Some questions in Nuclear Theory with a spanish flavour

Antonio Moro (U. Sevilla)
Joaquin Gómez Camacho (CNA)

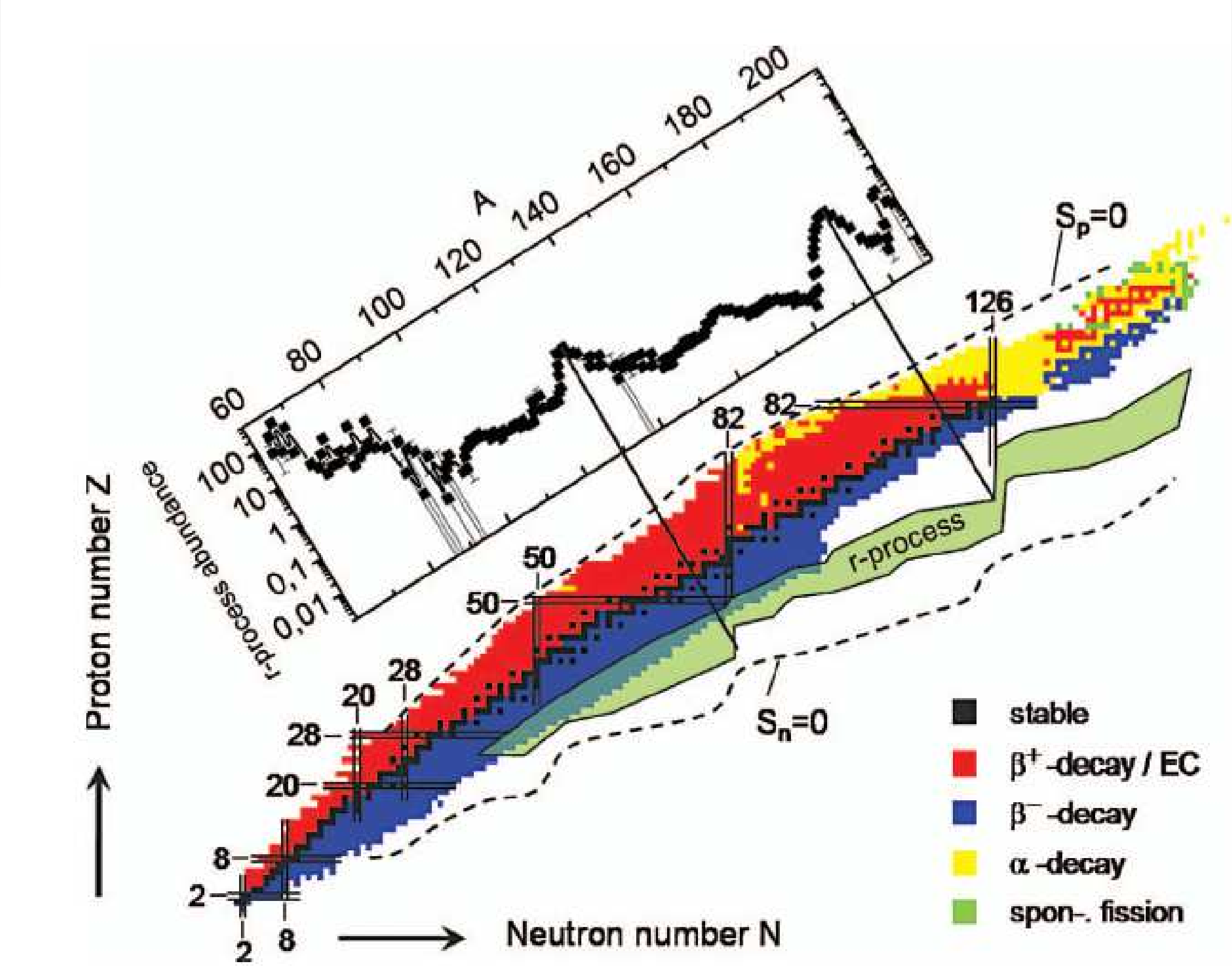
- Halo nuclei are made of inert cores and valence particles. Are cores really inert?

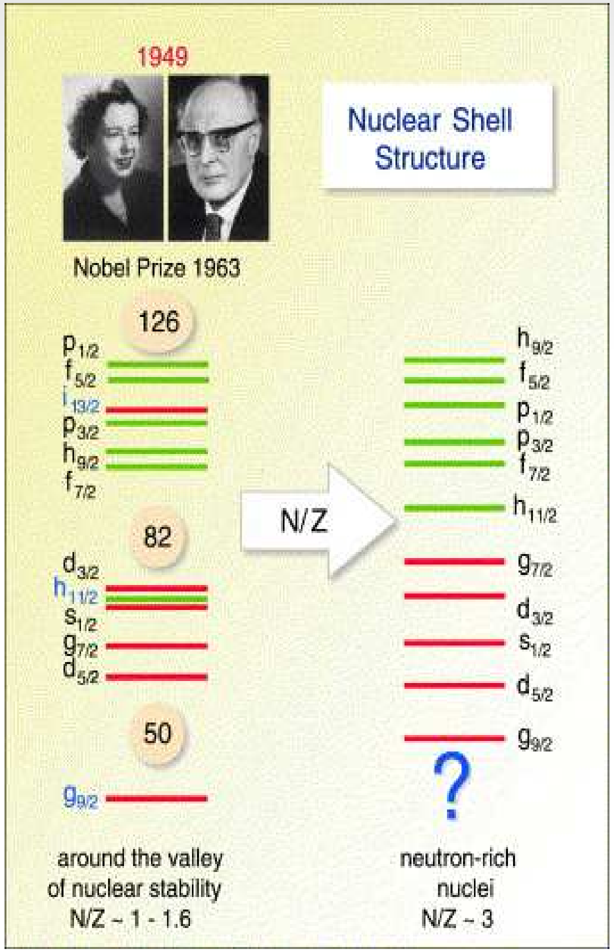
- Nuclei are specially stable when N or Z are magic numbers. Do they?

- Nuclei have a preferred shape, depending on their position in the chart of nuclides. Do they?

- Removal reactions measure spectroscopic factors. Do they?

Shell model

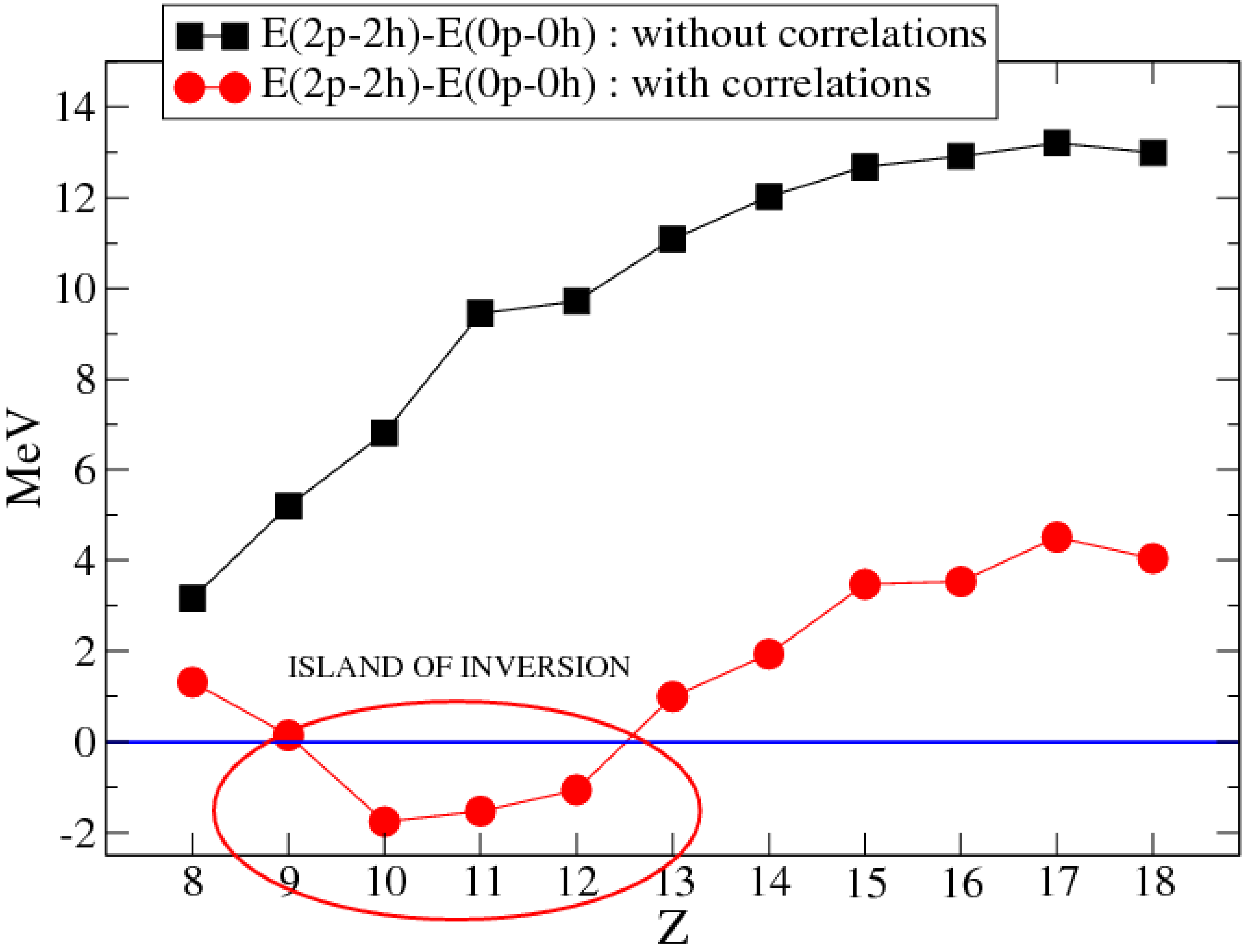

A
60
80
100
120
140
160
180
200
r-process abundance
100
10
1
0,1
0,01
S_p=0
S_n=0
126
82
82
50
50
28
28
20
20
8
8
2
2
r-process
Proton number Z
Neutron number N
stable
β⁺-decay / EC
β⁻-decay
α-decay
spon-. fission


1949
Nobel Prize 1963
Nuclear Shell Structure
126
$p_{1/2}$
$f_{5/2}$
$i_{13/2}$
$p_{3/2}$
$h_{9/2}$
$f_{7/2}$
82
$d_{3/2}$
$h_{11/2}$
$s_{1/2}$
$g_{7/2}$
$d_{5/2}$
50
$g_{9/2}$
N/Z
$h_{9/2}$
$f_{5/2}$
$p_{1/2}$
$p_{3/2}$
$f_{7/2}$
$h_{11/2}$
$g_{7/2}$
$d_{3/2}$
$s_{1/2}$
$d_{5/2}$
$g_{9/2}$
?
around the valley of nuclear stability N/Z ~ 1 - 1.6
neutron-rich nuclei N/Z ~ 3

