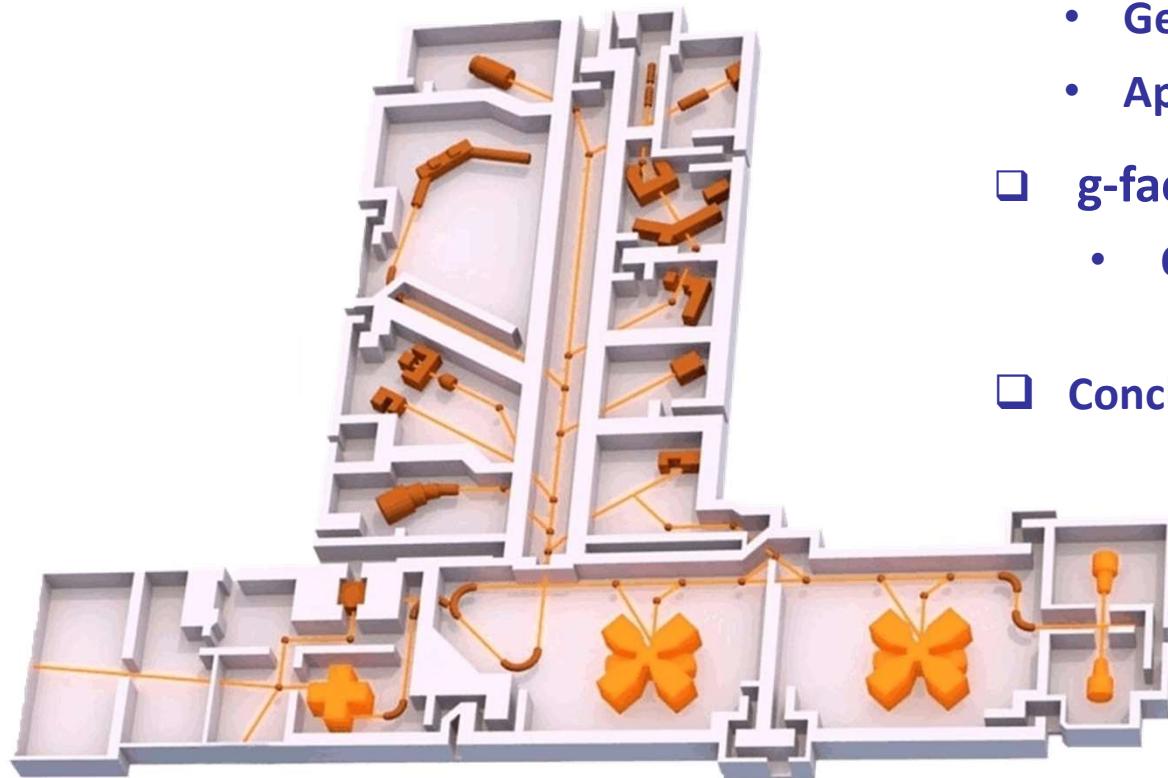
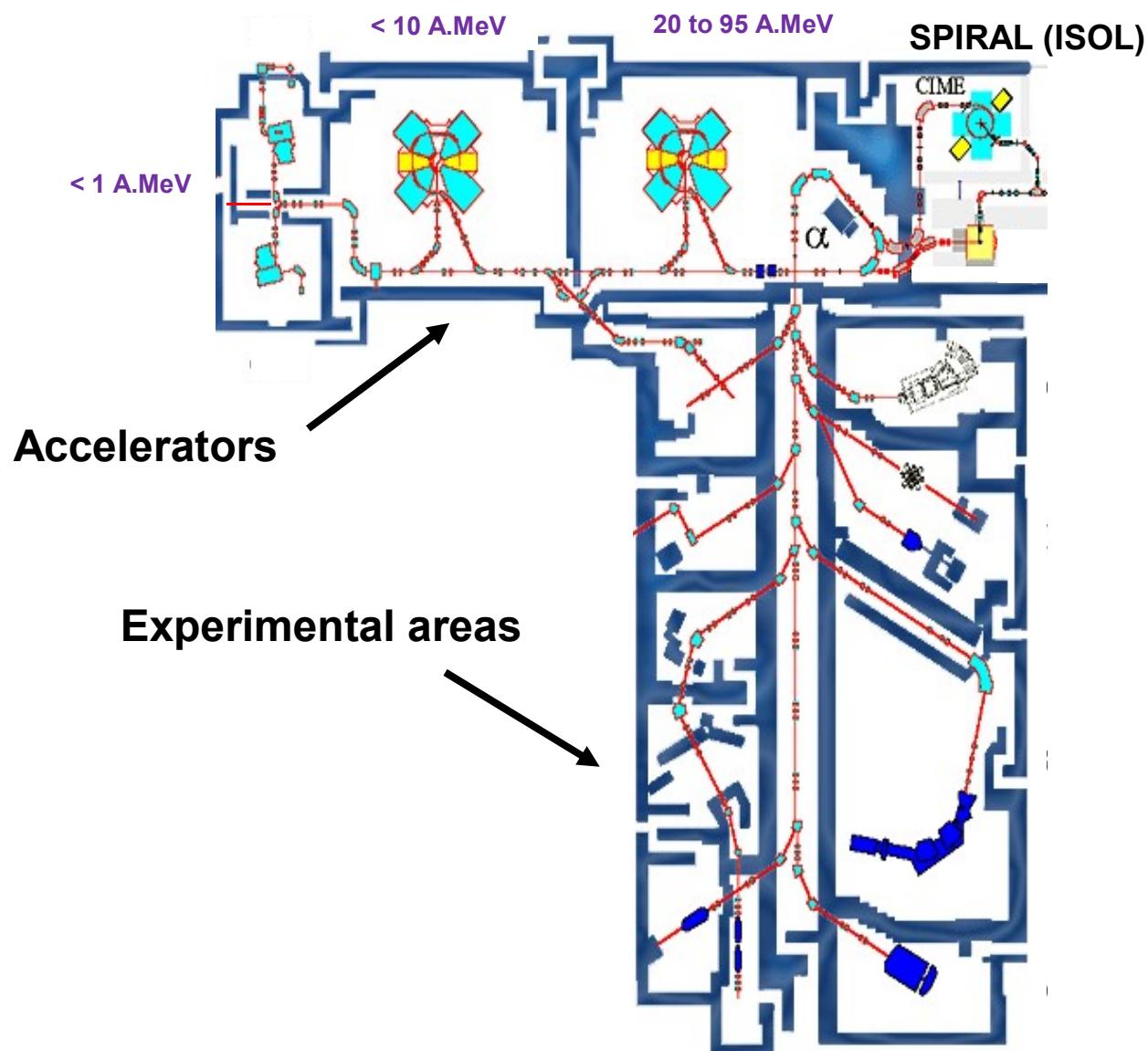


J.-C. Thomas, for the LISE collaboration

<http://pro.ganil-spiral2.eu/laboratory/experimental-areas/lise>

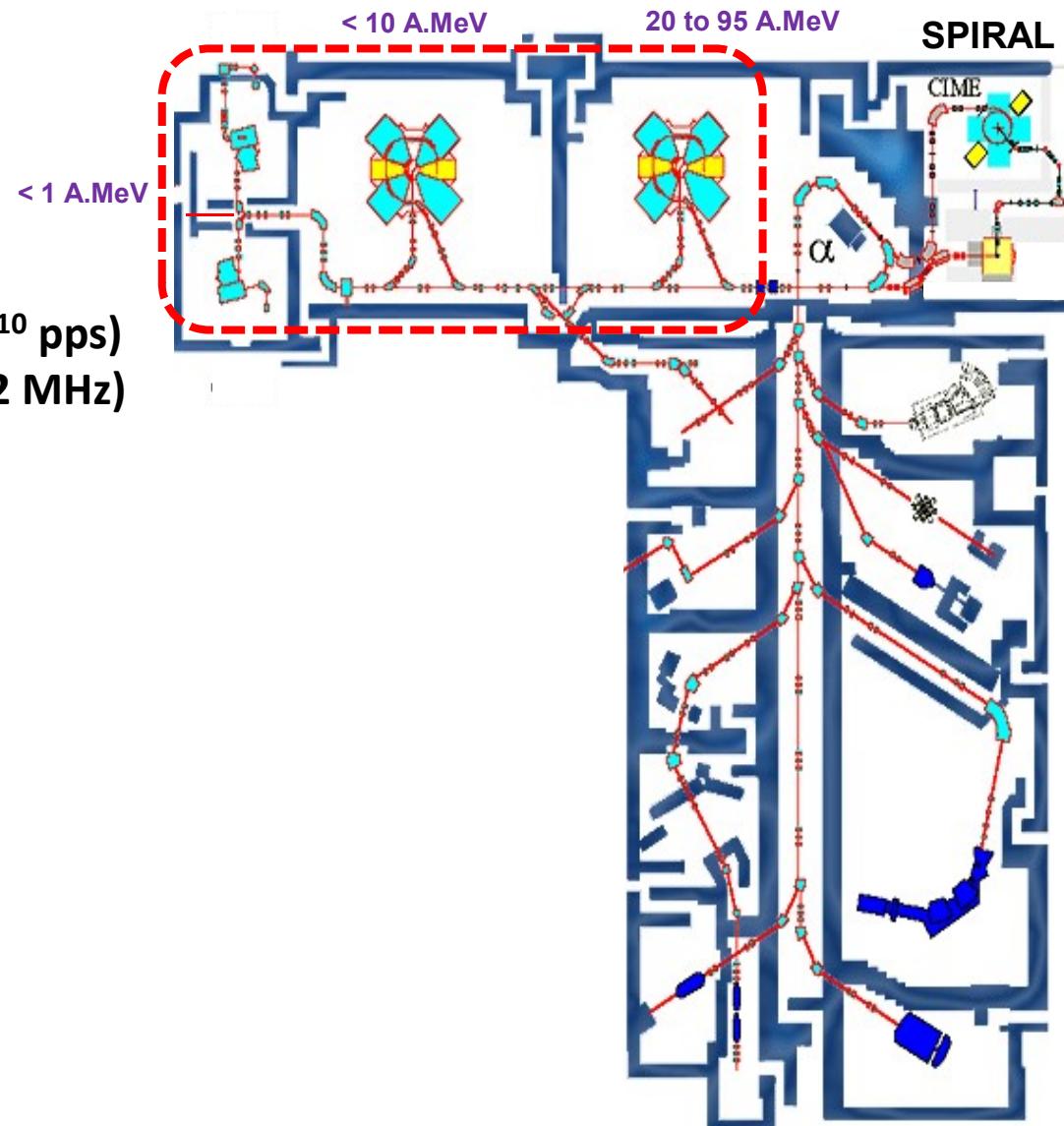


- The LISE spectrometer at GANIL
 - Generalities
 - Application to g-factor measurements
- g-factor measurements at LISE
 - Overview 1999-2016
 - TDPAD, HVTF, NMR
- Conclusion



