Characteristic decay patterns of the Linear-chain states in Carbon isotopes

T.Baba and M.Kimura
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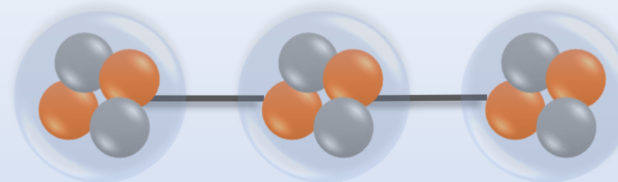
Linear-chain with valence neutrons

Linear-chain configuration of 3α clusters was suggested in 1950s.

Morinaga, Phys. Rev. **101**, 254 (1956).

Positive evidences have not been obtained, and linear-chain of 3α is unstable against the bending motion.



Y. Kanada-En'yo, Prog. Theor. Phys. **115**, 655 (2007).

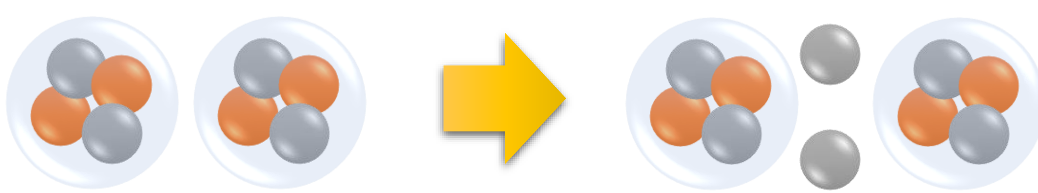
M. Chernykh *et al.*, Phys. Rev. Lett. **98**, 032501 (2007).

Instead of ^{12}C, neutron-rich C isotopes have attracted much interest because valence neutrons play a "glue-like" role.

N. Itagaki and S. Okabe, Phys. Rev. C **61**, 044306 (2000).

Ex) Be isotope (2α)

^{8}Be : Unbound **^{10}Be : Stable**



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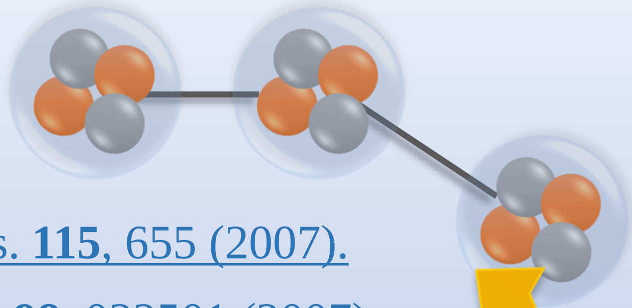

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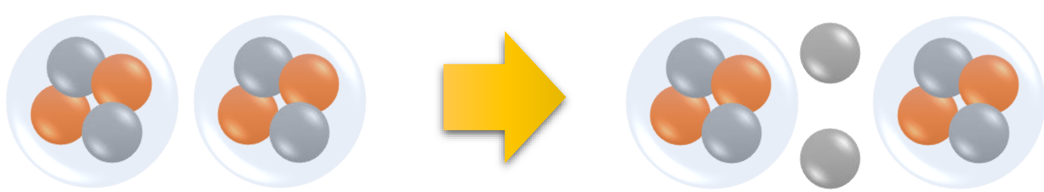

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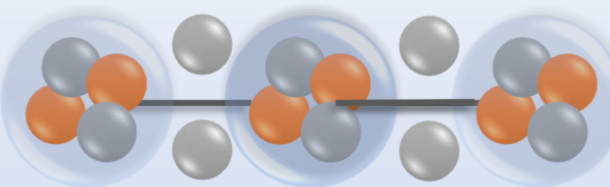

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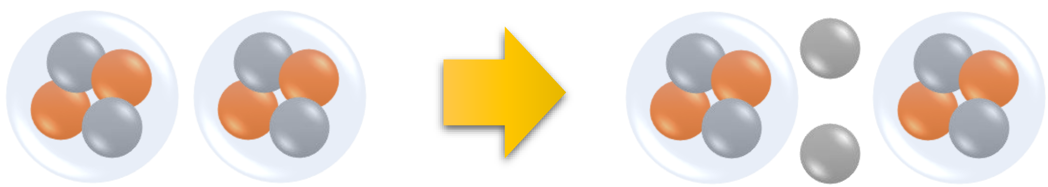

Experiments of ^{14}C

Recently, very interesting experimental data have been reported by some groups.

$\alpha(^{10}Be, \alpha)^{10}Be$ resonant scattering

M. Freer *et al.*, Phys. Rev. C **90**, 054324 (2014).
A. Fritsch *et al.*, Phys. Rev. C **93**, 014321 (2016).
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$^{9}Be(^{9}Be, ^{14}C^{*} \rightarrow \alpha + ^{10}Be)^{4}He$ break-up

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Observed resonances are close each other in spite of independent observation.
In addition, they also agree with the theoretical prediction. T. Suhara and Y. Kanada-En'yo, Phys. Rev. C **82**, 044301 (2010).

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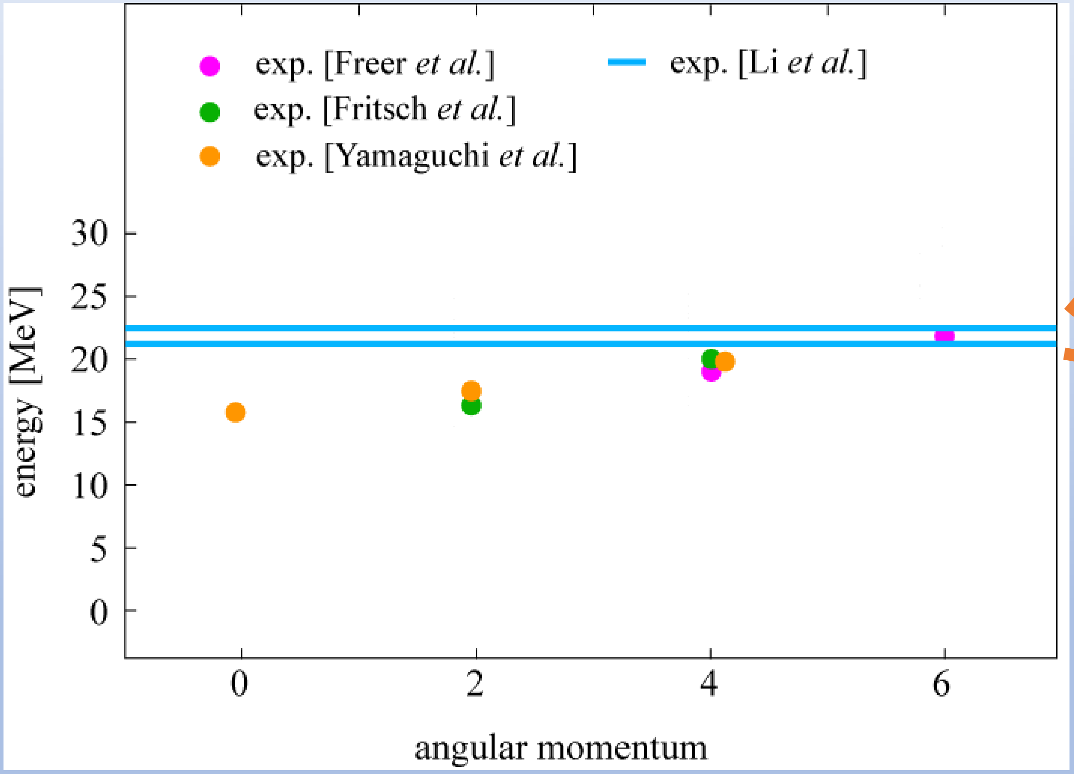
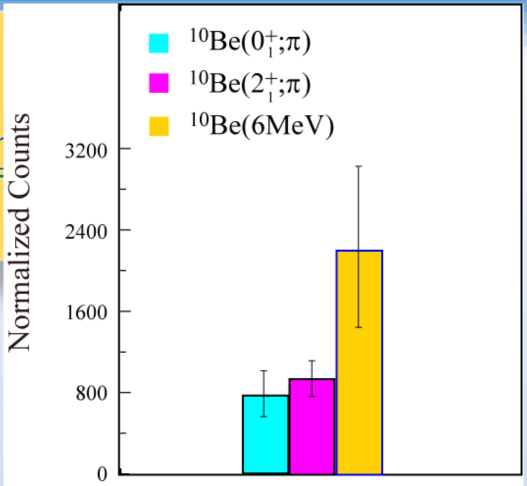
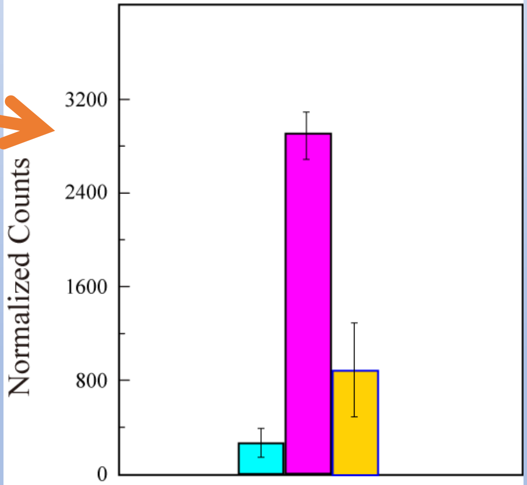




