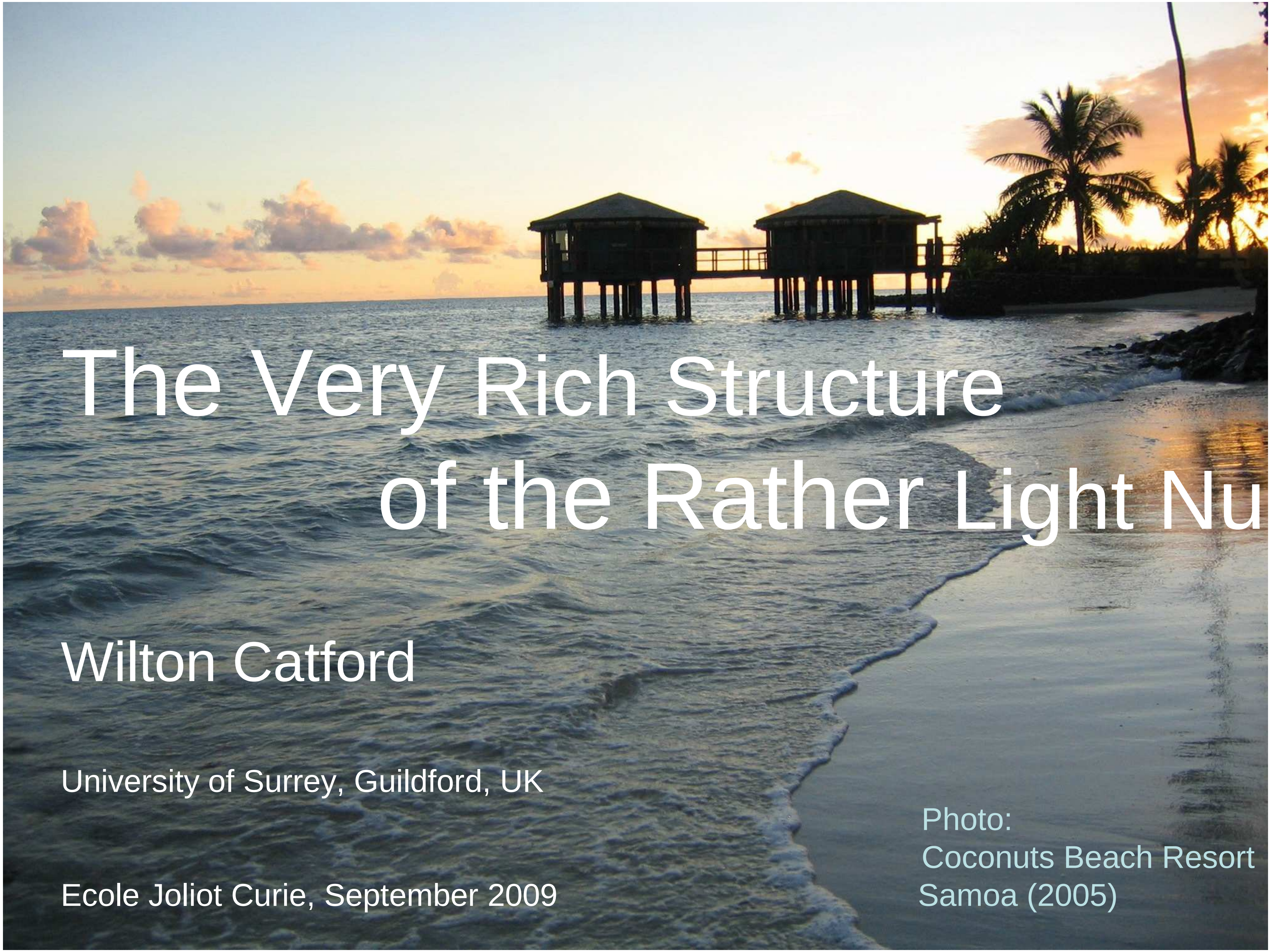


The Very Rich Structure of the Rather Light Nu

Wilton Catford

University of Surrey, Guildford, UK

Ecole Joliot Curie, September 2009

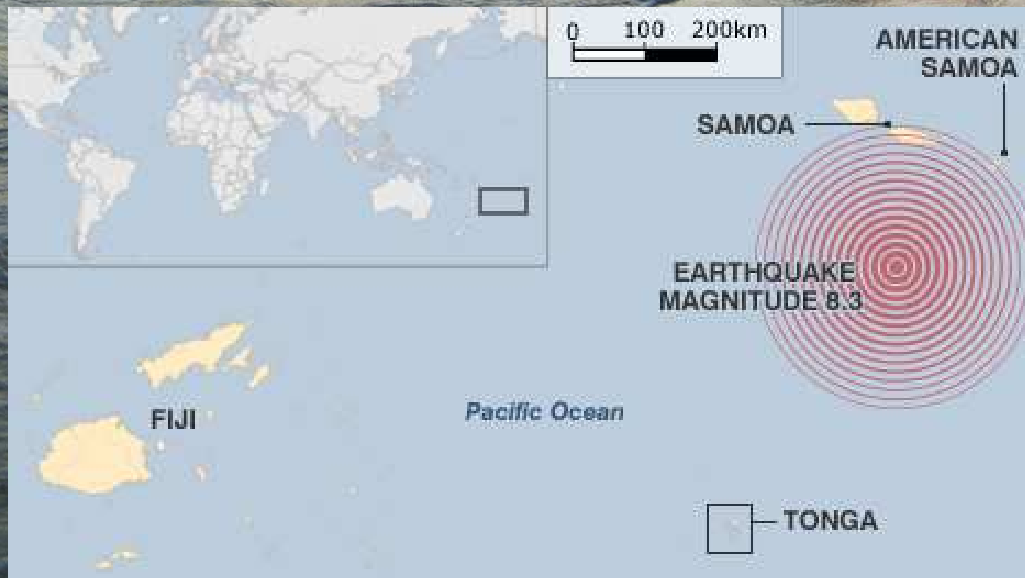
Photo:
Coconuts Beach Resort
Samoa (2005)

The Very Rich Structure of the Rather Light Nu

Wilton Catford

University of Surrey, Guildford, UK

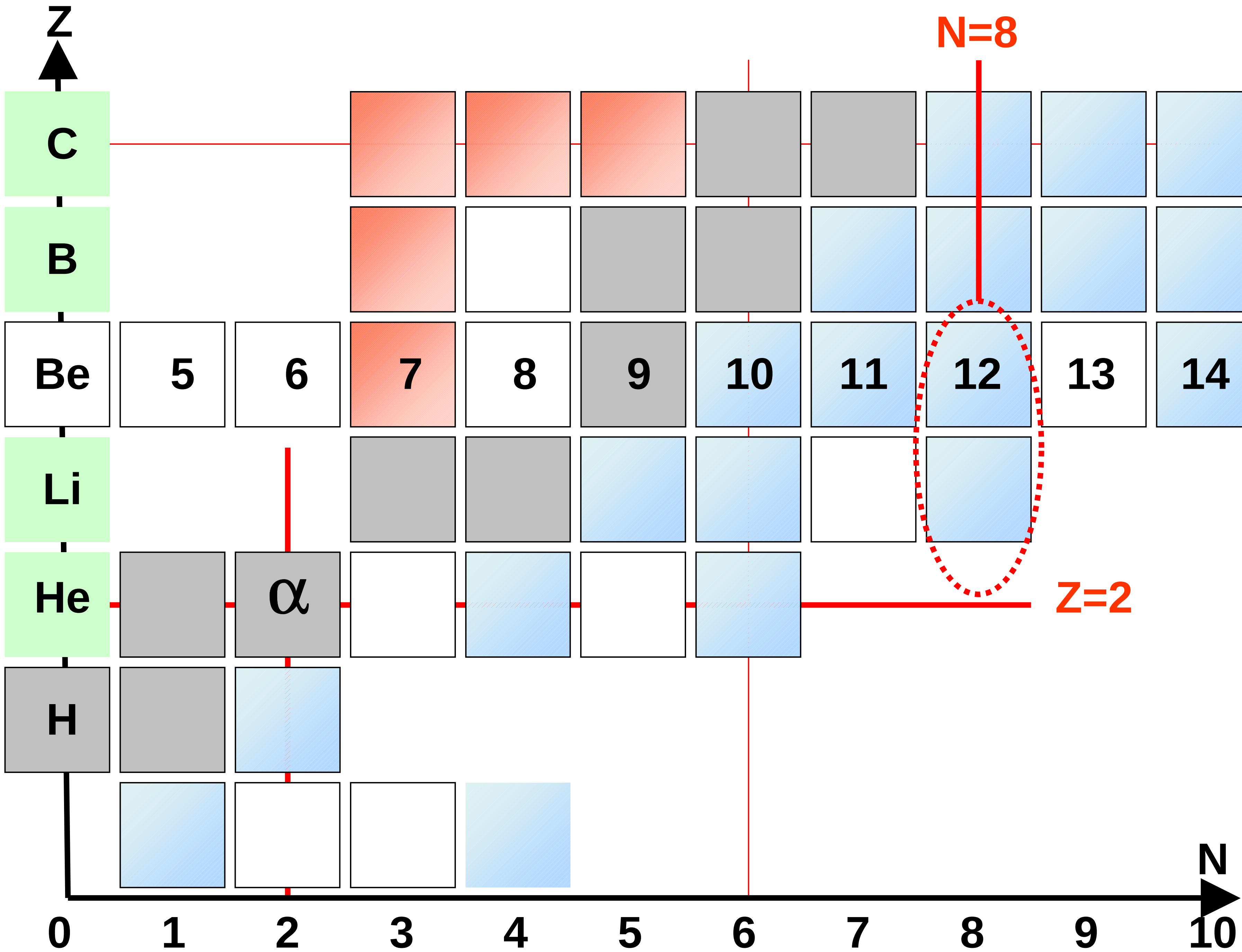
Ecole Joliot Curie, September 2009



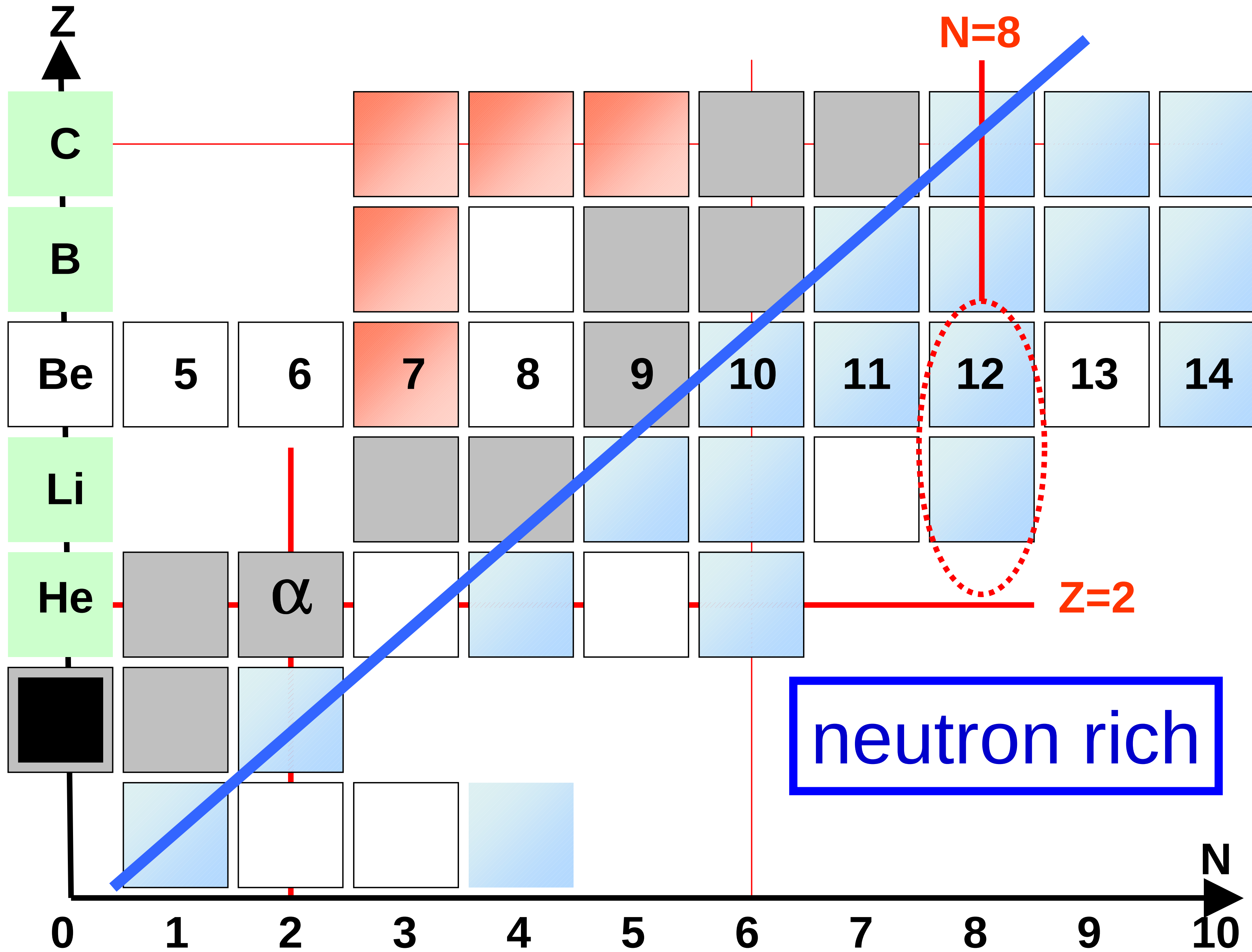
t

U.S. citizen Heather Penner, who works at Coconut Resort at Maninoa Siumu on the southern coast of Western Samoa walks through the remains of her Tsunami destroyed workplace.

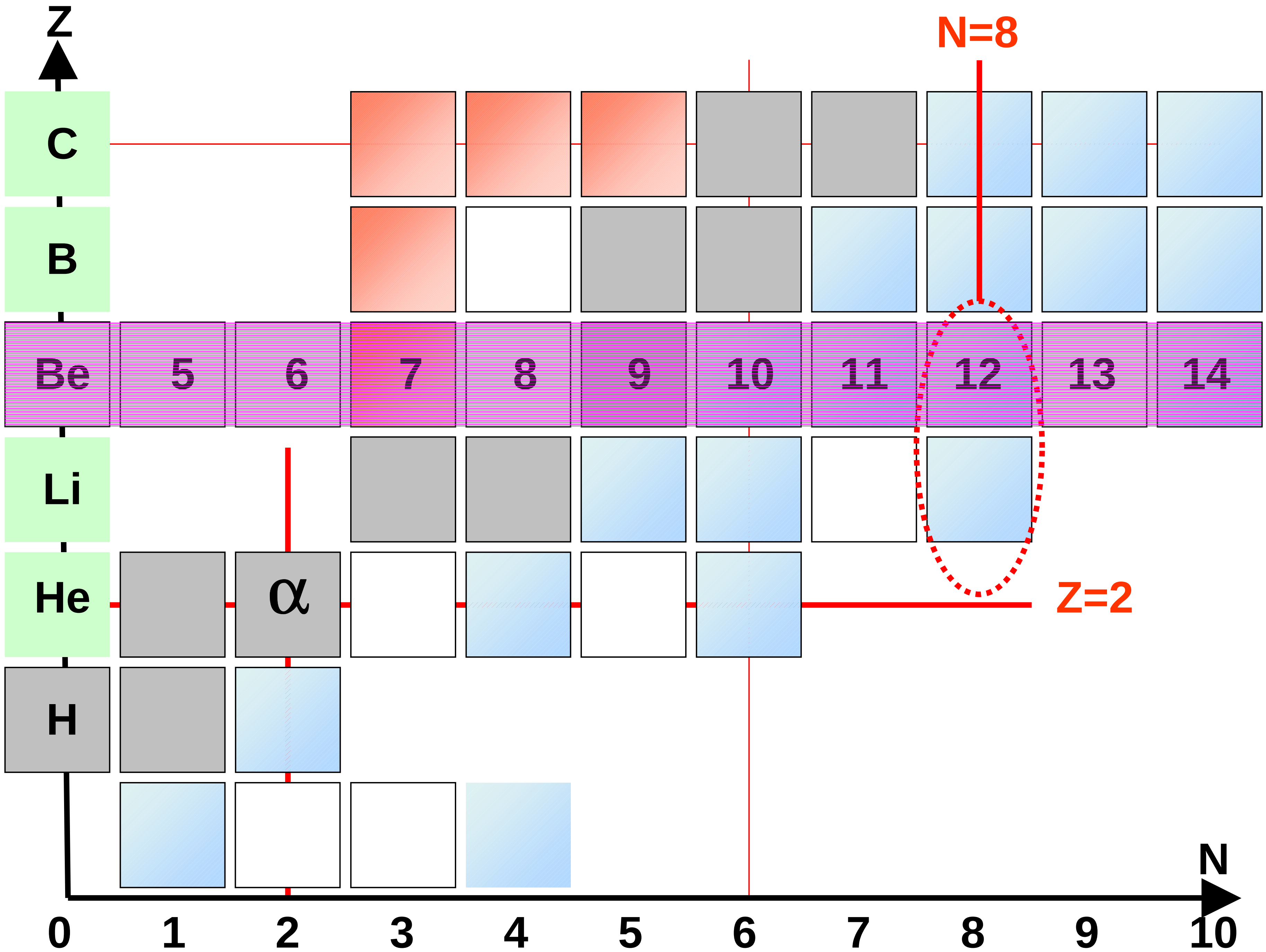
- Experimental overview of some nuclei, after all the theory
- Theorists…. Please interrupt and explain, if you like
- Rather light nuclei….
- Olivier will cover the heavier nuclei, later
- No equations, but some interesting phenomena…



Z
N=8
C
B
Be
5
6
7
8
9
10
11
12
13
14
Li
He
α
Z=2
H
N
0
1
2
3
4
5
6
7
8
9
10



Z
N=8
C
B
Be
5
6
7
8
9
10
11
12
13
14
Li
He
α
Z=2
neutron rich
N
0
1
2
3
4
5
6
7
8
9
10


Z
N=8
C
B
Be
5
6
7
8
9
10
11
12
13
14
Li
He
α
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N
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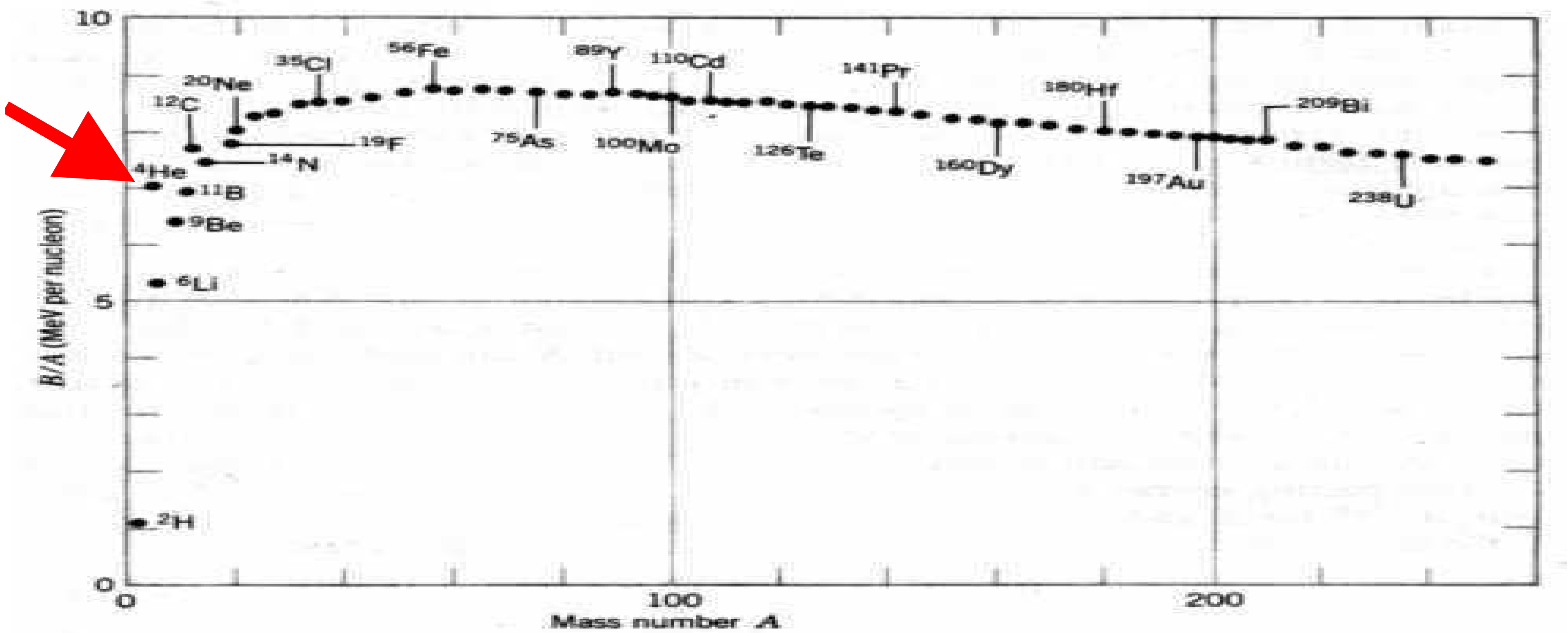
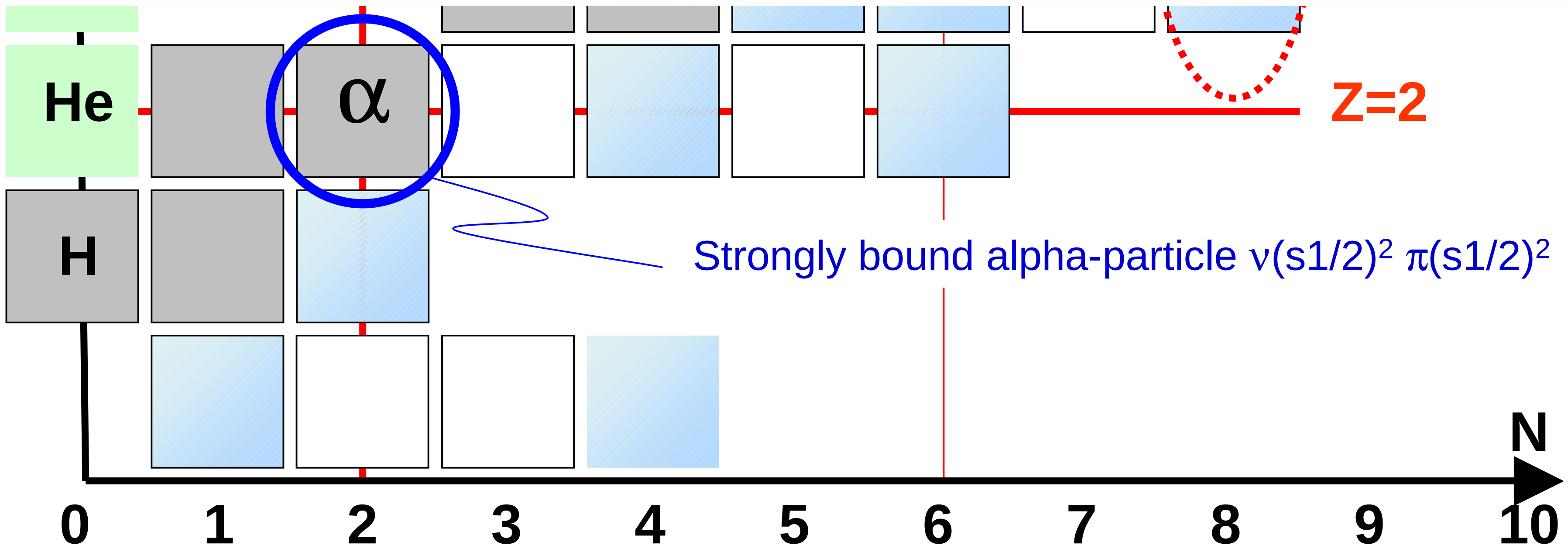
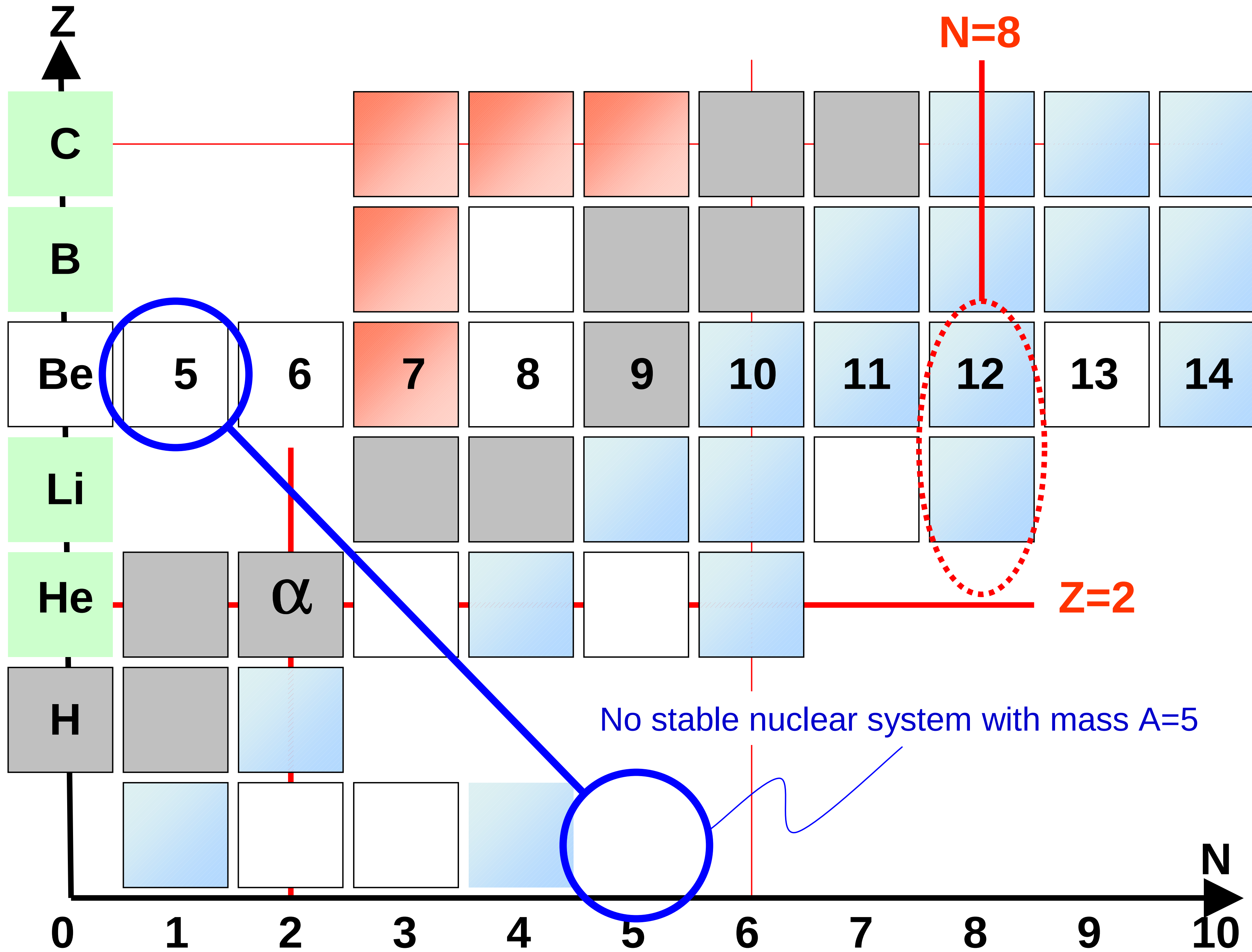
6
7
8
9
10