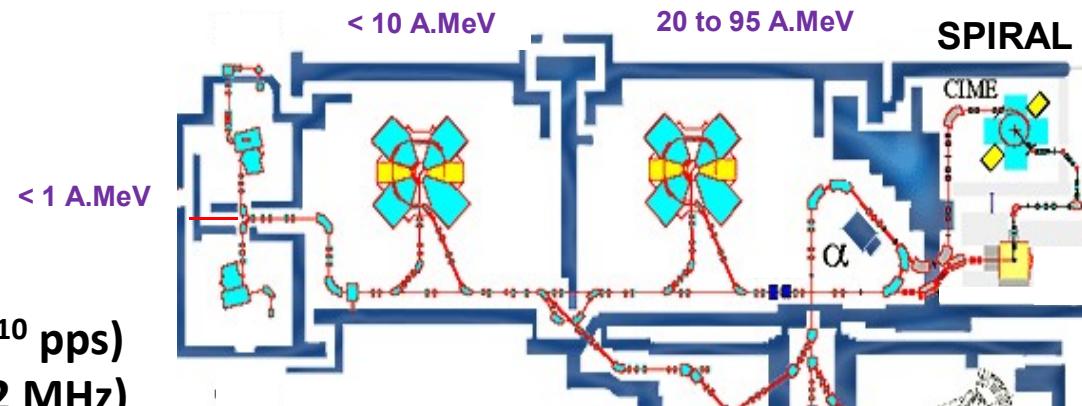
□ Stable heavy ion beams

- 2 ion sources: $^{12}\text{C}^{4+}$ to $^{238}\text{U}^{34+}$
- Fast chopper (beam on/off)
- 3 coupled cyclotrons
 -> up to 63 A.MeV for ^{112}Sn (3.10^{10} pps)
 -> ~2 ns bunches every 80 ns (~12 MHz)

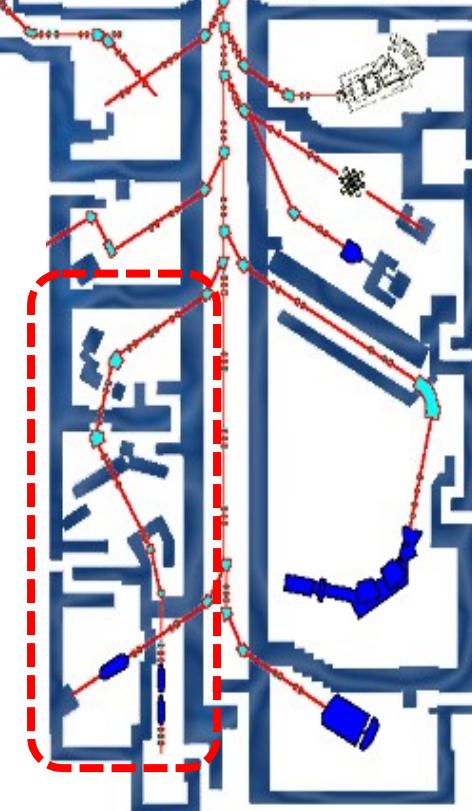
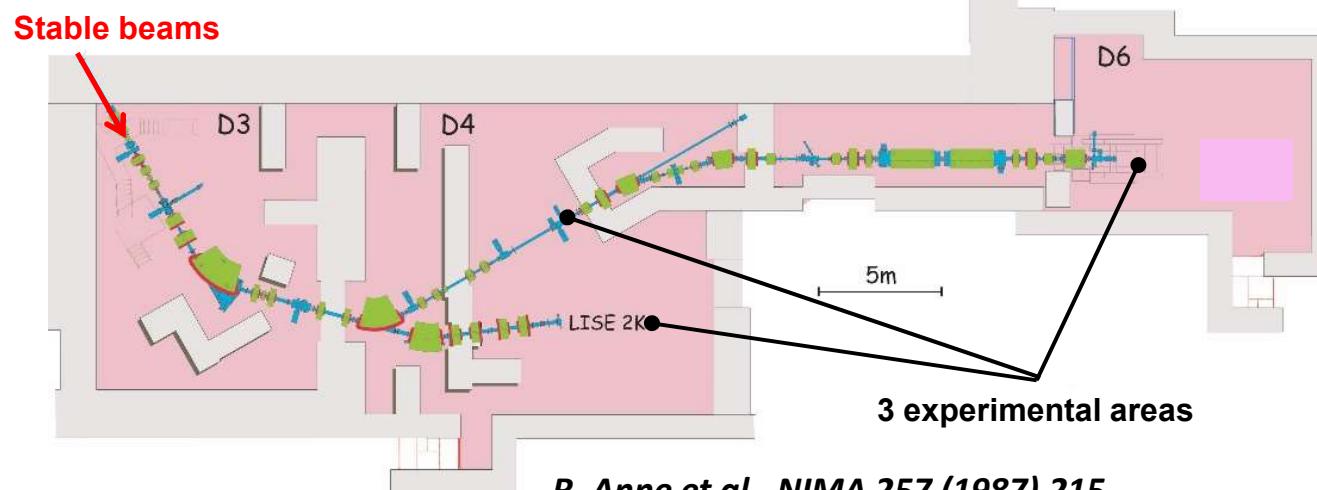


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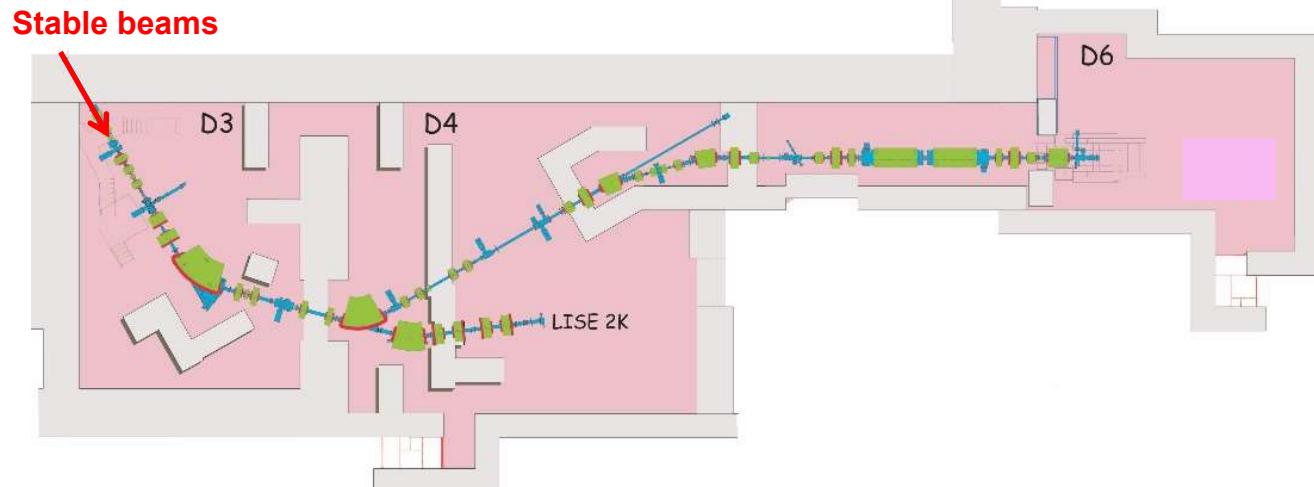
□ RIB production by in-flight fragmentation: the LISE spectrometer (1985)



□ Production of radioactive beams: In-flight fragmentation

- (Representative) stable beams

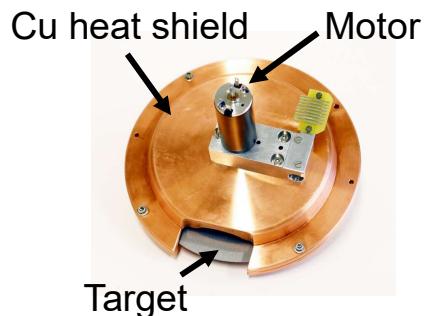
Ion	E (A.MeV)	I (pps)
$^{18}\text{O}^{8+}$	75	10^{13}
$^{36}\text{S}^{16+}$	78	$4 \cdot 10^{12}$
$^{48}\text{Ca}^{19+}$	60	$1.5 \cdot 10^{12}$
$^{58}\text{Ni}^{26+}$	75	10^{12}
$^{64}\text{Ni}^{26+}$	65	$9 \cdot 10^{11}$
$^{70}\text{Zn}^{28+}$	63	$4 \cdot 10^{11}$
$^{76}\text{Ge}^{30+}$	61	$7 \cdot 10^{11}$
$^{86}\text{Kr}^{34+}$	60	$6 \cdot 10^{11}$



<https://u.ganil-spiral2.eu/chartbeams/>

□ Production target

- (High power) target station: CLIM
 - up to 800 W of beam power loss inside the target
 - Ni, Ta and Be targets, up to $\sim 450 \text{ mg/cm}^2$
 - 10 mg/cm^2 C stripper

