Alpha Clustering in Nuclear Reactions Induced by Light Ions

C. Beck (IPHC Strasbourg)

- Introduction : alpha clustering in ^{12}C, ^{16}O, ^{20}Ne clusters in light neutron-rich nuclei
- Highly deformed shapes in ^{24}Mg,^{32}S,^{36}Ar,^{40}Ca
- Ternary fission and Hyperdeformation in $^{56}Ni^*$
- High-spin states in ^{16}O, ^{20}Ne and ^{24}Mg
- Clustering in neutron-rich nuclei
- Extended Ikeda diagram

Cluster12 Conference Summary (Catford)

10th International Conference on Clustering Aspects of Nuclear Structure and Dynamics IOP Publishing
Journal of Physics: Conference Series **436** (2013) 012085 doi:10.1088/1742-6596/436/1/012085

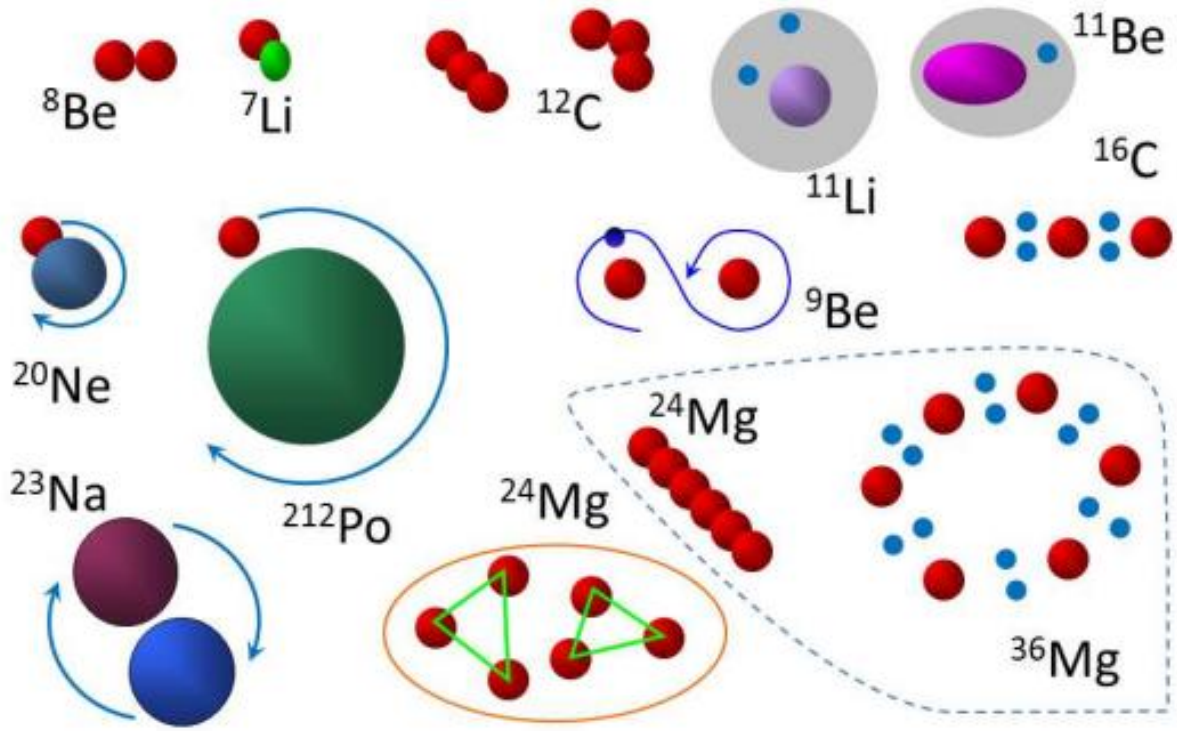
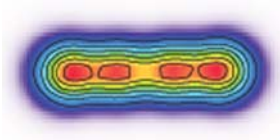


Figure 1. Different types of clustering in nuclei (adapted from Ref. [4]). Only those inside the dashed line were not discussed experimentally at this conference.

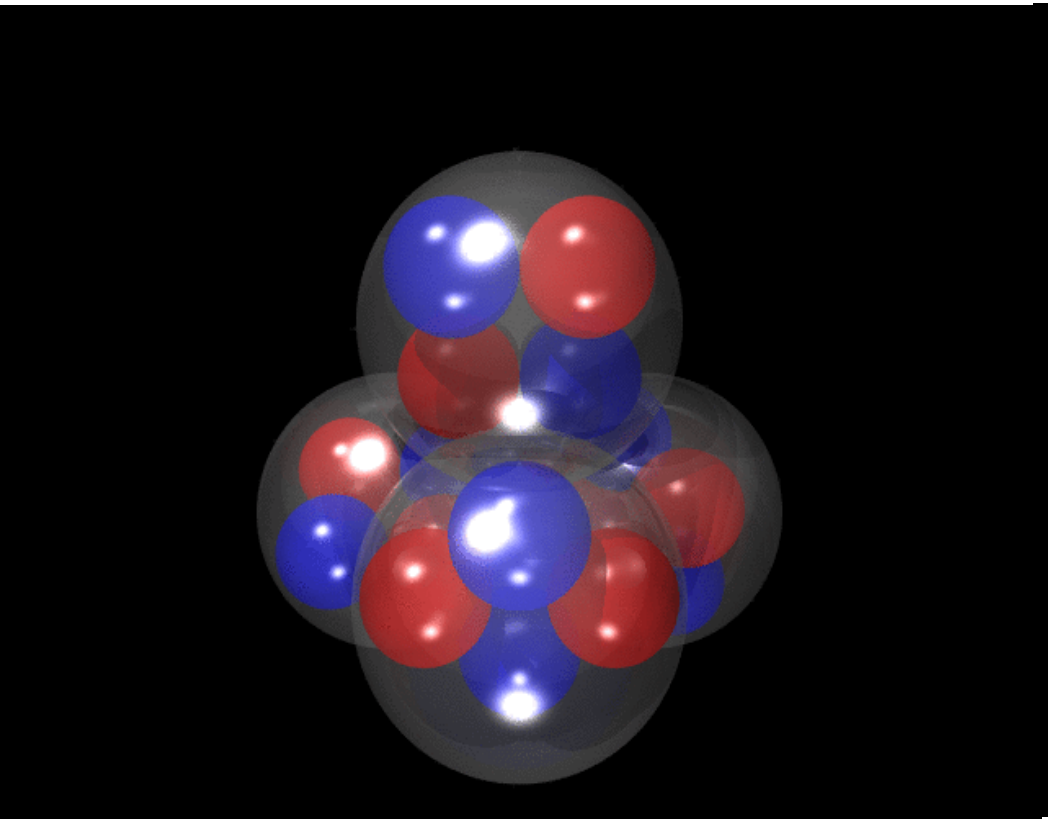
Alpha Clustering

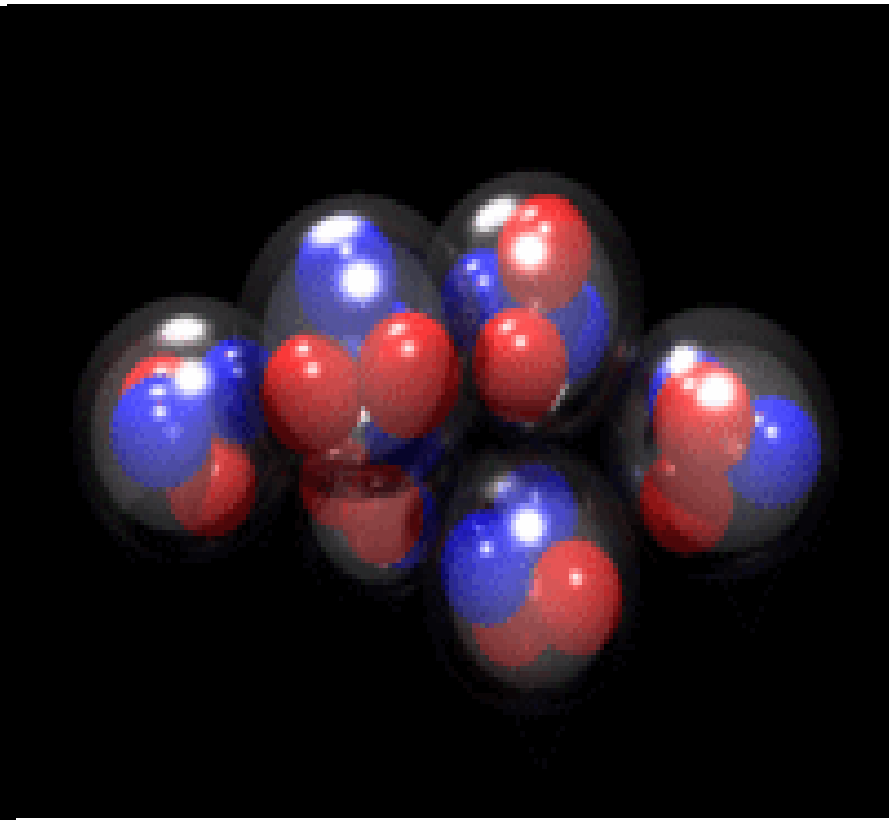


Gas-like BEC

^{16}O = 4 alphas

^{24}Mg = 6 alphas

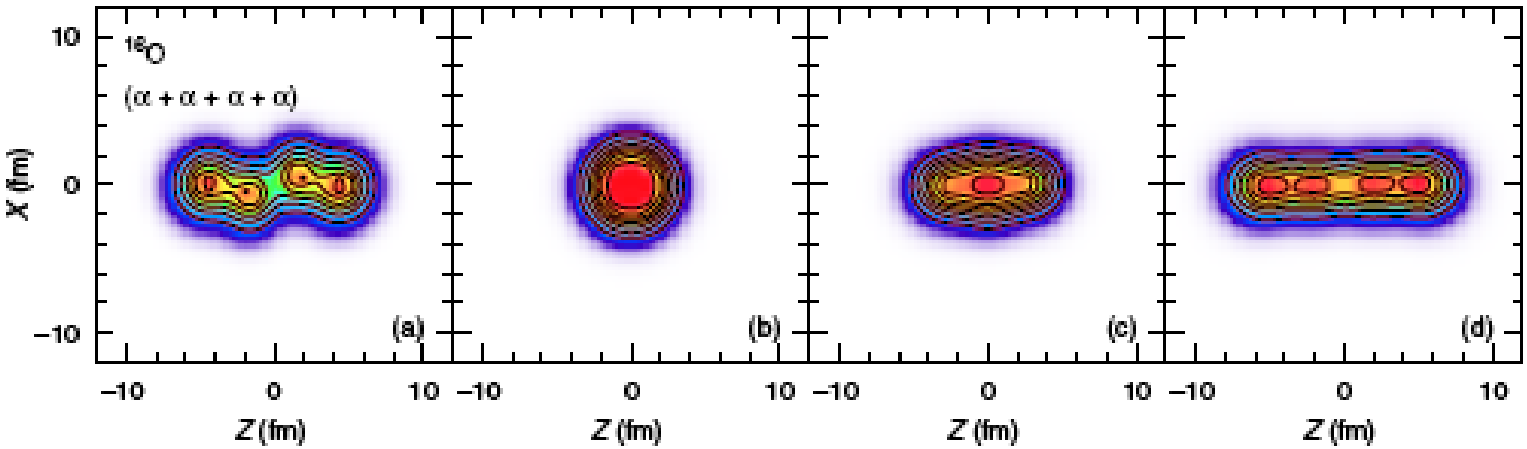




PRL 107, 112501 (2011) PHYSICAL REVIEW LETTERS week ending 9 SEPTEMBER 2011

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

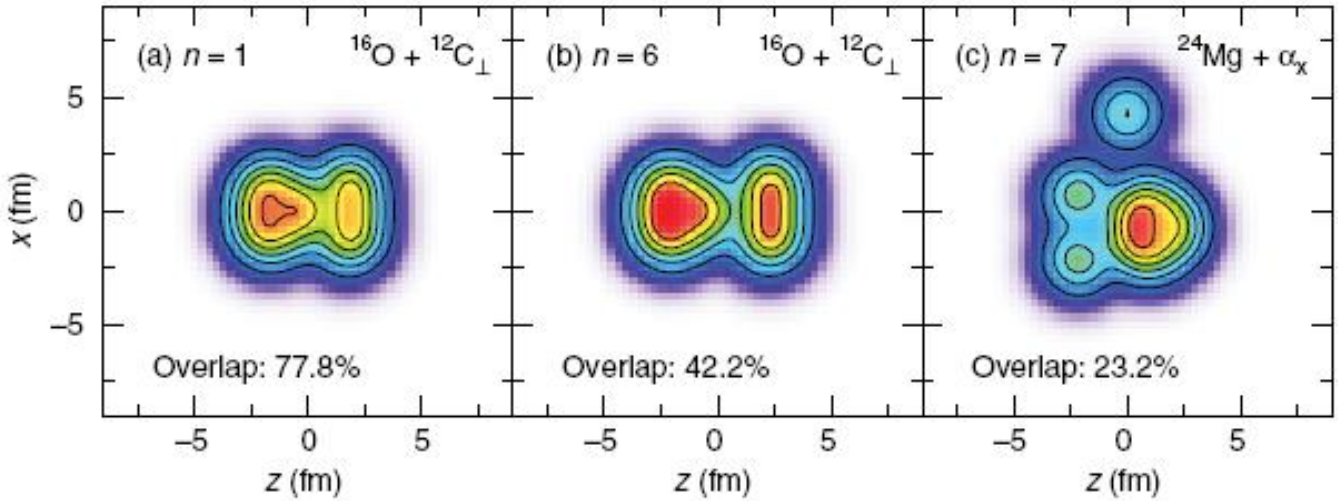
T. Ichikawa,[1] J. A. Maruhn,[2] N. Itagaki,[1] and S. Ohkubo[3,4]



PHYSICAL REVIEW C **86**, 031303(R) (2012)

Search for three-α states around an ^{16}O core in ^{28}Si

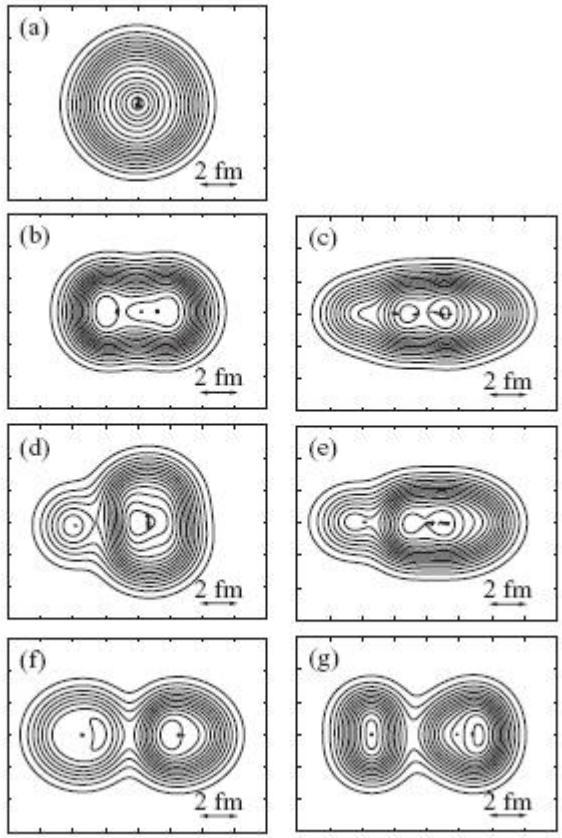
T. Ichikawa,[1] N. Itagaki,[1] Y. Kanada-En'yo,[2] Tz. Kokalova,[3] and W. von Oertzen[4]



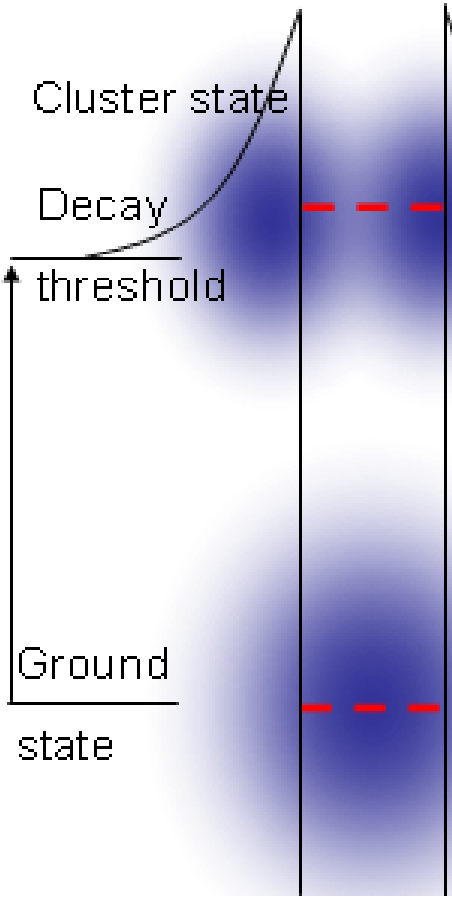
PHYSICAL REVIEW C **80**, 044316 (2009)