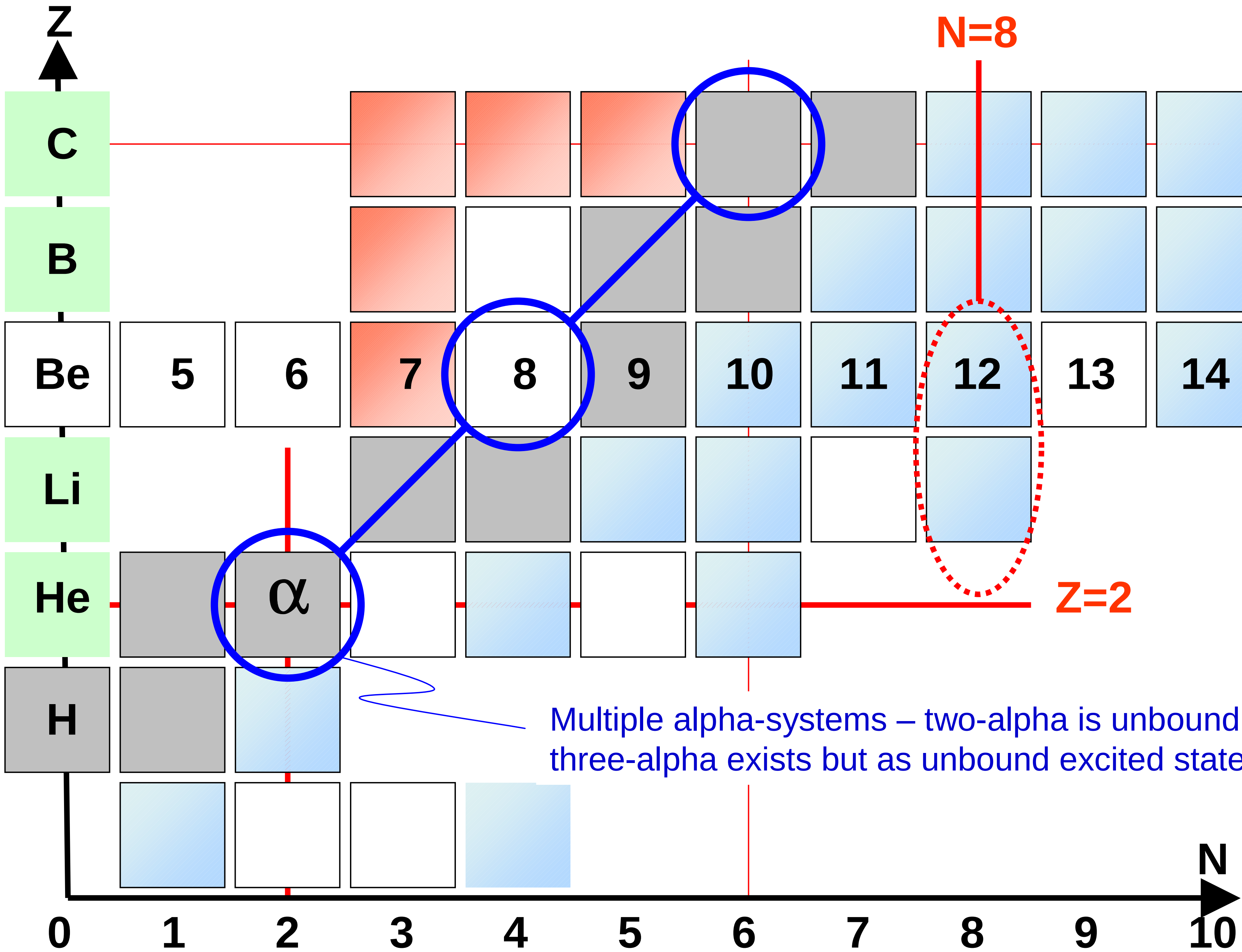
10
5
0
0
100
200
Mass number A
B/A (MeV per nucleon)
²H
⁶Li
⁹Be
¹¹B
⁴He
¹²C
¹⁴N
¹⁹F
²⁰Ne
³⁵Cl
⁵⁶Fe
⁷⁵As
⁸⁹Y
¹⁰⁰Mo
¹¹⁰Cd
¹²⁶Te
¹⁴¹Pr
¹⁶⁰Dy
¹⁸⁰Hf
¹⁹⁷Au
²⁰⁹Bi
²³⁸U



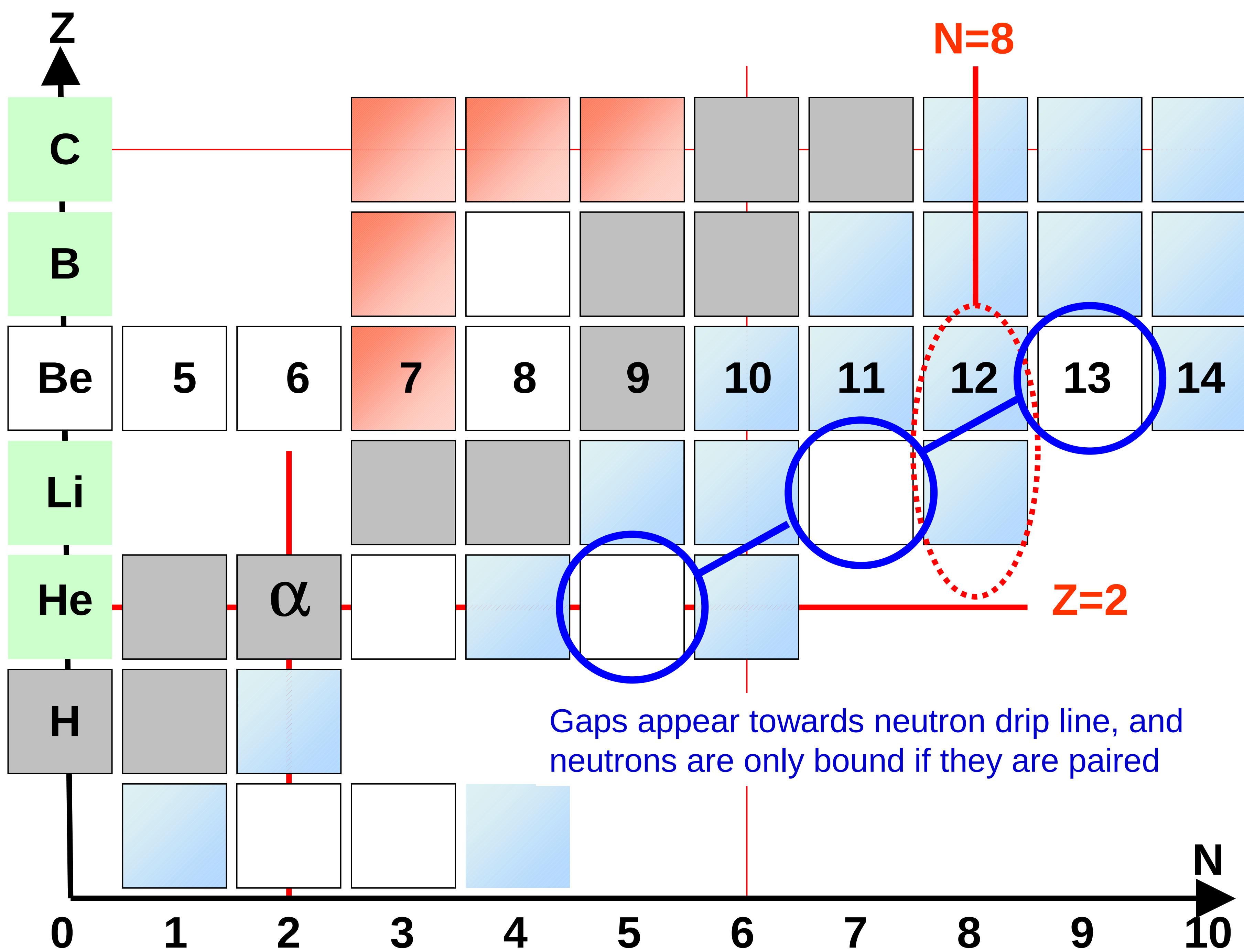
He
α
H
Z=2
Strongly bound alpha-particle ν(s1/2)² π(s1/2)²
N
0
1
2
3
4
5
6
7
8
9
10



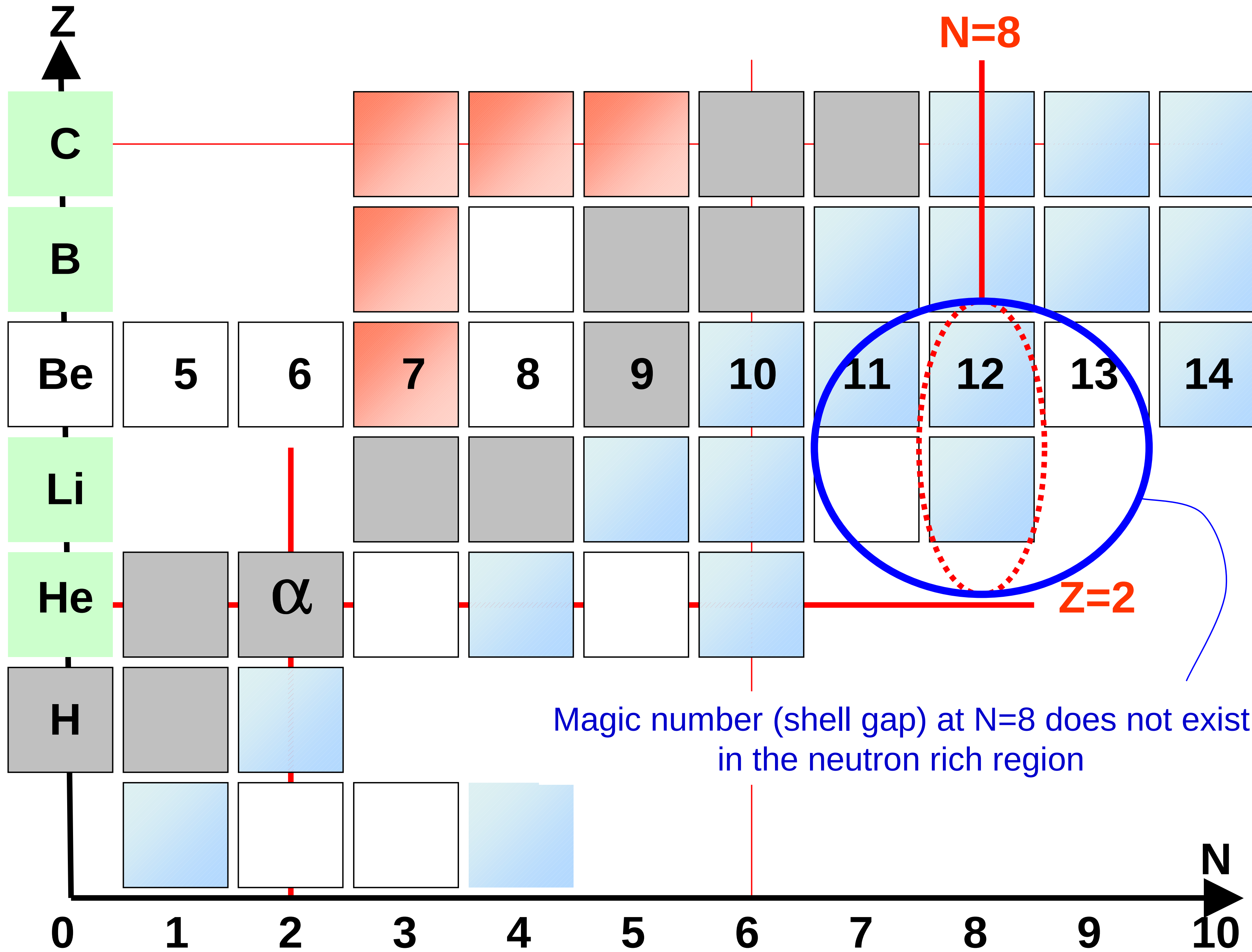
Z
N=8
C
B
Be
5
6
7
8
9
10
11
12
13
14
Li
He
α
Z=2
H
No stable nuclear system with mass A=5
N
0
1
2
3
4
5
6
7
8
9
10

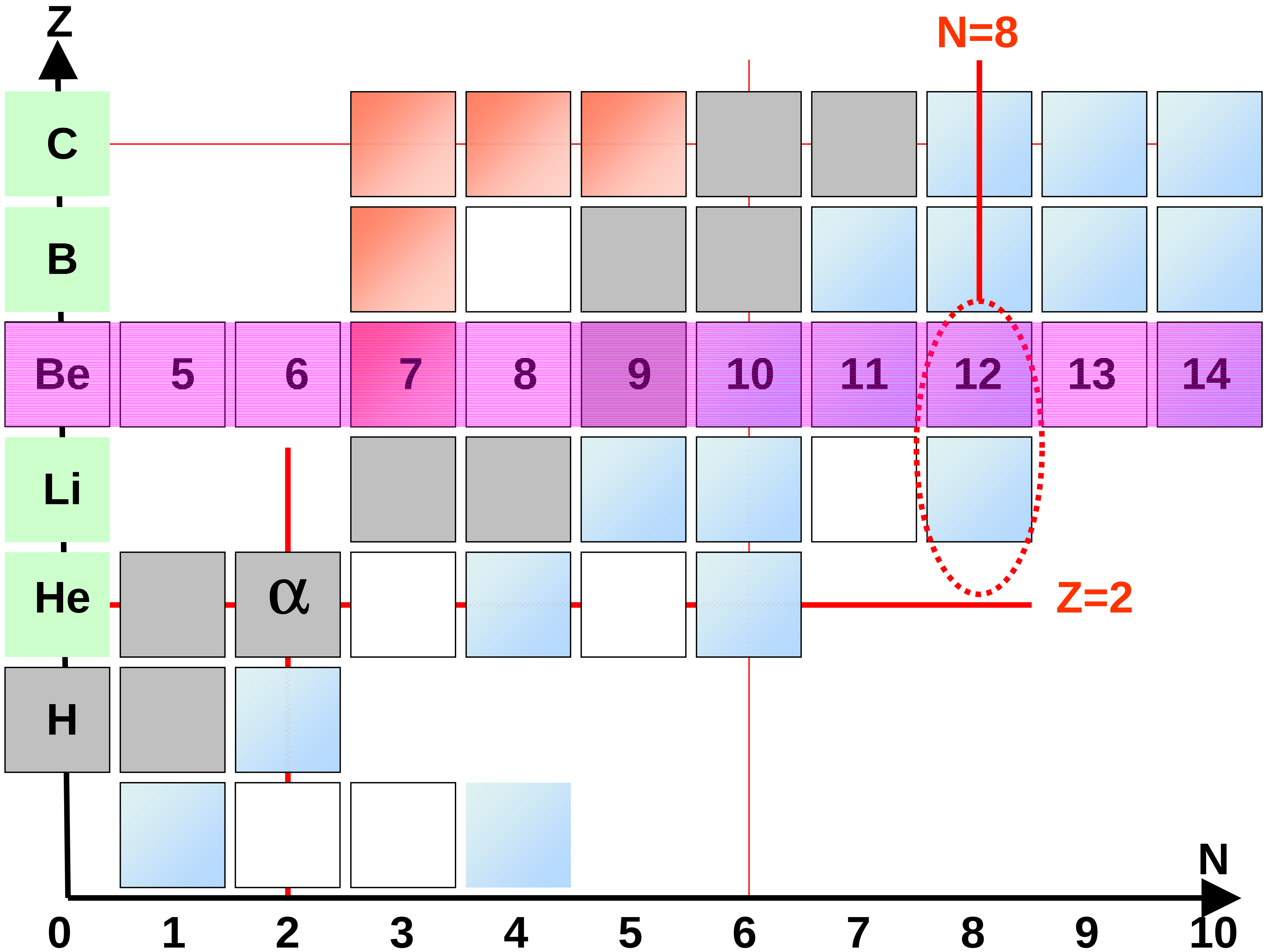


Z
N=8
C
B
Be
5
6
7
8
9
10
11
12
13
14
Li
He
α
Z=2
H
Multiple alpha-systems – two-alpha is unbound,
three-alpha exists but as unbound excited state
N
0
1
2
3
4
5
6
7
8
9
10

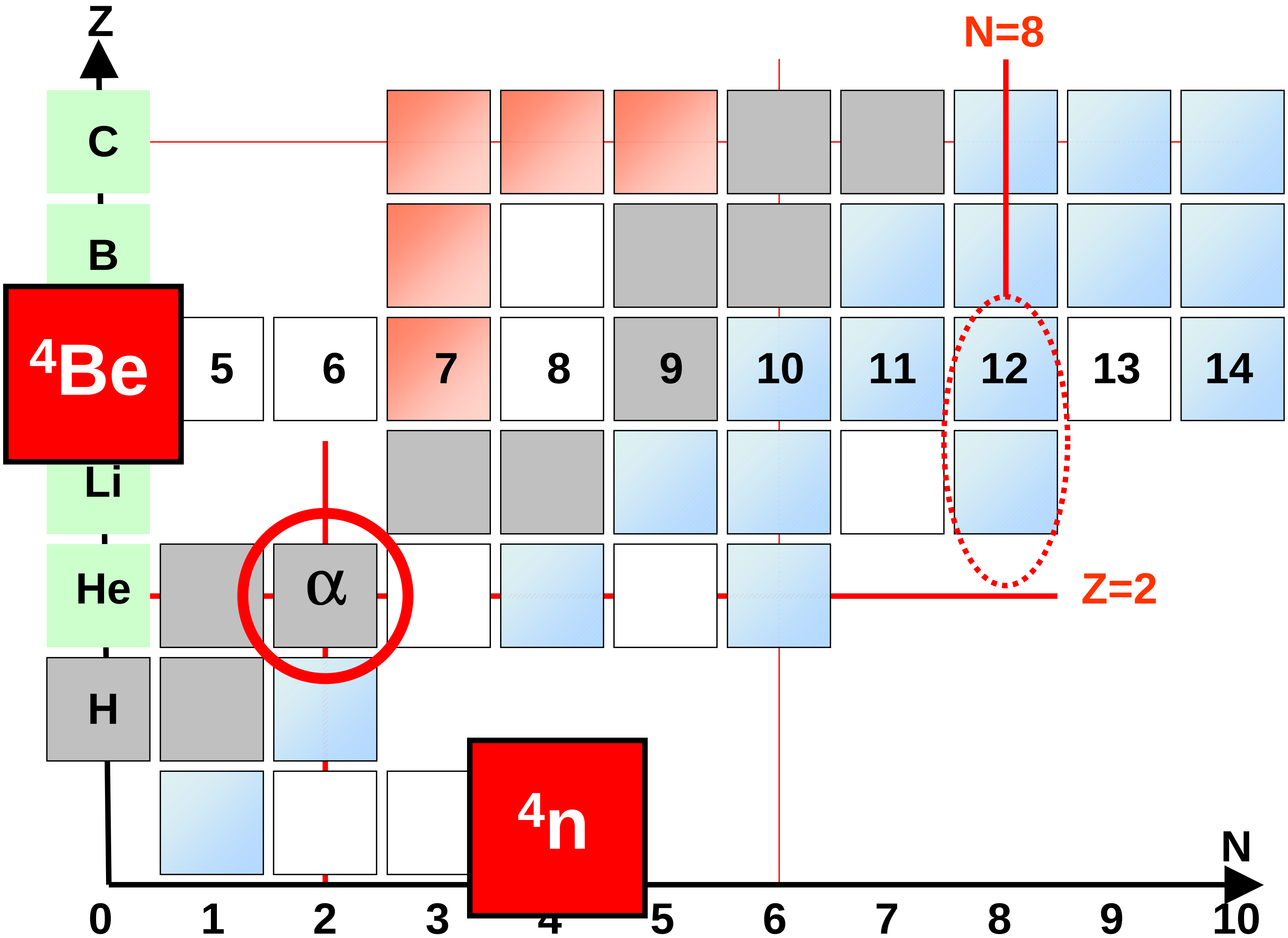


Z
N=8
C
B
Be
5
6
7
8
9
10
11
12
13
14
Li
He
α
Z=2
H
Gaps appear towards neutron drip line, and
neutrons are only bound if they are paired
N
0
1
2
3
4
5
6
7
8
9
10


Z
N=8
C
B
Be
5
6
7
8
9
10
11
12
13
14
Li
He
α
Z=2
H
Magic number (shell gap) at N=8 does not exist in the neutron rich region
N
0
1
2
3
4
5
6
7
8
9
10



Z
N=8
C
B
Be
5
6
7
8
9
10
11
12
13
14
Li
He
α
Z=2
H
N
0
1
2
3
4
5
6
7
8
9
10



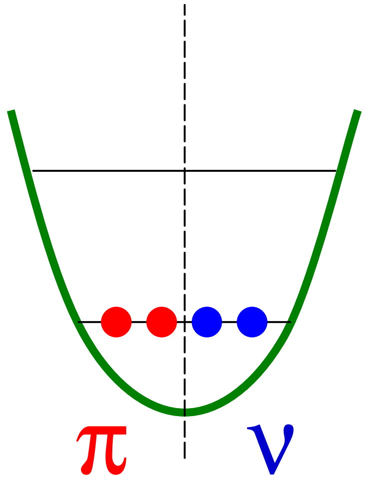
Z
N=8
C
B
4Be
5
6
7
8
9
10
11
12
13
14
Li
He
α
Z=2
H
4n
N
0
1
2
3
4
5
6
7
8
9
10

4-proton system doesn't exist…
proton repulsion and Pauli effects

^{4}Be

"Maximally symmetric" alpha-particle
has a particularly high binding energy

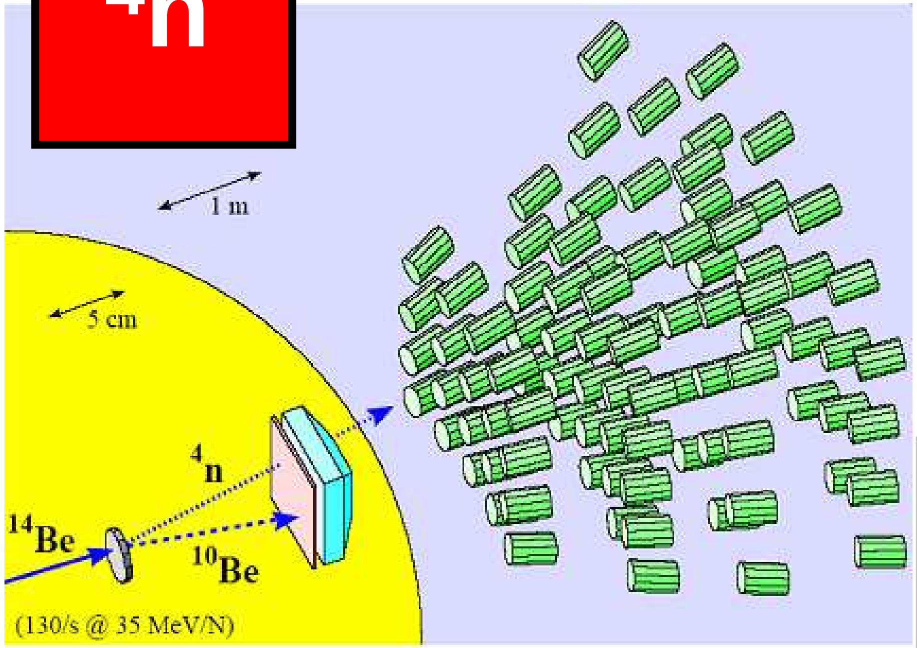
α



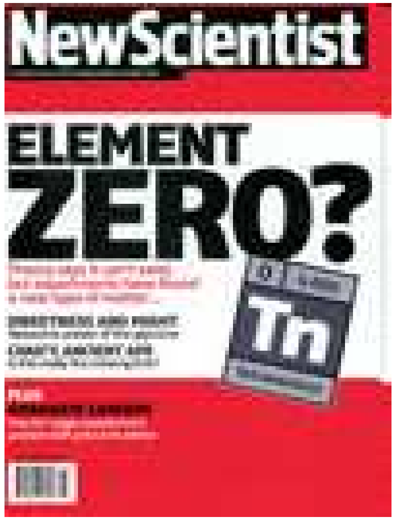
^{4}n

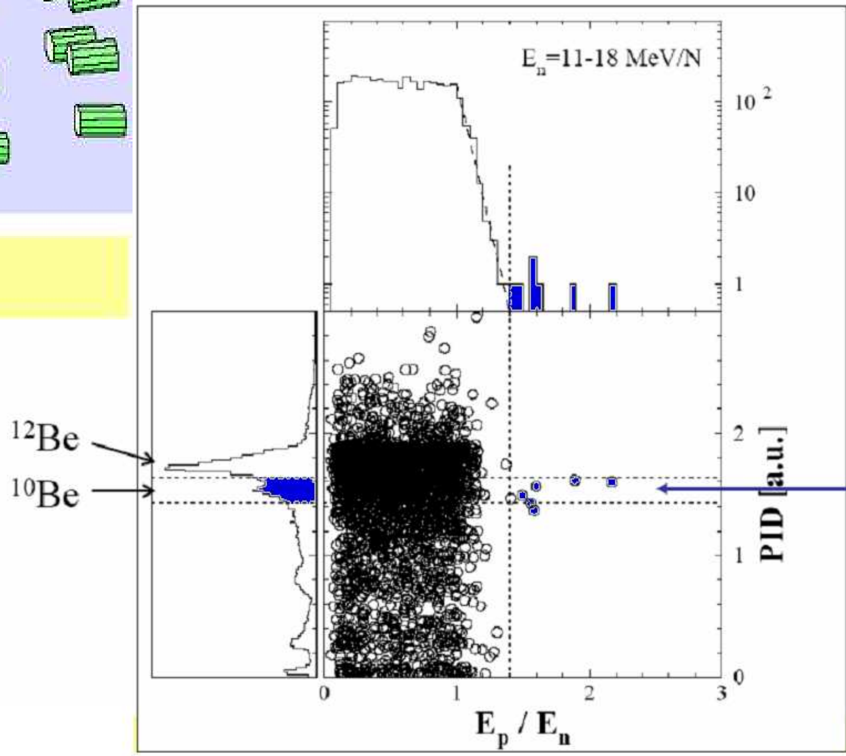
Could a 4-neutron system exist…?
no repulsion but still have Pauli effects
"Tetraneutron"

^{4}n



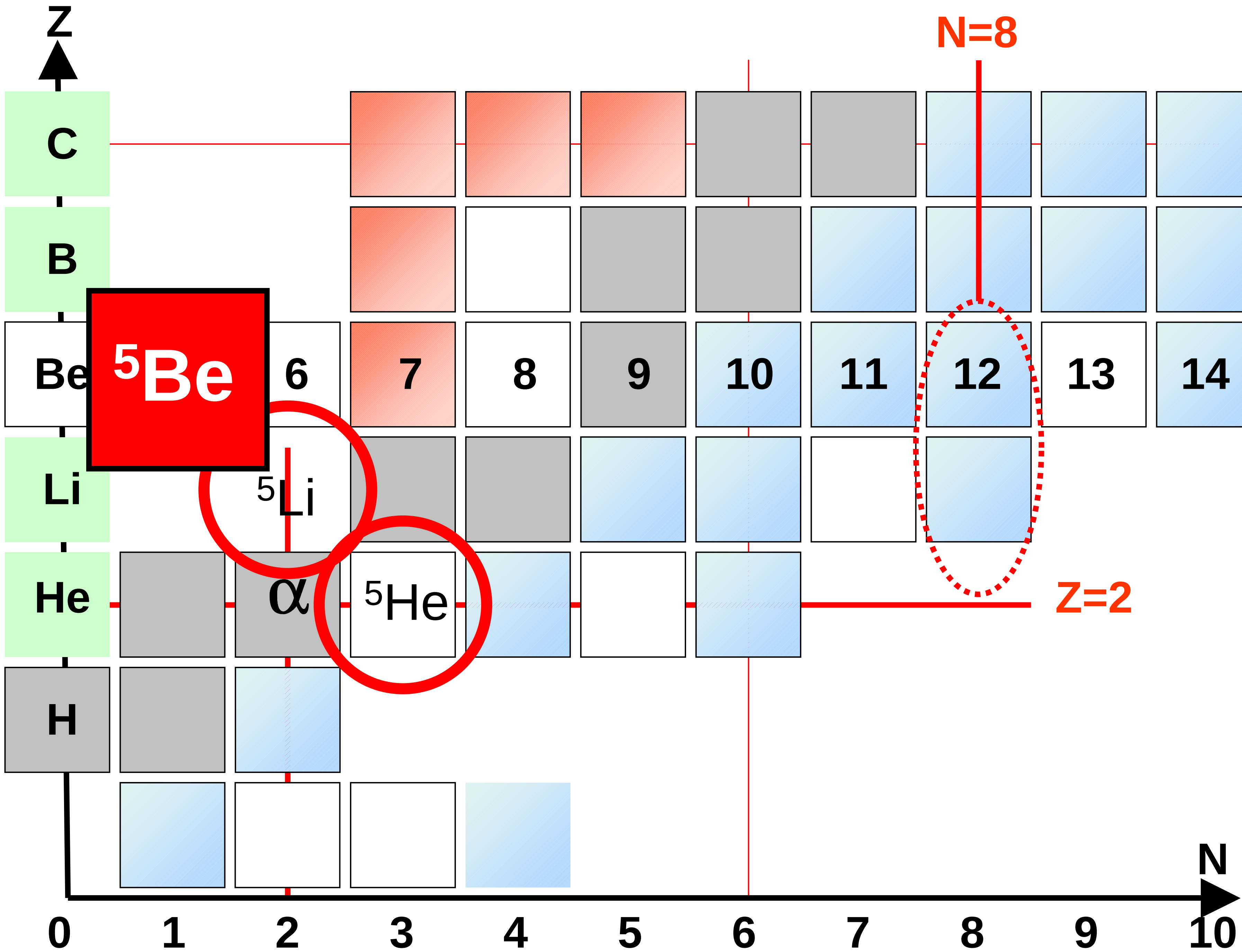
$S_{4n}(^{14}Be) = 5.2$ MeV



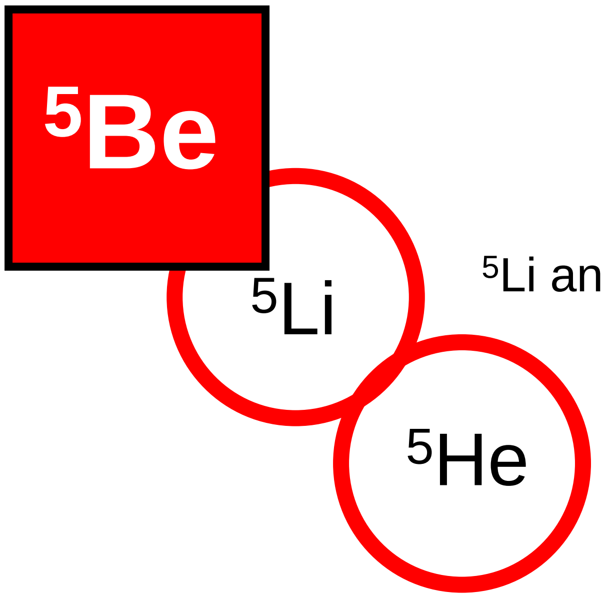


6 events
pileup < 0.8
"2σ signal"

