Neutron-skin structure and shell evolution

of weakly-bound neutron-rich EURISOL nuclei

in coupled-reaction channel studies

EURISOL

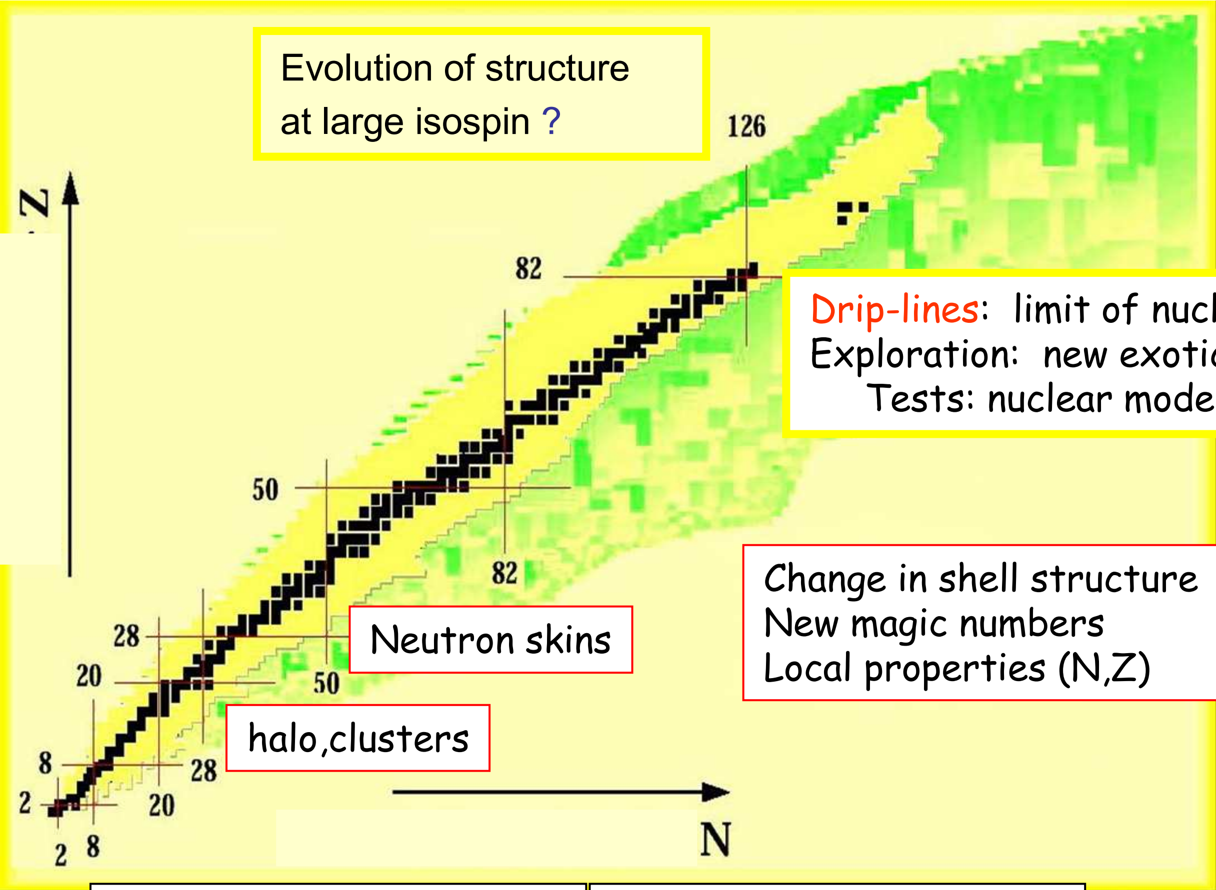
Physics & Instrumentation , Firenze, 14-18 January 2008

- *Structure studies at the drip-lines : exemples, + exp-theory* ρ_n , ρ_p
- GOAL with EURISOL: extended systematics of neutron rms radius and of neutron excitation along isotopic chains
- Probe the structure & spectroscopy at large isospin
  →Measure unbound states → detection devices
  Requirements for a new experimental set-up
- NEED FOR AN IMPROVED THEORETICAL FRAMEWORK OF STRUCTURE AND REACTIONS

V. Lapoux DAPNIA/SPhN

dapnia
cea
saclay

Nuclear structure towards the drip-lines : phenomena to explore & to understand



Evolution of structure
at large isospin ?

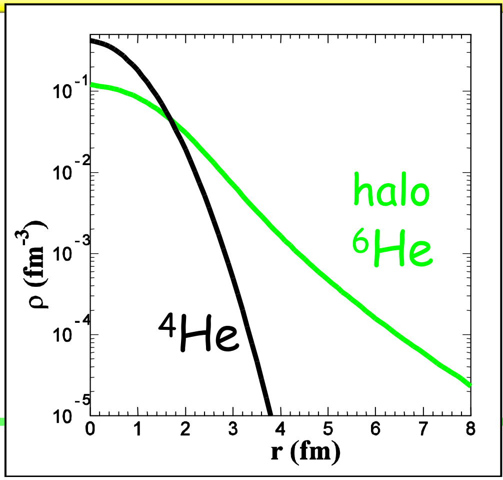
Drip-lines: limit of nuclear binding, large isospin
Exploration: new exotic structures → neutron-skin
Tests: nuclear modelling & interactions $V_{NN}(T_z)$

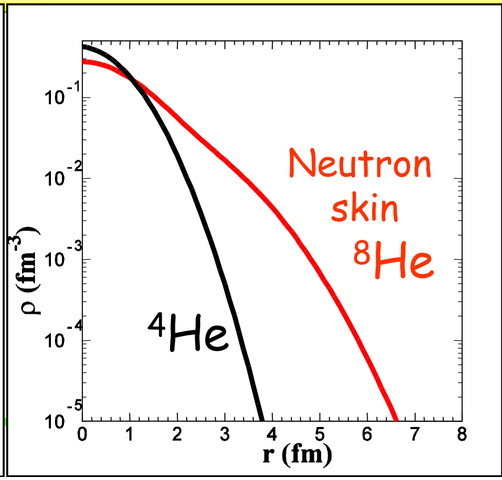
Neutron skins

halo,clusters

Change in shell structure
New magic numbers
Local properties (N,Z)

Weakly bound states ?
Continuum **coupling** ?
Isospin dependence ?



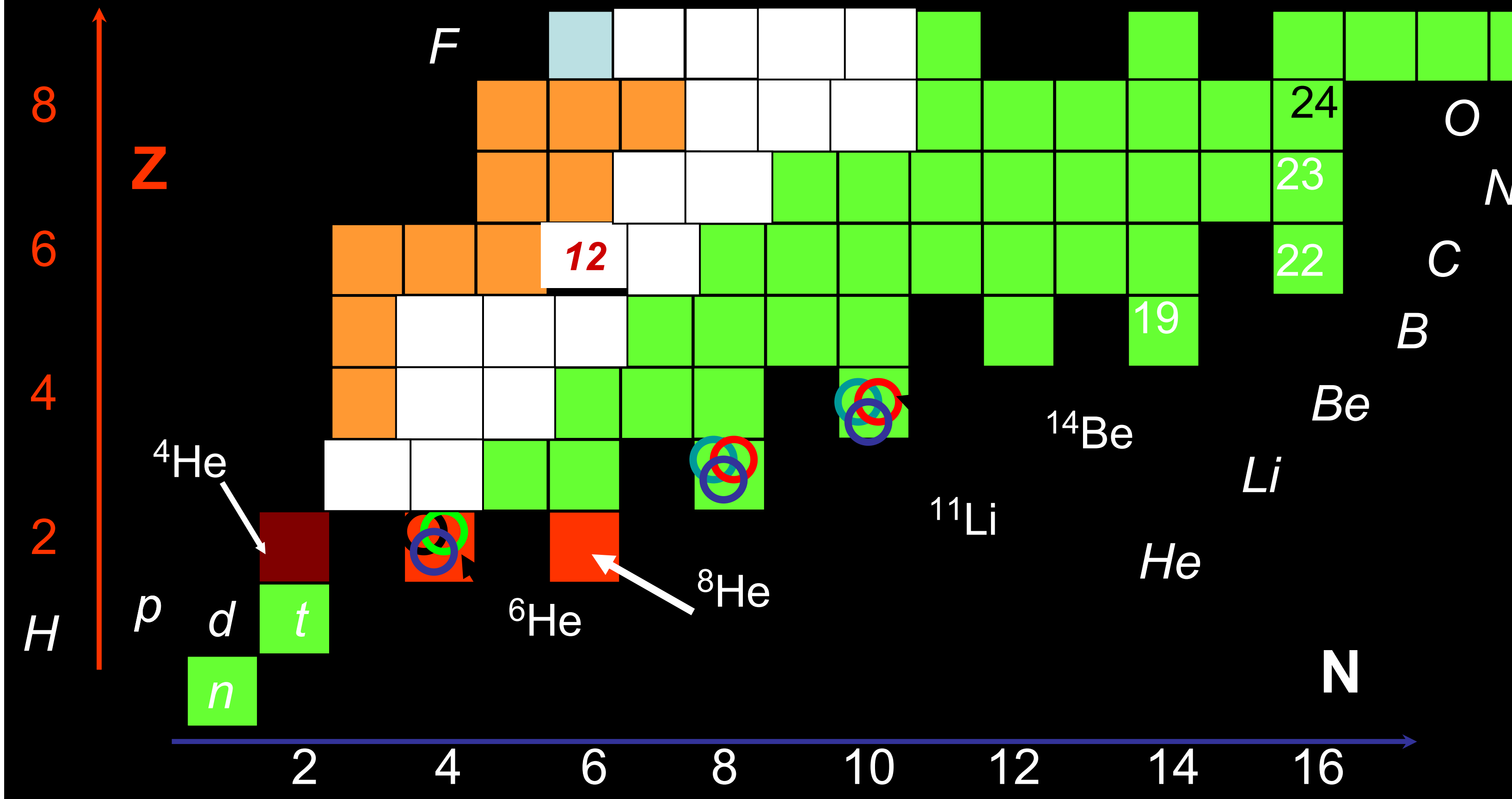


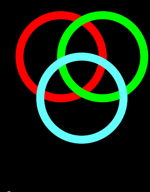
2008 : what is known ?
2016 : area to explore ?

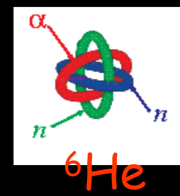
2008

Nuclear landscape towards the drip-lines

Testing ground



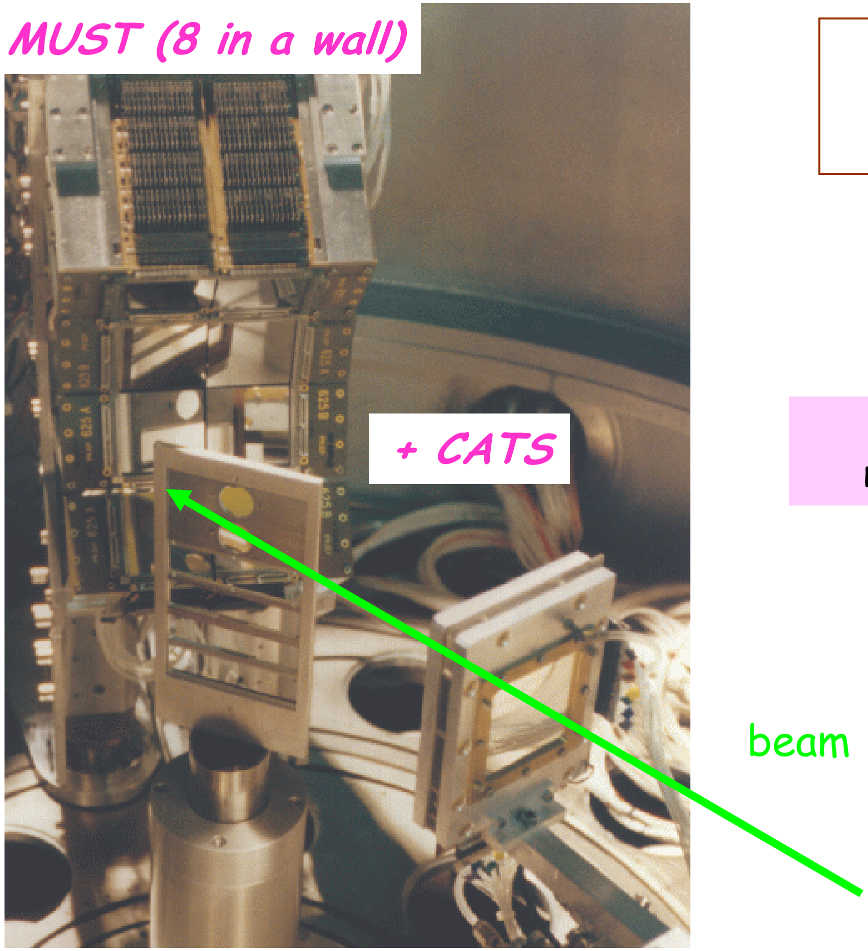




Very few drip-line nuclei have their identity card complete
→ Masses, size, densities, neutron excitation,
low-lying spectroscopy, Shell structure

Drip-line : ^{8}He
neutron-skin

Present techniques & results



MUST : Y.Blumenfeld et al., NIM A421, 421 ('99)

CATS : S. Ottini et al., NIM A431, 476 ('99).

