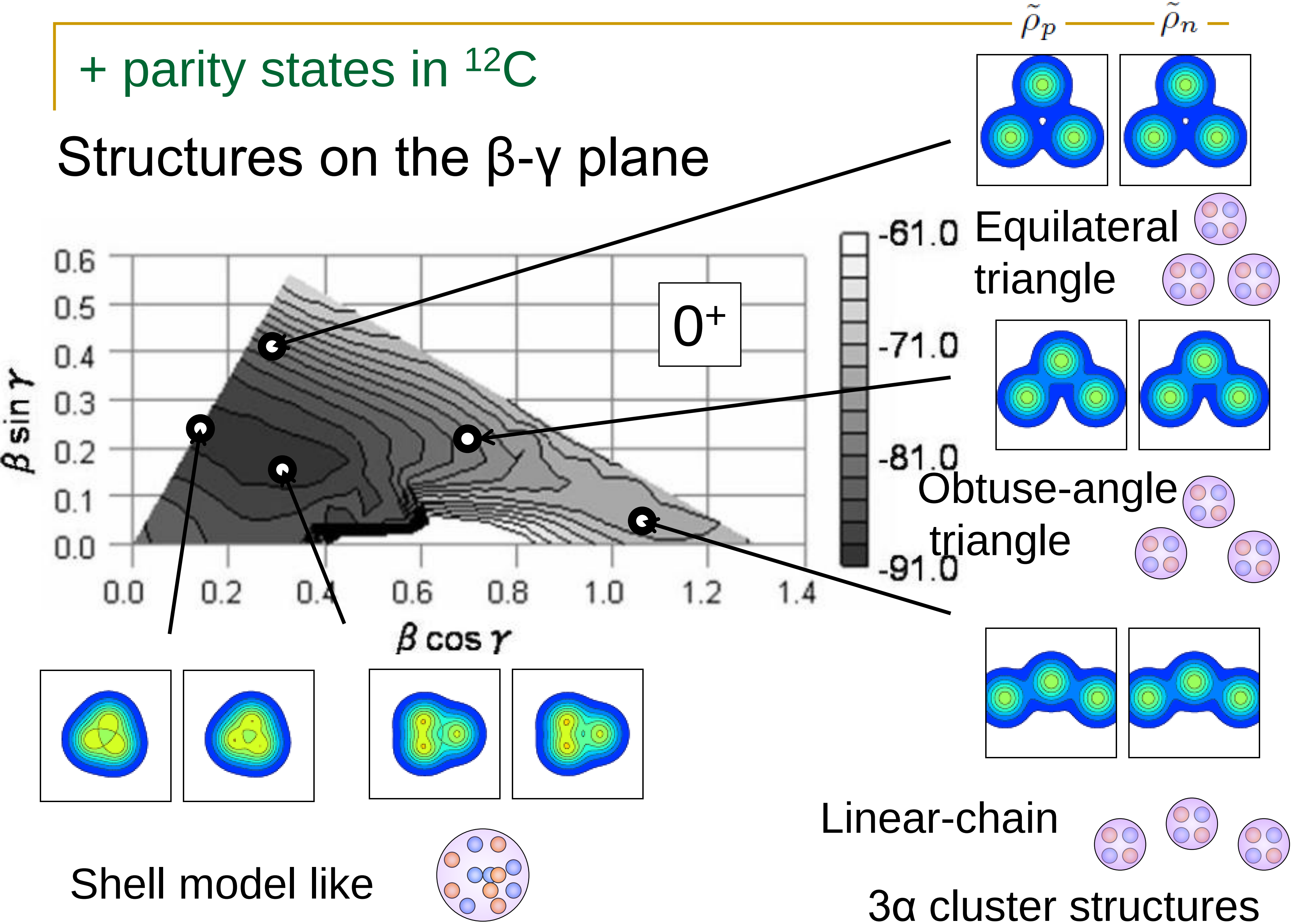
$$H^{\mathrm{eff}} = \sum_i t_i - T_{\mathrm{CM}} + \sum_{i<j} v_{ij}^{\mathrm{central}} + \sum_{i<j} v_{ij}^{\mathrm{LS}} + \sum_{i<j} v_{ij}^{\mathrm{Coulomb}}$$

The central force : The Volkov No.2 (M=0.6, B=H=0.125)

The LS force : The LS part of the G3RS (u=1600 [MeV])