F. M. MARQUÉS *et al.*
PHYSICAL REVIEW C, VOLUME 65, 044006


Z
N=8
C
B
Be
⁵Be
6
7
8
9
10
11
12
13
14
Li
⁵Li
He
α
⁵He
Z=2
H
N
0
1
2
3
4
5
6
7
8
9
10

There is no stable mass A=5 system



^{5}Li and ^{5}He exist as low-lying p-wave resonances

The resonances have asymmetric shapes due to the changing barrier penetrability as a function of the relative energy (alpha-nucleon)

AND

The **lineshape**
depends on the **production method**,
e.g. stripping from ^{6}Li or pickup onto ^{4}He

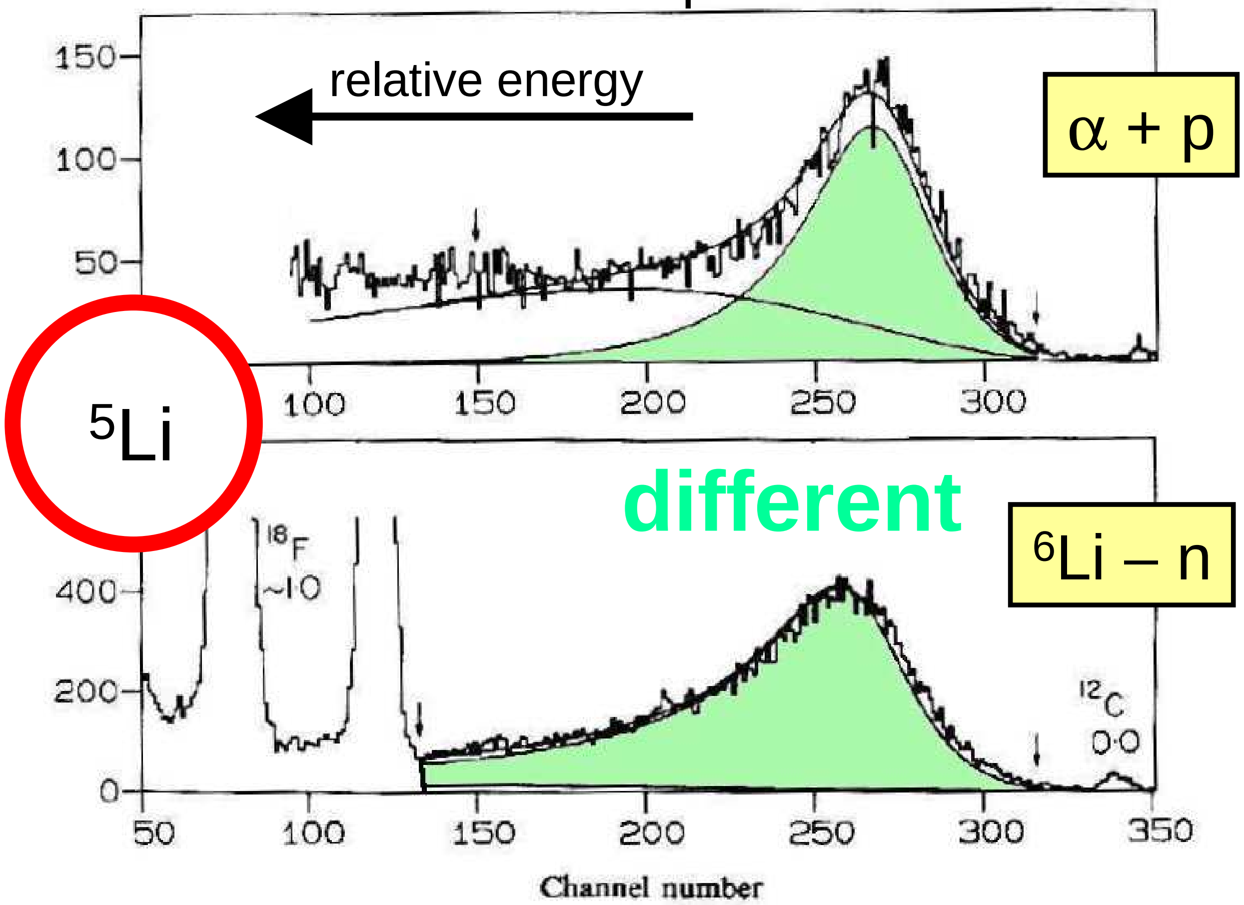
C. L. Woods, F. C. Barker,[A] W. N. Catford, L. K. Fifield and N. A. Orr

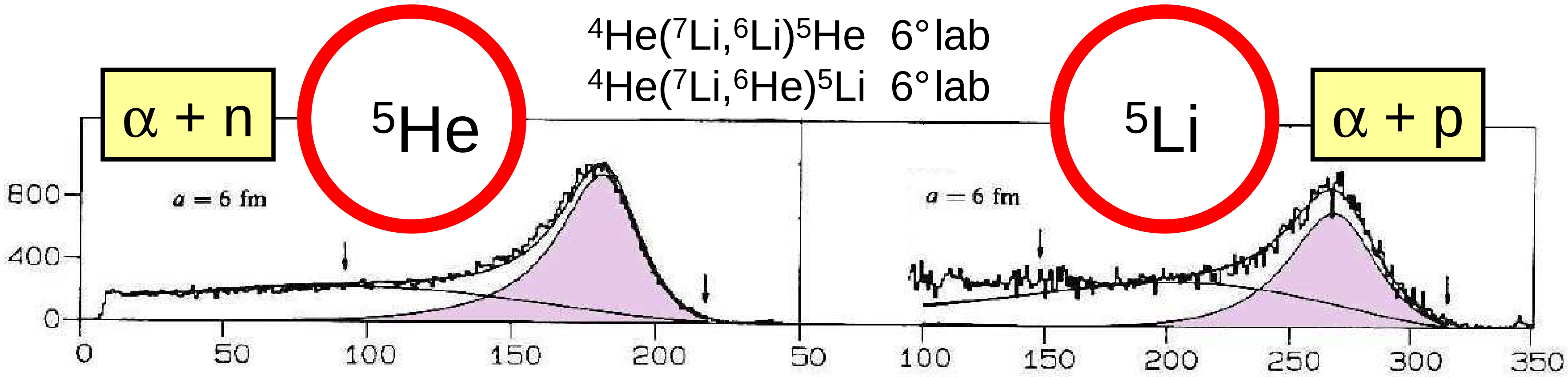
Aust. J. Phys., 1988, 41, 525–44

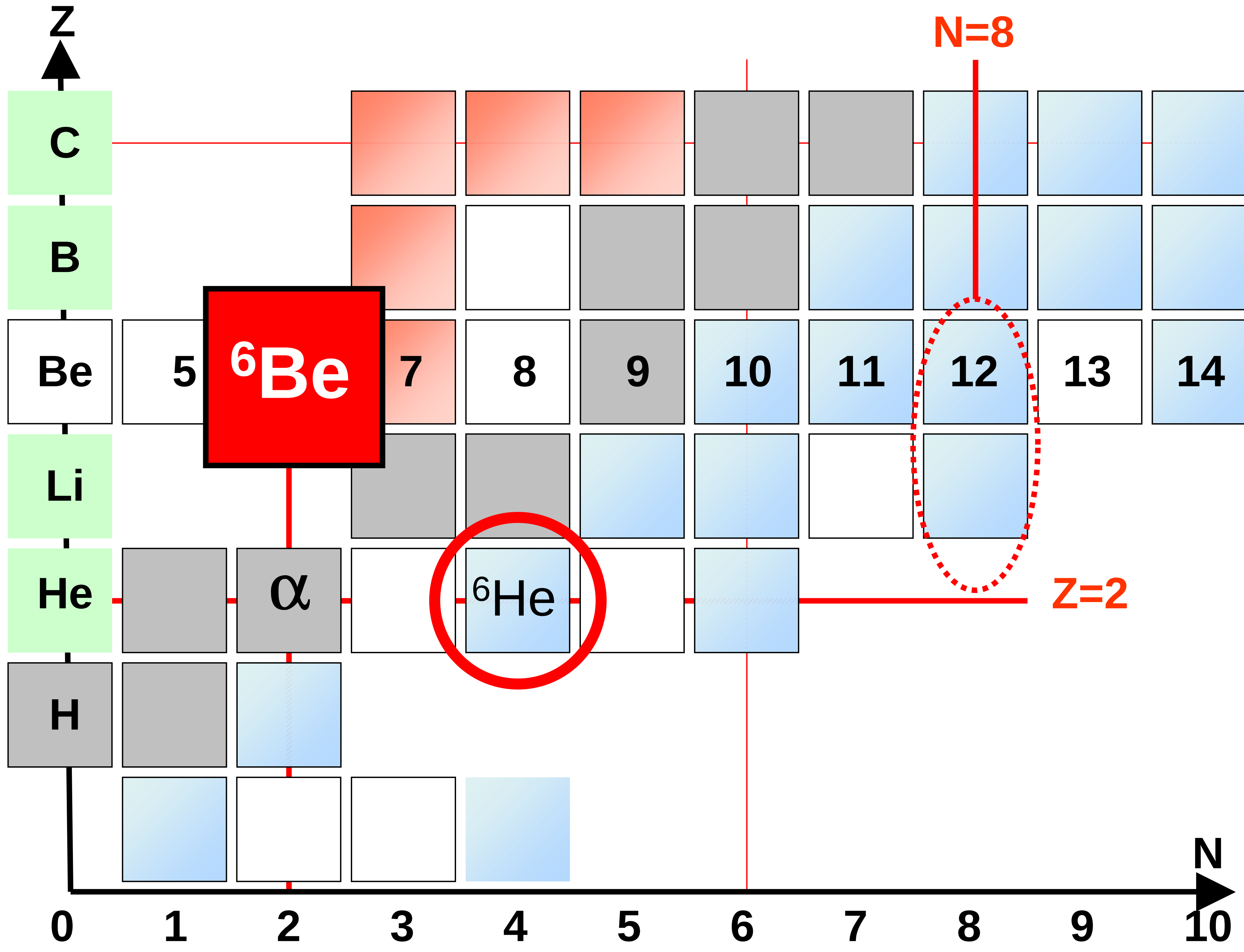
50 MeV ^{7}Li beam
$^{4}He(^{7}Li,^{6}He)^{5}Li$ 6° lab

Enge split pole spectro
$\Delta\Omega$ = 0.1°H x 2.5°V
Fit = 3/2– and 1/2– plus
high lying 3/2– and 1/2–

50 MeV ^{7}Li beam
$^{6}Li(^{13}C,^{14}C)^{5}Li$ 5.2° lab







Z
N=8
C
B
Be
5
^{6}Be
7
8
9
10
11
12
13
14
Li
He
α
^{6}He
Z=2
H
N
0
1
2
3
4
5
6
7
8
9
10

This is unbound, but observable as a low-lying resonance, and is the $T_z = -1$ analog of $T_z = 1$ weakly bound nucleus ^{6}He

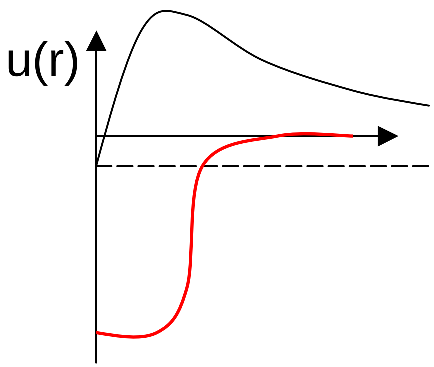
^{6}Be

Unbound by 1.372 MeV to α + p + p,
Width of 0^+ ground state resonance = 92 keV,
$(h/2\pi)$/width = $(6.578\times10^{-22}$ MeV.s)/0.092 ~ 10^{-20} s

^{6}He

Weakly bound, S_n = 1.867 MeV
(S_p = 26.52 MeV)
(β-decays, half-life = 806.7 ms)

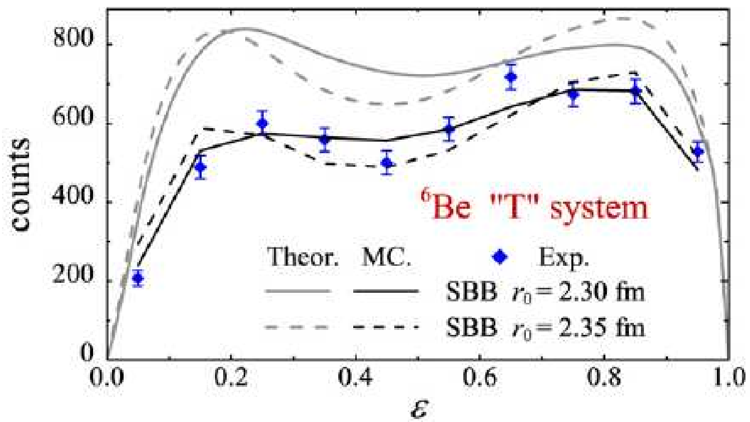
Neutron skin, or halo



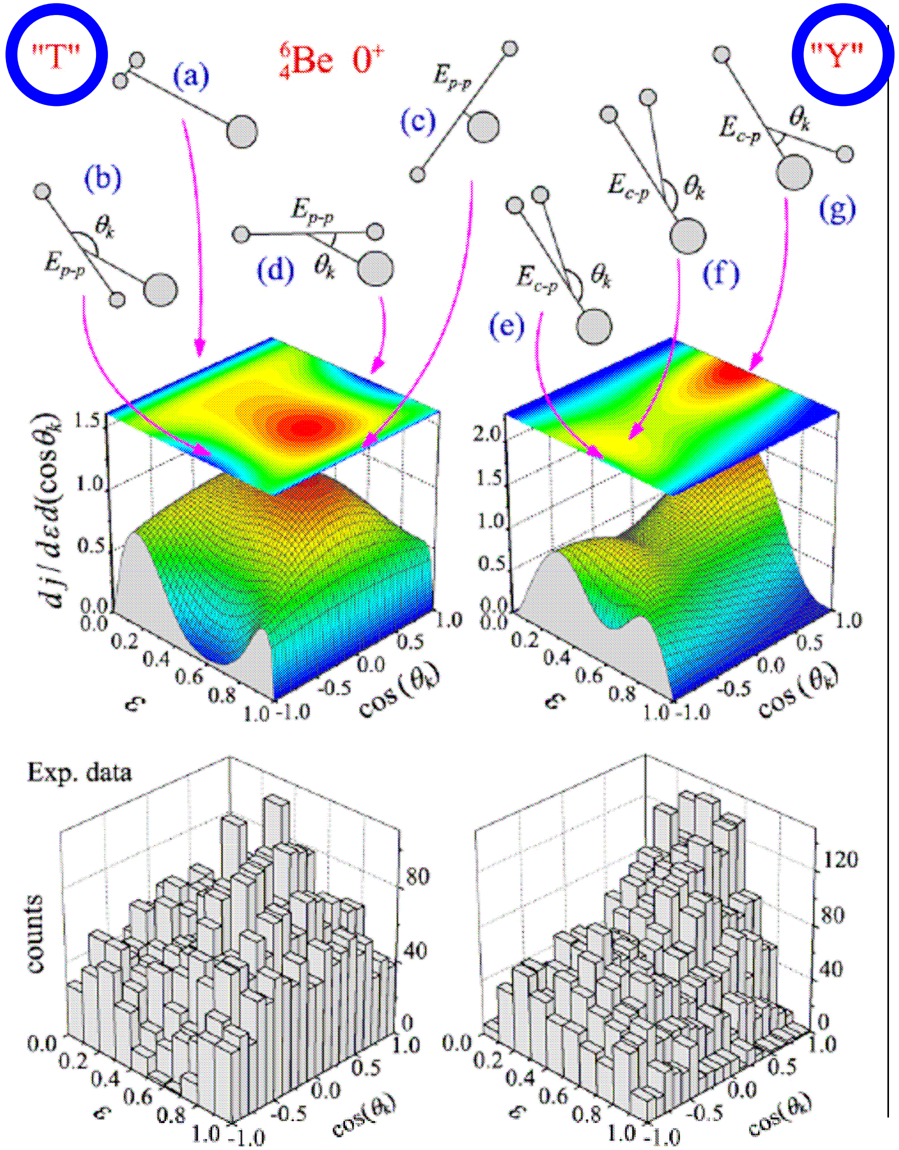
L.V. Grigorenko et al. / Physics Letters B 677 (2009) 30–35

Structure of unbound system
revealed by decay kinematics

^{6}Be



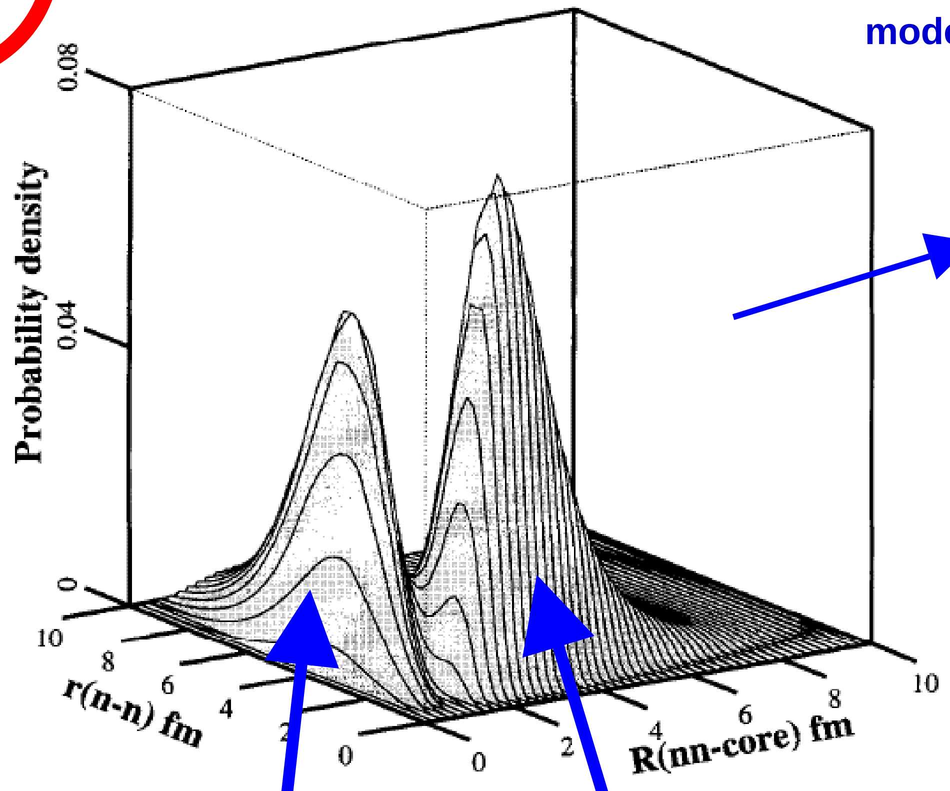
Double-hump from (0p)^2 structure,
Sensitivity to model parameters.



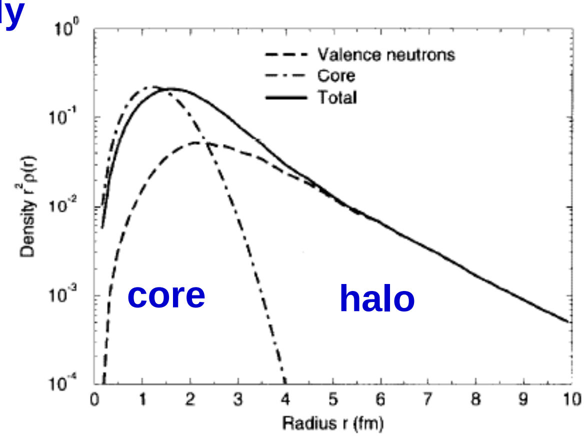
^{6}He

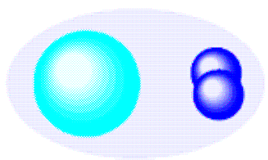
J.M. Bang | B.V. Danilin, V.D. Efros, J.S. Vaagen, M.V. Zhukov, I.J. Thompson

Physics Reports 264 (1996) 27–37

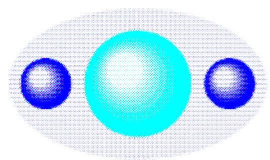


full three=body model

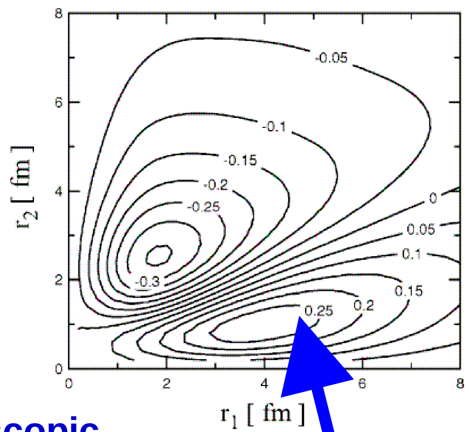




"cigar" configuration



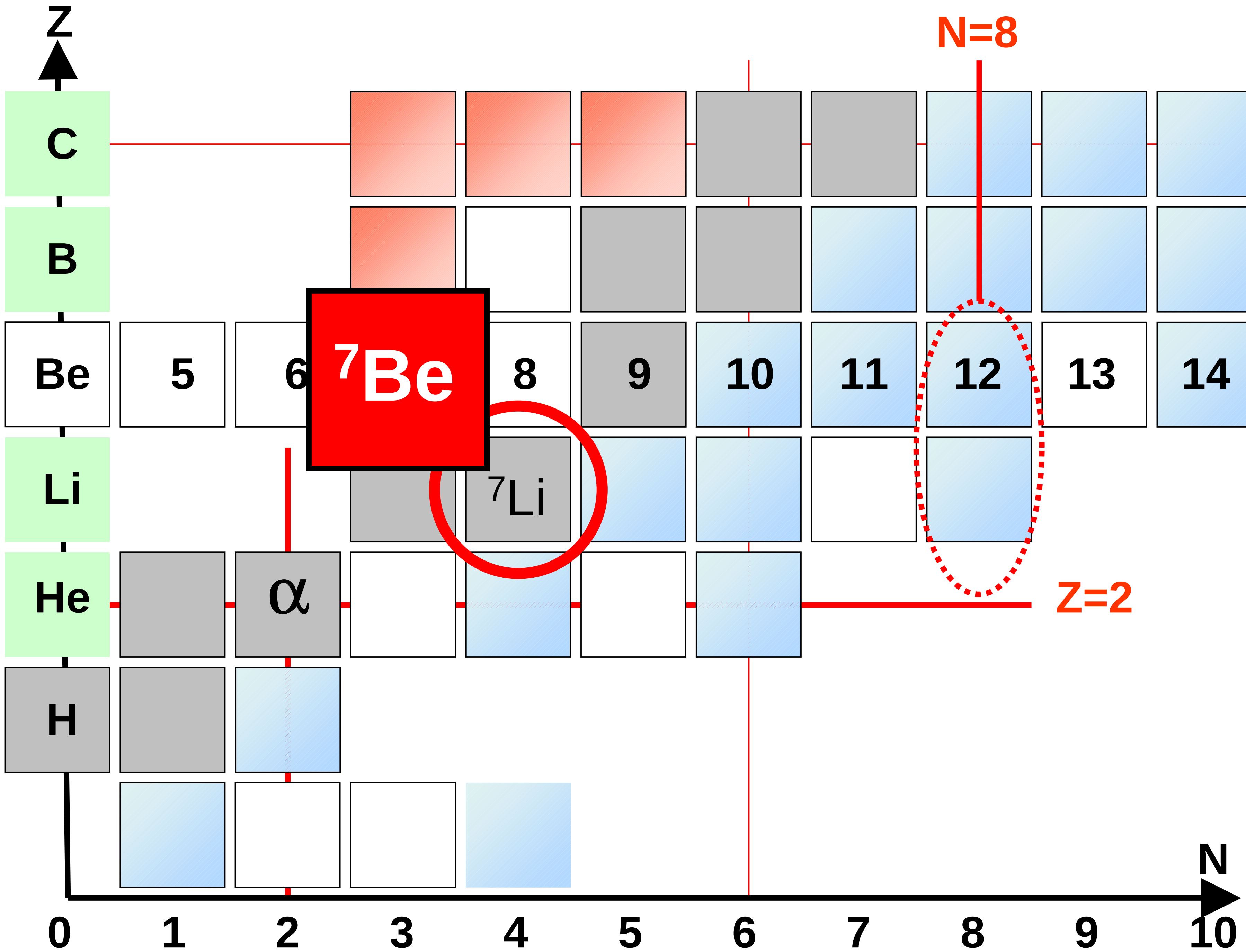
"dineutron"



microscopic cluster model

"dineutron"

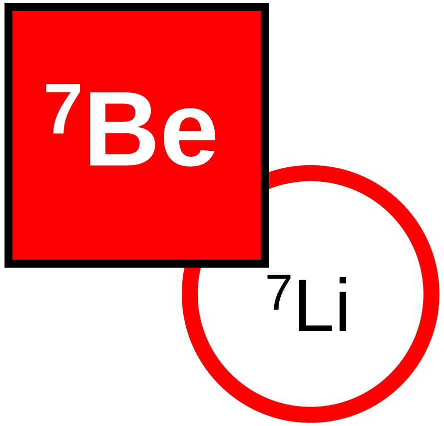
PHYSICAL REVIEW C 69, 014309 (2004) | Koji Arai



Z
N=8
C
B
Be
5
6
^{7}Be
8
9
10
11
12
13
14
Li
^{7}Li
He
α
Z=2
H
N
0
1
2
3
4
5
6
7
8
9
10

These A=7 nuclei are well described as orbiting clusters of α + ^{3}He/^{3}H

A "few-body model" (here, two-body) works very well, using **free-space properties** of the two clusters, after including Pauli approximately with nodal requirements.
(Fully antisymmetrized models also exist, of course, e.g. RGM, Brink model)
(Most cluster models do include full antisymmetrization.)

