Exotic structure of light nuclei

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JUSTIPEN workshop, Oak Ridge

Specific feature of nuclear systems

- Atomic nuclei

* Finite quantum systems consisting of P and N

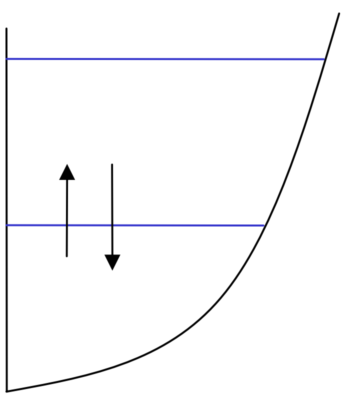
* These nucleons construct a self consistent mean field

* The nuclear interaction depends on the spin and isospin

* Non-central interaction plays an important role

* Magic number of the H.O. potential 2,8,20,40

LS → 2,8,28,50



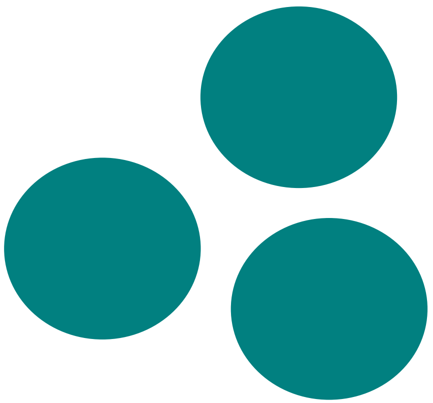
On the other hand…..

- ^{4}He is strongly bound (B.E. 28.3 MeV)
  Close shell configuration of the lowest shell

→ This can be a subunit of the nuclear system

If we assume each ^{4}He as $(0s)^4$
spatially localized at different position

α-cluster model

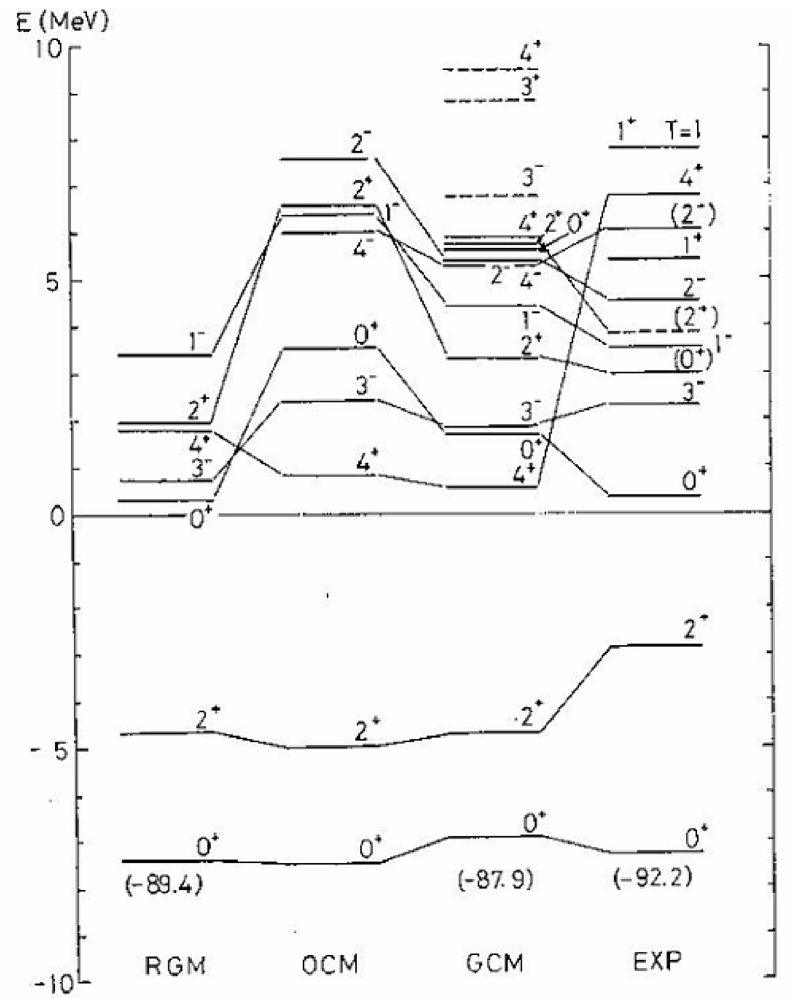


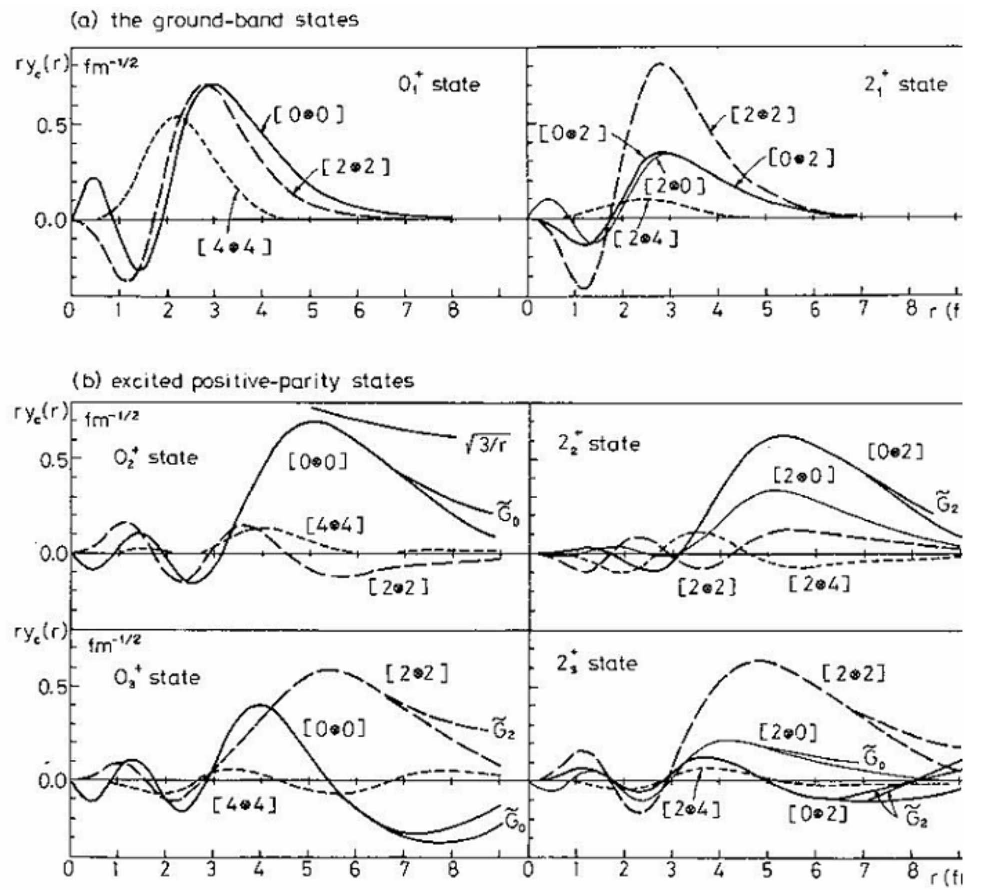
Non-central interactions do not contribute
although the origin of strong binding of α
is due to the tensor force (-68 MeV)
→ we consider that this is renormalized in the central part

Examples of 3αcalculations

3α calculations by RGM, GCM, OCM
Supplement of PTP 82 (1980)

