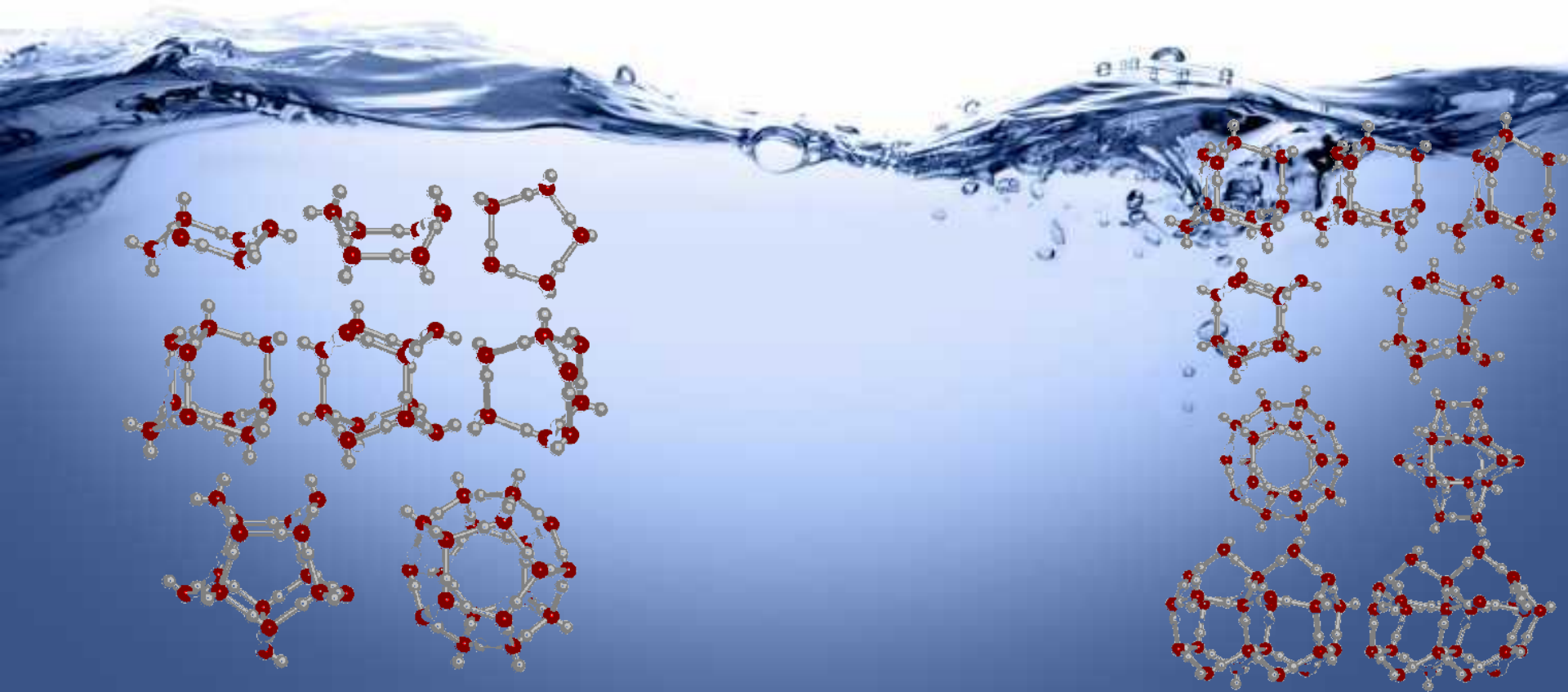
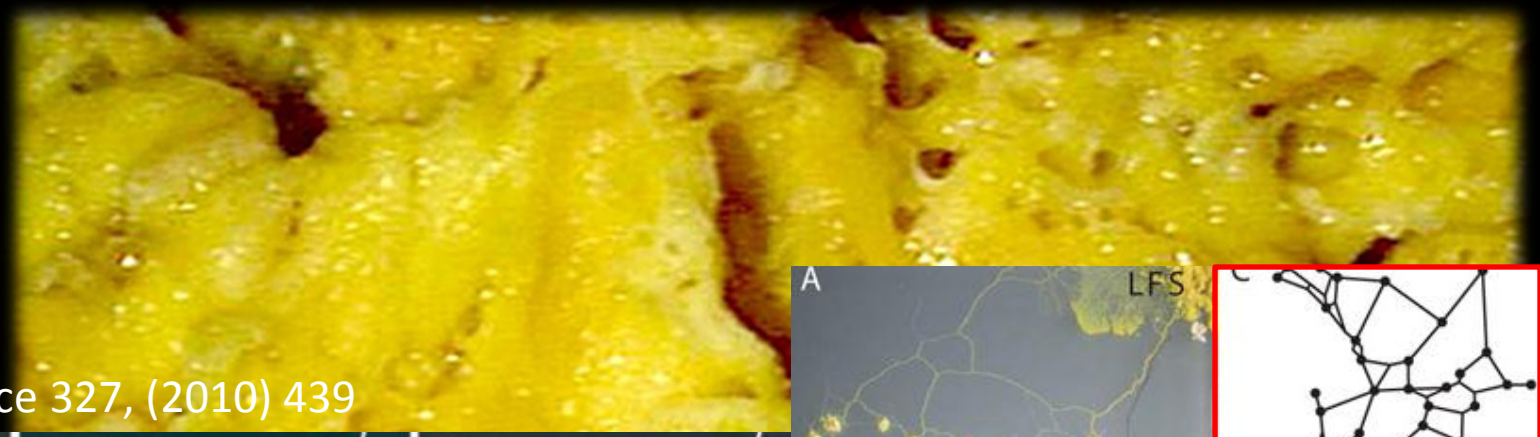
Simplicity from Complexity

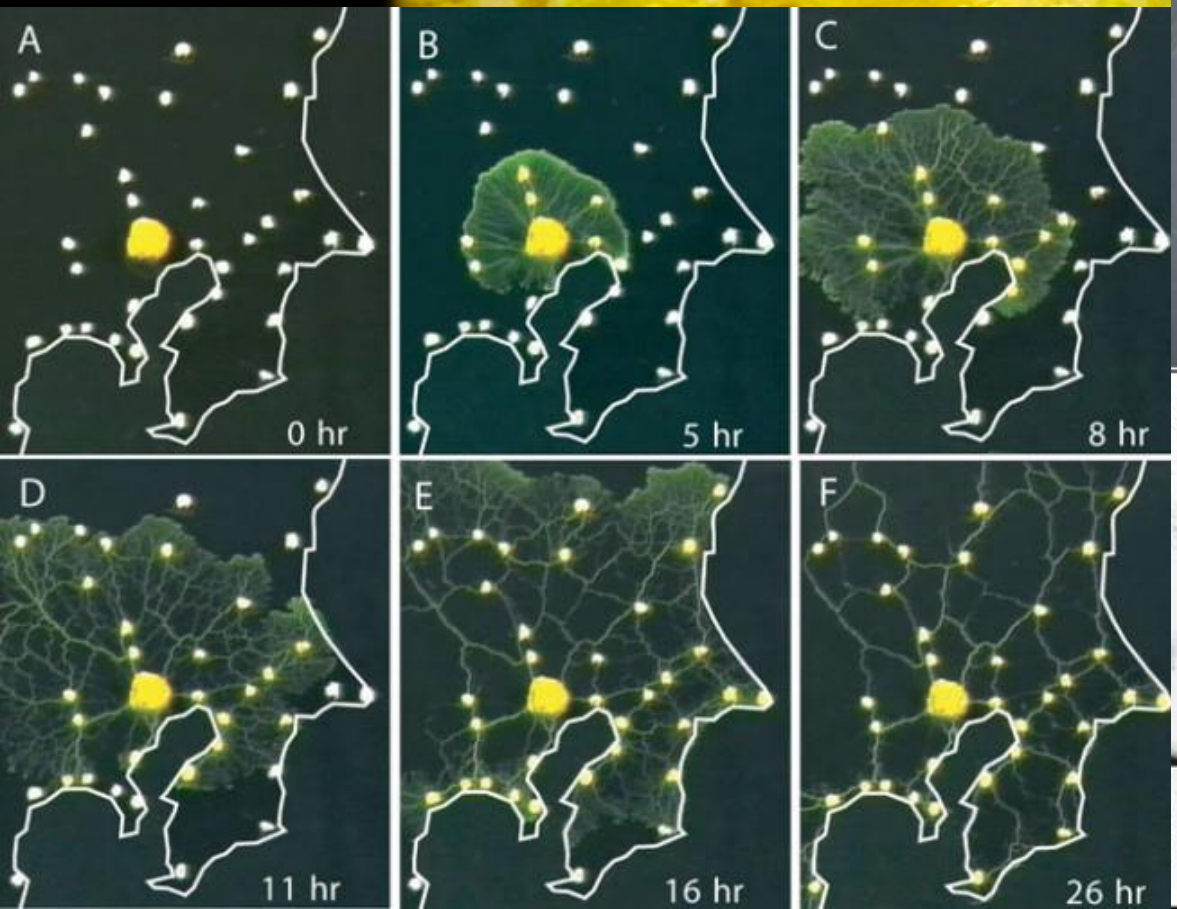
Martin Freer, School of Physics and Astronomy, University of Birmingham, UK
M.Freer@bham.ac.uk

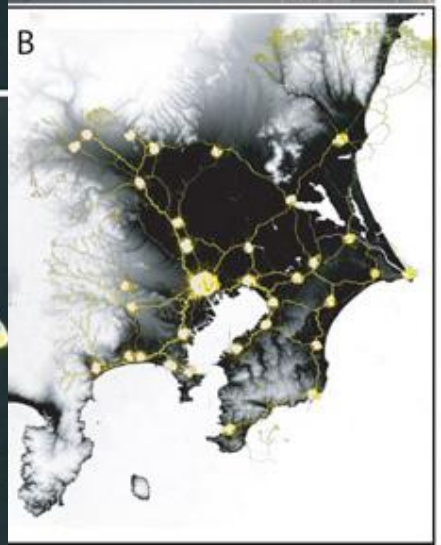


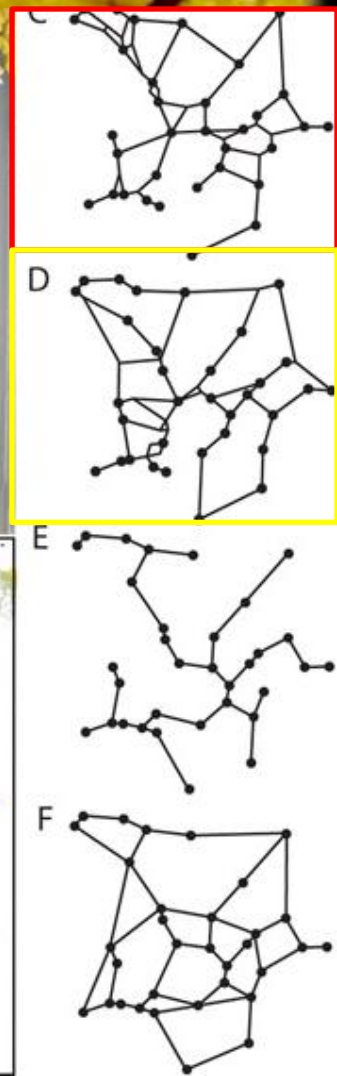
Slime Moulds

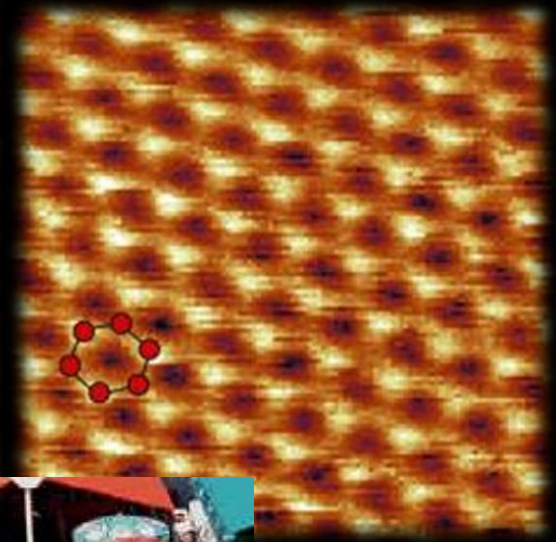


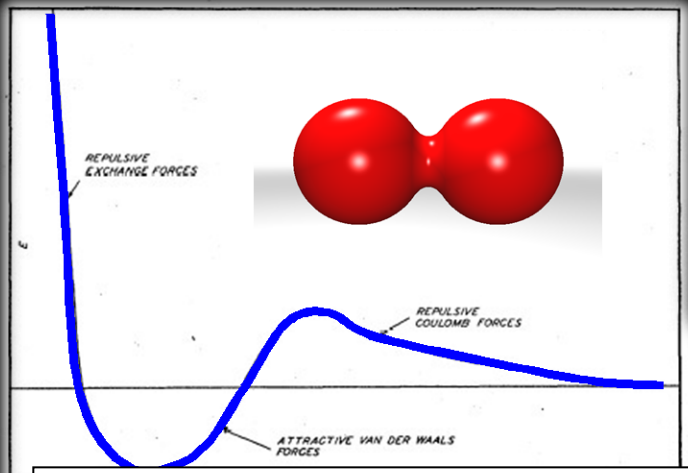
A Tero, et al, Science 327, (2010) 439



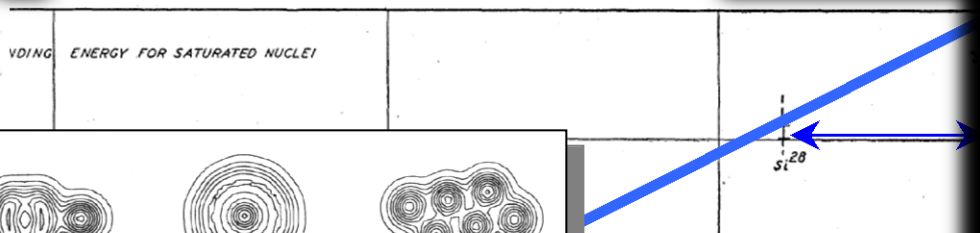


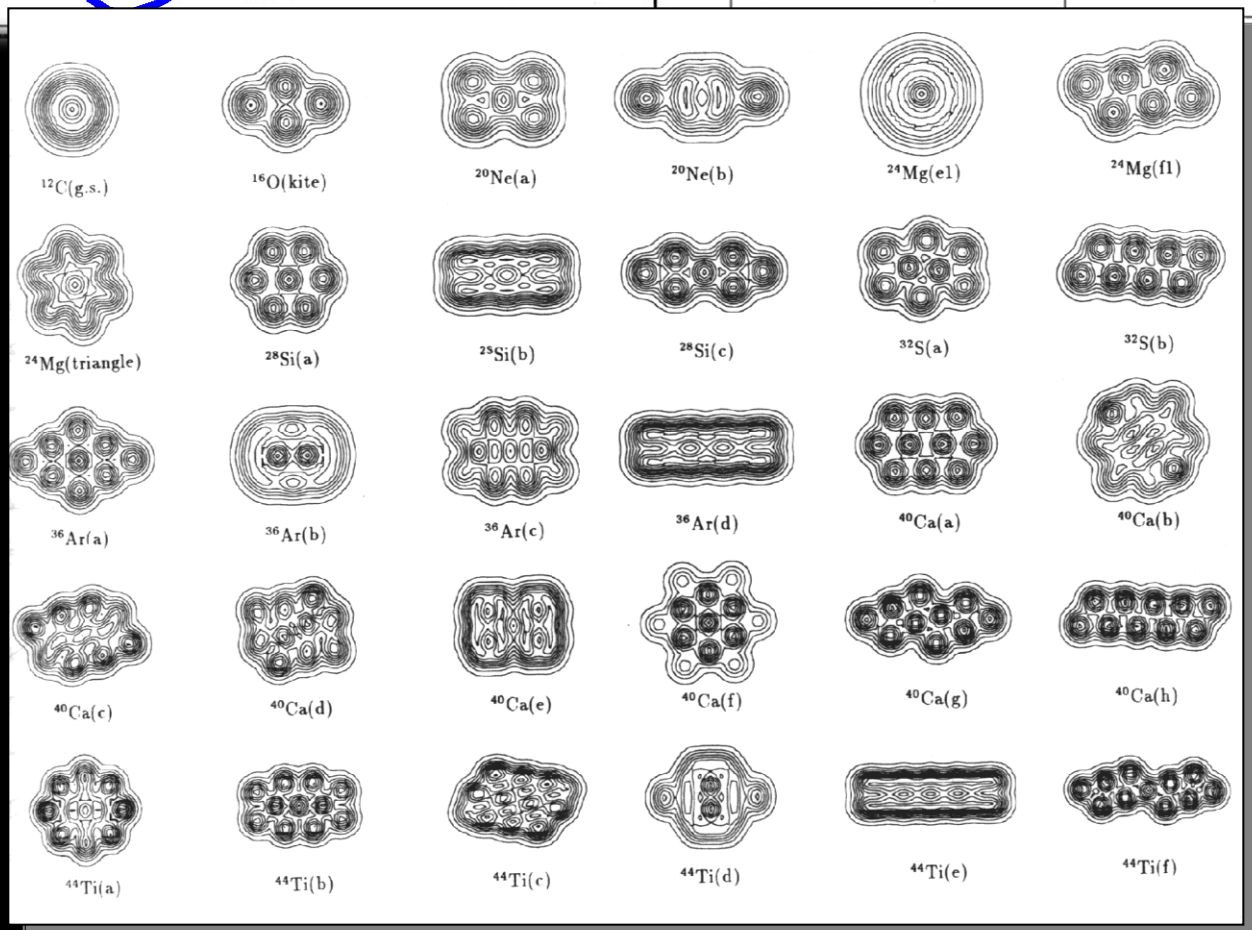


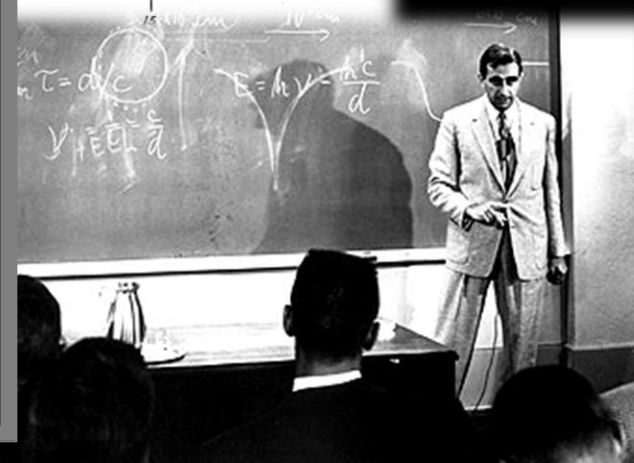


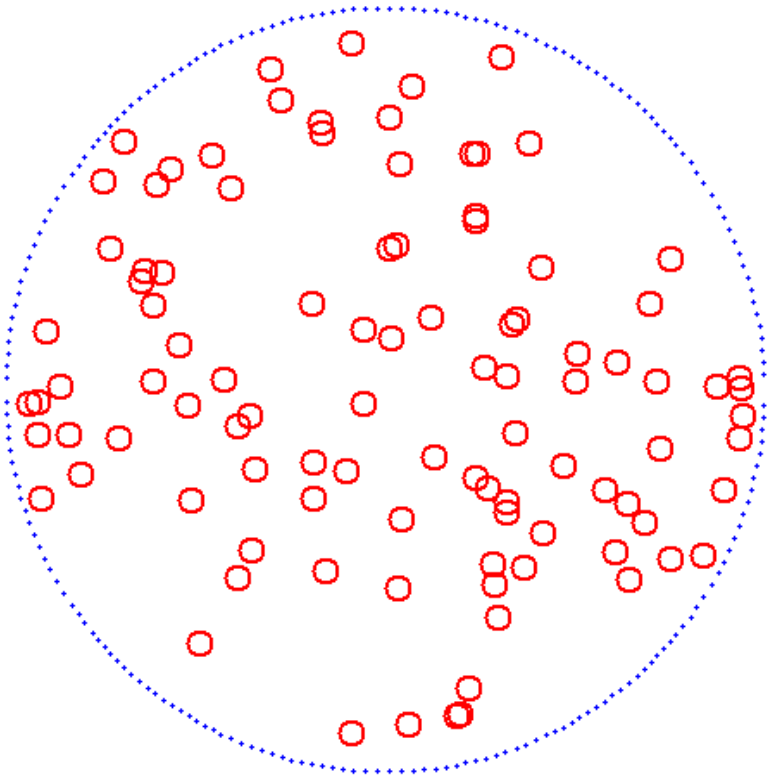


L.R. Hafstad and E. Teller, Phys. Rev. **54**, 681 (1938)