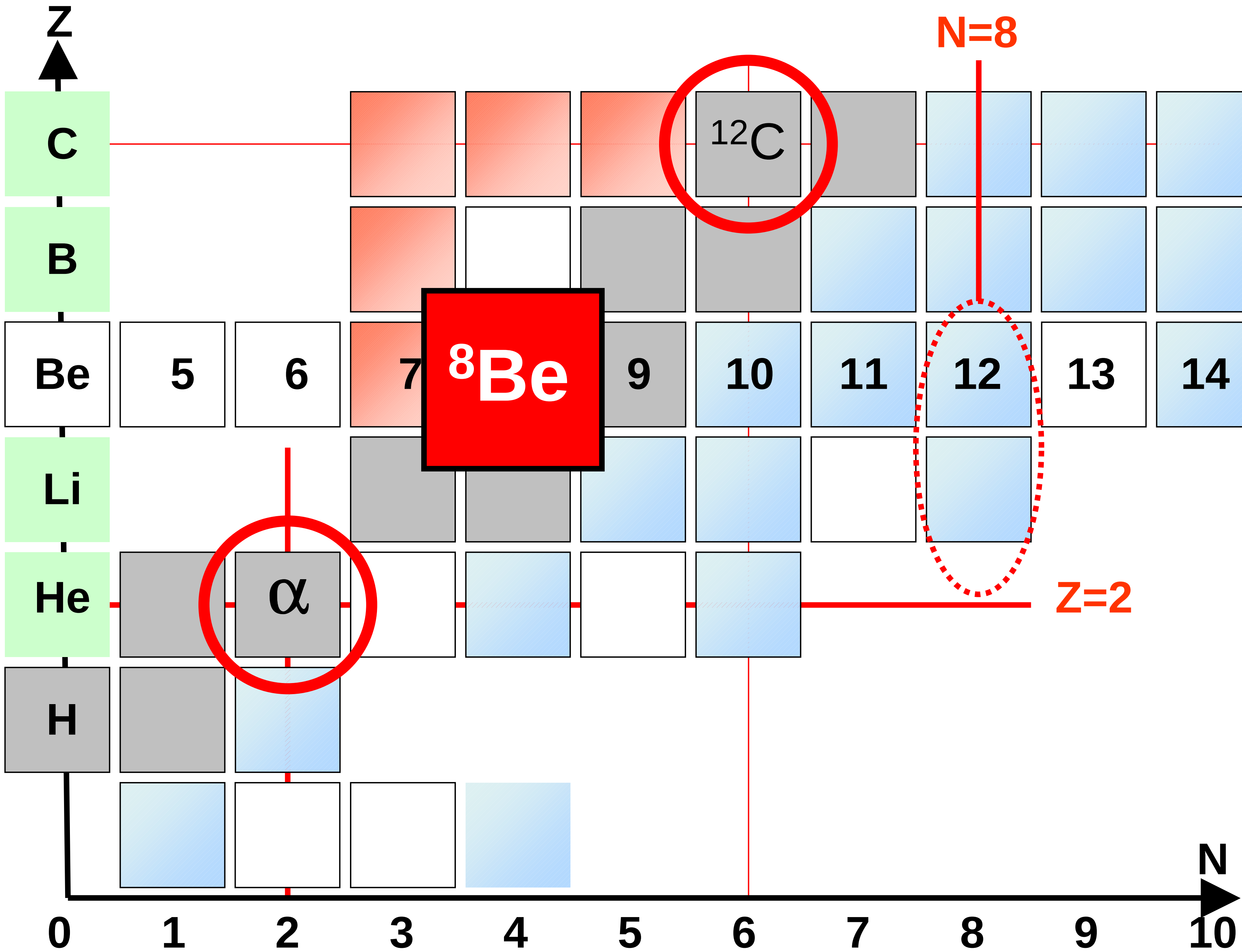


B Buck† and A C Merchant

J. Phys. G: Nucl. Phys. **14** (1988) L211–L216

The essence of this model is to describe ^{7}Li and ^{7}Be as α—^{3}H and α—^{3}He systems respectively, with the clusters having essentially unperturbed free space properties. The cluster core interaction is taken to have a Gaussian form, and its parameters are determined unambiguously from the experimentally measured properties of ^{7}Li and ^{7}Be. The relation of this elementary cluster model to the microscopic RGM has recently been investigated by Walliser and Fliessbach (1985), who conclude that as a model of ^{7}Li it is valid and useful, with a similar degree of justification to that of the nucleon picture of the deuteron.

Quantity	Experimental values	This calculation
$\langle r_c^2\rangle^{1/2}$	2.41 ± 0.10^c	2.43 ± 0.02
(fm)		
Q	-4.06 ± 0.03^d	-3.83 ± 0.13
(e fm^2)	-3.70 ± 0.08^e	
	-4.0 ± 1.1^f	
B(E2; ↑)	8.9 ± 0.6^d	7.75 ± 0.50
(e^2 fm^4)	8.3 ± 0.5^e	
	7.42 ± 0.14^f	
	6.7 ± 0.2^g	
	7.4 ± 0.1^h	
	8.3 ± 0.6^i	
$\langle r_m^2\rangle^{1/2}$	2.98 ± 0.05^g	2.78 ± 0.03
(fm)	2.70 ± 0.15^j	
Ω/μ_7	$\pm 2.9 \pm 0.1^g$	-2.48 ± 0.08
(fm)^2	$\pm 2.8 \pm 0.5^j$	
S_0	0.47 ± 0.02^k	0.51 ± 0.03
^{3}He(α, γ)^{7}Be	0.53 ± 0.03^l	
(keV b)	0.63 ± 0.04^m	
	0.51 ± 0.05^n	
	0.47 ± 0.05^o	
$dS/dE\|_0$ (mb)	-0.28 ± 0.04^n	-0.27 ± 0.04
S_0	0.100 ± 0.025^p	0.089 ± 0.030
^{3}H(α, γ)^{7}Li	0.134 ± 0.020^q	
(keV b)		
$dS/dE\|_0$ (mb)		-0.18 ± 0.04


Z
N=8
C
^{12}C
B
Be
5
6
7
^{8}Be
9
10
11
12
13
14
Li
He
α
Z=2
H
N
0
1
2
3
4
5
6
7
8
9
10

BE=
7.68 MeV/A

^{12}C

Three-α cluster state
Is not the ground state
E_x = 7654 keV
E_{rel} = 287.55 keV $\alpha + {}^{8}Be$
Width = 8.5 eV (some γ !)
(h/2p)/width ~ 0.1 fs
BE/A = **7.04** MeV

^{8}**Be**

Although it consists of two α-particles,
8Be itself is not bound

E_{rel} = 92 keV to $\alpha + \alpha$
Width = 5.57 eV, (h/2π)/width ~ 0.1 fs
BE/A = **7.06** MeV/A

BE=
7.07 MeV/A

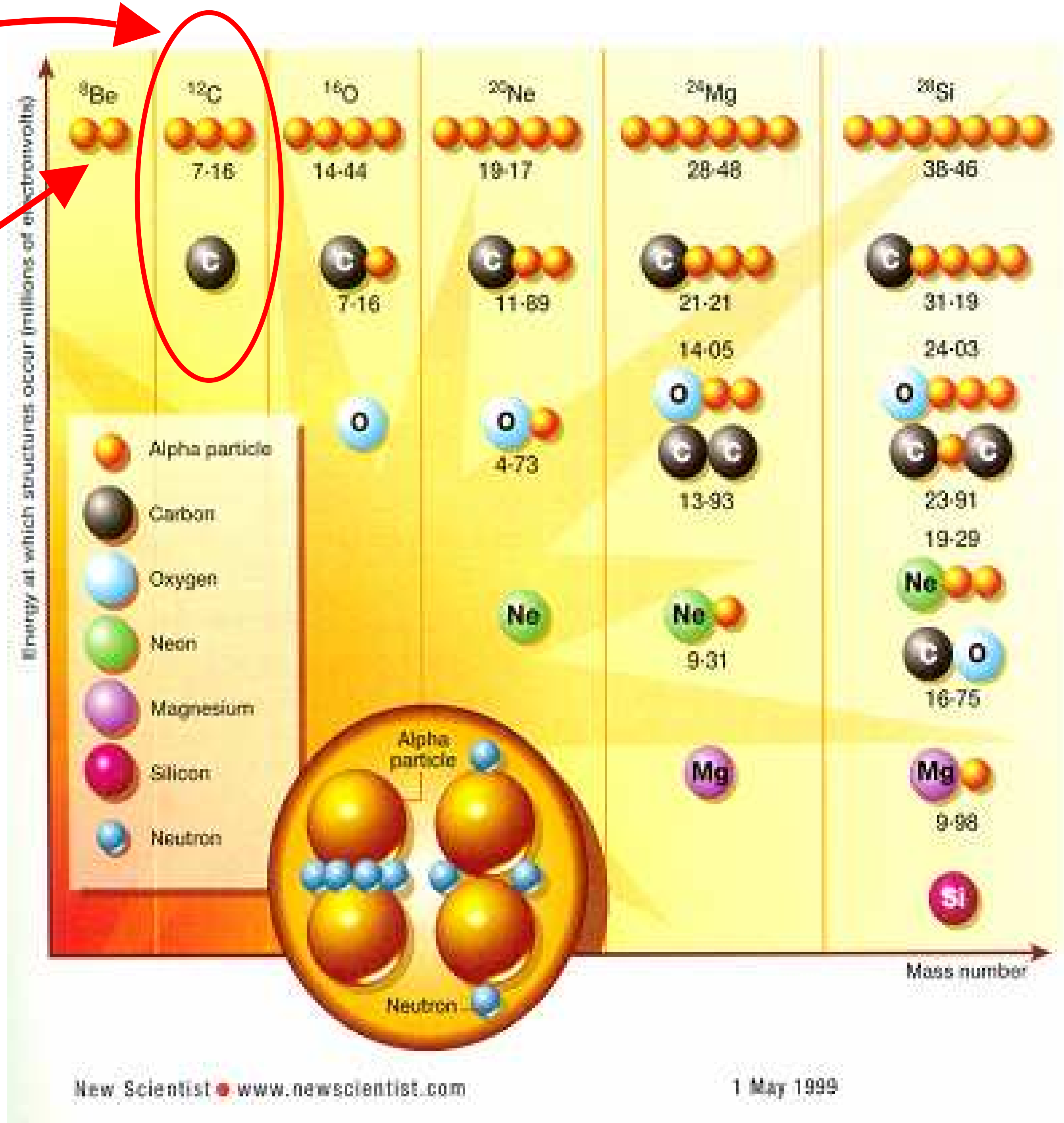
α

In summary, close to threshold we tend to see states with cluster structure…

(see Ikeda diagram…)

^{12}C

^{8}Be

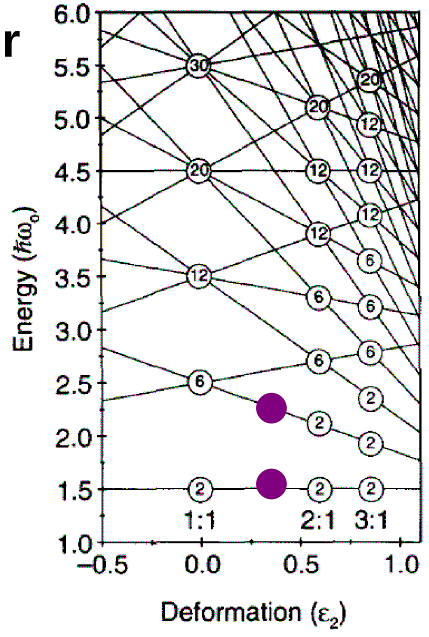


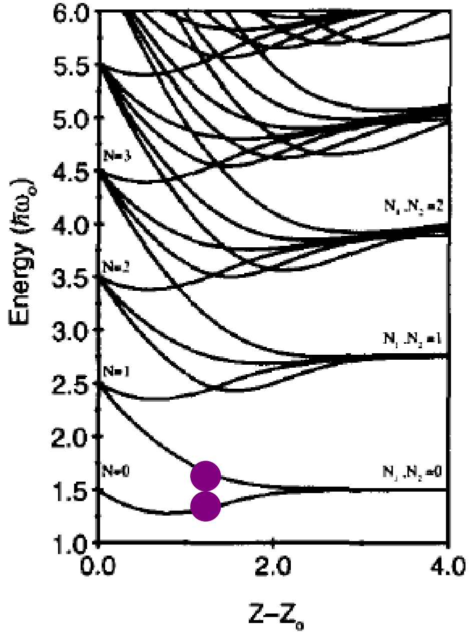
Ikeda Diagram

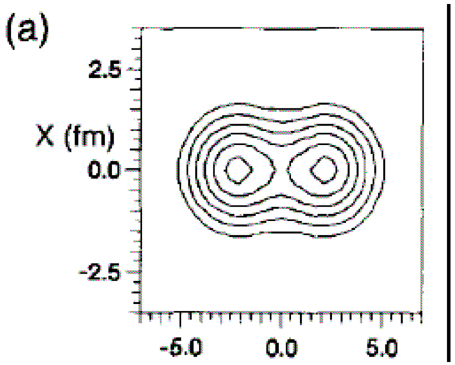
K. Ikeda et al.,
Prog. Th. Phys.
(Japan) Suppl.
Extra Number
(1968) p.464

In either the **deformed Harmonic Oscillator** or the **two centre Harmonic Oscillator**, The energy of the second 4 nucleons drops with deformation
This pushes towards deformation until surface tension limits the deformation

^{8}Be



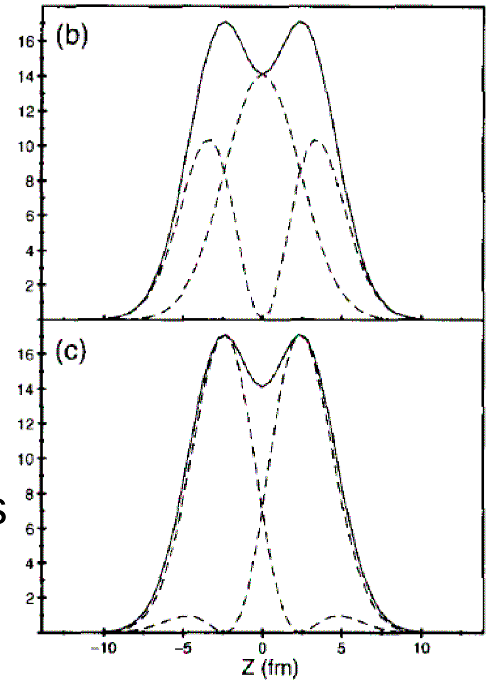




The projection of the matter density
In a DHO or TCHO shows "clusters"

The sum of the 2 Ψ quartet densities (one even, one odd parity) shows a dip indicating clustering.

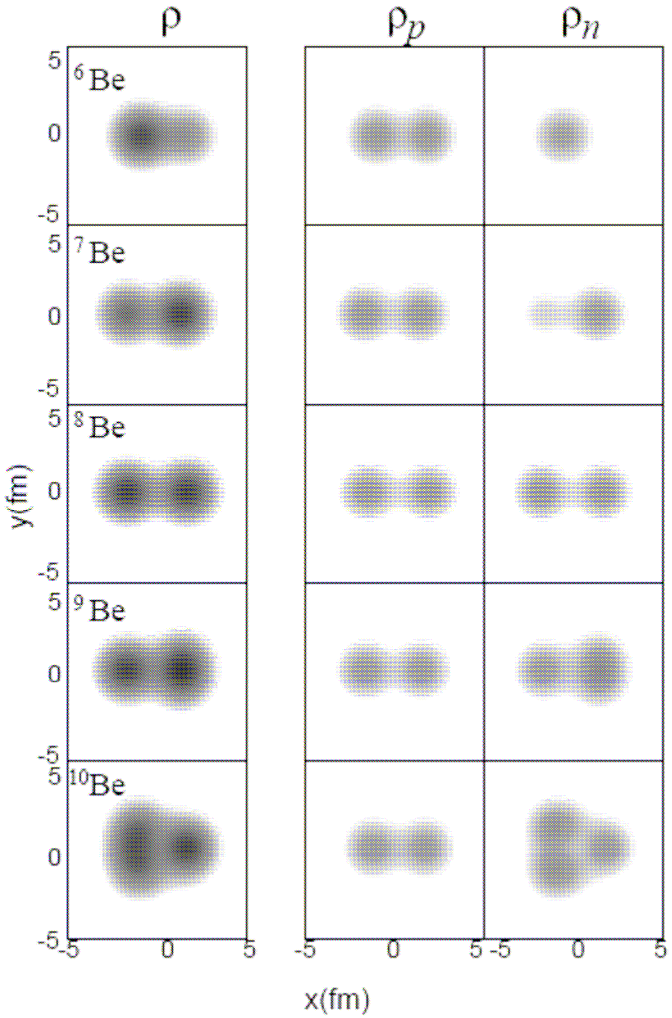
An alternative linear combination of wave functions Φ highlights the clustering

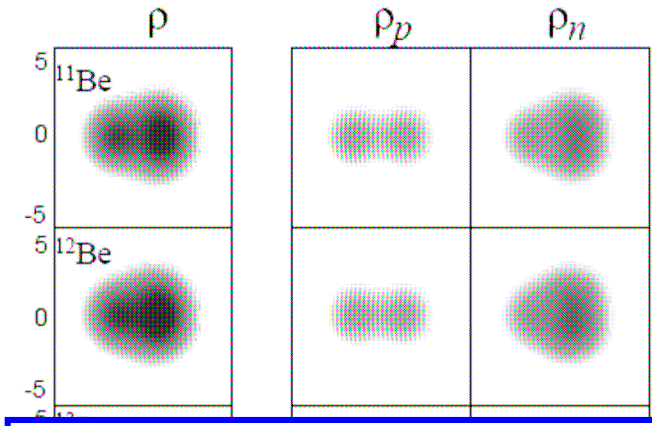


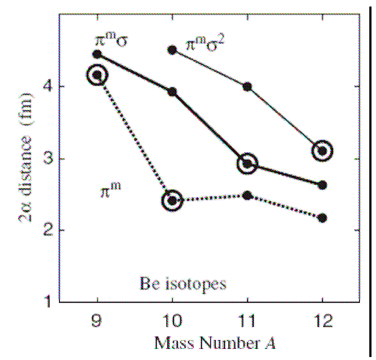
M. Freer[1], R.R. Betts, A.H. Wuosmaa
Nuclear Physics A 587 (1995) 36–54

Clustering **emerges** naturally in **Antisymmetrised Molecular Dynamics**
In which there are independent nucleons with **no assumed clustering**,
Here we see the predicted matter density for all beryllium isotopes
shown from ^{6}Be to ^{14}Be
On the left, **total** intrinsic matter density, then **proton** density, then **neutron** density

^{8}Be







Inter-alpha distance vs. mass, A

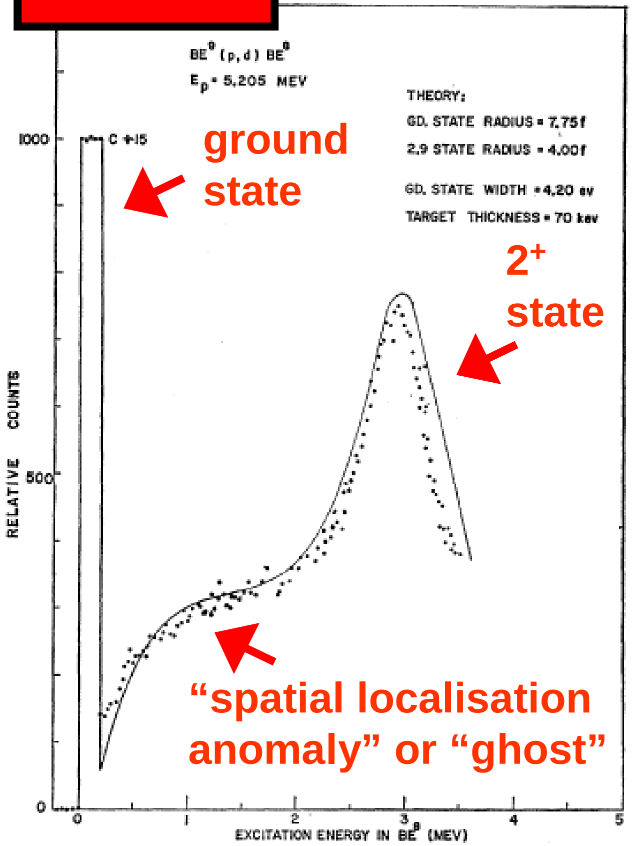
circled = gs

Y. Kanada-En'yo, M. Kimura, H. Horiuchi, C. R. Physique 4 (2003) 497

W. von Oertzen et al. / Physics Reports 432 (2006) 43–113

Ghosts

^{8}Be



"Excitation energy" spectrum of ^{8}Be deduced from energies of deuterons from

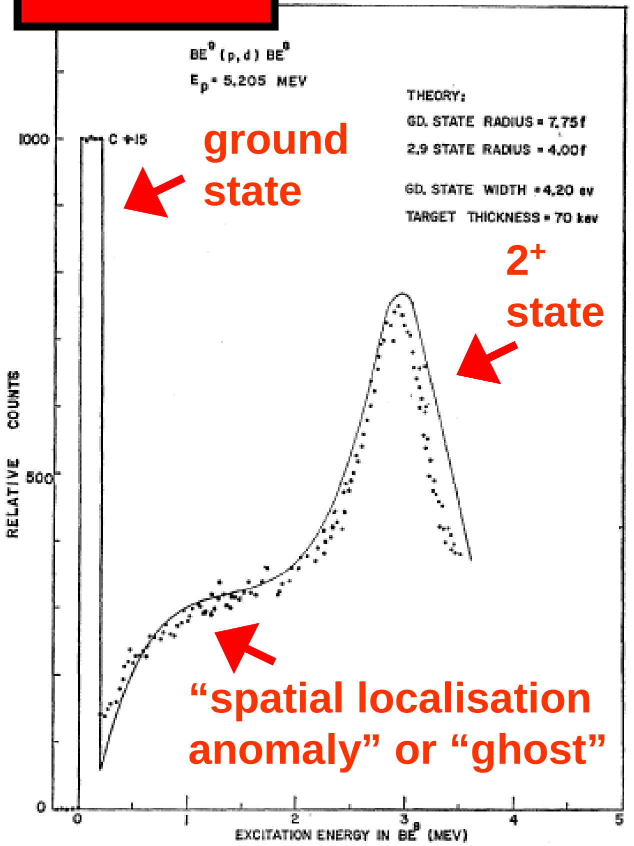
$$^{9}\mathrm{Be}(p,d)^{8}\mathrm{Be}$$

"Spatial localisation anomaly" in ^{9}Be(p,d)^{8}Be(α)α
E.H. Beckner et al, Phys. Rev. 123 (1961) 255

F. C. BARKER AND P. B. TREACY
Nuclear Physics **38** (1962) 33—49

Ghosts

^{8}Be



$$\rho_l^{(1)}(E) = \text{const.}\,\frac{\frac{1}{2}\Gamma_l}{(E_l+\Delta_l-E)^2+(\frac{1}{2}\Gamma_l)^2},$$

$$\Gamma_l = 2P_l\gamma_l^2, \qquad P_l = \rho A_l^{-2},$$

$$\Delta_l = -S_l^0\gamma_l^2, \qquad S_l^0 = \rho A_l^{-1}(\partial A_l/\partial\rho)-B_l,$$

$$A_l^2 = F_l^2+G_l^2.$$

Eq. (4) , E > 0

5. "Ghosts"

As was pointed out by Beckner *et al.* [3]) the plateau at an excitation energy of about 1 MeV in the cross section for the reaction Be^9(p, d) $Be^8(\alpha)$ He^4 is due to transitions through the Be^8 ground state. The ground state contribution, shown in fig. 1, has two peaks, the one corresponding to a Be^8 excitation $E \approx E_r = 0.094$ MeV and the other to $E \approx 1$ MeV. Such a behaviour is expected for all reactions of this type in which Be^8 occurs as the intermediate nucleus. However, usually the upper peak will be masked by the tail of the contribution from the 2.9 MeV state of Be^8 (as for example in the B^{11}(p, α) $Be^8(\alpha)$ He^4 reaction [3])). In general for reactions of the type (1) similar anomalous peaks, or "ghosts", might be expected in the spectra of excitation energies of nuclei B for which a level, well separated from other levels of the same spin and parity, exists close to a threshold, so that in an energy region above threshold the numerator in eq. (4) is increasing more rapidly than the denominator. For the same reason, similar ghosts might appear in the cross section for a normal resonance reaction

$$A+a \rightarrow B \rightarrow C+c$$

provided B has an isolated level near enough to either the (A+a) or the (C+c) threshold.

"Spatial localisation anomaly" in ^{9}Be(p,d)^{8}Be(α)α
E.H. Beckner et al, Phys. Rev. 123 (1961) 255

F. C. BARKER AND P. B. TREACY
Nuclear Physics **38** (1962) 33—49

^{12}C

Ghosts

7.654 MeV 0^{+} 3α state

Ghost of 7.654 MeV in ^{12}B β-decay

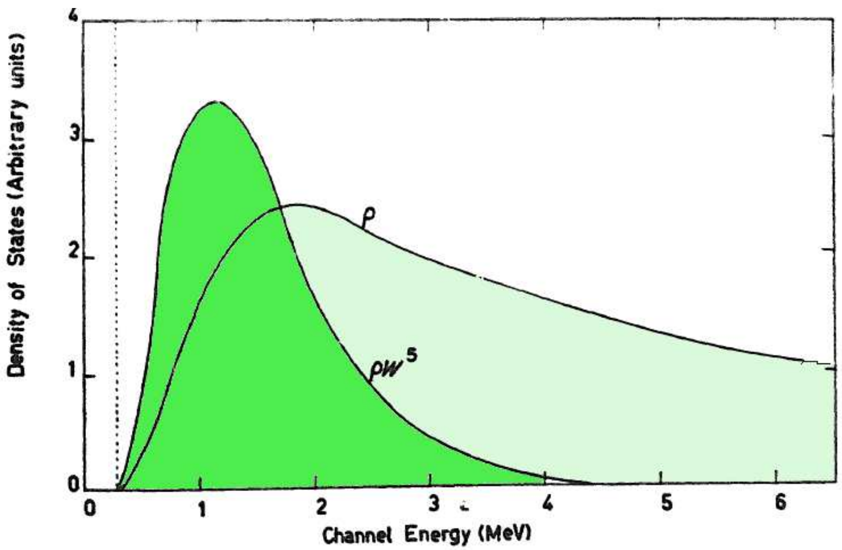


Fig. 3. Density-of-states function $\rho_0^{(1)}(E)$ associated with the break-up of the 7.66 MeV state of C^{1} into $Be^8+\alpha$, as a function of channel energy E. The dotted portion of the curve corresponds to th 7.66 MeV peak with a width of 8 eV and a height of 4×10^6. The curve labelled ρW^5 gives the yield o C^{12} from the β-decay of B^{12}, W being the available β-energy.

Ghost seen as resonance in p + ^{11}B

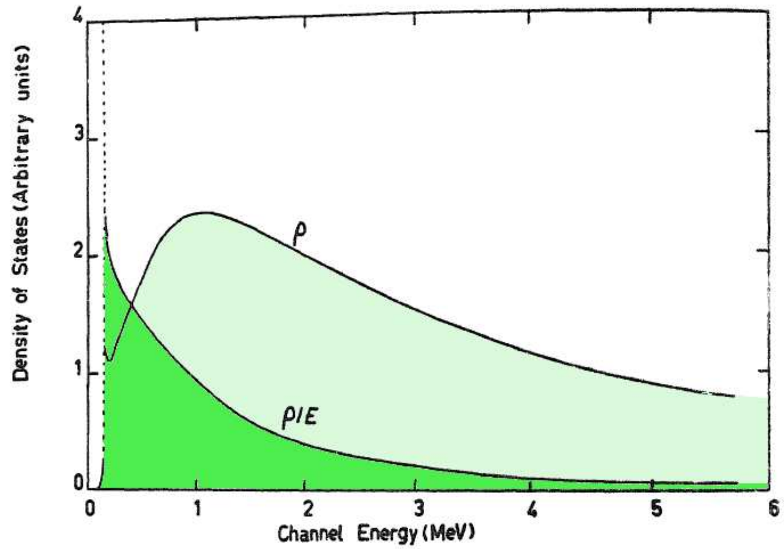
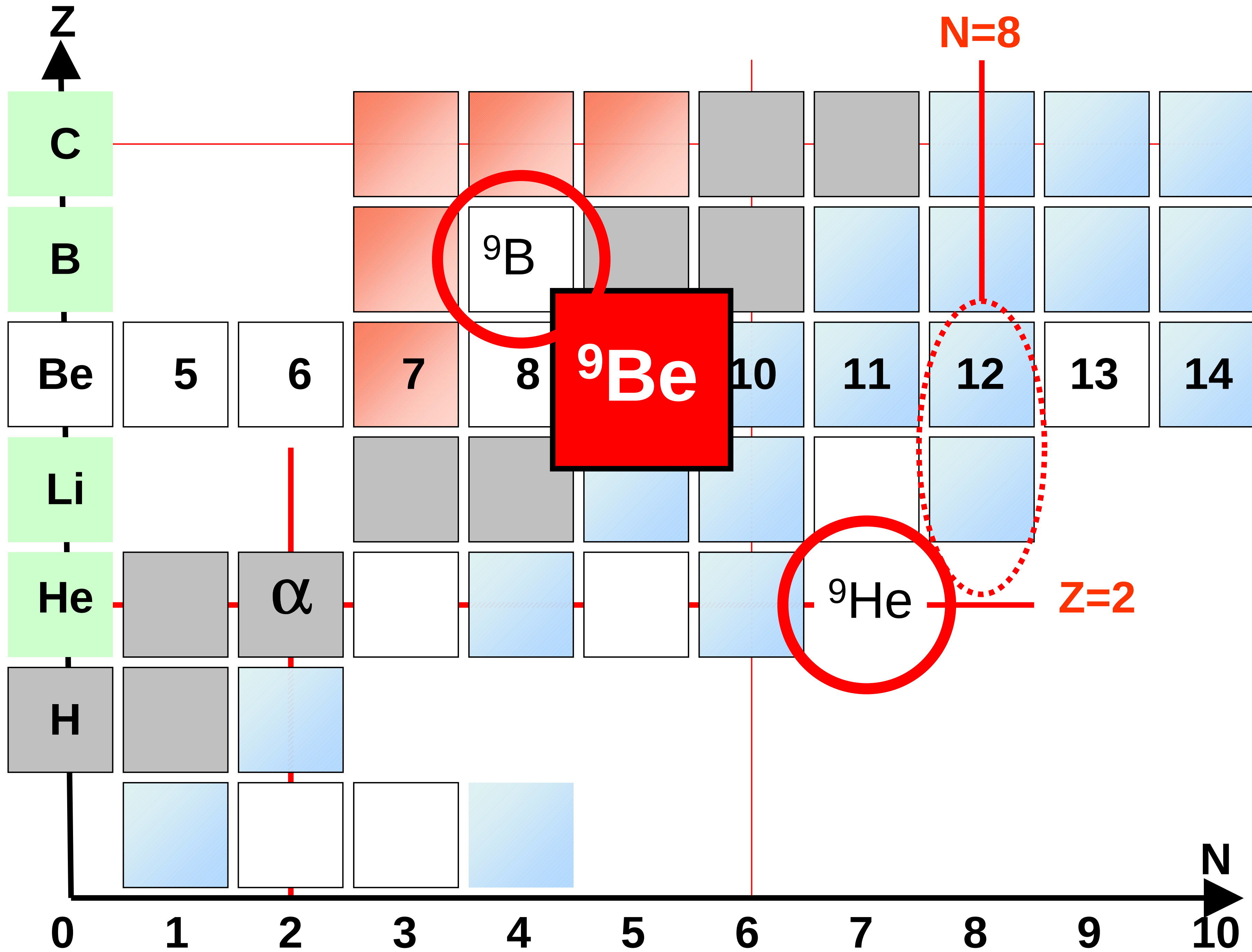


Fig. 4. Density-of-states function $\rho_1^{(1)}(E)$ associated with the break-up of the 16.11 MeV state of C^{12} into $B^{11}-p$, as a function of channel energy E. The dotted portion of the curve corresponds to the 16.11 MeV peak with a width of 5 keV and a height of 100. The curve labelled ρ/E gives the cross section for the reaction $B^{11}(p,\alpha)Be^8$ due to this state.