22.5 MeV [Li *et al.*]



21.4 MeV [Li *et al.*]

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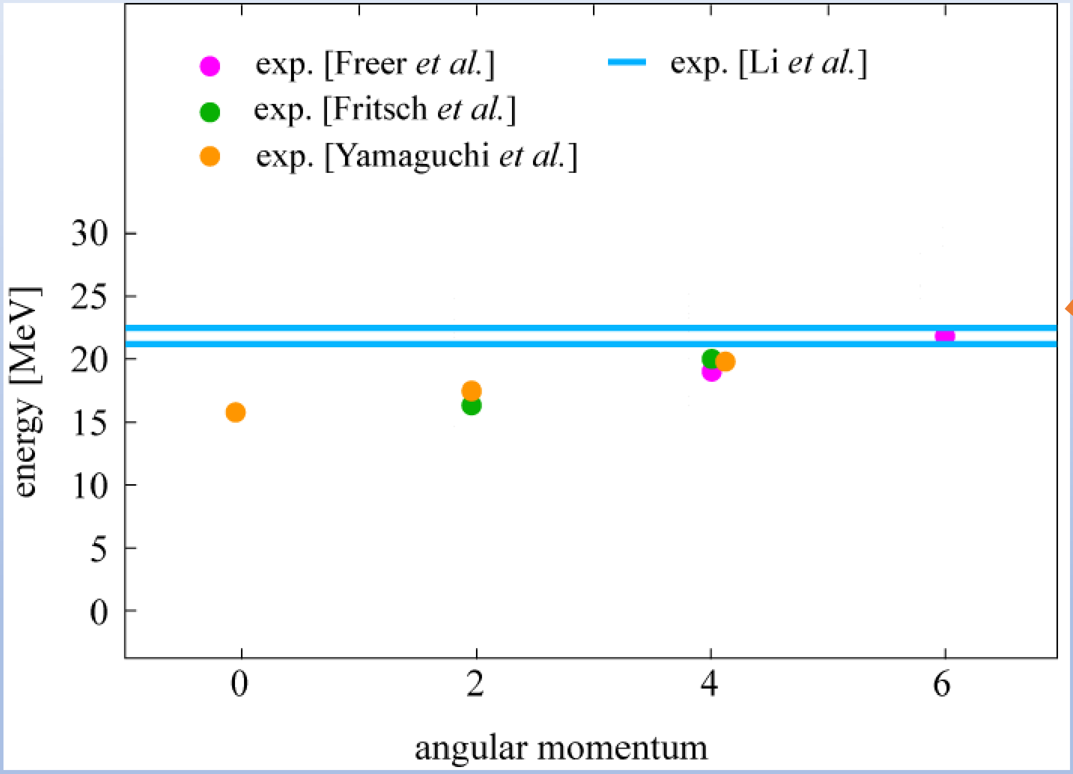
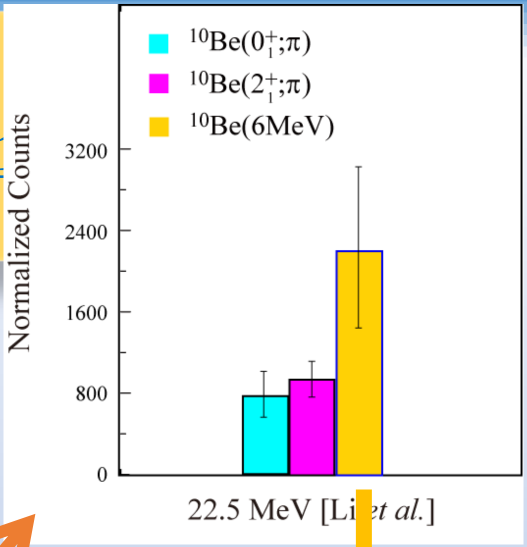
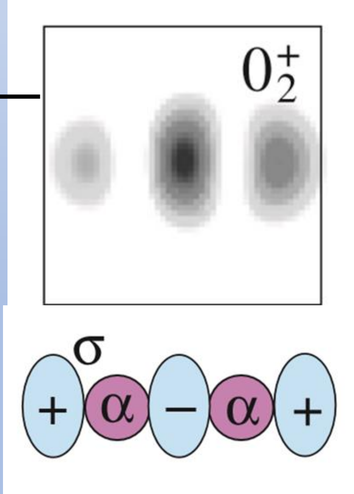


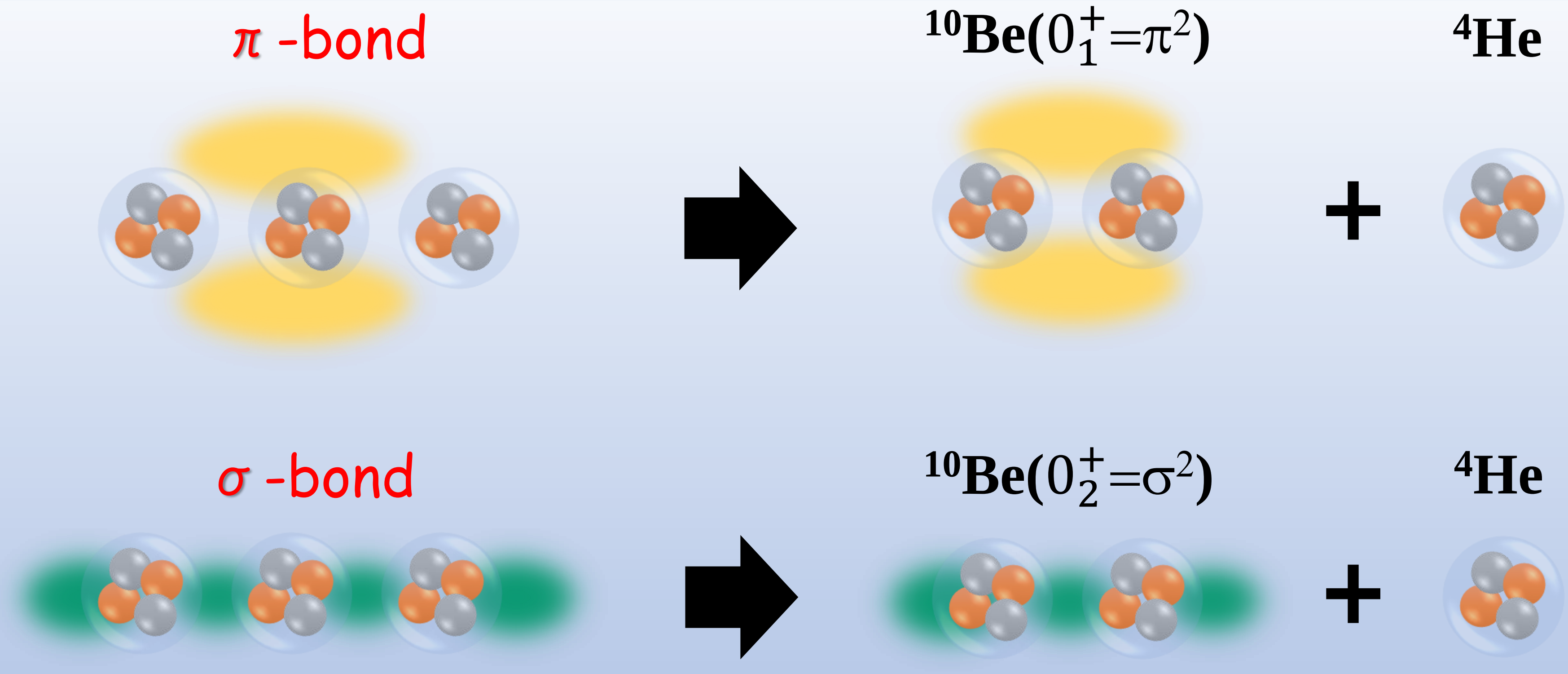


$^{10}Be(\sigma^2)$

6.18 MeV



Schematic picture of Linear-chain



By comparison with the new data, the unique decay pattern of two types of the linear-chain can be found and identified.

Purpose

We investigate the linear-chain configuration of ^{14}C and ^{16}C

① To confirm that the agreement between the observation and calculated π-bond linear-chain band is plausible by comparison with new some data in ^{14}C

② To show that the observed unique decay pattern of the resonances reported by Li *et al.* is similar to that of the calculated σ-bond linear-chain in ^{14}C

③ To predict the existence and details of linear-chain in ^{16}C for experimental data which will be reported

AMD

J.F.Berger, M.Girod, and D.Gogny, Comput. Phys. Comm. **63** (1991) 365.

Effective interaction

Gogny D1S interaction is exploited.

$$\hat{H} = \sum_{\mathrm{i}} \hat{t}_{\mathrm{i}} - \hat{t}_{\mathrm{cm}} + \sum_{\mathrm{i}<j} \hat{\mathrm{v}}_{\mathrm{ij}}^{\mathrm{NN}} + \sum_{\mathrm{i}<j\in p} \hat{\mathrm{v}}_{\mathrm{ij}}^{\mathrm{Coulomb}}$$

Intrinsic wave function

Single particle w.f. is the deformed Gaussian.

$$\Phi^{\pi} = \hat{P}^{\pi} \frac{1}{\sqrt{\mathrm{A}!}} \det\left[\varphi_{\mathrm{i}}(\vec{\mathrm{r}}_{\mathrm{j}})\right] \qquad \varphi_{\mathrm{i}}(\vec{\mathrm{r}}) = \exp\left[-\sum_{\sigma=x,y,z} \nu_{\sigma}\left(r_{\sigma} - \frac{Z_{i\sigma}}{\sqrt{\nu_{\sigma}}}\right)^{2}\right] \otimes \mathrm{a}_{\mathrm{i}}\chi_{\uparrow} + \mathrm{b}_{\mathrm{i}}\chi_{\downarrow} \otimes \tau_{\mathrm{i}}$$

Variation

The variation parameters ($\vec{\mathrm{Z}}_{\mathrm{i}}$, a_{i}, b_{i}, ν) are determined so that E^{π}, which is a sum of the energy and constraint potential is minimized.

$$\mathrm{E}^{\pi} = \frac{\langle \Phi^{\pi} | \hat{H} | \Phi^{\pi} \rangle}{\langle \Phi^{\pi} | \Phi^{\pi} \rangle} + v_{\beta}(\langle \beta \rangle - \beta)^{2} + v_{\gamma}(\langle \gamma \rangle - \gamma)^{2}$$

AMD+GCM

Angular momentum projection

After the variational calculation, the eigenstate of the total angular momentum is projected out.

$$\Phi^{\mathrm{J}\pi}_{\mathrm{MK}}(\beta,\gamma) = \widehat{\mathrm{P}}^{\mathrm{J}}_{\mathrm{MK}}\Phi^{\pi}(\beta,\gamma) = \frac{2\mathrm{J}+1}{8\pi^2}\int d\Omega\, \mathrm{D}^{\mathrm{J}*}_{\mathrm{MK}}(\Omega)\widehat{\mathrm{R}}(\Omega)\Phi^{\pi}(\beta,\gamma)$$

GCM

D. L. Hill and J. A. Wheeler, Phys. Rev. **89**, 1102 (1953).

The GCM calculation is performed by employing the quadrupole deformation parameters β, γ as the generator coordinate.

