Nuclear structure

Why ?

To identify the different phenomena at the origin of the nuclear properties

To develop models able to describe these phenomena

Test the models at their limits

High spin nuclei: to explore the nuclei at the limits of the angular momentum.

Heavy and super heavy nuclei: to explore the nuclei at the limits in charge.

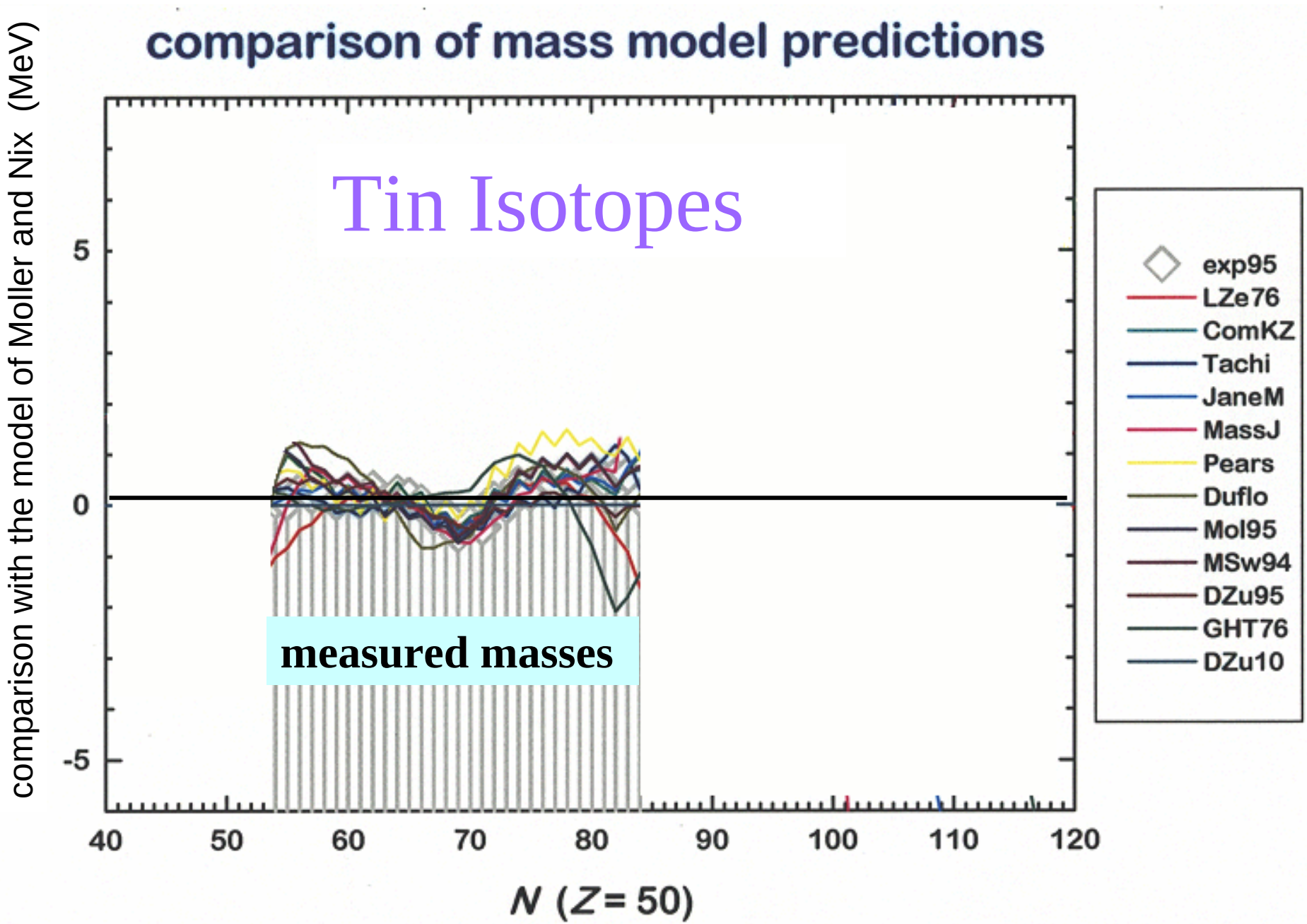
Exotic nuclei: to explore the nuclei at the limits in isospin.

How ?

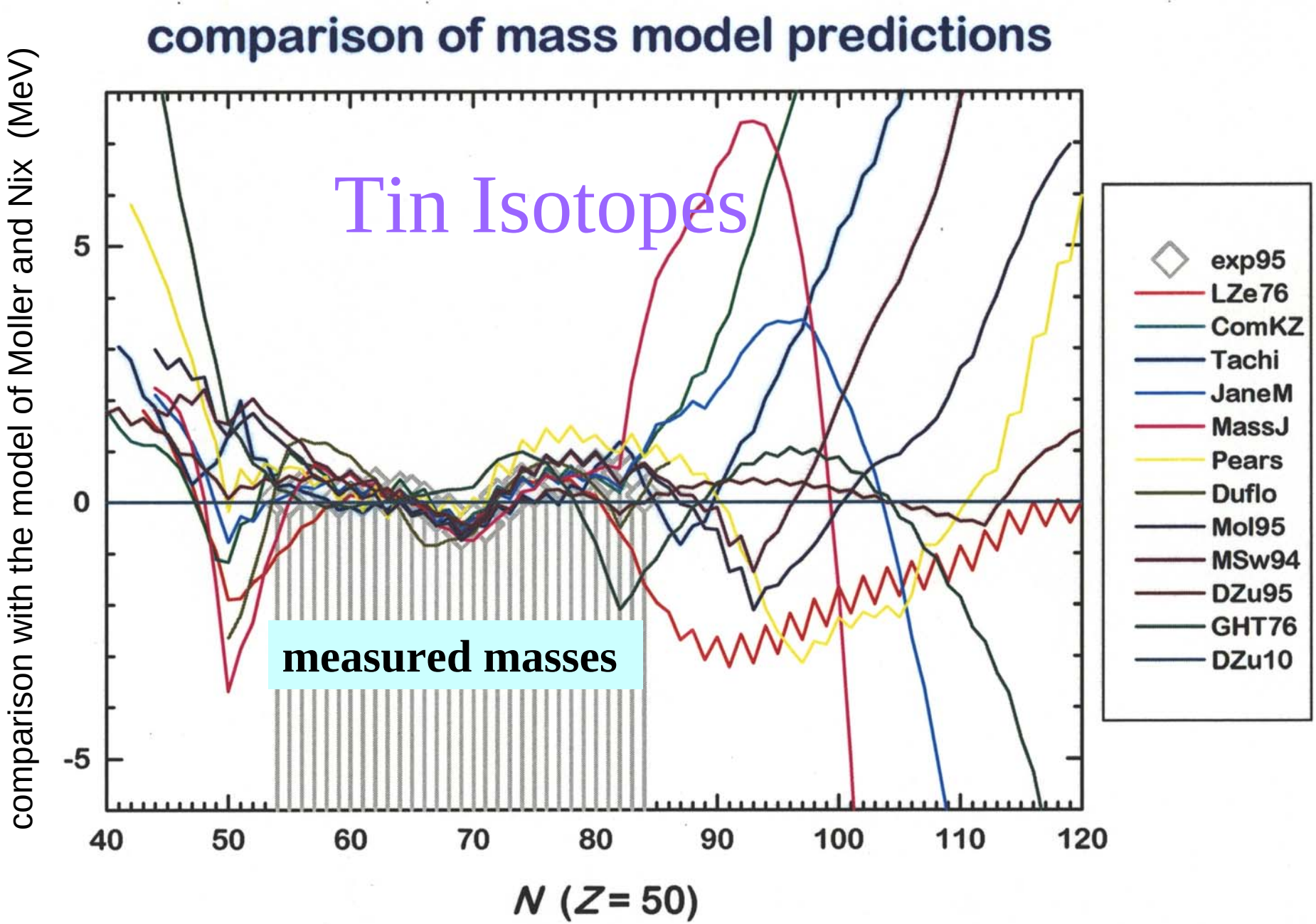
Development of exotic beams since 25 years

+

Development of new experimental devices

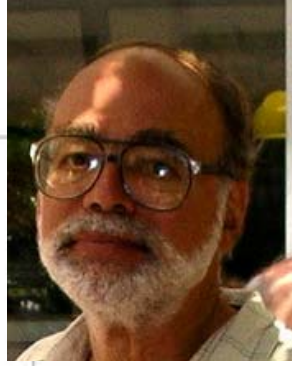


http://www-csnsm.in2p3.fr/

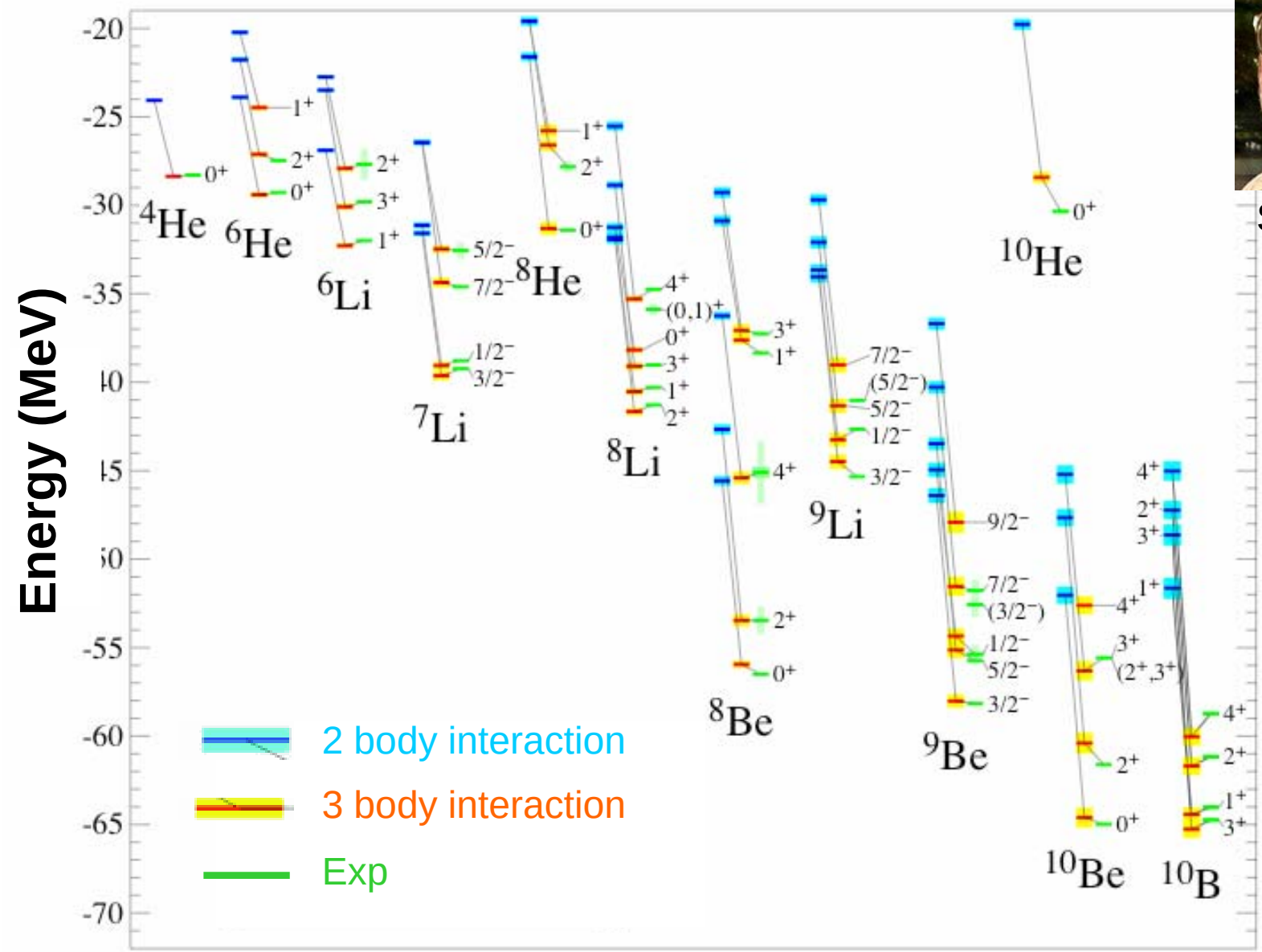


http://www-csnsm.in2p3.fr/

Binding energies of ground states and of the first excited states



S. Pieper



S. Pieper *et al.*, Phys. Rev. C64, (2001), 014001

4n ?

Predictions for a 4-neutron system

a lot of experiments since the 60's try to probe or not the existence of a tetraneutron .

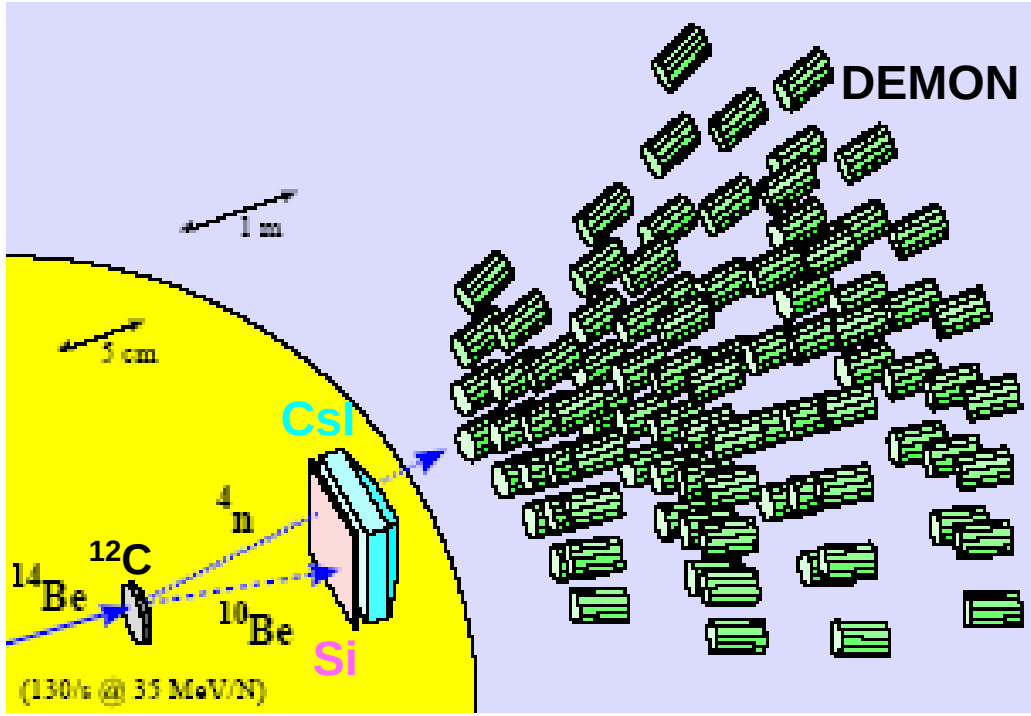
" I show that it does not seem possible to change modern nuclear Hamiltonians to bind tetraneutron without destroying many other successful predictions of those Hamiltonians.

This means that, should a recent experimental claim of a bound tetraneutron be confirmed, our understanding of nuclear forces will have to be significantly changed. "

S. C. Pieper, PRL 90, 252501, June 2003

"Extract" neutron clusters

▶ $|^{14}Be\rangle \equiv a\,|^{10}Be + {}^{4}n\rangle + \cdots$



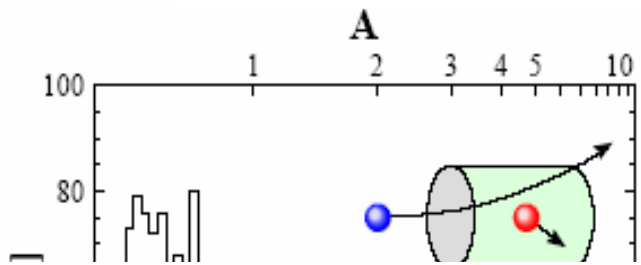
▷ *effective + clean + sensitive !!!*

▷ *technique similar to Chadwick's (1932) !*

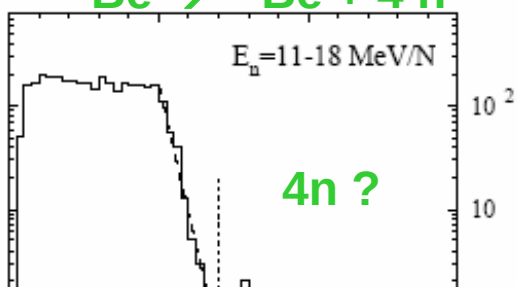
▷ *saturation (sensitive to low E_p) ...*

The ^{14}Be break-up experiment

^{14}Be → ^{12}Be + n



^{14}Be → ^{10}Be + 4 n



4n = The quest of the holy Graal for physicists in structure !

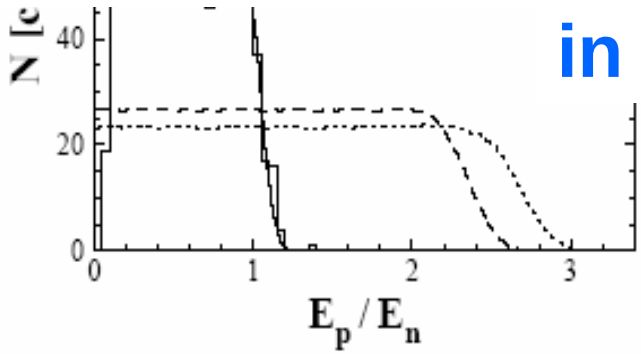


FIG. 2: Distribution of the ratio of proton energy, E_p (MeV), to the energy derived from the flight time, E_n (MeV/N), for data from the reaction C(^{14}Be,^{12}Be+n) (histogram) and for simulations of elastic scattering of ^{1,3,4}n (solid, dashed and dotted lines, respectively) on protons. The experimental resolution has been included in the simulations.

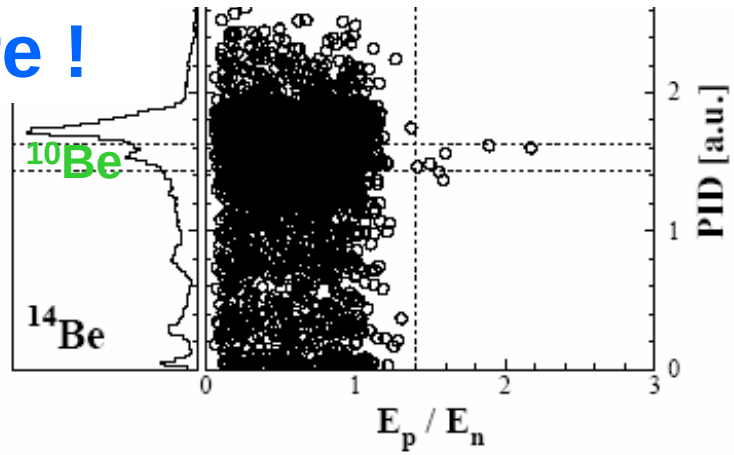


FIG. 5: Scatter plot and the projections onto both axes of the particle identification parameter PID defined in Eq. (1) vs E_p/E_n for the data from the reaction C(^{14}Be,X+n). The PID projection is displayed for all neutron energies. The dotted lines correspond to E_p/E_n = 1.4 and to the region centred on the ^{10}Be peak.

F. M. Marques et al., PRC 65, 044006 (2002)

Tools for structure studies

- Different ways to study the same problem !

  ex: shell closures with mass measurements, inelastic scattering, coulex, transfer reactions etc....

BUT

- Different ways to confirm a new feature !

  one information --> one piece of the puzzle in structure ....

