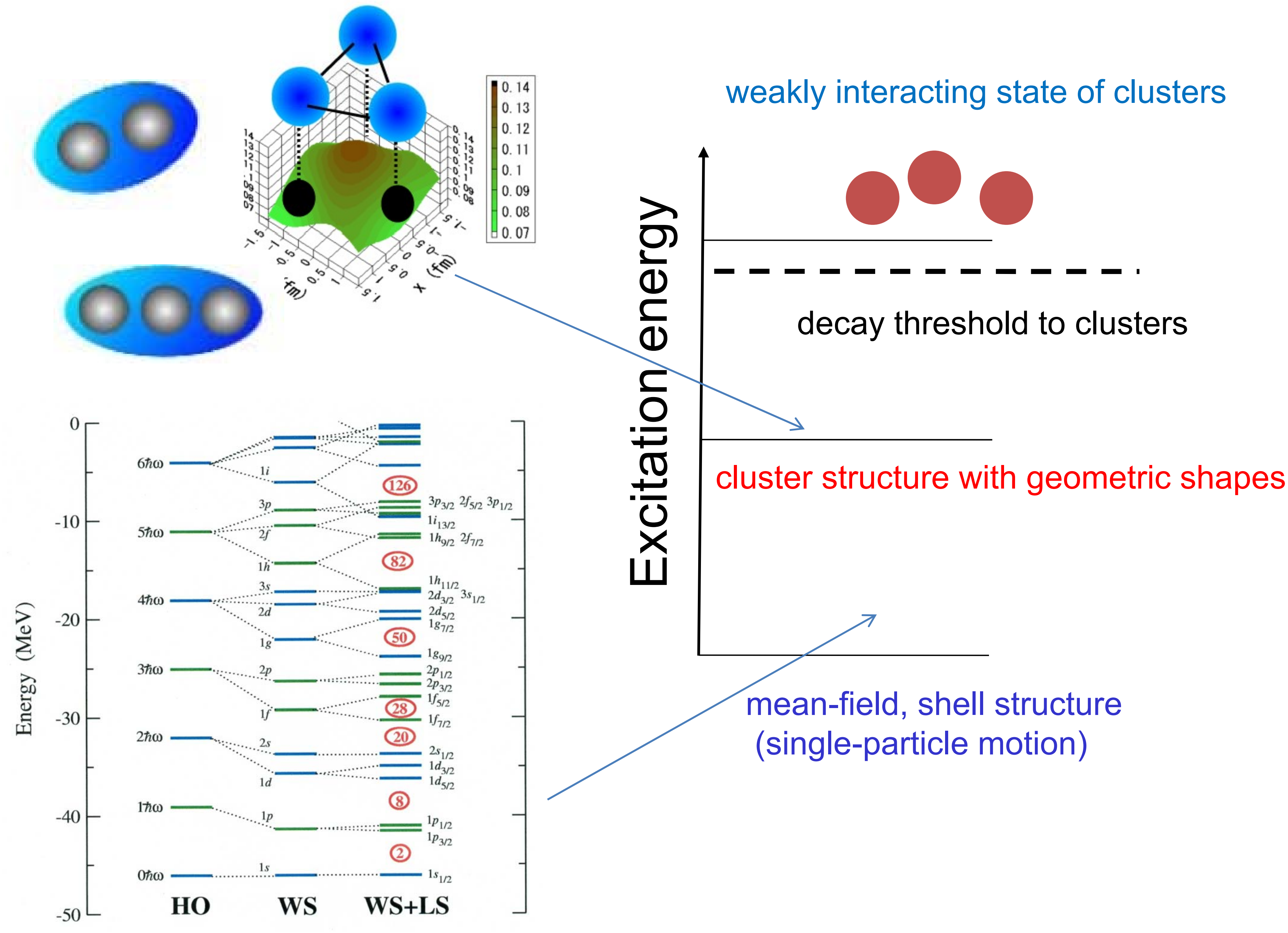
原子核における
ガス的クラスター状態・
幾何学的クラスター状態

Naoyuki Itagaki
Yukawa Institute for Theoretical Physics
Kyoto University



weakly interacting state of clusters
Excitation energy
decay threshold to clusters
cluster structure with geometric shapes
mean-field, shell structure
(single-particle motion)
Energy (MeV)
HO
WS
WS+LS
0
-10
-20
-30
-40
-50
6ħω
5ħω
4ħω
3ħω
2ħω
1ħω
0ħω
126
82
50
28
20
8
2
x (fm)
0. 14
0. 13
0. 12
0. 11
0. 1
0. 09
0. 08
0. 07

日本語による解説記事

日本物理学会誌 (2009年11月号840ページ)

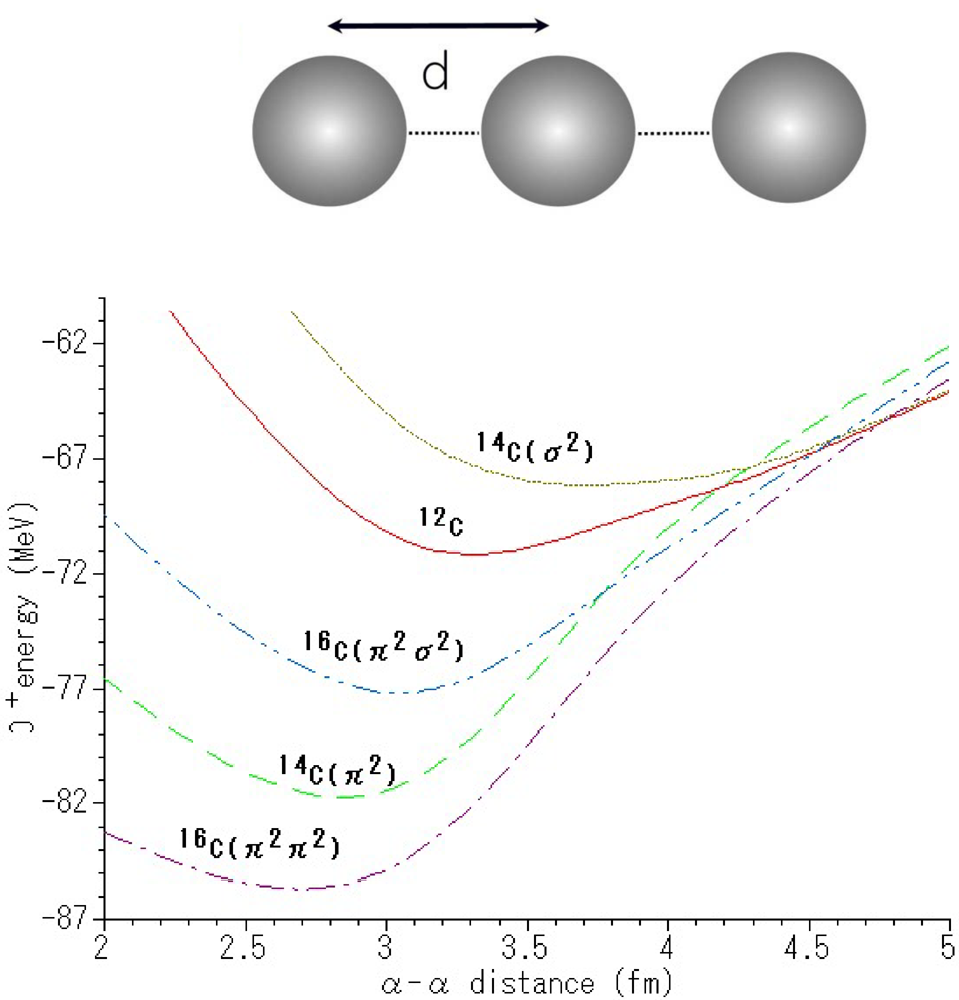
「最近の研究から」

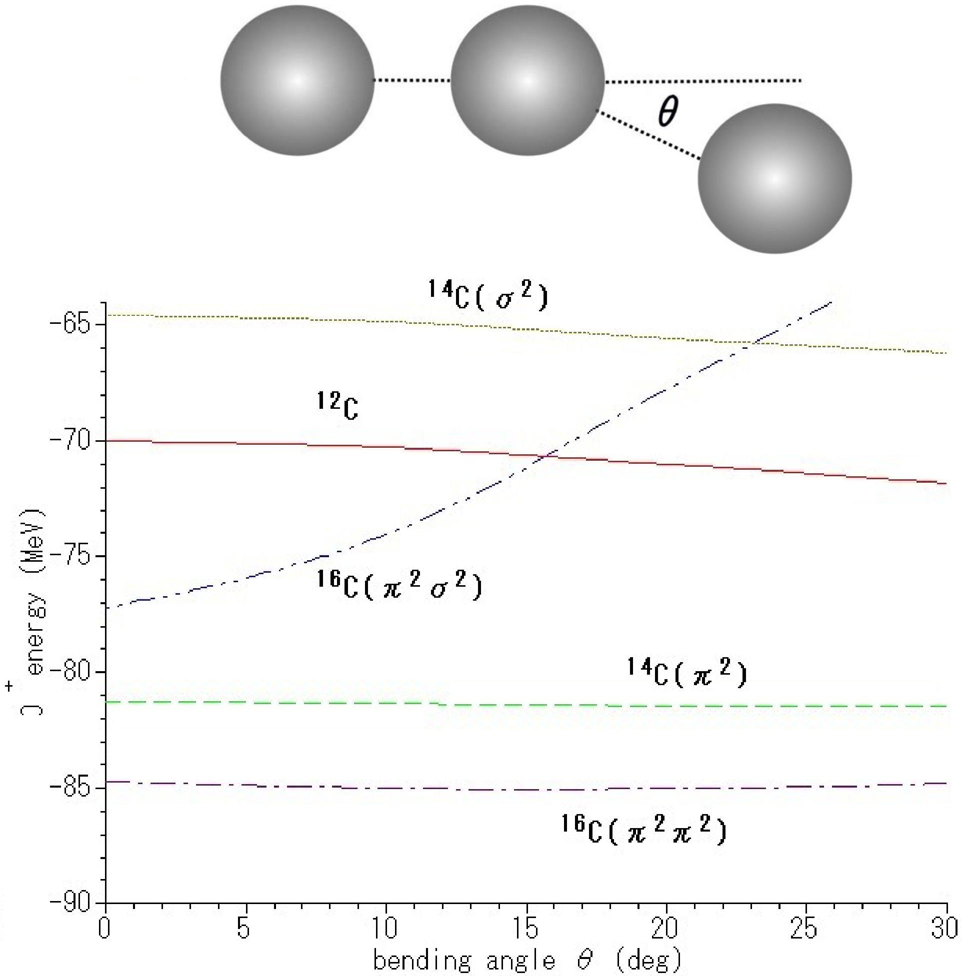
“中性子の果たす“糊”の効果とαクラスターの結合形態”

板垣直之	東京大学理学系研究科物理学専攻
Joachim A. Maruhn	フランクフルト大学理論物理学研究所
木村真明	北海道大学創成研究機構

In light neutron-rich nuclei

Gas like cluster states become stable with geometric shapes due to the glue effect of the neutrons?





