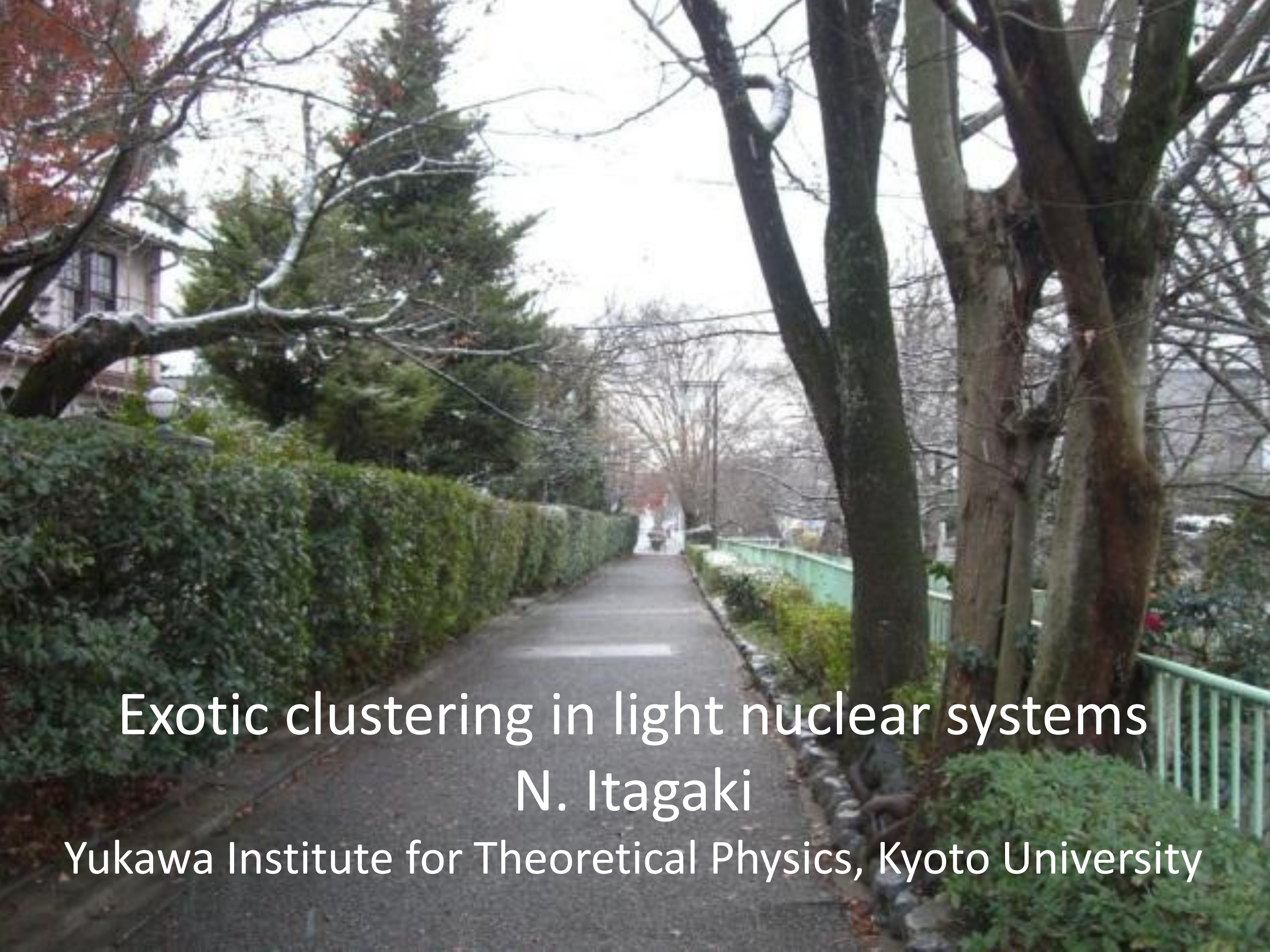
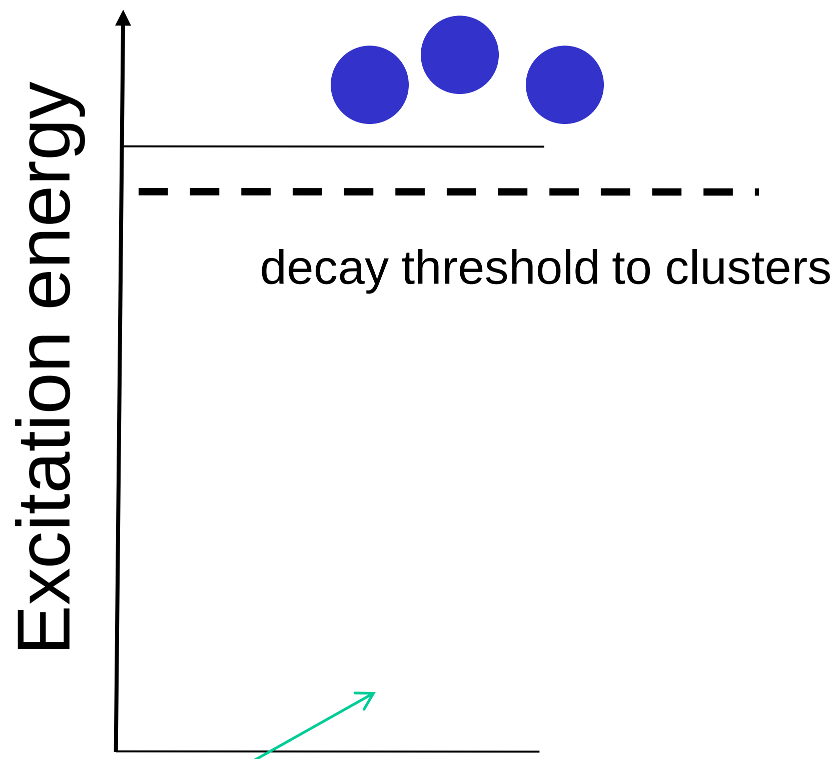
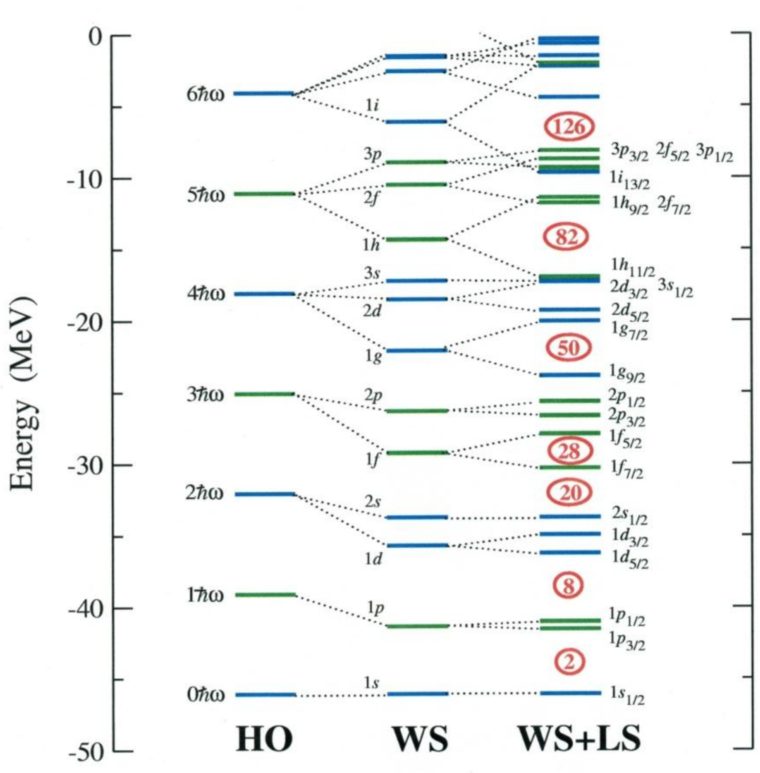


Exotic clustering in light nuclear systems

N. Itagaki
Yukawa Institute for Theoretical Physics, Kyoto University

weakly interacting state of
(strongly bound) clusters

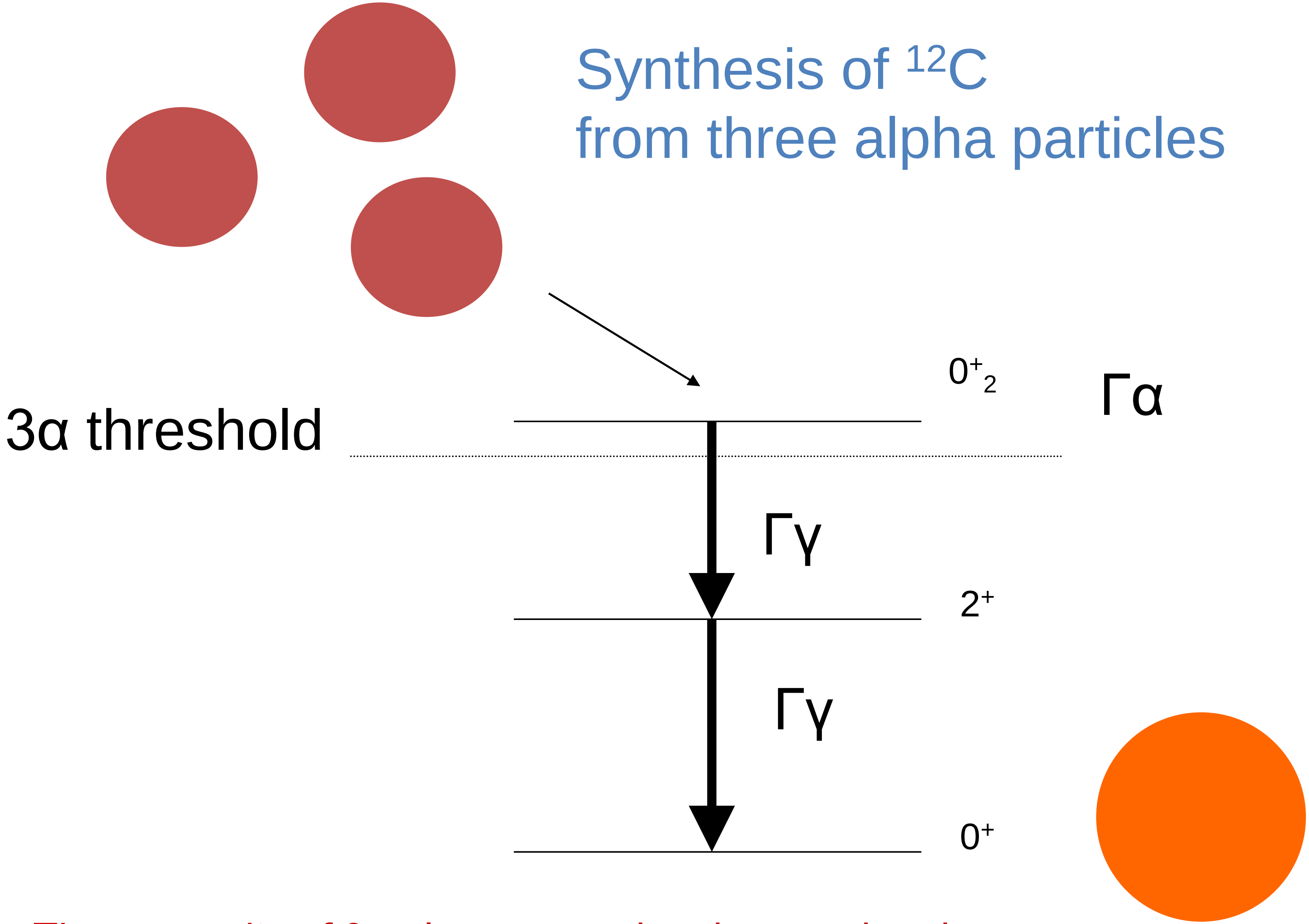




single-particle motion of
of protons and neutrons

Nuclear structure

Synthesis of ^{12}C from three alpha particles



The necessity of 3α-cluster state has been pointed out from astrophysical side, and experimentally confirmed afterwards

Microscopic Study of the Triple-α Reaction

A. S. Umar,[1] J. A. Maruhn,[2] N. Itagaki,[3] and V. E. Oberacker[1]
[1]*Department of Physics and Astronomy, Vanderbilt University, Nashville, Tennessee 37235, USA*
[2]*Institut für Theoretische Physik, Goethe-Universität, D-60438 Frankfurt am Main, Germany*
[3]*Department of Physics, University of Tokyo, Hongo, Tokyo 113-0033, Japan*
(Received 24 March 2010; published 27 May 2010)

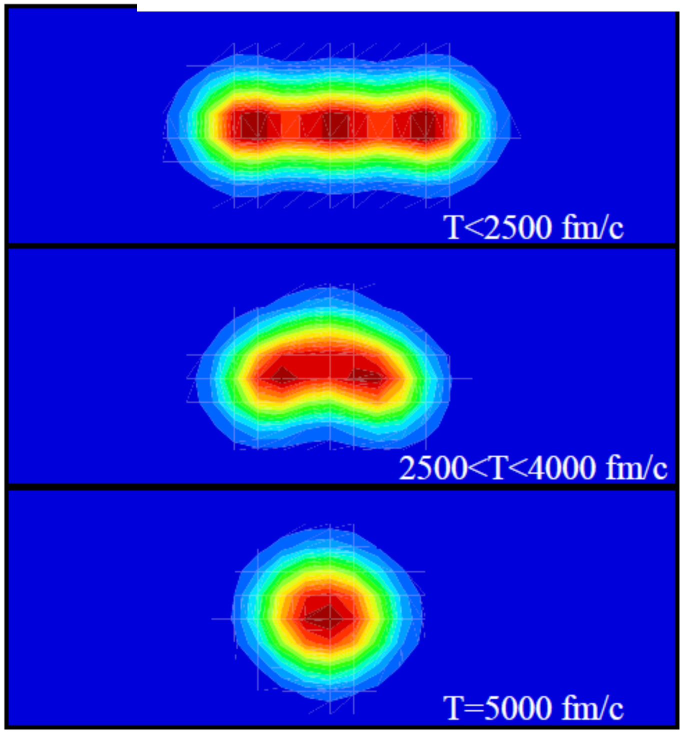


FIG. 1: (Color online) Selected density profiles from TDHF time-evolution of the ^{4}He+^{8}Be head-on collision for initial Be orientation angle $\beta = 0^\circ$ (see small graphs in Fig. 2) using the SLy4 interaction. The initial energy is $E_{\mathrm{c.m.}} = 2$ MeV. For $T < 2500$ fm/c the system vibrates about the linear chain configuration shown in the top pane, subsequently the system changes its mode to a bending configuration shown in the middle pane, and finally relaxes into a more compact configuration as shown in the bottom pane. Note that the region shown is only a part of the computational mesh.

