Clusterizations in exotic states of atomic nuclei

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I. Quasidynamical U(3) symmetry

Real U(3) dynamical symmetry is approximately valid in light nuclei.

Rowe et al, JMP 29 (1988) 572

In spite of strong symmetry breaking interactions the *quasidynamical (effective) U(3) symmetry* may survive even for heavy nuclei.

I. Quasidynamical U(3) symmetry

neither the (Hamiltonian) operator,
nor its eigenvectors are symmetric

Energy-eigenstates:

$$\Psi_{\alpha KJM} = \Sigma_{\xi\lambda\mu} C_{\alpha\xi\lambda\mu K} \Phi_{\xi\lambda\mu KJM}$$

$\Phi_{\xi\lambda\mu KJM}$ is a basis vector for an SU(3) irreducible representation,

$C_{\alpha\xi\lambda\mu K}$ are special, they are independent of JM

Matrix elements of the SU(3) generators between these states result in approximate matrix elements of an exact representation.

I. Quasidynamical U(3) symmetry

Jarrio et al, Nucl. Phys. A 528 (1991) 409
P.O. Hess et al, EPJ A 15 (2002) 449

Method :

effective U(3) quantum numbers based on the occupation of the asymptotic Nilsson orbits

Effective symmetry:

applicable also to light nuclei

real and effective U(3) quantum numbers coincide

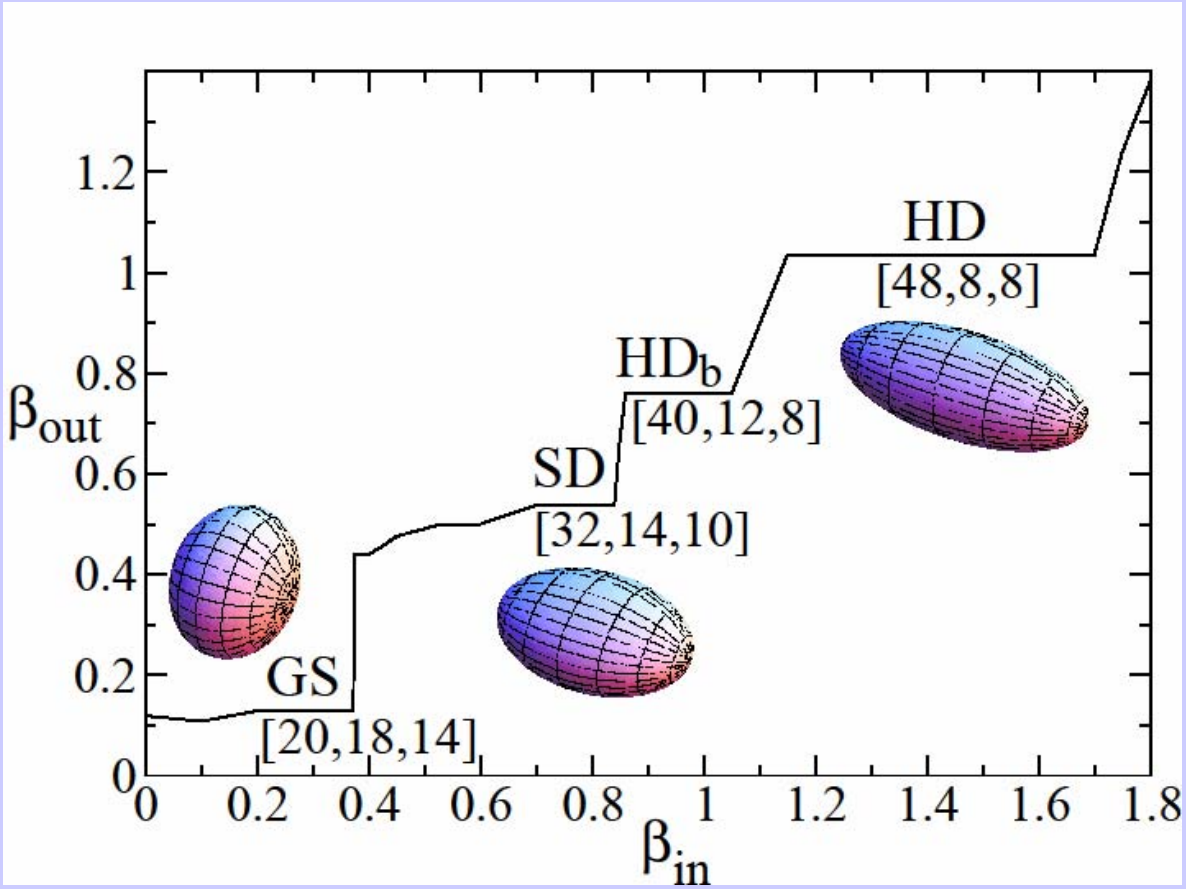
II. Shape isomers

self-consistency calculation → possible *shape isomers*

continuous variation of the quadrupol deformation (β_{in}) → Nilsson model → effective U(3) quantum numbers → β_{out} quadrupole deformation

For lighter nuclei our results are in a good agreement with those obtained from energy-minimum calculations.

^{36}Ar



J. Cseh et al. Phys. Rev. C 80(2009) 034320

III. Clusterizations

Pauli exclusion principle

Energy minimum principle

III. Clusterizations

a, Microscopic structure considerations

Wildermouth and Kanellopoulos, Nucl. Phys. 7 (1958) 150

For a binary cluster configuration the *U(3) selection rule* reads:

$$[n_1,n_2,n_3] = [n_1^{(1)},n_2^{(1)},n_3^{(1)}] \times [n_1^{(2)},n_2^{(2)},n_3^{(2)}] \times [n^{(R)},0,0]$$

Accompanied by a $U^{ST}(4)$ for the spin-isospin degrees of freedom.

III. Clusterizations

a, Microscopic structure considerations

U(3) selection rule in geometrical terms:

similarity of the quadrupole deformation of the cluster configuration and the shell-model state.

effective U(3), effective quantum numbers, selecion rule:

matching or mismatching of the average nucleon distributions in the cluster configuration and in the shell-model state

III. Clusterizations

a, Microscopic structure considerations

S: reciprocal forbiddenness

$$[\mathrm{n}_1, \mathrm{n}_2, \mathrm{n}_3] \quad \Leftrightarrow \quad \sum_{\mathrm{k}} \oplus [\mathrm{n}^{\mathrm{C}}_{1,\mathrm{k}}, \mathrm{n}^{\mathrm{C}}_{2,\mathrm{k}}, \mathrm{n}^{\mathrm{C}}_{3,\mathrm{k}}]$$

$$\min\left(\sqrt{(\Delta n_1)^2 + (\Delta n_2)^2 + (\Delta n_3)^2}\right)$$

$$\textit{where} \quad \Delta \mathrm{n}_{\mathrm{i}} = \left| n_i - n^c_{i,k} \right|$$

$$S = \frac{1}{1 + \min(\sqrt{(\Delta n_1)^2 + (\Delta n_2)^2 + (\Delta n_3)^2})}$$

S=0, and S=1 correspond to completely forbidden and allowed clusterizations, respectively

III. Clusterizations

a, Microscopic structure considerations

Another simple recipe, based on the microscopic picture: *Harvey's prescription.*

U(3) selection rule and Harvey's prescription are applied in a combined way.

