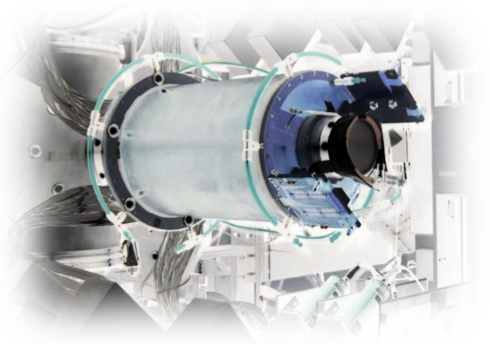
Recent results from direct reactions

Freddy Flavigny

Outline

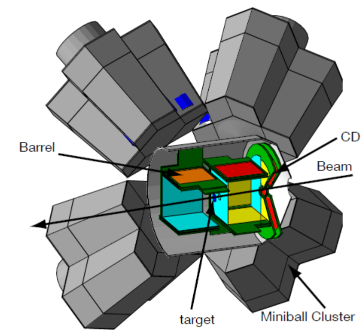
First spectroscopy of very exotic nuclei



$^{99\text{-}101}$Rb(p,2p)$^{98\text{-}100}$Kr

Shape transition @ N=60 around ^{100}Zr

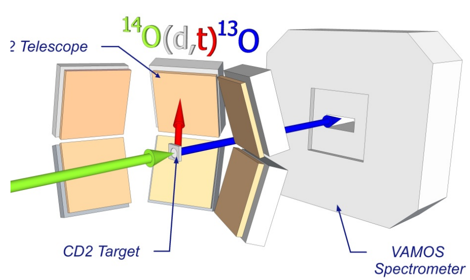
Microscopic nature of 0+ states



^{66}Ni(t,p)^{68}Ni

Two-neutron excitation above N=40

Reduction of single-particle strength

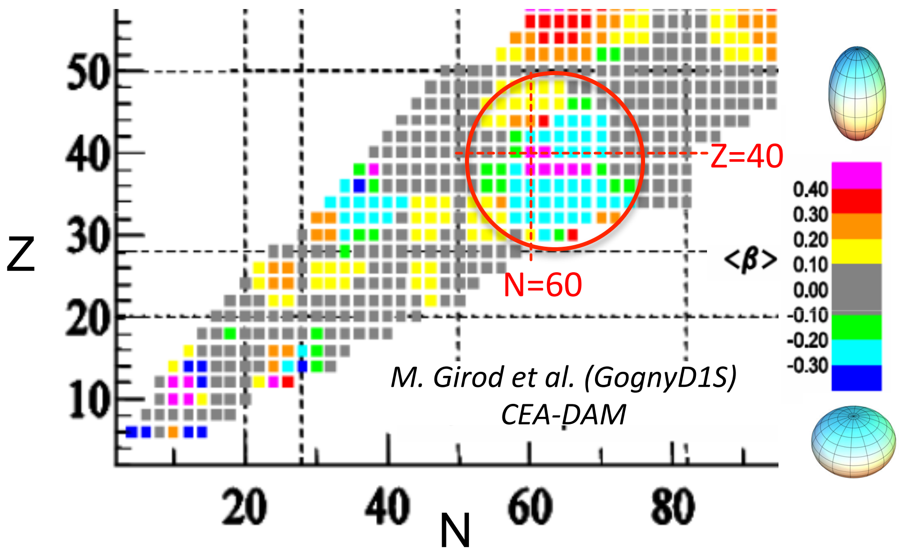


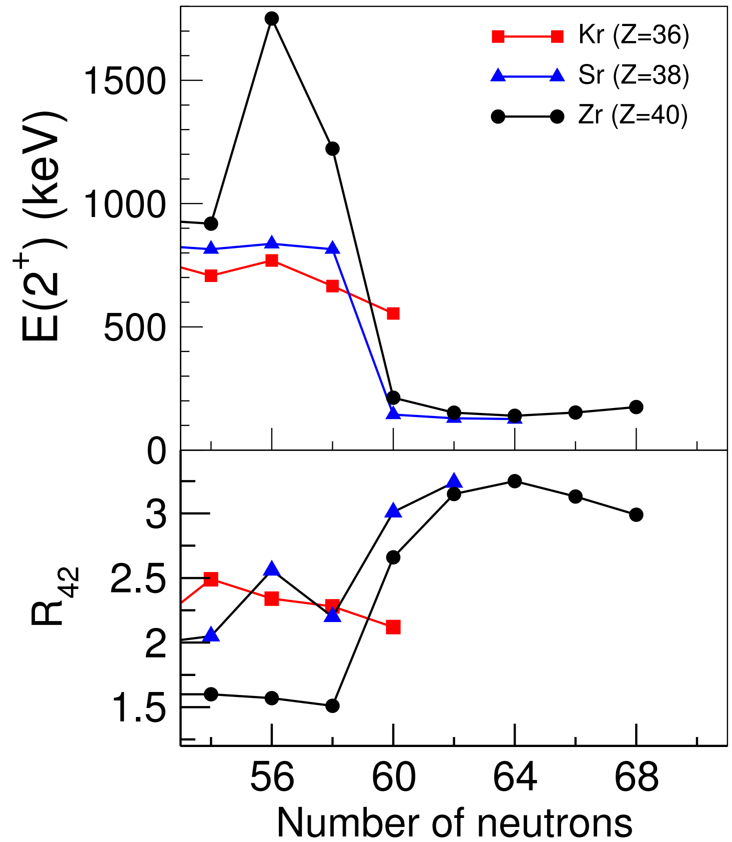
^{14}O,^{18}Ne(d,t) and (d,^{3}He)

Limits and uncertainties of the technique

Context: Shape transition @ N=60

Quadrupole deformation of nuclear ground state





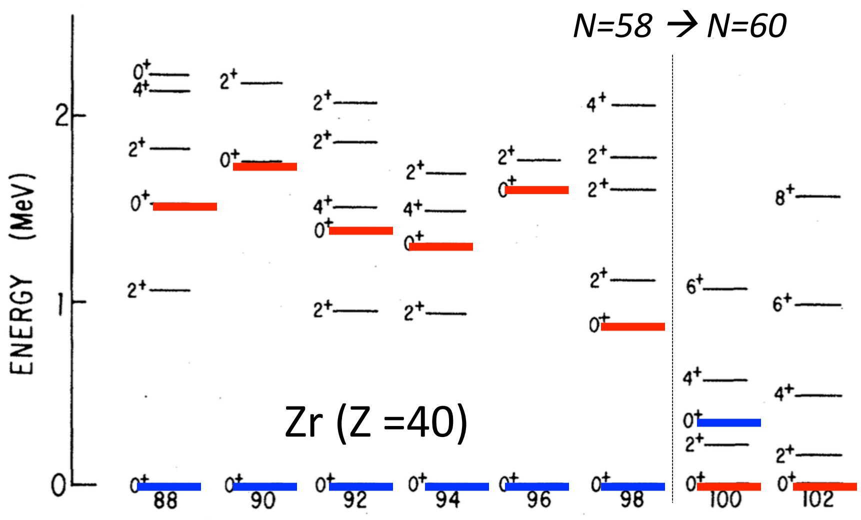
Sudden changes → Rich testing ground for models

Observables:

- Charge radii
- Masses
- $E(2^+_1)$
- R_{42}

^{96}Kr { *M. Albers et al., PRL108 062701 (2010)*
J. Dudouet et al., PRL118 162501 (2016)

Transition at N=60 in Zr,Sr : Shape Coexistence

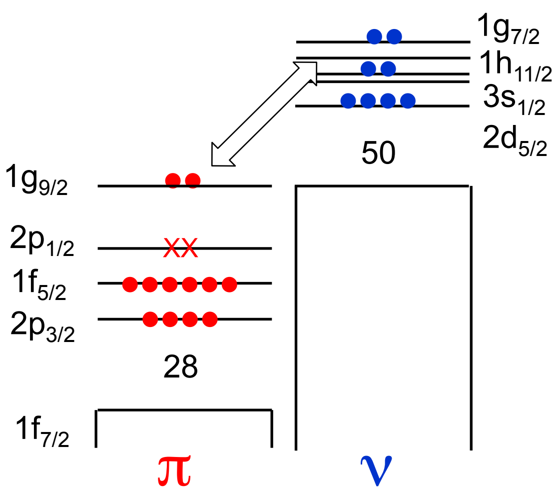


- 0^+_{ex} states lowering
- Large $\rho(E_0)$
- two-n and alpha transfer

K. Heyde and J.L. Wood, RMP83 (2011)

→ Crossing of coexisting configurations

Transition at N=60 in Zr,Sr : Shape Coexistence



^{98}Zr (0^+_{ex})

- $\pi(g_{9/2})$ protons excited above N=40
  - lower $\nu(g_{7/2})$
  - lower $\nu(h_{11/2})$
  - Group ν ESPEs

  → Enhance quadrupole def.

