「クラスター・シェル競合の最近の進展」

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「核力に基づいた原子核の構造と反応」京都大学基礎物理学研究所

Content

- イントロダクション
- クラスター・シェル競合の最近の発展・１ (アイソスピン・ミキシング)
- クラスター・シェル競合の最近の発展・２ (医療への応用)

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- クラスター・シェル競合の最近の発展・2 (医療への応用)

原子核構造

- シェル構造
- クラスター構造

原子核構造

``The Birth of Venus"
by Sandro Botticelli

- シェル構造
- クラスター構造

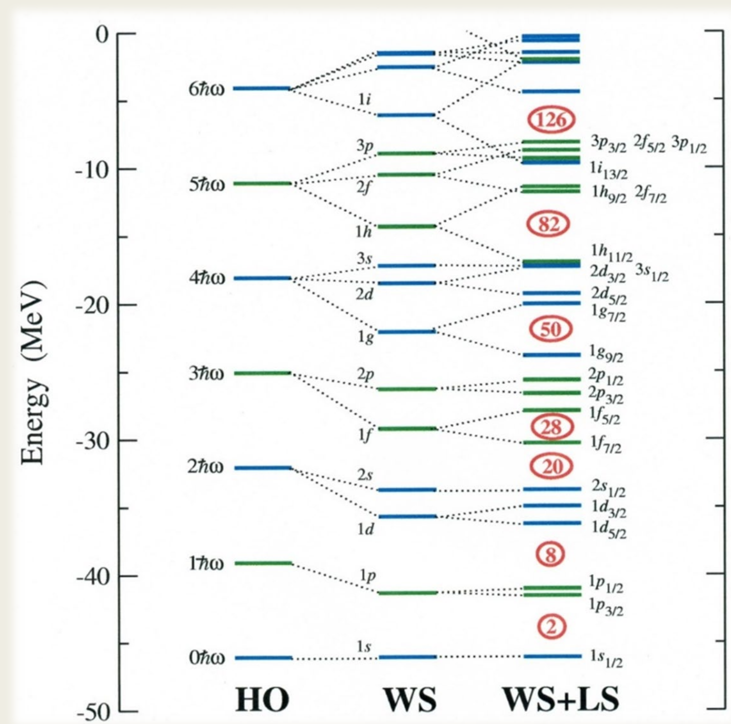
原子核構造

"The Birth of Venus"
by Sandro Botticelli

- シェル構造:
  それぞれの核子の一粒子運動

good j

- クラスター構造



原子核構造

- シェル構造:
  それぞれの核子の一粒子運動
- クラスター構造

  ^{4}Heは強く束縛しており (B.E. 28.3 MeV),
  原子核中で部分系足りうる

  → ^{4}He同士の相対の相互作用は比較的弱い

``Haystacks" by Claude Monet

Conventional α cluster model (Brink model)

spatial part of the single particle wave function

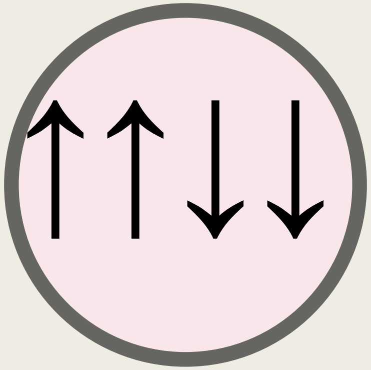
$$\exp[-\nu(\mathbf{r}-\mathbf{R})^2]$$

Locally shifted Gaussian form

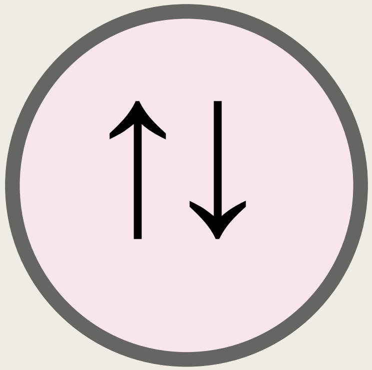
R: Gaussian center parameter

``simple α cluster”: 4 nucleons share same R

“Simple” α cluster



Dineutron クラスター



２中性子の空間部分の波動関数が同じなので、
スピンは反対称に組む

$$\frac{1}{\sqrt{2}}\{\,|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\} = |00\rangle \qquad S=0$$

非中心力が作用しない

2核子間相互作用

- Central

  v(r), v(r)($\boldsymbol{\sigma}_1$・$\boldsymbol{\sigma}_2$), v(r)($\boldsymbol{\tau}_1$・$\boldsymbol{\tau}_2$), v(r)($\boldsymbol{\sigma}_1$・$\boldsymbol{\sigma}_2$)($\boldsymbol{\tau}_1$・$\boldsymbol{\tau}_2$)

- 空間部分がRank 1の非中心力

  (トータルは回転対称)

  v(r)($\boldsymbol{\sigma}_1$+$\boldsymbol{\sigma}_2$)・**L**

非中心力
S=1が必要

- 空間部分がRank 2の非中心力

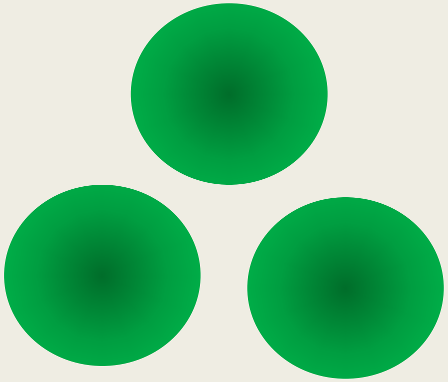
  (トータルは回転対称)

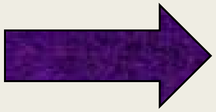
$$S_{12} = 3(\sigma_1 \bullet r)(\sigma_2 \bullet r)/r^2 - (\sigma_1 \bullet \sigma_2)$$

Tensor operator

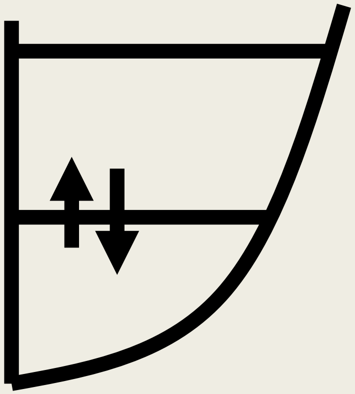
Cluster side

Shell model side

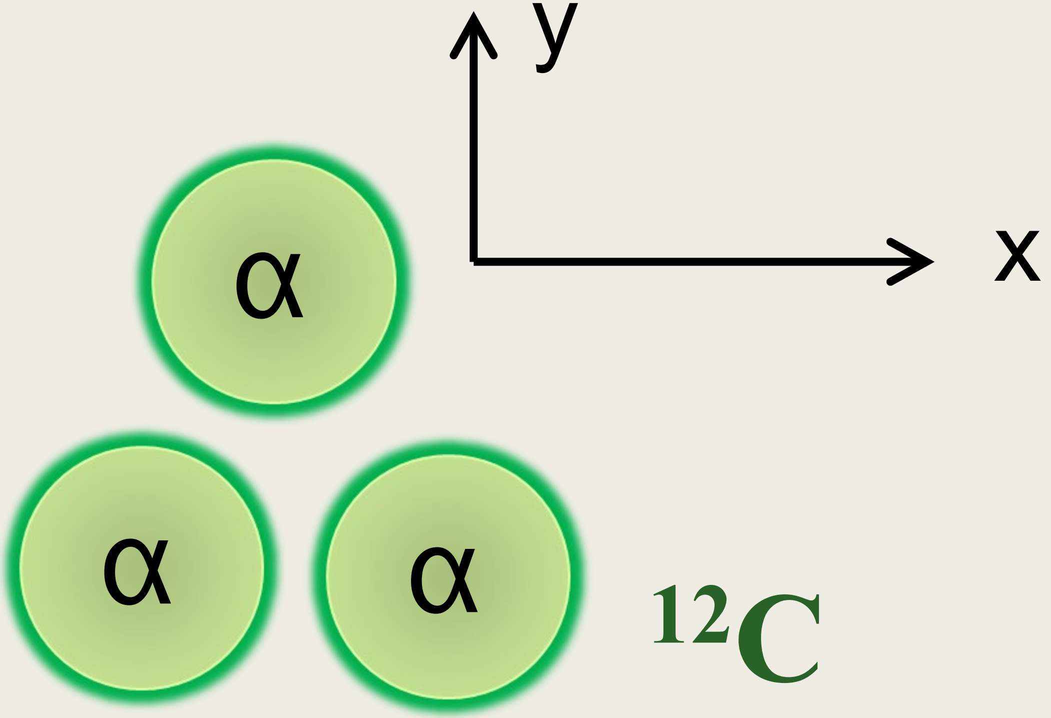




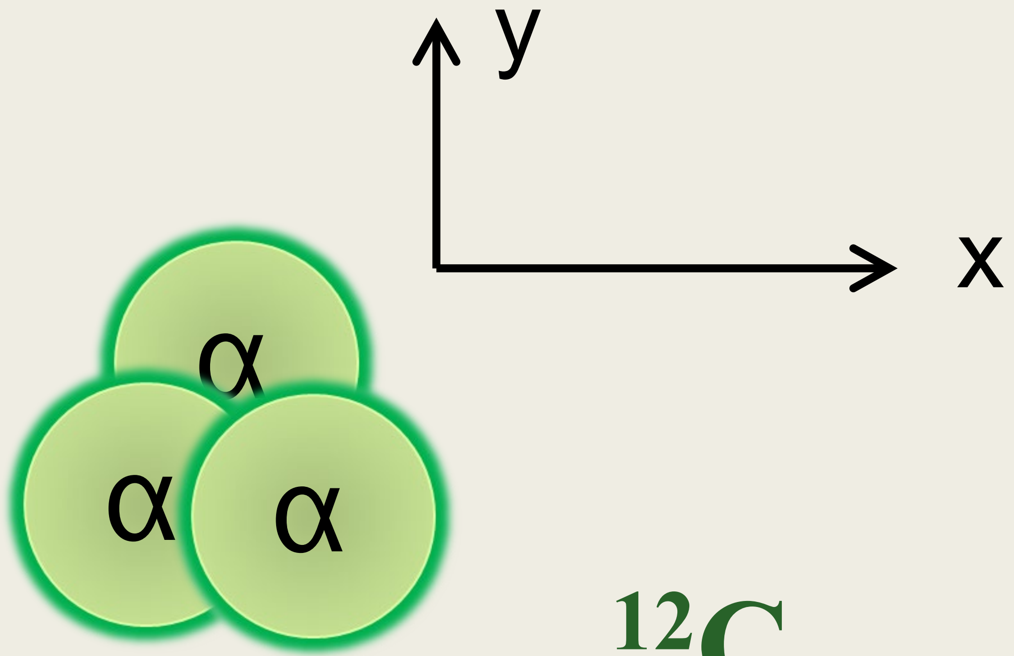
Our strategy



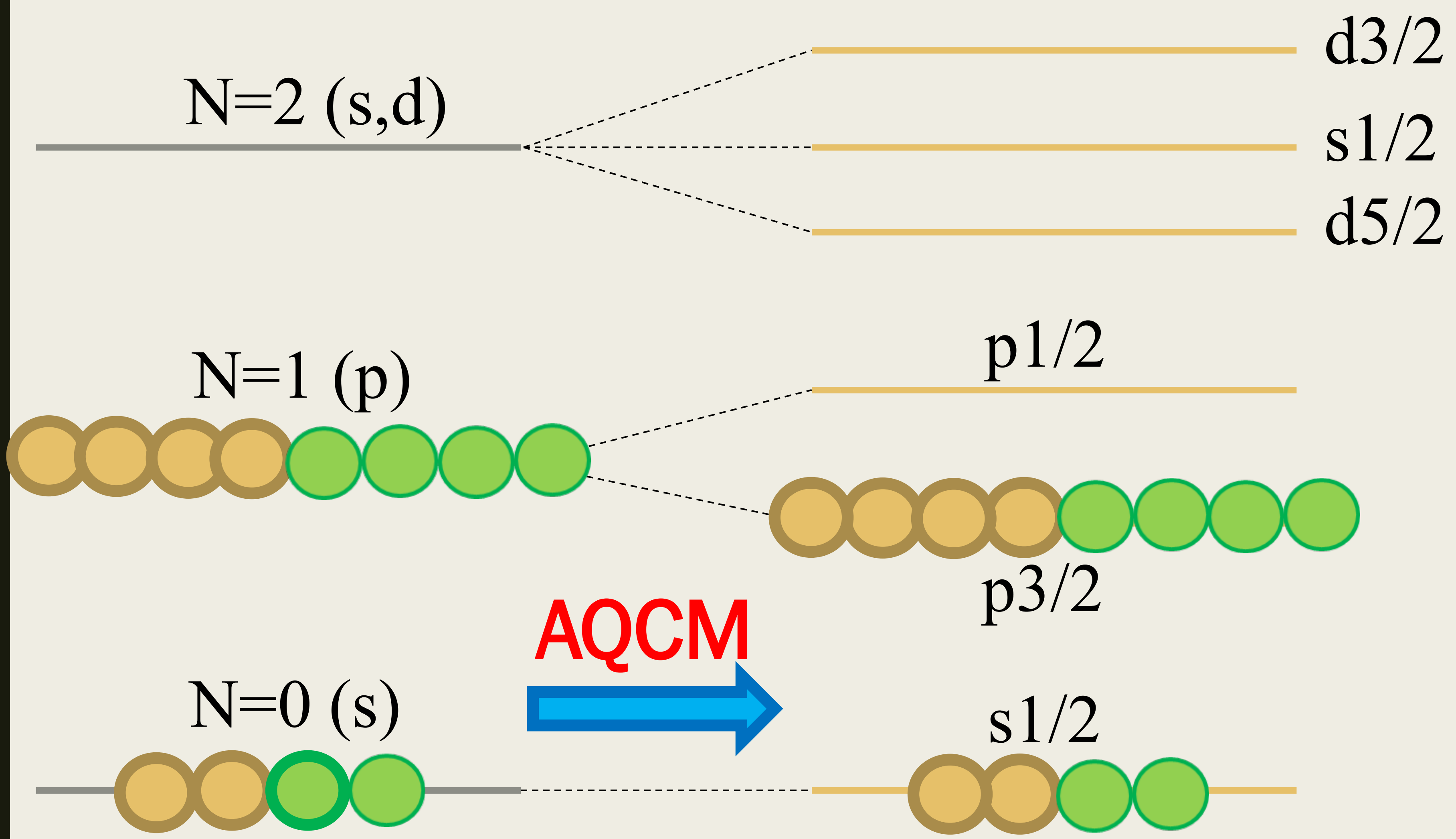
クラスター模型はシェル模型を包含する？



クラスター模型はシェル模型を包含する？



^{12}C



3次元調和振動子　jj-カップリングシェル模型

Antisymmetrized quasi-cluster model

spatial part of the single particle wave function

$$\exp[-\nu(\mathbf{r}-\mathbf{R})^2]$$

spin-orbit interaction: **l • s = (r x p) • s**

< r > → Gaussian center parameter **R**

< p > → zero, if **R** is real

Antisymmetrized quasi-cluster model

spatial part of the single particle wave function

$$\exp[-\nu(\mathbf{r}-\mathbf{R})^2]$$

spin-orbit interaction: $\mathbf{l} \cdot \mathbf{s} = (\mathbf{r} \times \mathbf{p}) \cdot \mathbf{s}$