III. Clusterizations

b, Energetic preferences

1. Binding energies

Buck et al. FBS 29 (2000) 53; PRC 61 (2000) 024314

$D(1,2) = [B(1) - B_L(1)] + [B(2) - B_L(2)]$.

larger value of D → more probable appearance

2. Double-folding calculations

Schneidman et al. PLB 526 (2002) 322; PRC 67 (2003) 014313

Dinuclear System Model (DNS)

DNS potential energy minimum → clusterizations of the system

IV. Case studies

HD state of ^{36}Ar

Clusterization in the shape isomers of ^{56}Ni nucleus

Superdeformation in ^{28}Si

Indication of HD state in ^{40}Ca

HD state of ^{36}Ar

SD state

Recent experimental results: Svensson et al, PRL 85 (2000) 2693.

Theoretical descriptions (Nilsson, mean-field, large scale shell, cluster)

J. Cseh et al, PRC 70 034311 (2004)

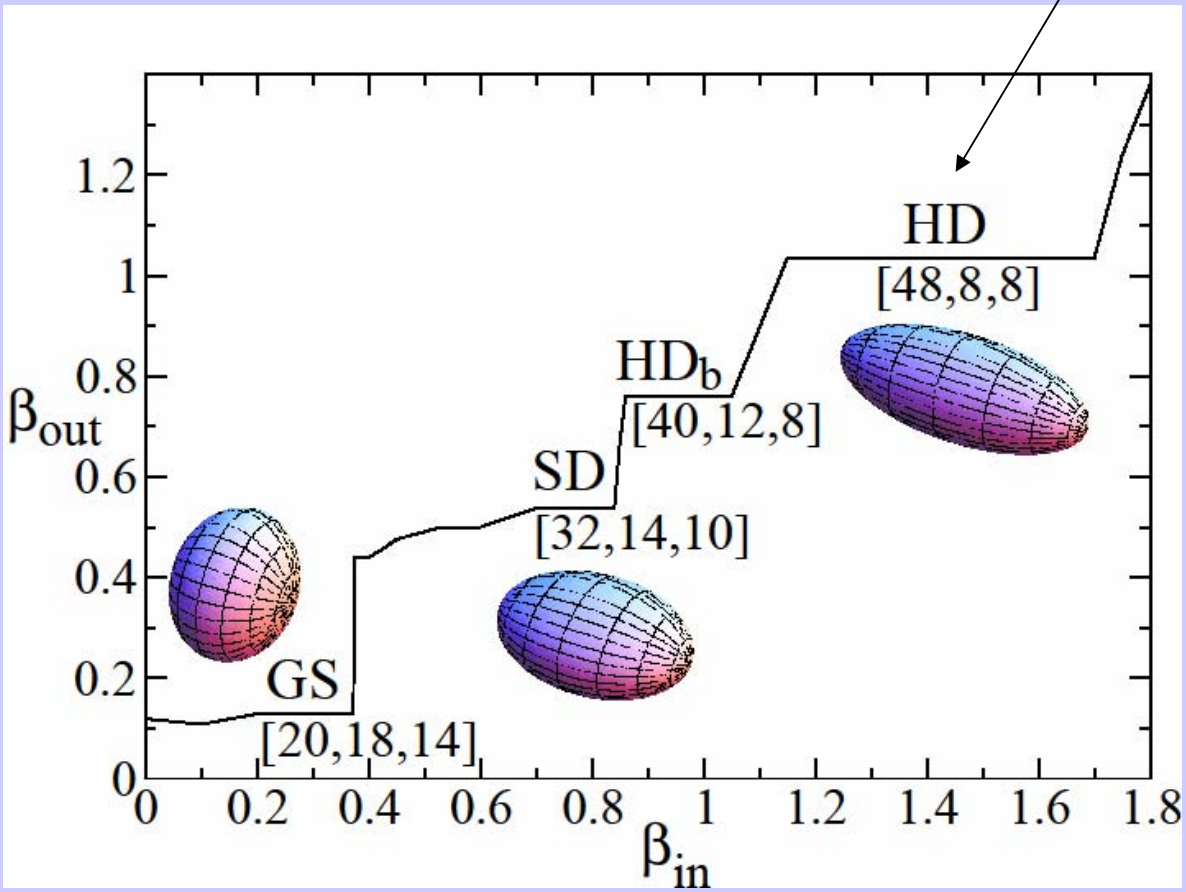
Possible binary clusterizations, also for GS and HD state.

Deformation-dependence of the clusterization.

HD state

Alpha cluster model prediction: Rae, Merchant, PLB 279 (1992) 207.

HD state of ^{36}Ar



HD state of ^{36}Ar

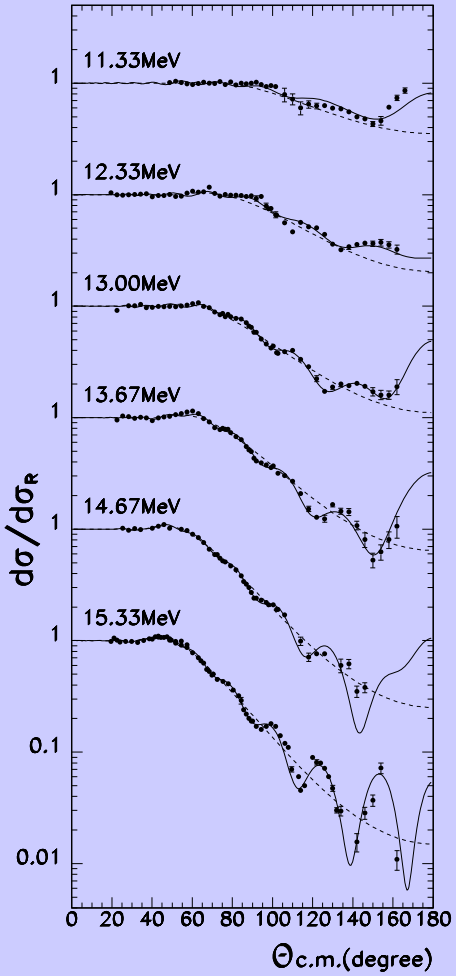
Preferred clusterizations in the HD state:
$^{24}Mg + {}^{12}C$ and $^{20}Ne + {}^{16}O$.