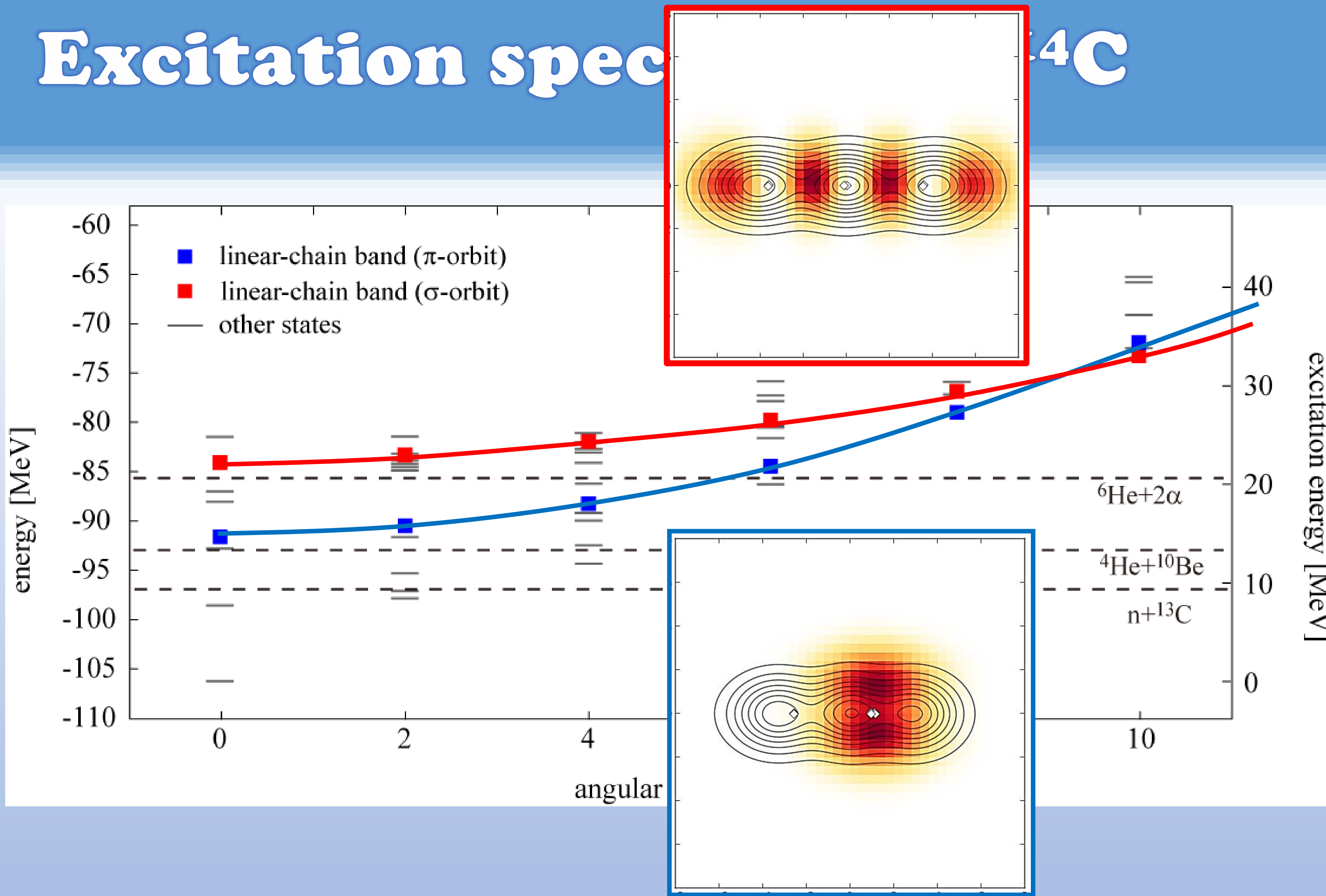
$$\Psi^{\mathrm{J}\pi}_{\mathrm{Mn}} = \sum_{i,K} c^{\mathrm{J}\pi}_{Kin}\Phi^{\mathrm{J}\pi}_{MK}(\beta_i,\gamma_i)$$

$$\sum_{i',K'} \mathrm{H}_{KiK'i'}c^{\mathrm{J}\pi}_{K'i'n} = \mathrm{E_n}\sum_{i',K'} \mathrm{N}_{KiK'i'}c^{\mathrm{J}\pi}_{K'i'n}$$

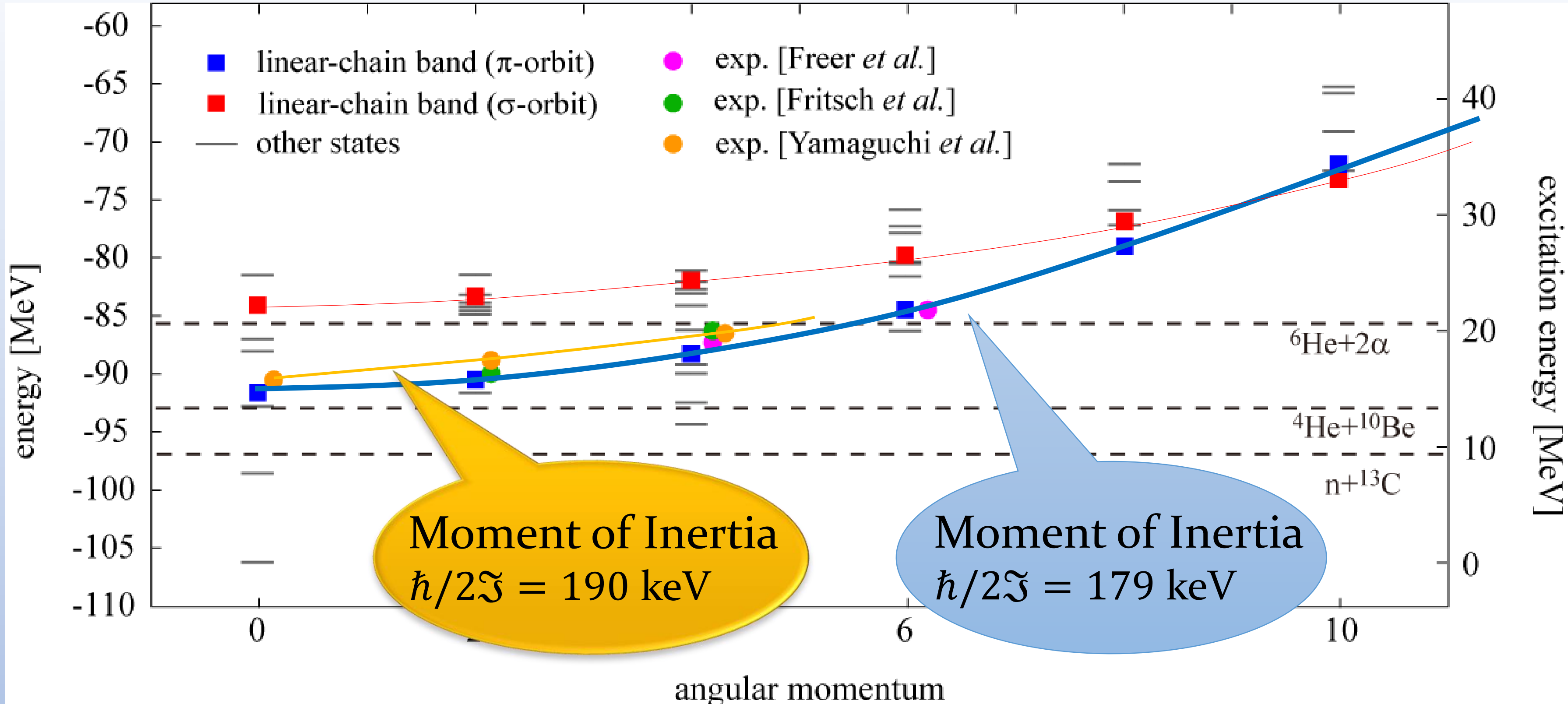
$$\mathrm{H}_{KiK'i'} = \left\langle \Phi^{\mathrm{J}\pi}_{MK}(\beta_i,\gamma_i)\middle|\widehat{H}\middle|\Phi^{\mathrm{J}\pi}_{MK'}(\beta_{i'},\gamma_{i'})\right\rangle$$

$$\mathrm{N}_{KiK'i'} = \left\langle \Phi^{\mathrm{J}\pi}_{MK}(\beta_i,\gamma_i)\middle|\Phi^{\mathrm{J}\pi}_{MK'}(\beta_{i'},\gamma_{i'})\right\rangle$$