  + complementary informations

- Tools depends on the beam energy and intensity

Tools for structure studies

Complexity

- Existence one (preferably 2)
- Mass measurements > a few per day
- β decay > a few per min — $E(2^+)$
- Inelastic scattering > 10 pps — Collectivity 2^+, 3^- states
- Coulomb excitation > 10^2 pps — B(E2)
- Breakup or knockout > 10^2 pps — Single particles properties
- Transfer Reactions >10^4 pps — Single particles properties, clustering

Energy regimes

< 5 MeV/nucleon REX-ISOLDE

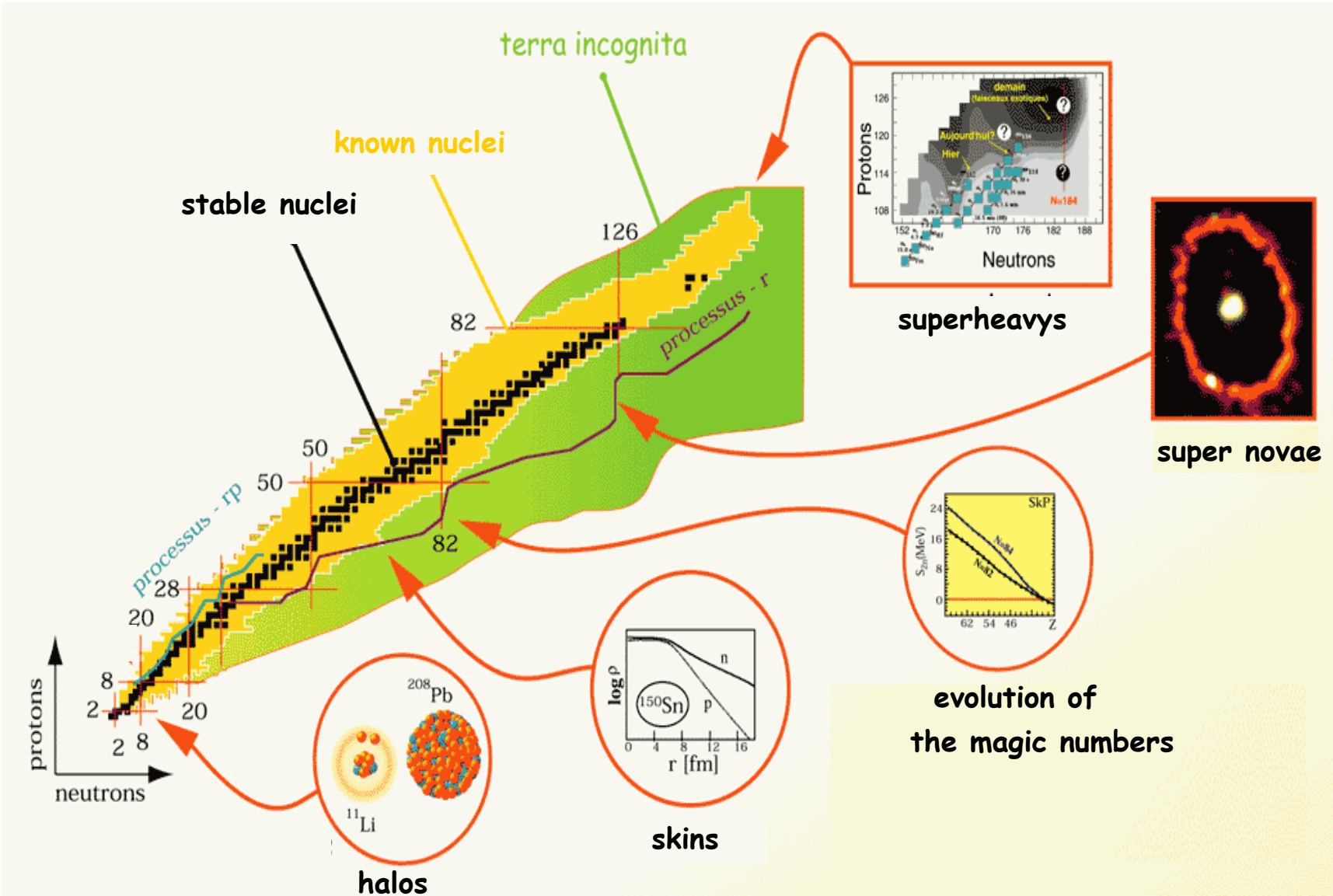
5-70 MeV/nucleon GANIL SISSI-SPIRAL

100-1000 MeV/nucleon GSI-FRS

Transfer

knockout

Nuclear structure at the driplines

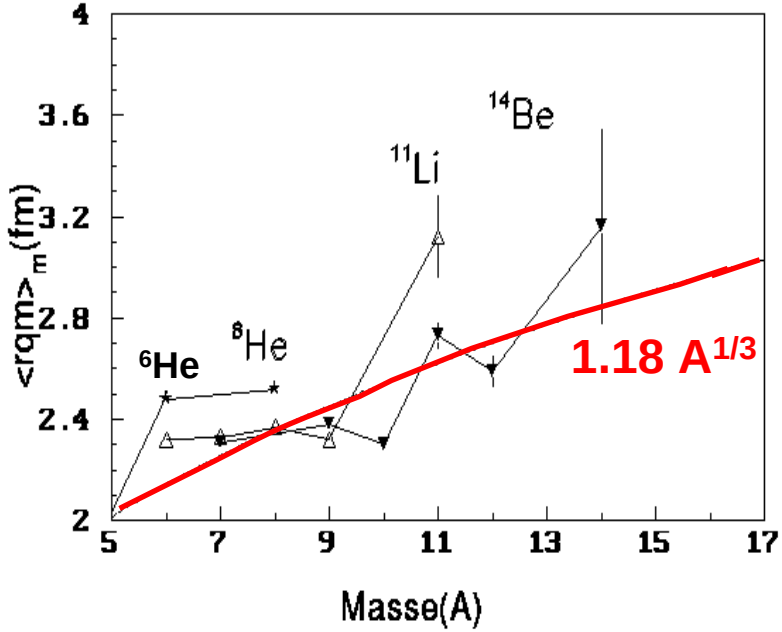


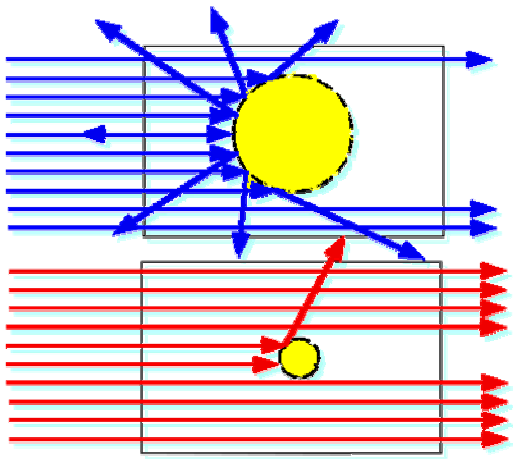
Halo nuclei

Halo nuclei

- **Exotic nuclei anormally big**

Measurement of reaction cross sections
I. Tanihata et al., Phys. Rev. Lett. 55 (1985) 2676

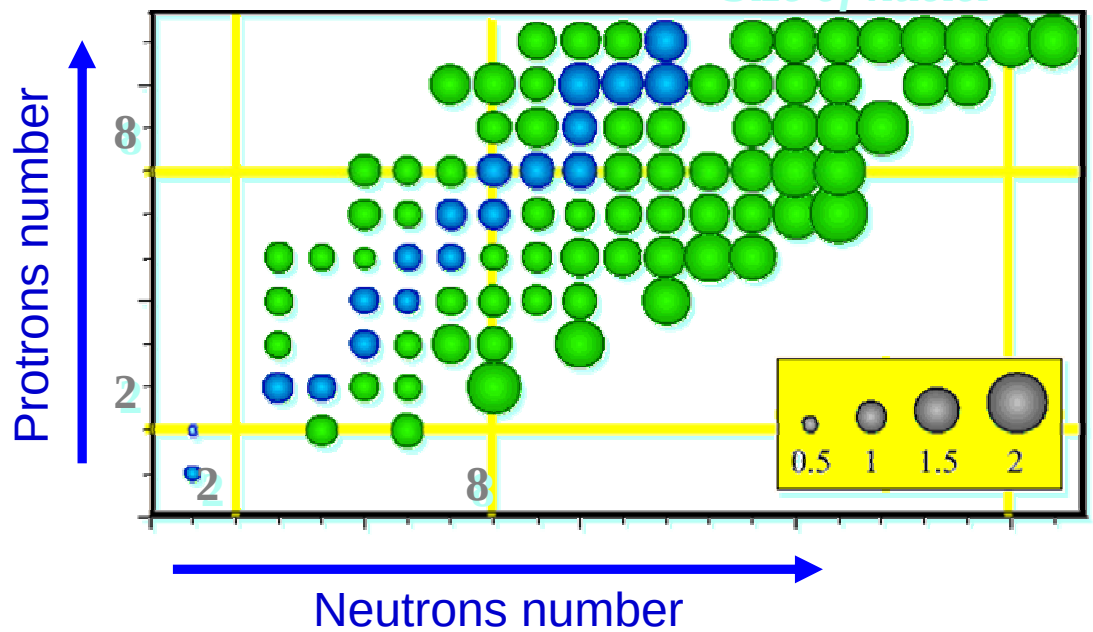




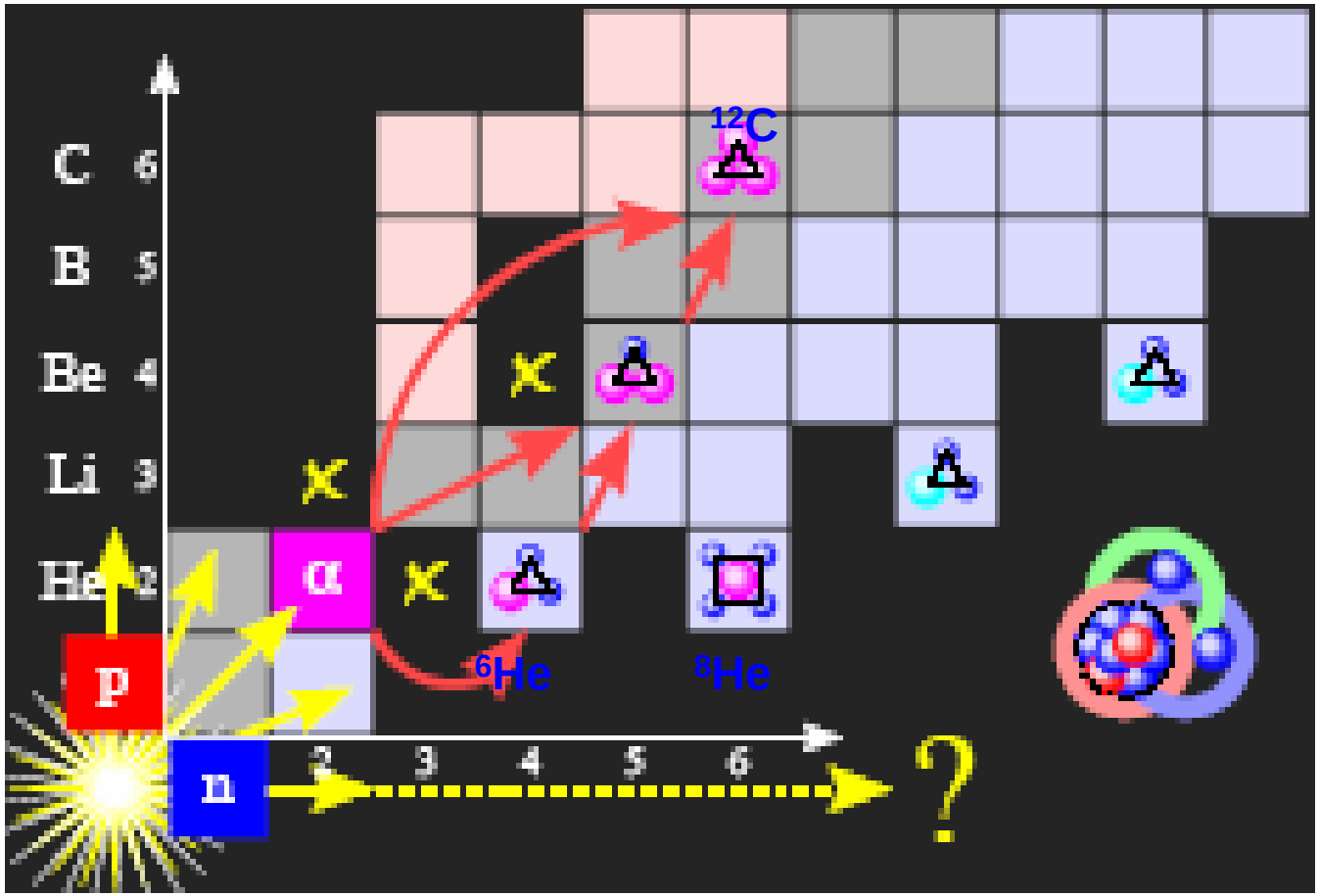
Rutherford's experiment

$$\sigma_R = \pi\,(R_{proj} + R_{target})^2$$

Size of nuclei

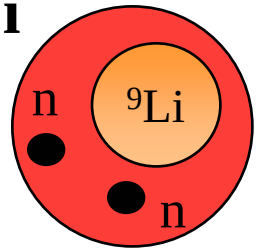


Halo nuclei

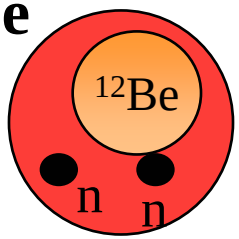


Borromean

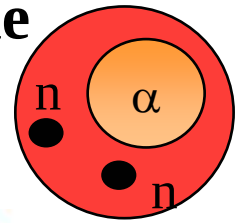
^{11}Li

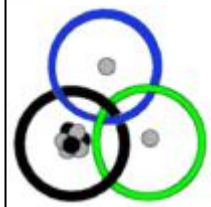


^{14}Be



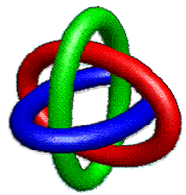
^{6}He





Heisenberg's principle

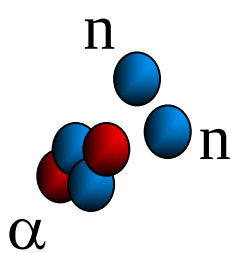
$\Delta x \, \Delta p \geq \hbar$

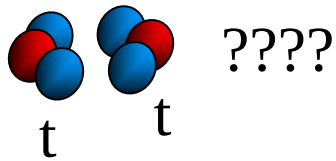


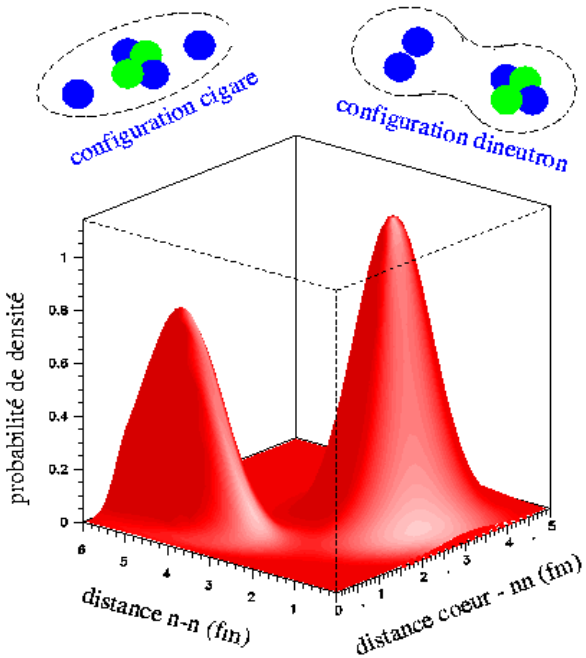
^{22}C, ^{17}Ne borromean

^{17}B, ^{19}C, ^{8}B one neutron, one proton halo

Ground state wave function of ^{6}He







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

- **^{6}He binding energy well reproduced with a t+t configuration**

  A. Csoto, PRC 48 (1993) 165

- **Microscopic calculations**

  $<^6He|^4He + n + n>$ 1.10 to 1.56

  $<^6He|t + t>$ 0.44 to 1.77

  Yu. F. Smirnov, PRC 15 (1977) 84

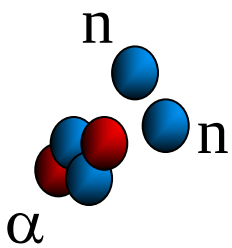
  K. Arai et al., PRC 59 (1999) 1432

- **Analogy with ^{6}Li**

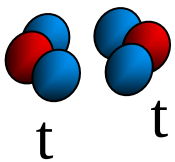
  $^6Li(p,^3He)\alpha$

  clusters α+d and ^{3}He+t same importance !!

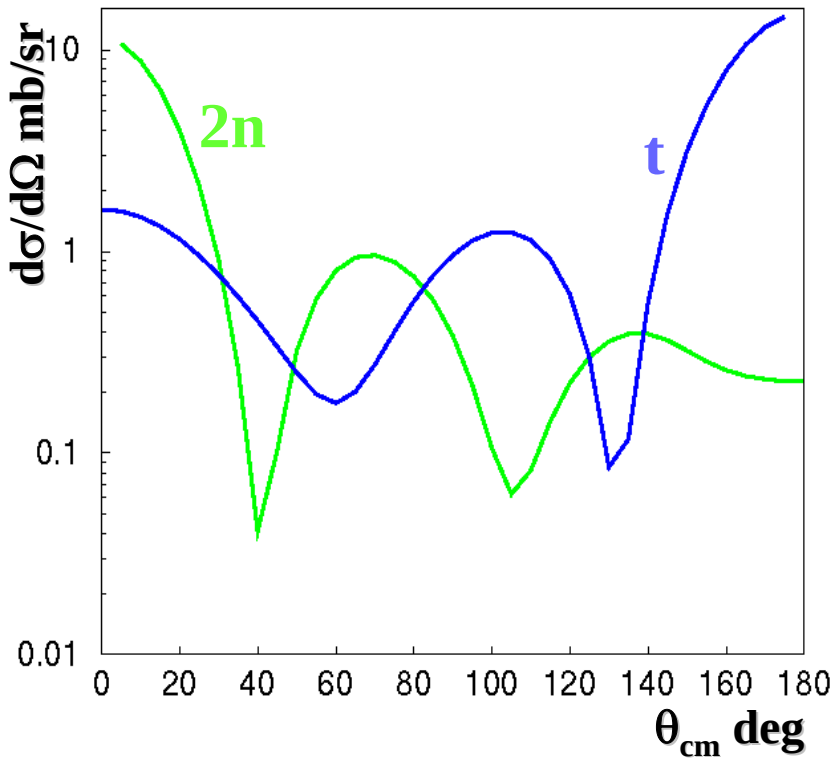
$$^{6}He + p \rightarrow \alpha + t$$



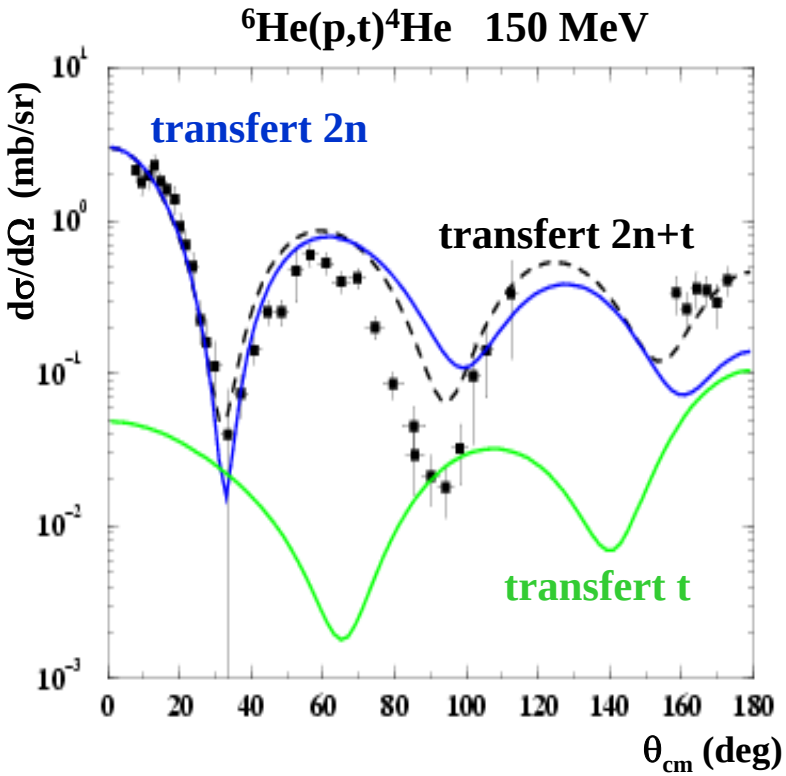
$$(^{4}He + 2n) + p \rightarrow \alpha + t$$