(p,p') probe
Particle spectroscopy

structure studies by (p,p') & (p,d) reactions
using GANIL/SISSI or SPIRAL beams
and MUST+CATS

Elastic scattering
sensitive to the
matter rms

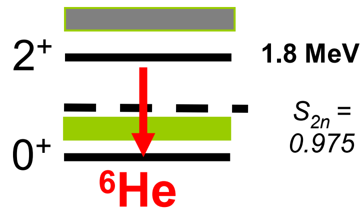
Inelastic scattering :
sensitive to the
shape of the density

Nuclear densities,
neutron excitation

C.Jouanne, VL. et al., $^{10,11}C(p,p')$
PRC **72**, 014308 ('05)

rms_m (^{10}C) : **2.42** $\pm$ 0.1 fm ; rms_m (^{11}C) : **2.33** $\pm$ 0.1 fm
[rms_m (^{12}C) : 2.30 (3) fm]

Weakly-bound nuclei
Unbound excited states
low-lying resonances

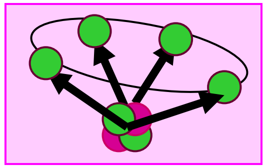


exotic He isotopes

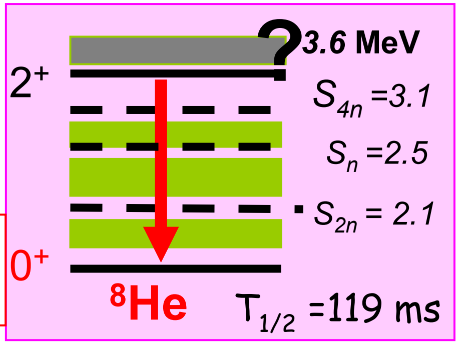
Halo, Neutron-skin structure

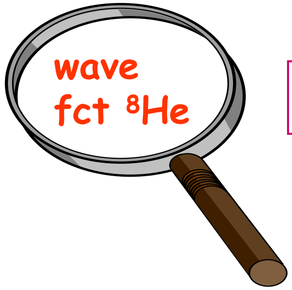
Prototype of (p,p') & direct reactions at low energy: $^8He(p,p')$

^8He ($T_{1/2}$= 119ms) I= 10^4 /s
reaction target CH_2

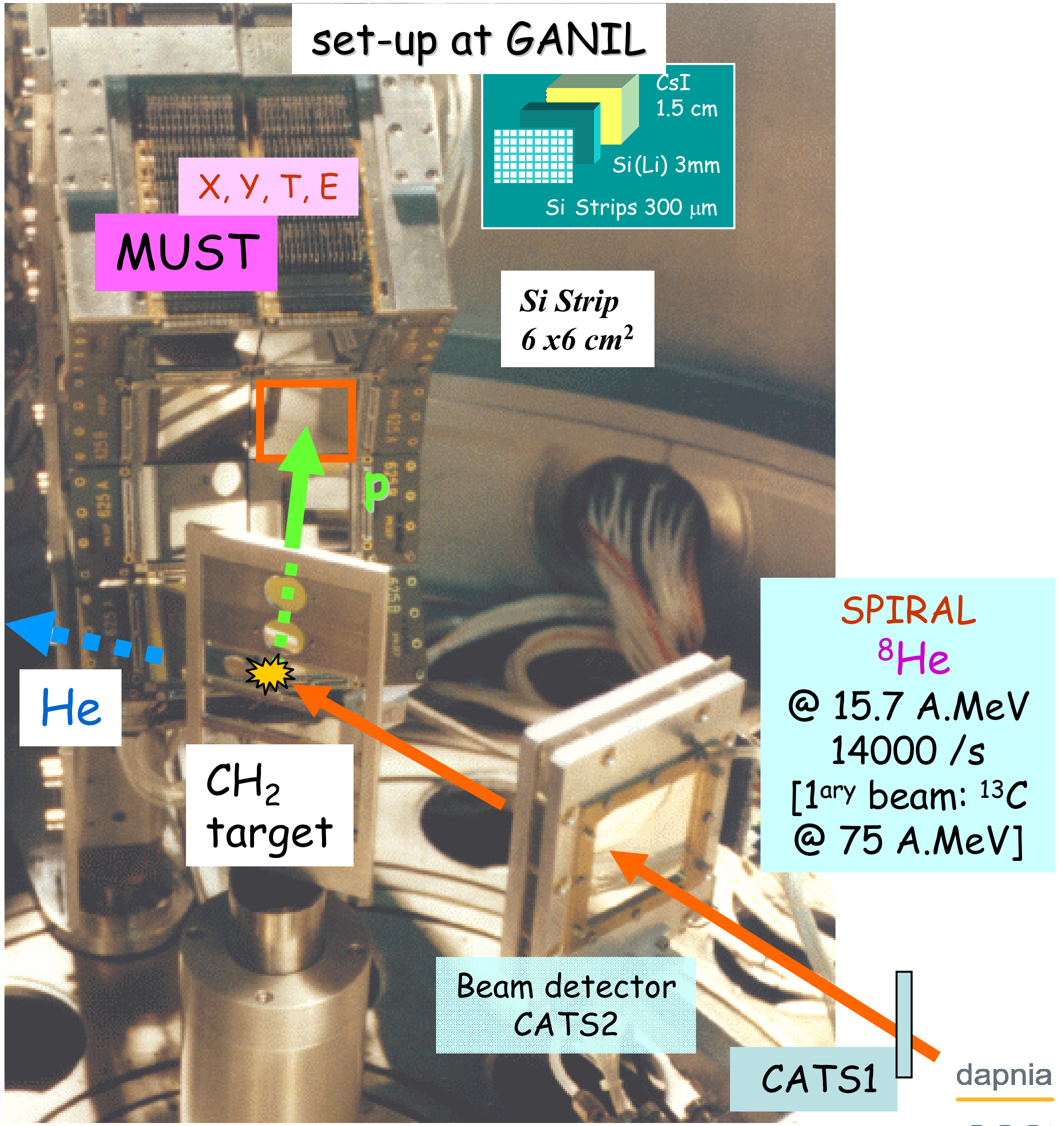


neutron-skin ?
Resonances





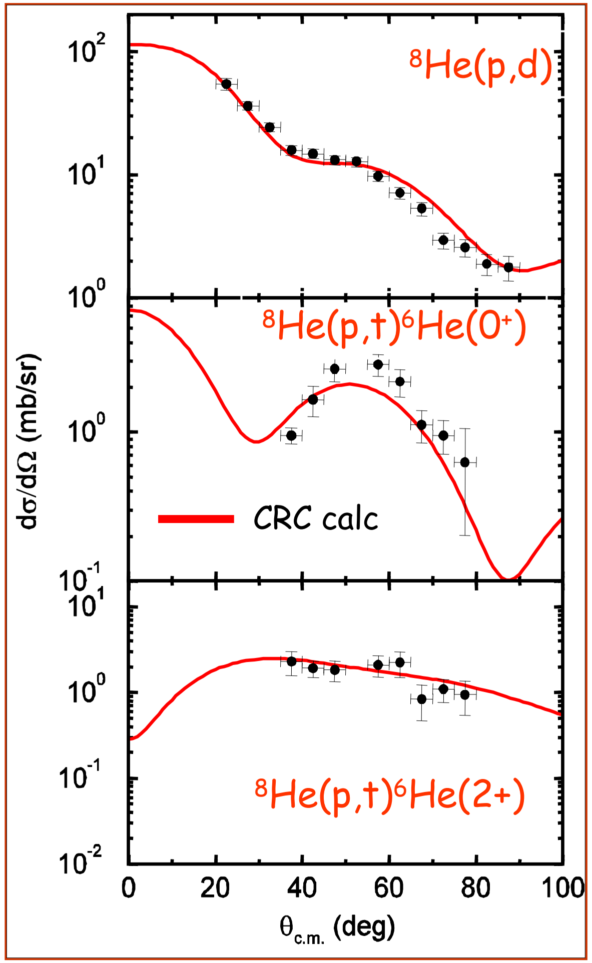
PROBE : $^8He(p,p')^8He^*$



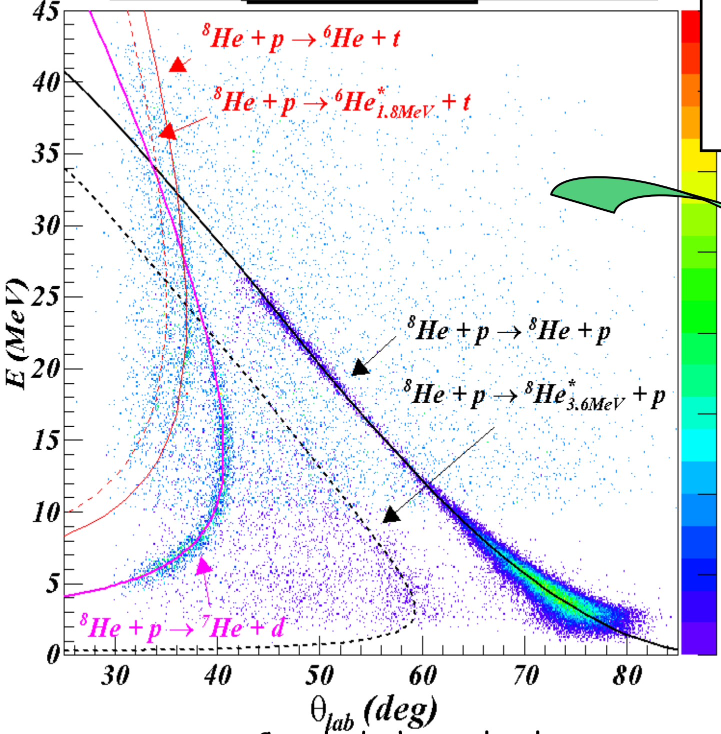
→ test of the validity of the densities
eg $^6He(p,p')$ @ 40.9 MeV/n GANIL-MUST
A. Lagoyannis et al., PLB **518**, 27 ('01)
2n-Halo features ^6He NP*A722*, 49c('03)

Collaboration : SPhN, GANIL, IPN-Orsay, FLNR-Dubna, Univ. Ioannina (Greece)

Structure of ^{8}He extracted from direct reactions on proton target

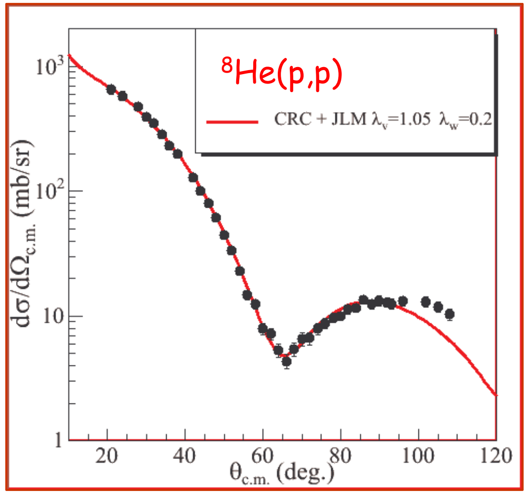


SPIRAL ^{8}He +p @ 15.7A.MeV



Coupled-channel calc.:
N. Keeley (SPhN)