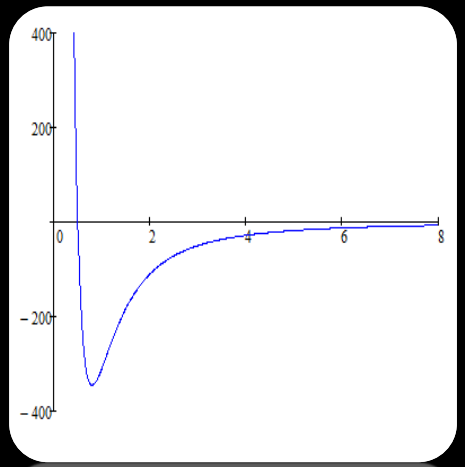




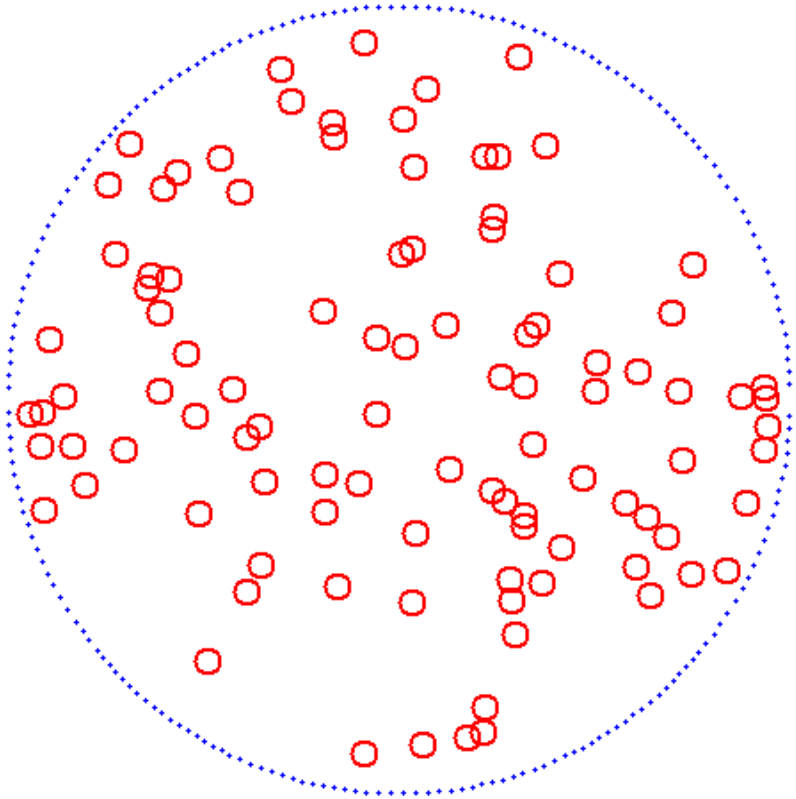


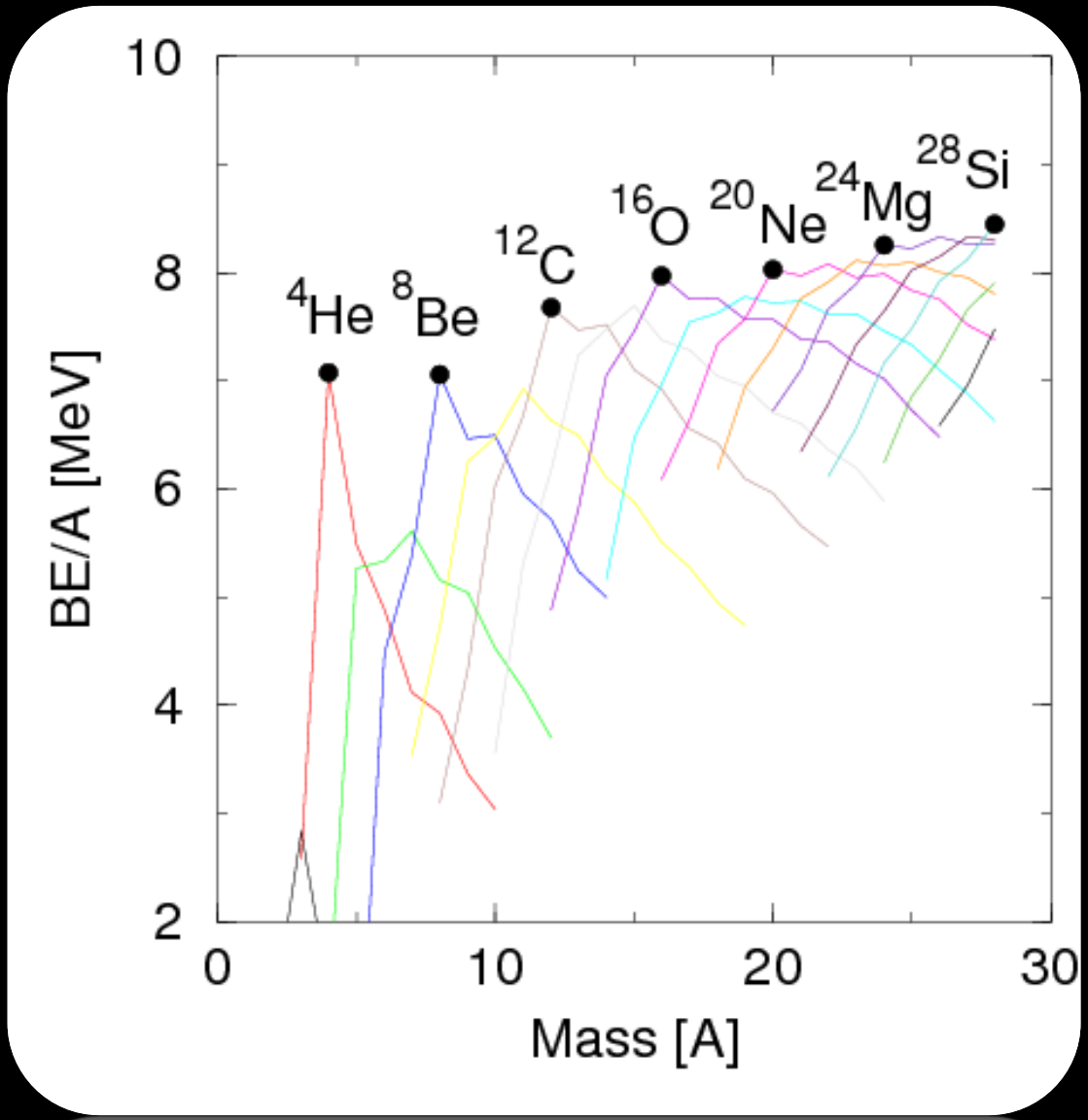


No Interaction



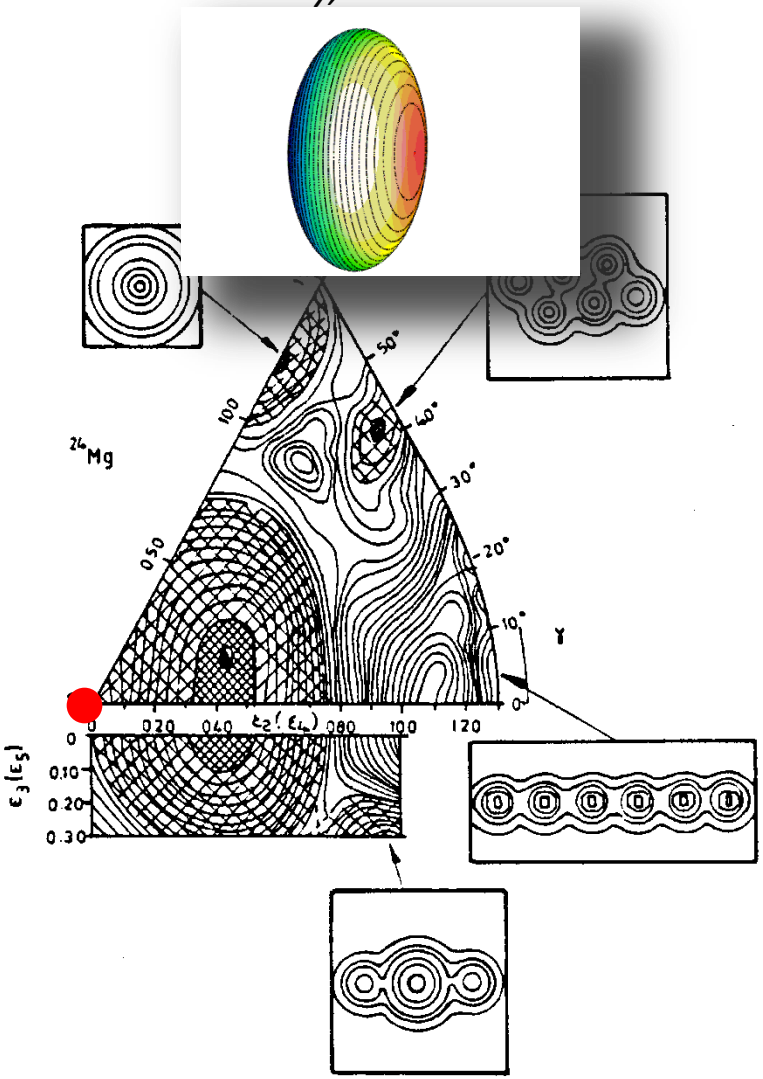
Finite Interaction

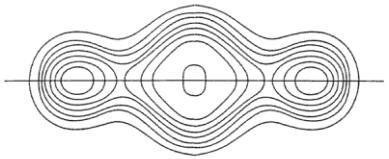


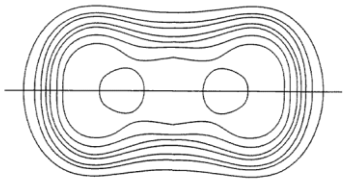

10
8
6
4
2
BE/A [MeV]
0
10
20
30
Mass [A]
4He
8Be
12C
16O
20Ne
24Mg
28Si

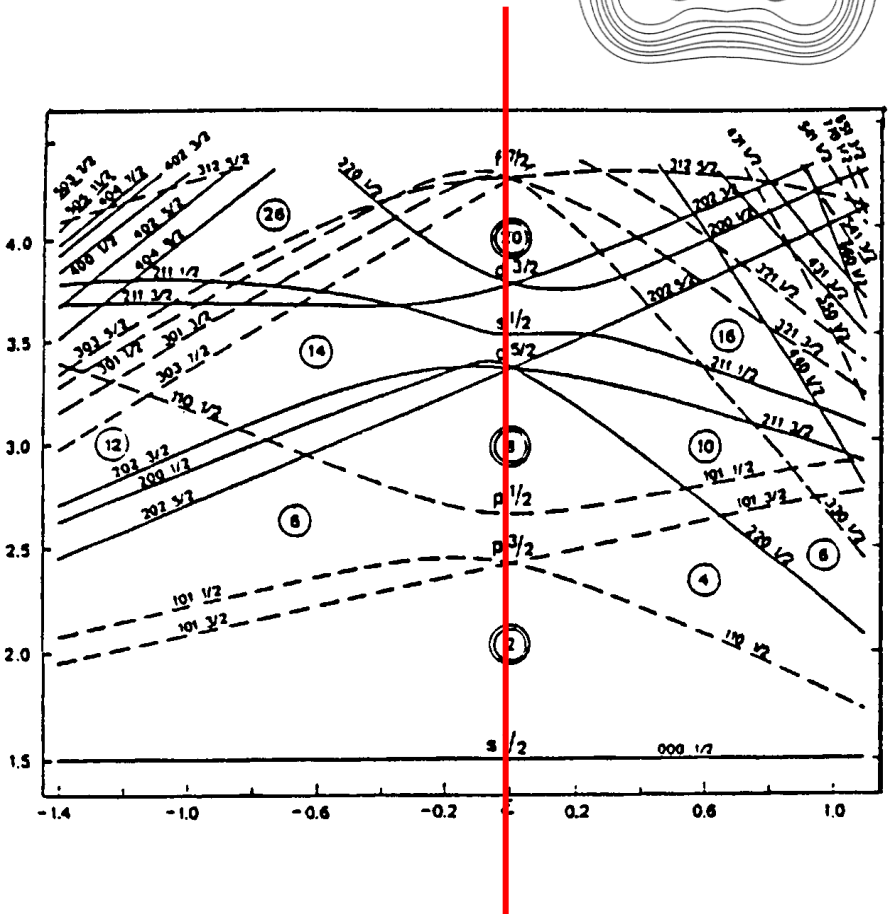
Clusters from the mean-field: ^{24}Mg

Nilsson-Strutinsky, Hartree-Fock





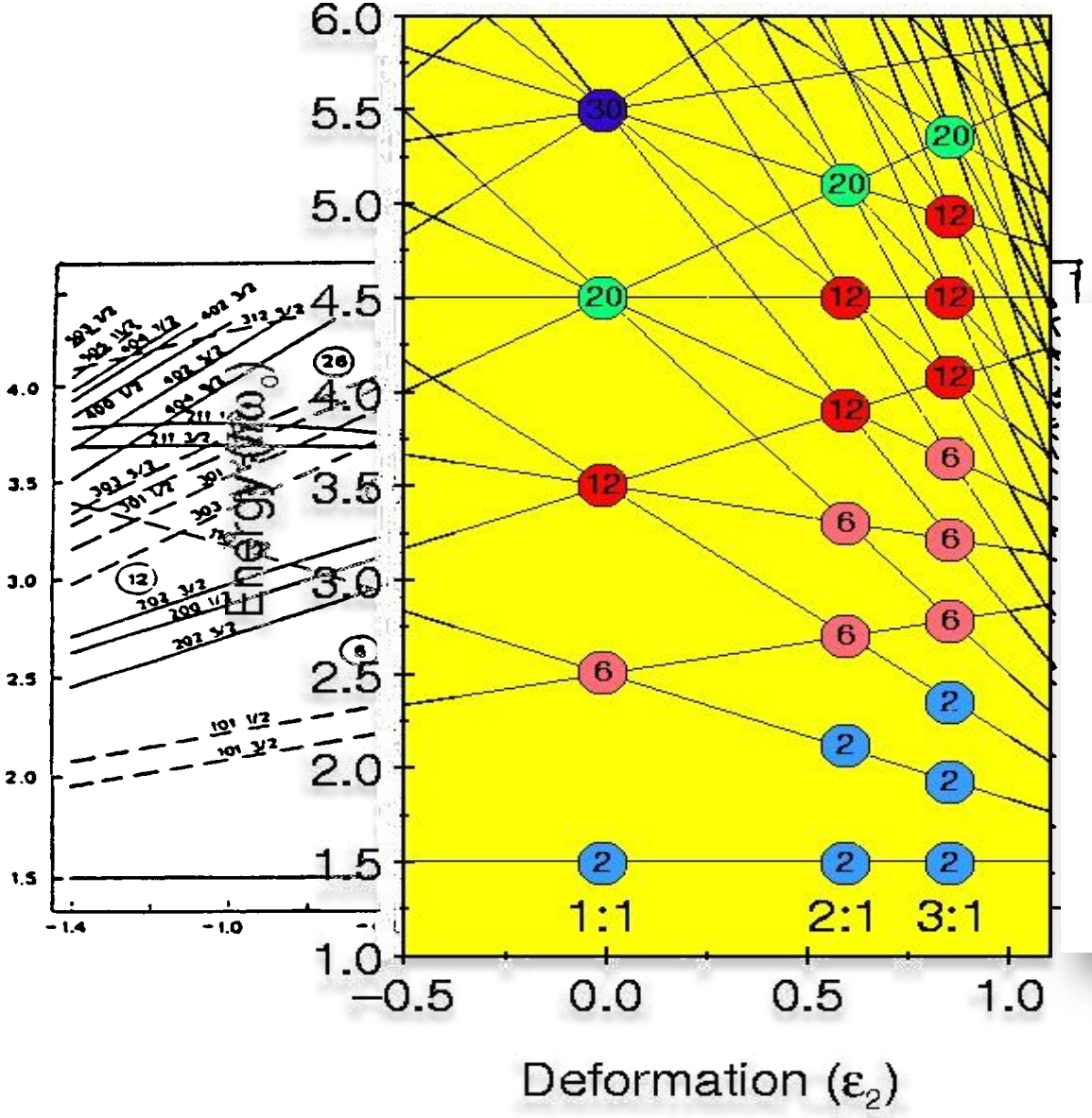


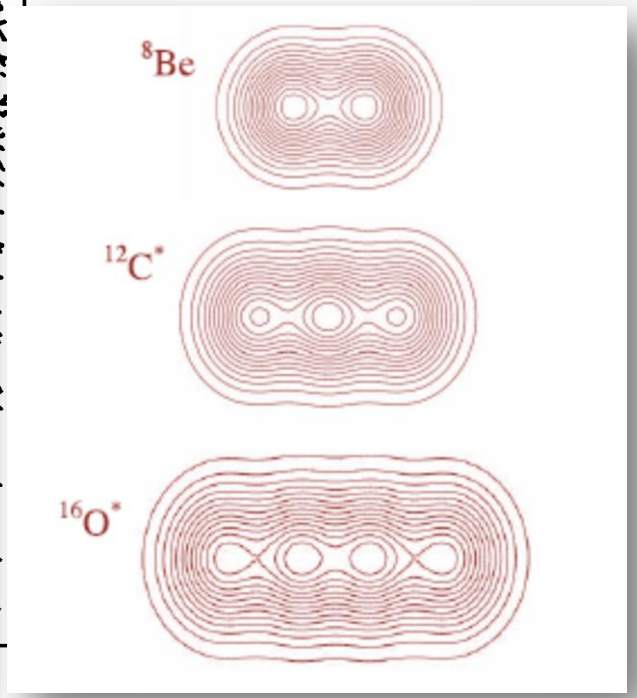


Fulton and Rae – J. Phys.G

Clusters from the mean-field: ^{24}Mg

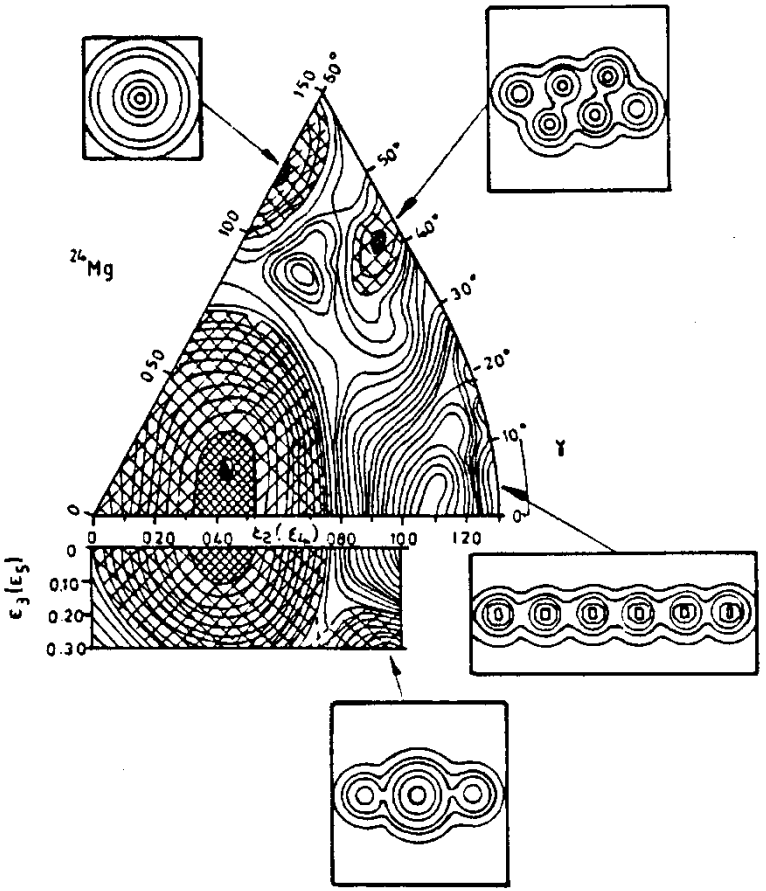
Nilsson-Strutinsky to Harmonic Oscillator