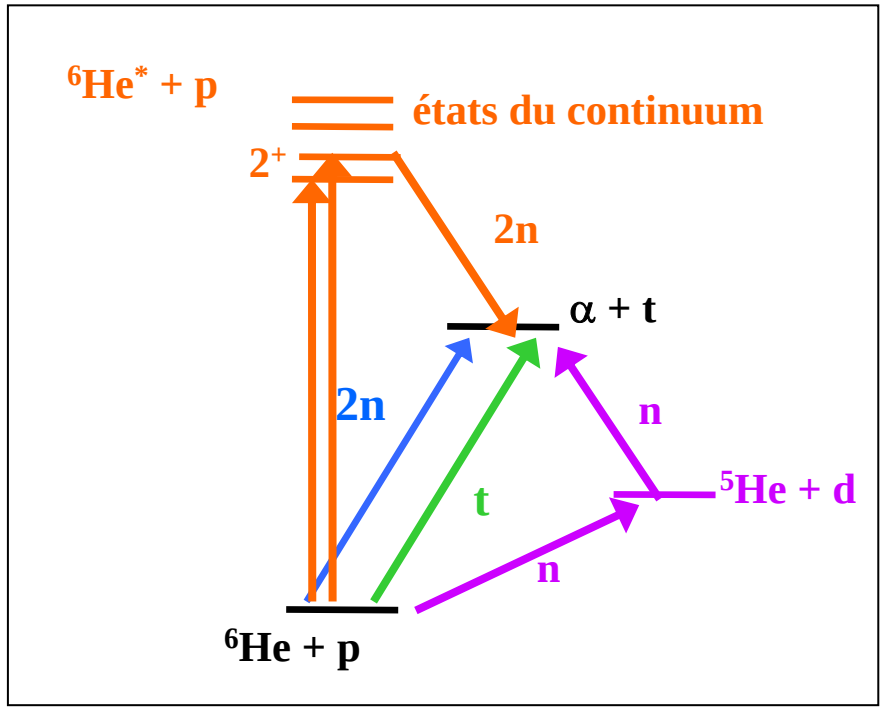


$$(t + t) + p \rightarrow t + \alpha$$



Ground state wave function of ^{6}He





Coupled channels calculations

Search for t+t clustering in ^{6}He
L.G et al., NPA, 378 (2004) 426c

Investigation of ^{6}He cluster structures
L.G et al., accepted in PRC

t+t exist but very small !!

Ground state wave function of ^{8}He

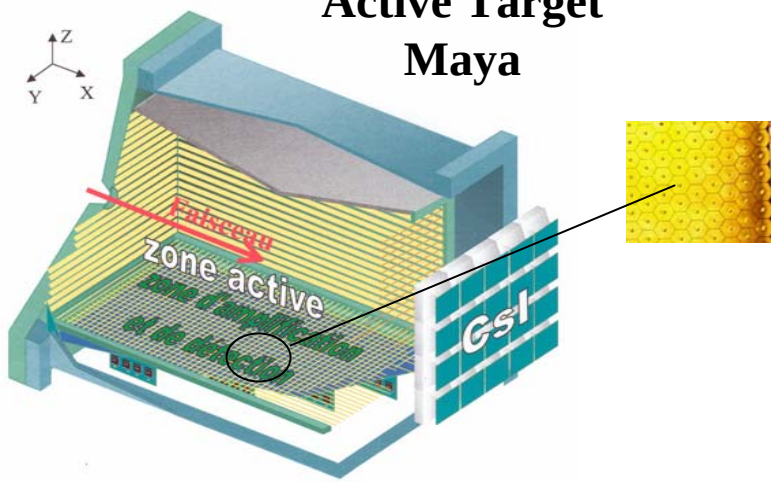
- ^{6}He(2^+) is predominant in the ^{8}He$_{g.s}$ wave function

| ^{6}He(2^+): 66%
| ^{6}He$_{g.s}$: 33%

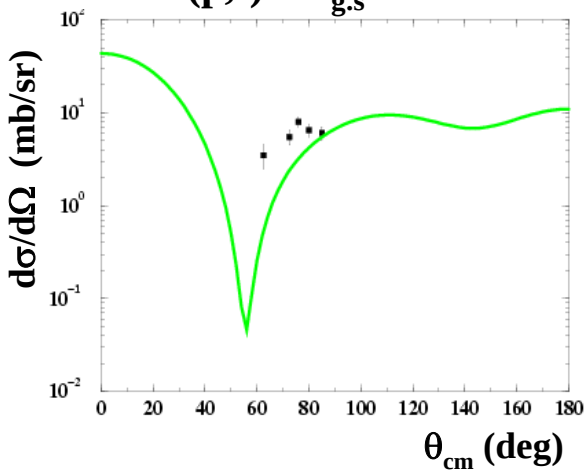
^{8}He(p,t)^{6}He$_{g.s}$, ^{8}He(p,t)^{6}He$_{2+}$
@ 60 MeV, Riken

A. Korsheninnikov, PRL 90 (2003) 082501

Active Target Maya



^{8}He(p,t)^{6}He$_{g.s}$ 3.9 MeV



W. Mittig, Ch. E Demonchy thesis

@ 3.9 MeV, Ganil/SPIRAL with MAYA

lower energy ⟶ higher cross sections

but optical potentials ?

compound nuclei ?

^{6}He(2^+), ^{6}He$_{g.s}$ same weight than Riken

Actar Project: GSI involved

Active Target

- detection gaz
  also used as a target

✓ very efficient

✓ Low detection threshold for particles

✓ used as a thick target

✓ Large angular acceptance

✓ Important reaction energy range

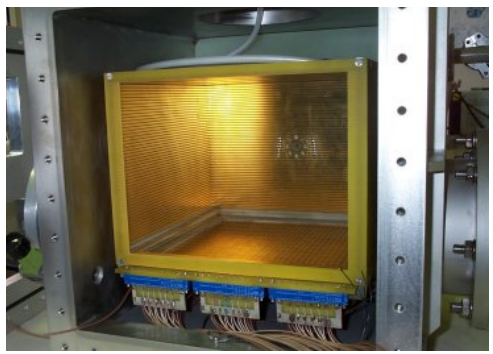
MAYA

■ **Experiment**

- elastic resonance scattering

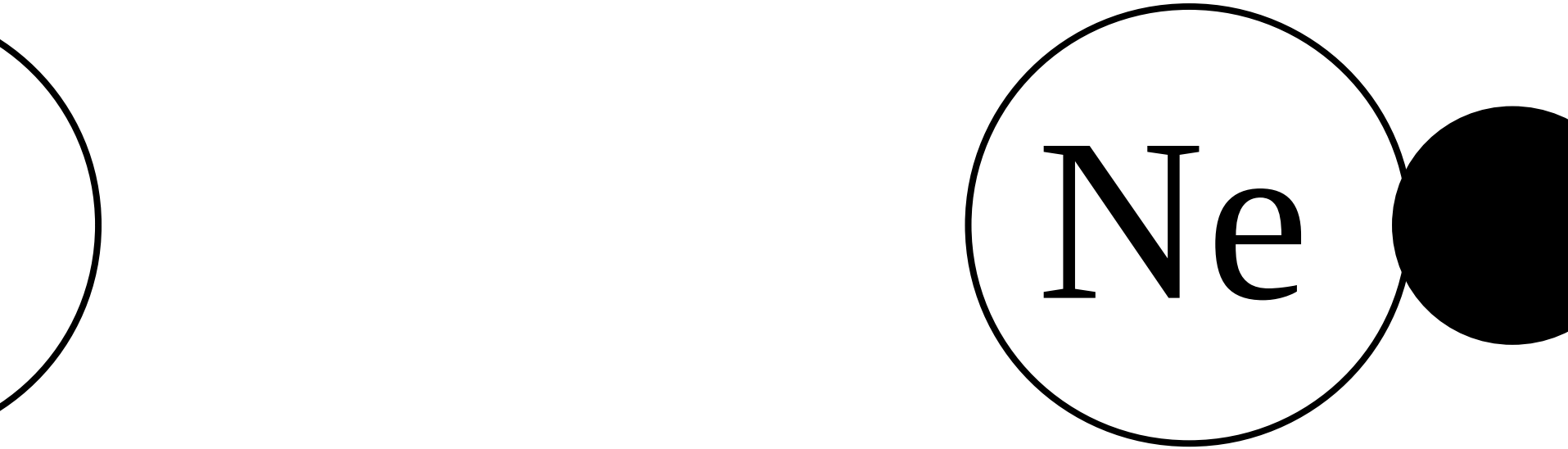
  $^{8}He + p \longrightarrow$ IAS of ^{9}He

- $^{26}F(d,^{3}He)^{25}O$



W. Mittig, C.E. Demonchy et al., GANIL

Molecular states



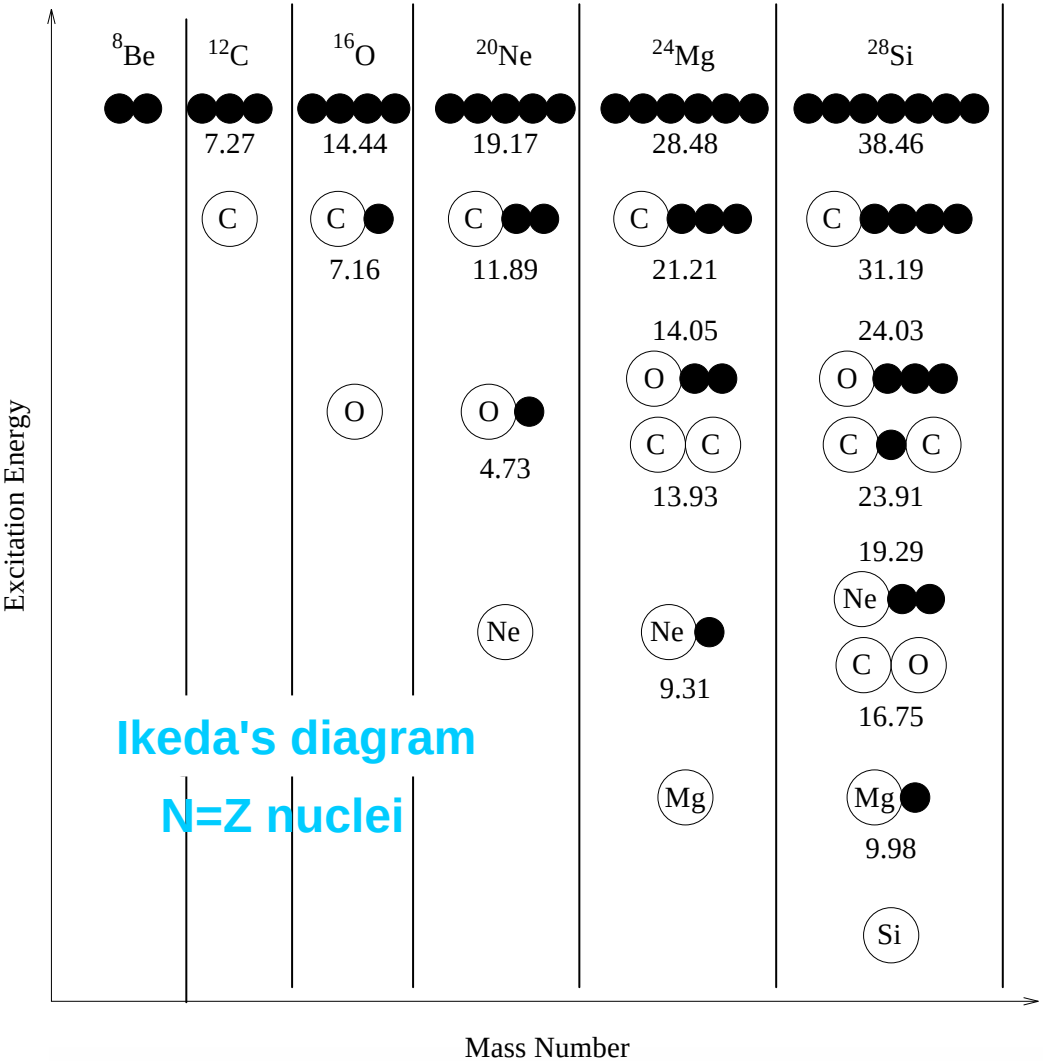
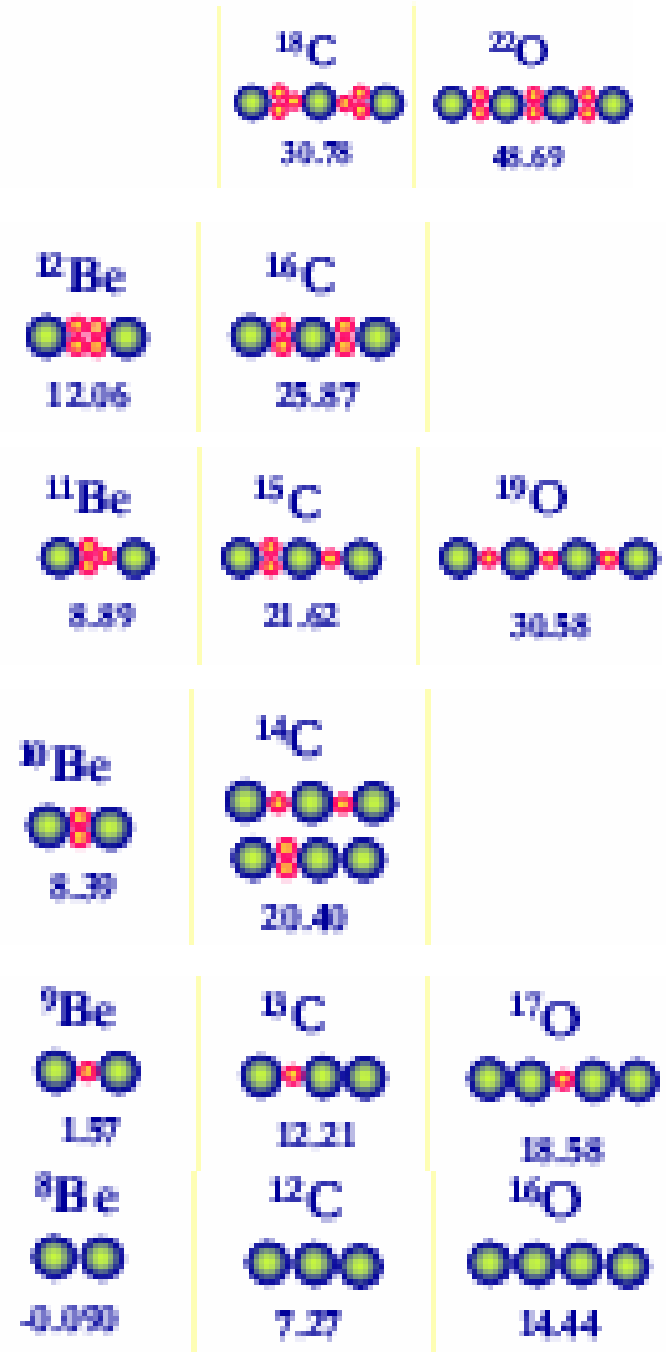


FIG. 1: The Ikeda threshold diagram for nuclei with α-clustering. Cluster structures are predicted to appear close to the associated decay thresholds. The energies needed for the decomposition of the normal nucleus into the structures are indicated in MeV (from [127]).

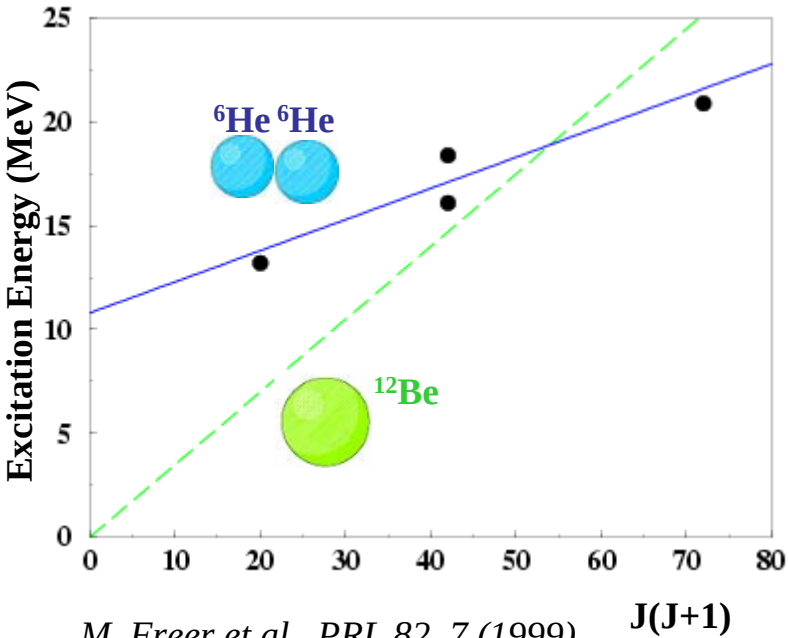
K. Ikeda, Suppl. Prog. Theor. Phys. 464, 1968



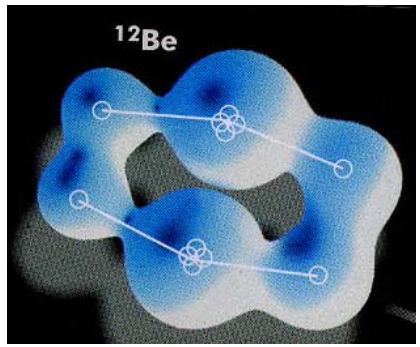
Wolfram von Oertzen, private comm.

New Structures

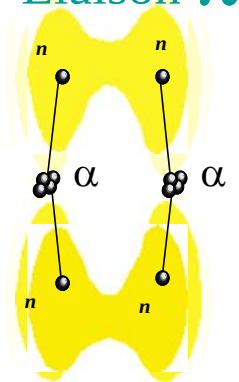
- **Inelastic Experiments**



M. Freer et al., PRL 82, 7 (1999)

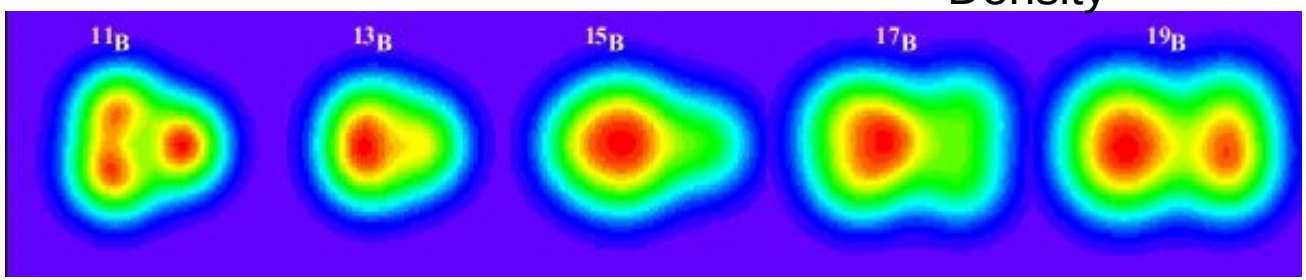


Liaison π



^{12}Be

Density

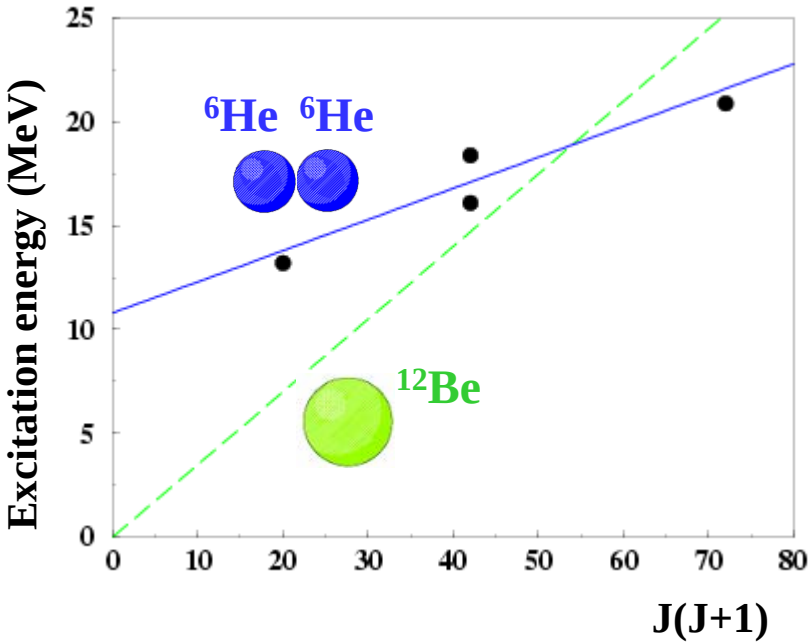


AMD calculations Kanada-Enyo, Horiuchi et al.