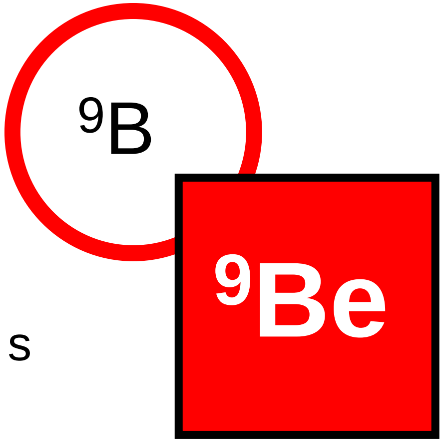
F. C. BARKER AND P. B. TREACY
Nuclear Physics **38** (1962) 33—49



Z
N=8
C
B
^{9}B
Be
5
6
7
8
^{9}Be
10
11
12
13
14
Li
He
α
^{9}He
Z=2
H
N
0
1
2
3
4
5
6
7
8
9
10

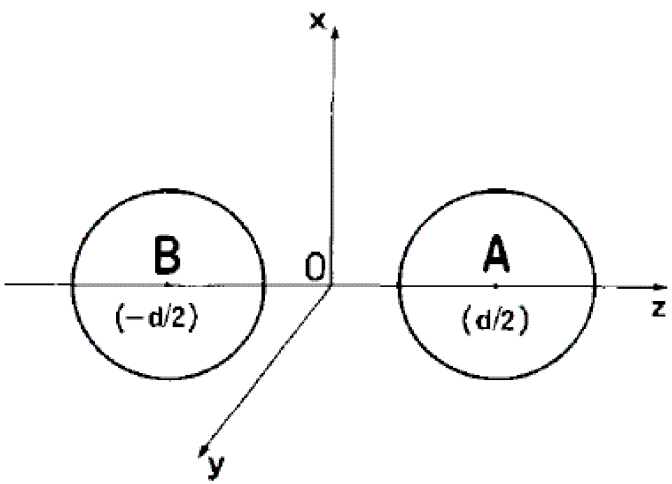
^{9}B has no bound states
and a key question is
the energy of the 1/2+
state that is predicted
but for which there is a
lot of poor quality data.

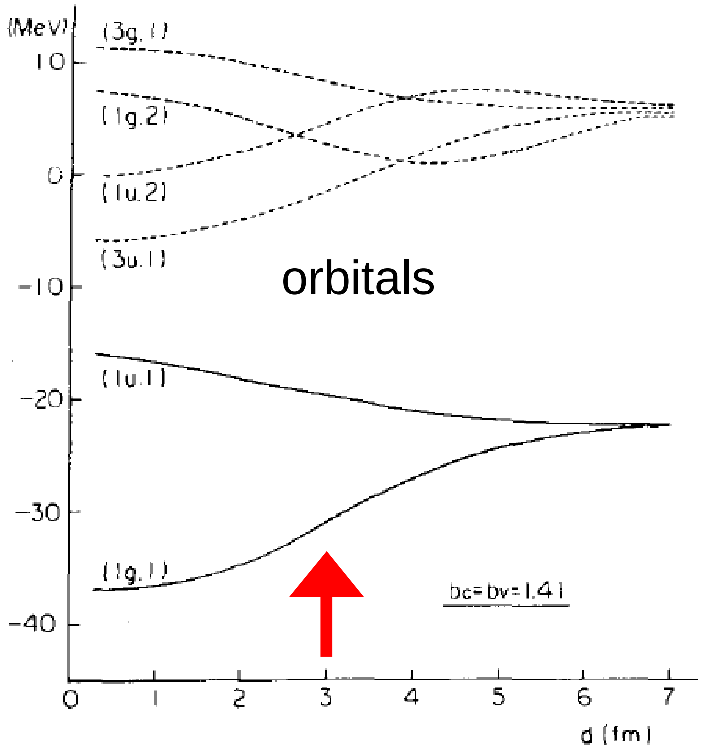
^{9}B to ^{8}Be + p 185 keV
^{9}B to $\alpha + \alpha$ + p 278 keV
Width = 0.54 keV, ~ 10^{-18} s



^{9}Be has a remarkable
“nuclear molecule” structure
based on two α-particles
and a valence neutron

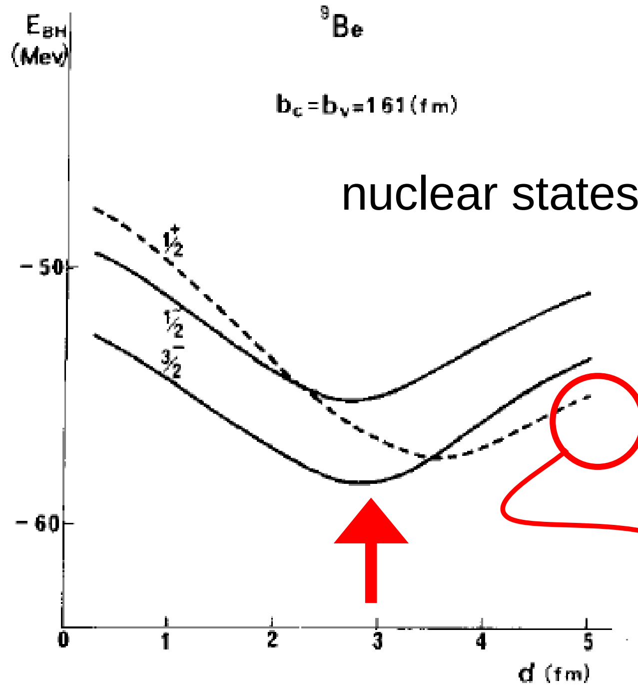
^{9}He is unbound and very neutron rich.
It can be observed as a resonance
in the ^{8}He + n system.
(is there level inversion like ^{11}Be?)
(1/2+ below 1/2– ?)





orbitals

^{9}Be

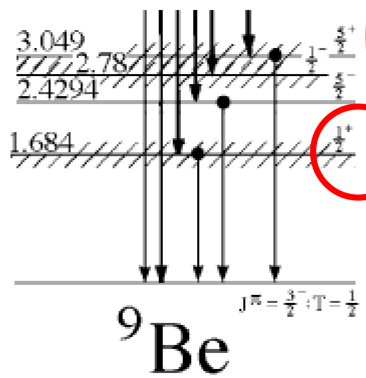


nuclear states

M. Seya, M. Kohno and S. Nagata

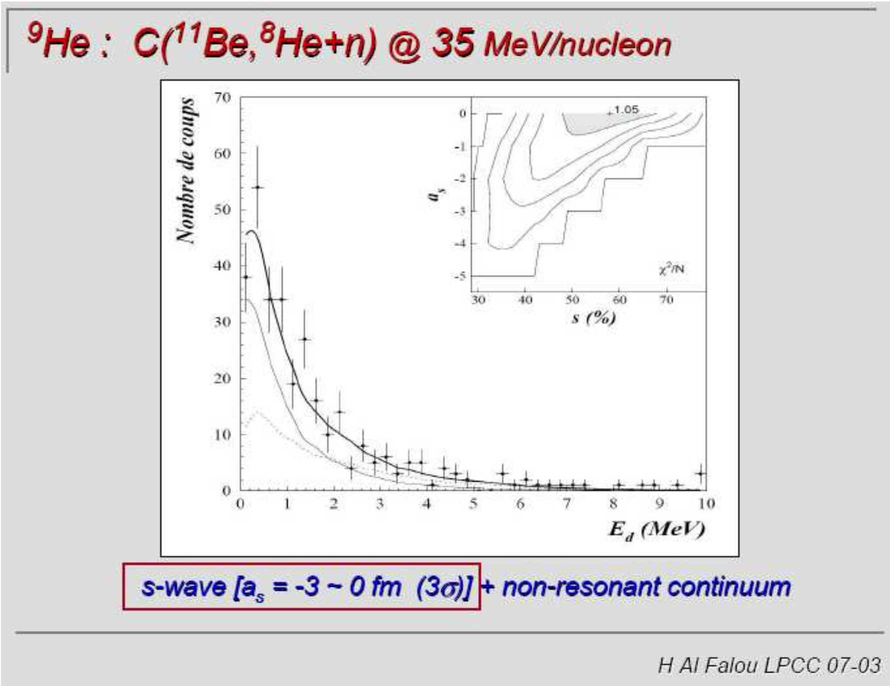
Progress of Theoretical Physics, Vol. 65, No. 1, January 1981

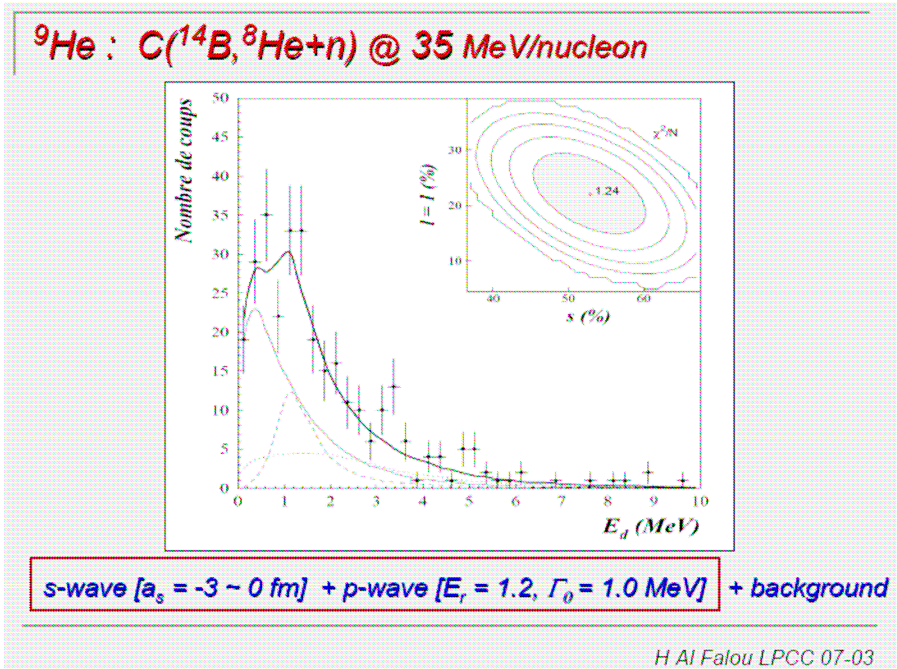
page 204



A favourite of **Alex Brown**, but in fact it proves the existence of nuclear **cluster** states…

… this turns out to be a successful prediction for ^{10}Be (see later)





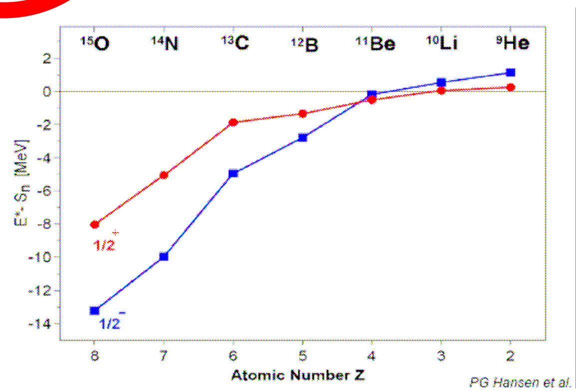
H. Al Falou, N.A. Orr, et al.

CHARISSA+DEMON at GANIL

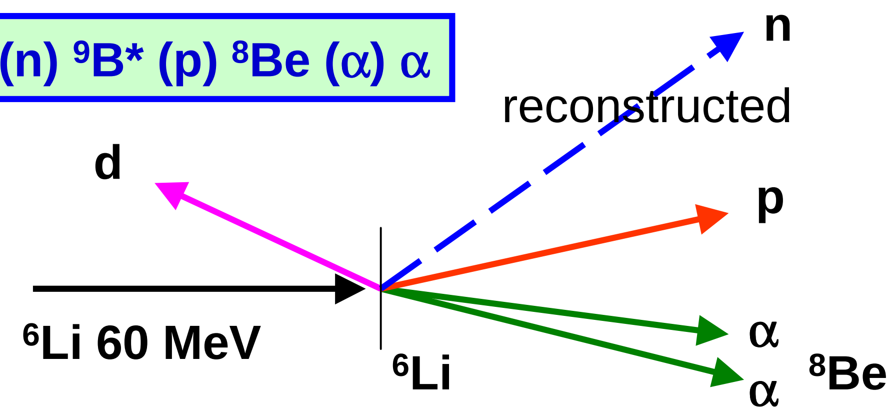
Reconstruct $\mathbf{E_{rel}(\ ^{8}He + n\ )}$ from measured angles and energies

Some evidence for persistence of **$1s_{1/2}$ and $0p_{1/2}$ level inversion** as seen in ^{11}Be and ^{10}Li

^{9}He



$^{6}Li\ (^{6}Li,d)\ ^{10}B\ (n)\ ^{9}B^{*}\ (p)\ ^{8}Be\ (\alpha)\ \alpha$

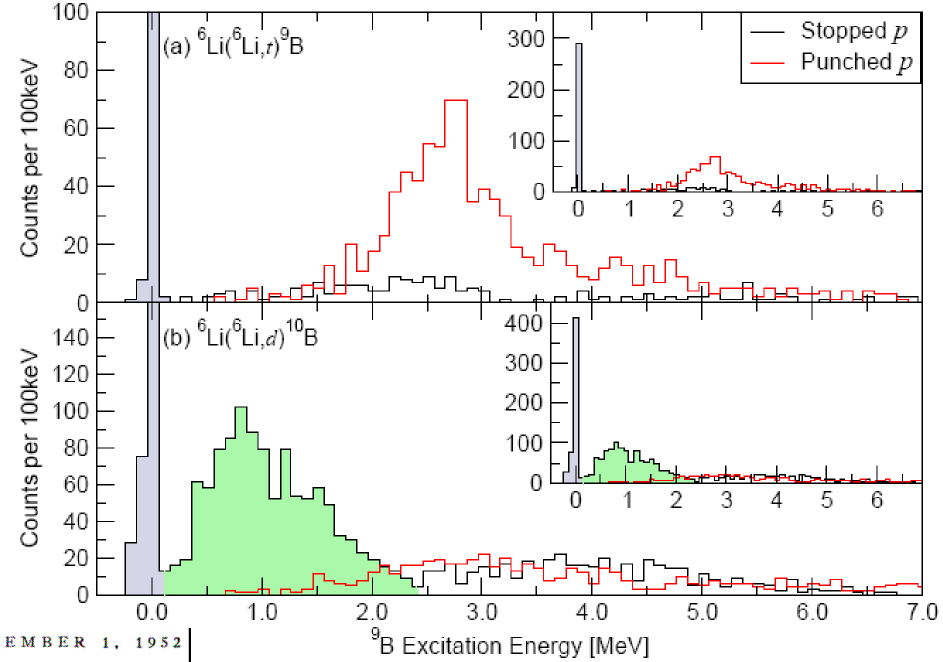


Ground state is $3/2^-$

^{9}B

The $1/2^+$ state can be compared to the ^{9}Be mirror (Thomas-Ehrman shift) (both are unbound for A=9)

Controversial…
- identity
- energy
- seems to be "too low"



Tamara Baldwin, Surrey, PhD 2007
TD Baldwin, WN Catford etal., submitted

PHYSICAL REVIEW VOLUME 88, NUMBER 5 DECEMBER 1, 1952

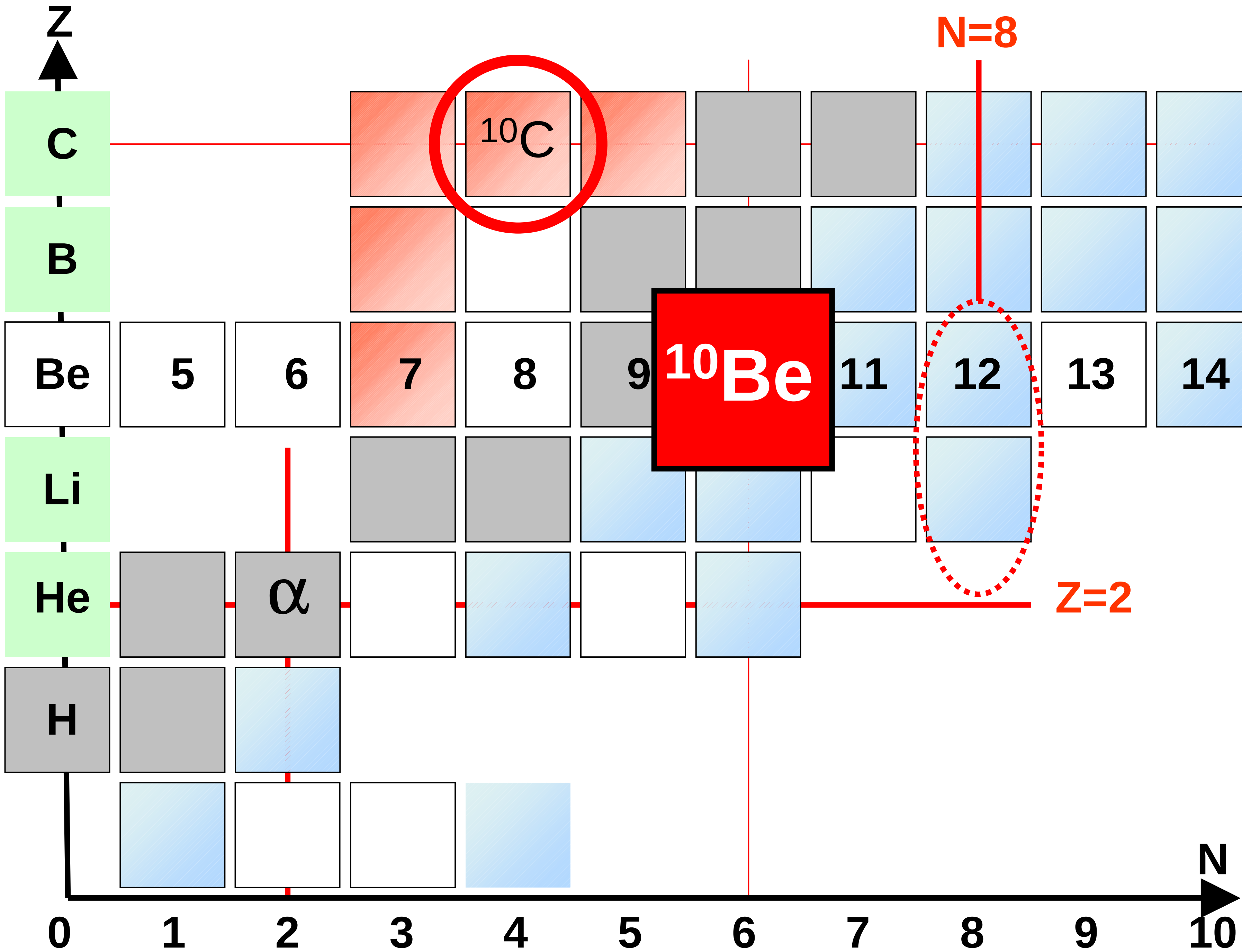
An Analysis of the Energy Levels of the Mirror Nuclei, C^{13} and N^{13}

R. G. THOMAS*
Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California

PHYSICAL REVIEW VOLUME 81, NUMBER 3 FEBRUARY 1, 1951

On the Displacement of Corresponding Energy Levels of C^{13} and N^{13}

JOACHIM B. EHRMAN*
Princeton University, Princeton, New Jersey



Z
N=8
C
^{10}C
B
Be
5
6
7
8
9
^{10}Be
11
12
13
14
Li
He
α
Z=2
H
N
0
1
2
3
4
5
6
7
8
9
10

^{10}C

^{10}C is the analog of ^{10}Be,
with two protons replacing two valence neutrons – do the same structures exist ?

Lifetime = 19.3 s
One bound excited 2^+ state

^{10}Be

^{10}Be shows molecular structure,
but mostly in the excited states.

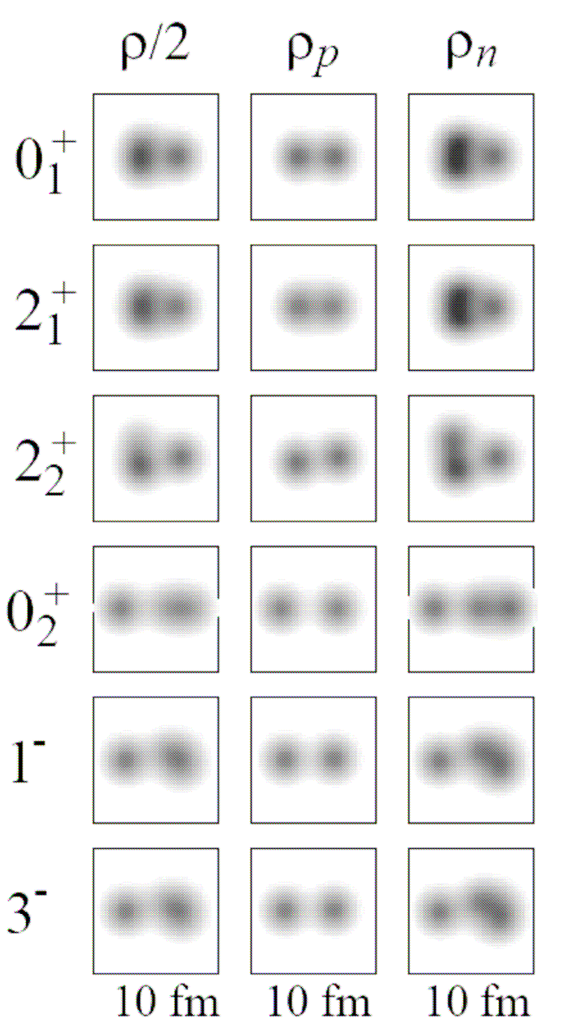
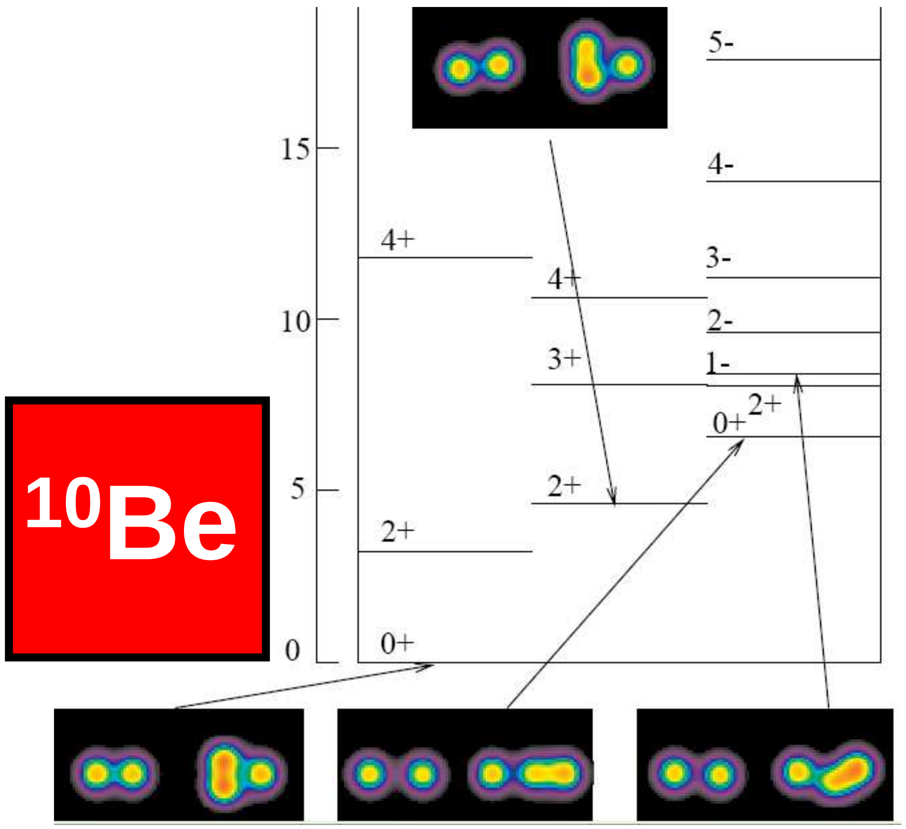
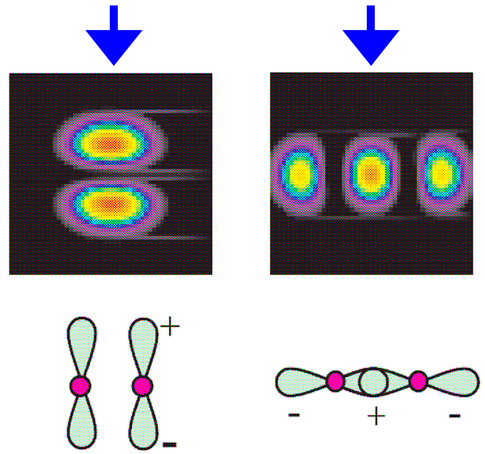


Fig. 30. The intrinsic structure of the excited states of ^{10}Be obtained by VAP calculations. The density distribution of matter, protons and neutrons of the intrinsic states are shown at left, middle and right, respectively. The density is integrated along the axis perpendicular to adequate planes. The figures are for the results with the interaction (g).