Excitation spec ^{14}C



Comparison with resonant scattering

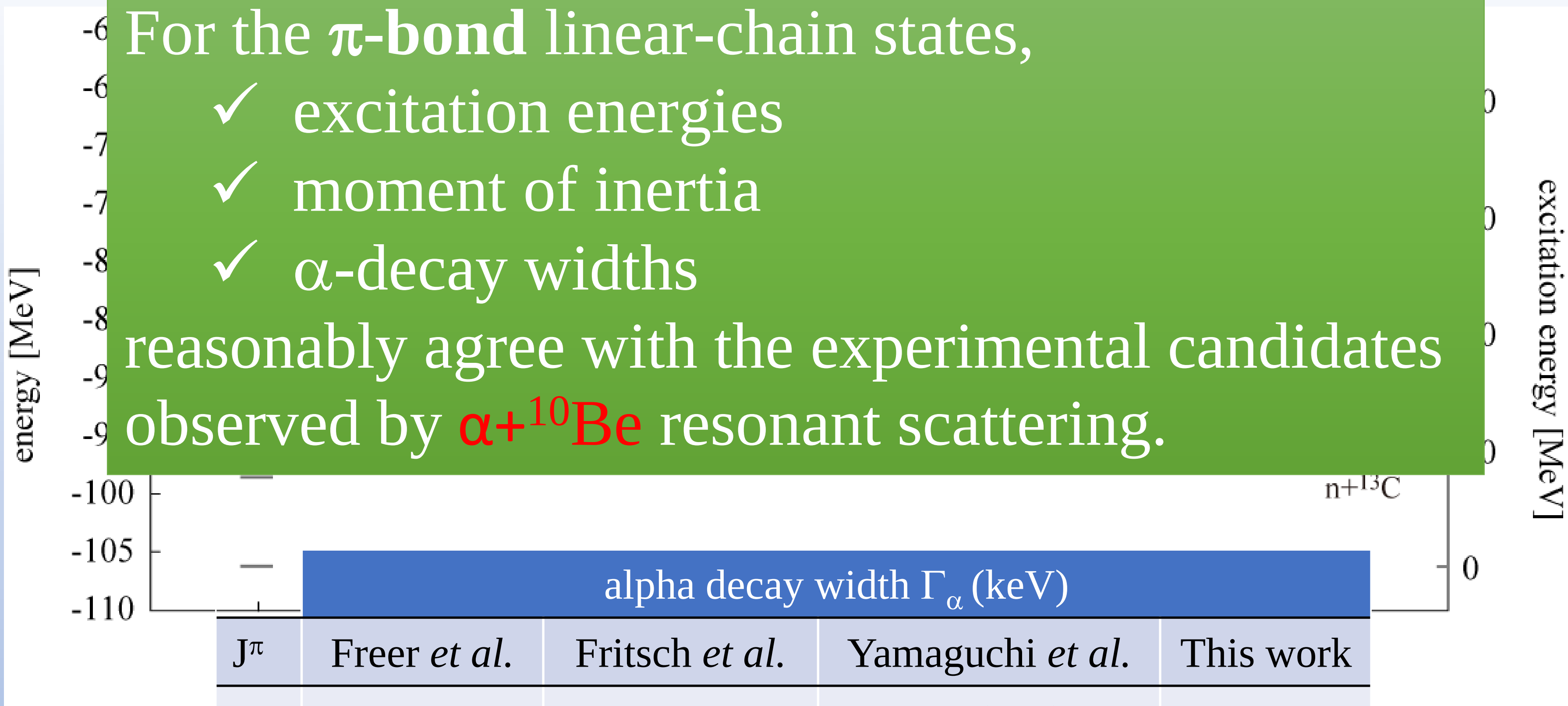


Comparison with resonant scattering

For the **π-bond** linear-chain states,

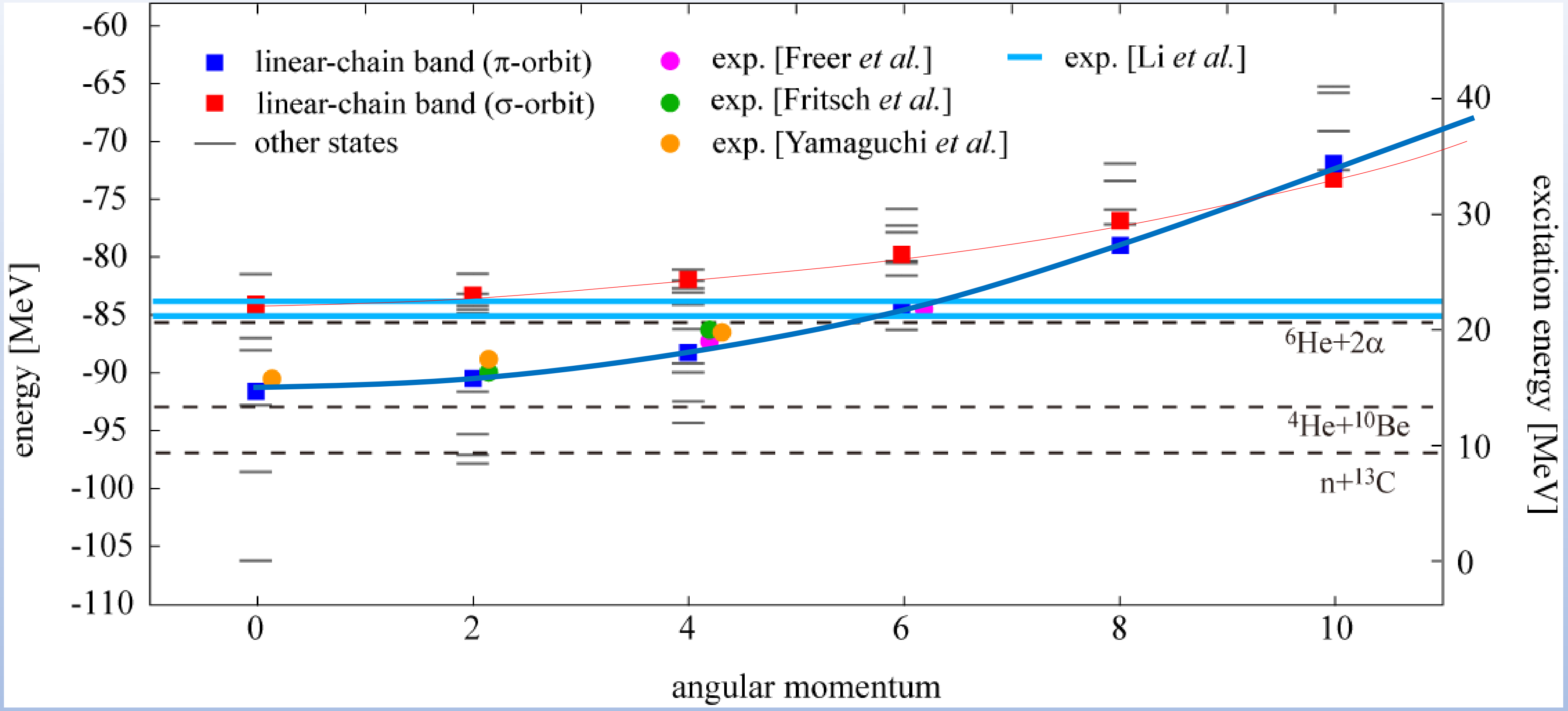
- ✓ excitation energies
- ✓ moment of inertia
- ✓ α-decay widths

reasonably agree with the experimental candidates observed by $\alpha+{}^{10}Be$ resonant scattering.



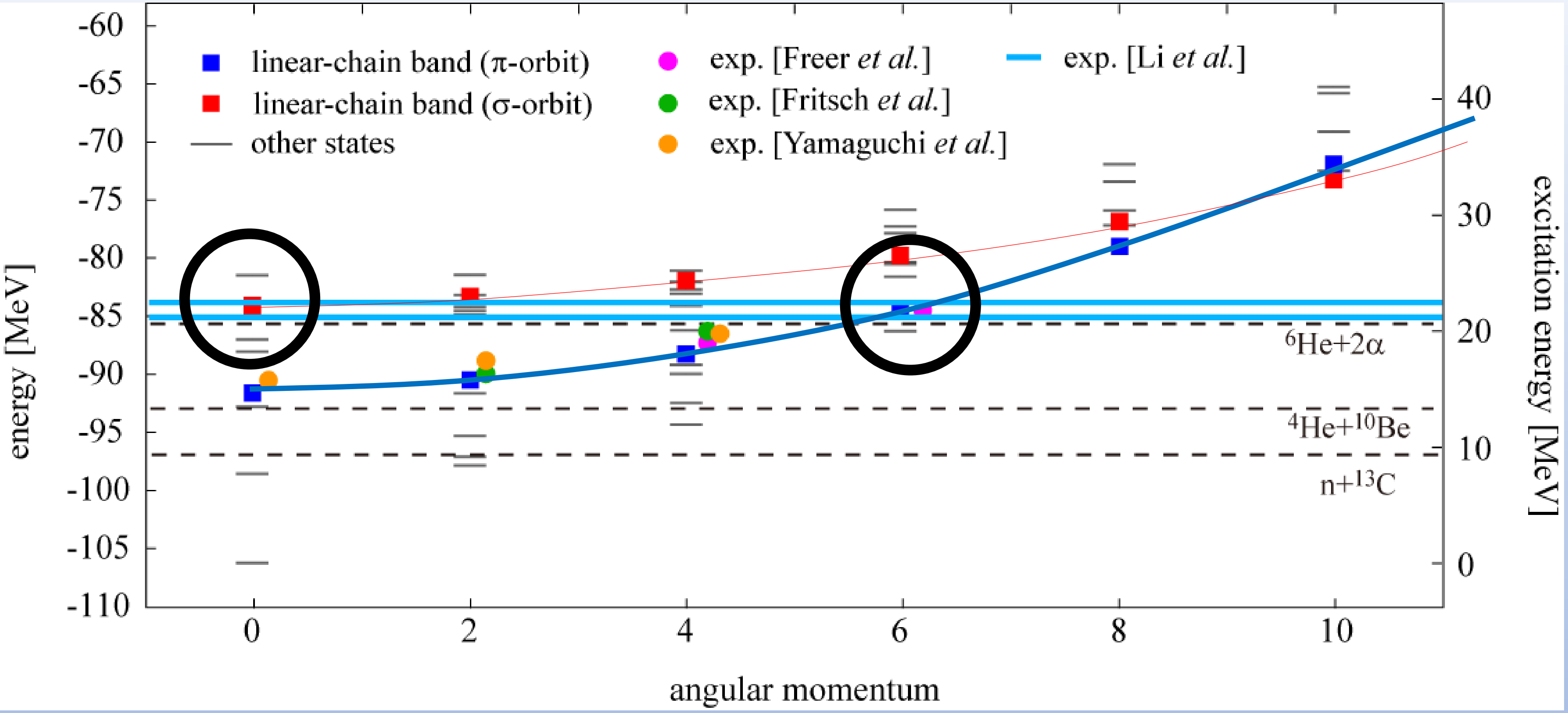
	alpha decay width Γ_α (keV)			
J^π	Freer *et al.*	Fritsch *et al.*	Yamaguchi *et al.*	This work
0^+			760(250)	250
2^+		290	190(55)	214
4^+	200	340	45(18)	149
6^+	300			123