M. Kamimura, NP A351 (1981)

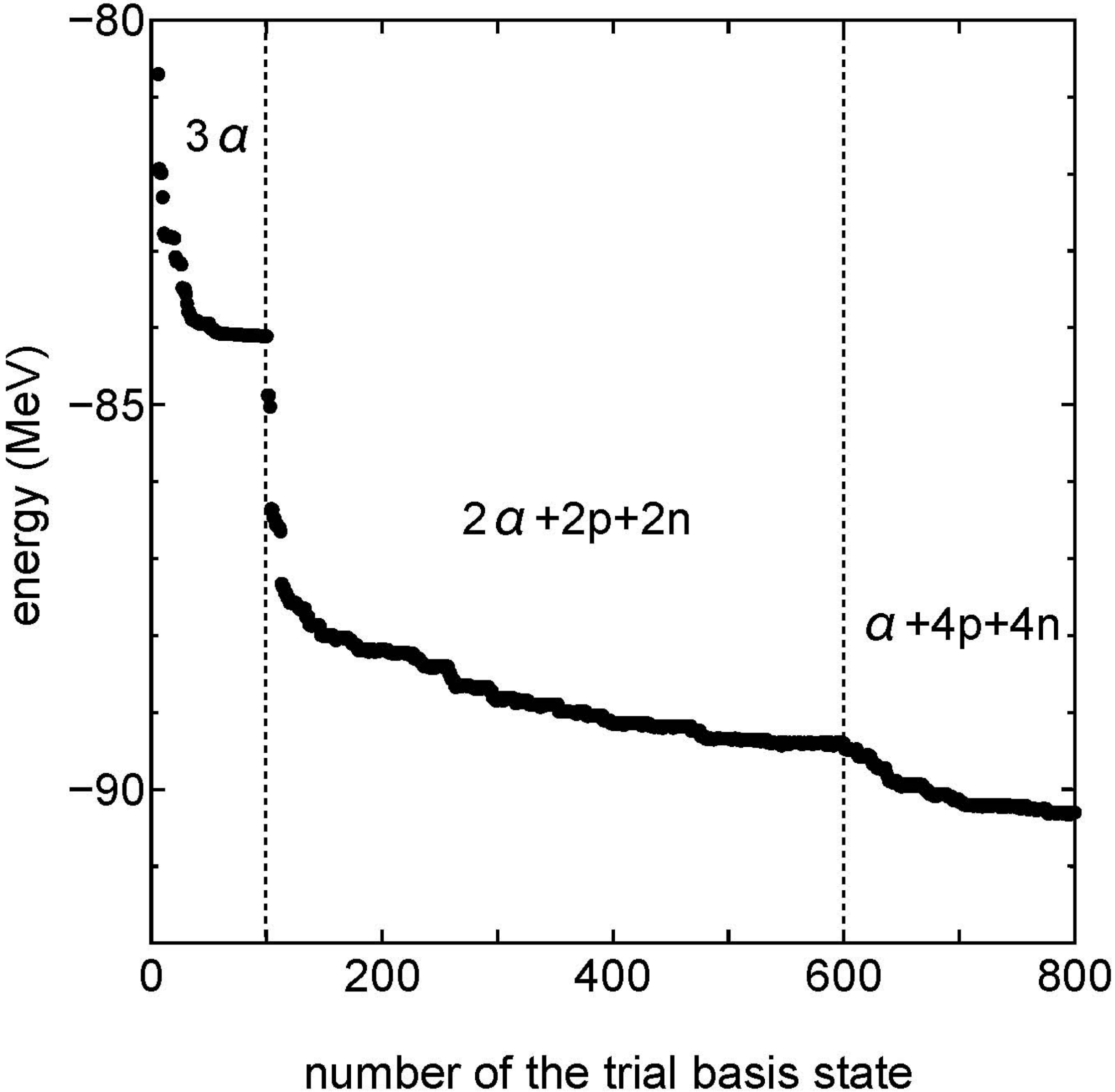




The mechanism to break the cluster structure

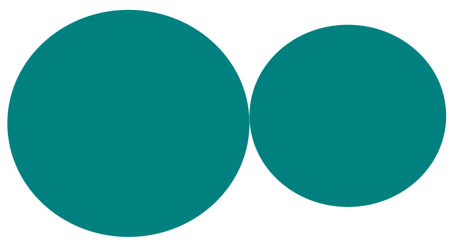
“dissolution” of the custers

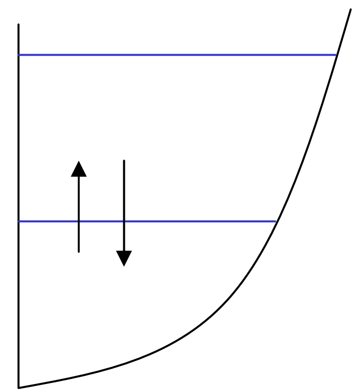
$^{12}C\ 0^+$ energy convergence



N. Itagaki, S. Aoyama, S. Okabe, and K. Ikeda, PRC70 (2004)

• How we can express the cluster-shell competition in a simple way as a general concept of the nuclear structure?





What is the order parameter of the transition?

How the effect of the spin-orbit interaction can be implanted in the wave function?

We introduce a general and simple model to describe this transition by only introducing a parameter Λ

We can include the contribution of the spin-orbit interaction in a very simplified way:

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

r → Gaussian center parameter

p → imaginary part of the Gaussian center parameter

We transform the Gaussian center parameter **R** as:

$$\mathbf{R} \rightarrow \mathbf{R} + \Lambda(i\,\mathbf{S}\times\mathbf{R})$$

Simplified Method to include the Spin-orbit Interaction (SMSO)

N. Itagaki, H. Masui, M. Ito, and S. Aoyama, Phys. Rev. C 71 (2005) 064397

Hamiltonian

$$\hat{H} = \sum_{i=1} \hat{t}_i - \hat{T}_{c.m.} + \sum_{i>j} \hat{v}_{ij},$$

2-body effective interaction

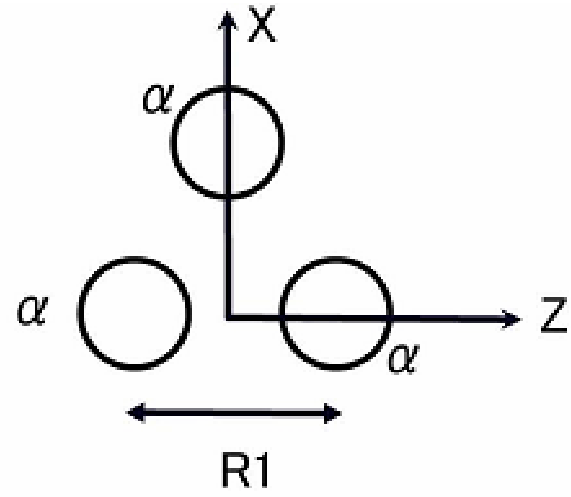
$$V(r) = \quad (W - M P^\sigma P^\tau + B P^\sigma - H P^\tau) \\ (V_1 \exp(-r^2/c_1^2) + V_2 \exp(-r^2/c_2^2)),$$

where $W = 1 - M$, $M = 0.60$ and $B = H = 0.125$. For the spin-orbit term, we introduce the G3RS potential[38] as

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

where $d_1 = 5.0$ fm^{-2}, $d_2 = 2.778$ fm^{-2}, $V_0 = 2000$ MeV,

^{12}C case



1: Place the α-cluster to be broken on the x-axis

FIG. 4: The coordinate system for ^{12}C. Three α-clusters have an equilateral triangular configuration on the xz-plane. R_1 represents the distance between two α-clusters on the z-axis and remaining α-cluster is placed on the x-axis.

2: Change the Gaussian Center of this cluster from $R\,\mathbf{e}_x \rightarrow R\,(\mathbf{e}_x \pm i\Lambda\mathbf{e}_y)$