- Substantial reconfiguration of nucleons

  → Reduced mixing between conf.

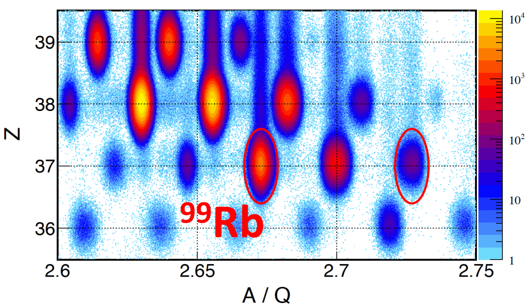
P. Federmann and S. Pittel
PLB 69, 4 (1977)
PRC20, 820 (1979)

Togashi et al.,
PRL117 1722502 (2016)
^{68}Ni + $\pi(pf_5gds)$ $\nu(gdsh_{11}f_7p_3)$

Question: What happens when removing protons?

Experiment: $^{99-101}$Rb(p,2p)$^{98-100}$Kr

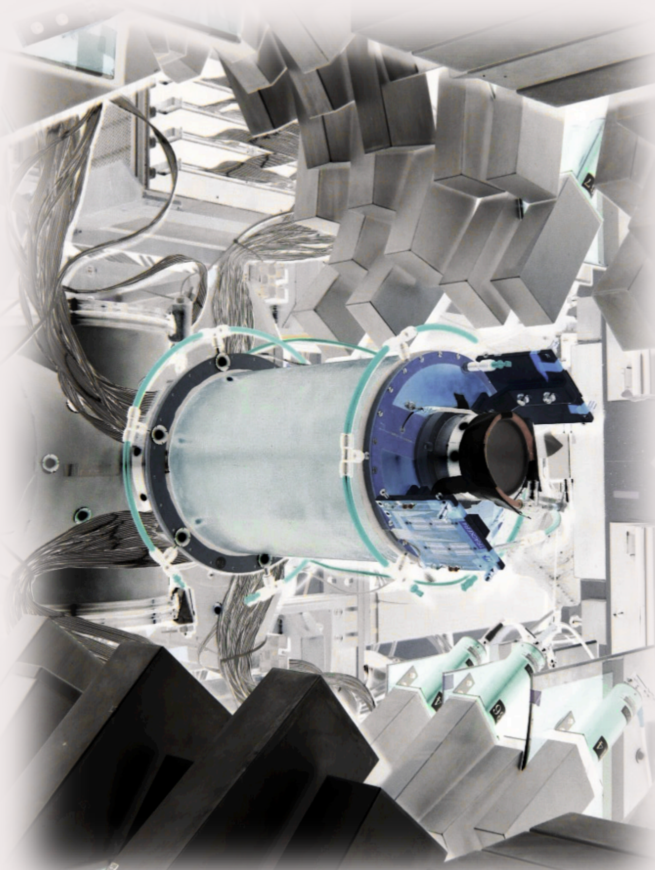
PID in BigRIPS



^{99}Rb: 220 s^{-1}

^{101}Rb: 16 s^{-1}

E = 260 A.MeV

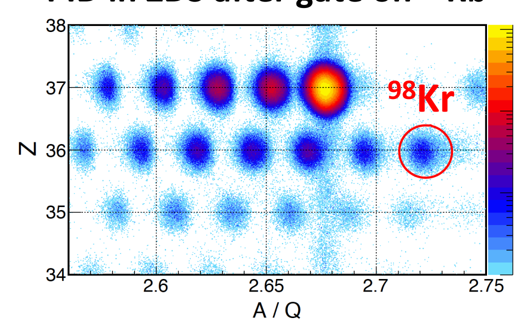


DALI2

- 182 NaI(Tl) scintillators
- 35% efficiency @ 500kev
- 9% resolution (FWHM) @ 662 keV
- ~15-160° angular coverage

Takeuchi et al, NIM A 763 (2014)

PID in ZDS after gate on ^{99}Rb



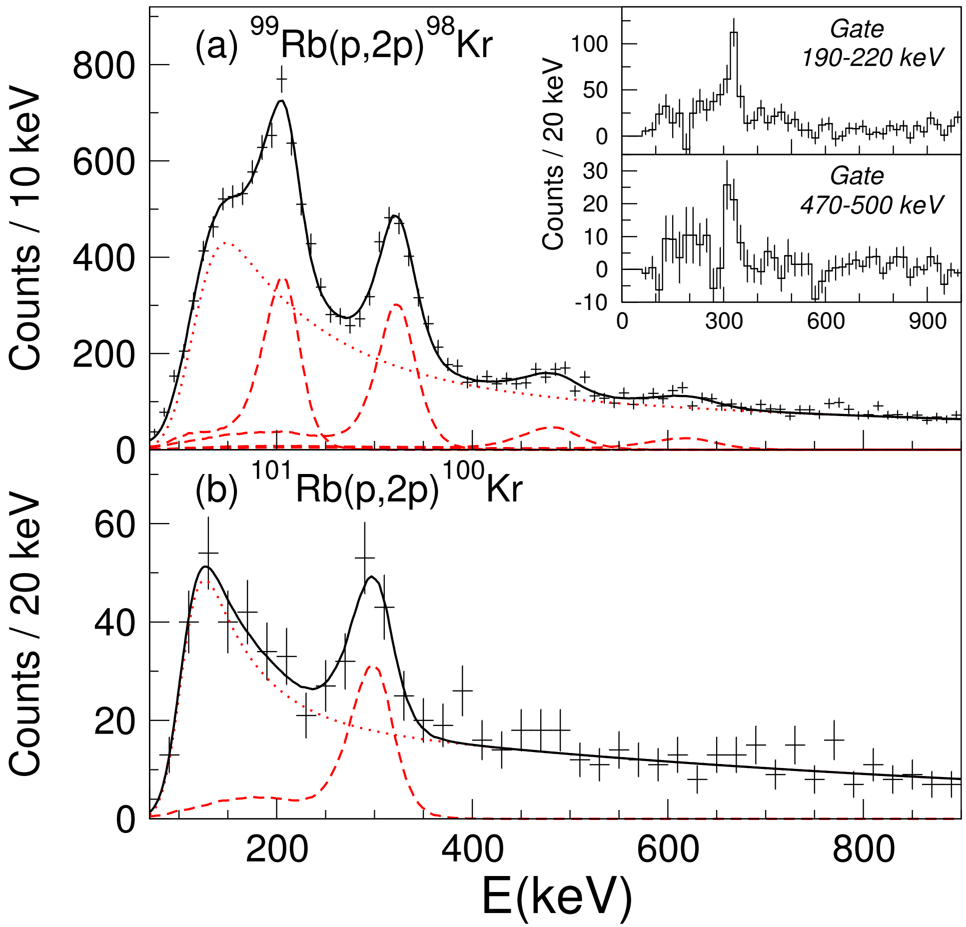
MINOS

- LH2 target +TPC
- Thick target → high luminosity
- Reaction vertex → Doppler correction
- >95% 1p detection efficiency

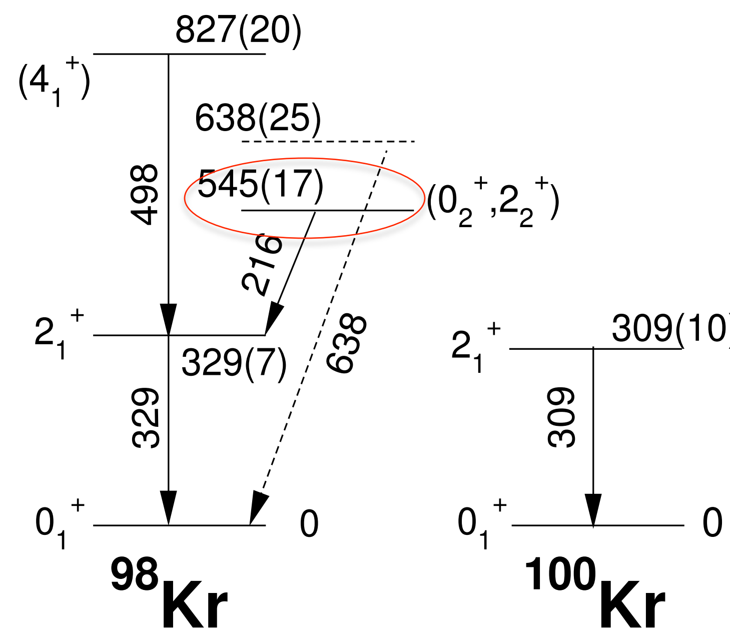
Obertelli et al, EPJA 50 (2014)

^{98,100}Kr: Results

Experimental spectra



Level schemes



Intruder configuration:

- First evidence in n-rich Kr isotopes
- Large direct population (p,2p)