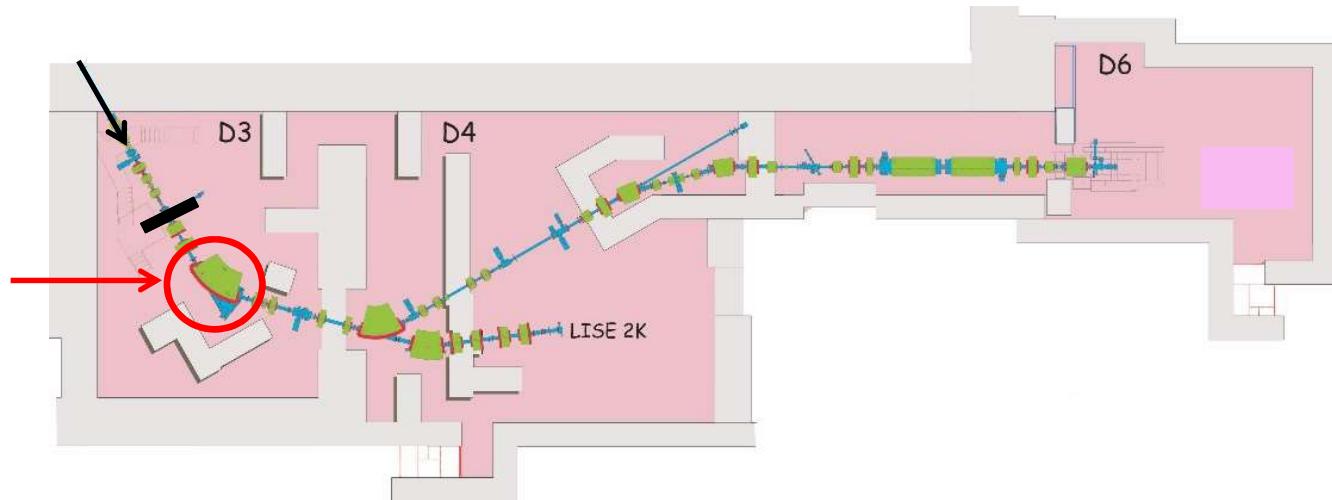
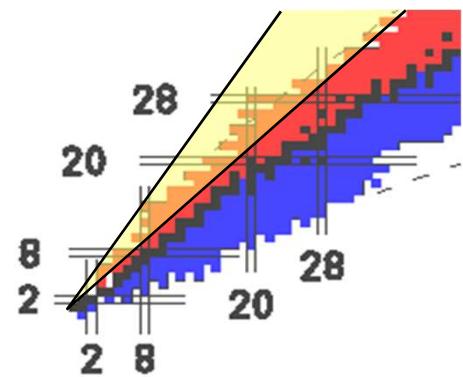


- Optimal target for g-factor measurements
-> Be 100 to 200 mg/cm^2
 - Higher production cross sections
 - Lower energy straggling
 - Lower e- pick-up probability

□ Secondary beam selection

- Fragment selection

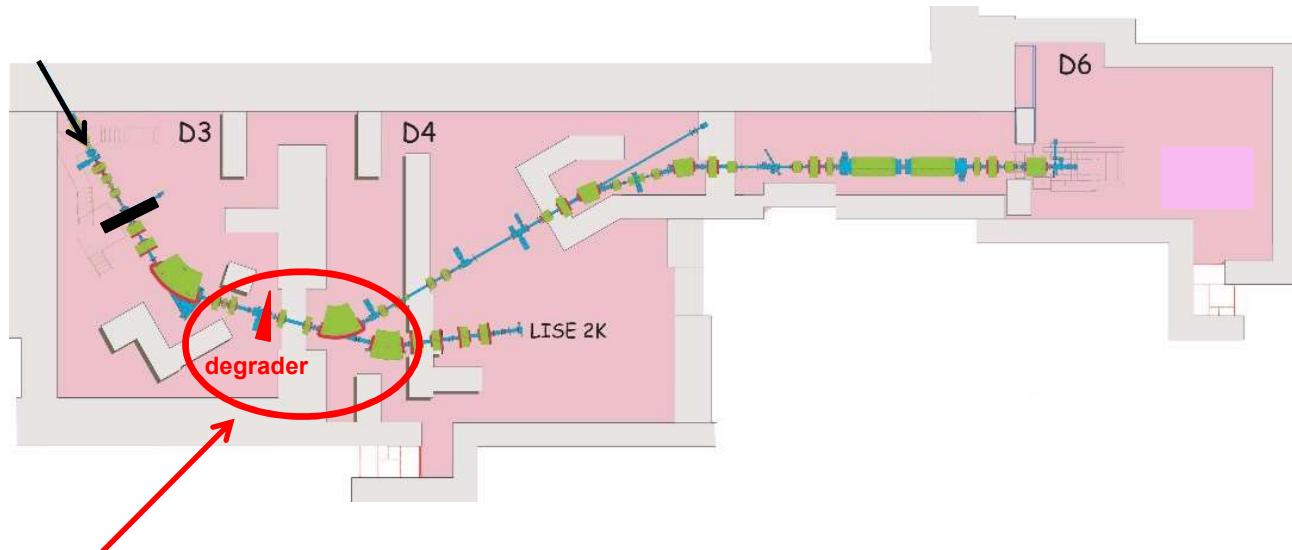
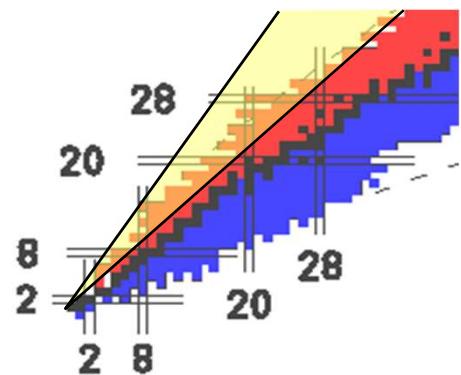
- 1st dipole: $B_p \sim A v / Z$



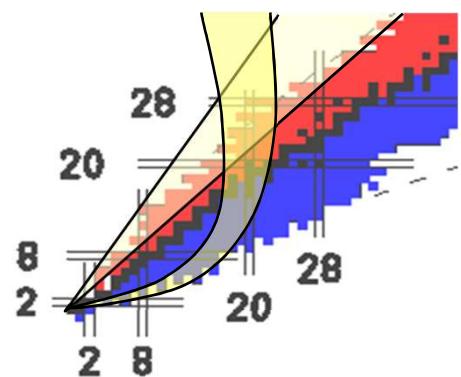
□ Secondary beam selection

- Fragment selection

- 1st dipole: Av/Z



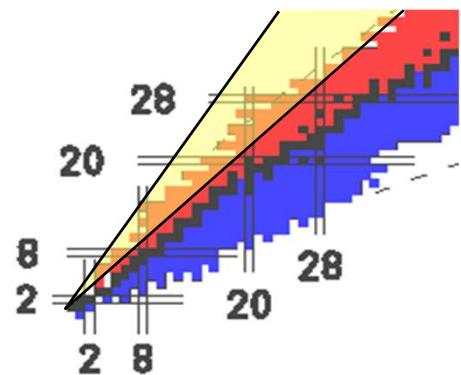
- 2nd dipole + achromatic degrader (A^3/Z^2)



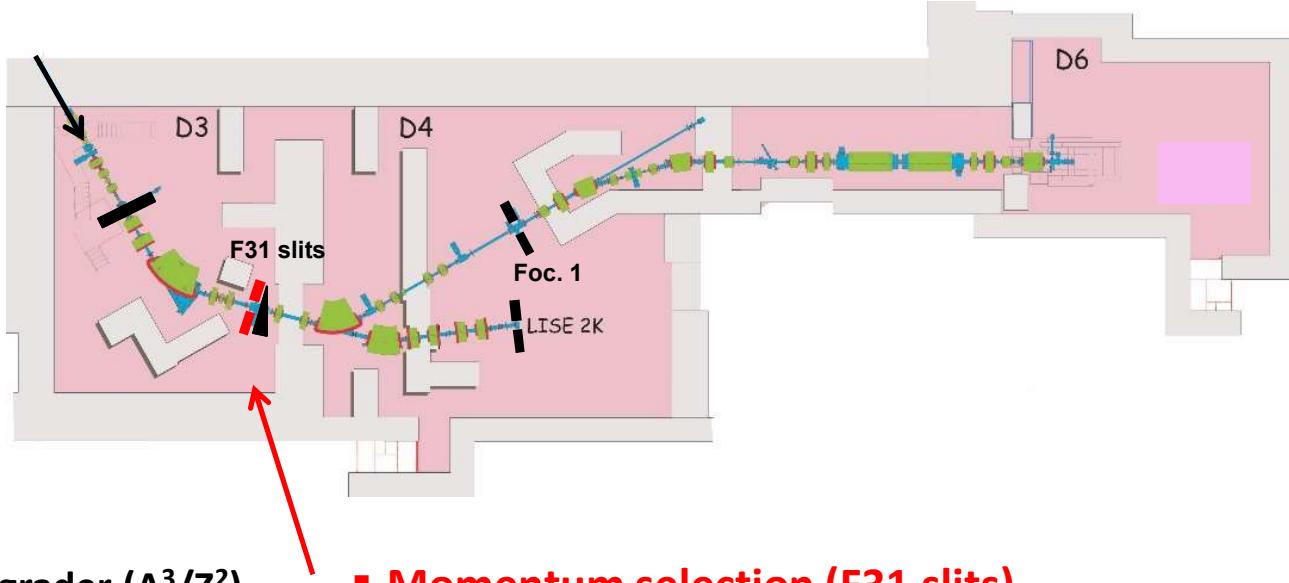
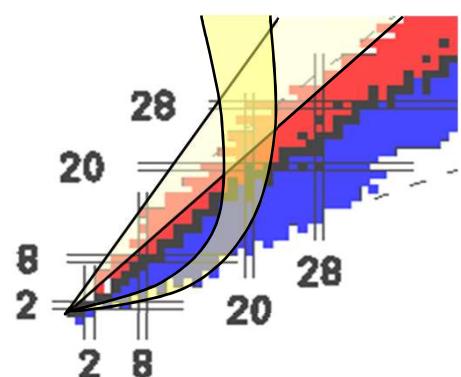
□ Secondary beam selection

- Fragment selection

- 1st dipole: Av/Z



- 2nd dipole + achromatic degrader (A^3/Z^2)

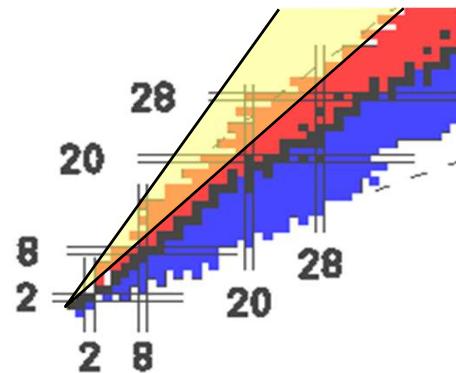


- Momentum selection (F31 slits)
- Position selection (Foc. 1)