+ → spin-up

- → spin-down

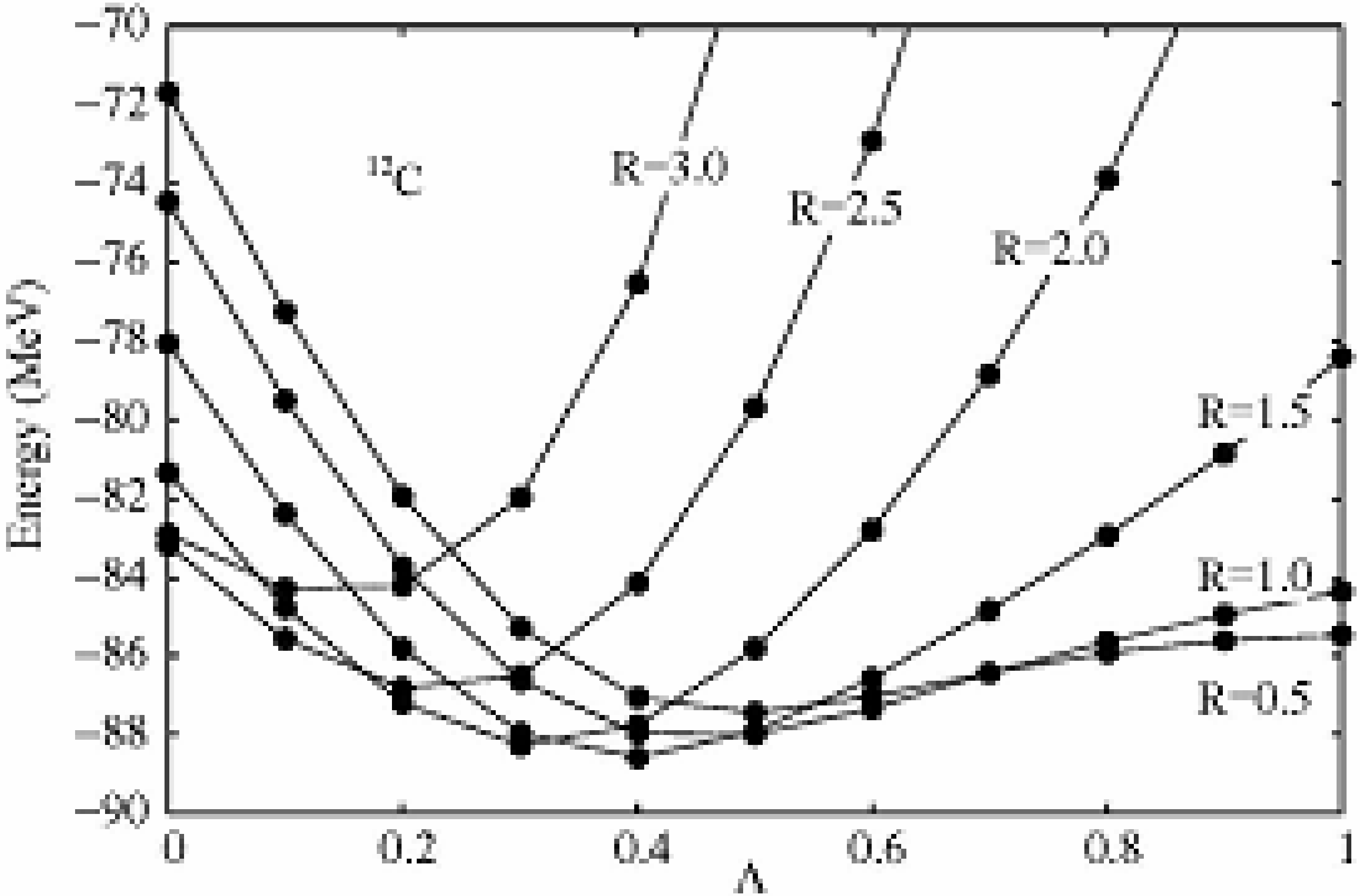
We introduce Λ for one α-cluster on the x axis. Similarly to Eqs. (7) and (8), the $\vec{z}$ parameters of the spin-up proton and spin-up neutron are changed to have the imaginary parts with a positive value

$$\vec{z}/\sqrt{\nu} = (\sqrt{3}R_1/2)(\vec{e}_x + i\Lambda\vec{e}_y), \tag{9}$$

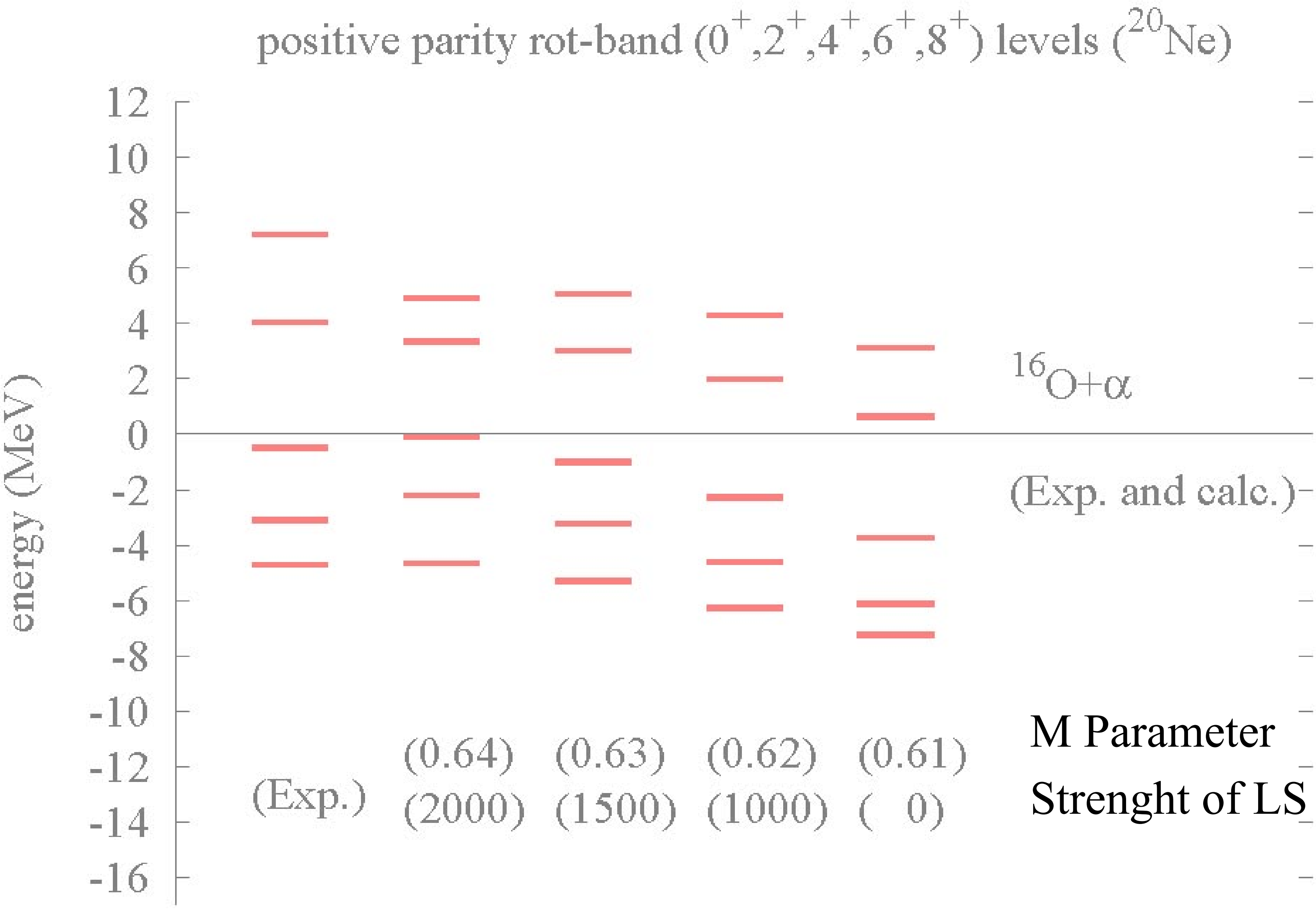
and those for the spin-down proton and spin-down neutron are changed to have the imaginary parts with a negative value

$$\vec{z}/\sqrt{\nu} = (\sqrt{3}R_1/2)(\vec{e}_x - i\Lambda\vec{e}_y). \tag{10}$$

^{12}C case



Energy (MeV)
Λ
12C
R=3.0
R=2.5
R=2.0
R=1.5
R=1.0
R=0.5
-70
-72
-74
-76
-78
-80
-82
-84
-86
-88
-90
0
0.2
0.4
0.6
0.8
1


positive parity rot-band (0+,2+,4+,6+,8+) levels (20Ne)
energy (MeV)
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
16O+α
(Exp. and calc.)
(Exp.)
(0.64)
(2000)
(0.63)
(1500)
(0.62)
(1000)
(0.61)
(0)
M Parameter
Strenght of LS

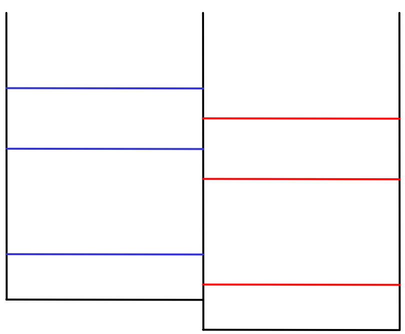
In weakly bound (low-density) systems,
strongly bound subsystems become important than uniform distribution

α-correlation is always important in neutron-rich nuclei?

