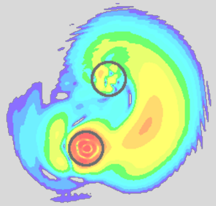
Reaching for the infinities : Nuclear Physics - « High » energy

M. Assié, IJCLab

with the help of F. Hammache, E. Clément, B. Fernandez-Dominguez, T. Roger, O. Sorlin, D.Beaumel, J-J Valiente-Dobon, S Koyama and many others…



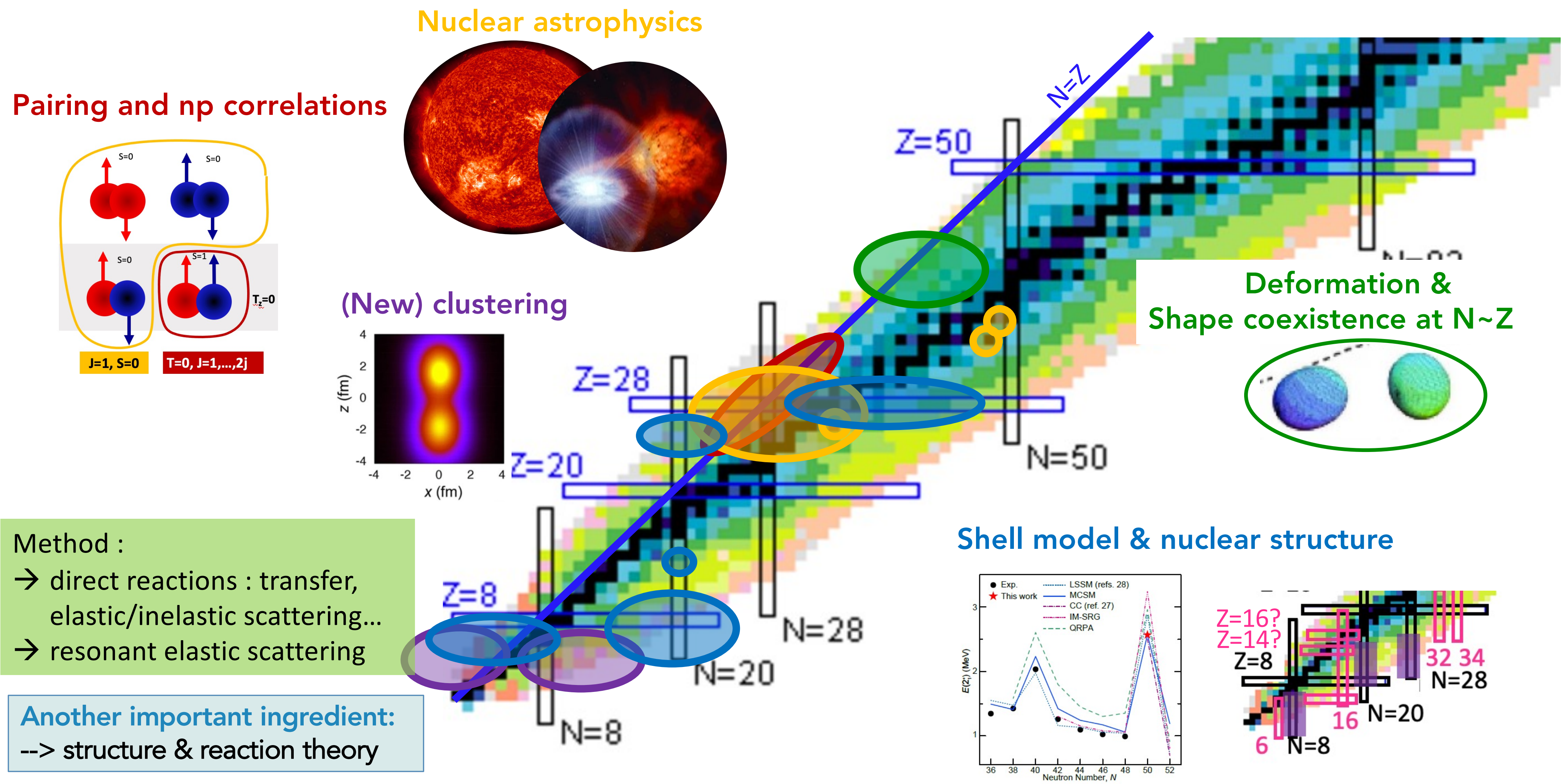
Physics program at GANIL:

- Nuclear astrophysics
- Pairing, clusters
- Shape coexistence
- Shell evolution

Instruments :

- beams
- set-ups
- targets

Overview of the perspectives for nuclear physics at GANIL



Beam

Radioactive
Spiral 1 beams
<~ 10 A MeV

Reactions

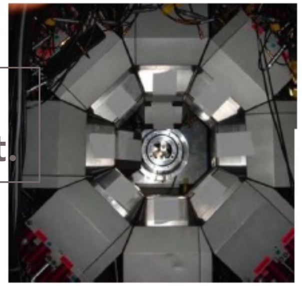
Coulomb excitation

Elastic/inelastic scatt.
Resonant elastic scatt.

Transfer (stripping)

Detection

gamma-rays



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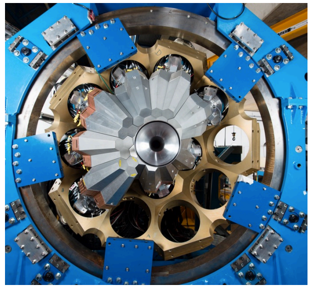
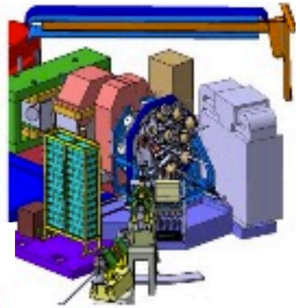


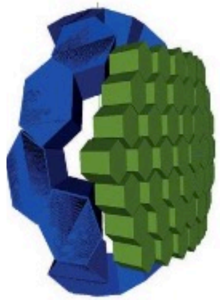
AGATA

heavy residues



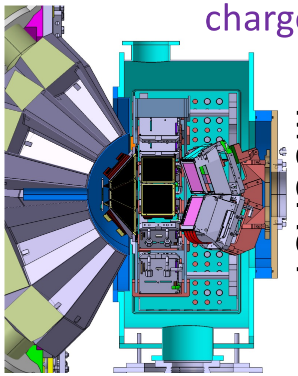
VAMOS

neutrons

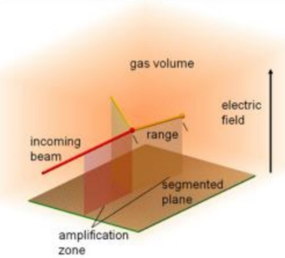


NEDA

charged particles



MUGAST



ACTAR

Availability @ GANIL

Beam

Radioactive Spiral 1 beams <~ 10 A MeV

Fragmentation beams LISE (intermediate energy)

Reactions

Coulomb excitation

Elastic/inelastic scatt.
Resonant elastic scatt.

Transfer (stripping)

Beam intens. > 10^4pps + BTD

Transfer reactions :
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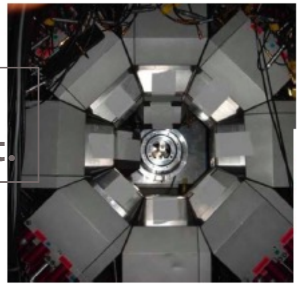
- stripping ?

Elastic/inelastic scatt.

Detection

gamma-rays



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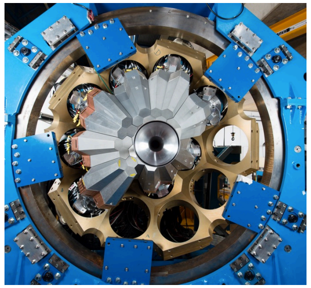

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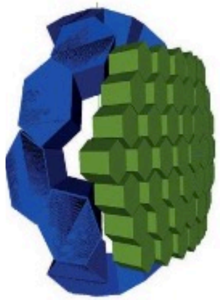

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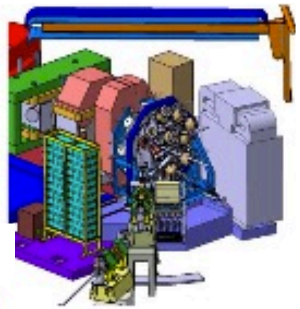

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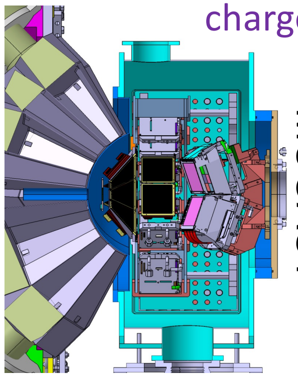

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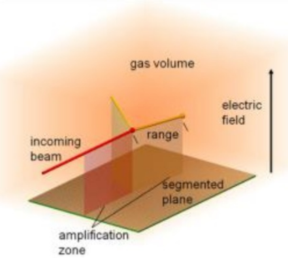

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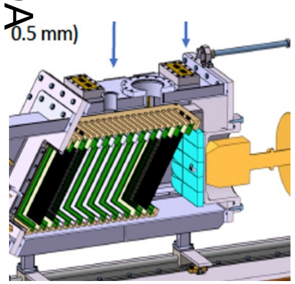

ZDD

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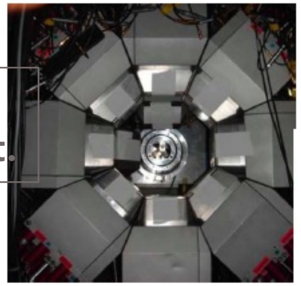

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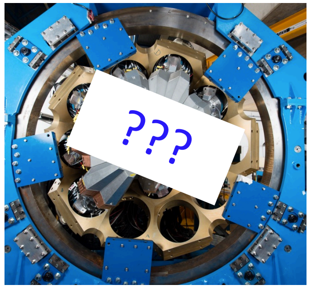

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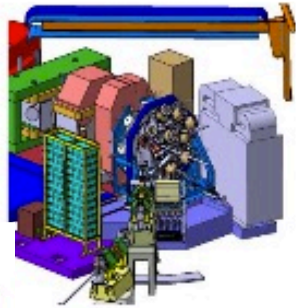

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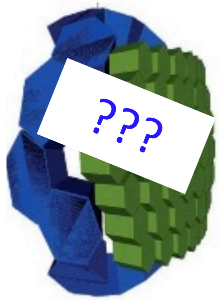

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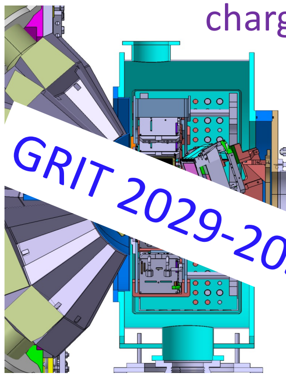

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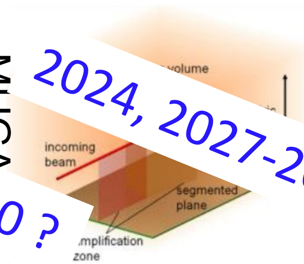
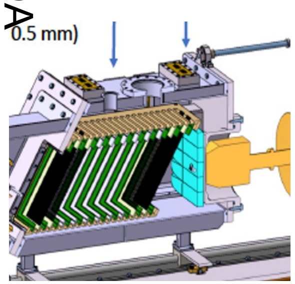


ACT



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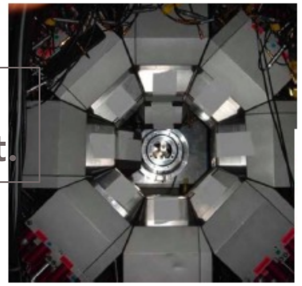
- **Elastic/inelastic scatt.**