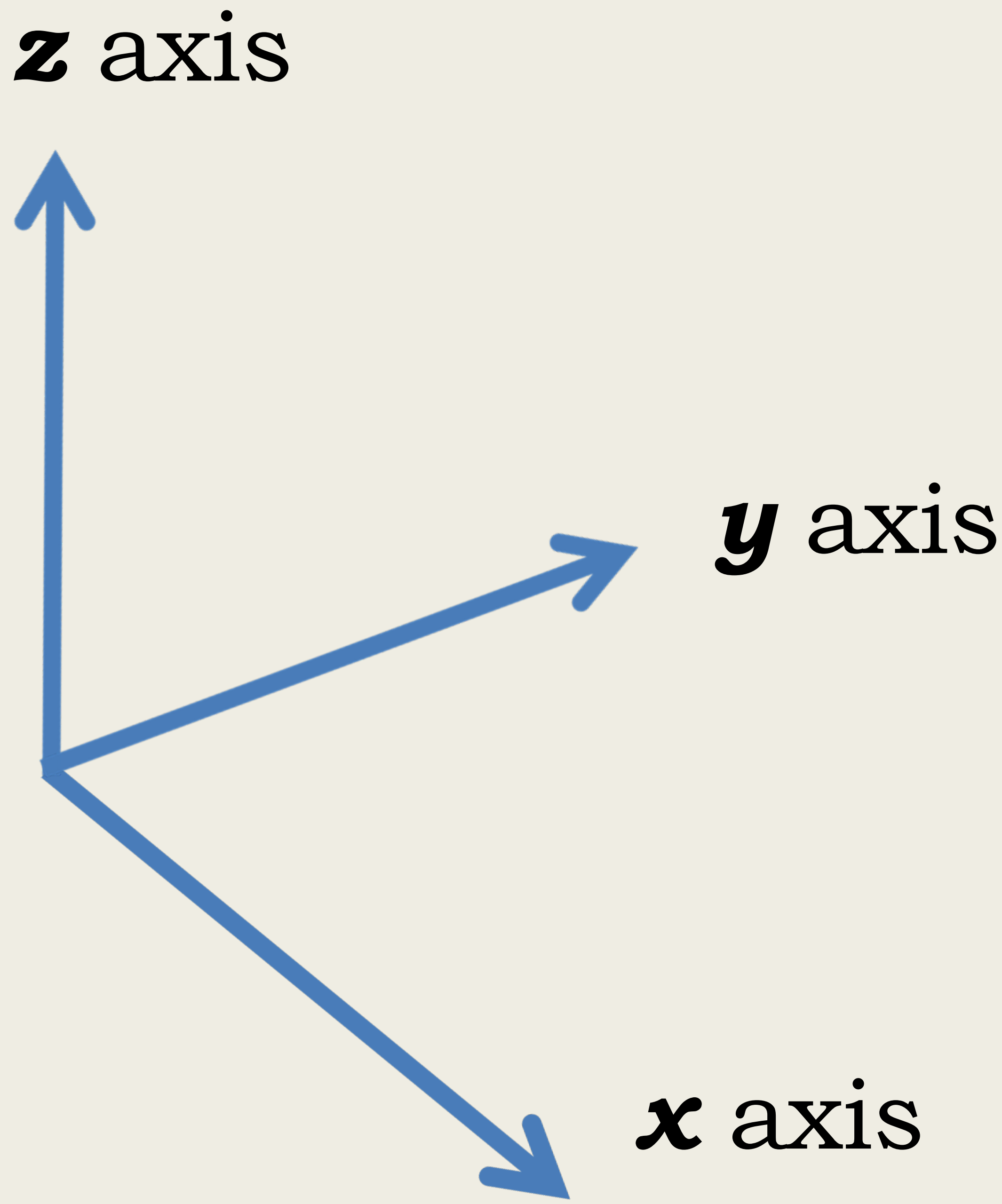
$< \mathbf{r} >$ → Gaussian center parameter **R**

$< \mathbf{p} >$ → imaginary part of **R**

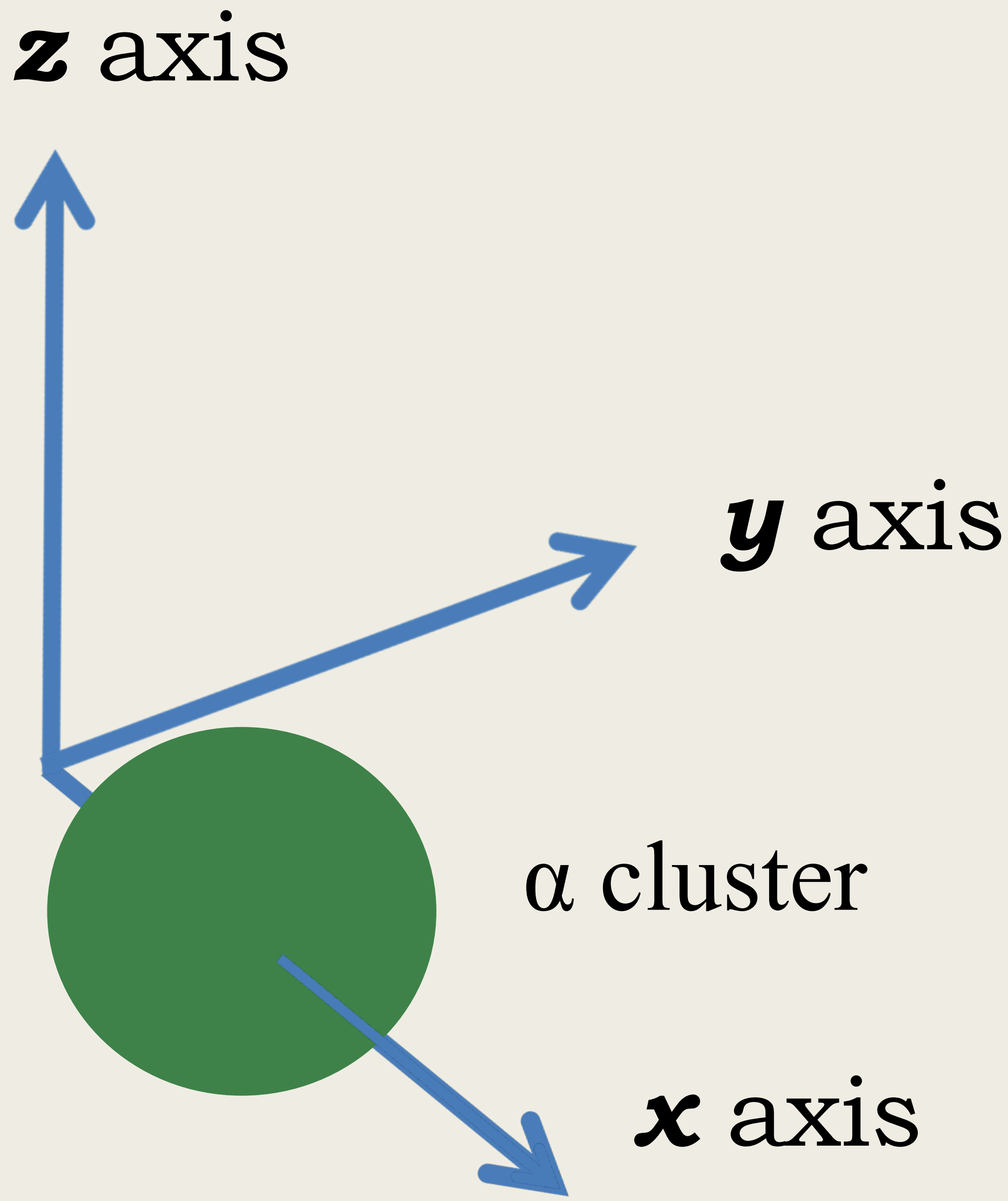
$$(\mathbf{r} \times \mathbf{p}) \cdot \mathbf{s} = (\mathbf{s} \times \mathbf{r}) \cdot \mathbf{p}$$

R → **R** + i Λ (**e**_spin x **R**)