Of course “not always”

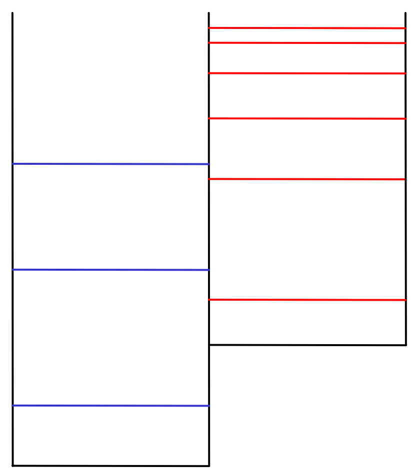
Normal nuclei

proton neutron



Neutron-rich nuclei

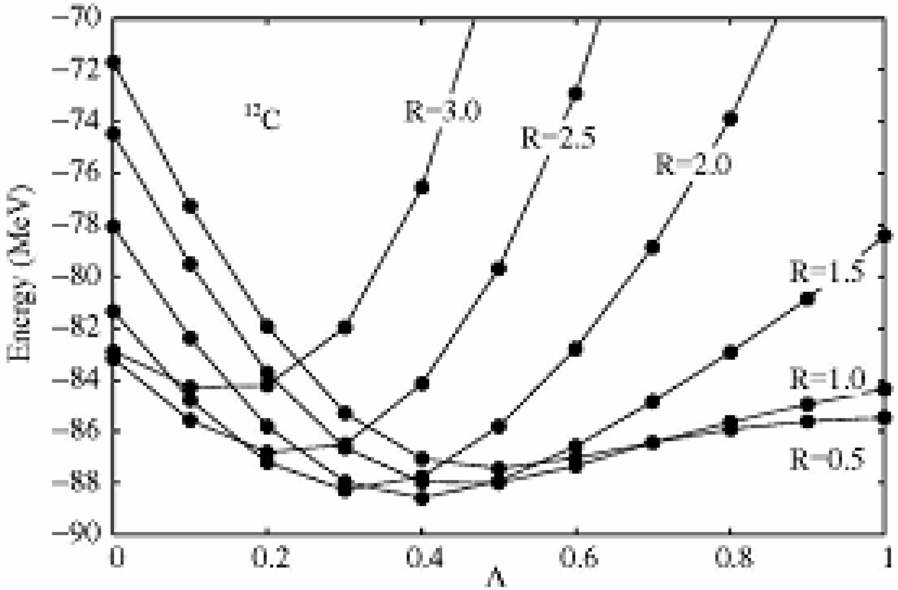
proton neutron



In neutron-rich nuclei,
protons are deeply bound
↓
Cluster-distance shrinks

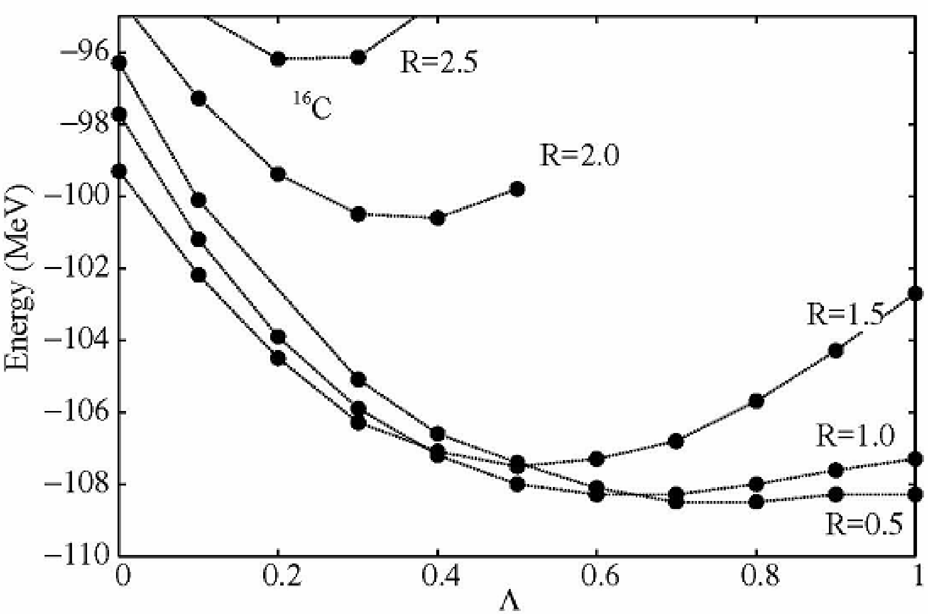
glue-like role of Λ
in hyper nuclear systems