Shell inversion

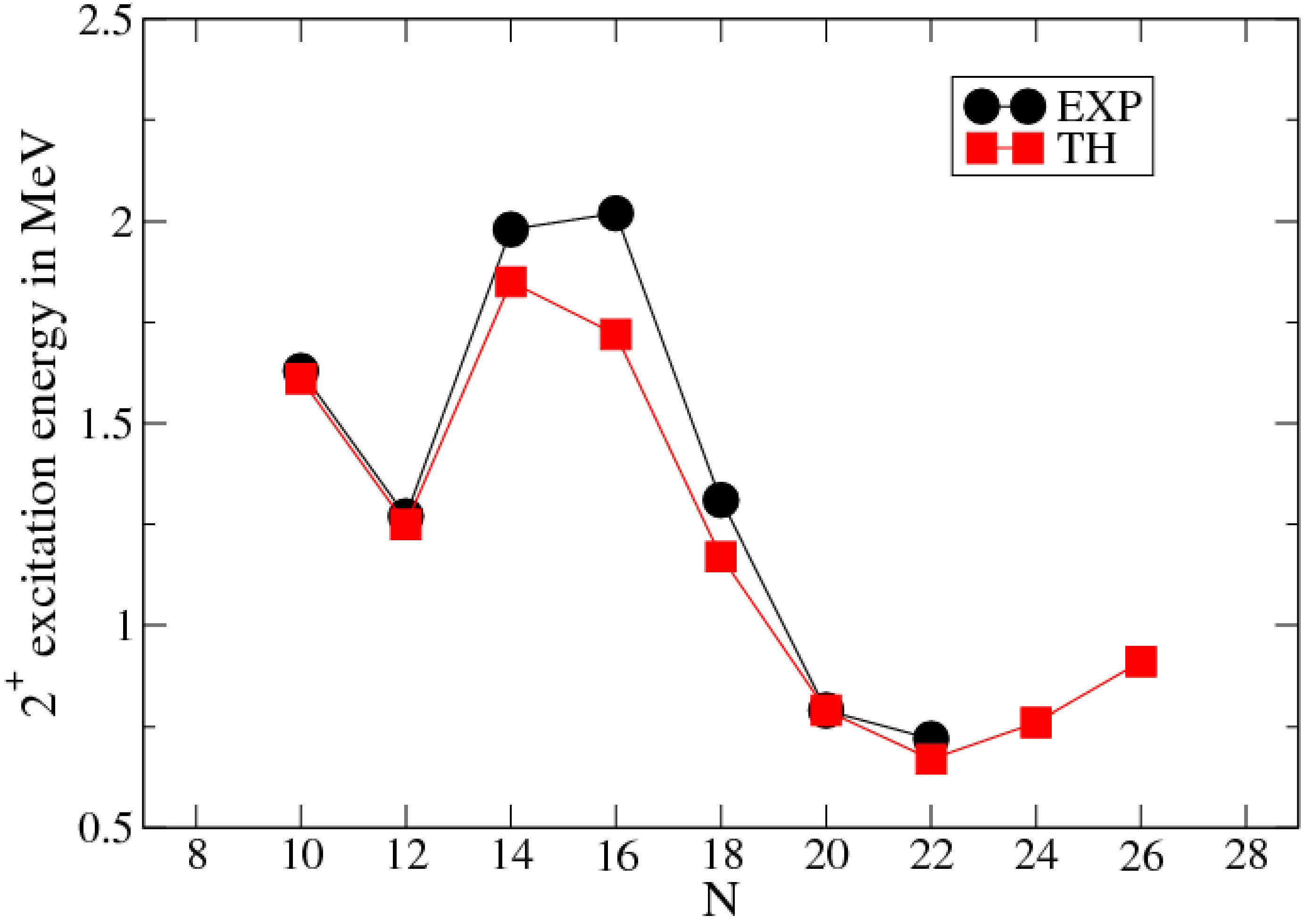
- N=20 and N=28 are closed shells. Do they remain so for neutron rich sd shell nuclei?
- PRC 90, 014302 (2014) *Merging of the islands of inversion at N = 20 and N = 28*. E. Caurier, F. Nowacki,1 and A. Poves
- sdpf shell model calculations, $8<Z<20$, $8<N<40$

2p-2h energy for N=20



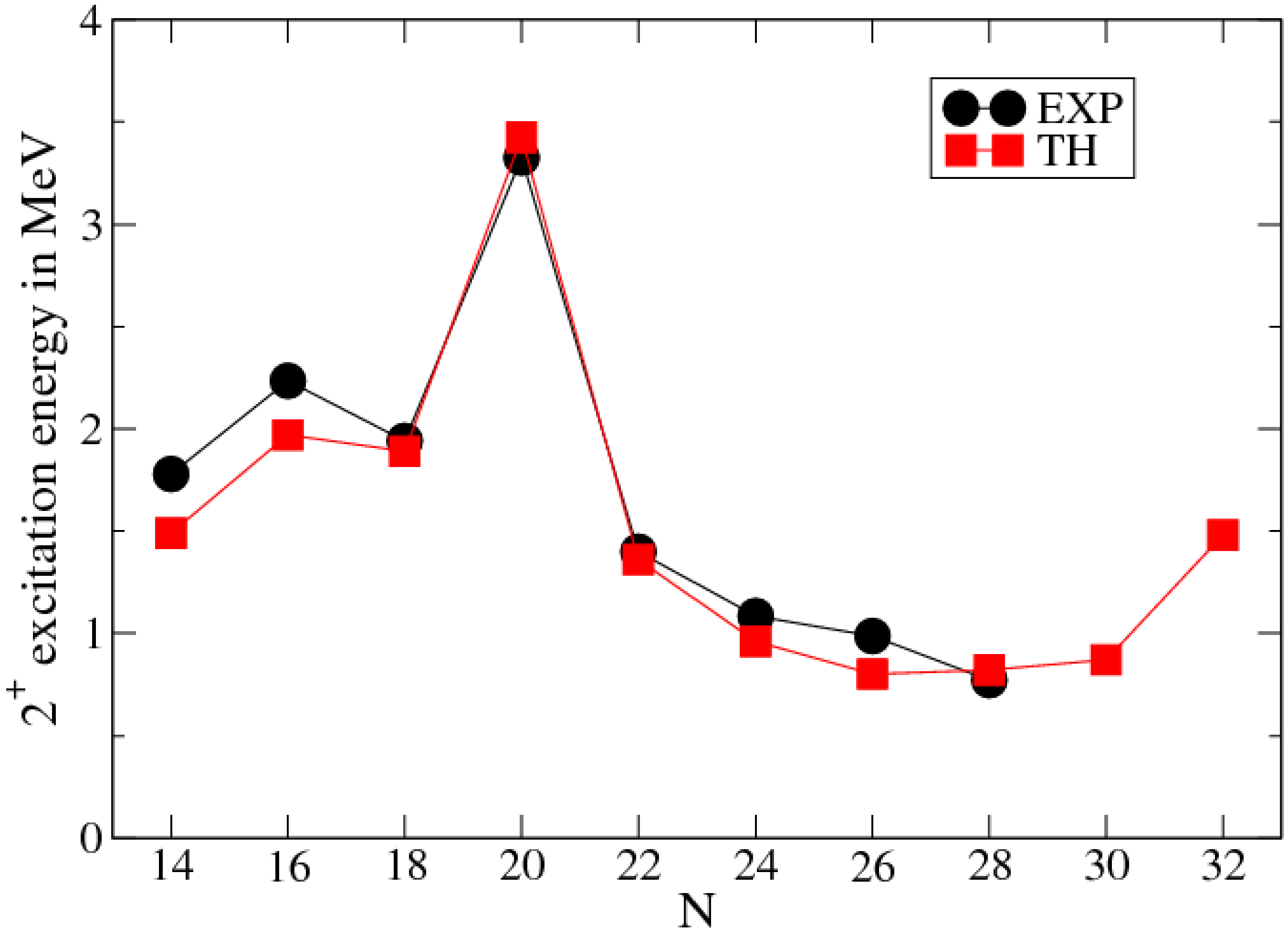
The reduction of the shell gap, and the effect of correlations make 2p-2h configurations preferred to closed shell 0p-0h for N=20, for Ne, Na and Mg

Ne Isotopes (Z=10)



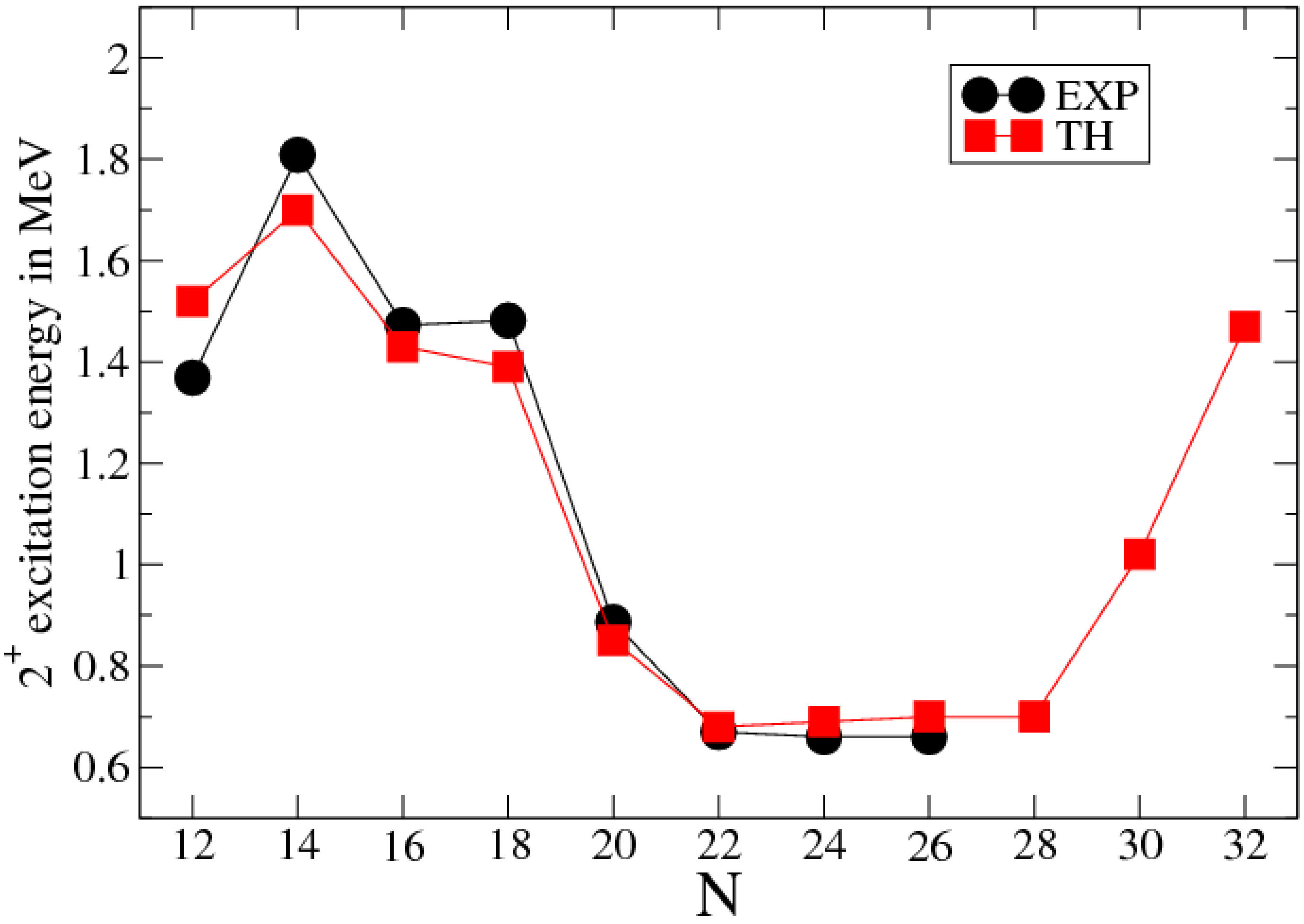
32Ne (N=20) is not in a neutron closed shell. 2p-2h configurations dominate. The energy of the 2+ state drops.

Si Isotopes (Z=14)



34Si (N=20) is a neutron closed shell, but 42Si (N=28) is not. 2p-2h configurations dominate and the energy of the 2+ state drops for N=28.