^{98,100}Kr: Comparison with theory

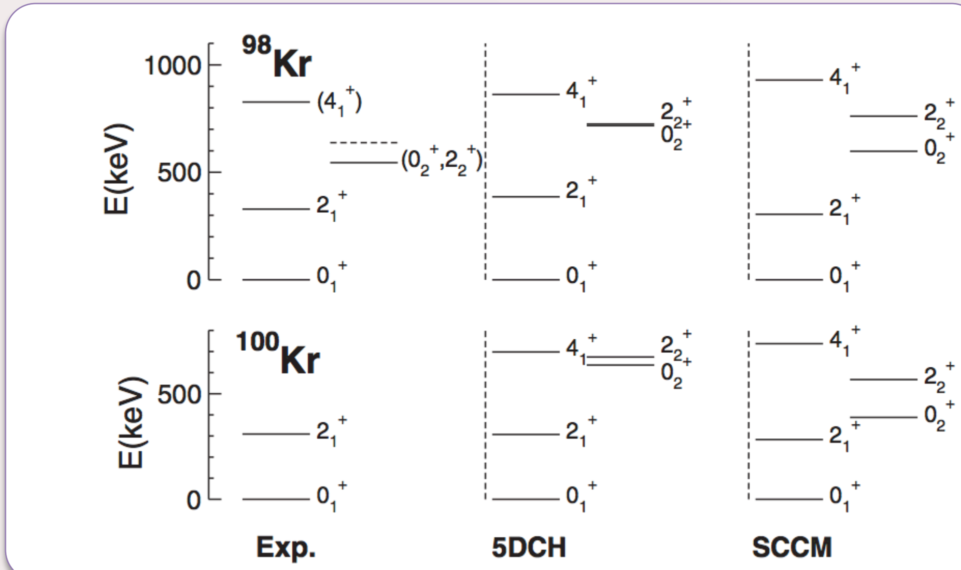
Beyond mean-field calc.
(Gogny D1S int.)

- 5-D Collective Hamiltonian + GOA

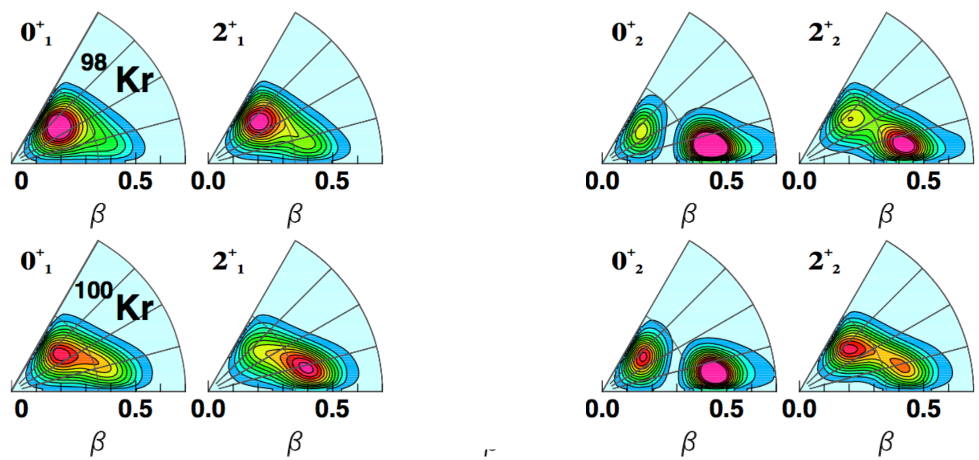
  J.-P. Delaroche, M. Girod, J. Libert (CEA-DAM)

- SCCM (or PCM)

  T. Rodriguez, PRC90 034306 (2014)

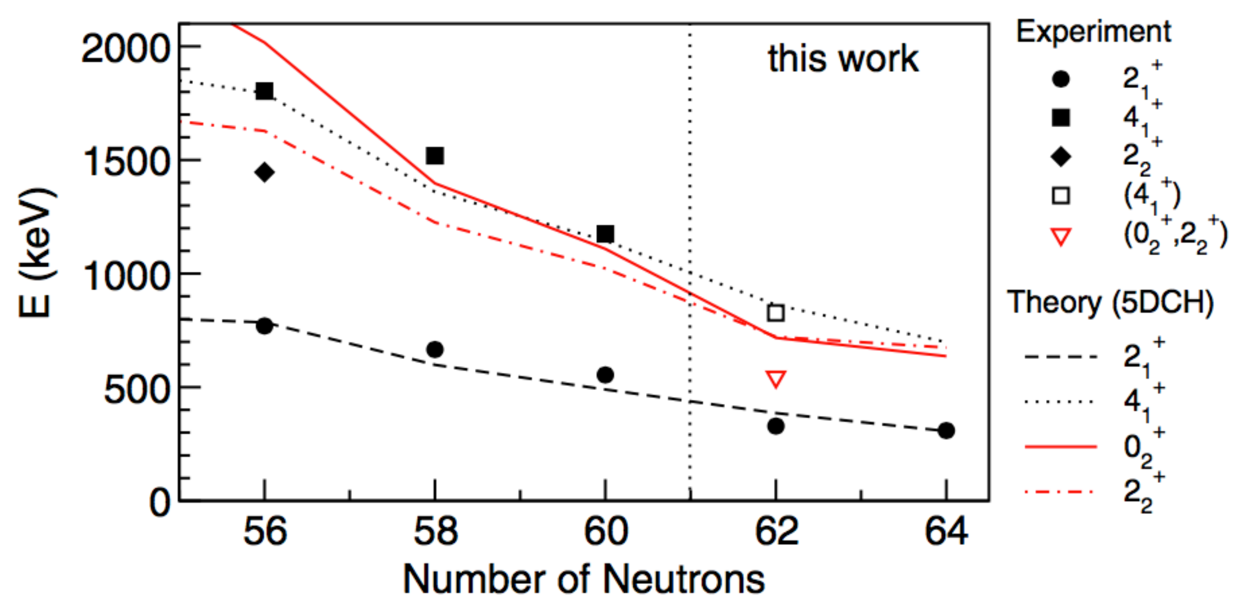


Probability densities in the β,γ deformation space



- Shape coexistence

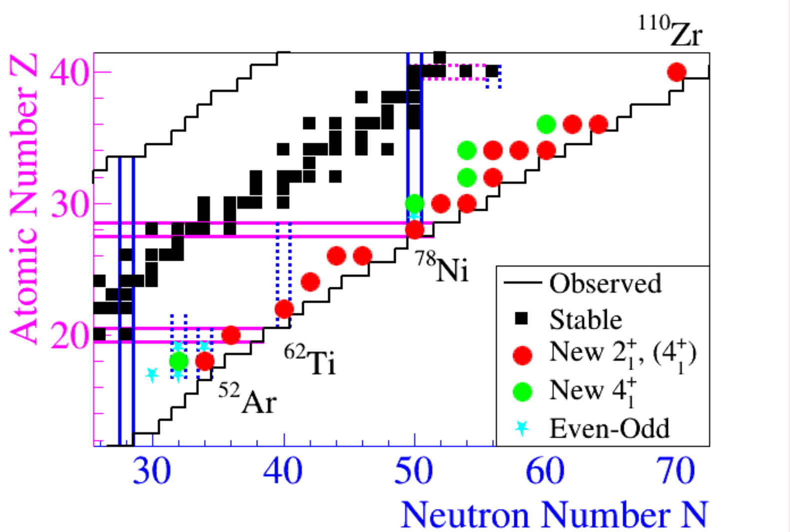
$^{98,100}Kr$: Conclusion



Perspectives:

- Investigate differences between calculations with Gogny D1S
- Large-scale shell model calculation extended to Sr, Kr, Se
- Characterize experimentally excited bands, Coulex, Lifetimes in $^{94,96}Kr$

SEASTAR results



- **Spokespersons:** P. Doornenbal and A. Obertelli (RIKEN – CEA-Saclay)
- Multiyear campaign:
  - 2014 ~^{78}Ni
  - 2015 ~^{110}Zr and south
  - 2017 ~^{52}Ar, ^{62}Ti

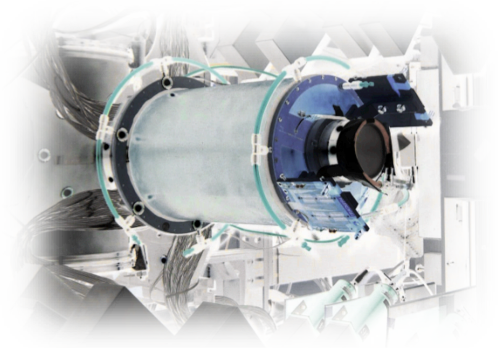
  About 3 weeks of BT in total

✓ ^{66}Cr and ^{70,72}Fe, Extension of N=40 IOI	C. Santamaria et al., PRL **115** 192501 (2015)
✓ ^{110}Zr - well deformed, no magicity, no tetrah.	N. Paul et al., PRL **118** 032501 (2017)
✓ Shape evolution in $^{88\text{-}94}$Se	S. Chen et al., PRC **95** 041302(R) (2017)
✓ Coexisting configurations in ^{98}Kr	F. Flavigny et al., PRL 118 242501 (2017)
✓ Triaxiality of ^{84,86,88} Ge	M. Lettman et al., PRC **96** 011301(R) (2017)
✓ ^{81,82,83,84}Zn, Shell evolution beyond N=50	C. Shand et al., PLB **773** 492 (2017)
✓ ^{79}Cu, Persistence of Z=28 around ^{78}Ni	L. Olivier et al., PRL accepted.