Y. Kanada-En'yo and H. Horiuchi
Progress of Theoretical Physics Supplement No. 142, 2001

J. Phys. G: Nucl. Part. Phys. **24** (1998) 1499–1503.





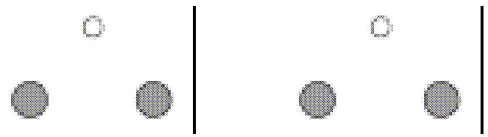
(a) π **bond** (b) σ **bond**

valence neutrons occupy genuine molecular orbitals

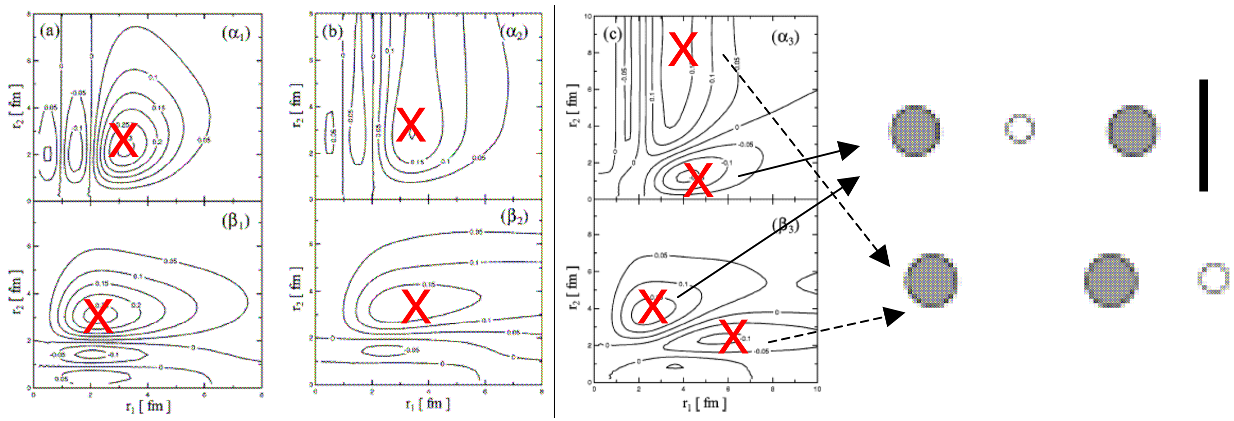
Koji Arai*
Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom
PHYSICAL REVIEW C **69**, 014309 (2004)

Microscopic cluster model (as for ^{6}He earlier)

^{10}Be



3/2– 1/2– 1/2+



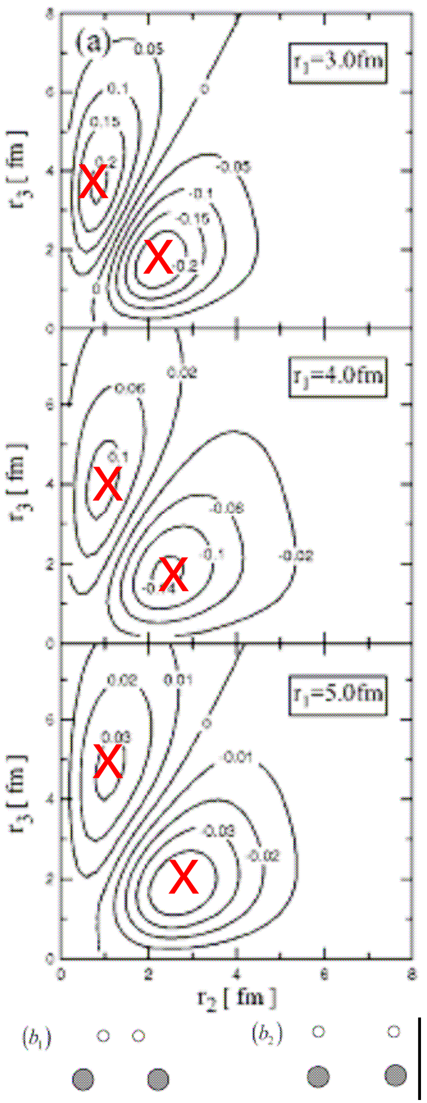
^{9}Be results

Coexistence of two configurations

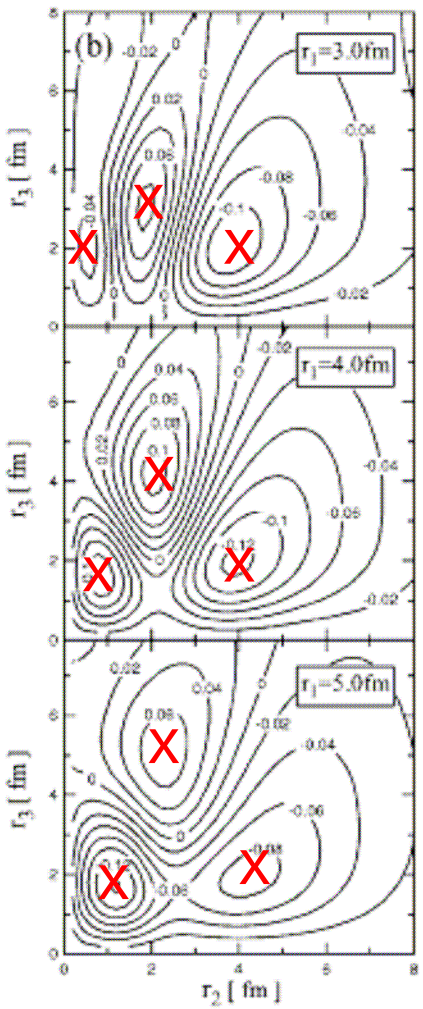
Necessary, to explain high binding of 1/2+

Koji Arai*
Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom
PHYSICAL REVIEW C **69**, 014309 (2004)

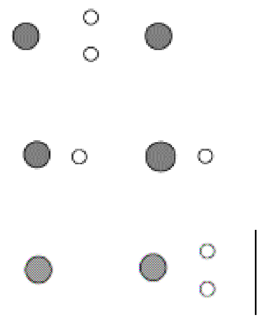
g.s. 0^+



excited 0^+



^{10}Be

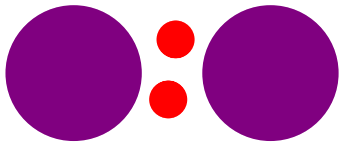


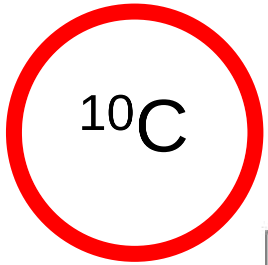
^{10}Be results

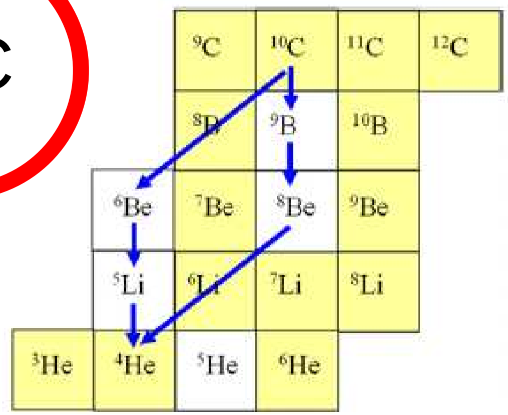
Coexistence of THREE configurations

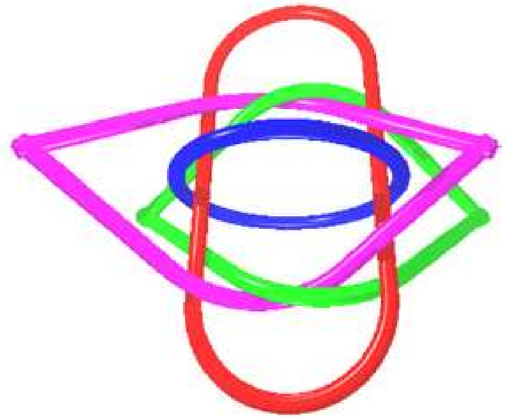
Necessary, to explain covalent molecular 0+

Super- Borromean… “Brunnian”



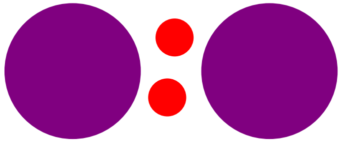


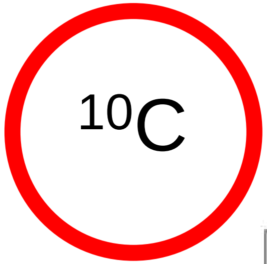




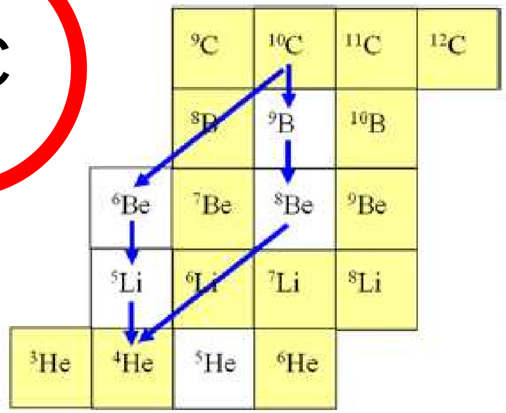
Rep. Prog. Phys. **70** (2007) 2149–2210

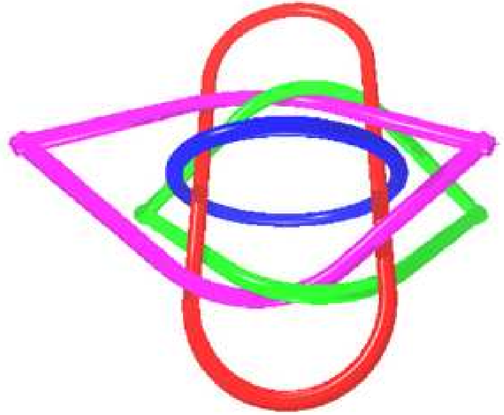
Martin Freer





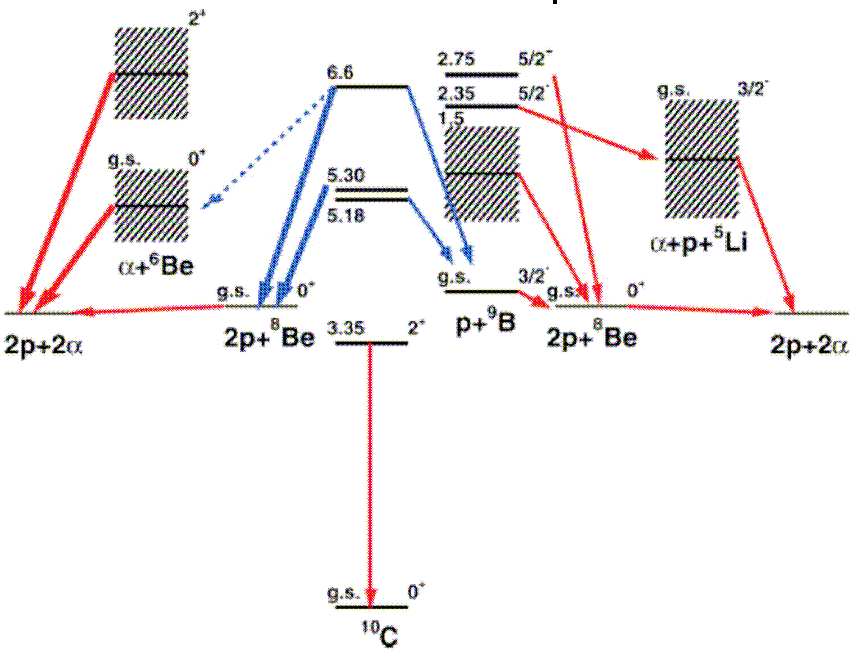
Super- Borromean… "Brunnian"





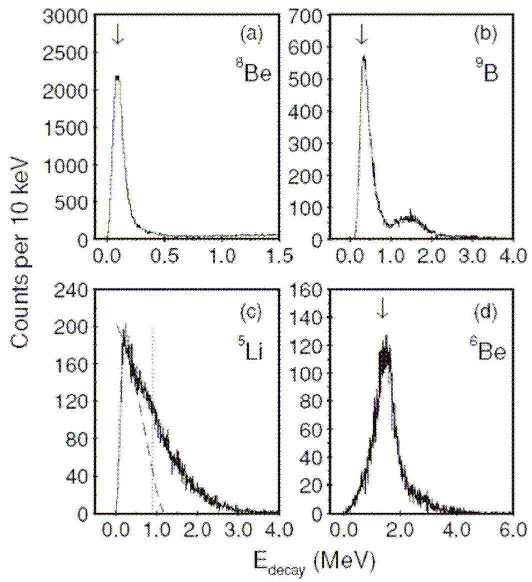
^{10}C @ 10.7 MeV/A on ^9Be Texas A&M

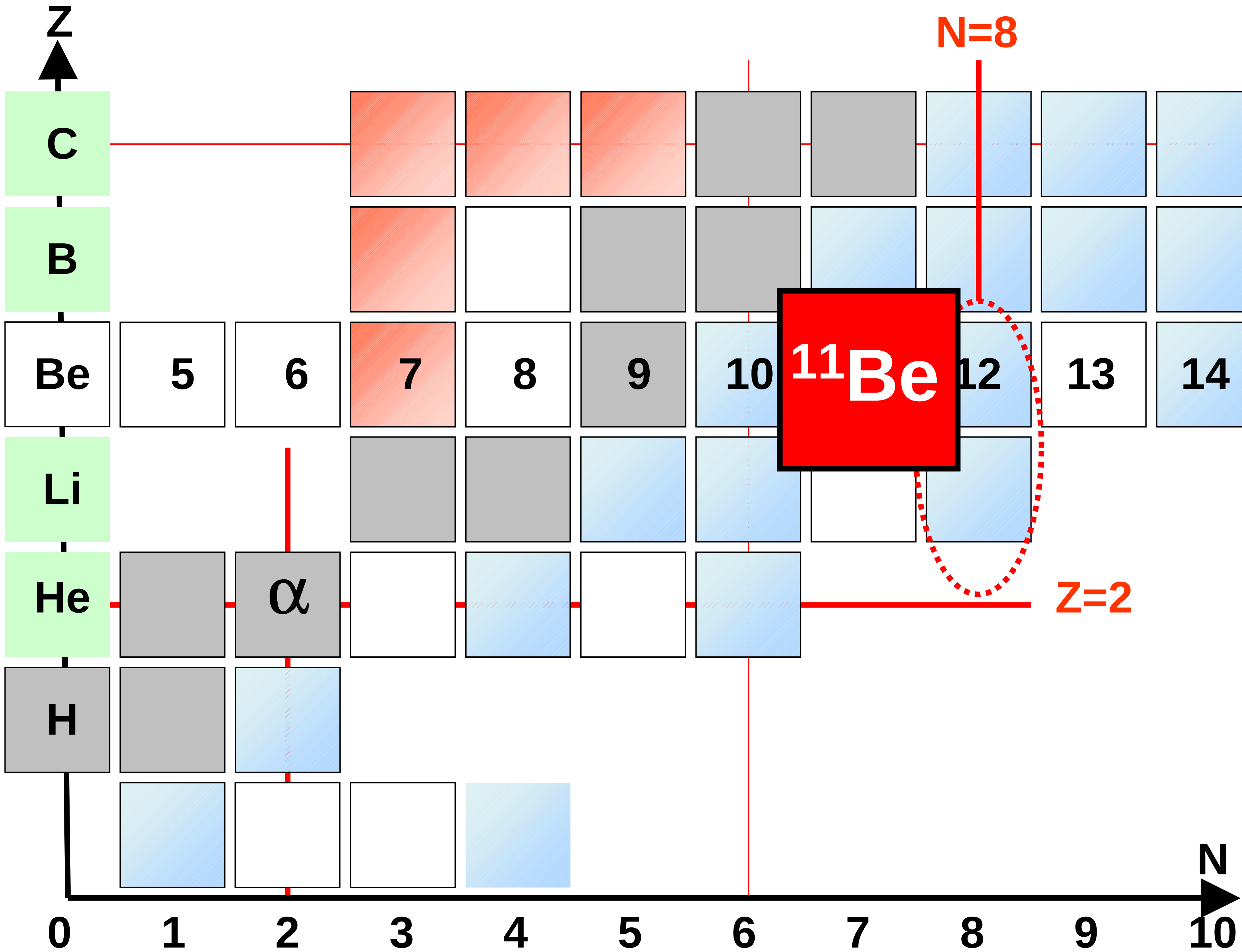
R. J. CHARITY *et al.*
PHYSICAL REVIEW C **75**, 051304(R) (2007)



^{10}C @ 33.3 MeV/A on ^{12}C GANIL

N. CURTIS *et al.*
PHYSICAL REVIEW C **77**, 021301(R) (2008)





Z
N=8
C
B
Be
5
6
7
8
9
10
^{11}Be
12
13
14
Li
He
α
Z=2
H
N
0
1
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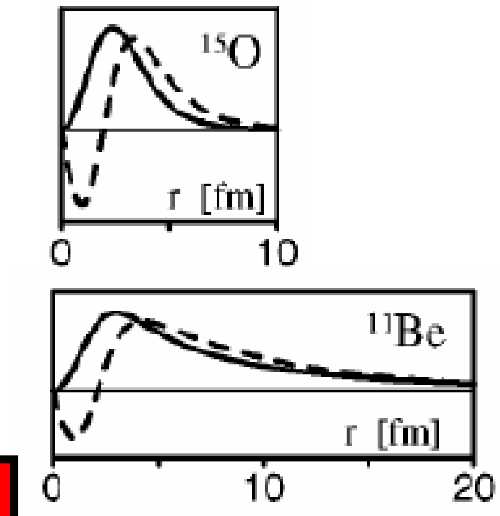
Weakly bound
S_n = 0.xx MeV
Halo nucleus



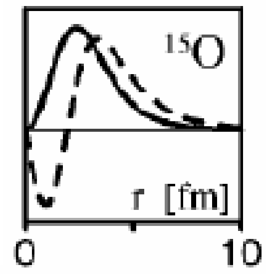
^{11}Be

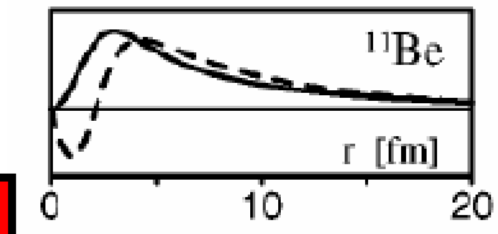
This is a classic single-neutron halo nucleus,
where the weak binding automatically leads to a halo

Both the intruder $1/2^+$ ground state and the low $1/2^-$ state have a halo – despite the centrifugal barrier for the $p_{1/2}$ state.

The halo is not pure, however, and there is a component of the ground state in which the deformed core is excited to 2^+ and a d-wave neutron is coupled to give spin 1/2.

Weakly bound
S_n = 0.xx MeV
Halo nucleus





^{11}Be

Structure of unstable light nuclei

D.J. Millener

Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Nuclear Physics A 693 (2001) 394–410

Abstract

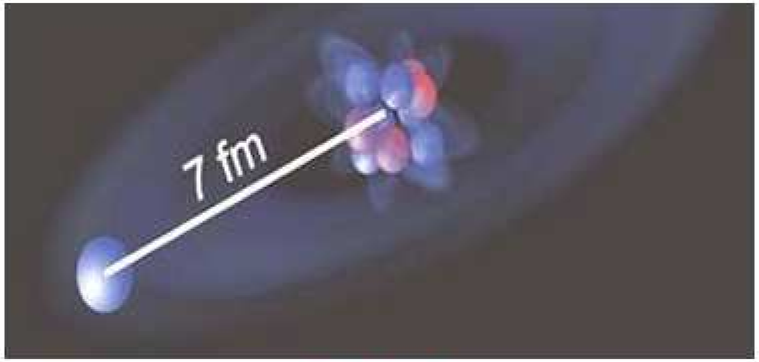
The structure of light nuclei out to the drip lines and beyond up to $Z \sim 8$ is interpreted in terms of the shell model. Special emphasis is given to the underlying supermultiplet symmetry of the p-shell nuclei which form cores for neutrons and protons added in sd-shell orbits. Detailed results are given on the wave functions, widths, and Coulomb energy shifts for a wide range of non-normal parity states in the p-shell.

IOP A website from Institute of Physics Publishing

physicsworld.com

Lasers take a measure of halo nucleus

Mar 9, 2009 2 comments



Halo nucleus

Physicists in Europe and North America have measured the radius of an unusual beryllium isotope containing a single neutron a long way from the rest of the nuclear core. Although the radii of other such "halo" isotopes have been determined before, this is the first time that the measurement has been made on a nucleus with just a single halo neutron. The researchers found that the halo neutron in beryllium–11 is, on average, about 7 fm (7×10^{-15} m) from the nuclear core, which itself has a radius of about 2.5 fm.

Measurements and calculations

The new study was carried out at the ISOLDE facility at CERN by Wilfried Nörtershäuser at the University of Mainz and colleagues in Germany, Canada and Switzerland (*Phys. Rev. Lett.* **102** 062503).

The experiment involved producing four different isotopes of beryllium (with 7, 9 10 and 11 nucleons) by firing a 1.4 GeV proton beam into a uranium-carbide target. This created beryllium atoms, which were then ionized using a laser and accelerated to 50 kV. Transitions in electron energy levels were induced by firing two ultraviolet laser beams at the ions. One beam was fired straight at the oncoming ions, while the other was fired in the opposite direction from behind the ions to cancel out the experimental uncertainty in the kinetic energy of the ions.

^{11}Be

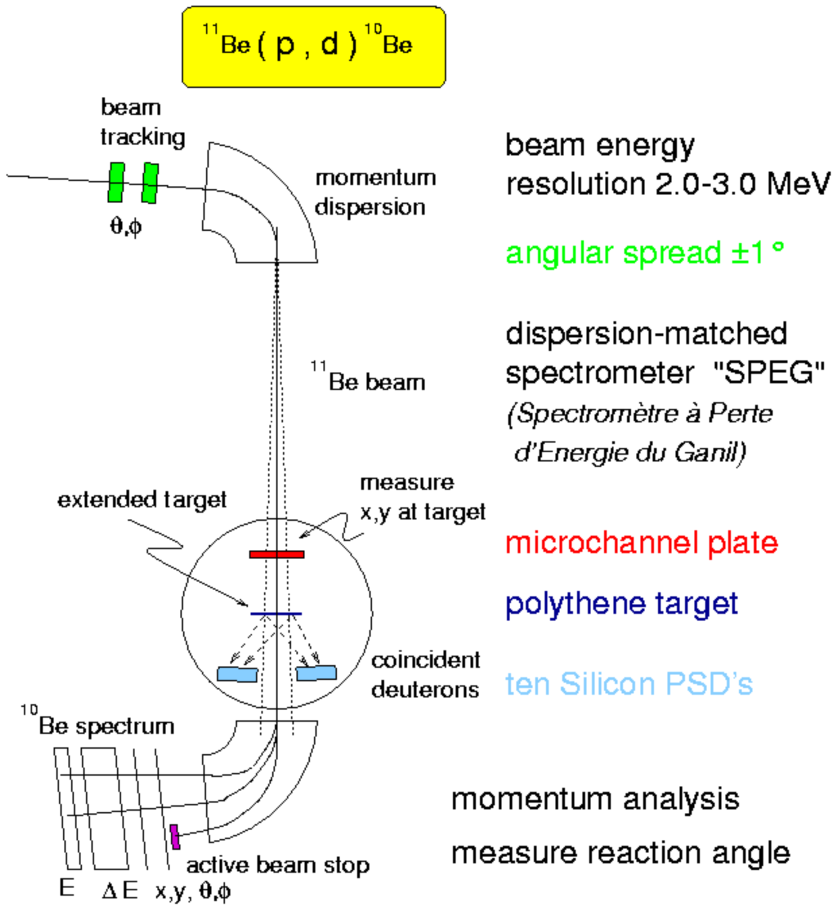
Measuring ^{11}Be structure as superposition of
1^{0}Be$(0^{+})+\nu(s_{1/2})$ and ^{10}Be$(2^{+})+\nu(d_{5/2})$

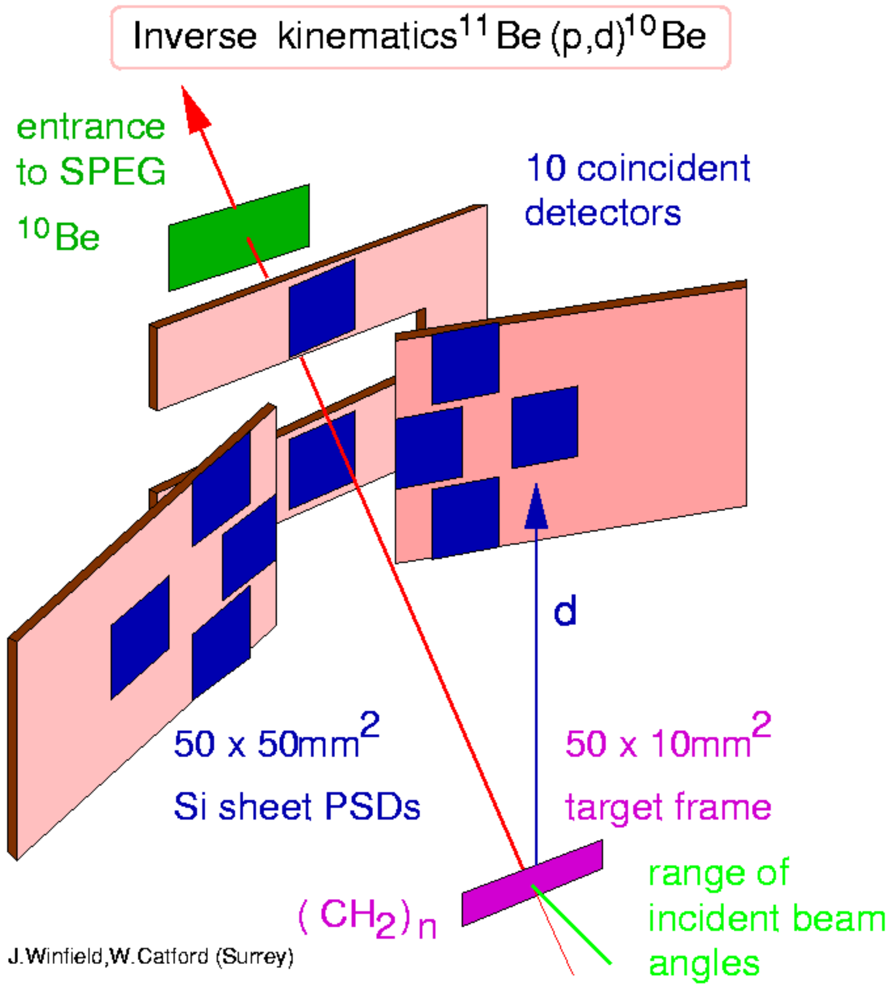
Removal of last neutron via (p,d) transfer

^{11}Be

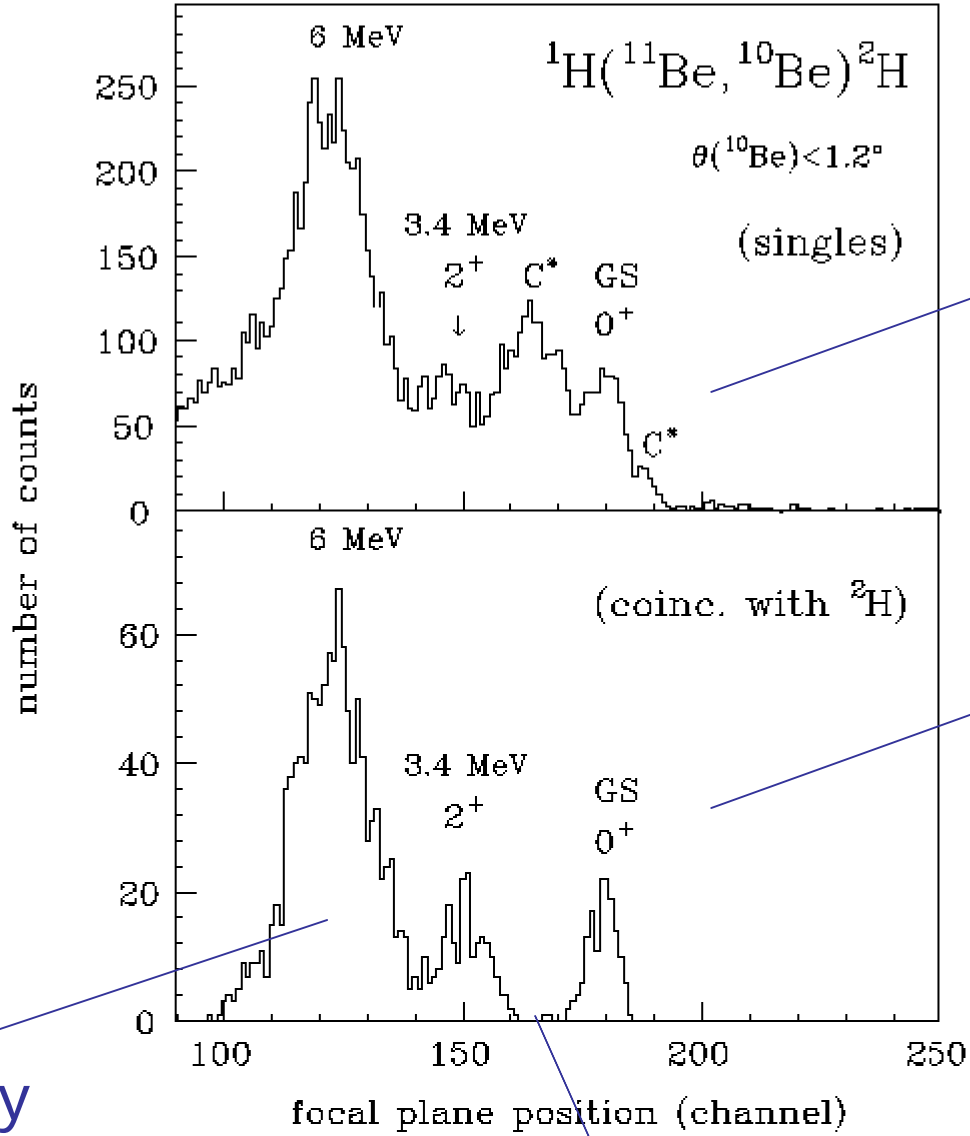
J.S. Winfield et al. / Nuclear Physics A 683 (2001) 48–78