N. Itagaki, S. Okabe, K. Ikeda, and I. Tanihata
Phys. Rev. C **64** 014301 (2001).

Collaboration with Frankfurt group J.A. Maruhn et al.

- No assumption of cluster structure a priori,

  the model is mean-field model
- Interactions are quite general ones

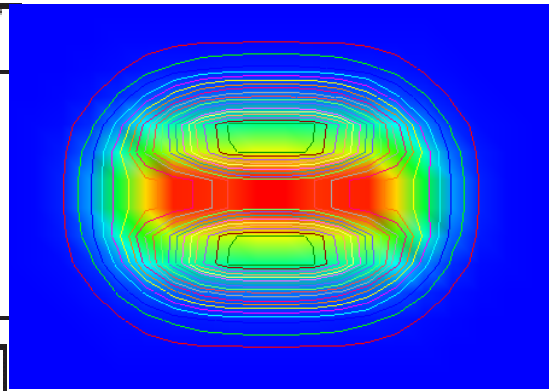
  (Skyrme interactions designed for many nuclei including heavier ones)
- Feasibility was already suggested by Ohta and Yabana several years ago

Linear-chain structure of three clusters in ^{16}C and ^{20}C

J.A. Maruhn, N. Loebl, N. Itagaki, and M. Kimura
Nucl. Phys. A 833 1-17 (2010).

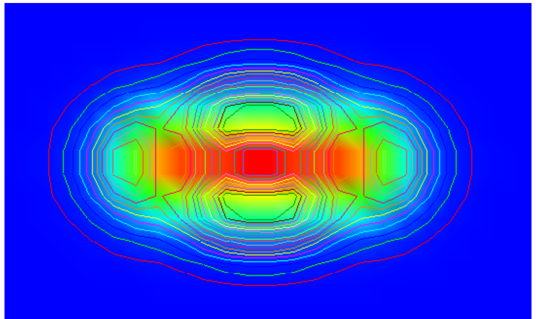
^{16}C

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

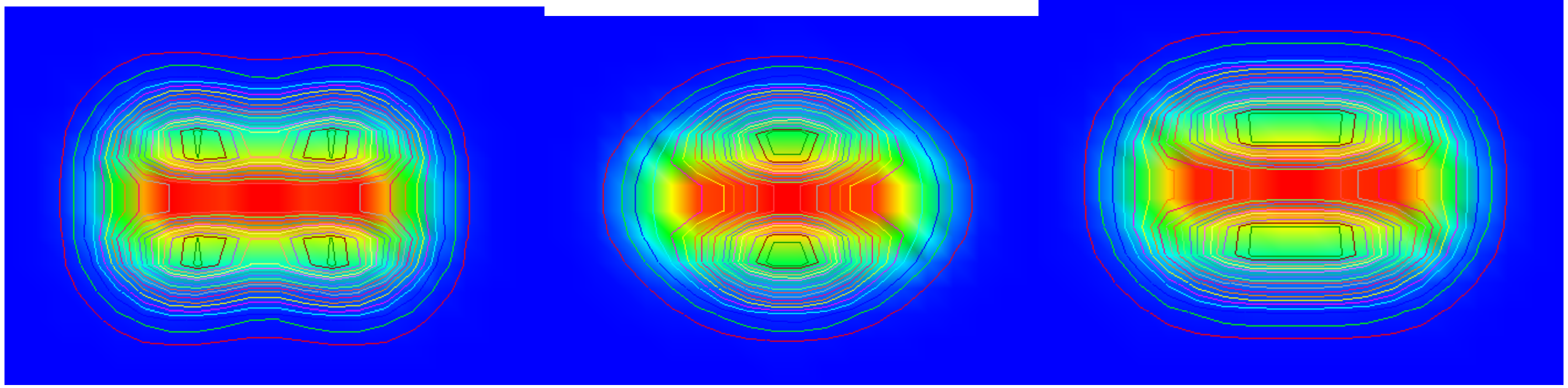


$K^\pi=1^-$

Force	$\beta_{g.s.}$	$\pi^2\delta^2$	$\pi^2\pi'^2$	$\pi^2\delta\pi'$	$\pi^2\sigma\pi'$	$\pi^2\delta\pi''$
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