Targets for physics

gamma-rays



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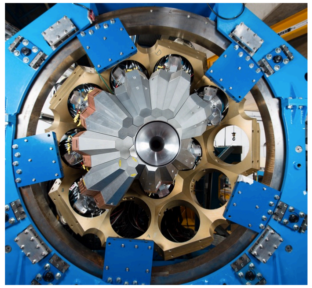

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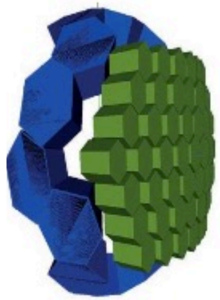

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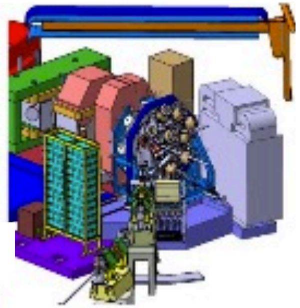

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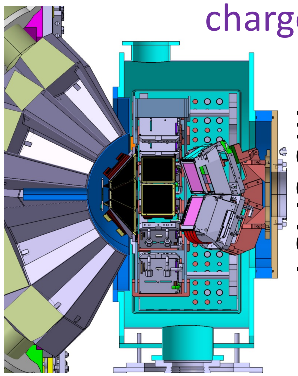
charged particles



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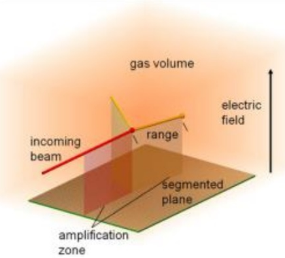
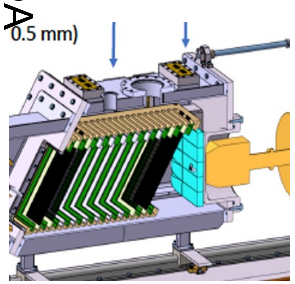


ACTAR



ZDD

Targets for physics:

✓ **Typical solid targets** : CH_2, CD_2, **$^{6\text{-}7}$LiF -->OK**

Typical reactions:

- one-nucleon transfer (d,p), (p,d) ---- (d,^{3}He), (^{3}He,d),
- two-nucleon transfer (p,^{3}He),(^{3}He,p),(d,^{4}He) --- (t,p),(p,t)
- triton, ^{3}He transfer : (p, ^{4}He), (^{4}He,p),(t,^{6}Li)
- alpha transfer (d, ^{6}Li),(^{7}Li,t),(^{6}Li,d)
- elastic scattering (p,p'),(d,d'),(^{4}He,^{4}He')

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(to be tested @ ALTO)

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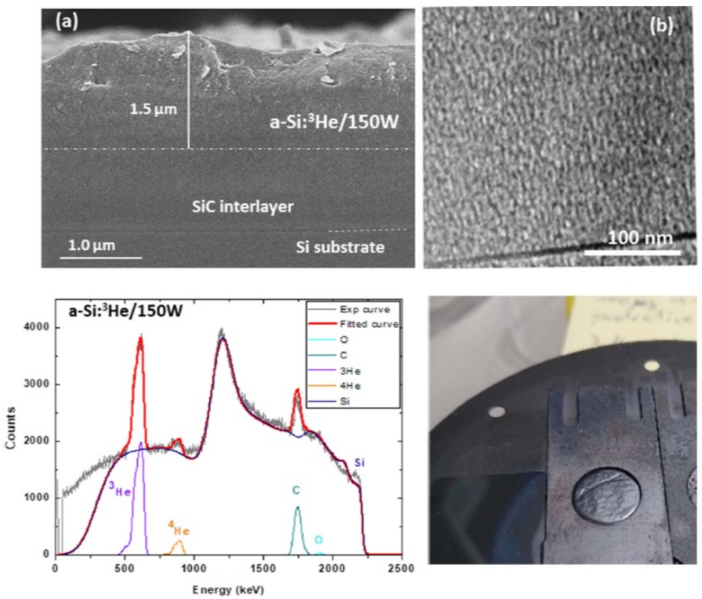
"Solid ^{3}He targets"

- Magnetron sputtering technique under quasi-static flux conditions
- Gas nanobubbles trapped within a nanoporous solid matrix (amorphous silicon)

^{3}He areal density: ca 5 – 7 x 10^{18} at/cm^2

Al backing: 7.4 µm



Fernández+, Materials and Design 2020

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N.Séréville, F. Hammache & M. Assié

✓ **Cryogenic targets** :
✓✗ **CHyMENE** - **windowless** H target
(*still under development @ CEA, A. Gillibert*)

Typical reactions:
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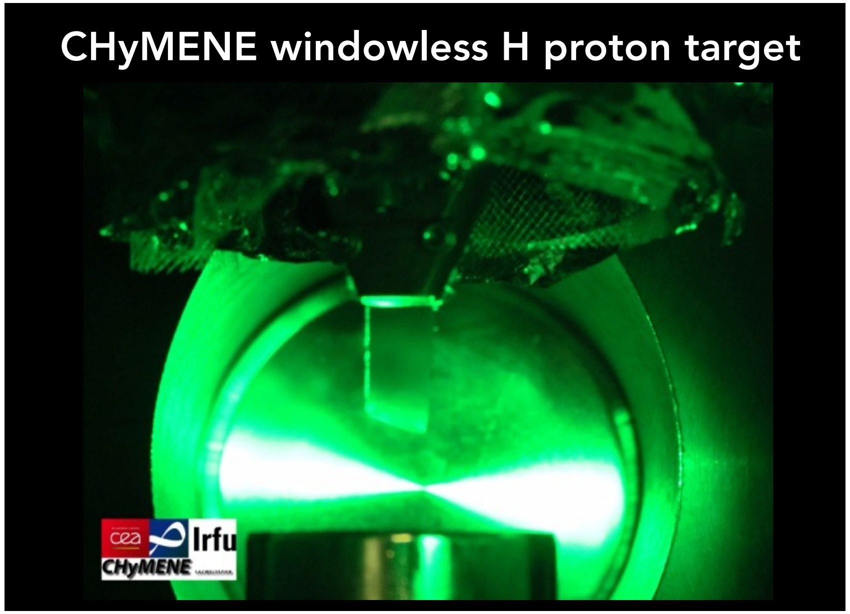

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N.Séréville, F. Hammache & M. Assié

✓ **Cryogenic targets** :

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(*still under development @ CEA, A. Gillibert*)

✓ **HeCTOr** ^{3}He target (*M.Pierens, M. Assié* IJCLab)
already used during the MUGAST-AGATA-VAMOS campaign

Typical reactions:
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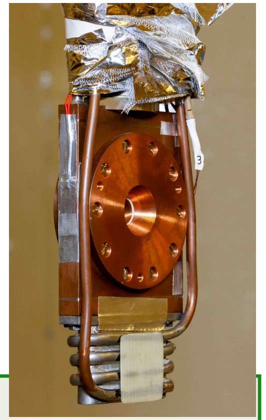
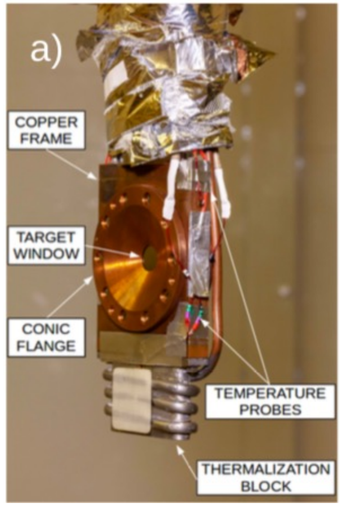


- Ø 16 mm
- Opening angle 60 deg.
- Havar windows=3.8um
- T ~ 6-7 K. / P up to 1 bar
- Equivalent thickness 2 mg.cm^3
- ^{3}He recycling (2.5l)
- LHe open circuit

F. Galtarossa et al, NIMA (2022)



M. Pierens, V. Delpech,
F. Galet, H. Saugnac (IJCLab)
A. Giret & J. Goupil (GANIL)

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✓ **Cryogenic targets** :
✓✗ **CHyMENE** - H target
(*still under development @ CEA, A. Gillibert*)

✓ **HeCTOr** ^{3}He target (*already used at GANIL*)
--> new version under development : ANR **ATRACT** + **^{3}He active target (ACTAR-^{3}He)**
Marlène ASSIE (IJCLab)
Thomas Roger (GANIL)

Typical reactions:
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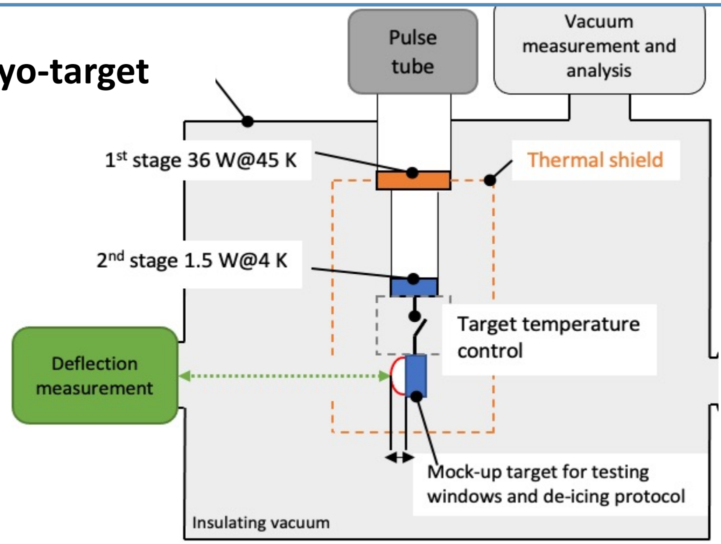
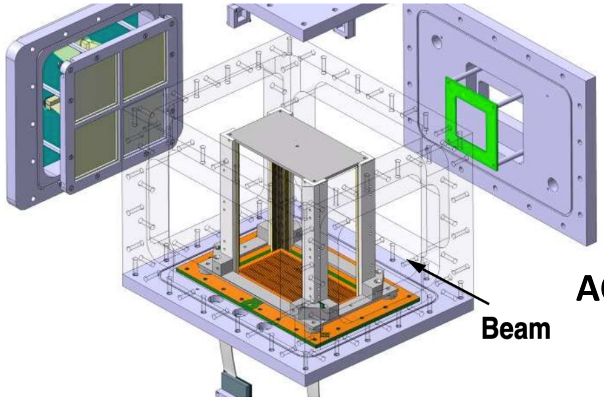
Cryo-target





ACTAR-^{3}He

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--> **new version** under development : ANR **ATRACT + ^{3}He active target (ACTAR-^{3}He)**

✗ **Tritium targets :** no development on-going in Europ,
commercial version available with only 40 ug/cm^2
Activity : 10 GBq

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F. Hammache, N. de Séréville (IJCLab), F. de Oliveira (GANIL), G. Lotay (U of Surrey)