S. Fortier et al. / Physics Letters B 461 (1999) 22–27





Focal plane spectrum from SPEG magnetic spectrometer



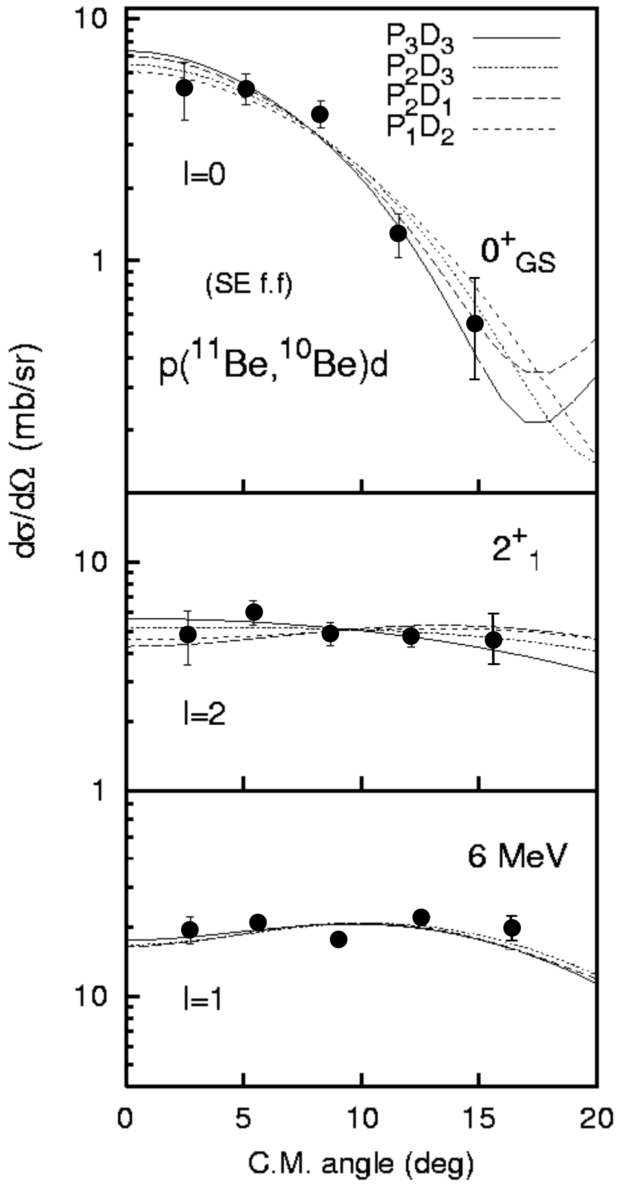
singles

coincidence

gamma-ray broadening

carbon background removed

Separation Energy form factor



0^+ 2^+

α^2 β^2

~~0.49~~ ~~0.51~~

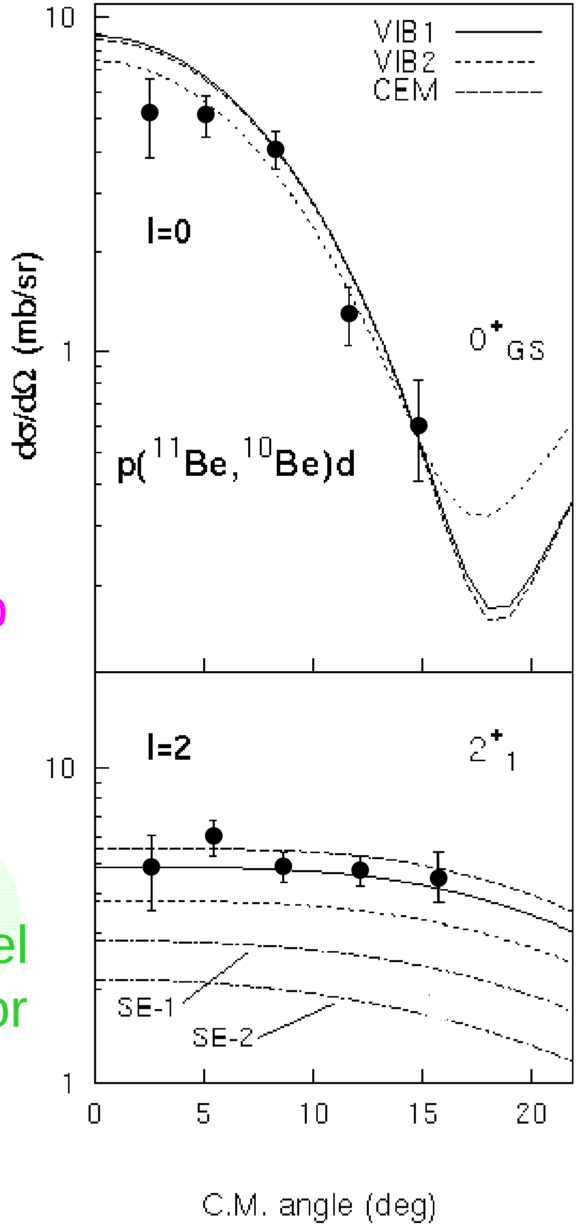
- poor form factor
- no core coupling
- no $^{11}Be/d$ breakup

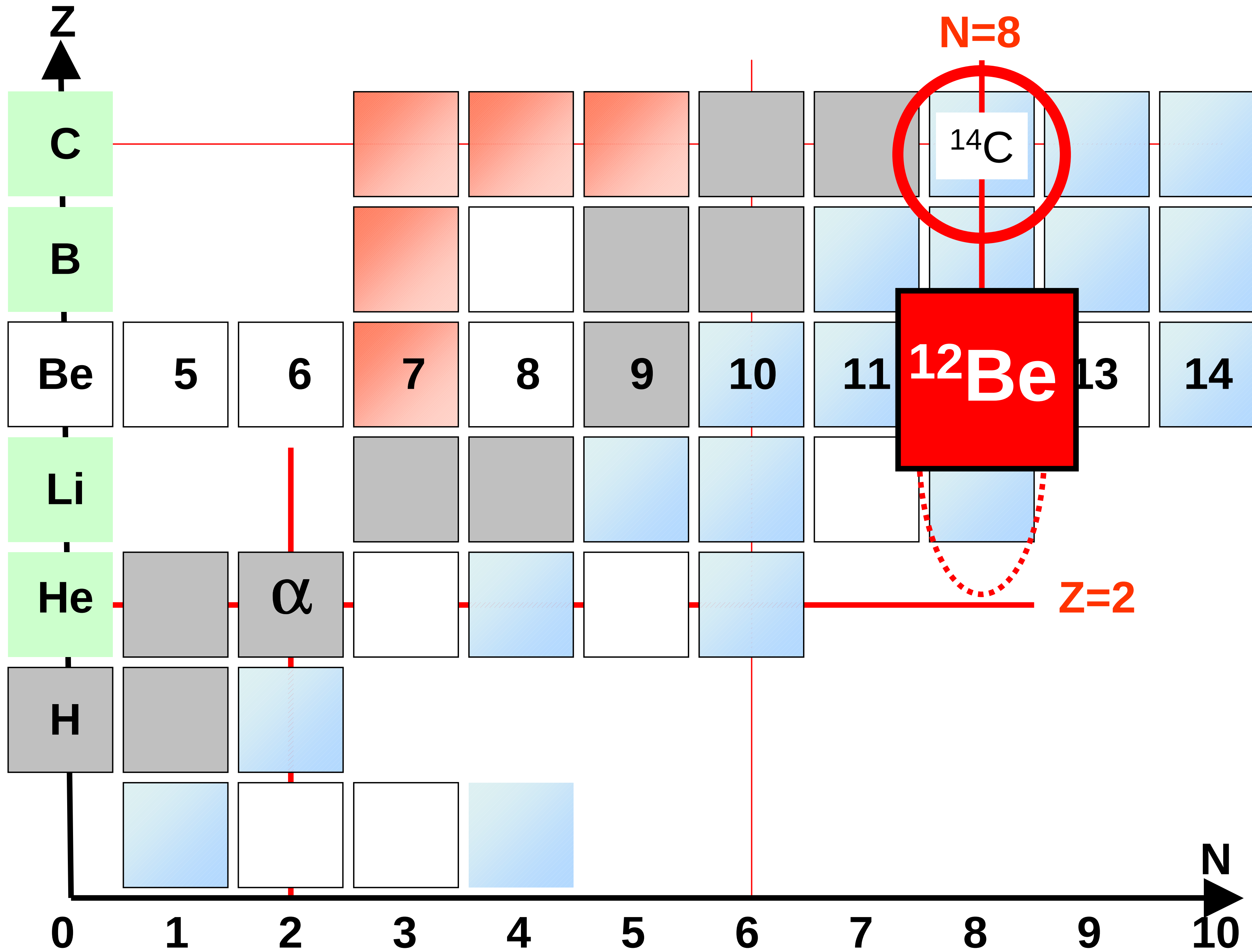
0.84 0.16

- vibrational model
- core-excited model
- realistic form factor

$\left\{ \begin{array}{c} 0.74 \quad 0.19 \\ \text{Shell model} \end{array} \right\}$

Vibrational form factor





Z
N=8
C
^{14}C
B
Be
5
6
7
8
9
10
11
^{12}Be
13
14
Li
He
α
Z=2
H
N
0
1
2
3
4
5
6
7
8
9
10

^{14}C is **magic** –
p3/2 protons closed
p1/2 neutrons closed
N=8 closure is good

S_p = 20.832 MeV
S_n = 8.177 MeV
S_α = 12.012 MeV

(see next slide)

^{14}C

^{12}Be

^{12}Be sees a **total collapse** of magicity.. just by the…

…removal of two protons but keeping N=8

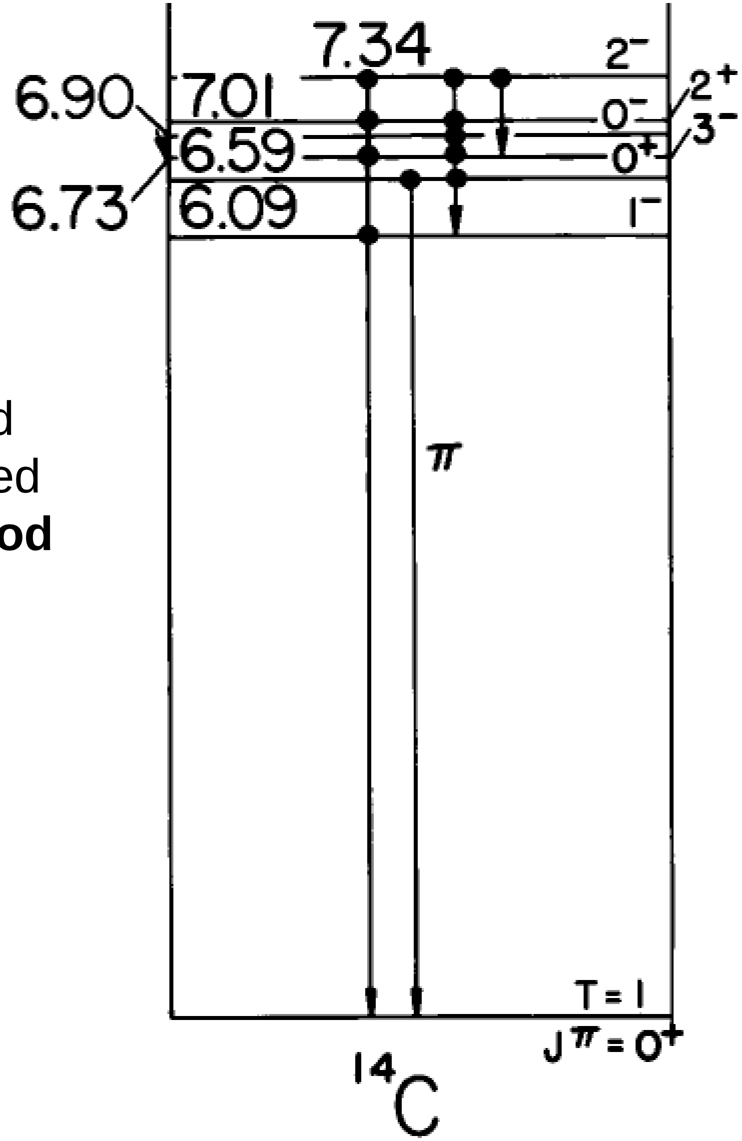
Excited states in ^{12}Be seem to show ^{6}He+^{6}He clustering behaviour.

^{14}C is **magic** –
p3/2 protons closed
p1/2 neutrons closed
N=8 closure is good

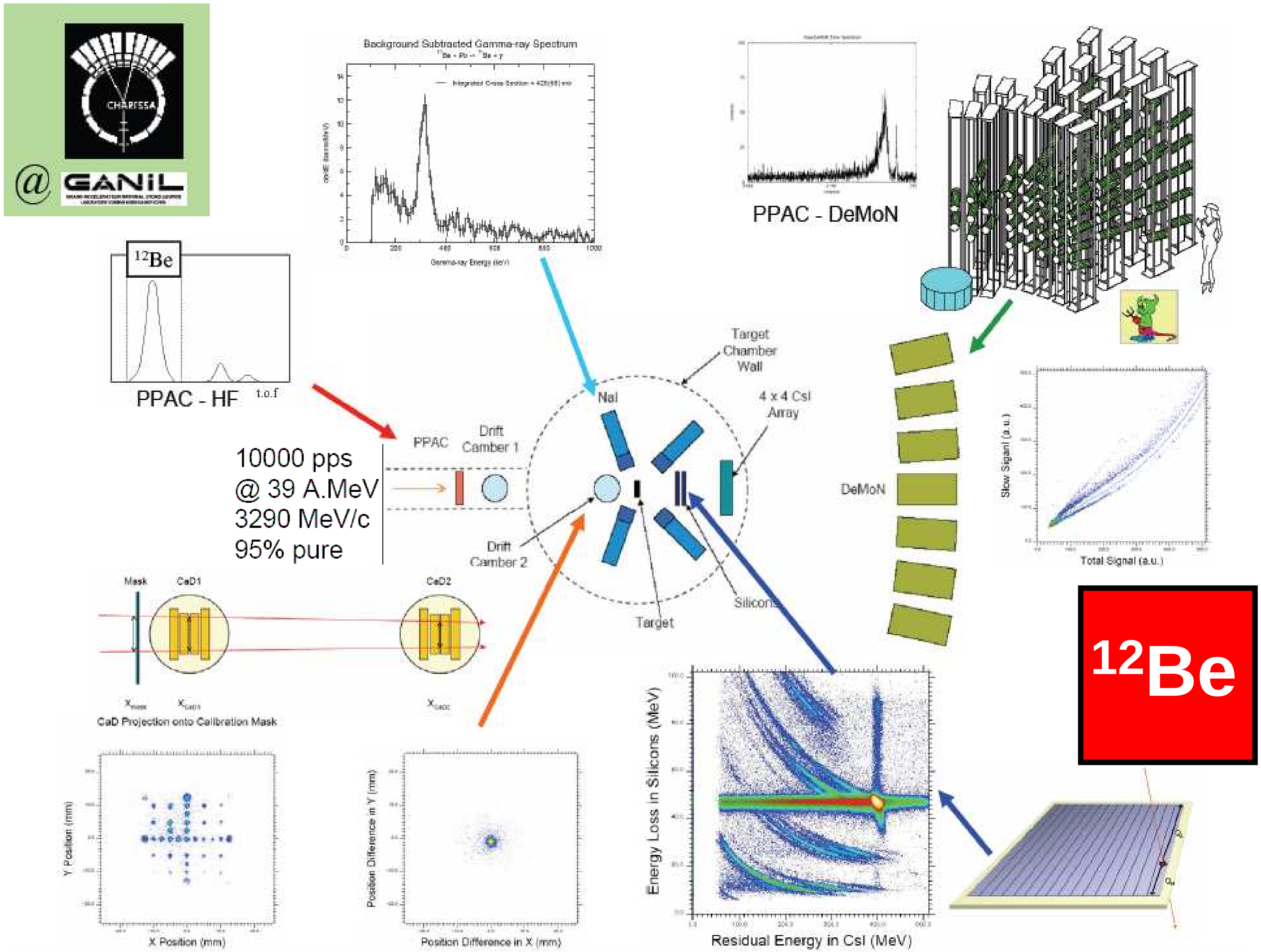
S_p = 20.832 MeV

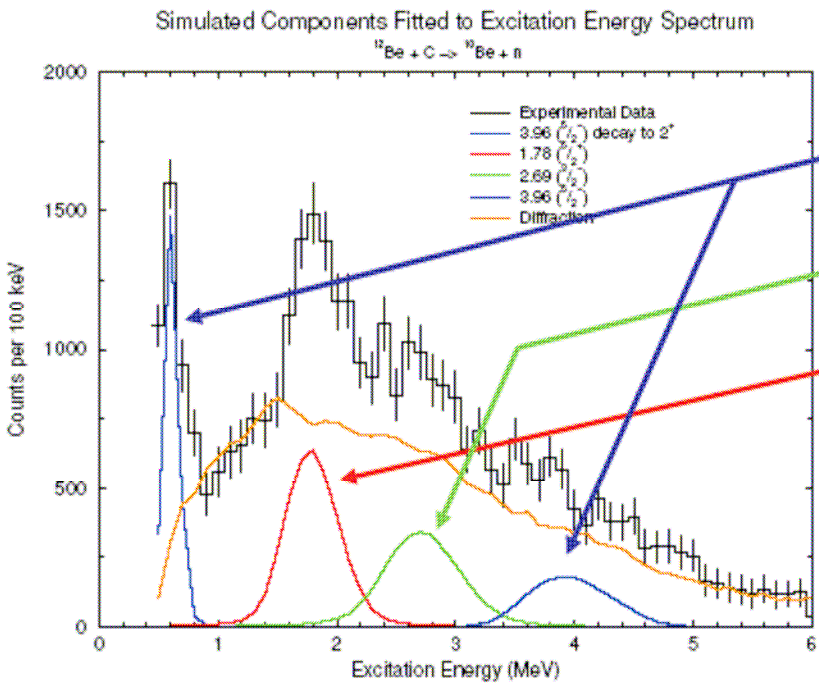
S_n = 8.177 MeV

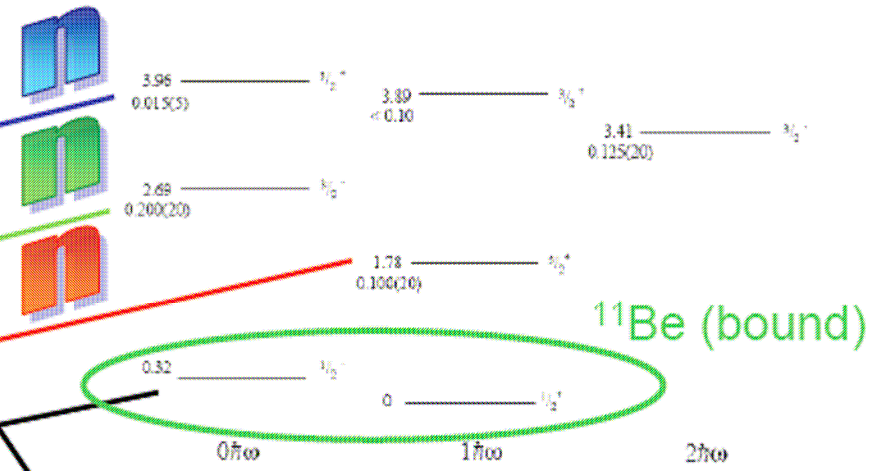
S_α = 12.012 MeV



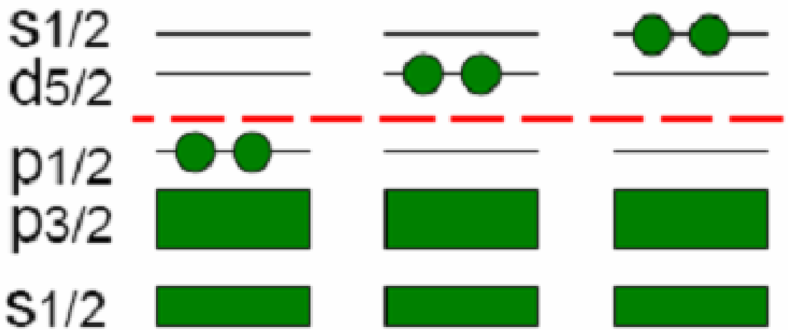
^{14}C


Background Subtracted Gamma-ray Spectrum
Gamma-ray Energy (keV)
PPAC - DeMoN
12Be
PPAC - HF
t.o.f
Target
Chamber
Wall
NaI
4 x 4 CsI
Array
PPAC
Drift
Camber 1
10000 pps
@ 39 A.MeV
3290 MeV/c
95% pure
Drift
Camber 2
DeMoN
Silicons
Target
Slow Signal (a.u.)
Total Signal (a.u.)
Mask
CaD1
CaD2
CaD Projection onto Calibration Mask
Energy Loss in Silicons (MeV)
Residual Energy in CsI (MeV)
Y Position (mm)
X Position (mm)
Position Difference in Y (mm)
Position Difference in X (mm)
12Be

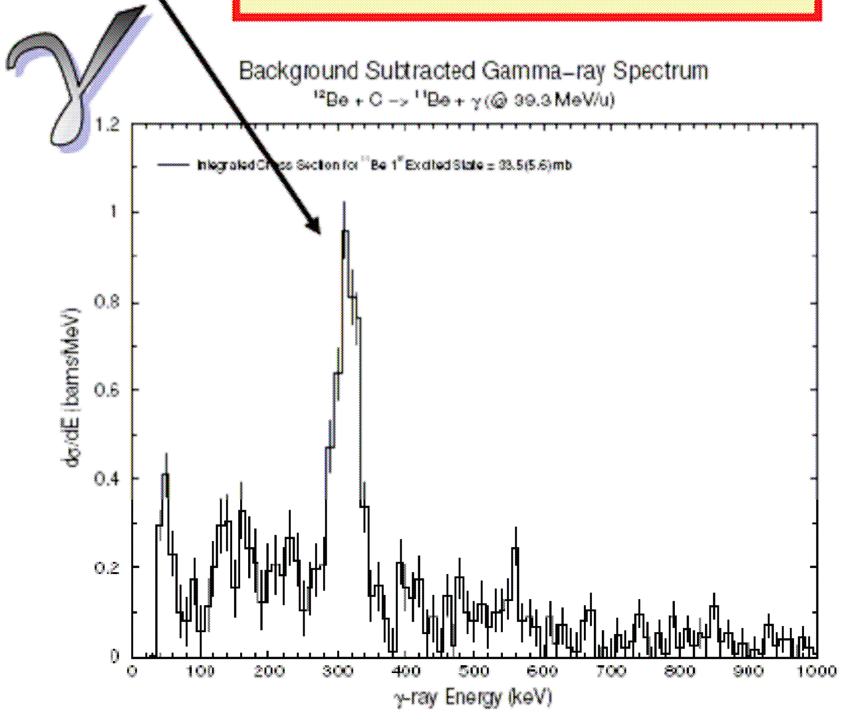




$^{12}Be \rightarrow {}^{11}Be$

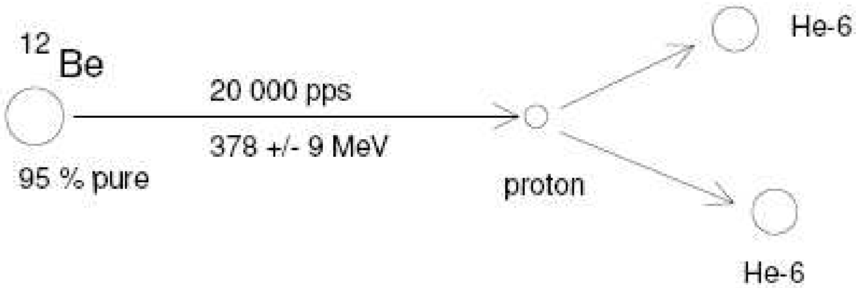


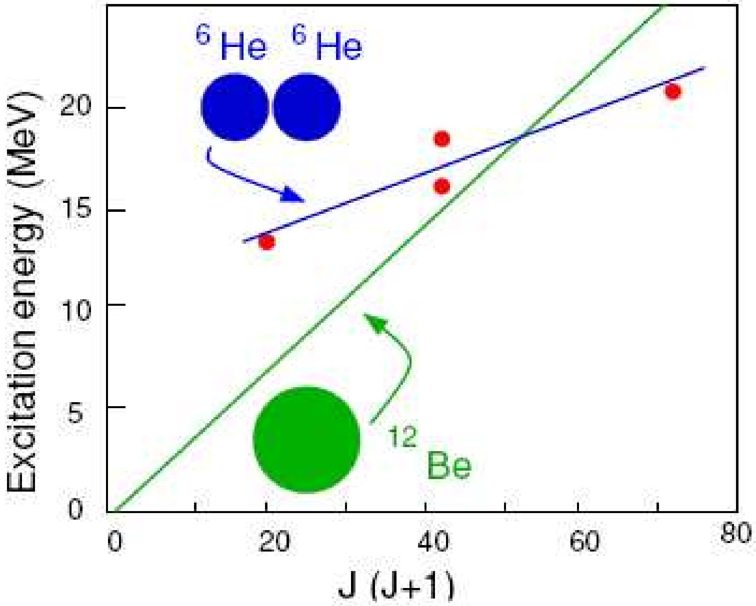
Occupancy	0.44	0.48	0.56
Percent	30%	32%	38%



Steve Pain et al., PRL **96**, 032502 (2006)

^{12}Be

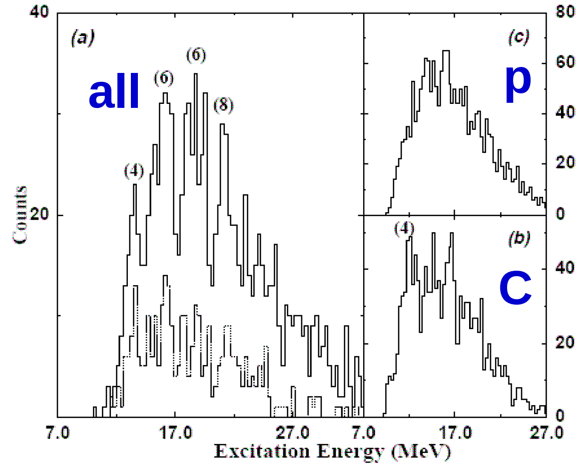




M. Freer *et al.*, Phys. Rev. Lett., **82** (1999) 1383

Ground state – a more normal deformation,
Excited band – 2:1 ^6He+^6He cluster configuration

But note :

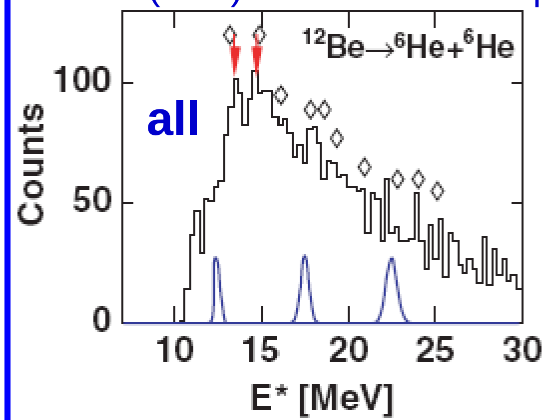


Phys. Rev. Lett. **82**, 1383 (1999).