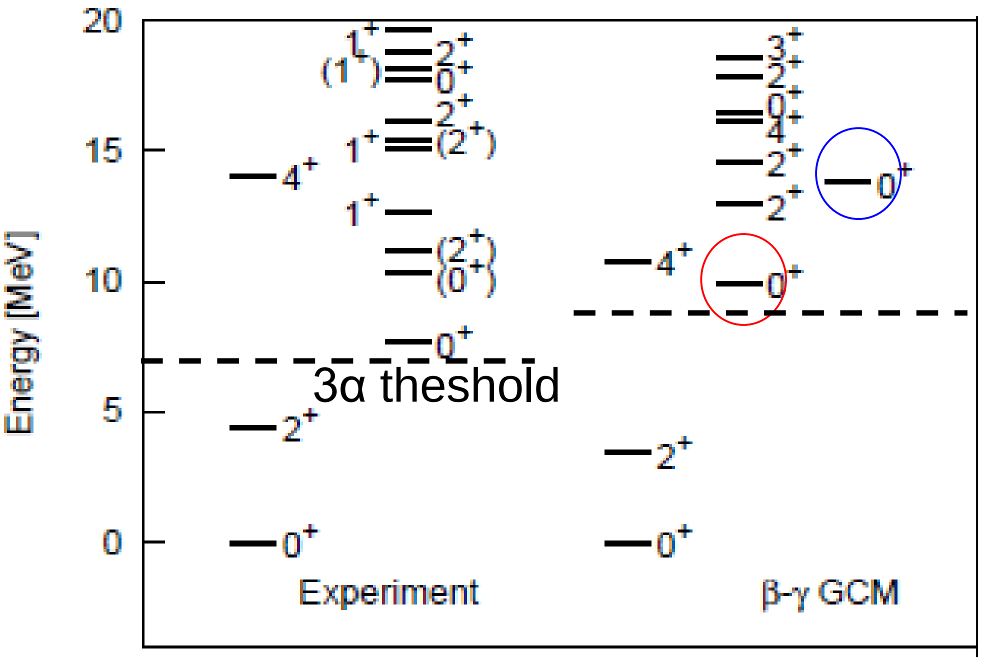
+ parity states in ^{12}C

Structures on the β-γ plane

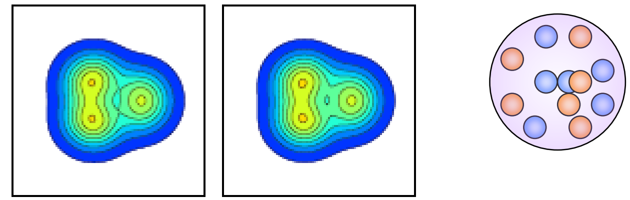


+ parity states in ^{12}C

Structures of 0^+ states

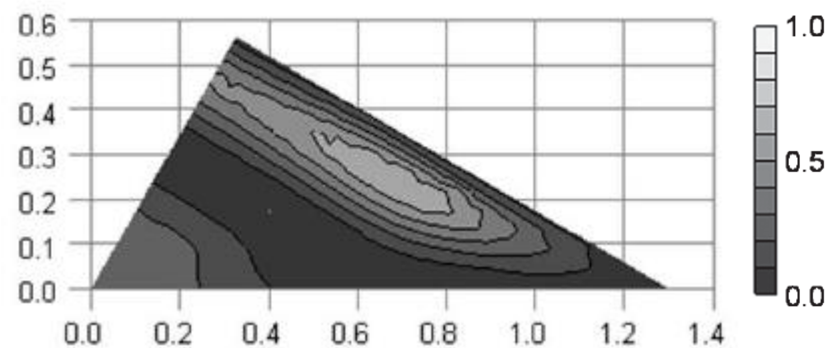


0^+_1: shell model-like

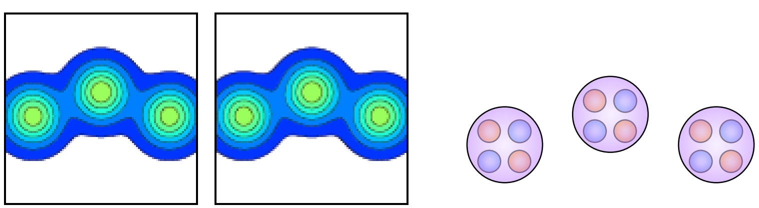


0^+_2: various 3α configurations
gas-like state

GCM amplitude

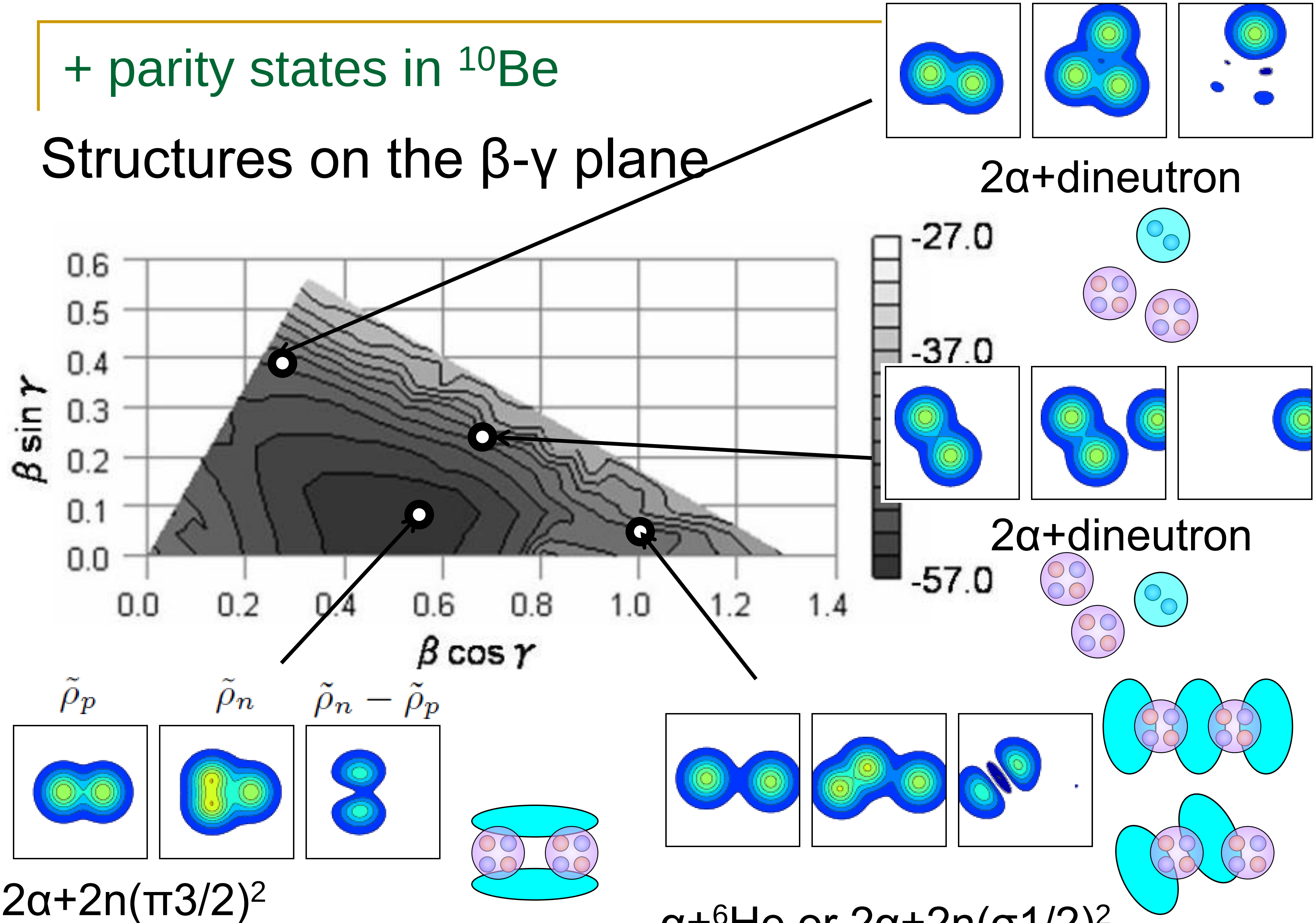


0^+_3: bent linear-chain



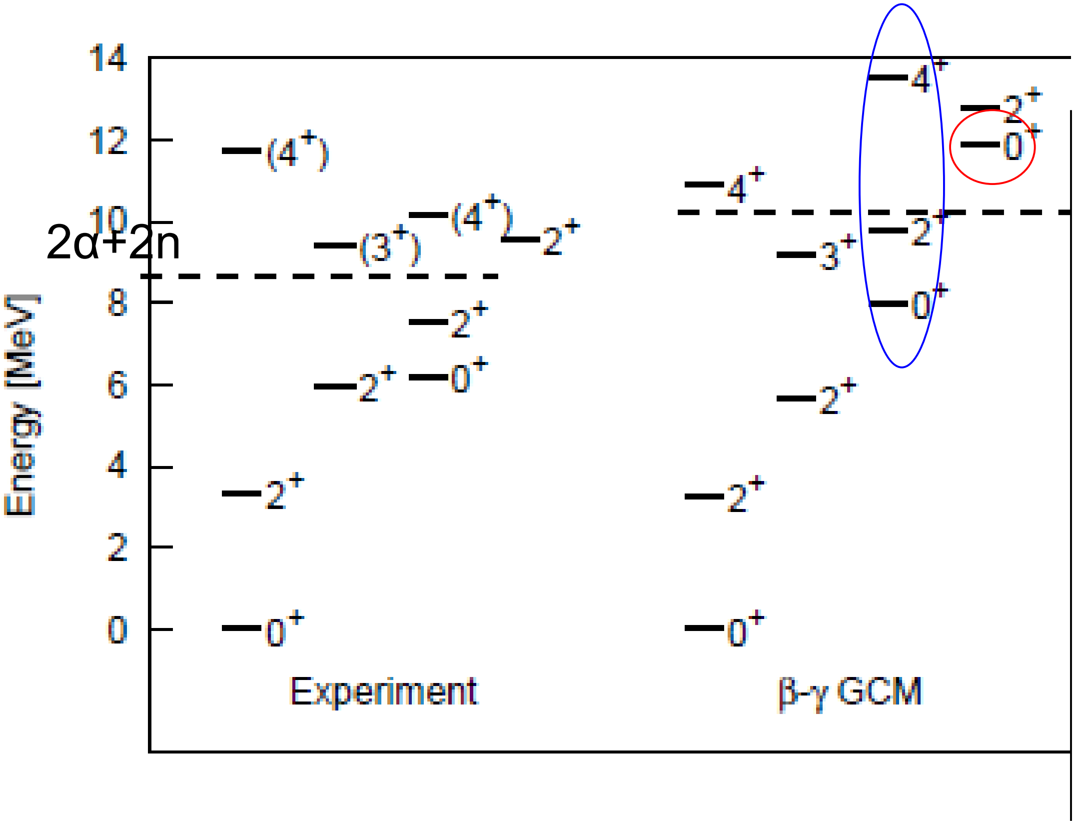
+ parity states in ^{10}Be

Structures on the β-γ plane

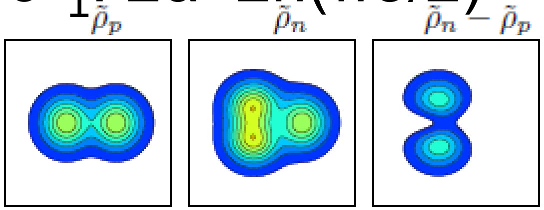


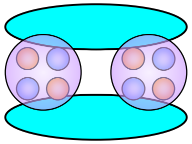
+ parity states in ^{10}Be

Structures of 0^+ states