Also, cluster structure
disappears due to
the spin-orbit interaction



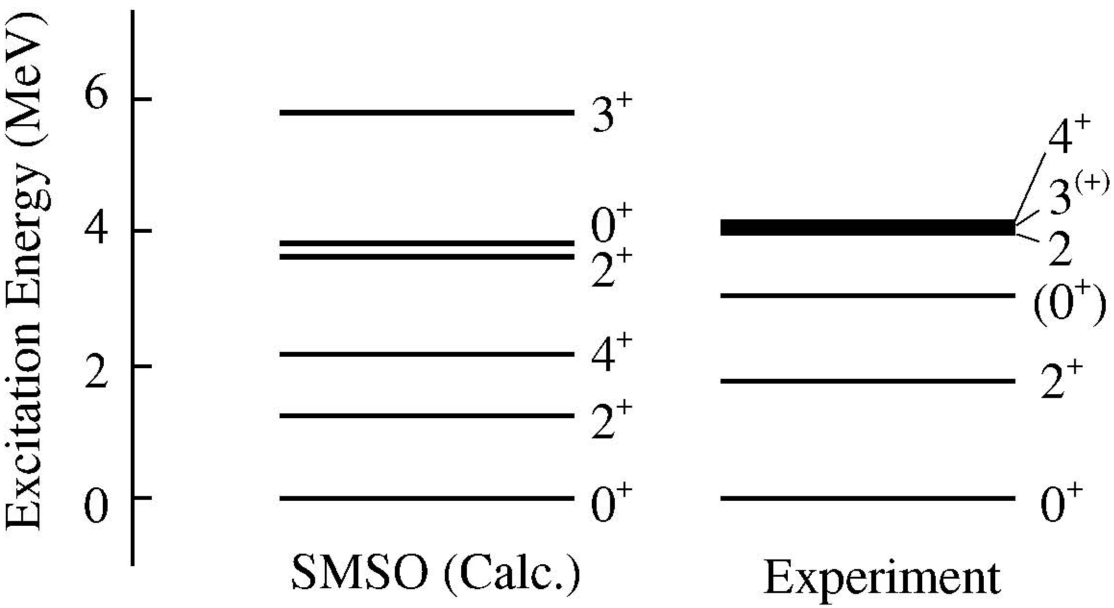
^{12}C

H. Masui and N.I.
submitted to PRC



^{16}C

Levels of ^{16}C



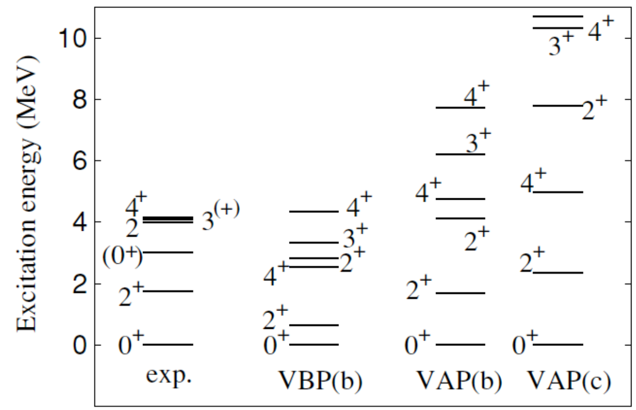
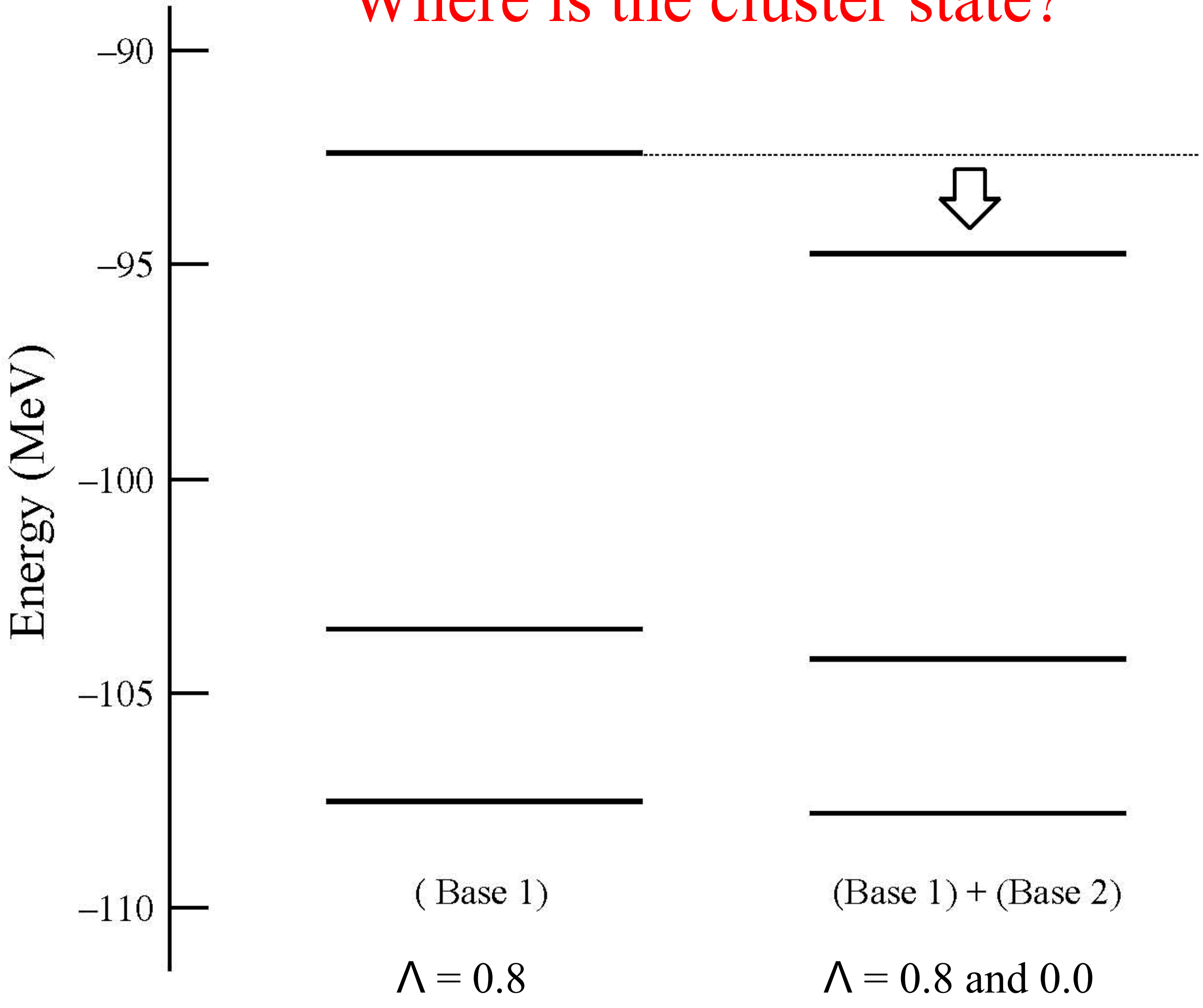


FIG. 5. Level scheme of the low-lying states of ^{16}C. The theoretical results obtained by the VAP and VBP calculations with the interaction parameter set (b) as in case 3 of MV1 with $m = 0.576$, $u_{ls} = 1500$ MeV and parameter set (c) as in case 1 of MV1 with $m = 0.62, u_{ls} = 3000$ MeV are illustrated with the experimental data.

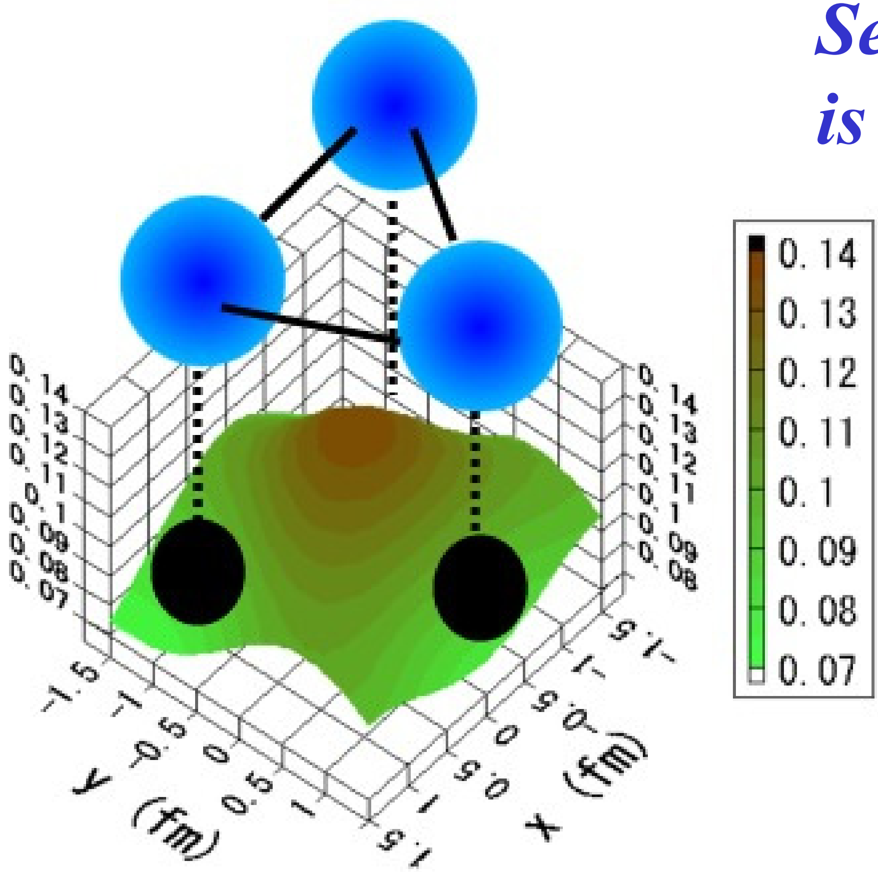
Y. Kanada-En'yo, PRC71 (2005), 014310.

Where is the cluster state?



0^+ states of ^{16}C

Equilateral triangular shape of 3α with valence neutrons



Second 0⁺ state of ¹²C is gas-like state of 3α

Second 0^+ band of ^{14}C is a candidate to have this configuration

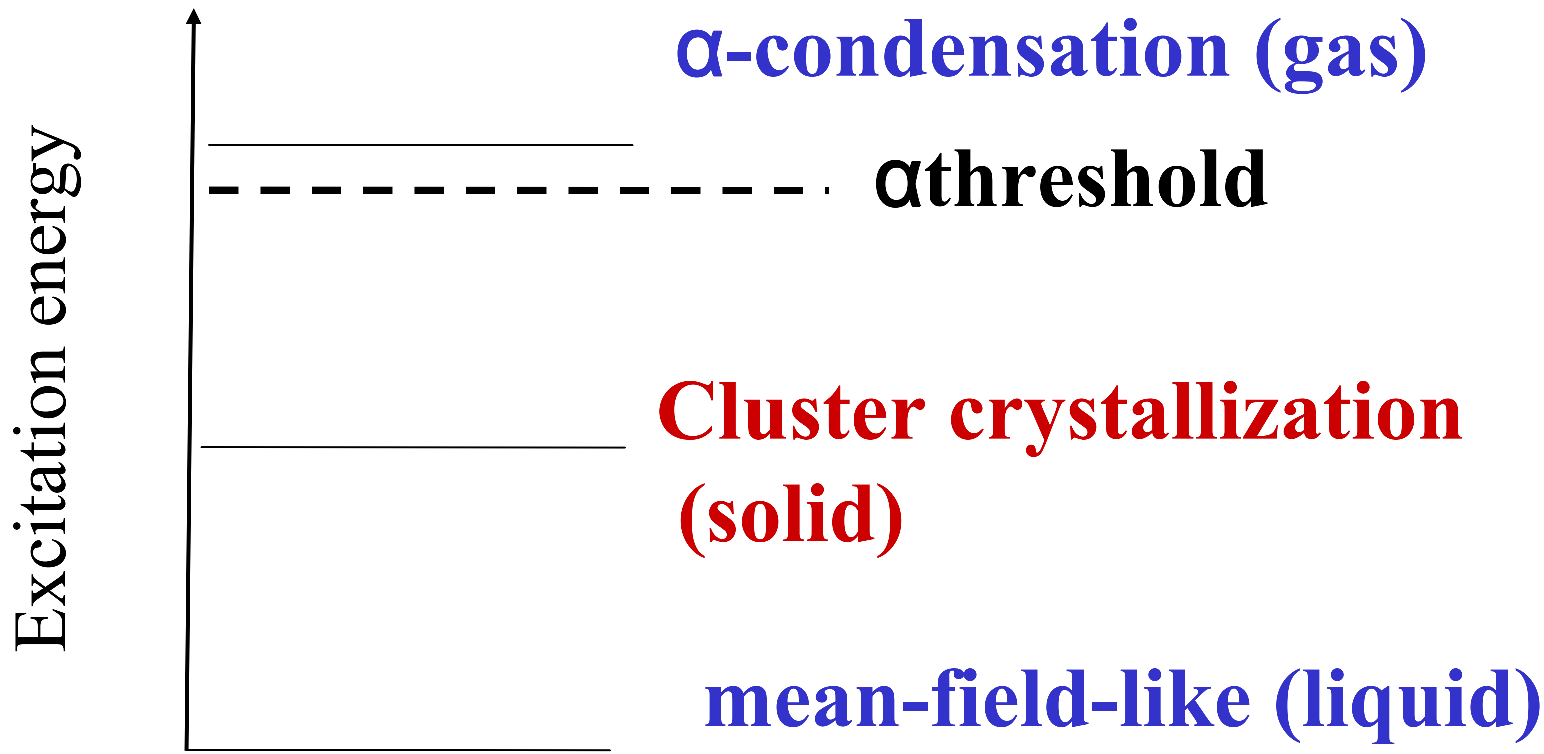
N. Itagaki, T. Otsuka, K. Ikeda, and S. Okabe, PRL 04 (2004) 142501