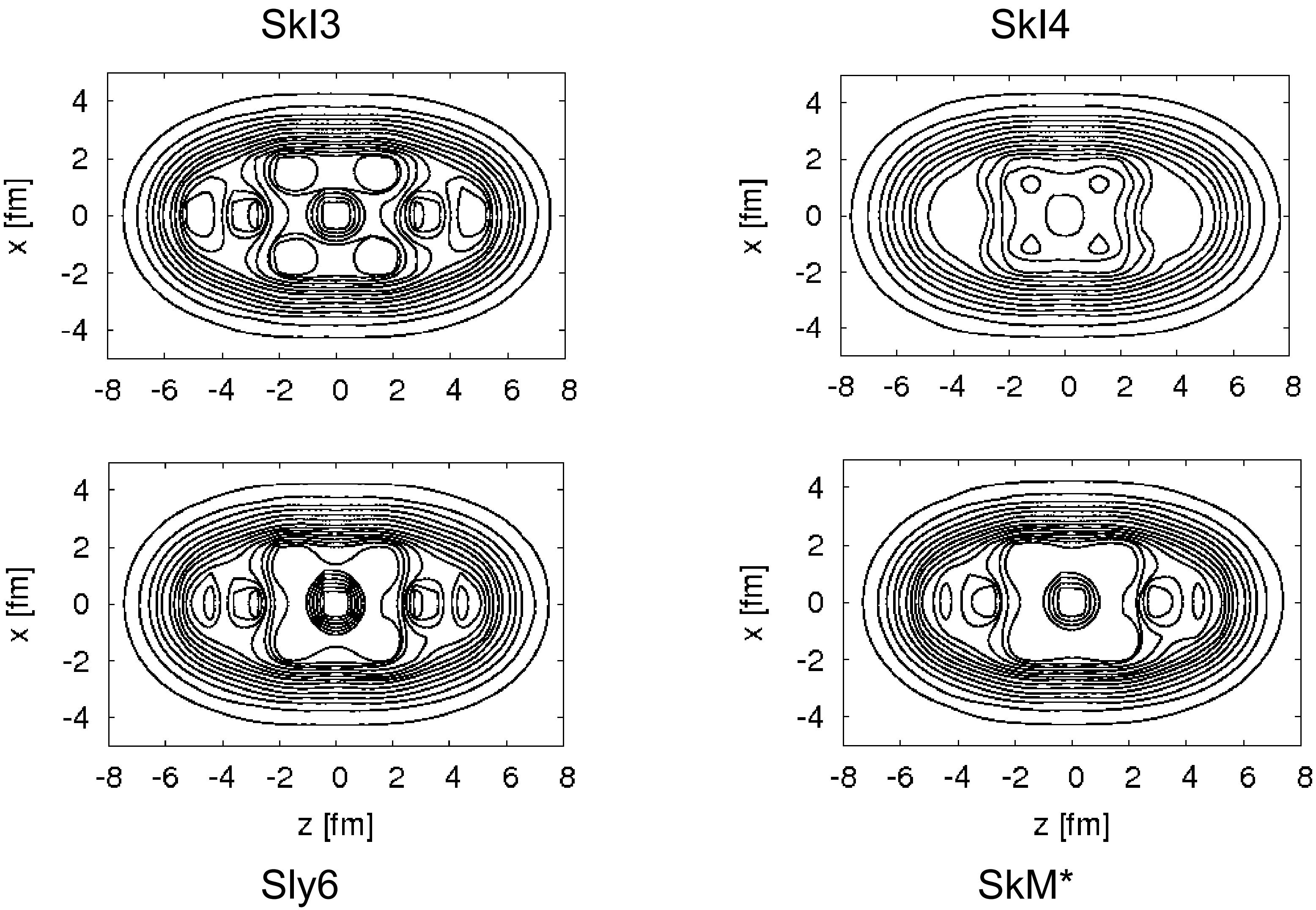


$K^\pi=1^+$



$K^\pi=0^+$ $K^\pi=0^+$ $K^\pi=2^+$

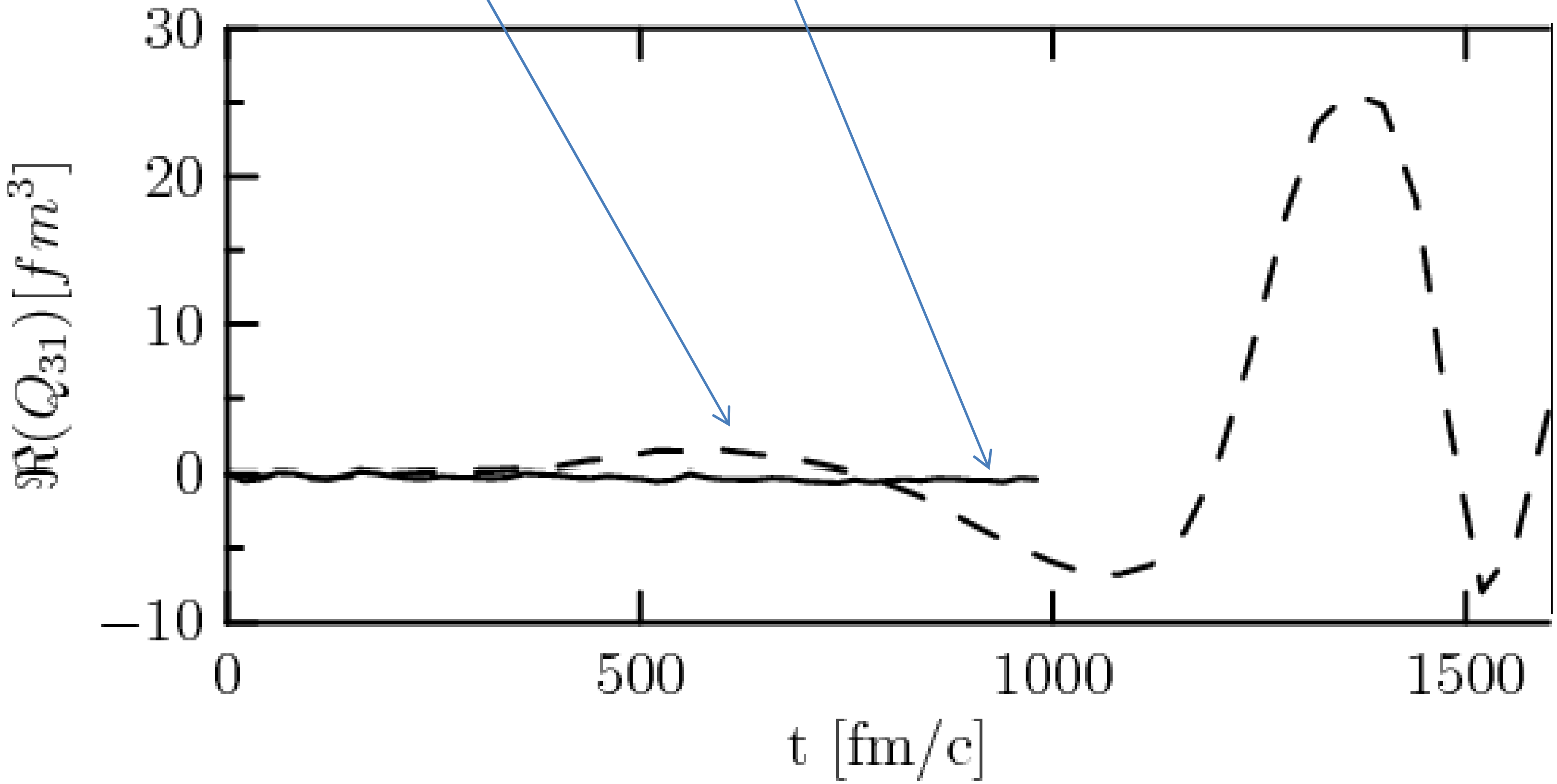
^{20}C Chain States



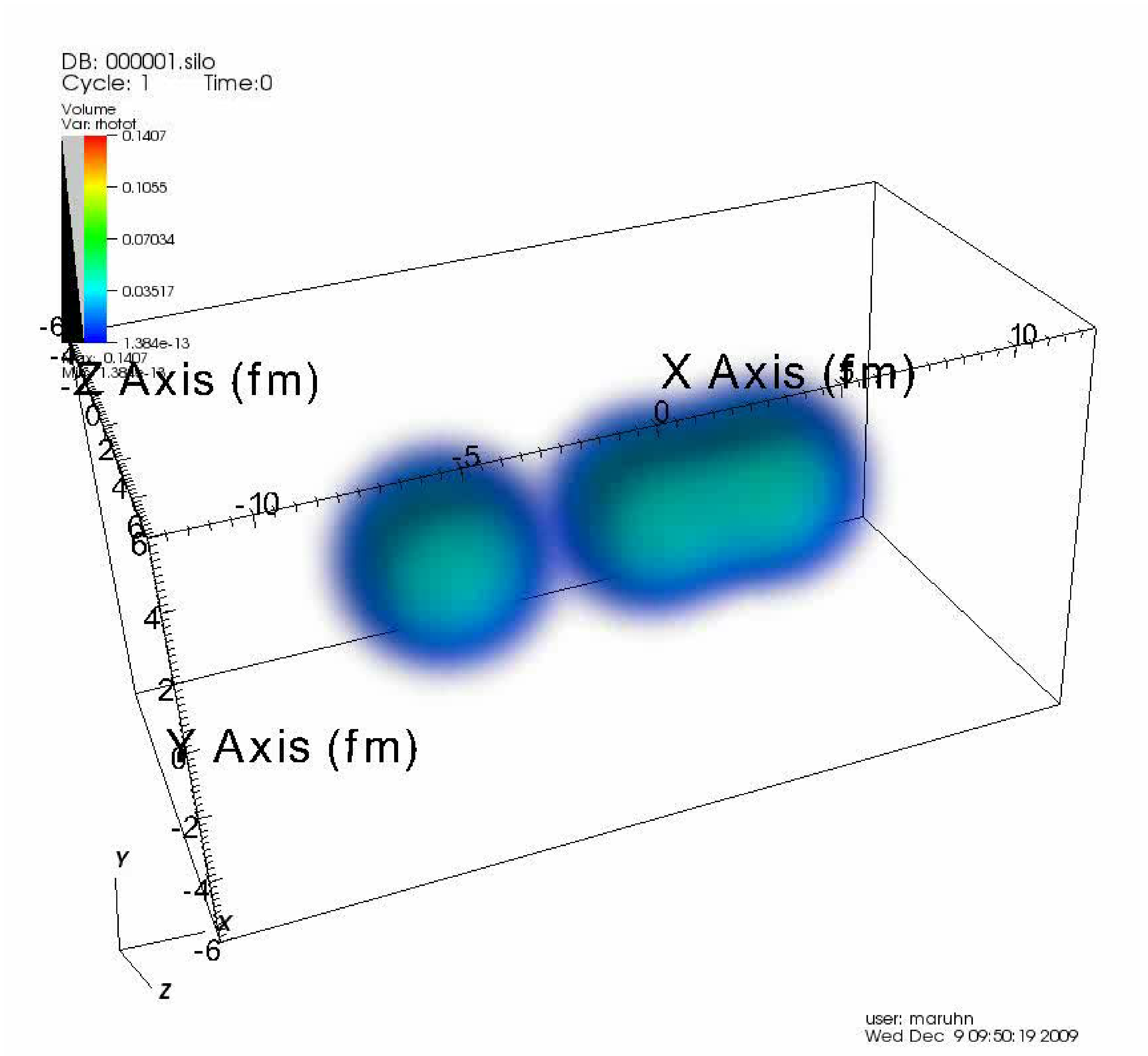
Stability against bending motion

Time Dependent Hartree-Fock

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



Characteristic oscillation modes of 3alpha chain state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0.07034
0.03517
1.384e-13
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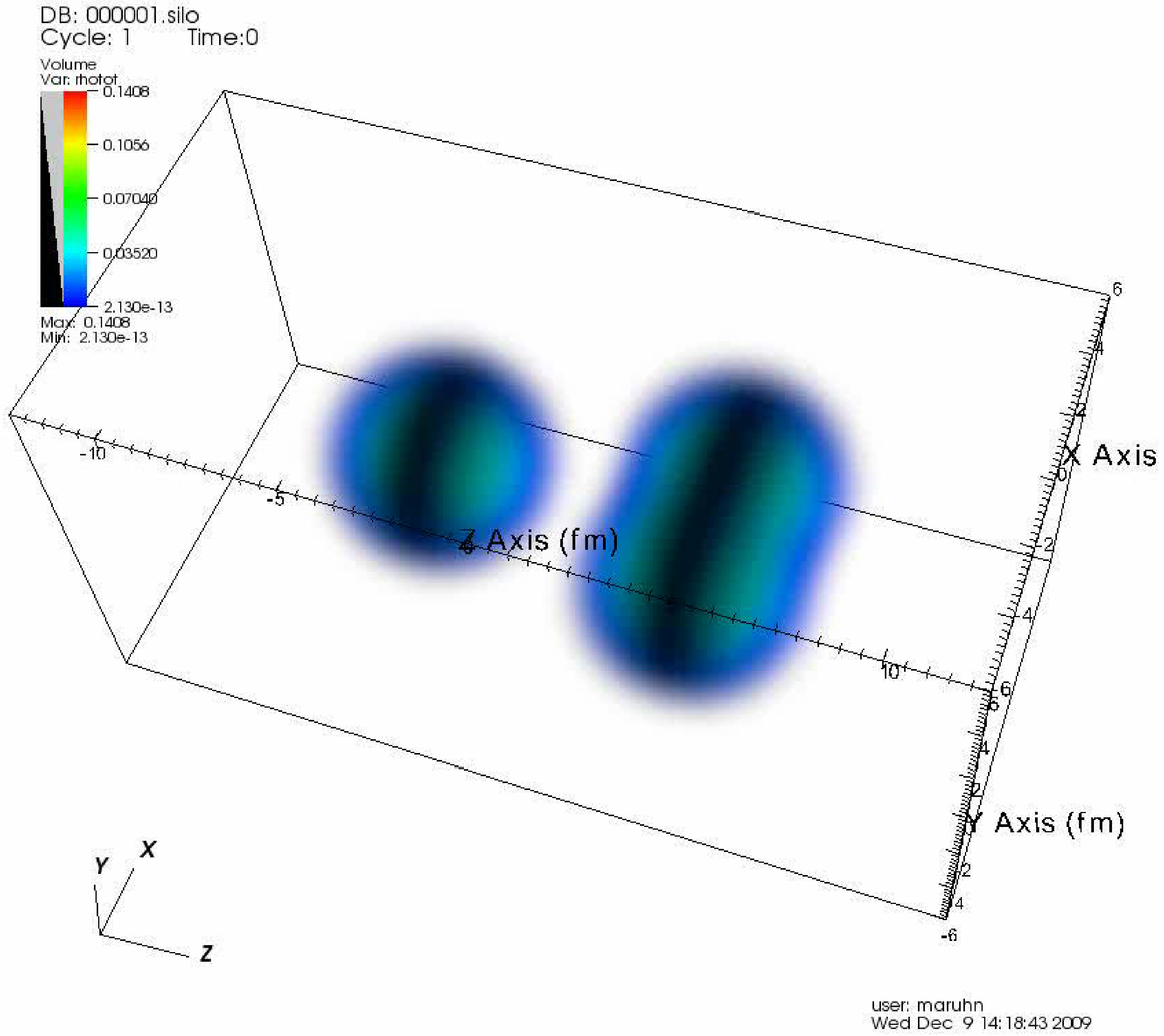
X Axis (fm)
Y Axis (fm)
user: maruhn
Wed Dec 9 09:50:19 2009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0.03520
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Max: 0.1408
Min: 2.130e-13
Z Axis (fm)
X Axis
Y Axis (fm)
user: maruhn
Wed Dec 9 14:18:43 2009

Microscopic Study of the Triple-α Reaction

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[3]*Department of Physics, University of Tokyo, Hongo, Tokyo 113-0033, Japan*
(Received 24 March 2010; published 27 May 2010)

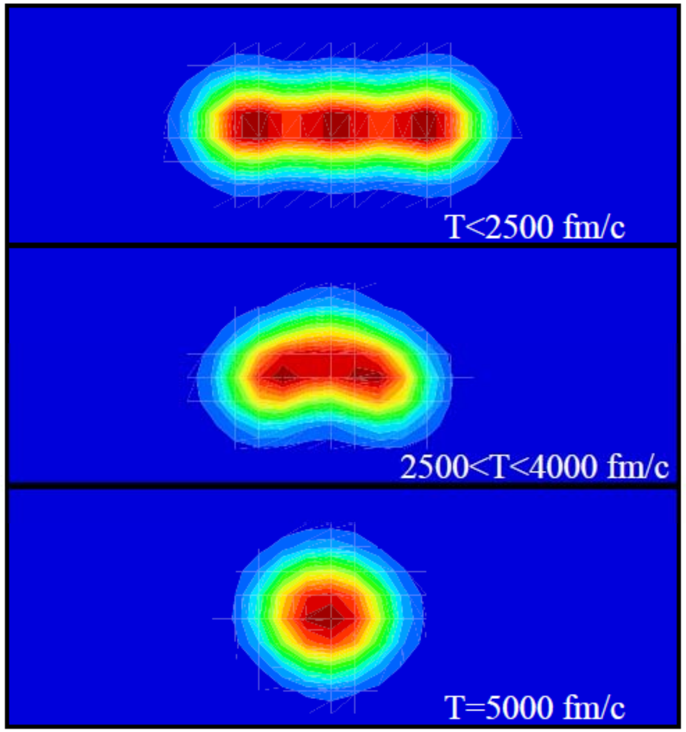


FIG. 1: (Color online) Selected density profiles from TDHF time-evolution of the ^{4}He+^{8}Be head-on collision for initial Be orientation angle $\beta = 0^\circ$ (see small graphs in Fig. 2) using the SLy4 interaction. The initial energy is $E_{\mathrm{c.m.}} = 2$ MeV. For $T < 2500$ fm/c the system 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.