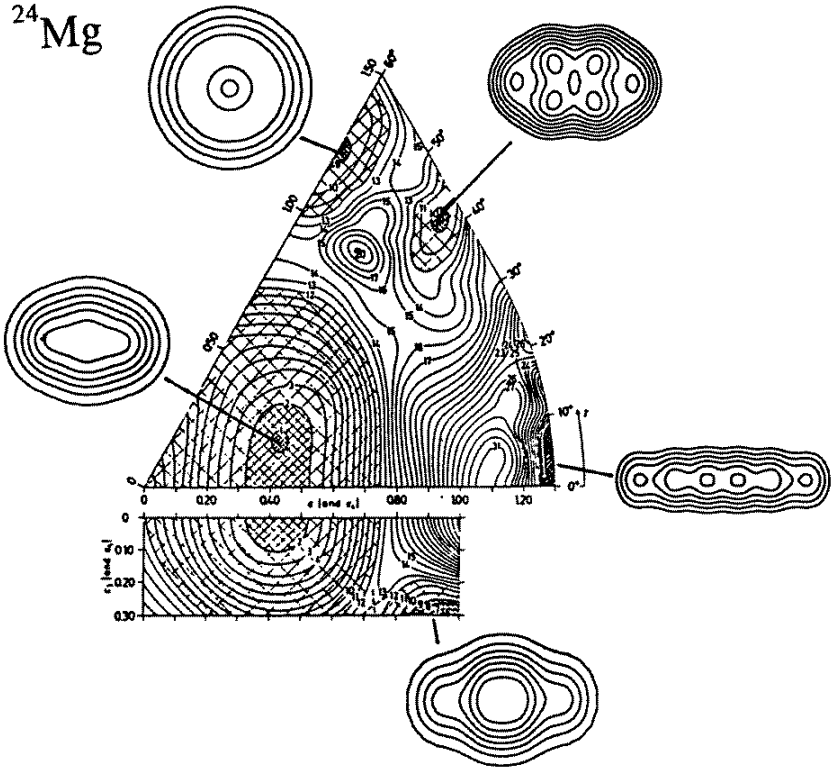




Clusters from the mean-field: Symmetries

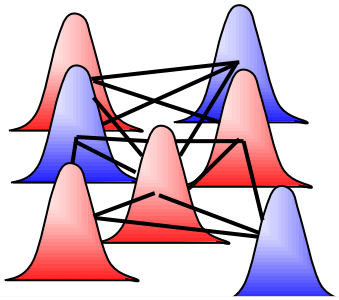
Nilsson-Strutinsky, Alpha Cluster Model, Harmonic Oscillator

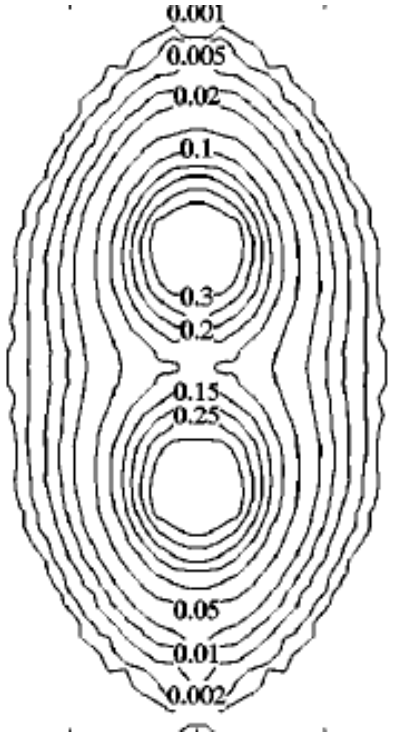


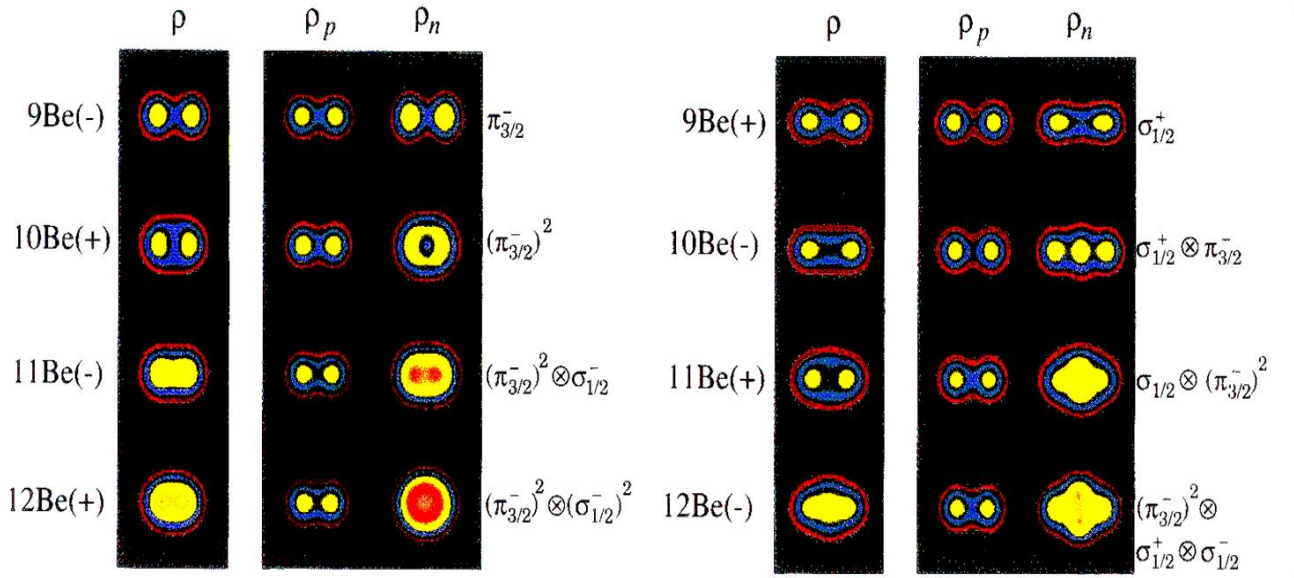


Fulton, Rae, Leander, Larsson, Freer, Merchant

Clusters in Microscopic Models
AMD, GFMC



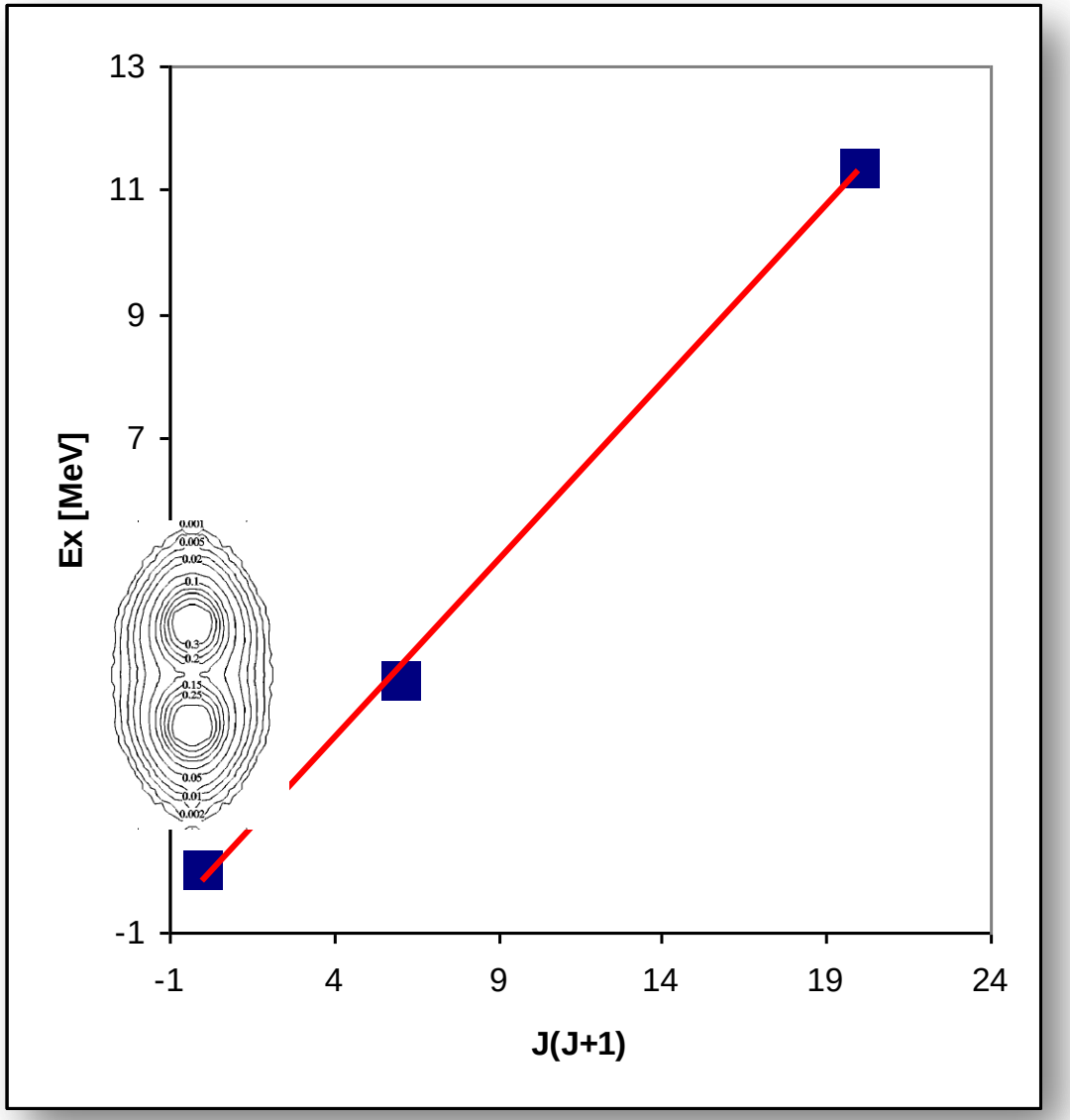




R. B. Wiringa, Steven C. Pieper, J. Carlson, and V. R. Pandharipande, Phys. Rev. C **62**, 014001 (2000)

Kanada En'yo

Experimental Evidence for Cluster Correlations: ^{8}Be



Rotational Energy:

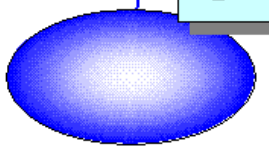
$$E = \frac{1}{2}\Im\omega^2$$

$$L = \Im\omega$$

$$E = \frac{1}{2\Im}L^2$$

$$E = \frac{\hbar^2}{2\Im}L(L+1)$$

$$\Im = M.r^2$$



What about experiment? 1938: Hafstad and Teller Predictions

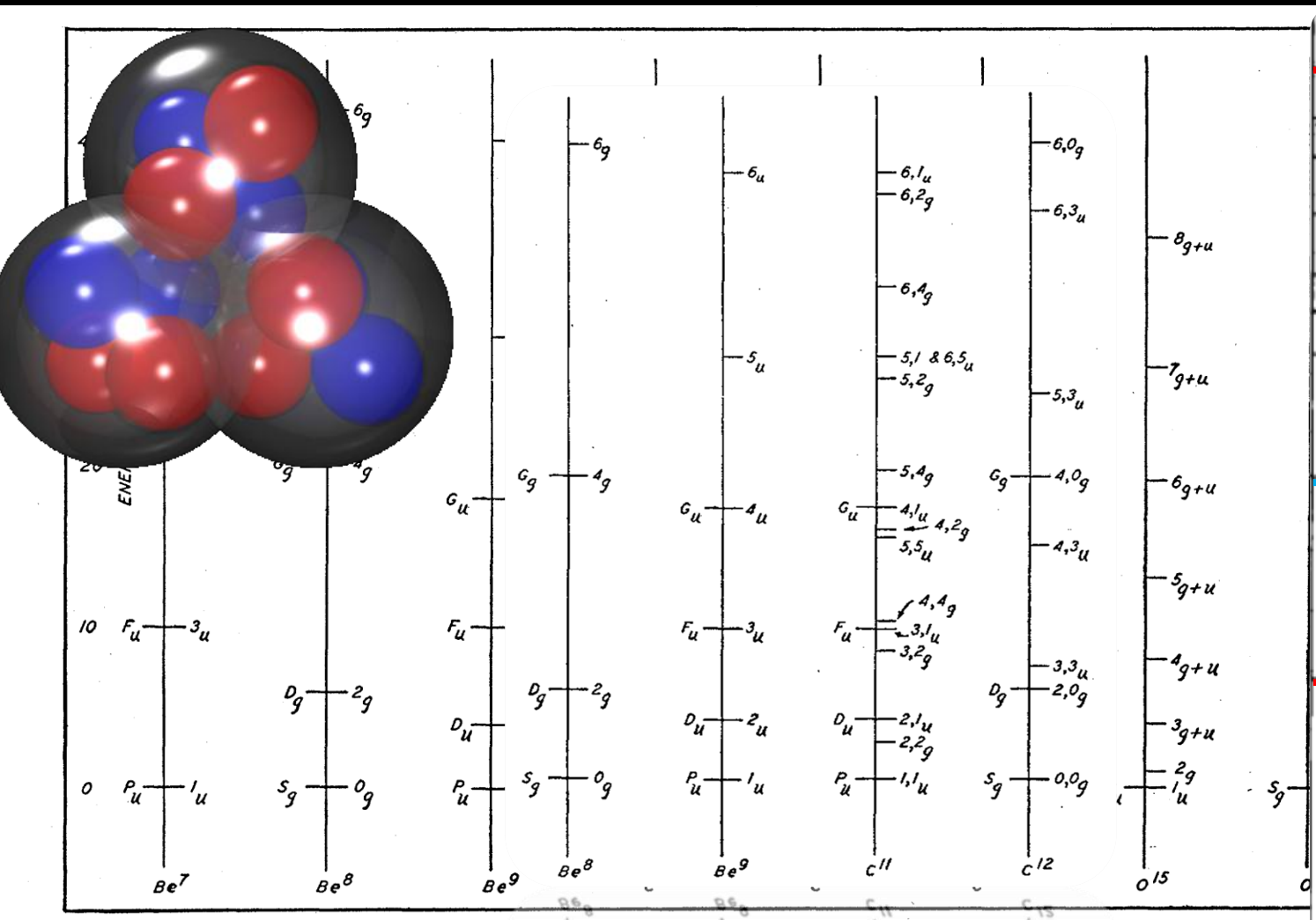


FIG. 6. Excited states of nuclei: Comparison of independent-particle model (left) to alpha-par
with energy scales adjusted to agree with D level of Be^8 ($_g$ = even, $_u$ = odd)

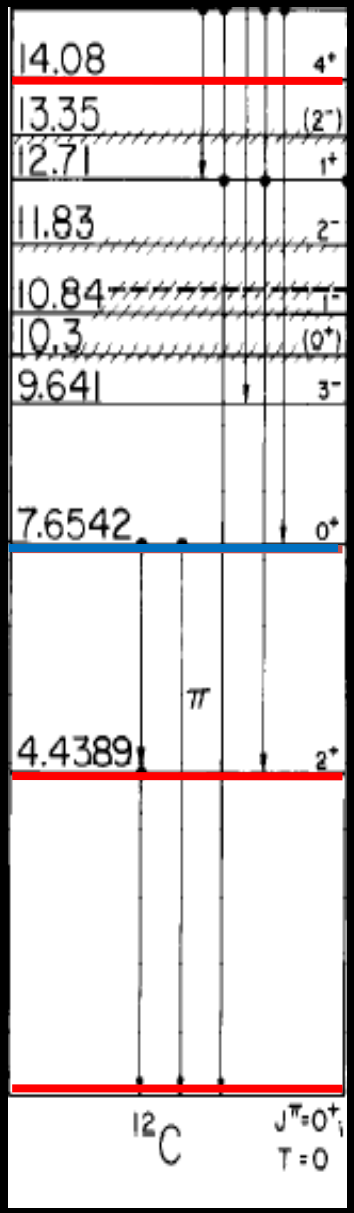
^{12}C – the Hoyle-state

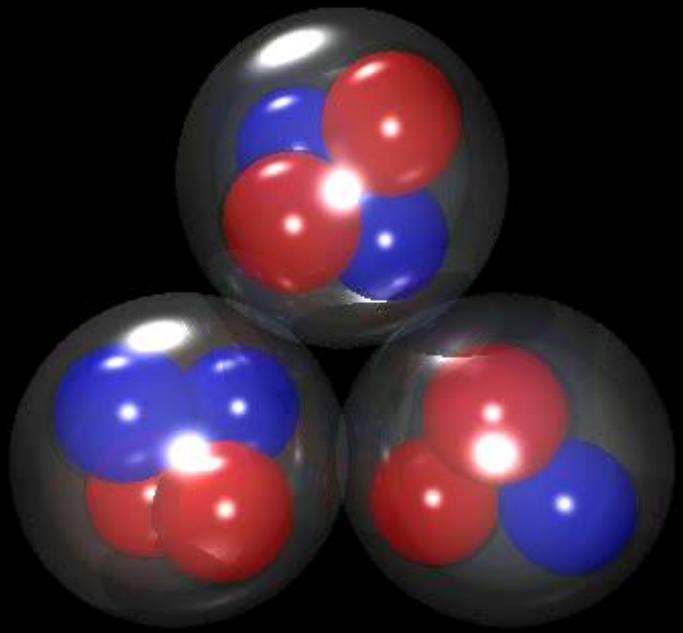
F. Hoyle, D. N. F. Dunbar, W. A. Wenzel, *Phys. Rev.* **92**, 1095 (1953) .

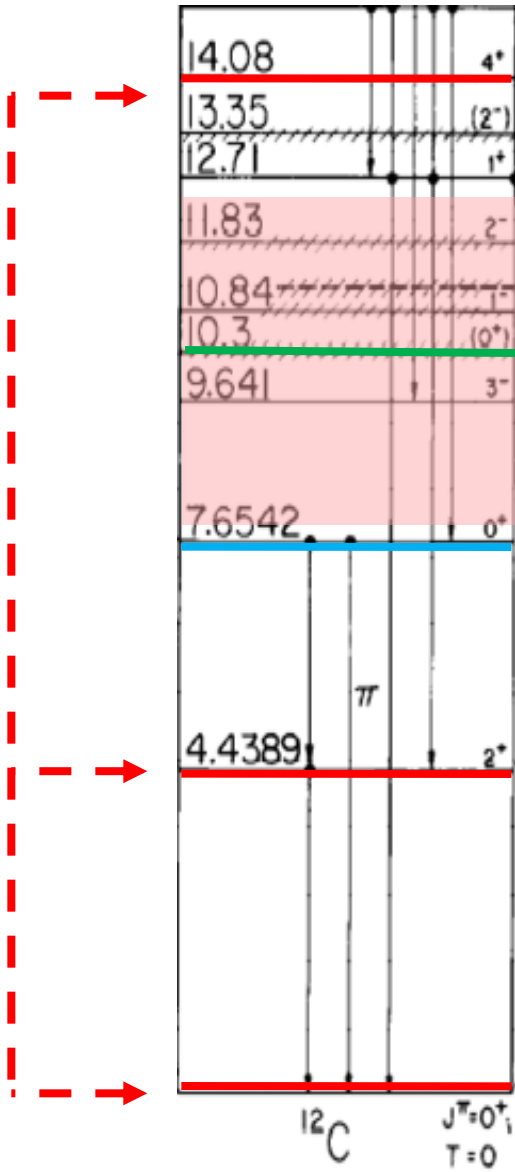
C. W. Cook, W. A. Fowler, T. Lauritsen, *Phys. Rev.* **107**, 508 (1957)