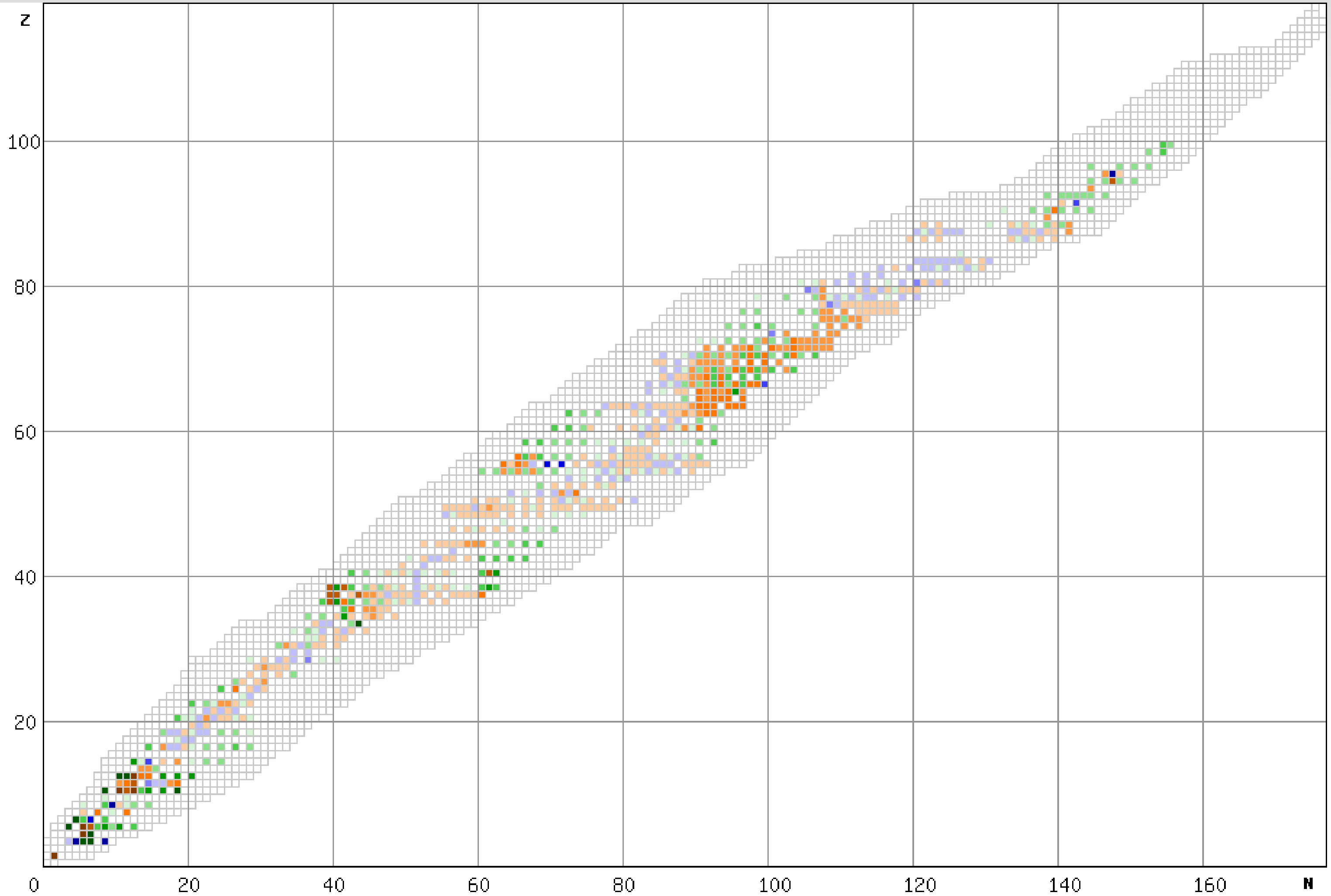
Mg Isotopes (Z=12)



32Mg (N=20) is not a neutron closed shell, and theory predicts 40Mg (N=28) is not either.

Is theory right?

Shapes in nuclei



Nuclei in closed shells are spherical, and in open shells are deformed.

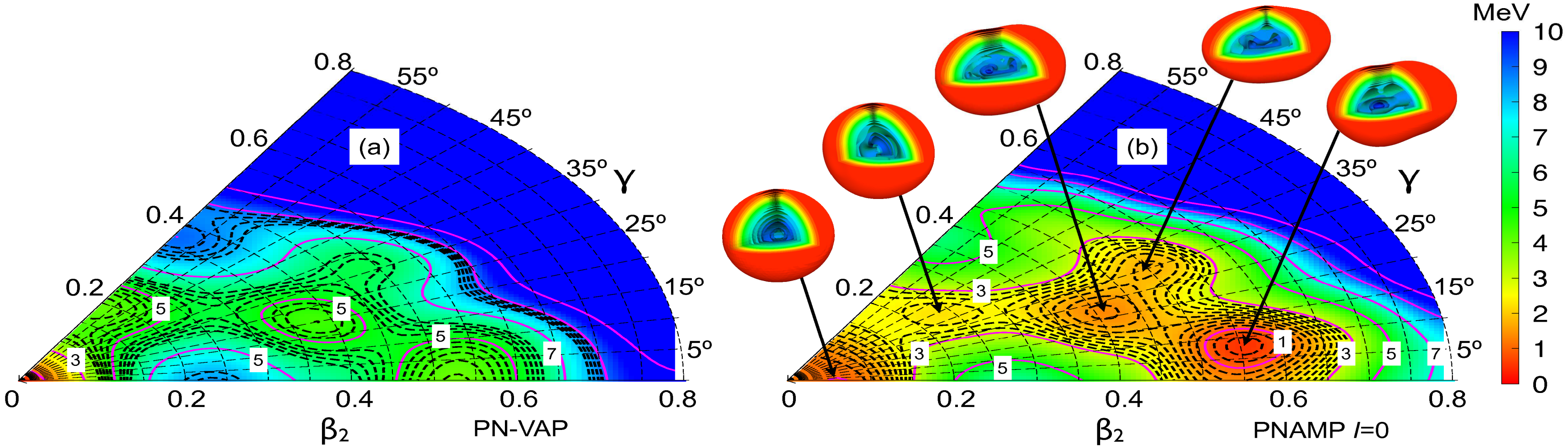
80Zr (Z=N=40). Shape coexistence

- N,Z=40 is a closed sub-shell. What is the shape of 80Zr?
- Multiple shape coexistence in the nucleus 80Zr

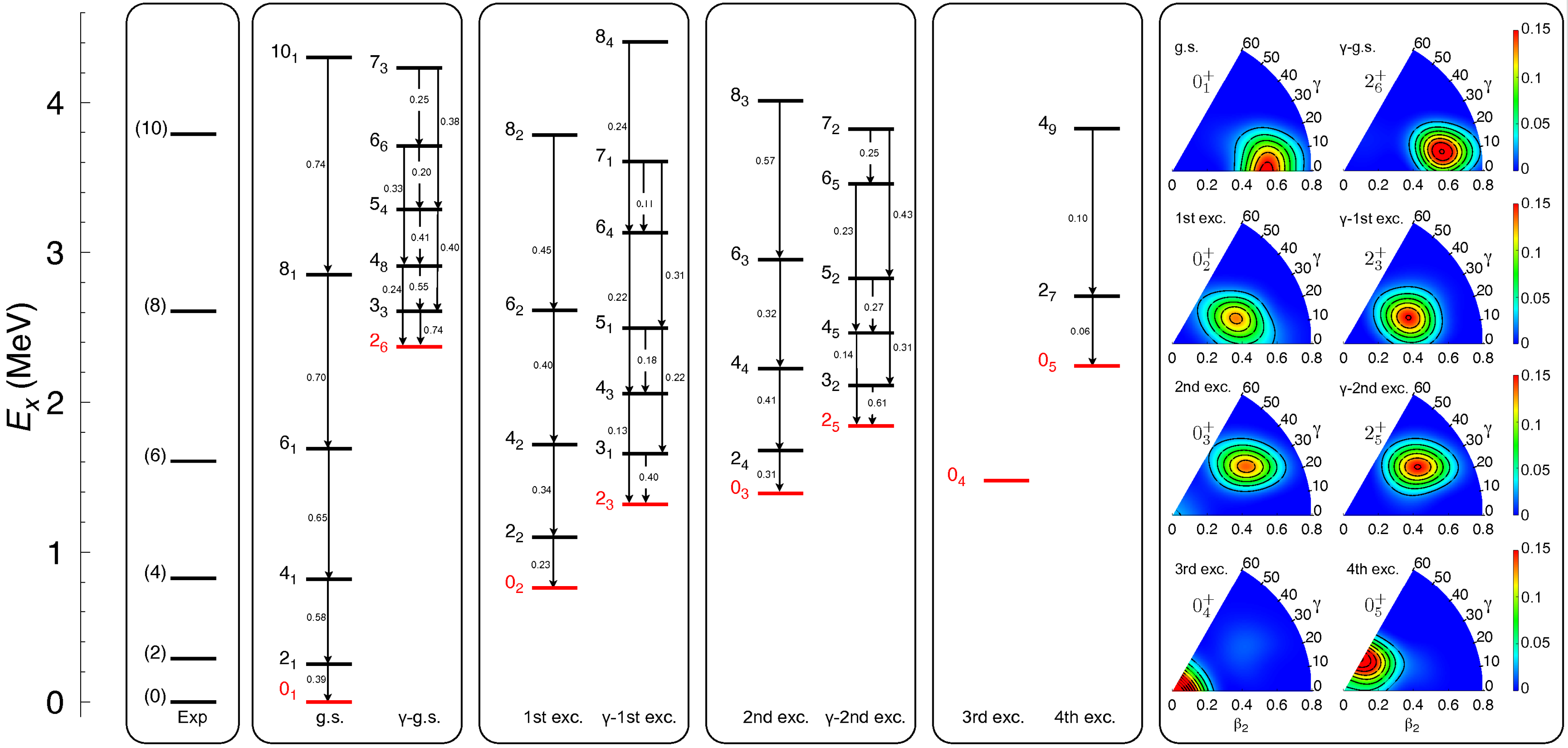
Tomás R. Rodríguez, J. Luis Egido

Phys. Lett. B 705 (2011) 255–259

- (Beyond the) Mean Field calculation.



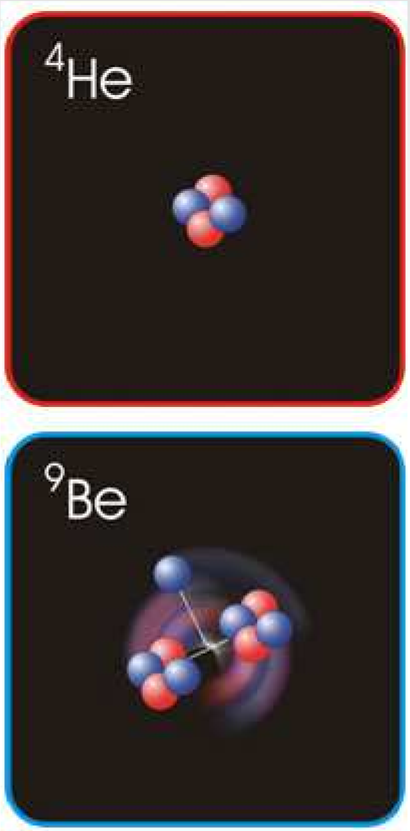
Spherical, prolate deformed, oblate deformed and two tri-axial shapes appear.

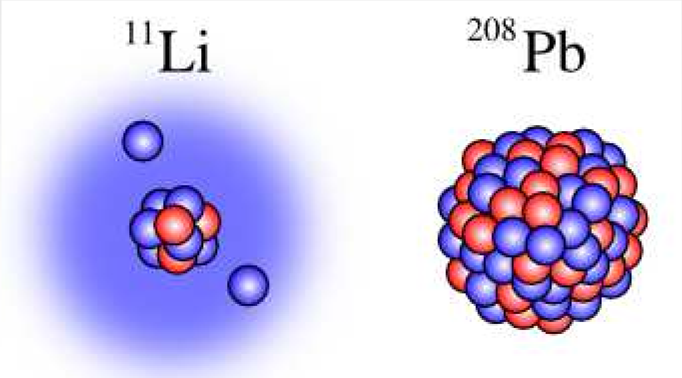


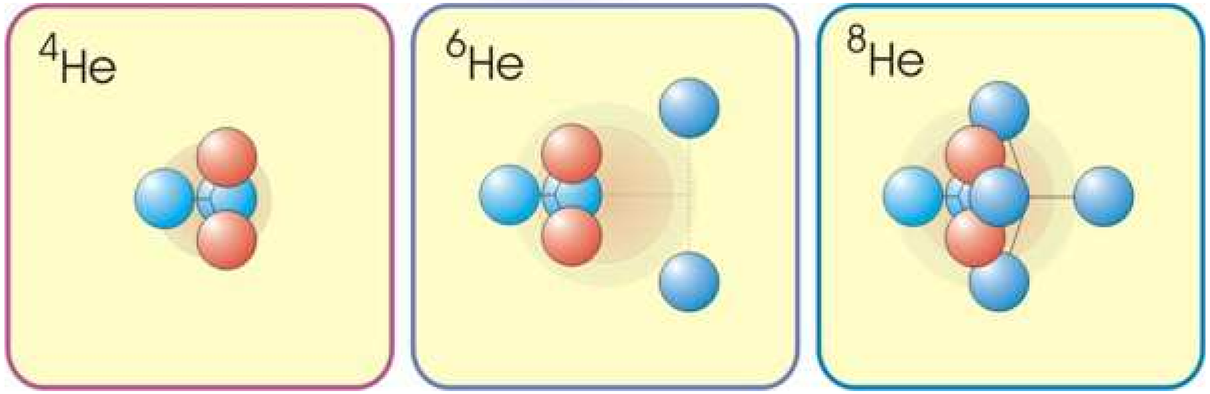
Theory explains the observed strongly deformed g.s band.
It predicts two tri-axial, a spherical and an oblate band.