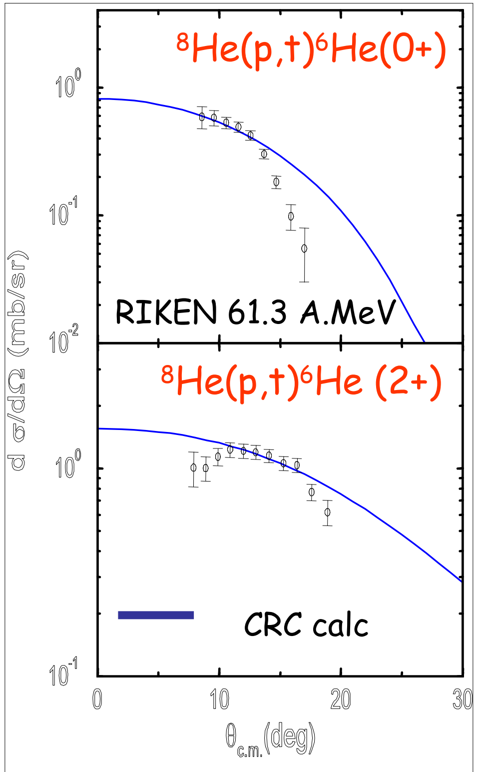
F. Skaza PhD SPhN
F. Skaza, N. Keeley, VL *et al.*,
PLB **619**. 82 ('05)
N. Keeley *et al.*, PLB **646**,222('07)



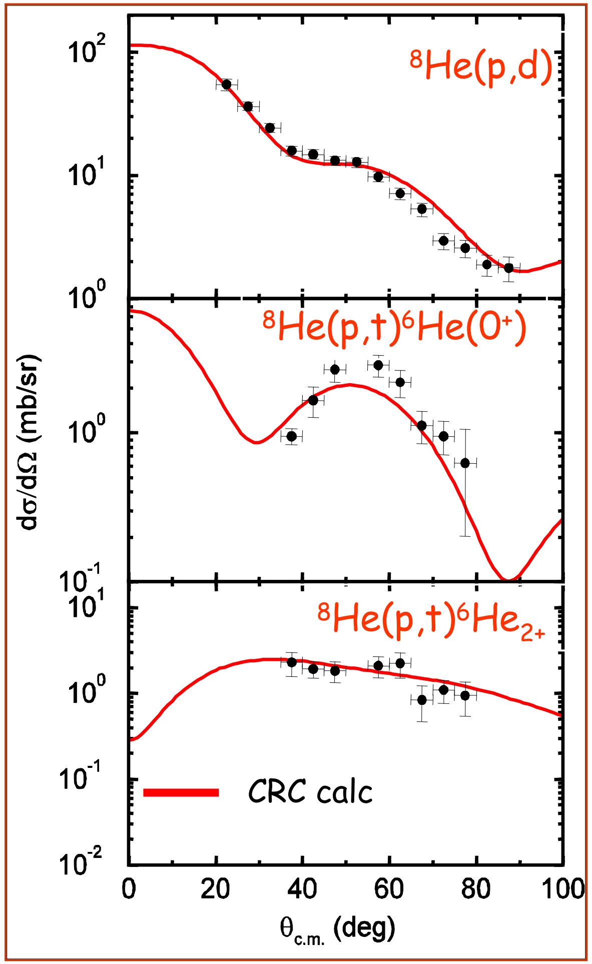
Structure of ground state & search for unbound excited states
→ spectroscopy of light charged particles p,d,t (MUST)
→ measurements of resonances in ^{8}He NPA 788c, 260 ('07)
→ angular distributions ; analysis in **coupled reaction channels**
PLB **619**. 82 ('05) ; **646**, 222 ('07)

Structure of ^{8}He extracted from direct reactions on proton target

CRC Coupled-reaction channel analysis:
N. Keeley (SPhN, Inst. A. Soltan)



Data: A. A.Korsheninnikov et al, PRL **90**, 082501 ('03)

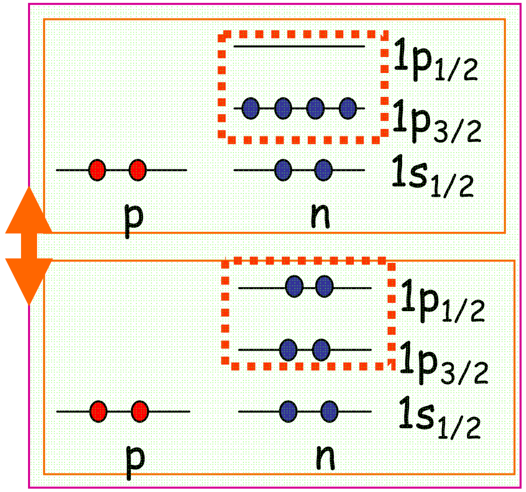


Data: SPIRAL-MUST [1-2]
F. Skaza et al., PRC ('07)
N. Keeley et al, PLB **646**, 222('07)

^{8}He(p,d)^{7}He $C2S$ = 4.4 ± 1.3
[CCBAanalysis]
CRC (p,p) (p,d) C^2S = 3.4 ± 1.3
PLB 619. 82 ('05)

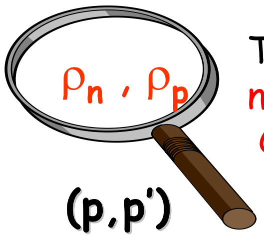
(p,t)→ wave function of ^{8}He%^{6}He
[^{8}He/^{6}He(0+)] =1 ;
[^{8}He/^{6}He(2+)] =0.014

Consistent with results from quasi-free scattering of ^{8}He measured at GSI,
LV Chulkov et al, NP*A759*, 43('05)

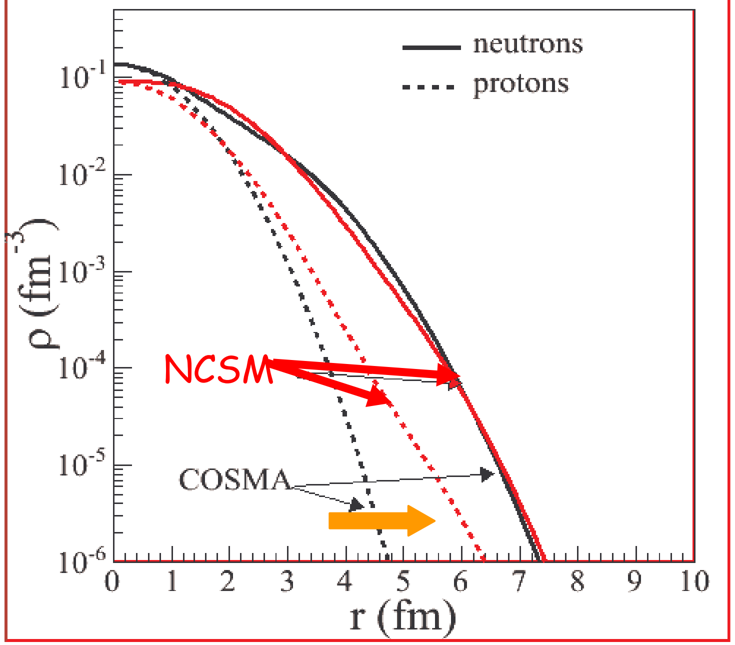


Configuration mixing :
$(p3/2)^4$ and $(p3/2)^2\,(p1/2)^2$

conclusions ... prospectives



Test of the validity of ^{8}He gs densities using (p,p) :
neutron-skin features close to NCSM densities
COSMA not valid



^{8}He	Rms (fm)		
	Proton	Neutron	Matter
COSMA 5-body	1.69	2.74	2.52
HF+corr Sagawa	1.95	2.67	2.51
NCSM, Navrátil	2.00	2.59	2.46

NCSM (No Core Shell Model)
(*V3eff 4hw, 13MeV*)

~~COSMA: Alpha+4n~~

Validation of no-core shell model calculations (NCSM) for gs

(p,p') mainly sensitive to the neutron excitation ;
Transition densities 2+ → 0+ : NCSM calc. overestimate the p & n excitations

Test of transition densities ; Analysis in progress → **CRC (p,p')** *Coupling with the (p,t)*

NEUTRON-SKIN THICKNESS: ~ 0.6 +/- 0.05 fm

Participants of the experiment ^{8}He(p,p')

SPIRAL E405S

CEA-SACLAY DSM/DAPNIA/SPhN :
N. Alamanos, F. Auger, A. Drouart, A. Gillibert, V. Lapoux,
L. Nalpas, E. Pollacco, R. Raabe, J-L. Sida, F. SKAZA (PhD).
IPN-Orsay : D. Beaumel, Y. Blumenfeld, F. Delaunay, E. Becheva, J-A. Scarpaci
Ganil : L. Giot, P. Roussel-Chomaz
FLNR - Dubna S. Stepantsov, R. Wolski University of Ioannina A. Pakou

INTERPRETATION

ANALYSIS :

Microscopic densities P. Navrátil + interaction Argonne
H. Sagawa HF +correlations
Futur : cf M . Ploszajczak Ganil

JLM potential: code Dietrich (Livermore) ; **form factors** (*home made, VL)*
+ **CRC** calc. N. KEELEY
With the Fresco code (IJ Thompson, Surrey Univ).

COLLABORATION MUST2

CEA DAPNIA, GANIL, IPN-Orsay

- DAPNIA SEDI E. Atkin, P. Baron, F. Druillole, F. Lugiez, B. Paul, M. Rouger ;
- SPhN : A. Drouart, A. Gillibert, V. Lapoux, L. Nalpas, E. Pollacco
- IPN-Orsay SED: P. Edelbruck, L Lavergne, L. Leterrier, A. Richard, M. Vilmay, E. Wanlin,
- Structure Y. Blumenfeld, D. Beaumel, E. Becheva
- GANIL GIP M. Boujrad, L. Olivier, B. Raine, F. Saillant M. Tripon, *Physics* P. Roussel Chomaz

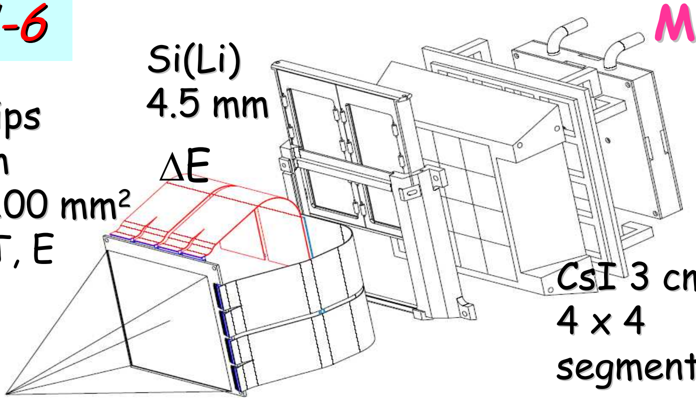
MEASUREMENTS AND ANALYSIS OF REACTIONS IN COUPLED- CHANNELS

Present techniques

2004-6

MUST2

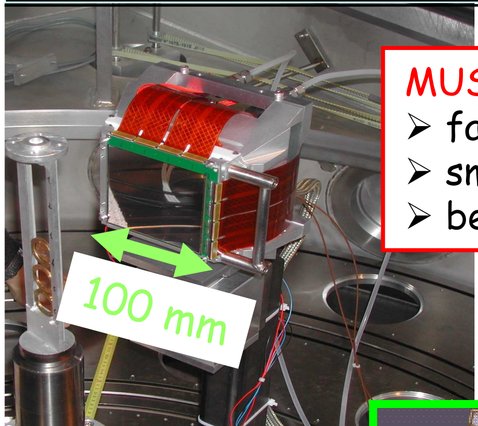
Si strips
300 µm
100 x 100 mm²
X, Y , T, E
128X
128Y



collaboration : CEA-DAPNIA, GANIL, IPN-Orsay

Developed by :
- DAPNIA/SEDI : µ-electronics R&D ASIC
- GANIL
- IPN Orsay

Increased compactity due to the ASIC technology
(*Application Specific Integrated Circuit)*
→ coïncidences particle - γ