Nuclear astrophysics

-- **Type I X-ray bursts**

. Sensitive study --> few tens of reactions play an important role

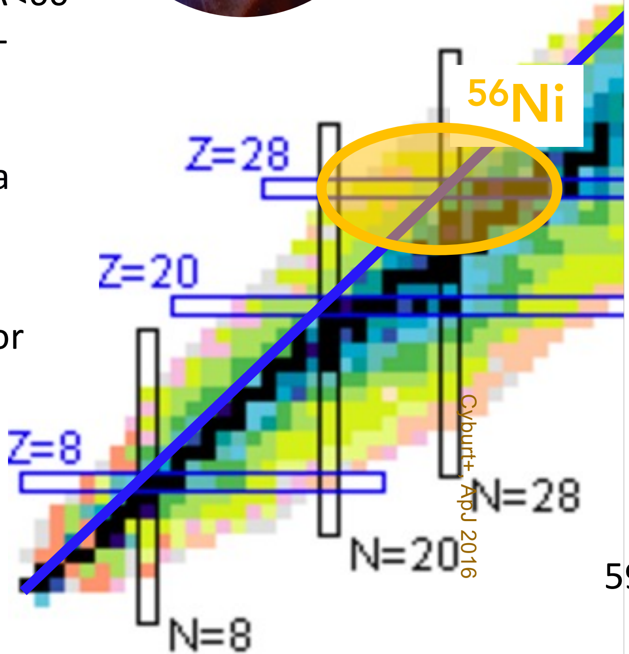
➟ (α,p) process: (α,p)(p,γ) up to A<60

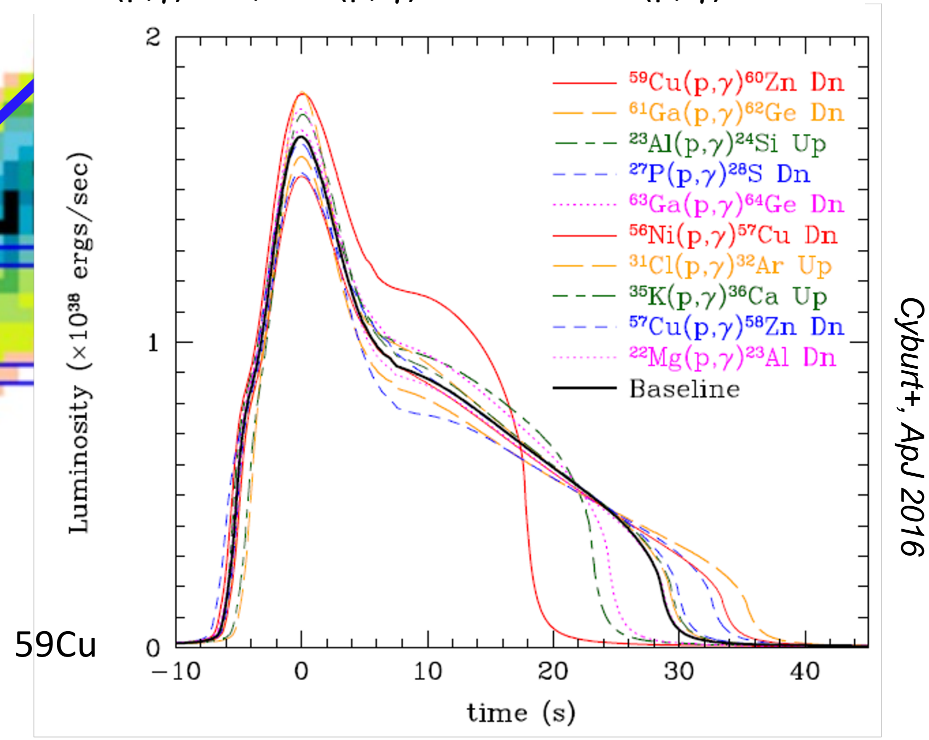
➟ rp-process: (p,γ) reactions & β+ decay

- Probing the ^{56}Ni waiting point via ^{55}Co(*d,p*) and ^{57}Ni(*d,p*) transfer (mirror reactions)
- Determination of reaction rate for ^{59}Cu(p,γ) via ^{59}Cu(^{3}He,dγ)

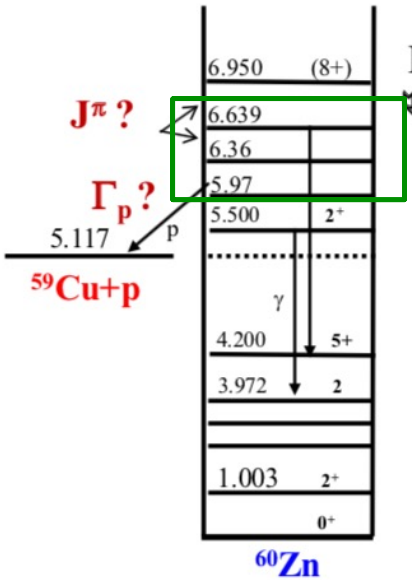
Most important effect on the light curve :

^{59}Cu(p,γ)^{60}Zn, ^{56}Ni(p, γ)^{57}Cu and ^{57}Cu(p, γ)^{58}Zn





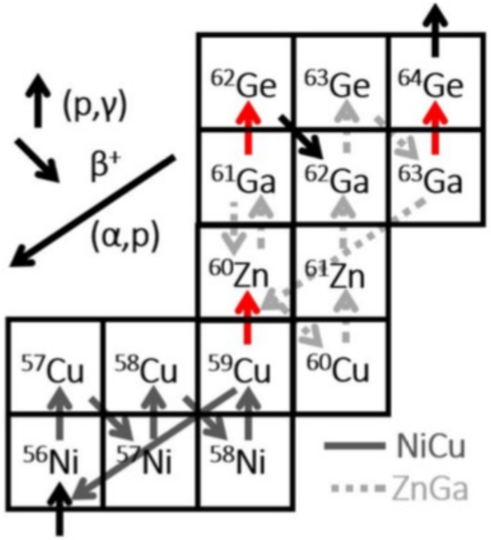
- **Case of ^{59}Cu(p,γ)^{60}Zn** studied through ^{59}Cu(^{3}He,d)^{60}Zn (the most sensitive reaction according to *Cyburt et al*)
  - ➞ determination of the proton spectroscopic factor : $S_p \Longrightarrow \Gamma_p$
  - ➞ orbital angular momentum: ℓ

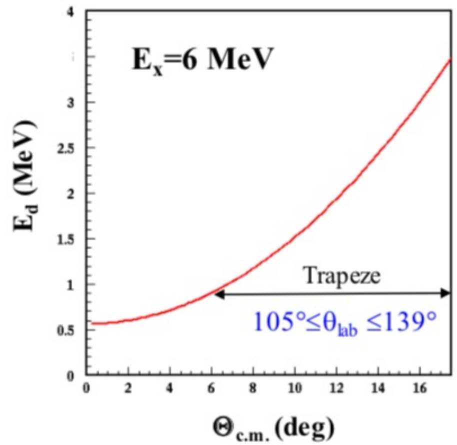


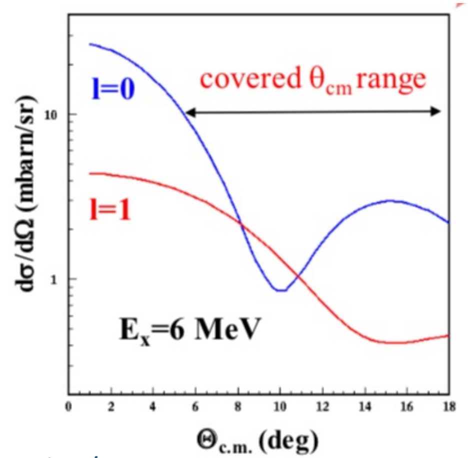
Er=782 – 1510 keV

Ex~5.9 -6.63 MeV

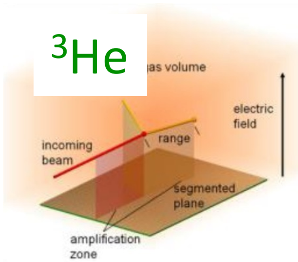
Astrophysical region of interest @ T=10^{9}K



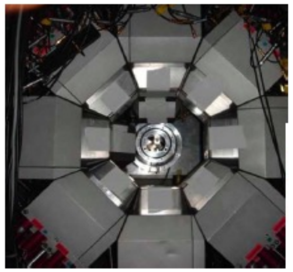




^{59}Cu beam



ACTAR



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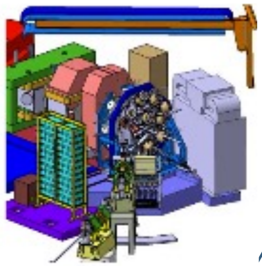


VAMOS

F. Hammache, N. de Séréville (IJCLab), G. de Angelis, F. Recchia (INFN, LNL)

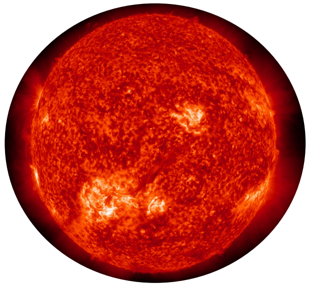
Nuclear astrophysics

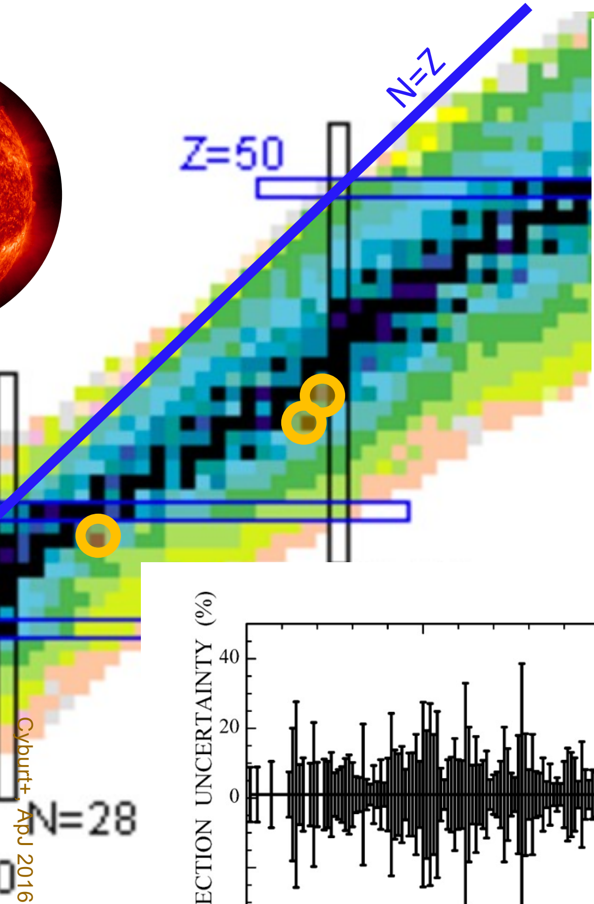
-- **Massive stars ($M>8M_{\odot}$): weak s-process**

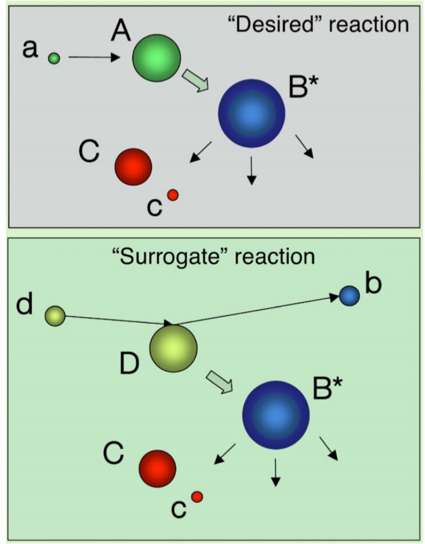
When direct measurement of (n,γ) cross-sections is not available