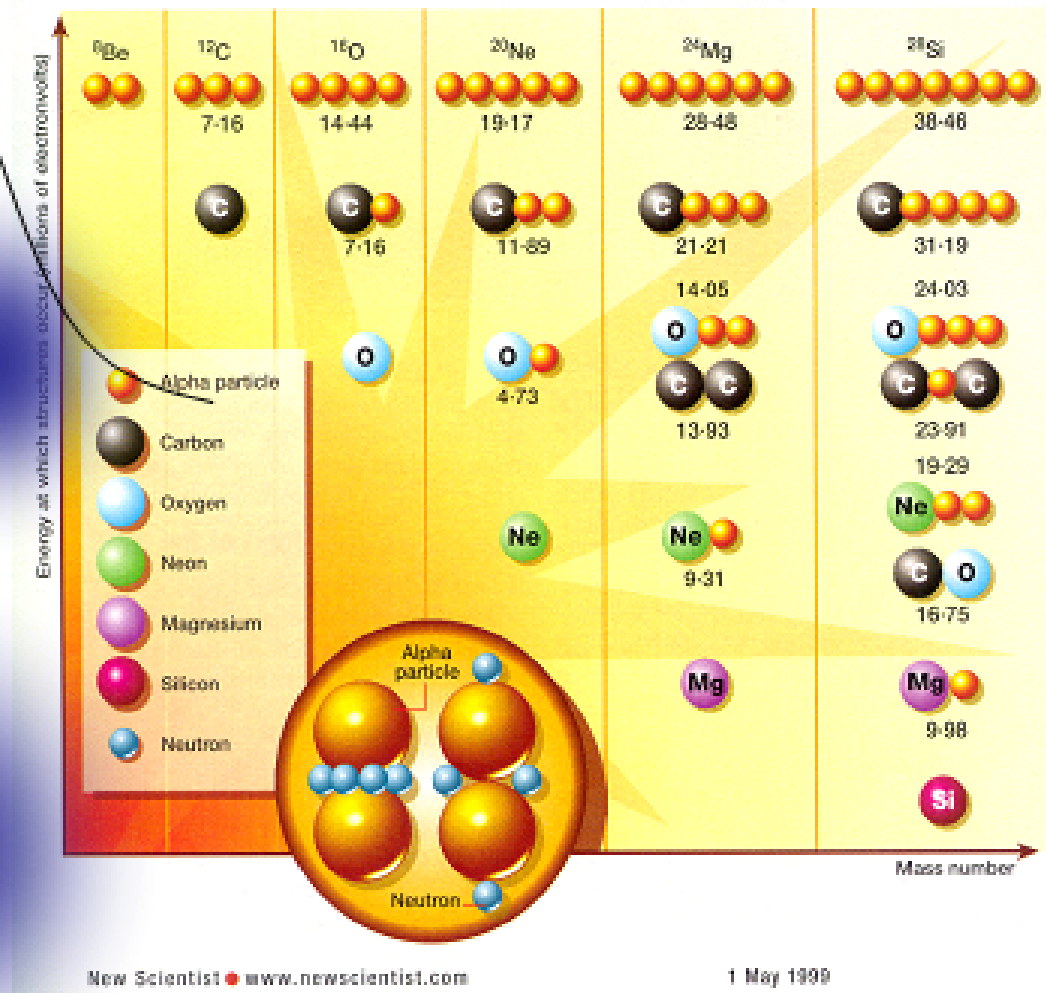
Cluster structures and superdeformation in ^{28}Si

Yasutaka Taniguchi (谷口億宇),[1] Yoshiko Kanada-En'yo (延与佳子),[2] and Masaaki Kimura (木村真明)[3]



Cluster states always appear close to thresholds Why?

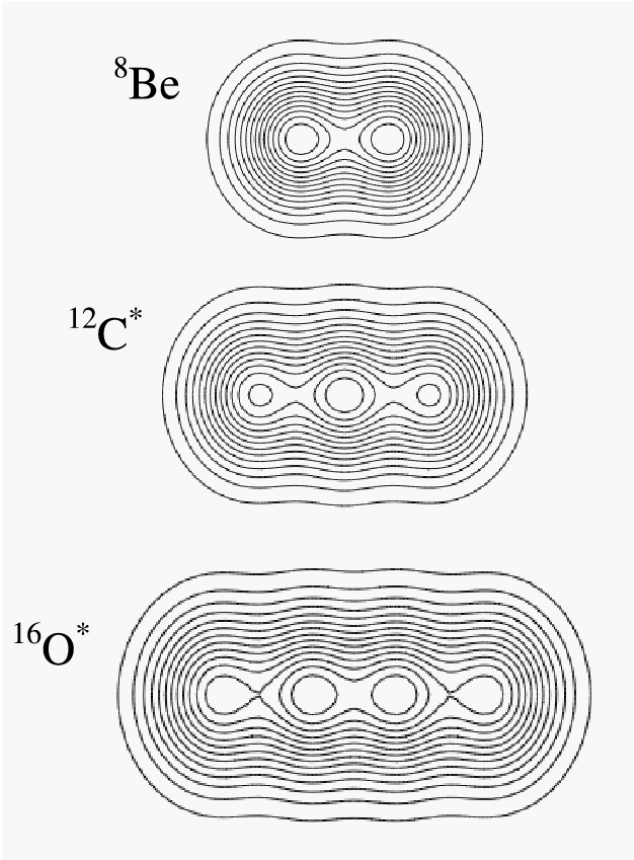


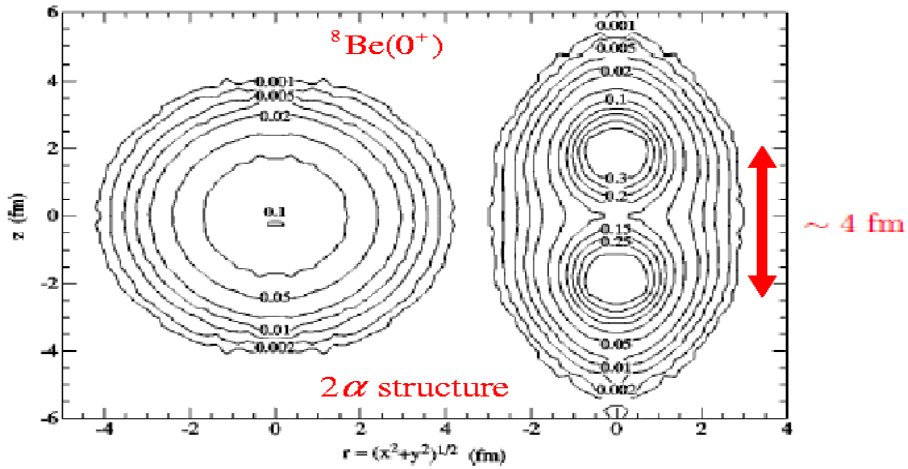


K. Ikeda, et al. Suppl. Prog. Phys. (Japan) Extra Nos. (1968) 464

Density distributions of ^{8}Be, ^{12}C and ^{16}O

Deformed harmonic oscillator (M. Freer)





Quantum Monte Carlo *ab initio* Method (R.B. Wiringa. S.C. Pieper, P. Navratil)

Ab initio No-Core Shell Model (J.P. Draayer, J.P. Vary)

Light alpha-like nuclei: open questions

- Are ^{12}C alpha-cluster states built on the 0_2^+ Hoyle state ? Yes see M. Gai

  But still no evidence of 2^+ state at 11.16 MeV (iThemba LABS)

- Hoyle state equivalent in ^{16}O : experiments ?

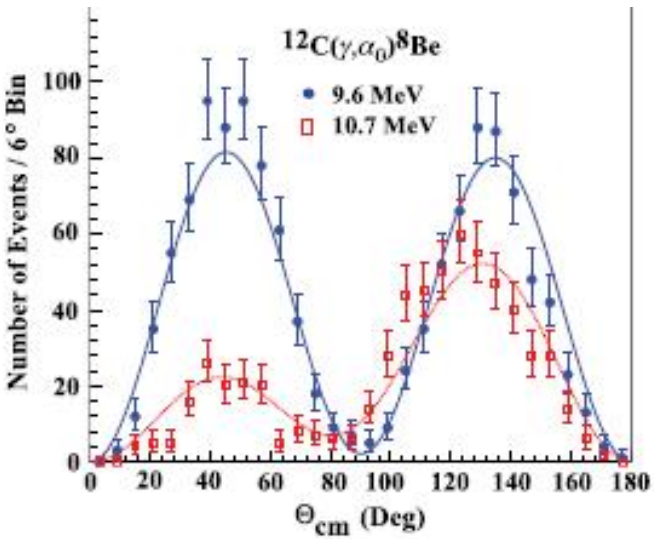
- Is ^{20}Ne a “Morinaga” nucleus (chain states) ?

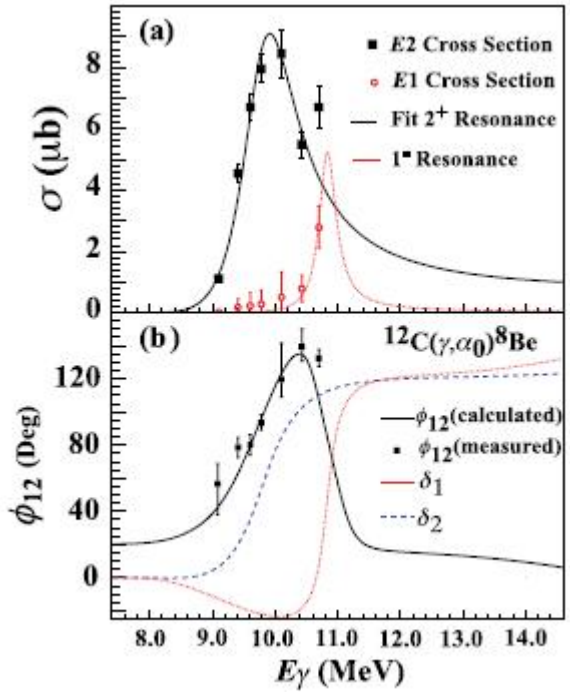
  BEC in ^{24}Mg see T. Kawabata

PRL 110, 152502 (2013) PHYSICAL REVIEW LETTERS week ending 12 APRIL 2013

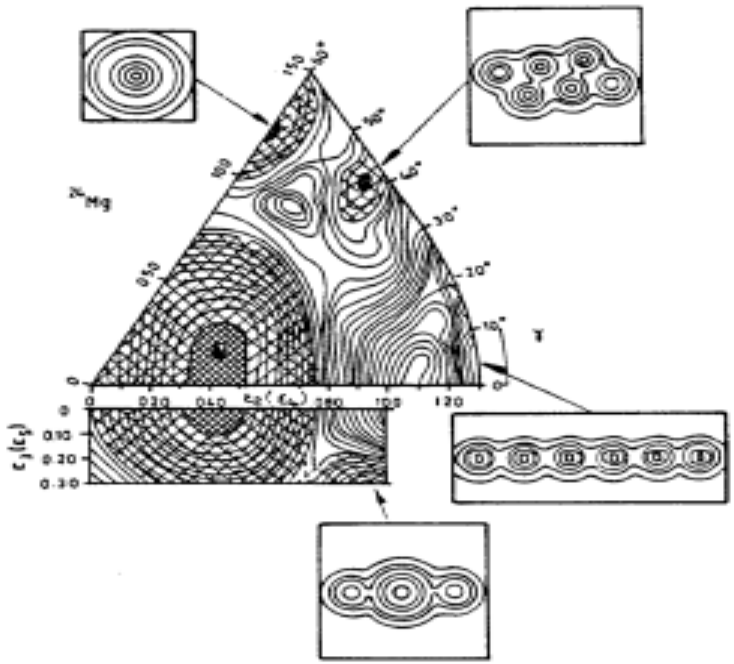
Unambiguous Identification of the Second 2^+ State in ^{12}C and the Structure of the Hoyle State

W. R. Zimmerman,[1,2] M. W. Ahmed,[2,3] B. Bromberger,[4] S. C. Stave,[2] A. Breskin,[5] V. Dangendorf,[4] Th. Delbar,[6] M. Gai,[1,7] S. S. Henshaw,[2] J. M. Mueller,[2] C. Sun,[2] K. Tittelmeier,[4] H. R. Weller,[1,2] and Y. K. Wu[2]

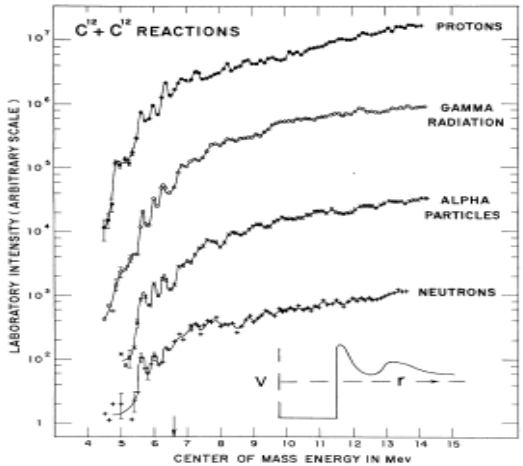




Superdeformation in ^{24}Mg



Molecular resonances in $^{12}C + ^{12}C$



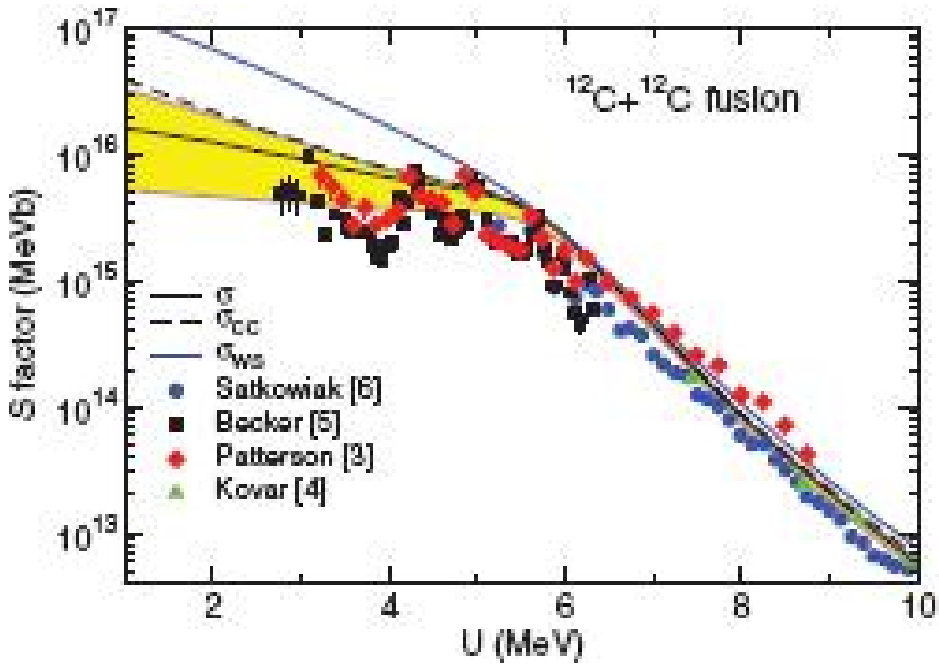
Molecular resonances in $^{12}C + ^{12}C$

D.A. Bromley et al.
Phys. Rev. Lett. (1960)

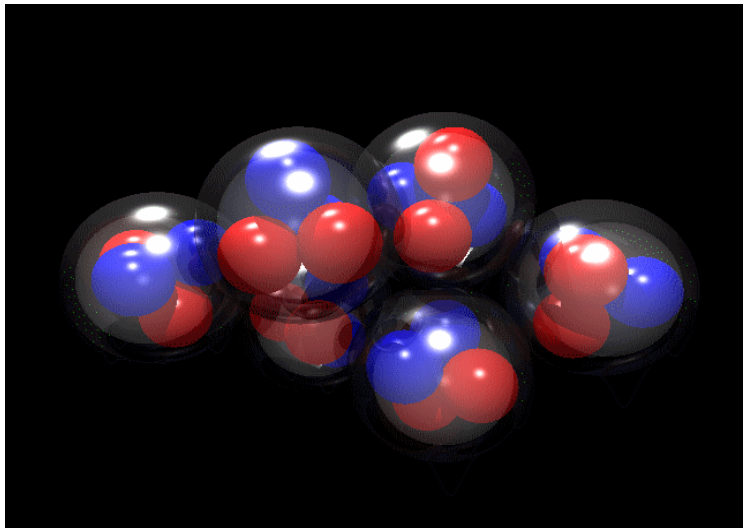
PRL 110, 072701 (2013) PHYSICAL REVIEW LETTERS week ending 15 FEBRUARY 2013

Origin and Consequences of $^{12}C + ^{12}C$ Fusion Resonances at Deep Sub-barrier Energies

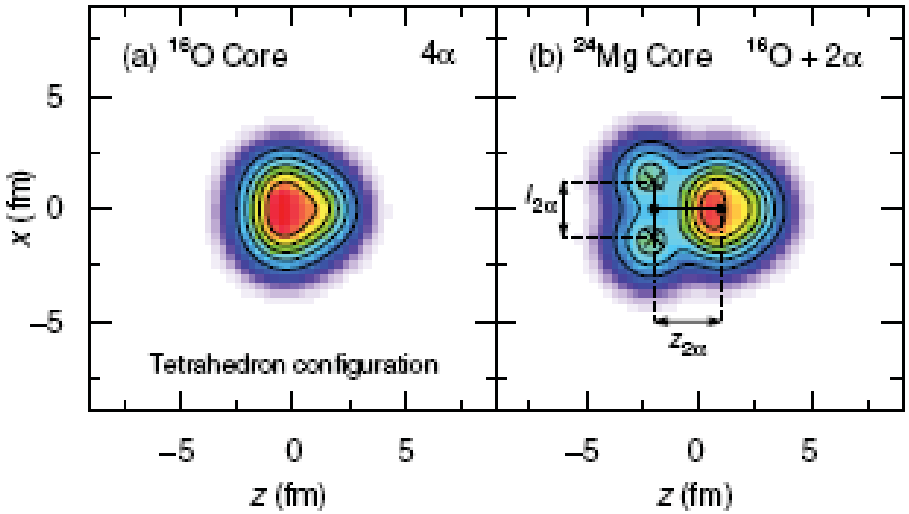
C. L. Jiang,[1] B. B. Back,[1] H. Esbensen,[1] R. V. F. Janssens,[1] K. E. Rehm,[1] and R. J. Charity[2]