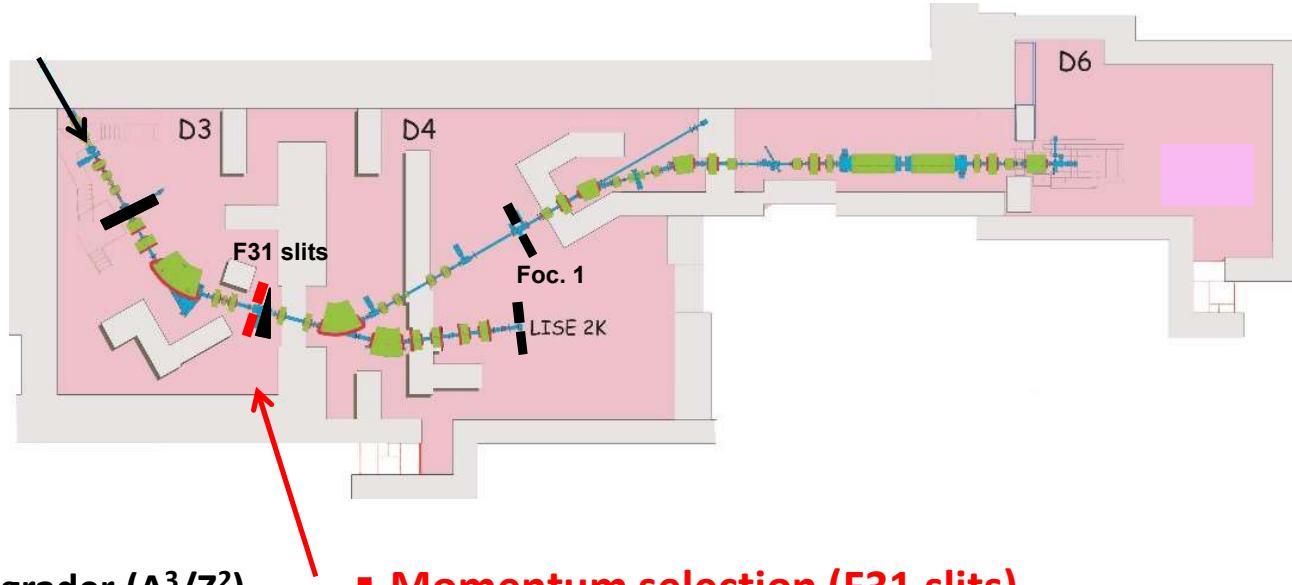
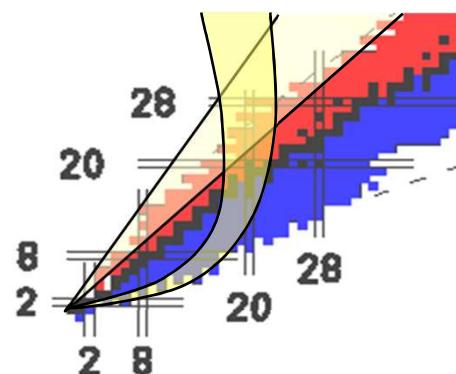
□ Secondary beam selection

- Fragment selection

- 1st dipole: Av/Z



- 2nd dipole + achromatic degrader (A^3/Z^2)



- Momentum selection (F31 slits)
- Position selection (Foc. 1)

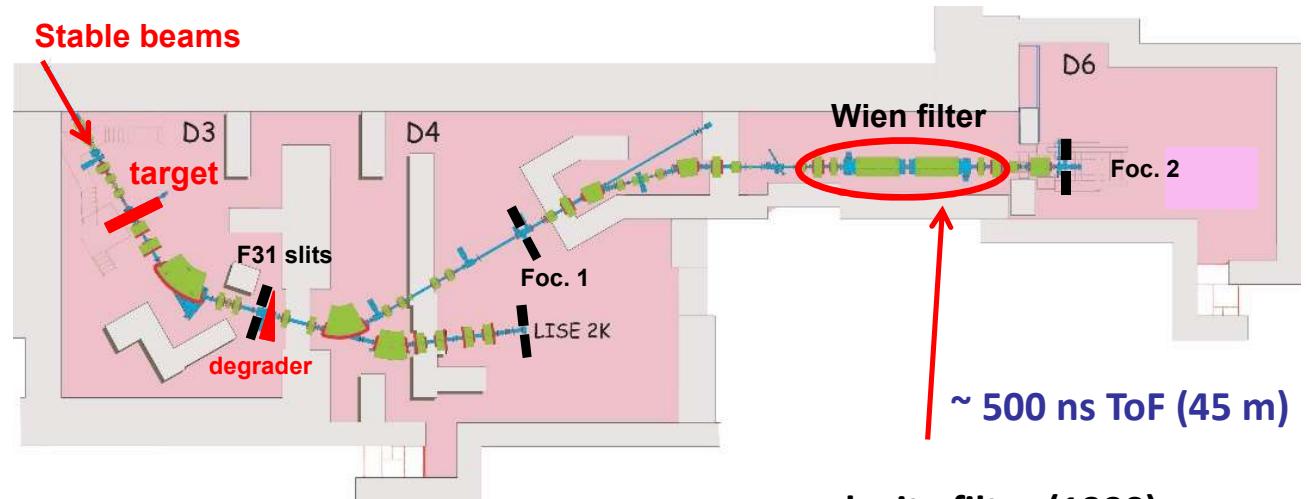
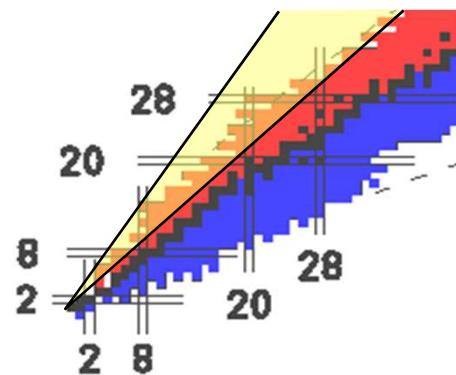
	Angular acceptance (msr)	Momentum acceptance (%)	Max rigidity (Tm)
LISE	1.0	$\pm 2.5\%$	3.2
LISE2000	3.5		4.3

-> For 30-50 AMeV fragments: ~ 50% transmission to F31
~ 200 to 300 ns ToF (20 m)

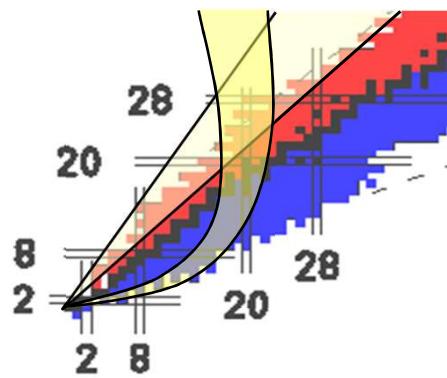
□ Secondary beam selection

- Fragment selection

- 1st dipole: Av/Z

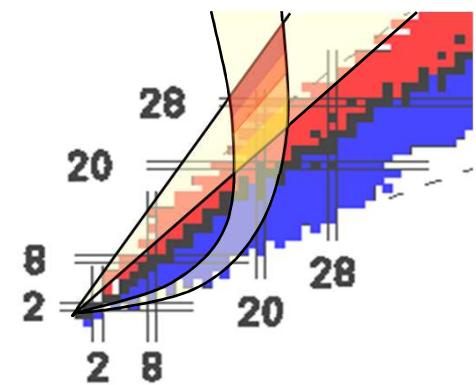


- 2nd dipole + achromatic degrader (A^3/Z^2)



- Momentum selection (F31 slits)
- Position selection (Foc. 1)

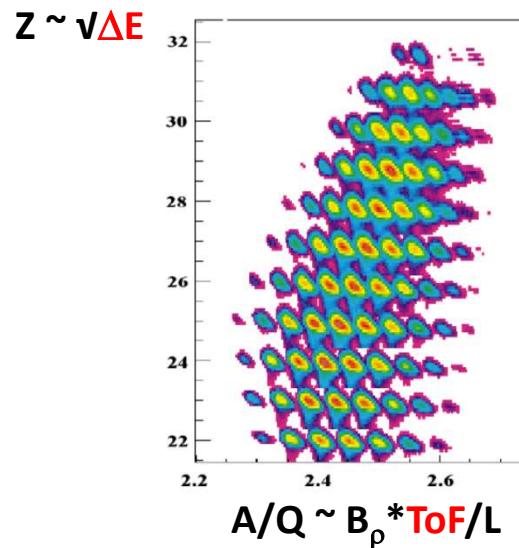
- velocity filter (1990)
+ vertical selection (Foc. 2)



R. Anne et al., NIMB 70 (1992) 276

□ Fragment identification / Spectrometer tuning

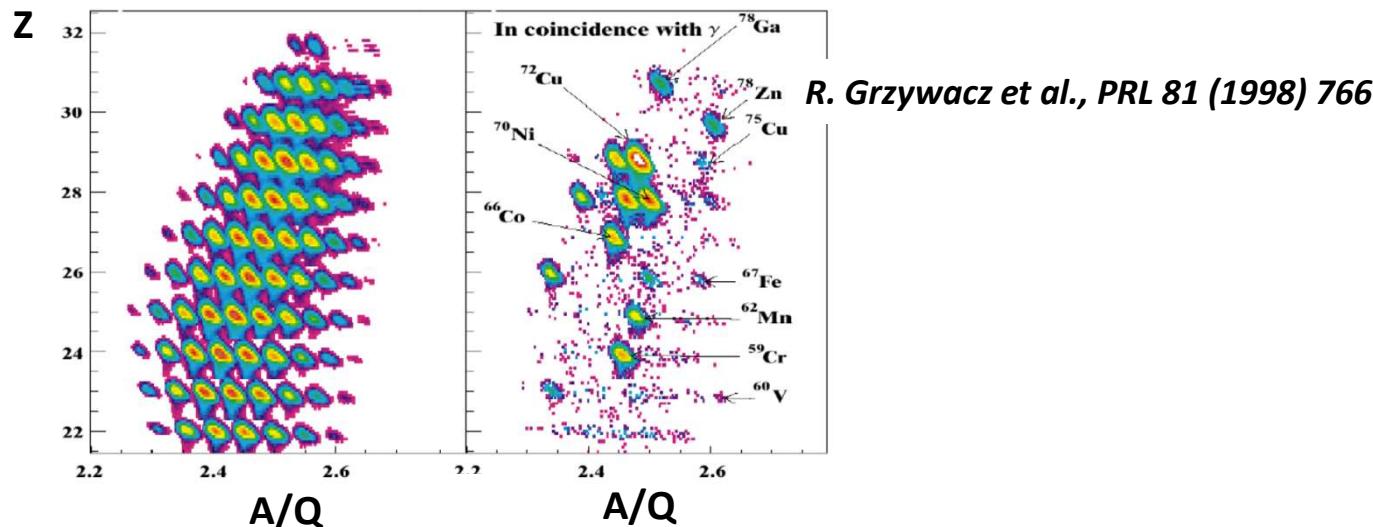
- ΔE -ToF



$^{86}\text{Kr} + ^{nat}\text{Ni}$ @ 60 AMeV
R. Grzywacz et al., PRL 81 (1998) 766