HD state of ^{36}Ar

Experimental verification

^{24}Mg(^{12}C,^{12}C)^{24}Mg S. Paolo experiment

No satisfactory description with potential scattering.
2007-2008: potential + resonances:

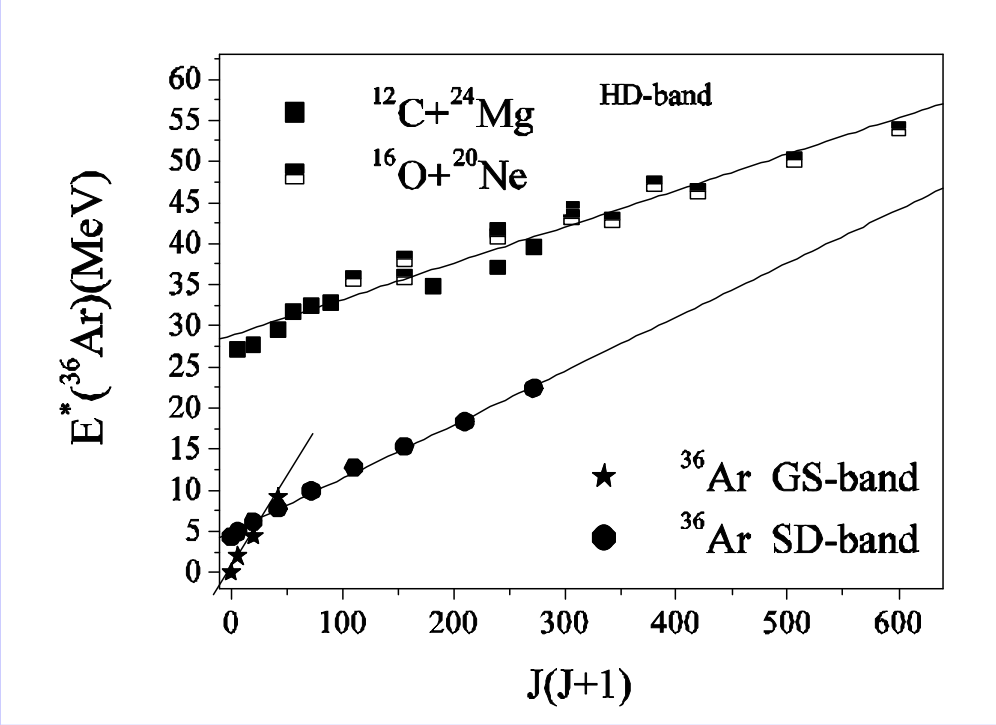


W. Sciani, Y. Otani, A. Lépine-Szily, E. A. Benjamim, L. C. Chamon, R. Lichtenthaler Filho, J. Darai, J. Cseh, PRC 80(2009) 034319

HD state of ^{36}Ar

Experimental verification

Conclusion of $^{24}Mg + ^{12}C$ scattering + previous $^{20}Ne + ^{16}O$ results

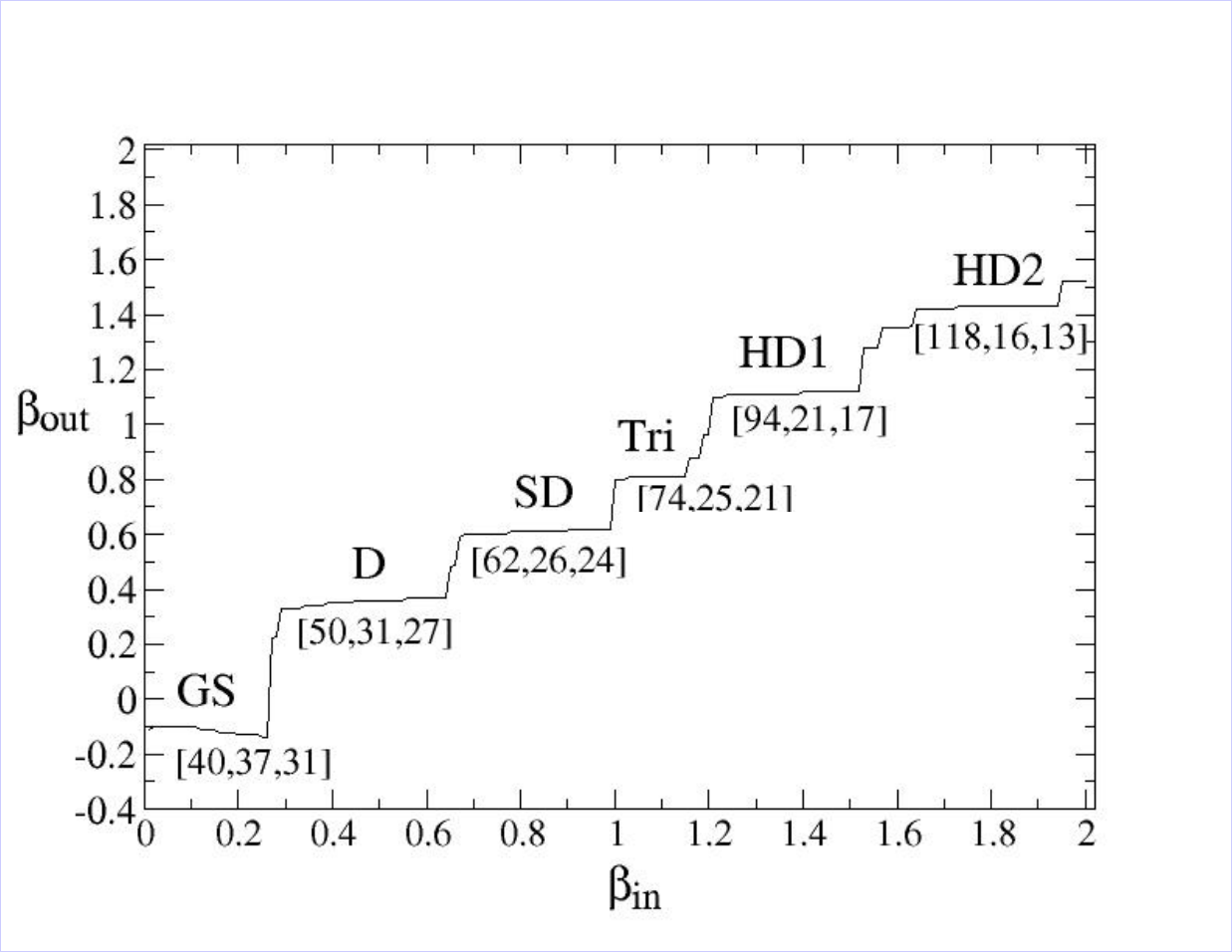


Moment of inertia: is the same as the theoretically predicted moment of inertia.

Reaction channels coincide with our preferred clusterizations.