Is theory right?

3 body structures





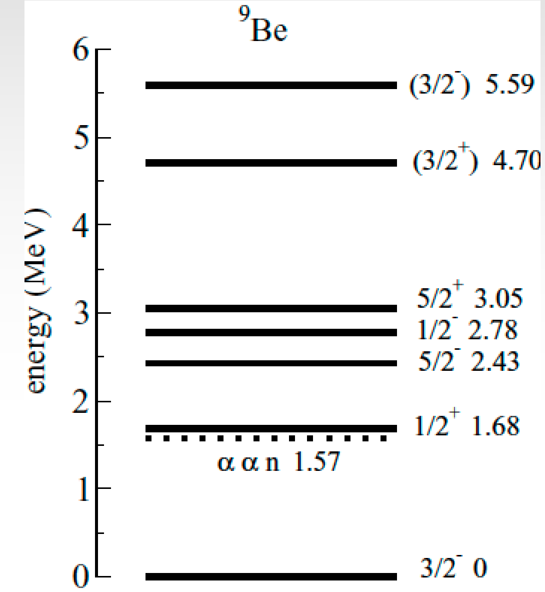


- M. Rodriguez-Gallardo et al. 3-body continuum discretization.

- E. Garrido et al. 3-body resonances through complex rotations.

Structure and decay of three-body resonances (E. Garrido et al)

- ✓ Three-body resonance wave functions can be computed through the complex-rotated hyperspherical adibatic expansion method.
- ✓ The energy distribution of the fragments and the branching ratio for direct and sequential decay can be computed for reactions like, i.e., ^{9}Be + γ→ ^{9}Be* →α+α+n



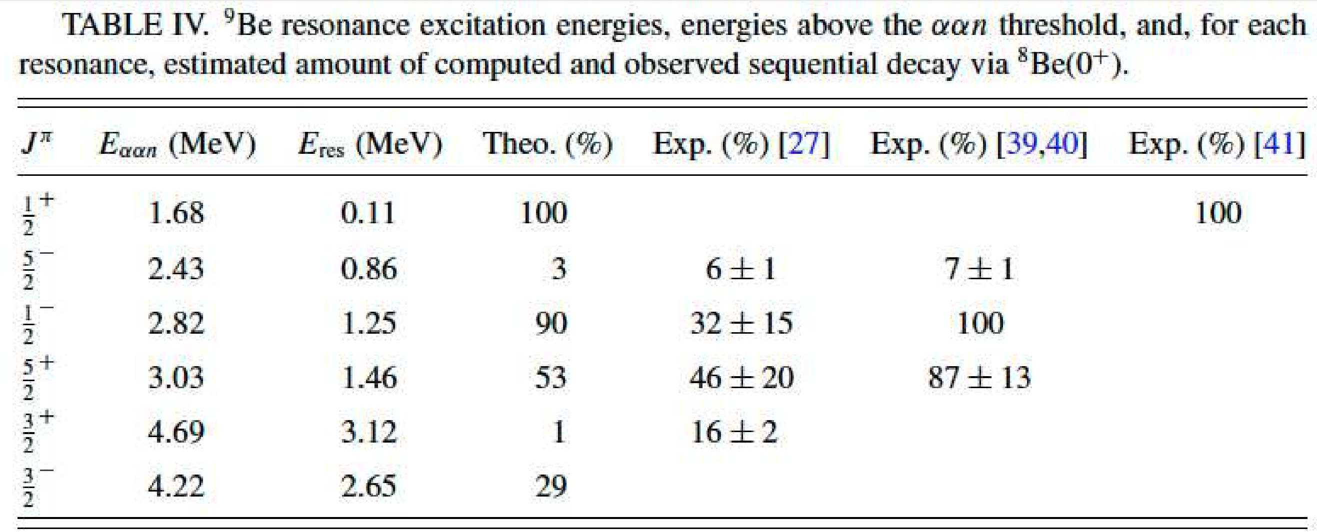
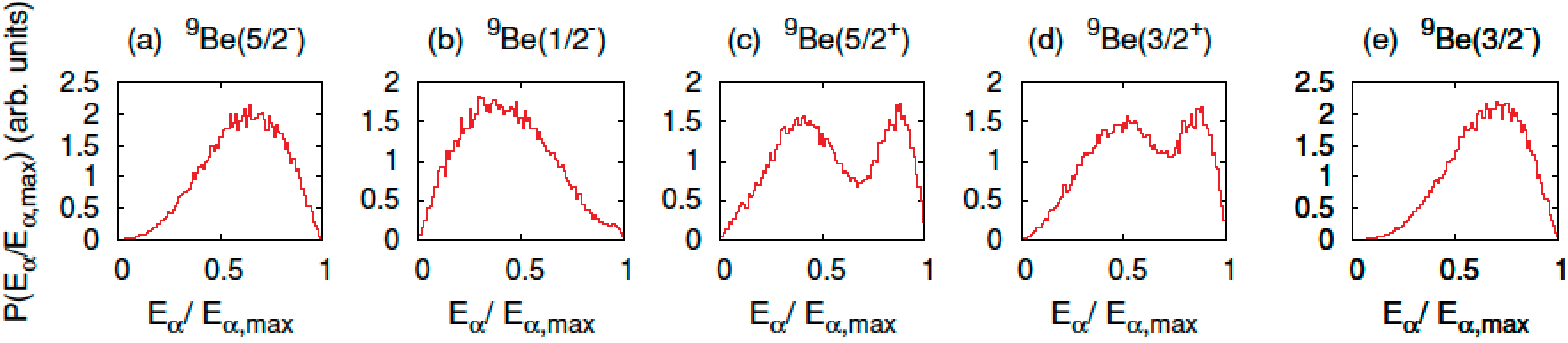


TABLE IV. ^{9}Be resonance excitation energies, energies above the $\alpha\alpha n$ threshold, and, for each resonance, estimated amount of computed and observed sequential decay via ^{8}Be(0^+).

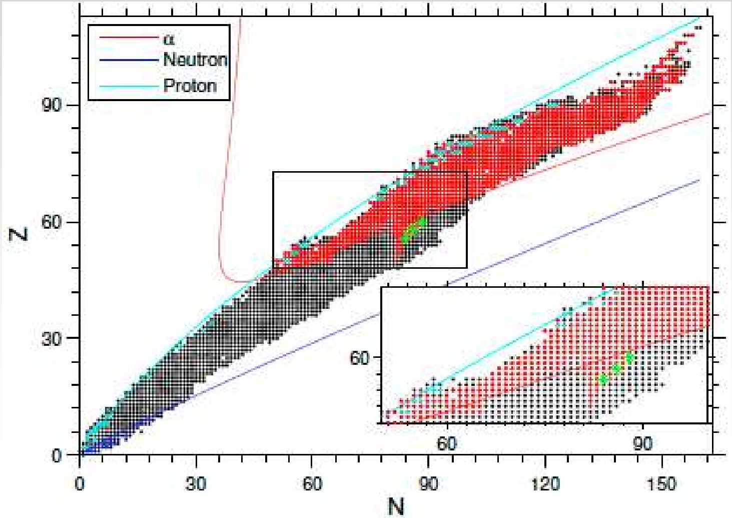
J^π	$E_{\alpha\alpha n}$ (MeV)	$E_{\rm res}$ (MeV)	Theo. (%)	Exp. (%) [27]	Exp. (%) [39,40]	Exp. (%) [41]
$\frac{1}{2}^+$	1.68	0.11	100			100
$\frac{5}{2}^-$	2.43	0.86	3	6 ± 1	7 ± 1	
$\frac{1}{2}^-$	2.82	1.25	90	32 ± 15	100	
$\frac{5}{2}^+$	3.03	1.46	53	46 ± 20	87 ± 13	
$\frac{3}{2}^+$	4.69	3.12	1	16 ± 2		
$\frac{3}{2}^-$	4.22	2.65	29			

α-particle energy distribution after resonance decay into α+α+n



Borromean Structures in medium heavy nuclei

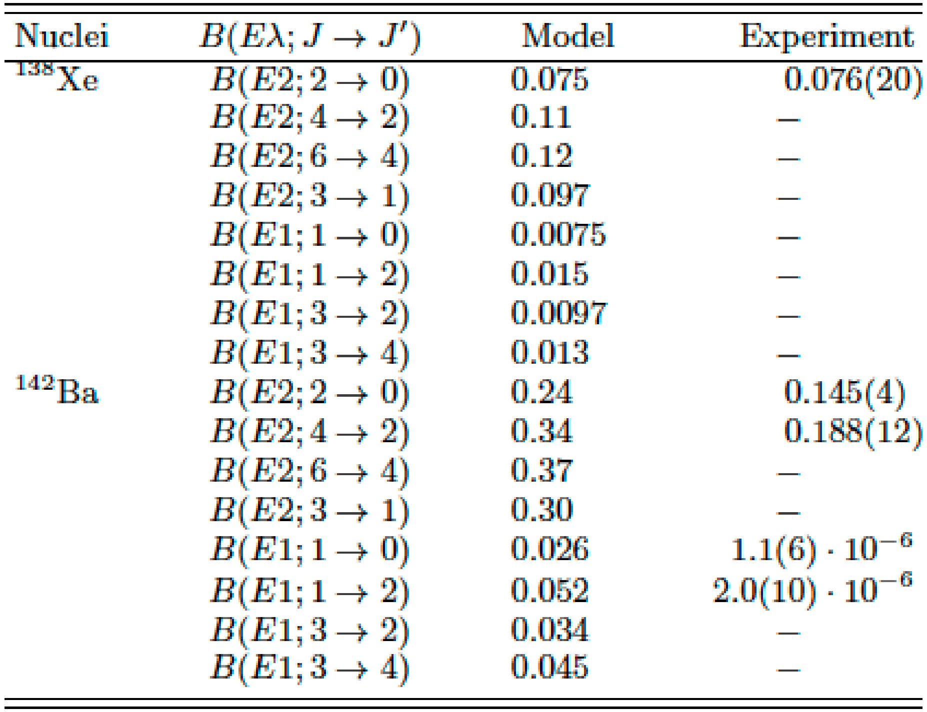
- ✓ Borromean nuclear cluster structures are expected at the corresponding driplines.
- ✓ We locate the regions in the nuclear chart with the most promising systems corresponding to possible borromean two-alpha structures.