Molecular states in ^{10,12}Be

Inelastic scattering

Clustering of excited states

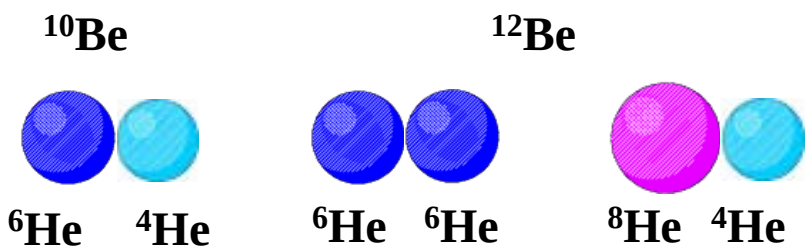


M. Freer et al., PRL 82, 1383 (1999)

Knockout

Test of a new method

Clustering in the ground state



Collaboration CHARISSA:

N. Orr, M. Marques, LPC Caen M. Freer, Univ. de Birmingham

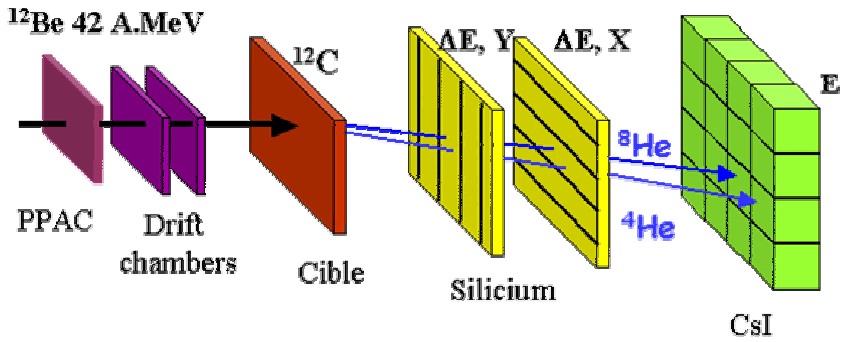
F. Carstoiu, Univ. de Buccarest

Molecular states of ^{10,12}Be

- **Analogy with one nucleon knockout**

Momentum distribution p $\rightarrow$ ***l***

$\sigma_{-\alpha}$ $\rightarrow$ ***Spectroscopic factor***



Molecular states of ^{10,12}Be

- **Analogy with one nucleon knockout**

  Momentum distribution p → *l*

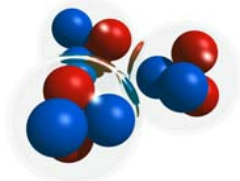
  $\sigma_{-\alpha}$ → *Spectroscopic factor*

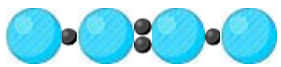
  Theory under progress ....
  Comparison with a Glauber's model

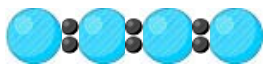
- **Future**

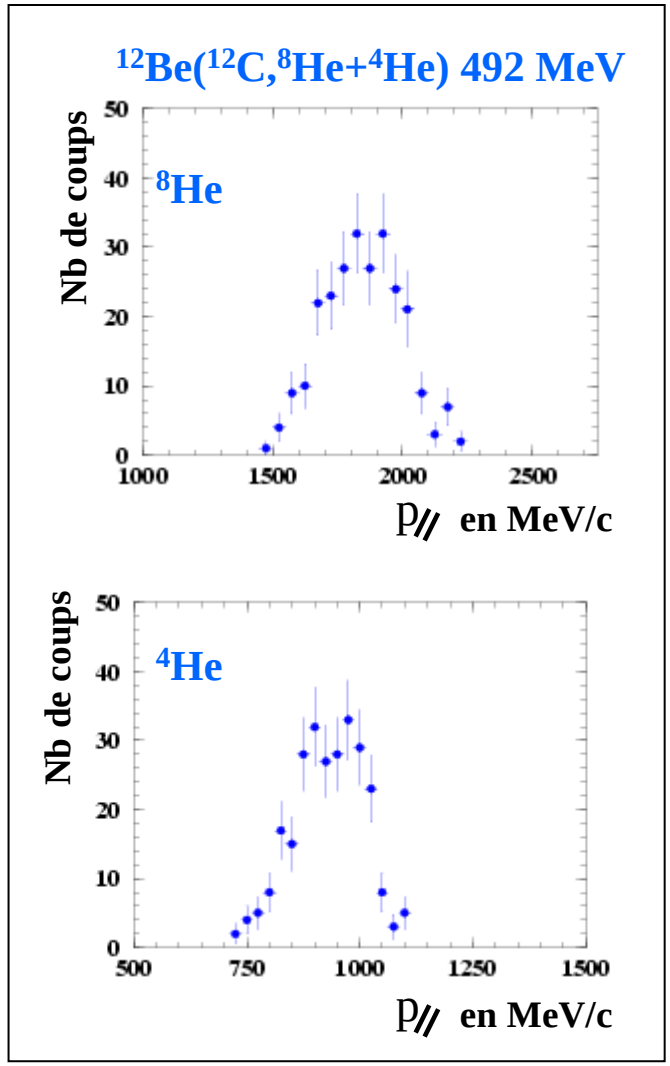
  Test october 2005

  - ^{12}C → α + ^{8}Be



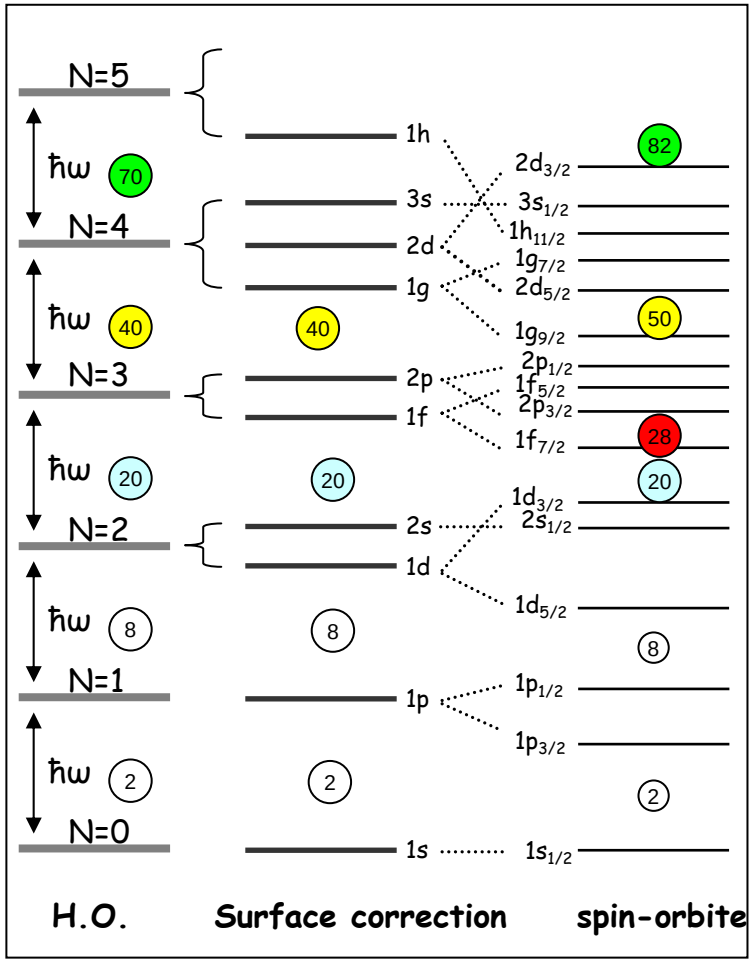
  -  ^{16}C  ^{20}O

     ^{18}C  ^{22}O



Shell evolution

Shell model



- Shell model (~1950):
  - Nucléon = independant particle move in an average potential created by the ensemble of the other nucleons
  - Reproduces many properties of the nuclei
  - Magic numbers : ***(2,8,20,28,50,82,…)***

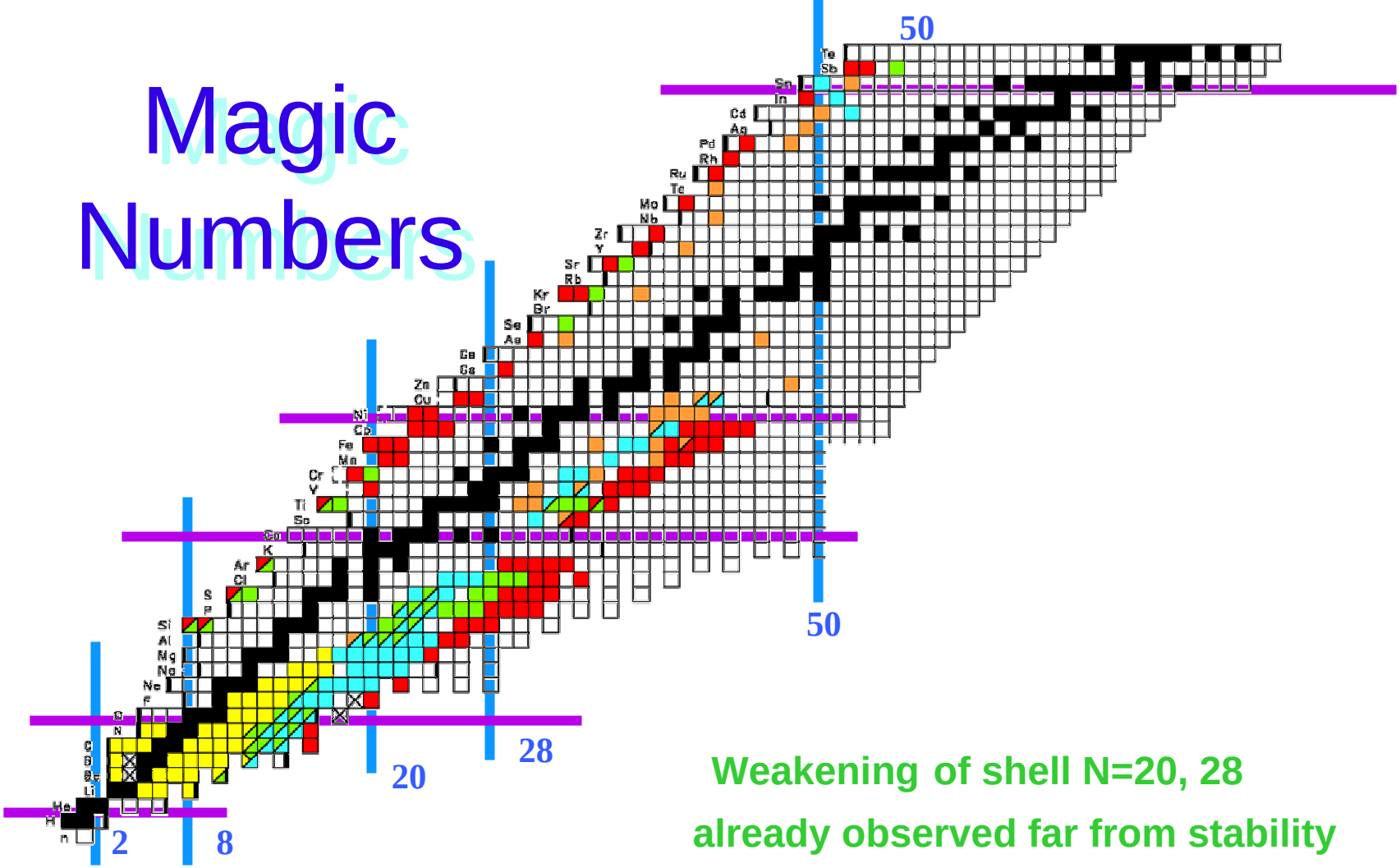
J. Hans D. Jensen

Maria Goeppert Mayer

Discovery of the magic numbers

Nobel prize 1963

Magic Numbers



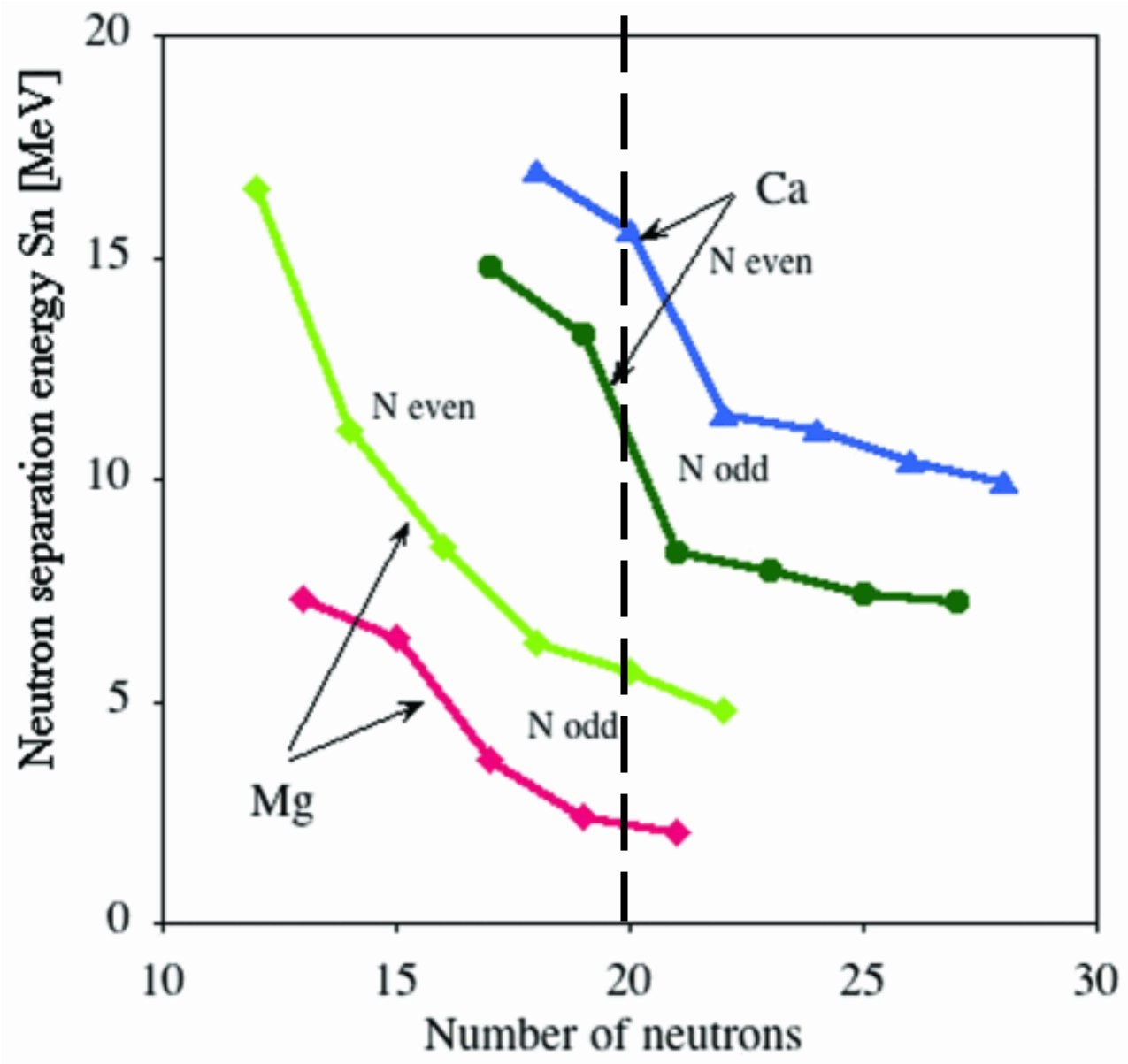
protons number

Neutrons number

Weakening of shell N=20, 28

already observed far from stability

N = 20


Neutron separation energy Sn [MeV]
20
15
10
5
0
10
15
20
25
30
Number of neutrons
Ca
N even
N odd
N even
N odd
Mg

New magic numbers

- $V_{\sigma\tau}$ monopole interaction:

coupling of proton-neutron spin-orbit partners

but missing in n-rich nuclei

the spin orbit partner of the valence neutrons are not occupied by protons

- N = 16 **neutron proton interaction πd5/2 - υd3/2**

Experimental Evidence from - in beam fragmentation, PRC 69 (2004) 034312

- longitudinum momentum distribution

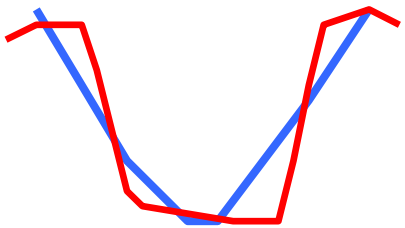
^{28}O (N=20) ?

- N = 34 **neutron proton interaction πf7/2 - υf5/2**

T. Otsuka et al., Phys. Rev. Lett. 87 (01) 082502

Evolution of magicity with increasing N/Z

Study of Z magic nuclei: O, Ca, Ni, Sn isotopic chains



N ~ Z

Diffuse surface

N >> Z

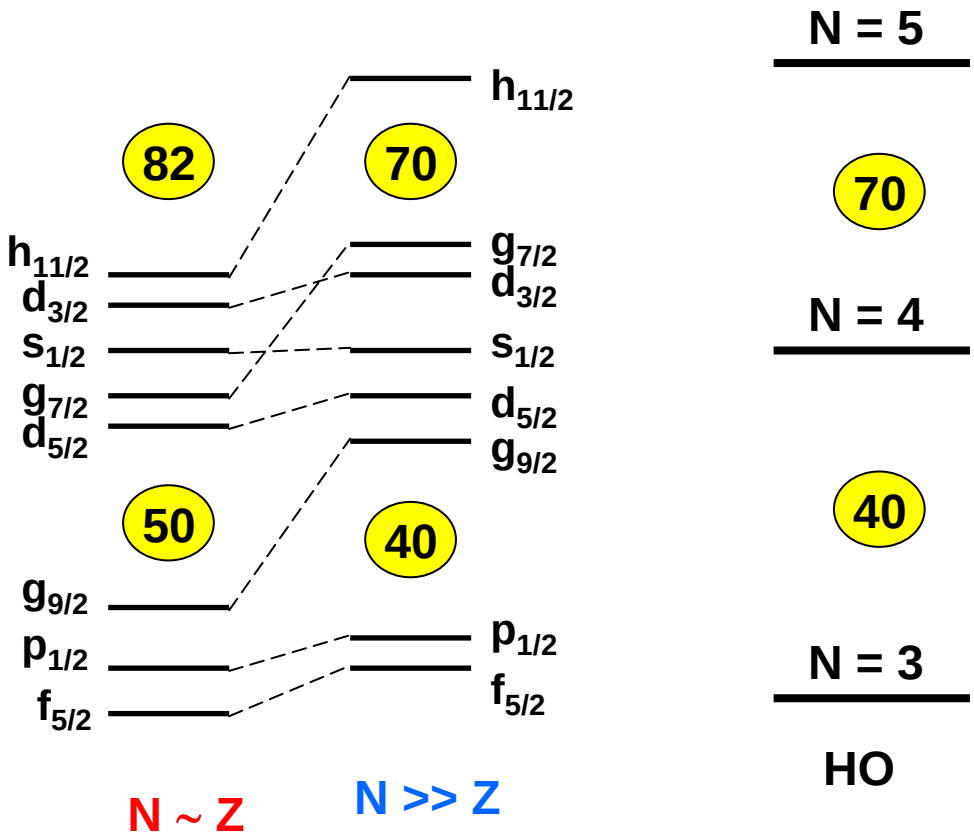
weakening

of spin orbit potential

ex: ^{68}Ni (N=40)

B(E_2) small -→ magic nuclei ?