B(E2) values ($2^+ \rightarrow 0^+$ e^2fm^4)

^{12}C	6.49	(8.2±0.1)
^{14}C	5.06	(3.74±0.5)
^{16}C	0.67	(0.63)

effective charge
1.3e for protons
0.4e for neutrons

“Phase” of nuclei



Direct inclusion of non-central interactions
(spin-orbit and tensor) and their competition

$$\textbf{Spin-orbit} = [\mathbf{L}\,\mathbf{S}]_{00}$$

$$\textbf{Tensor} = [\sigma^1 \sigma^2\, \mathbf{Y}_{2m}]_{00}$$

Non-central interactions do not contribute
in the Nα systems

To study intruder states or exotic structure (second 0^+ state of ^{12}C)

Starting with the cluster model

Cluster-shell competition

↓

extend the model space
to take into account
non-central interactions

Nuclear Structure Physics

↑ ↑ ↑

From the analyses on nucleon-nucleon interactions
(GFMC, NCSM, UMOA, Low-k)

Direct inclusion of the Tensor terms is the one of the first things to do for improving the interaction

2 features of the Tensor interaction:

- Shorter range part (strong)

  → this is the origin of strong binding of ^{4}He

  2nd-order perturbation (2p2h) like

- Longer range part (weak)

  → this gives the energy levels correct J^πdependence

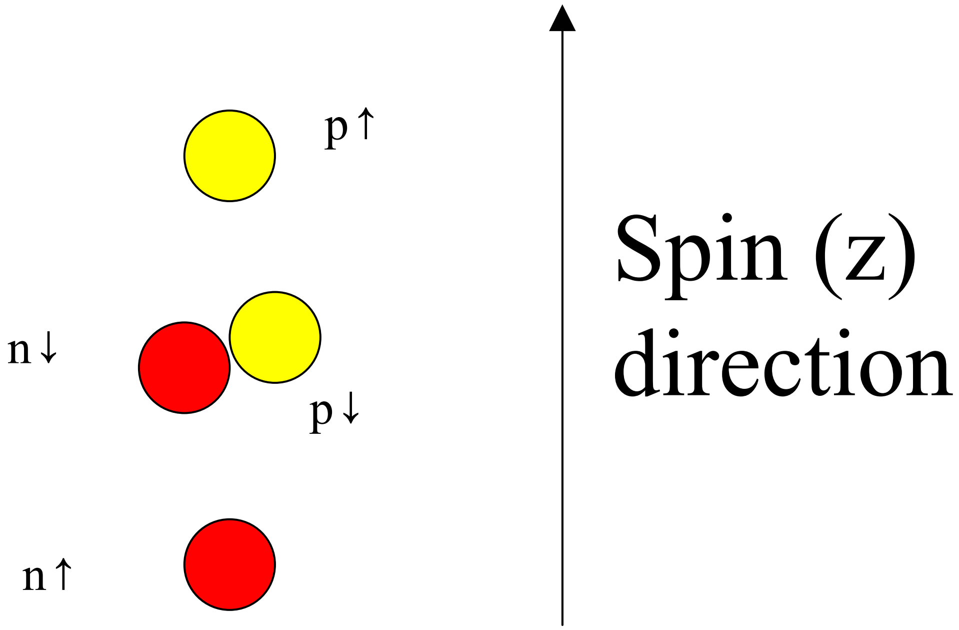
  1st-order perturbation like

How we can break the α cluster to take into account the (shorter range of) tensor contribution?

in a simple way

Model 1

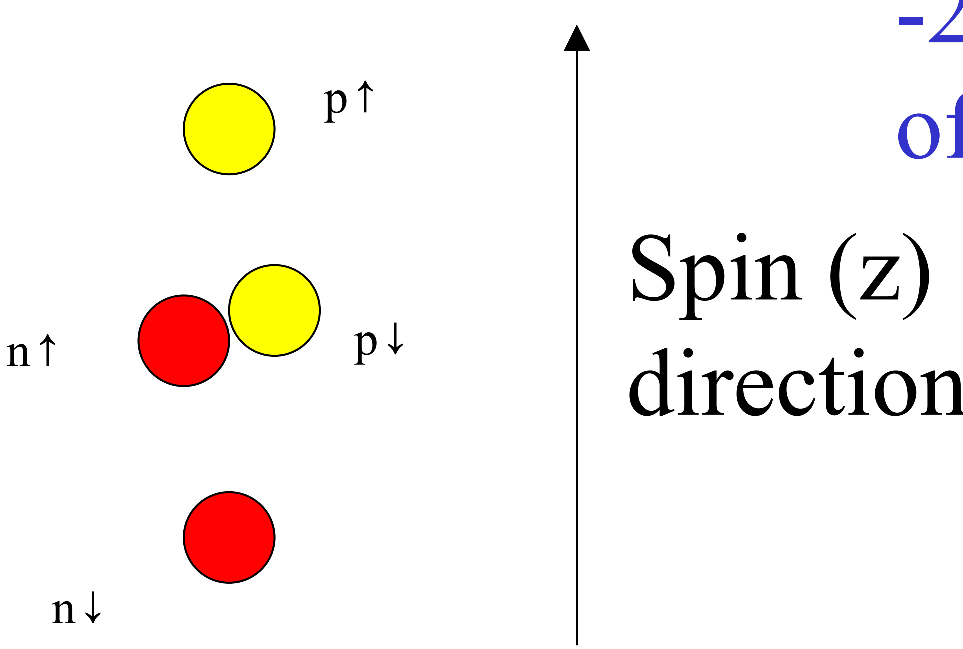
-31.03 MeV
compared to
-27.57 MeV
of the $(0s)^4$ model



Tensor interaction acts between
proton spin-up and neutron spin-up,
but it is cancelled by the presence of
spin-down neutron located in between them

Model 2

-33.83 MeV compared to -27.57 MeV of the $(0s)^4$ model



Simplified method to include Tensor contribution (SMT)

Transformation for ^{4}He

$$\vec{z}_{p\uparrow}/\sqrt{\nu} = d\vec{e}_z,$$

$$\vec{z}_{p\downarrow}/\sqrt{\nu} = 0,$$

$$\vec{z}_{n\uparrow}/\sqrt{\nu} = 0,$$

$$\vec{z}_{n\downarrow}/\sqrt{\nu} = -d\vec{e}_z.$$

"d" is from 0 to 7 fm in steps of 0.7 fm (11 basis states)