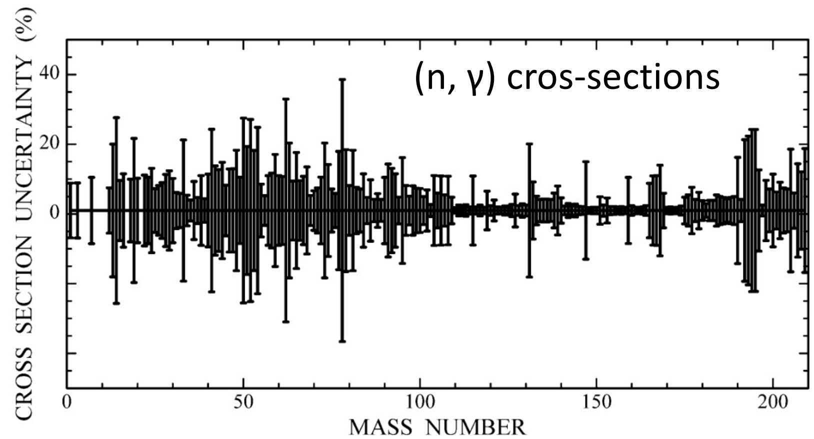
➟ surrogate method (error bar ~20-30%)

- s-branchings : ^{79}Se, **^{85}Kr**
- Stellar model test : ^{59}Fe

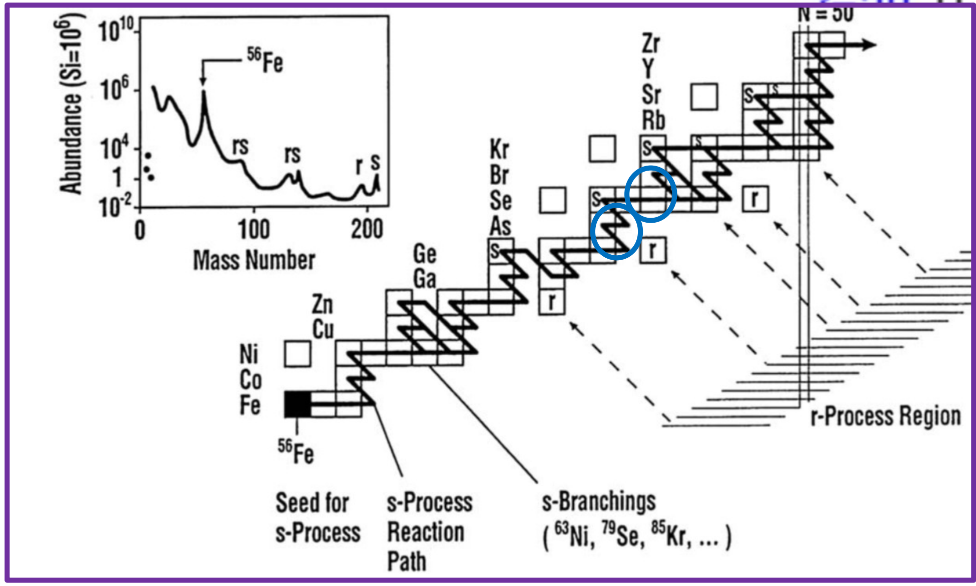








F. Käppeler, NPA (2006)



Production of ^{60}Fe in massive stars through ^{59}Fe(n,ɣ)via the surrogate reaction ^{59}Fe(d,p)

F. Hammache, N. de Séréville (IJCLab)

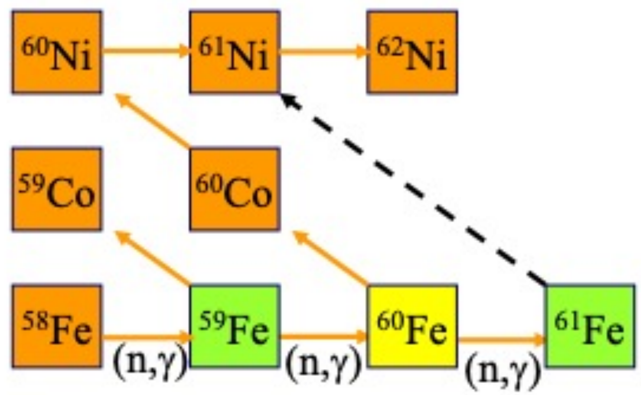
- **Case of ^{60}Fe(p,ɣ)^{60}Zn** studied through surrogate reaction ^{59}Fe(d,p)

  ➞ ^{60}Fe observed in the galaxy (RHESSI, INTEGRAL) through its ɣ-ray emission in: *(Smith04, Wang07, Binss16, Wallner16, Fimiani16)*

  . galactic cosmic rays (CRIS/ACE)

  . deep-ocean crusts & sediments

  . in lunar soils

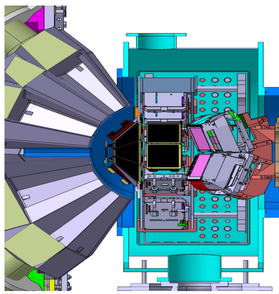


- Production of ^{60}Fe in massive stars through weak s-process and released in ISM by subsequent Core Collapse supernovae *(Limongi et al ApJ06)*

Two reactions of interest ^{59}Fe(n,ɣ)^{60}Fe & ^{60}Fe(n,ɣ)^{61}Fe (*Giron2017, GANIL*-LISE)

highly uncertain !

^{59}Fe,^{85}Kr,^{79}Se beams →



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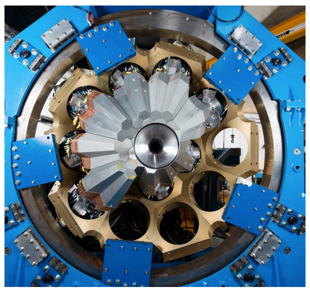


AGATA

VAMOS

Overview of the perspectives for nuclear physics at GANIL : pairing and clustering

D. Beaumel, V. Girard-Alcindor (IJCLab), B. Fernandez-Dominguez (U. of Santiago), G.F. Grinyer (Regina U.), S. Koyama (GANIL), D. Suzuki (RIKEN)

-- Clustering

-- Probing **neutron molecular orbitals** and **alpha clustering** through elastic/inelastic scattering **(d,d')** and **(^{4}He,^{4}He')**

^{48}Cr, ^{52}Fe, ^{56}Ni (d,^{6}Li)

-- New clustering

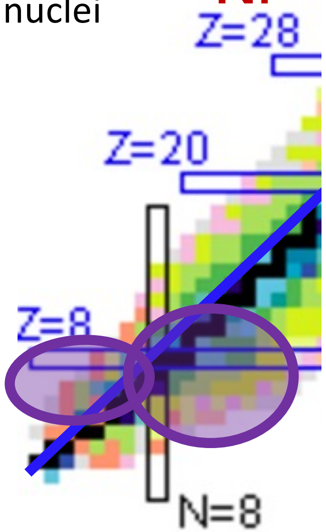
Search for ^{3}He and t clusters in the g.s. of **proton-rich and neutron-rich** nuclei (resp.)

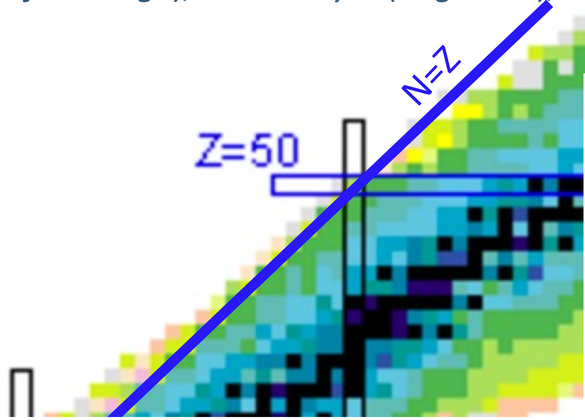
^{8,9,11}Li (^{4}He,p) ^{11,12,14}Be

^{10,12}Be (^{4}He,p) ^{13,15}B

^{10,12}Be (p,^{4}He) ^{7,9}Li

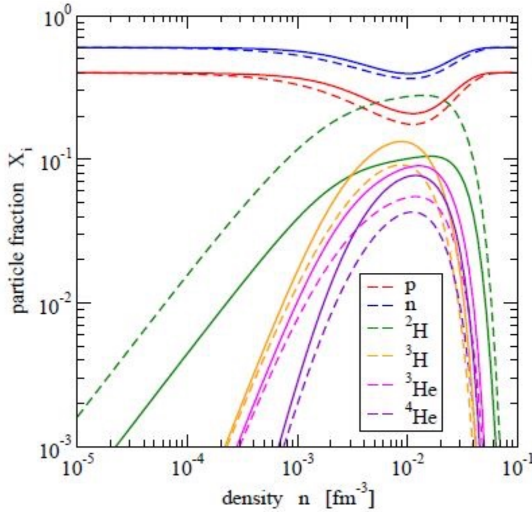
^{14,16}C (p,^{4}He) ^{11,13}B

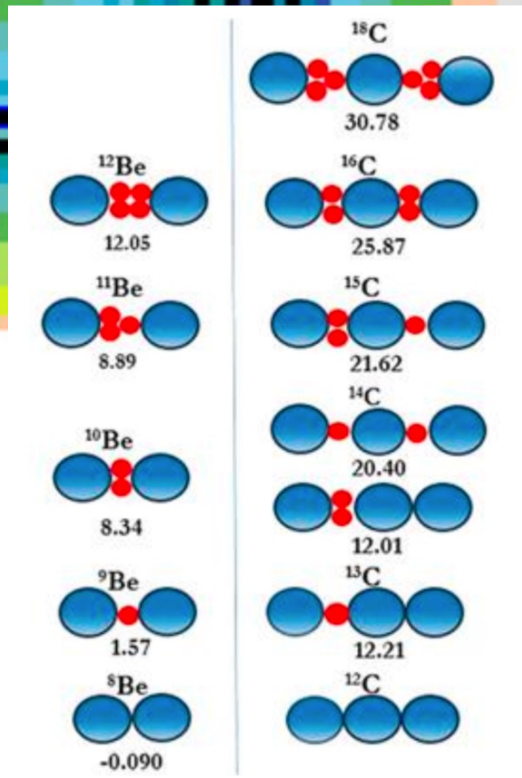




S.Typel, J.Phys.Conf.Ser.420,012078(2013)

Theory: All kind of clusters should be formed at low density

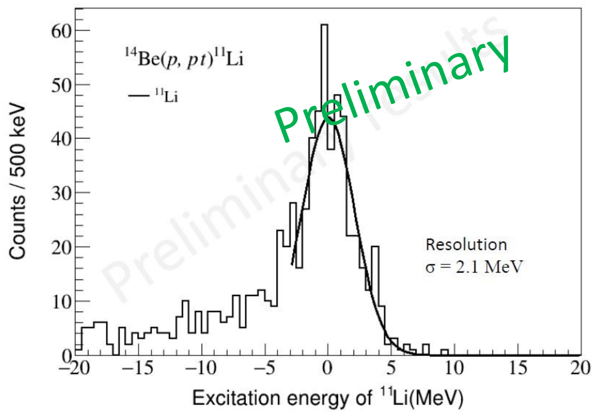




Probing new clustering in the light nuclei using transfer reactions

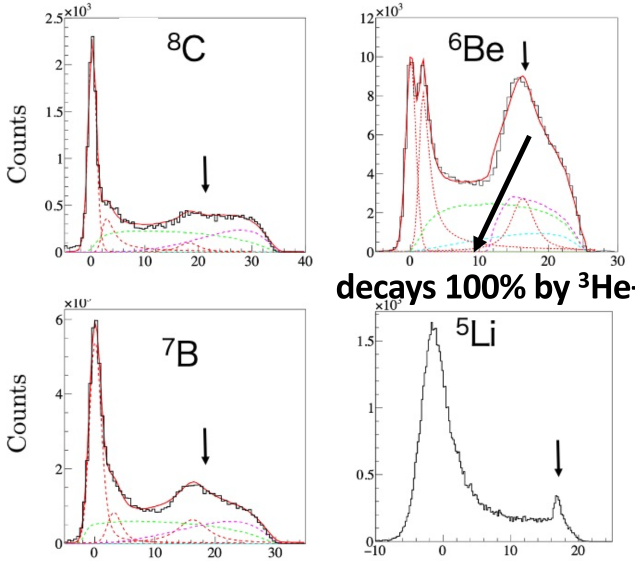
D. Beaumel, V. Girard-Alcindor (IJCLab), S. Koyama (GANIL) , D. Suzuki (RIKEN) B. Fernandez-Dominguez (U. of Santiago)

<u>At RIKEN</u>, triton formation at the surface of neutron-rich light nuclei via ^{14}Be(p,pt)^{11}Li



First evidence of triton clustering at the surface of n-rich (halo) nuclei

<u>At GANIL:</u> Systematic observation of resonance around 16 MeV in N=2 isotones



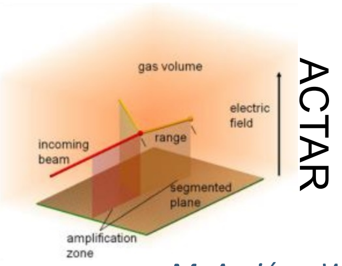
Evidence of ^{3}He clustering in p-rich nuclei ?