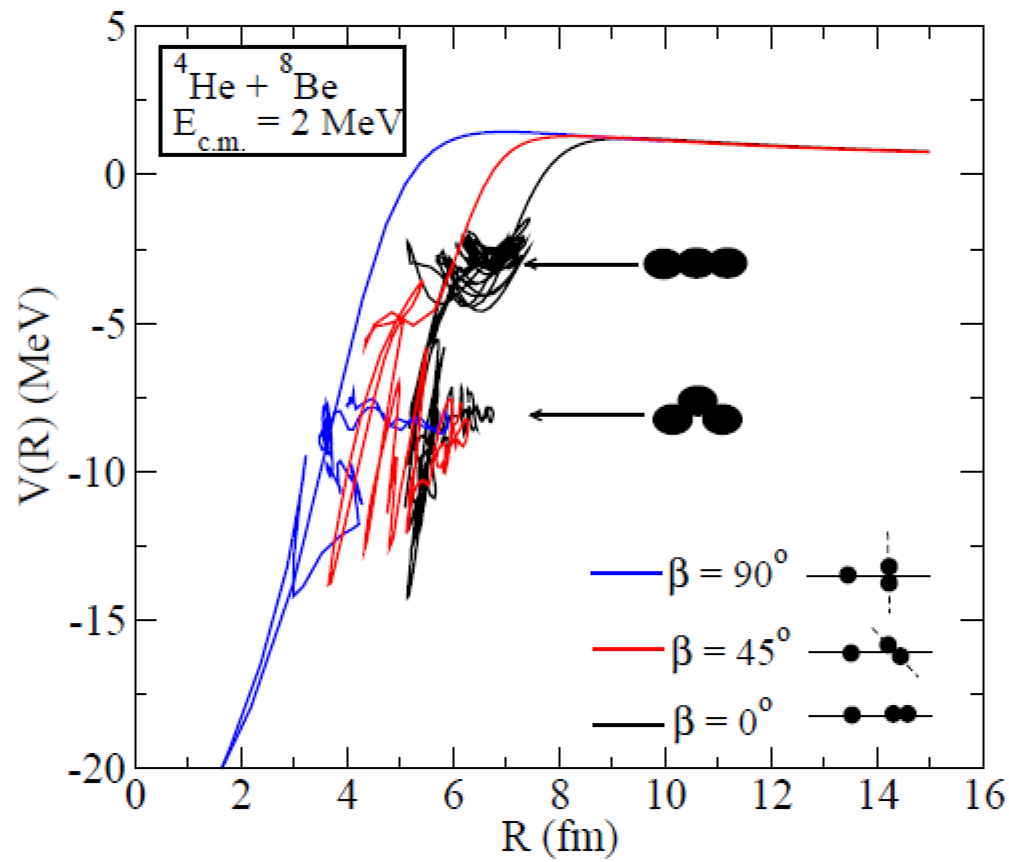
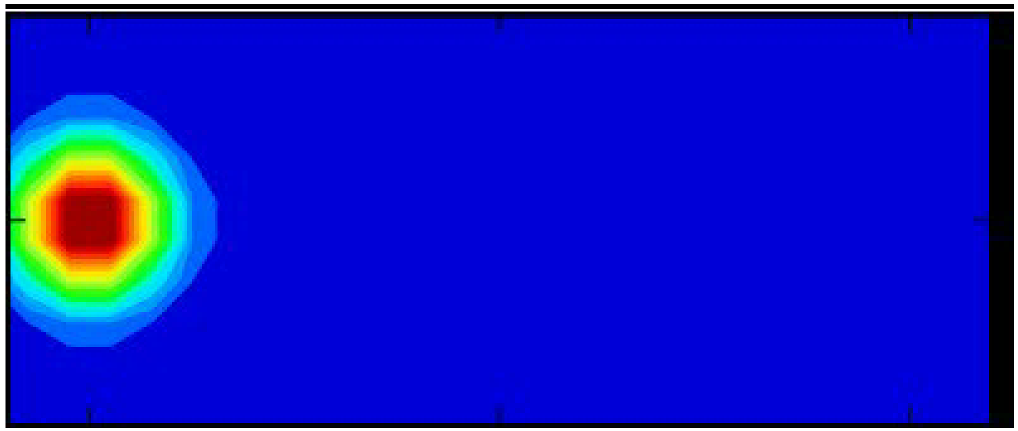
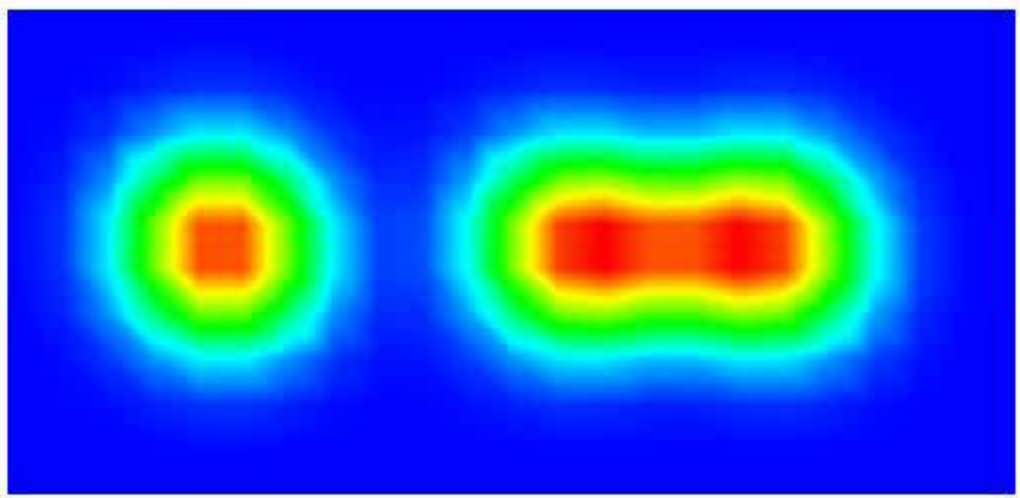


FIG. 2: (Color online) Potential energy curves for the collision of the ^{4}He+^{8}Be system as a function of R for three initial alignments of the Be nucleus and at $E_{\mathrm{c.m.}} = 2$ MeV.





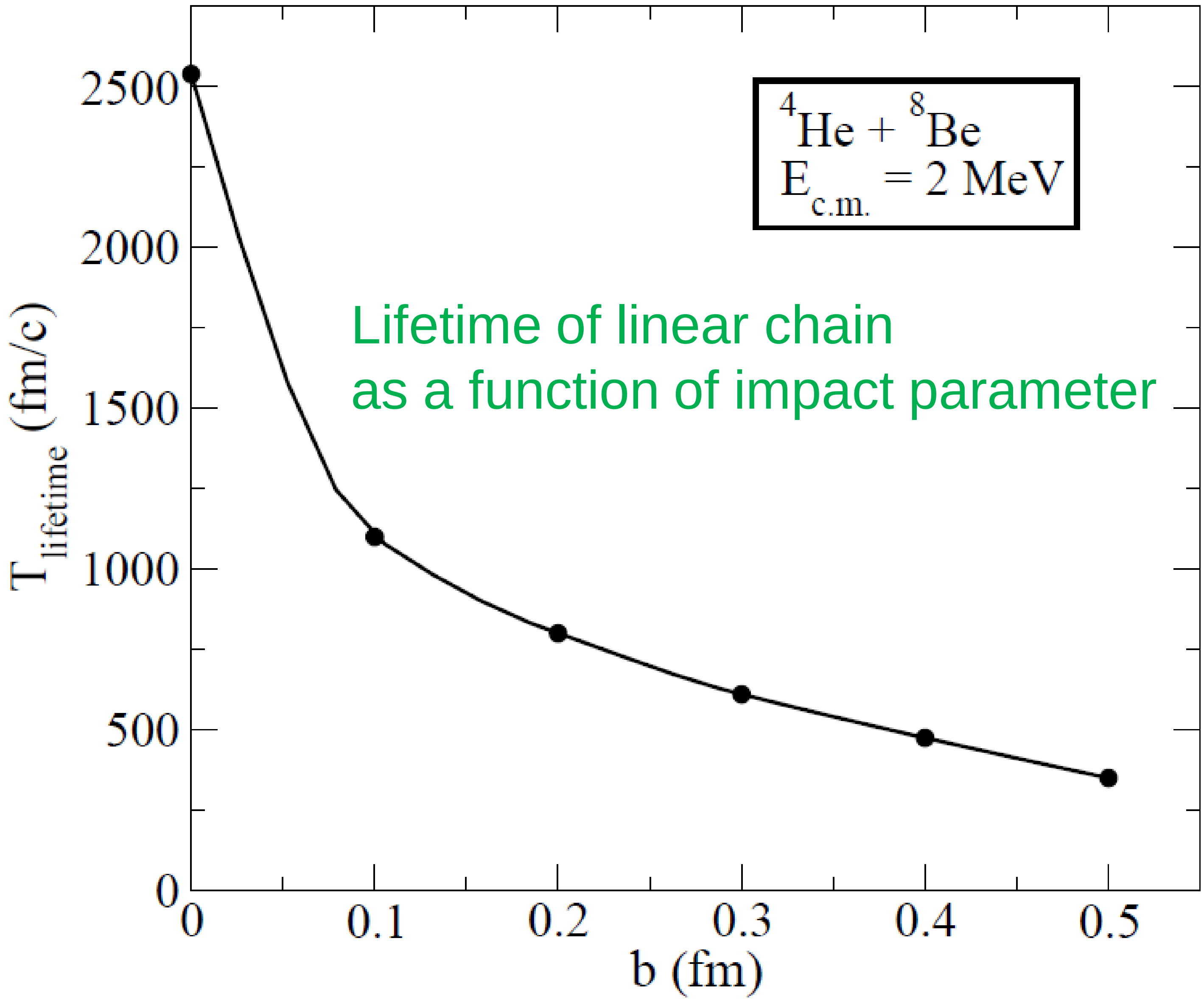
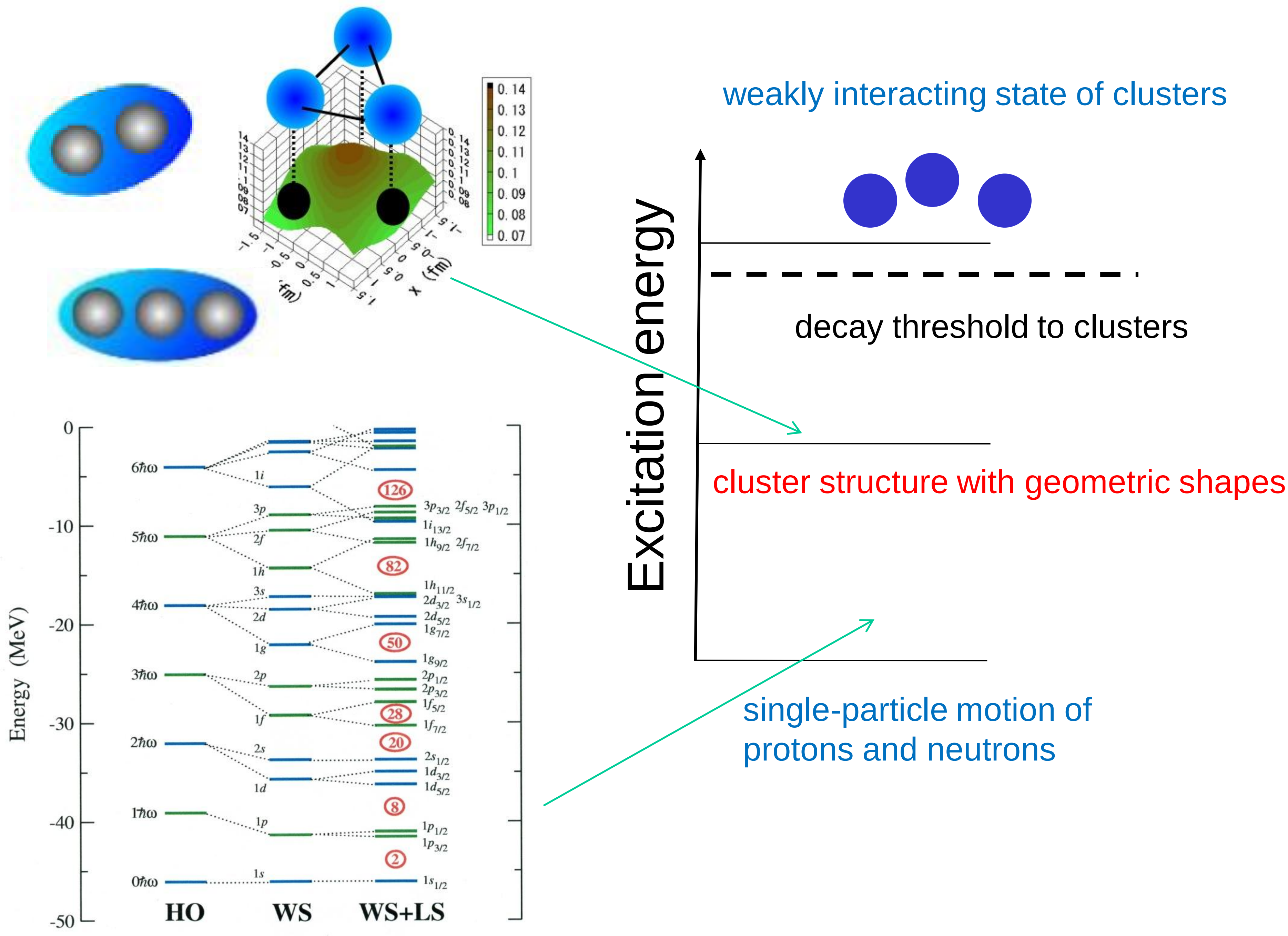
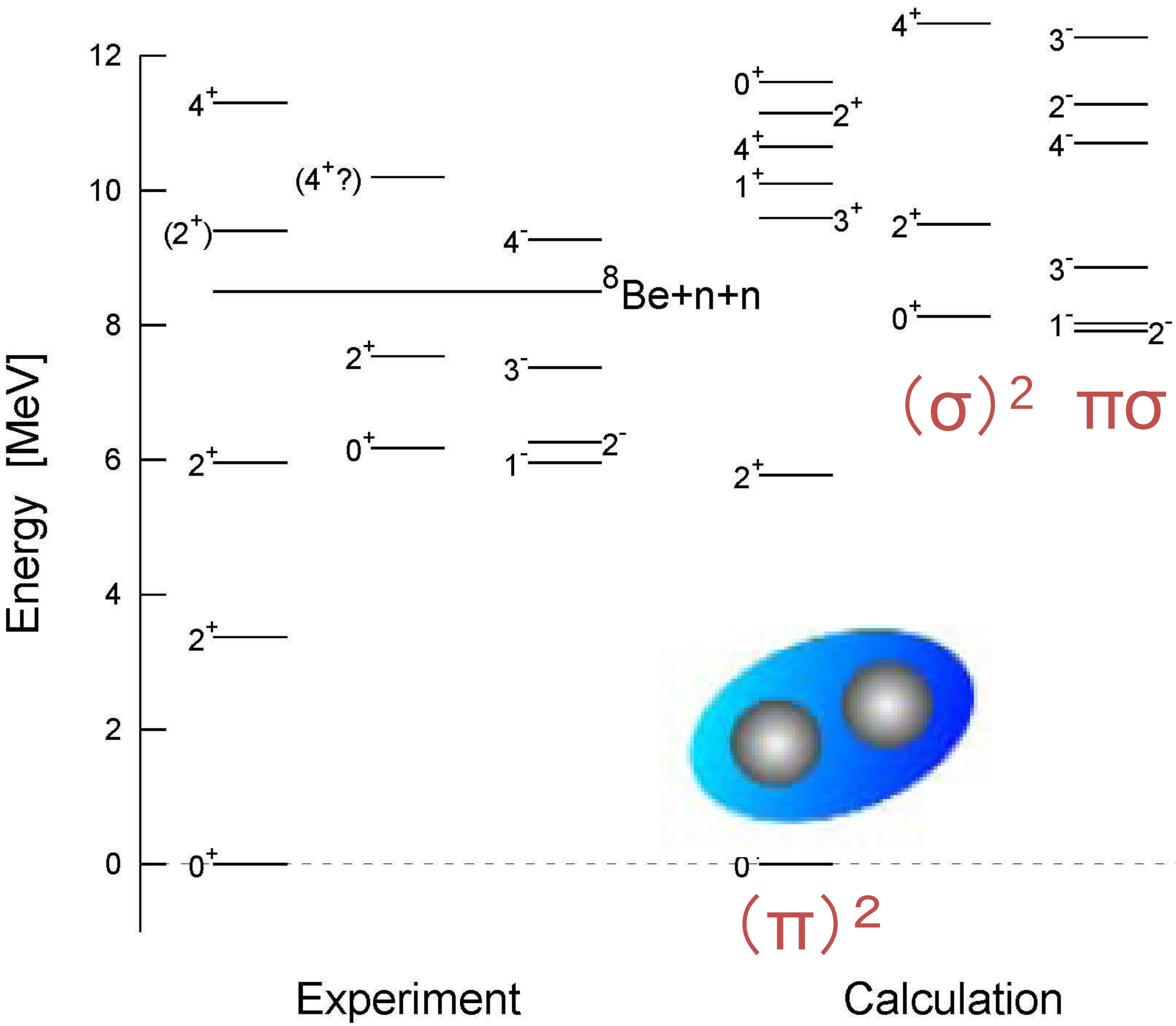