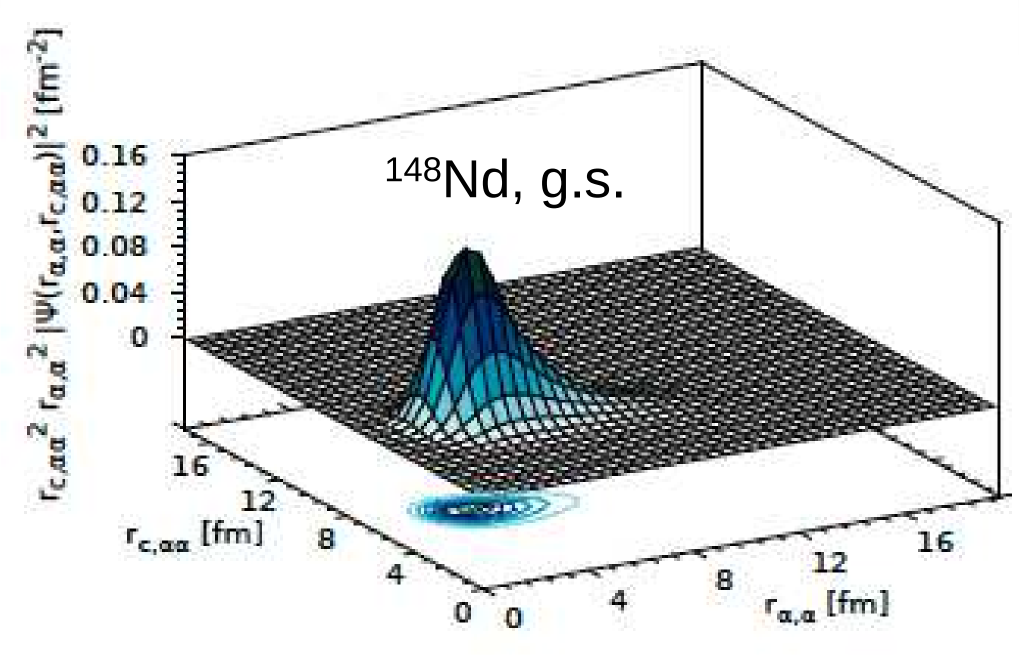
Theoretical alpha (red), neutron (dark blue), and proton (light blue) driplines.
Marked in green: ^{140}Ba, ^{144}Ce (^{140}Ba+α), ^{148}Nd (^{140}Ba+2α)

Examples

^{144}Ce = ^{140}Ba+α
^{148}Nd = ^{140}Ba+α+α
^{138}Xe = ^{134}Te+α
^{142}Ba = ^{134}Te+α+α



Nuclei	$B(E\lambda; J \to J')$	Model	Experiment
^{138}Xe	$B(E2; 2 \to 0)$	0.075	0.076(20)
	$B(E2; 4 \to 2)$	0.11	–
	$B(E2; 6 \to 4)$	0.12	–
	$B(E2; 3 \to 1)$	0.097	–
	$B(E1; 1 \to 0)$	0.0075	–
	$B(E1; 1 \to 2)$	0.015	–
	$B(E1; 3 \to 2)$	0.0097	–
	$B(E1; 3 \to 4)$	0.013	–
^{142}Ba	$B(E2; 2 \to 0)$	0.24	0.145(4)
	$B(E2; 4 \to 2)$	0.34	0.188(12)
	$B(E2; 6 \to 4)$	0.37	–
	$B(E2; 3 \to 1)$	0.30	–
	$B(E1; 1 \to 0)$	0.026	$1.1(6) \cdot 10^{-6}$
	$B(E1; 1 \to 2)$	0.052	$2.0(10) \cdot 10^{-6}$
	$B(E1; 3 \to 2)$	0.034	–
	$B(E1; 3 \to 4)$	0.045	–



In all the cases the alpha-particles are located at the surface of the core nucleus. The lowest three-body bound states resemble a slightly contracted 8Be nucleus outside the core

- Weakly bound nuclei (both light and heavy) present structures in the continuum due to 3-body correlations.
- Theory can describe 3-body correlations in the continuum (resonant and non-resonant).
- Coincidence measurements of charged fragments (and/or neutrons) would be a challenge for theory. For example, 2 alpha correlations in Be-induced reactions.
- Is theory right?

Halos and Cores

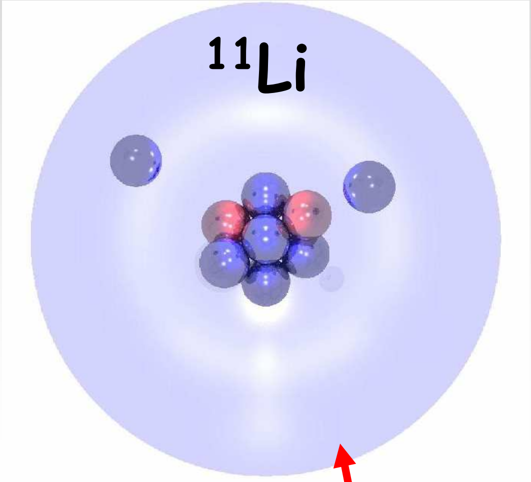
➔ Nuclei close to drip-lines (Sn~0 or Sp~0)

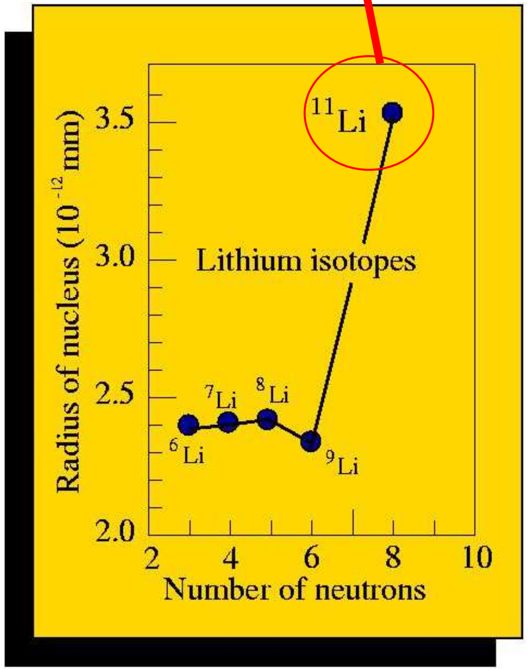
➔ 1 or 2 loosely bound nucleons moving far away from a compact *core*.

- ✓ 1n haloes: ^{11}Be
- ✓ 2n haloes (Borromean): ^{6}He, ^{11}Li
- ✓ 1p haloes: ^{8}B, ^{17}Ne.

Reactions

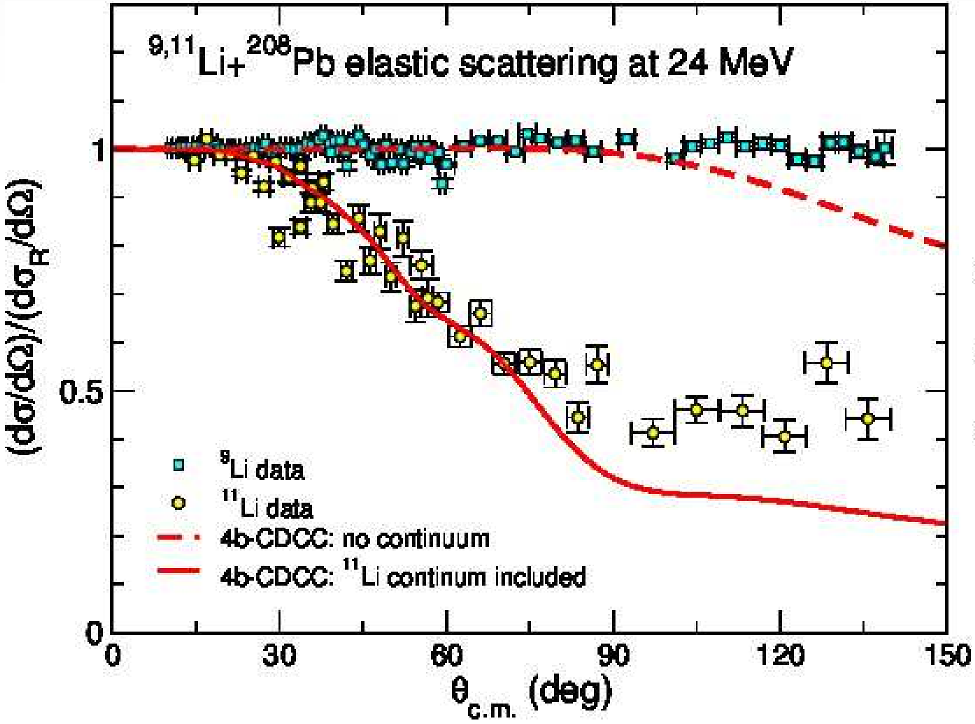
- ➢ Large reaction cross sections
- ➢ Narrow momentum distributions of fragments arising from breakup
- ➢ Large B(E1) strengths

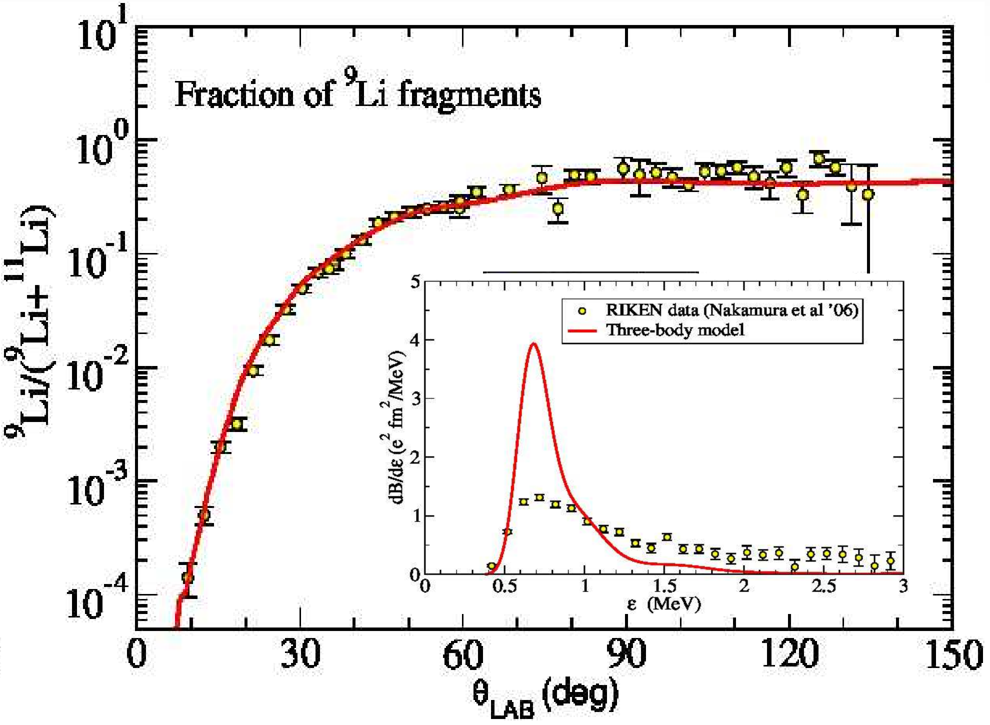




^{11}Li+^{208}Pb elastic scattering: the largest deviation from Rutherford formula ever observed

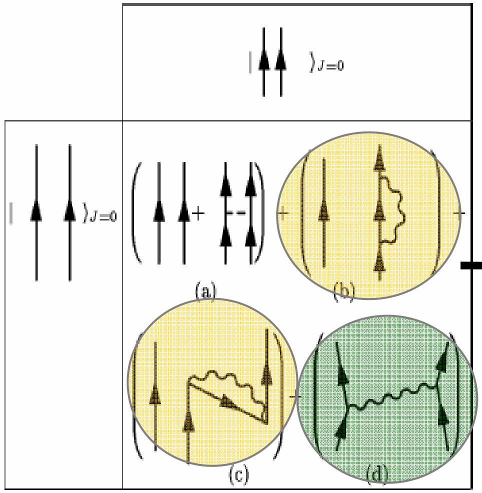
- ^{11}Li very weakly-bound (S_{2n}=370 KeV)
- ^{11}Li structure highly distorted by the electric field of a Pb target
- Large breakup yield (^{9}Li)





Structure and reaction calculation assuming an inert 9Li Core.
M. Rodriguez-Gallardo. 4b-CDCC

Effects of core polarization in light halo nuclei.