<u>Experiments @GANIL</u>

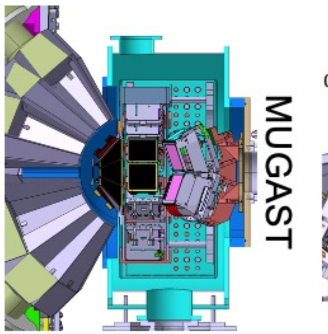
- Triton and ^{3}He at the surface of light n-rich nuclei through (p,^{4}He), (^{4}He,p) and (t,^{6}Li)
- **In 2024** : neutron-rich Be isotopes via (p,alpha)

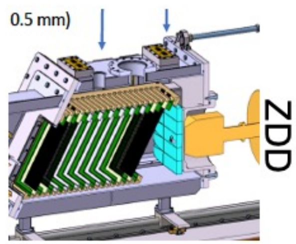
--> Further program in the proton-rich and neutron-rich light nuclei (in particular C)

⇨ Intense primary beam for LISE : ^{12}C, ^{18}O beams
⇨ ^{8,9,11}Li, ^{10,12}Be Spiral1 beams at 1-15 AMeV ~10^3-10^4 pps
⇨ ^{17}F Spiral1 beam
⇨ active targets / cryogenic targets / tritium / solid …



M. Assié --- Wo





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M. Assié (IJCLab), G. De France (GANIL), G.F. Grinyer (Regina U.)

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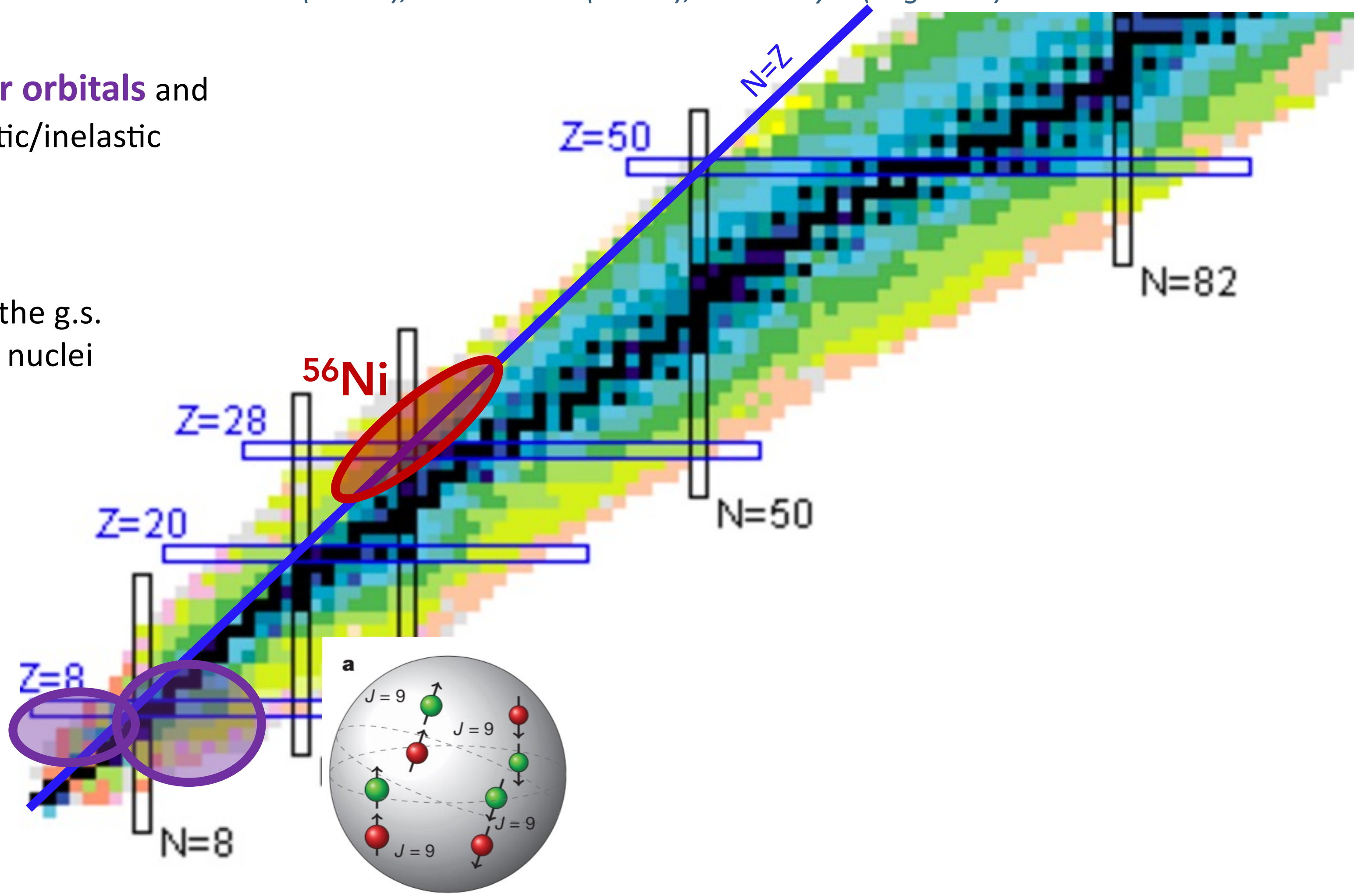
-- **Two-proton emission**

. Determination of the ^{17}F(p,α)^{14}O resonant transfer reaction rate and **2p decay** from **^{18}Ne** excited states with ACTAR



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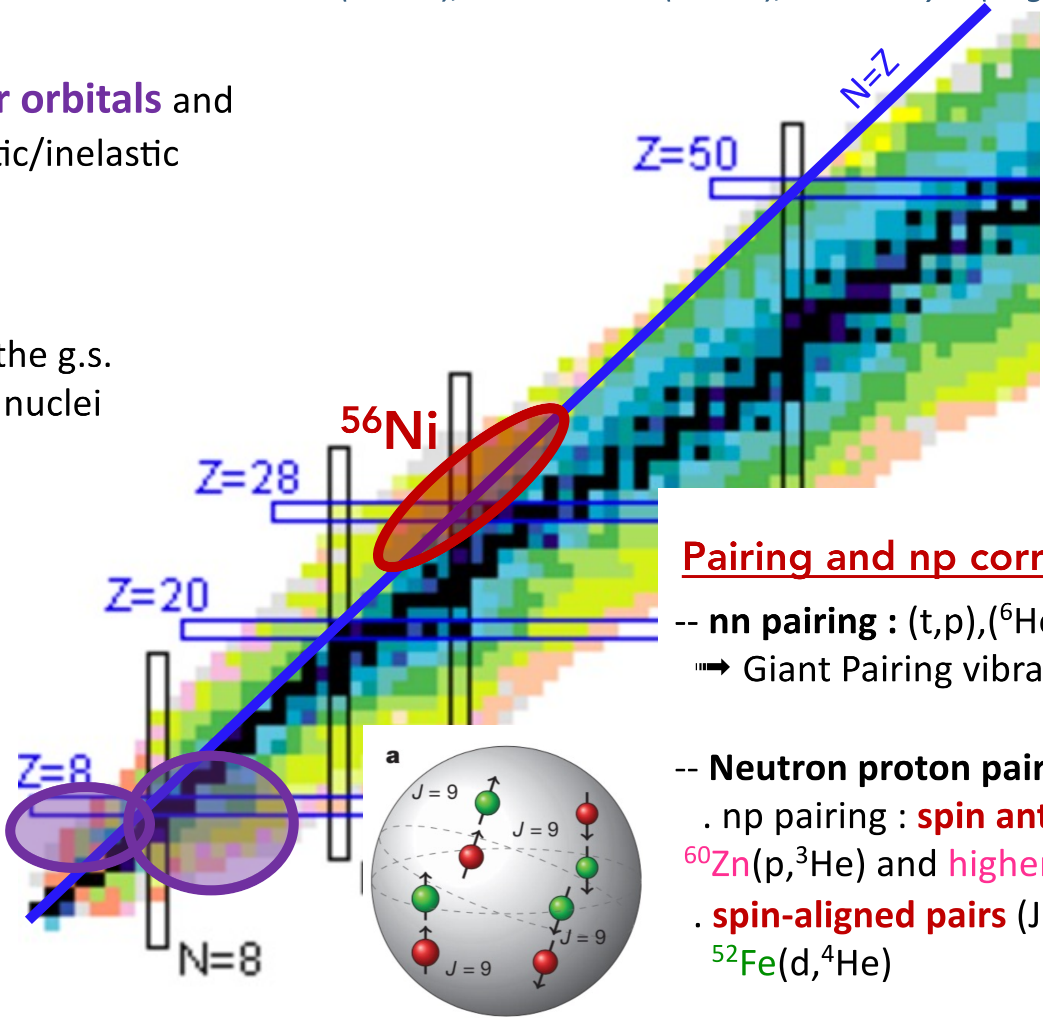
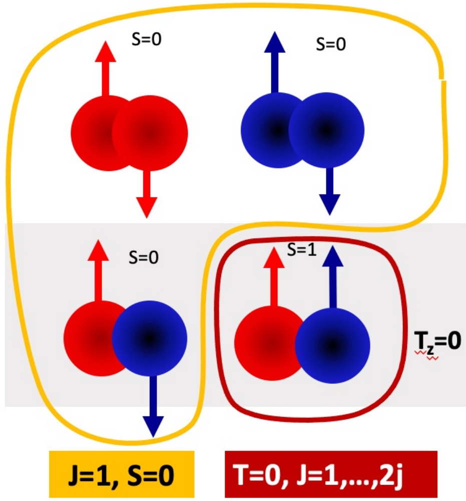




Pairing and np correlations

-- **nn pairing :** (t,p),(^{6}He,^{4}He) on n-rich nuclei
➡ Giant Pairing vibration in heavy nuclei ?