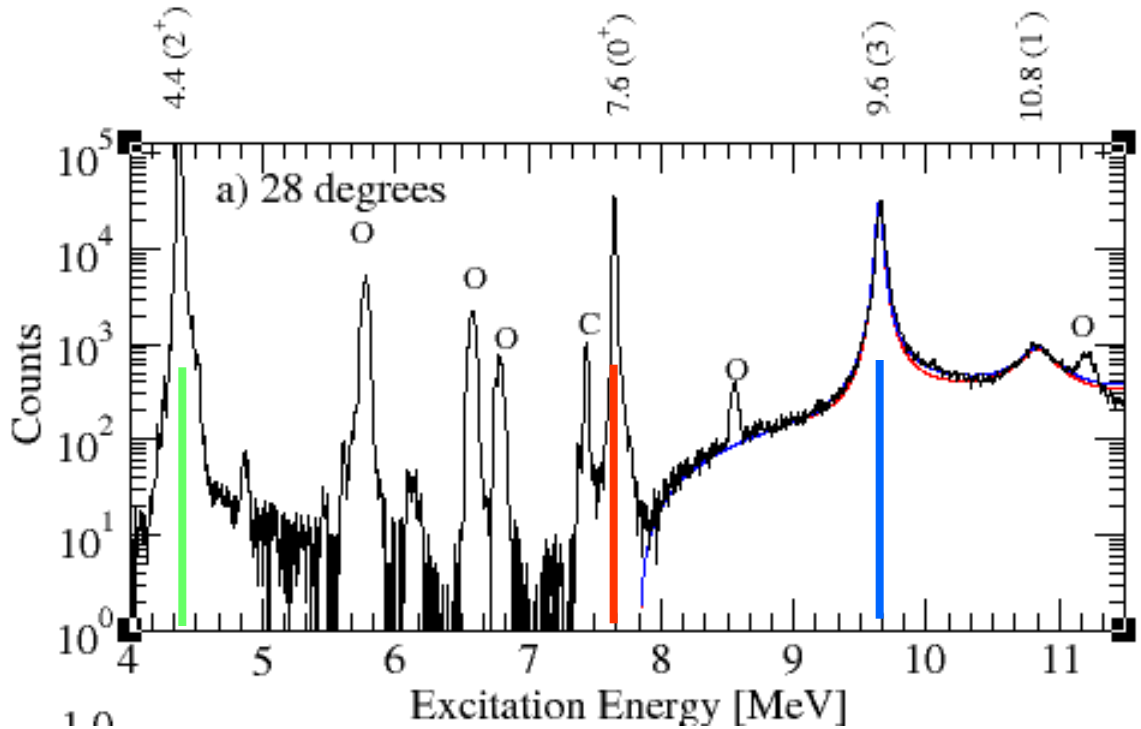
Fred Hoyle

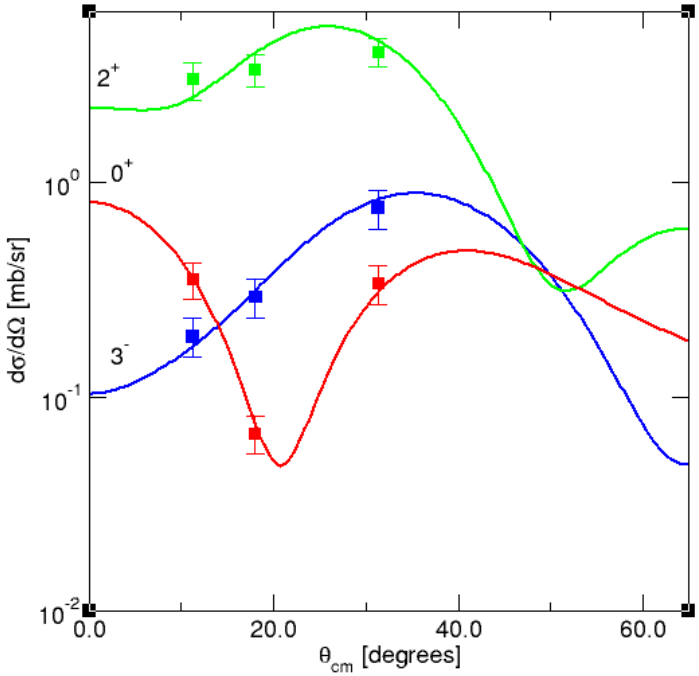
0^+



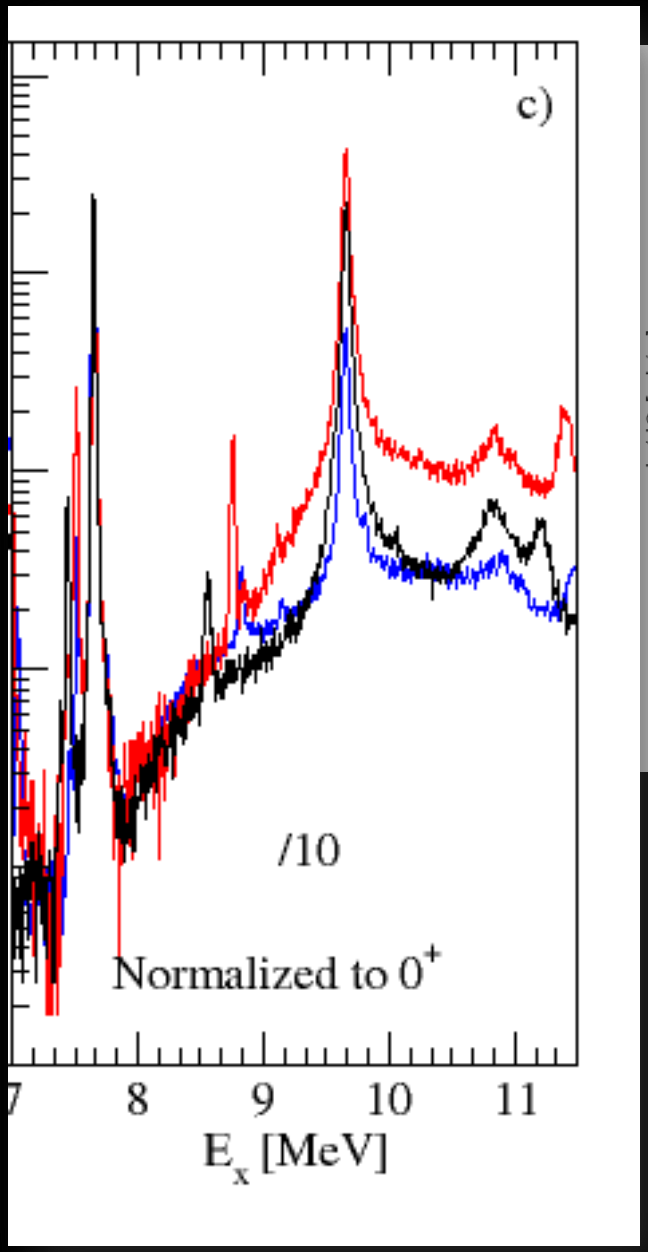


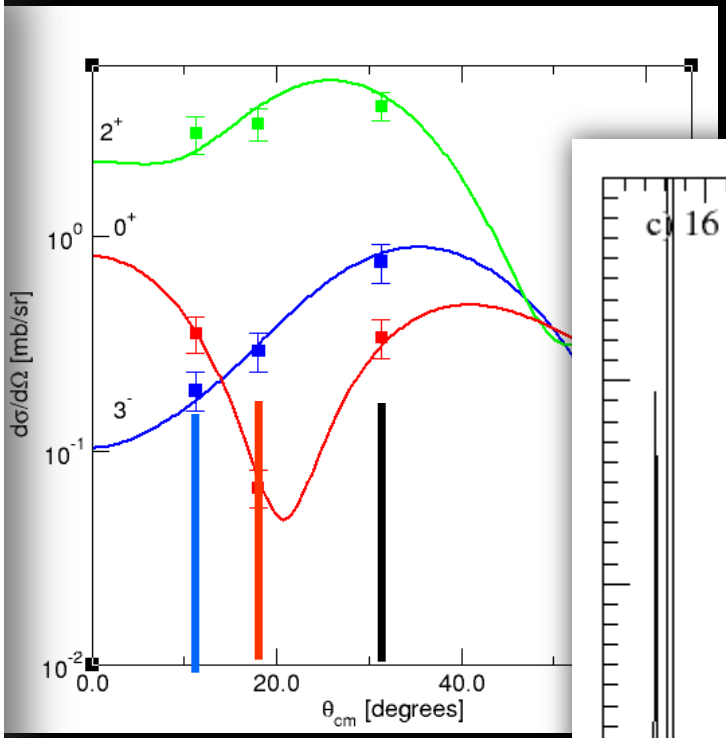

14.08
4+
13.35
(2-)
12.71
1+
11.83
2-
10.84
1-
10.3
(0+)
9.641
3-
7.6542
0+
π
4.4389
2+
12C
Jπ=0+
T=0



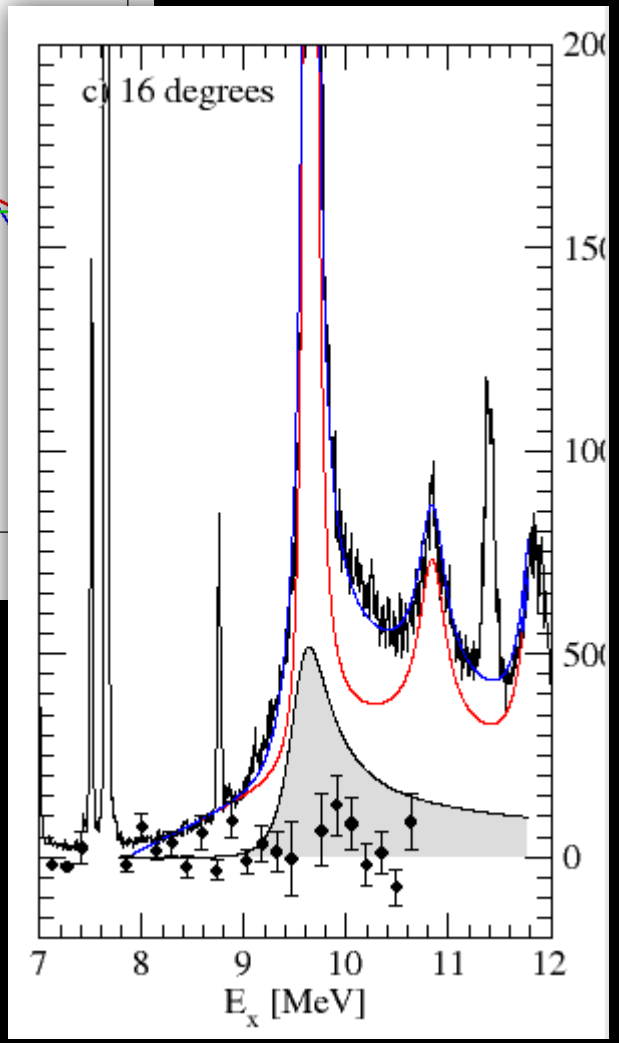


Experiment:-
66 MeV protons
K600 spectrometer
iThemba Labs, SA
23 keV resolution



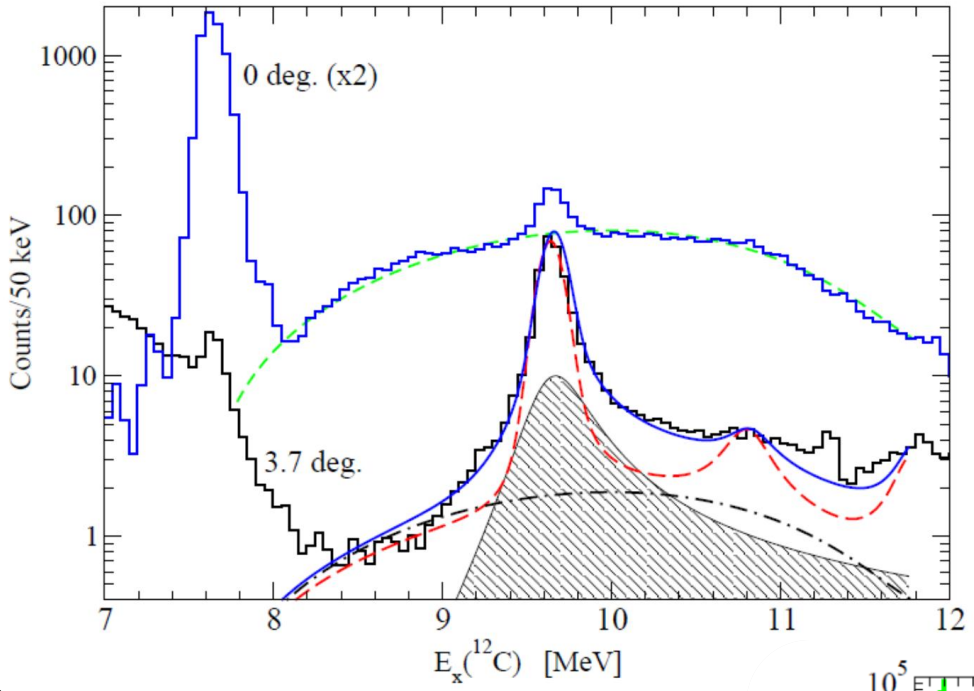


Ex=9.6(1) MeV
Γ = 600(100) keV

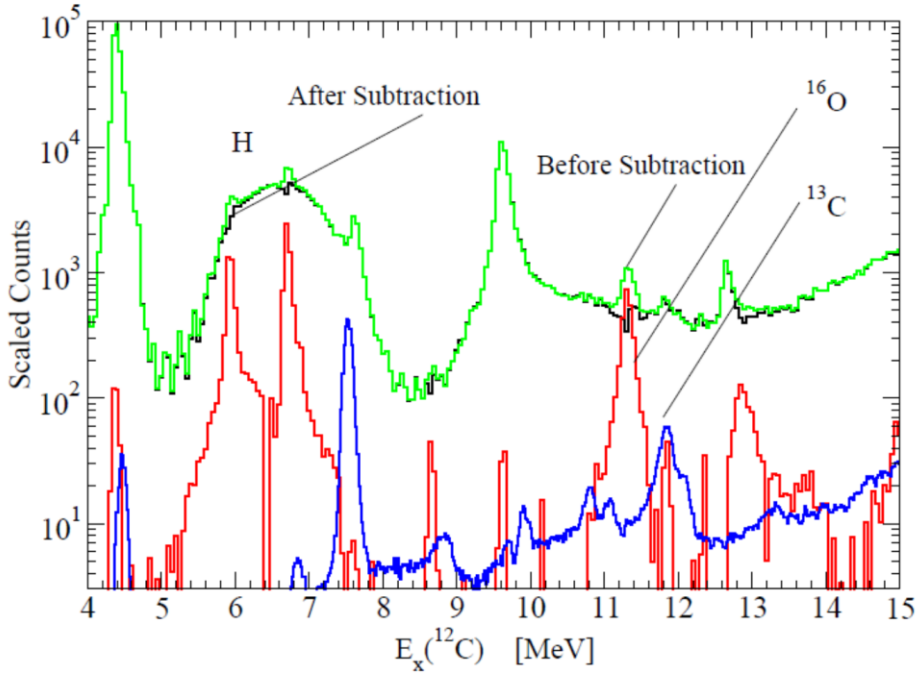


Analysis of the $^{12}C(\alpha, \alpha')$ data - RCNP

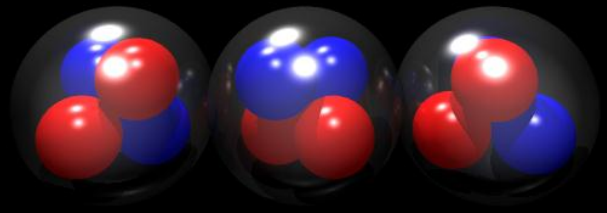
Thanks:
Itoh-san
Kawabata-san



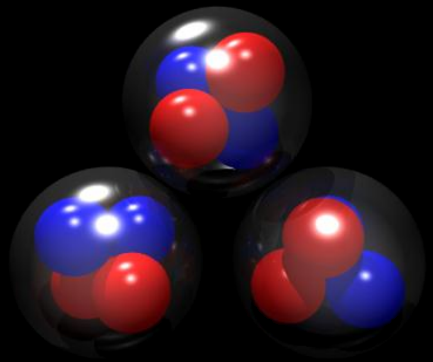
Background analysis



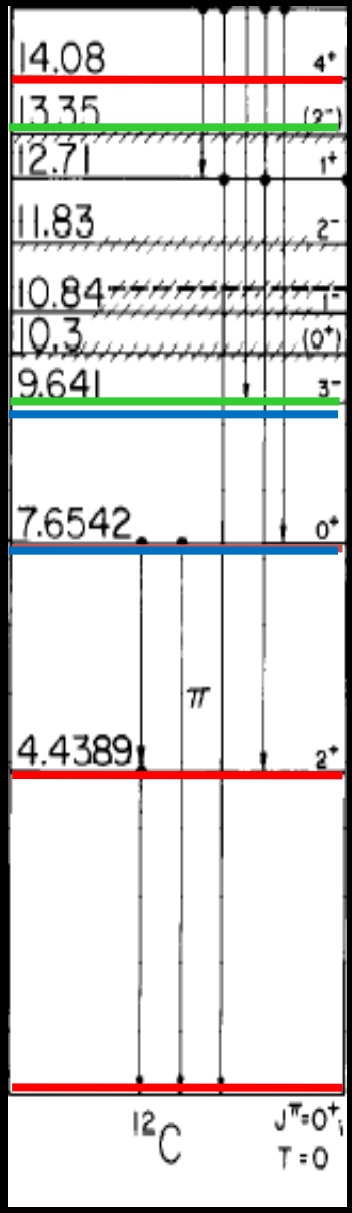
What does a 0^+ - 2^+ energy separation of 2 MeV imply?
(charge radius of ^{4}He = 1.673 fm)



$E(0^+) – E(2^+)$ =
1 MeV [0.8 MeV]



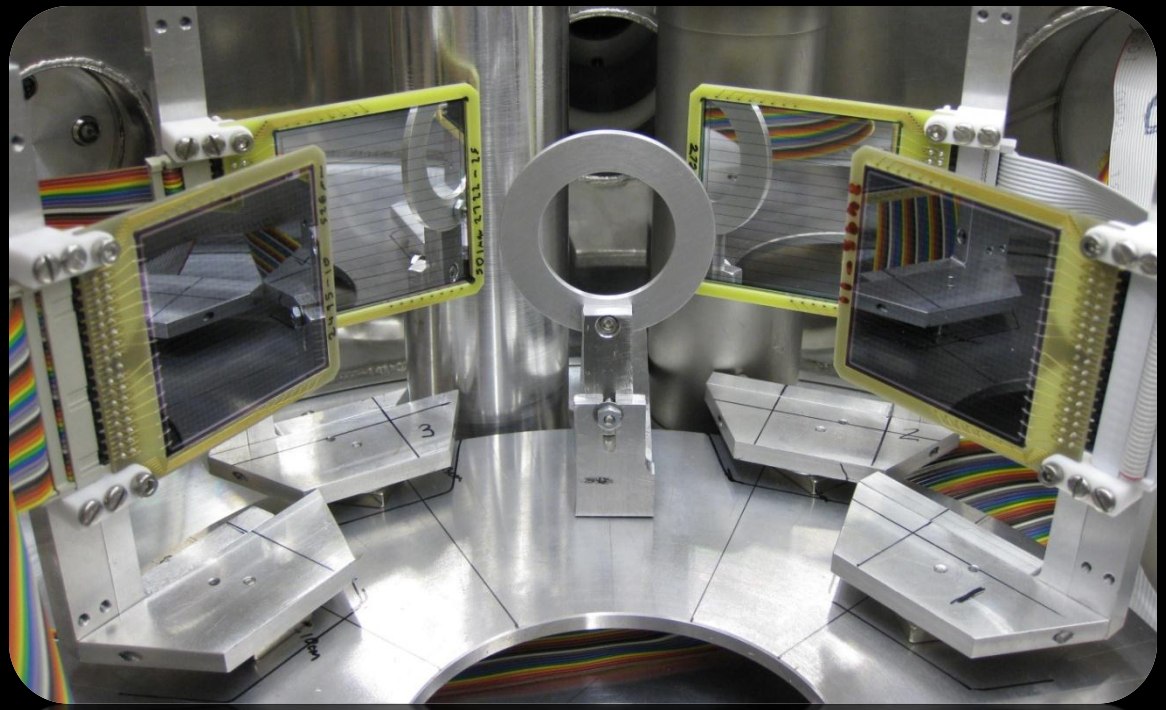
$E(0^+) – E(2^+)$ = 2.00 MeV

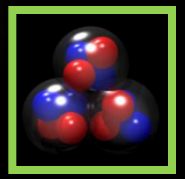


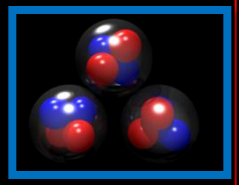
A new ^{12}C state at 13.3 MeV?