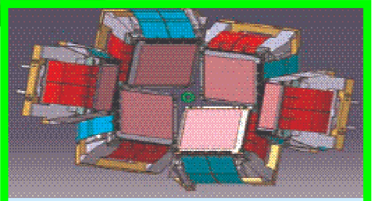


MUST1 → MUST2: improvments
- factor 3 in active area
- smaller volume of PAmp : x 6
- better time resolution

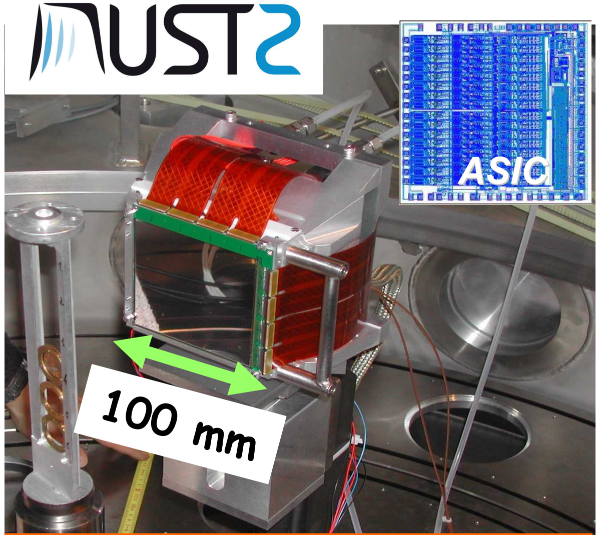
Exotic shapes and resonances

collaboration MUST2:
SPIRAL +
Futur SPIRAL2

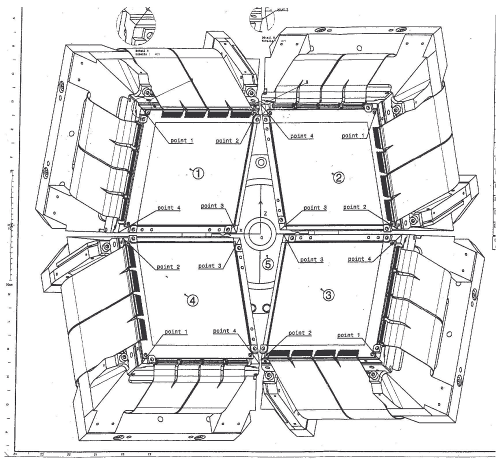
One-particle state
Spectroscopic factors


MUST2

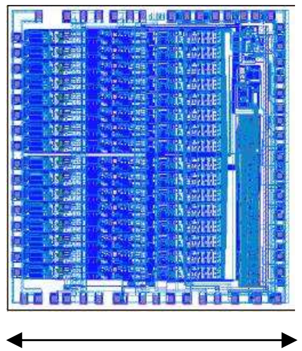
Evolution of neutron excitation
Mn vs *N* along isotopic chains



MUST2 collaboration:
DAPNIA, GANIL et IPN-Orsay



Compact electronics : ASIC
(Application Specific Integrated Circuit)
DAPNIA/SEDI



Chip d'ASIC:

- 16 voies
- pre-amp.
- ampli.
- fast ampli.
- LE discri.
- TAC
- multipX

Performances

Dynamics in e**nergy** : 0.3 - 50/250MeV

Rate : 2MHz ; TM :10 % @ 2kHz

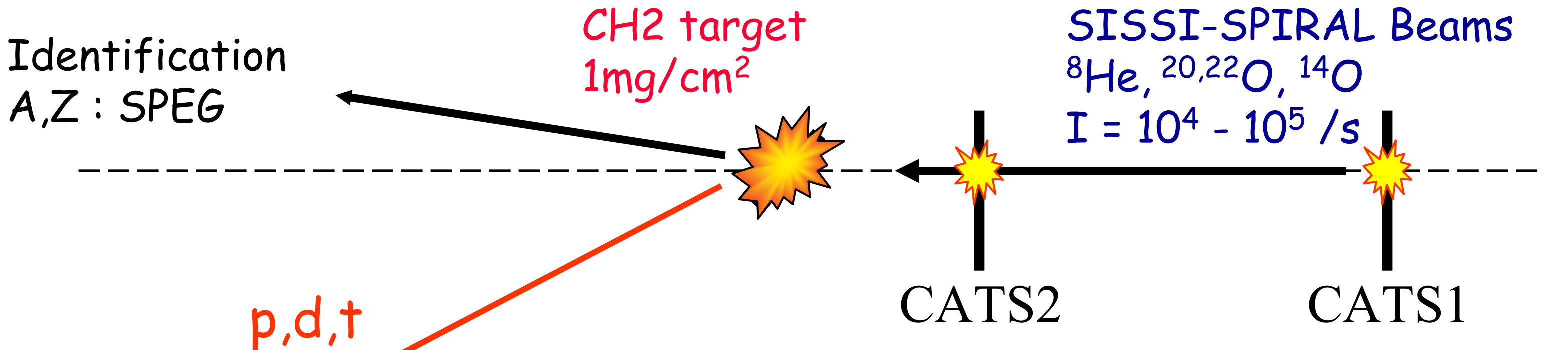
Dt ~250 ps (alphas 5.5 MeV) ;
Threshold 300 keV
Resolution in E at 5 MeV : 35 keV (Si) ;
80-130 keV (SiLi) ; CsI~150 keV

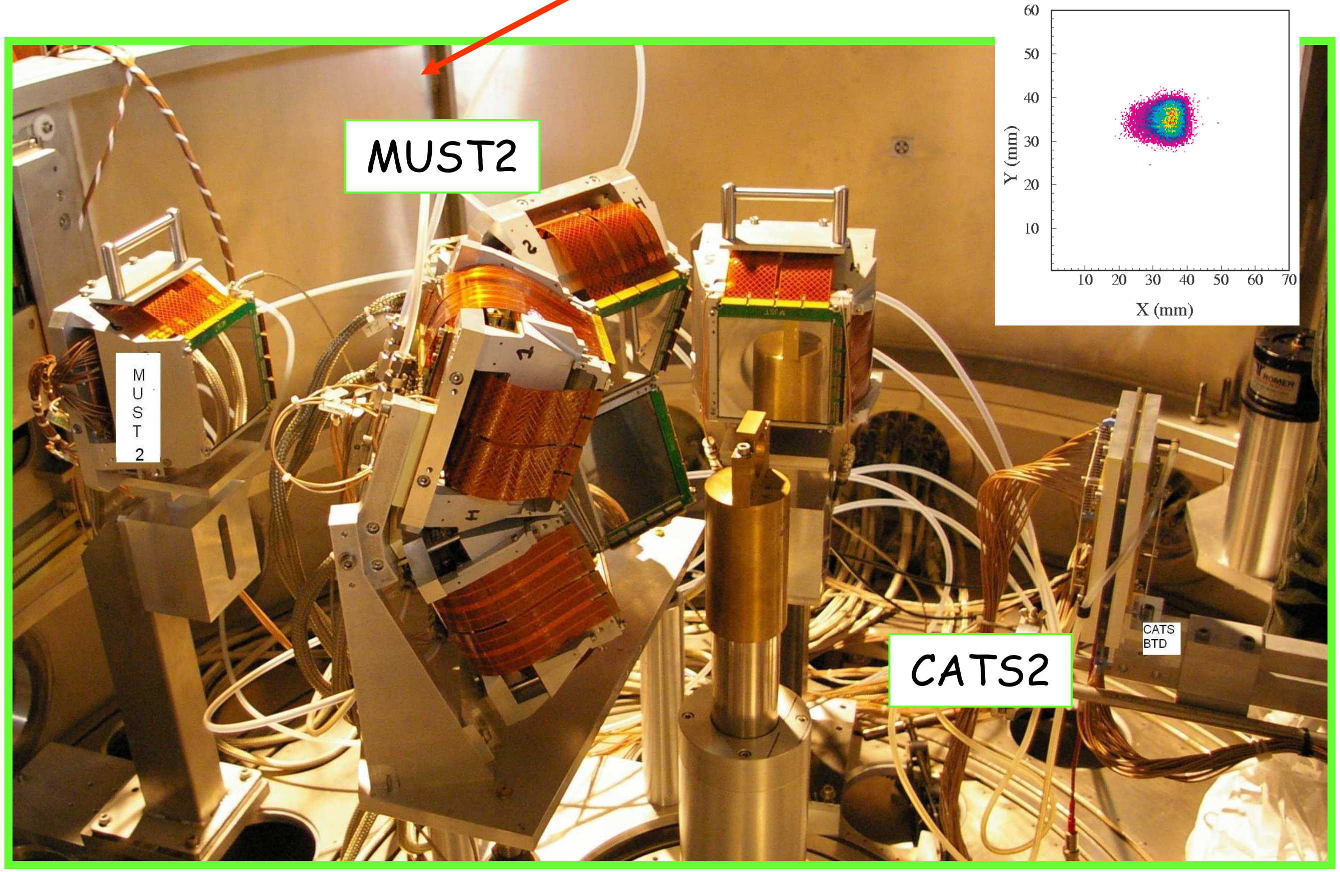
Dx, Dy ~0.7mm ;

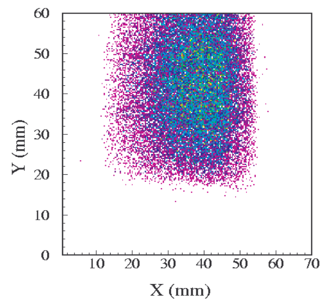
Angular resolution ~0.5^{o} at 15cm from target

specificity : identification **E-TOF**
→ Identification A,Z : p,d,t, $^{3-8}$He, Li

Experimental set-up with MUST2







MUST2 @ d=15 cm

5-25 deg $_{lab}$ (15-80 c.m.)
Sect. Eff (p,t)
~ 5 10^{-3} – 0.5 mb/sr

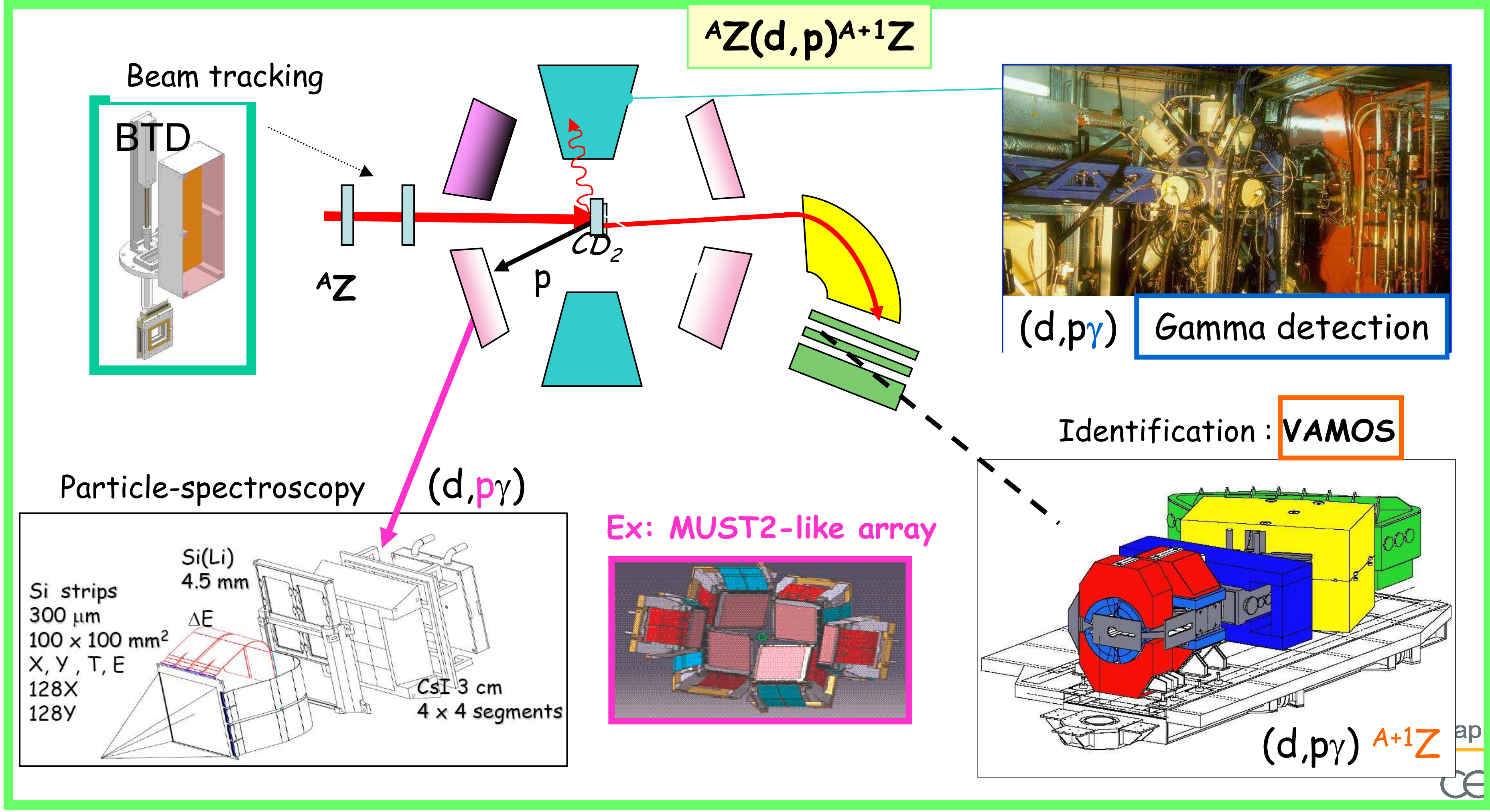
Transfer reactions ; coupling betwen particle and gamma spectroscopy