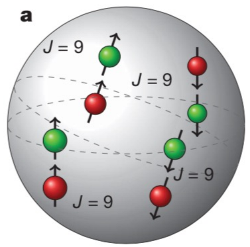
-- **Neutron proton pairs (in N=Z nuclei)**
. np pairing : **spin anti-aligned pairs** (Cooper pairs) ^{60}Zn(p,^{3}He) and higher mass N=Z nuclei
. **spin-aligned pairs** (J=J_{max}=7 in $f_{7/2}$ shell) :
^{52}Fe(d,^{4}He)

np pairs in the fp shell nuclei: anti-aligned and maximum aligned pairs

▶ **Search for T=0 spin-aligned pairs**

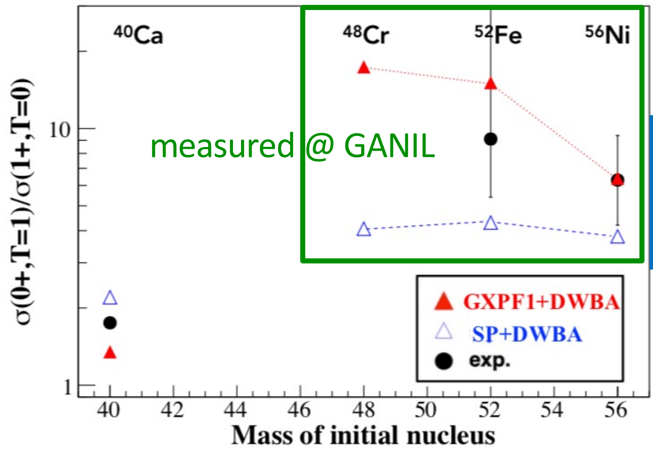
Spin-aligned pairs : slightly stronger attraction than anti-aligned
Spin-aligned scheme found in ^{92}Pd ($g_{9/2}$ shell)

B. Cederwall et al, Nature (2010)



➟ Spin-aligned scheme in *f*-shell through transfer (d,^{4}He**γ**) or (^{3}He,p**γ**)

Towards *p*- and *g*-shells



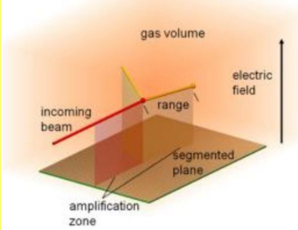
▶ **Search for T=0 pairing (spin anti-aligned pairs i.e. Cooper-like pairs)**

For the moment, T=0 pairing is elusive in the experimental data from the *sd*- and *f*-shell. In the *f*-shell, the spin-orbit hinders the T=0 channel, what about the *p*- and *g*-shells ?

⇨ ^{52}Fe (LISE) from ^{58}Ni primary beam OK !

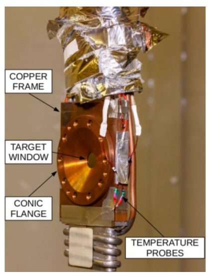
⇨ ^{60}Zn Spiral1 beam at 10^5 pps
+ any N=Z nucleus of heavier mass (Ge, Ga…)

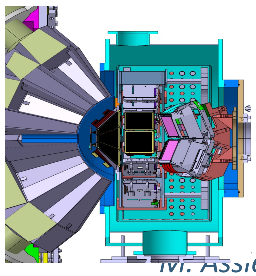
ACTAR-^{3}He



ACTAR

^{3}He cryogenic target (ATRACT)





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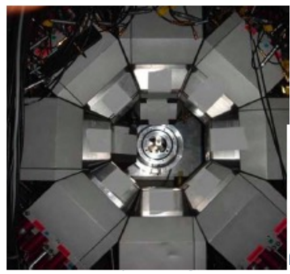
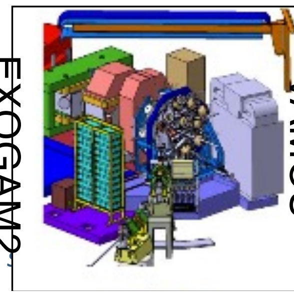


EXOGAM2



VAMOS

Overview of the perspectives for nuclear physics at GANIL : shape coexistence

E. Clément (GANIL), J-J Valiente-Dobon (INFN-LNL)

Deformation & shape coexistence around N~Z

-- **Mixing of shape coexistence**

➟ via **two-nucleon transfer:**

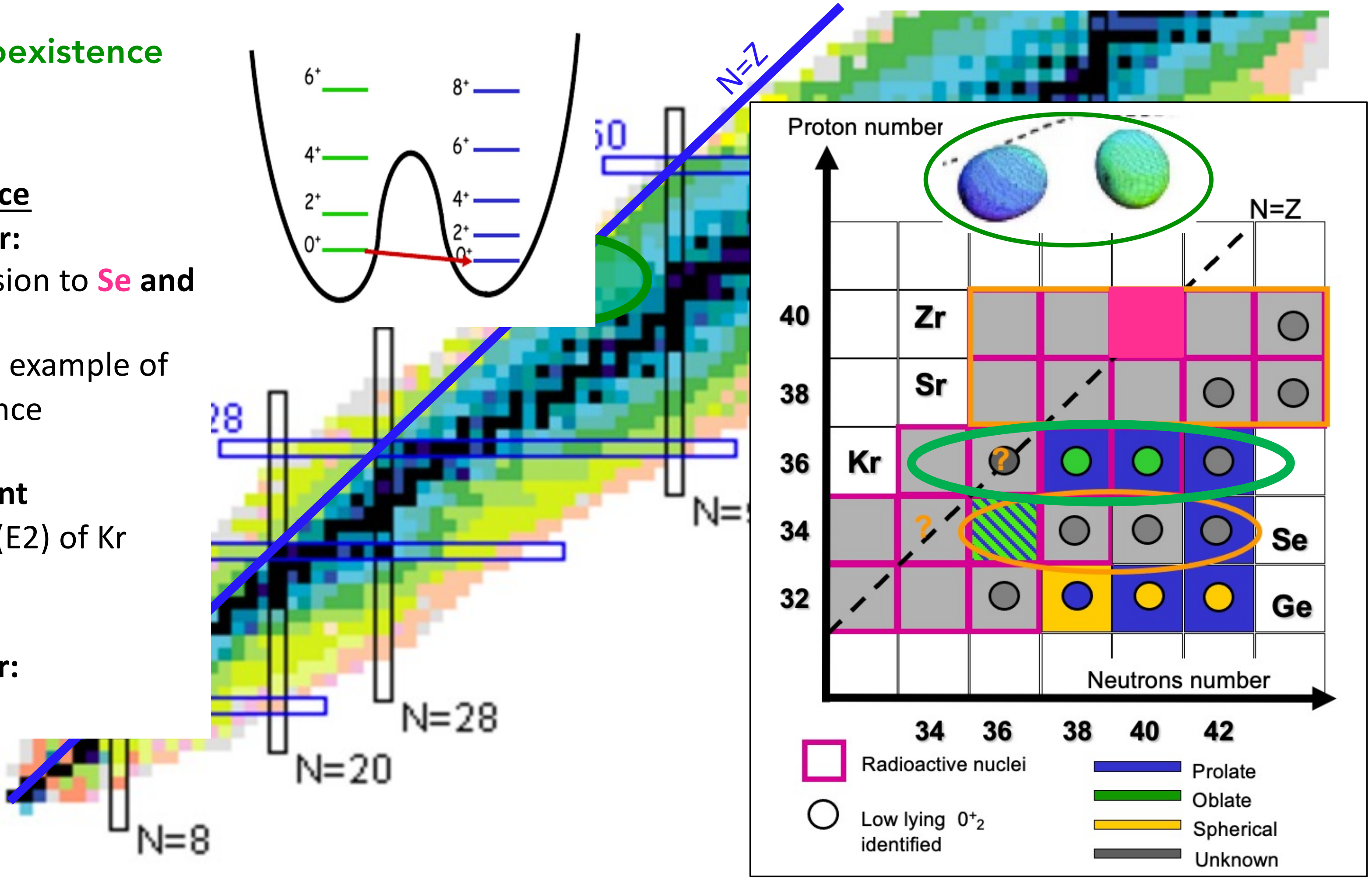
- **(t,p)** on ^{74}Kr (and extension to Se **and** Ge isotopes ?)
- ^{78}**Sr(**^{3}**He,n)**^{80}**Sr** a unique example of multiple shape coexistence

➟ via **lifetime measurement**

^{73,75,77}Br(d,n) to measure B(E2) of Kr isotopes

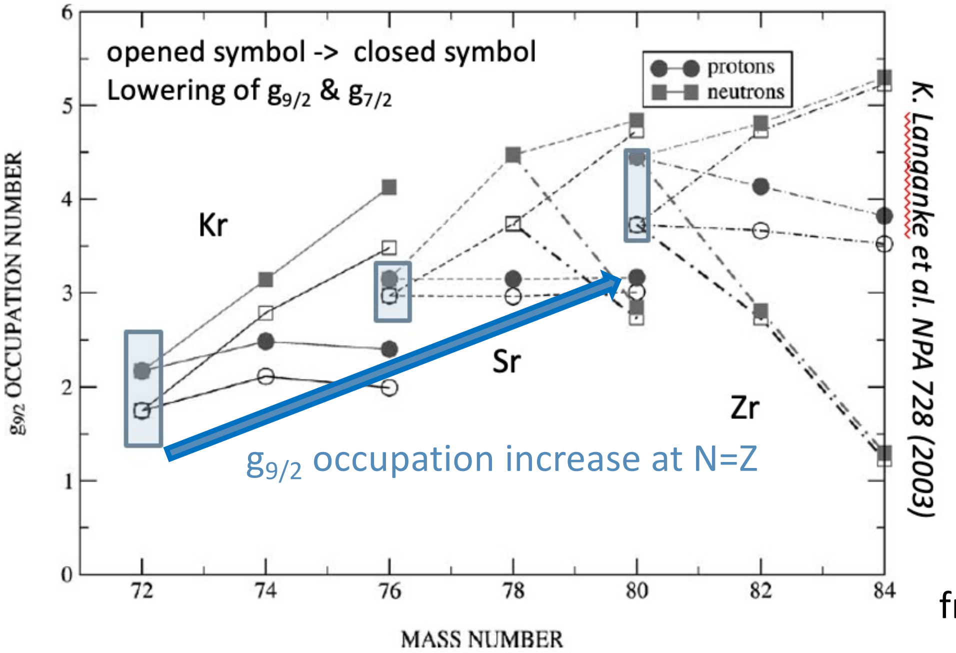
➟ via **one-nucleon transfer:**

(d,p) on Kr isotopes

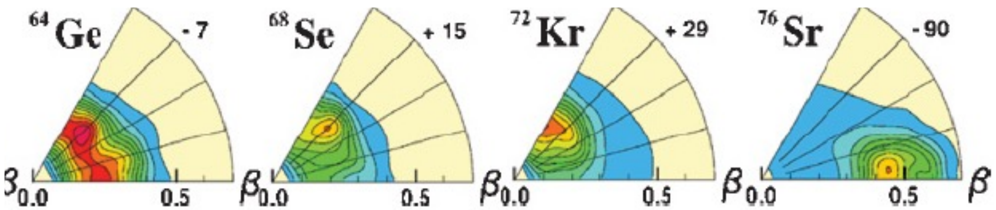


Detailed spectrocopy along Kr chain to reveal shape coexistence mechanism

E. Clément (GANIL)

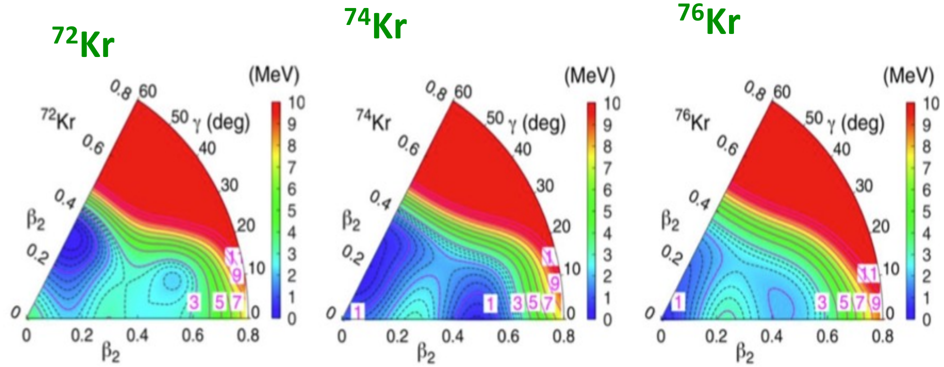


more and more axial (prolate or oblate)deformation

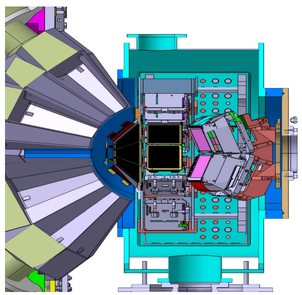


-- **Measurement of single particle levels via ^{73,74,75,76,77}Kr(d,p)** to highlight the **microscopic origin of shape coexistence** (already performed at TRIUMF for Sr isotopes)