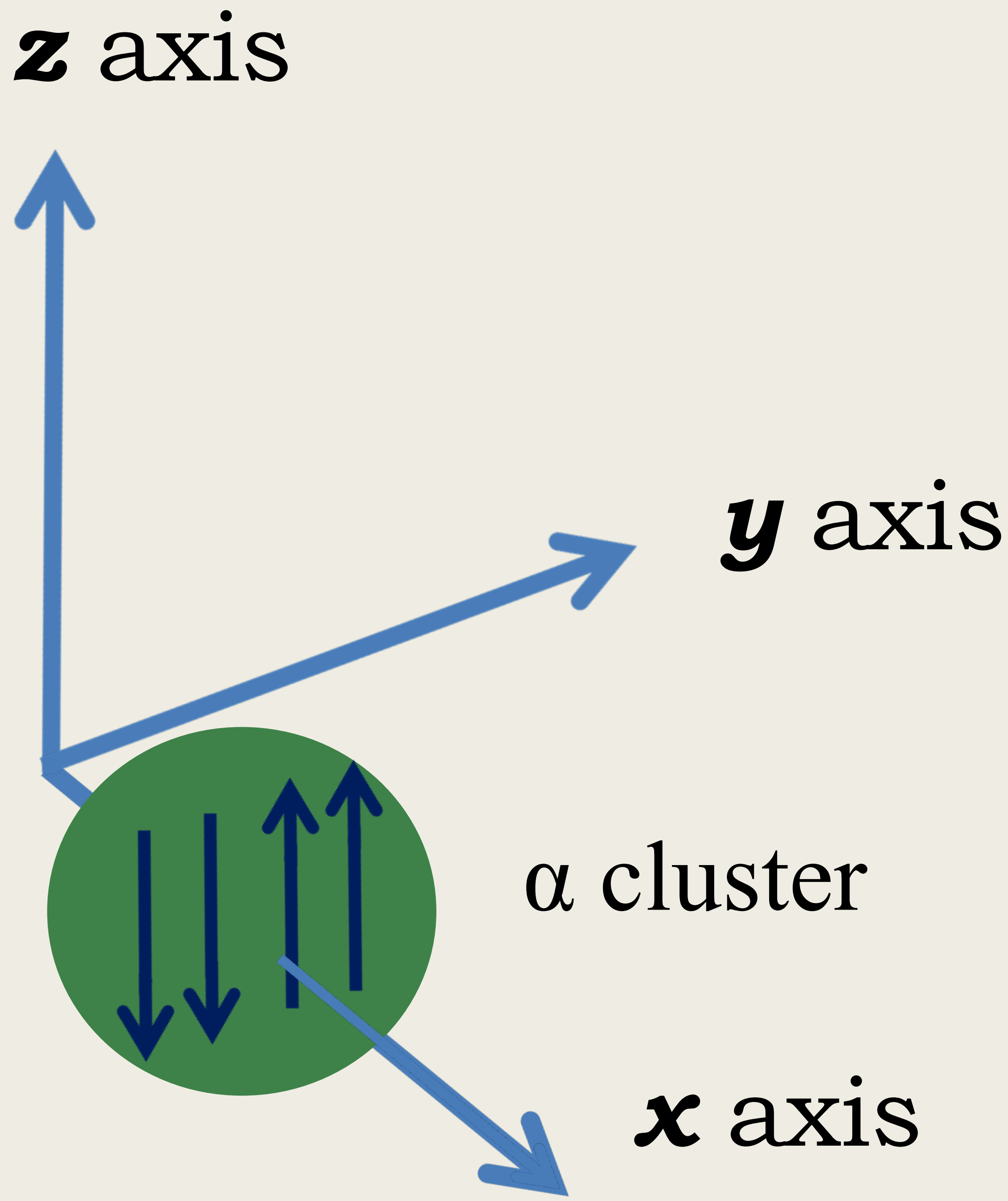
α cluster → quasi cluster



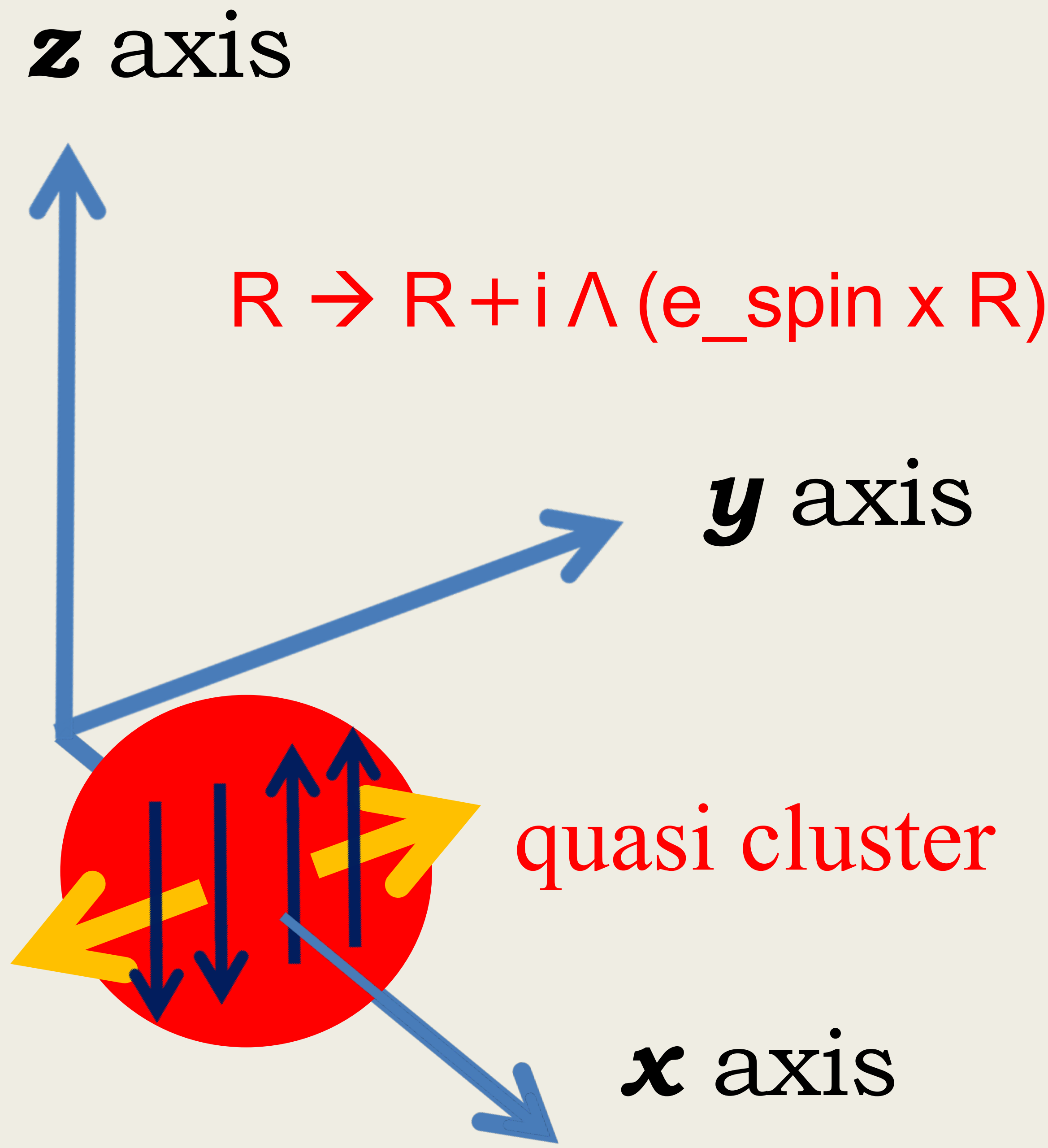
z axis
y axis
x axis



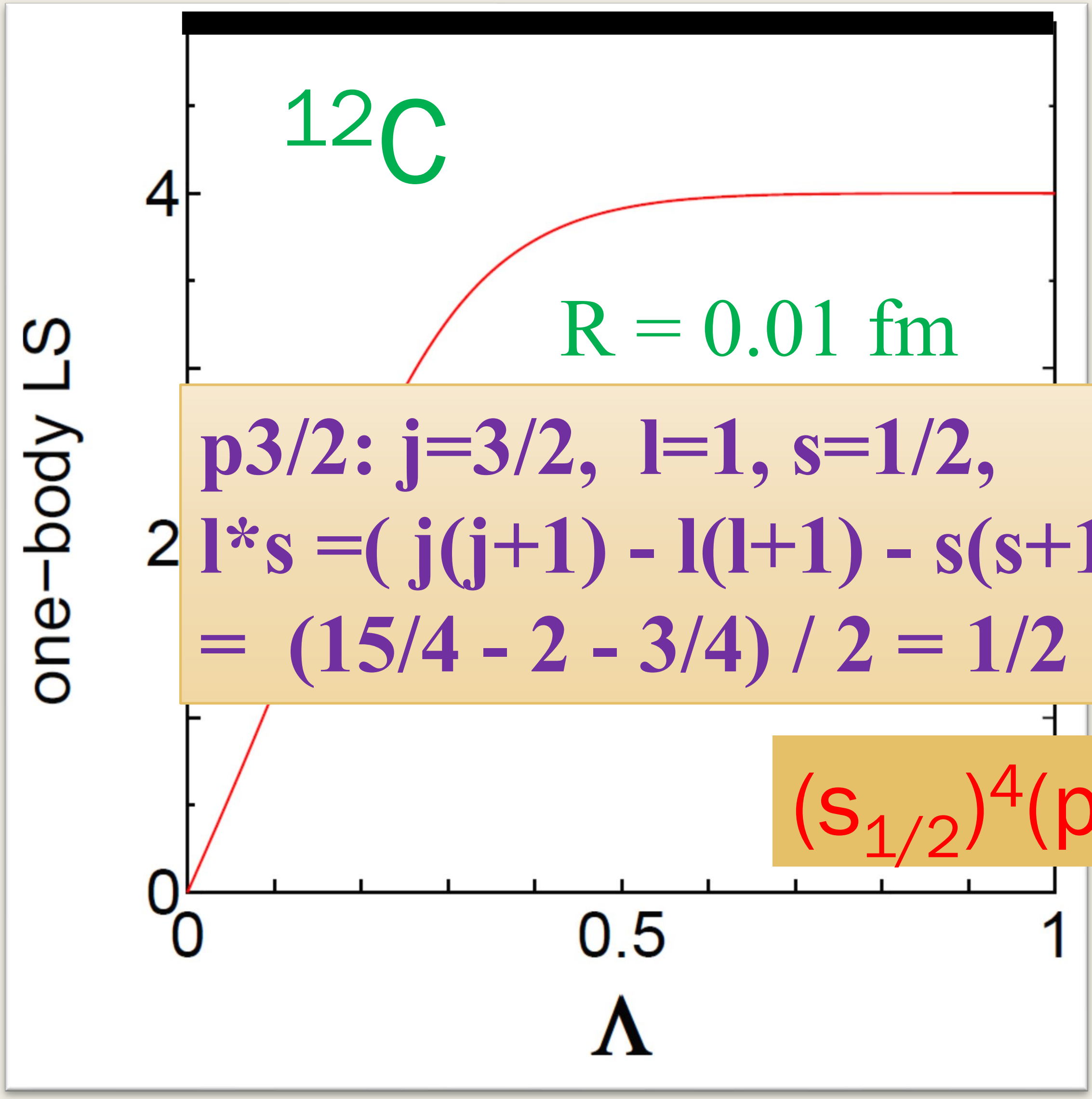
z axis
y axis
α cluster
x axis



z axis
y axis
α cluster
x axis


z axis
R → R + i Λ (e_spin x R)
y axis
quasi cluster
x axis

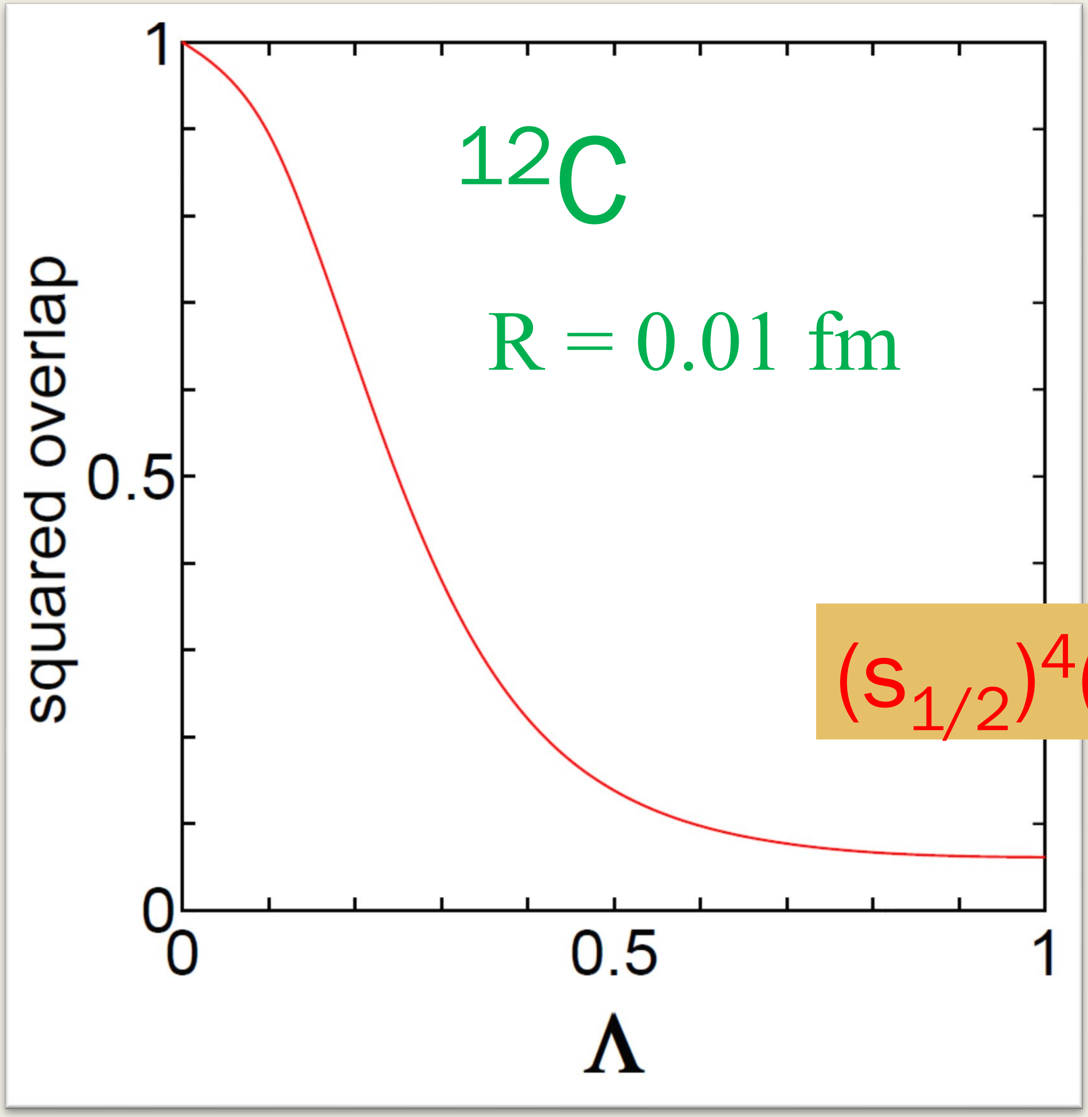
One-body spin-orbit operator $\sum_{i=0}^{A} L_i \bullet S_i$



p3/2: j=3/2, l=1, s=1/2,
l*s =(j(j+1) - l(l+1) - s(s+1))/2
= (15/4 - 2 - 3/4) / 2 = 1/2

$(s_{1/2})^4(p_{3/2})^8$

^{12}C squared overlap with Λ=0



$(s_{1/2})^4(p_{3/2})^8$

Tohsaki interaction

Akihiro Tohsaki, Phys. Rev. C **49**, 1814 (1994)

$$\hat{V}_{central} = \frac{1}{2}\sum_{ij} V_{ij}^{(2)} + \frac{1}{6}\sum_{ijk} V_{ijk}^{(3)},$$

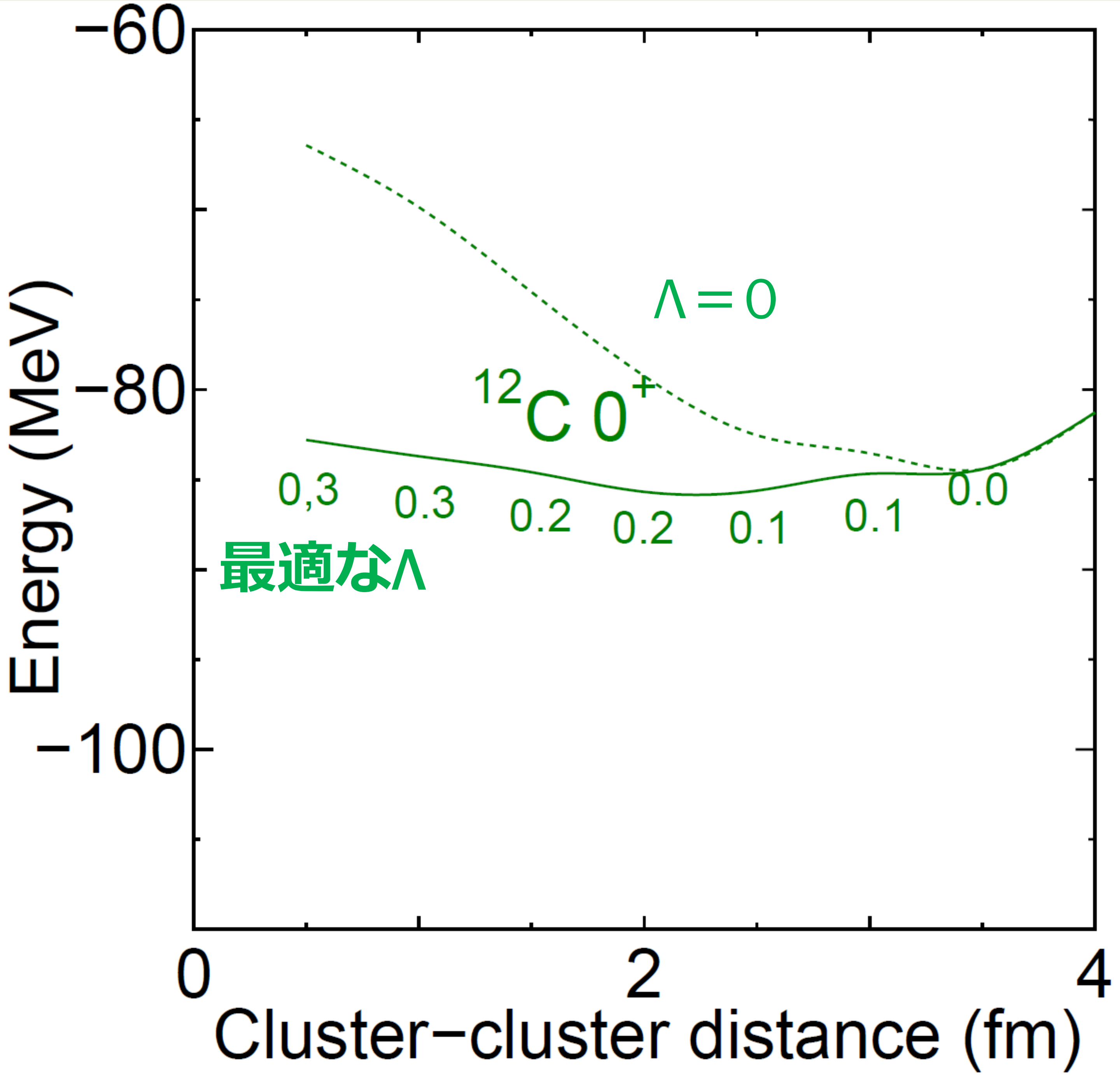
where $V_{ij}^{(2)}$ and $V_{ijk}^{(3)}$ consist of three terms,

$$V_{ij}^{(2)} = \sum_{\alpha=1}^{3} V_{\alpha}^{(2)} \exp[-(\vec{r}_i - \vec{r}_j)^2/\mu_\alpha^2](W_\alpha^{(2)} + M_\alpha^{(2)} P^r)_{ij},$$