^{24}Mg: ^{12}C+^{12}C vs ^{16}O+2 alpha



T. ICHIKAWA *et al.*

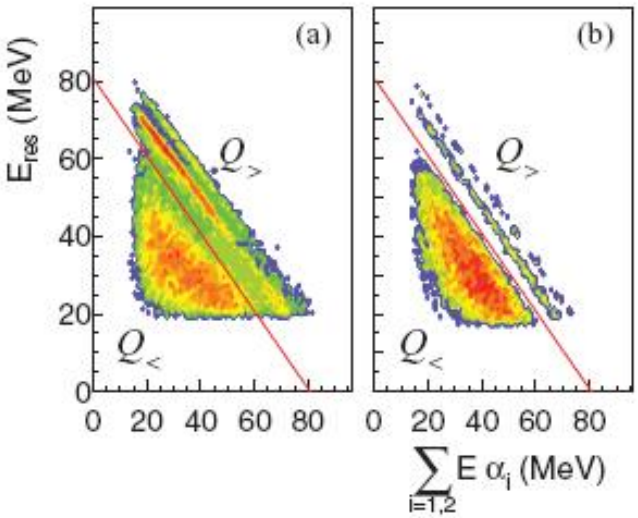


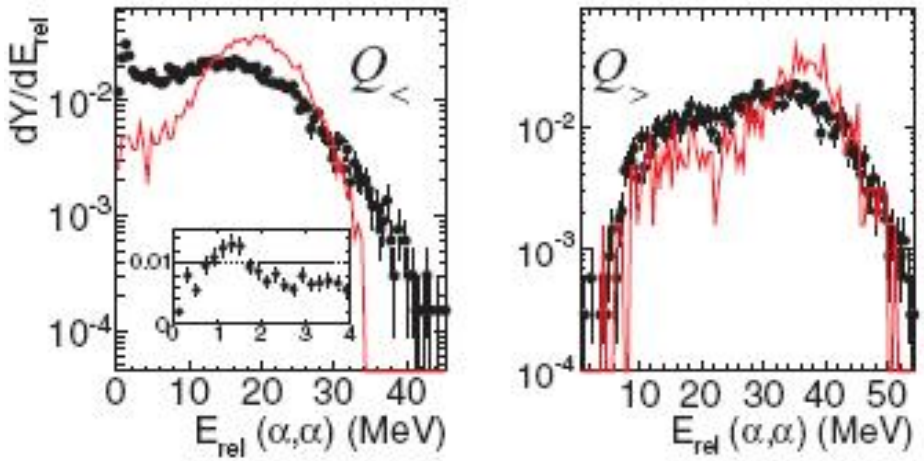
PHYSICAL REVIEW C **87**, 054614 (2013)

α-clustering effects in dissipative $^{12}C + ^{12}C$ reactions at 95 MeV

G. Baiocco,[1,2,*] L. Morelli,[1] F. Gulminelli,[2] M. D'Agostino,[1] M. Bruno,[1] U. Abbondanno,[3] S. Barlini,[4,5] M. Bini,[4,5] S. Carboni,[4,5] G. Casini,[5] M. Cinausero,[6] M. Degerlier,[7] F. Gramegna,[6] V. L. Kravchuk,[6,8] T. Marchi,[6,9] A. Olmi,[5] G. Pasquali,[4,5] S. Piantelli,[5] and Ad. R. Raduta[10]

- 16O – alpha – alpha resonances ?





$^{24}Mg^{*}$ => ^{16}O + alpha + alpha (Osaka Spectro)

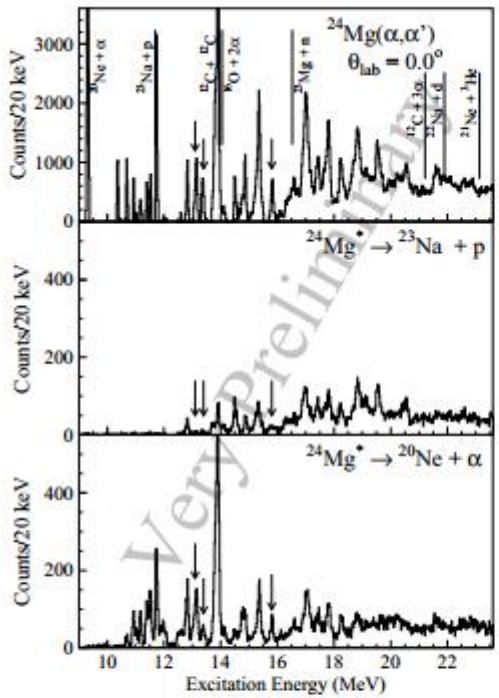


Figure 4. Excitation energy spectra in the $^{24}Mg(\alpha, \alpha')$ reaction at E_x = 9–23.6 MeV taken from the singles measurement (top) and from the coincidence measurements with decay protons (middle) and α particles (bottom). The vertical arrows show the 0^+ states at 13.1, 13.4, and 15.8 MeV.

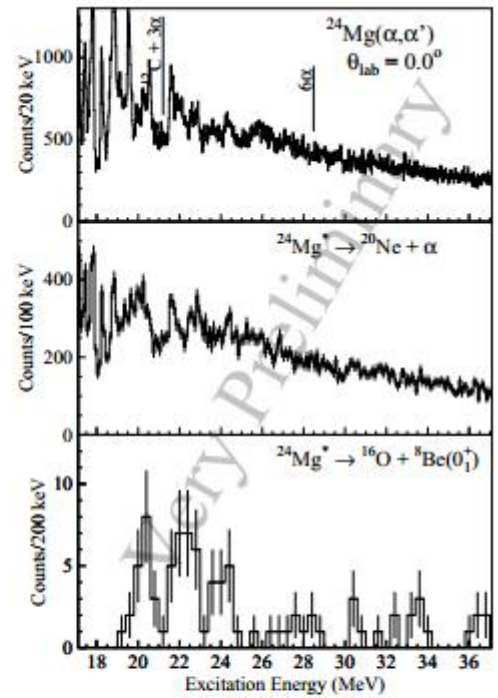
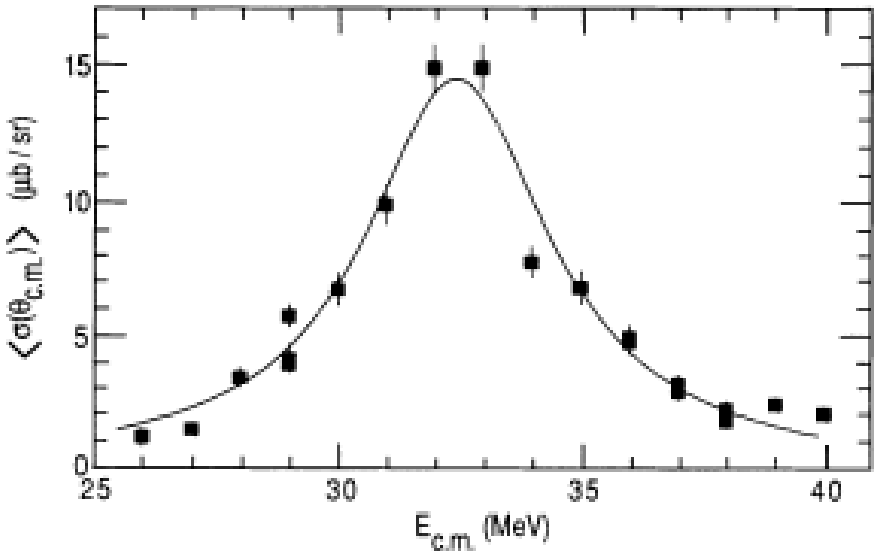


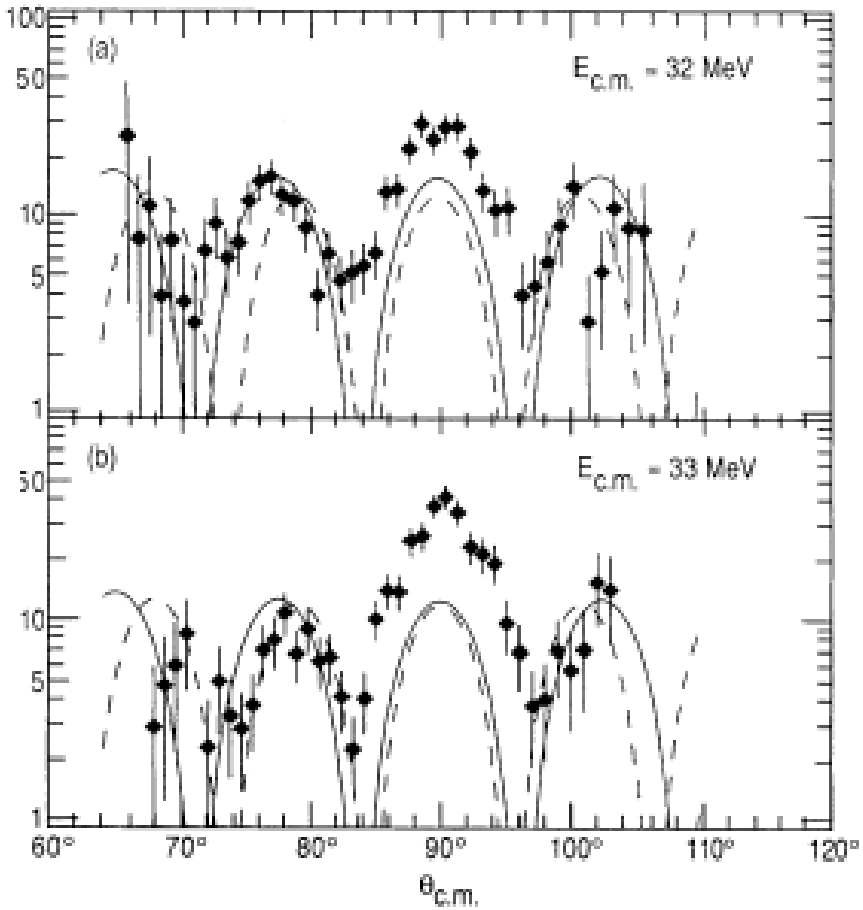
Figure 5. Excitation energy spectra in the $^{24}Mg(\alpha, \alpha')$ reaction at E_x = 17.1–37.1 MeV taken from the singles measurement (top) and from the coincidence measurements with decay α particles (middle) and ^{8}Be (bottom).

VOLUME 68, NUMBER 9 PHYSICAL REVIEW LETTERS 2 MARCH 1992

Evidence for Alpha-Particle Chain Configurations in ^{24}Mg

A. H. Wuosmaa, R. R. Betts, B. B. Back, M. Freer, B. G. Glagola, Th. Happ, D. J. Henderson,





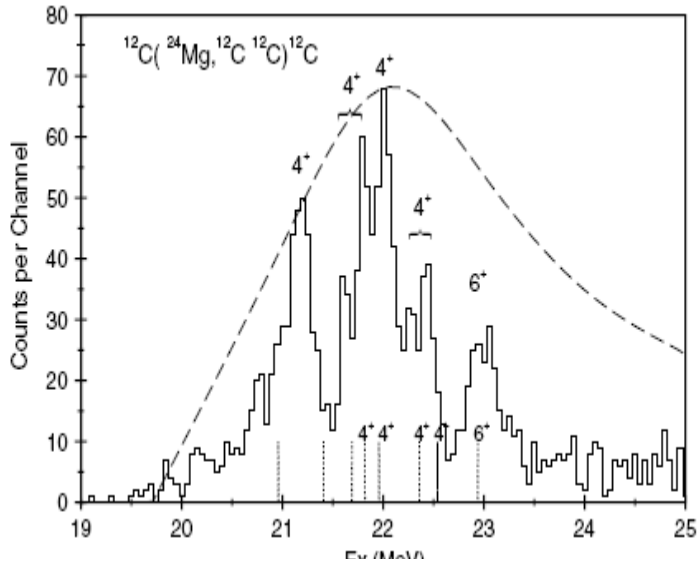
Resonant Breakup States in ^{24}Mg

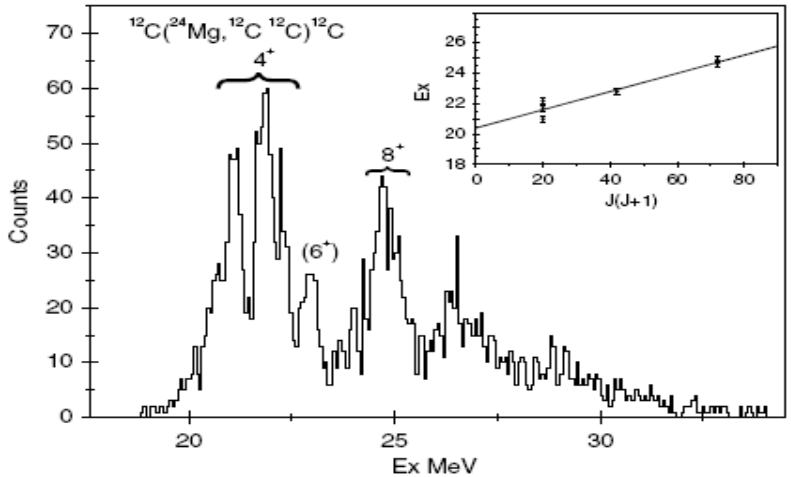
- Inelastic breakup of $^{24}Mg^*$ in $^{24}Mg+^{12}C$ @ 130 MeV

- Experiments from the Charissa Collaboration

- Three ^{12}C fragments in the exit channel

B. Fulton *et al.* Phys. Lett. **B181** (1986).





SD band in ^{28}Si (D. Jenkins)