O. Sorlin et al., PRL 88, 092501 (1994)



Dobaczewski et al., PRL 72, 981 (1994)

Shopping List of Nuclei

SPIRAL II, FAIR — — — — > EURISOL

N = 16 ^{24}O, ^{25}O, ^{25}F, ^{26}Ne

N = 20 all nuclei in the region of ^{32}Mg, called the magic inversion land

N = 34 N = 40

Z = 20 ^{48}Ca.....^{54}Ca..... ^{60}Ca

Calcium isotopes chain

N = 40 N = 50

Z = 28 ^{56}Ni.....^{68}Ni..... ^{78}Ni

Nickel isotopes chain

N = Z = 50 ^{100}Sn

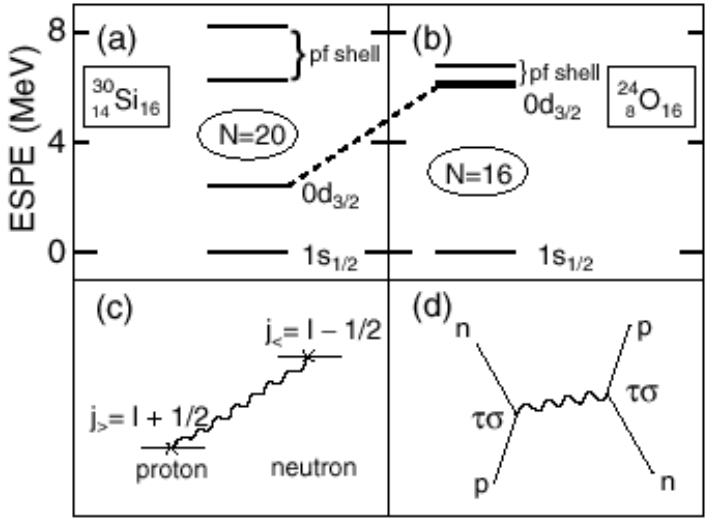
Vladimir,

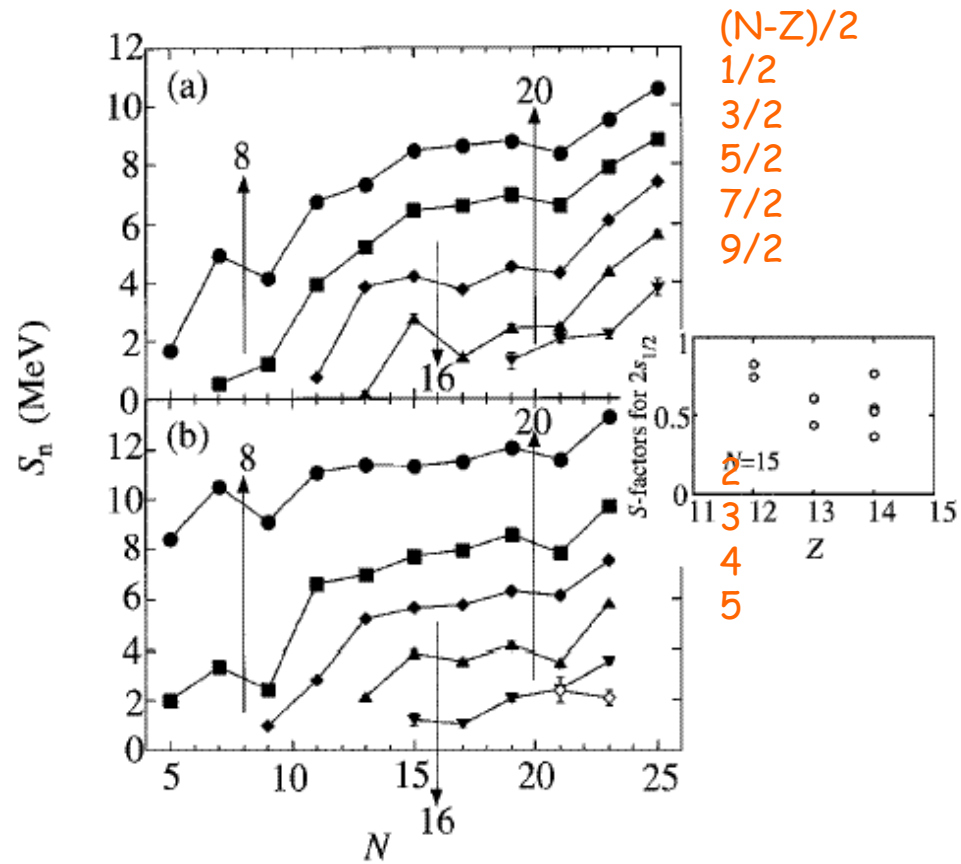
Is it so boring ?

Modification de la structure en couches loin de la stabilité

T. Otsuka et al., Phys. Rev. Lett. 87 (01) 082502

A. Ozawa et al., Phys. Rev. Lett. 84 (00) 5493

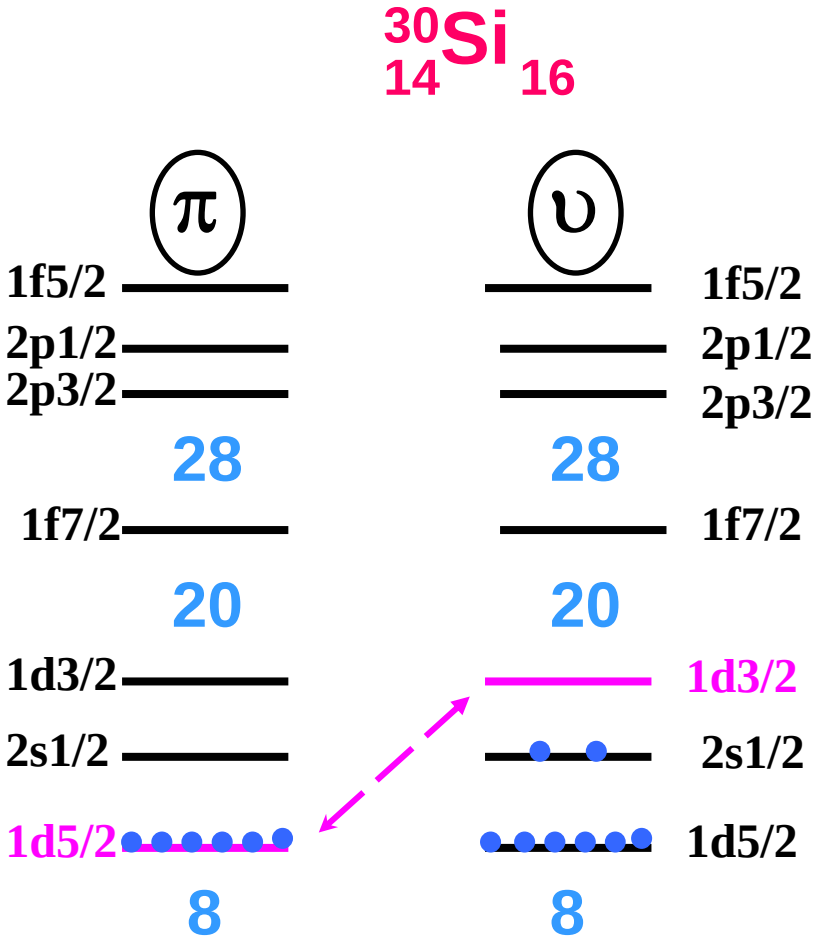




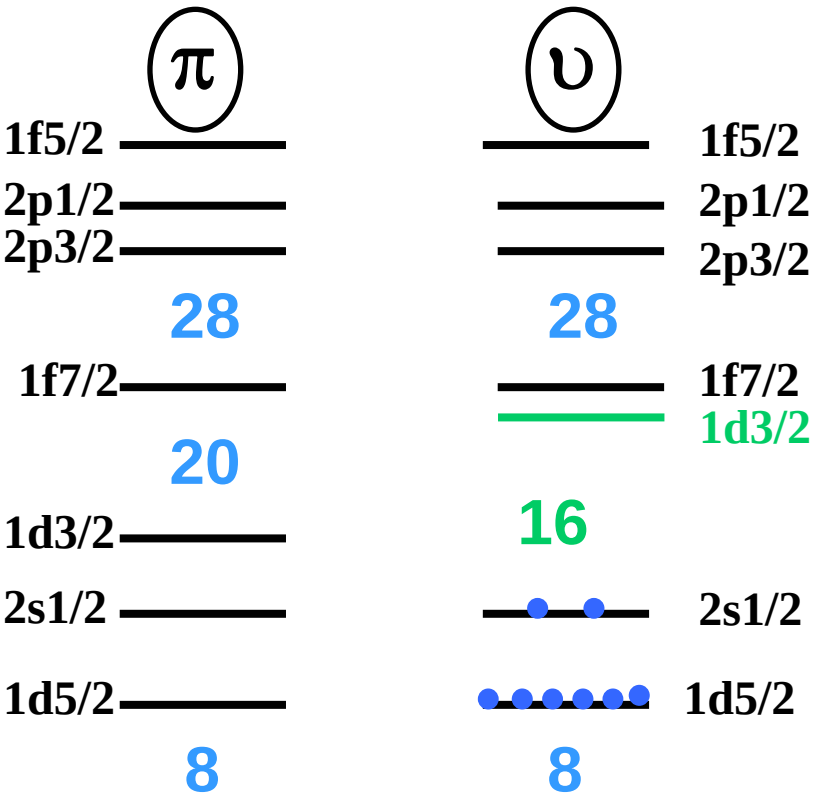
Observation complémentaire:
Augmentation des sections efficaces de réaction dans la même région de noyaux.

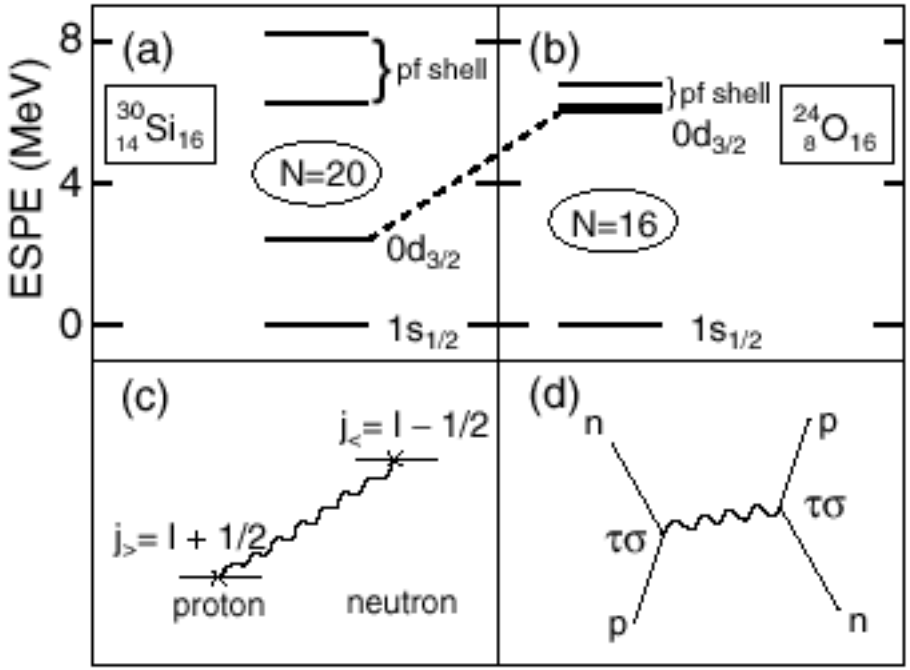
N = 34

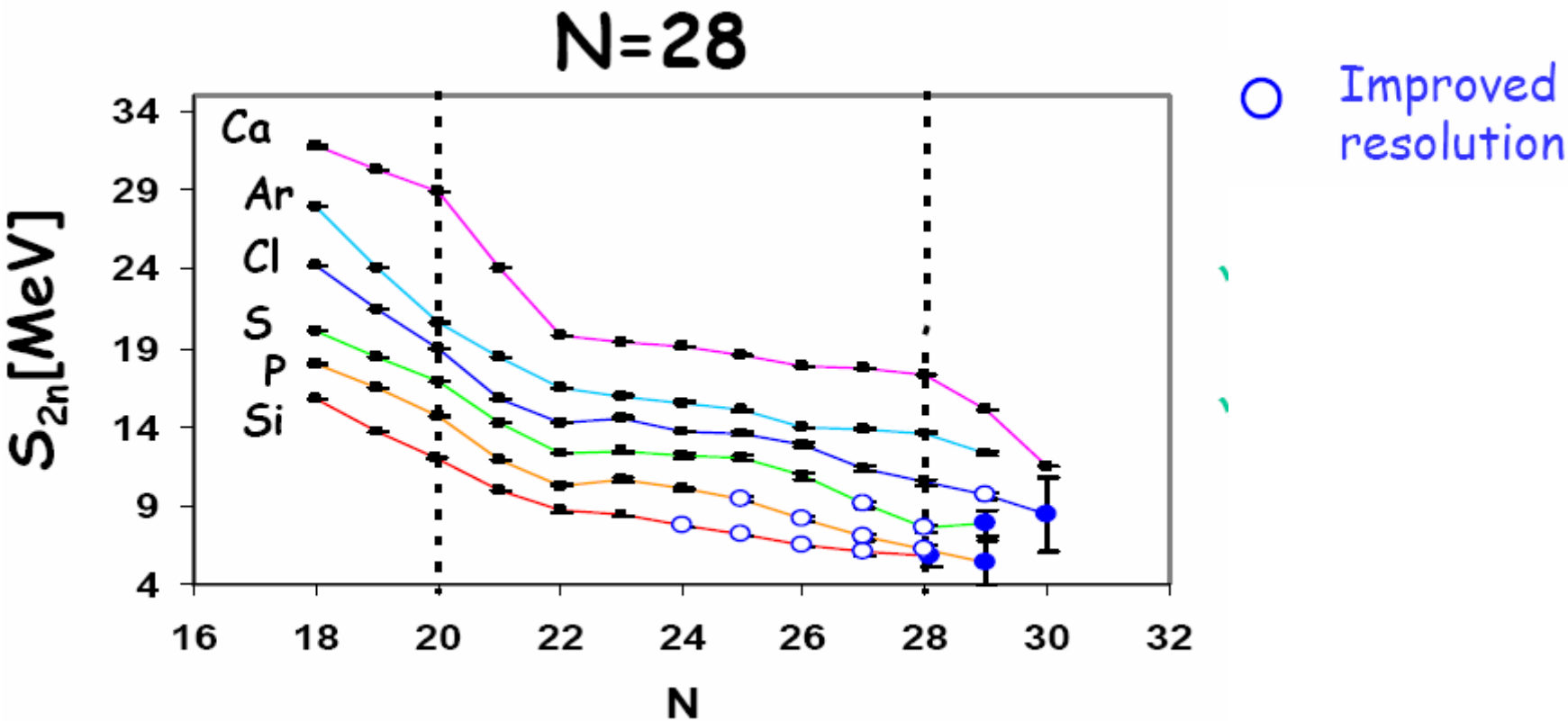
N = 16


30 14 Si 16
π
υ
1f5/2
2p1/2
2p3/2
28
1f7/2
20
1d3/2
2s1/2
1d5/2
8
1f5/2
2p1/2
2p3/2
28
1f7/2
20
1d3/2
2s1/2
1d5/2
8

$^{24}_{8}O_{16}$


π
υ
1f5/2
2p1/2
2p3/2
28
1f7/2
20
1d3/2
2s1/2
1d5/2
8
1f5/2
2p1/2
2p3/2
28
1f7/2
1d3/2
16
2s1/2
1d5/2
8

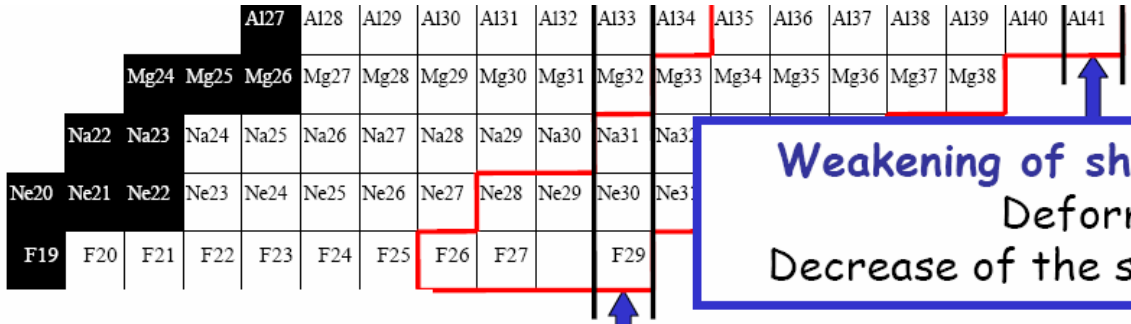

ESPE (MeV)
8
4
0
(a)
$^{30}_{14}Si_{16}$
pf shell
N=20
$0d_{3/2}$
$1s_{1/2}$
(b)
pf shell
$0d_{3/2}$
$^{24}_{8}O_{16}$
N=16
$1s_{1/2}$
(c)
$j_< = l - 1/2$
$j_> = l + 1/2$
proton
neutron
(d)
n
p
τσ
τσ
p
n



✓New masses:

^{42}Si, ^{44}P, ^{45}S, ^{47}Cl

✓Weakening of shell N=28



Weakening of shell closure N=28

Deformation

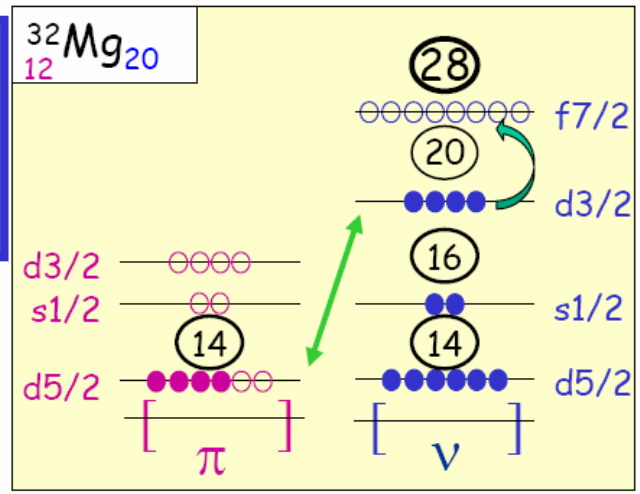
Decrease of the spin-orbit coupling

Reorganisation of shell structure around N=20

Deformation

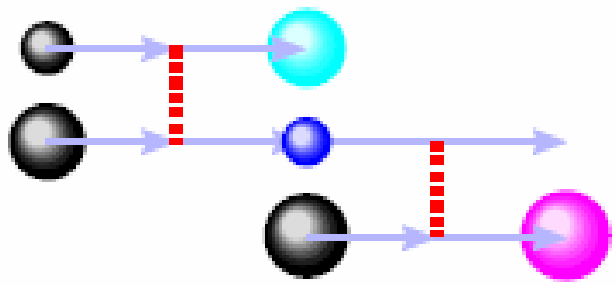
Neutron-Proton Interaction

(Otsuka et al. Eur. Phys. J. A 13 (2002) 69)