Charged-particle spectroscopy
Thin target CH_2 , CD_2 1 mg/cm2

Complete kinematical reconstruction
access to bound and unbound states

I (> 5. 10^3/s)

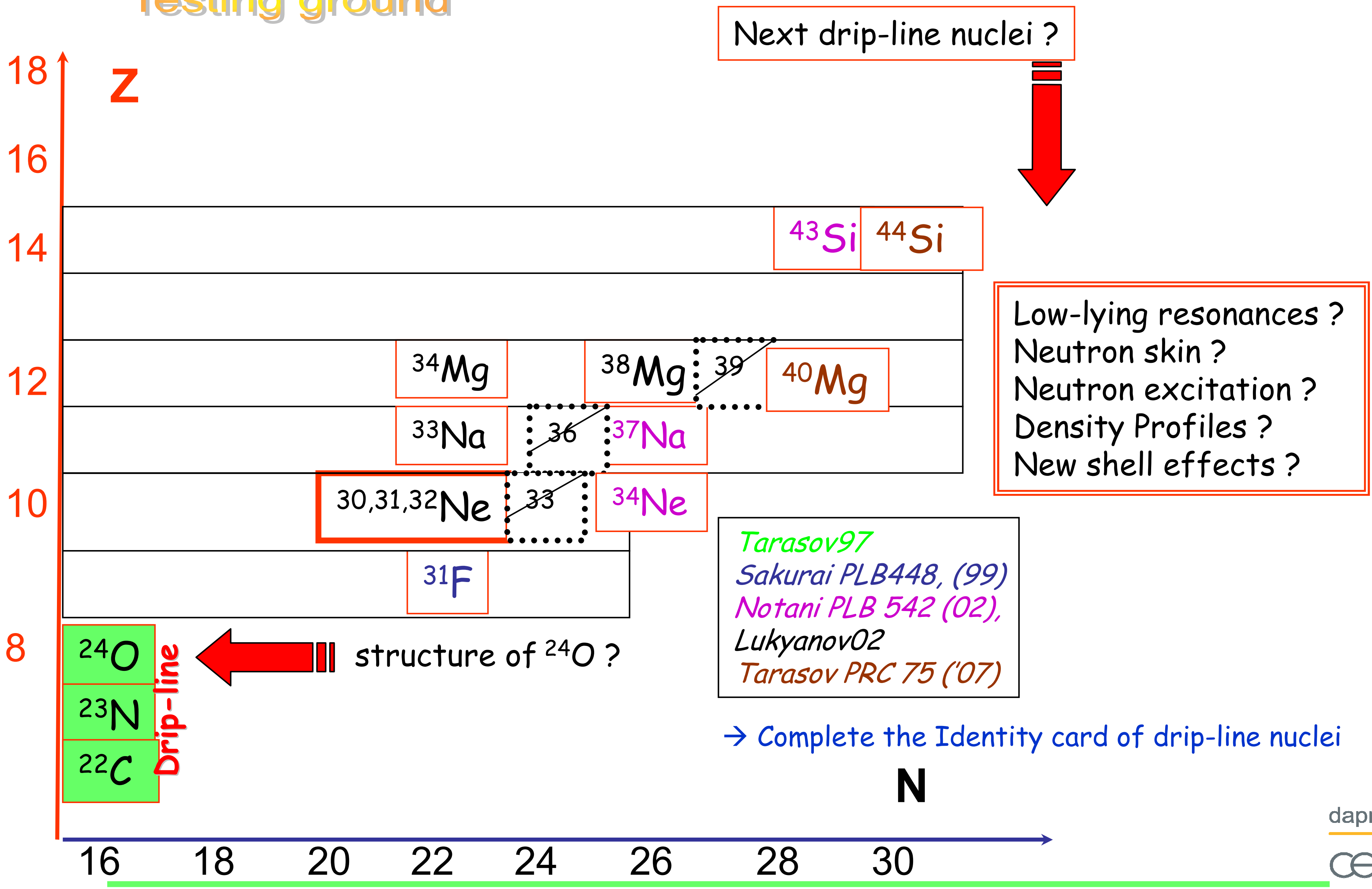
ex : SPIRAL2 ^{96}Kr @ 10MeV/n I= 10^4 /s ^{96}Kr(d,p)^{97}Kr, (d,d') (d,t)
EURISOL n-rich Ne, Ca, Ni, Kr, Sn @ 20-50MeV/n I > 10^5 /s



2008

Nuclear landscape towards the drip-lines

Testing ground



Drip-line studies

SPIRAL2, RIBF, EURISOL

Drip-lines : limit of nuclear binding, large isospin
Exploration : new structures of exotic nuclei
Tests : nuclear modelling & interactions $V_{NN}(T_z)$

FIND NEW REGIONS OF INTEREST

→ Nuclei with large matter extension (neutron-skin, superdeformation…)

→ New shell gaps

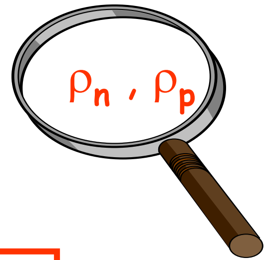
→ ***EXTENSION OF*** *the systematics of neutron excitation along isotopic chains*

MEANS to Probe the structure & spectroscopy at large isospin

Measure unbound states

➔ ***EXPLORATION:***

Spectroscopy of low-lying resonances, unbound states,
neutron excitation, exotic excitation modes
soft dipole resonance and transition densities
Halo,skin features of weakly-bound exotic nuclei

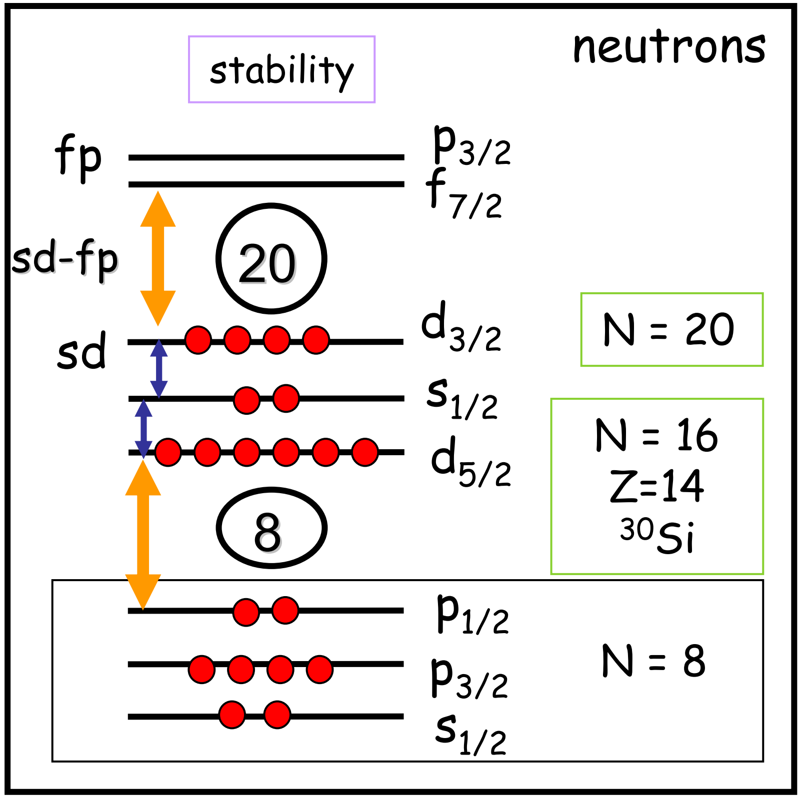


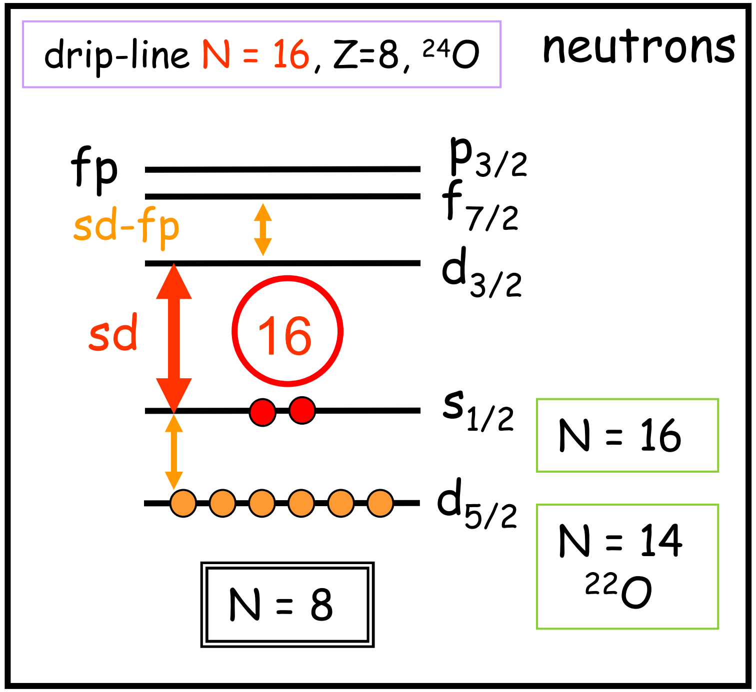
local shell change : like N=16 (34, 70..) indicated by
Ex(2+), B(E2) S_{2n}, and evolution of neutron excitation

SIMPLE PROBE : (p,p') combined to Coulex information
direct reactions in inverse kinematics, missing mass method

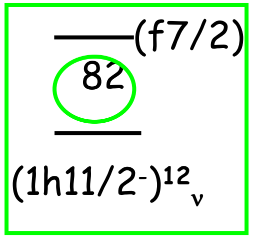
Shell effects far away from stability with new generations of RIB s

systematics of neutron excitations vs *N*
Search for new magic numbers





N=16 → Learnt from 1st generation of RIBs



Local properties (Z,N)
N=34,40,70 instead of N=50,82 ?