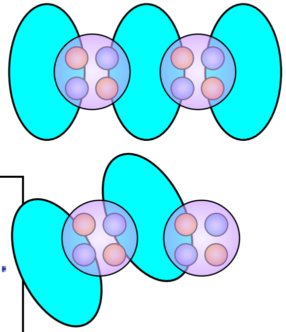
0^+_1: $2\alpha+2n(\pi 3/2)^2$

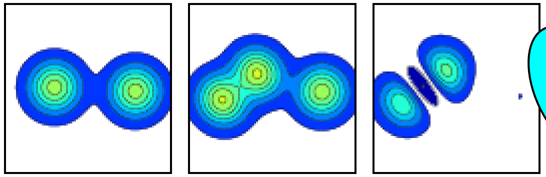




0^+_2: $\alpha+{}^6$He

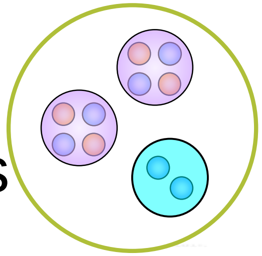
$2\alpha+2n(\sigma 1/2)^2$

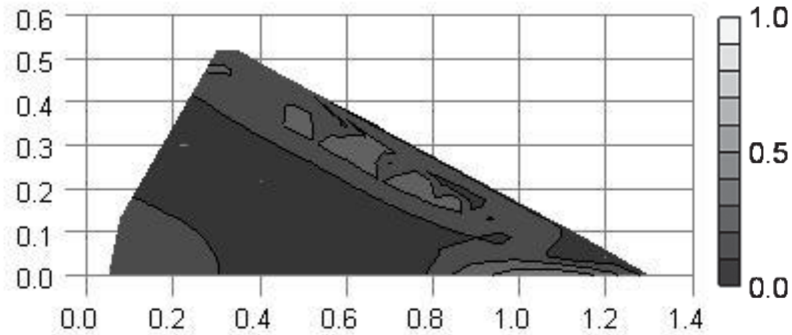




0^+_3: 2α+dineutron

Gas-like states



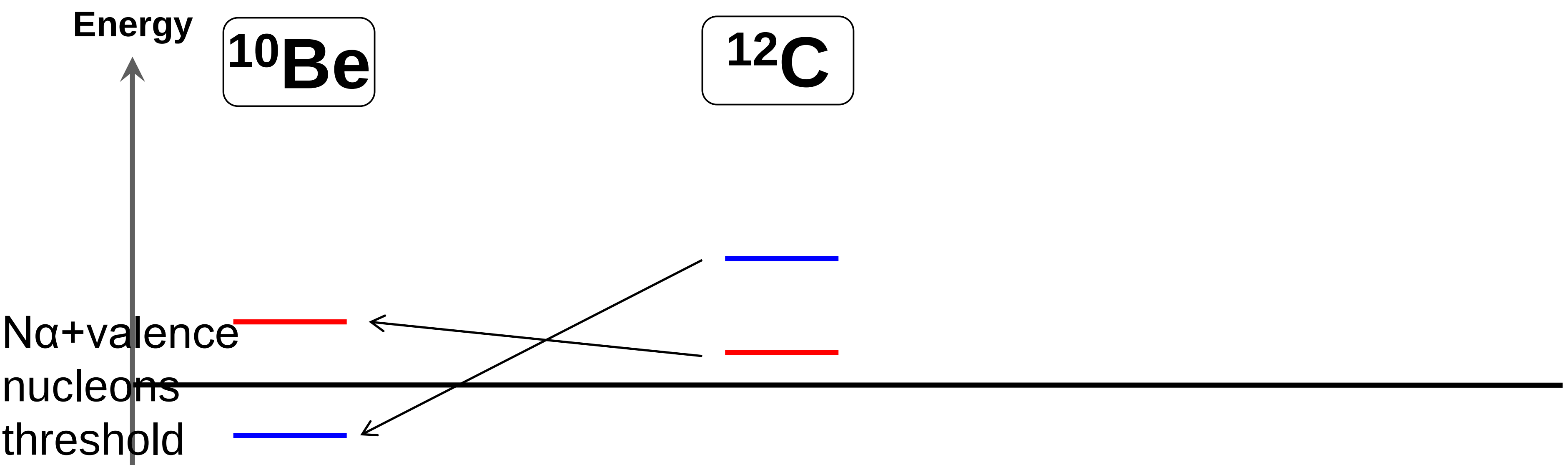


・There are gas-like and linear-chain states.

・The order is reversed from ^{12}C.

Gas-like and linear-chain states

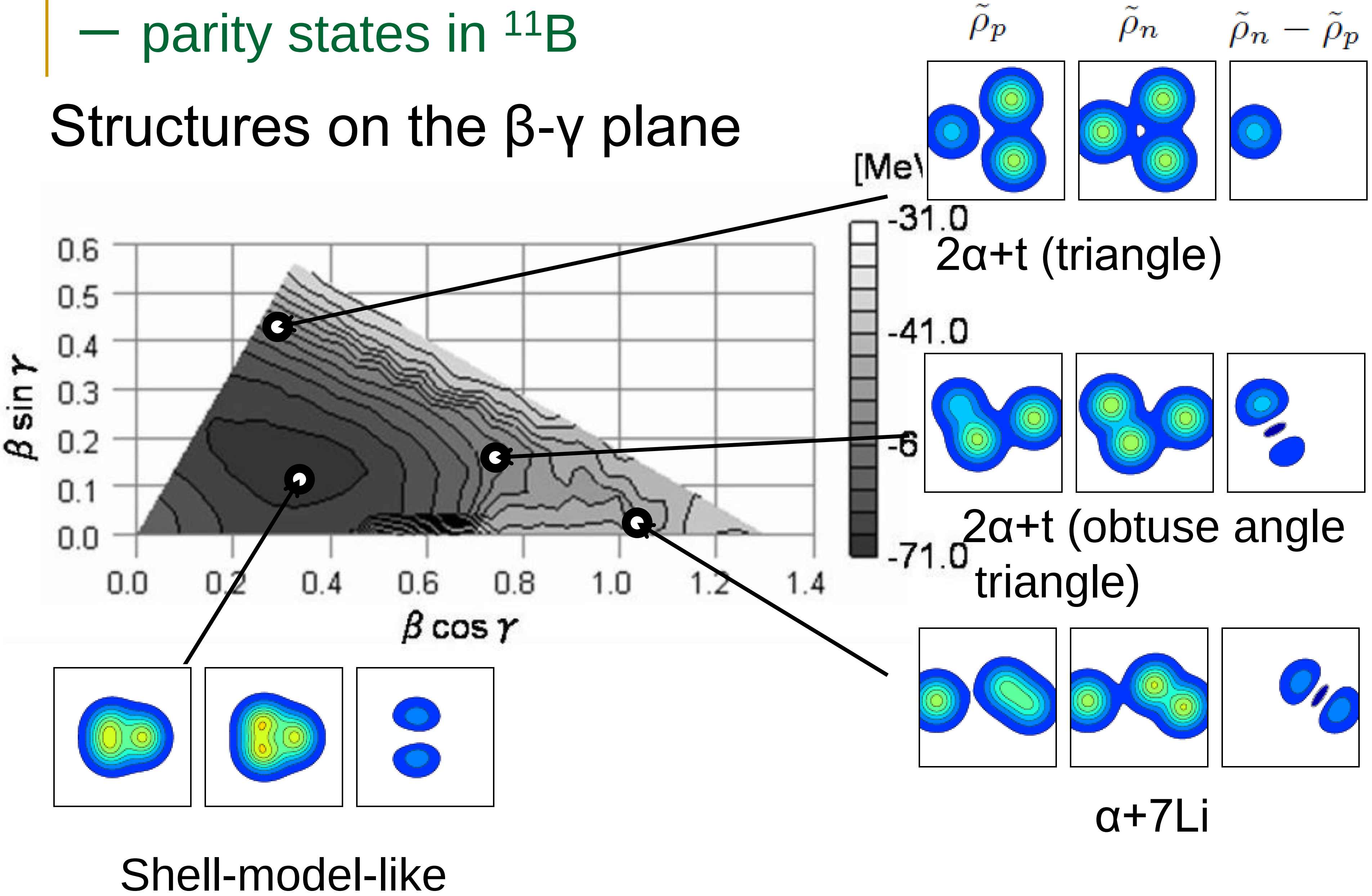
Gas-like state
Linear-chain state



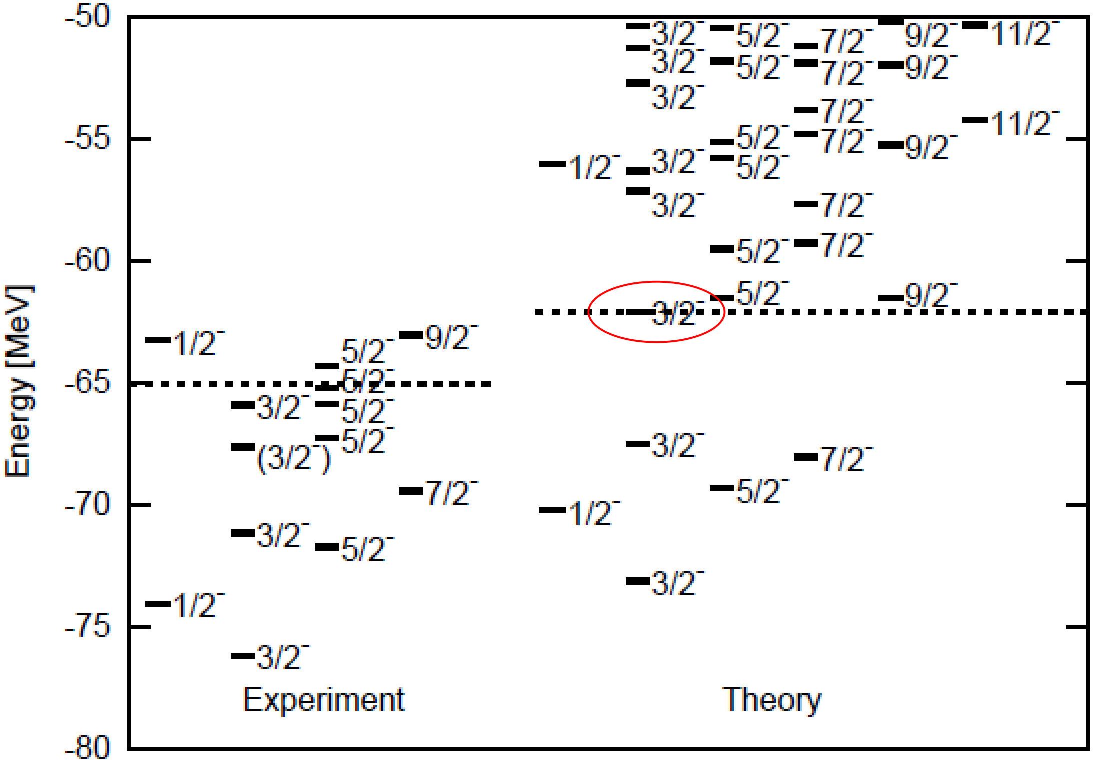
The order is reversed.
The linear chain state gains energy due to the effect of excess neutrons occupying the molecular orbit.