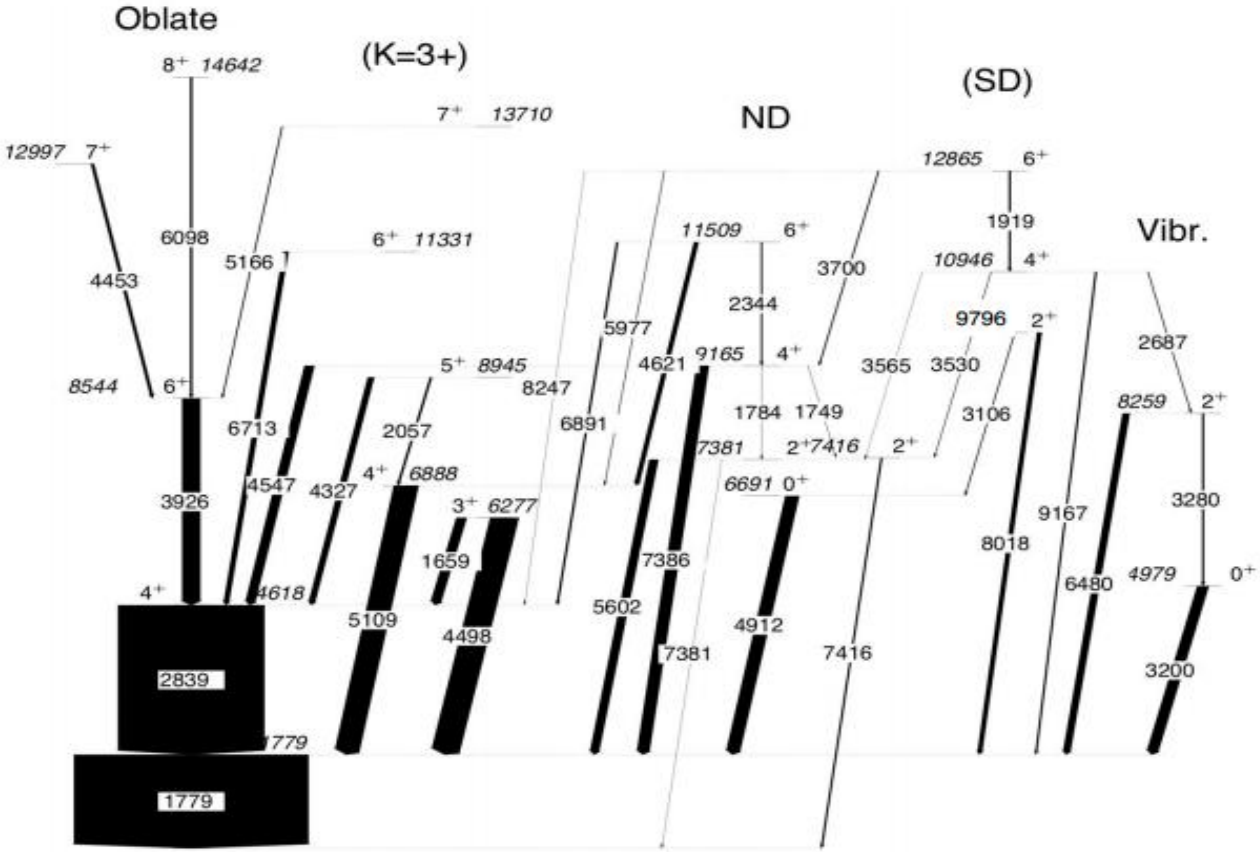
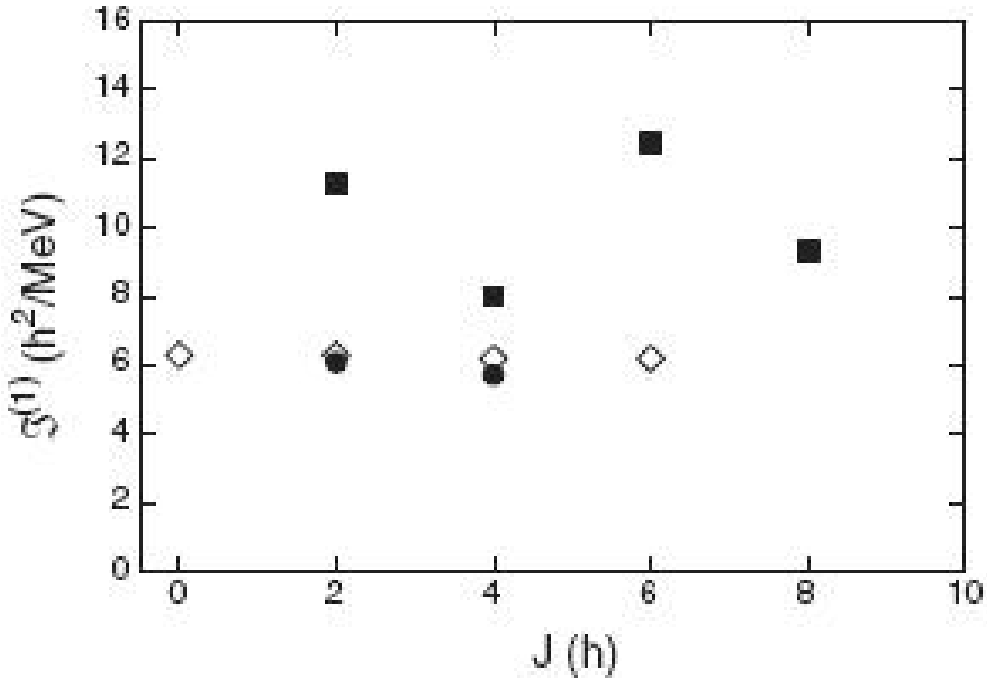
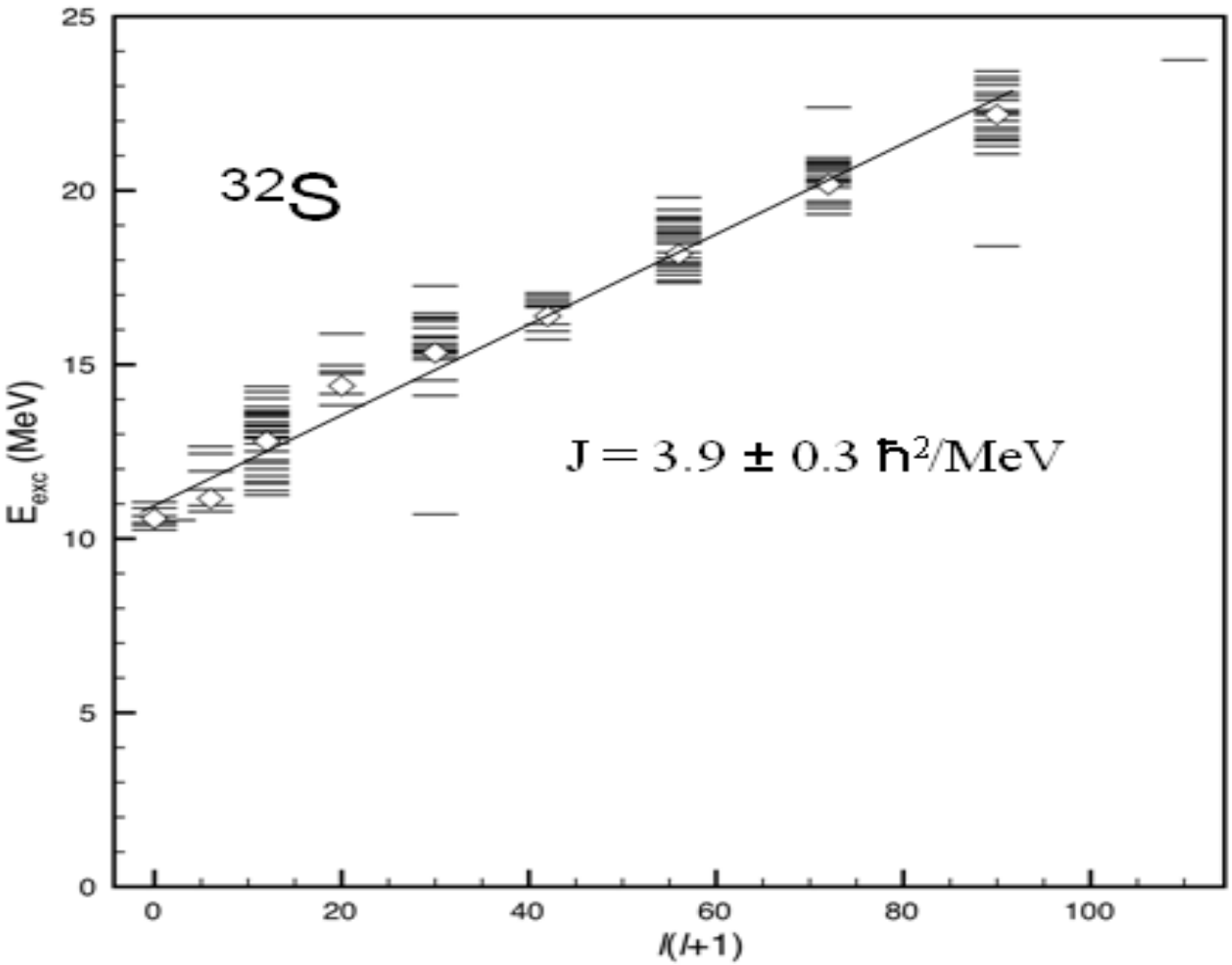


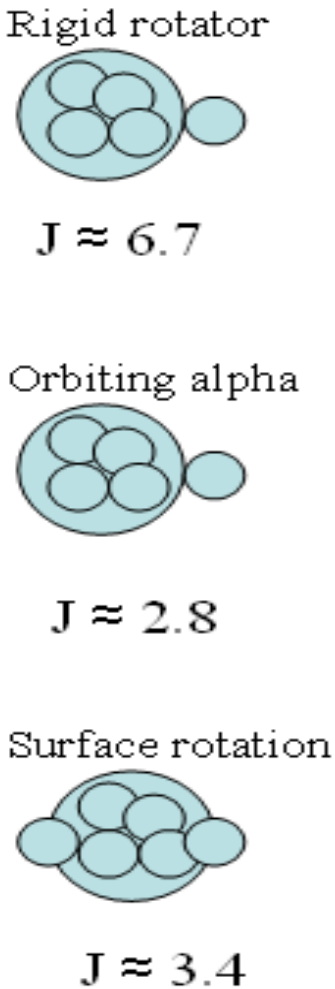
Figure 1. Subset of positive-parity levels in ^{28}Si derived from the analysis of the Gammasphere dataset . Excited states and transition energies are labeled with their energy in keV, while the width of the arrows corresponds to the relative intensity of the observed transitions. The different structures are labeled according to previous assignments as oblate, prolate (ND), vibrational and with different K values

^{28}Si moment of inertia vs AMD results (Taniguchi)

D. G. JENKINS *et al.*

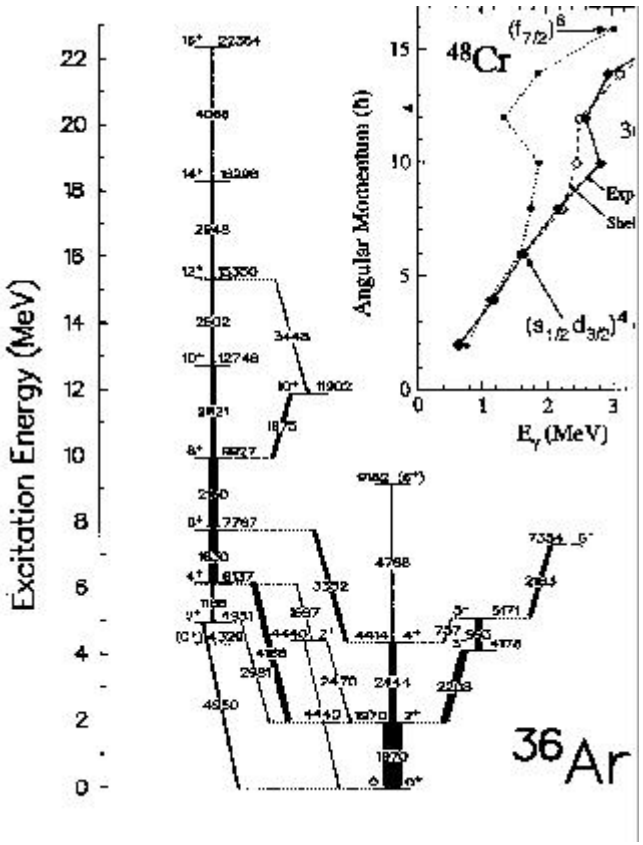


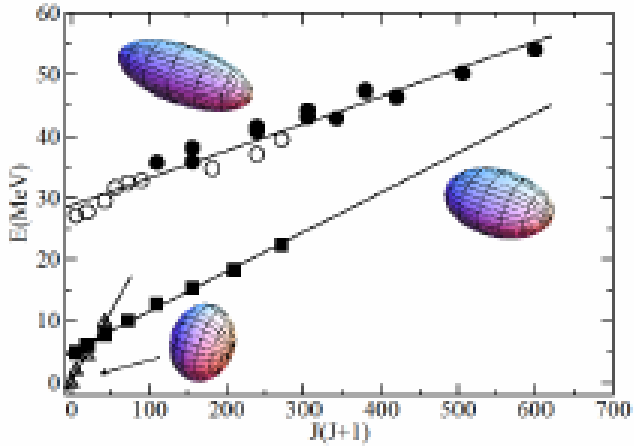




^{32}S rotational bands (see Eur.Phys.Jour. A **46** (2010) 5)

Superdeformation vs Resonances in ^{36}Ar





SD and HD deformed bands in ^{36}Ar

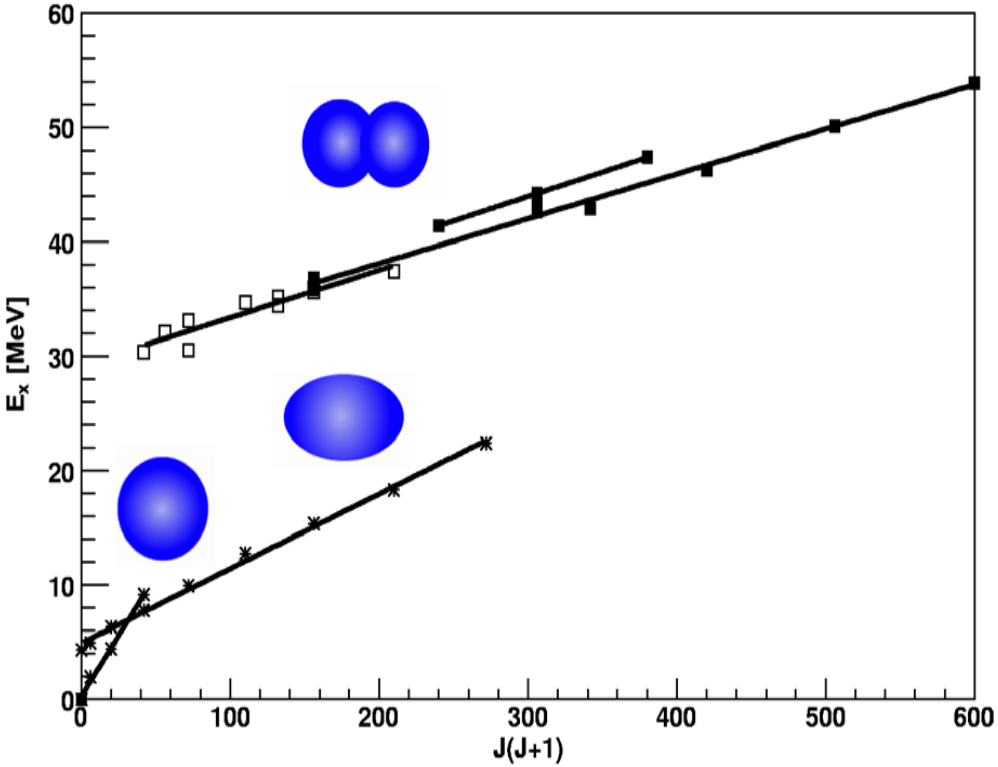
Moment of inertia:

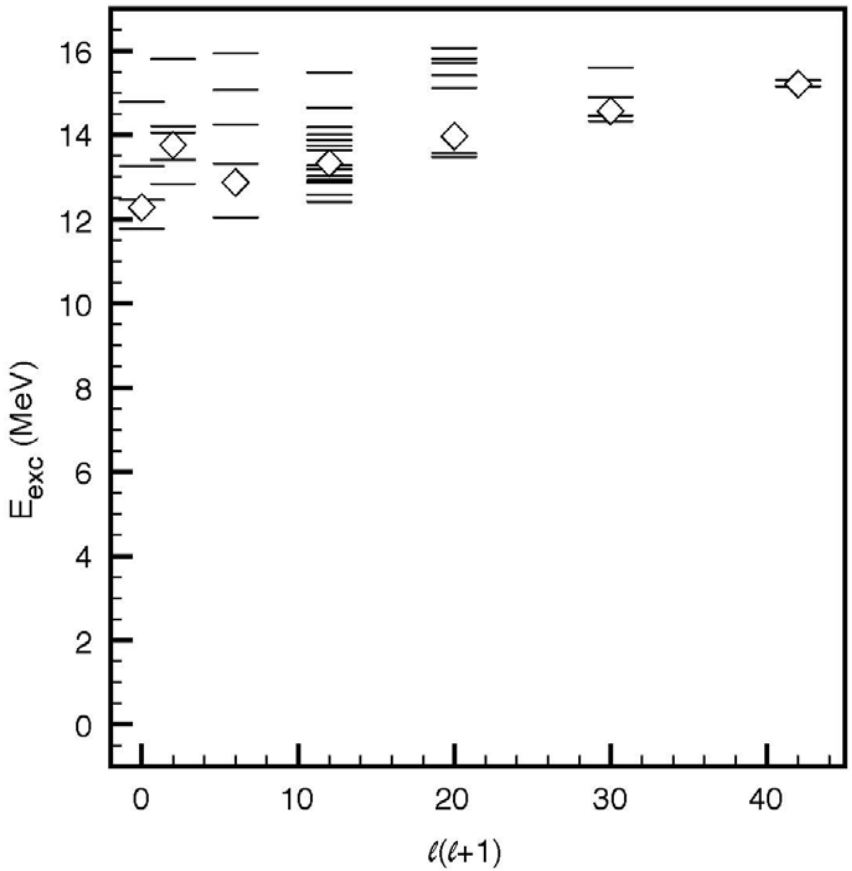
$I(SD) = 2.4 \times 10^5$ Mev fm^2/c^2

$I(res) = 4.1 \times 10^5$ MeV fm^2/c^2

C.E. Svensson *et al*. Phys. Rev. Lett**.** **85**, 2693 (2000).

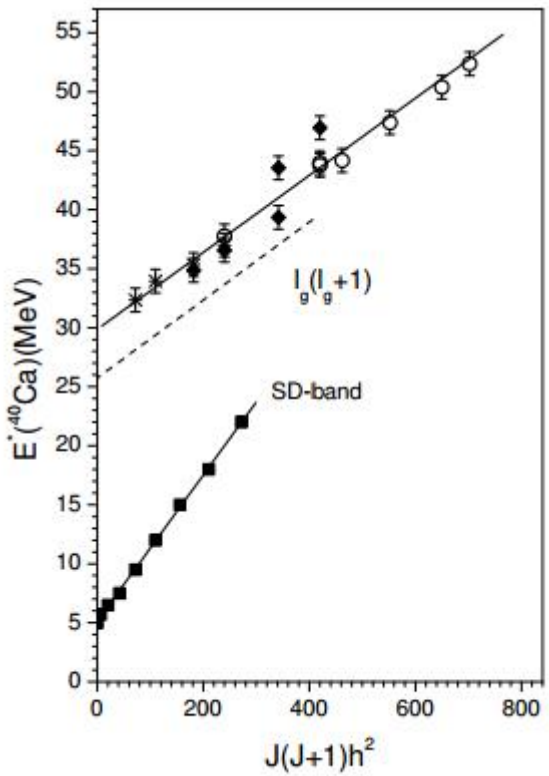
Resonances in ^{36}Ar from $^{12}C+^{24}Mg$ scattering