M. Freer *et al.*

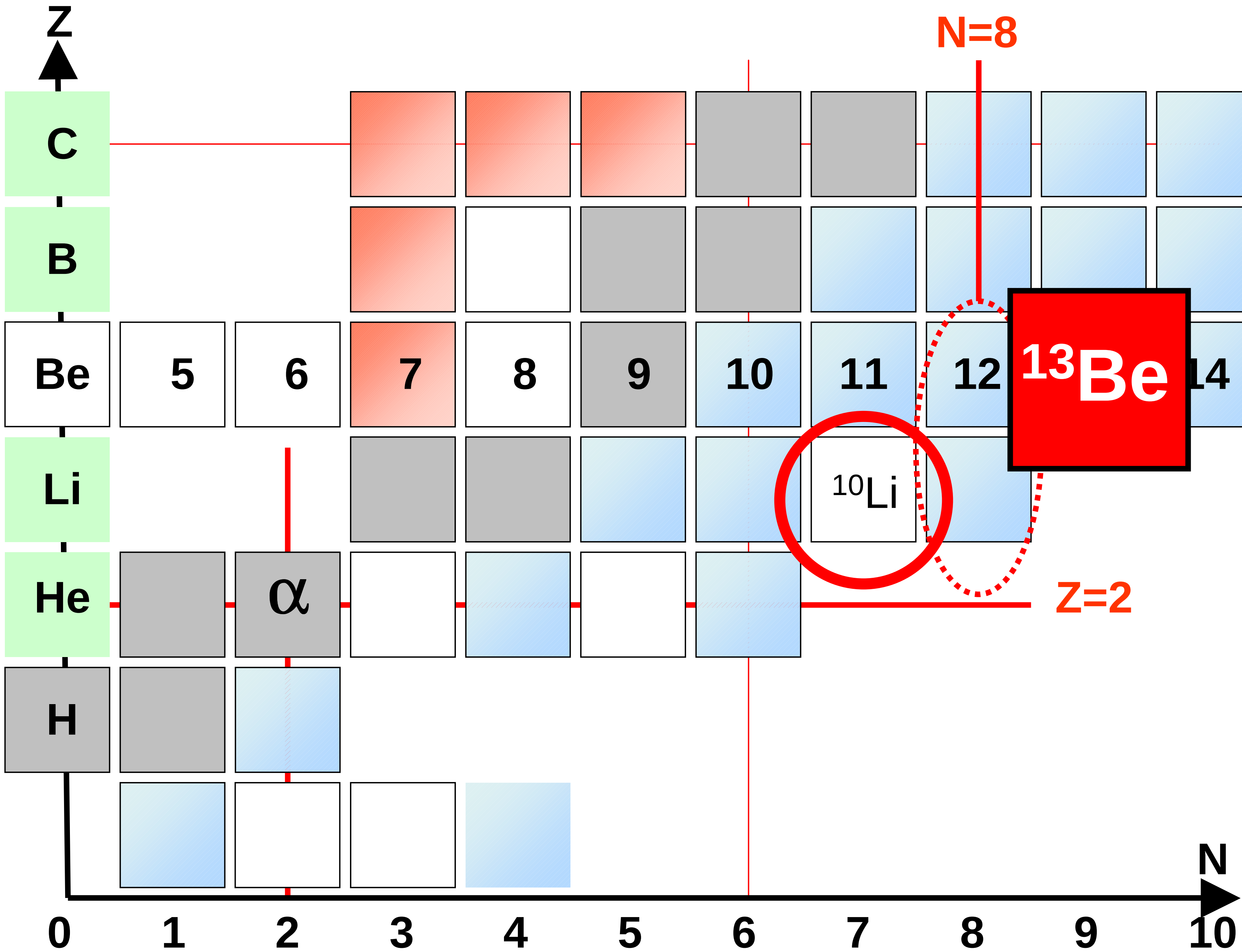
31.5 (±0.8) MeV/A   2 x 10^4 pps

50.0 (±0.5) MeV/A   1 x 10^5 pps



PHYSICAL REVIEW C **76**, 064313 (2007)

R. J. CHARITY *et al.*


Z
N=8
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14
Li
^{10}Li
He
α
Z=2
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0
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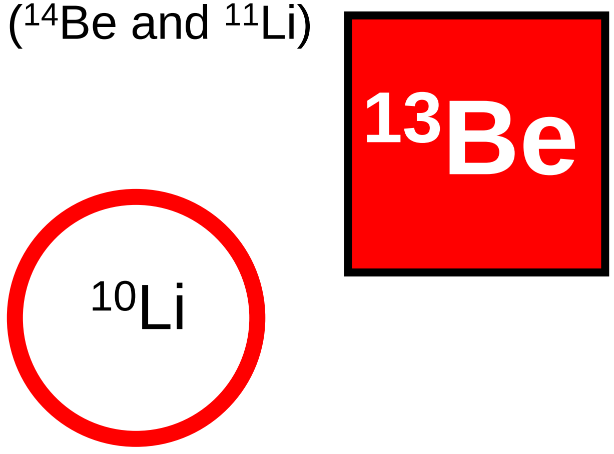
Both ^{13}Be and ^{10}Li are unbound sub-systems
of bound halo systems (^{14}Be and ^{11}Li)



If we remove a single neutron from the bound halo system
And then observe the other neutron and the core nucleus,
And then reconstruct the relative momentum…

Do we measure the neutron-core interaction in an accurate manner,
or do we observe some vestige of the structure in the original halo…?

How well do reconstructed resonances in the sub-system resemble the actual sub-system and how much are they a remnant of the initial state? Are standard resonance line-shapes expected? …. (YES)

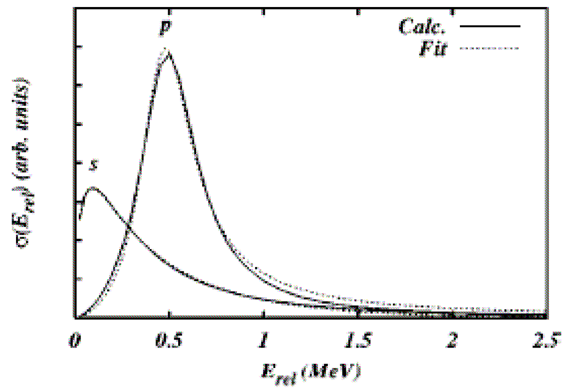


FIG. 7. The ^{11}Li 1n-stripping energy distributions in the no-recoil transparent limit (solid curves) are compared to fits obtained from Eq. (20) and Eqs. (21) and (22) (dashed curves). Shown are the s- and p-wave components of the $s23$ wave function.

Calculated reaction products compared with resonances

^{13}Be

^{10}Li

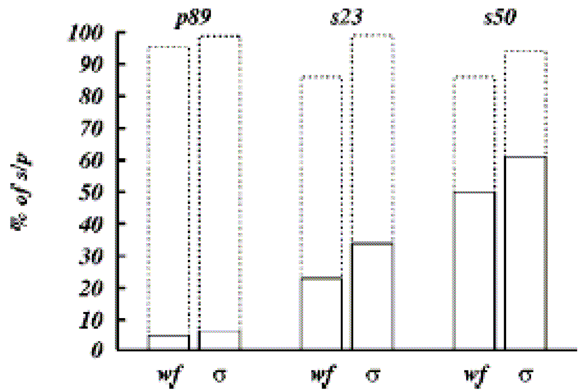
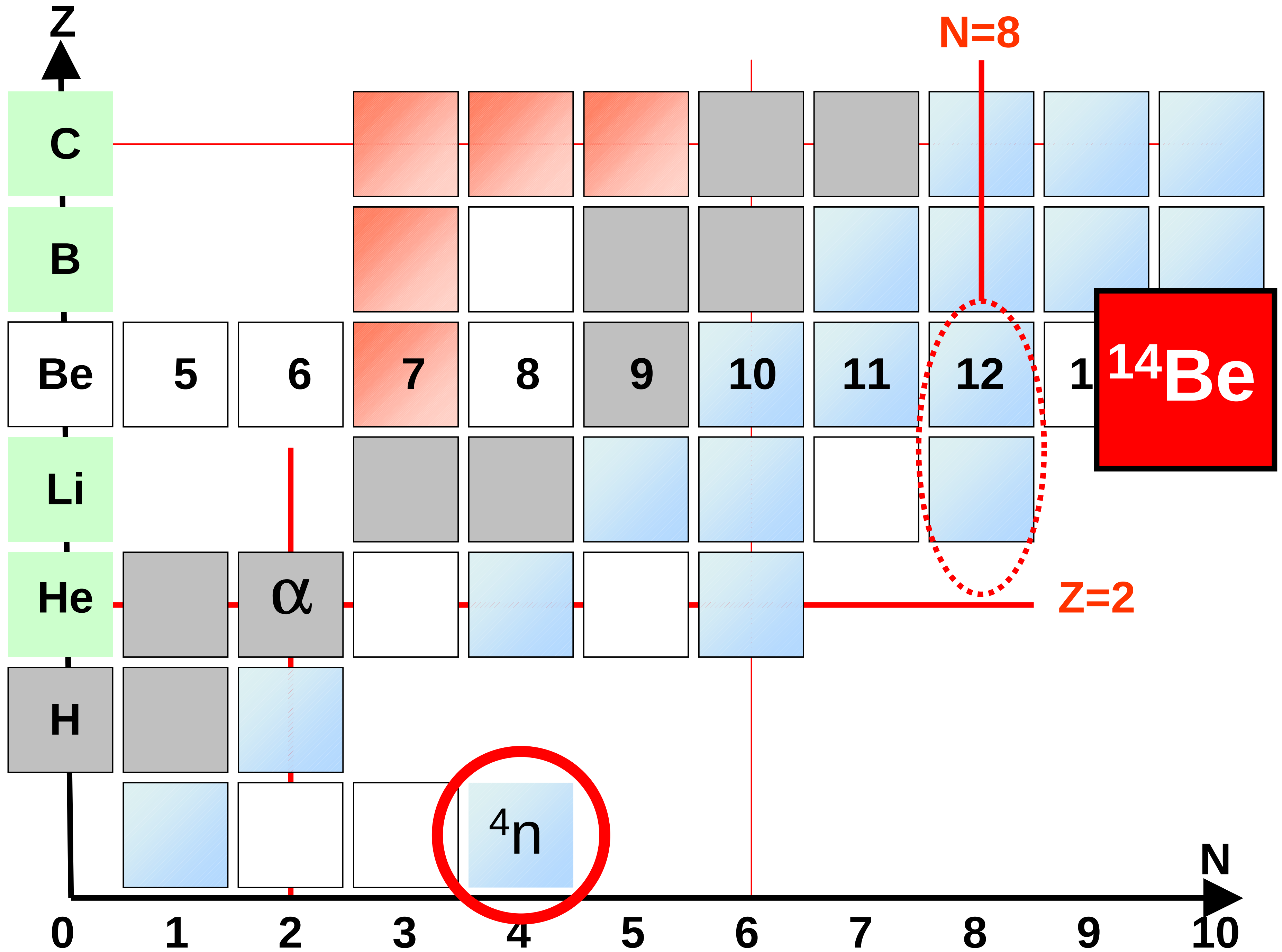


FIG. 6. Percentage of s and p waves in the various models, comparing the probabilities in the wave functions (wf) to the probabilities in the neutron-core final states (σ).

For several structure models, comparison of relative peak strengths in reaction with relative strengths in the initial wavefunction

G. F. BERTSCH, K. HENCKEN, AND H. ESBENSEN
PRC 37 (1998) 1366



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^{14}Be
Li
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H
^{4}n
N
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4
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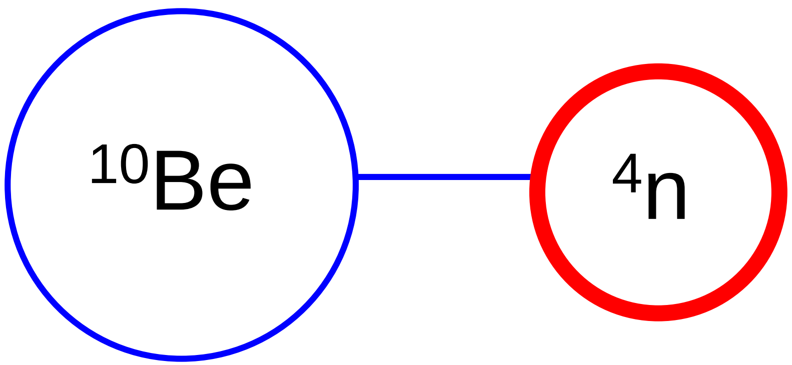
(see next slide)

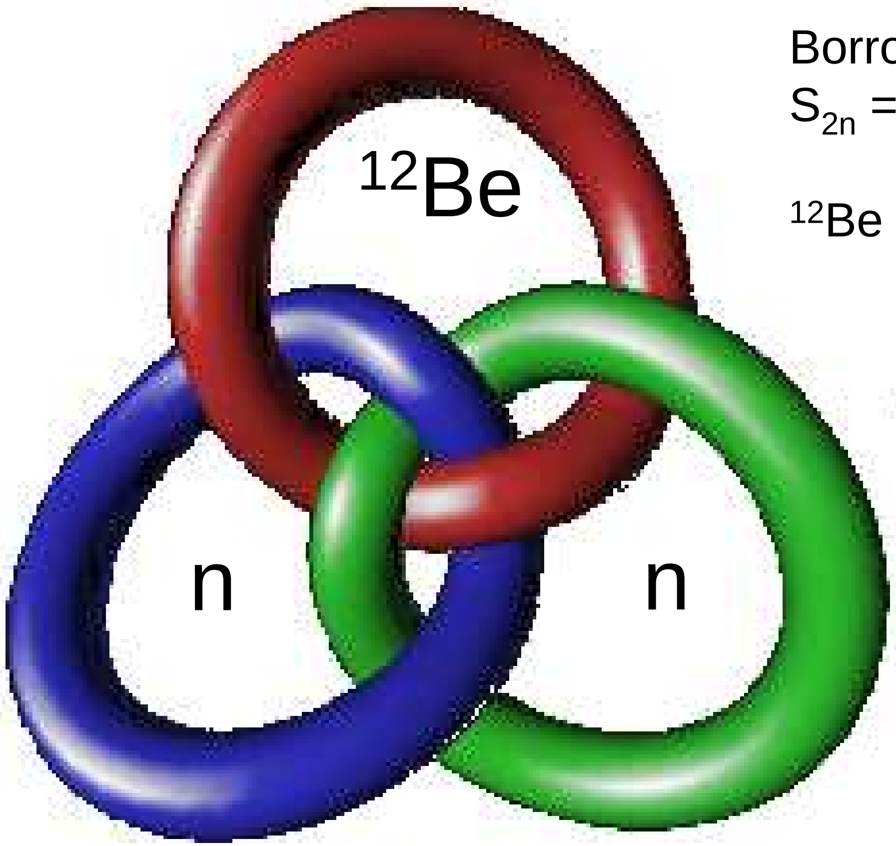
Borromean halo nucleus
S_{2n} = 1.12 MeV

^{12}Be S_n = 3.17 MeV

^{14}Be



There may be a component of the ground state that has this structure, which may account for the observation of the “tetraneutron” events (possible 4n resonance?)



Borromean halo nucleus
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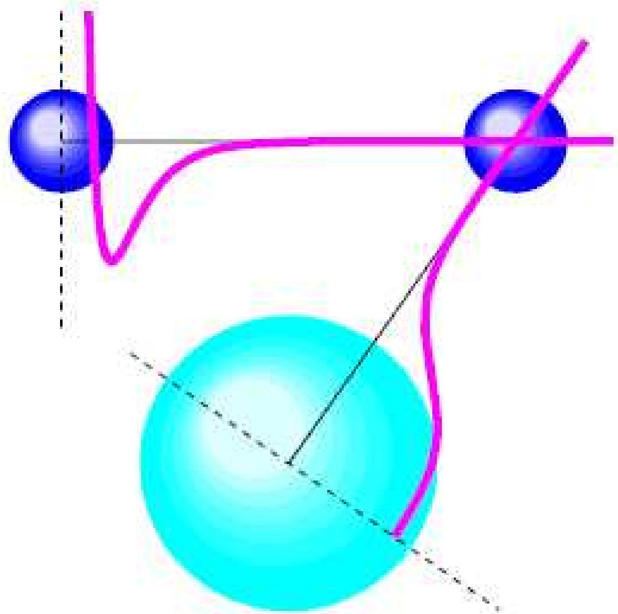
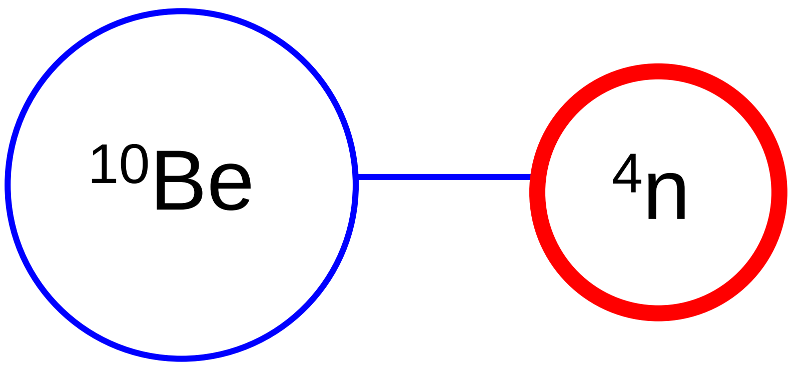




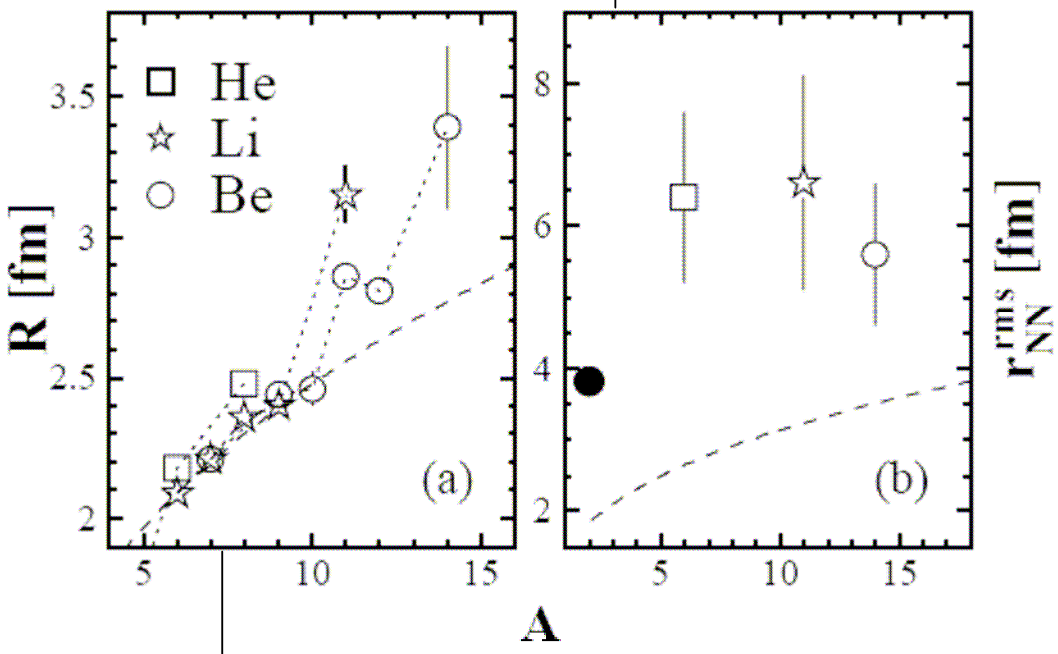
rms separations for core and neutrons in few-body **^{11}Li** model, compared to ranges of potentials

M.V. Zhukov *et al.*, Phys. Rep. **231**, 151 (1993).

Interferometry between the two neutrons at GANIL/DEMON measures their rms separation in the ^{14}Be source

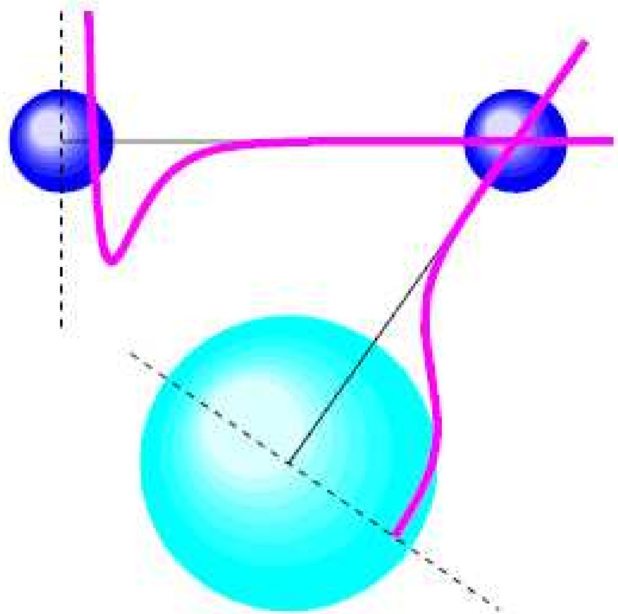
^{14}Be

F. M. MARQUES *et al.*
Physics Letters B 476 (2000) 219–225
PHYSICAL REVIEW C **64** 061301(R)



I. Tanihata *et al.*, Phys. Rev. Lett. **55**, 2676 (1985); Phys. Lett. B **206**, 592 (1988).

The interaction radius from total cross section measurements is clearly larger for halo nuclei



rms separations for core and neutrons in few-body ^{11}**Li** model, compared to ranges of potentials

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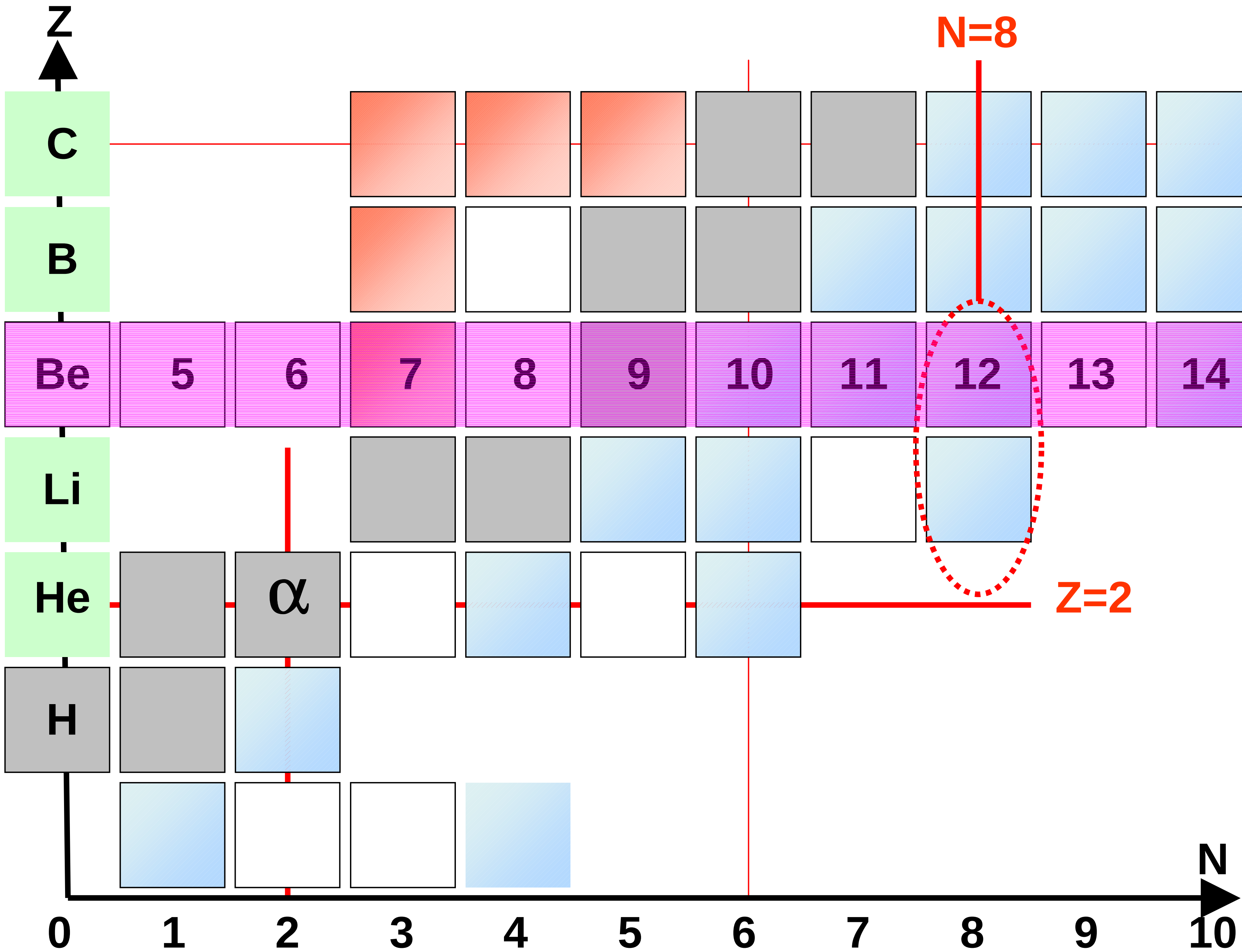
Z
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Li
He
α
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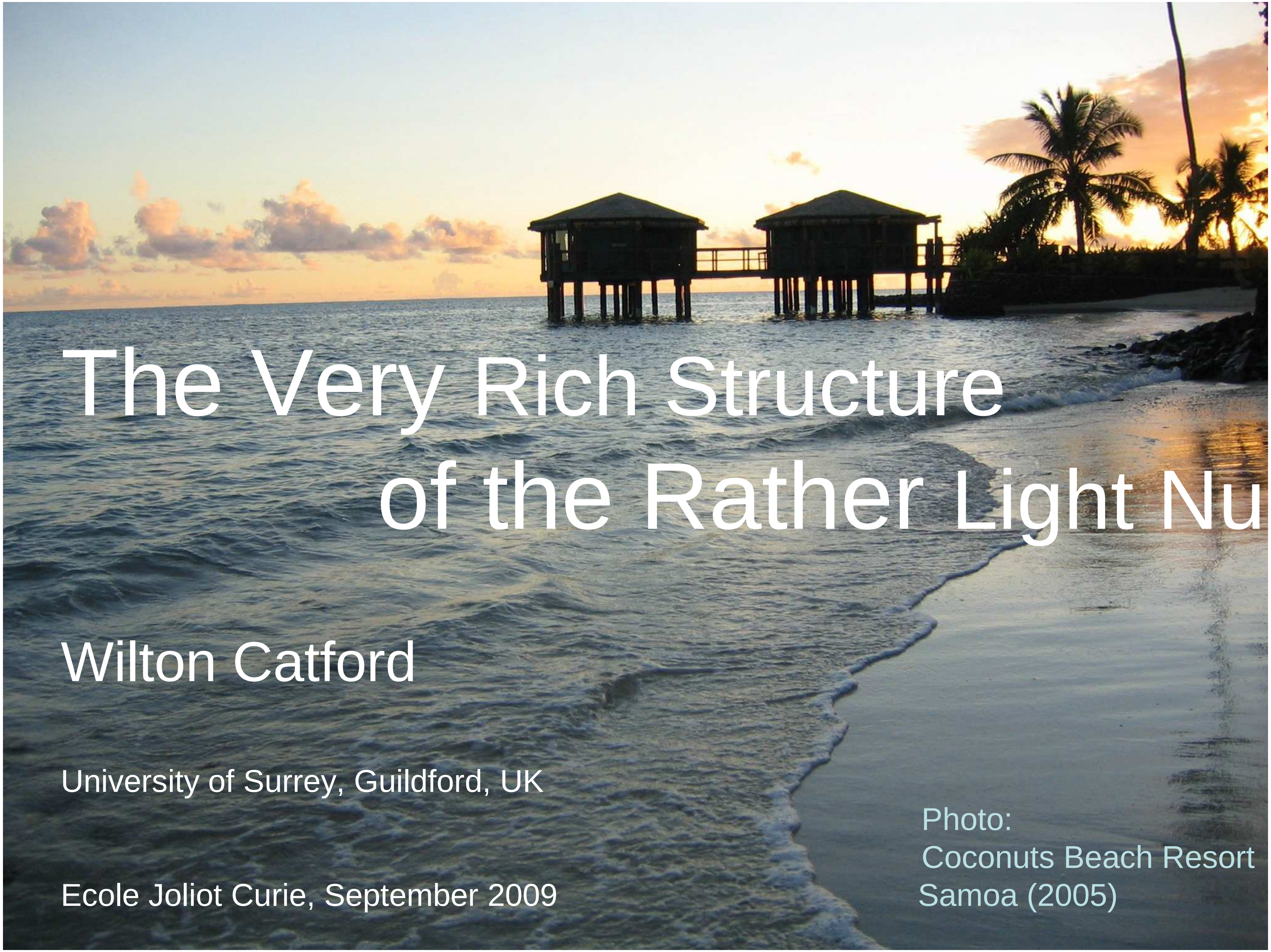
The Very Rich Structure
of the Rather Light Nu
Wilton Catford
University of Surrey, Guildford, UK
Ecole Joliot Curie, September 2009
Photo:
Coconuts Beach Resort
Samoa (2005)