□ Fragment identification / Spectrometer tuning

- ΔE -ToF
- Ion-delayed γ -ray coincidences

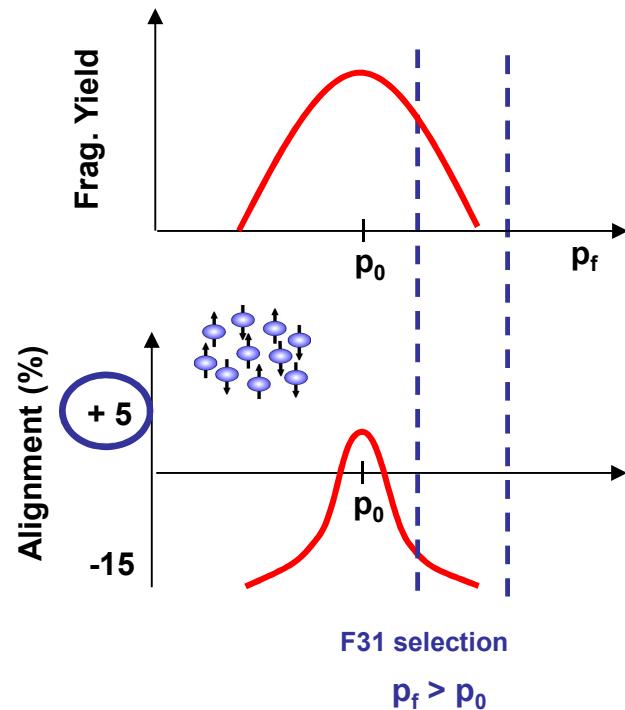


NB1: isomeric ratio of typically 20-30%

NB2: Ions are ~fully stripped for the fragmentation of $Z \leq 30-32$ projectiles
e.g. ^{70}Zn @ 63 AMeV + 150 mg/cm² Be -> Q<Z ~5%

□ Nuclear orientation of the fragmentation products

- TDPAD experiments
- > Aligned sample selecting the outer part(s) of the momentum distribution



-> Representative production yield: $\sim 10^4$ pps/mb/ 10^{11} pps using a 150 mg/cm^2 Be target

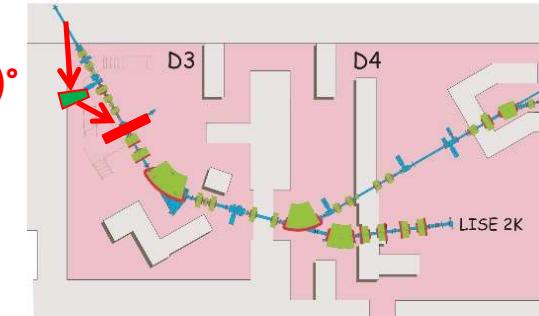
□ Nuclear orientation of the fragmentation products

- NMR (NQR) experiments

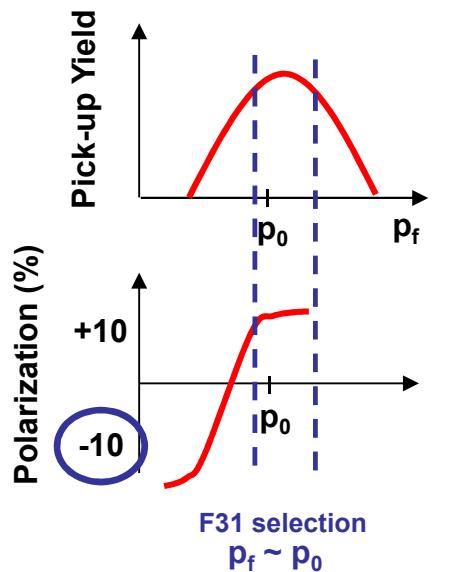
-> Polarized sample selecting off-axis fragments (beam angle on the target)

=> Factor ~5 to 10 intensity reduction

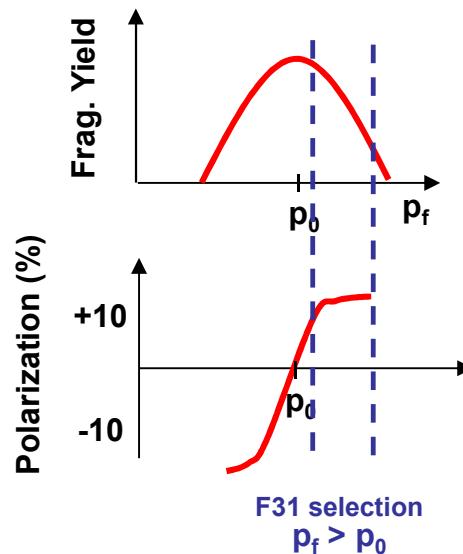
+ selection of part of the momentum distribution



-> Pick-up reactions: central part



-> Fragmentation: outer part



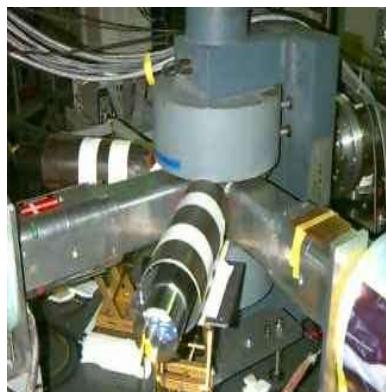
□ TDPAD experiments: 1999-2008

G. Georgiev, CSNSM , J.-M. Daugas, CEA-DAM-DIF et al.

-> nuclear structure in the vicinity of closed shells

-> competition between s.p. structure and collectivity, underlying mechanisms

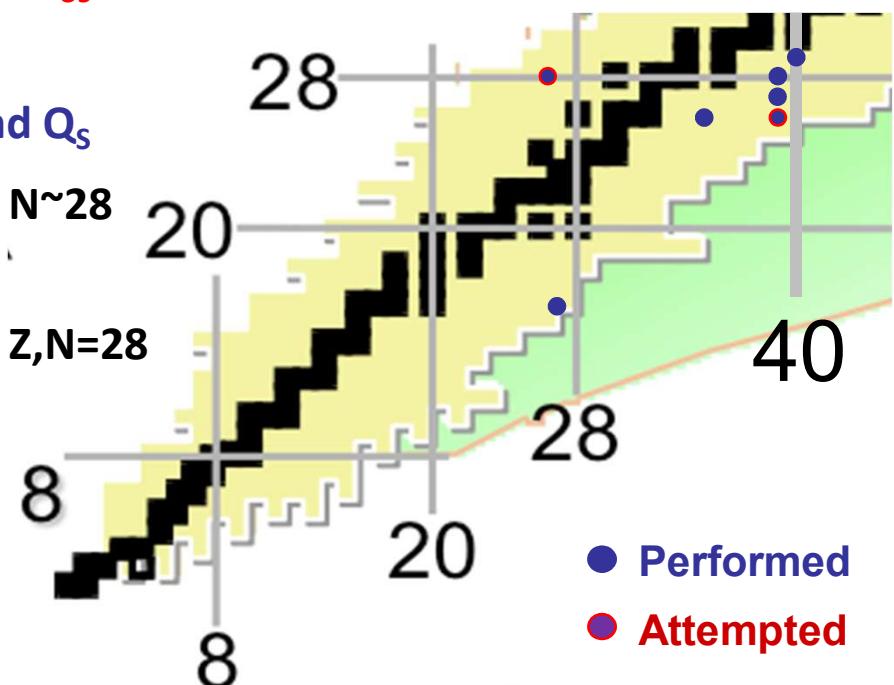
1999



Physics cases

- $\nu g_{9/2}$ orbital in the vicinity of ^{68}Ni
-> $^{67\text{m}}\text{Ni}_{39}$, $^{69\text{m}}\text{Cu}_{40}$, $^{65\text{m}}\text{Fe}_{39}$
- $\nu g_{9/2}$ orbital at N=35
-> $^{61\text{m}}\text{Fe}_{35}$ g-factor and Q_s
- Shape coexistence at N~28
-> $^{43\text{m}}\text{S}_{27}$
- Mirror asymmetry at Z,N=28
-> $^{54\text{m}}\text{Ni}_{26}$ / $^{54\text{m}}\text{Fe}$

2007



□ Physics case

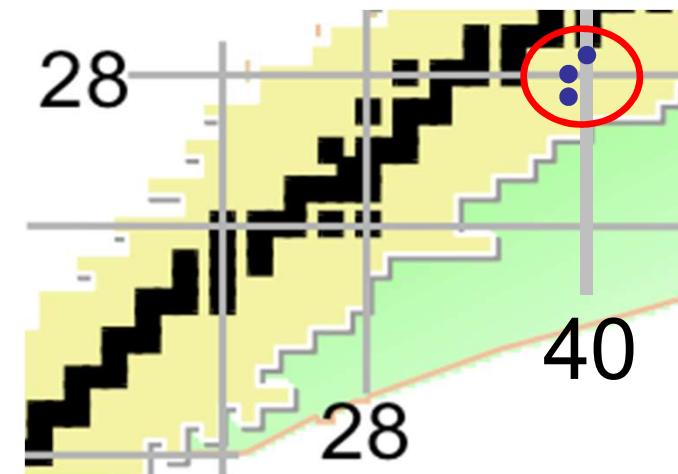
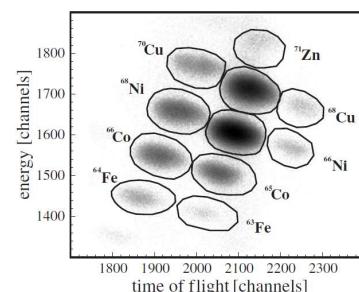
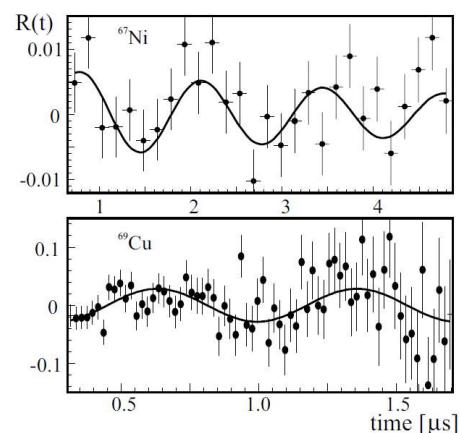
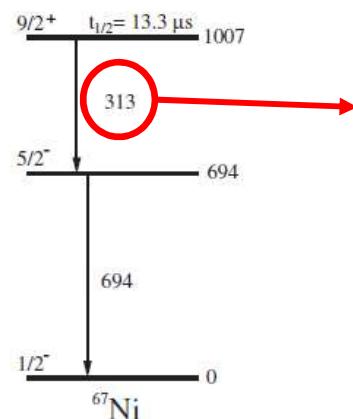
- π - ν interaction in ^{68}Ni -1*v*/+1*π*
 -> $^{67\text{(m)}}\text{Ni}_{39}$; $^{69\text{(m)}}\text{Cu}_{40}$; $(^{66\text{(m)}}\text{Co}_{39})$