➟ systematic extension to **Se and Zr**



from theory: g.s. oblate $\nu(g_{9/2})^2$ | g.s. oblate/prolate $\nu(g_{9/2})^3$ | g.s. prolate $\nu(g_{9/2})^4$



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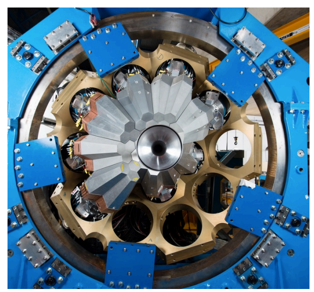

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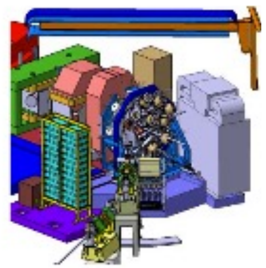


VAMOS

Overview of the perspectives for nuclear physics at GANIL: Shell evolution and 3N forces

O. Sorlin, E. Clément (GANIL), I. Zanon (INFN-LNL), B. Fernandez-Dominguez (U. Santiago)

Shell model & nuclear structure

-- **3N forces**

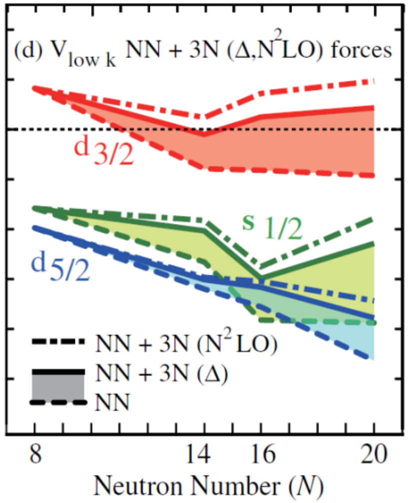
. ^{24}O is the last bound isotopes : striking anomaly !

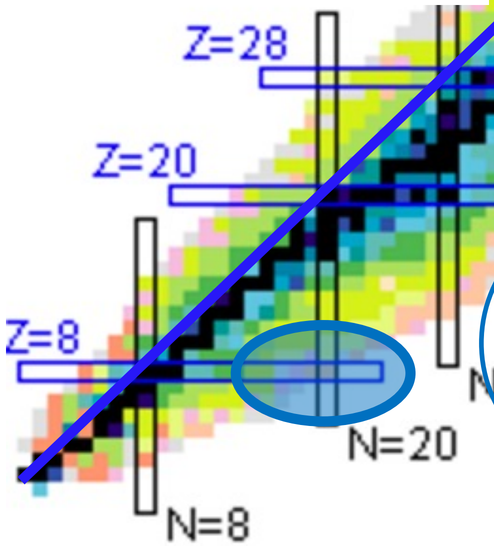
→ need for **3N forces** to understand it

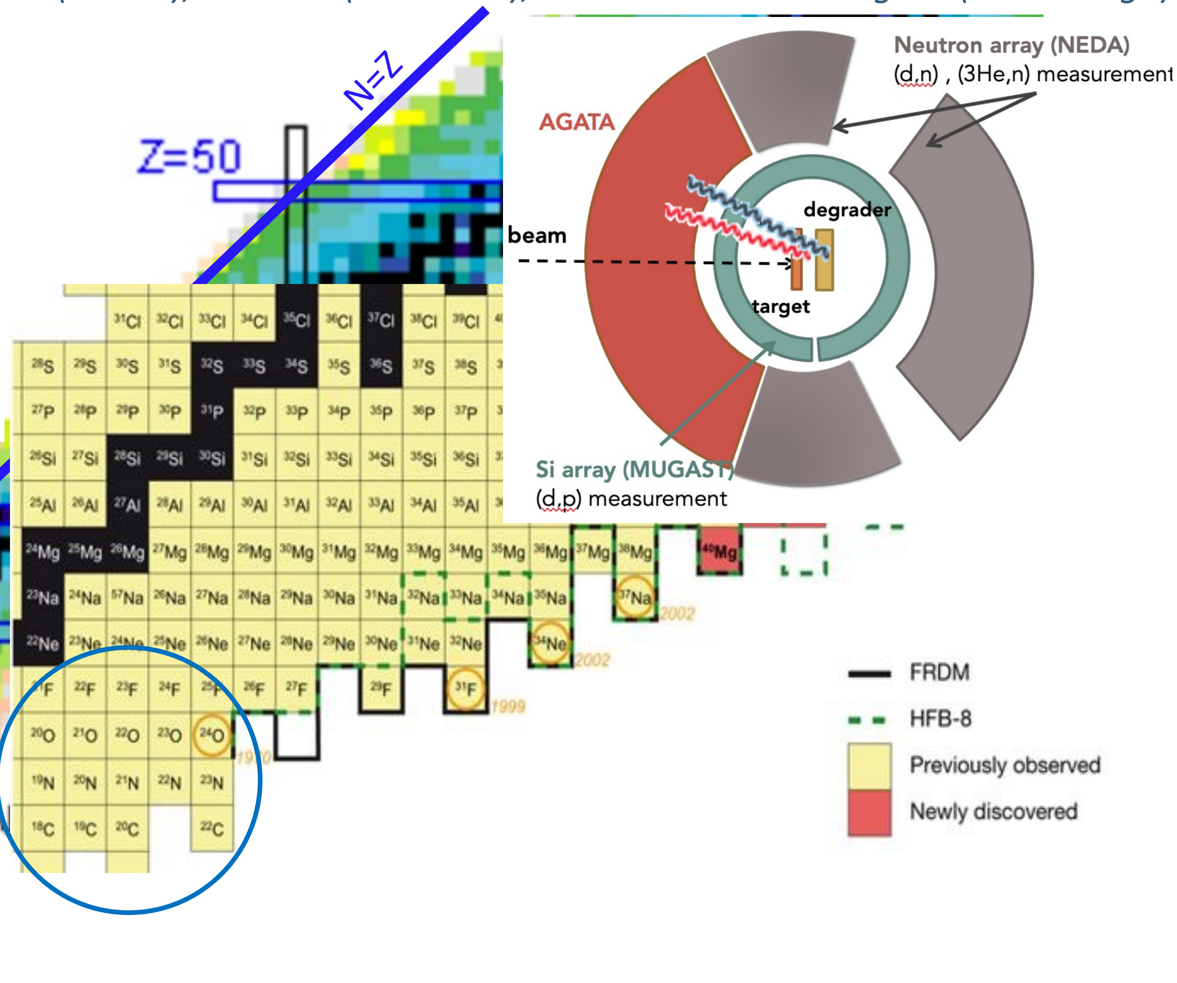
--> Constraining ab-initio models towards the dripline:

^{19}O(d,pɣ) measured at GANIL (under publication)

^{23}Ne(d,pɣ) to be measured !







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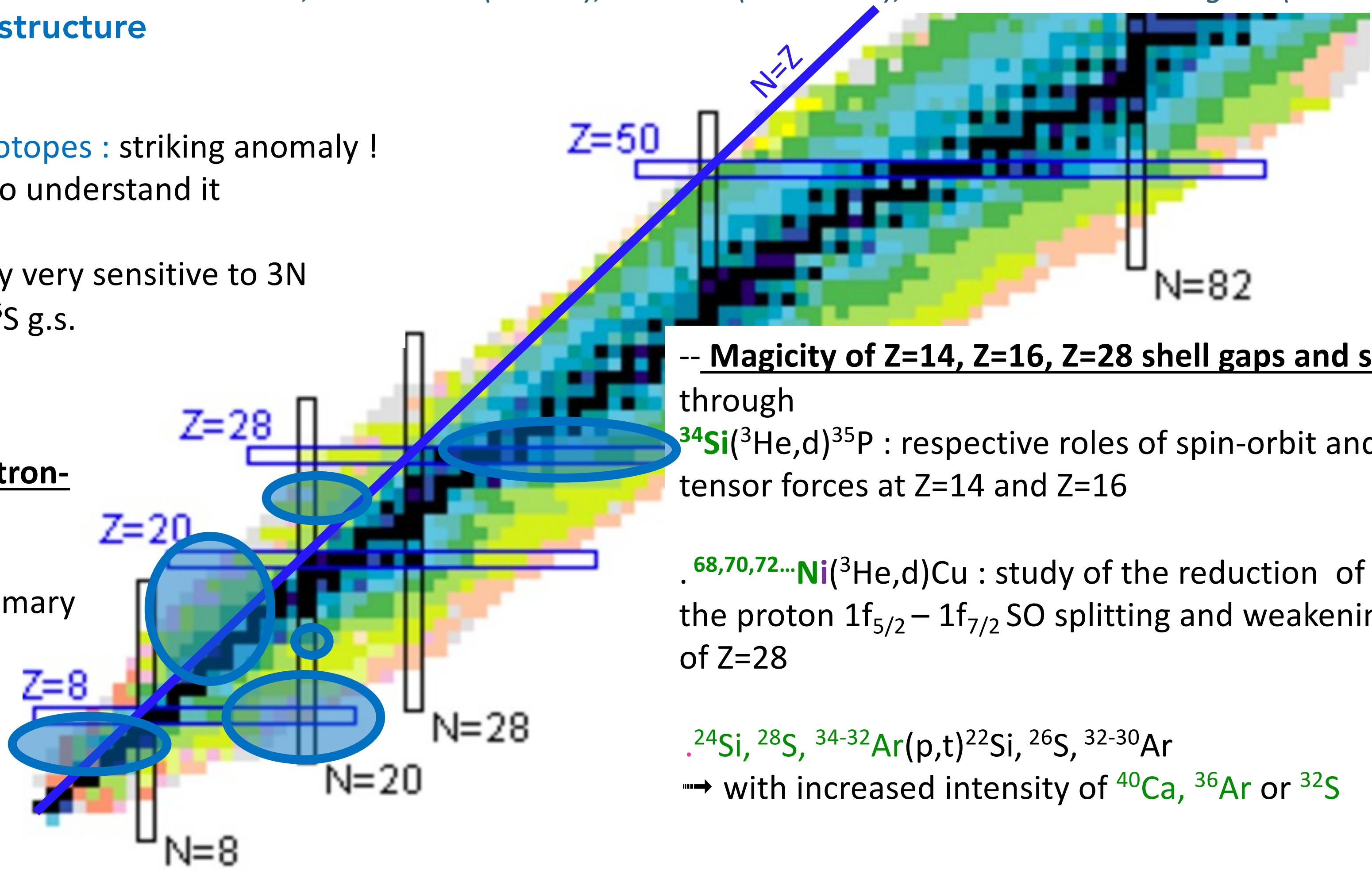
Shell model & nuclear structure

-- **3N forces**

. ^{24}O is the last bound isotopes : striking anomaly !
➞ need for **3N forces** to understand it

. Above A>22, g.s. energy very sensitive to 3N forces ➞ determine ^{22}Si, ^{26}S g.s.