Clusterization in the shape isomers of ^{56}Ni

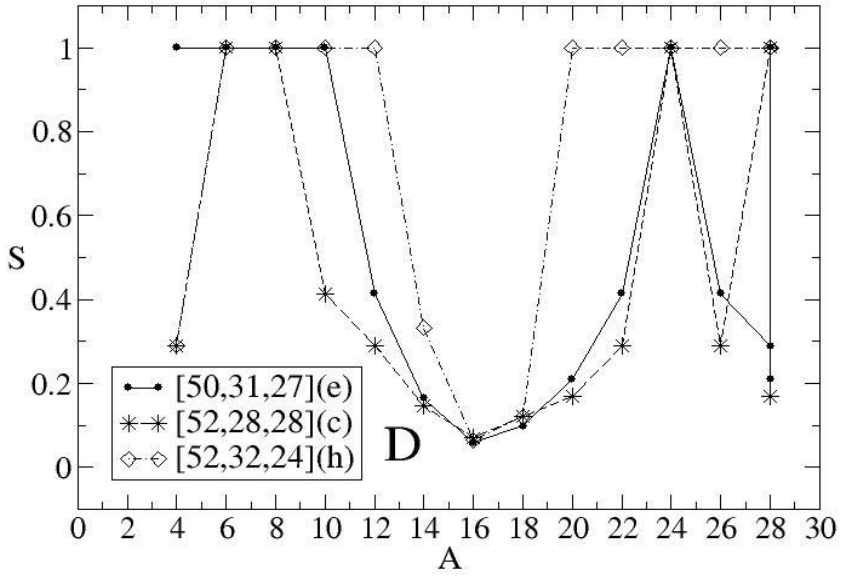
J. Darai, J. Cseh et al. Phys. Rev. C 84 (2011) 024302

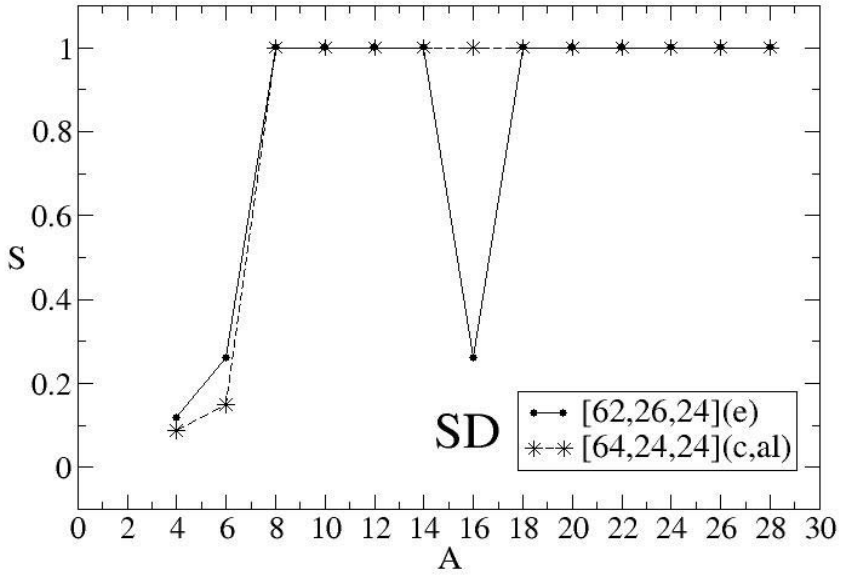


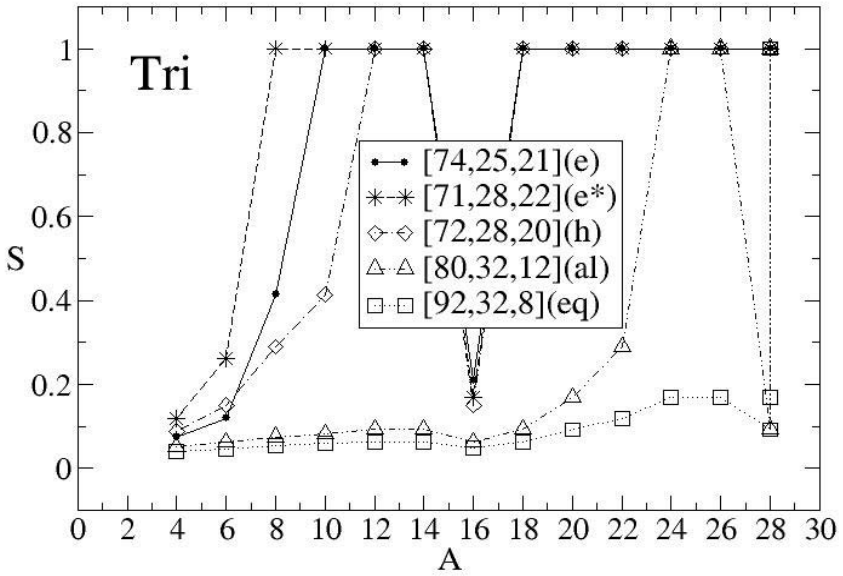
J. Zhang, A. C. Merchant, W. D. Rae, Phys. Rev. C 49 562 (1994): SD, Tri, HD as well