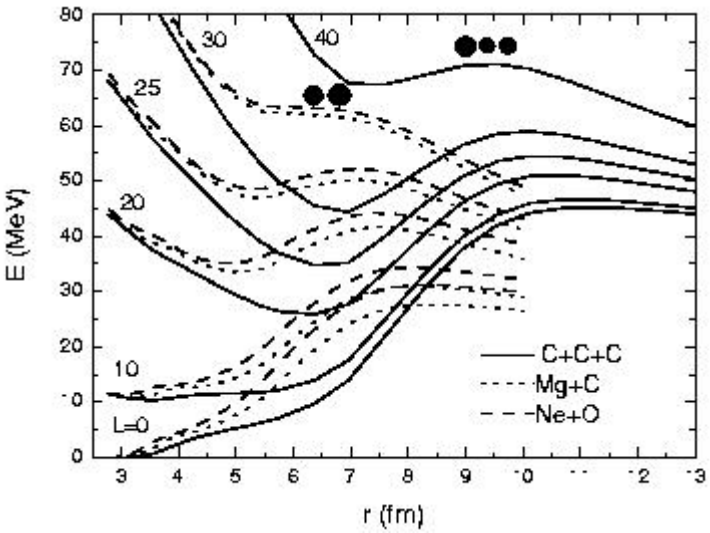


Resonances in ^{40}Ca from $^{12}C+^{28}Si$ scattering

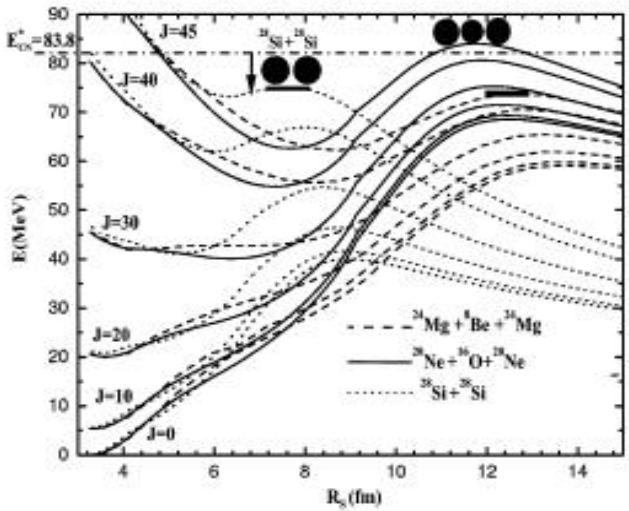
- Sao Paulo data



Generalized LDM: ternary fission



^{36}Ar



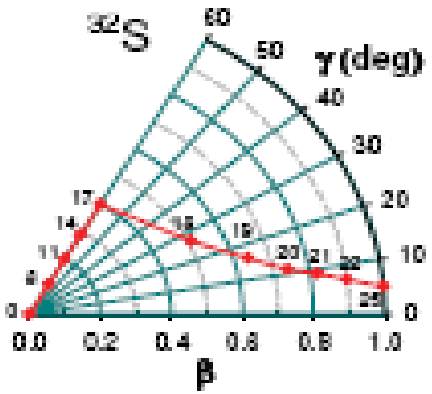
^{56}Ni

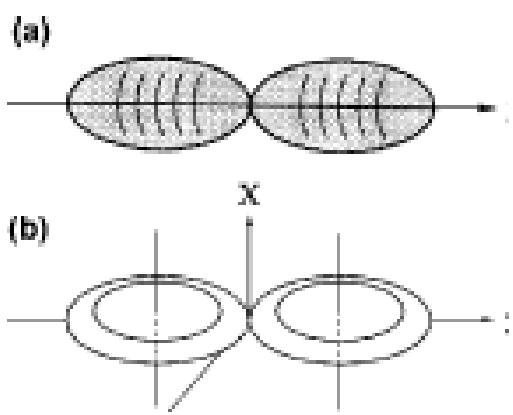
G. Royer (private communications)

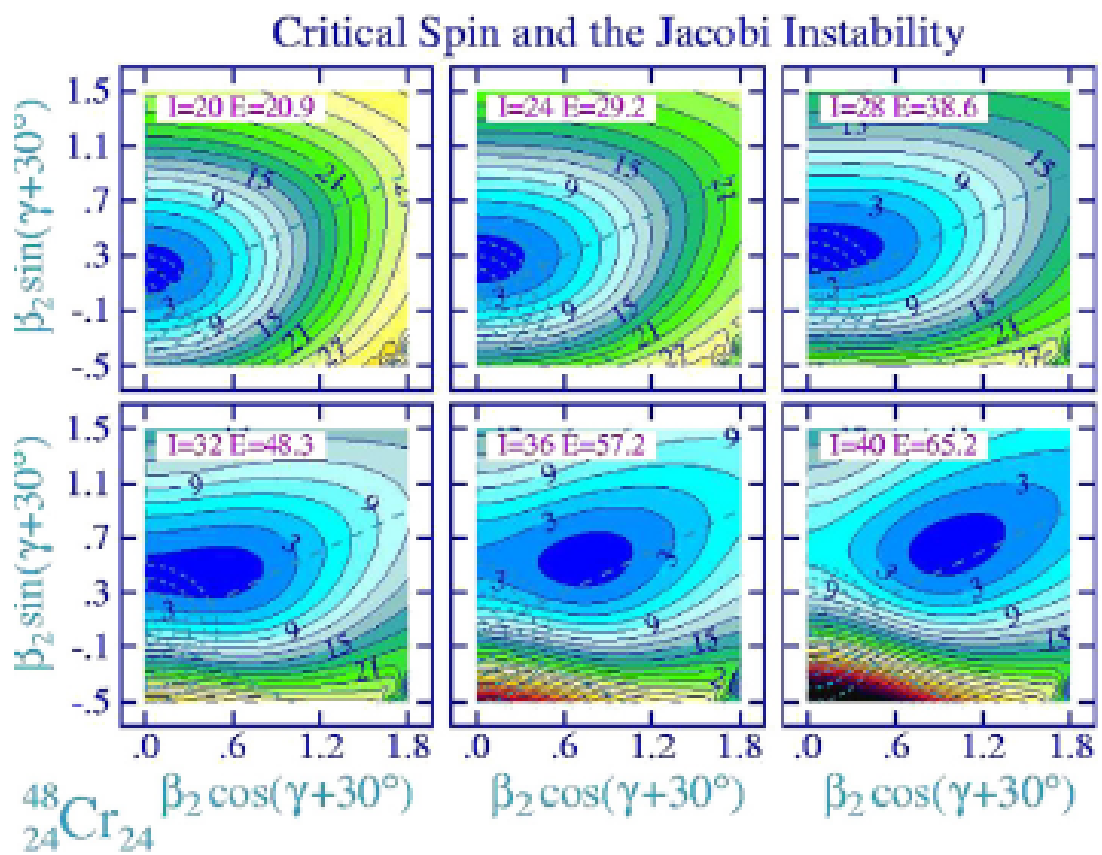
G. Royer, C. Bonilla, R.A. Ghergescu, Phys. Rev. C **67,** 034315 (2003).

Clustering, Hyperdeformation and Jaccobi

M.-D. Salsac et al. / Nuclear Physics A 801 (2008) 1–20

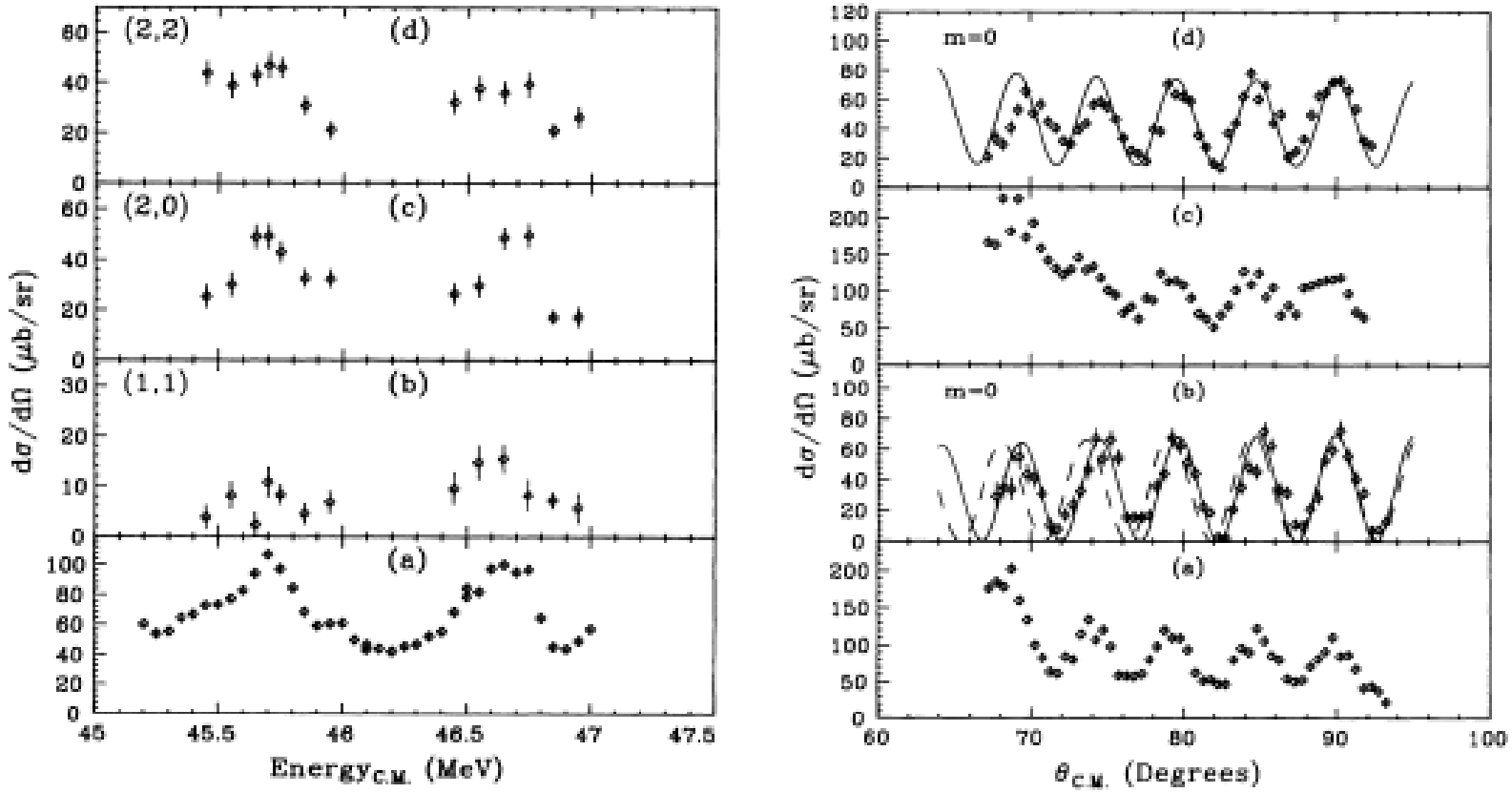






$^{24}Mg + ^{24}Mg$ molecular resonances

VOLUME 58, NUMBER 13 PHYSICAL REVIEW LETTERS 30 MARCH 1987



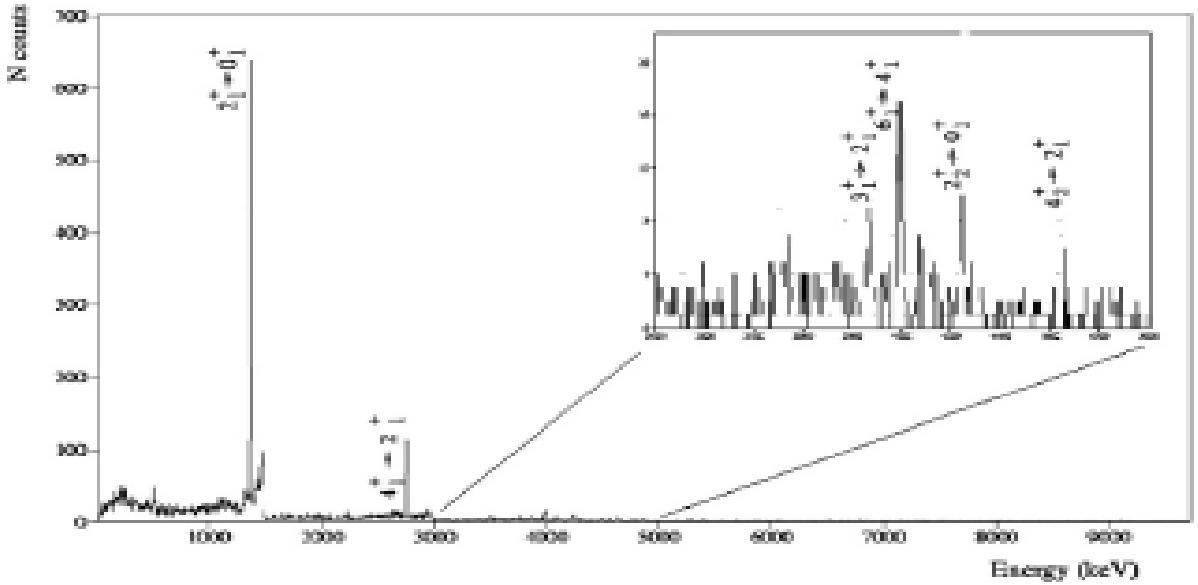
$^{24}Mg+^{24}Mg$ at Legnaro

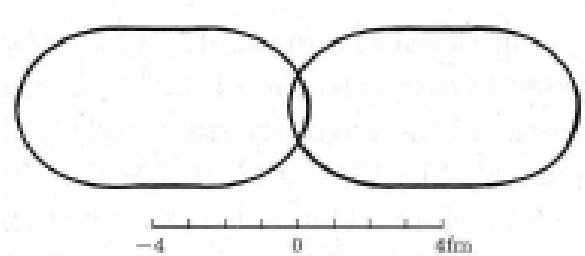
GASP/Euclides

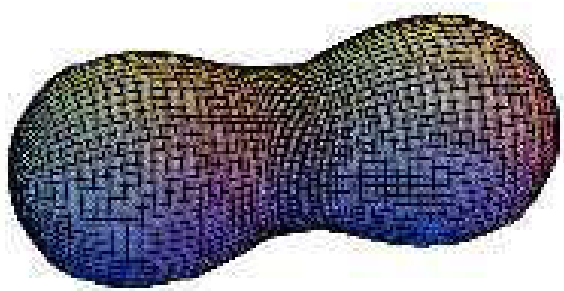
Prisma/Clara

Figure 1. View of the CLARA-PRISMA setup. The CLARA array of Clover detectors is on the left, followed by the quadrupole and dipole magnets, and the focal plane detector of PRISMA can be seen on the right.

^{24}Mg states populated by 36 h resonance







EPJ Web of Conferences 21, 02002 (2012)

Clustering effects in ^{48}Cr composite nuclei produced via ^{24}Mg + ^{24}Mg reaction A. Di Nitto, A. Brondi, G. La Rana, R. N. Gelli Moro, P. Nadtochy, E. Vardaci

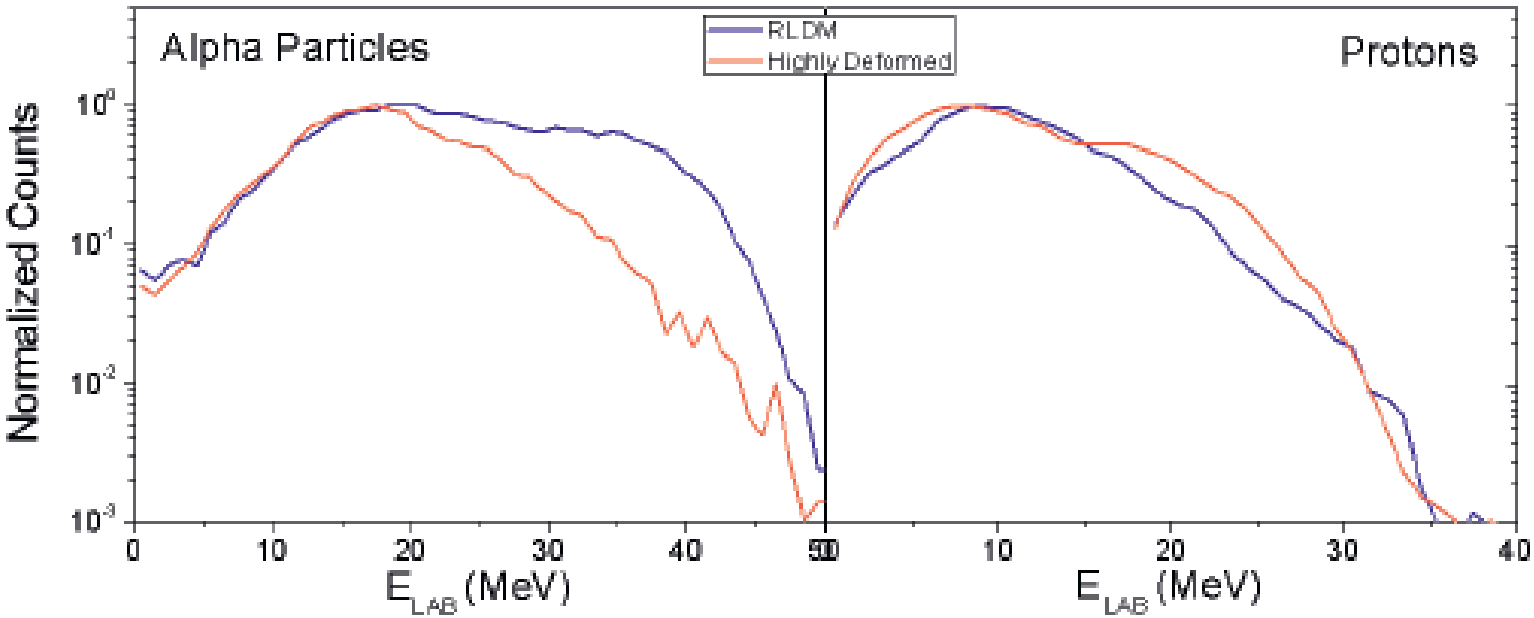


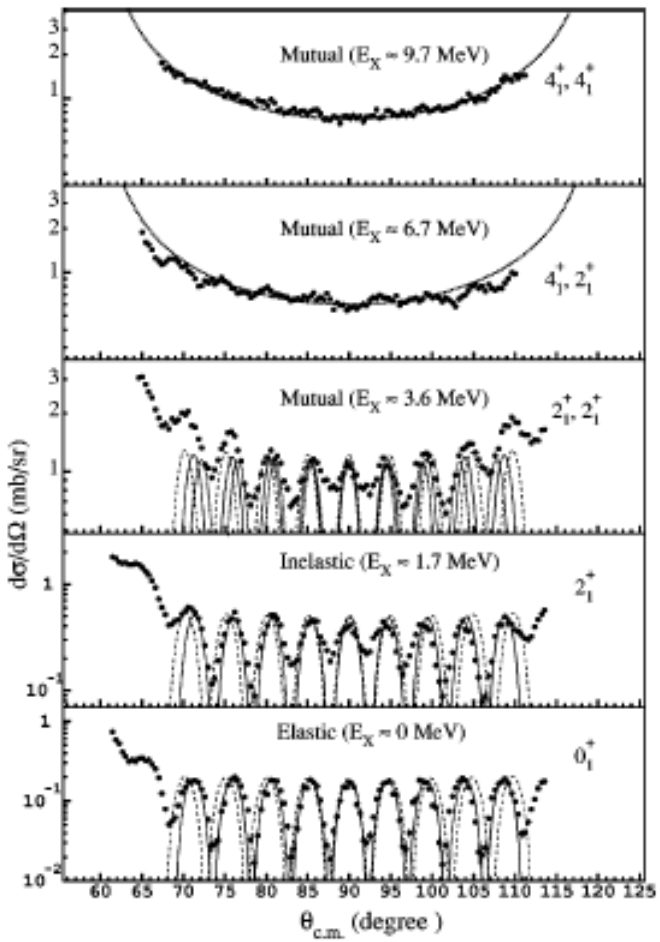
Fig. 6. Energy spectra of alpha particles and protons simulated at θ_{lab} = 42.7° in coincidence with ERs.