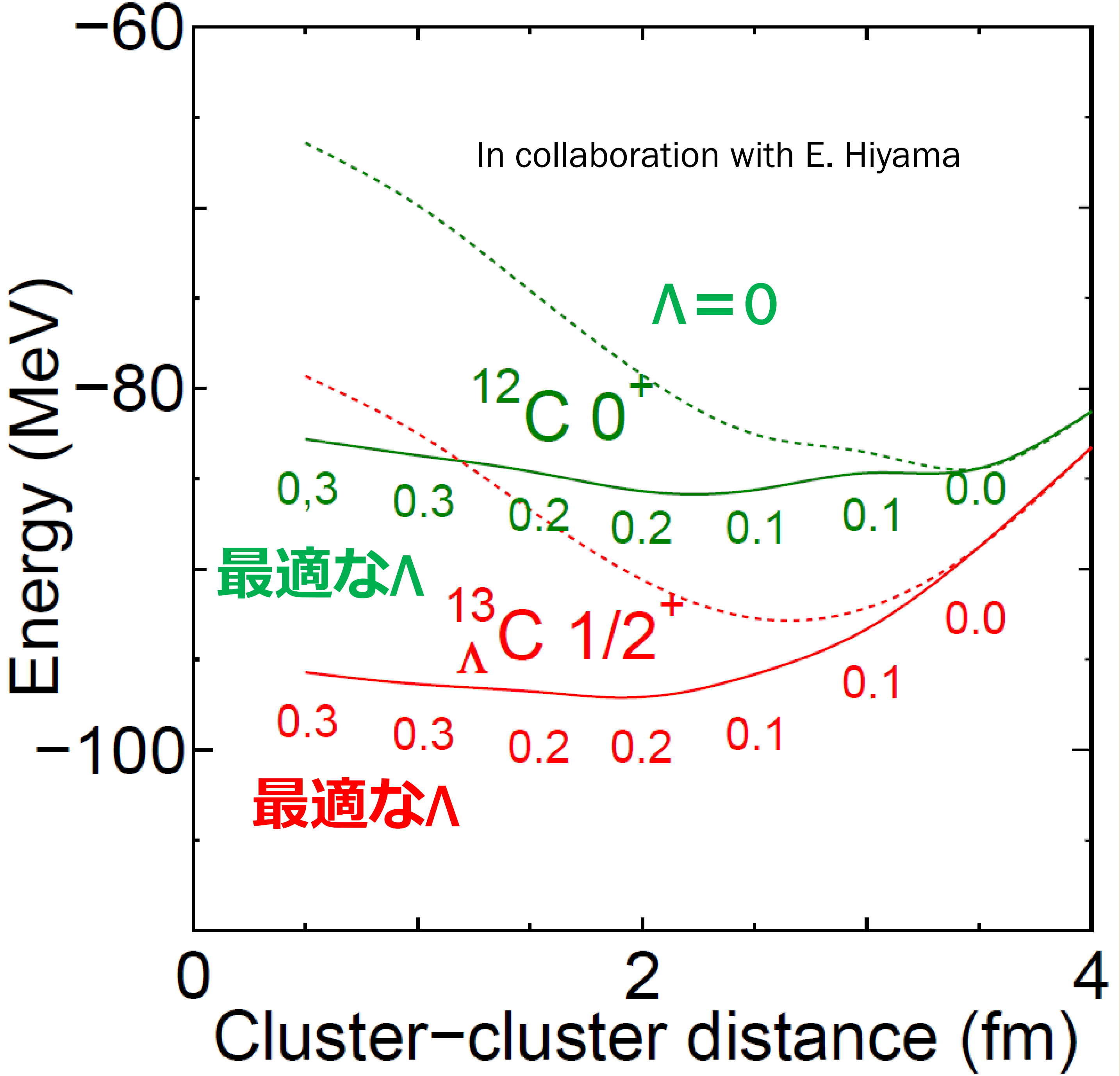
$$V_{ijk}^{(3)} = \sum_{\alpha=1}^{3} \quad V_\alpha^{(3)} \exp[-(\vec{r}_i - \vec{r}_j)^2/\mu_\alpha^2 - (\vec{r}_i - \vec{r}_k)^2/\mu_\alpha^2]$$
$$\times \quad (W_\alpha^{(3)} + M_\alpha^{(3)} P^r)_{ij}(W_\alpha^{(3)} + M_\alpha^{(3)} P^r)_{ik}.$$

Spin-orbit interaction

- RealisticなTamagaki potentialを借りてきて、強さを調節する。^{4}He+nのphase shiftを合わせるものよりも少し弱めを用いる



−60
−80
−100
Energy (MeV)
0
2
4
Cluster−cluster distance (fm)
Λ＝0
^{12}C 0$^+$
0,3
0.3
0.2
0.2
0.1
0.1
0.0
最適なΛ



In collaboration with E. Hiyama
Λ=0
^{12}C 0$^+$
0,3
0.3
0.2
0.2
0.1
0.1
0.0
最適なΛ
$^{13}_{Λ}$C 1/2$^+$
0.0
0.1
0.3
0.3
0.2
0.2
0.1
最適なΛ
Energy (MeV)
−60
−80
−100
0
2
4
Cluster−cluster distance (fm)

After GCM with respect to R

In collaboration with E. Hiyama

^{12}C

	Energy (0^+)	One-body LS
$\Lambda = 0$	-86.82	0.00
optimal Λ	-90.41	1.86

After GCM with respect to R

In collaboration with E. Hiyama

		Energy (0^+)	One-body LS
^{12}C	$\Lambda = 0$	-86.82	0.00
	optimal Λ	-90.41	1.86
		Energy ($1/2^+$)	One-body LS
$^{13}_{\Lambda}C$	$\Lambda = 0$	-93.46	0.00
	optimal Λ	-98.93	2.37

After GCM with respect to R

In collaboration with E. Hiyama

		Energy (0^+)	One-body LS
^{12}C	$\Lambda = 0$	-86.82	0.00
	optimal Λ	-90.41	1.86
		Energy ($1/2^+$)	One-body LS
$^{13}_{\Lambda}C$	$\Lambda = 0$	-93.46	0.00
	optimal Λ	-98.93	2.37
		Energy (0^+)	One-body LS
$^{14}_{\Lambda\Lambda}C$	$\Lambda = 0$	-103.32	0.00
	optimal Λ	-110.68	2.69

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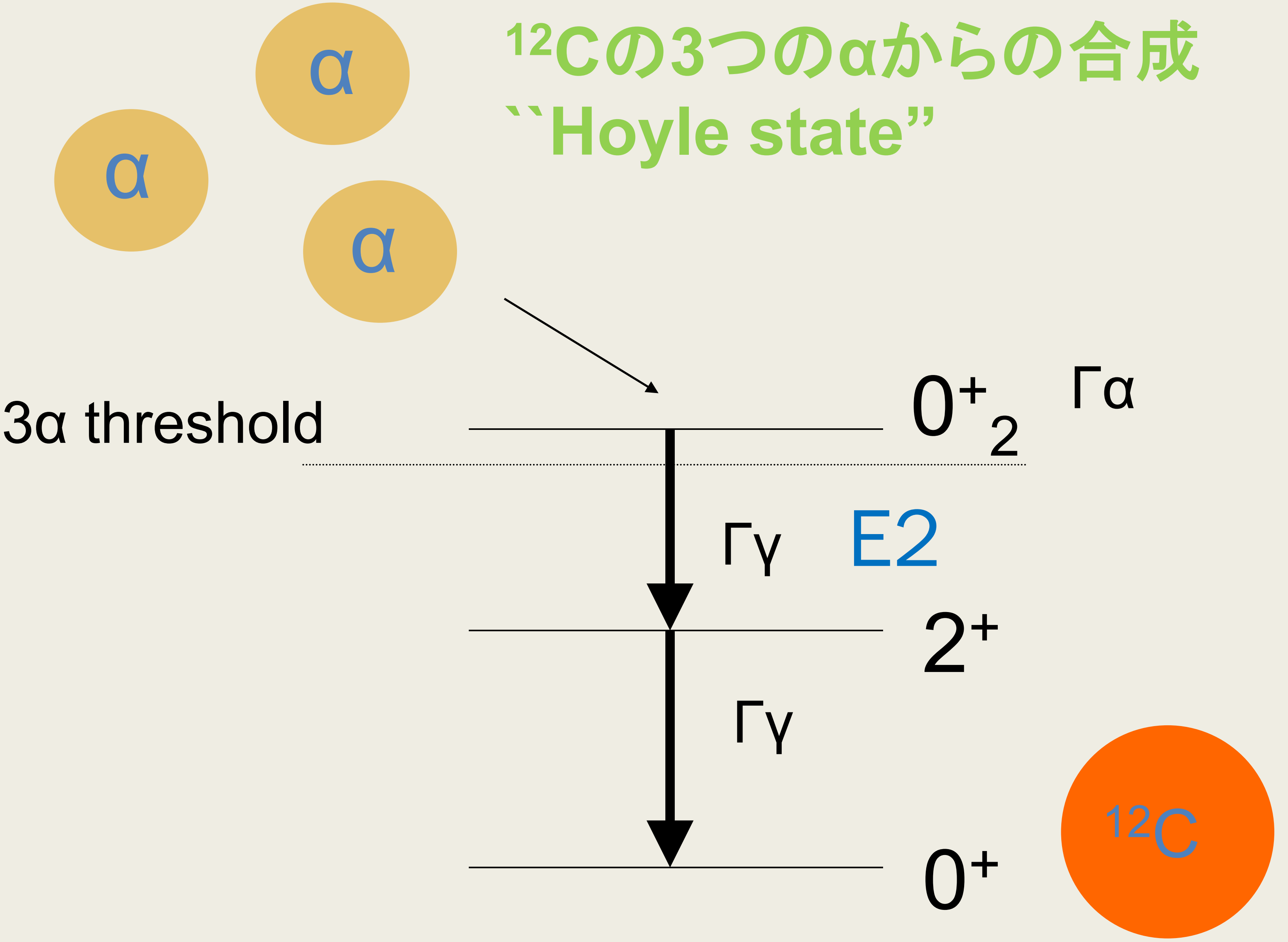
^{12}Cの3つのαからの合成
``Hoyle state”



3α構造を持った状態がここにあるべきと理論的に予言され
すぐに実験的に確かめられた

Physics Letters B 817 (2021) 136283

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

First experimental determination of the radiative-decay probability of the 3_1^- state in ^{12}C for estimating the triple alpha reaction rate in high temperature environments