Comparison with breakup reaction



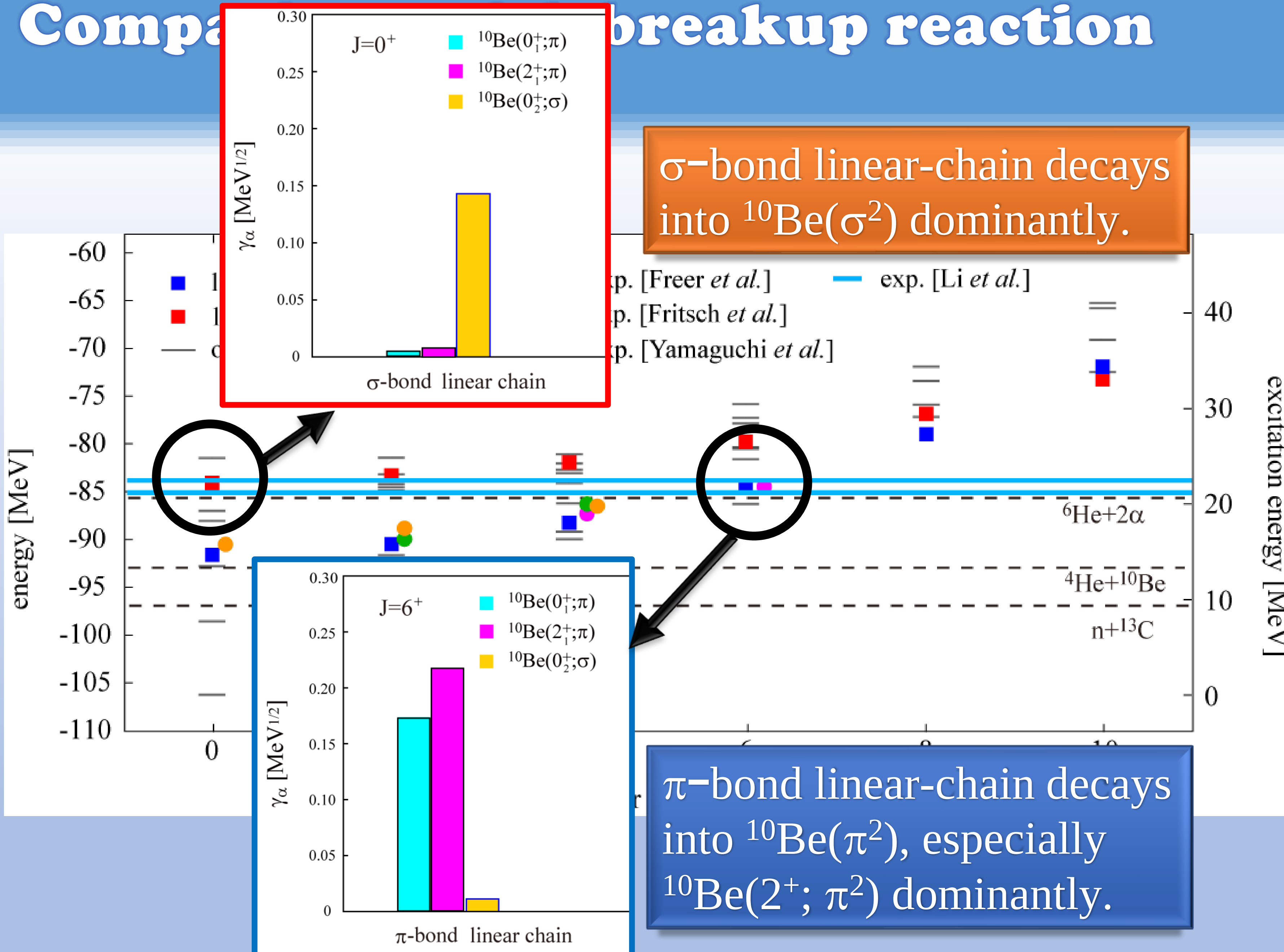
The σ−bond linear-chain states are candidates of the higher-lying states reported by the breakup reaction.

Comparison with breakup reaction



To clarify the configuration of the observed resonances, we focused on the decay patterns of two linear-chain state.

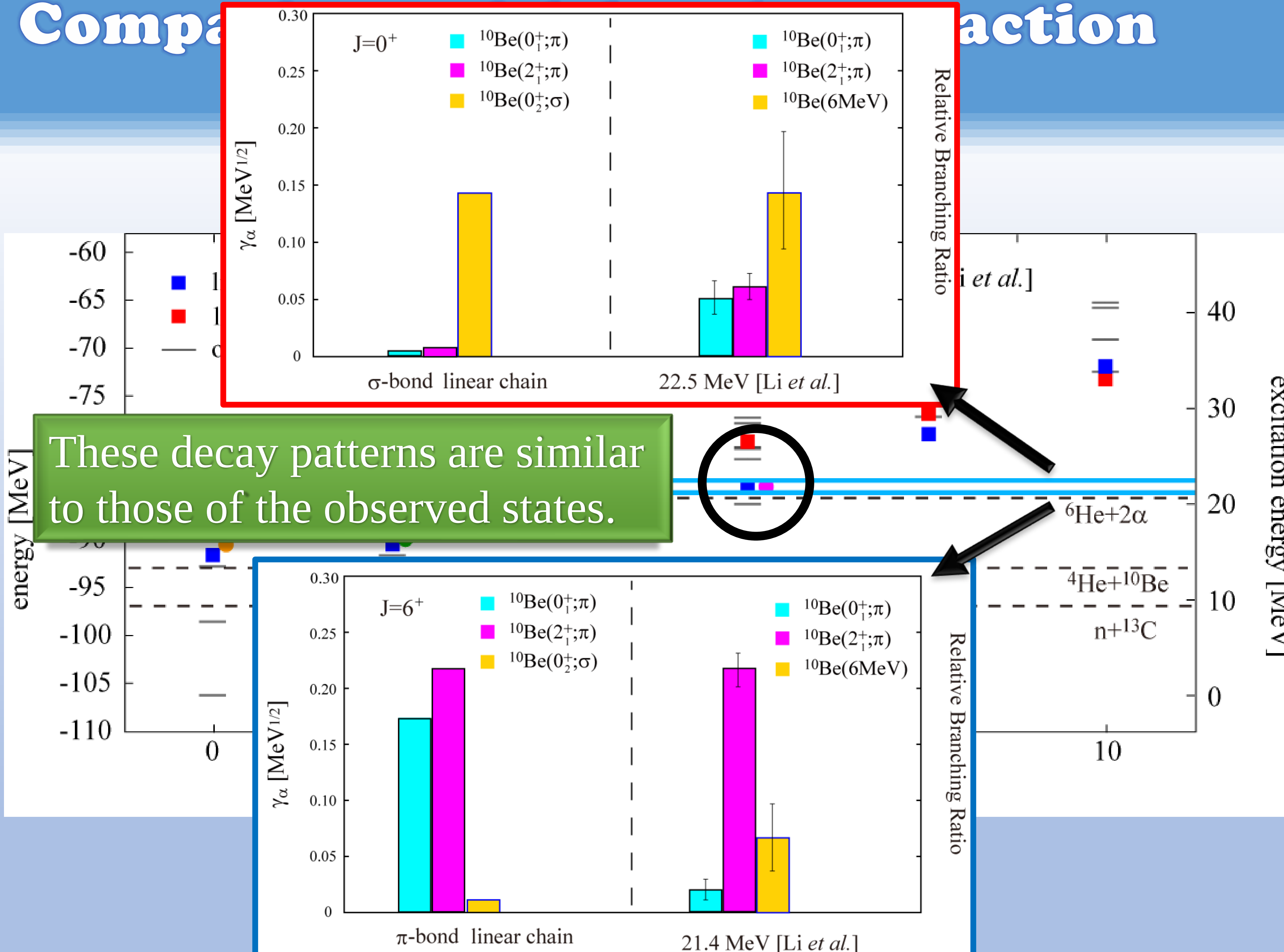
Compa… breakup reaction



σ−bond linear-chain decays into ^{10}Be(σ^2) dominantly.