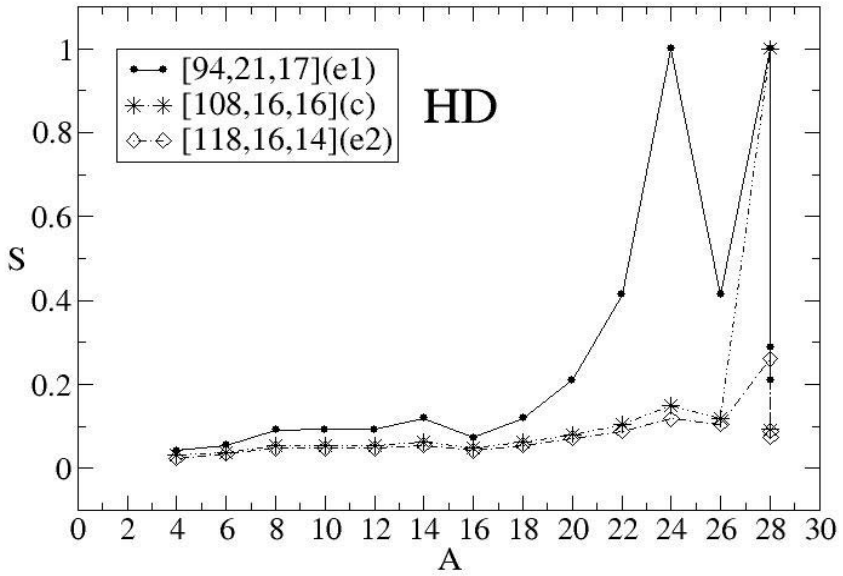
^{56}Ni

J. Darai, J. Cseh et al. Phys. Rev. C 84 (2011) 024302

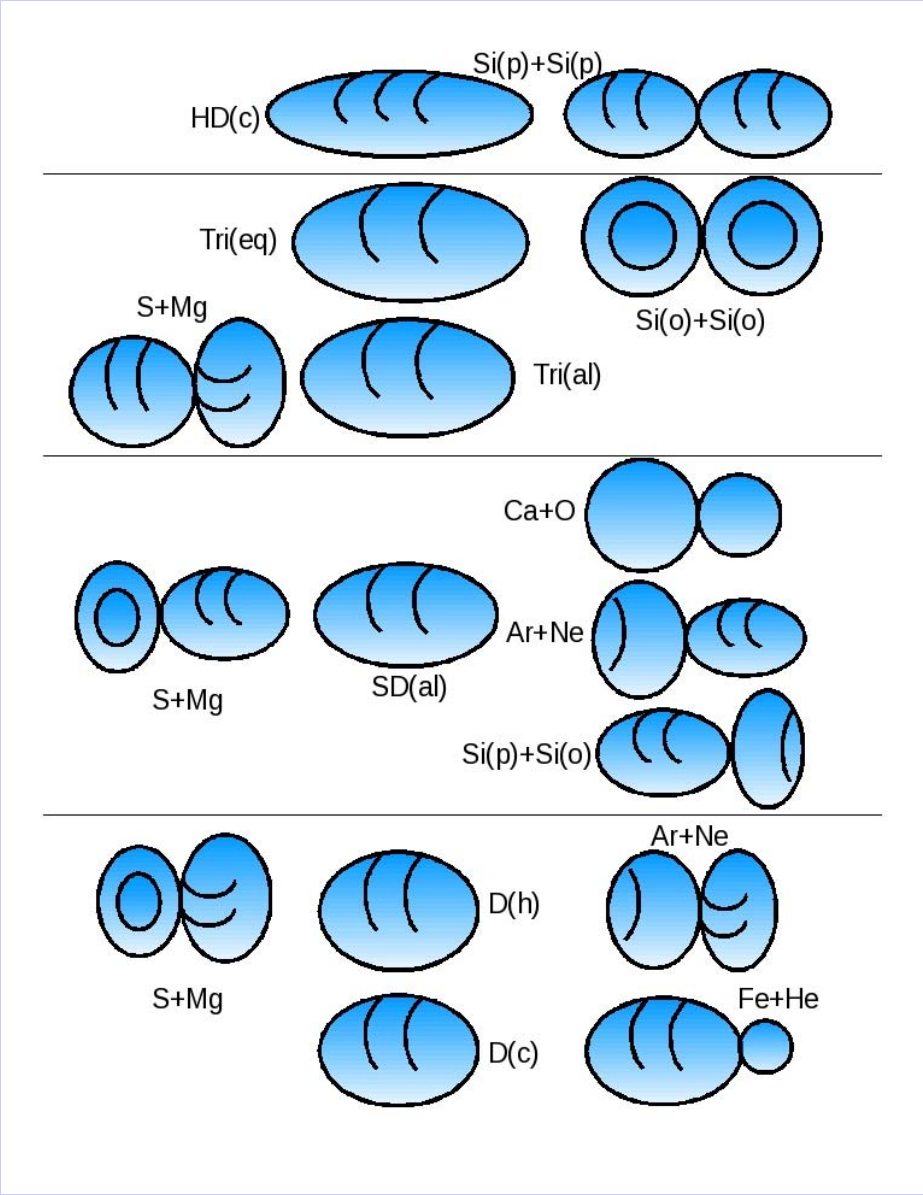








^{56}Ni



Shape isomers of the ^{56}Ni nucleus and their amalgamation from two clusters.

Clusterization in the shape isomers of ^{56}Ni

Ternary clusterization

PRELIMINARY

W. von Oertzen et al., Eur. Phys. J A36, 279 (2008)
Ternary fission events from the decay of the ^{56}Ni compound nucleus
^{32}S + ^{24}Mg
incident energy: ^{28}Si + ^{28}Si resonance
(R. Betts et al., Phys. Rev. Lett. 47, 23 (1981))
→ HD ?

From our systematic calculations
Triaxial state: ^{24}Mg+^{32}S
^{24}Mg+^{16}O+^{16}O
^{28}Si(o) +^{28}Si(o)
→Triaxial

HD state: ^{24}Mg+^{32}S
^{24}Mg+^{16}O+^{16}O

Superdeformation in ^{28}Si

Y. Taniguchi, Y. Kanada-En'yo and M. Kimura, Phys. Rev. C 80 (2009) 044316

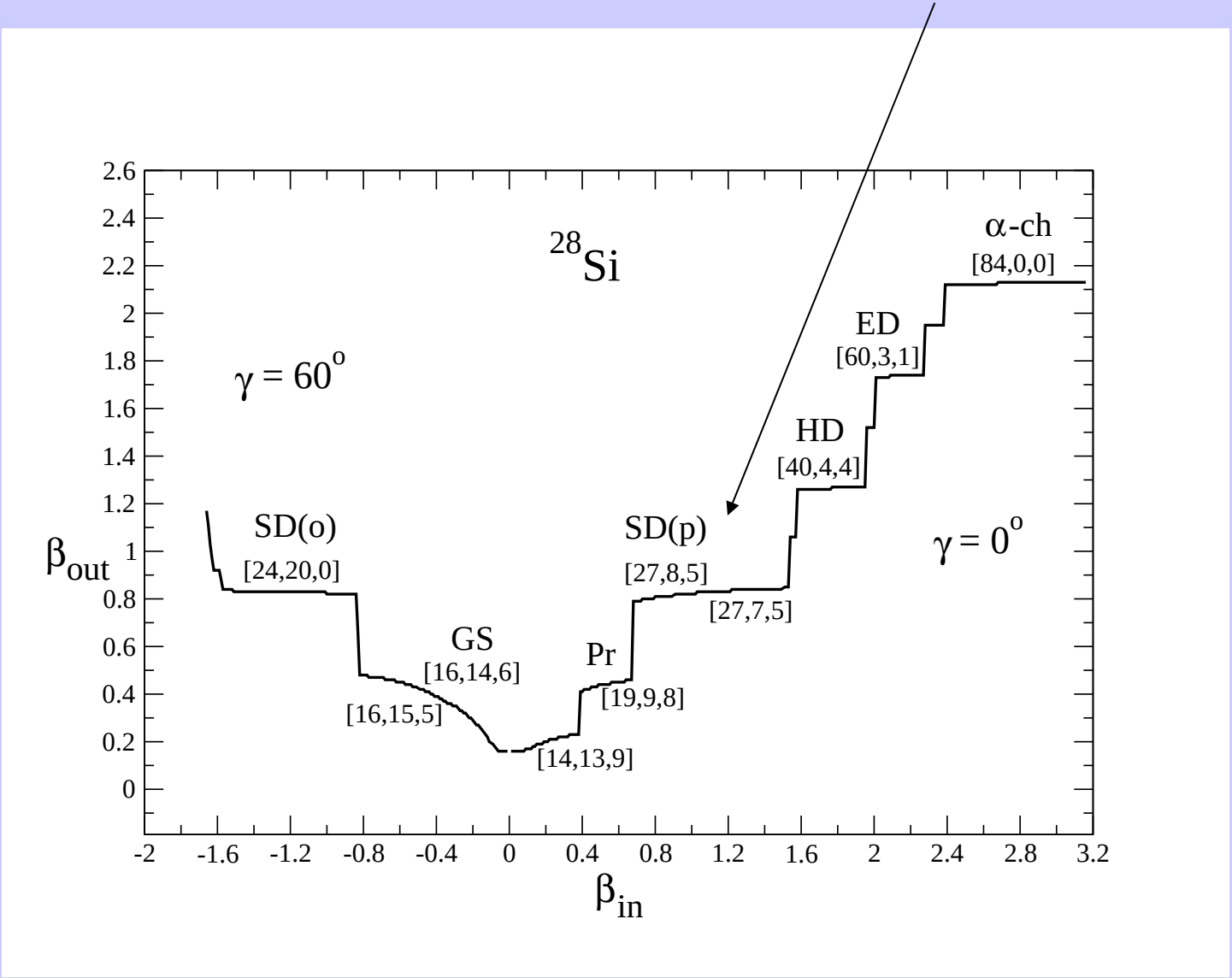
SD state:
^{24}Mg + α
4p4h configuration

$$I \approx 6 \frac{\hbar^2}{MeV}$$

"excited prolate band"
S. Kubono et al., Nucl. Phys. A 457, 461 (1986)
^{12}C(^{20}Ne,α)^{28}Si