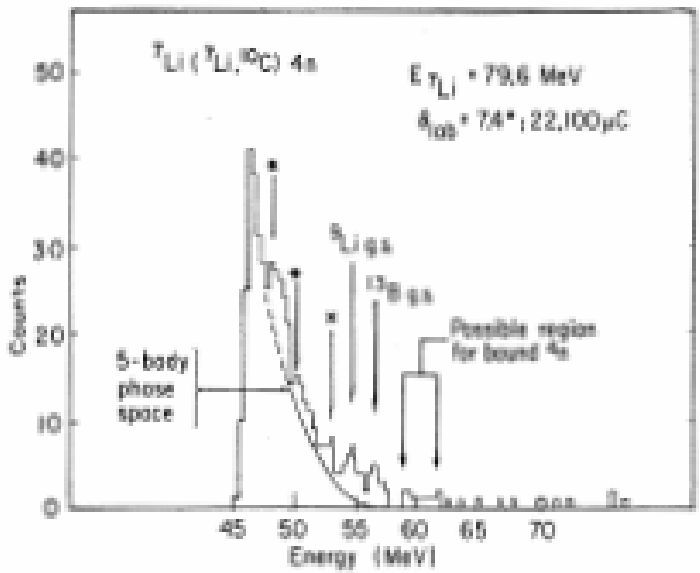
1960s-2000s : a long (unsuccessful) quest

- *two-step reactions :*
  - ▷ $p + W \xrightarrow{(Al)} {}^{A}n + {}^{70}Zn \rightarrow {}^{72}Zn\ [(t,p)]$
  - ▷ ${}^{208}Pb\,(\pi^-,\pi^+)\,{}^{4}n \xrightarrow{({}^{208}Pb)} {}^{212}Pb + \gamma$



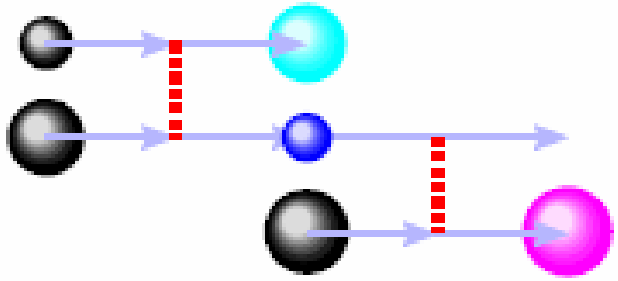
- *π charge exchange :*
  - ▷ ${}^{3}H\,(\pi^-,\gamma)\,3n$
  - ▷ ${}^{\{3,4\}}He\,(\pi^-,\pi^+)\,\{3,4\}n$

- *multinucleon transfer :*
  - ▷ ${}^{7}Li + {}^{11}B \rightarrow {}^{14}O + 4n$
  - ▷ ${}^{7}Li + {}^{7}Li \rightarrow {}^{\{10,11\}}C + \{4,3\}n$



- *backgrounds + cross-sections ...*

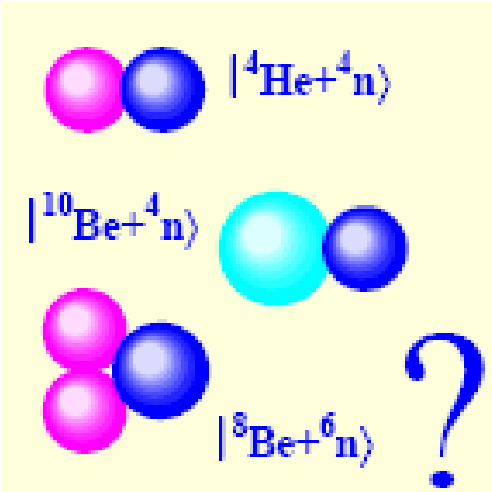
1960s-2000s : a long (unsuccessful) quest



- *two-step reactions :*
  - $p + W \xrightarrow{(Al)} {}^{A}n + {}^{70}Zn \rightarrow {}^{72}Zn\ [(t,p)]$
  - ${}^{208}Pb\,(\pi^-,\pi^+)\,{}^{4}n \xrightarrow{({}^{208}Pb)} {}^{212}Pb + \gamma$

- *π charge exchange :*
  - ${}^{3}H\,(\pi^-,\gamma)\,3n$
  - ${}^{\{3,4\}}He\,(\pi^-,\pi^+)\,\{3,4\}n$

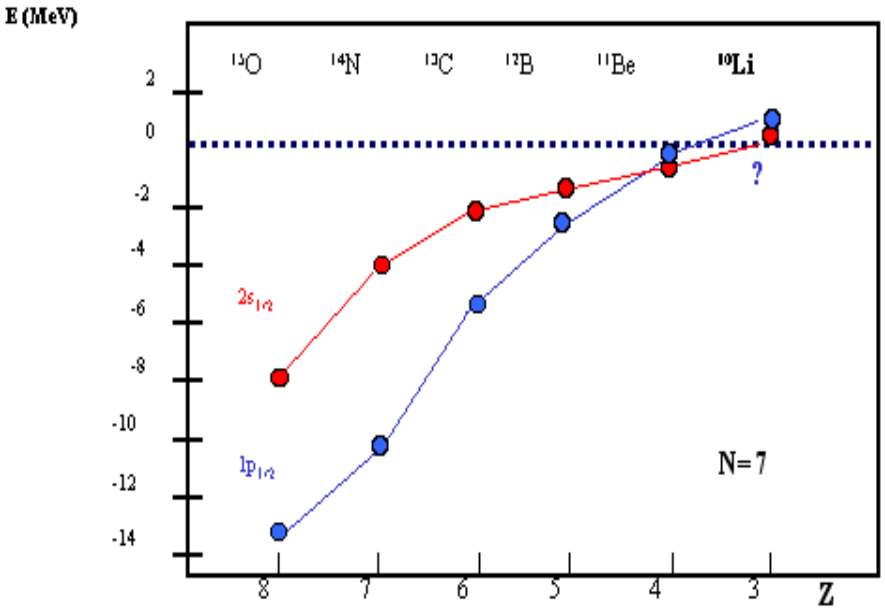
- *multinucleon transfer :*
  - ${}^{7}Li + {}^{11}B \rightarrow {}^{14}O + 4n$
  - ${}^{7}Li + {}^{7}Li \rightarrow {}^{\{10,11\}}C + \{4,3\}n$



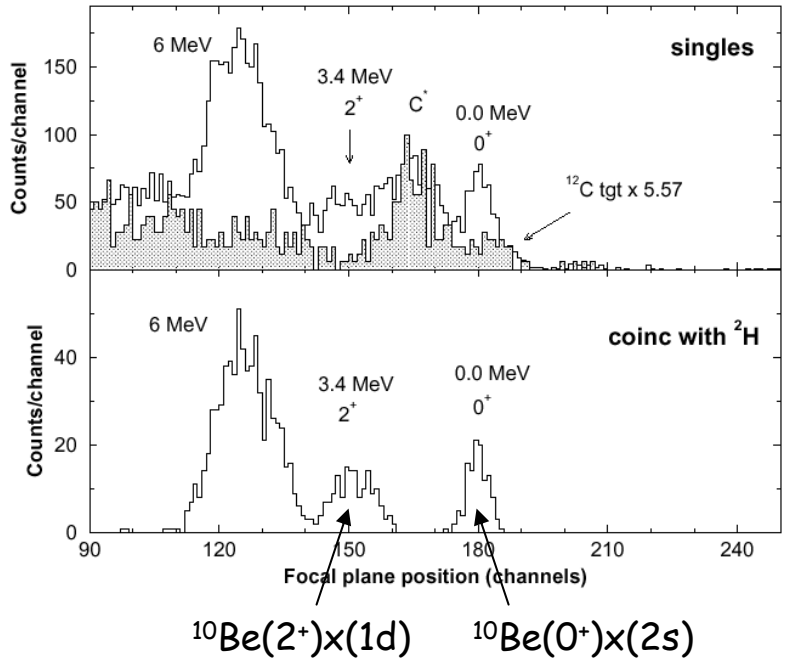
- *look inside very n-rich nuclei !!!*

Modification de la structure en couches loin de la stabilité

—Inversion des couches $1p_{1/2}$ et $2s_{1/2}$ pour les noyaux riches en neutrons



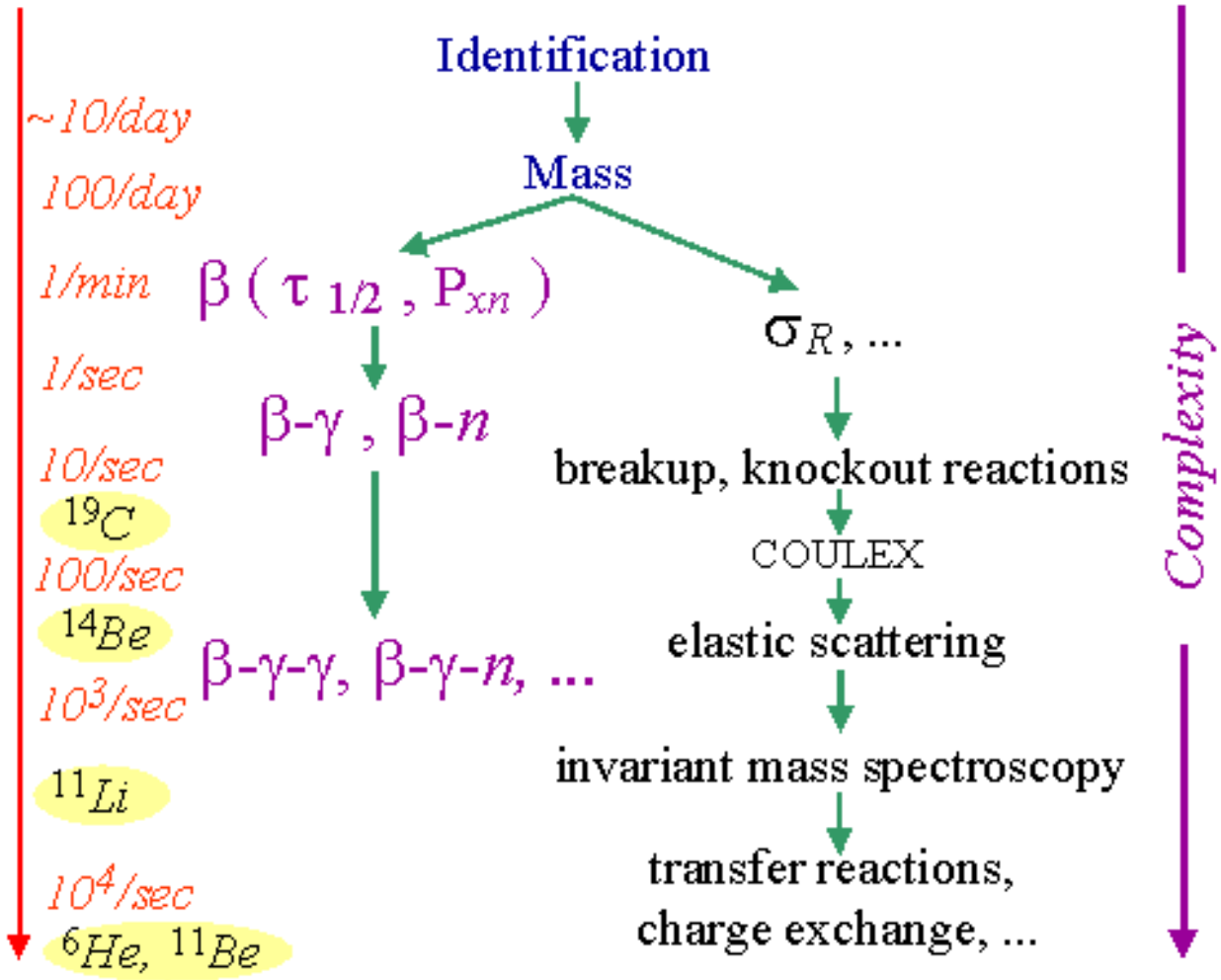
$^{11}Be(p,d)^{10}Be$



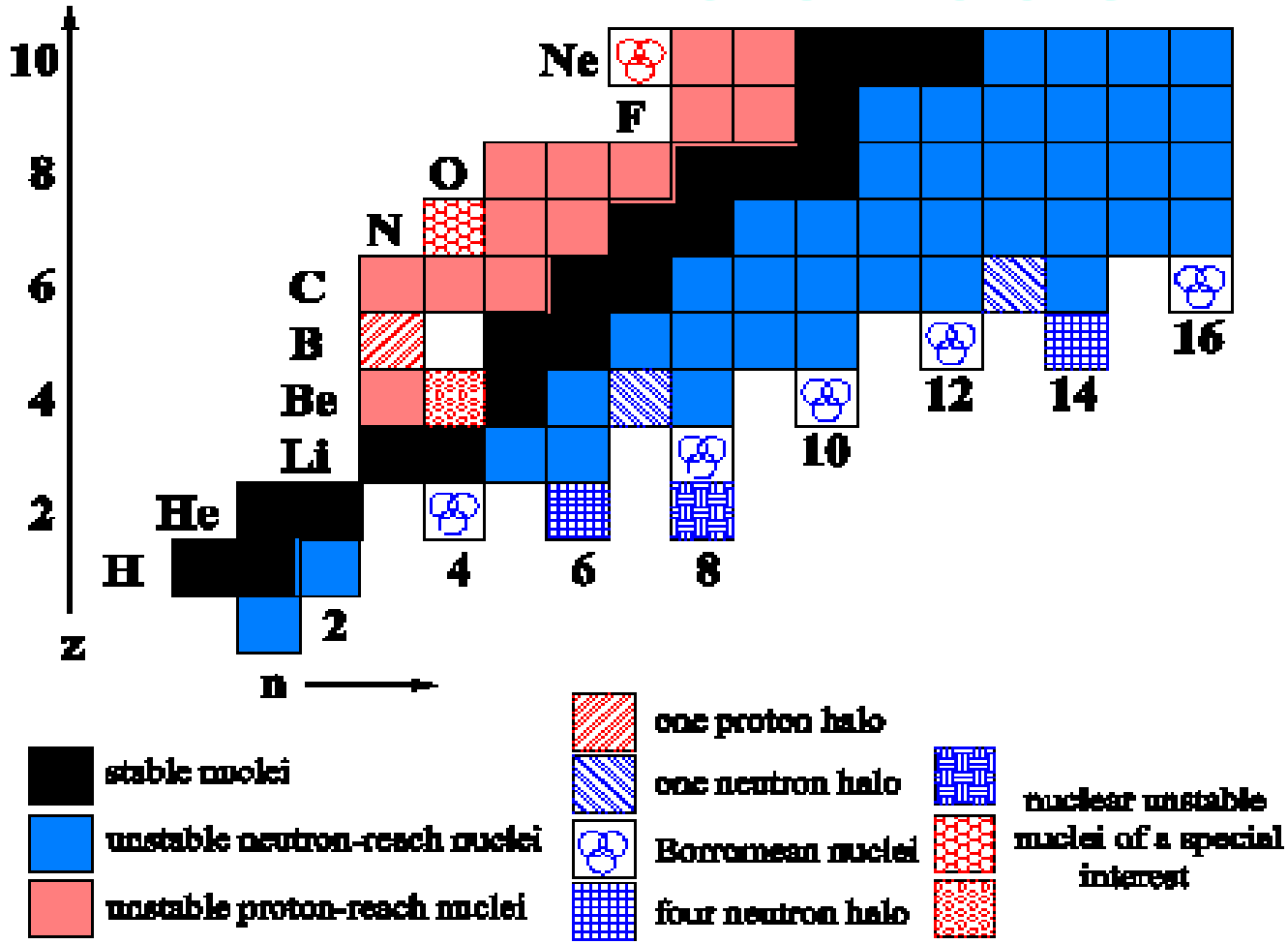
J. Winfield et al, Nucl. Phys. A683(2001) 48

Tools for structure studies

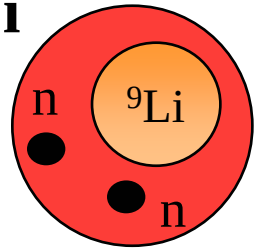
The evolution in experimental complexity with beam intensity



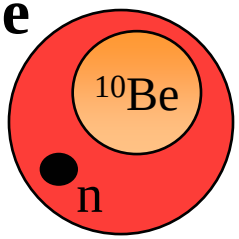
Halo nuclei



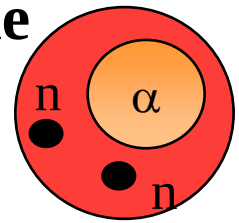
^{11}Li



^{11}Be



^{6}He

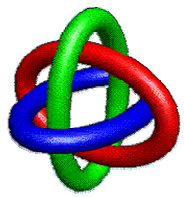


^{17}B, ^{19}C, ^{8}B one neutron, one proton halo

^{22}C, ^{17}Ne borromean

^{6}He, ^{11}Li, ^{14}Be

Borroméen



Faisceaux

GANIL - SISSI fragmentation : (déjà mesurés)

^{16}C 40 MeV/A : ^{18}O 63 MeV/A + ^{9}Be 800 mg/cm^2 ----> 10^4 pps

^{20}O 43 MeV/A : ^{40}Ar 77 MeV/A + ^{12}C 360 mg/cm^2 ----> 5 10^3 pps

^{22}O 46 MeV/A : ^{36}S 77 MeV/A + ^{12}C 540 mg/cm^2 ----> 1200 pps

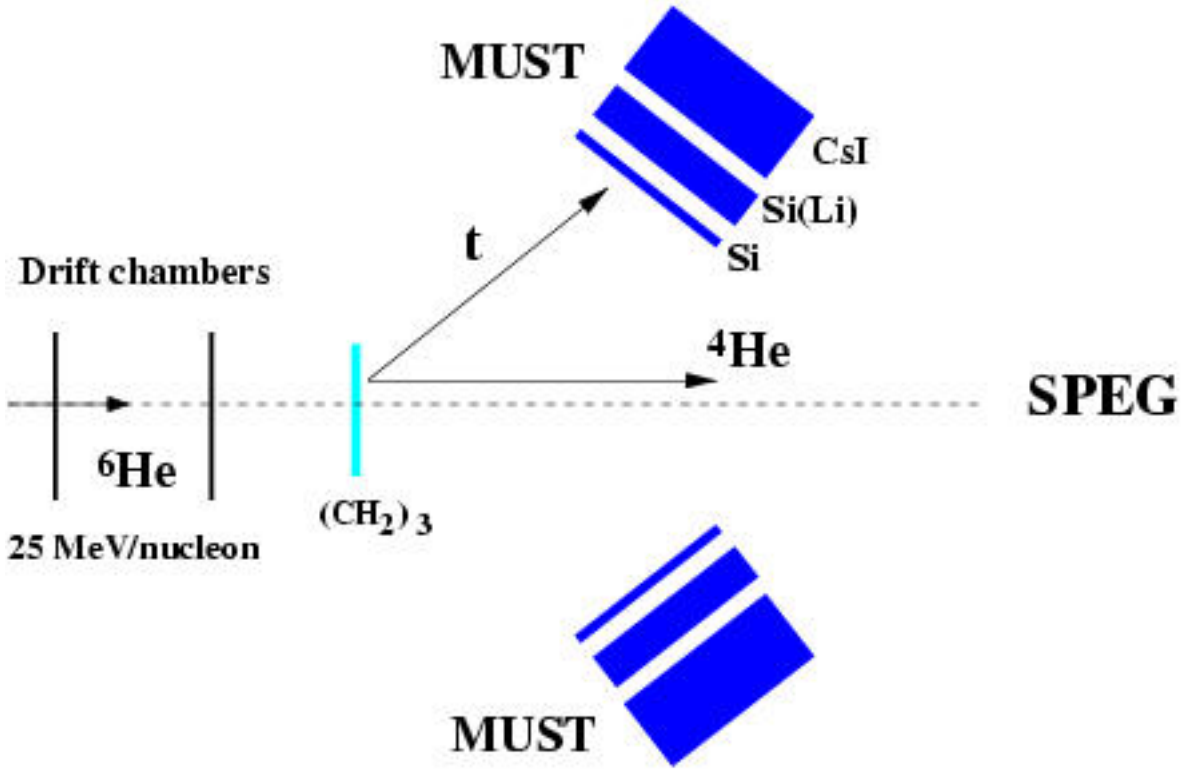
^{25}F 40 MeV/A : ^{36}S 77 MeV/A + ^{12}C 530 mg/cm^2 ----> 200 pps

GANIL - SISSI fragmentation : (estimation code LISE)

^{18}C 40 MeV/A : ^{40}Ar 77 MeV/A + ^{12}C 360 mg/cm^2 ----> 3 10^3 pps

GANIL - SPIRAL II :

^{68}Ni : 10^5 pps rapport spiral II, p7


MUST
CsI
Si(Li)
Si
t
Drift chambers
^{4}He
SPEG
^{6}He
$(CH_2)_3$
25 MeV/nucleon
MUST

Fonction d'onde de l'^{6}He: t + t ?