+ about 15 analysis ongoing

Outline

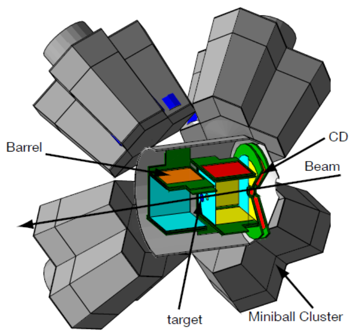
First spectroscopy of very exotic nuclei



$^{99-101}$Rb(p,2p)$^{98-100}$Kr

Shape transition @ N=60 around ^{100}Zr

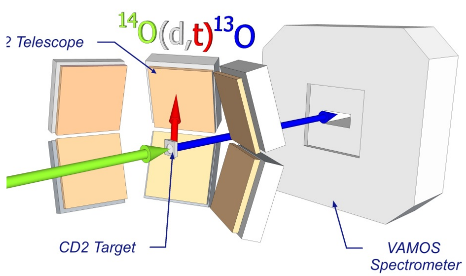
Microscopic nature of 0+ states



^{66}Ni(t,p)^{68}Ni

Two-neutron excitation above N=40

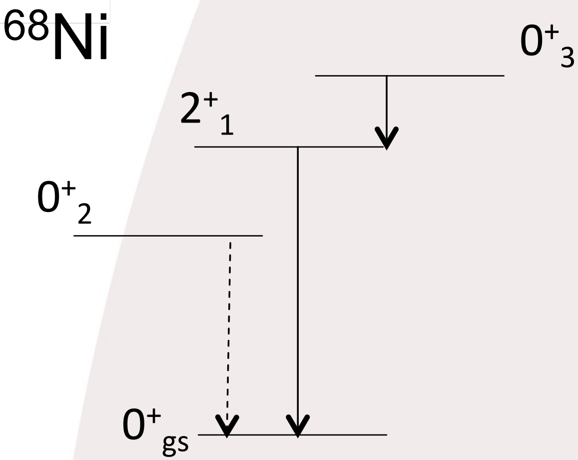
Reduction of single-particle strength

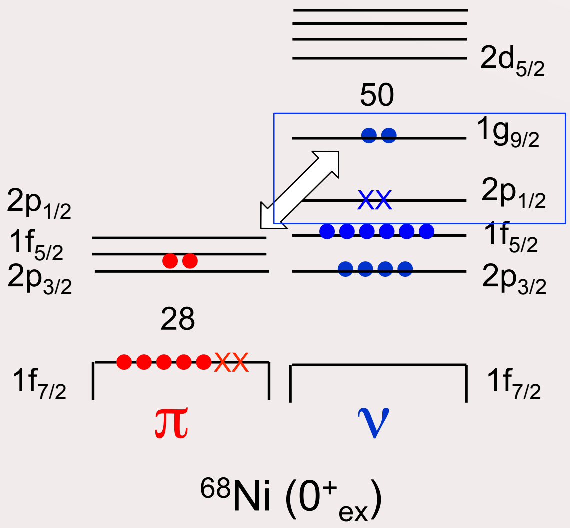


^{14}O,^{18}Ne(d,t) and (d,^{3}He)

Limits and uncertainties of the technique

Analogy Z=40 and N=40





Experimental setup: $^{66}Ni(t,p)^{68}Ni$

KU LEUVEN

ISOLDE

Resonant Laser Ion Source
- Z-selectivity

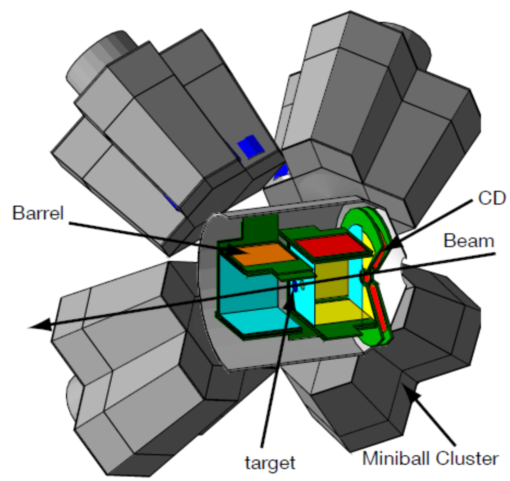
Mass separation
- A/Q-selectivity

Post-acceleration (REX-ISOLDE)

$^{66}Ni(t,p)^{68}Ni$

- Beam energy: 2.6 MeV/u
- Intensity ~2.0 x 10^6 pps
- Beam purity >86%
- Target : 500 mg/cm²
  ^3H loaded Ti (40 mg/cm² ^3H)
- Measurement time: ~ 100h

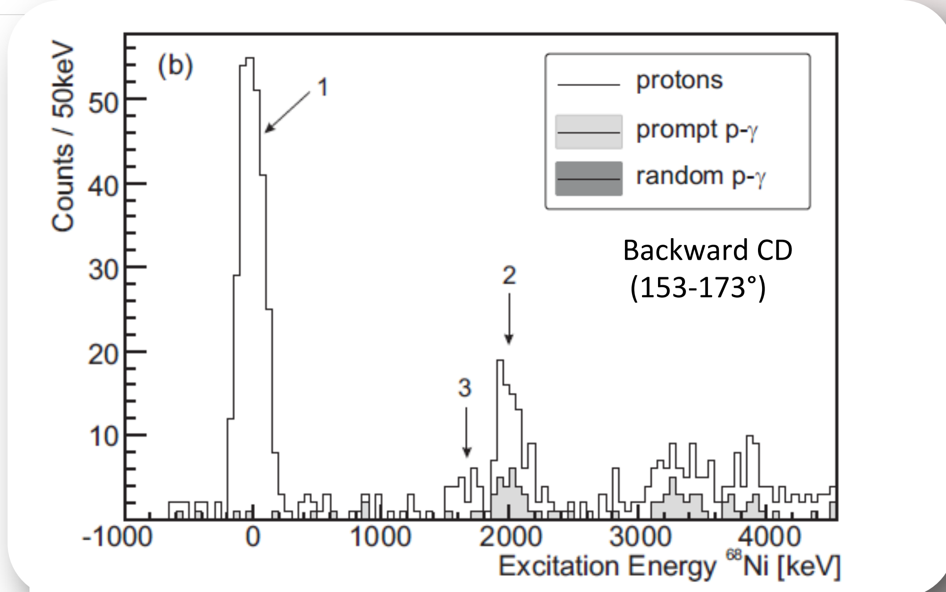
- Proton detection in T-REX:
  - Identification
  - Energy
  - Angular distribution
- γ detection in Miniball:
  - Energy
  - Angular distribution
    (Doppler correction)

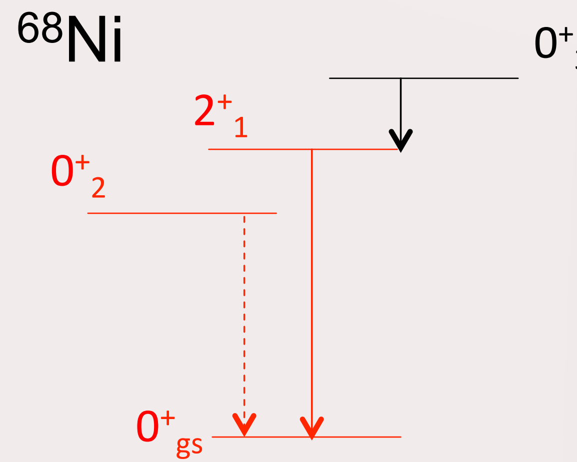


- 8 DE-E_{rest} Barrel det.
- 1 DE-E_{rest} CD detectors

- 8 Miniball triple (HPGe) clusters
- Crystals: 6-fold segmented
- 5% efficiency at 1.33 MeV

Results – Excitation Energy





CD backward data only

- **Population of 0_2^+ and 2^+_1 states**

E = 1621(28) keV - **4.8(16) % of gs**
E = 2033(10) keV - **28(4) % of gs**

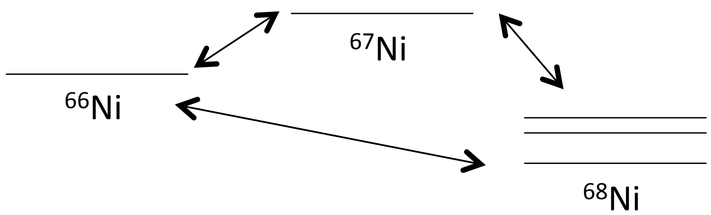
- Non-observed direct population of 0_3^+ , 2_2^+ and 2^+_3 states