→ EURISOL

Going closer to driplines with higher intensities : opened physics fields

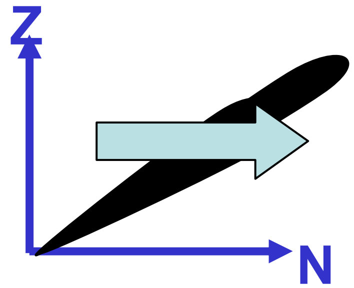
Prospectives

Exotic shapes and resonances

One-particle state
Spectroscopic factors

Evolution of neutron excitation
Mn vs *N* along isotopic chains

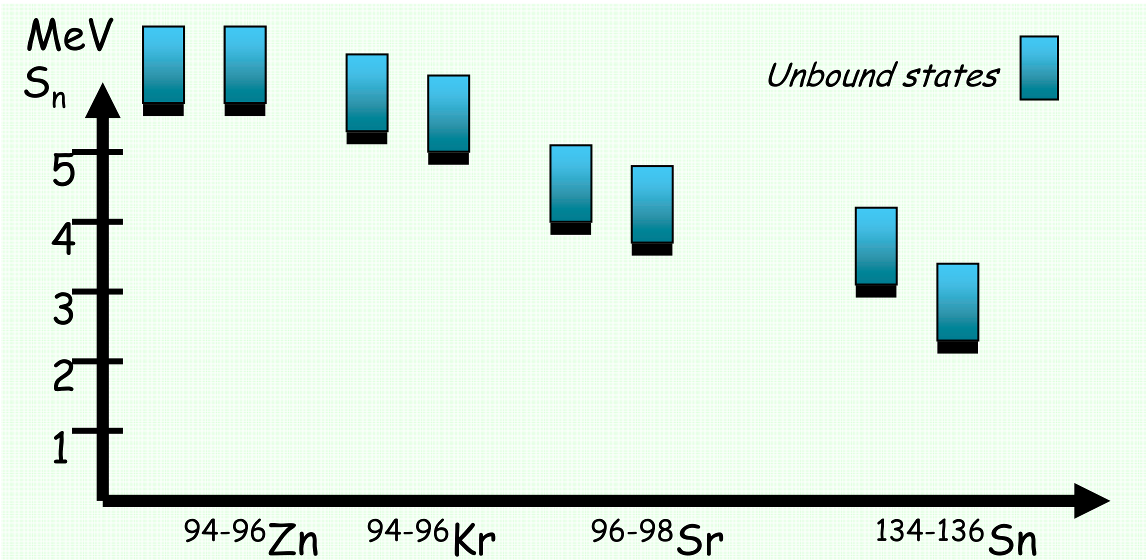
Skin and halos
Soft collective modes
Alpha-clusters
states



2012+ SPIRAL2 — 2020+ EURISOL

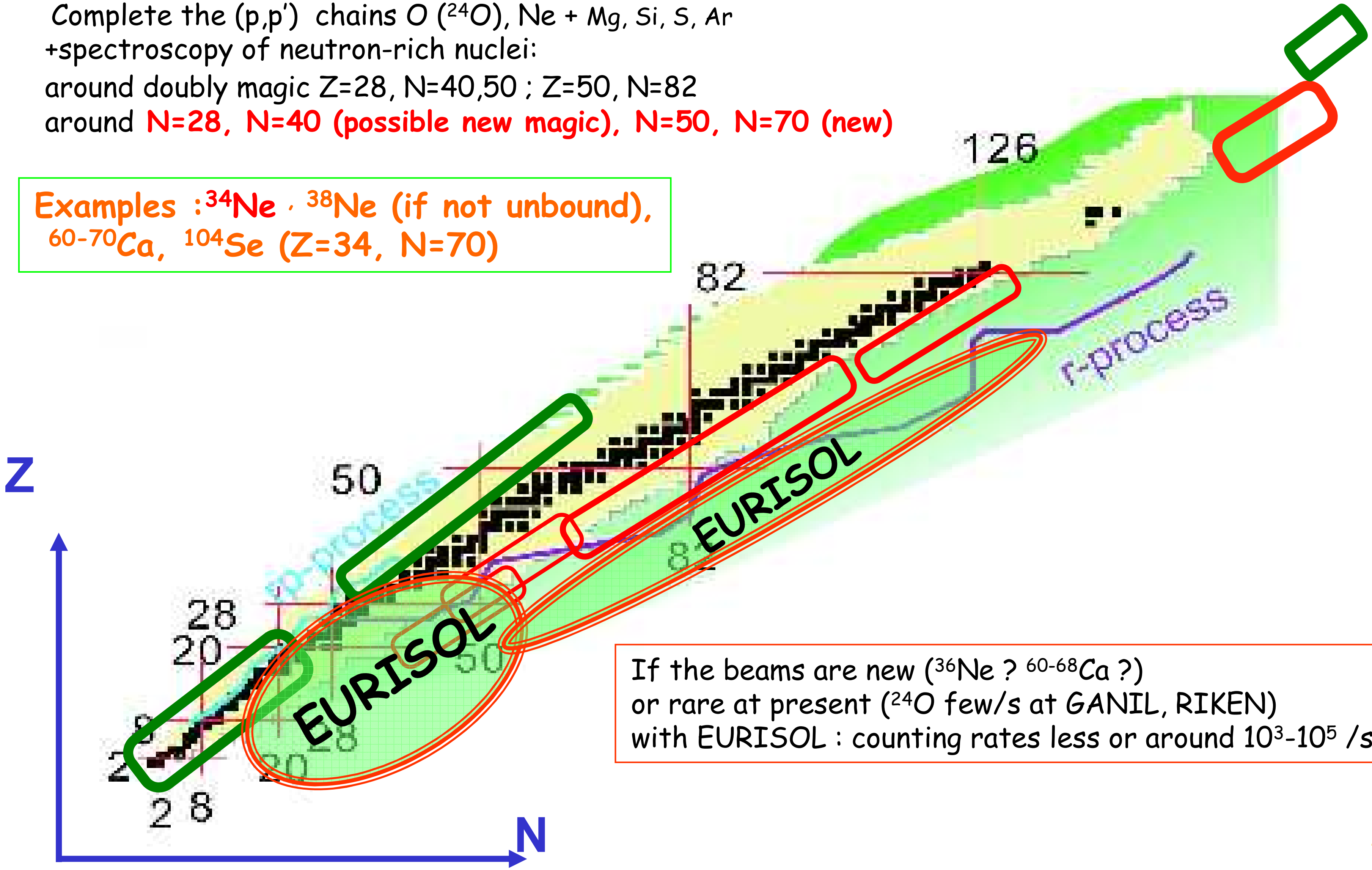
Beams Variety A,Z
Limit of nuclear binding, I ↑

Far ..far away



Which beams ? We want to gain in exoticity

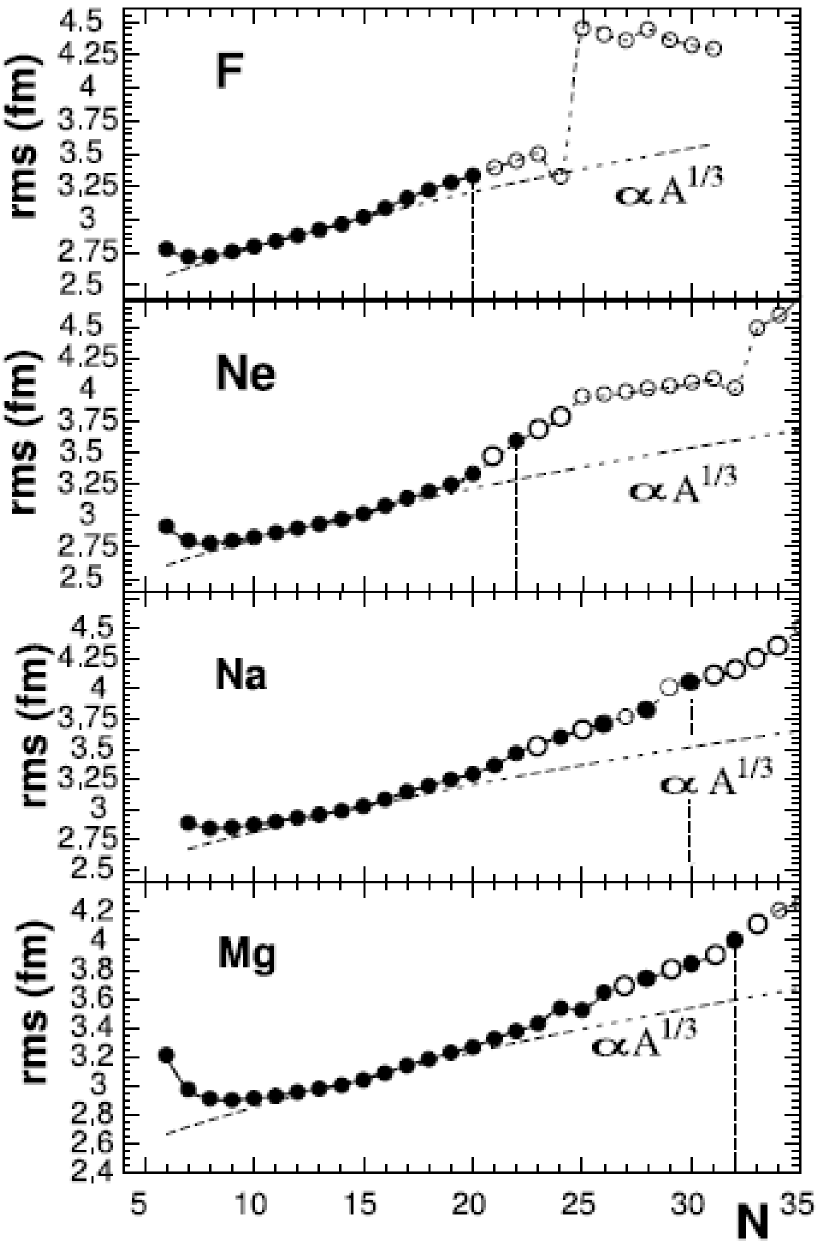
Complete the (p,p') chains O (^{24}O), Ne + Mg, Si, S, Ar
+spectroscopy of neutron-rich nuclei:
around doubly magic Z=28, N=40,50 ; Z=50, N=82
around **N=28, N=40 (possible new magic), N=50, N=70 (new)**

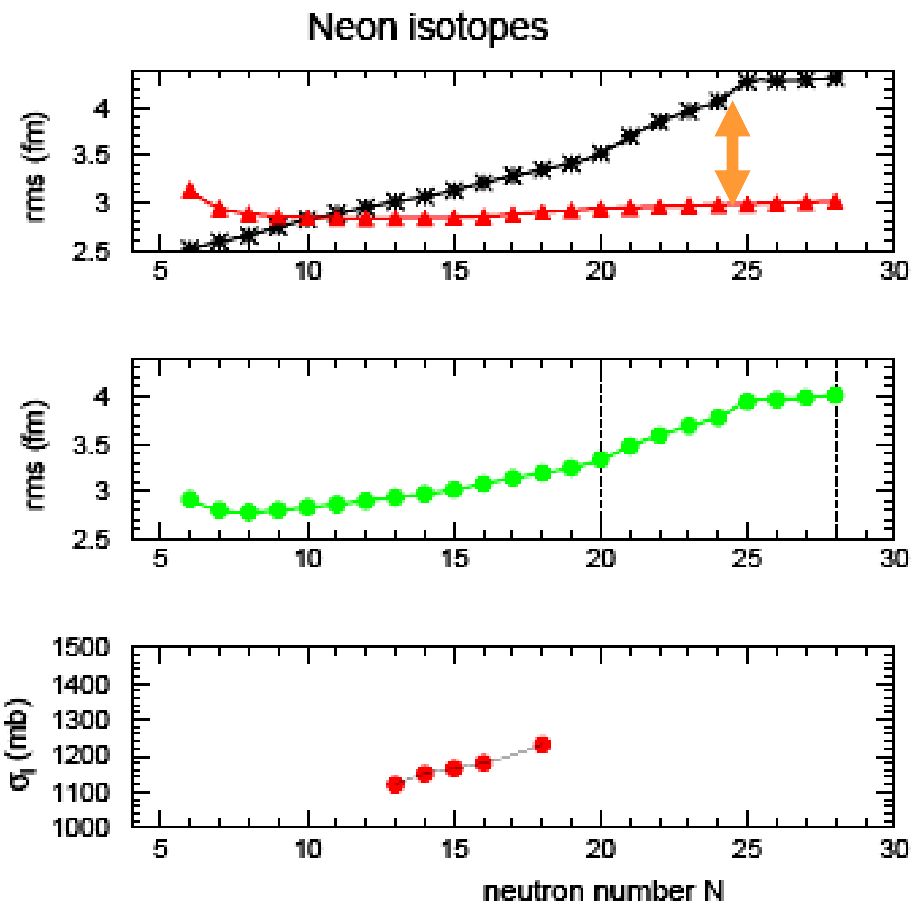


Examples : ^{34}Ne , ^{38}Ne (if not unbound), $^{60-70}$Ca, ^{104}Se (Z=34, N=70)