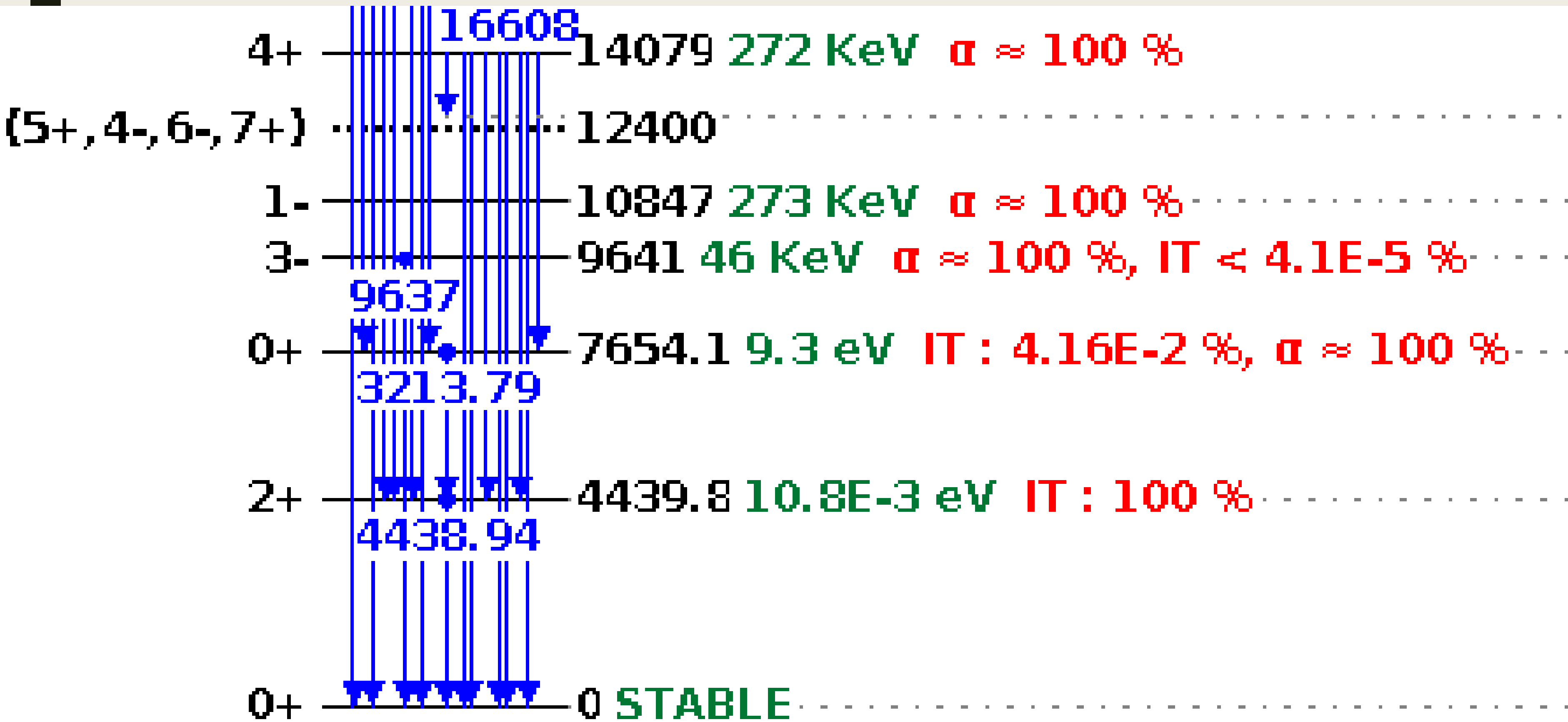
M. Tsumura [a,*,1], T. Kawabata [b], Y. Takahashi [a], S. Adachi [b], H. Akimune [c], S. Ashikaga [a], T. Baba [a], Y. Fujikawa [a], H. Fujimura [d], H. Fujioka [e], T. Furuno [b], T. Hashimoto [f], T. Harada [g], M. Ichikawa [a], K. Inaba [a], Y. Ishii [a], N. Itagaki [h], M. Itoh [i], C. Iwamoto [j], N. Kobayashi [k], A. Koshikawa [a,2], S. Kubono [g,l], Y. Maeda [m], Y. Matsuda [i,3], S. Matsumoto [a], K. Miki [n], T. Morimoto [a], M. Murata [k], T. Nanamura [a], I. Ou [o], S. Sakaguchi [p], A. Sakaue [g,4], M. Sferrazza [q], K.N. Suzuki [a], T. Takeda [a], A. Tamii [k], K. Watanabe [a], Y.N. Watanabe [r], H.P. Yoshida [k], J. Zenihiro [a]

M. Tsumura et al. Phys. Lett. B**817** 136283 (2021)

S_α= 7.36659 MeV

S_p=15.95668 MeV

^{12}C



https://www.nndc.bnl.gov/nudat3/

	0^+_2	3^-_1
$\Gamma_{rad}/\Gamma_{tot}$ (present)	$1.3^{+1.2}_{-1.1} \times 10^{-6}$	$(2.6 \pm 0.7) \times 10^{-2}$
$\Gamma_{rad}/\Gamma_{tot}$ (previous) [25]	$< 8.2 \times 10^{-7}$(95%C.L.)	$(2.21 \pm 0.07) \times 10^{-2}$
Γ_{tot} (eV) [25]	$(46 \pm 3) \times 10^3$	0.40 ± 0.05

M. Tsumura et al. Phys. Lett. B**817** 136283 (2021)

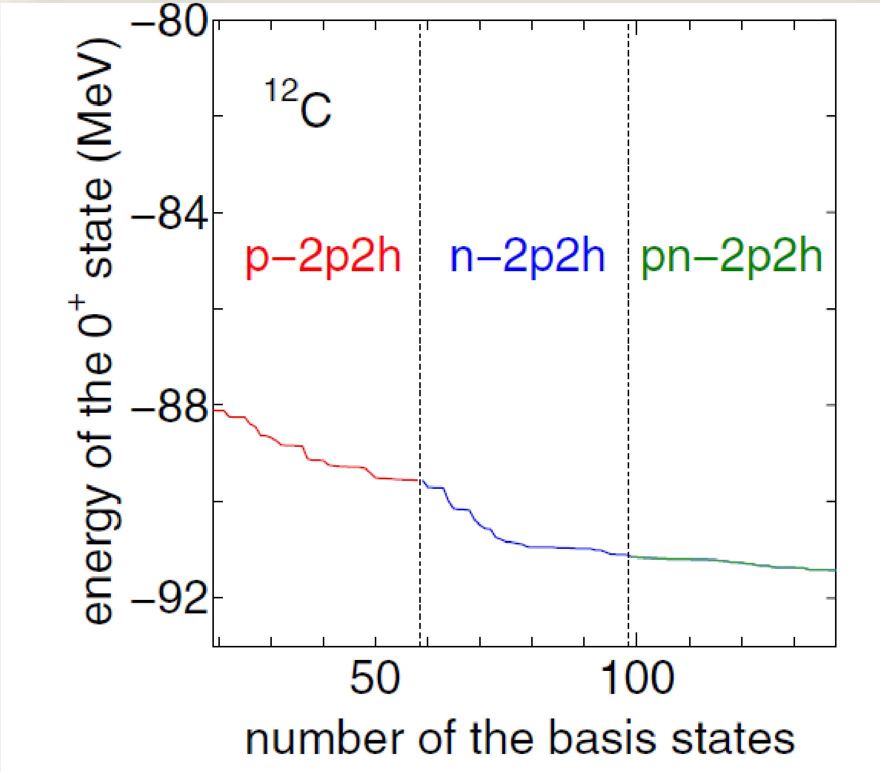
Basic information

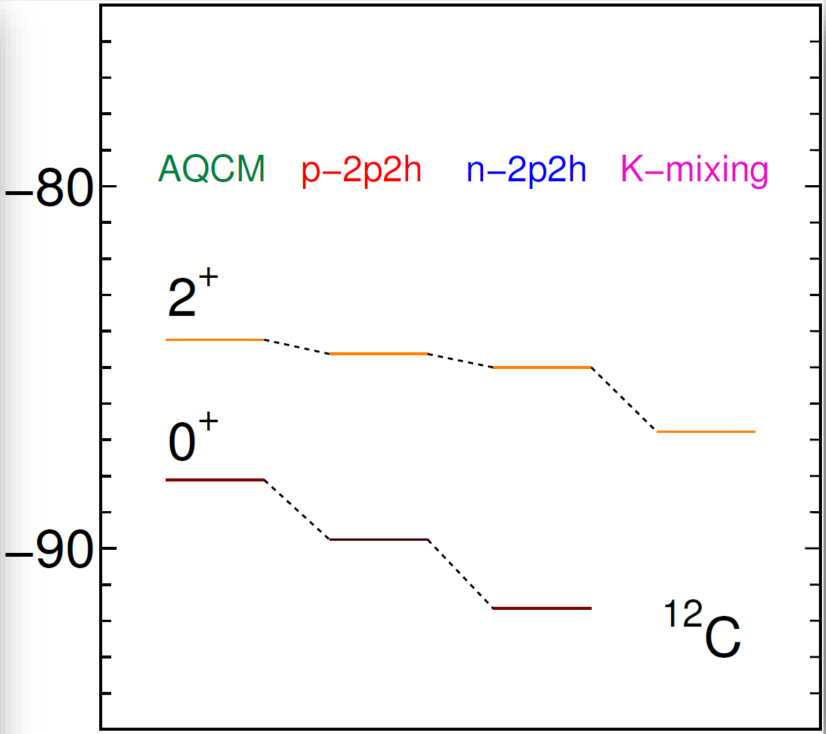
- $E_x(2^+)$= 4.4398221 MeV
- $E_x(3^-)$= 9.6415 MeV
- $B(E\lambda\uparrow)\ (2J_{ground}+1) = B(E\lambda\downarrow)\ (2J_{ex}+1)$
- $\Gamma = 8\pi\ [\ (\lambda+1)\ /\ \lambda(2\lambda+1)!!^2\ ]\ [\ E_\gamma / \hbar c\ ]^{2\lambda+1} e^2\ B(E\lambda\downarrow)$
- Γ (E1, $3^- \rightarrow 2^+$) (meV) =
  1.4732 x 10^5 x $B(E1\downarrow)(e^2fm^2)$

$B(E1\downarrow)$が10^{-4} e^2fm^2のオーダー以上で必要
(E3は幅にはあまり効かない)

まずはアイソスピンが破れていないといけない

AQCM+2p2h configurations of the shell model

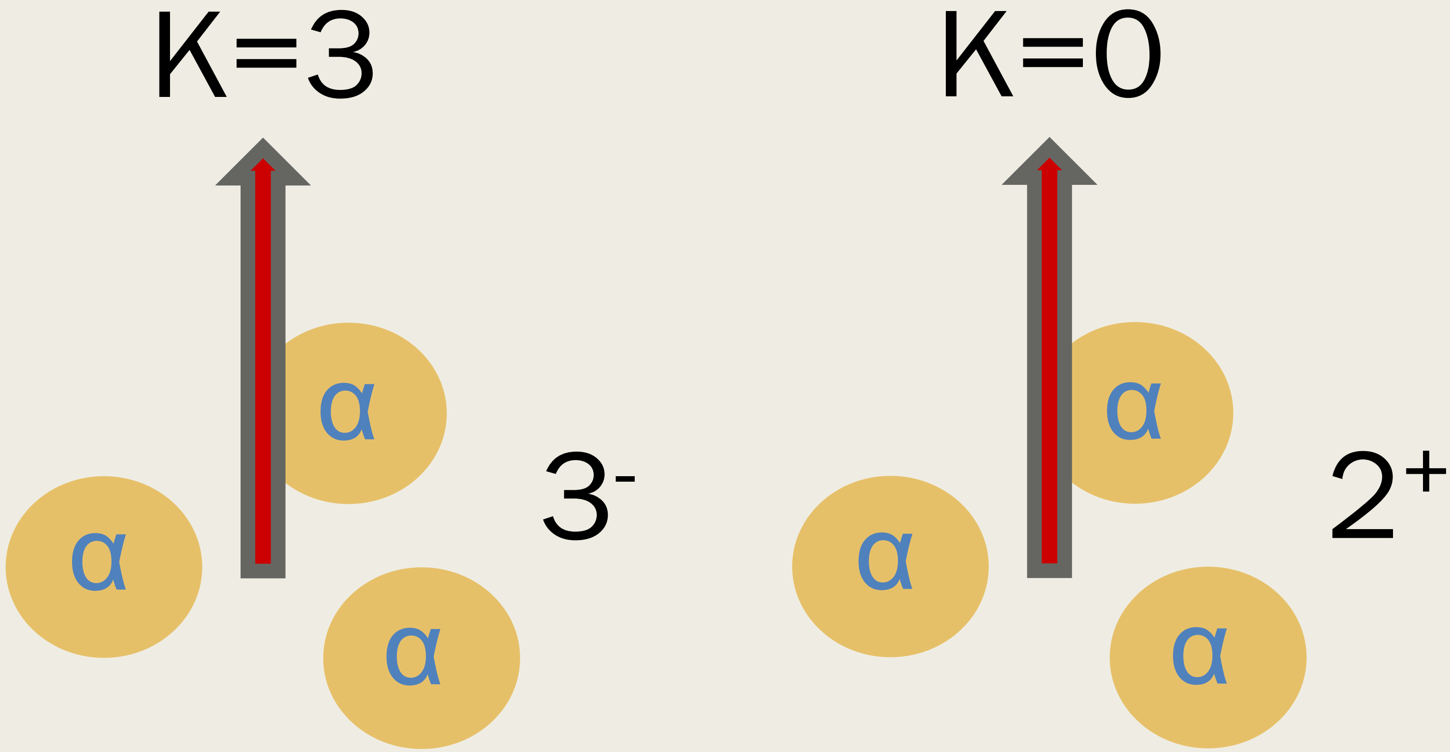




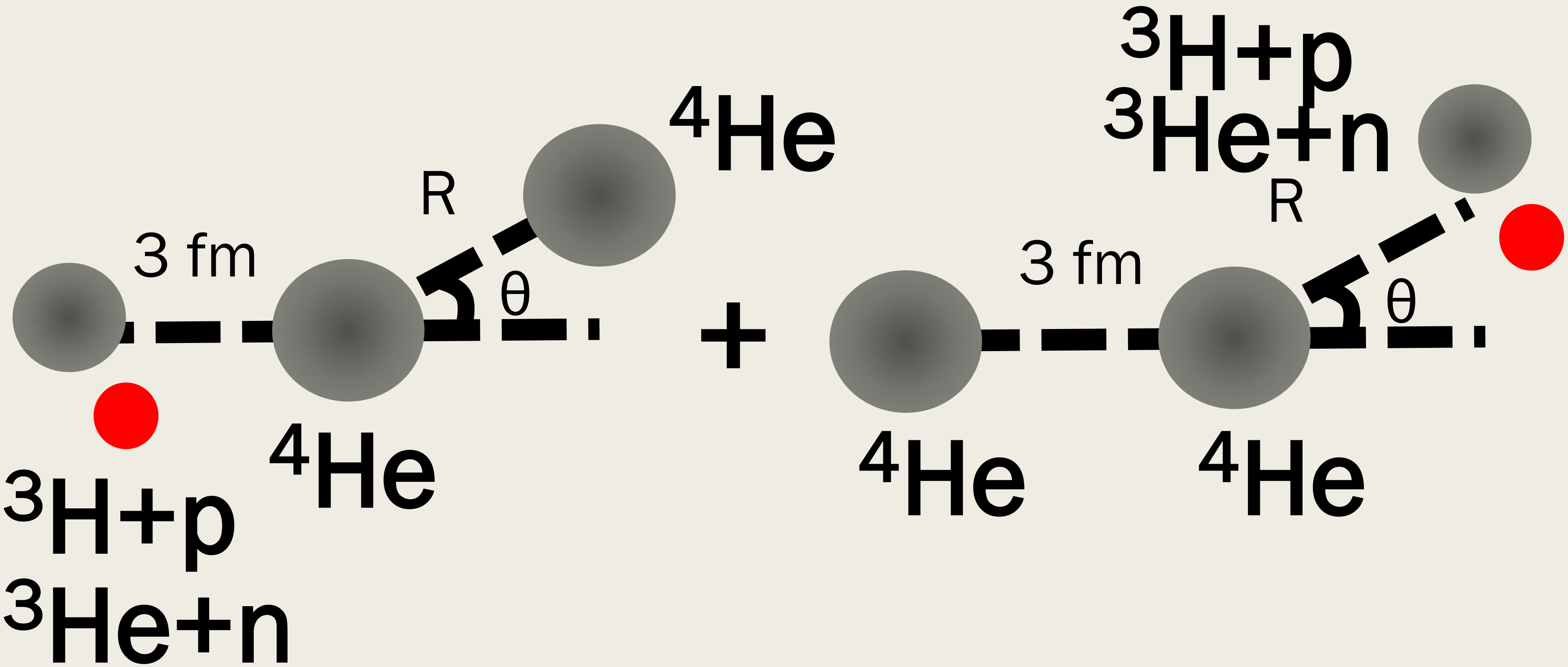
Small mixing of T=1 components (~10^{-3})
due to the Coulomb interaction judging from T^2