− parity states in ^{11}B

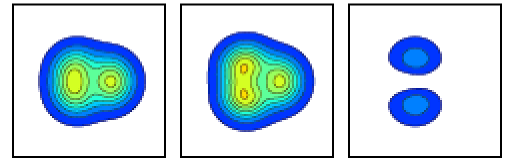
Structures on the β-γ plane

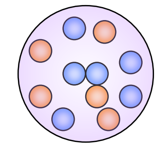


− parity states in ^{11}B

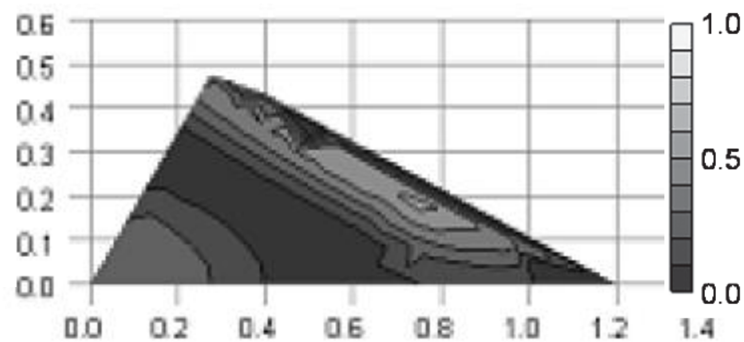


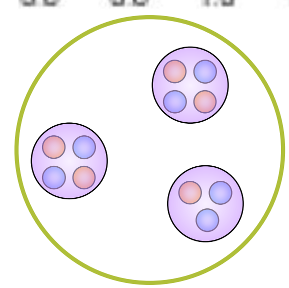
$3/2^-_{1,2}$: Shell-model-like





$3/2^-_3$: various 2α+t configurations (Gas-like state)



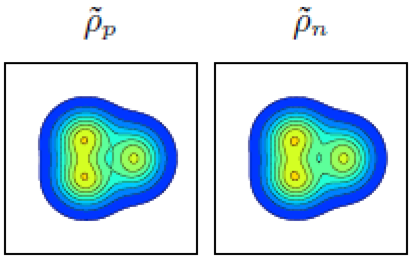


In − parity states, there is a gas-like state.

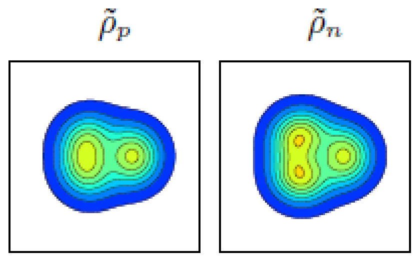
Gas-like states and E0 transition strength in N=6

^{12}C	^{11}B	^{10}Be
$0^+_1 \rightarrow 0^+_2$	$3/2^-_1 \rightarrow 3/2^-_3$	$0^+_1 \rightarrow 0^+_3$
$M_p = 6.67$ fm^2	$M_p = 5.42$ fm^2	$M_p = 3.45$ fm^2
$M_n = 6.60$ fm^2	$M_n = 6.82$ fm^2	$M_n = 6.68$ fm^2