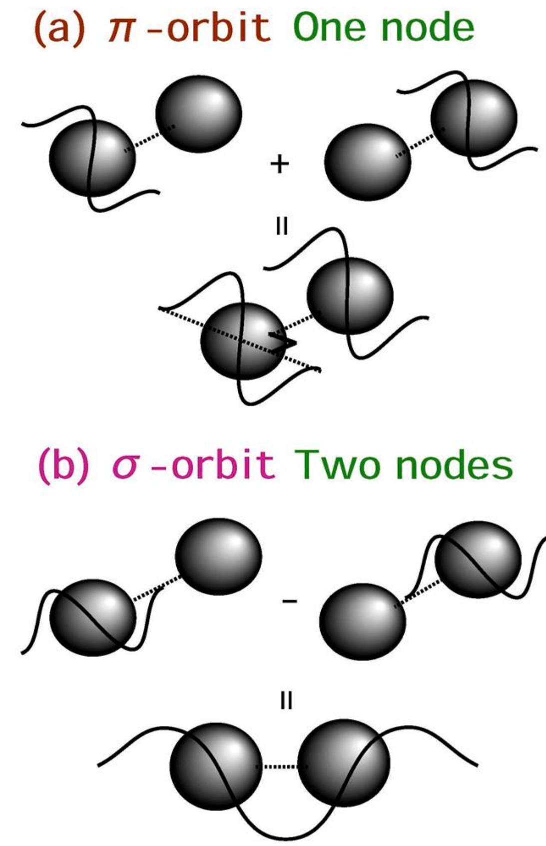
FIG. 4: Time spent in the linear chain configuration as a function of the impact parameter b for the ^{4}He+^{8}Be system at $E_{\mathrm{c.m.}} = 2$ MeV and $\beta = 0^o$ alignment.



weakly interacting state of clusters
Excitation energy
decay threshold to clusters
cluster structure with geometric shapes
single-particle motion of
protons and neutrons
Energy (MeV)
0
-10
-20
-30
-40
-50
HO
WS
WS+LS
0ħω
1ħω
2ħω
3ħω
4ħω
5ħω
6ħω
1s
1p
1d
2s
1f
2p
1g
2d
3s
1h
2f
3p
1i
2
8
20
28
50
82
126
1s1/2
1p3/2
1p1/2
1d5/2
1d3/2
2s1/2
1f7/2
1f5/2
2p3/2
2p1/2
1g9/2
1g7/2
2d5/2
2d3/2 3s1/2
1h11/2
1h9/2 2f7/2
1i13/2
3p3/2 2f5/2 3p1/2
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
x (fm)

^{10}Be

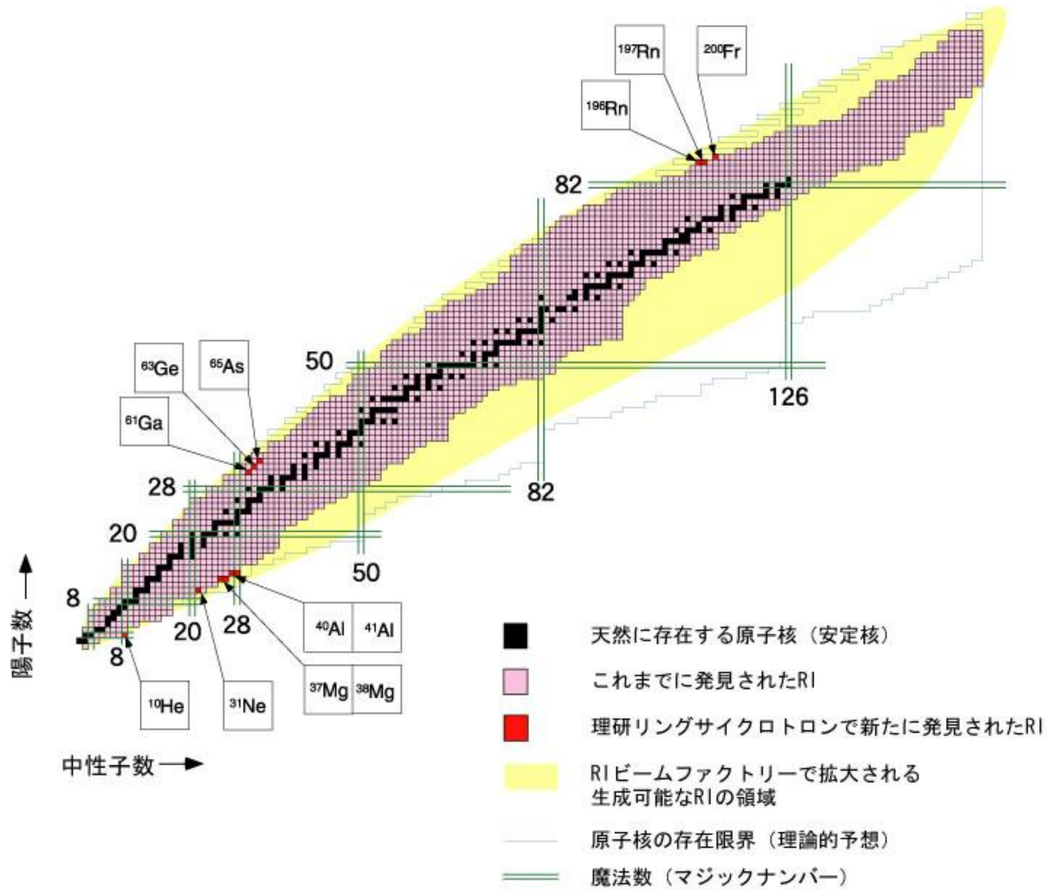




N. Itagaki and S. Okabe, Phys. Rev. C **61** 044306 (2000)

1000個に及ぶ新RIの発見

RIビームファクトリーで得られる重イオン（１次ビーム）エネルギーは、あらゆる核種についてRIビーム発生に必要なエネルギー（核子あたり百メガ電子ボルト以上）を大幅に上回ります。その結果、現在世界トップクラスの性能を誇る理研リングサイクロトロンのビームをもってしても十数個程度しか発見できなかった新RIの種類が飛躍的に増大し、その数は、千個にも及ぶと予想されます。これらの新RIの性質を系統的かつ詳細に調べることが、宇宙の元素合成のメカニズムの謎を解明する手掛かりとなります。更には、実験に利用可能な強度が得られるRIの種類も大幅に増加し、原子核物理学の分野のみならず基礎物理学の問題から生物・医学の分野にわたって新たなプローブを提供することもできます。



Physics of Neutron-rich nuclei

RI Beam Factory project
(RIKEN)

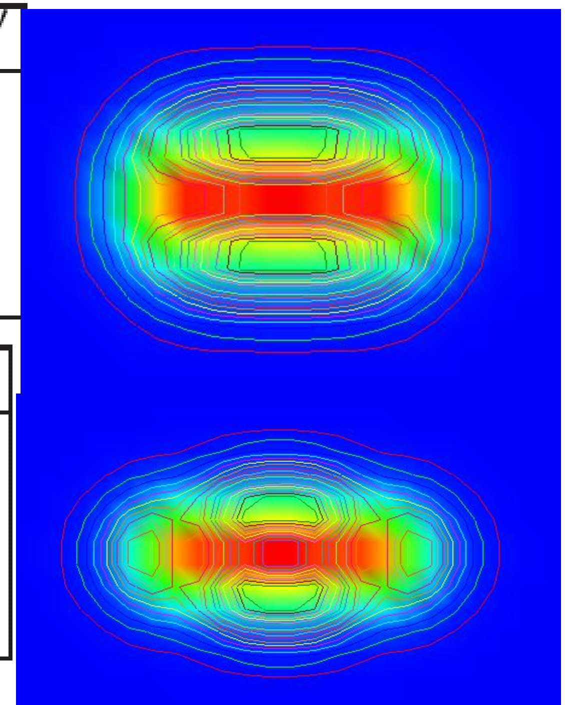
How about in neutron-rich nuclei?

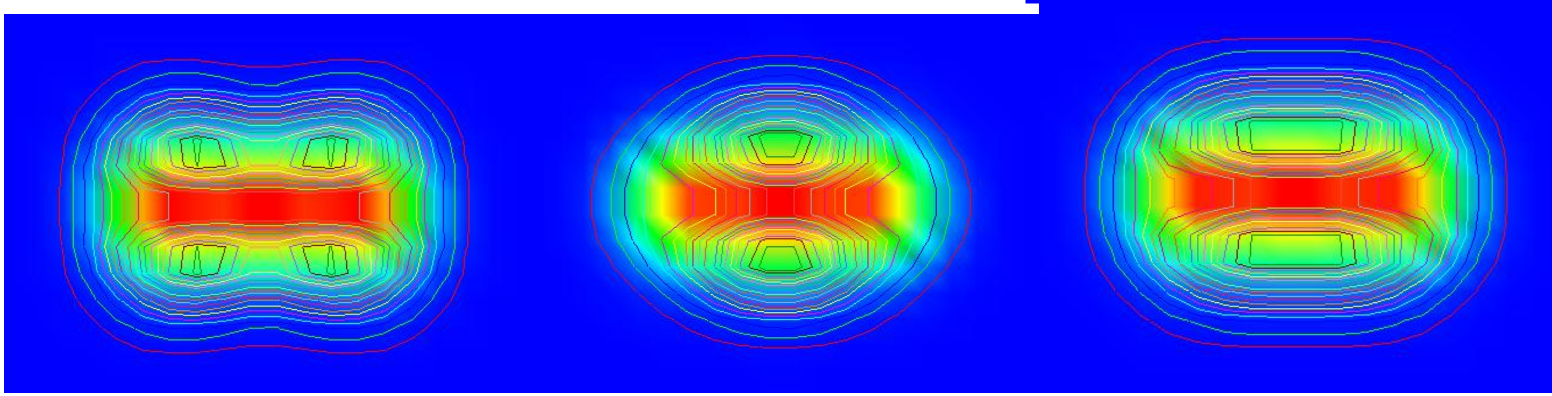
It becomes stable due to the glue effect of the neutrons?

Interactions (Skyme) and model space are ones for mean-field models

Force	E_B	$\pi^2\delta^2$	$\pi^2\pi'^2$	$\pi^2\delta\pi'$	$\pi^2\sigma\pi'$	$\pi^2\delta\pi''$
SkI3	101.5	19.5	14.5	17.0	19.1	17.5
SkI4	100.8	19.9	15.7*	17.6	19.7	18.0
Sly6	100.6	18.9	15.4*	17.0	19.0	17.3
SkM*	115.0	17.5	16.4*	16.9	19.7	17.0

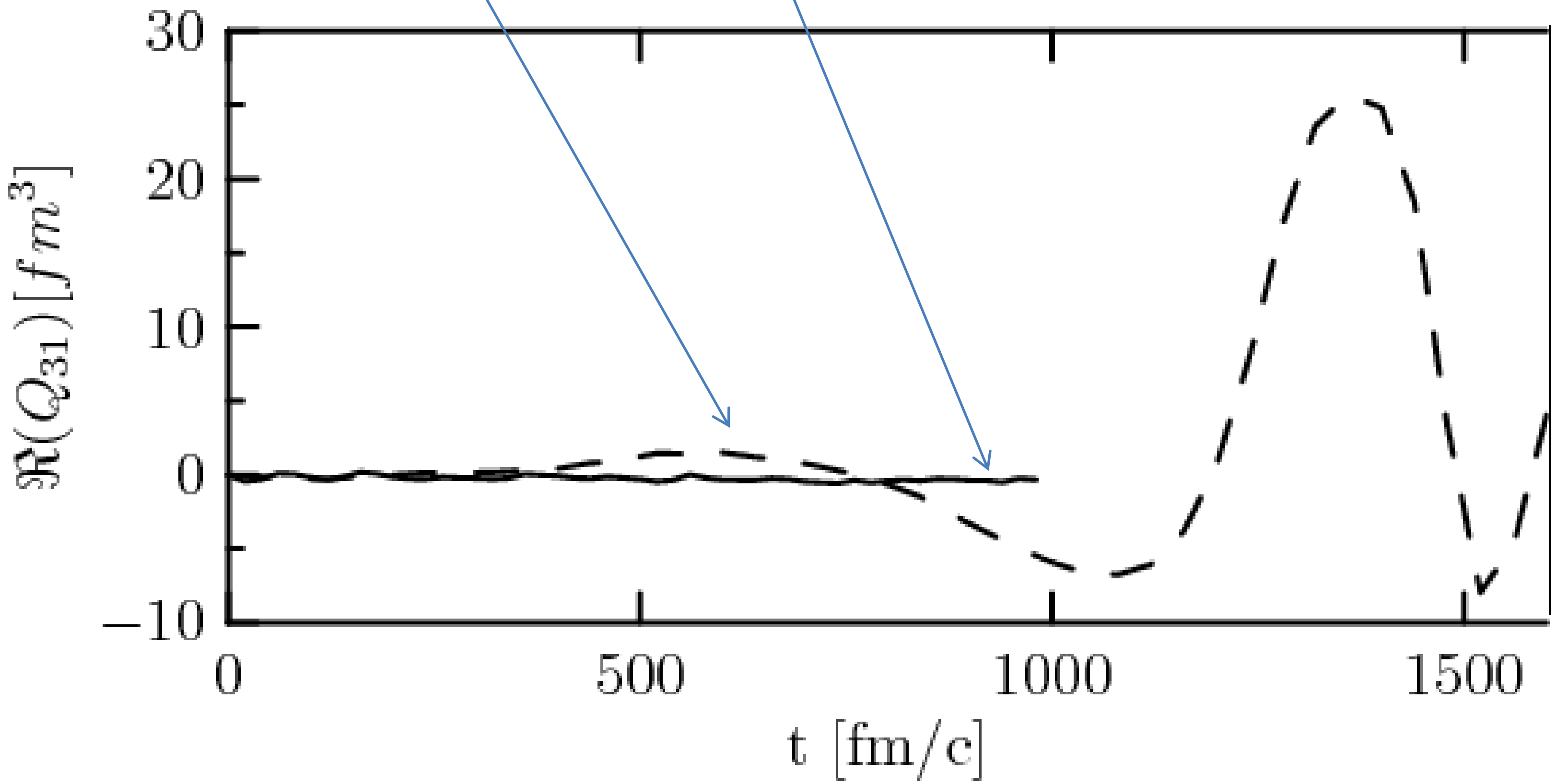
Force	$\beta_{\mathrm{g.s.}}$	$\pi^2\delta^2$	$\pi^2\pi'^2$	$\pi^2\delta\pi'$	$\pi^2\sigma\pi'$	$\pi^2\delta\pi''$
SkI3	0.34	0.82	0.69	0.76	0.88	0.76
SkI4	0.33	0.80	0.68*	0.75	0.86	0.74
Sly6	0.32	0.81	0.68*	0.75	0.87	0.75
SkM*	0.28	0.79	0.66*	0.73	0.85	0.73





Stability against bending motion

Solid ^{20}C (pi^4 sigma^2 delta^2)
Dotted ^{16}C (pi^4)



Linear Chain Structure of Four-α Clusters in ^{16}O

T. Ichikawa,[1] J. A. Maruhn,[2] N. Itagaki,[1] and S. Ohkubo[3,4]

[1]*Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*
[2]*Institut fuer Theoretische Physik, Universitaet Frankfurt, D-60438 Frankfurt, Germany*
[3]*Department of Applied Science and Environment, University of Kochi, Kochi 780-8515, Japan*
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(Received 17 June 2011; published 9 September 2011)

We investigate the linear chain configurations of four-α clusters in ^{16}O using a Skyrme cranked Hartree-Fock method and discuss the relationship between the stability of such states and angular momentum. We show the existence of a region of angular momentum (13–18$\hbar$) where the linear chain configuration is stabilized. For the first time we demonstrate that stable exotic states with a large moment of inertia ($\hbar^2/2\Theta \sim 0.06$–$0.08$ MeV) can exist.