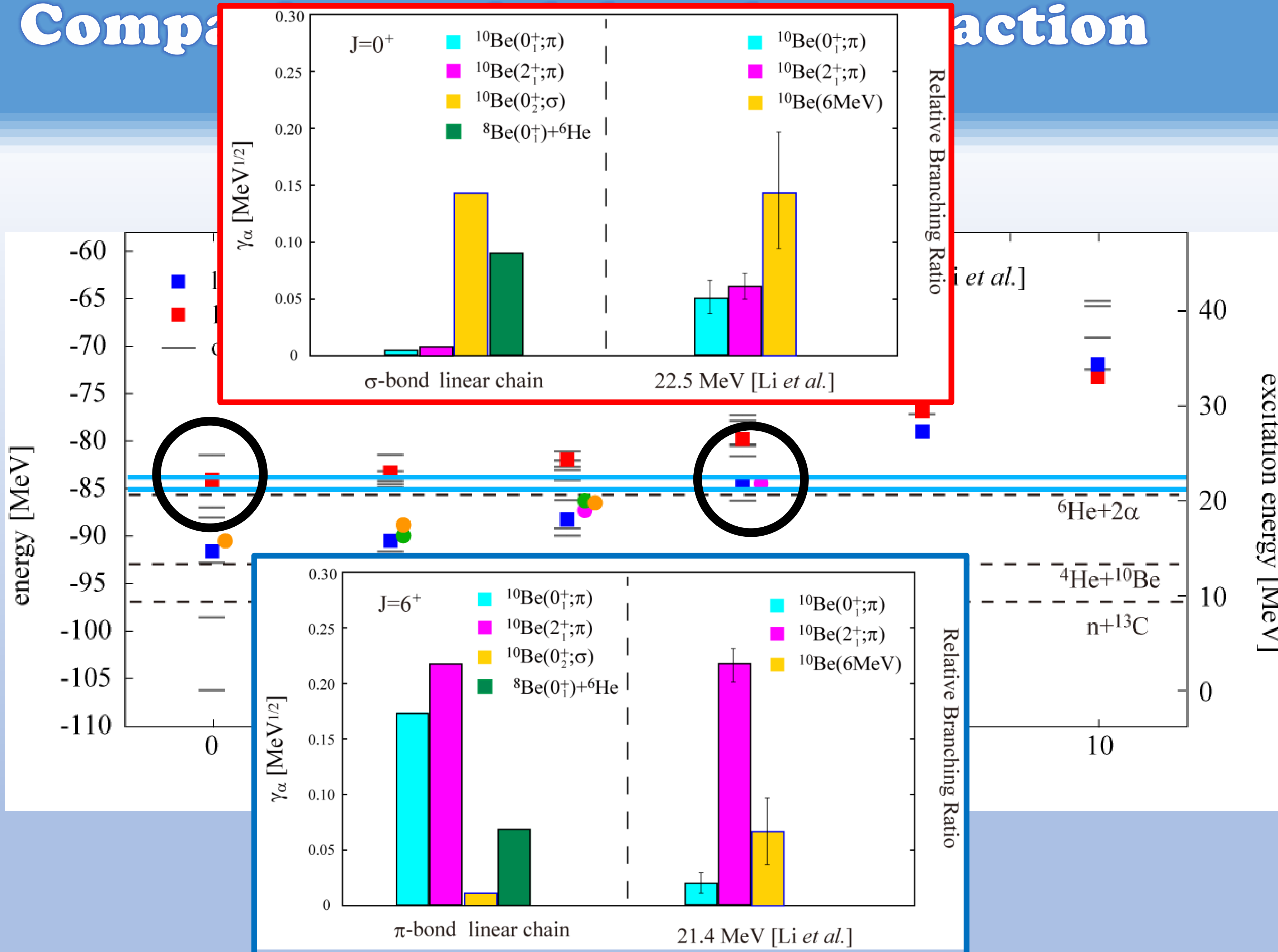
π−bond linear-chain decays into ^{10}Be(π^2), especially ^{10}Be(2^+; π^2) dominantly.

Compa… …action



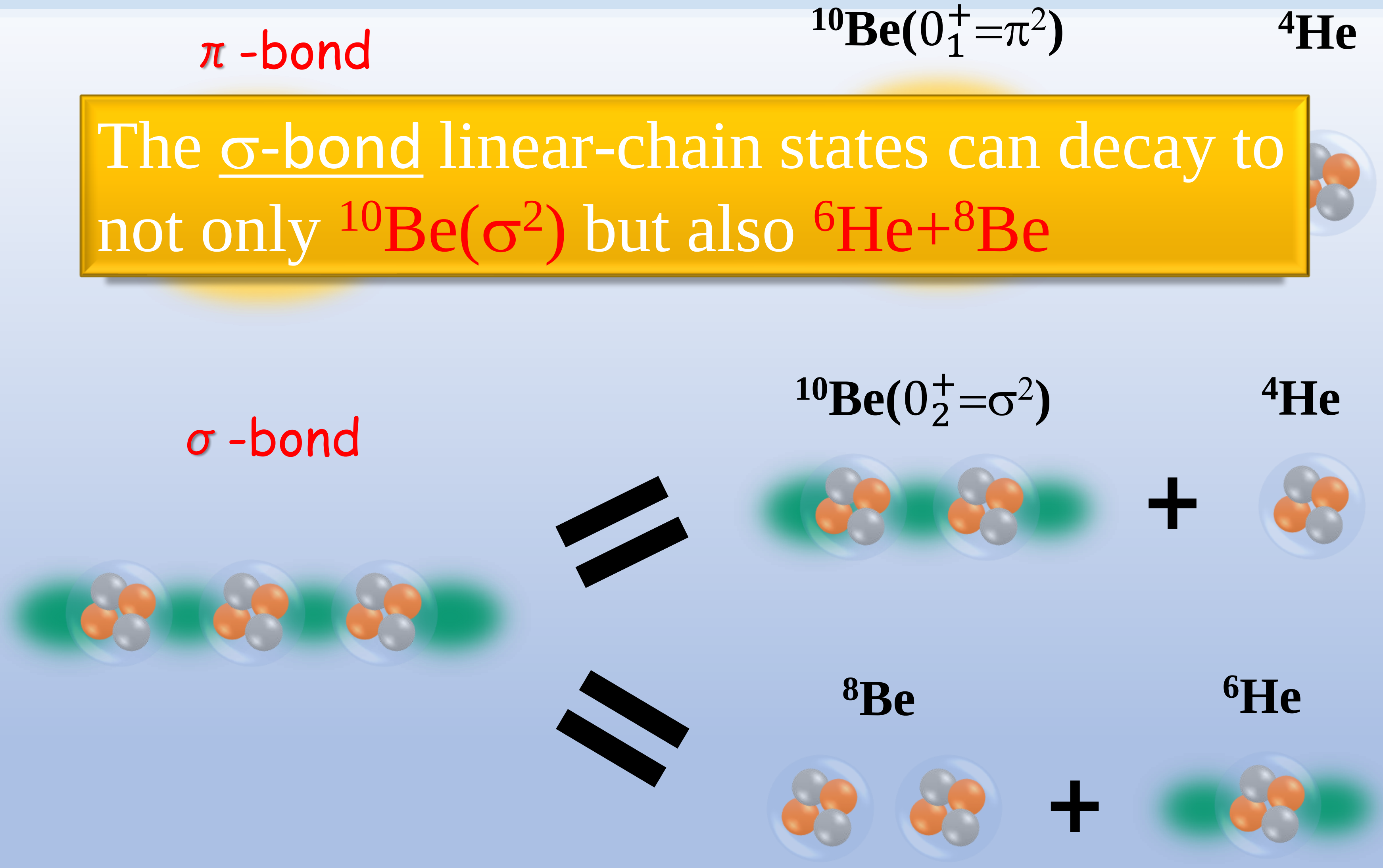
These decay patterns are similar to those of the observed states.

Compa… action



Revised schematic picture

The σ-bond linear-chain states can decay to not only ^{10}Be(σ^2) but also ^{6}He+^{8}Be