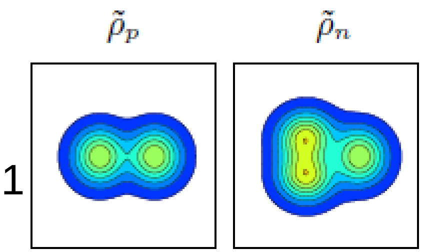
0^+_1

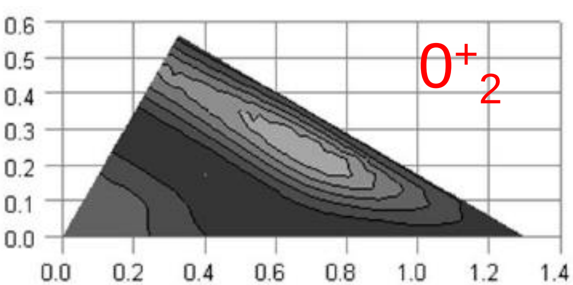


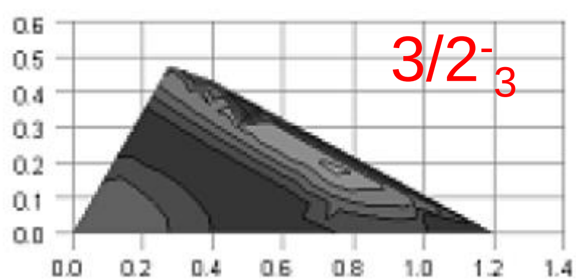
$3/2^-_1$

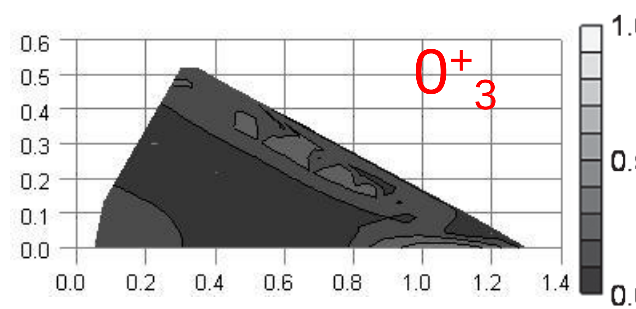


0^+_1

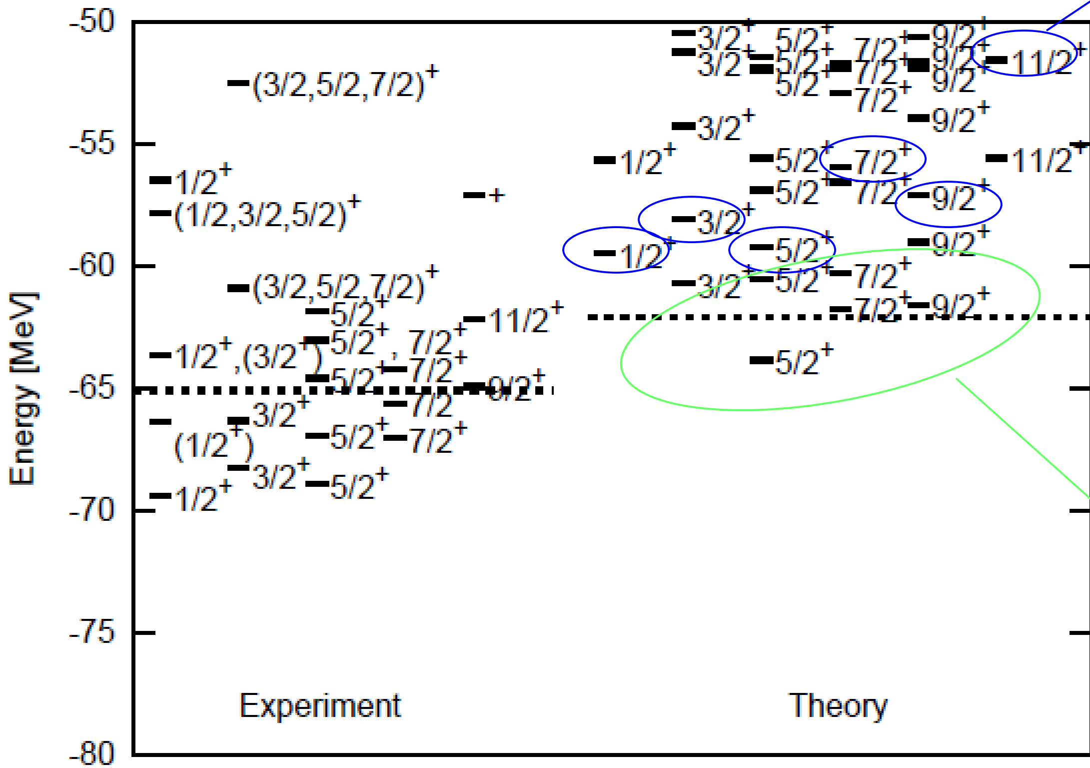


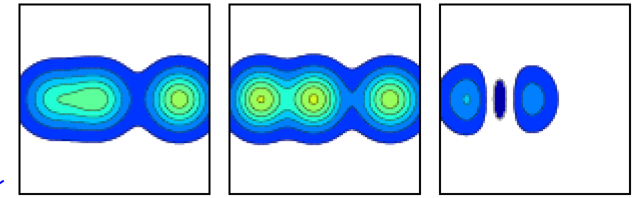






+ parity states in ^{11}B

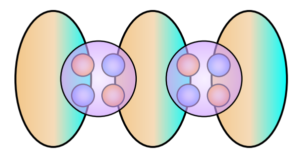




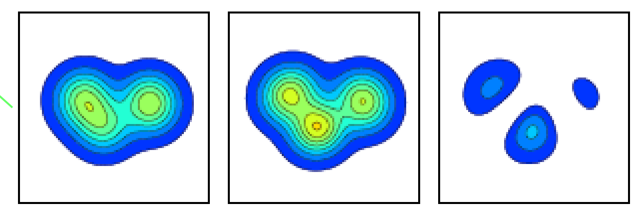
2α+2n+p

2n, p occupy $(\sigma 1/2)^3$

Linear-chain like state



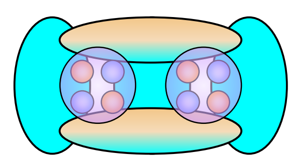
n $(\sigma 1/2)^2$
p $(\sigma 1/2)$



2α+2n+p

2n occupy $(\pi 3/2 \sigma 1/2)$

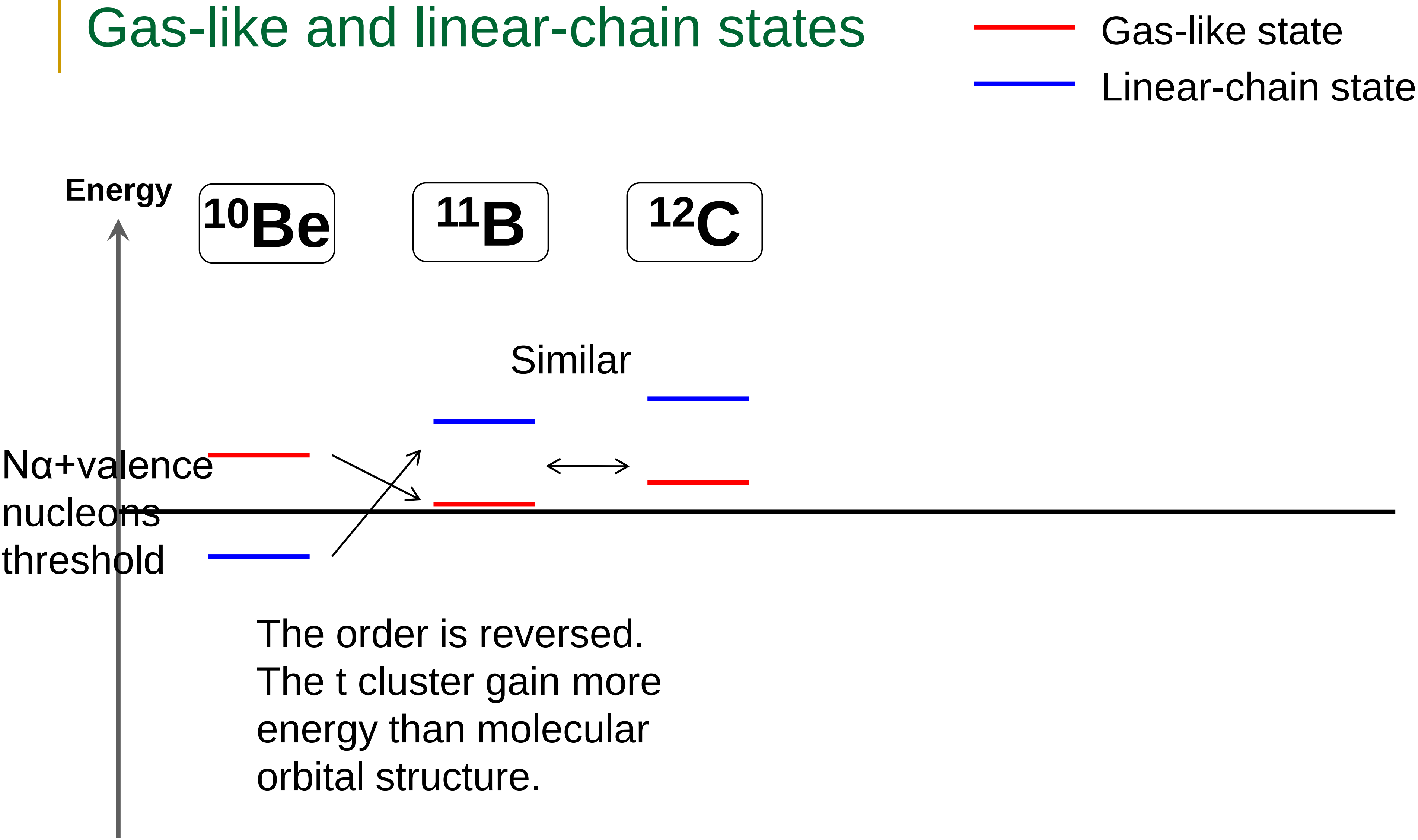
p occupies $(\pi 3/2)$



n $(\pi 3/2 \sigma 1/2)$
p $(\pi 3/2)$

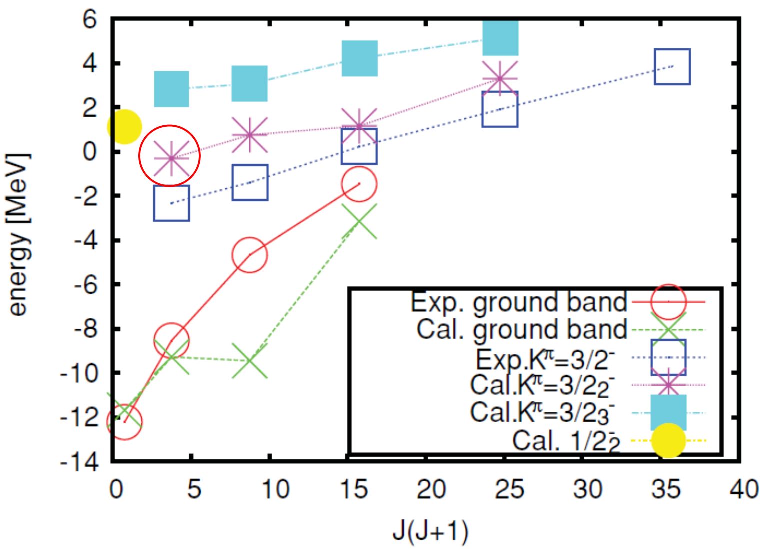
In + parity states, there is linear-chain states.
The order is same with ^{12}C.

Gas-like and linear-chain states

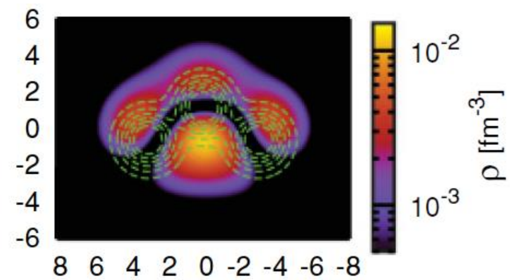


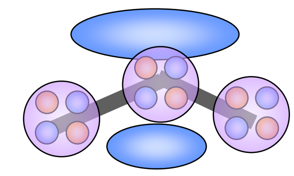
The order is reversed.
The t cluster gain more energy than molecular orbital structure.

Structures in ^{13}C

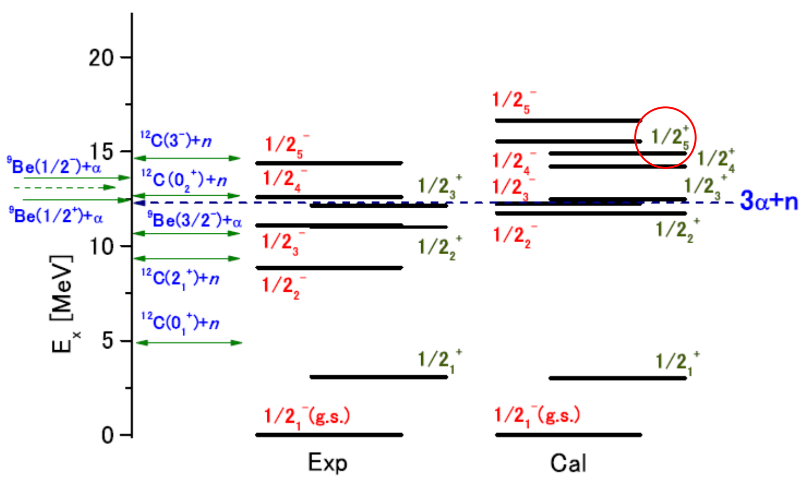


GCM calculation of 3α+n
A bent linear chain structure appears near the 3α+n threshold (3/2$^-_2$ state)