□ Experiment

- $^{76}\text{Ge}^{30+}$ @ 61 AMeV
 -> few 10^3 pps, cocktail beam

□ Results

- $^{67\text{m}}\text{Ni}$ ($J^\pi = 9/2^+$, $T_{1/2} = 13 \mu\text{s}$)
 -> $|g| = 0.125(6)$ at variance from expected value
 -> hint for $\pi f_{7/2}$ - $\pi f_{5/2}$ excitations across Z=28



G. Georgiev et al, JPG 28 (2002) 2993; EPJA 20, 93 (2003); PhD Thesis, IKS Leuven 2001

- $^{69\text{m}}\text{Cu}$ ($J^\pi = 13/2^+$, $T_{1/2} = 0.36 \mu\text{s}$)
 -> $E^* = 2741 \text{ keV}$, $|g| = 0.23(3)$
 -> $\pi p_{3/2} \otimes \{(\nu p_{1/2} \text{ or } \nu f_{5/2})^{-1} \otimes \nu g_{9/2}\}$
- $^{66\text{m}}\text{Co}$ ($J^\pi = (5^+)$, $T_{1/2} = 0.83 \mu\text{s}$)
 -> $E^* = 175 \text{ keV}$, $|g| = 0.157(9)$

□ Physics case

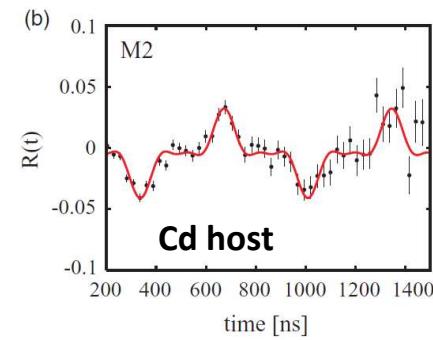
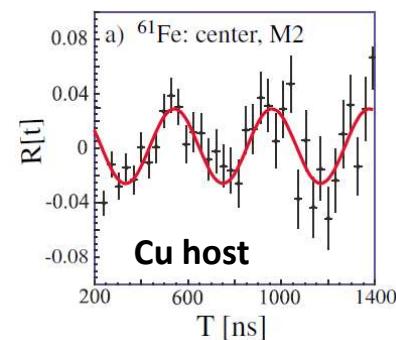
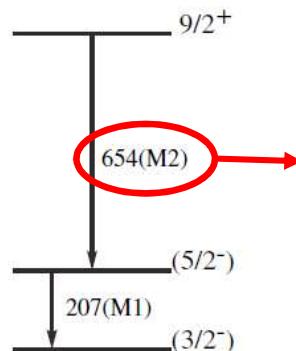
- Study of the $\nu g_{9/2}$ intruder orbital
-> $^{61m}\text{Fe}_{35}$

□ Experiment

- $^{64}\text{Ni}^{26+}$ @ 55&65 AMeV, few 10^{11} pps
-> up to 10^4 pps, ~15% alignment, beam on/off

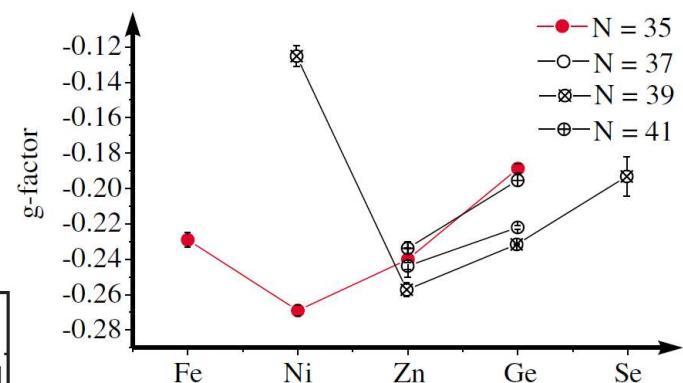
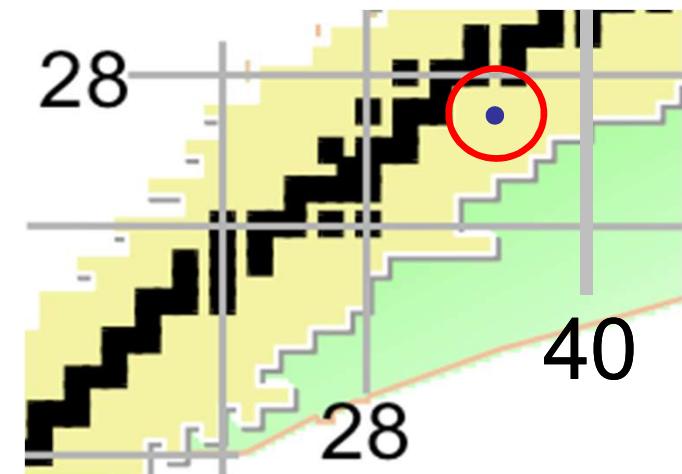
□ Results

- ^{61m}Fe ($J^\pi = 9/2^+$, $T_{1/2} = 239$ ns)
-> $E^* = 871$ keV; $g = -0.229(2)$; $|Q_S| = 41(6)$ efm²
-> fragmentation of the π w.f.; moderate deformation



^{61}Fe

I. Matea et al., PRL 93, 142503 (2004) N. Vermeulen et al., PRC 75, 051302R (2007)



□ Physics case

- Weakening of the N=28 shell closure

-> $^{43(m)}S_{27}$

□ Experiment

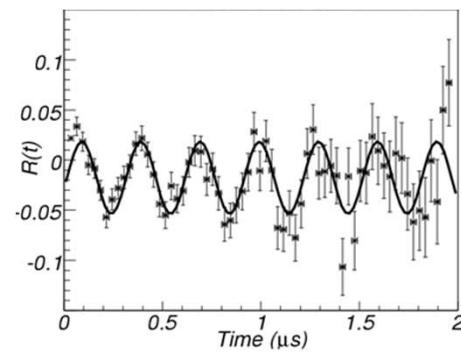
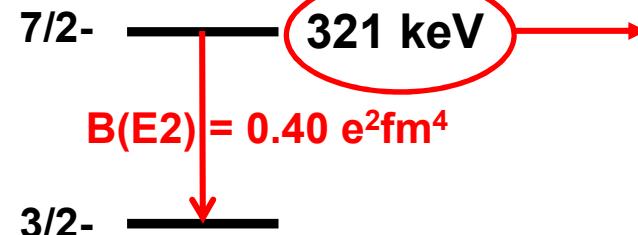
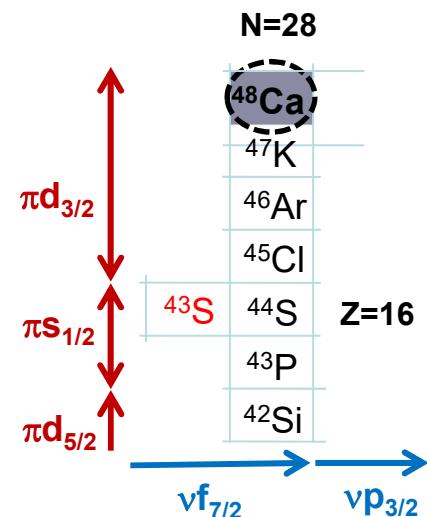
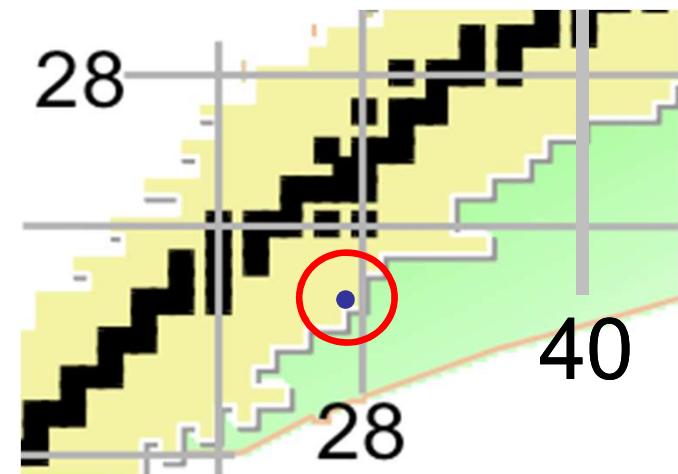
- $^{48}\text{Ca}^{19+}$ @ 60 AMeV, $3 \cdot 10^{11}$ pps – LISE2k

□ Results

- ^{43m}S ($J^\pi = 7/2^-$, $T_{1/2} = 415$ ns)

-> $E^* = 321$ keV; $g = -0.317(4)$

-> Shape coexistence between a prolate (intruder) g.s. and a moderately* deformed iso.