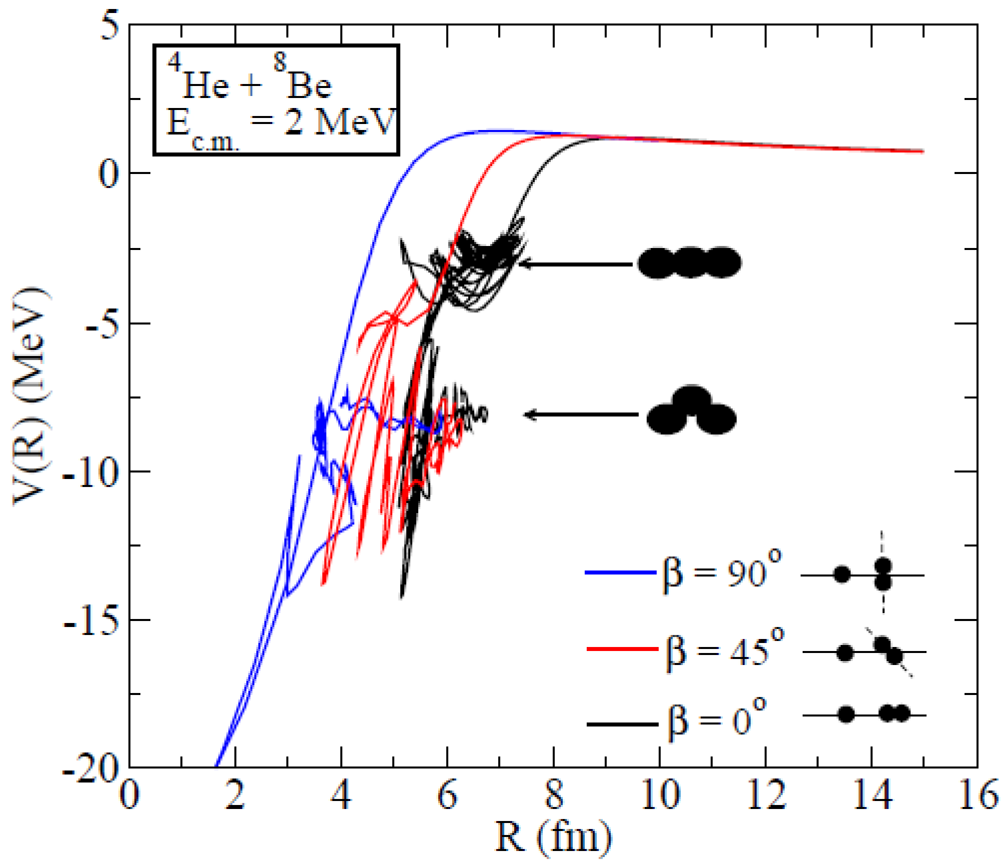


FIG. 2: (Color online) Potential energy curves for the collision of the ^{4}He+^{8}Be system as a function of R for three initial alignments of the Be nucleus and at $E_{\mathrm{c.m.}} = 2$ MeV.

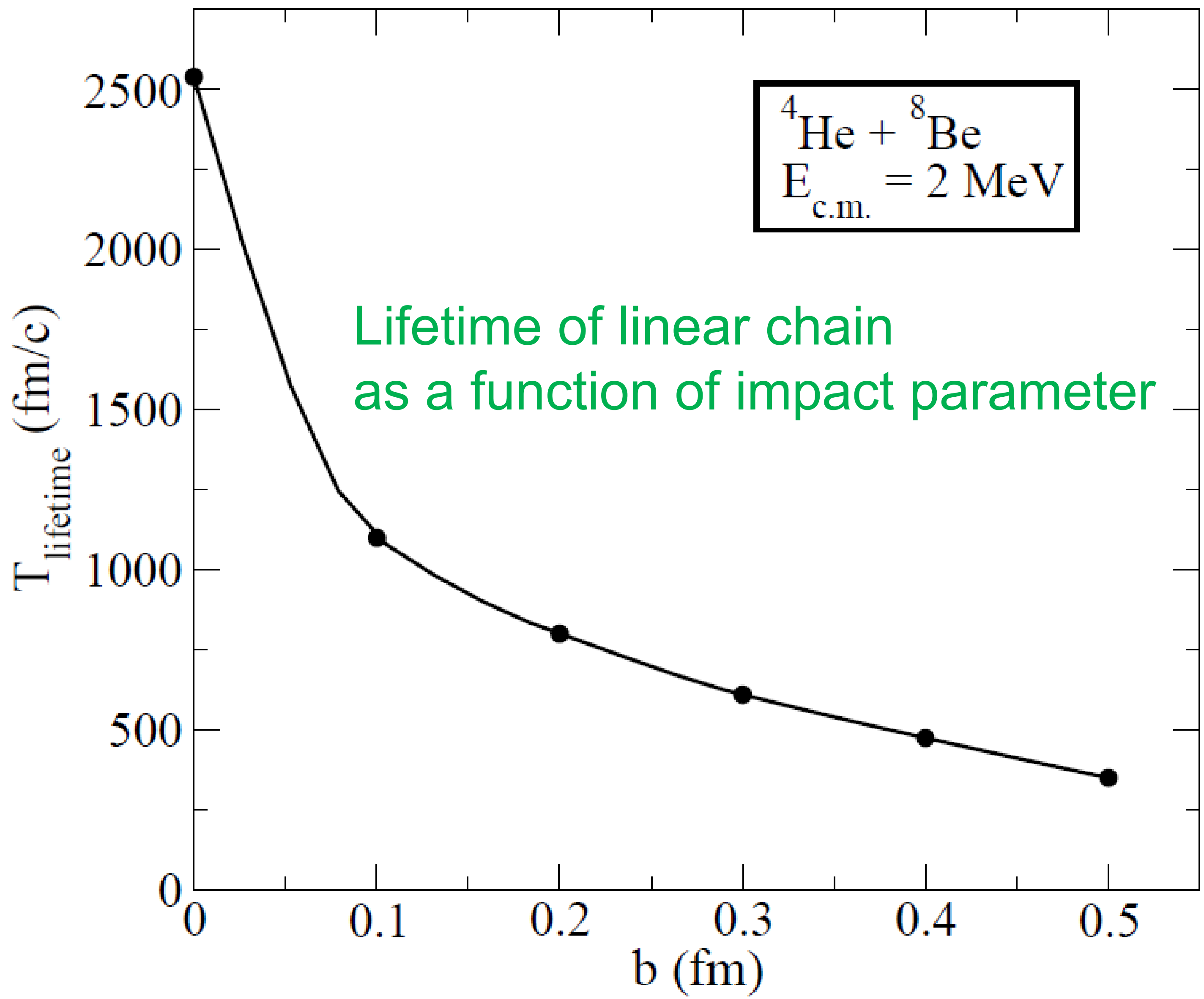
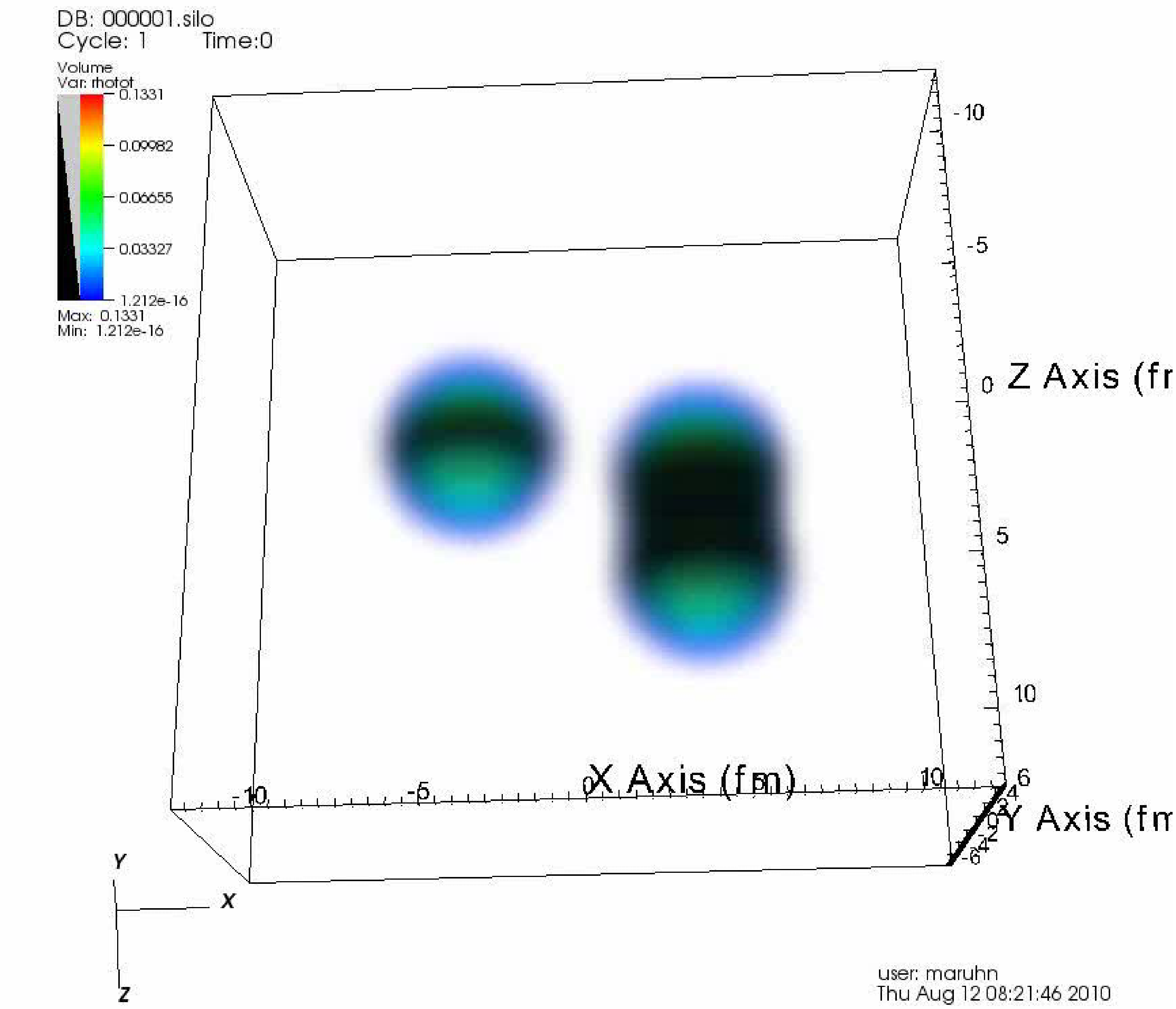


FIG. 4: Time spent in the linear chain configuration as a function of the impact parameter b for the ^{4}He+^{8}Be system at $E_{c.m.} = 2$ MeV and $\beta = 0^o$ alignment.