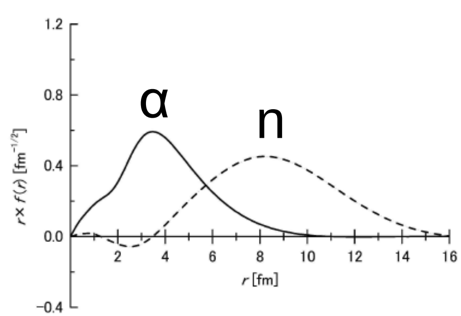


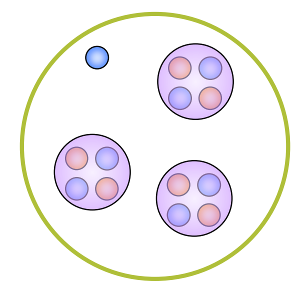


N. Furutachi and M. Kimura, Phys. Rev. C **83**, 021303(R) (2011).



OCM calculation of 3α+n
A 3α+n gas-like state appear above the 3α+n threshold (1/2$^+_5$ state)

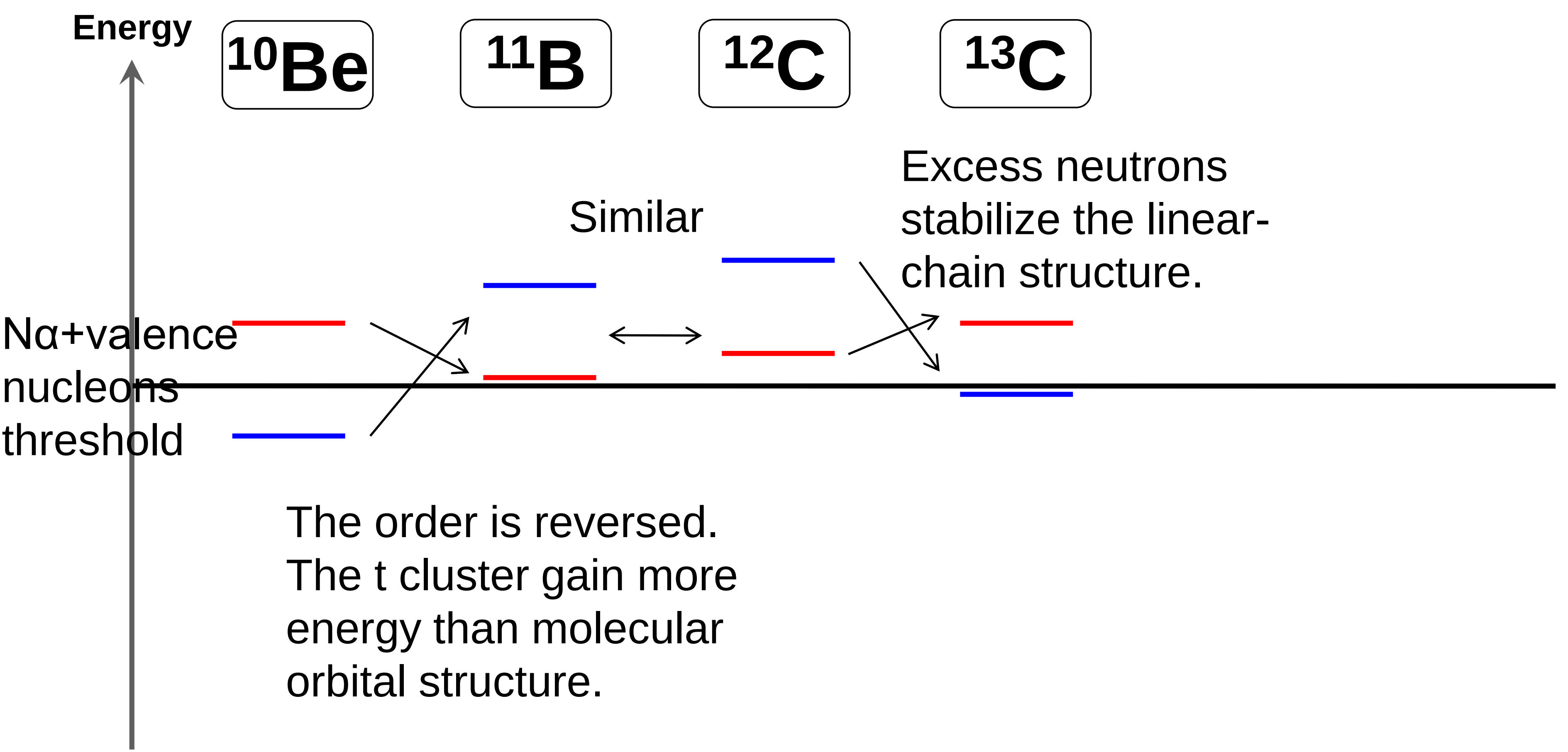




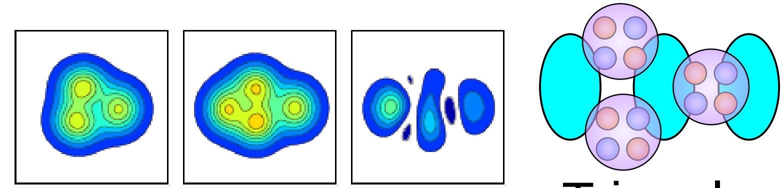
T. Yamada and Y. Funaki, Phys. Rev. C **92**, 034326 (2015).