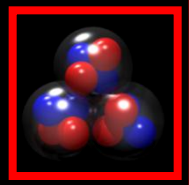
M. Freer,[1] S. Almaraz-Calderon,[2] A. Aprahamian,[2] N.I. Ashwood,[1] M. Barr,[1] B. Bucher,[2] P. Copp,[3] M. Couder,[2] N. Curtis,[1] X. Fang,[2] F. Jung,[2] S. Lesher,[3] W. Lu,[2] J.D. Malcolm,[1] A. Roberts,[2] W.P. Tan,[2] C. Wheldon,[1] and V.A. Ziman[1]

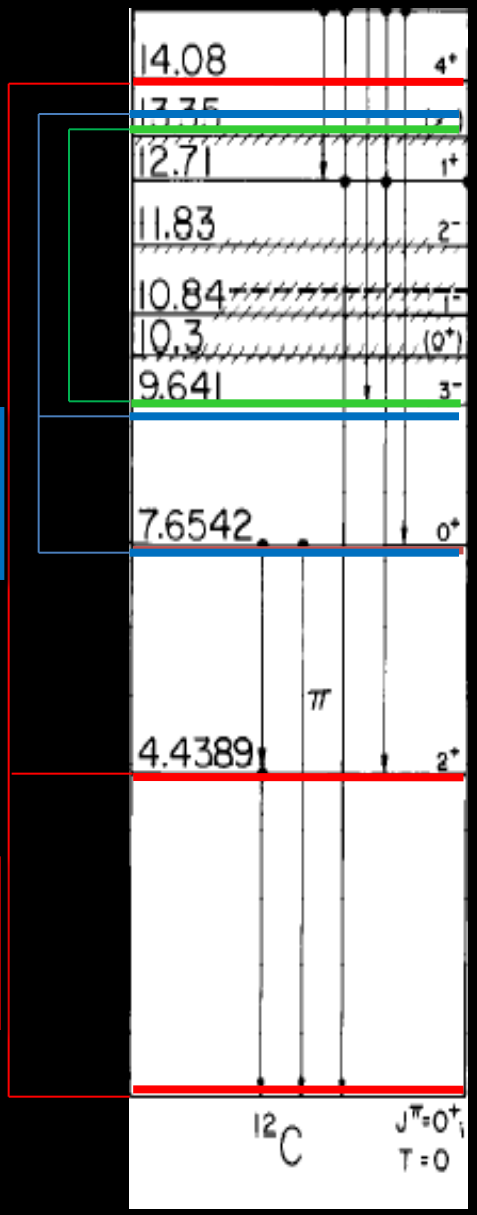
[1] *School of Physics and Astronomy, University of Birmingham, Birmingham, B15 2TT, UK*
[2] *Institute for Structure and Nuclear Astrophysics, Department of Physics, University of Notre Dame, Notre Dame, IN 46556, USA*
[3] *Department of Physics, University of Wisconsin - La Crosse, La Crosse, WI 54601, USA*





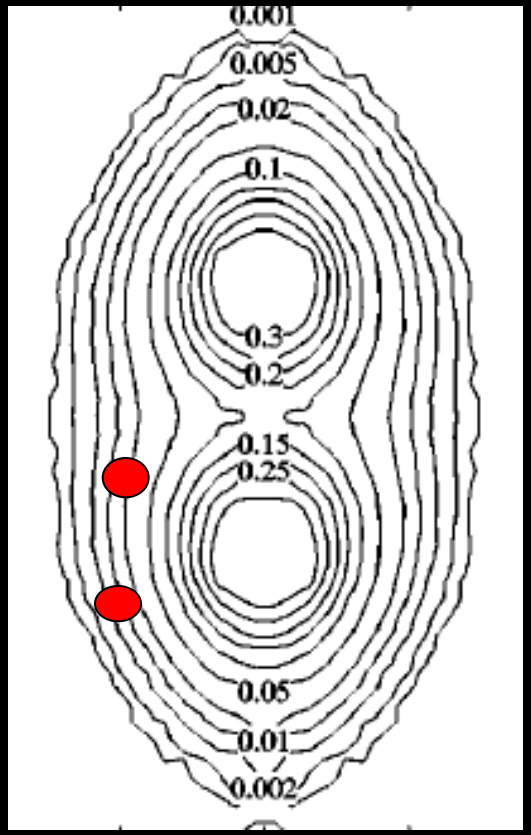






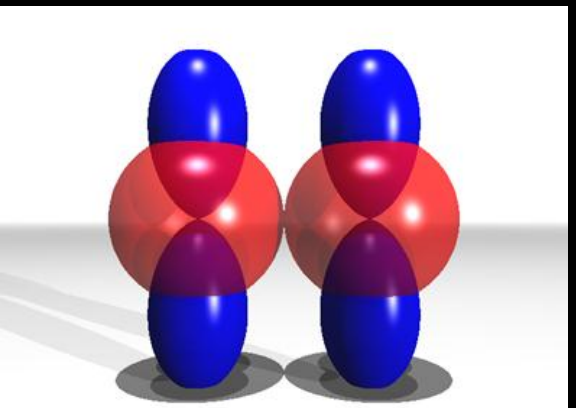
Neutron-rich clusters

^{8}Be+2n



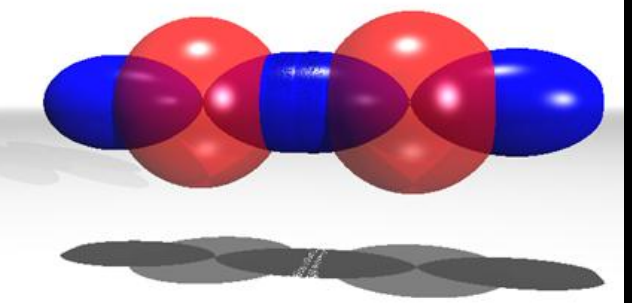
R. B. Wiringa, Steven C. Pieper, J. Carlson, and V. R. Pandharipande, Phys. Rev. C **62**, 014001 (2000)