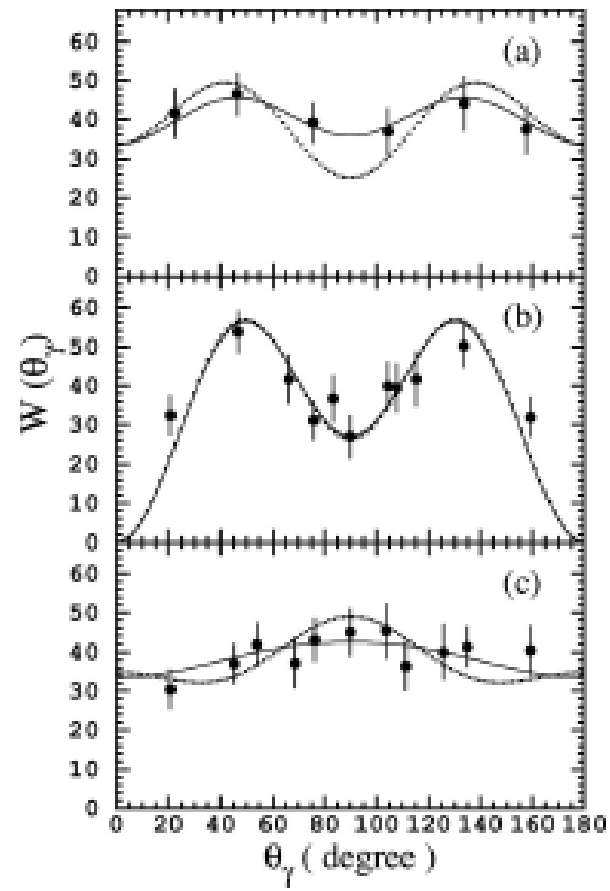
RAPID COMMUNICATIONS

PHYSICAL REVIEW C, VOLUME 60, 041303

Vanishing spin alignment: Experimental indication of a triaxial $^{28}Si+^{28}Si$ nuclear molecule

R. Nouicer,[1,*] C. Beck,[1] R. M. Freeman,[1] F. Haas,[1] N. Aissaoui,[1] T. Bellot,[1] G. de France,[1,†] D. Disdier,[1] G. Duchêne,[1] A. Elanique,[1,3] A. Hachem,[1] F. Hoellinger,[1] D. Mahboub,[1,3] V. Rauch,[1] S. J. Sanders,[4] A. Dummer,[4] F. W. Prosser,[4]





^{56}Ni alpha breakup (Maya @ Ganil)

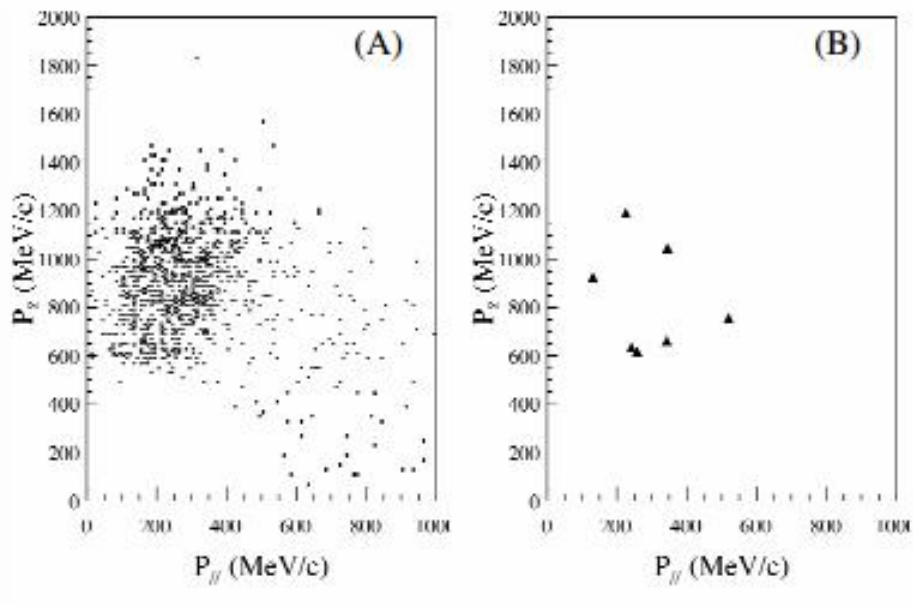
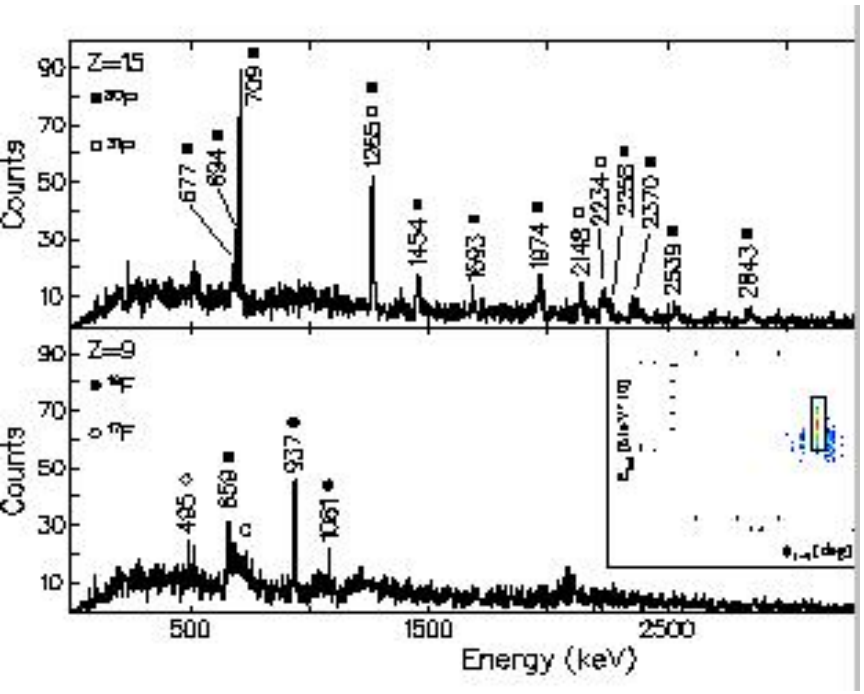
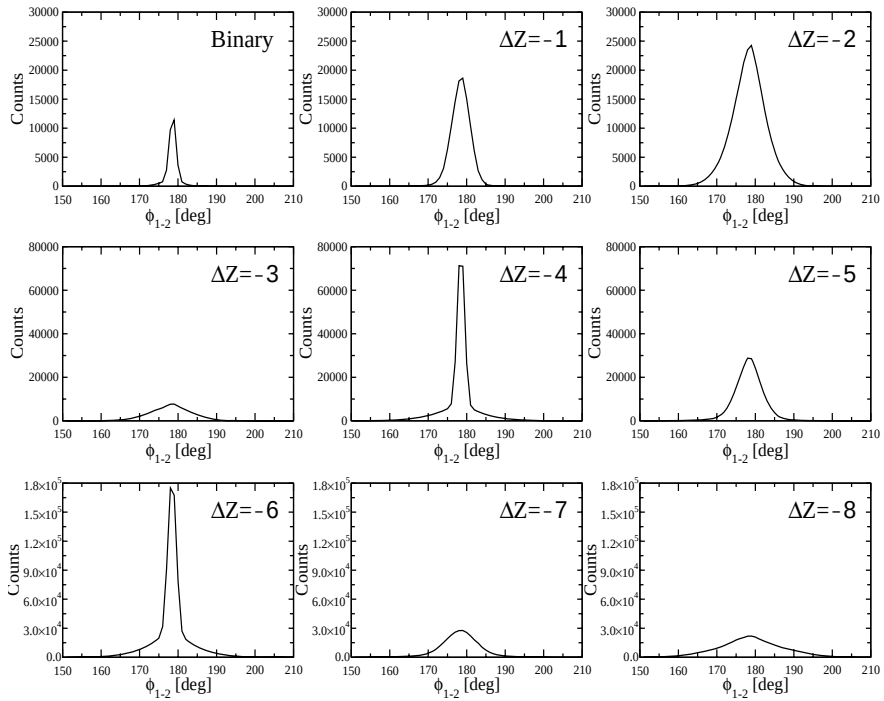


Figure 4. (A) The experimental momentum distributions of alpha particles from events with multiplicity larger than 5. (B) The momentum distribution for one event with the multiplicity seven.

Ternary Fission in ^{56}Ni





Gamma-ray spectra (P and F isotopes)
C. Wheldon *et al.* Nucl. Phys. A **811**, 276 (2008).

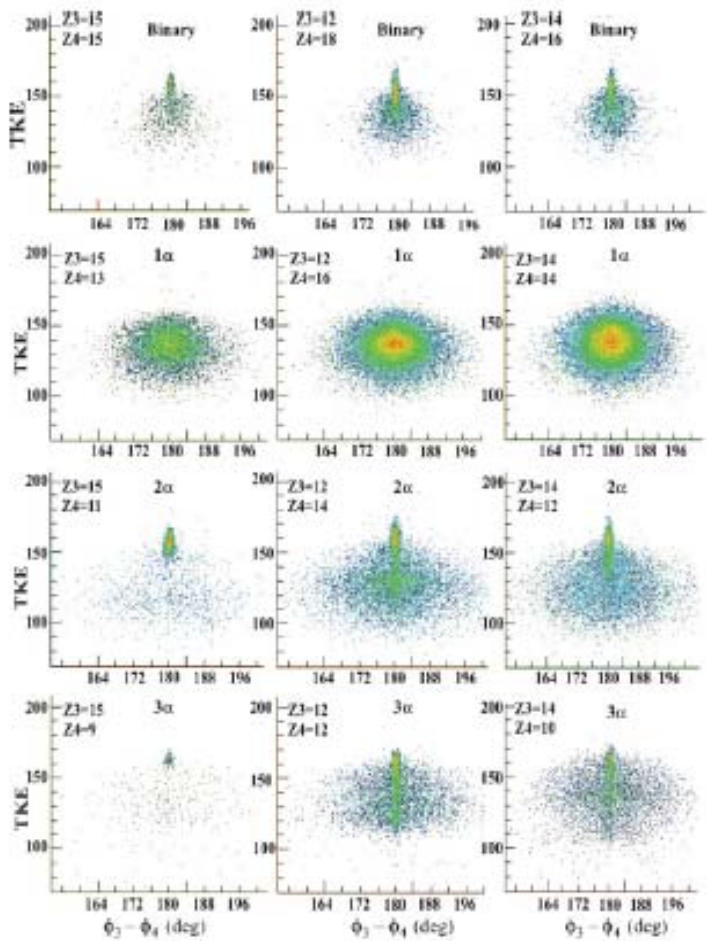
Out-of-plane Angular Correlations
W. von Oertzen *et al.*
Eur. Phys.Jour. A **36,** 279 (2008).

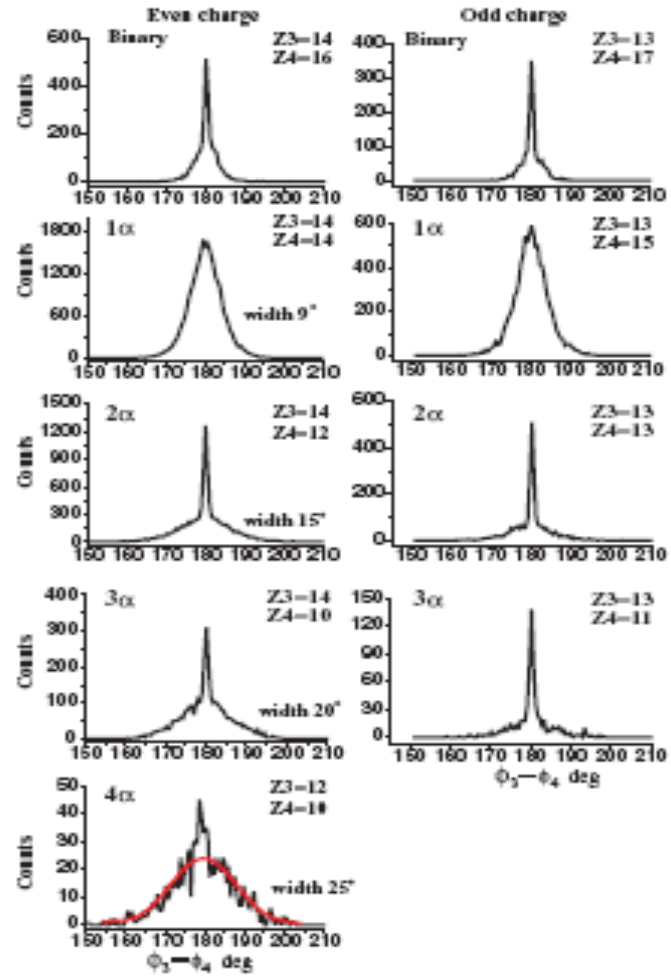
$^{32}S+^{24}Mg$ at E_{lab} = 165.4 MeV

$^{36}Ar+^{24}Mg$: out-of-plane angular correlations

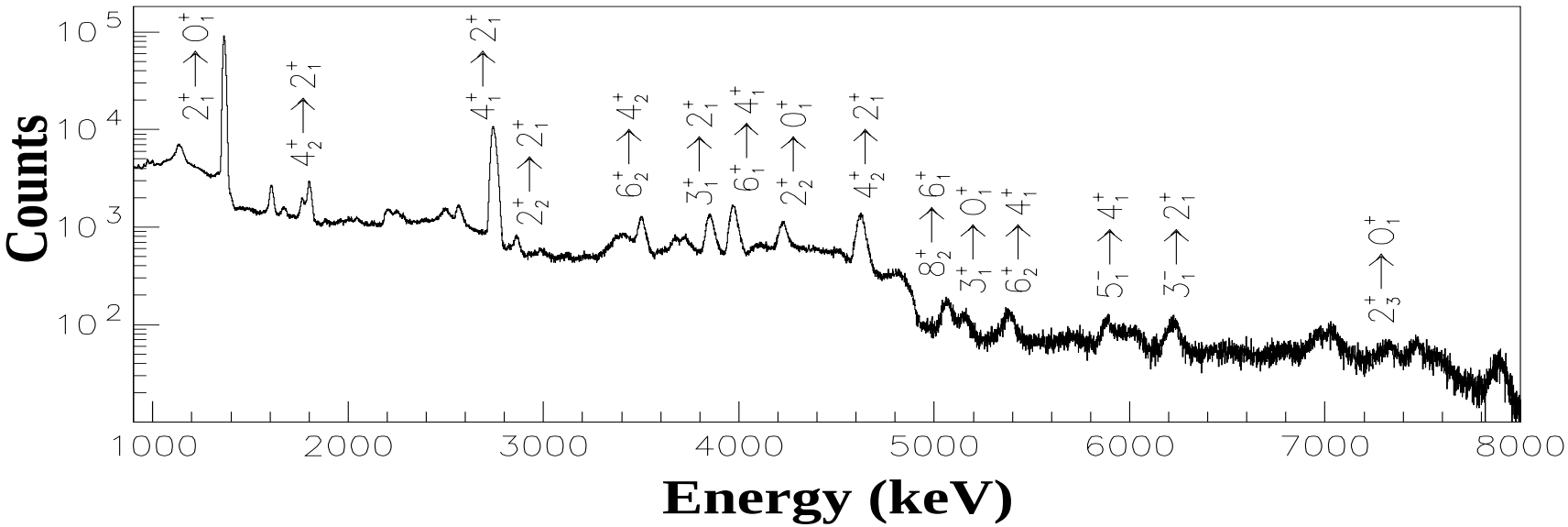
W. VON OERTZEN *et al.*

PHYSICAL REVIEW C 78, 044615 (2008)





^{24}Mg gamma-ray spectrum



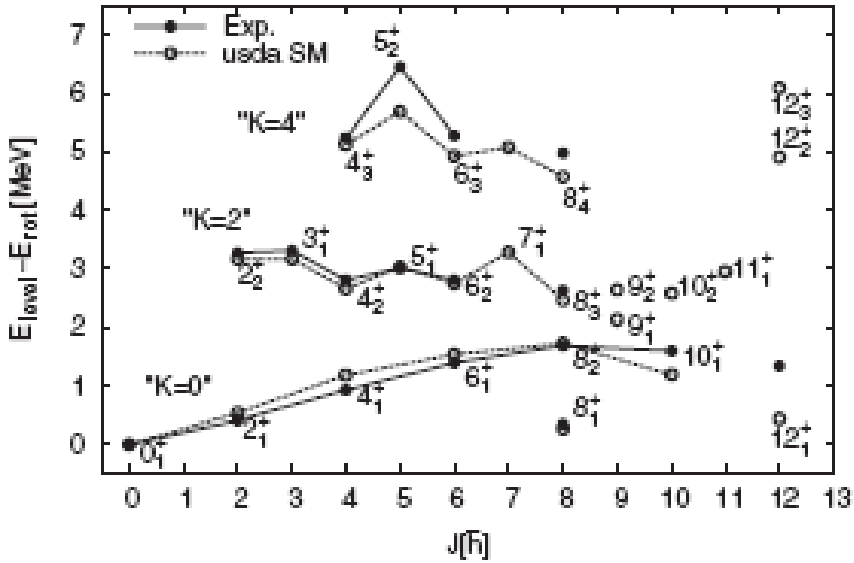
C. Beck *et al*., Nucl. Phys. **A734**, 453 (2003); Phys. Rev. C **80,** 034604 (2009).