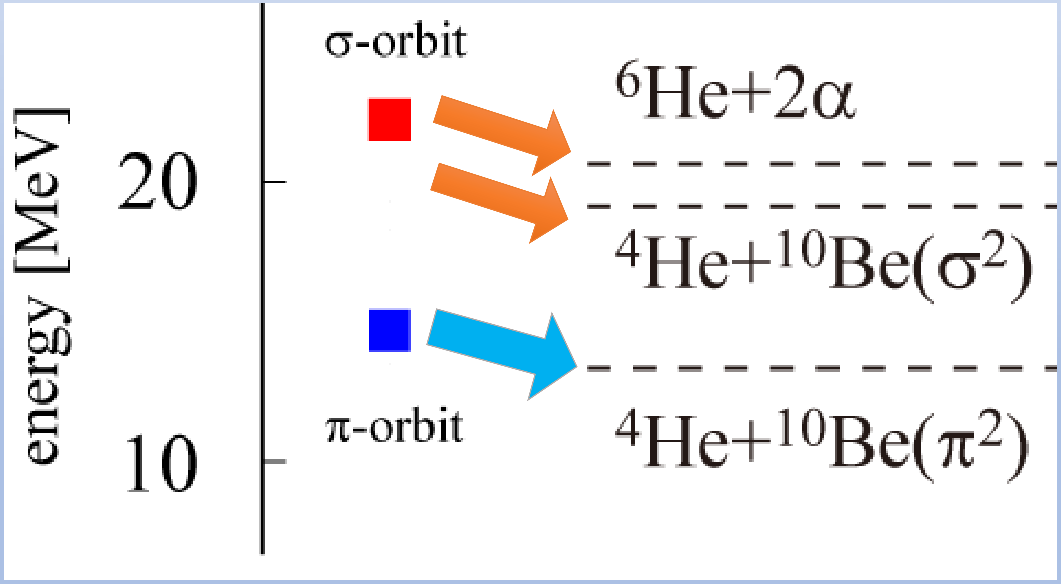


Summary

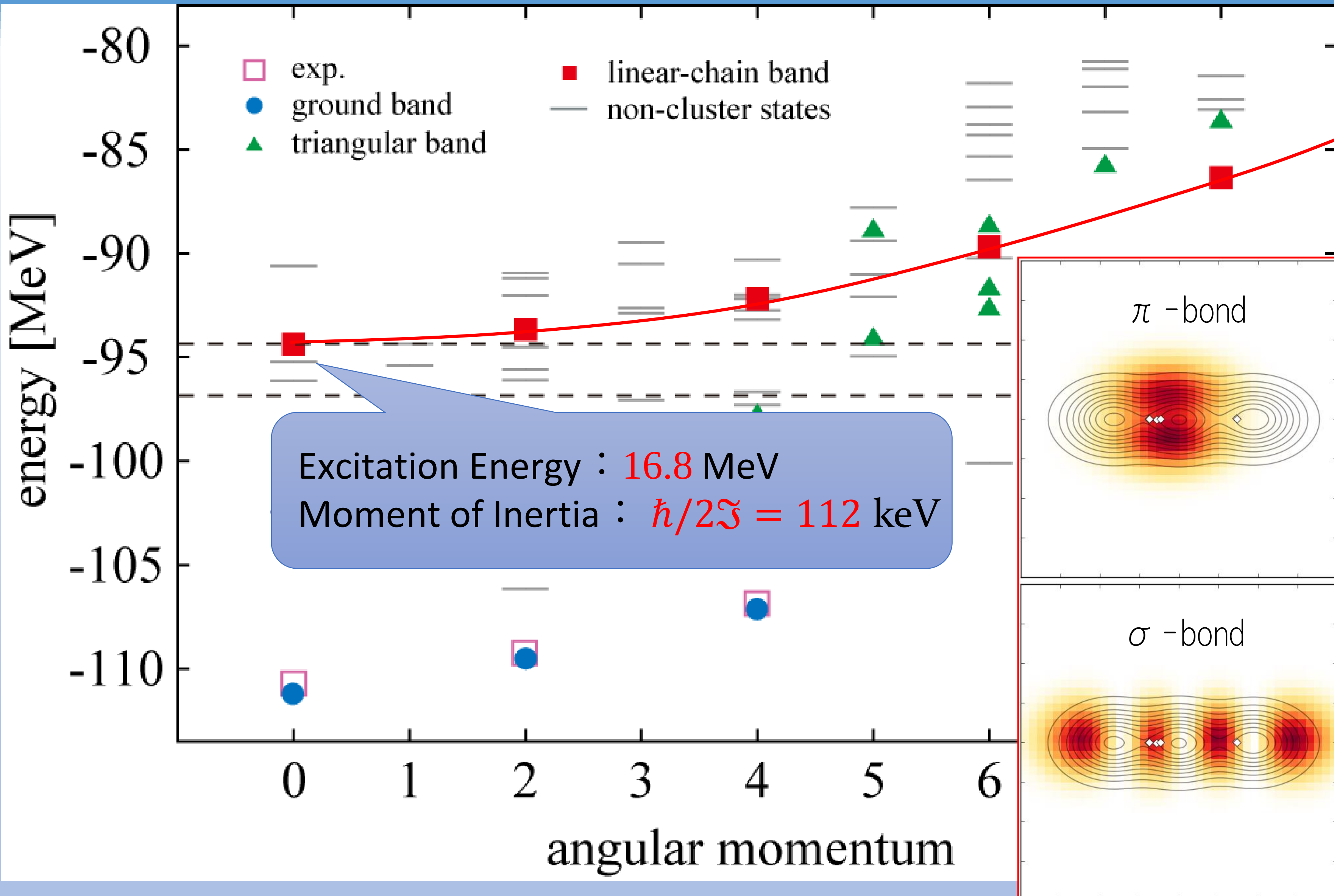
T.B. and M. Kimura, Phys. Rev. C **95**, 064318 (2017).

T.B. and M. Kimura, arXiv:1801.05323.

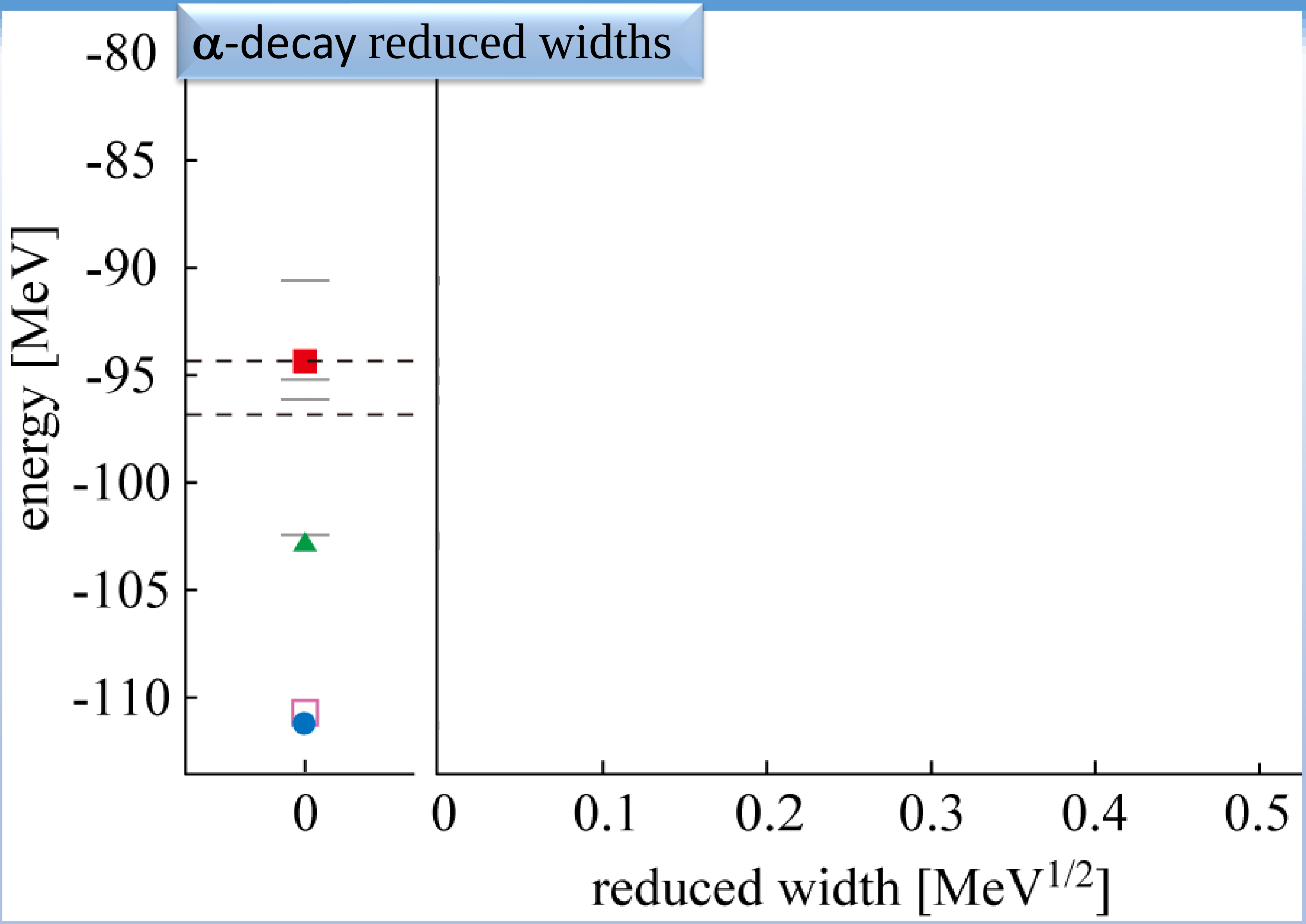
- Using the AMD, we show that the excitation energies and α-decay widths of π-bond linear-chain in ^{14}C are close to the experimental values.
- The σ-bond linear-chain states can be good candidates of high-lying states. In addition, $^{6}He+2\alpha$ three-body sequence decay is its plausible signature.
- The linear-chain also decays to the $^{8,10}Be(2^+)$ as well as to the ground state of $^{8,10}Be$. This is a strong evidence of the linear-chain.
- In ^{16}C, the excitation energies and decay widths of linear-chain are obtained. We also provide some evidences for the existence of linear-chain configuration.



Excitation spectrum of ^{16}C



Decay widths of ^{16}C



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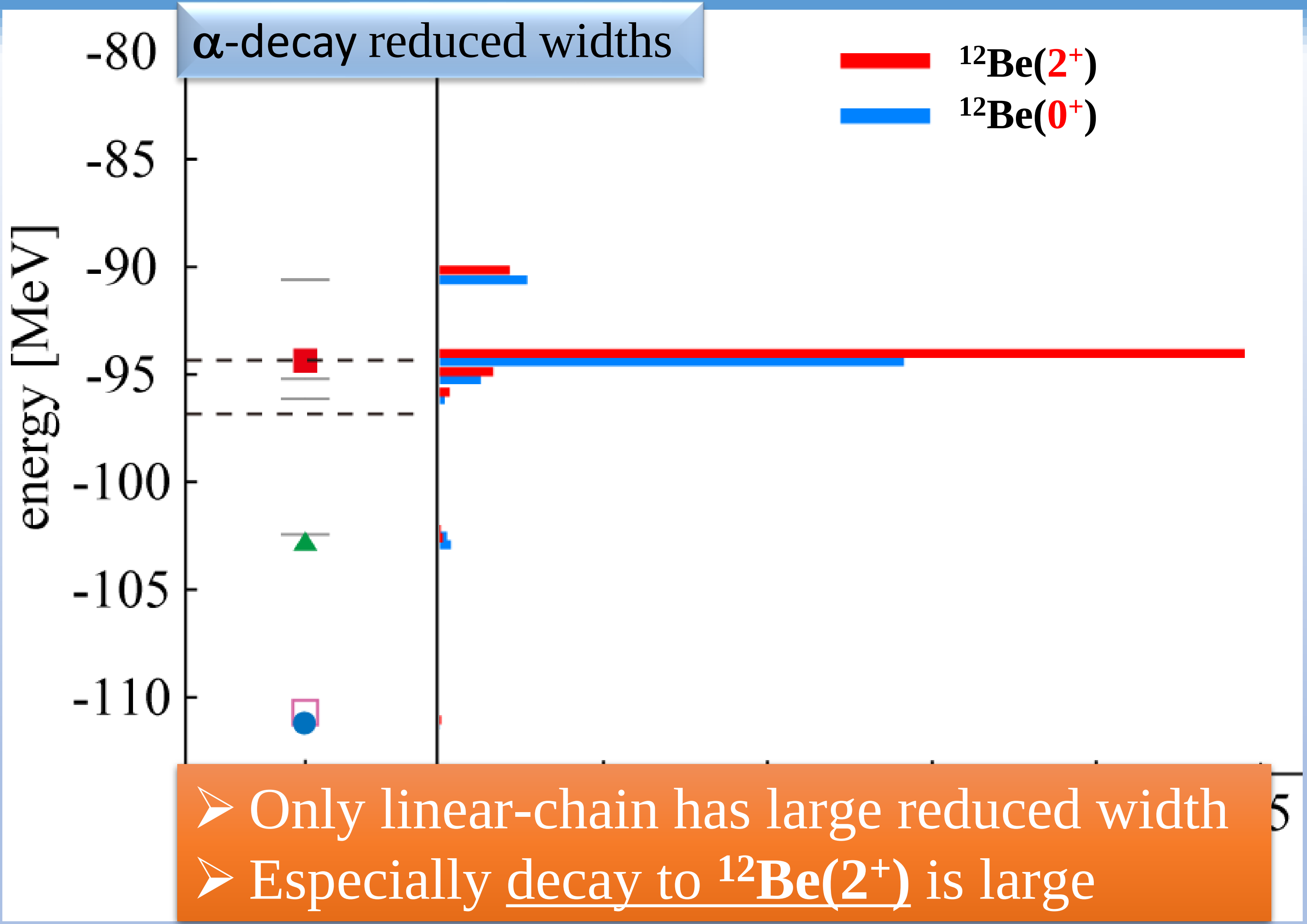


- Only linear-chain has large reduced width
- Especially <u>decay to $^{12}Be(2^+)$</u> is large

Why Linear-Chain Decay to 2^+?