Nuclear Field Theory Energy Dependent Hamiltonian

	E_bind (MeV)	2s1/2^2	1p1/2^2	1d5/2^2	spx1-	sdx2+	pdx3-
11Li(GS)	0.40	0.45	0.55	0.04	0.70	0.10	0.00
12Be(GS)	3.10	0.37	0.51	0.61	0.10	0.35	0.33
12Be(EXC.)*	1.10	0.76	0.49	0.27	0.01*	0.32	0.14

Table 2. Amplitudes (full wave normalized to 1)

(*)Proper 1- to be calculated

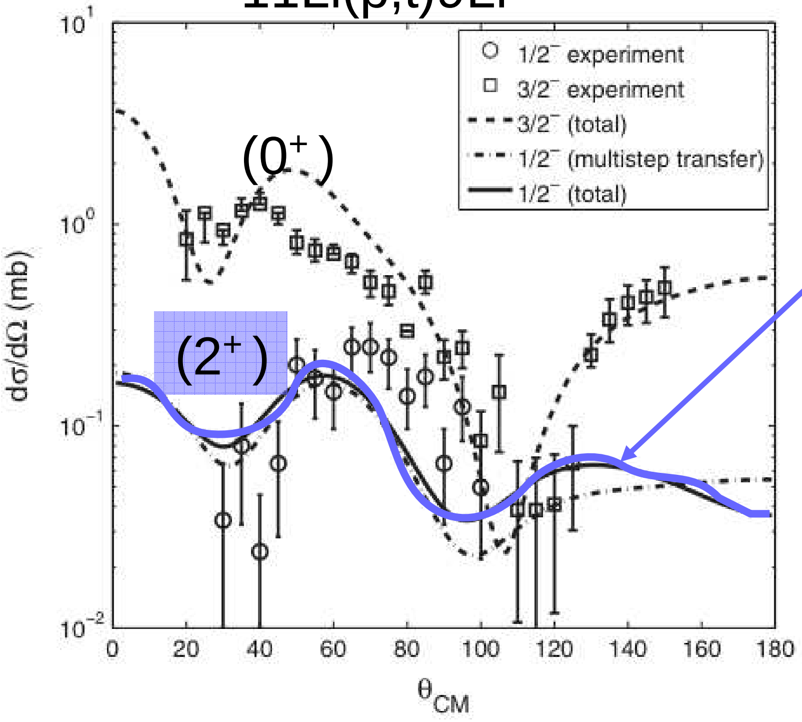
-11Li stability, Parity inversion, Spectr. factors,,,

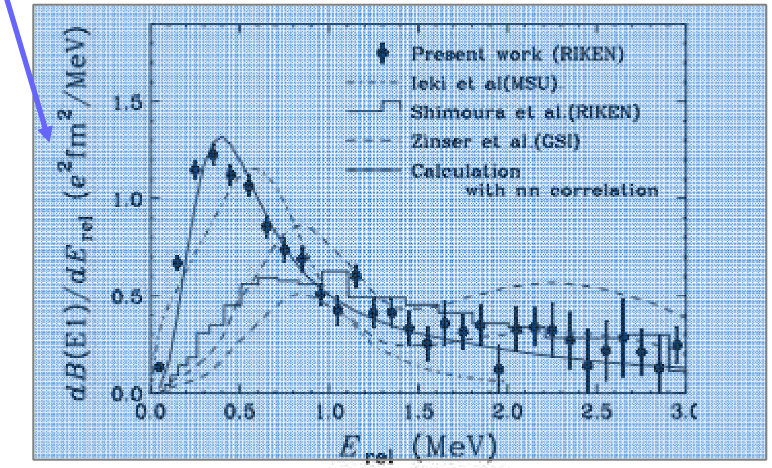
- Cross sections to 2+ and 3-, expected for 12Be(p,t)10Be.

- Low lying 0+ exc. in 12Be, isomer close to threshold => A secondary spectroscopy;

PossibleDipole Strength at low energy based on 12Be(EXC.) similar to 11Li's?

11Li(p,t)9Li

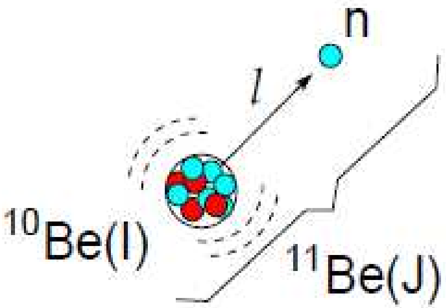




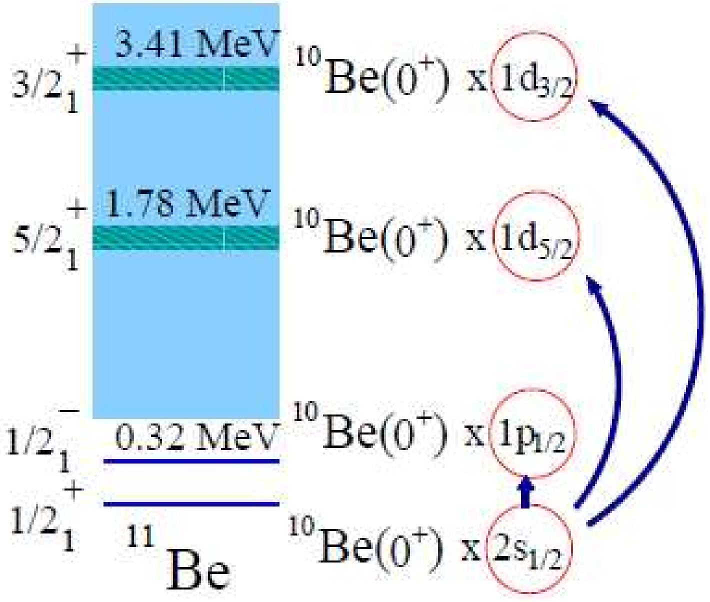
G. Potel et al., PRL 105 (2010) 172502

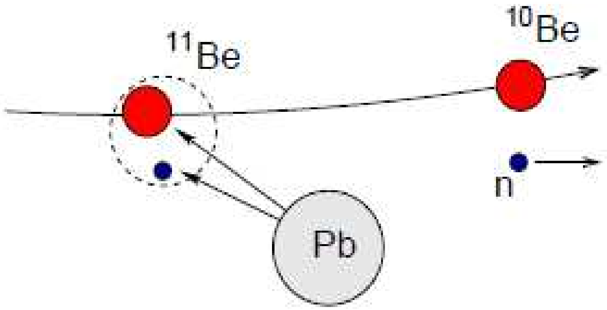
Core excitation in reactions: *frozen-halo* picture

$$\Psi_{JM}(\vec{r},\xi) = \left[\varphi^{J}_{\ell,j}(\vec{r}) \otimes \Phi_I(\xi)\right]_{JM}$$

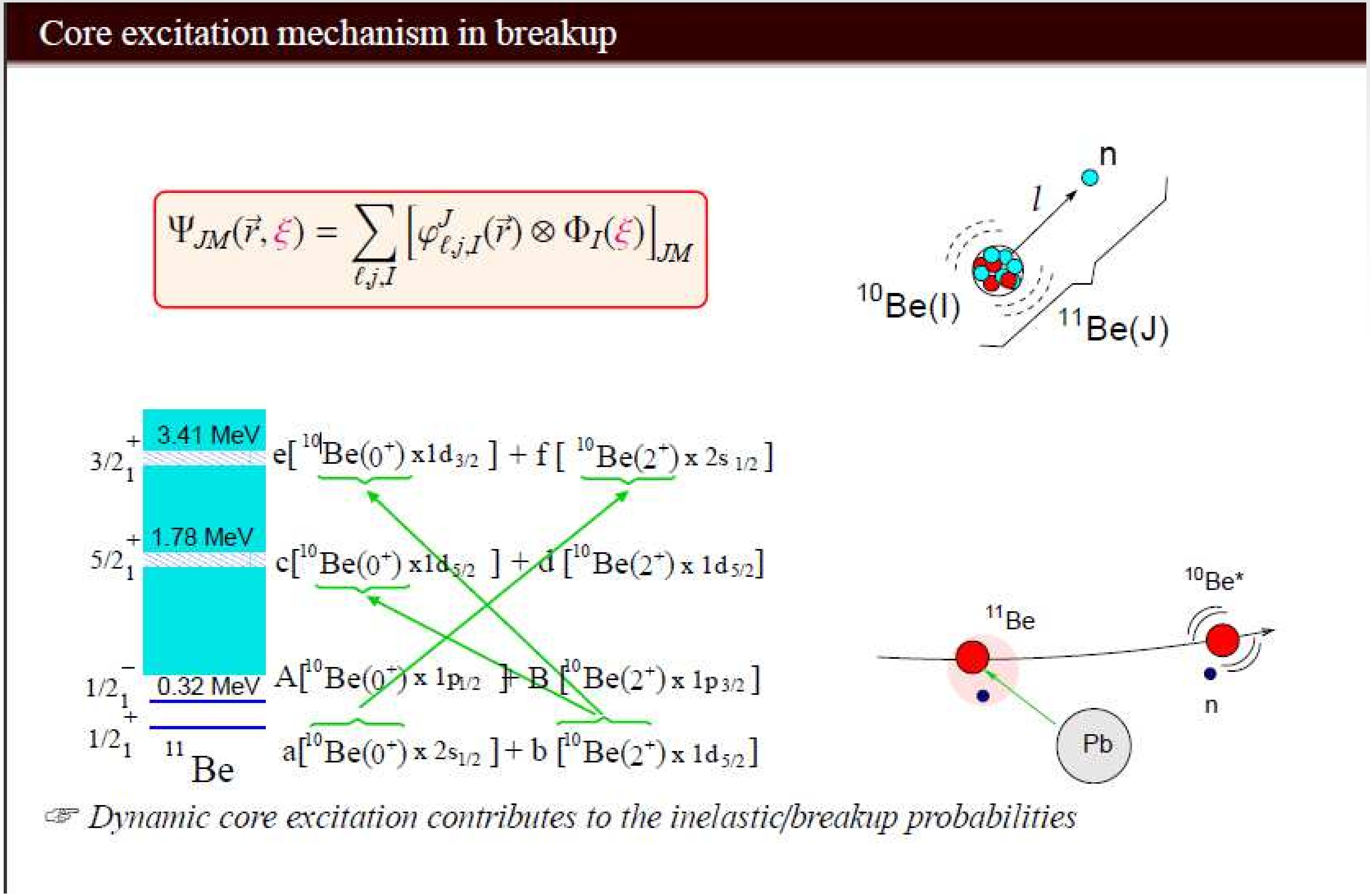


- ➪ $\varphi^{J}_{\ell,j}(\vec{r})$= valence particle wavefunction
- ➪ $\Phi_I(\xi)$= core wavefunction (*frozen*)





How does the excitation of the core affect the reaction dynamics?



Core excitation mechanism in breakup

$$\Psi_{JM}(\vec{r},\xi) = \sum_{\ell,j,I}\left[\varphi^{J}_{\ell,j,I}(\vec{r})\otimes\Phi_{I}(\xi)\right]_{JM}$$

$e[^{10}\mathrm{Be}(0^+)\times 1d_{3/2}] + f[^{10}\mathrm{Be}(2^+)\times 2s_{1/2}]$

$c[^{10}\mathrm{Be}(0^+)\times 1d_{5/2}] + d[^{10}\mathrm{Be}(2^+)\times 1d_{5/2}]$

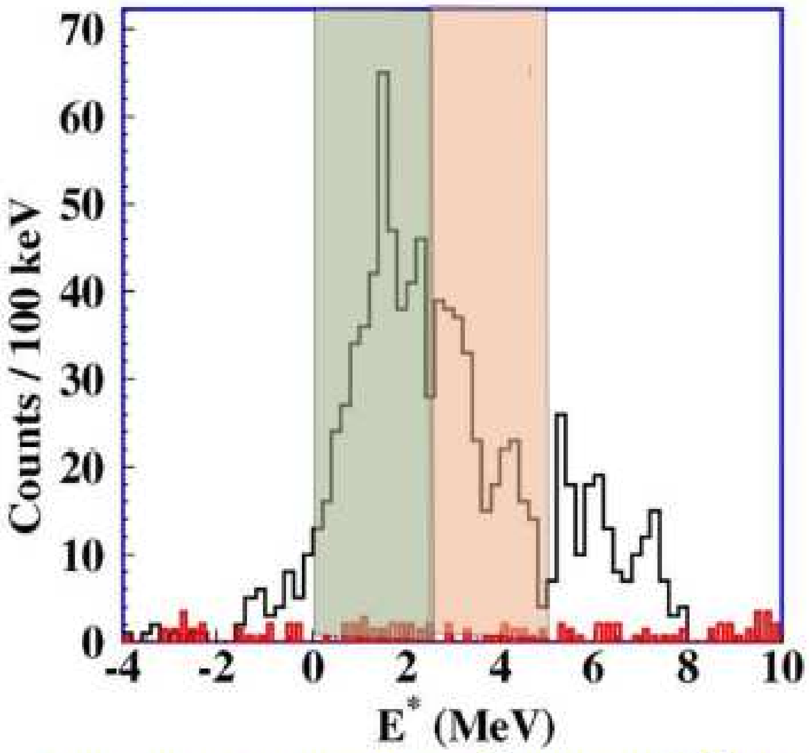
$A[^{10}\mathrm{Be}(0^+)\times 1p_{1/2}] + B[^{10}\mathrm{Be}(2^+)\times 1p_{3/2}]$