- Population of high-spin states of the g.s. band up to the 8^+ state
- No sign of the occurrence of the 10^+ state discovered by Wiedenhoever *et al.,* Phys. Rev. Lett. **87** (2001). 12^+ sate ?

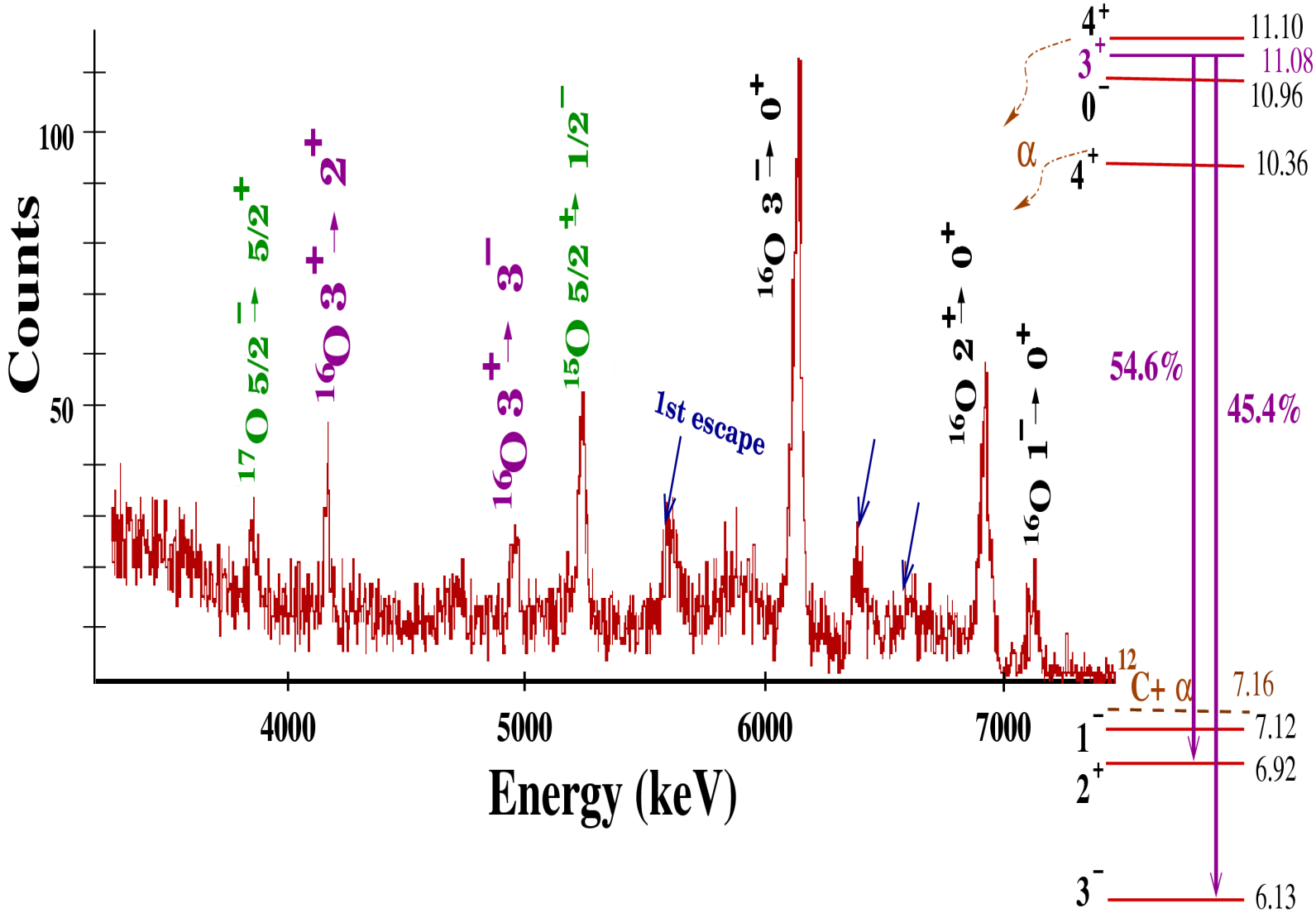
PHYSICAL REVIEW C 85, 034311 (2012)

High-spin spectrum of ^{24}Mg studied through multiparticle angular correlations

E. S. Diffenderfer,* L. T. Baby, D. Santiago-Gonzalez, N. Ahsan, A. Rojas,† A. Volya, and I. Wiedenhöver
Florida State University, Tallahassee, Florida 32306, USA



New partial level scheme for ^{16}O



New interest in ^{16}O spectroscopy

* Search for Bose-Einstein Condensates in ^{16}O

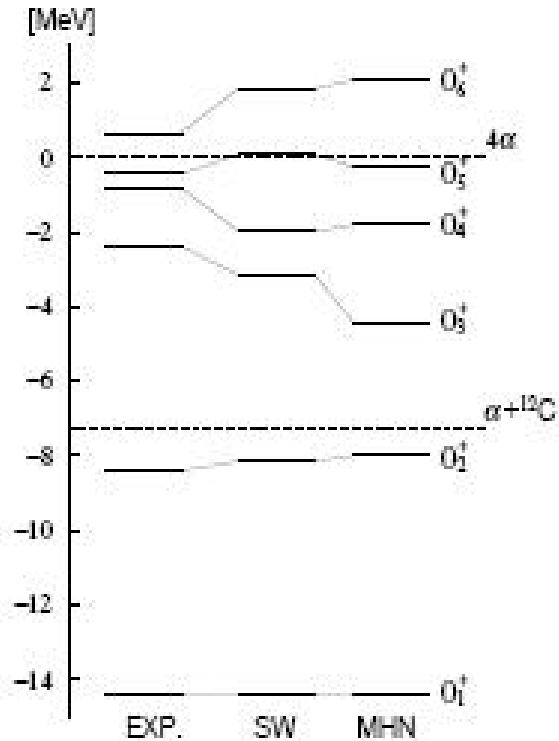
* Equivalence of a (alpha + $^{12}C_{Hoyle\_state}$) configuration in BEC.

  Y. Funaki *et al.* Phys. Rev. Lett. **101,** 082502 (2008).

* Need of new experimental results.

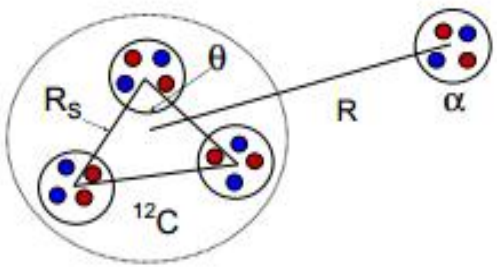
  C. Beck *et al.*, Phys. Rev. C **80**, 034604 (2009).

  Experimental Programme at iThemba LABS (Cape Town)

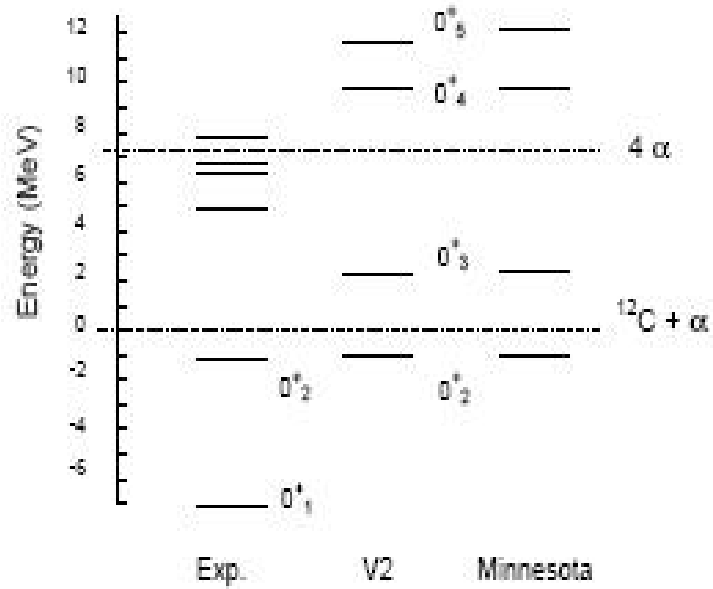


^{16}O spectroscopy M.Dufour et al.

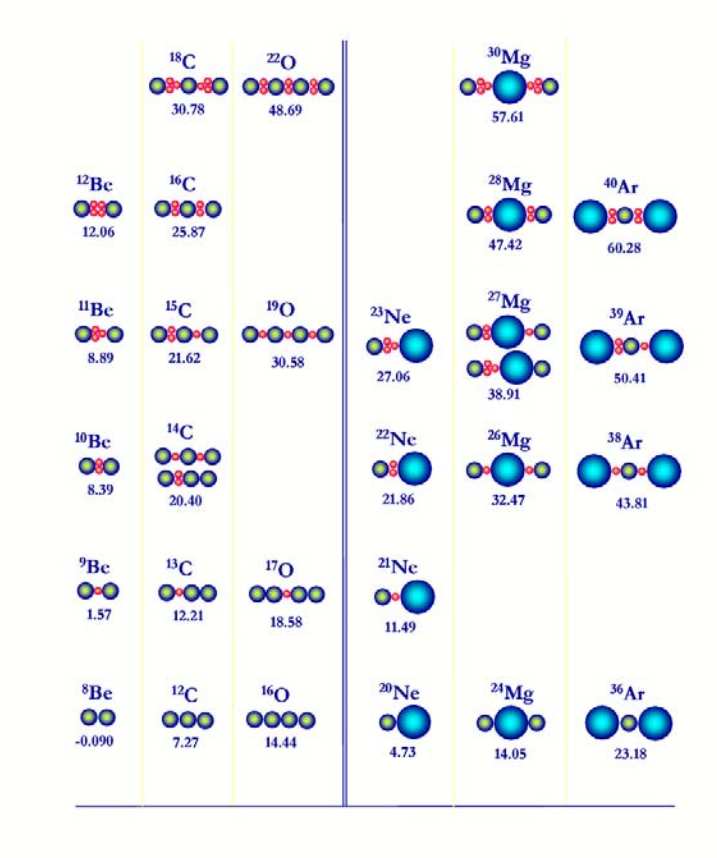
- ^{12}C+alpha

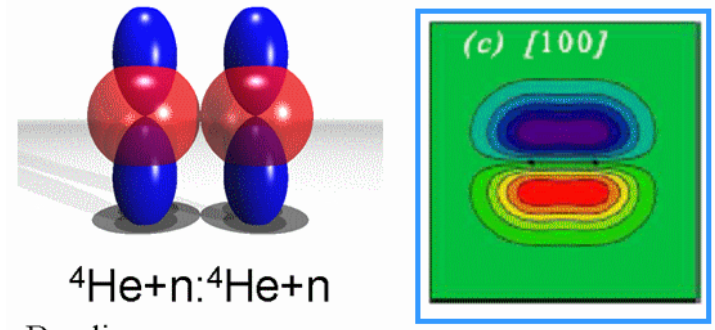


GCM calculations for ^{16}O



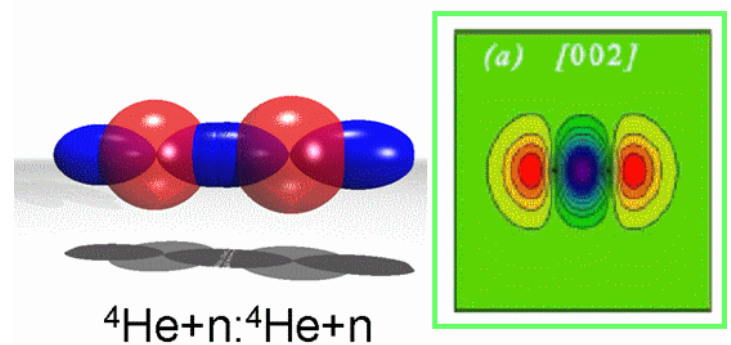
Extended Ikeda diagram (W. von Oertzen)





^{4}He+n:^{4}He+n

Bonding π



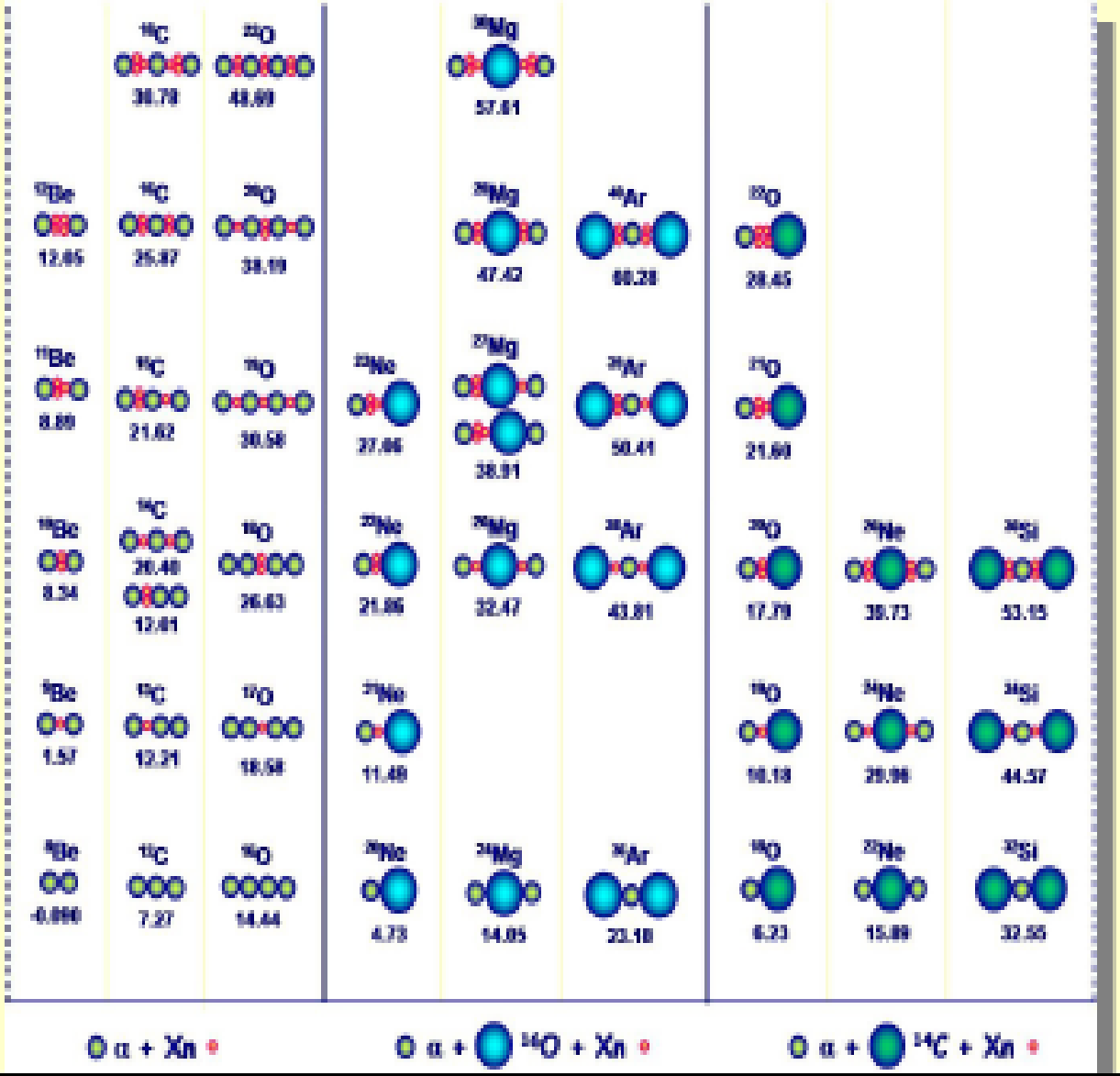
^{4}He+n:^{4}He+n

Bonding σ

The main spherical clusters are α–particles ^{16}O and ^{14}C!

With valence neutrons they can form covalent composite molecules [1].

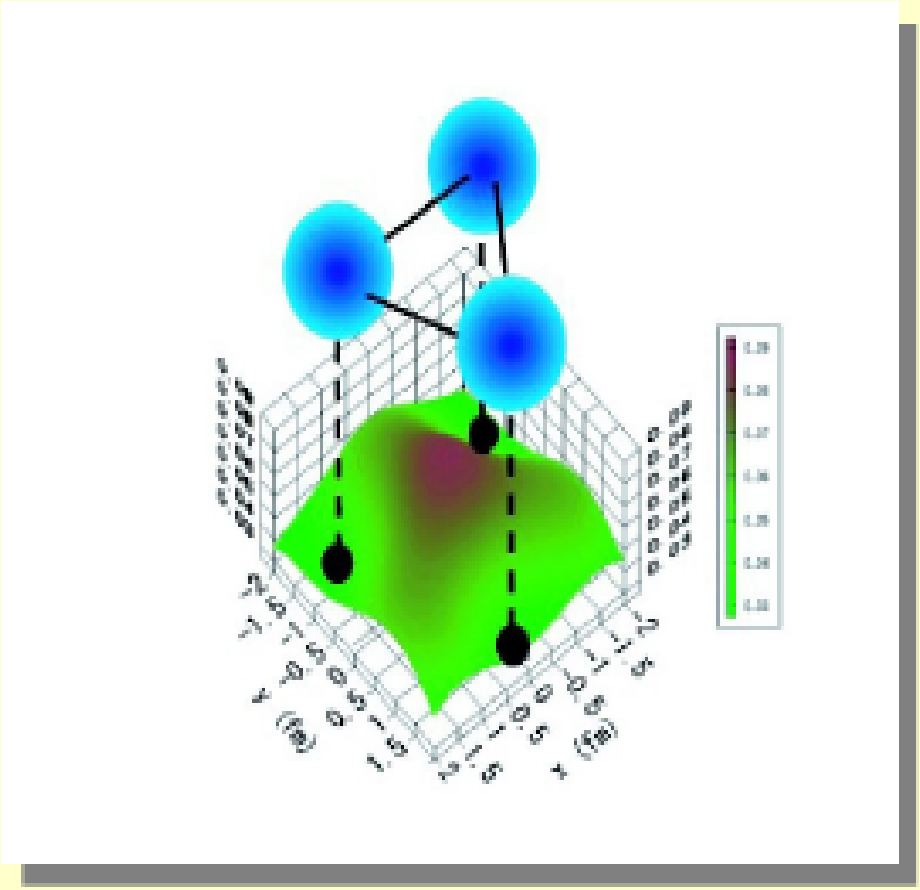
The energies are the thresholds for cluster decomposition [2].