Naoyuki Itagaki and Tomoya Naito Phys. Rev. C **103** 044303 (2021)

Isospinの混じりの問題に加え、3^-におけるK=1の混じりも必要！



^{12}C = 2α+3N+N模型



Positions of N = n or p, 25 states generated using random numbers proportional to ± $\exp[-r_i^2/\sigma^2]$, σ = 1 fm,

(we use same random numbers for p and n to guarantee the room for isoscalar configurations)

^{12}C B(E1↓) Sz=0

	1	2	3	4	5	6	7	8	9
R (fm)	1	1	1	2	2	2	3	3	3
θ	π/4	2π/4	3π/4	π/4	2π/4	3π/4	π/4	2π/4	3π/4
2^+ (MeV)	-81.1	-84.3	-81.5	-88.3	-89.7	-87.9	-83.3	-86.9	-83.5
3^- (MeV)	-74.2	-74.0	-74.8	-80.5	-80.5	-80.5	-80.0	-80.2	-80.5
B(E1↓) (e^2fm^2)	1.14×10^{-7}	4.61×10^{-7}	2.85×10^{-7}	1.84×10^{-8}	1.21×10^{-7}	8.99×10^{-7}	1.09×10^{-7}	1.96×10^{-6}	1.45×10^{-6}

^{12}C B(E1↓) Sz=1

	1	2	3	4	5	6	7	8	9
R (fm)	1	1	1	2	2	2	3	3	3
θ	π/4	2π/4	3π/4	π/4	2π/4	3π/4	π/4	2π/4	3π/4
2^+ (MeV)	-53.8	-55.3	-54.3	-60.0	-62.0	-58.9	-50.9	-57.0	-52.3
3^- (MeV)	-50.0	-52.0	-51.6	-53.4	-54.5	-54.3	-49.0	-50.4	-51.7
B(E1↓) (e^2fm^2)	5.04×10^{-3}	2.43×10^{-3}	3.09×10^{-3}	7.63×10^{-5}	3.17×10^{-3}	8.69×10^{-5}	2.97×10^{-4}	1.81×10^{-3}	1.10×10^{-3}

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SCIENTIFIC REPORTS

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First experimental proof of Proton Boron Capture Therapy (PBCT) to enhance protontherapy effectiveness

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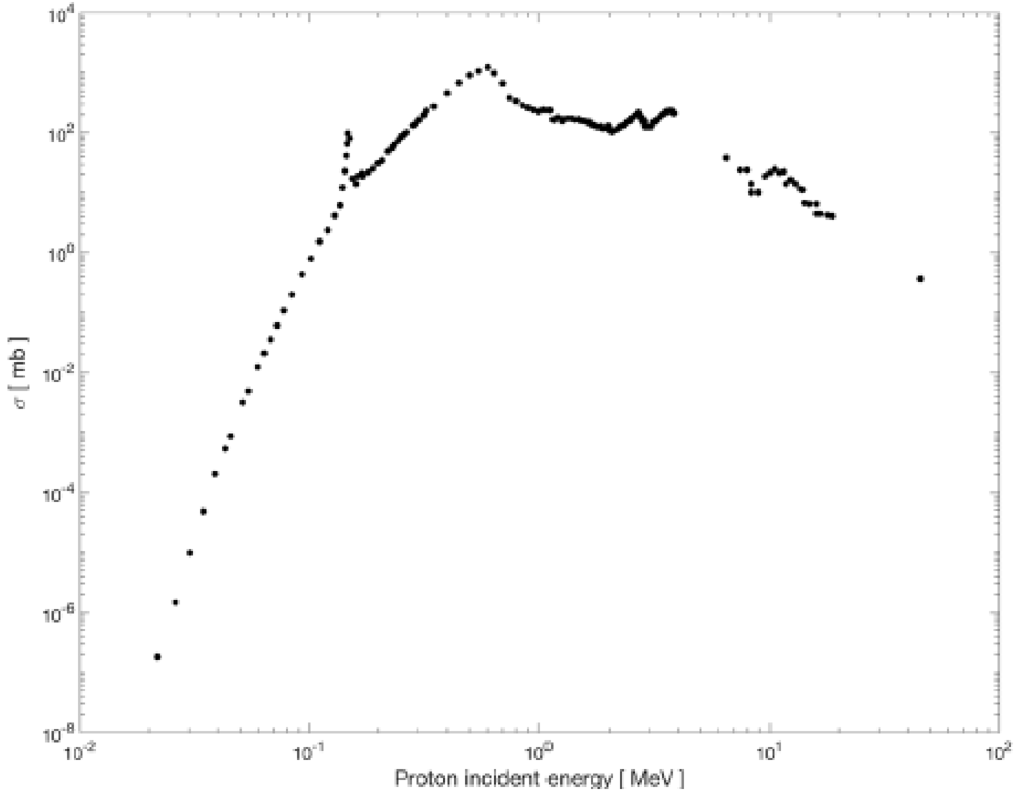
G. A. P. Cirrone[1], L. Manti[2,3], D. Margarone[4], G. Petringa[1,5], L. Giuffrida[4], A. Minopoli[2], A. Picciotto[6], G. Russo[7,1], F. Cammarata[7,1], P. Pisciotta[1,5], F. M. Perozziello[2,3], F. Romano[8,1], V. Marchese[1], G. Milluzzo[1,5], V. Scuderi[1,4], G. Cuttone[1] & G. Korn[4]

Protontherapy is hadrontherapy's fastest-growing modality and a pillar in the battle against cancer. Hadrontherapy's superiority lies in its inverted depth-dose profile, hence tumour-confined irradiation. Protons, however, lack distinct radiobiological advantages over photons or electrons. Higher LET (Linear Energy Transfer) ^{12}C-ions can overcome cancer radioresistance: DNA lesion complexity increases with LET, resulting in efficient cell killing, i.e. higher Relative Biological Effectiveness (RBE). However, economic and radiobiological issues hamper ^{12}C-ion clinical amenability. Thus, enhancing proton RBE is desirable. To this end, we exploited the $p + {}^{11}B \rightarrow 3\alpha$ reaction to generate high-LET alpha particles with a clinical proton beam. To maximize the reaction rate, we used sodium borocaptate (BSH) with natural boron content. Boron-Neutron Capture Therapy (BNCT) uses ^{10}B-enriched BSH for neutron irradiation-triggered alpha particles. We recorded significantly increased cellular lethality and chromosome aberration complexity. A strategy combining protontherapy's ballistic precision with the higher RBE promised by BNCT and ^{12}C-ion therapy is thus demonstrated.



$p + {}^{11}B$で
^{12}CのEx = 16 MeV
領域を作り、
そこからのα崩壊で
がん細胞を破壊

Figure 8. Experimental cross sections. Proton-^{11}B total reaction cross section for the most probable α_1 channel decay (from EXFOR database).

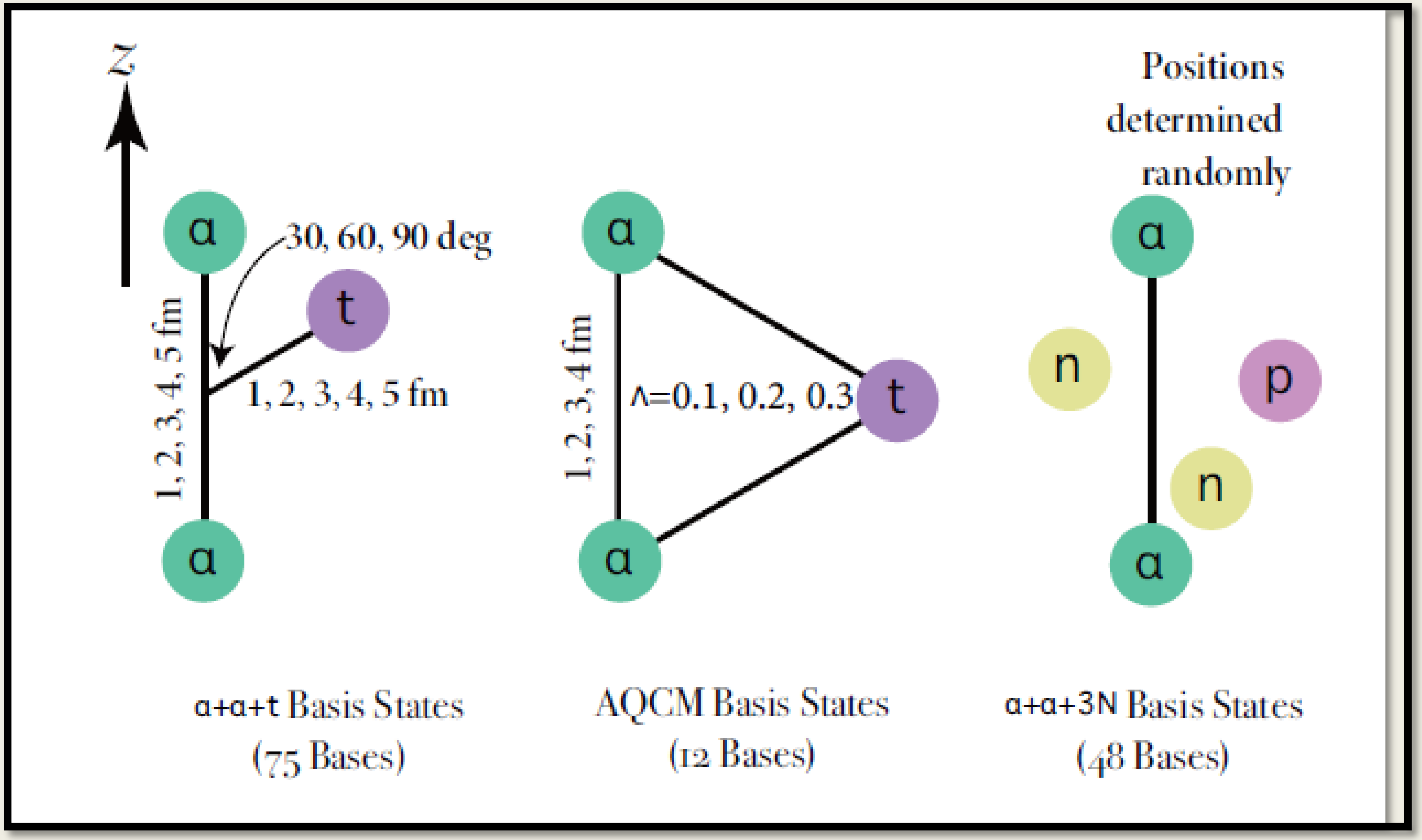
^{12}C

Sα= 7.36659 MeV
Sp=15.95668 MeV

14079 *5*	4+	272 keV *6* % α ≈ 100
15110 *3*	1+	43.6 eV *10* % IT = 95.9 % α = 4.1
15440 *40*	(2+)	1.77 MeV *20* % α ≈ 100
16106.0 *8*	2+	5.3 keV *2* % IT = 0.27 % p = 0.41 % α = 99.3