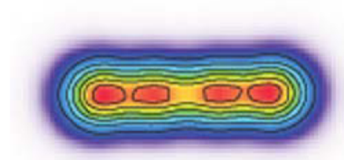
DOI: 10.1103/PhysRevLett.107.112501 PACS numbers: 21.60.Jz, 21.30.Fe, 21.60.Cs

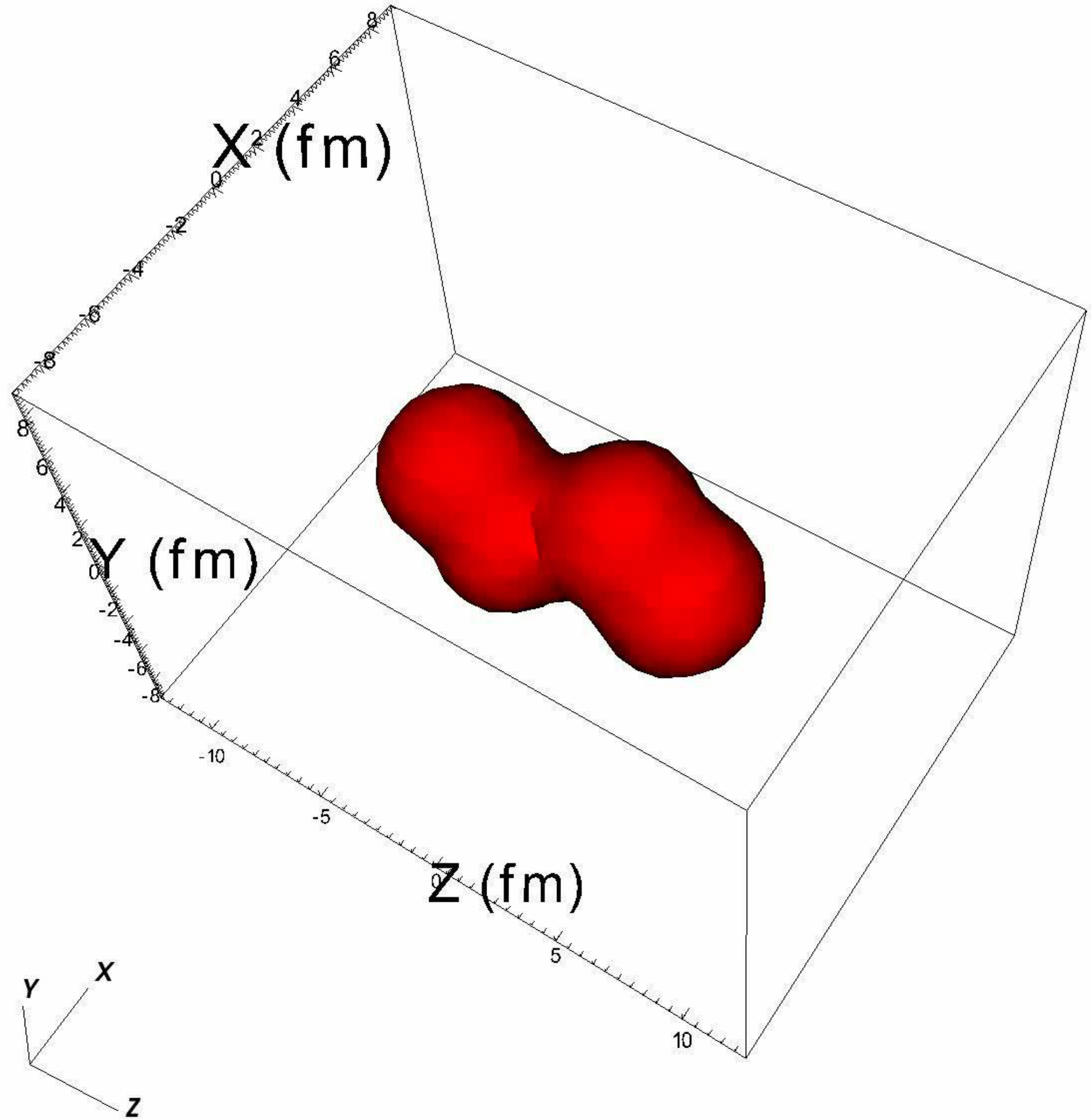
Phys. Rev. Lett. **107**, 112501
(issue of 9 September 2011)
Title and Authors

9 September 2011

Rod-Shaped Nucleus

We picture atomic nuclei as spherical globs of protons and neutrons, although they can also be egg-shaped. Now calculations published 9 September in *Physical Review Letters* show that an even more exotic shape is possible: a rapidly spinning nucleus can form into a linear chain of several small clusters of neutrons and protons. Such exotic nuclear states could play important intermediary roles in the





X (fm)
Y (fm)
Z (fm)
8
6
4
2
0
-2
-4
-6
-8
-10
-5
0
5
10
Y
X
Z

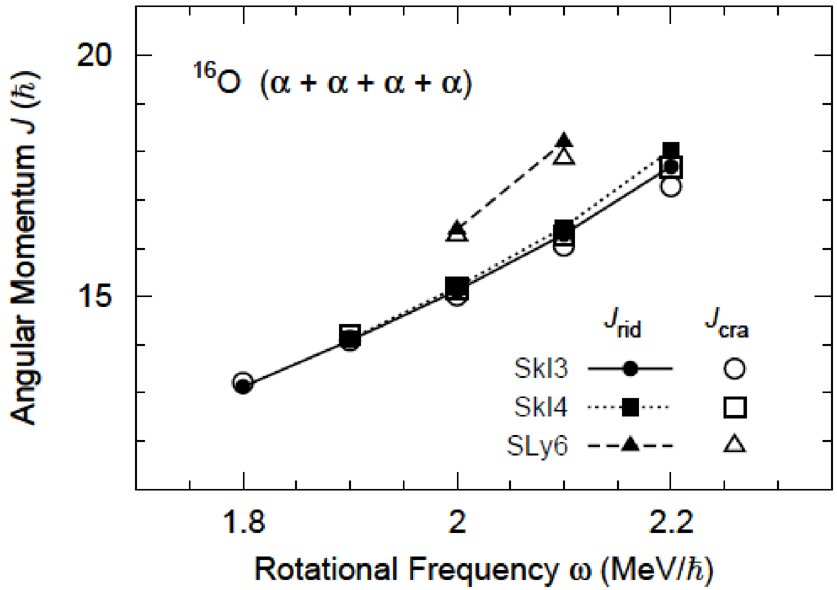


FIG. 5: Angular momentum as a function of rotational frequency ω for the Skyrme forces. The lines with solid symbols denote the calculated results for the rigid-body moment of inertia, while the open symbols denote the results for the cranking method.

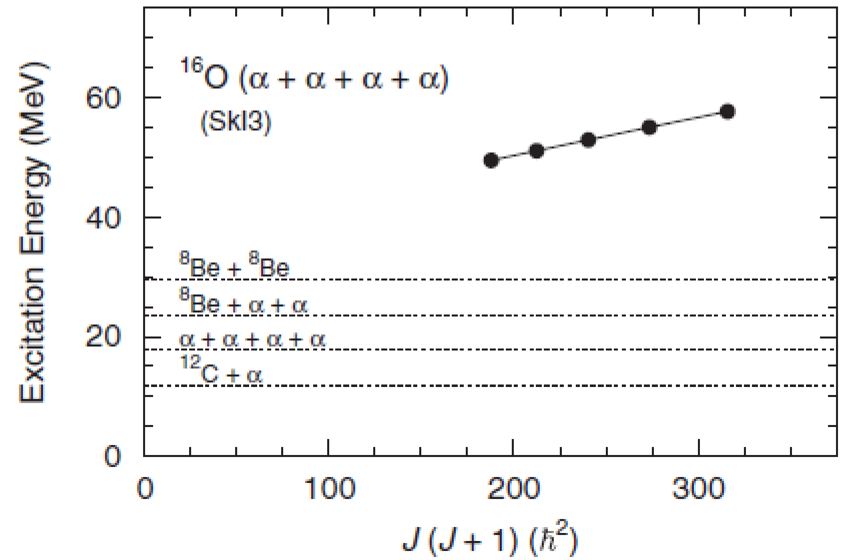
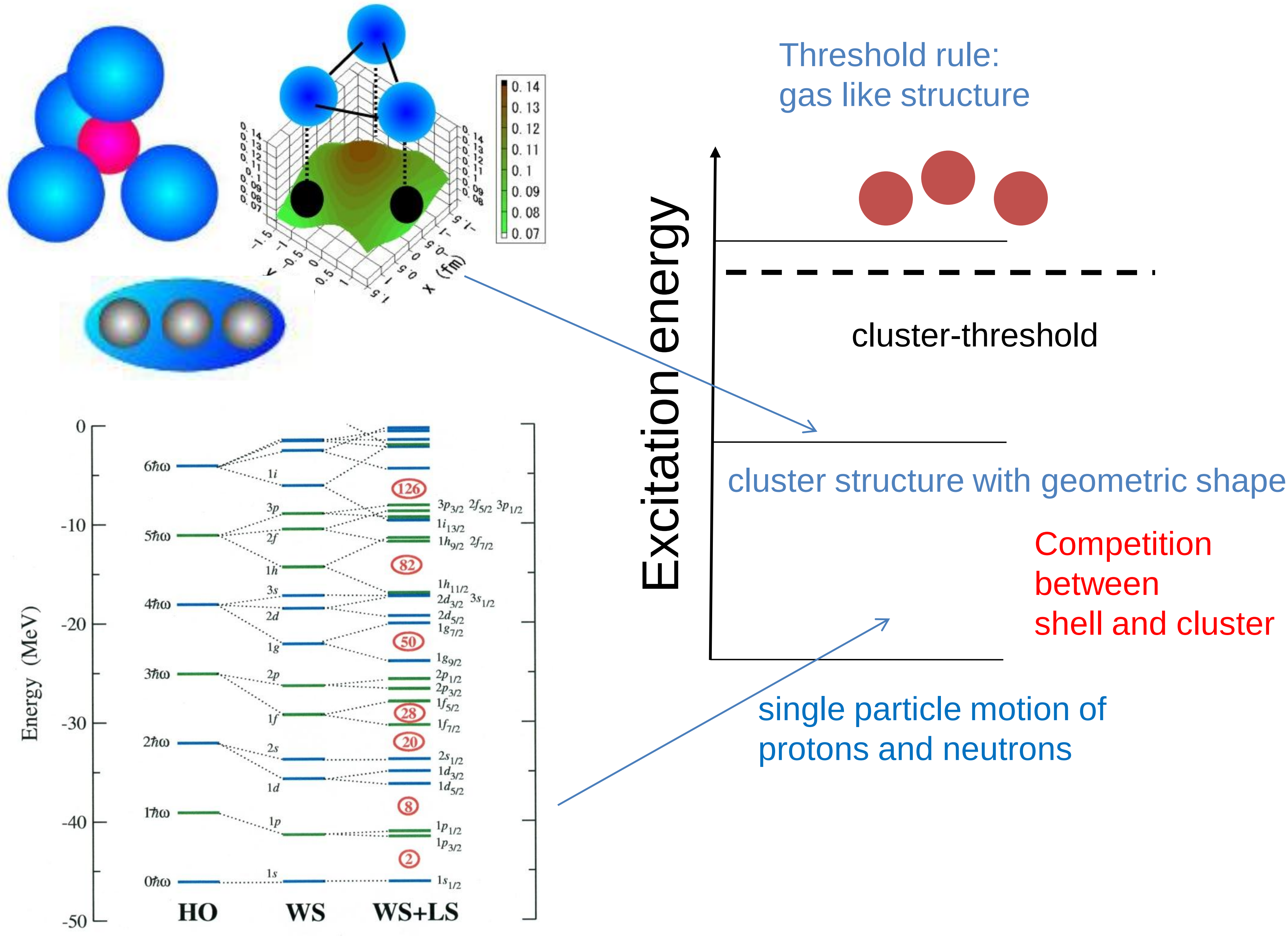


FIG. 6. Calculated excitation energies of the four-α linear chain states with the SkI3 force versus the angular momentum. The dotted lines denote the corresponding cluster-decomposition threshold energies.



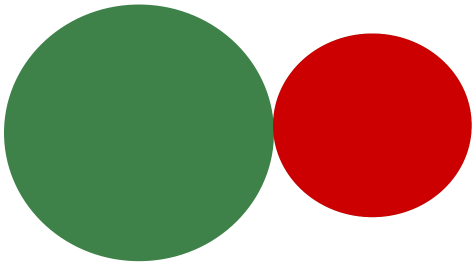
Threshold rule:
gas like structure
Excitation energy
cluster-threshold
cluster structure with geometric shape
Competition
between
shell and cluster
single particle motion of
protons and neutrons
x (fm)
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
Energy (MeV)
0
-10
-20
-30
-40
-50
HO
WS
WS+LS
0ħω
1ħω
2ħω
3ħω
4ħω
5ħω
6ħω
1s
1p
1d
2s
1f
2p
1g
2d
3s
1h
2f
3p
1i
126
82
50
28
20
8
2

What is the key mechanism for the cluster-breaking?

Spin-orbit interaction is driving force
of breaking α clusters and restoring
the single particle motions of nucleons

Is there some control parameter in the cluster wave function to take into account the spin-orbit contribution?

^{20}Ne case



Cluster model – ^{16}O+alpha model

Present model – ^{16}O+quasi cluster

Four nucleons in the quasi cluster perform single particle motions around ^{16}O

Simplified modeling of cluster-shell competition in ^{20}Ne and ^{24}Mg

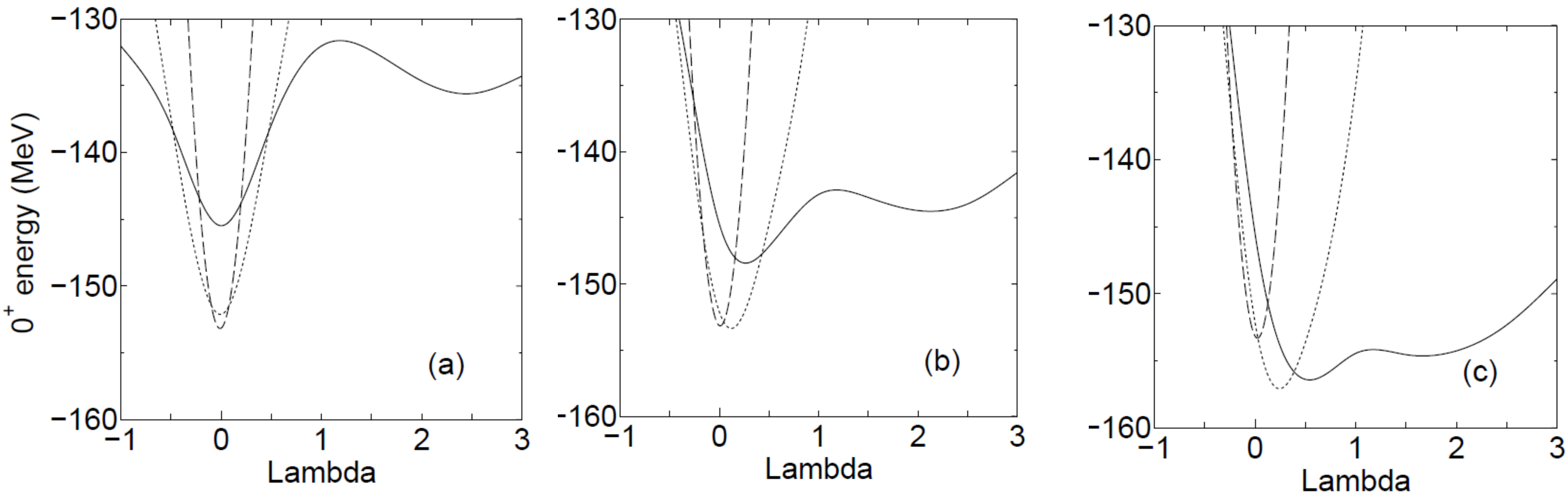
N. Itagaki, M. Ploszajczak, and J. Cseh, Phys. Rev. C **83** 014302 (2011).