Linear chain states can be excited even in the case of finite impact parameters?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Volume
Var: rhotot
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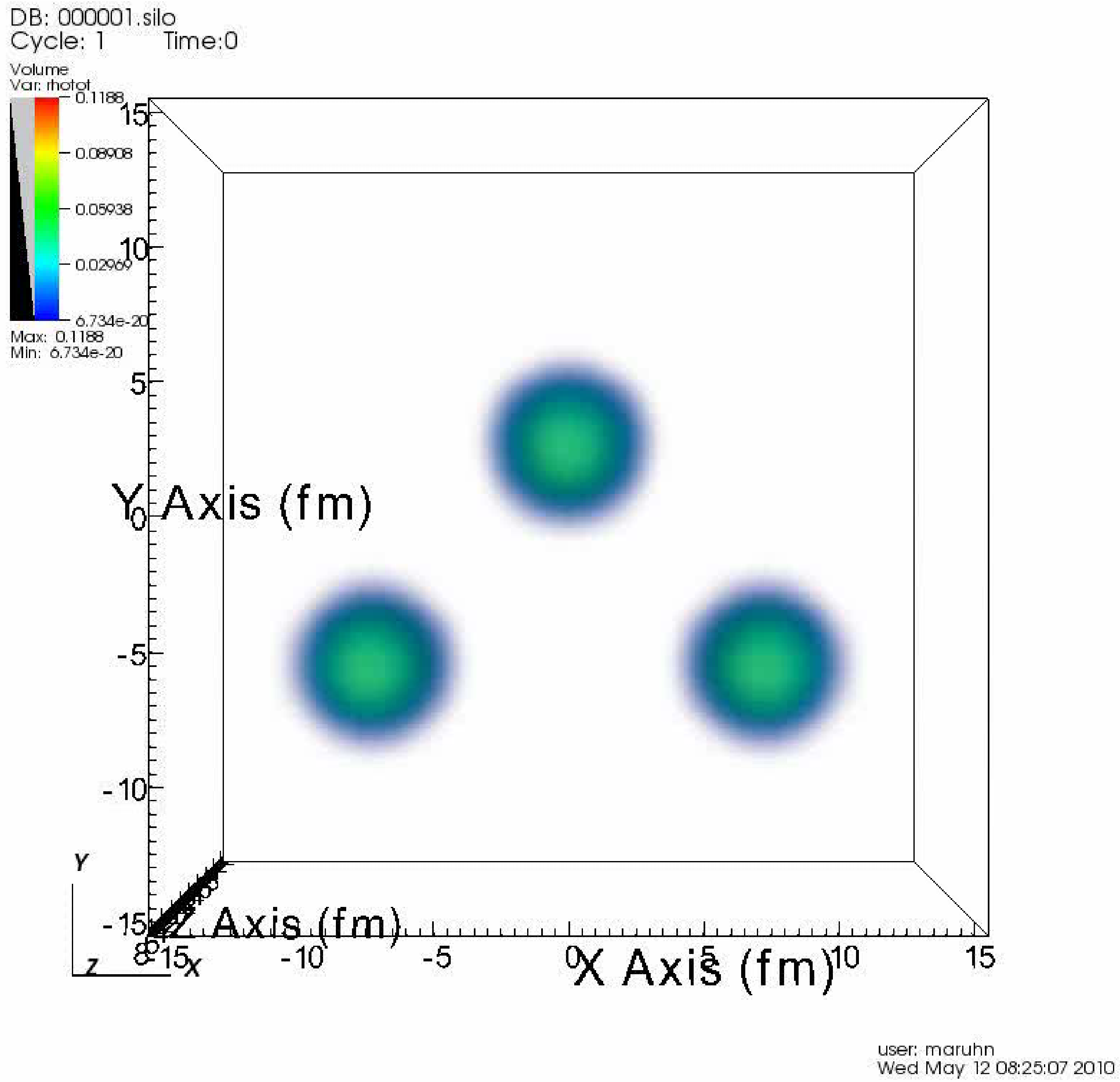
0.09982
0.06655
0.03327
1.212e-16
Max: 0.1331
Min: 1.212e-16
Z Axis (fr
X Axis (fm)
Y Axis (fm
user: maruhn
Thu Aug 12 08:21:46 2010



DB: 000001.silo
Cycle: 1 Time:0
Volume
Var: rhotot
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0.08908
0.05938
0.02969
6.734e-20
Max: 0.1188
Min: 6.734e-20
Y Axis (fm)
Z Axis (fm)
X Axis (fm)
15
10
5
0
-5
-10
-15
user: maruhn
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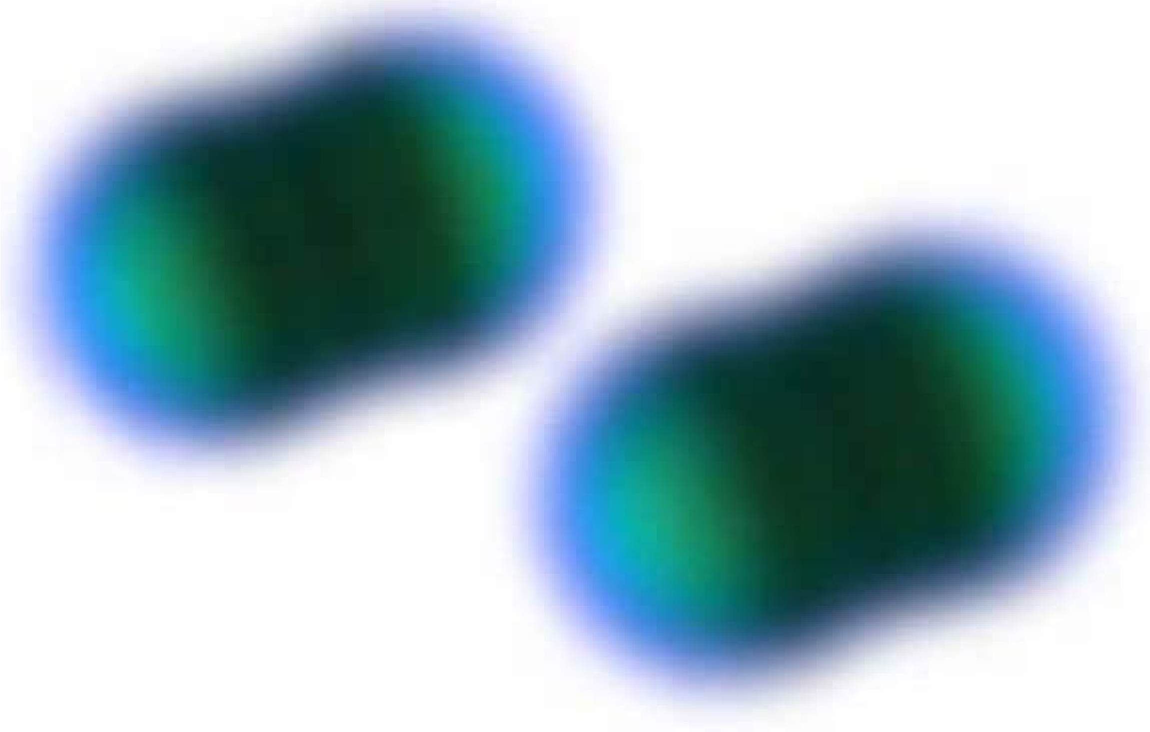

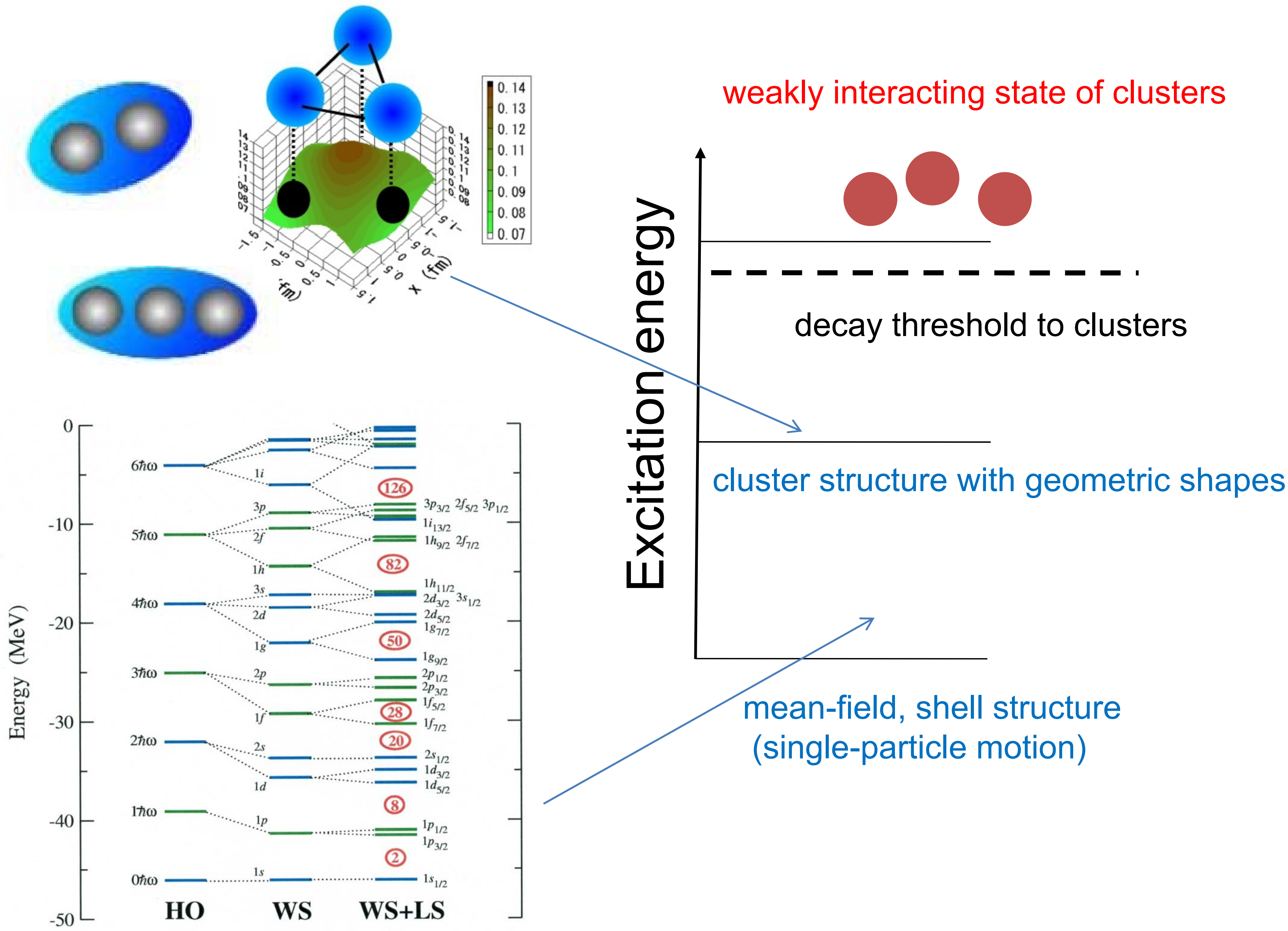

weakly interacting state of clusters
Excitation energy
decay threshold to clusters
cluster structure with geometric shapes
mean-field, shell structure
(single-particle motion)
Energy (MeV)
0
-10
-20
-30
-40
-50
HO
WS
WS+LS
2
8
20
28
50
82
126