If the beams are new (^{36}Ne ? $^{60-68}$Ca ?)
or rare at present (^{24}O few/s at GANIL, RIKEN)
with EURISOL : counting rates less or around 10^3-10^5 /s

Evolution of the neutron skin thickness : ex of Neon isotopes

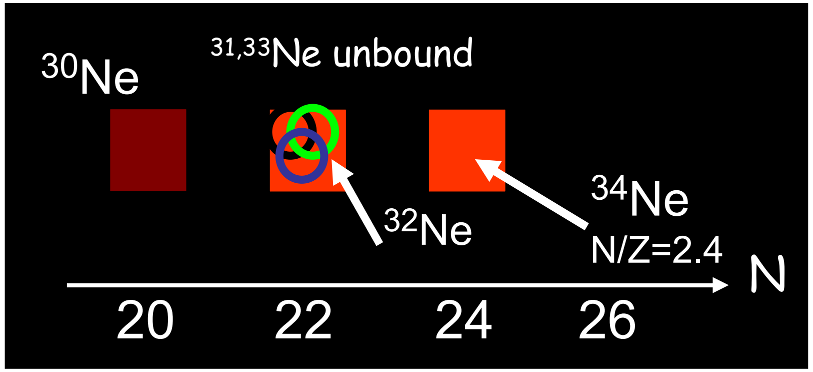


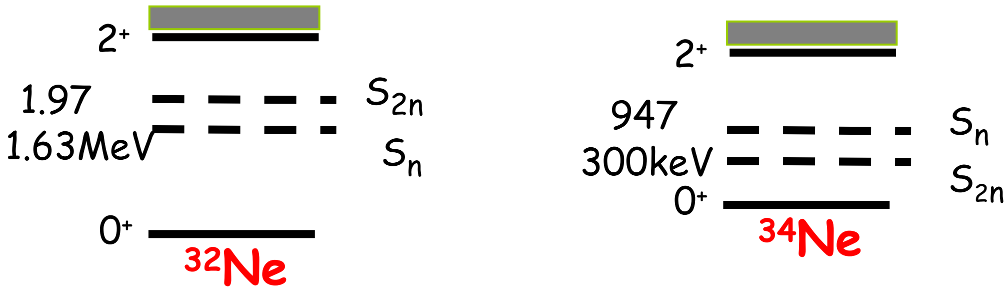


Density functional.calc. with R. Lombard's code

Similar trend in HFB-def (Sly4) calc of
J Dobaczewski, M.V. Stoitsov, *et al.*,
PRC**68**, 054312('03)

Neutron-skin structure of ^{34}Ne via direct reactions on proton target





^{34}Ne(p,p')^{34}Ne*

^{34}Ne +p → p' + ^{34}Ne* → p + ^{32}Ne + 2n

p' + ^{34}Ne* → p + ^{30}Ne + 4n

Neutron-skin structure of ^{34}Ne via direct reactions on proton target

All reactions to be considered in the Coupled-Reaction channel scheme:

$^{34}Ne(p,p')^{34}Ne^*$

$^{34}Ne + p \rightarrow p' + {}^{34}Ne^* \rightarrow p + {}^{32}Ne + 2n$

$p' + {}^{34}Ne^* \rightarrow p + {}^{30}Ne + 4n$

ELASTIC SCATTERING
Needed → to fix the entrance channel in the scattering theory

$^{34}Ne(p,d)^{33}Ne$ Q(p,d)=1.27# MeV [ame03]

$^{34}Ne + p \rightarrow d + {}^{33}Ne$ unbound $\rightarrow d + {}^{32}Ne + n$

$d + {}^{33}Ne^* \rightarrow d + {}^{30}Ne + 3n$

Low S_n, S_{2n}, S_{4n},...

Phase space background due to neutrons produced by decaying unbound states

$^{34}Ne(p,t)^{32}Ne$ Q(p,t)=8.18# MeV [ame03]

$^{34}Ne + p \rightarrow$ $\rightarrow t + {}^{32}Ne$

$\rightarrow t + {}^{32}Ne^* \rightarrow t + {}^{31}Ne^* + n$

$\rightarrow t + {}^{30}Ne + 2n$

light recoil in a particle detector in coincidence with ^{A}Z ID of forward focused heavy fragments in spectrometer
+ additional neutron detection

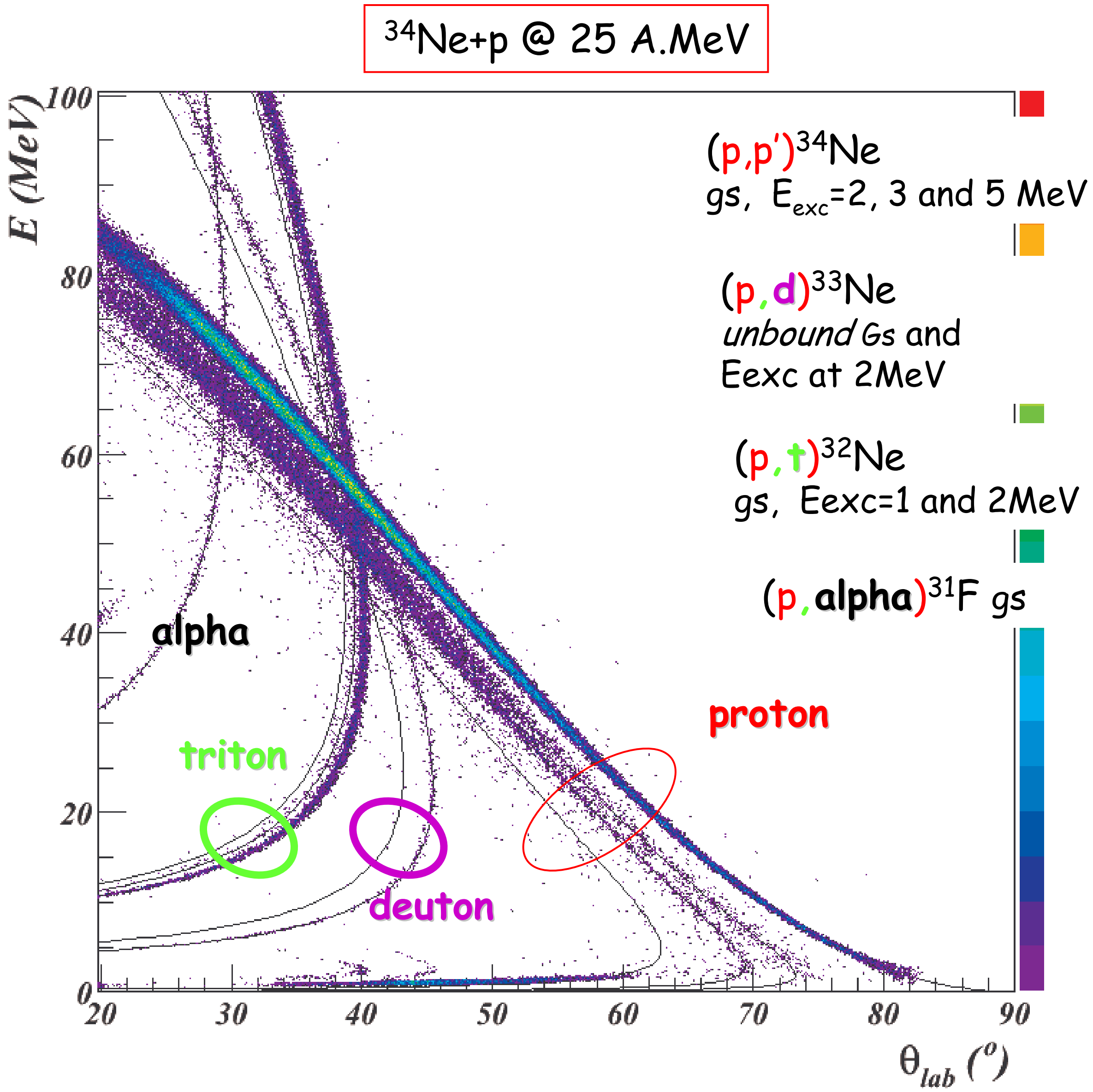
$^{34}Ne(p,alpha)^{31}F$ Q(p,alpha)=1.696# MeV [ame03]

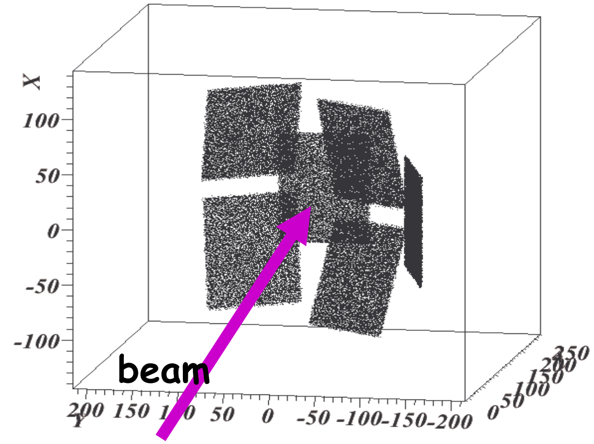
$^{34}Ne + p \rightarrow$ $\rightarrow \alpha + {}^{31}F$

ID, E vs Theta of LCP

dapnia cea saclay

Neutron-skin structure of ^{34}Ne via direct reactions on proton target





Improved detection for EURISOL experiments

2016 Wishes for Coupled Detection devices

Charged-Particle spectroscopy
→needed to explore unbound states
Thin light targets p, d
ΔE ~ 400keV to 1 MeV
(p,p'), (p,d) (p,t)

+

Inverse kinematics :
good Energy resolution in Eexc
requires : beam profile on target
→ beam tracking detectors

+

Gamma-ray spectroscopy
→ needed to separate
close excited states
Thick target ΔE ~ 20keV
(d,p) @ 9 MeV/n

+ A,Z ID of heavy fragment
in a spectrometer
or SiLi CsI array
+ NEUTRON DETECTION

Steps beyond in the detection :

- ASIC technology
(*Application Specific Integrated Circuit*)
(compacity of all devices)

- Mixed detection
(gamma+ charged particles
+… neutrons) :
Ex : Ge + Si + scintillator
in a crystal-Ge-Si ball array

-Higher multiplicities in LCP arrays (3,4,..)

challenges in acquisition systems :

synchronize separated arrays & triggers
needs to reduce dead time

ANALYSIS OF (D,P) CROSS SECTIONS…

Successful analysis for the stable nuclei [cf ^{40}Ca(d,p)]: E=7, 8, 9,10, 11, 12 MeV
Lee,..Schiffer, Satchler, Drisko, PR 136 4B ('64) ^{40}Ca(d,p) ^{41}Ca a test of the validity of the DWBA
Satchler Direct nuclear reactions, Clarendon Press, Oxford Univ Press 1983

« The DWBA was shown to be inappropriate for the analysis of (*d*, *p*) reactions some 30 years ago, due to the importance of the deuteron breakup channel. »

Ex : N. Timofeyuk & RC Johnson, PRC 59, 1545 (' 99) : d break-up included within the adiabatic approach from Johnson & Soper

Analysis of the ^{16}O(d,p)^{17}O, ^{10}Be(d,p)^{11}Be, and ^{11}Be(p,d)^{10}Be reactions.