0^+_3 (2512 keV) < 2% based on 478 keV transition
2^+_2 (2744 keV) < 4% based on 709 keV transition
2^+_3 (4026 keV) < 3% based on 1515 keV transition

Results – Angular Distributions

Two-neutron transfer :

Direct + Sequential



Parameters of our calculations:

- Finite-range DWBA (code FRESCO[1])
- Glob. Pot. : ^{3}H+^{66}Ni and ^{1}H+^{68}Ni
- Two nucleon overlap amplitudes (TNA's)

$$| < {}^{66}\mathrm{Ni}(0^{+}_{gs}) \, | a_{nlj} a_{nlj} | \, {}^{68}\mathrm{Ni}(0^{+}_{i}) > |^{2}$$

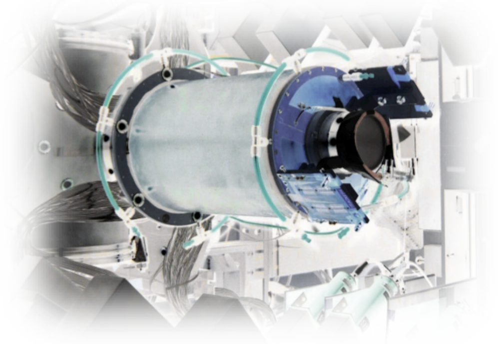
- Interaction A3DA
- Model space : full fpgd
- Performed by T. Otsuka, Y. Tsunoda

- **Detailed benchmark of shell model configurations involved in 0+ states**

INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

Outline

First spectroscopy of very exotic nuclei

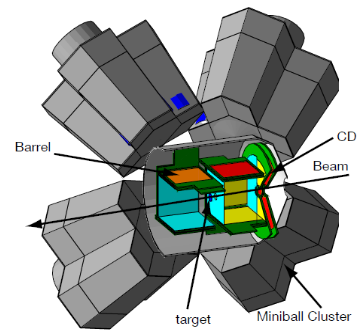


RIKEN NISHINA CENTER

$^{99-101}$Rb(p,2p)$^{98-100}$Kr

Shape transition @ N=60 around ^{100}Zr

Microscopic nature of 0+ states

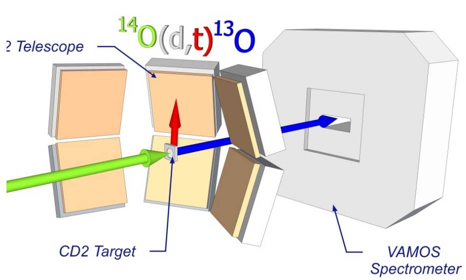


ISOLDE

^{66}Ni(t,p)^{68}Ni

Two-neutron excitation above N=40

Reduction of single-particle strength



GANIL spiral2 laboratoire commun CEA/DRF CNRS/IN2P3

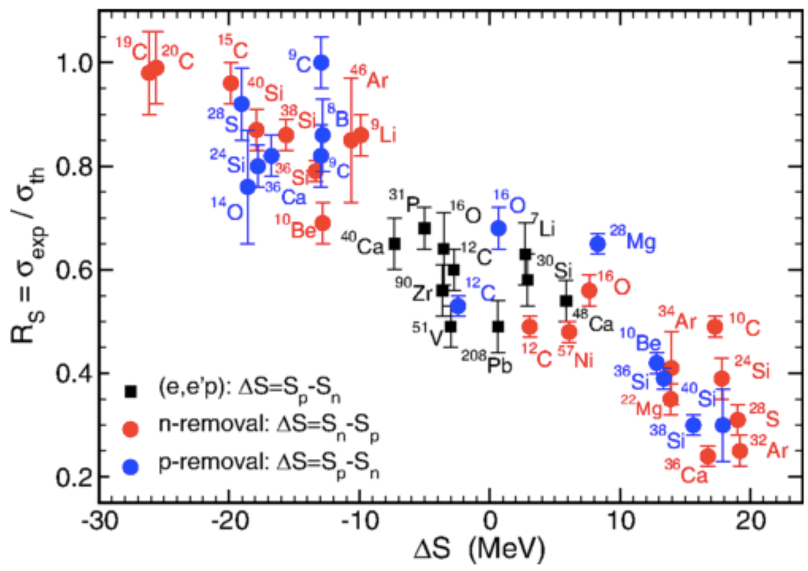
^{14}O,^{18}Ne(d,t) and (d,^{3}He)

Limits and uncertainties of the technique

Nucleon removal from exotic nuclei

Intermediate energy Knockout

J.A. Tostevin and A. Gade, Phys. Rev. C **90**, 057602 (2014)

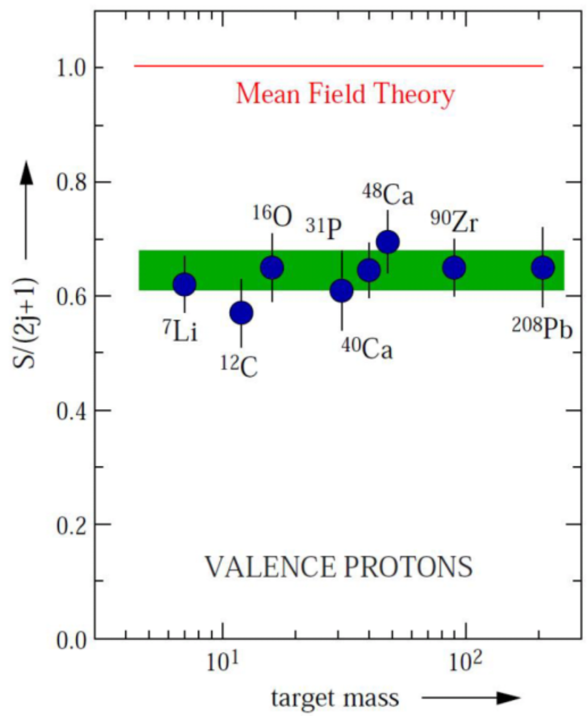


- **Disagreement between th. and exp.**

$$\sigma_{th} = C^2 S_{th}\ \sigma_{sp}$$

2 possible sources: (structure or reaction)

(e,e'p) reactions



[W. Dickhoff, C. Barbieri, PNP**52**, 377 (2004)]

Program @ GANIL-SPIRAL

Questions :

1. **How are evolving spectroscopic factors extracted from transfer for high ΔS ?**

*[F.F. et al., Phys. Rev. Lett. **110** 122503 (2013)]*

2. **What are the main systematic uncertainties due to the reaction model interpretation ?**

[F.F. et al., submitted to Phys. Rev C (2017)]

Experimental Data Set

E569s

- $^{14}O + d \rightarrow {}^{13}O + t$
- $^{14}O + d \rightarrow {}^{13}N + {}^{3}He$
- $^{14}O + d \rightarrow {}^{14}O + d$

18 MeV/u

E655s

- $^{18}Ne + d \rightarrow {}^{17}Ne + t$
- $^{18}Ne + d \rightarrow {}^{17}F + {}^{3}He$
- $^{18}Ne + d \rightarrow {}^{18}Ne + d$

17 MeV/u

Published data (direct kinematics)

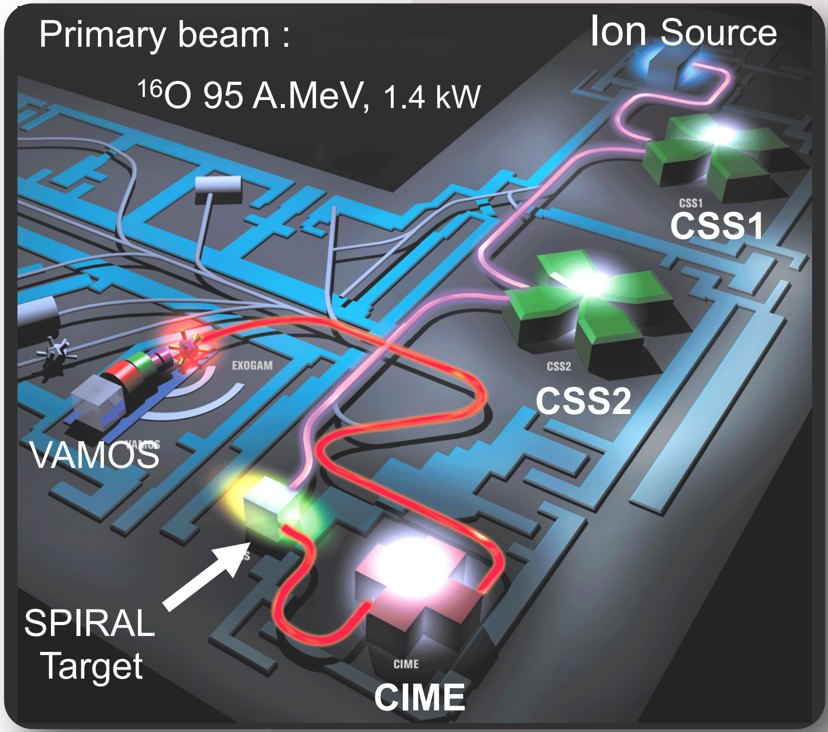
- $^{16}O + d \rightarrow {}^{15}O + t$
- $^{16}O + d \rightarrow {}^{15}N + {}^{3}He$
- $^{18}O + d \rightarrow {}^{17}N + {}^{3}He$