Alpha Cluster Condensation in ^{12}C and ^{16}O

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[4]*FB Physik, Universität Rostock, D-18051 Rostock, Germany*

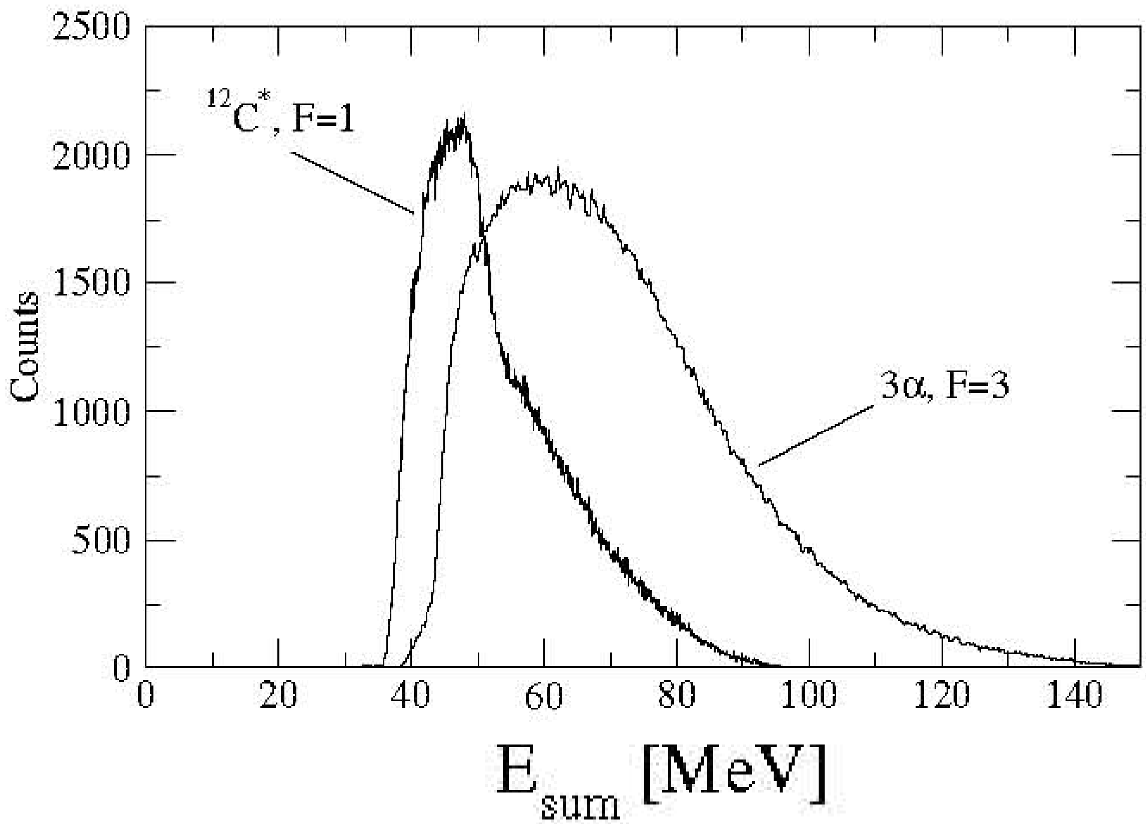
$$\begin{aligned}\Phi = & \int d\vec{R}_1 d\vec{R}_2 \cdots d\vec{R}_n \\ & \mathcal{A}\ G_1(\vec{R}_1)G_2(\vec{R}_2)G_3(\vec{R}_3)\cdots G_n(\vec{R}_n) \\ & \times \exp[-(\vec{R}_1^2+\vec{R}_2^2+\vec{R}_3^2\cdots\vec{R}_n^2)/\sigma^2] \\ = & \ \mathcal{A}\prod_{i=1}^{n}\int d\vec{R}_i\ G_i(\vec{R}_i)\exp[-\vec{R}_i^2/\sigma^2],\end{aligned}$$

THSR wave function

Discussion for the gas-like state of alpha's moves on to the next step – to heavier regions

Gas-like state of three alpha's around ^{40}Ca?

Tz. Kokalova et al. Eur. Phys. J A23 (2005)



^{28}Si+^{24}Mg
→ ^{52}Fe

Enhancement of emission of gas-like states from the compound state in low-energy regions compared with the sequential α emission

Is it due to the lowing of the Coulomb barrier for the gas-like state?

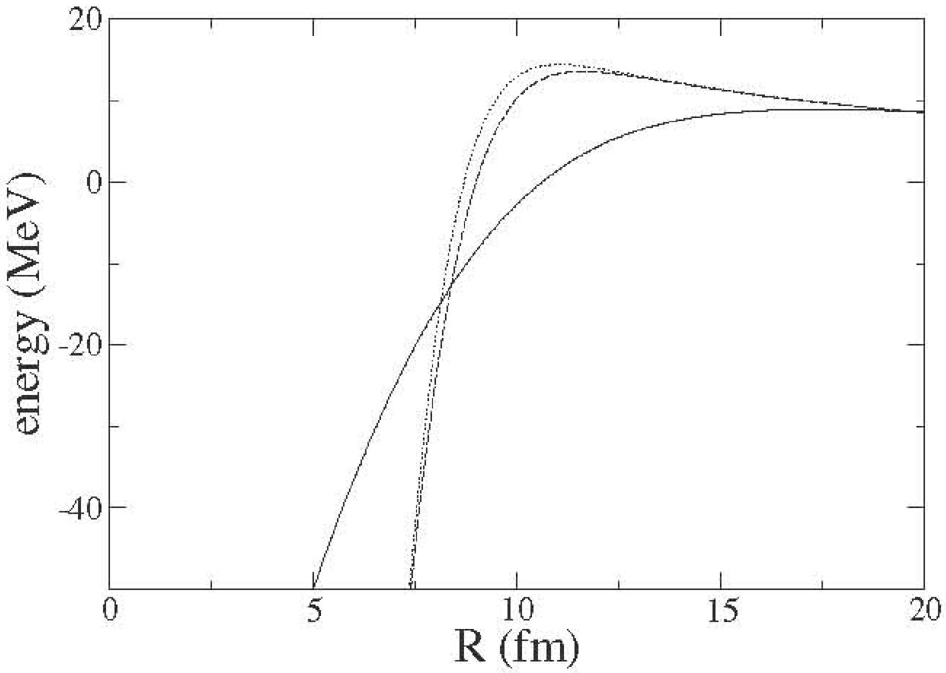


FIG. 1. The folded potential (V in the text) for ^{12}C emission as a function of the distance (R in the text) between the ^{12}C and the ^{40}Ca core. The solid, dashed, and dotted lines correspond to the condensed, cluster, and ground states of ^{12}C, respectively.

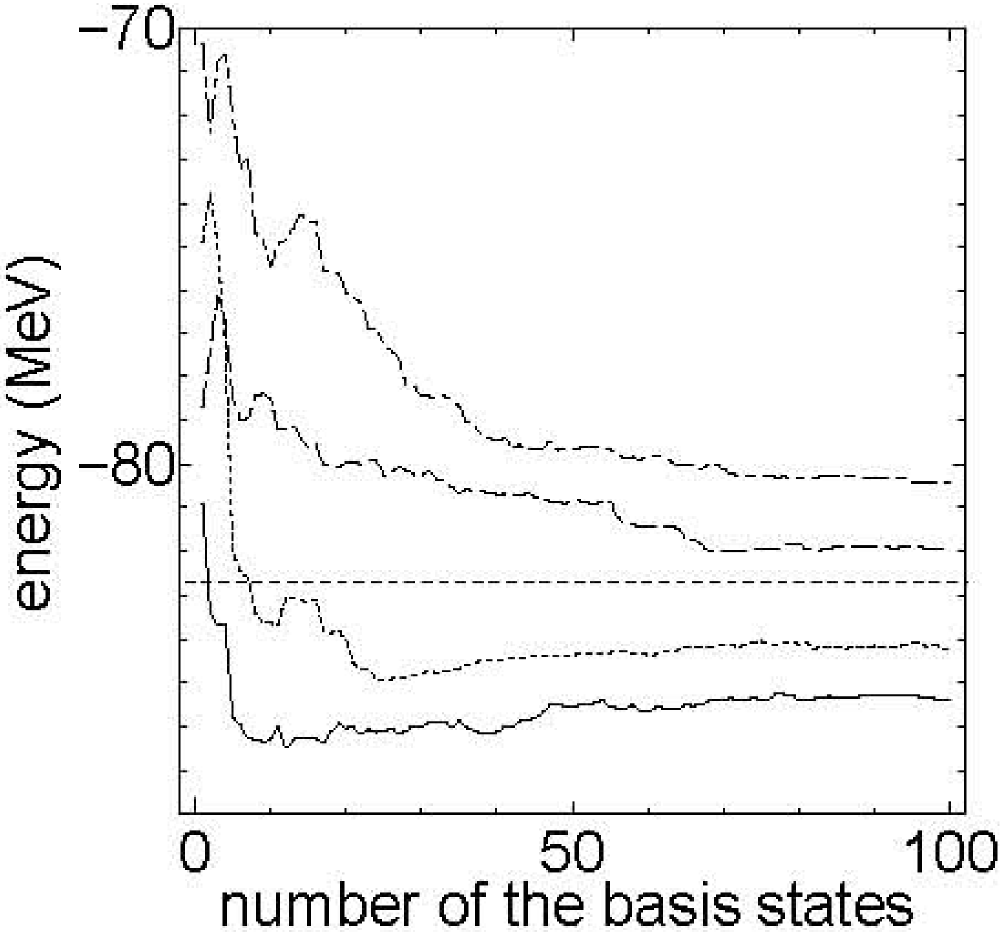
Tz. Kokalova, N.Itagaki, C. Wheldon, and W von Oertzen, PRL 96 (2006)

To apply THSR wave function to heavier systems, we must simplify it

Integral over {**R**i} in the THSR wave function is performed by Monte Carlo integration

Virtual THSR wave function

N.Itagaki., M. Kimura, M. Ito, C. Kurokawa, and W. von Oertzen, Phys. Rev. C **75** 037303 (2007)



3α

Solid, dotted, dashed, dash-dotted → σ = 2,3,4,5 fm

r.m.s. radius of ^{12}C (fm)