G3RS interaction spin-orbit term

$$V_{ls} = V_0(e^{-d_1 r^2} - e^{-d_2 r^2})P(^3\mathrm{O})\vec{L}\cdot\vec{S}$$

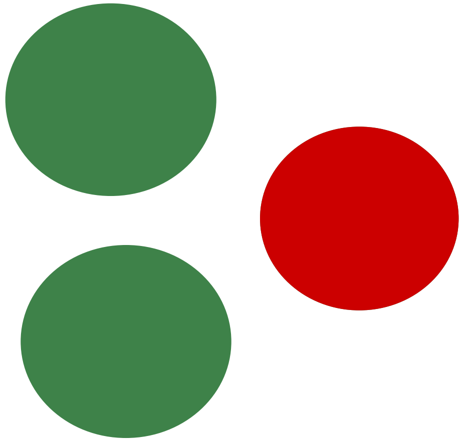
Total energy of ^{20}Ne

$V_0 = 0$ MeV $\quad V_0 = 1000$ MeV $\quad V_0 = 2000$ MeV



Solid, Dotted, Dashed lines → R = 0.5, 2.0, 4.0 fm

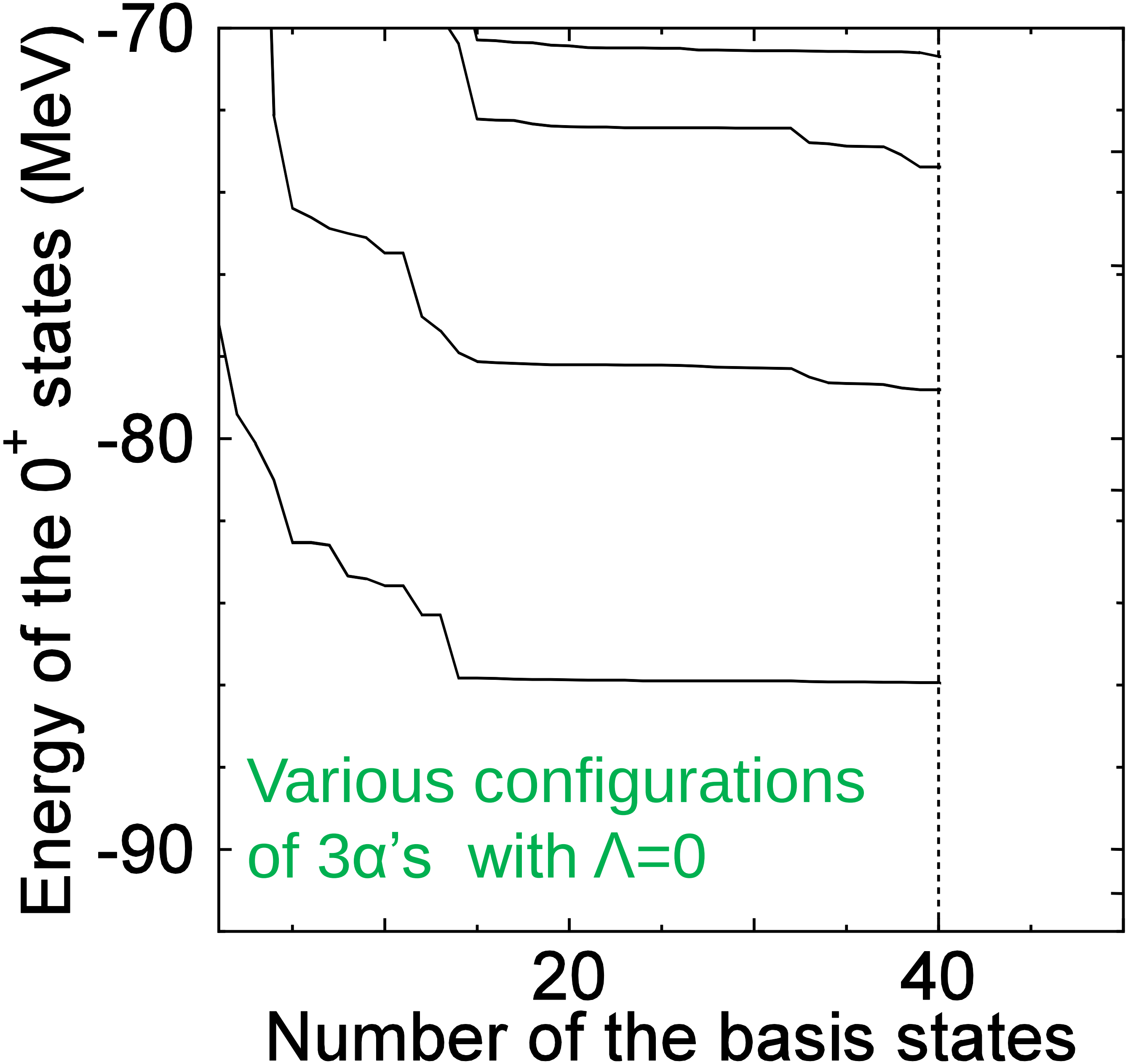
- ^{12}C case



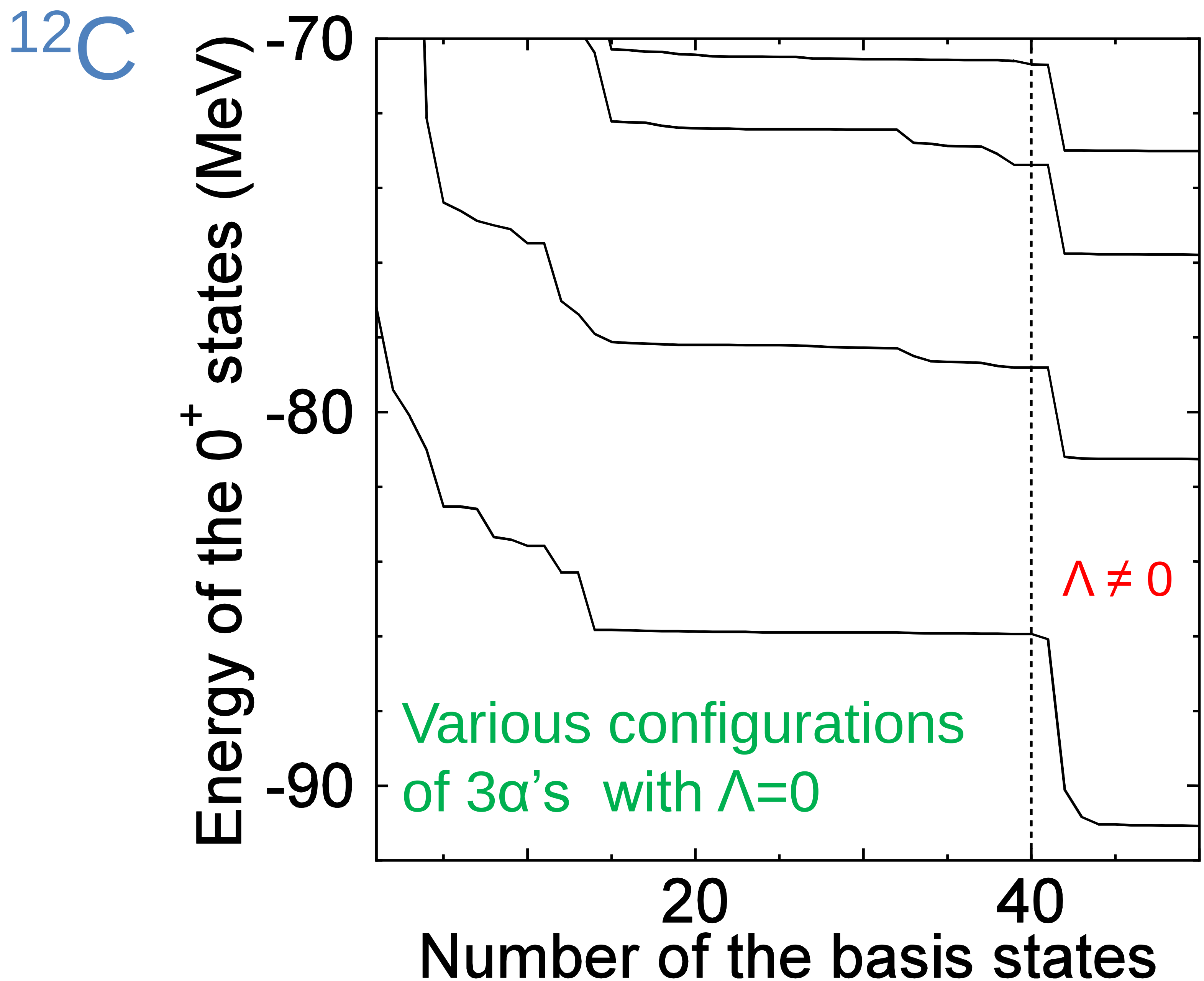
3alpha model $\Lambda = 0$

2alpha+quasi cluster Λ = finite

^{12}C



Energy of the 0+ states (MeV)
-70
-80
-90
20
40
Number of the basis states
Various configurations
of 3α's with Λ=0



12C
-70
-80
-90
Energy of the 0+ states (MeV)
20
40
Number of the basis states
Λ ≠ 0
Various configurations
of 3α's with Λ=0

Λ is a good tool to prepare
the α breaking configurations

However this is a control parameter
introduced in the wave function
and not an observable

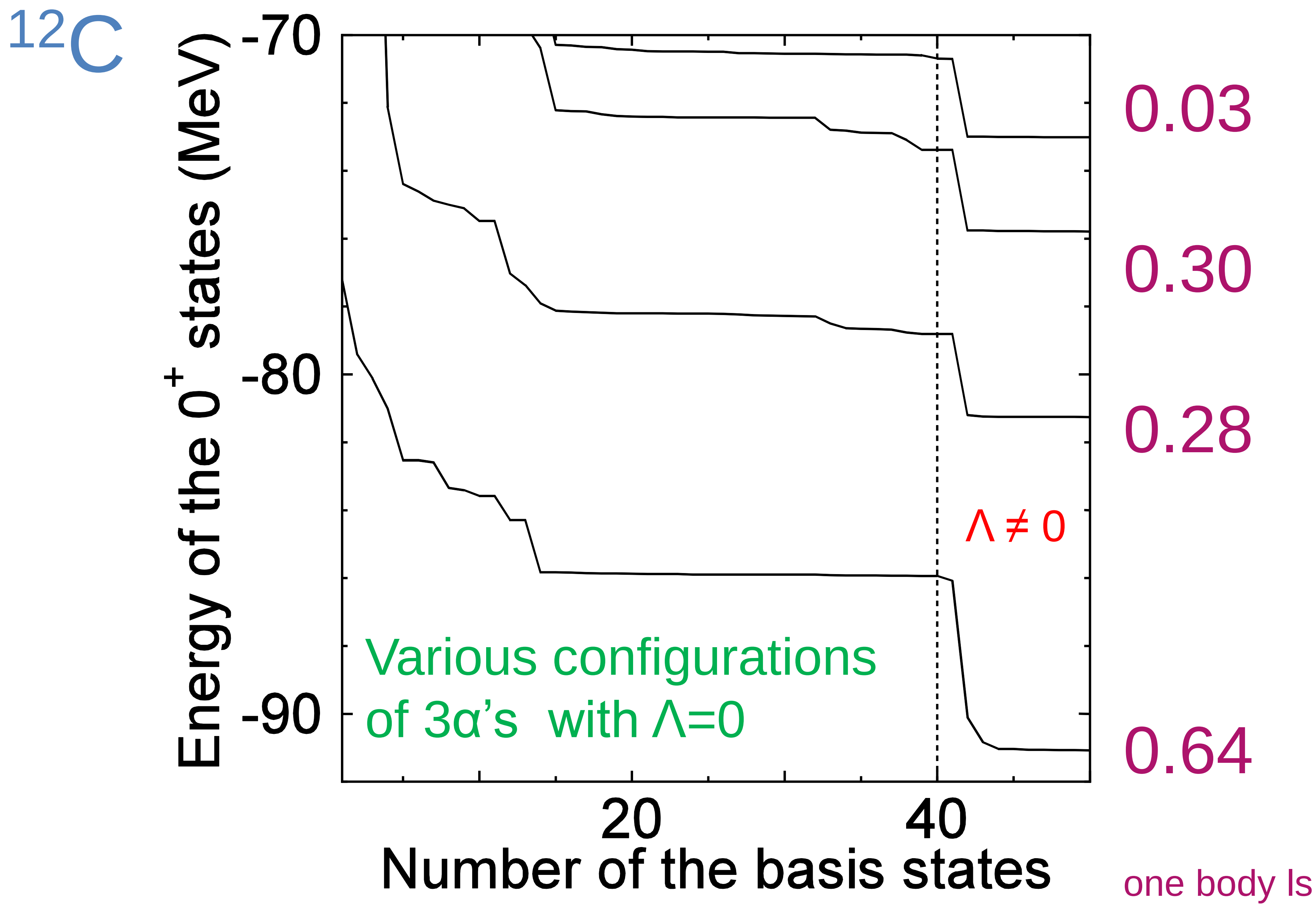
After superposing Slater determinants with different Λ values, it is difficult to estimate the extent to which the α cluster is broken

We need to introduce an operator and calculate the expectation value of α breaking

What is the operator related to the α breaking?