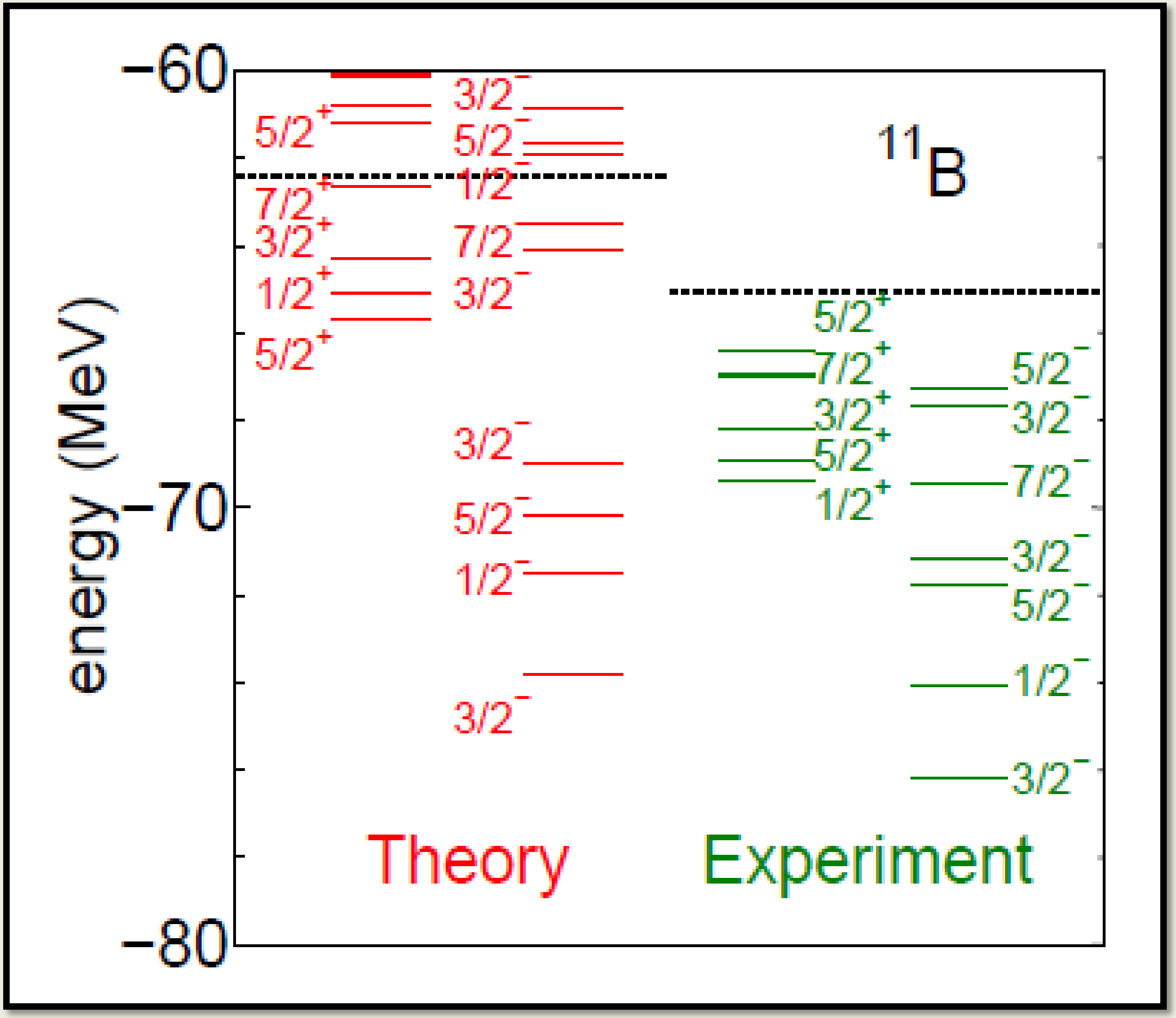
https://www.nndc.bnl.gov/nudat3/

核構造としての興味
「^{11}Bの基底状態でα+α+tクラスターは融け残っており、３αの種となり得るか？」



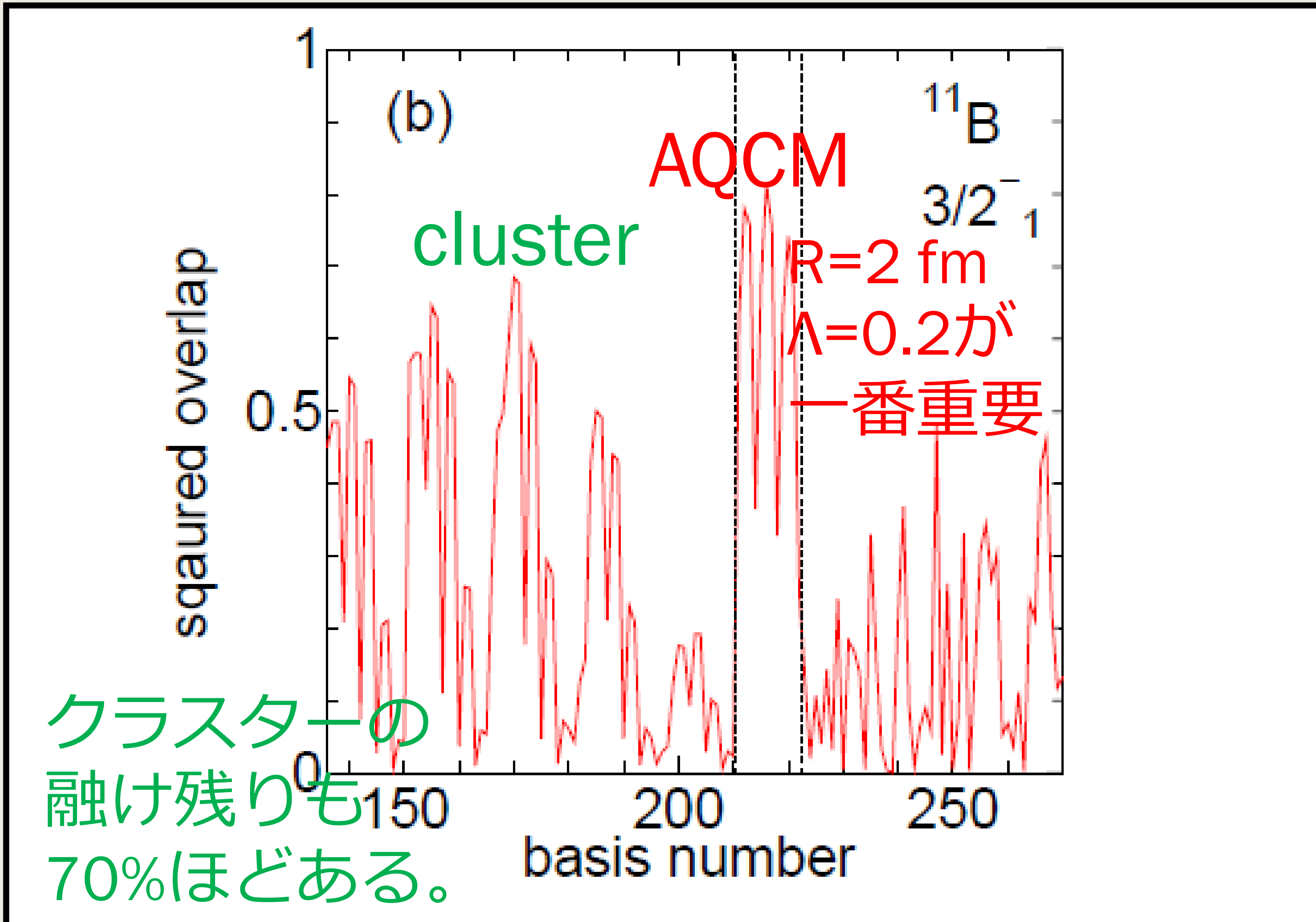
Naoyuki Itagaki, Tomoya Naito, Yuichi Hirata

https://arxiv.org/abs/2109.09957



Naoyuki Itagaki, Tomoya Naito, Yuichi Hirata

https://arxiv.org/abs/2109.09957



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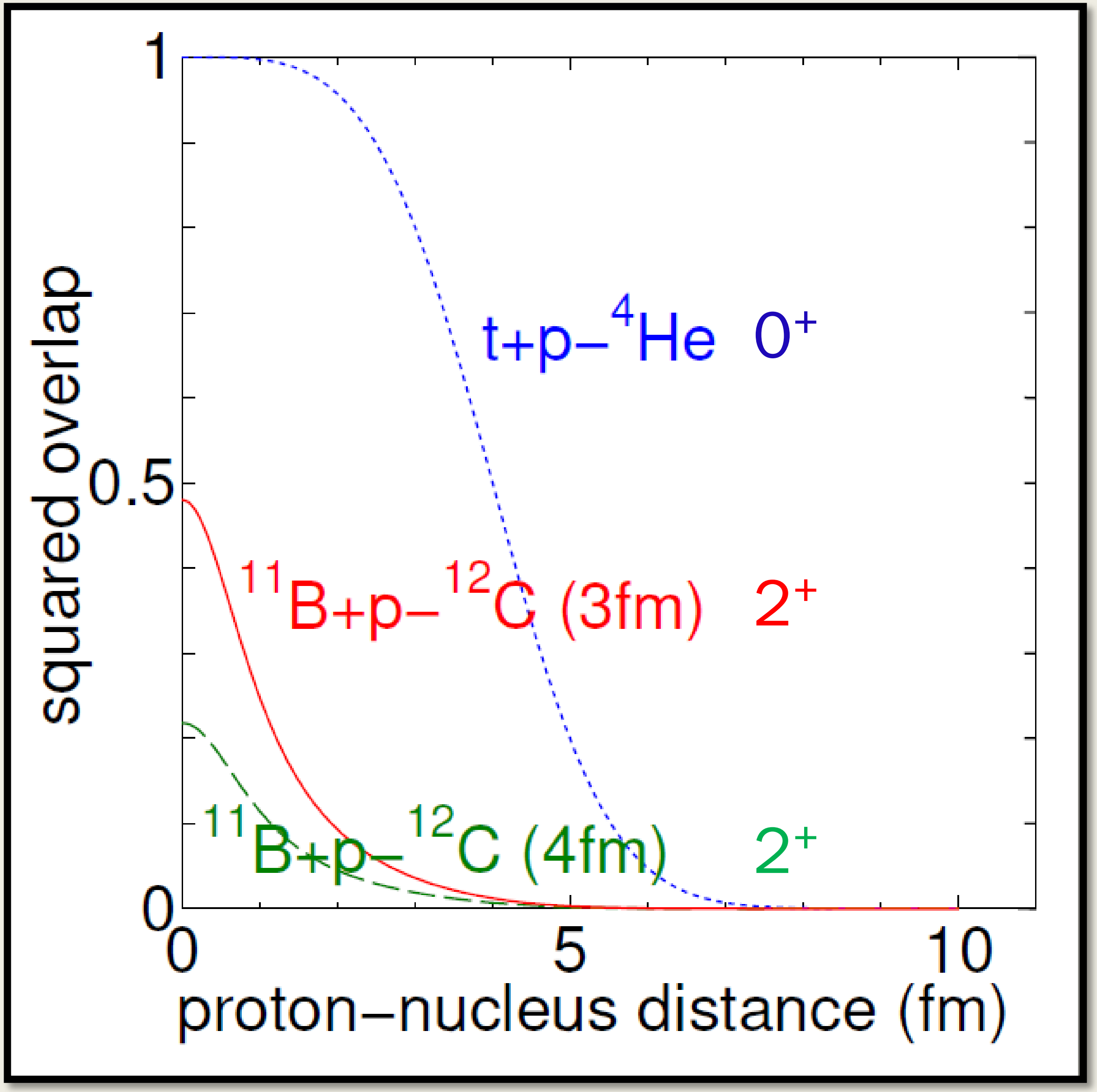

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まとめ

- AQCMを用いて、クラスター模型の波動関数を jj-coupling shell modelに変換できる。
- ^{12}Cの基底状態は、3αが微妙に融けた状態である。
- 炭素では、付与するΛ粒子の数と共に、クラスター・シェル競合した状態から「jjシェル・ドミナント化」が起る。
- jj-coupling shell modelの励起配位を混ぜ合わせることにより、isospin mixingと微少E1遷移の効果を議論可能になりつつある。
- ^{11}Bのクラスター構造は医療への応用が期待されており、クラスターの成分が70%程度融け残っていることが確認される。

Back up slides

PHYSICAL REVIEW C **70**, 054307 (2004)

Cluster-shell competition in light nuclei

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We demonstrate whether the cluster structure dissolves or remains when the shell-model-like model space is introduced in addition to the cluster model space in light nuclei. Although the binding energies of ^{8}Be, ^{10}Be, and ^{10}B become larger by about 1–2 MeV by adding shell-model-like basis states to the $\alpha+\alpha+N+N+\cdots$ basis states, the α-α structure is a dominant configuration of the ground states. However, α-breaking wave functions strongly mix in ^{12}C, and the decrease of the energy from the 3α configuration by about 6 MeV is a clue to resolving a long-standing problem of the binding energies of ^{12}C and ^{16}O. The improved version of antisymmetrized molecular dynamics (AMD), AMD superposition of selected snapshots (AMD triple-S), is used to show the cluster-shell competition of these nuclei.

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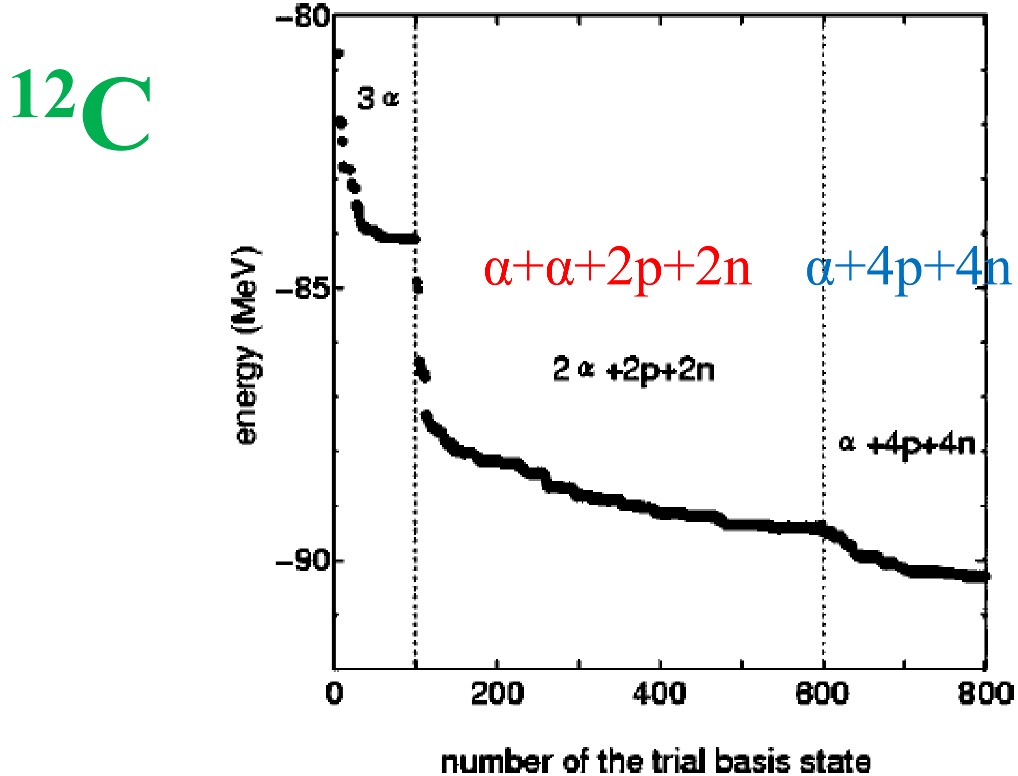

FIG. 6. The energy convergence of ^{12}C (0^+) with respect to the number of trial AMD basis states. The basis states from 1 to 100 are those of the 3α model space, and those from 101 to 600 are $\alpha+\alpha+2p+2n$ model space with relative α-α distances of 2, 3, and 4 fm. After 601, the wave functions with the shell-model-like $\alpha+4p+4n$ model space are added.