- We show that linear-chain structure decays to $^{10}Be(2^+)$

Decay patterns depend on cluster structure

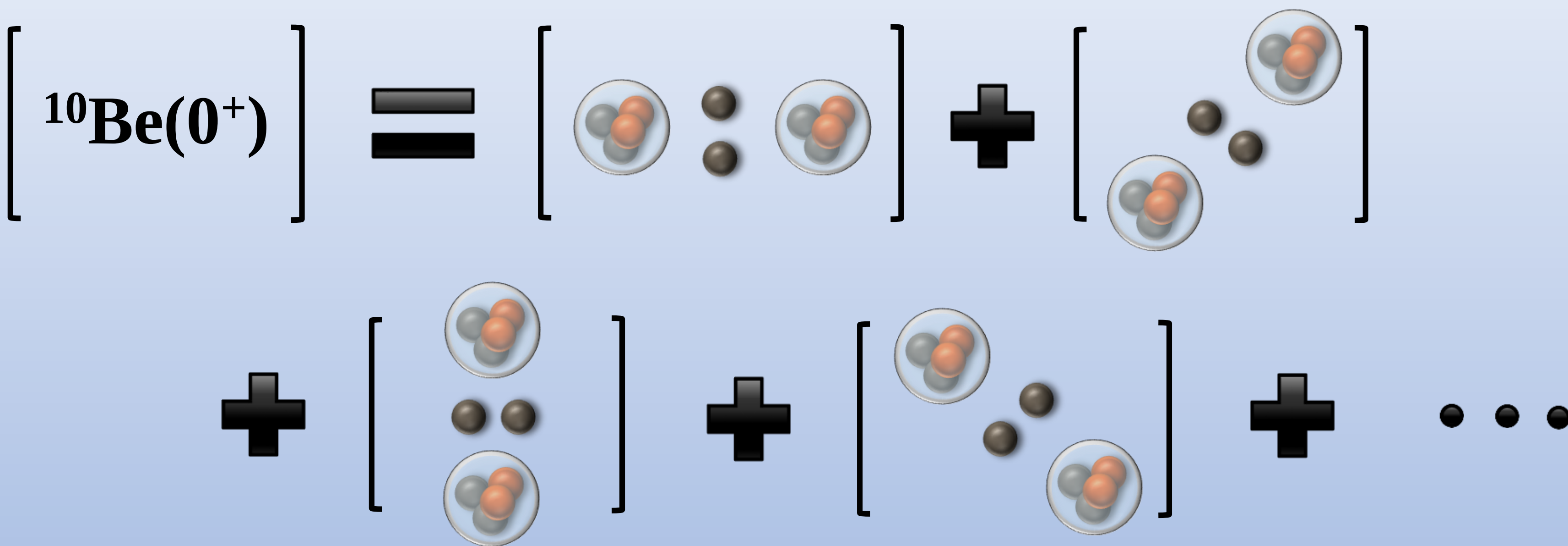
Y. Suzuki, H. Horiuchi, and K. Ikeda, Prog. Theor. Phys. Vol **47**, No. 5 (1972).

Gas-like cluster structure (weak coupling)	→ decay to Be(0^+)
Linear-chain structure (strong coupling)	→ decay to Be(2^+)

Why Linear-Chain Decay to 2^+?

- We show that linear-chain structure decays to ^{10}Be(2^+)

angular momentum: $J = 0$ → wave function is isotropic



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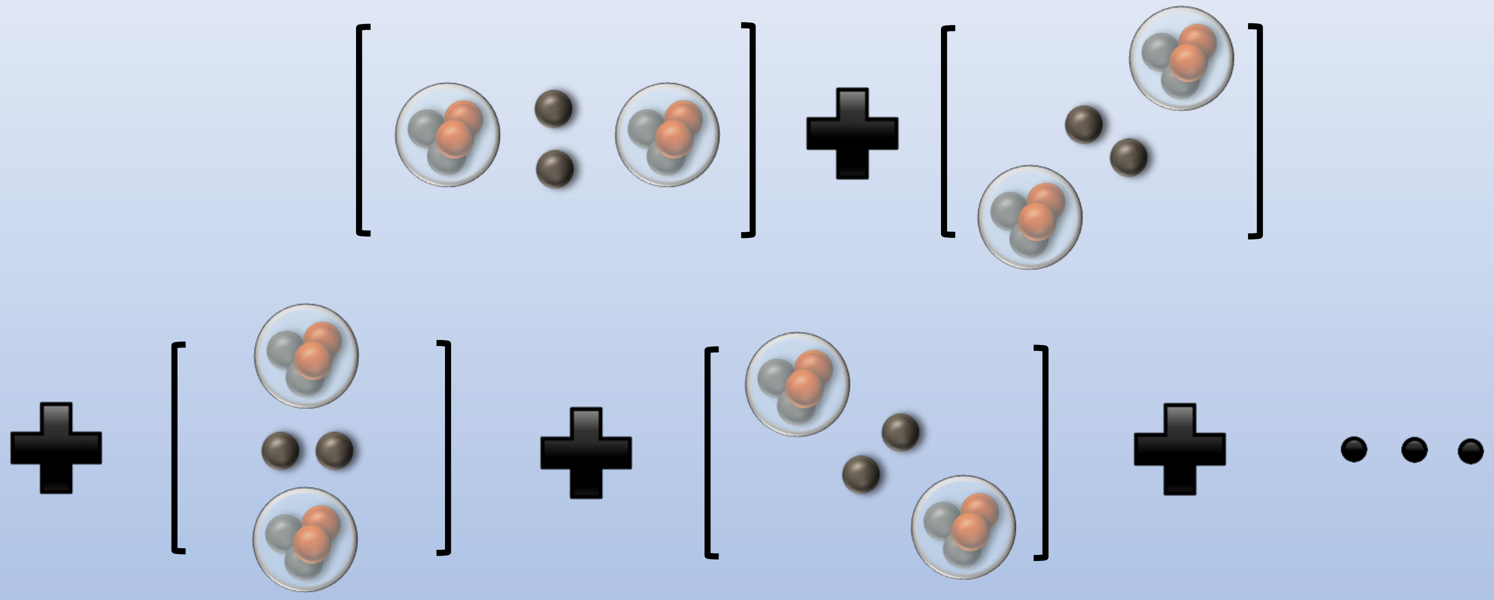
If ^{14}**C** decays to only ^{10}**Be(0^+)**…



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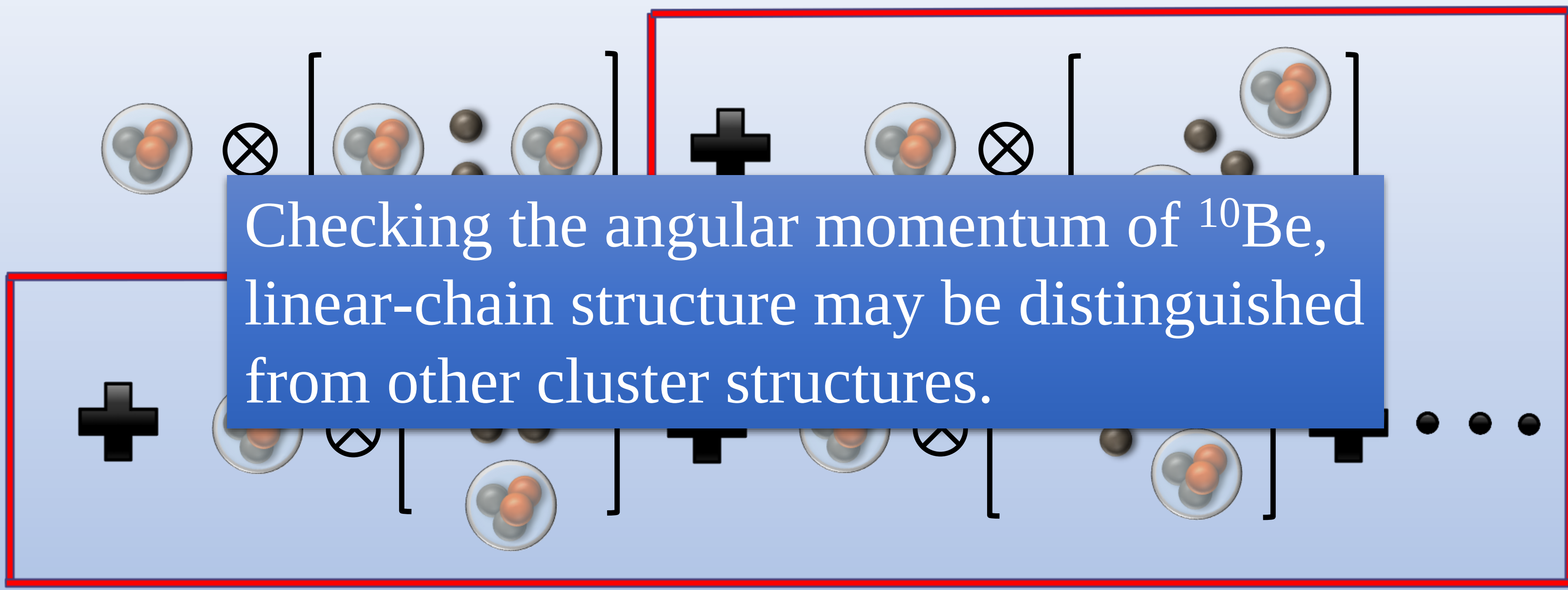

Checking the angular momentum of ^{10}Be, linear-chain structure may be distinguished from other cluster structures.

Linear-chain does NOT include them!

Linear-chain does <u>not only</u> decay to ^{10}**Be(0^+)**.