Building of Nuclear Molecules



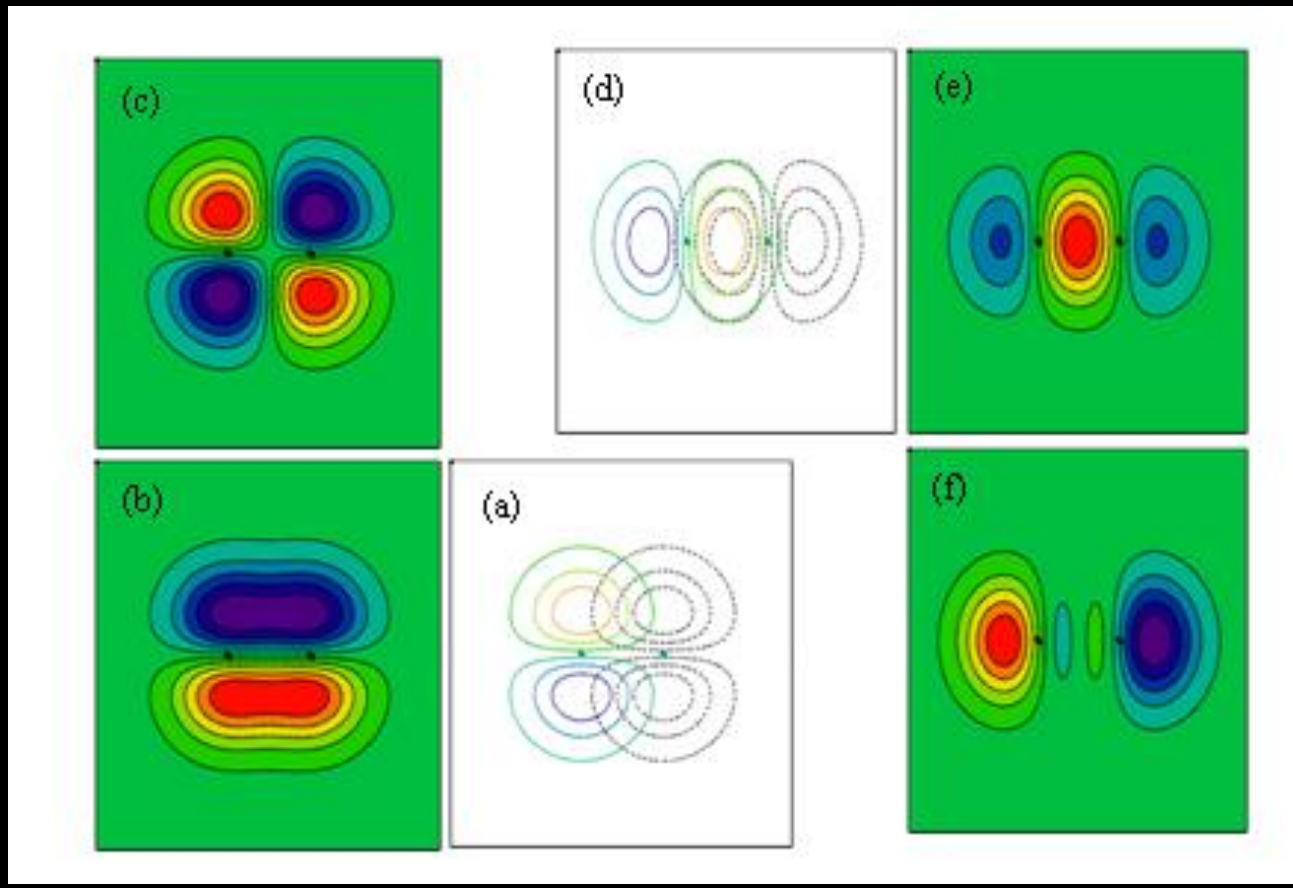
$^4He+n:^4He+n$

Bonding π

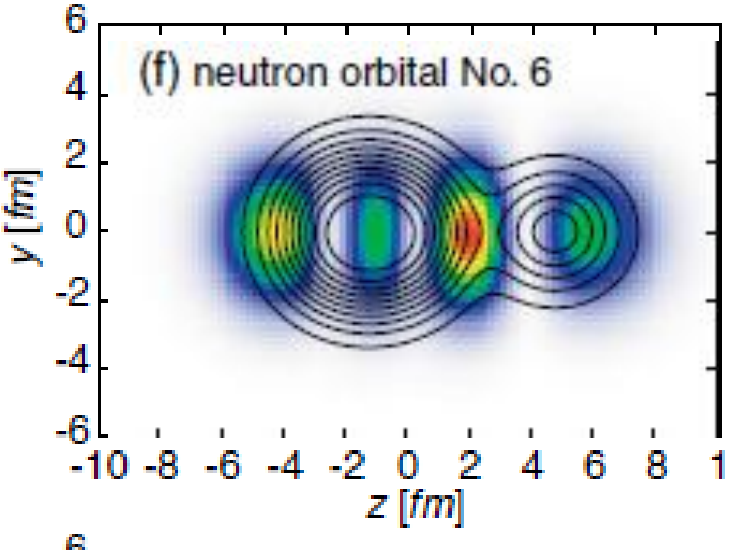


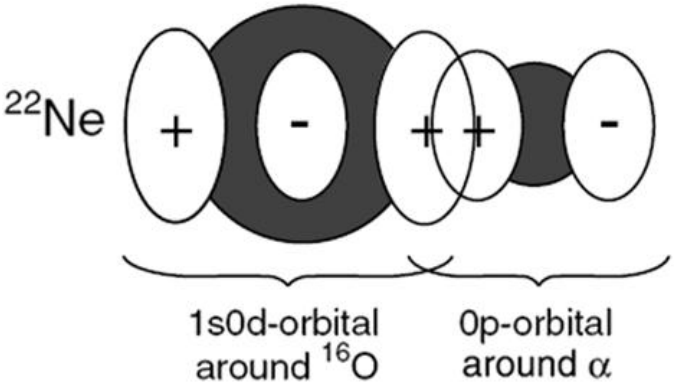
$^4He+n:^4He+n$

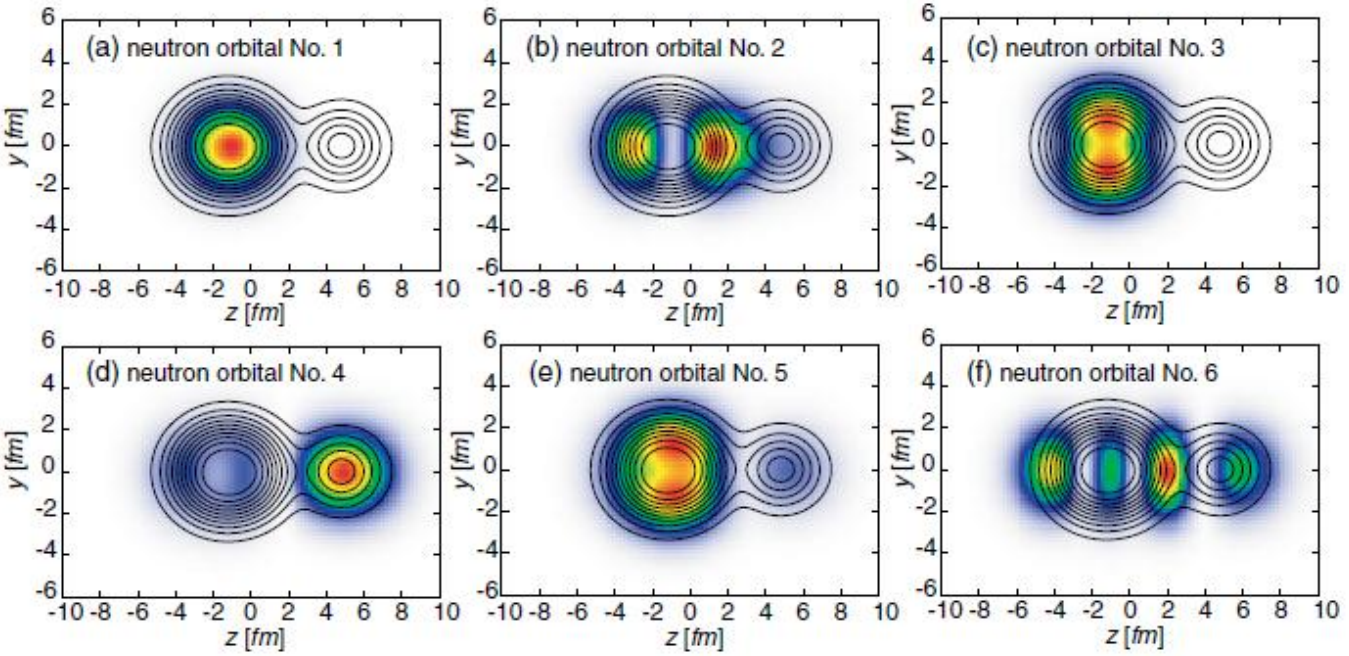
Bonding σ



The nucleus ^{22}Ne

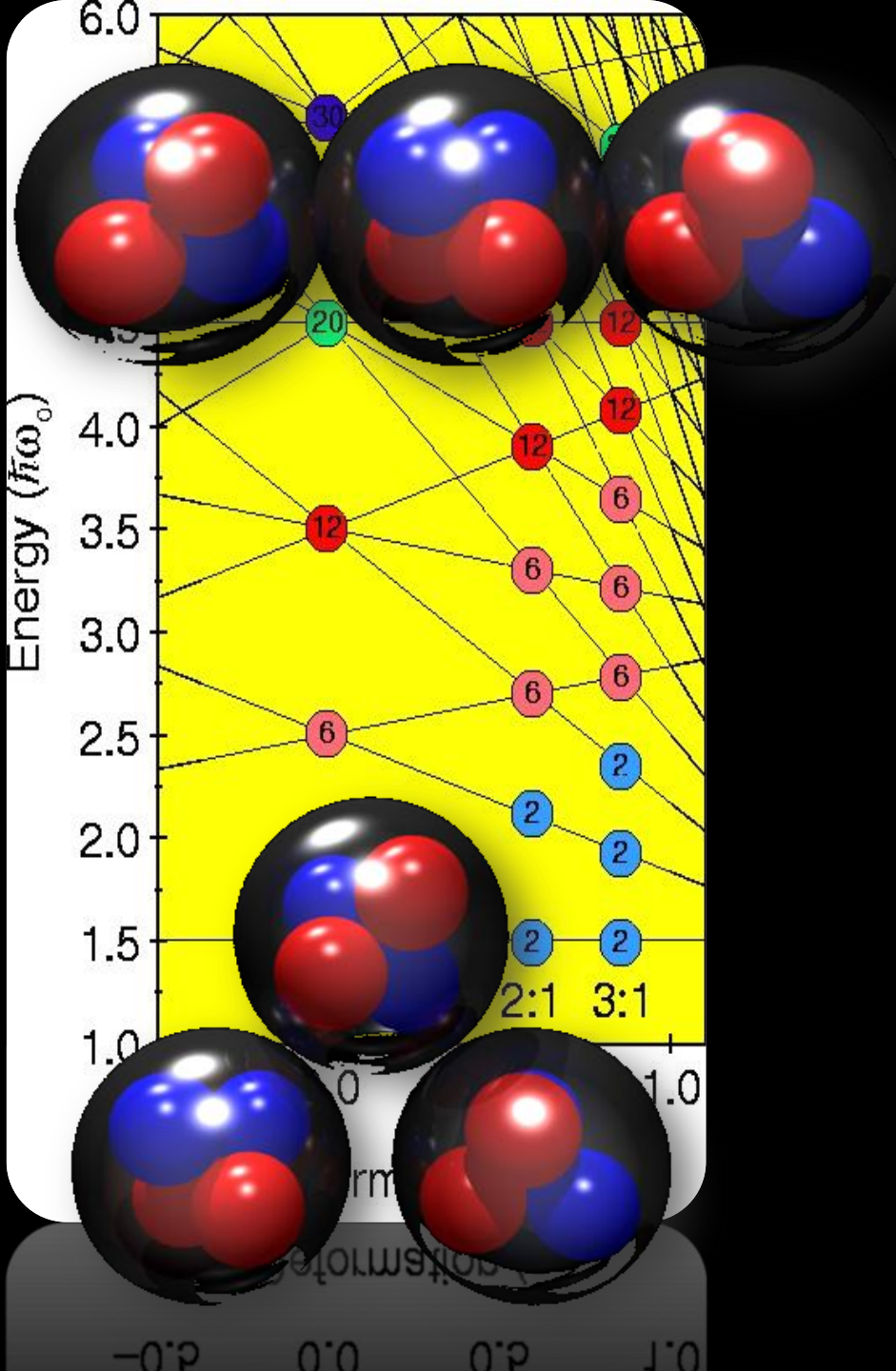


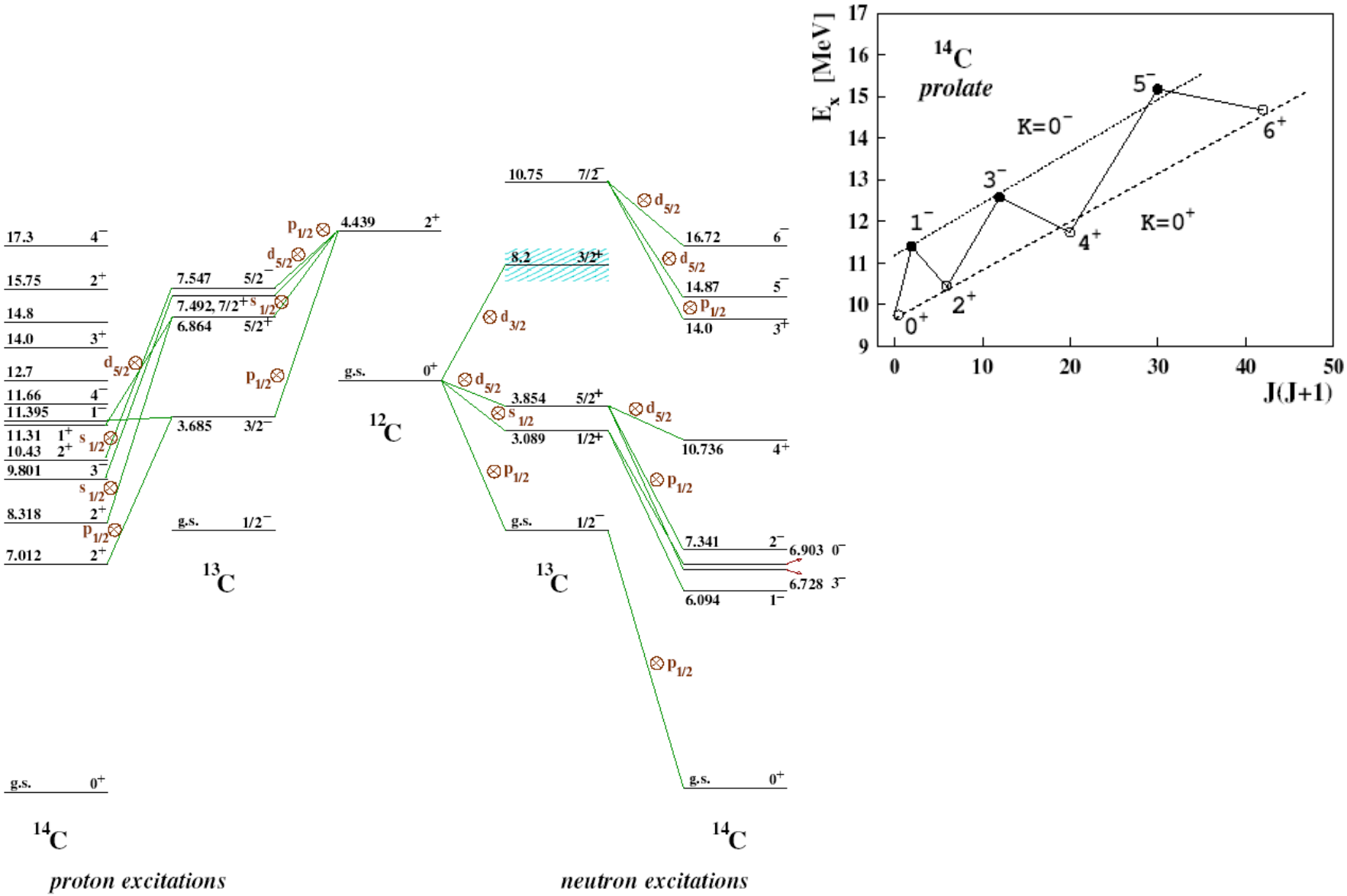


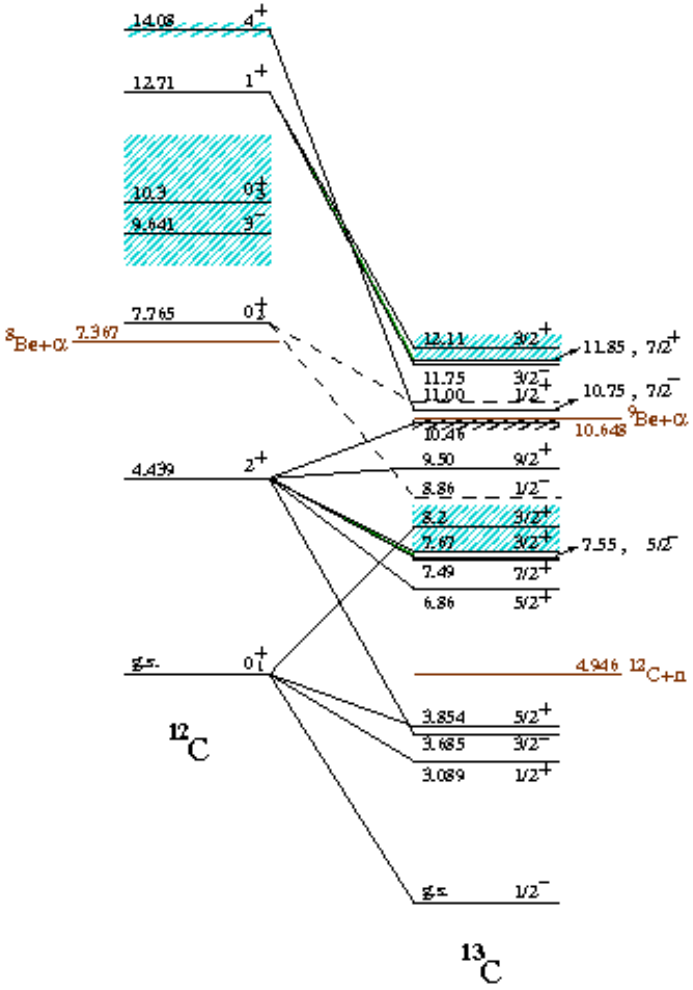


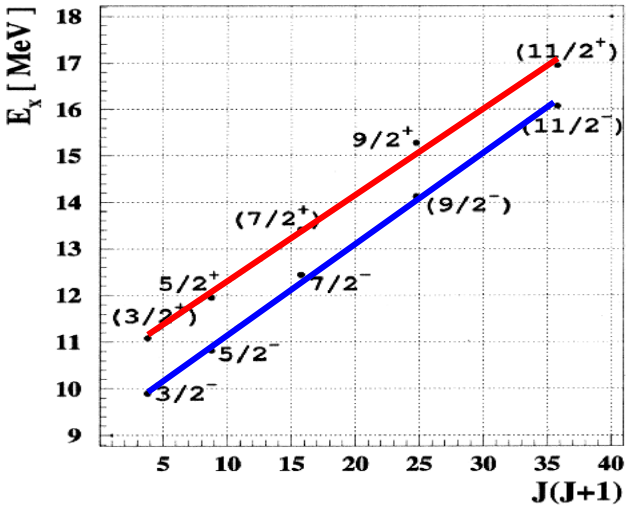
Kimura

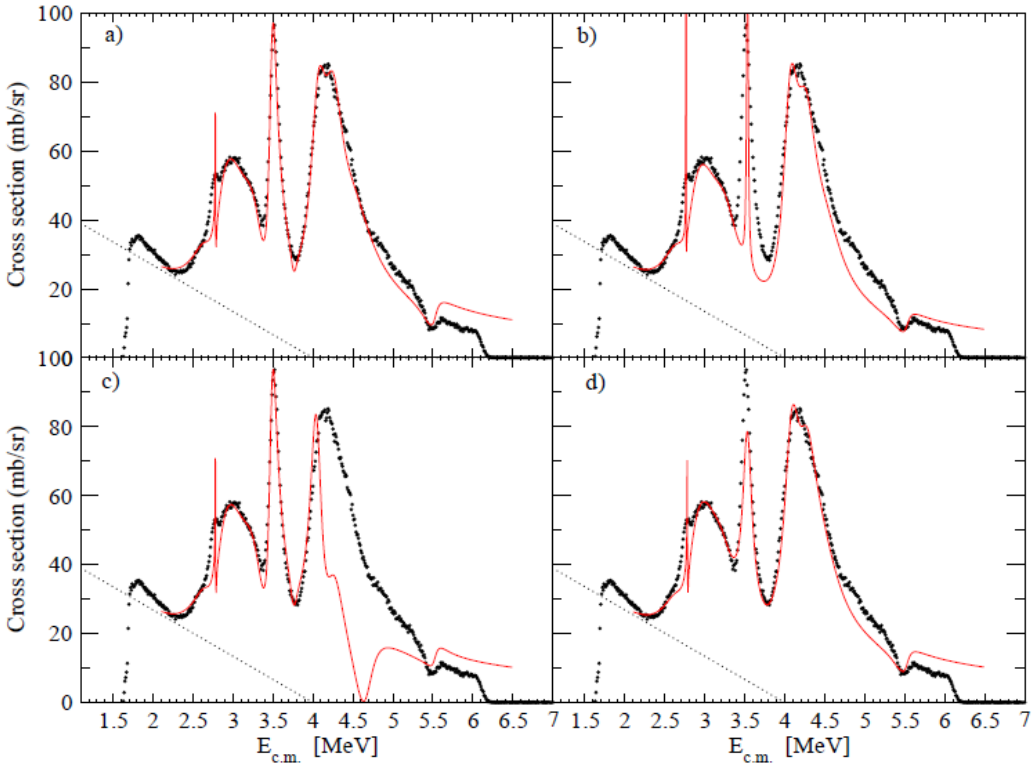
Summary:
clustering appears naturally due to high binding energy of alpha-quartet
and is enhanced by symmetries



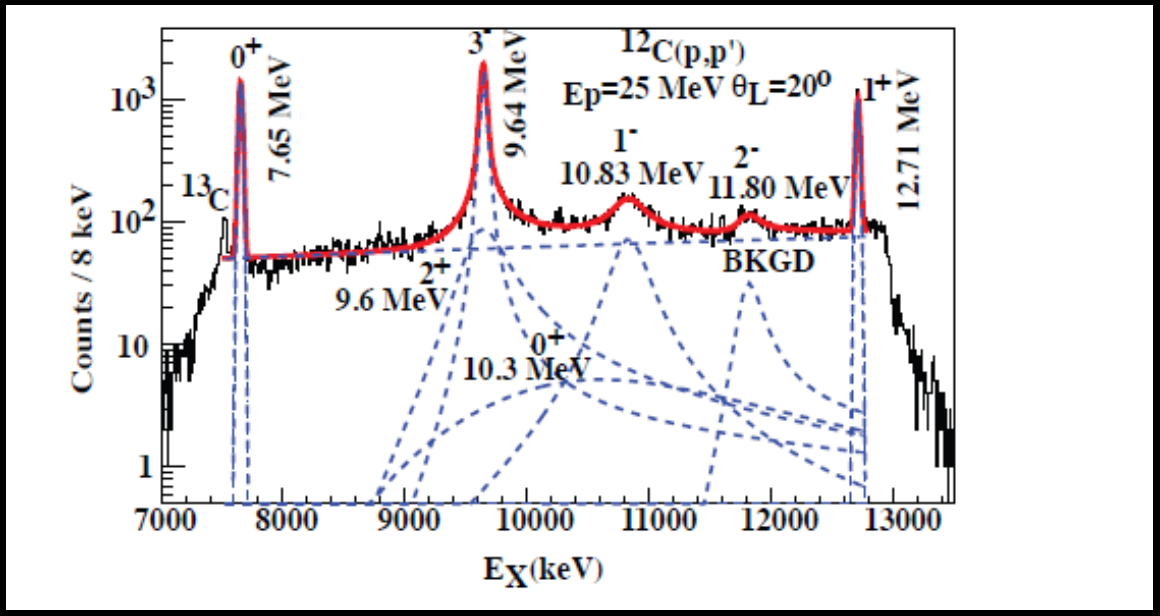

17.3 4⁻
15.75 2⁺
14.8
14.0 3⁺
12.7
11.66 4⁻
11.395 1⁻
11.31 1⁺
10.43 2⁺
9.801 3⁻
8.318 2⁺
7.012 2⁺
d5/2
s1/2
p1/2
g.s. 0⁺
14C
proton excitations
7.547 5/2⁻
7.492, 7/2⁺
6.864 5/2⁺
3.685 3/2⁻
g.s. 1/2⁻
13C
4.439 2⁺
12C
g.s. 0⁺
10.75 7/2⁻
8.2 3/2⁺
d3/2
3.854 5/2⁺
3.089 1/2⁺
g.s. 1/2⁻
13C
16.72 6⁻
14.87 5⁻
14.0 3⁺
10.736 4⁺
7.341 2⁻
6.903 0⁻
6.728 3⁻
6.094 1⁻
g.s. 0⁺
14C
neutron excitations
14C
prolate
Ex [MeV]
J(J+1)
K=0⁻
K=0⁺
1⁻
2⁺
3⁻
4⁺
5⁻
6⁺
0⁺







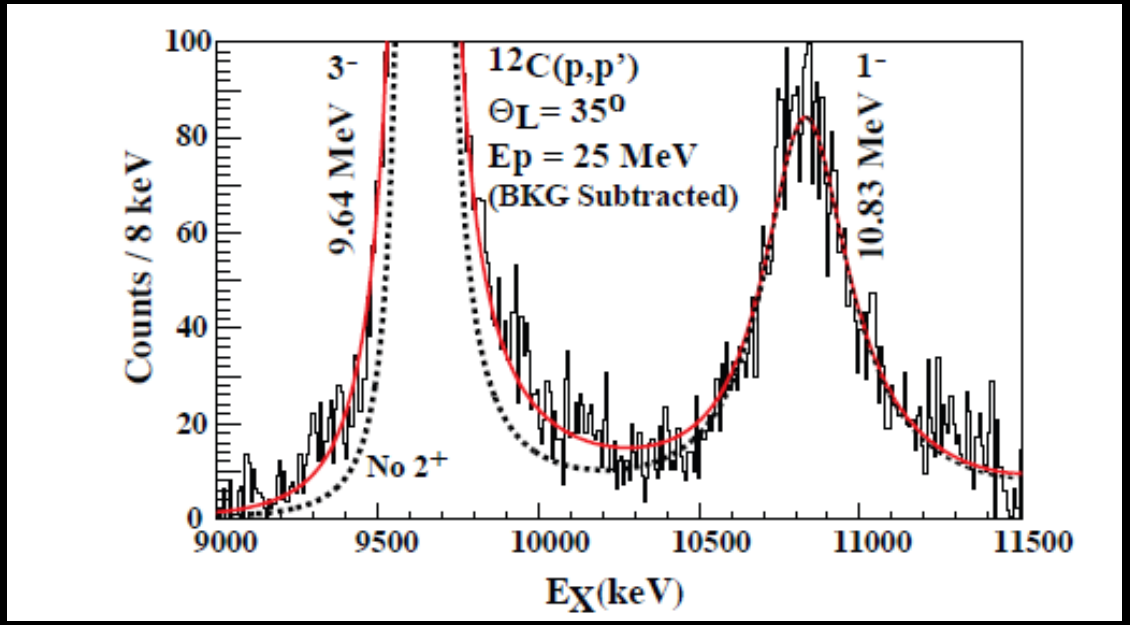
Zagreb 2011
9Be+alpha

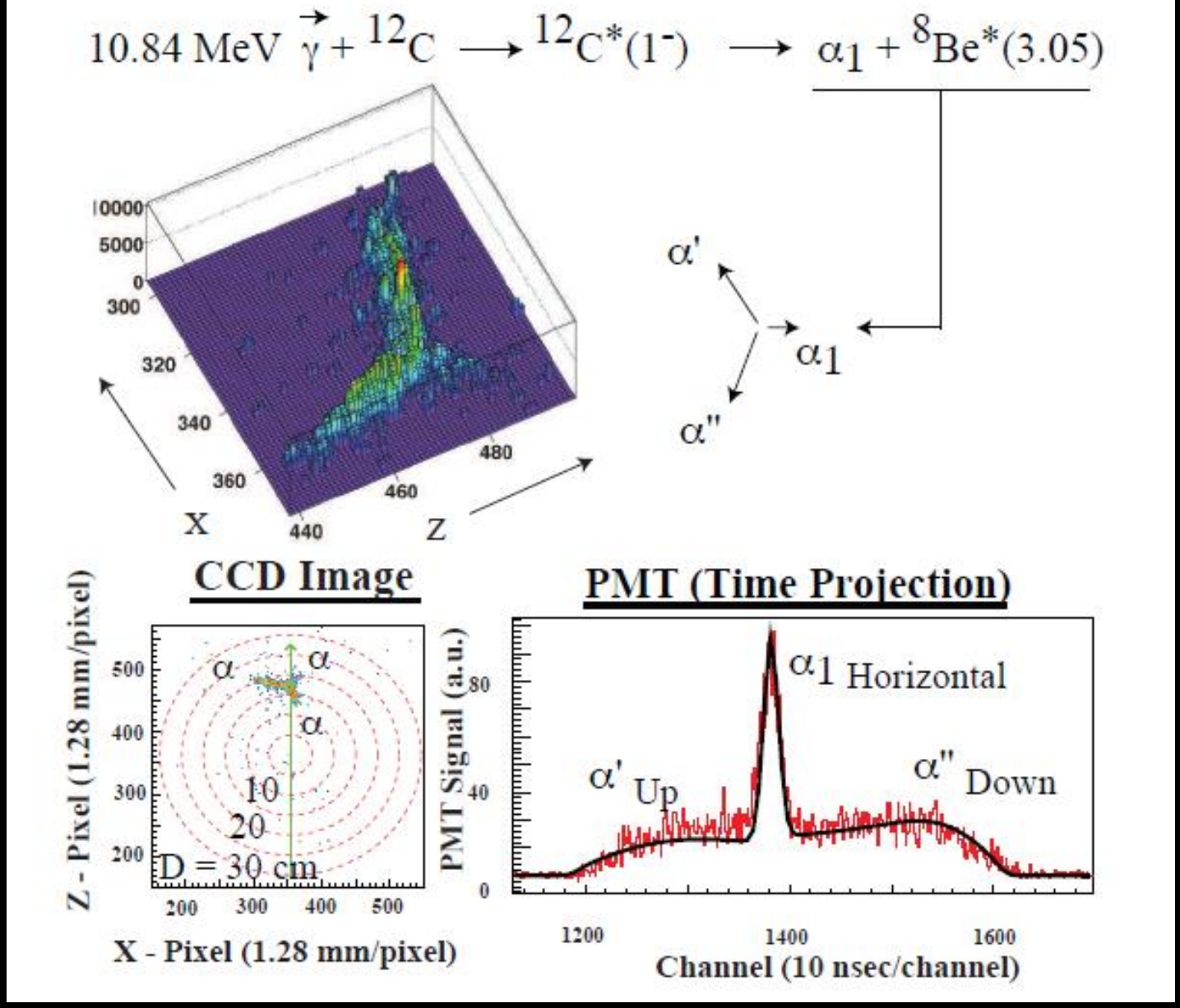


Yale Measurements

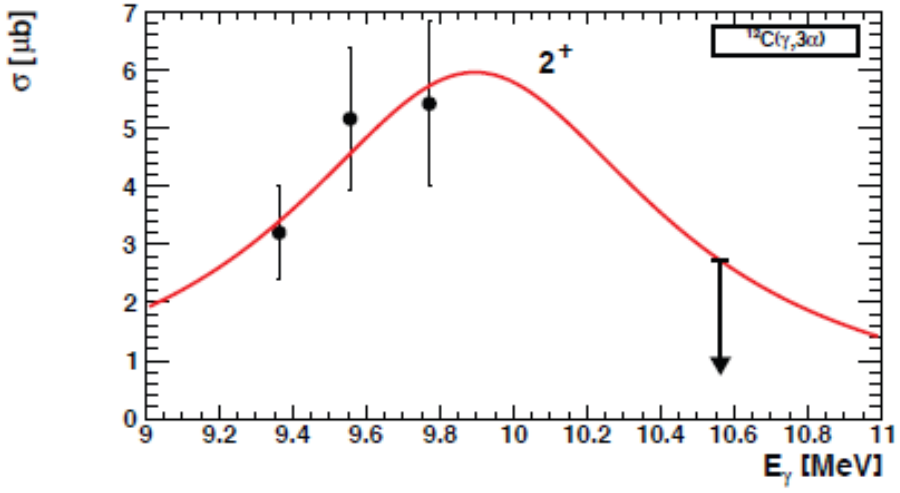
^{12} C(p,p') 25 MeV

Moshe Gai et al.





Optical TPC measurements; Moshe Gai et al.



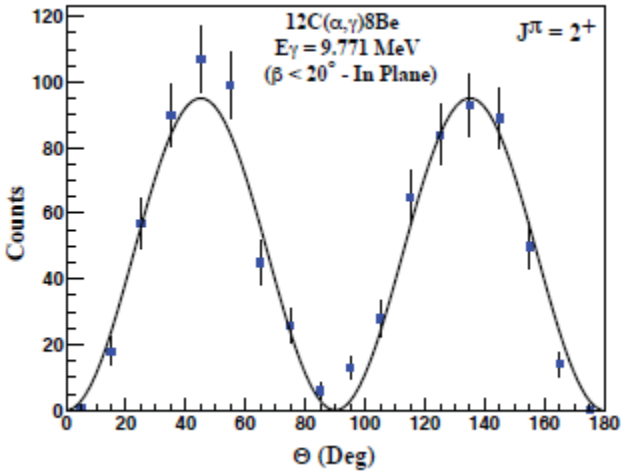


Fig. 7. Preliminary measured excitation curve.