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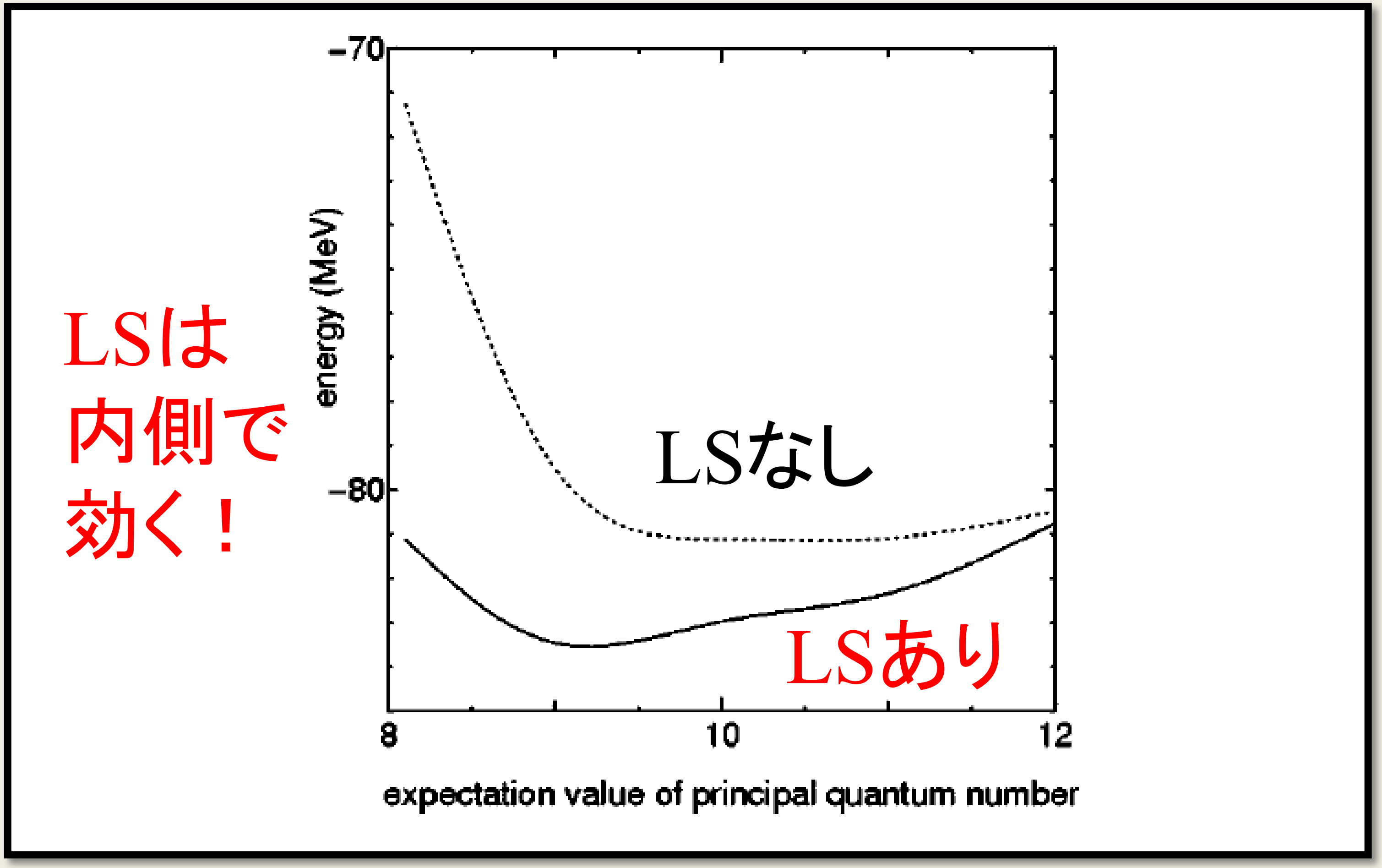
^{12}C (3αを崩したもの)



主量子数n

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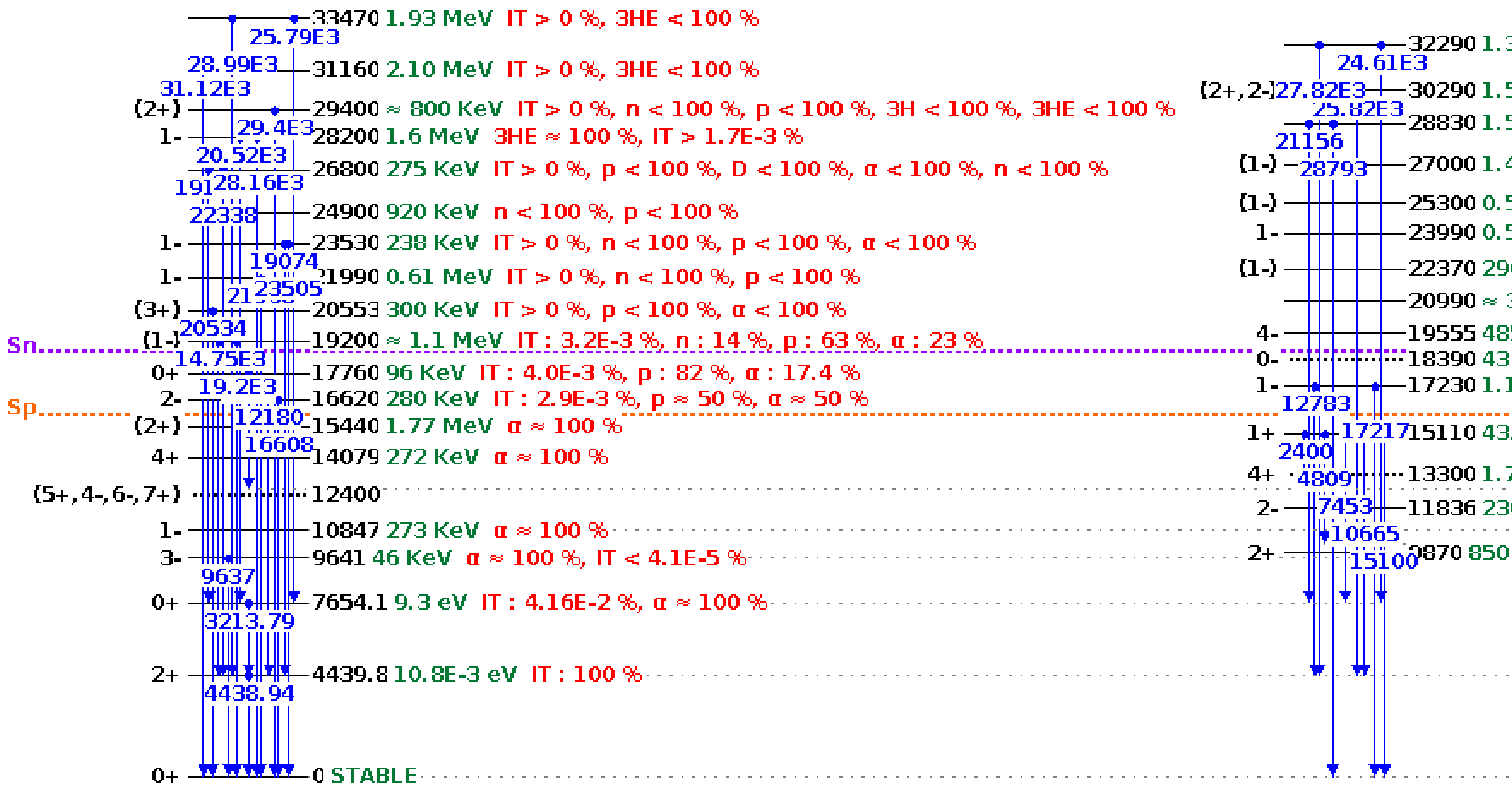
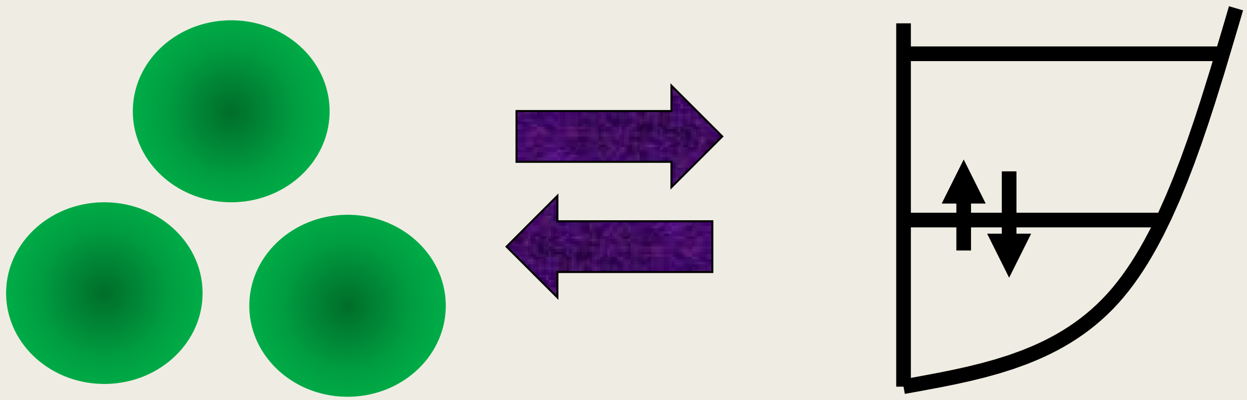
Q(α)= -7366.59 keV

^{12}C

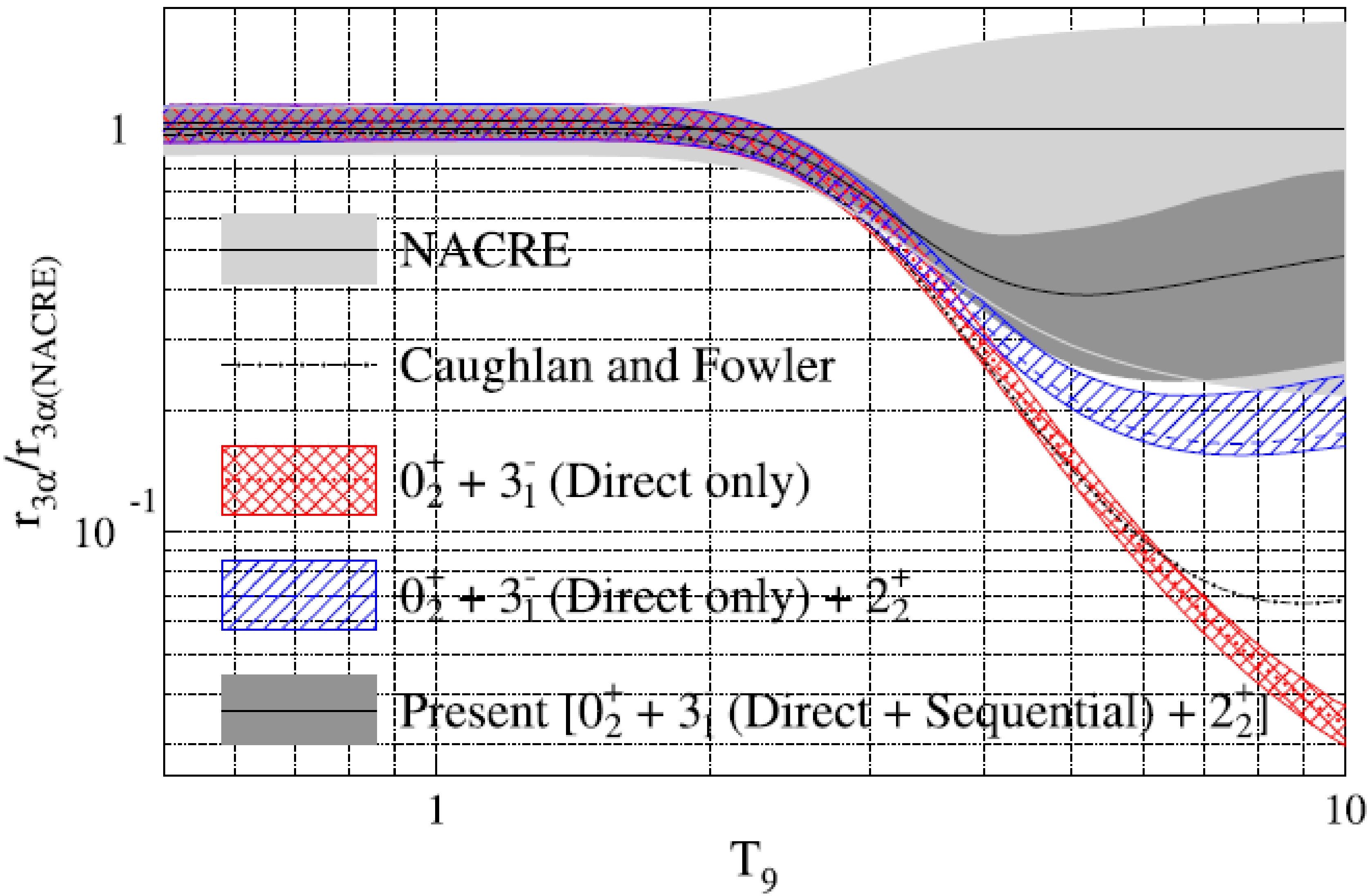


https://www.nndc.bnl.gov/nudat3/

Cluster side **Shell model side**



From "Competition"
To "Confluence"



M. Tsumura et al. Phys. Lett. B**817** 136283 (2021)