$$\sum_{i=protons} (\boldsymbol{l}^{*}\boldsymbol{s})_i$$

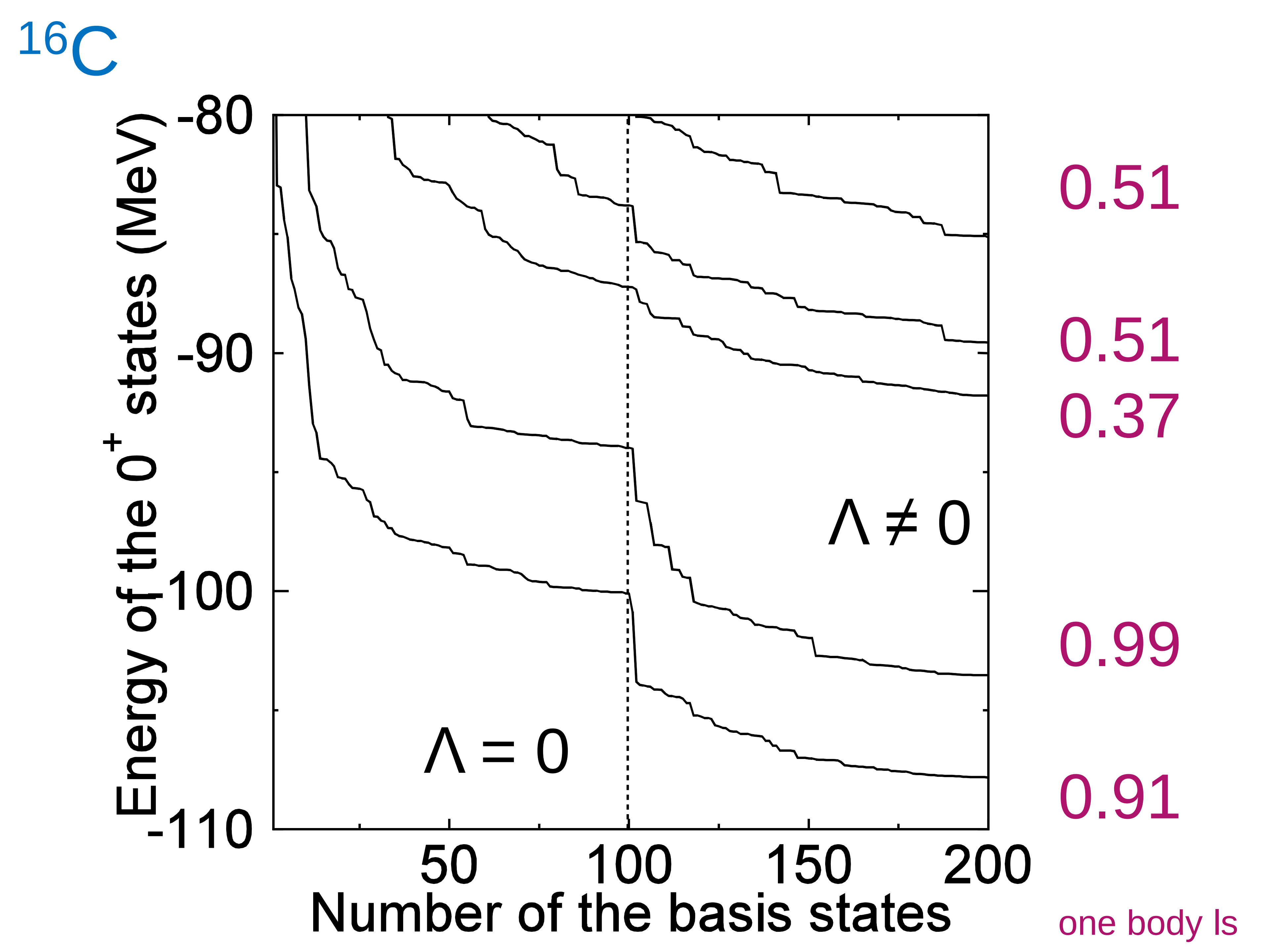
one-body spin-orbit operator for the proton part



^{12}C
-70
-80
-90
Energy of the 0^+ states (MeV)
20
40
Number of the basis states
Various configurations
of 3α's with Λ=0
Λ ≠ 0
0.03
0.30
0.28
0.64
one body ls

How about cluster-shell competition in neutron-rich nuclei?

We generate many Slater determinants with different configurations for the valence neutrons and superpose them



^{16}C
-80
-90
-100
-110
Energy of the 0^+ states (MeV)
50
100
150
200
Number of the basis states
$\Lambda \neq 0$
$\Lambda = 0$
0.51
0.51
0.37
0.99
0.91
one body ls

Lifetime Measurement of the 2_1^+ State in ^{20}C

M. Petri,[1,*] P. Fallon,[1] A. O. Macchiavelli,[1] S. Paschalis,[1] K. Starosta,[2,3,4] T. Baugher,[3,4] D. Bazin,[3] L. Cartegni,[5] R. M. Clark,[1] H. L. Crawford,[3,6] M. Cromaz,[1] A. Dewald,[7] A. Gade,[3,4] G. F. Grinyer,[3] S. Gros,[1] M. Hackstein,[7] H. B. Jeppesen,[1] I. Y. Lee,[1] S. McDaniel,[3,4] D. Miller,[3,4] M. M. Rajabali,[5] A. Ratkiewicz,[3,4] W. Rother,[7] P. Voss,[3,4] K. A. Walsh,[3,4] D. Weisshaar,[3] M. Wiedeking,[8] and B. A. Brown[4]

[1]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*Department of Chemistry, Simon Fraser University, Burnaby, British Columbia, V5A 1S6, Canada*
[3]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[4]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[5]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[6]*Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA*
[7]*Institut für Kernphysik der Universität zu Köln, D-50937 Köln, Germany*
[8]*Lawrence Livermore National Laboratory, Livermore, California 94551, USA*
(Received 21 January 2011; published 30 August 2011)

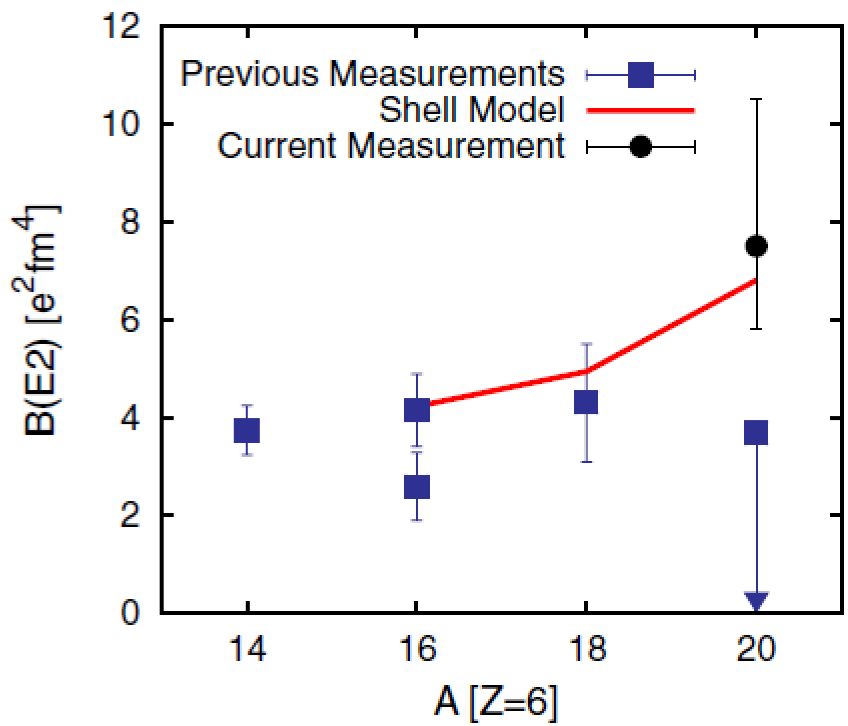


FIG. 3 (color online). $B(E2; 2_1^+ \rightarrow 0_{g.s.}^+)$ trend in even mass carbon isotopes for $A = 16$–20 including only statistical errors.

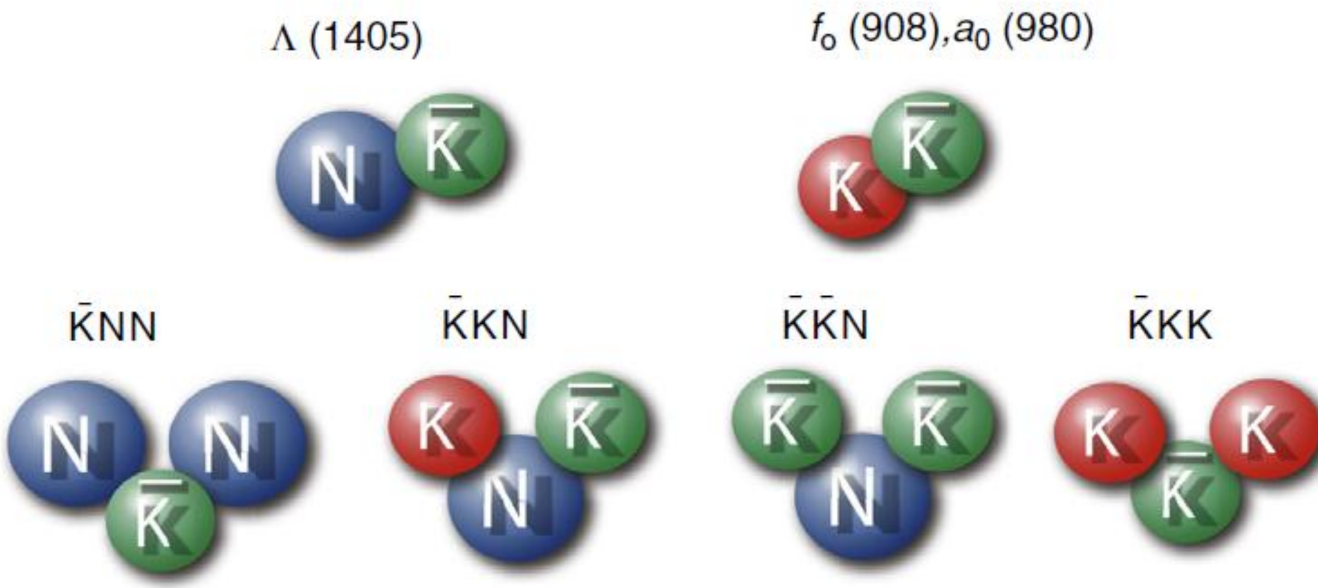


Fig. 15. Family of kaonic few-body states.

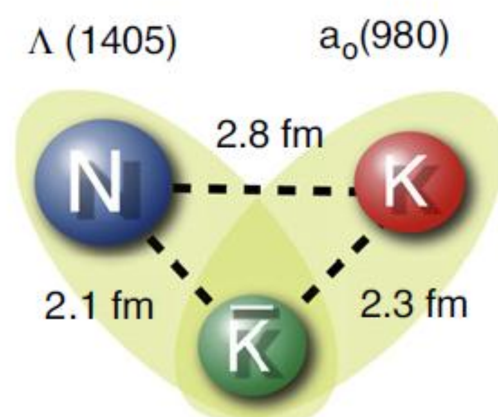


Fig. 16. Schematic structure of the $\bar{K}KN$ quasi-bound state with the inter-hadron distances.

Summary

- Nuclear structure changes as a function of excitation energy
- Cluster structure appears around the decay threshold, and geometric configurations are stabilized in neutron-rich nuclei
- We can simultaneously discuss the cluster-shell competition in the ground state and appearance of cluster states in the excited states

Summary

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Summary

- Nuclear structure changes as a function of excitation energy
- Cluster structure appears around the decay threshold, and geometric configurations are stabilized in neutron-rich nuclei
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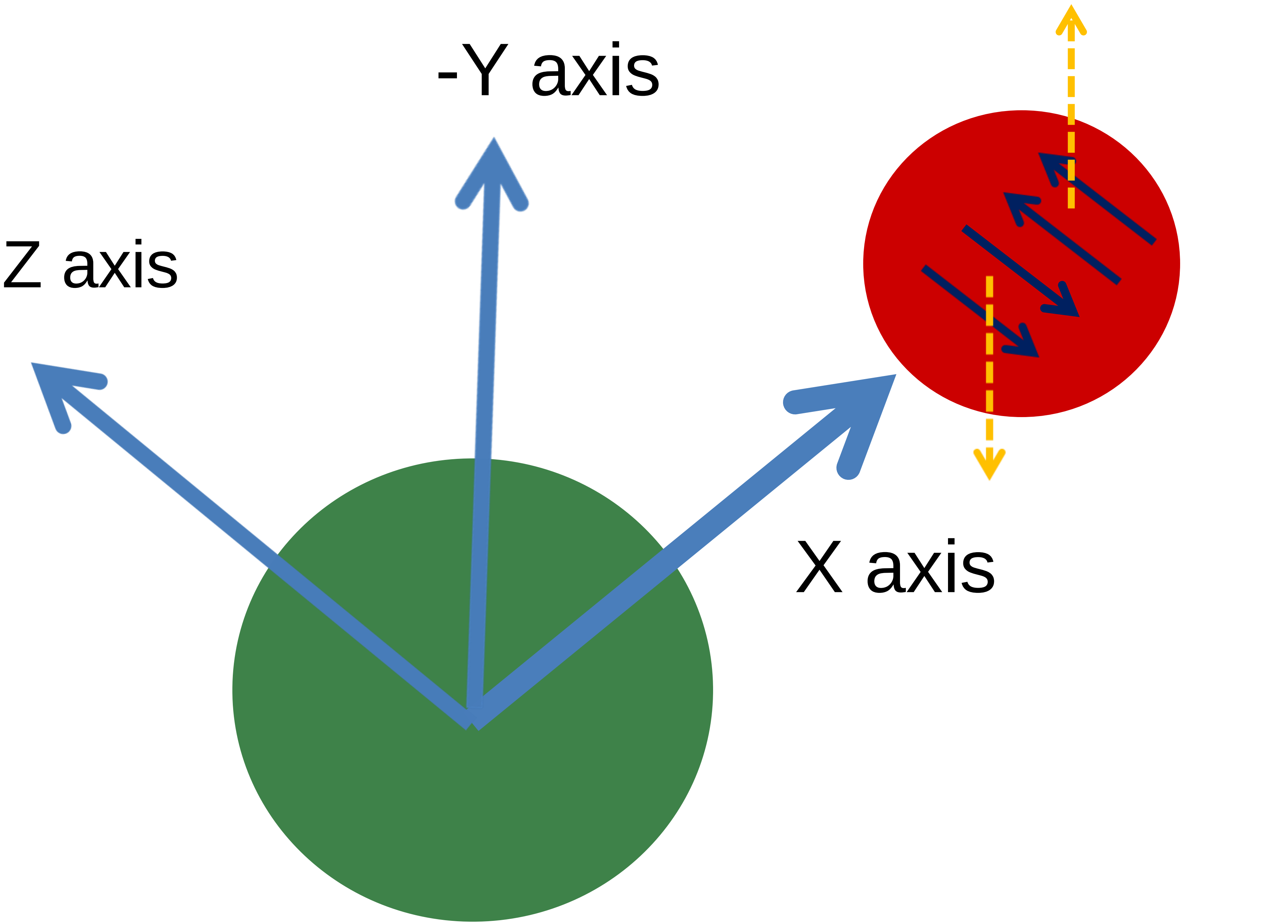
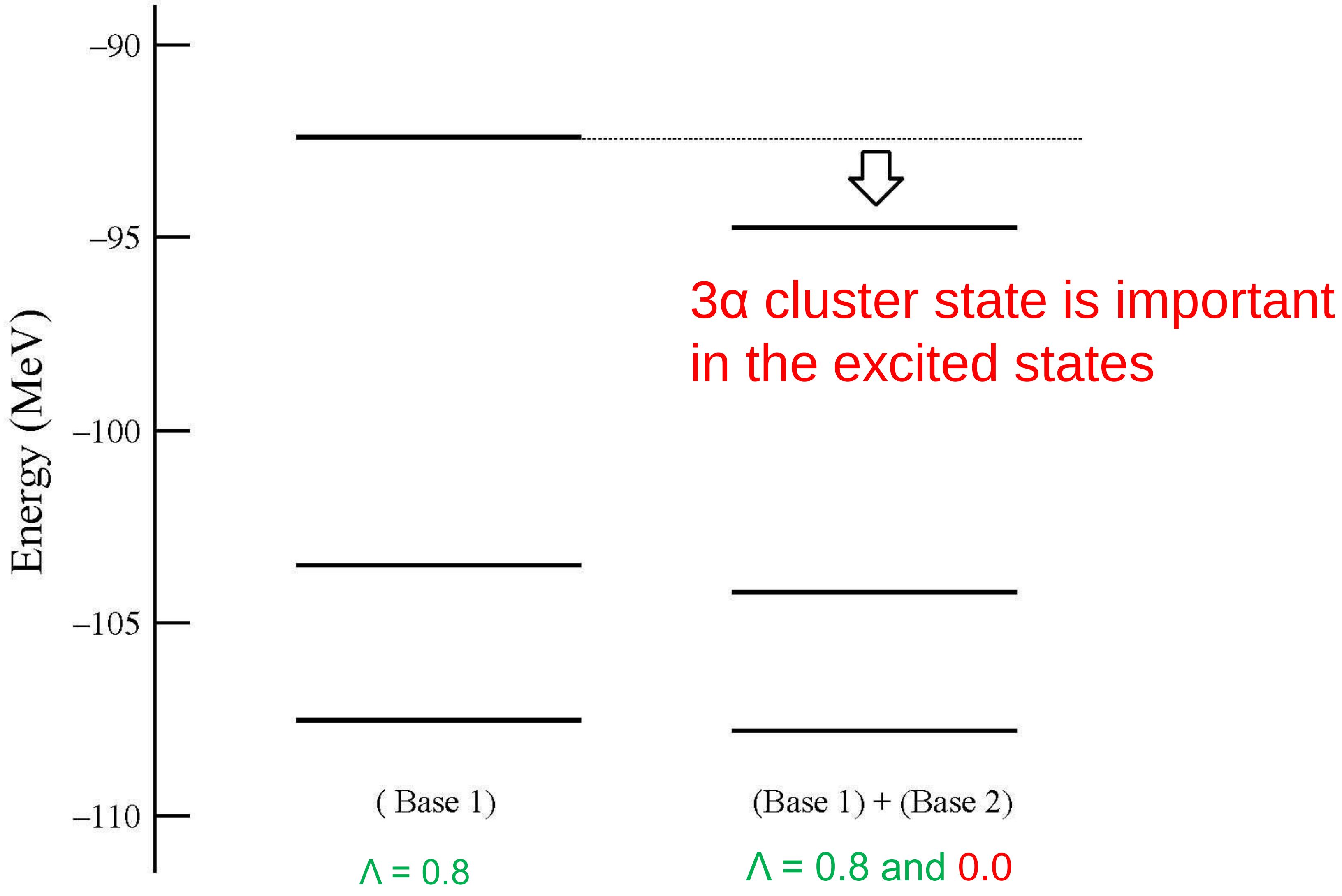

-Y axis
Z axis
X axis

The optimum values of the parameters R_1 and Λ for the carbon isotopes.