$\sigma = 3$	$\sigma = 4$	$\sigma = 5$	Micro	Cond
3.06	3.60	4.38	3.47	3.83

Alpha cluster state around ^{40}Ca core

N. Itagaki, Tz. Kokalova, and W. von Oertzen, Phys. Rev. C **82**.014312 (2010).

$$\Psi = \sum_{k=1}^{m} P^{\pi} P^{J}_{MK} \Psi_k ,$$

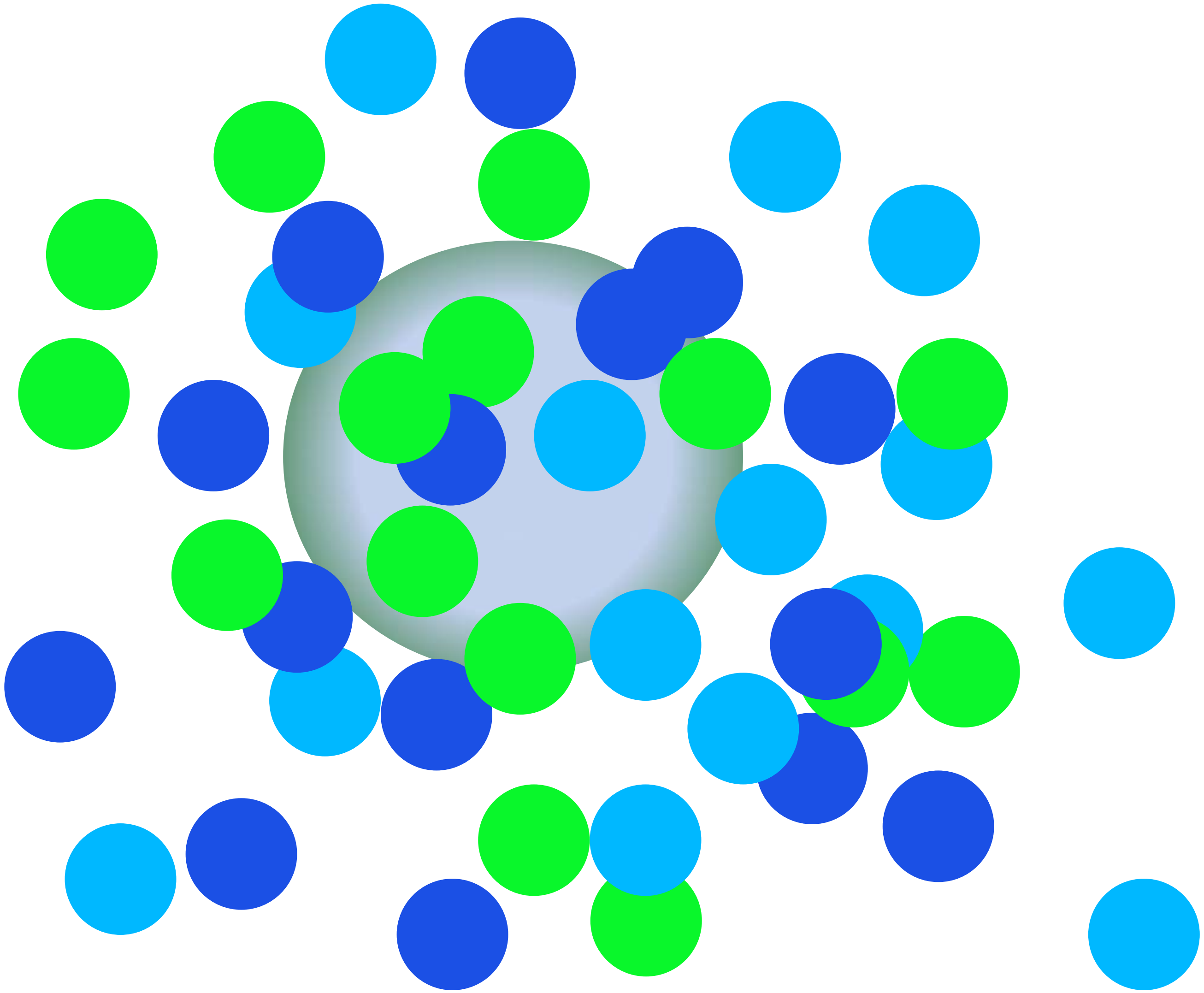
$$\Psi_k = [\mathcal{A}\phi(^{40}\mathrm{Ca})\ G_1(\vec{r}_1, \vec{R}_1) G_2(\vec{r}_2, \vec{R}_2) G_3(\vec{r}_3, \vec{R}_3)]_k$$

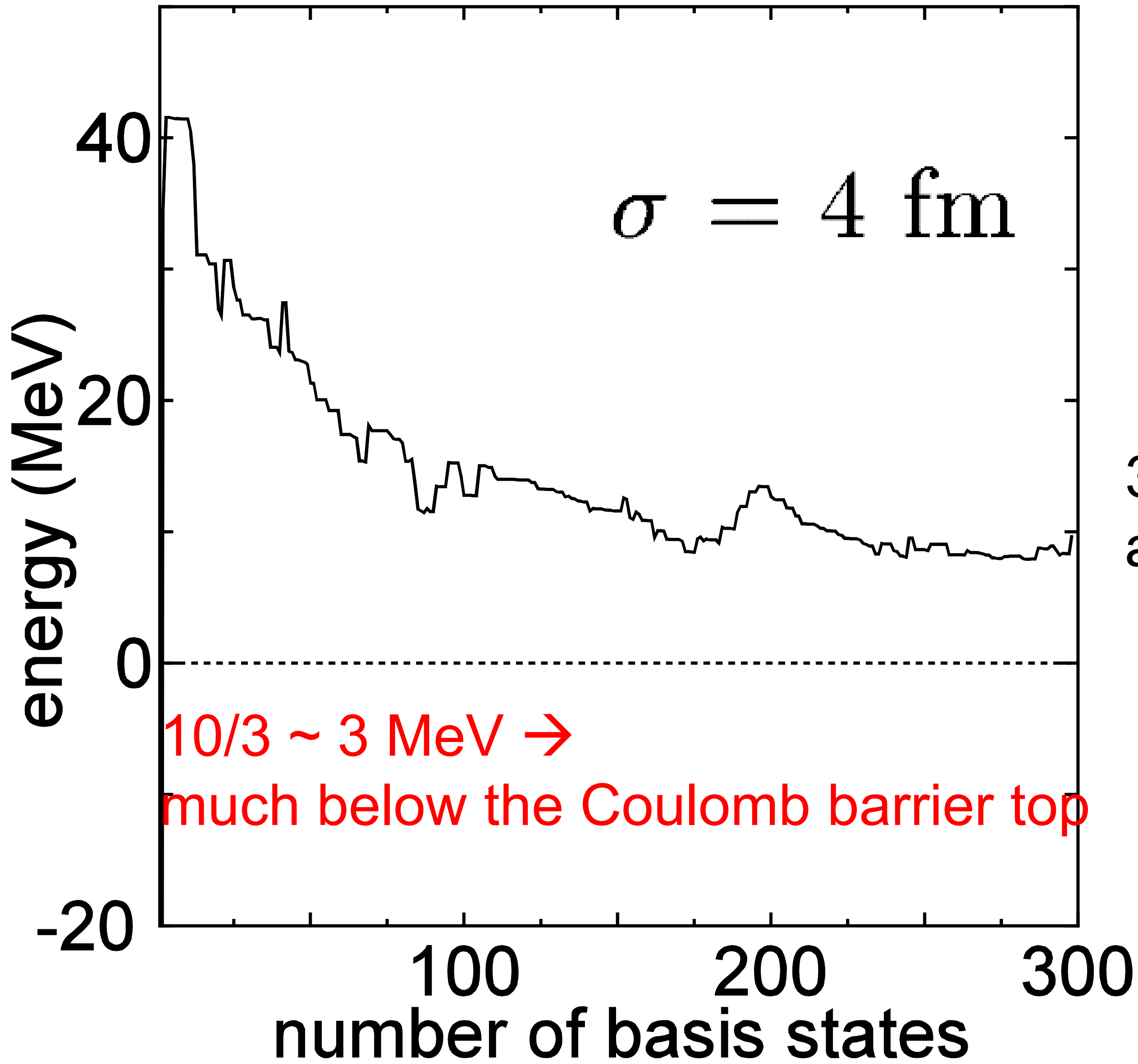
Gi = $\exp[-\nu(\vec{r}_i - \vec{R}_i)^2]$

Gaussian centre parameters ($\{\vec{R}_i\}$) are randomly generated by the weight function W with a Gaussian shape:

$$W(\vec{R}_i) \propto \exp[-\vec{R}_i^2/\sigma^2].$$

Concept of the virtual THSR wave function





3alpha state
around ^{40}Ca core

N. Itagaki, Tz. Kokalova, and W. von Oertzen, Phys. Rev. C **82**.014312 (2010).

Potential +Coulomb energy for one alpha around ^{40}Ca

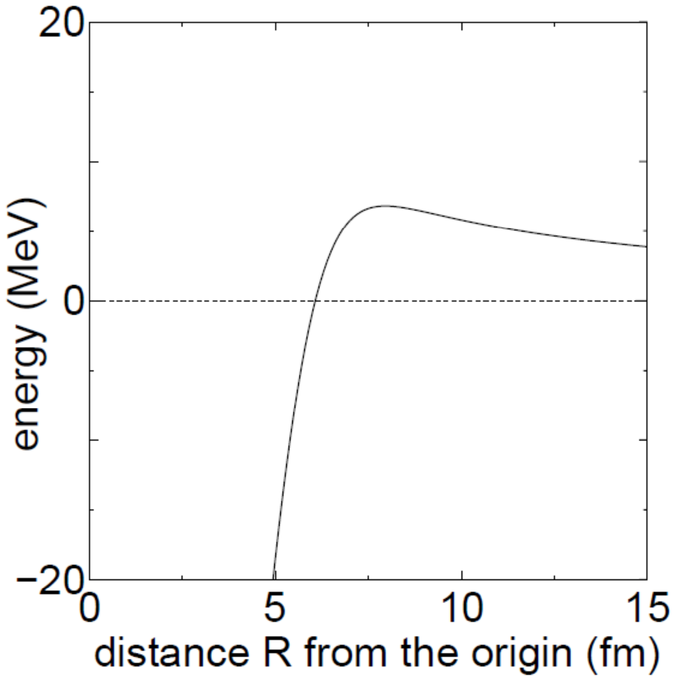


FIG. 1: The expectation value of potential plus Coulomb energies for the relative motion between one α cluster and ^{40}Ca as a function of relative distance R (fm) (before the angular momentum projection).