[1] W. von Oertzen,
Eur. Phys. J. A 11 (2001) 403.

[2] K. Ikeda et al.,
Prog. Theor. Phys. , Extra Suppl.
(Jap.), (1968) 464.

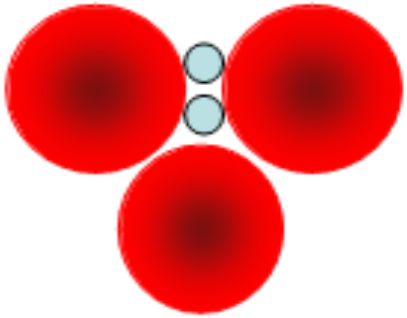
Triangular configurations in ^{14}C (N. Itagaki)



- The positions of the alpha-particles is shown. The neutron density is shown as green-red profile.
- $K^{\pi} = 0^{+}$ band starting at 6.59 MeV.
- $K^{\pi} = 3^{-}$ band starting at 9.80 MeV.

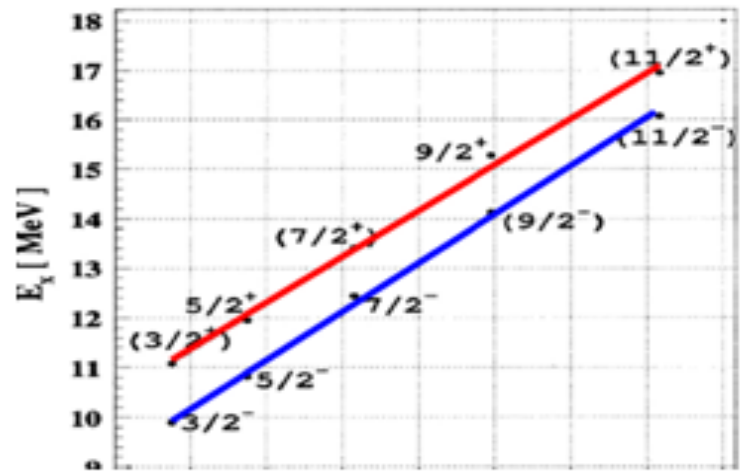
^{14}C molecular states from dimers to polymers

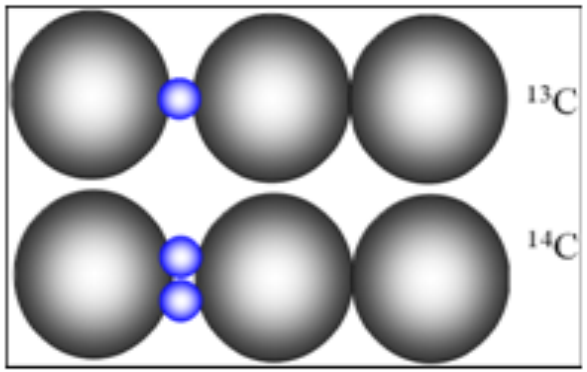
$$\Psi(^{14}C^*) = \frac{1}{\sqrt{1+\Delta}}\left[\,\left|\alpha_1 \frac{n}{n} \alpha_2\ \alpha_3\right\rangle \pm \left|\alpha_1\ \alpha_2 \frac{n}{n} \alpha_3\right\rangle\,\right]$$



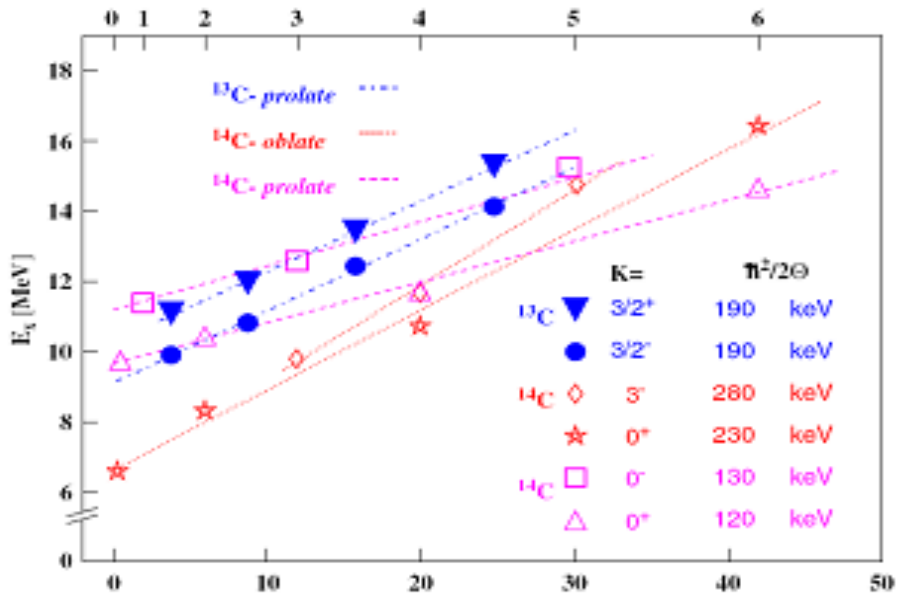
prolate

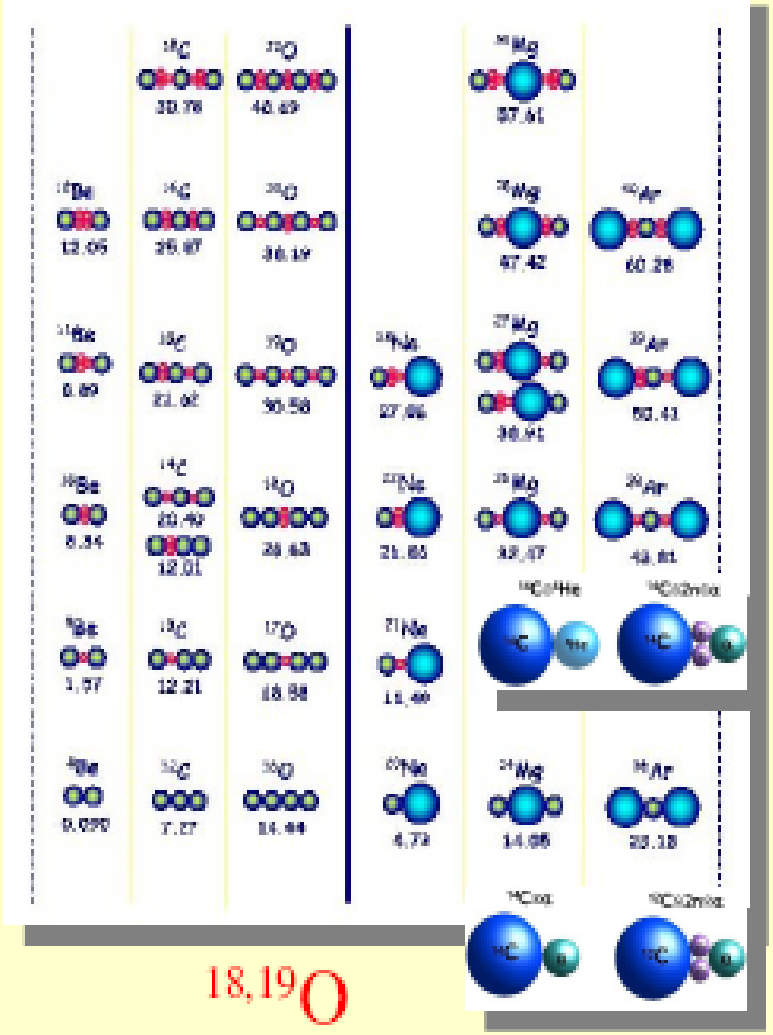
oblate





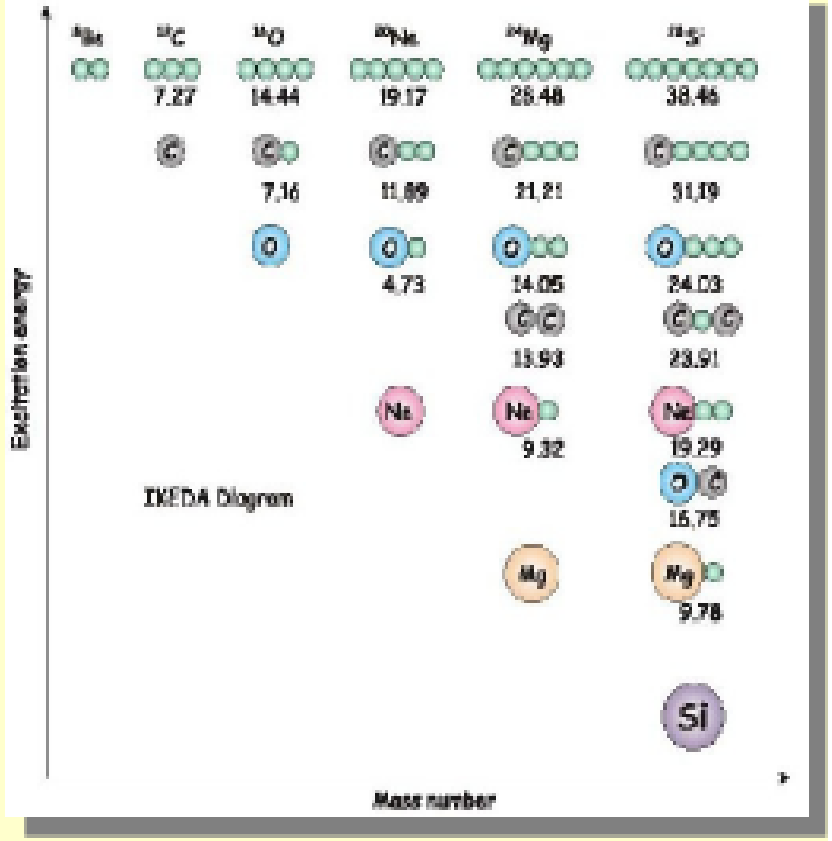
von Oertzen and Milin





$^{18,19}O$

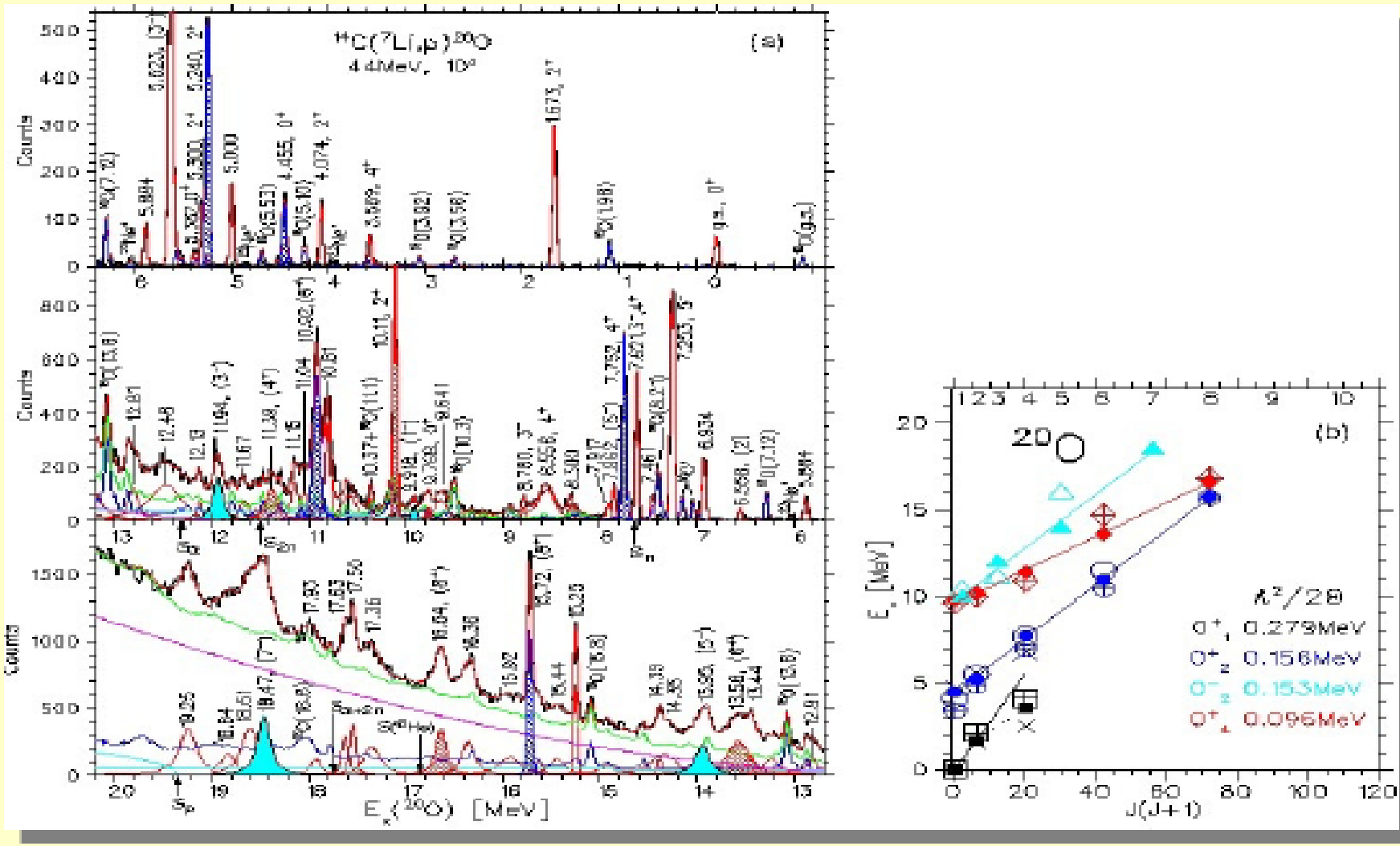
^{20}O



Extended Ikeda Diagram:
W. von Oertzen,
EPJ A 11 (2001) 403

K. Ikeda et al.,
Prog. Theor. Phys. ,
Extra Suppl. (Jap.),
(1968) 464.

New: with ^{14}C – cluster: W. von Oertzen et al., EPJ A 41 (2009)



Rotational bands in ^{20}O

Summary and Conclusions

- Large 4pi-gamma/fragment detection useful tool for gamma-ray spectroscopy: $^{32}S+^{24}Mg$ and $^{24}Mg+^{12}C$ collisions
- Possible Ternary Cluster Decay of the Hyperdeformed $^{56}Ni^*$ and $^{60}Zn^*$ nuclei
- Alpha Condensates (BEC) in ^{16}O-^{20}Ne-^{24}Mg ?
- Clustering effects in neutron-rich nuclei as expected by Extended Ikeda diagram

List of Collaborators

- C.Beck, S. Courtin, D. Curien, O. Dorvaux, A. Goasduff, D. Lebhertz, A. Nourreddine, P. Papka, M. Rousseau, A. Sanchez I Zafra, M.D. Salsac, F. Azaiez, and P. Bernarczyk,

  IPHC and Universite de Strasbourg),France

- W. von Oertzen, G. Gebauer, C. Wheldon, G. Efimov, V. Zherebchevsky, S. Thummerer, Tz. Kokalova, Ch. Schulz, H.G. Bohlen, and D. Kamanin

  HMI and Freie Universitat Berlin, Germany

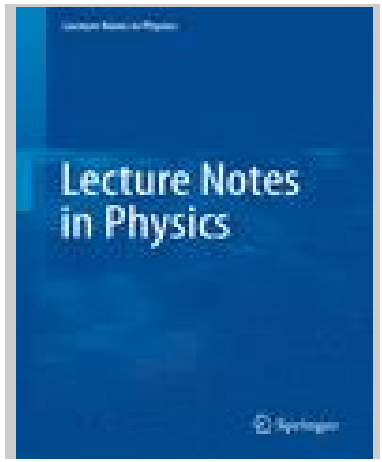
- G. de Angelis, A. Gadea, S. Lenzi, D.R. Napoli, and S. Szilner

  INFN Lab. Naz. Legnaro, Padova, Italy

- **Acknowledgments**: J. Cseh, M. Freer, Y. Kanada-En'yo, M. Milin, M. Norrby, Y. Taniguchi

New Lecture Notes in Physics Series: "Clusters in Nuclei – Vol.1-3"

LECTURE NOTES IN PHYSICS
Volume 818, 2010, DOI: 10.1007/978-3-642-13899-7



Clusters in Nuclei
Volume 1

Christian Beck

Clusters in Nuclei, Vol.2 Lecture Notes in Physics
Volume 848 2012
Editors: Christian Beck
ISBN: 978-3-642-24706-4

Vol.3 (in press) 2013