-- **Shell evolution in the neutron-deficient nuclei :**
$^{10\text{-}11}$C, ^{50}Mn, ^{46}Cr, ^{43}Ti
➞ with ^{16}O, ^{50}Cr and ^{46}Ti primary beams



-- **Magicity of Z=14, Z=16, Z=28 shell gaps and size** through
^{34}Si(^{3}He,d)^{35}P : respective roles of spin-orbit and tensor forces at Z=14 and Z=16

. **$^{68,70,72...}$Ni**(^{3}He,d)Cu : study of the reduction of the proton $1f_{5/2} - 1f_{7/2}$ SO splitting and weakening of Z=28

. ^{24}Si, ^{28}S, $^{34\text{-}32}$Ar(p,t)^{22}Si, ^{26}S, $^{32\text{-}30}$Ar
➞ with increased intensity of ^{40}Ca, ^{36}Ar or ^{32}S

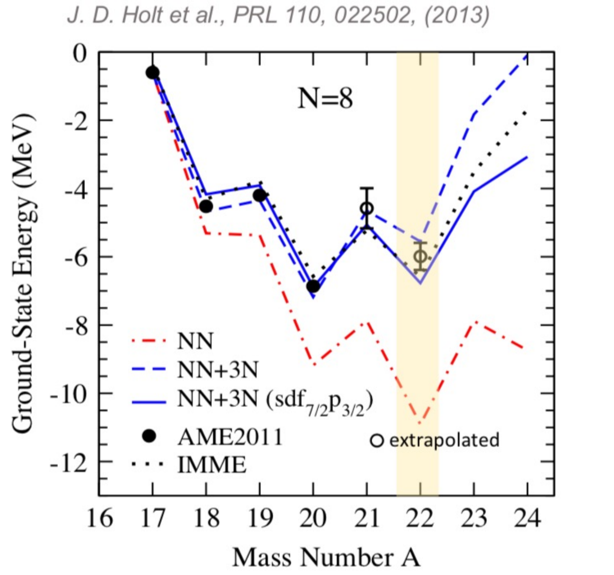
.

Probing proton shell gaps Z=14 and 16

B. Fernandez-Dominguez (U. Santiago)

-- **Spectroscopy of ^{22}Si and ^{26}Si via ^{24}Si, ^{28}S(p,t)^{22}Si, ^{26}S:** proposed at OEDO-RIKEN in 2018 - not run - at GANIL ?

ground states

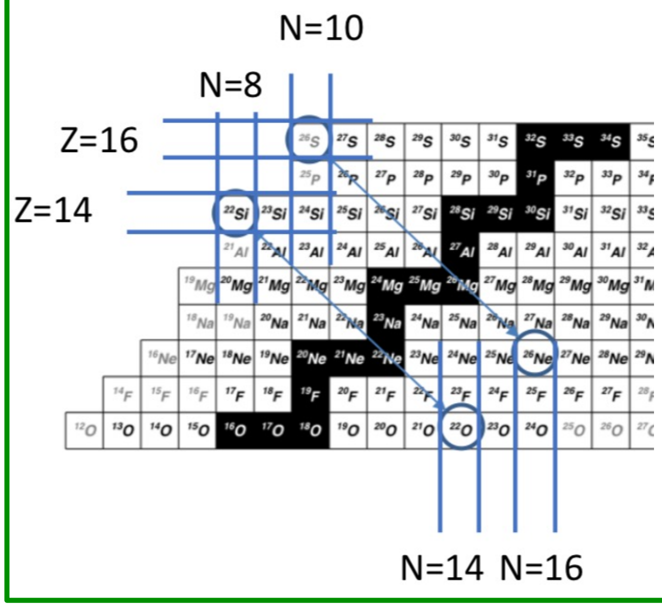


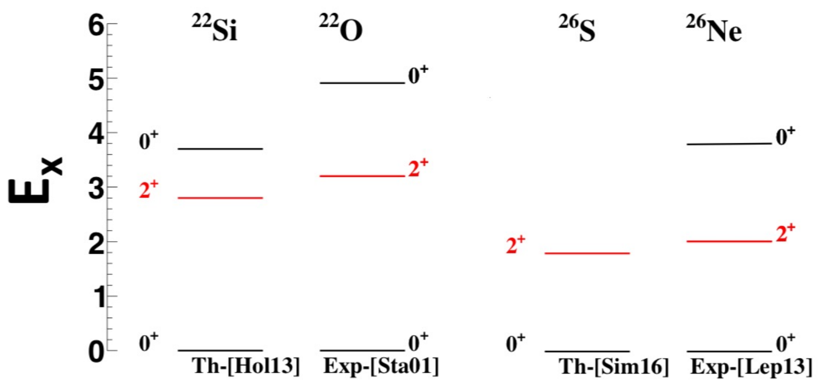
. NN+3N key repulsive contributions
. For A>22, the g.s. energy is very sensitive to NN+3N
. Extended charge radius : 2p-halo ?

excited states

Isospin symmetry: new shell closure at Z=14 and 16 ?

No experimental data available !



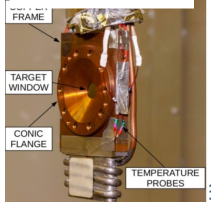


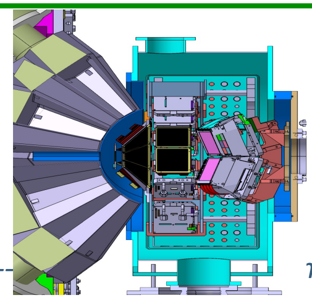
Study of magicity at Z=14,16 from 2^+ or 0^+_2

^{40}Ca, ^{36}Ar or ^{32}S

^{24}Si, ^{28}S beams at LISE

LH target





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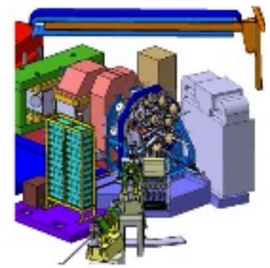


VAMOS

Summary of the perspectives for nuclear physics at GANIL

Another important ingredient:
--> structure & reaction theory

Nuclear astrophysics

- ^{55}Co(*d,p*) and ^{57}Ni(*d,p*)
- ^{59}Cu ^{56}Ni, ^{57}Cu (^{3}He,dγ)

} Type I X-ray bursts

- ^{59}Fe, ^{85}Kr, ^{79}Se (d,p) <-- surrogate } massive stars

(New) clustering

- ^{8,9,11}Li (^{4}He,p) & (^{4}He,^{4}He')
- ^{10,12}Be (^{4}He,p) & (^{4}He,^{4}He')
- ^{14,16}C (p,^{4}He) ^{11,13}B
- ^{9,10}C (t,^{6}Li)
- ^{48}Cr, ^{52}Fe, ^{56}Ni (d,^{6}Li)

} t,^{3}He, ^{4}He clusters

- ^{17}F(p,α)^{14}O } 2p-emitters

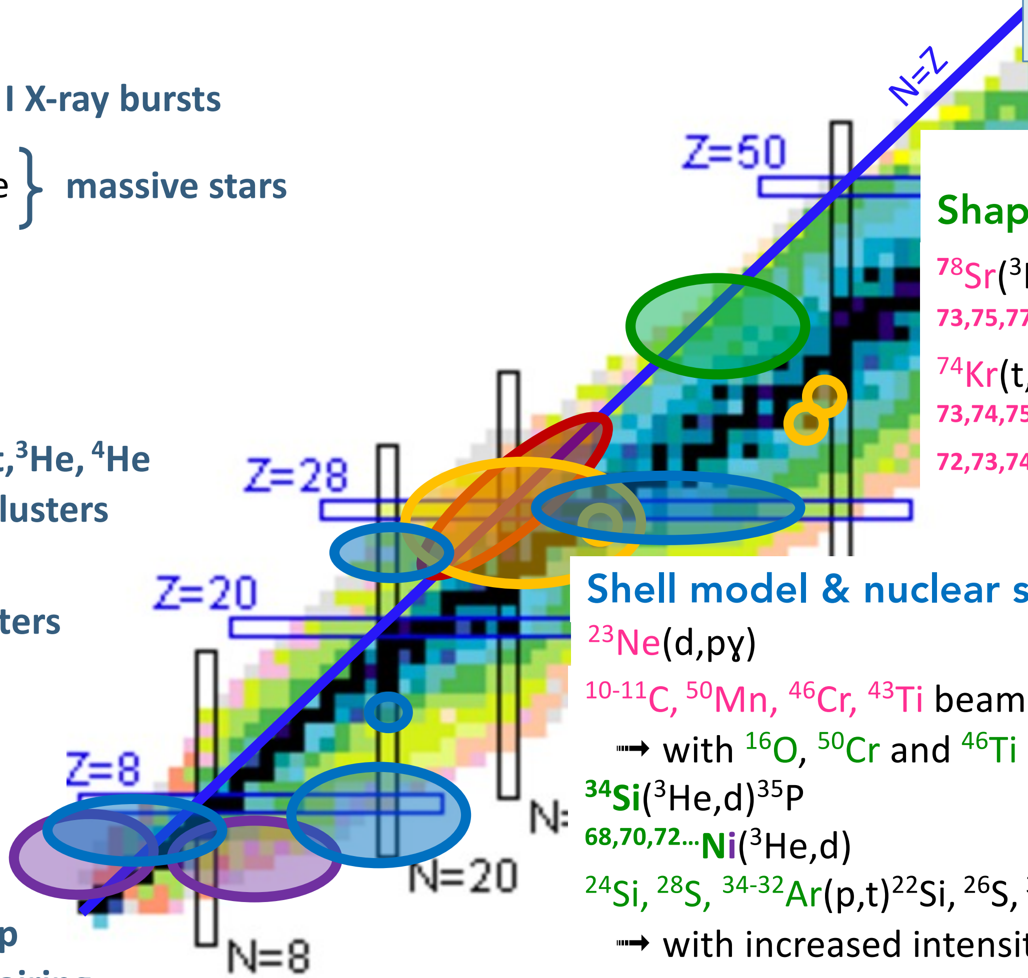
Pairing and np correlations

- ^{6}He(^{208}Pb, ^{210}Pb)^{4}He
- ^{6}He(^{116}Sn, ^{118}Sn)^{4}He

} GPV

- ^{52}Fe(d,^{4}Heγ)
- ^{60}Zn (^{3}He,pγ)
- and N=Z beams above Zn

} np pairing



Deformation & Shape coexistence at N~Z

- ^{78}Sr(^{3}He,nγ)^{80}Sr
- ^{73,75,77}**Br**(d,nγ)
- ^{74}Kr(t,p)

} shape coexistence

- ^{73,74,75,76,77}Kr(d,pγ)
- ^{72,73,74,75,76}Sr(d,pγ)

} underlying nuclear strut.

Shell model & nuclear structure

- ^{23}Ne(d,pγ) } 3N forces
- $^{10\text{-}11}$C, ^{50}Mn, ^{46}Cr, ^{43}Ti beams
  - ➟ with ^{16}O, ^{50}Cr and ^{46}Ti primary beams
- ^{34}**Si**(^{3}He,d)^{35}P
- $^{68,70,72...}$**Ni**(^{3}He,d)
- ^{24}Si, ^{28}S, $^{34\text{-}32}$Ar(p,t)^{22}Si, ^{26}S, $^{32\text{-}30}$Ar
  - ➟ with increased intensity of ^{40}Ca, ^{36}Ar or ^{32}S

} shell evolution