Comprehensive analysis method for (*d*,*p*) stripping reactions ; test calc. : ^{12}C(d,p)@ 25 MeV ^{10}Be(*d*, *p*) @ 12 and 25 MeV , N. Keeley,* N. Alamanos, and V. L, **PRC 69, 064604 ('04)**

We know that average properties & parameterizations are working for stable beams (~300 species)
ONLY SMALL PART of all 2000 RIB, even more 3000 possible ones …

MEASURE ELASTIC SCATTERING to estimate coupling effects (virtual coupling potential related to excited states, compound nucleus effects…

needed for coupling scheme … MEASURE INELASTIC SCATTERING (d,d ') (p,p ')

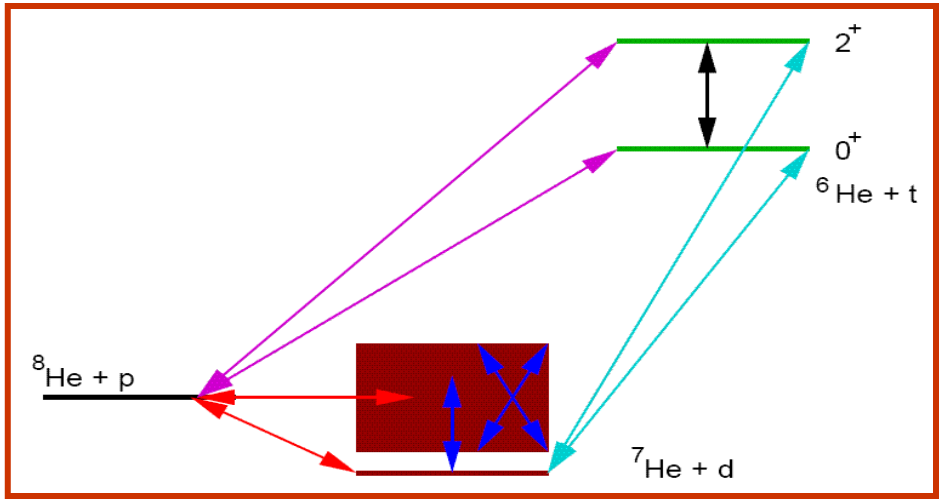
DO THE BEST POSSIBLE CALCULATIONS !!!!
DWBA is a limited framework, turns out to be WRONG for strongly-coupled channels

CRC calculations, CDCC
Cf Nick Keeley JOLIOT-CURIE '07

EURISOL : a new theoretical framework

Probe for the structure : (p,p')
But flux shared between several reaction channels → elastic and transfer reactions
+ competition between main reaction channels
NEED TO DEFINE THE APPROPRIATE SCATTERING THEORY

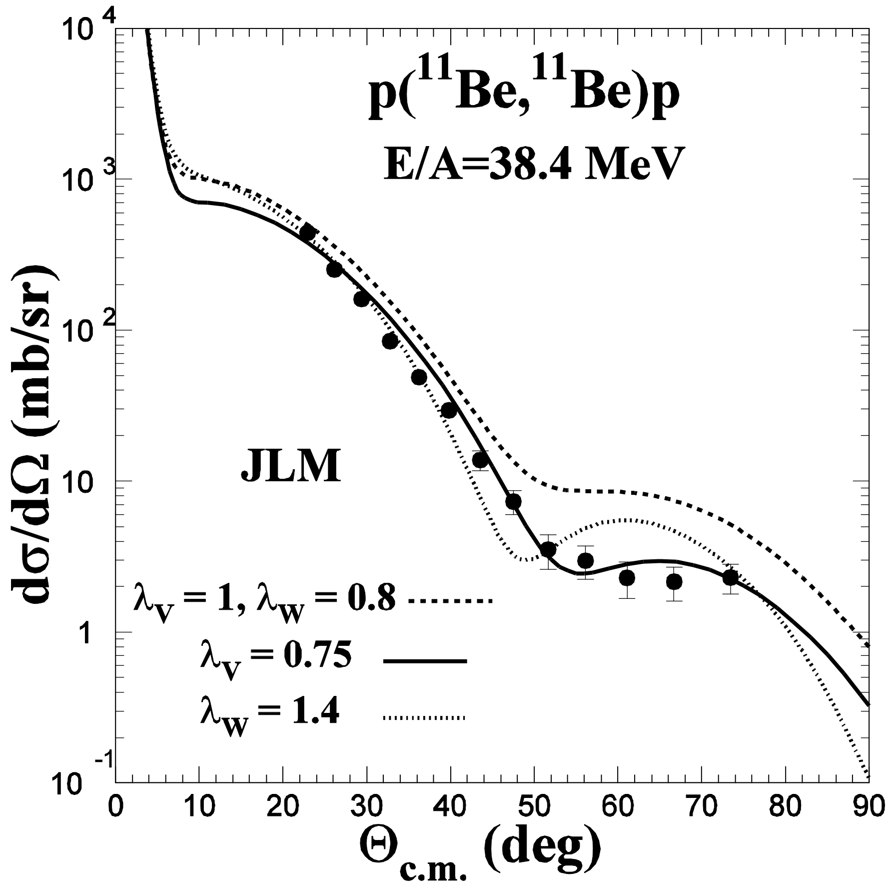
State of the art :
Coupled reaction channel analysis
→ explicit channel coupling
+Microscopic potentials

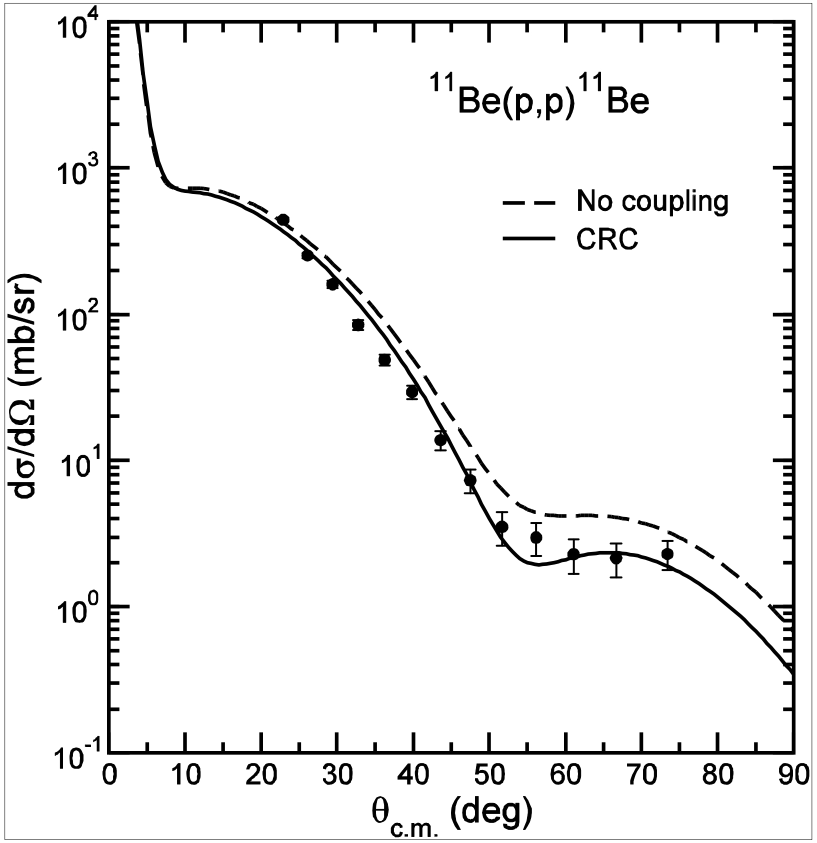


- **Accurate data covering a large angular domain**
- **Elastic : entrance OM potential under control (p,p)**
- Check role of continuum coupling
- Sensitivity to the detailed structure of exotic nuclei,
- Test unusual shape +unbound states
- Compare to models (SM, HFB, BCS+QRPA, AMD)

FUTURE: Structure and reaction on the same footing

EURISOL : a new theoretical framework





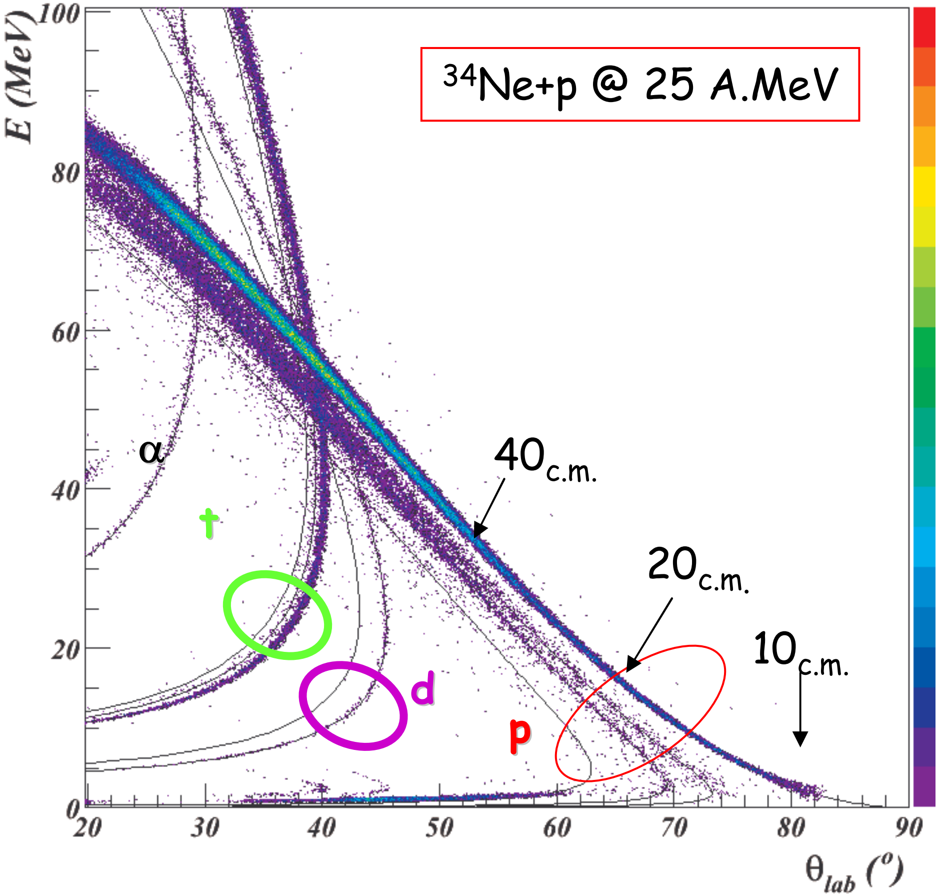
Data+ Virtual coupling potential for elastic scattering of ^{10,11}Be on p
V. L *et al.*, PLB **658**, 198 ('08)

Strong pickup-coupling effect on p+^{11}Be elastic scattering
N. Keeley and V. L PRC **77**, 014605 ('08)

CRC calc :^{11}Be(p,d)^{10}Be* pickup to the 5.960 MeV 1- and 6.263 MeV 2- doublet of excited states in ^{10}Be

FUTURE WORKS

Improvment of exp set-up + Theoretical framework



Present (1st generation) intensities : few part/s
Needed : (at least) 10^3-10^5 /s

Measurement to unbound states:
Particle-spectroscopy
→Large enough **intensities** → **EURISOL**

→Large angular coverage
all reactions measured simultaneously
Elastic and transfer
→Low particle threshold :small c.m. angles

→ Possible to carry out
full coupled-reaction channel analysis

→EXTRACT form factors from (p,p')
→ spectroscopic factors from (d,p)

suitable range of beam energies
for (p,p') and (d,p) : E ~ 10-30 MeV/n

In 2016+: new beams of neutron-rich Ne, Ca, Ni, Kr, Sn isotopes…
→ Access to neutron-thickness evolution + change in shell structure

Theoretical framework for the analysis of direct reactions

PROTOTYPE-STUDY: ^{8}He(p,p') & (p,d) : PLB **619**, 82('05)

Usual framework: DWBA, not valid, need to operate with CRC

The usual ingredients and models based on past studies for stable nuclei must be put into question *A PRIORI*

How good (potential, framework) is really good for exotic beams ?

Validity of optical potentials ?

Examine the assumptions in the case of weakly-bound nuclei or for specific coupling (large spectrosocpic factors, enhanced excitation etc..)

To be checked by measuring *carefully* the elastic scattering ,

→TESTING GROUND FOR THE INTERACTION POTENTIAL AND THE REACTION MODEL

Enhanced effects in the case of weakly-bound exotic nuclei

Coupling to continuum, 3-body many-body correlations

Shell structure embedded in the continuum

→**Use the predictions of improved structure theories de structure to take into account** these effects and the isospin-dependence of the nuclear interaction

Improved approach (best we can do today)

- COMPLEX MICROSCOPIC POTENTIALS
  → to test the validity of nuclear density
- FORMALISM in COUPLED REACTION CHANNELS
  → To include the coupling to excitations AND to **reaction channels**