Gas-like and linear-chain states

Gas-like state
Linear-chain state

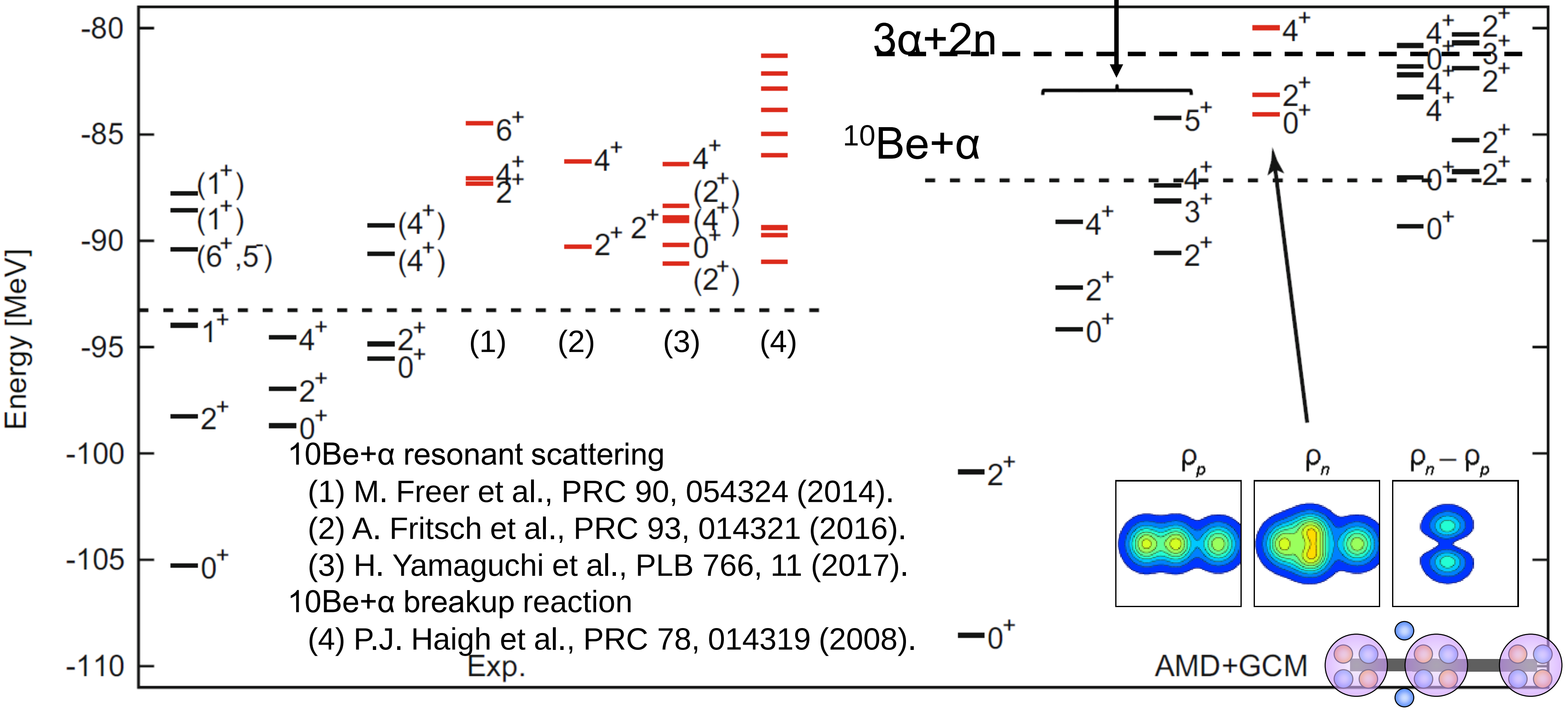


+ parity states in ^{14}C



Triangle

Energy level



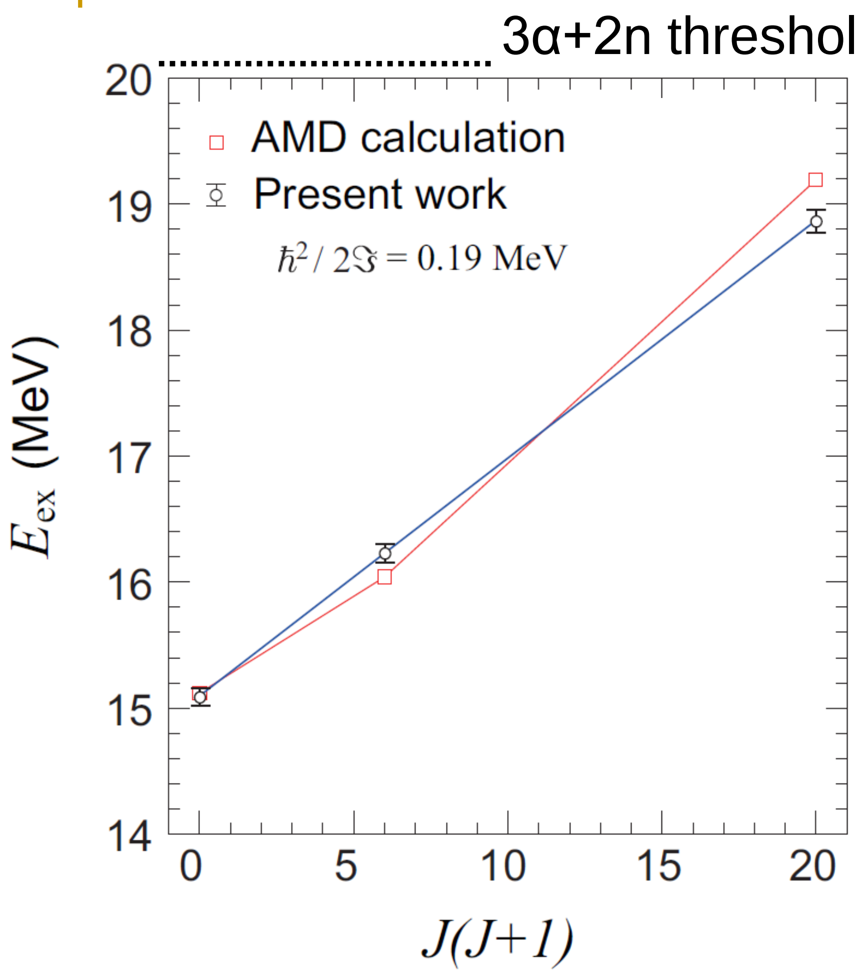
TS. and Y. kanada-En'yo, Phys. Rev. C **82**, 044301 (2010).
M. Kimura, TS, and Y, Kanada-En'yoEur. Phys. J. A 52, 373 (2016)

Linear-chain

There are linear chain states but no gas-like state.
Excess neutrons stabilize the geometric structure.

N. Itagaki, et al, PRL (2004).

Comparison with ^{10}Be+α resonant scattering exp.



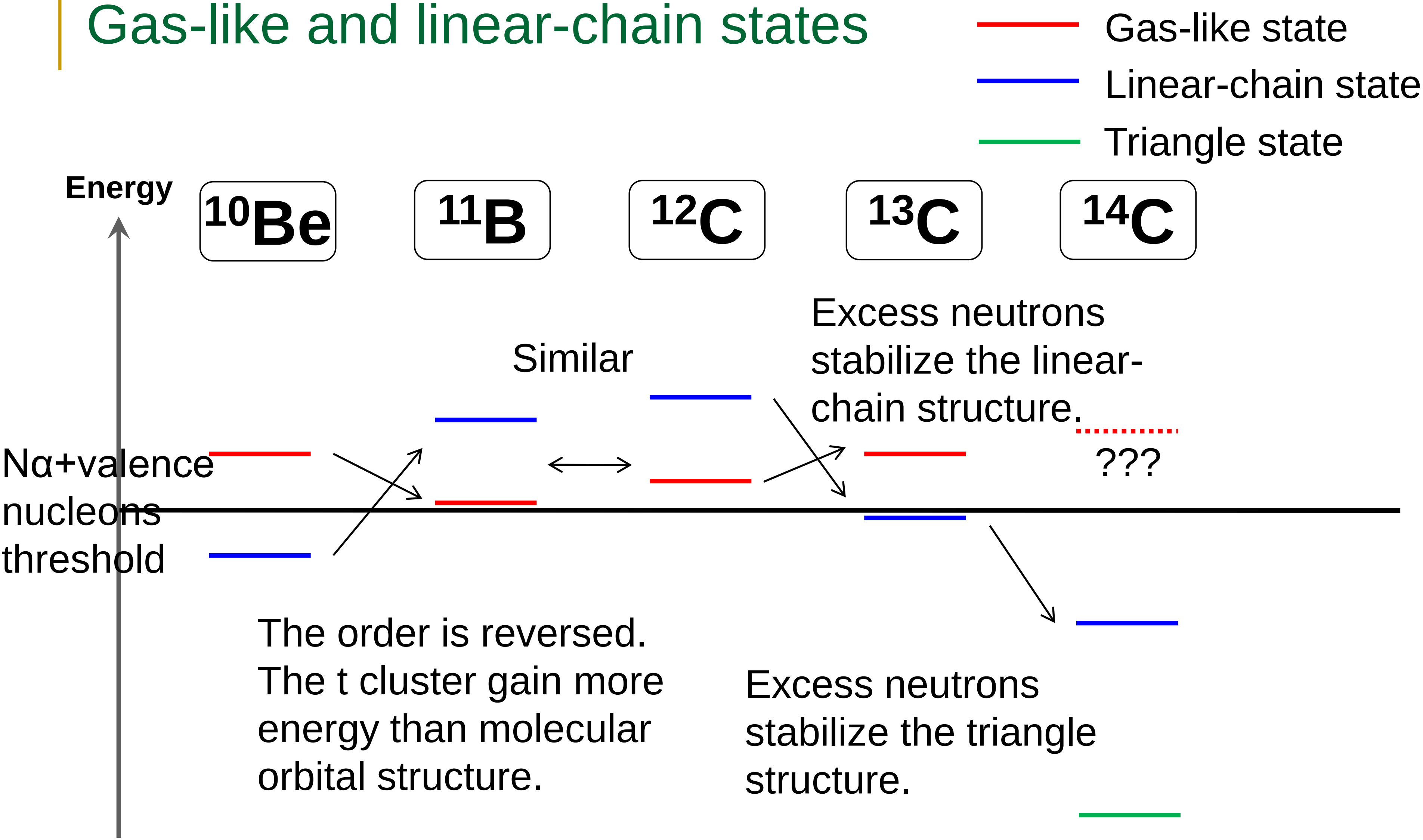
	Present Work			Suhara & En'yo [18]		
E_{ex} (MeV)	J^π	Γ_α (keV)	θ^2_α	E_{ex} (MeV)	J^π	θ^2_α
14.21	(2^+)	17(5)	3.5%			
14.50	1^-	45(14)	4.5%			
15.07	$\mathbf{0^+}$	**760(250)**	**34(12)%**	**15.1**	$\mathbf{0^+}$	**16%**
16.22	$\mathbf{2^+}$	**190(55)**	**9.1(27)%**	**16.0**	$\mathbf{2^+}$	**15%**
16.37	(4^+)	15(4)	3.0%			
16.93	(2^+)	270(85)	10.3%			
17.25	(1^-)	190(45)	5.5%			
18.02	(3^-)	31(19)	1.3%			
18.63	5^-	72(48)	9.4%			
18.87	$\mathbf{4^+}$	**45(18)**	**2.4(9)%**	**19.2**	$\mathbf{4^+}$	**9%**

H. Yamaguchi et al., Phys. Lett. B 766, 11 (2017).

$$\theta_\alpha^2 = \frac{\Gamma_\alpha}{\Gamma_w} \qquad \Gamma_w = \frac{2\hbar^2}{\mu R^2} P_l$$