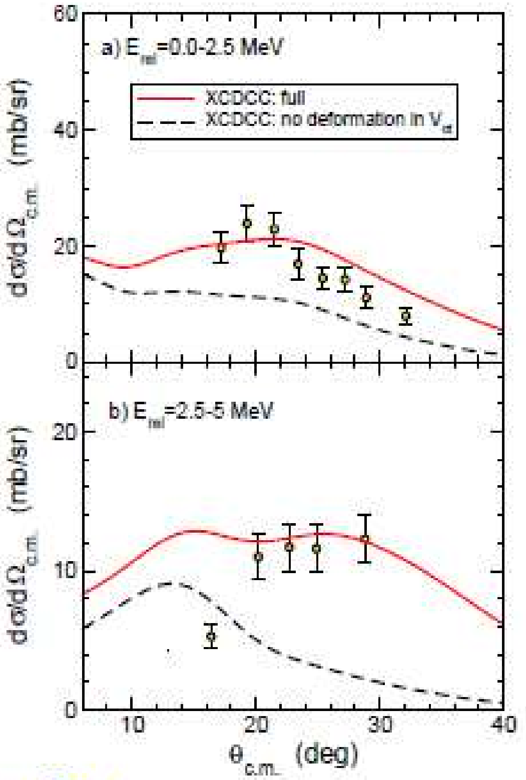
$a[^{10}\mathrm{Be}(0^+)\times 2s_{1/2}] + b[^{10}\mathrm{Be}(2^+)\times 1d_{5/2}]$

☞ *Dynamic core excitation contributes to the inelastic/breakup probabilities*

Eg: importance of core excitation in resonant breakup of ^{11}Be

Data: *Shrivastava et al, PLB596 (2004) 54* (MSU)

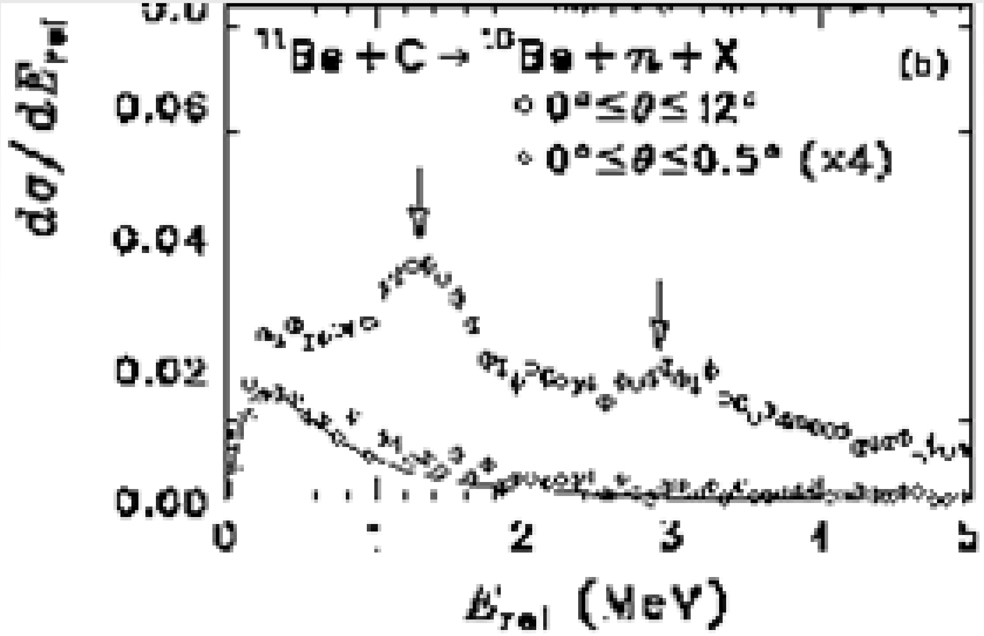




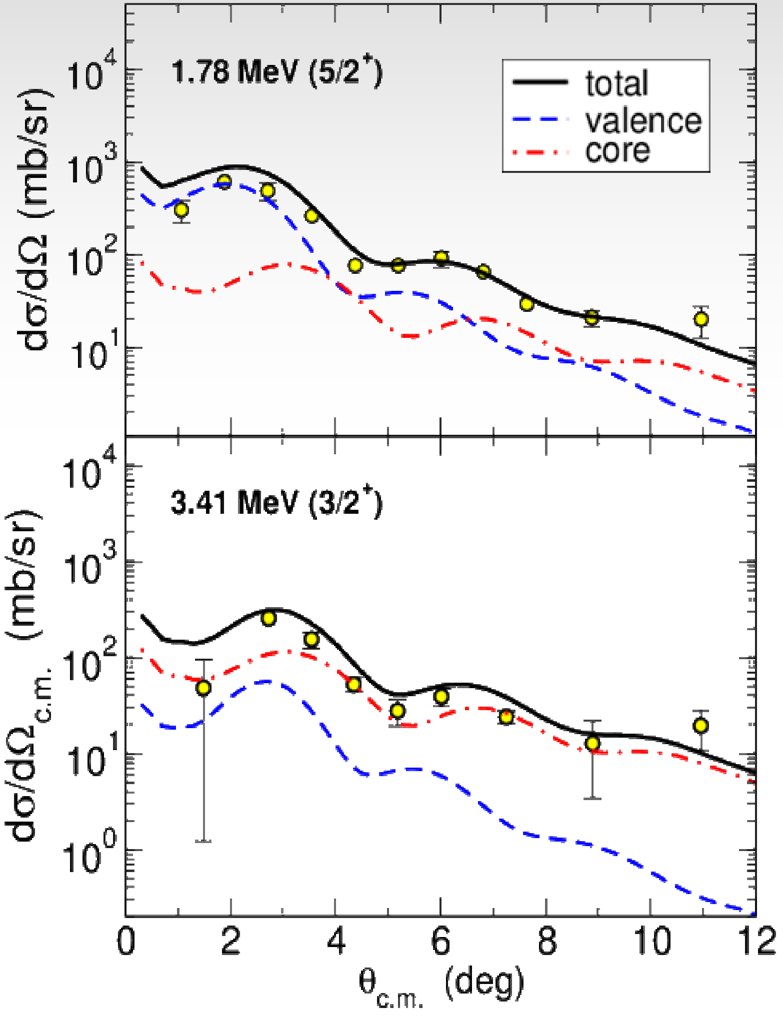
☞ *Core-excitation gives a large contribution to nuclear breakup!*

(*A.M.M. and R. Crespo, PRC 85, 054613 (2012); R.de Diego et al, arXiv:1312.5684*)

Effect of core excitation in resonant breakup



RIKEN data: Fukuda et al, PRC70, 054606 (2004)



A.M.Moro and J.A. Lay,
PRL109, 232502 (2012

- NFT calculations indicate that core polarization affects halo neutron interacions and s.p. levels. 9Li and 10Be cores have a large probability of being in an excited state in 11Li and 12Be g.s.
- Continuum Coupled Channels calculations including core excitation (XCDCC) indicate that 11Be have comparable probabilities of being excited through core exitation and through halo particle excitation.

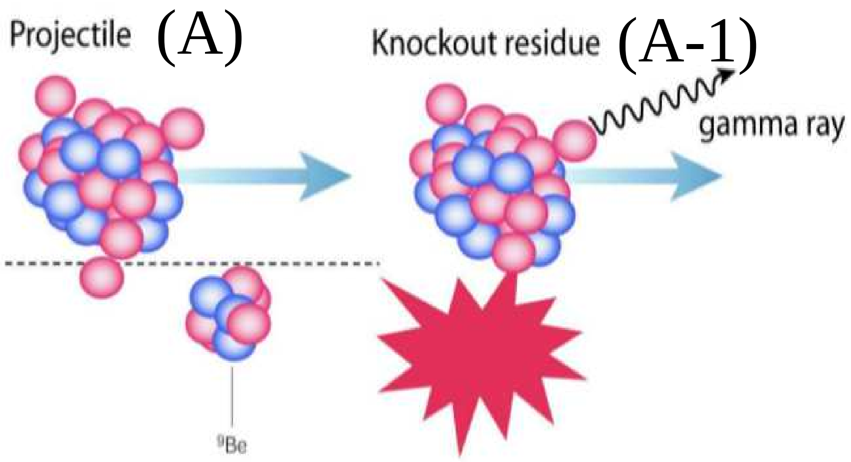
Is theory right?

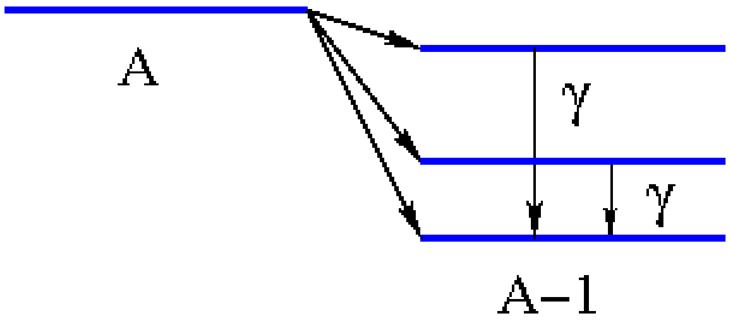
Intermediate energies (~10^2 MeV/u)

- Dominated by nuclear forces → but Coulomb still important at small scattering angles (large impact parameters)

Observables:

- Momentum distributions → nuclear sizes and single-particle contents (l,s,j)
- Angle-integrated cross sections → spectroscopic factors





Extracting physical information from knockout experiments

Theoretical cross section:

$$\sigma(j^\pi) = \left(\frac{A}{A-1}\right)^{N} \underbrace{C^2 S(j^\pi)}_{\text{Structure theory}} \overbrace{\sigma_{sp}(j, S_N + E_x[j^\pi])}^{\text{Reaction theory}}$$

CoM correction – needed
for CI SM with HO basis

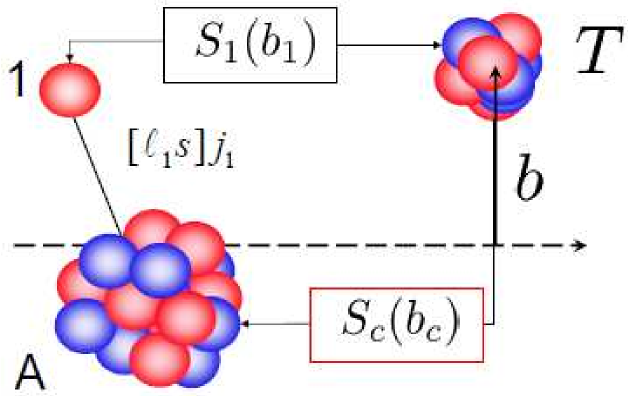
A. E. L. Dieperink and T. de Forest, PRC 10, 533 (1974)

P.G. Hansen and J. A. Tostevin, Annu. Rev. Nucl. Sci. 53, 219 (2003)

$$\sigma_{sp}(j, S_N) = \sigma_{sp}^{strip}(j, S_N) + \sigma_{sp}^{diffr}(j, S_N)$$

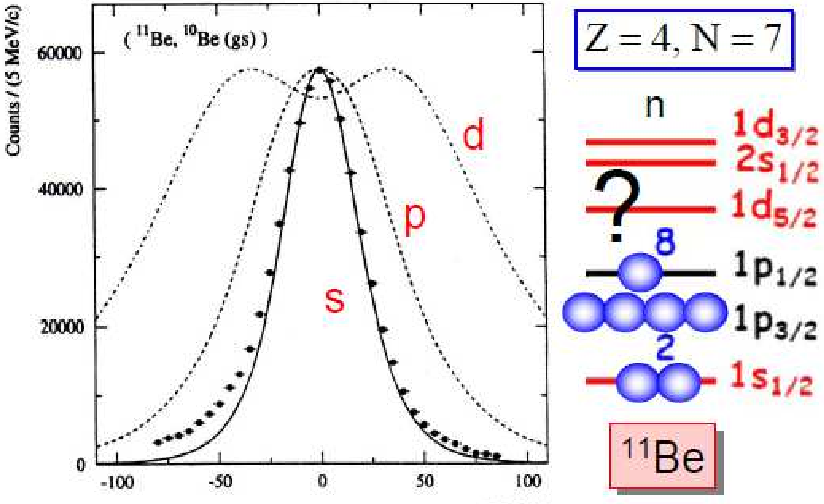
J. A. Tosetvin, J. Phys. G. 25, 735 (1999)