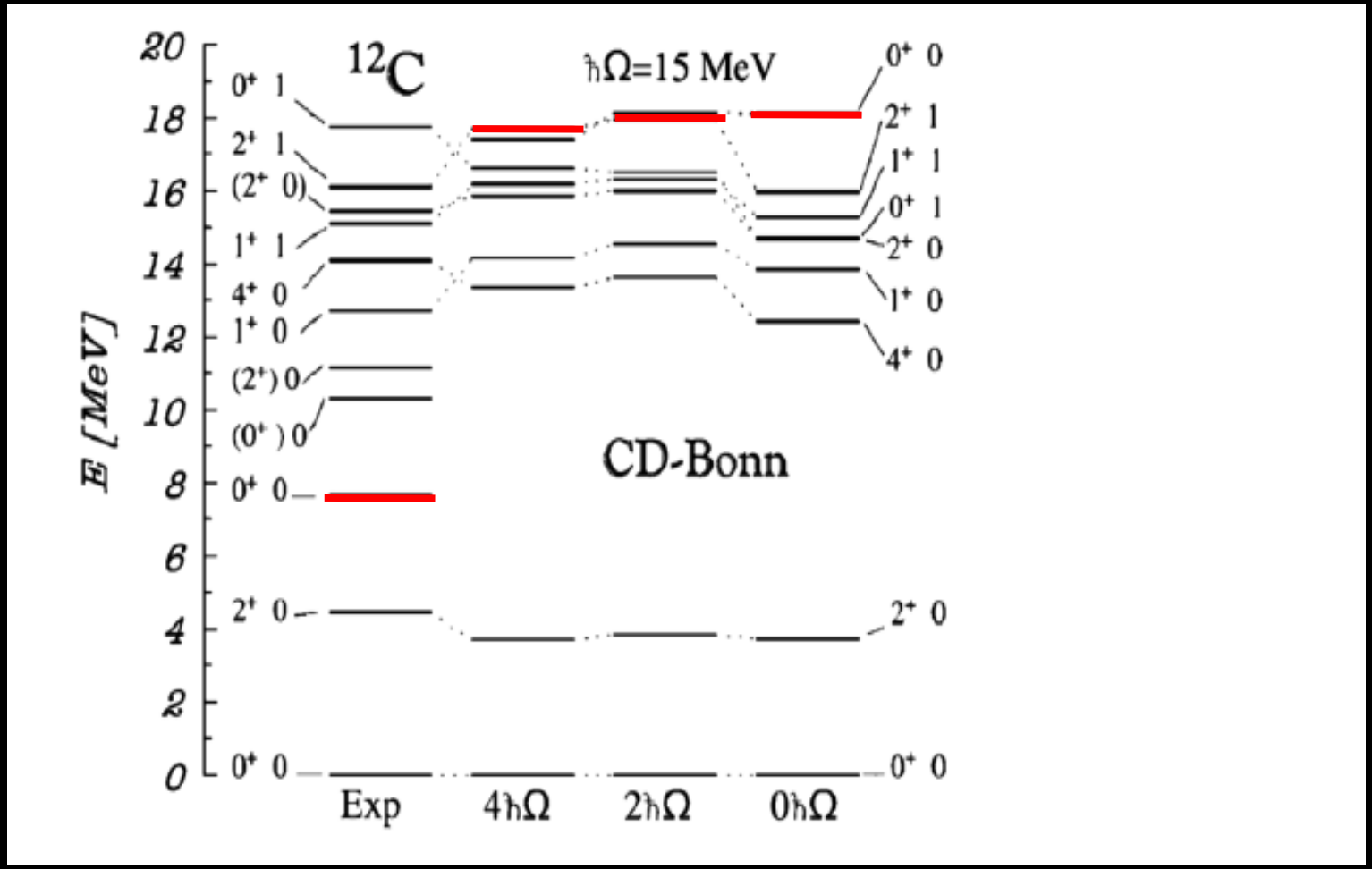
The structure of ^{12}C and stellar helium burning *

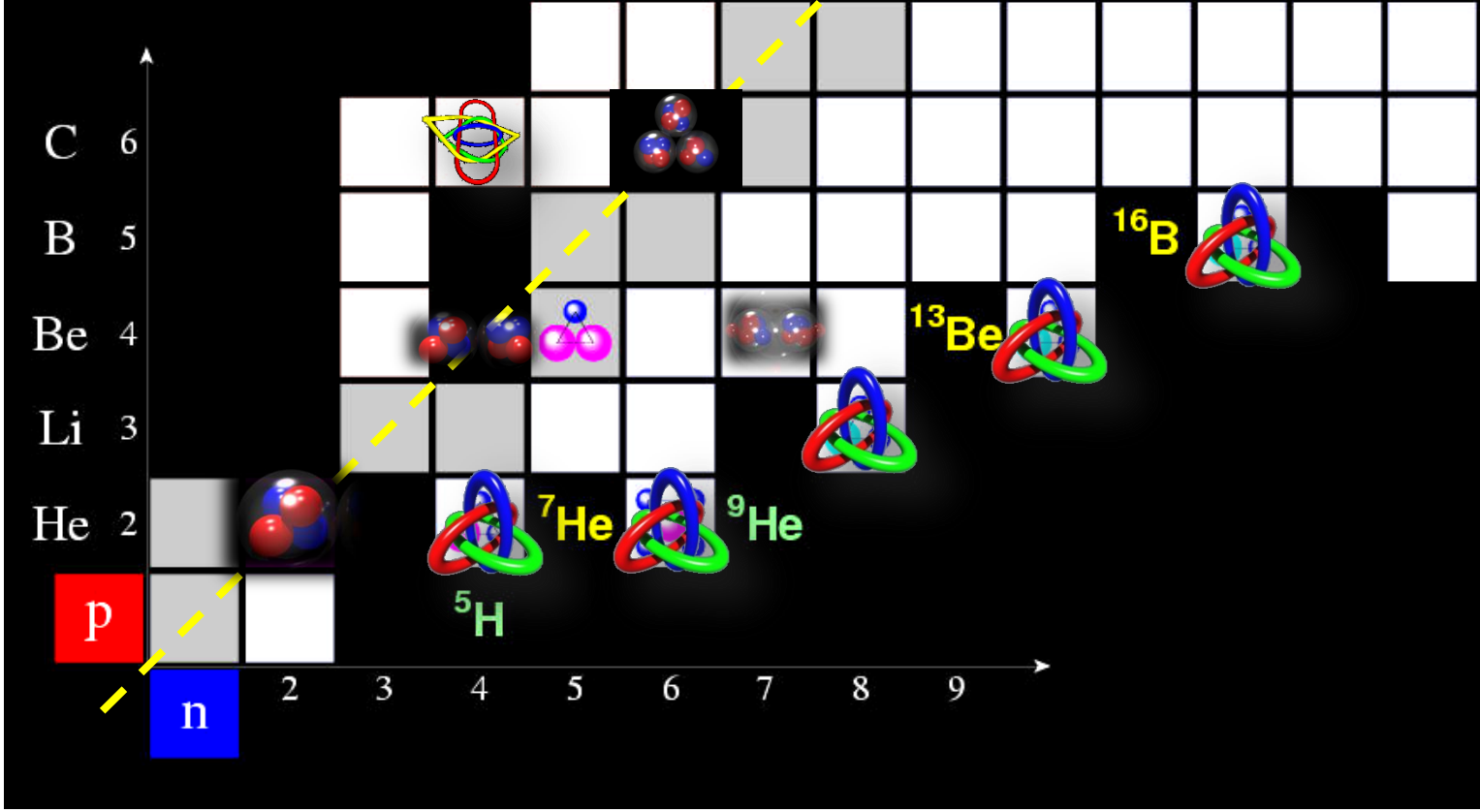
Moshe Gai
for the UConn-Yale-Duke-Weizmann-PTB-UCL Collaboration

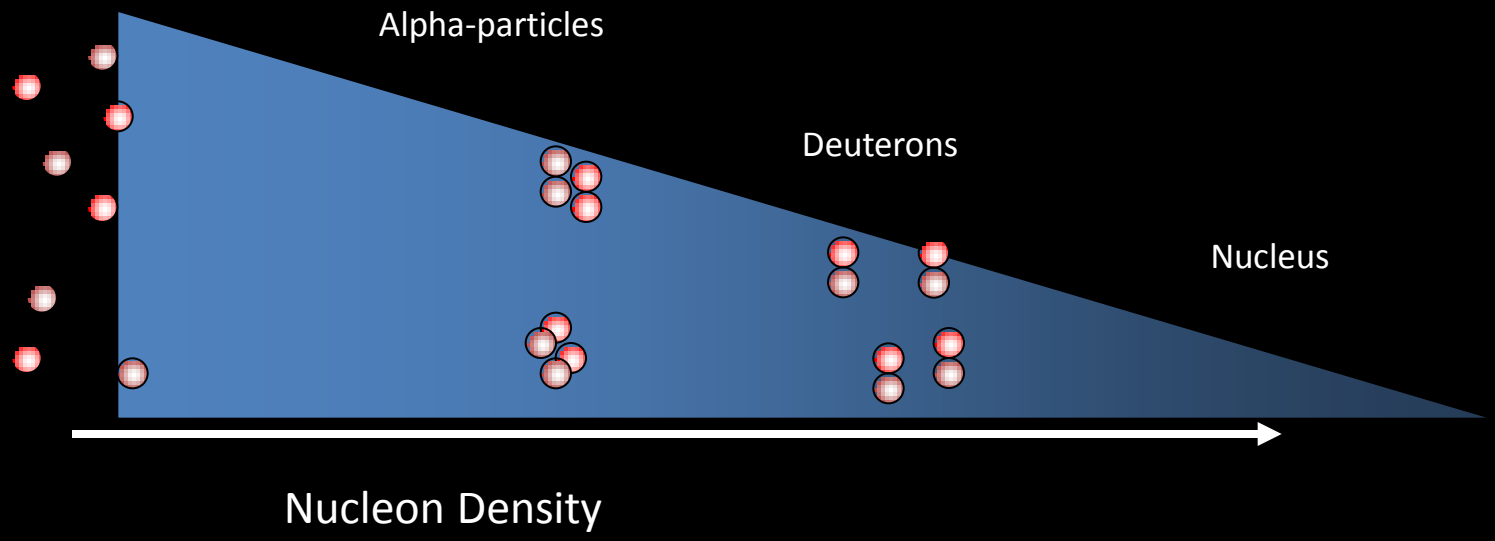
Laboratory for Nuclear Science at Avery Point
University of Connecticut, 1084 Shennecossett Rd, Groton, CT 06340-6097, USA
email: moshe.gai@yale.edu

No core “shell model” calculations

Navratil P, Vary J P and Barrett B R 2000 *Phys. Rev. Lett.* **84** 5728

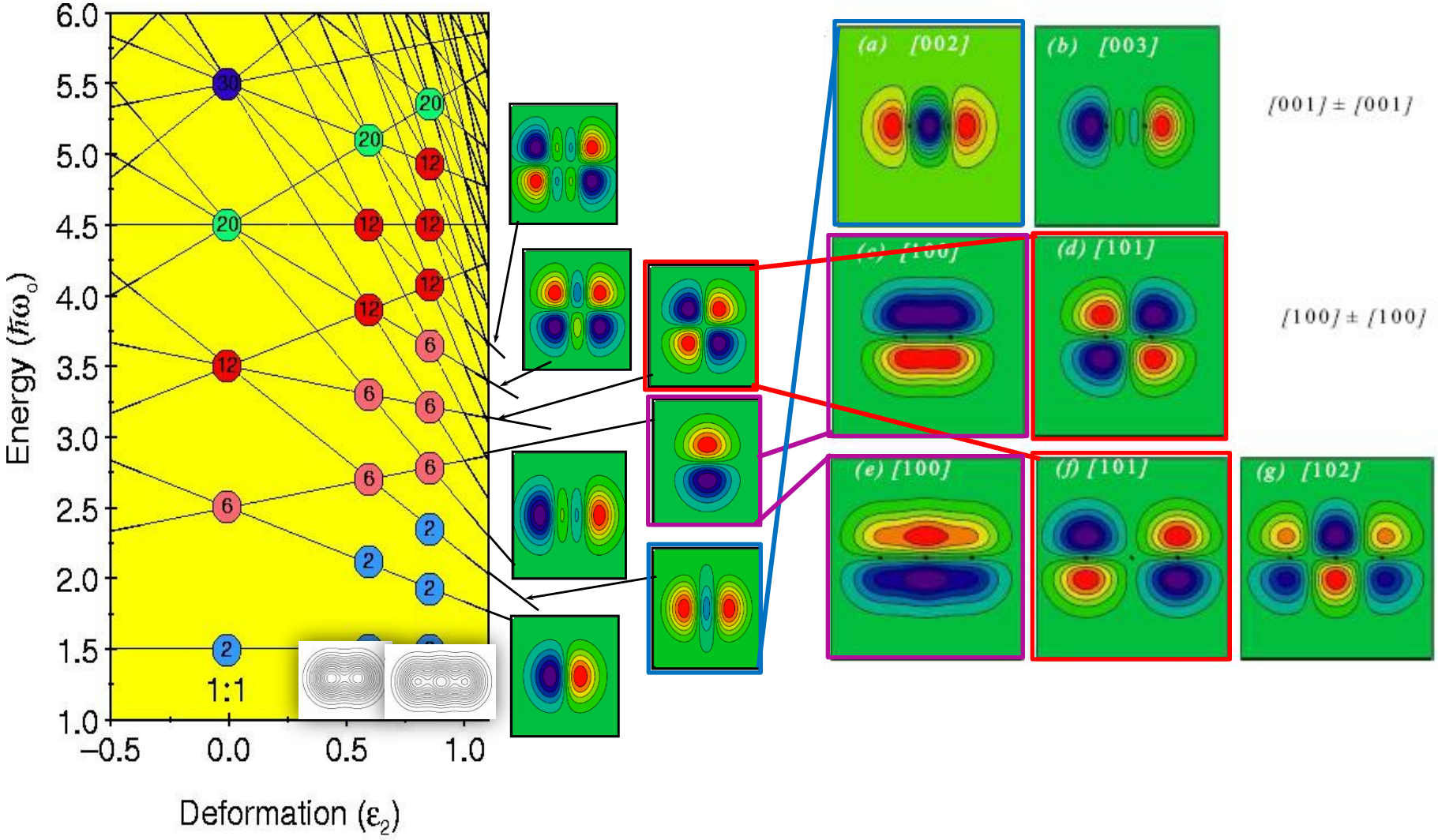



C 6
B 5
Be 4
Li 3
He 2
p
n
2 3 4 5 6 7 8 9
^{5}H
^{7}He
^{9}He
^{13}Be
^{16}B

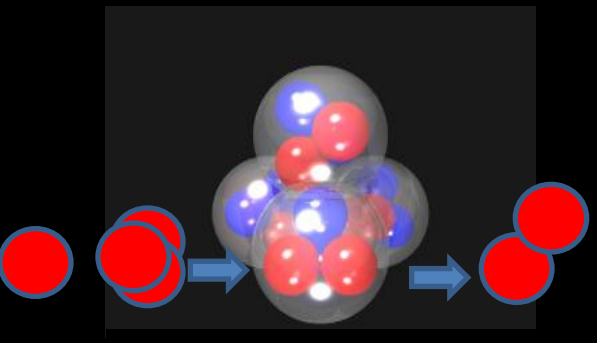

Alpha-particles
Deuterons
Nucleus
Nucleon Density

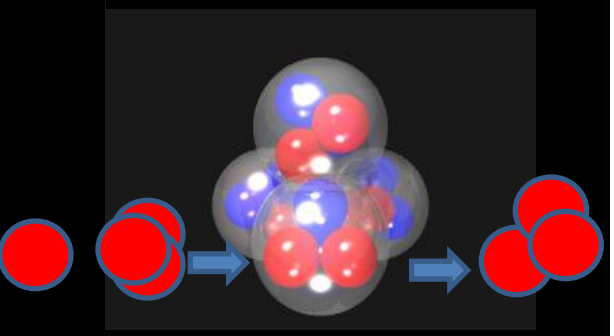
Soap Films and Steiner Points

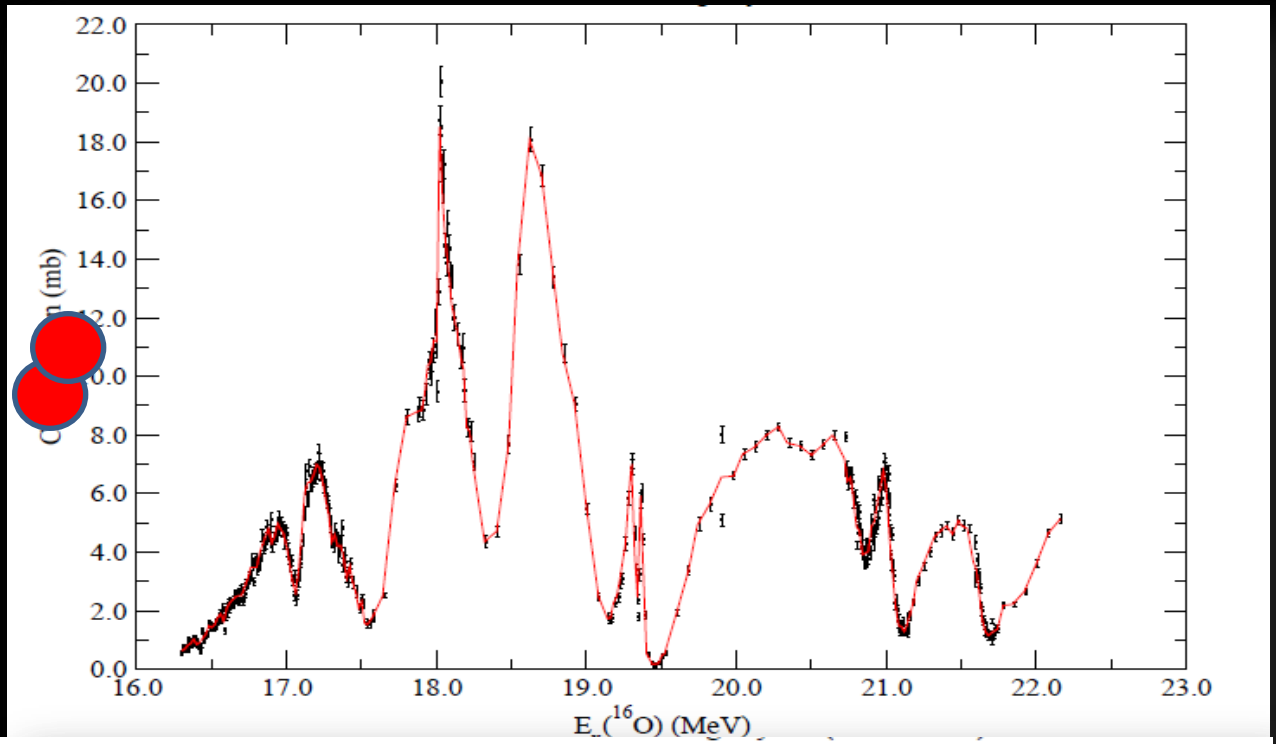
Connection to the deformed Harmonic oscillator