26 MeV/u and 14 MeV/u

Why ^{14}O and ^{18}Ne :

- ✓ Large value ΔS = 18.6 MeV
- ✓ ^{14}O is a Closed-shell nucleus,
- ✓ Beam intensity high enough for $(d,{}^{3}H)$ $(d,{}^{3}He)$

Beam and Experimental Setup (E569s, E655s)



SPIRAL Beams: $^{14}O^{8+}$ **and** $^{18}Ne^{10+}$

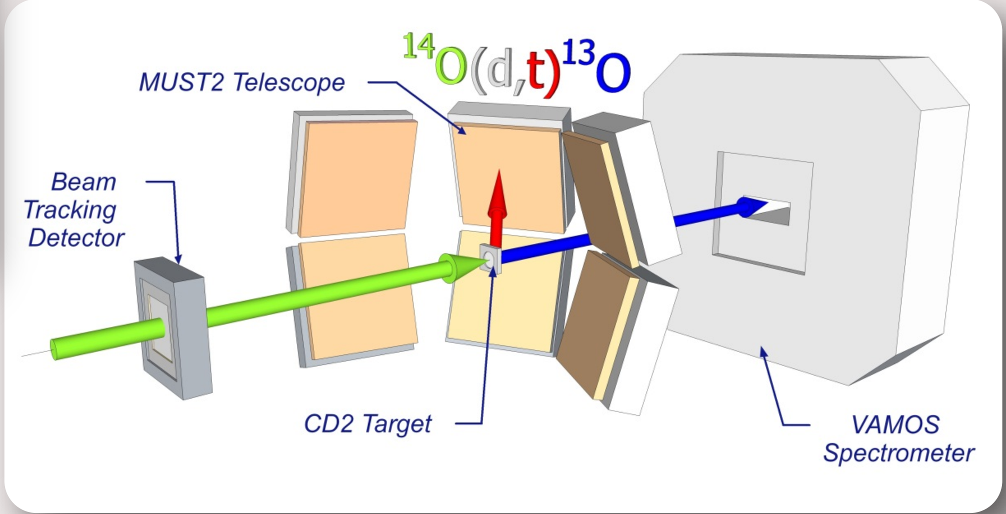
Intensity: 6.10^{4} and XX pps

Energy: 18-16 A.MeV

CD2 targets: 0.5,1.5 and 8.5 mg.cm^{-2}

Reactions: (d,d), (d,^{3}H) and (d,^{3}He)

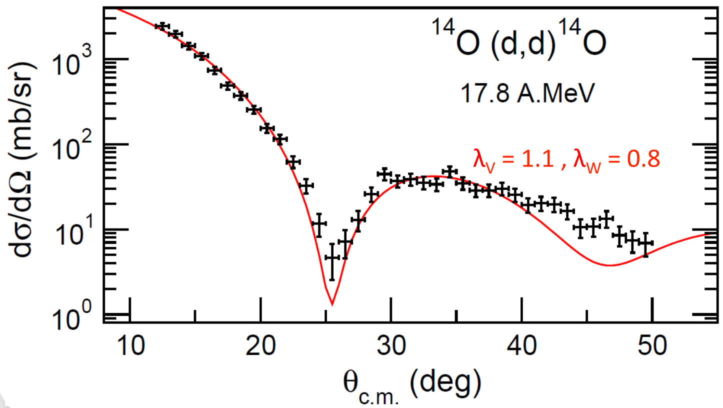
- *6 MUST2 Telescopes:*
  10x10 cm^{2} 300µm DSSSD + SiLi or CsI
- *VAMOS spectrometer in dispersive mode*



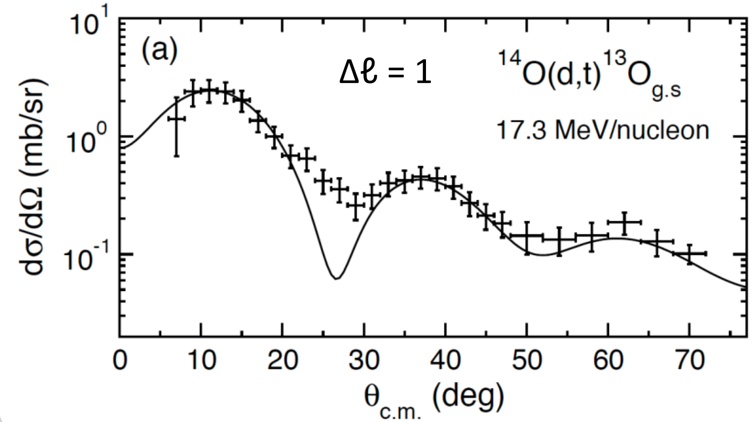
Fully exclusive measurements

Experimental Data Set

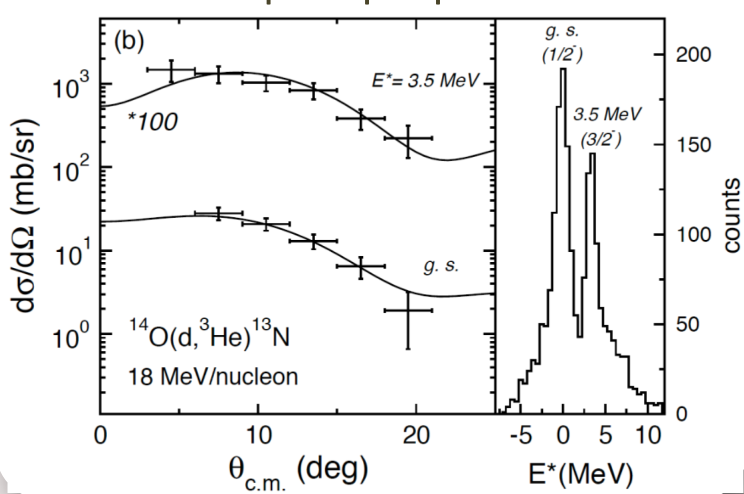
Elastic channel



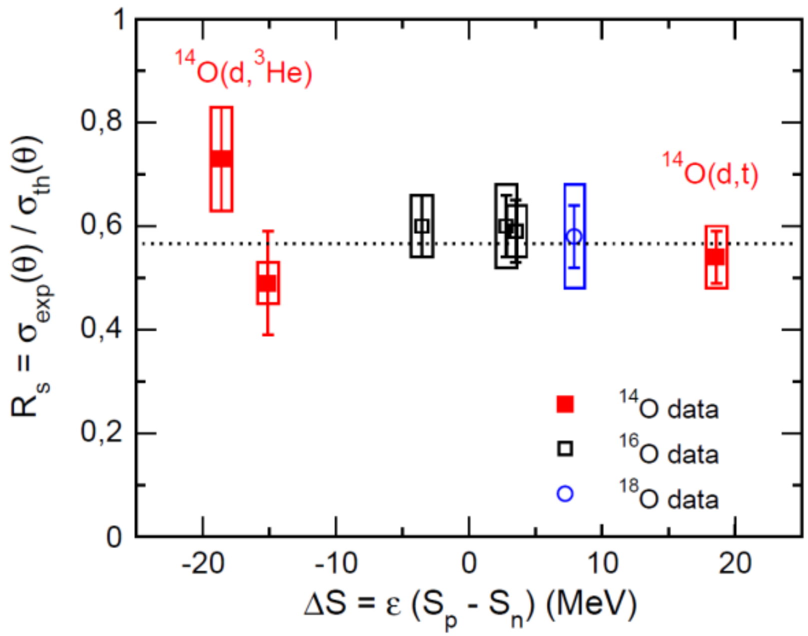
One-neutron pickup channels



One-proton pickup channel



Results with WS overlap functions



δ (RMS) → δr$_o$ → box

Error bars due to exp. Uncertainties

OFs : WS (HFB constrained)
C^2S_{th}: Shell model with WBT interaction

$$\sigma_{th}(\theta) = C^2 S_{th}\, \sigma_{sp}(\theta)$$

$$R_s = \alpha \,.\, \Delta S + \beta$$

α = +0.0004(24)(12) MeV^{-1}

$\beta = R_s(0)$ = 0.538(28)(18)