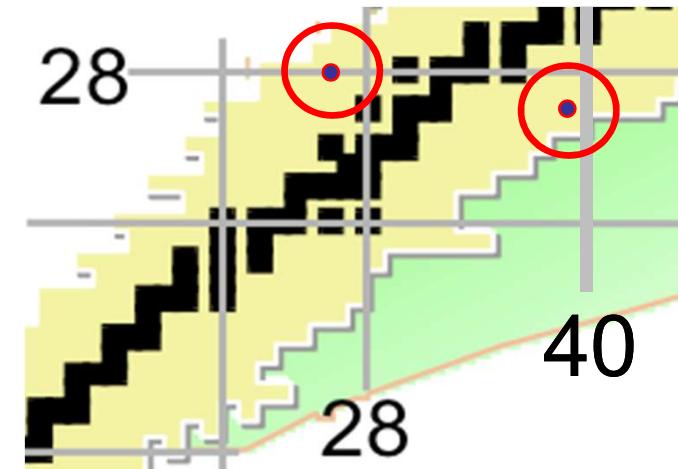
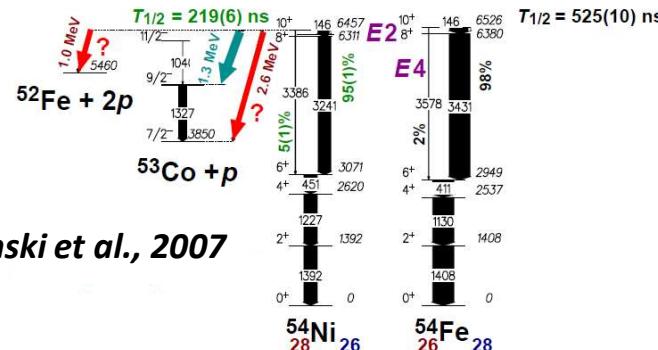
L. Gaudefroy et al. PRL 102, 092501 (2009)

* See also R. Chevrier et al., PRL 108, 162501 (2012)

□ Physics case

- Mirror symmetry and Z=28 shell gap

-> $^{54m}\text{Ni}_{26}$ $J^\pi = 10^+$ from $^{58}\text{Ni}^{26+}$ @ 75 AMeV – LISE2k

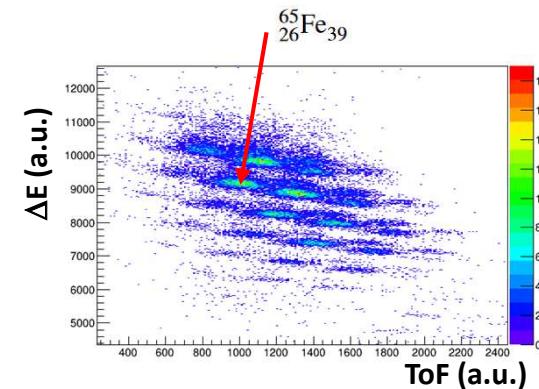
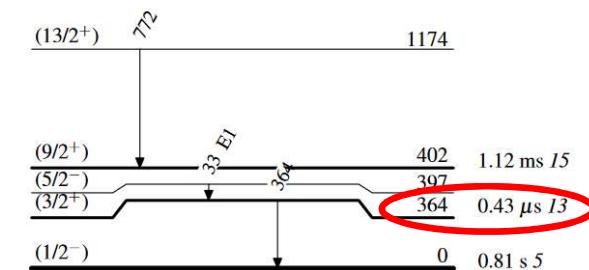


□ Physics case

- Nuclear structure and deformation in the vicinity of ^{68}Ni

-> $^{65m}\text{Fe}_{39}$ $J^\pi = (3/2^+)$ from $^{70}\text{Zn}^{28+}$ @ 70 AMeV, $5 \cdot 10^{11}$ pps

G. Georgiev et al., 2008



□ Results

- Few 100 pps, very low (<1-10 %) purity
- > No measurements possible

□ High velocity transient field technique: 2008

G. Georgiev, CSNSM, A. Stuchbery ANU, et al.

-> interplay between s.p. structure and collectivity in the vicinity of ^{68}Ni

-> g-factor measurement of the coulomb excited $^{72}\text{Zn } 2_1^+$ state

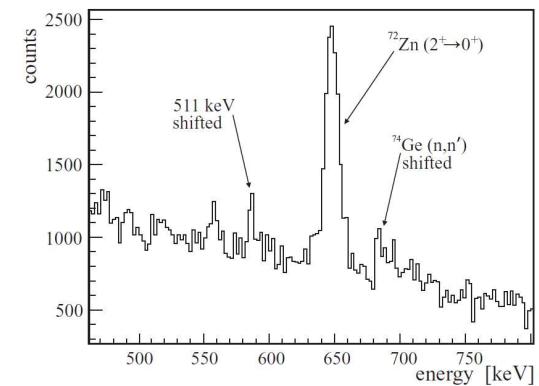
□ Experiment

- $^{76}\text{Ge}^{30+}$ @ 59 AMeV, few 10^{11} pps

-> $\sim 3 \cdot 10^5$ ^{72}Zn pps, 75 % purity

-> smaller p_{1s} polarization than expected (Gd)

-> higher vacuum deorientation (charge state distribution)



□ Results

E. Fiory et al., PRC 85, 034334 (2012)

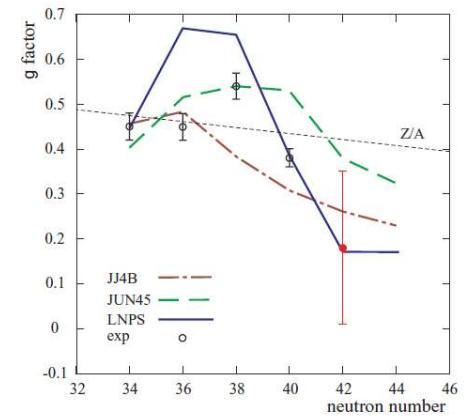
- ^{72}Zn ($J^\pi = 2^+$, $T_{1/2} = 18$ ps)

-> $E^* = 653$ keV; $g = 0.17$ (16)

-> lowering of the g-factor associated with:

- partial occupation of higher ν orbits ($g_{9/2}$, $d_{5/2}$)
- π excitations above the pf shell

=> ^{72}Zn as a transitional nucleus between ^{70}Zn (spherical) and ^{74}Zn (deformed)



□ **β -NM(Q)R experiments: 2000-2016**

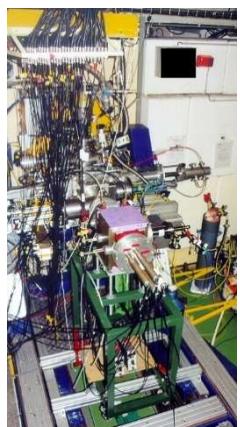
G. Neyens et al., IKS Leuven; Univ. of Athens, GANIL, CEA-DAM-DIF, CSNSM

-> nuclear structure and deformation near closed shells

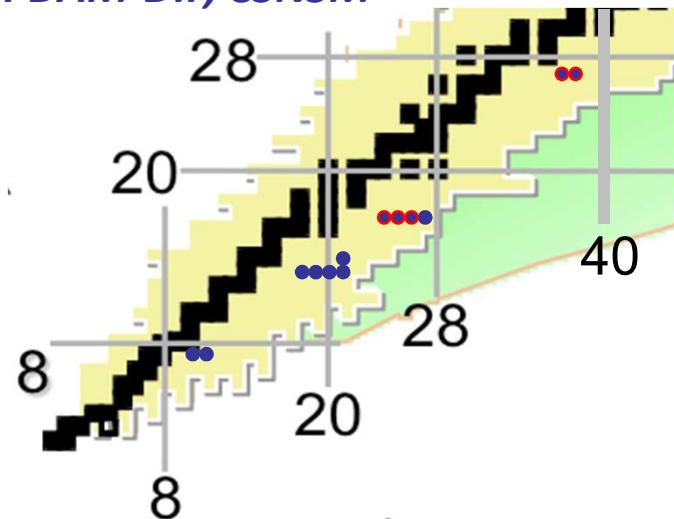
-> s.p. mixing and ν -pair excitations

=> Probing transitional regions of the nuclear chart

2000



2016

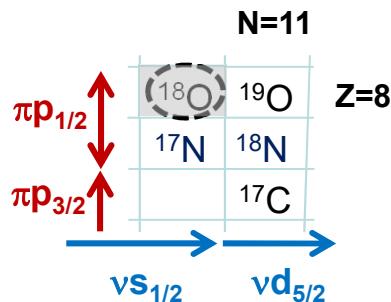


Physics cases

- ν -state configuration at N=11
-> (Z=7) $^{17-18}\text{N}_{10-11}$
- Border of the N=20 island of inversion
-> (Z=13) $^{31-34}\text{Al}_{18-21}$ crossing N=20
- Vanishing of the N=28 shell closure
-> (Z=17) $^{41-44}\text{Cl}_{24-27}$
- Configuration mixing at Z=28/N=40
-> (Z=27) $^{64-65}\text{Co}_{37-38}$

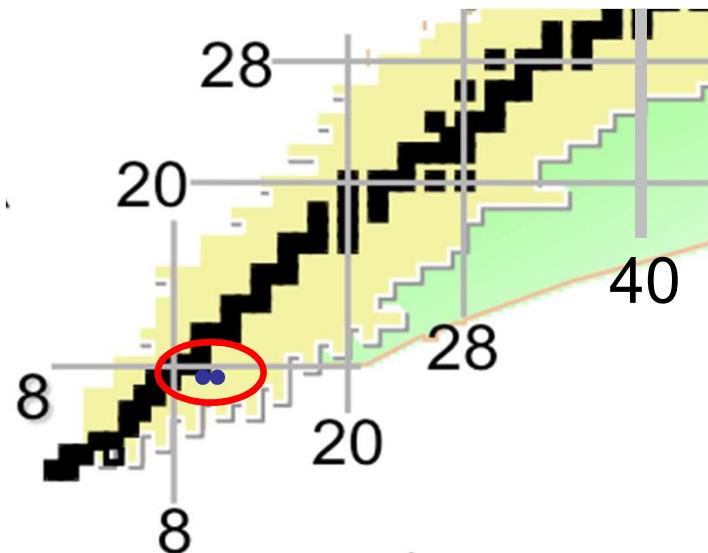
□ Physics case

- Nuclear structure at N=11
- > g-factors of (Z=7) $^{17-18}\text{N}_{10-11}$



□ Experiment

- $^{18}\text{O}^{8+}$ @ 75 AMeV, $8 \cdot 10^{11}$ pps
- > $2-1 \cdot 10^5$ pps, ~95 % purity for $^{17-18}\text{N}$