Superdeformation in ^{28}Si

PRELIMINARY



J. Zhang, W. D. M. Rae, A. C. Merchant, Nucl. Phys. A 575 61 (1994): SD as well

Superdeformation in ^{28}Si

PRELIMINARY

selection rules + energetic preference

^{24}Mg+α and the ^{12}C+^{16}O clusterizations are the most probable

AMD, as well as our calculations → strong ^{24}Mg+α component

D. Jenkins et al.: review, particular focus on ^{24}Mg(α,γ) as well as ^{12}C(^{20}Ne,α)^{28}Si reactions

Superdeformation in ^{28}Si

Brenneisen et al., Z. Phys. A 352, 149 (1995)
^{27}Al(p,γ)^{28}Si, ^{24}Mg(α,γ)^{28}Si

6^+ state at 12.86 MeV: was populated in the (α, γ) but not in the (p,γ) reaction
4^+ state at 10.945 MeV
2^+ state at 9796 keV

$6^+ \rightarrow 4^+$ via a relatively intense E2 transition

rotational band $I \approx 6\frac{\hbar^2}{MeV}$

Superdeformation in ^{28}Si

PRELIMINARY

Recent analysis by D. Jenkins et al.: in-beam gamma-ray spectroscopy study of ^{28}Si with Gammasphere
$^{12}C(^{20}Ne,\alpha)^{28}Si$

- confirmation the location and assignment of previous experimentally observed candidate states.
- additional decay branches have been located:
ie. 2^+ state at 9.796 MeV → the 0^+ state in the prolate band at 6.691MeV.
- the associated moment of inertia is in good agreement with the theoretical calculations.

Superdeformation in ^{28}Si

PRELIMINARY

to extract B(E2) values for transitions:

recent in-beam+

P.M. Endt, Nucl. Phys. A 633, 1 (1998);
P.M. Endt, Nucl. Phys. A 521, 1 (1990)
Brenneisen et al., Z. Phys. A 352, 149 (1995)

- a large transition strength is seen for the 6+ → 4+ transition
- the transitions to the oblate ground state band are strongly retarded, while the transitions to the prolate band are enhanced.

candidate SD state

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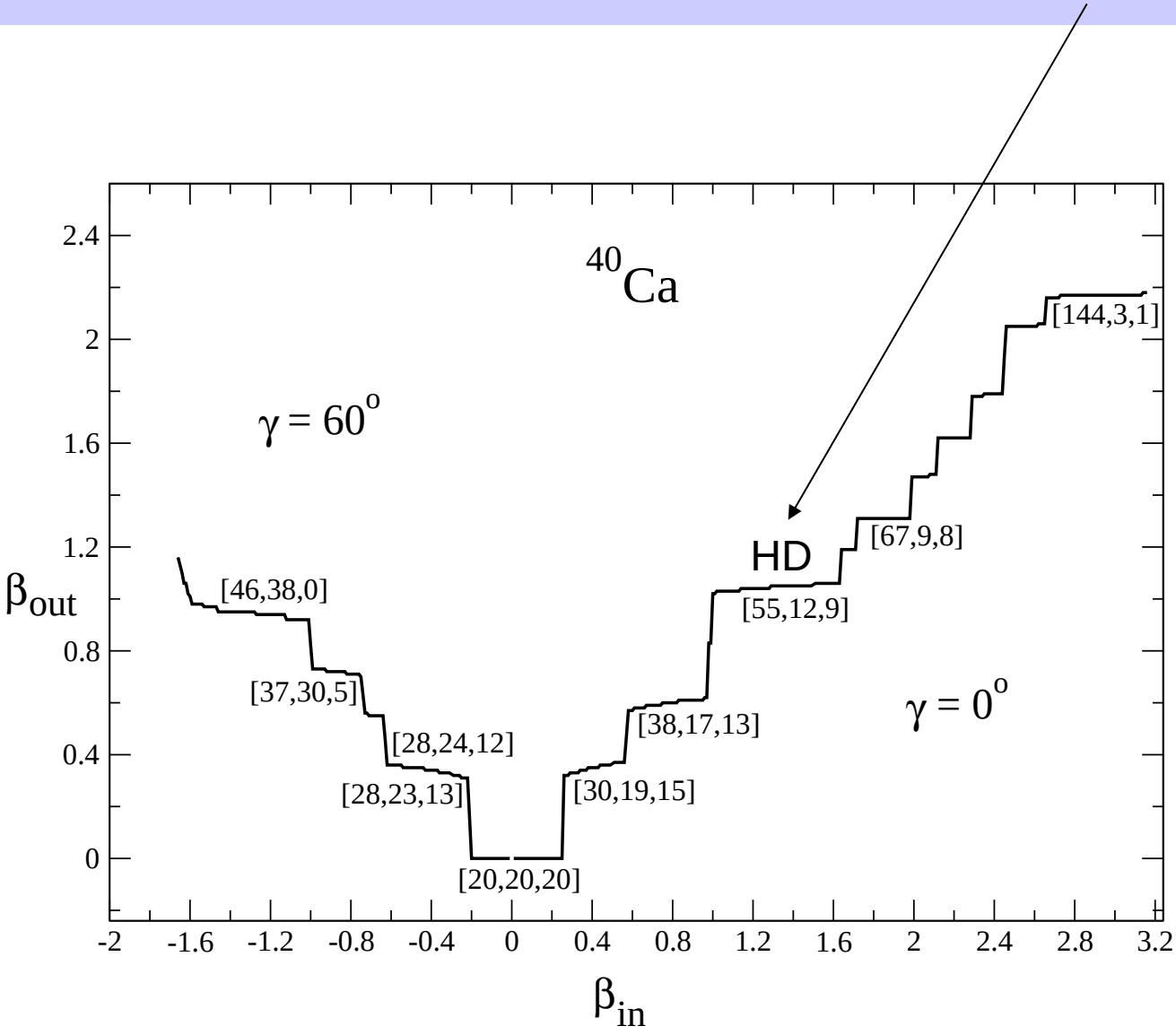
Indication of HD state in ^{40}Ca PRELIMINARY