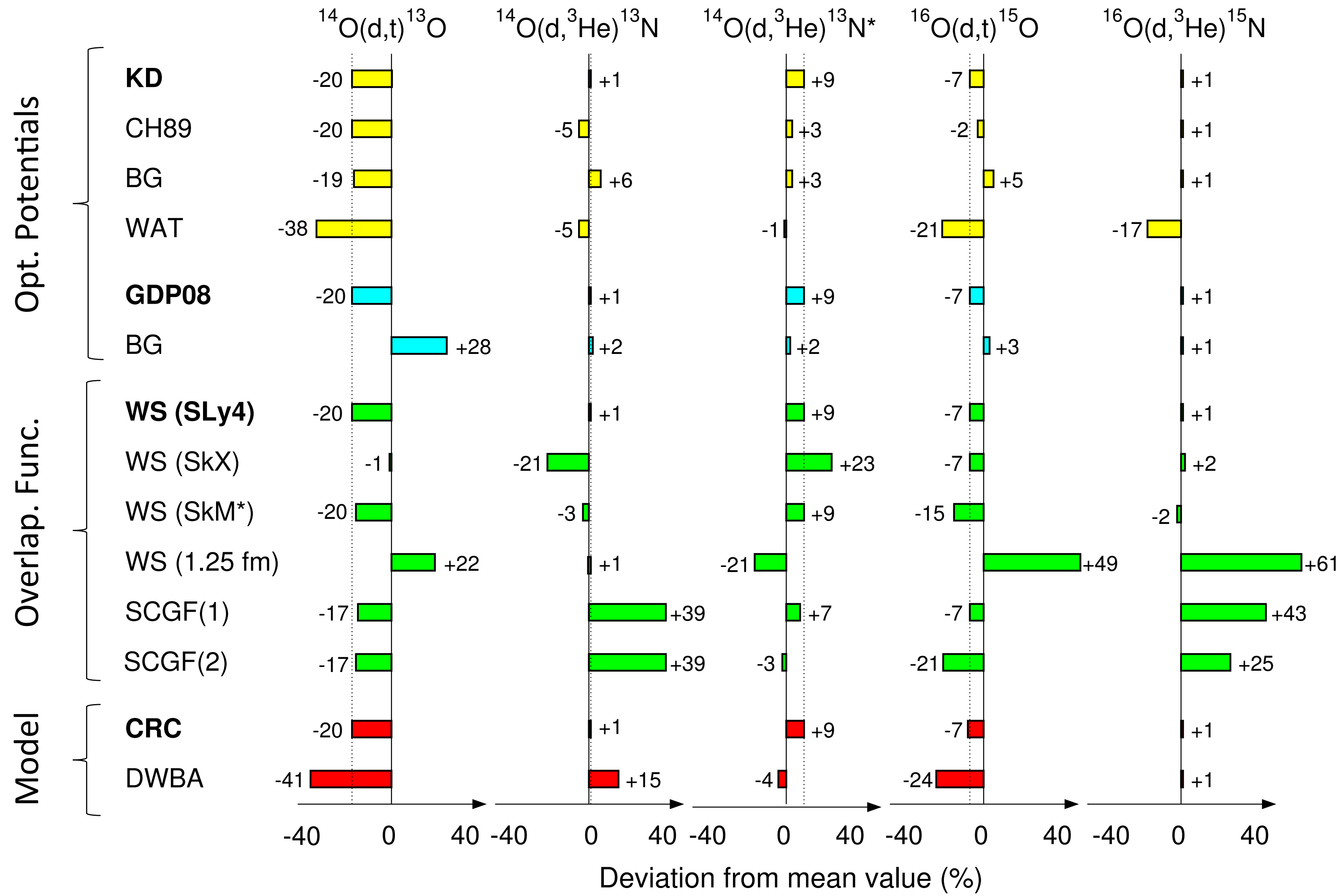
Exp. Error (1 set)

Stdrd. error from 48 data sets

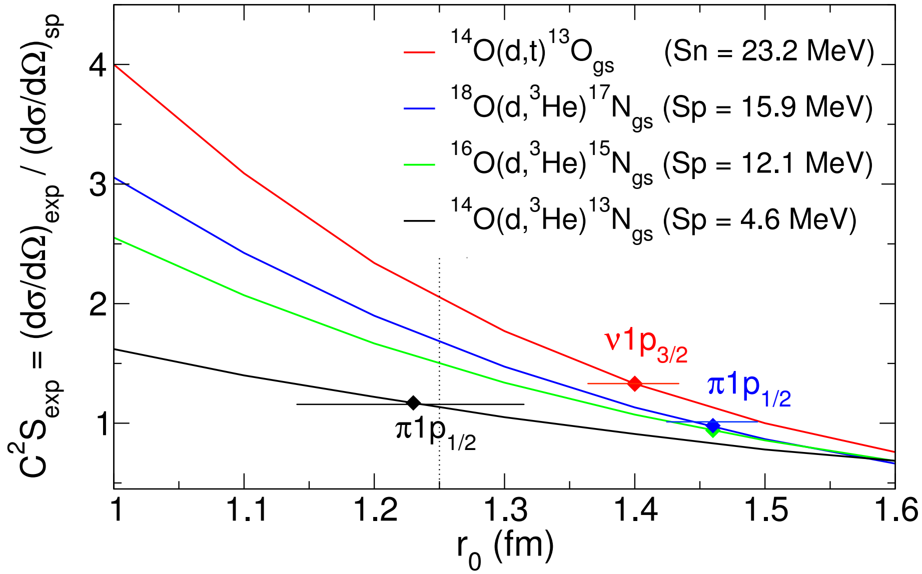
Choices to be made

- **Potentials**
  - Input channels
  - Output channels
- **Framework**
  - DWBA
  - ADWA
  - CCBA
  - CRC
- **Overlap functions**
  - Woods Saxon geometry
    - ~~Historical (1.25; 0.65) fm~~
    - HF constrained
  - Ab-initio

Quantitative Estimation of model dependances



r_0 dependance



Potentials used: (KD+GDP08)

Linear fit (a*r0+b) between 1.3 fm and 1.5:

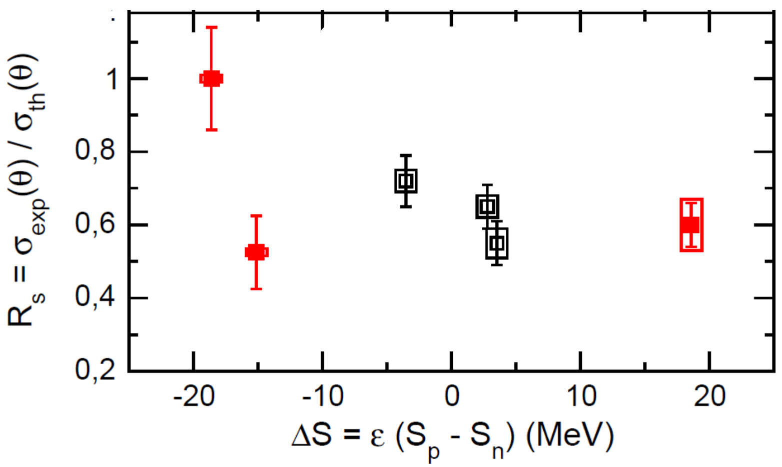
Reaction	$S_{n,p}$ (MeV)	a (slope)
$^{14}O(d,t)^{13}O$	23.2	-3.85
$^{18}O(d,^{3}He)^{17}N$	15.9	-3.00
$^{16}O(d,^{3}He)^{15}N$	12.1	-2.4
$^{14}O(d,^{3}He)^{13}N$	4.6	-1.35

- The $C^2S_{exp}(r_0)$ dependence is enhanced if the transfered nucleon is more bound
  - For r_0 in [1; 1.25] fm, this effect becomes even larger (non linear)

Ex. for 14O(d,t): for r_0= 1.40 fm ⇒ $C^2S_{exp} \approx 1.3$
for r_0= 1.25 fm ⇒ $C^2S_{exp} \approx 2.1$

(≈ 11% change) (≈ 60% change)