	E	T	V^c	V^{clm}	V^{ls}	V^t	r.m.s. radius
SMT	−33.83	53.23	−78.10	0.83	0.14	−9.92	1.66
$(0s)^4$	−27.57	43.77	−72.14	0.79	0	0	1.73
Exp.	−28.297						1.63 ± 0.03^a 1.40 ± 0.05^b

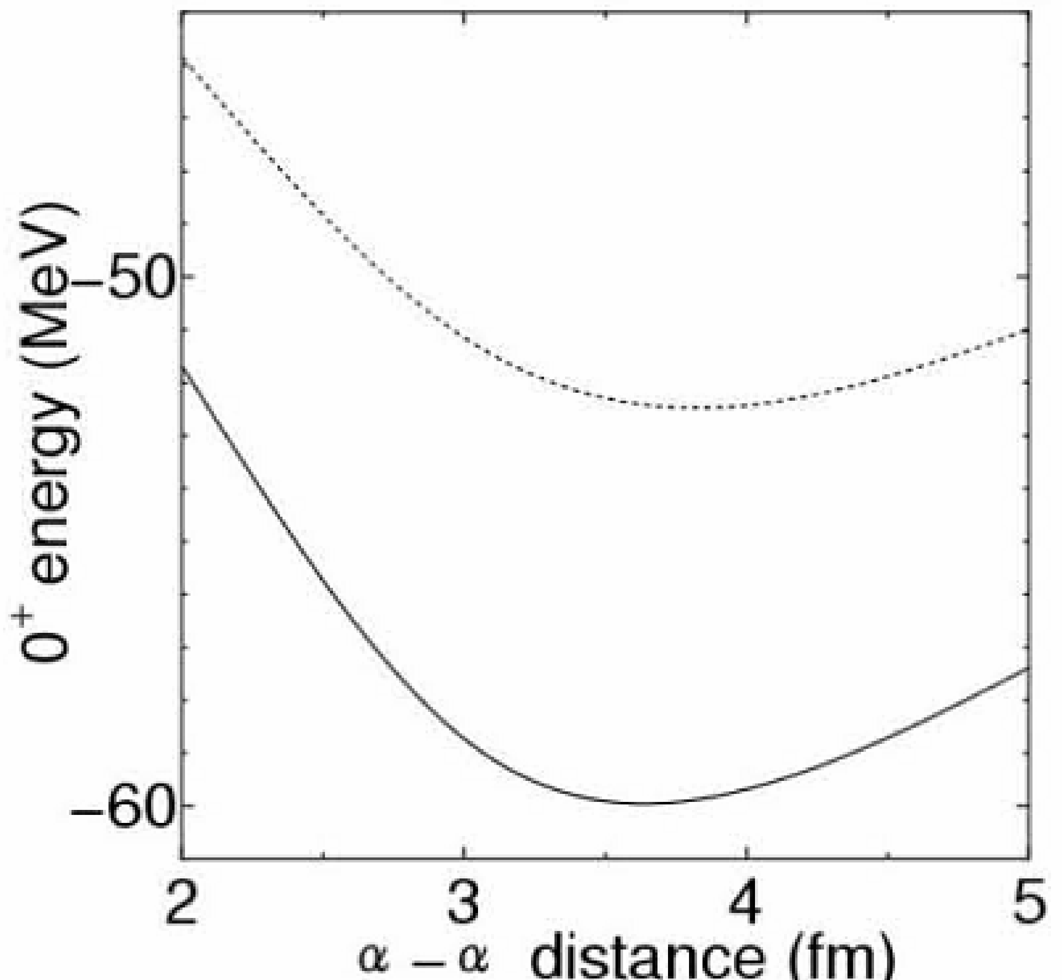


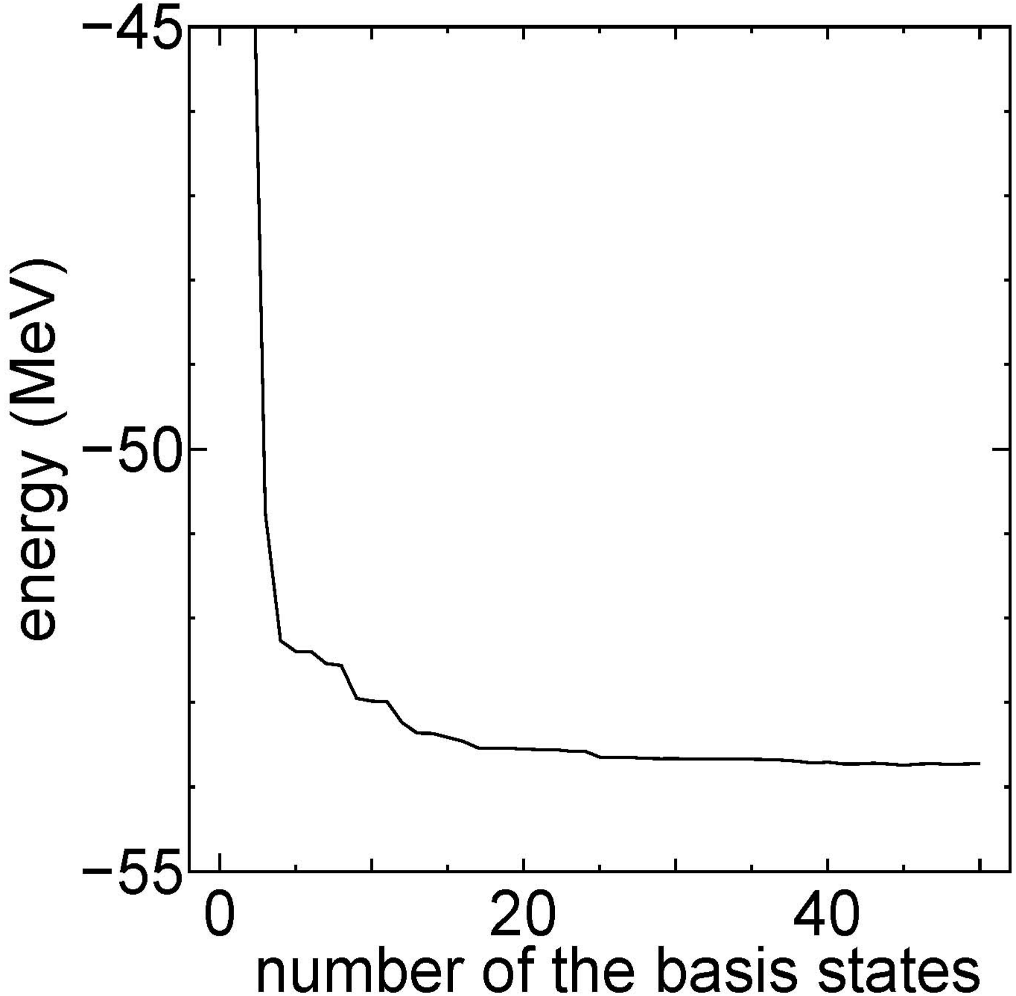
FIG. 3: The 0^+ energy curves of ^{8}Be as a function of the distance between the centers of the two ^{4}He. Both the results of SMT (solid line) and of the $(0s)^4$ configuration for each α-cluster (dotted line) are presented.