- **Energie de liaison de l'^{6}He**
  reproduite
  avec une configuration triton-triton
  A. Csoto, PRC 48 (1993) 165

- **Calculs microscopiques**

  TISM: $S_{t\text{-}t} = 1.77$ Yu. F. Smirnov, PRC 15 (1977) 84
  $S_{\alpha\text{-}2n} = 1.12$

  RGM: $S_{t\text{-}t} = 0.49$ K. Arai et al., PRC 59 (1999) 1432

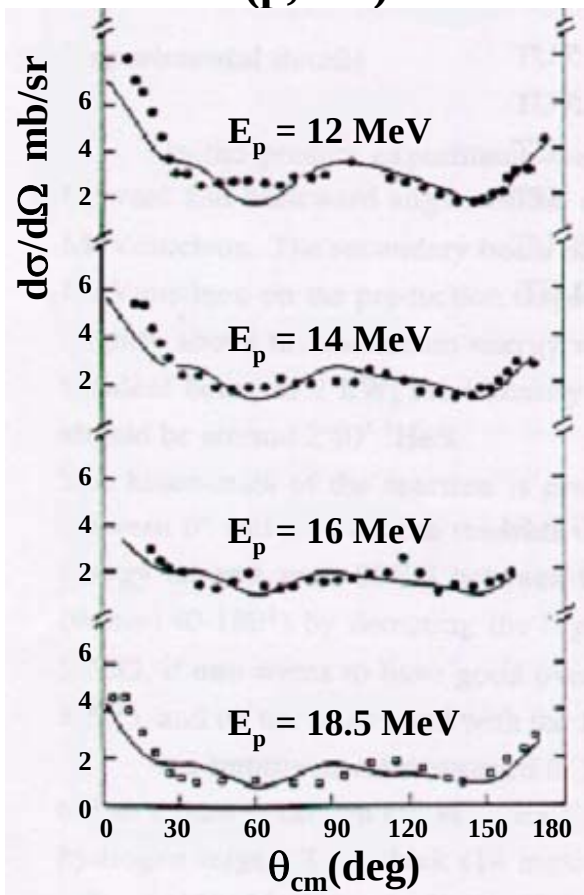
- **Analogie avec ^{6}Li**
  ^{6}Li(p,^{3}He)α: clusters α+d et ^{3}He+t

  $(\alpha + d) + p \longrightarrow {}^3He + \alpha$

  $({}^3He + t) + p \longrightarrow \alpha + {}^3He$

  $\longrightarrow$ $S_{\alpha\text{-}d}$ 0.69
  $S_{3He\text{-}t}$ 0.44

^{6}Li(p,^{3}He)^{4}He



M.F Werby et al., PRC 8 (1973) 106

DWBA

- $A + a \longrightarrow B + b$

  $\{B+x\} + a \longrightarrow B + \{a+x\}$

  x: nucléon(s) transféré(s)

  ici: t, 2n

- $\dfrac{d\sigma}{d\Omega}$ dépend de T_{AB} : élément de matrice de la réaction

- $T_{AB} = \langle \chi^{-}_{bB} \Phi_b \Phi_B \,|\, W_{bB} \,|\, \Psi^{+}_{aA} \rangle$ post

  $\chi^{+}_{aA} \Phi_a \Phi_A$ DWBA

- $W_{bB} = V_{bB} - U_{bB}$

  $V_{aB} + V_{xB}$ décrit la diffusion élastique de b+B

Voies couplées

- $\Psi_{CRC} = \sum_i \Phi_i^t \, \Phi_i^p \, \chi_i^{t-p}$

  cible

  projectile

i=a,b,c…

partitions de masse

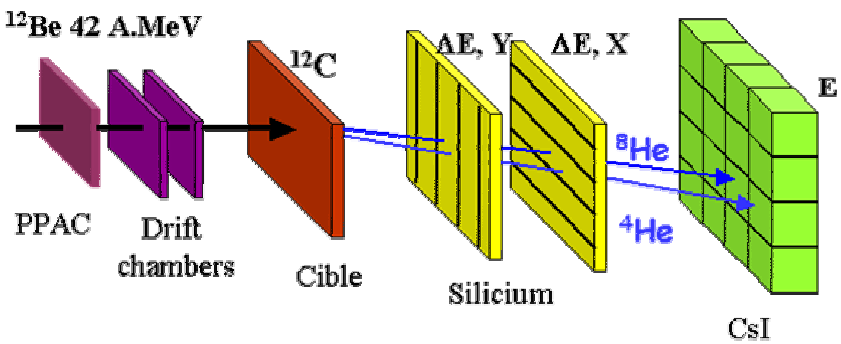
Exemple: 6He + p, 5He + d, 4He + t

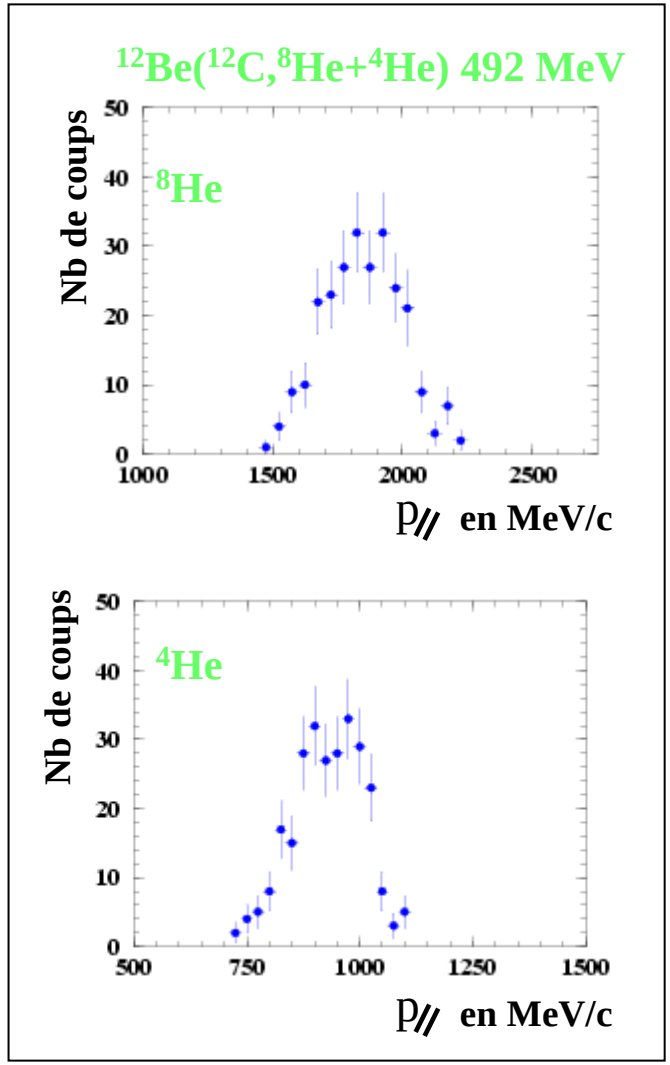
- $(H-E)\Psi_{CRC} = 0$

- **Projection**
  sur les différents états d'une partition de masse
  ↳ **Système d'équations intégro-différentielles couplées reliant les inconnues** χ_i^{t-p}

- **Résolution système + conditions asymptotiques**
  ↳ **Amplitudes de diffusion** f_{ab} , f_{bc}
  ↳ **Section efficace différentielle de la réaction**

Etats moléculaires du ^{10,12}Be





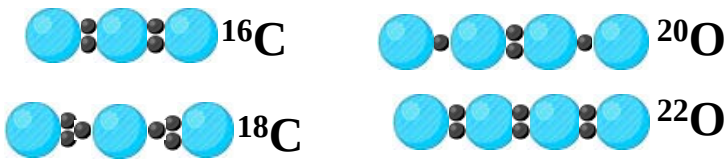
- **Méthode**

- distributions $p_{//}$ et $p_{\perp}$ expérimentales des fragments chargés

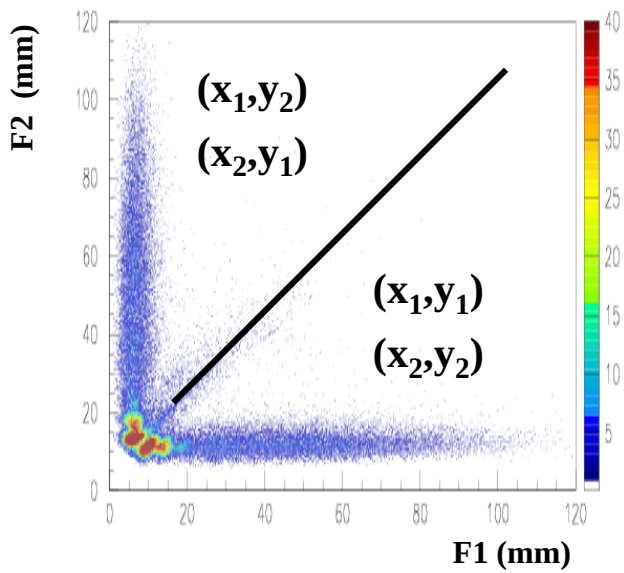
- comparaison modèle de Glauber (F. Carstoiu)

- simulation Monte-Carlo:
  convolution distributions moment théoriques avec effets expérimentaux

- **Futur**

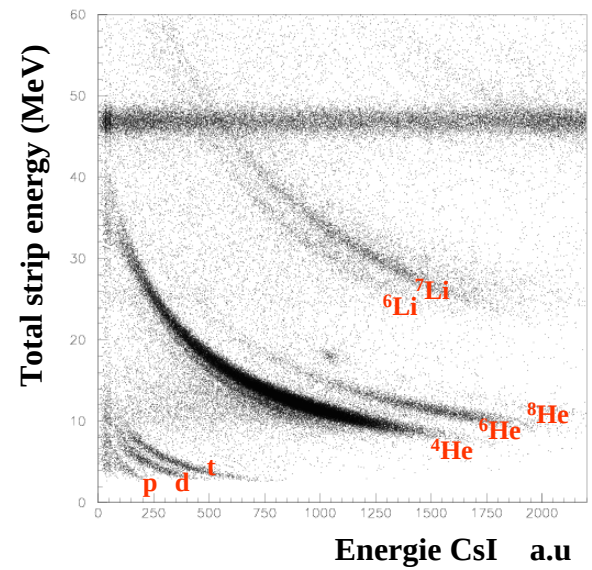


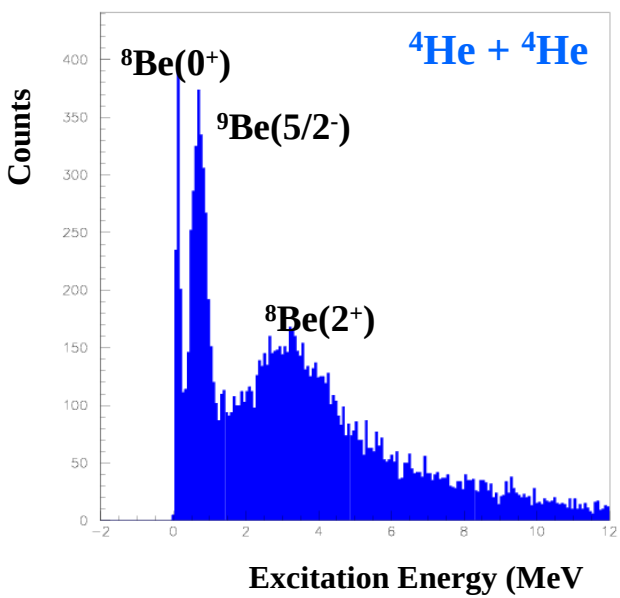
2 Events correlation

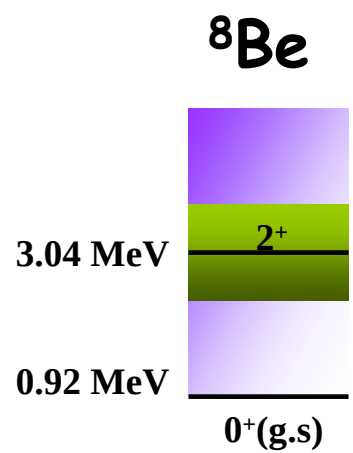


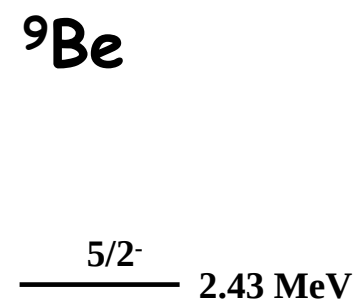
F1 and F2
Fonctions de corrélation

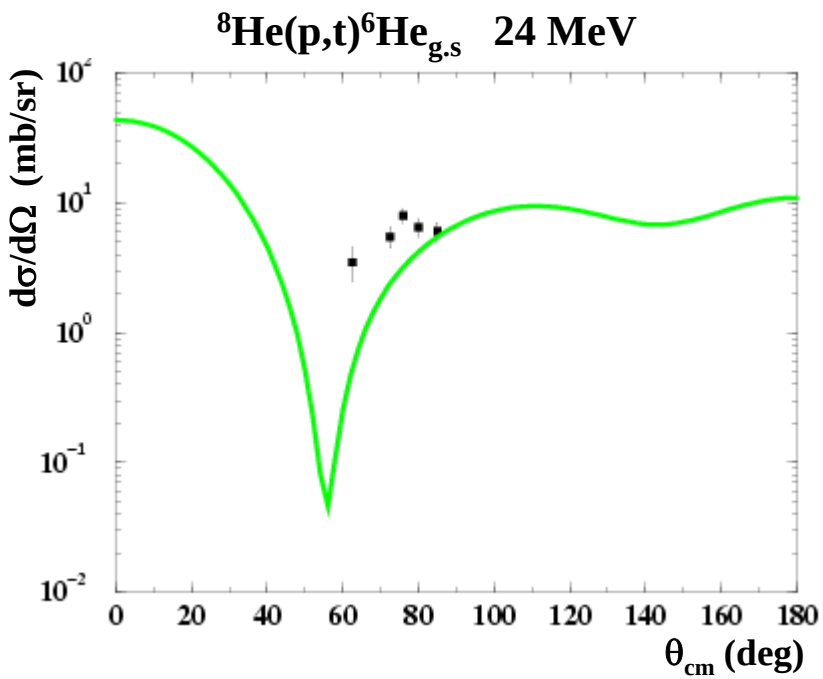
- x_1, x_2, y_1, y_2
  precise position
  (charge division)
- px_1, px_2, py_1, py_2
  rough position
  (strip number)