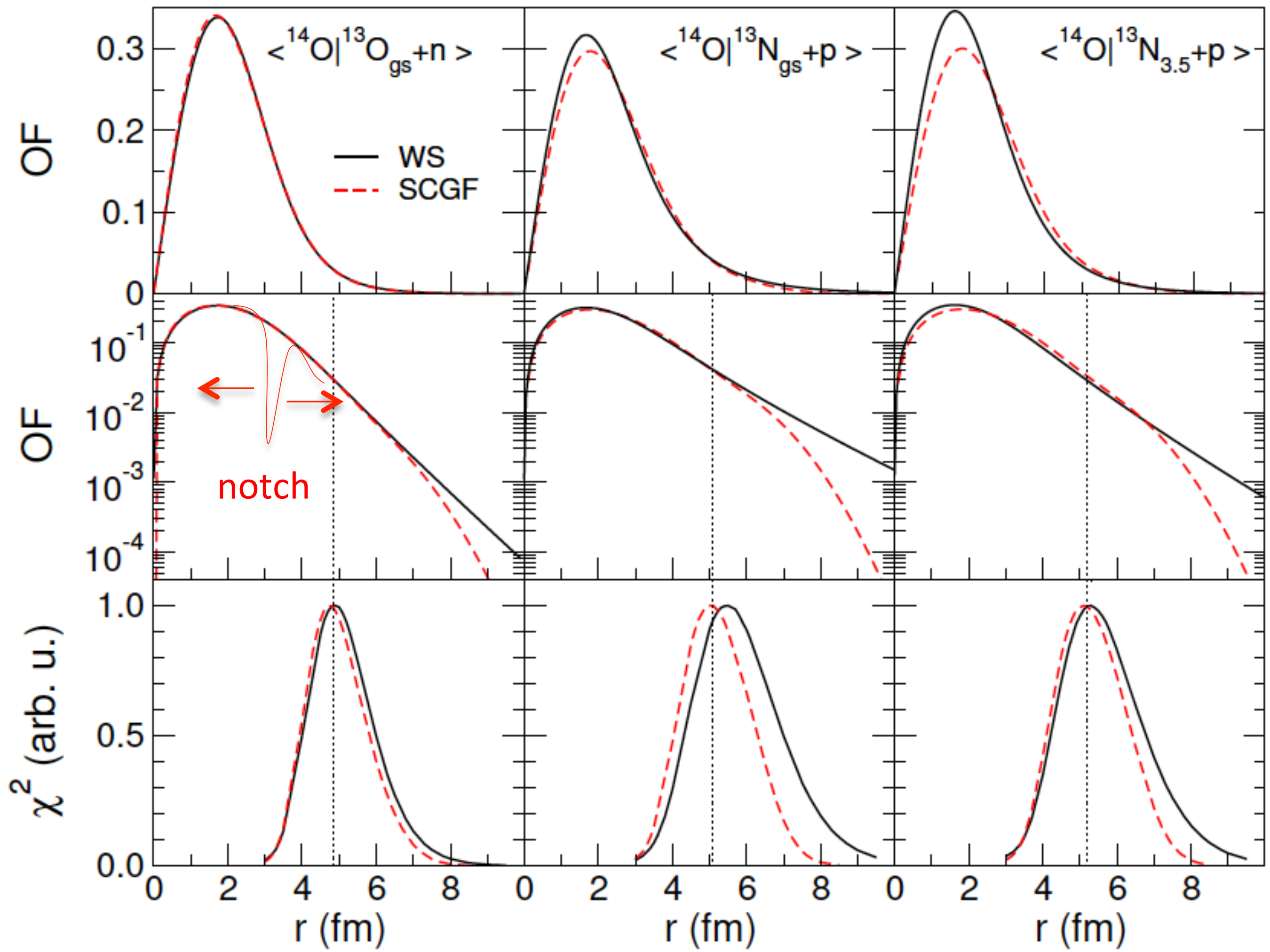
Results with ab-initio overlaps



Consistent ab-inito SF_{th} and overlaps (from C. Barbieri and A. Cipollone)

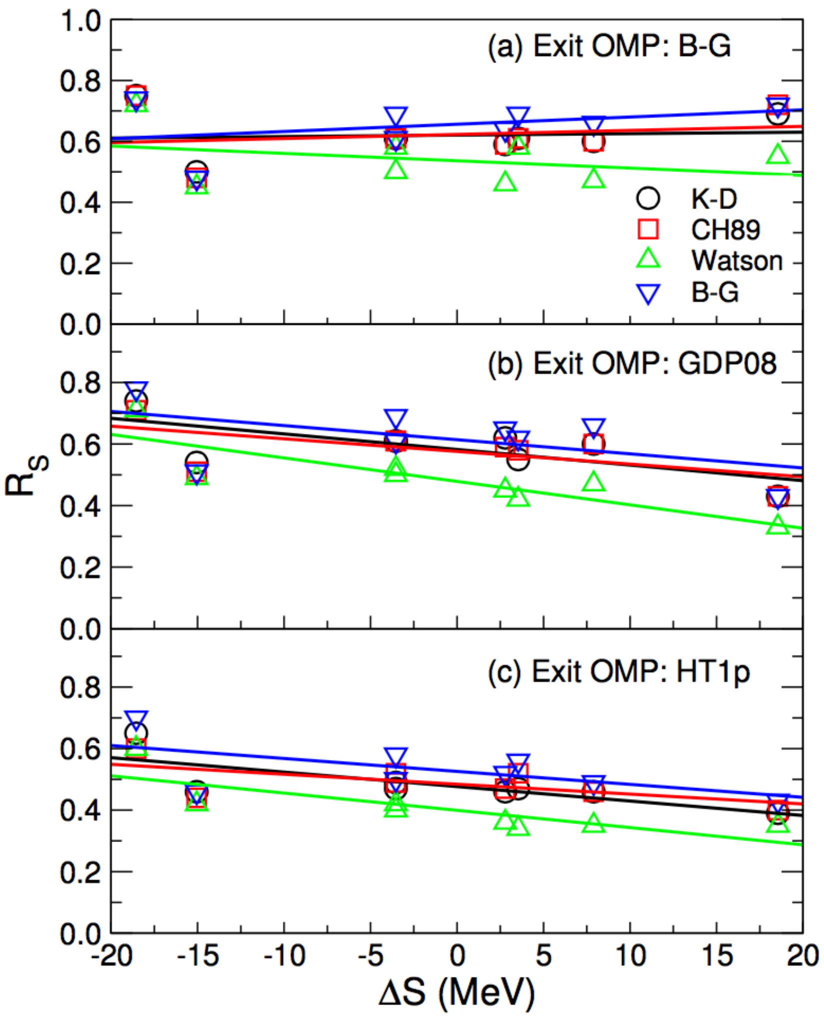
- Single-particle Green's function (SCGF)
- Chiral 2-body + 3-body int. (cutoff λ=1.88 fm^{-1})

Radial sensitivity: Notch test



→ Notch test: $\chi^2 = \Sigma((d\sigma/d\Omega)_{pert} - (d\sigma/d\Omega)_{un})^2/(d\sigma/d\Omega)_{un}^2$

Conclusions



For all reasonable combination of parameters considered:

No significant variation of Rs with ΔS

BUT

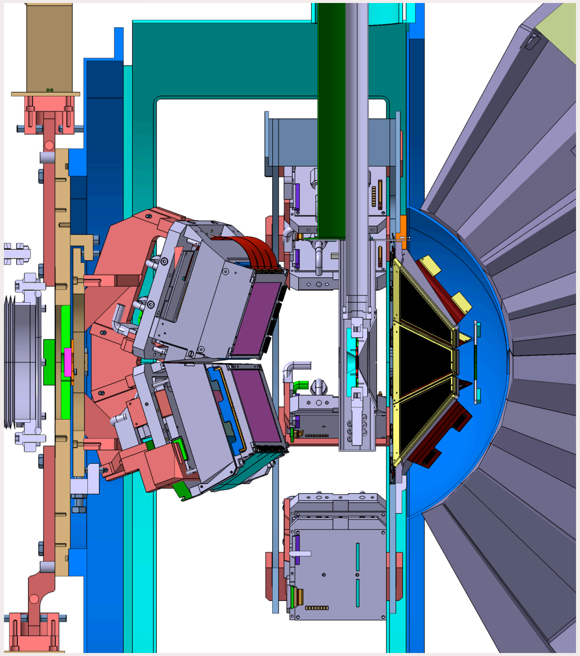
For a given reaction, specific choices can lead to extreme values.

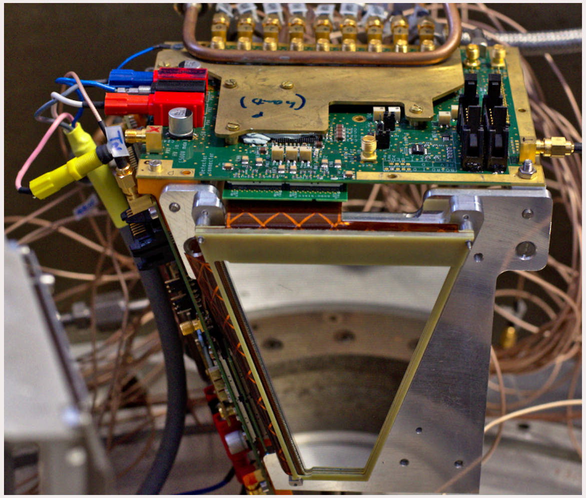
Perspectives for direct reactions in GANIL

Short-mid term:

- MUST2 experiments at LISE:
  - $^{11}C(p,t)^{9}C$ and ^{14}O accepted
  - +3 propositions submitted
- MUGAST @ VAMOS with AGATA:
  - Several LOIs
  - +2 propositions submitted
  - 5 det. + chamber available.
- MUGAST @ LISE with EXOGAM (LPC caen)
- ACTAR (see dedicated talk)
- GASPARD developments (M. Assié)
  - PSA tests with trapezoid + PACI (next week)

What about longer term ?





Thank you
and all the collaborators involved!