Long range part of the tensor contribution simplest case → B isitopes

- We introduce α+α+p+n+n… model for the B isotopes
- The tensor interaction acts between the proton in the p3/2 orbit and neutrons

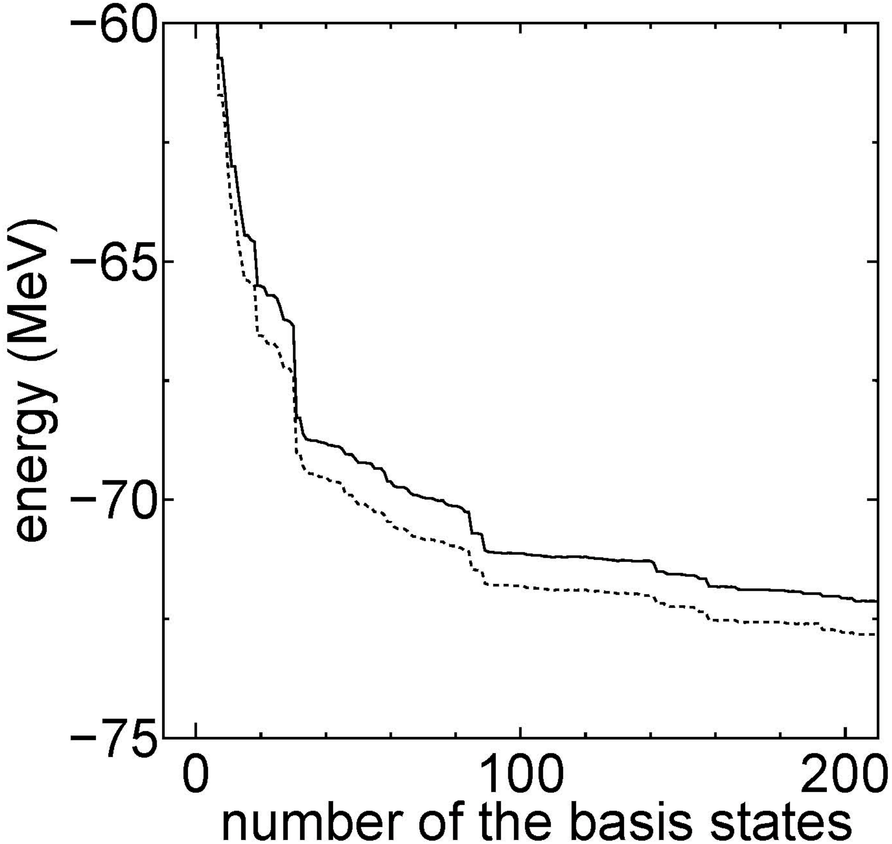
Tensor contributions inside the α clusters

^{9}B energy convergence



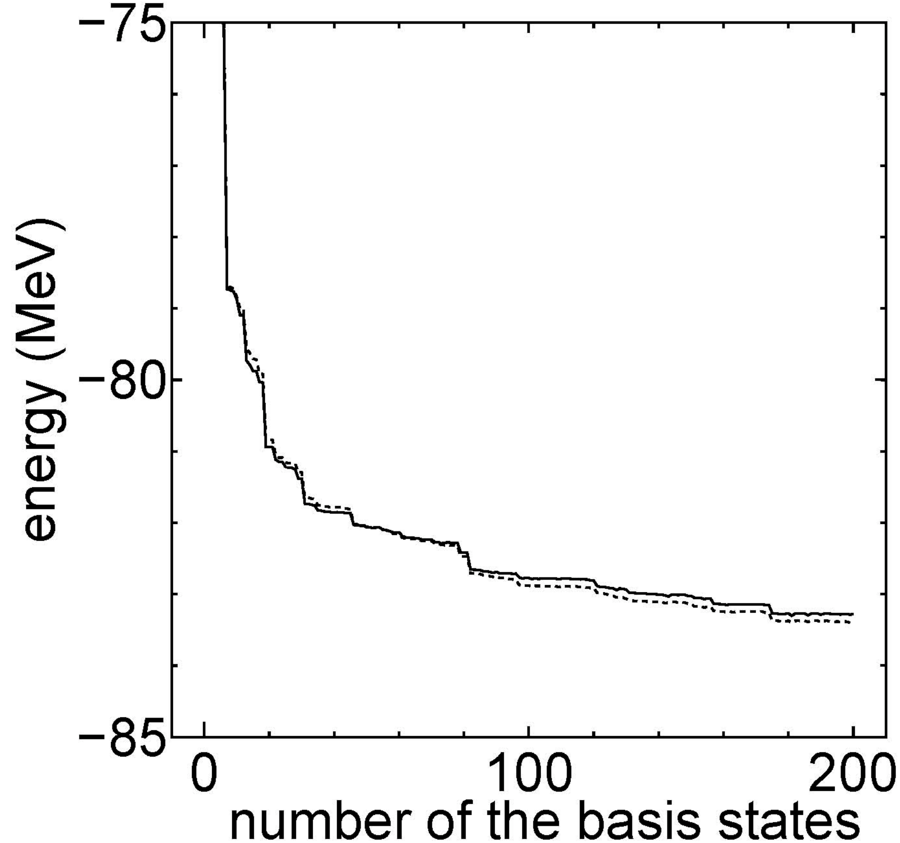
^{11}B energy convergence

Solid – with tensor
Dotted – without tensor



^{13}B energy convergence

Solid – with tensor
Dotted – without tensor



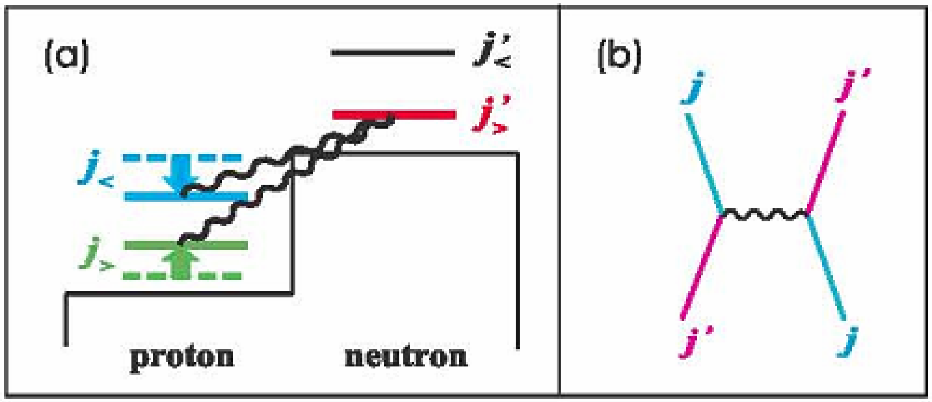


FIG. 1 (color). (a) Schematic picture of the monopole interaction produced by the tensor force between a proton in $j_{>,<} = l \pm 1/2$ and a neutron in $j'_{>,<} = l' \pm 1/2$. (b) Exchange processes contributing to the monopole interaction of the tensor force.

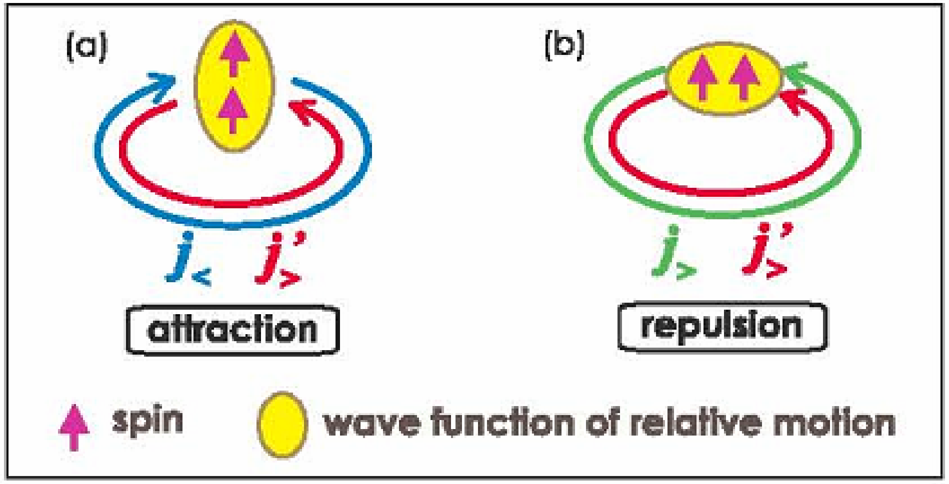


FIG. 2 (color). Intuitive picture of the tensor force acting two nucleons on orbits j and j'.

T. Otsuka, T. Suzuki, R. Fujimoto,
H. Grawe and Y. Akaishi,
Phys. Rev. Lett. **95**, 232502 (2005)

Tensor contribution in C isotopes

(MeV)	^{11}C	^{12}C	^{13}C	^{14}C	^{16}C
With tensor	-64.8	-89.3	-93.8	-106.2	-109.2
Without T	-65.6	-91.4	-95.5	-106.3	-111.6
Δ	+0.9	+2.1	+1.7	+0.1	+2.4

↑

Competition between
the spin-orbit and tensor contributions

Conclusion

- Cluster shell competition is important in light nuclei especially in C isotopes
- Cluster states with geometric shapes are stabilized by valence neutrons in neutron-rich nuclei
- Direct inclusion of the tensor contribution is a challenging subject,

  * How we can beak ^{4}He in a simple way?

  * Contribution of the long range part in B and C isotopes

  * How the central part of the interaction should be modified?