Indication of HD state in ^{40}Ca PRELIMINARY

HD state in good agreement with

J. Zhang, W. D. M. Rae, A. C. Merchant, Nucl. Phys. A 575 61 (1994)

G. Leander and S. E. Larsson, Nuclear Physics A 239 93 (1975)

Preferred clusterizations:

$^{28}Si+^{12}C$

$^{24}Mg+^{16}O$

Indication of HD state in 40Ca PRELIMINARY

Experimental verification

$^{12}C+^{28}Si$ S. Paolo experiment

No satisfactory description with potential scattering.

potential + resonances

observed resonances: $J^{\pi\iota}$=8+, 10+, 13-, 15- and 18+

they belong to a rotational band in ^{40}Ca
HD band

V. Summary, outlook

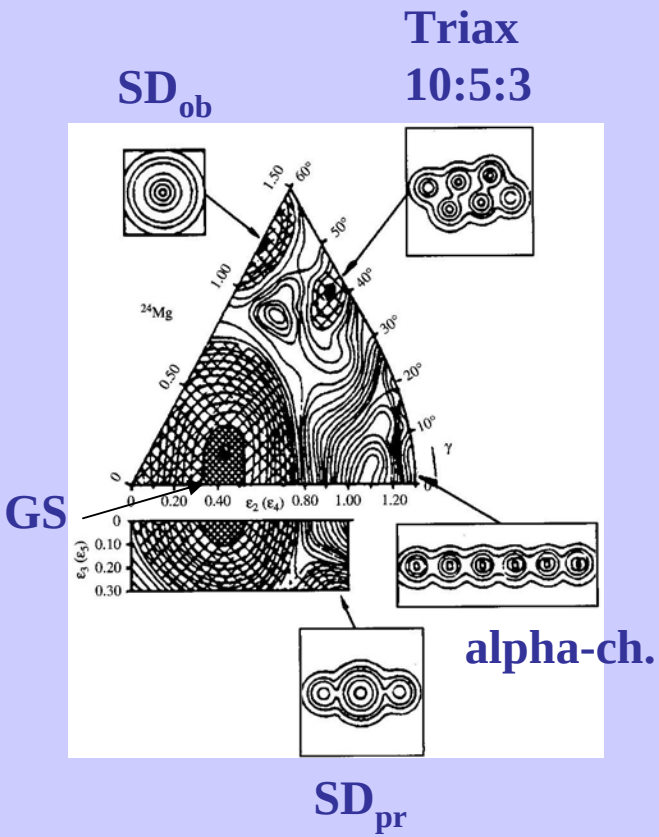
Symmetry-considerations can be helpful in studying the *shape isomers*, *cluster configurations* and their interrelations.

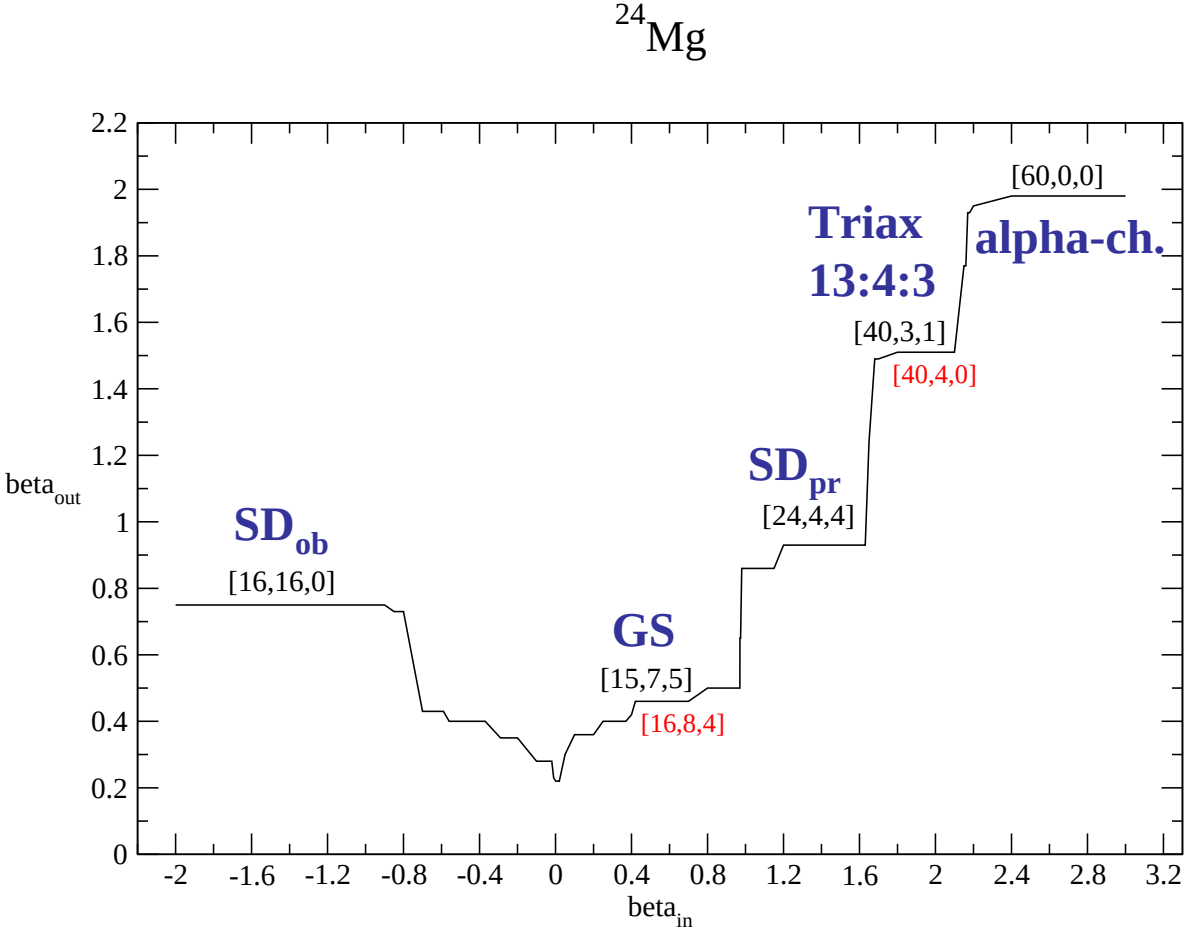
They can predict the reaction channels which populate shape isomers.

The methods we applied seem to be applicable in heavier nuclei too.

We think, that the preferred cluster configurations are those which are favored by the energetics, and which are Pauli-allowed.