Stripping of a nucleon – nucleon 'absorbed'



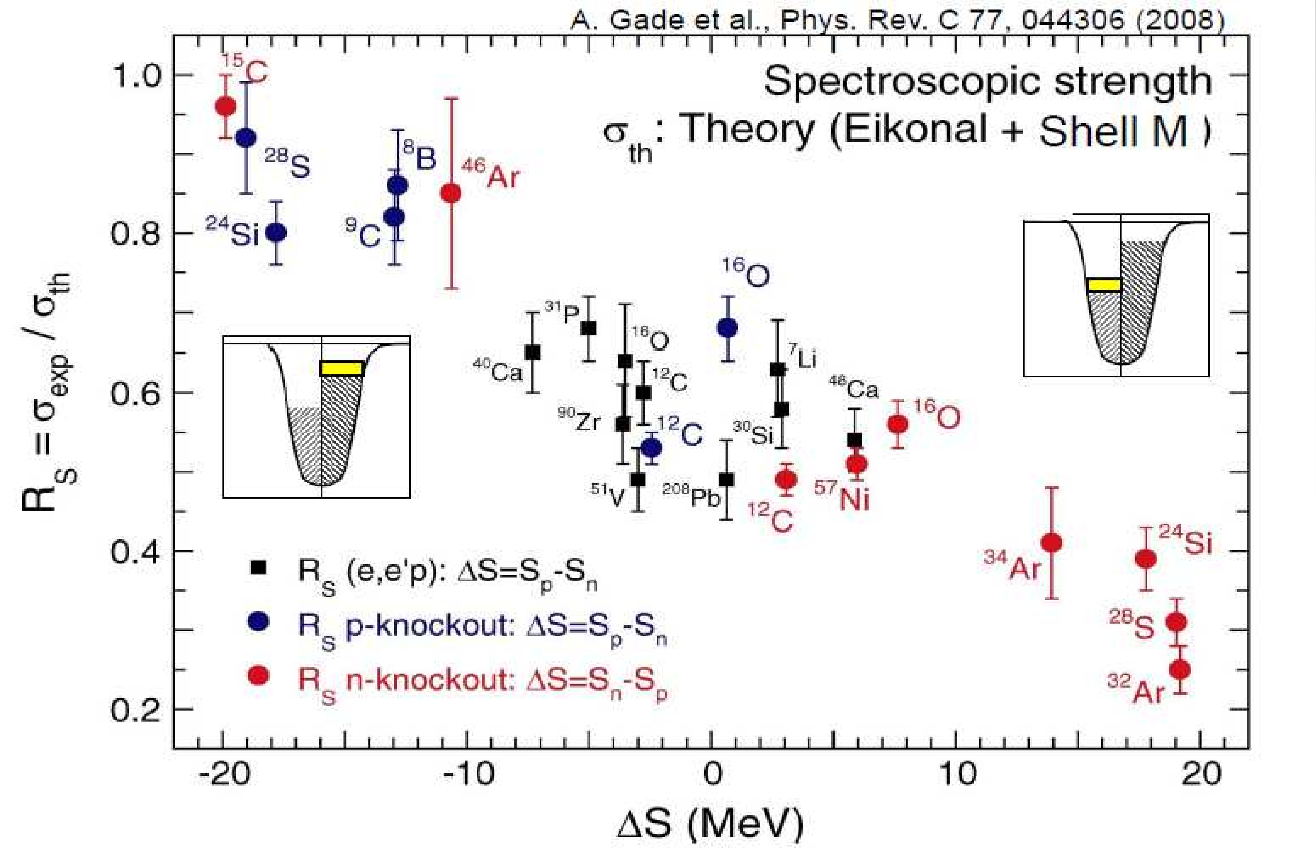
$$\sigma_{strip} = \int \mathbf{db}\ \langle\phi_0 \,||S_c|^2\,(1-|S_1|^2)|\,\phi_0\rangle$$

Residue momentum ^{11}Be→^{10}Be – halo case



T. Aumann et al. PRL 84 (2000) 35

Spectroscopic factor controversy



A. Gade et al., Phys. Rev. C 77, 044306 (2008)

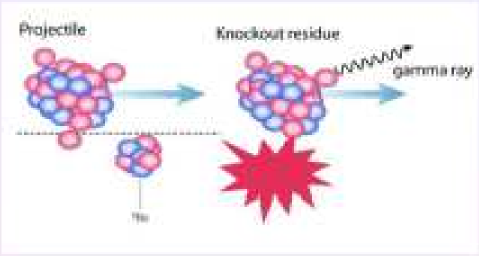
- Knock-out measurements systematically give small values, compared to theory, for the spectroscopic factors of protons (neutrons) in neutron (proton) rich nuclei.

- Either the structure model (shell model) is wrong, or the reaction model (eikonal) is wrong, or the observable (knockout) is not adequate to obtain spectroscopic factors.

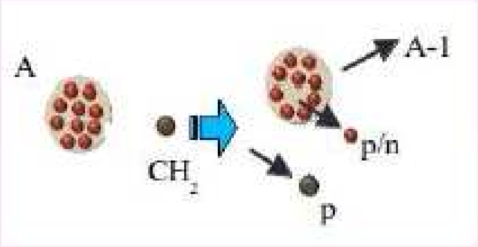
- A different observable is required to settle this. (e,e’p) would be ideal, but not yet available.

QFS vs Knock-out

☞ Due to strong absorption, knockout experiments probe the nuclear wave functions at the surface (with larger cross sections for more weakly-bound nucleons) ⇒ eikonal methods successful.

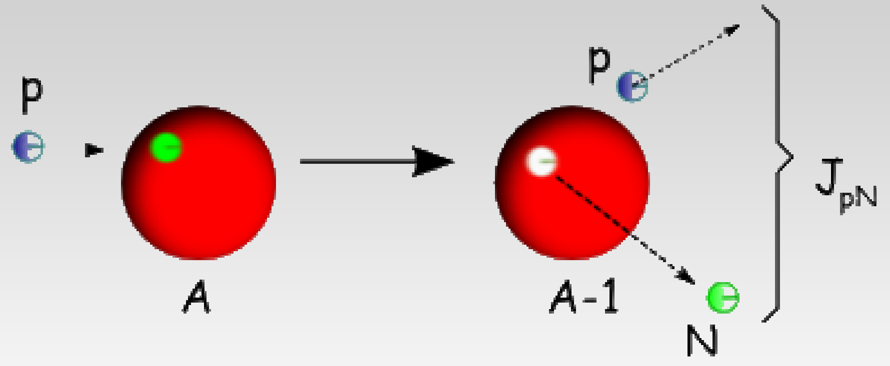


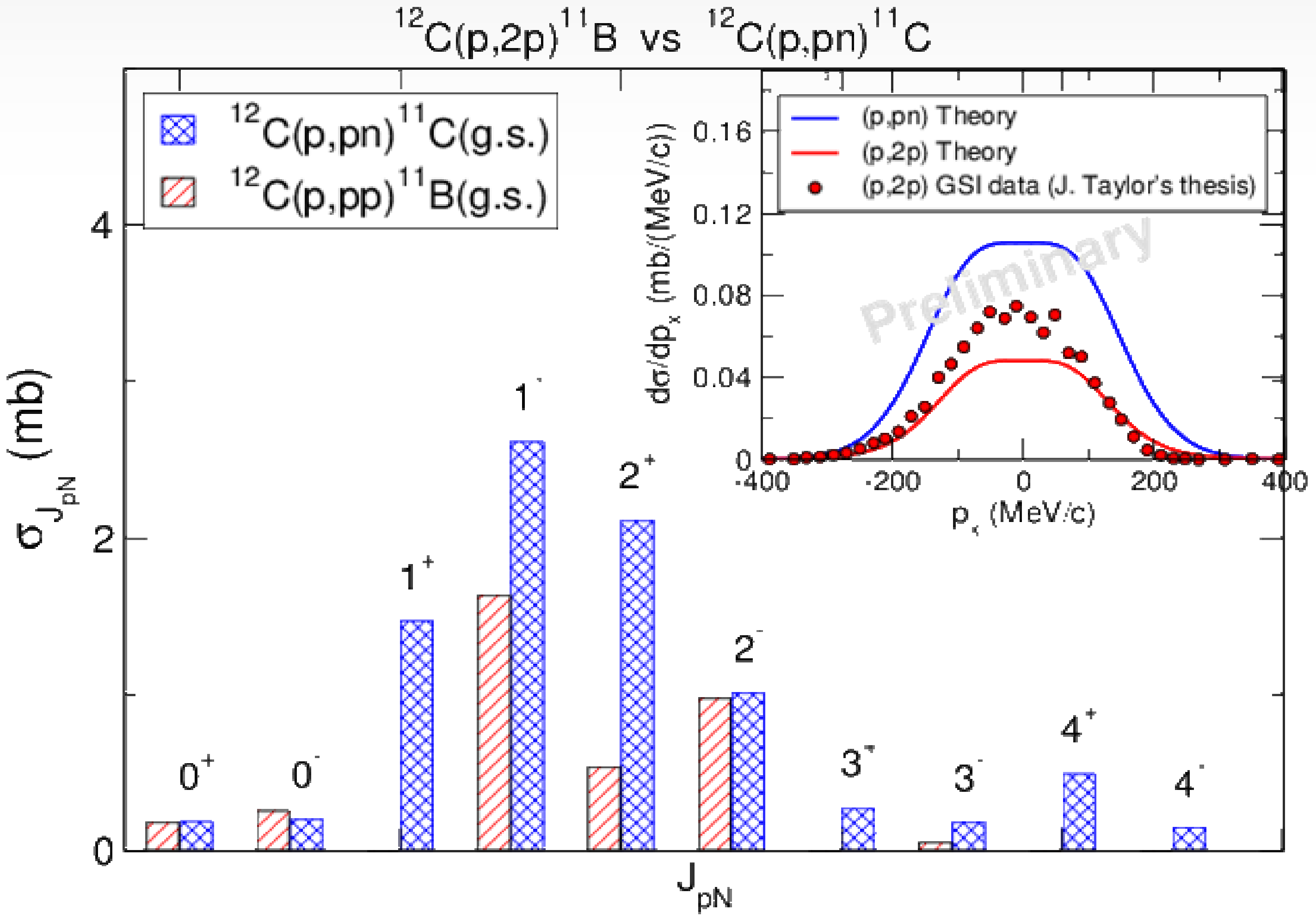
☞ Fully exclusive QFS experiments in inverse kinematics (GANIL, GSI) will provide a finer insight into the interior, but no suitable frameworks are available.



Old DWIA theories and codes must be revisited, improved and eventually supplemented with more sophisticated formalisms (Faddeev, CDCC?)

Transfer to the continuum for QFS (A. Moro)




$^{12}C(p,2p)^{11}B$ vs $^{12}C(p,pn)^{11}C$

Some answers …

- Halo nuclei are made of inert cores and valence particles. Are cores really inert?

Not quite. They can polarize, affecting the halo structure, and excite, affecting the halo induced reactions.

- Nuclei are specially stable when N or Z are magic numbers. Do they?

Definitely not for neutron rich. Mg isotopes could be deformed both for N=20 and for N=28.

- Nuclei have a preferred shape, depending on their position in the chart of nuclides. Do they?

Different shapes can coexist in a single nucleus. 80Zr has prolate, triaxial, oblate and spherical shapes coexisting.

- Removal reactions measure spectroscopic factors. Do they?

Knockout reactions may be biased to the periphery of the nucleus. Alternative observables, like (p,pN) should be used to contrast.

… but Nature, this is experiment, has the last word.

Thanks for your attention!