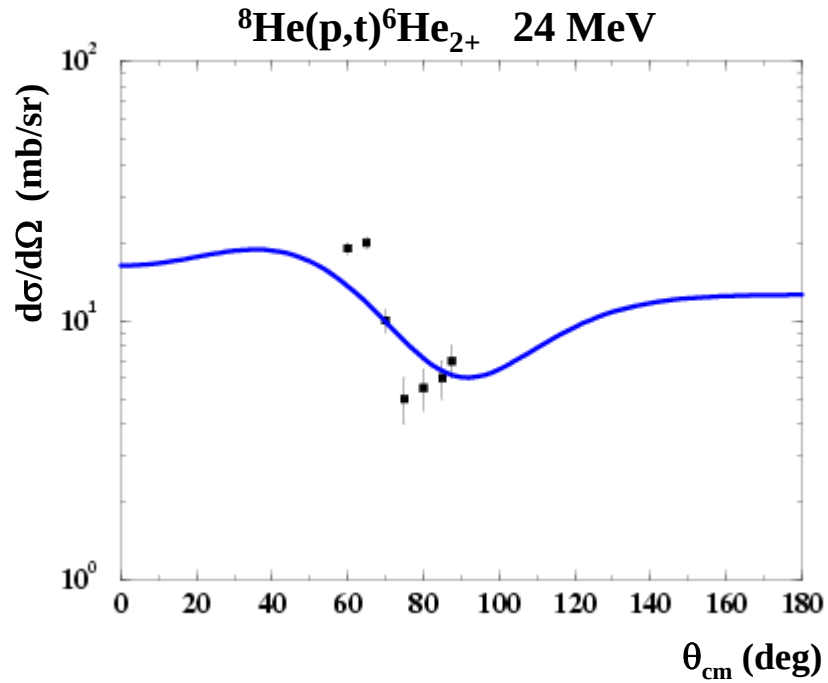


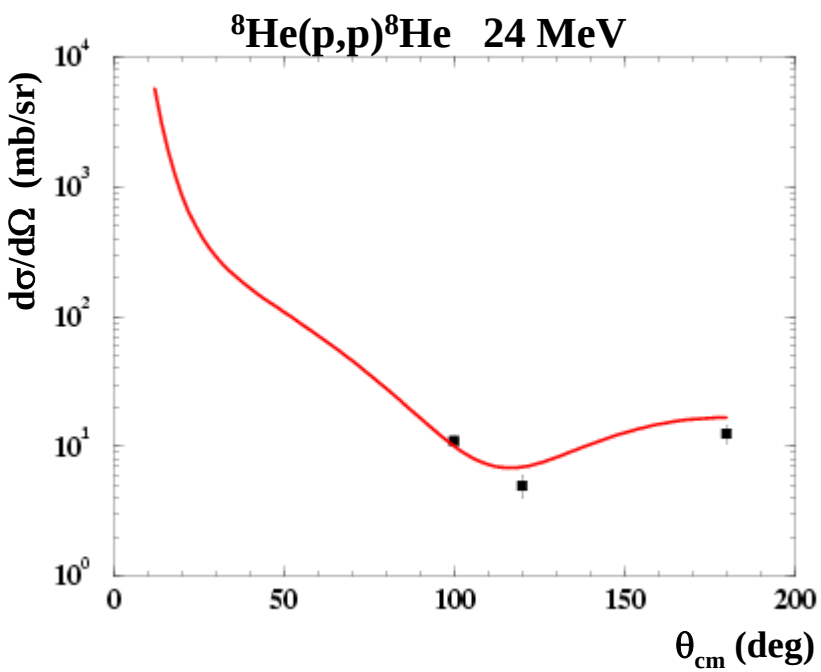


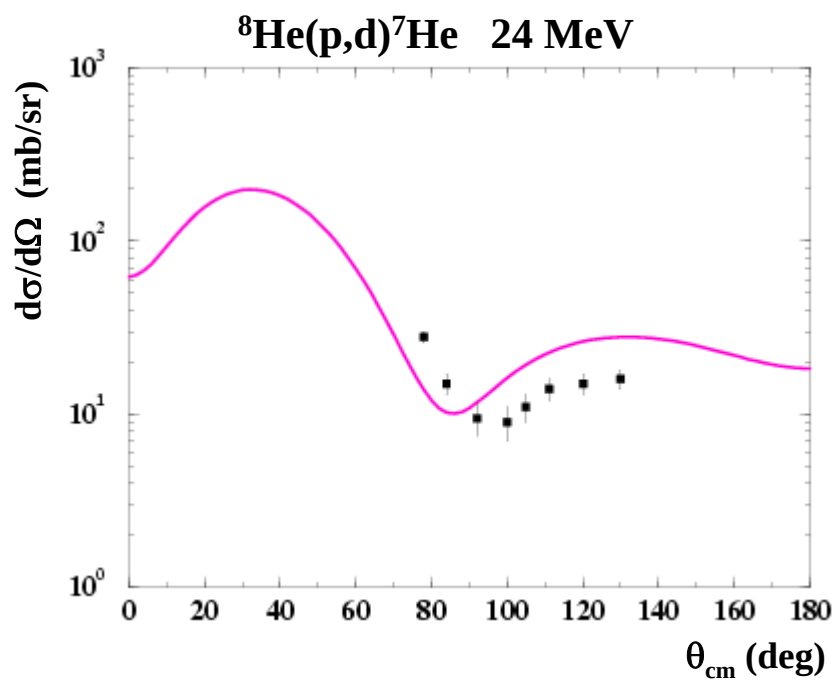


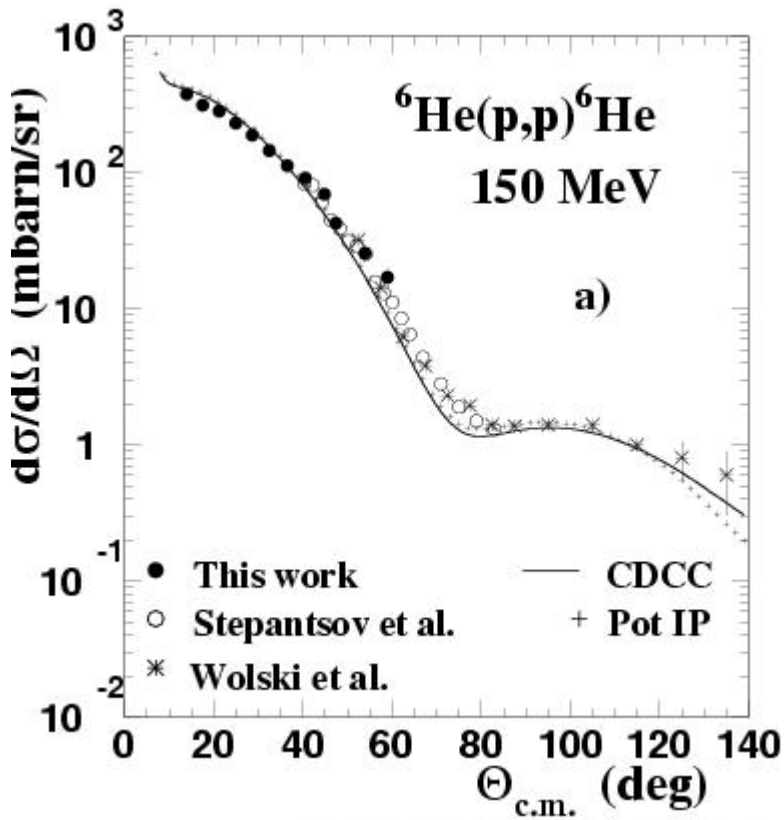


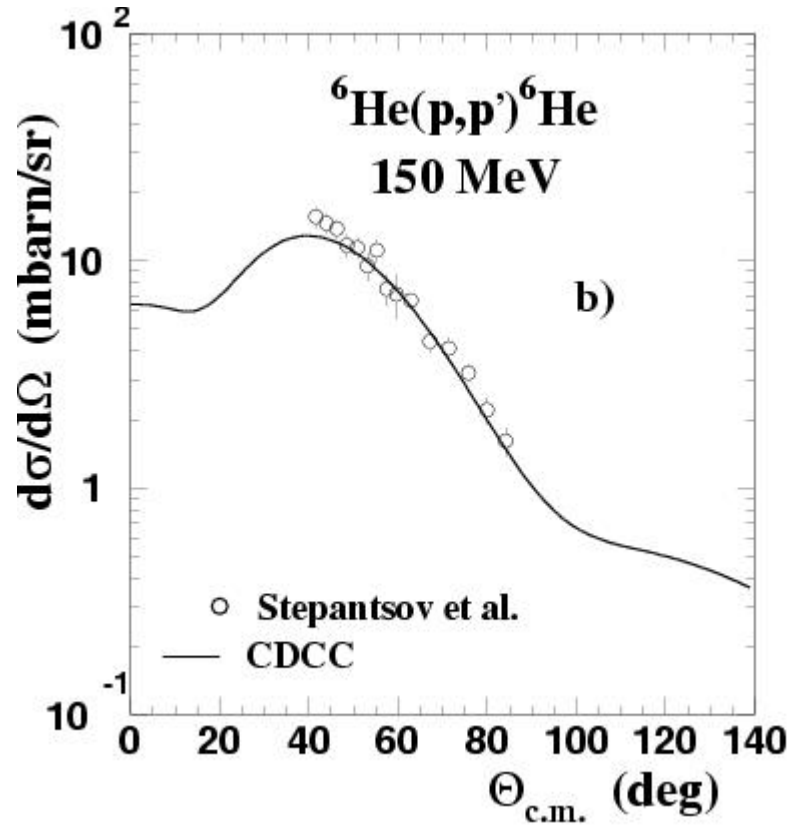

^{8}He(p,t)^{6}He$_{g.s}$ 24 MeV
dσ/dΩ (mb/sr)
θ$_{cm}$ (deg)


^{8}He(p,t)^{6}He$_{2+}$ 24 MeV
dσ/dΩ (mb/sr)
θ$_{cm}$ (deg)

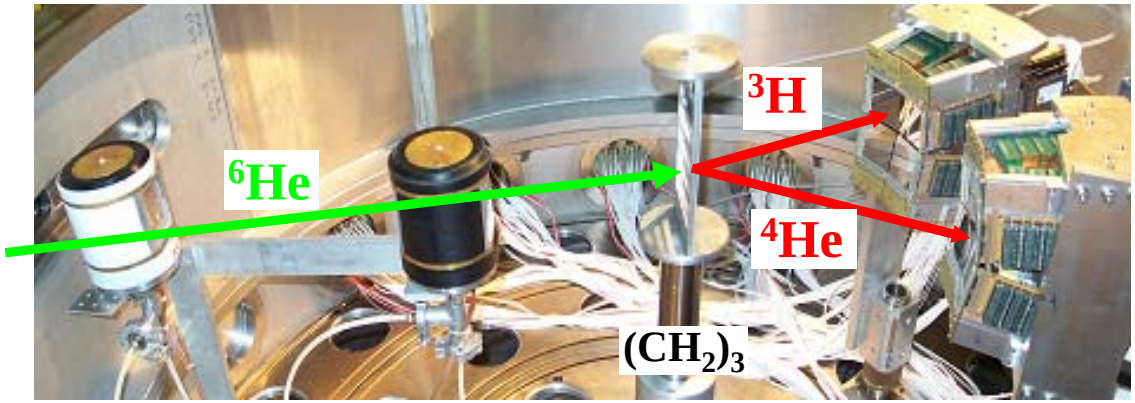

^{8}He(p,p)^{8}He 24 MeV
dσ/dΩ (mb/sr)
θ$_{cm}$ (deg)


^{8}He(p,d)^{7}He 24 MeV
dσ/dΩ (mb/sr)
θ$_{cm}$ (deg)


^{6}He(p,p)^{6}He
150 MeV
a)
This work
Stepantsov et al.
Wolski et al.
CDCC
Pot IP
dσ/dΩ (mbarn/sr)
Θ$_{c.m.}$ (deg)


^{6}He(p,p')^{6}He
150 MeV
b)
Stepantsov et al.
CDCC
dσ/dΩ (mbarn/sr)
Θ$_{c.m.}$ (deg)

Dispositif expérimental



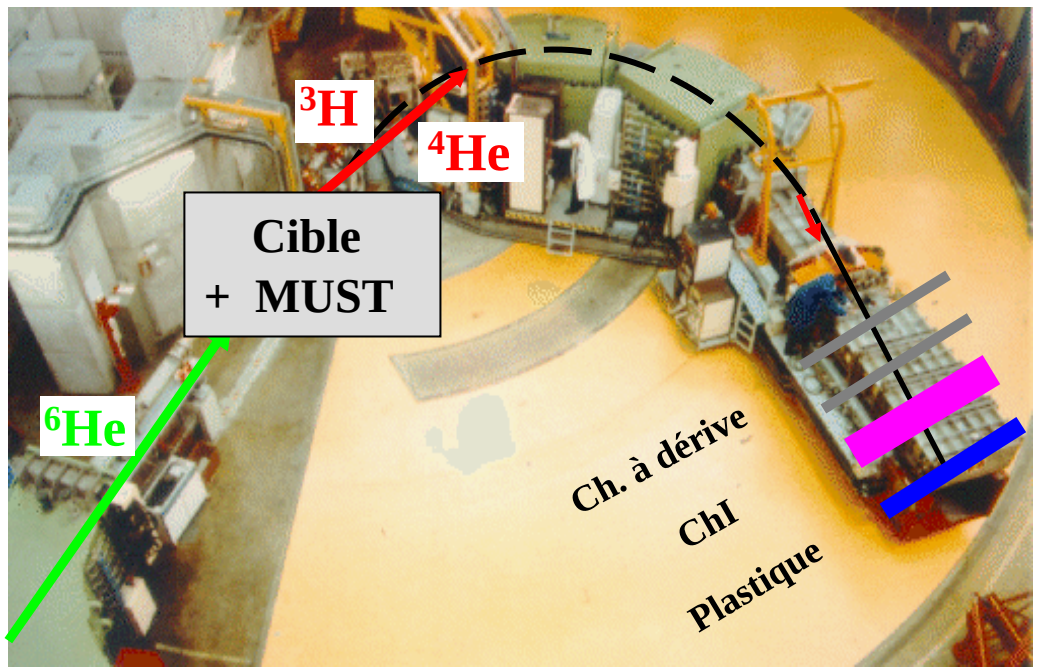
$^6He + p \longrightarrow {}^3H + {}^4He$

Détection: ^{4}He et ^{3}H

MUST

ou

SPEG

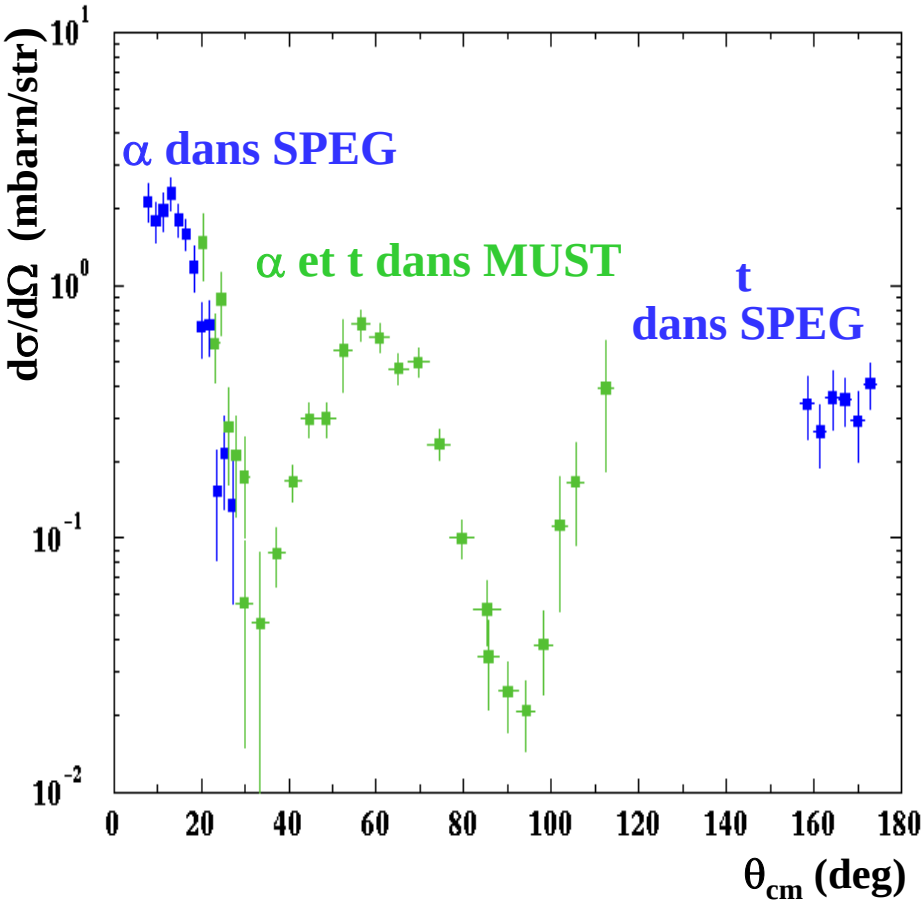


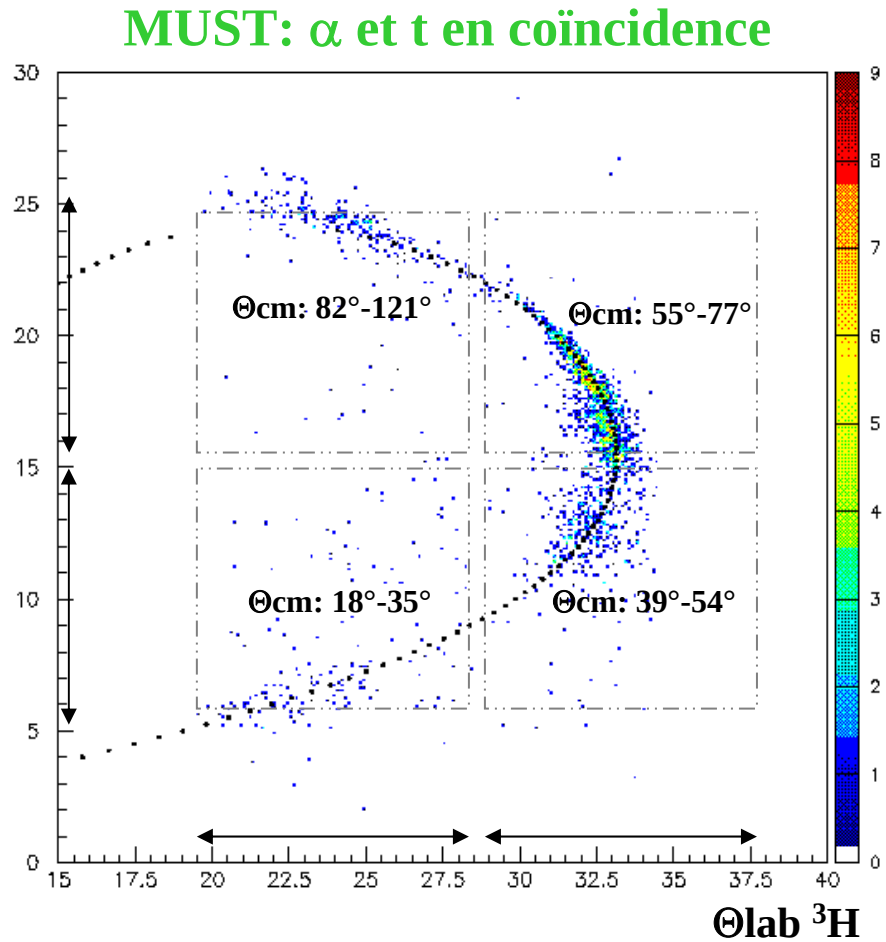
Collaboration:

Ganil

Dapnia, IPNO,
Bruyères-le-Châtel

$^6He(p,t)^4He$ 150 MeV



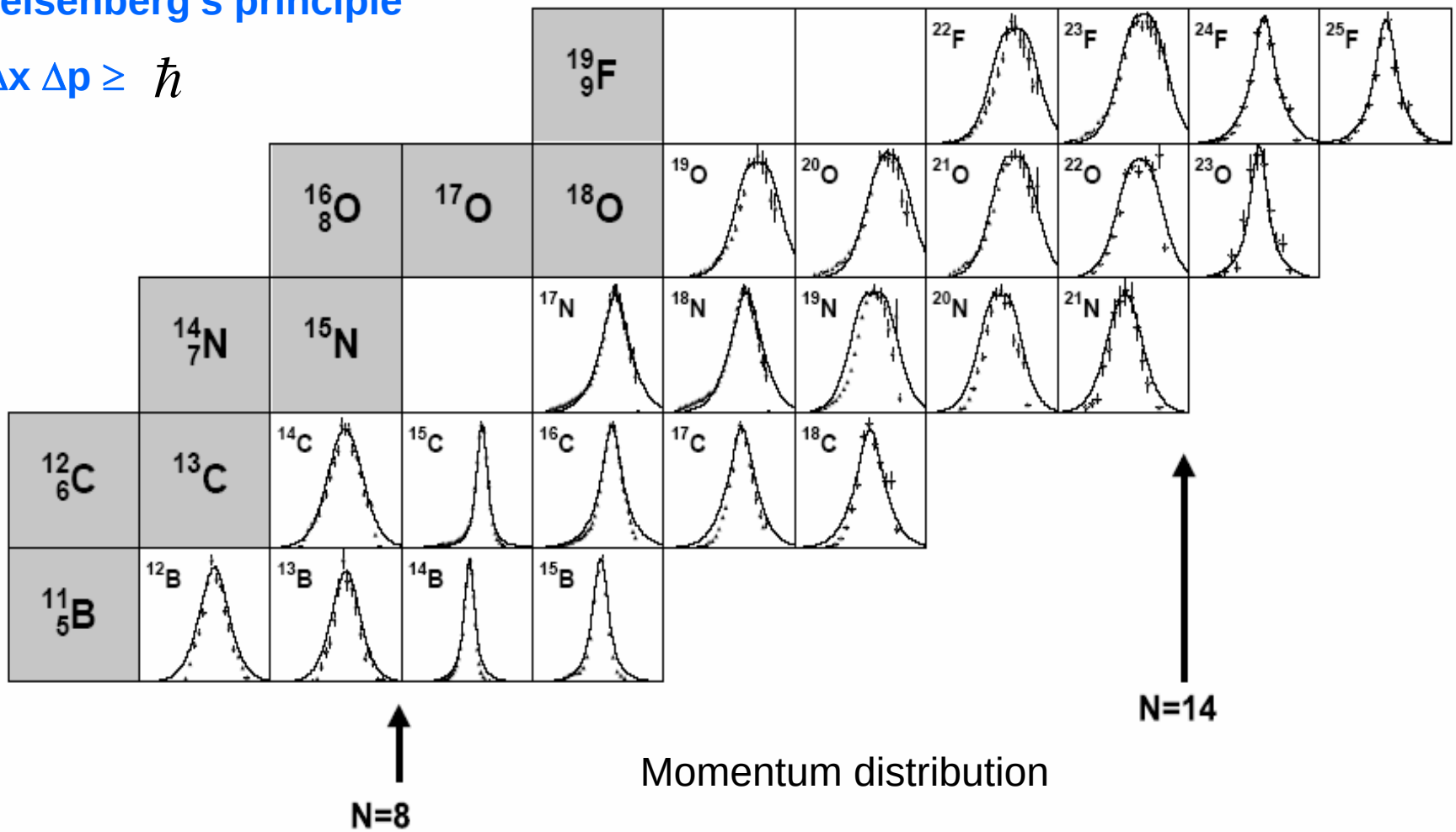


→ **bon accord entre les données obtenues avec SPEG et MUST**

Single-Neutron Removal: p-sd shell

Heisenberg's principle

$\Delta x \, \Delta p \geq \hbar$



Momentum distribution

Expt v 's Glauber Theory + Shell Model: Sauvan, et al., PRC (2004)