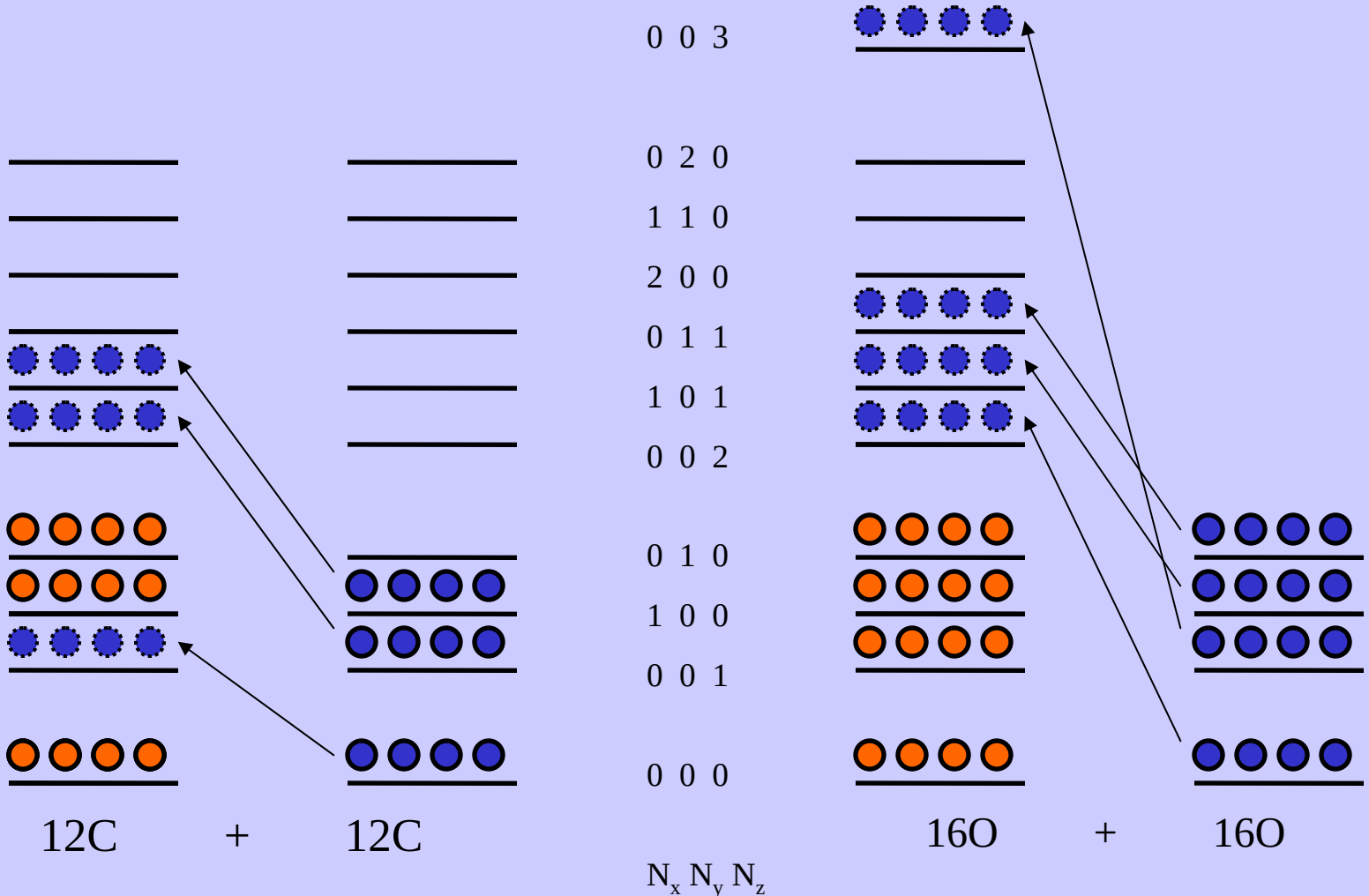
Thank you!


Triax
10:5:3
SD$_{ob}$
GS
alpha-ch.
SD$_{pr}$
^{24}Mg


^{24}Mg
beta$_{out}$
beta$_{in}$
SD$_{ob}$
[16,16,0]
GS
[15,7,5]
[16,8,4]
SD$_{pr}$
[24,4,4]
Triax
13:4:3
[40,3,1]
[40,4,0]
alpha-ch.
[60,0,0]

Harvey's prescription

Only the number of quanta along the molecular axis (z) can change, while the numbers along the two other directions remain unchanged.



^{56}Ni

TABLE I: Energetic preferences of alpha-cluster-like configurations in ^{56}Ni. Here D(1, 2) stands for the binding-energy-difference, thus the larger value corresponds to more probable appearance. U means potential energy, calculated from the dinuclear system model, therefore, smaller values correspond to more stable cluster configurations. pp indicates the pole-to-pole configuration, typical in DNS calculations with axial symmetry, while m stands for the orientation corresponding to the microscopic consideration. (It is usually more compact than the pp configuration.) All values are in MeV. See Table I for the notation of the states.

$C_1 + C_2$	D(1,2)	U(pp)	U(m)
^{4}He + ^{52}Fe	10.88	-0.17	0.1 GS(e) -0.1 GS(c) -0.1 D(e) -0.1 D(c)
^{8}Be + ^{48}Cr	3.61	9.8	6.4 D(e) 6.7 D(c) 6.7 D(h) 9.7 SD(e) 10.0 SD(al) 6.4 Tri(e*)
^{12}C + ^{44}Ti	2.11	11.8	9.5 D(h) 14.5 SD(e) 14.5 SD(al) 10.9 Tri(e) 13.5 Tri(e*) 14.3 Tri(h)
^{16}O + ^{40}Ca	2.57	17.0	16.4 SD(al)
^{20}Ne + ^{36}Ar	-1.11	20.4	19.0 D(h) 20.0 SD(e) 21.2 SD(al) 22.6 Tri(e) 21.5 Tri(e*) 22.0 Tri(h)
^{24}Mg + ^{32}S	0.65	19.2	16.3 D(e) 21.0 D(c) 18.3 D(h) 21.0 SD(e) 19.8 SD(al) 20.4 Tri(e) 18.4 HD(e1) 20.6 Tri(e*) 18.6 Tri(h) 17.9 Tri(al)

TABLE I: Energetic preferences of alpha-cluster-like configurations in ^{56}Ni. Continuation of the previous table, with the same notations.

$C_1 + C_2$	D(1,2)	U(pp)	U(m)
^{28}Si(p) + ^{28}Si(p)	3.37	16.0	16.4 D(c) 14.5 D(h) 17.5 SD(e) 18.1 SD(al) 16.6 Tri(e) 16.1 Tri(e*) 16.1 Tri(h) 17.0 HD(e1) 16.0 HD(c)
^{28}Si(o) + ^{28}Si(o)	3.37	13.3	15.3 D(e) 17.4 D(c) 15.7 D(h) 14.7 SD(e) 15.7 SD(al) 18.0 Tri(e) 16.0 Tri(e*) 17.0 Tri(h) 14.8 Tri(al) 16.0 Tri(eq)
^{28}Si(o) + ^{28}Si(p)	3.37	16.1	15.0 D(h) 17.4 SD(e) 16.1 SD(al) 18.5 Tri(e) 16.0 Tri(e*) 16.8 Tri(h) 15.1 Tri(al)