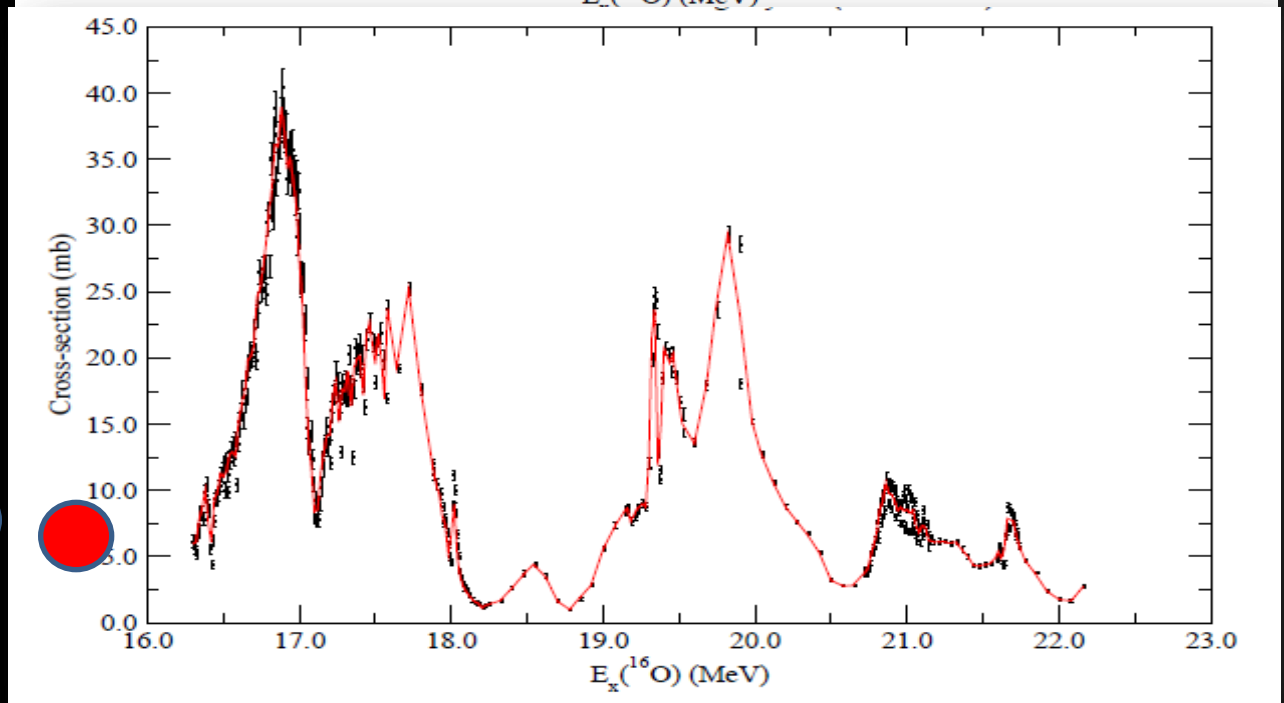


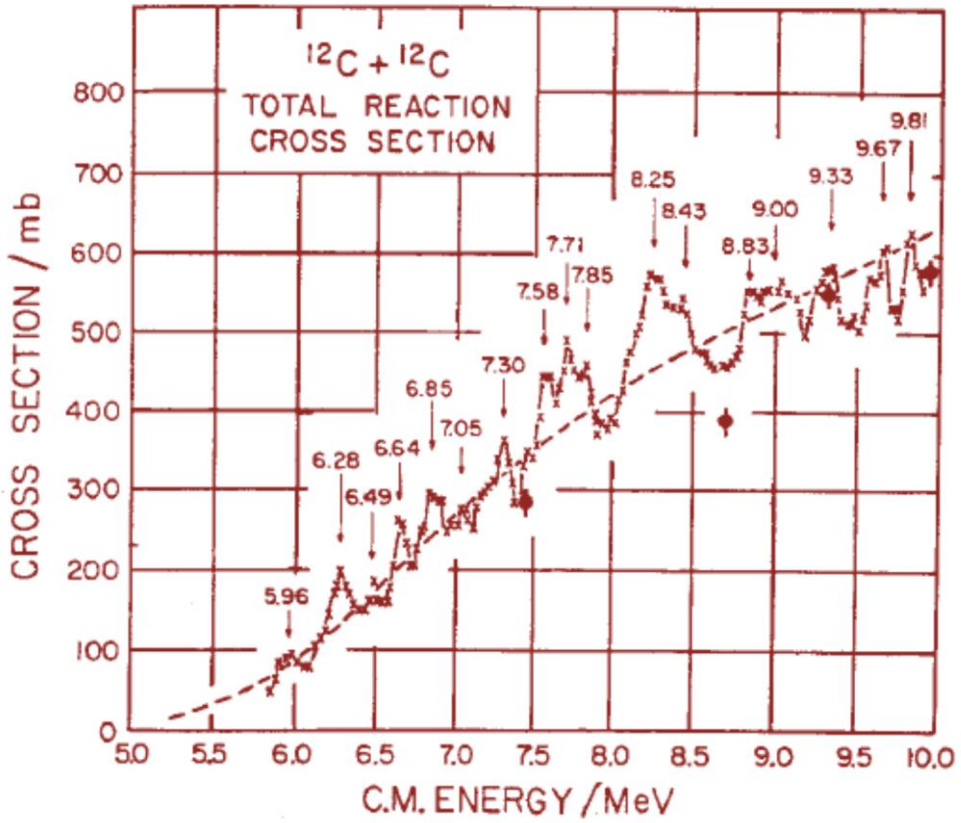
Neil Curtis

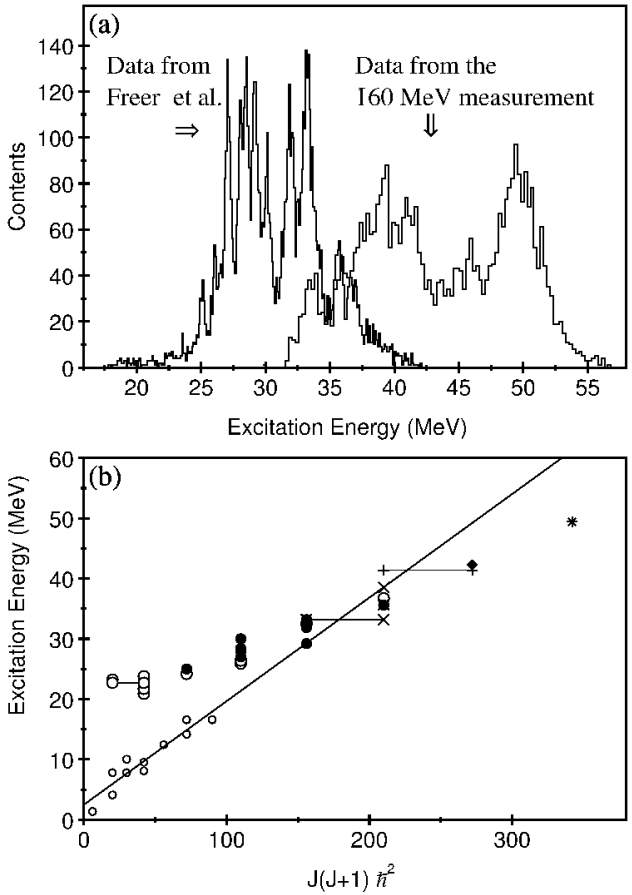




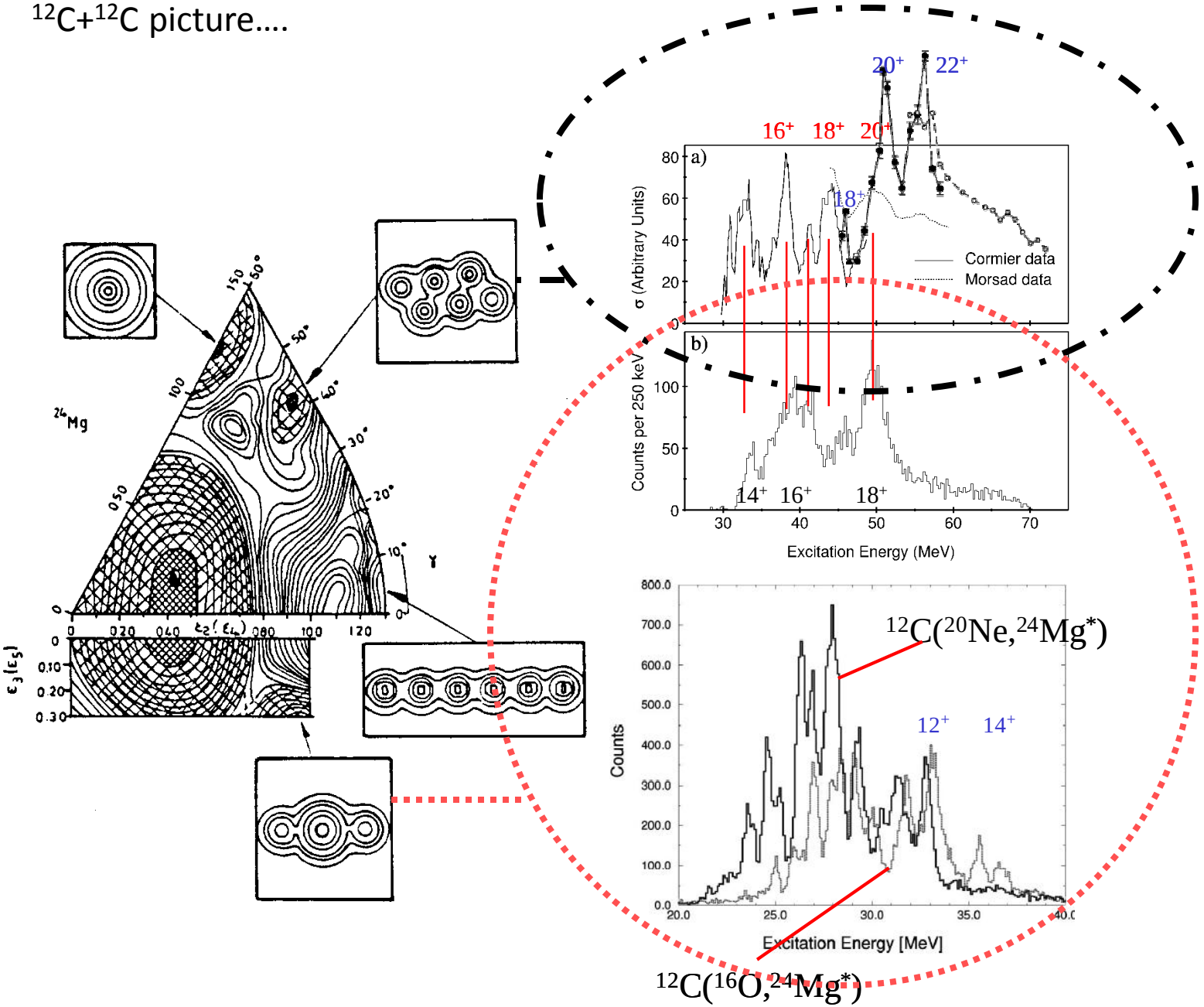

22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
16.0
17.0
18.0
19.0
20.0
21.0
22.0
23.0
E_(16O) (MeV)

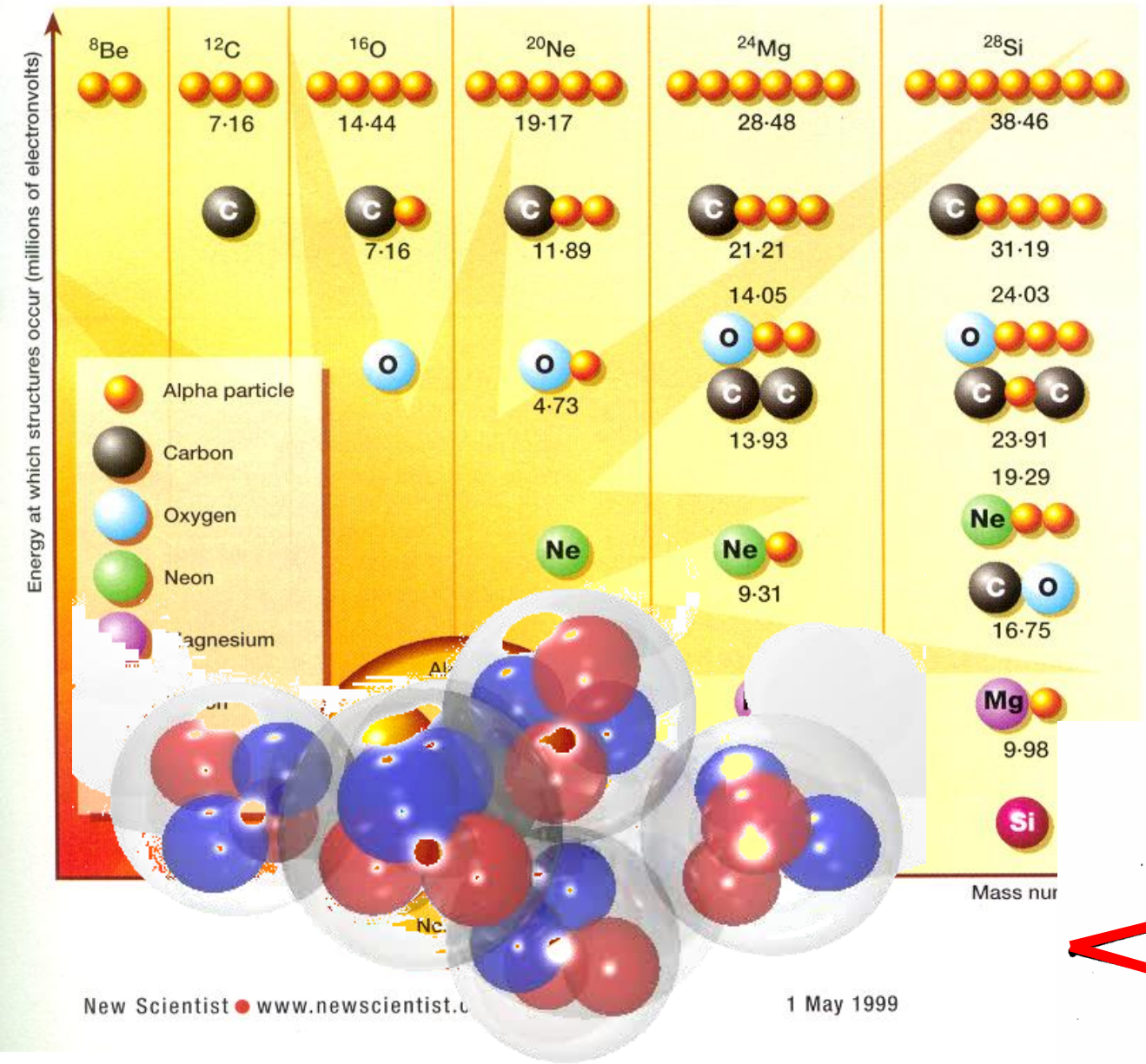

45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Cross-section (mb)
16.0
17.0
18.0
19.0
20.0
21.0
22.0
23.0
Ex(16O) (MeV)

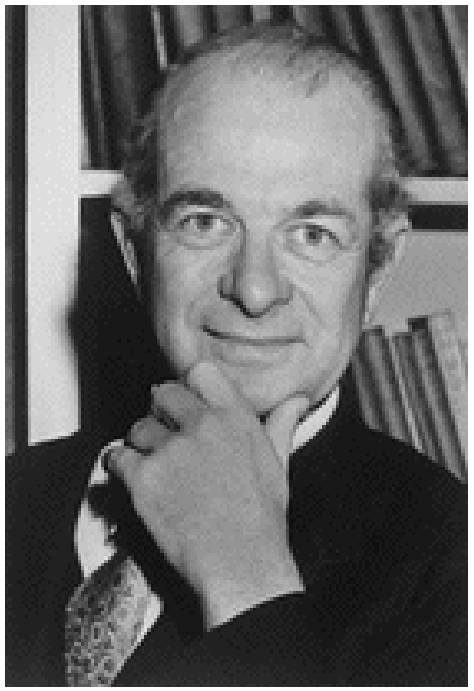

$^{12}C + ^{12}C$
TOTAL REACTION
CROSS SECTION
CROSS SECTION / mb
C.M. ENERGY / MeV
5.96
6.28
6.49
6.64
6.85
7.05
7.30
7.58
7.71
7.85
8.25
8.43
8.83
9.00
9.33
9.67
9.81


(a)
Data from
Freer et al.
Data from the
160 MeV measurement
Contents
Excitation Energy (MeV)
(b)
Excitation Energy (MeV)
J(J+1) $\hbar^2$

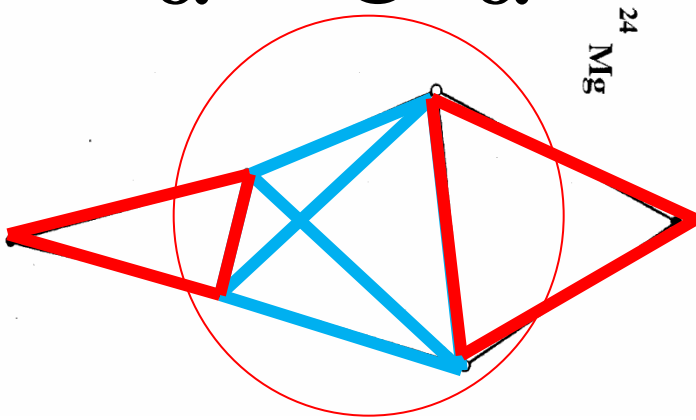
$^{12}C+^{12}C$ picture….







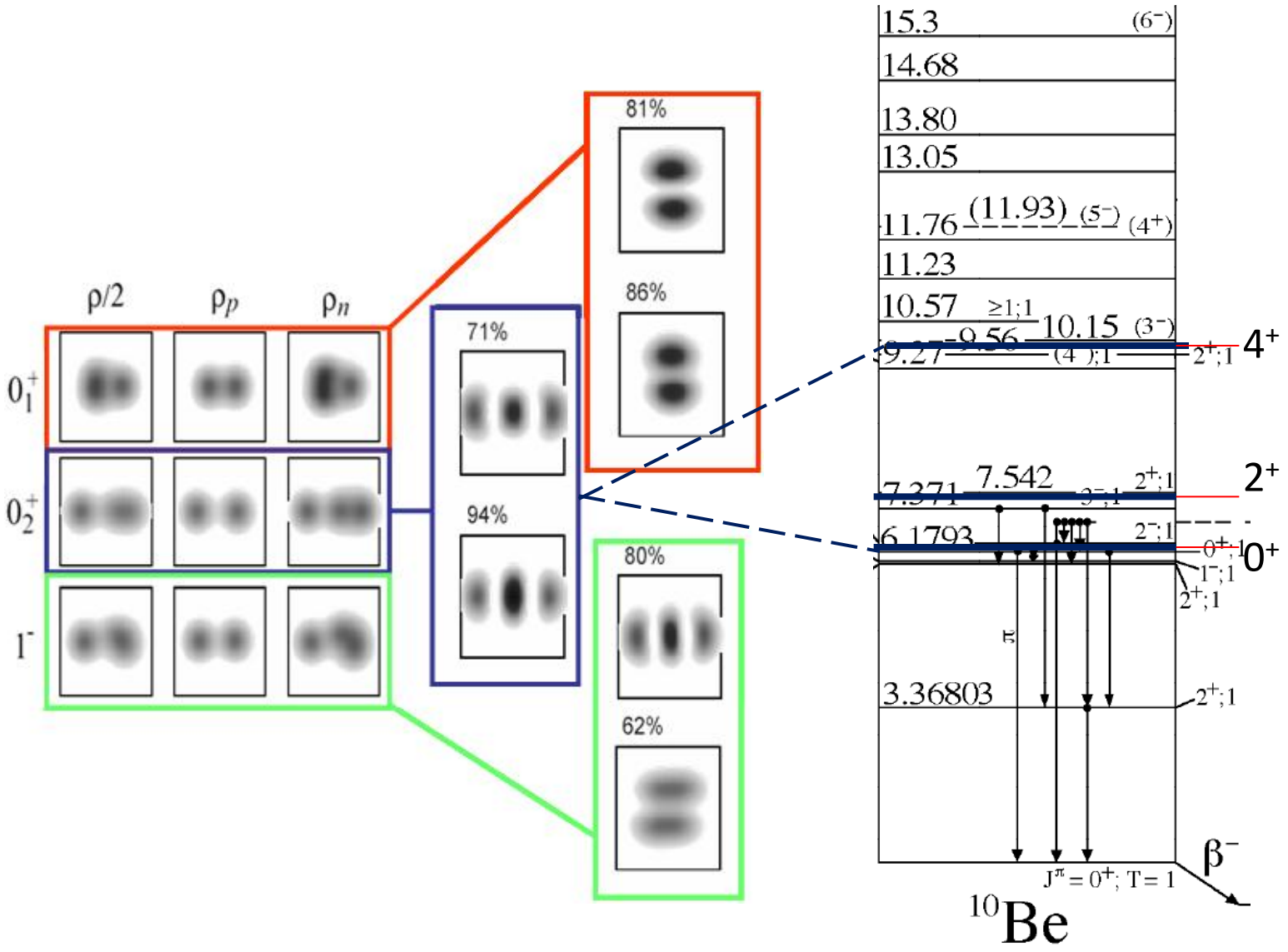
$\alpha + {}^{16}O + \alpha$



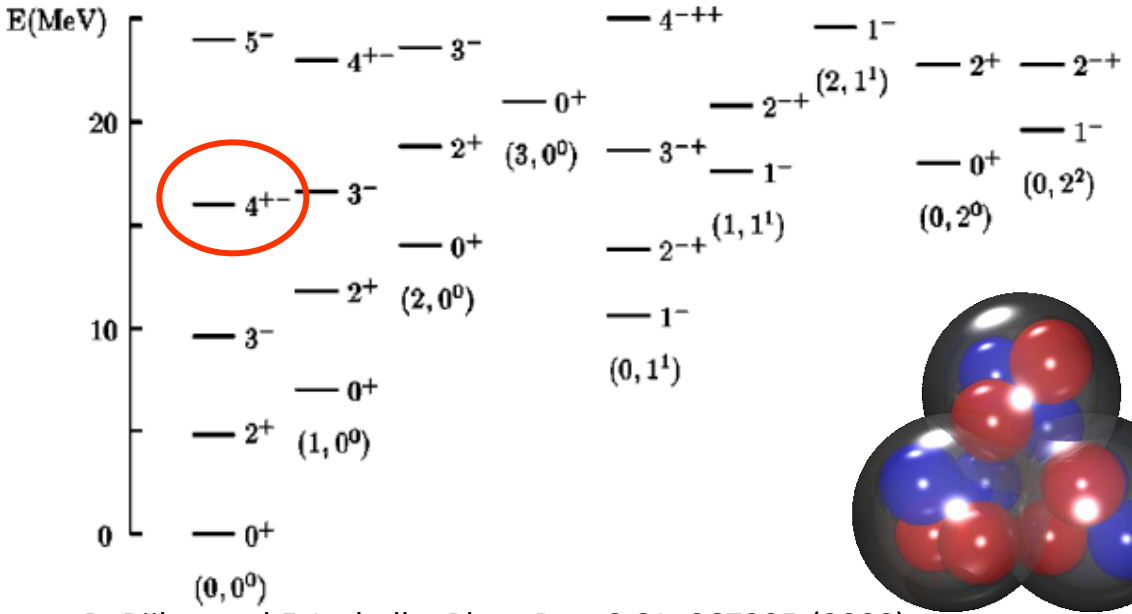
Pauling, I., 1973, *Phys. Rev. Lett.*, **35**, 1480.

${}^{12}C + {}^{12}C$

The nucleus ^{10}Be



Kanada En'yo



R. Bijker and F. Iachello, Phys. Rev. C 61, 067305 (2000).