	^{12}C	^{14}C	^{16}C
R (fm)	1.5	0.5	0.5
Λ	0.4	0.8	0.8
E (MeV)	-88.6	-106.4	-108.5

H. Masui and N.Itagaki, Phys. Rev. C 75 054309 (2007)

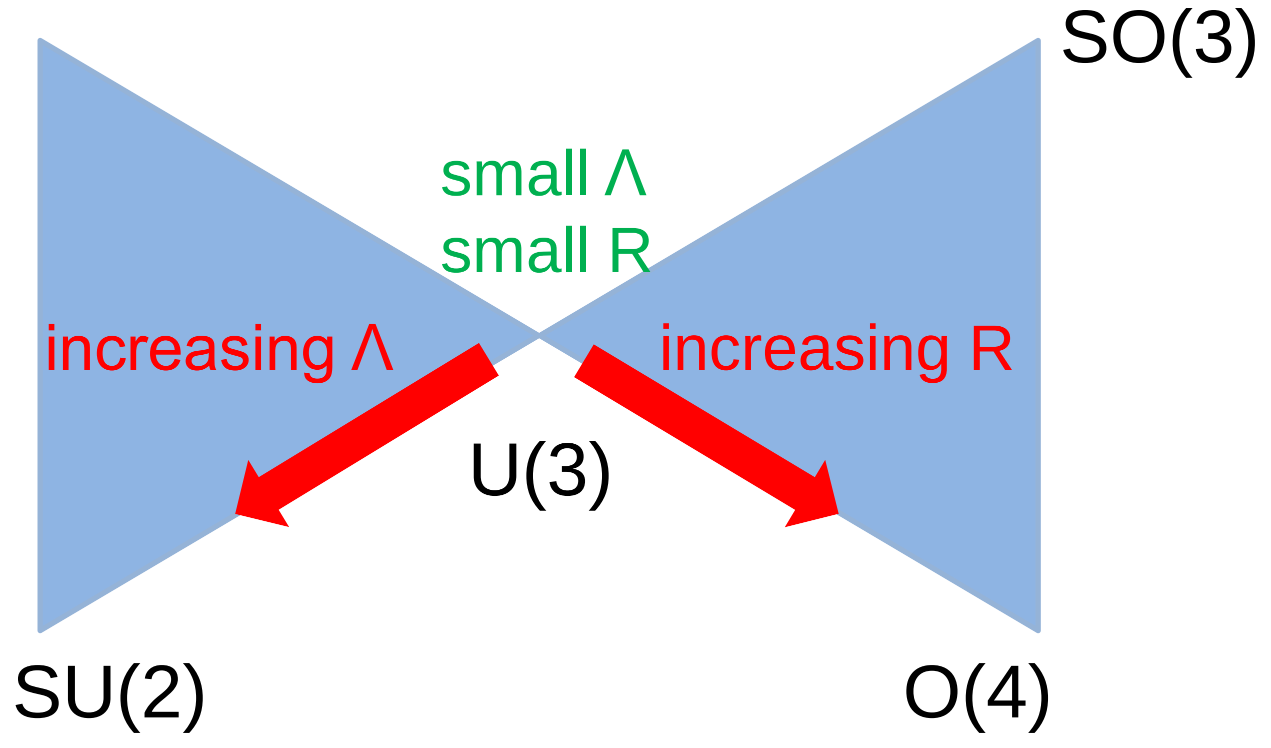
H. Masui and N.Itagaki, Phys. Rev. C 75 054309 (2007)



0$^+$ states of ^{16}C

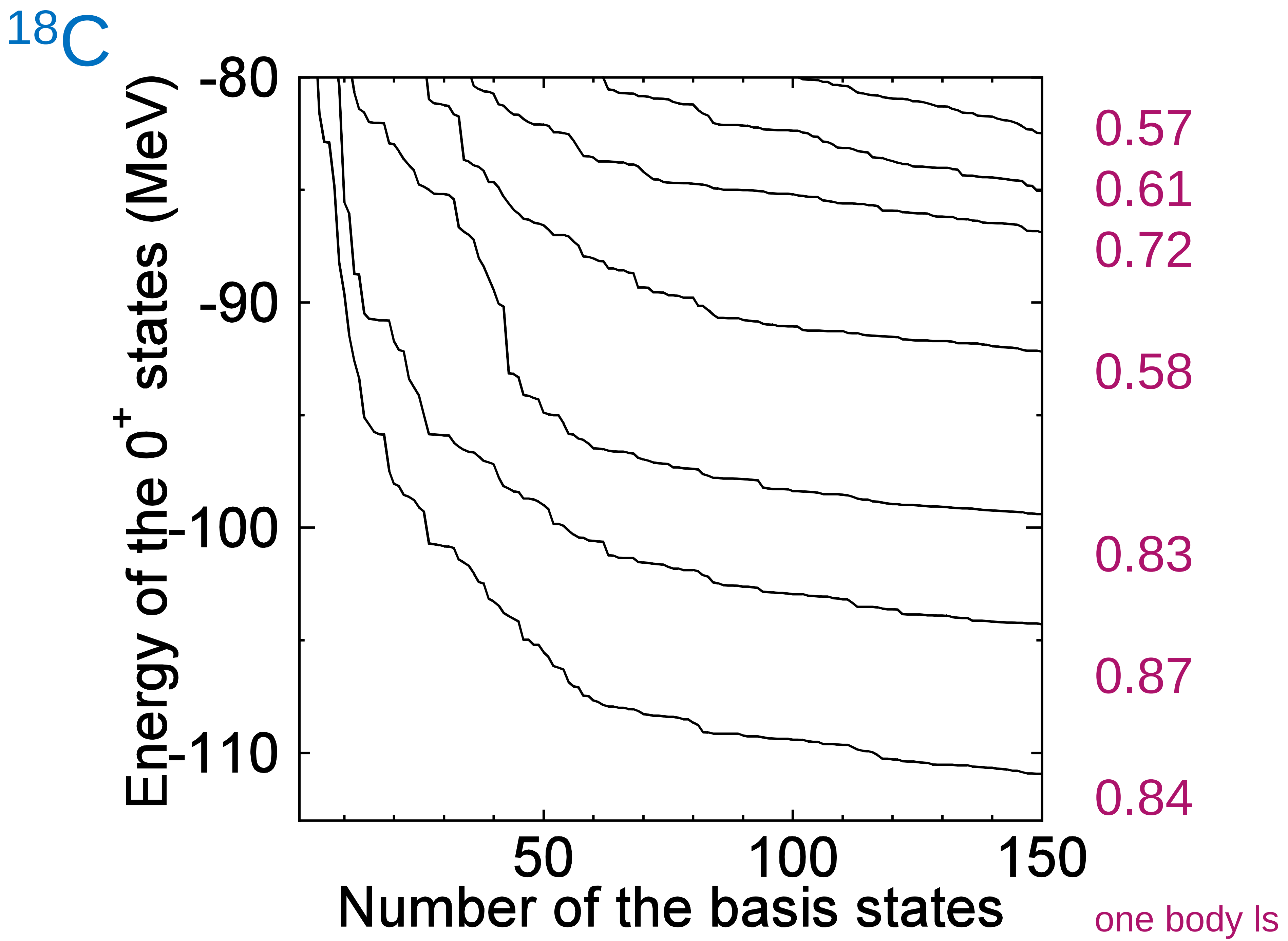
Shell model　　　Cluster model

independent particle state　　　weak coupling state



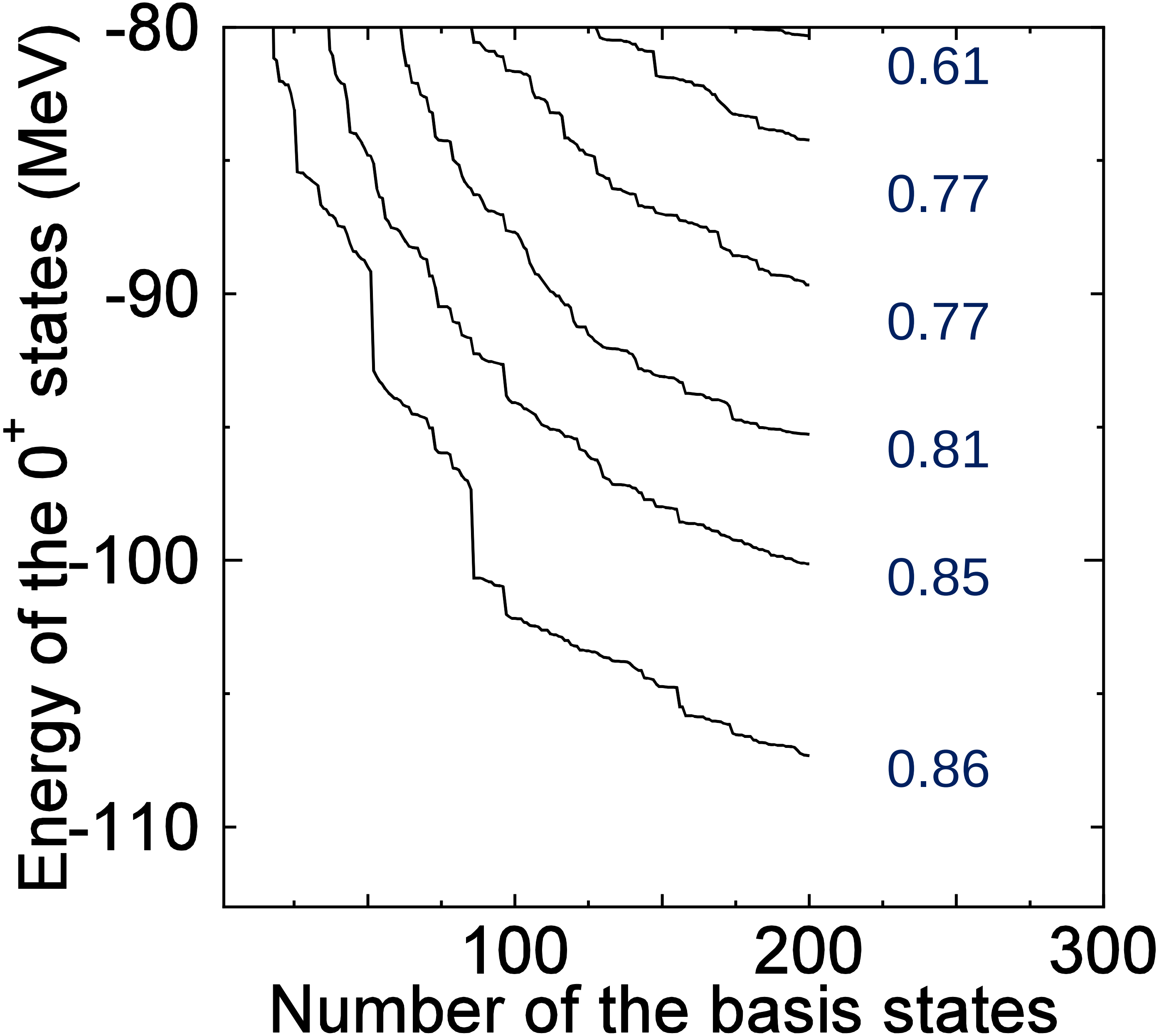
jj-coupling state　　　rigid rotor state

N. Itagaki, M. Ploszajczak, and J. Cseh, Phys. Rev. C 83 014302 (2011)



18C
-80
-90
-100
-110
Energy of the 0+ states (MeV)
50
100
150
Number of the basis states
0.57
0.61
0.72
0.58
0.83
0.87
0.84
one body ls

^{20}C



single particle LS

$$V_{ls} = V_0(e^{-d_1 r^2} - e^{-d_2 r^2})P(^3\mathrm{O})\vec{L}\cdot\vec{S}$$

^{20}Ne

After GCM

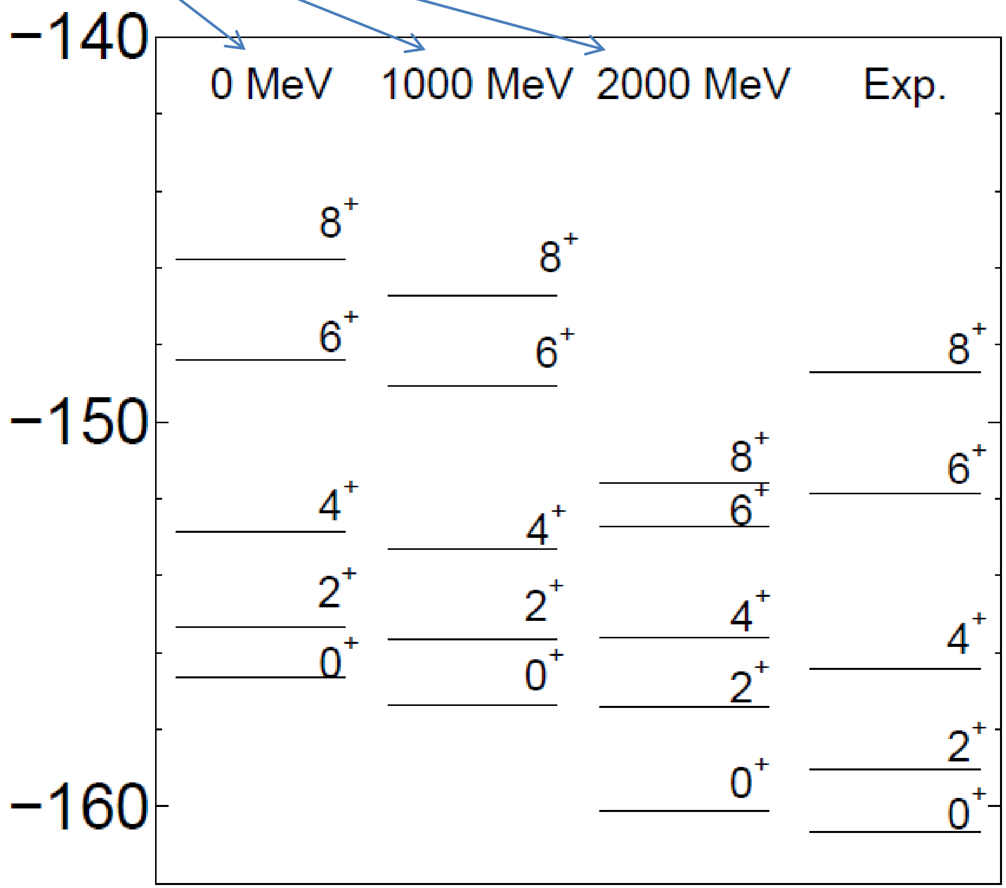


FIG. 1: The GCM calculations of yrast levels in ^{20}Ne for three different values of the strength of the spin-orbit interaction: $V_0 = 0, 1000, 2000$ MeV, are compared with the experimental data (Exp.). For more details, see the description in the text.