THSR wave function

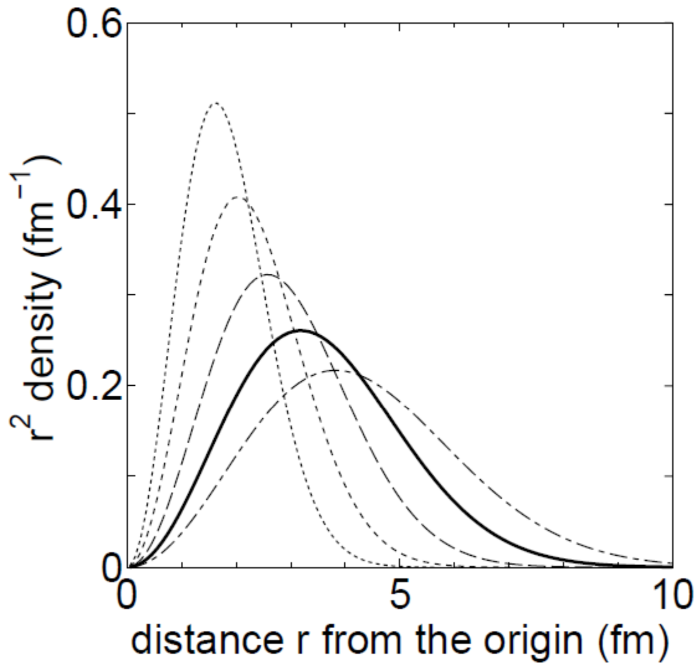


FIG. 2: Density distribution of THSR wave function. This is the case of only one α cluster without the ^{40}Ca core. The densities are multiplied by r^2. The cases from $\sigma = 1$ fm (dotted line) to 5 fm (dash-dotted line) with a step of 1 fm are shown. The solid line is for $\sigma = 4$ fm.

N. Itagaki, Tz. Kokalova, and W. von Oertzen, Phys. Rev. C **82**.014312 (2010).

Height of the Coulomb barrier, σ = 7 fm

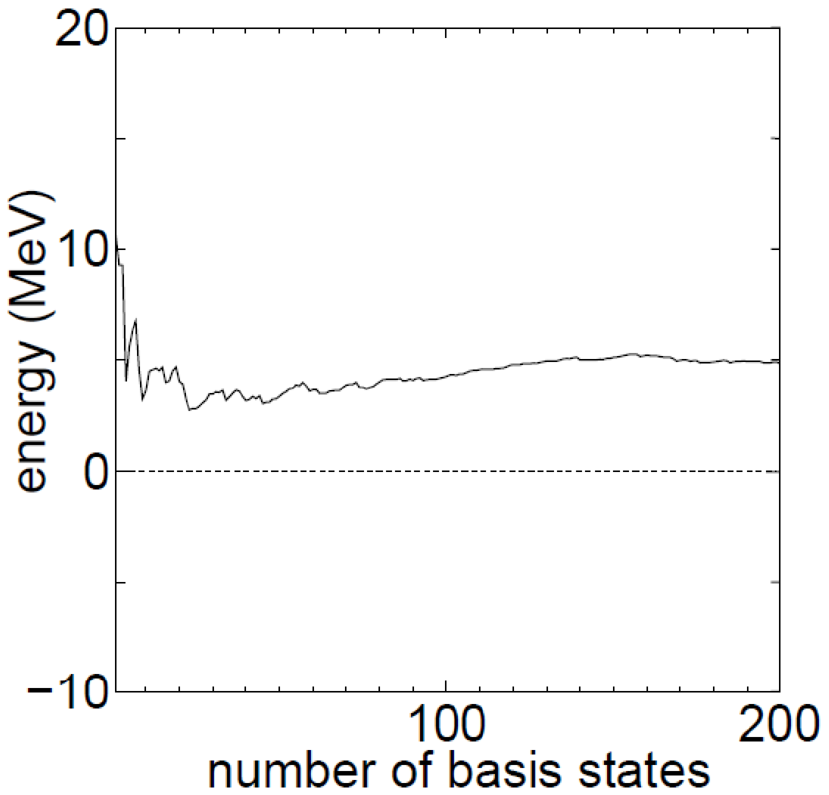
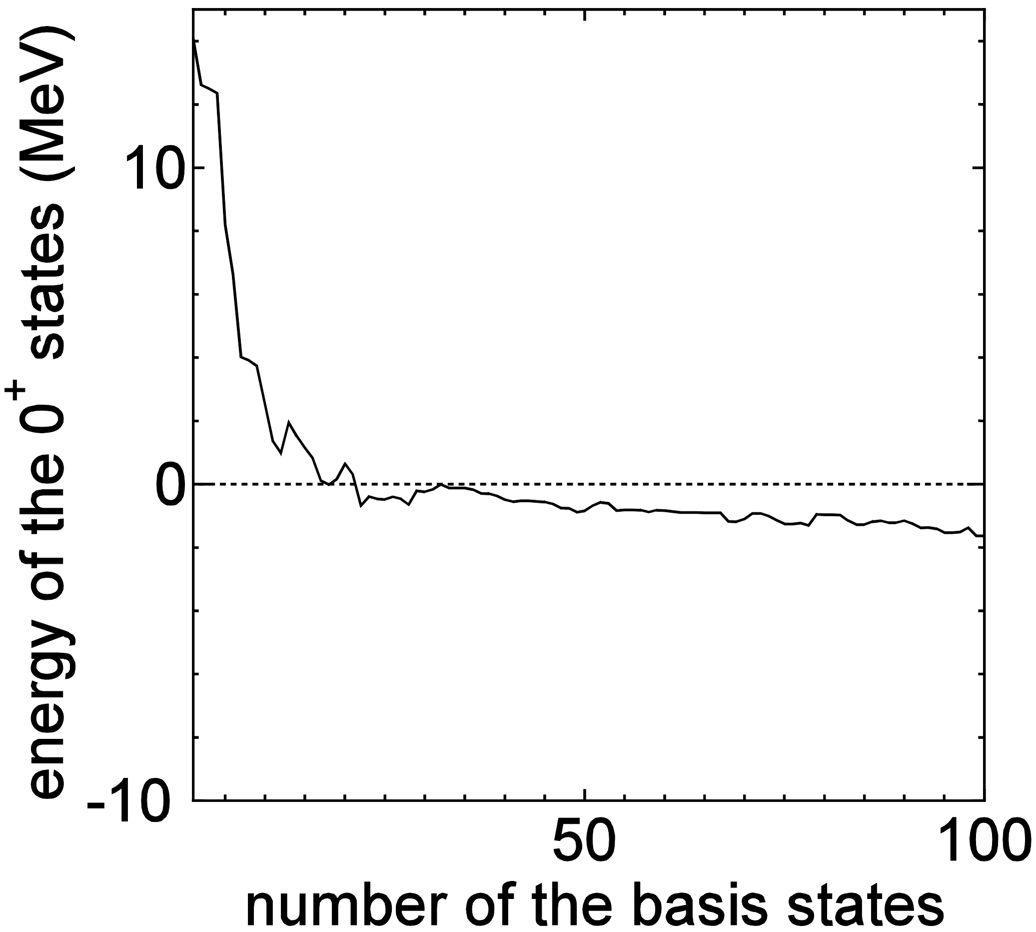


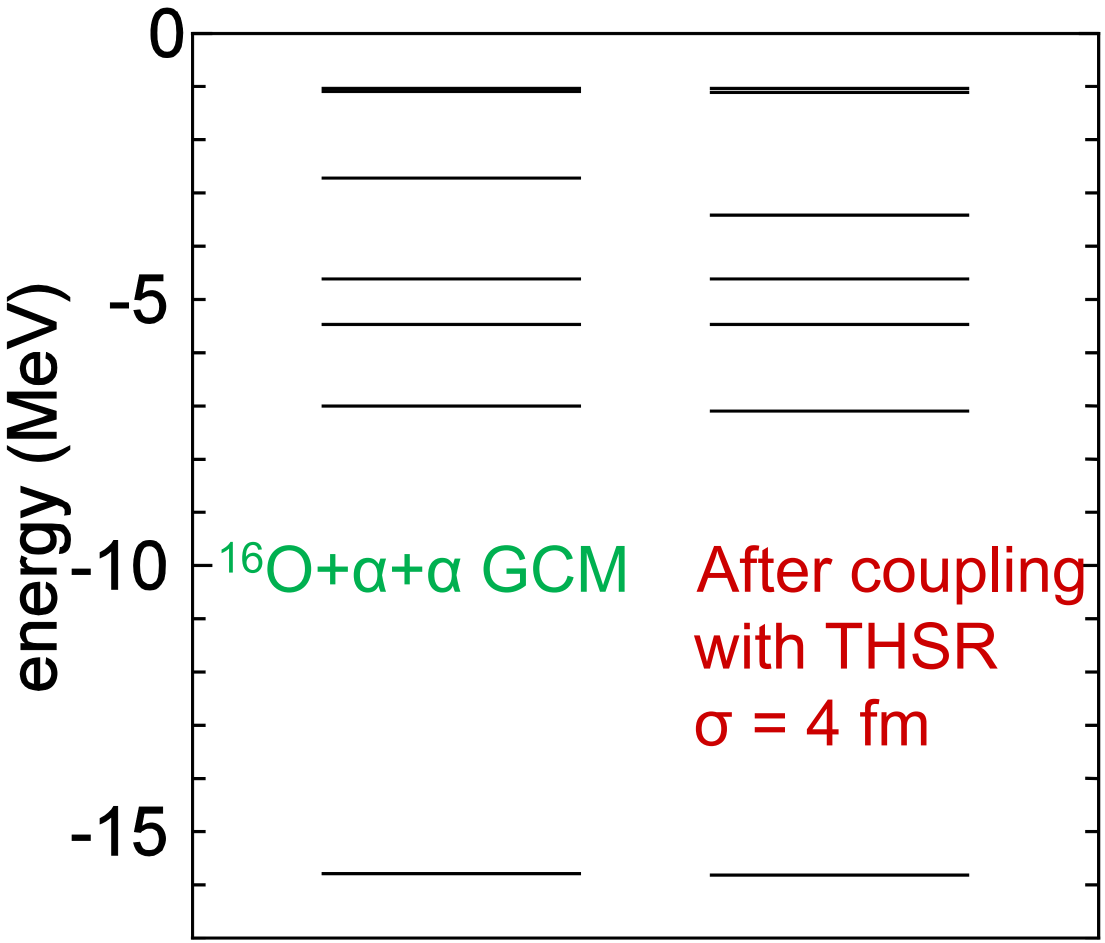
FIG. 5: The energy convergence of one α cluster around ^{40}Ca for the case of $\sigma = 7$ fm.

N. Itagaki, Tz. Kokalova, and W. von Oertzen, Phys. Rev. C **82**.014312 (2010).

$^{24}Mg = {}^{16}O+\alpha+\alpha$, σ = 4 fm



0^+ states of ^{24}Mg



Visitors of Yukawa Institute for Theoretical Physics, Kyoto University

- Peter Schuck (Orsay)

  28 November - 2 December 2010

- Joachim A. Maruhn (Frankfurt)

  JSPS short-term visitor, March 2011

- Pierre Descouvemont (Brussels)

  Guest professor of Kyoto University, FY2012 for 3 months

Conclusions

- Geometric configurations of clusters are stabilized by valence neutrons, and linear chain configurations of three alpha's are examples
- The study on Gas-like cluster state can be extended to heavier nuclei, and the three-alpha state around ^{40}Ca has the energy below the threshold energy when the spatial extension is comparable to the second 0^+ state of ^{12}C
- Coupling effect between the gas-like state and normal cluster states can be taken into account in the case of ^{16}O+2alpha's