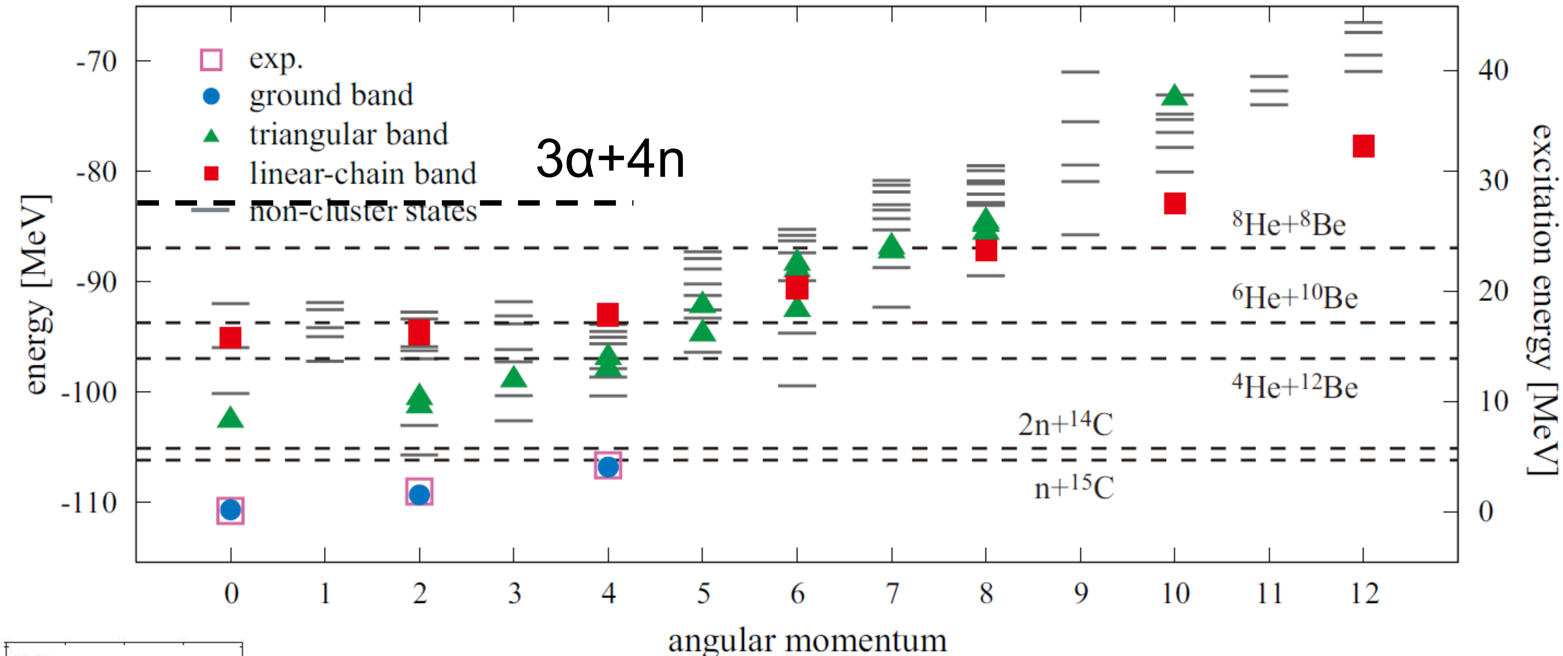
- Good agreement (energy and moment of inertia)
- The calculation qualitatively reproduces the experimental width.
- Good candidate for the linear-chain state.

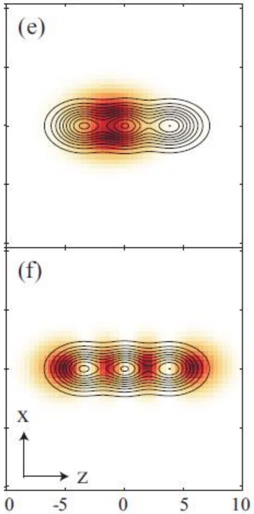
Gas-like and linear-chain states



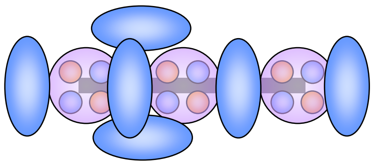
Structures in ^{16}C

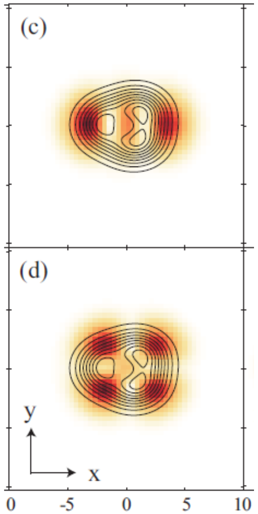
T. Baba, Y. Chiba, and M. Kimura, Phys. Rev. C **90**, 064319 (2014).



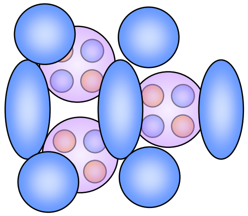


Linear-chain structure



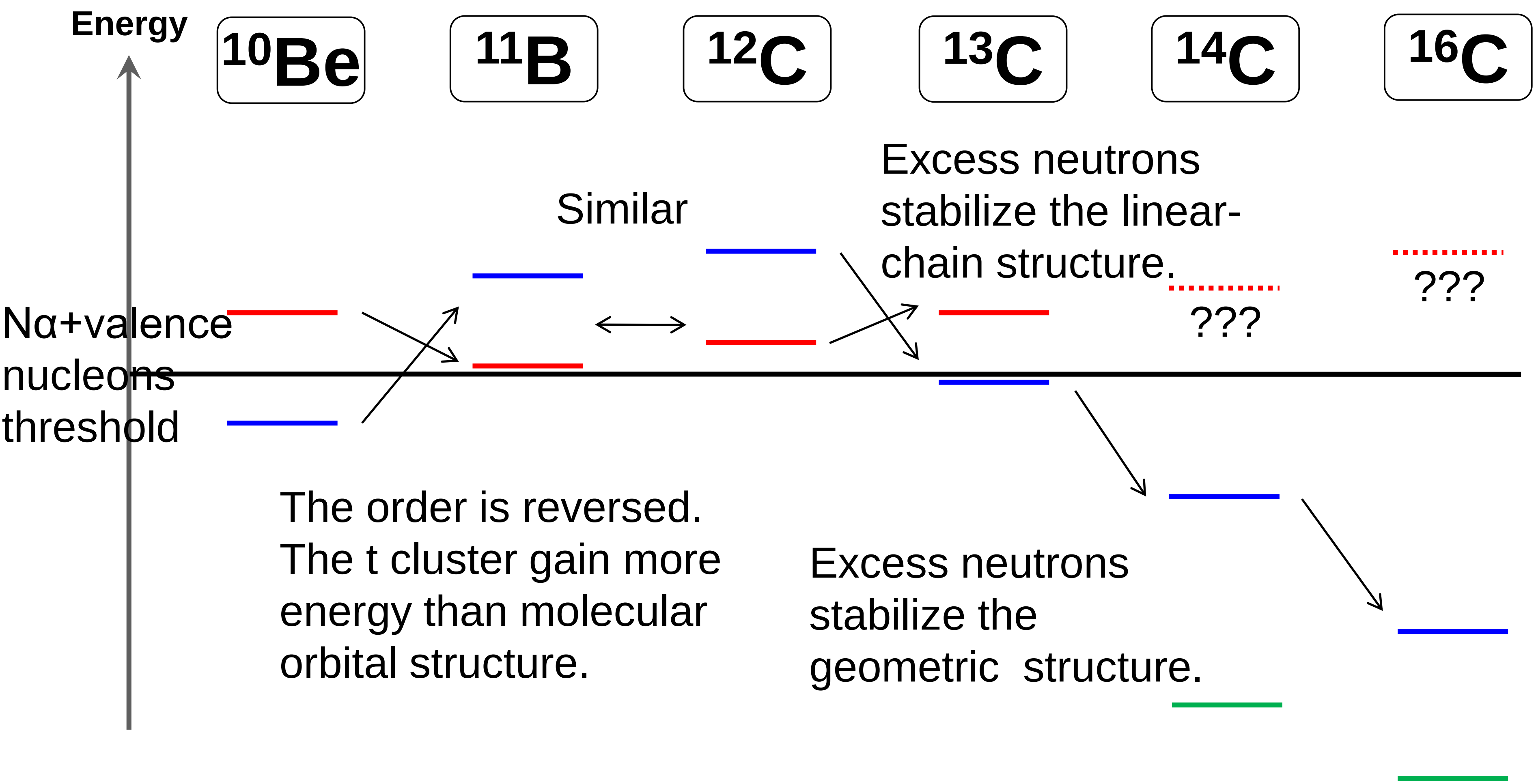


Equilateral triangular structure



Gas-like and linear-chain states

Gas-like state
Linear-chain state
Triangle state



Summary

Linear-chain and gas-like structures in nuclei near ^{12}C

・^{10}Be, ^{11}B, and ^{12}C have gas-like states of 2α+dineutron, 2α+t, and 3α structures, respectively（M_n (g.s→gas state) are almost same values.）

・There are 3α+Xn linear chain structures in neutron-rich C isotopes universally.（Good agreement of theoretical and experimental results in ^{14}C）

・Excess neutrons stabilize the linear chain structures, and therefore, these appear below the 3α+Xn threshold.

・When multiple excess neutrons are added, triangular structures of 3α clusters appear in low energy region.

Future plan

・ Is there 3α+2n（3α+4n）gas-like state in ^{14}C（^{16}C）?