Give wave functions an initial boost factor with r=3fm, α=1fm
Then do time-dependent calculation.
Result shows long-term return to ground state, but some oscillations before.

$$A \frac{\exp[iQ(\vec{r})]}{1+e^{(r-r_0)/\alpha}}$$

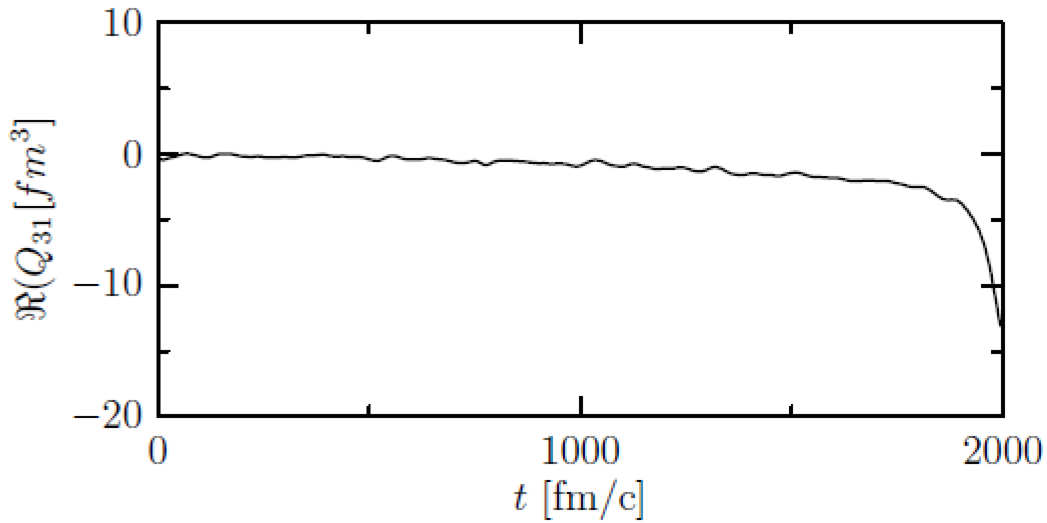


Figure 9: Time-dependent reaction of the chain state in ^{20}C to a slight bending-type excitation. Plotted is the $\Re(Q_{31})$ expectation value described in the text for an excitation of 0.04 MeV relative to the unperturbed chain-state energy.

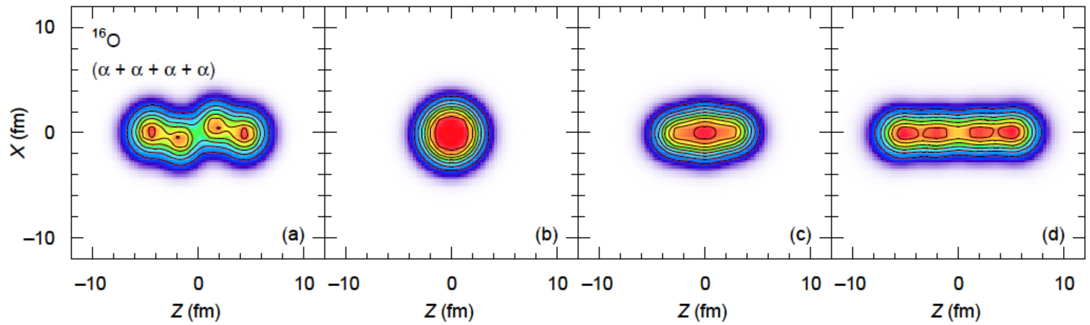


FIG. 2: (Color online) Total nucleon density distribution calculated using the cranking method for (a) the initial wave function, (b) the ground state, (c) the quasi-stable state, and (d) the four-α linear chain state. The isolines correspond to multiples of 0.02 fm^{-3}. We normalize the color to the density distribution at the maximum of each plot.

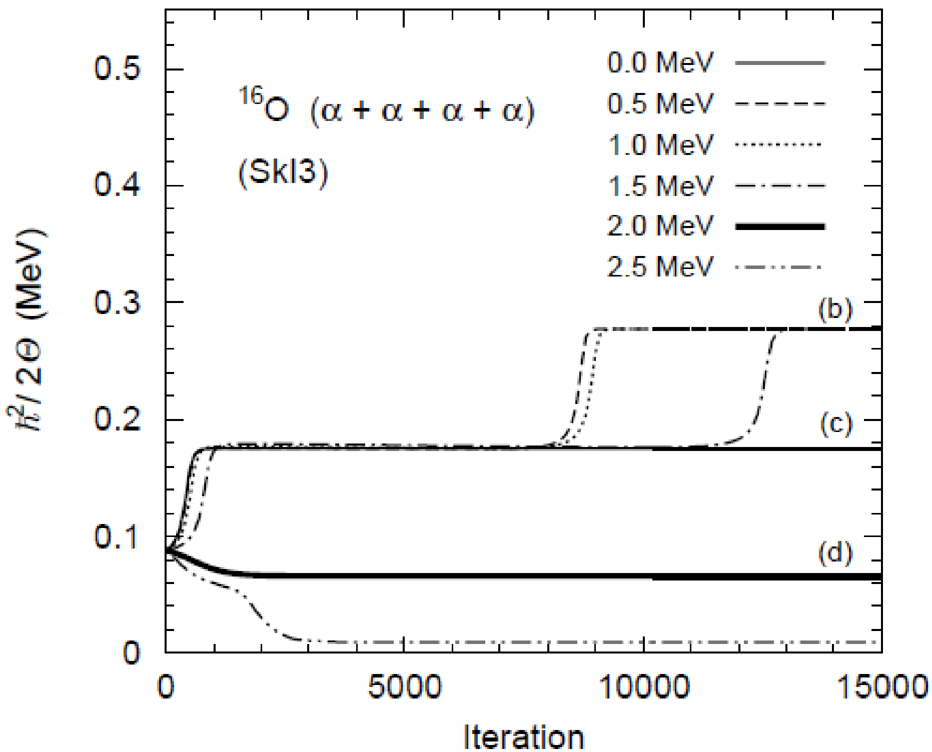


FIG. 3: Coefficient of the rotational energy, $\hbar^2/2\Theta$, calculated using the cranking method versus the HF iterations with various rotational frequencies ω. The symbols (b), (c), and (d) correspond to the density distributions given in Fig. 2.

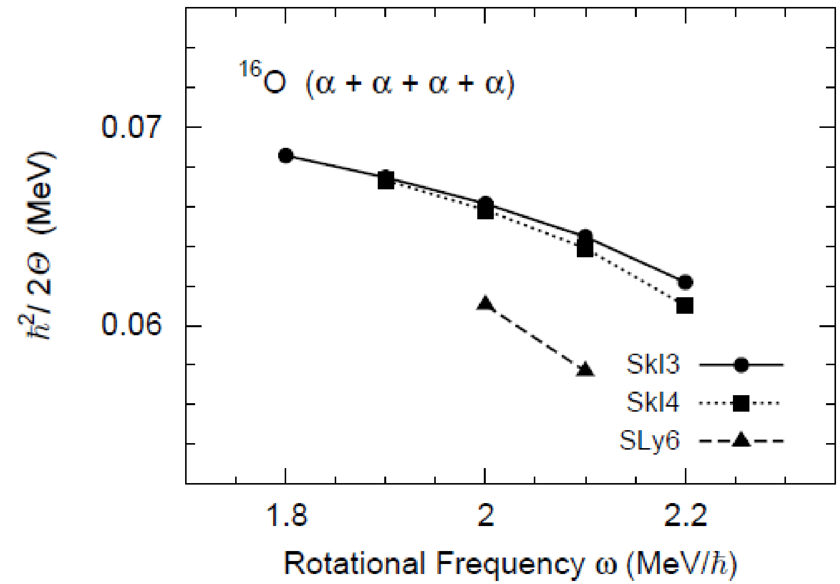


FIG. 4: Coefficient of the rotational energy $\hbar^2/2\Theta$ as a function of rotational frequency ω. The lines correspond to the different Skyrme forces as indicated.

Single particle wave function of nucleons in quasi cluster (spin-up):

$$\psi_i = \left(\frac{2\nu}{\pi}\right)^{\frac{3}{4}} \exp[-\nu(\vec{r} - \vec{\zeta}_i/\sqrt{\nu})^2]$$

$$\vec{\zeta}/\sqrt{\nu} = R(\vec{e}_x + i\Lambda\vec{e}_y)$$

Quasi cluster is along x
Spin direction is along z
Momentum is along y

$$\psi_i = \left(\frac{2\nu}{\pi}\right)^{\frac{3}{4}} \exp[-\nu\vec{r}^2 - \vec{\zeta}^2 + 2\nu\vec{r}\cdot\vec{\zeta}/\sqrt{\nu}]$$

the cross term can be Taylor expanded as:

$$\exp[2\nu\vec{r}\cdot\vec{\zeta}/\sqrt{\nu}] = 1 + \sum_{k=1}^{\infty} \frac{1}{k!}(2\nu R(x + i\Lambda y))^k$$

For $\Lambda = 1$, one finds:

$$\exp[2\nu\vec{r}\cdot\vec{\zeta}/\sqrt{\nu}] = 1 + \sum_{k=1}^{\infty} \frac{1}{k!}\frac{1}{s_k}(2\nu r R)^k Y_{kk}(\Omega)$$

For $\Lambda = 1$

the single particle wave function in the quasi cluster becomes

$$
\begin{aligned}
\psi_i = \left(\frac{2\nu}{\pi}\right)^{\frac{3}{4}} \{1 \; &+ \; s_1^{-1} 2\nu r_i R Y_{11}(\Omega_i) \\
&+ \; (1/2!) s_2^{-1} (2\nu r_i R)^2 Y_{22}(\Omega_i) \\
&+ \; (1/3!) s_3^{-1} (2\nu r_i R)^3 Y_{33}(\Omega_i) \\
&+ \; \cdots + (1/n!) s_n^{-1} (2\nu r_i R)^n Y_{nn}(\Omega_i) \\
&+ \; \cdots \} \exp[-\nu r_i^2].
\end{aligned}
$$

for the spin-up nucleon (complex conjugate for spin-down)

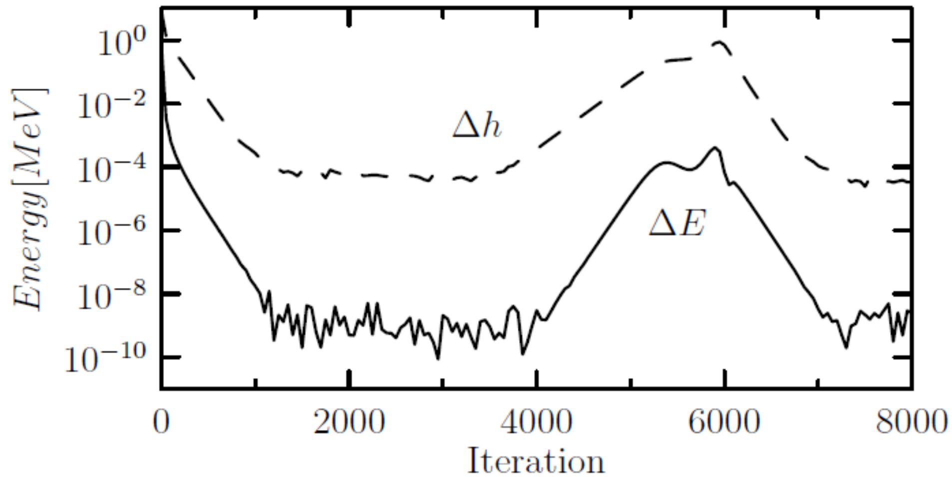


Figure 1: Convergence behavior in a static HF iteration showing an intermediate quasistable state of ^{16}C. Plotted are the relative change in total energy from one iteration to the next, $\Delta E = |\frac{E_{n+1} - E_n}{E_n}|$ and the average fluctuation in the single-particle energies as defined in Eq.(eq:hfluct).

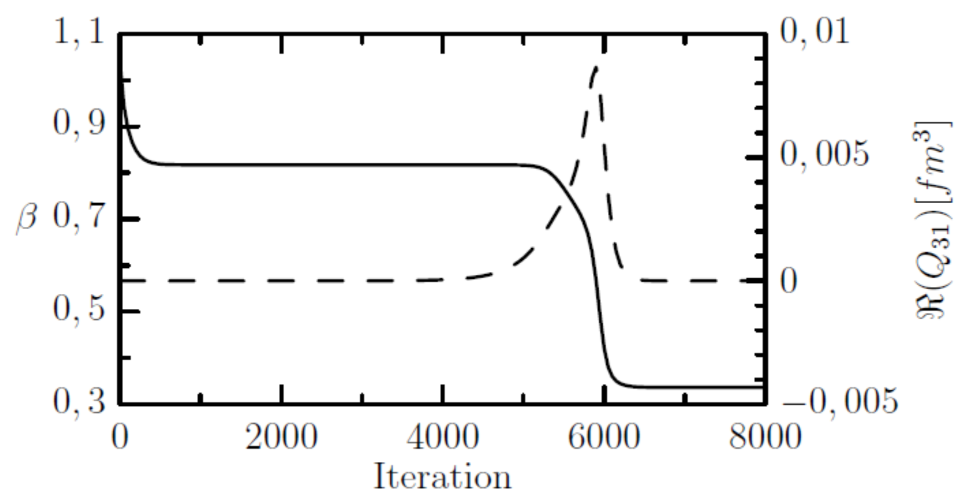


Figure 2: Convergence behavior in a static HF iteration showing an intermediate quasistable state of ^{16}C. Plotted are the quadrupole deformation parameter β (full curve) and the $\Re(Q_{31})$ expectation value described in the text (dashed curve).

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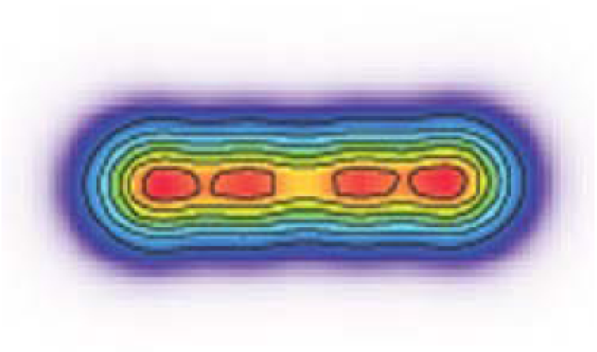
Rod-Shaped Nucleus

We picture atomic nuclei as spherical globs of protons and neutrons, although they can also be egg-shaped. Now calculations published 9 September in *Physical Review Letters* show that an even more exotic shape is possible: a rapidly spinning nucleus can form into a linear chain of several small clusters of neutrons and protons. Such exotic nuclear states could play important intermediary roles in the formation of carbon-12 and oxygen-16--elements essential for life--in the interiors of stars. The authors' new technique for calculating such structures also allows for the study of even more exotic arrangements.



Phys. Rev. Lett. **107**, 112501 (2011)

All in a row. A spinning oxygen-16 nucleus can spread out into a linear chain of four clusters, according to calculations. This is the first clear evidence for such a "linear-chain" state.

The shape of a nucleus has important effects on nuclear reactions, such as those

How we can stabilize such states?

- Adding valence neutrons
- Orthogonalizing to low-lying states
- Rotating the system