□ Results

- Commissioning of a more sensitive β -NMR setup : $0.02 < |g| < 4$; $\epsilon_\beta \sim 15\%$
- Evidence for complex ν -coupling configurations
- > ^{18}N = transition between ^{19}O (spherical) and ^{17}C (deformed)

$\begin{array}{c} \text{p}_{1/2} \\ \text{Z}=8 \\ \pi \end{array}$
 $\begin{array}{c} \text{d}_{5/2} \\ \text{N}=8 \\ \nu \end{array}$

 $^{17}\text{N} (J^\pi = 1/2^-, T_{1/2} = 4.2 \text{ s})$

 $\pi(p_{1/2})^{-1} \otimes \nu \{(s_{1/2})^{+2}\}_{J=0} + \{\nu(sd)^{+2}\}_{J=2+}$

 $|g_{\text{exp}}| = 0.7102(4)$

 $g_{\text{Schmidt}} = -0.528$

$\begin{array}{c} \text{p}_{1/2} \\ \text{Z}=8 \\ \pi \end{array}$
 $\begin{array}{c} \text{d}_{5/2} \\ \text{N}=8 \\ \nu \end{array}$

 $^{18}\text{N} (J^\pi = 1^-, T_{1/2} = 619 \text{ ms})$

 $\pi(p_{1/2})^{-1} \otimes \{\nu(d_{5/2})^{+3}\}_{J=3/2+}$

 $|g_{\text{exp}}| = 0.3273(4)$



M. De Rydt et al., NIMA 612 (2009) 112
M. De Rydt et al., PRC 80 (2009) 037306

□ Physics case

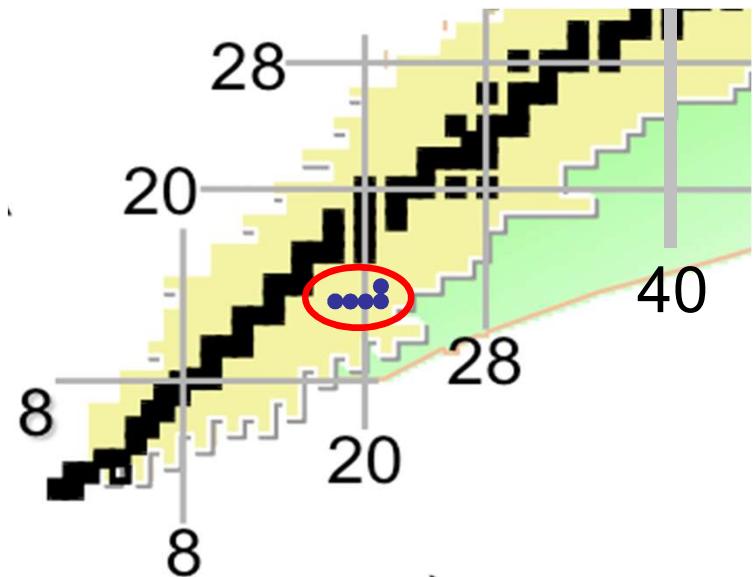
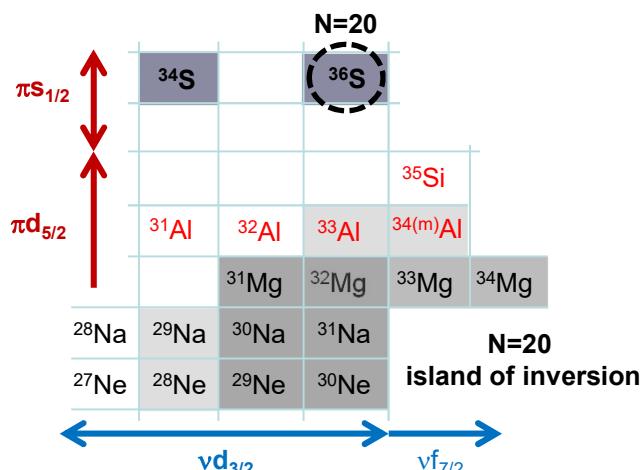
- Island of inversion at N=20
- > g-factors and Q_s of (Z=13) $^{31-34}\text{Al}_{17-21}$

□ Experiment

- $^{36}\text{S}^{16+}$ @ 78 AMeV, $8 \cdot 10^{11}$ pps
- > $10^3 - 10^4$ pps, >80% purity for $^{31-34}\text{Al}$

□ Results

- Mapping of the border of the island of inversion
- Evidence for significant 2p-2h ν -excitations at N=20,21
- 1p-1h character of the 1+ isomeric state in ^{34}Al
- > Al = transition between Si (outside) and Mg (inside)



$^{31-34}\text{Al} - \beta\text{-NMR}$: D. Borremans et al., PLB 537 (2002) 45

P. Himpe et al., PLB 643 (2006) 257, PLB 658 (2008) 203

$^{35}\text{Si} - \beta\text{-NMR}$: G. Neyens et al., EPJST (2007) 149

$^{31,33}\text{Al} - \beta\text{-NQR}$: M. De Rydt et al., PLB 678 (2009) 344

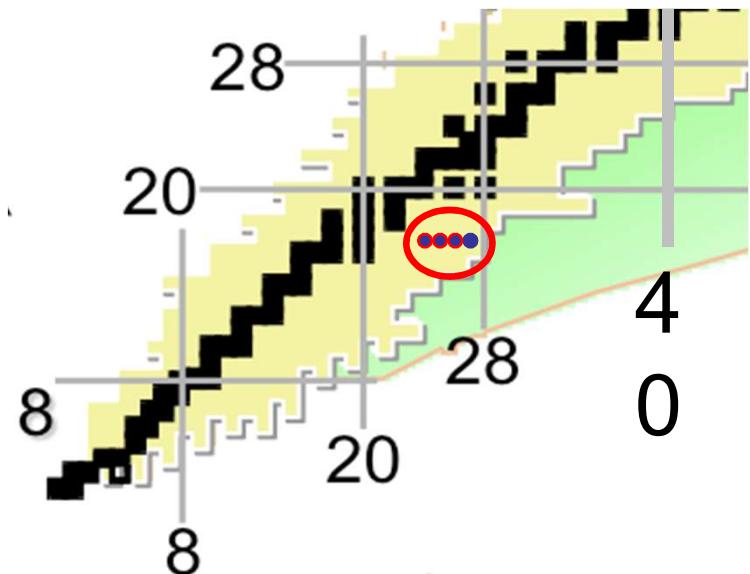
K. Shimada et al., PLB 714 (2012) 246

H. Heylen et al., PRC 94 (2016) 034312

$^{32,34m}\text{Al} - \beta\text{-NM/QR}$: Z.Y. Xu et al., PLB 782 (2018) 619

□ Physics case

- Weakening of the N=28 closed shell south ^{48}Ca
- Near degeneracy of the $\pi s1/2$ and $\pi d3/2$ orbitals
-> g-factor of (Z=17) $^{41-44}\text{Cl}_{24-27}$



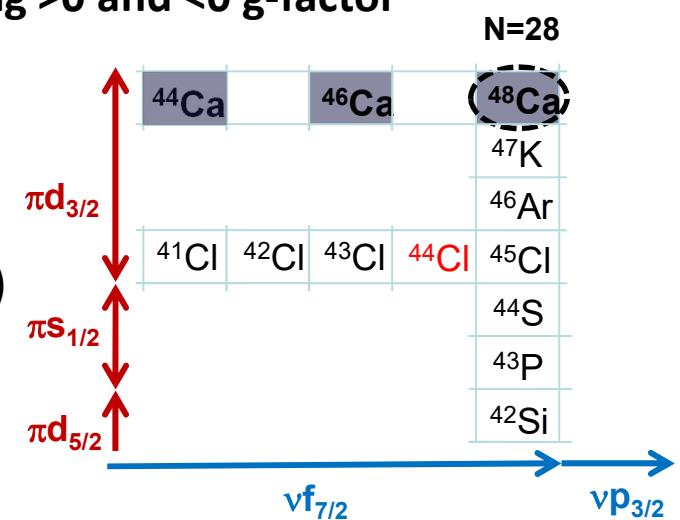
□ Experiment

- $^{48}\text{Ca}^{19+}$ @ 60 AMeV, 3-9 10^{11} pps
-> $2 \cdot 10^4 - 3 \cdot 10^3$ pps, >80% purity for $^{41-44}\text{Cl}$

□ Results

- No resonance found for $^{41,43}\text{Cl}$ within large g-factor ranges ($J^\pi = 1/2^+$ or $3/2^+$)
- Nor for ^{42}Cl , scanning $J^\pi = (1-3)^-$: fragmented w.f. involving >0 and <0 g-factor configurations from $\pi(s_{1/2}, d_{3/2}) \times \nu(f_{7/2}, p_{3/2})$ couplings
- $^{44}\text{Cl} |g| = (-) 0.2749(2)$ in agreement with $J^\pi = 2^-$ and a mixed $(\pi s_{1/2})^1 \otimes (\nu f_{1/2})^1 + (\pi d_{3/2})^3 \otimes (\nu p_{3/2})^1$ configuration
-> Cl = transition between Ar (spherical) and S (deformed)

M. De Rydt et al., PRC 81 (2010) 034308 + PhD thesis, IKS Leuven, 2010



□ Physics case

- Shell structure close to the doubly magic ^{68}Ni nucleus
- M1 excitation across Z=28
- E2 excitation driven by the proximity of the $\nu g_{9/2}$ orbit (“N=40 island of inversion”)
-> g-factor of (Z=27) $^{64-65}\text{Co}_{37-38}$

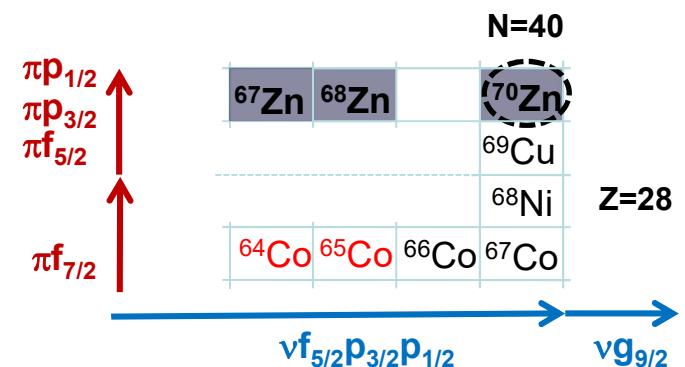
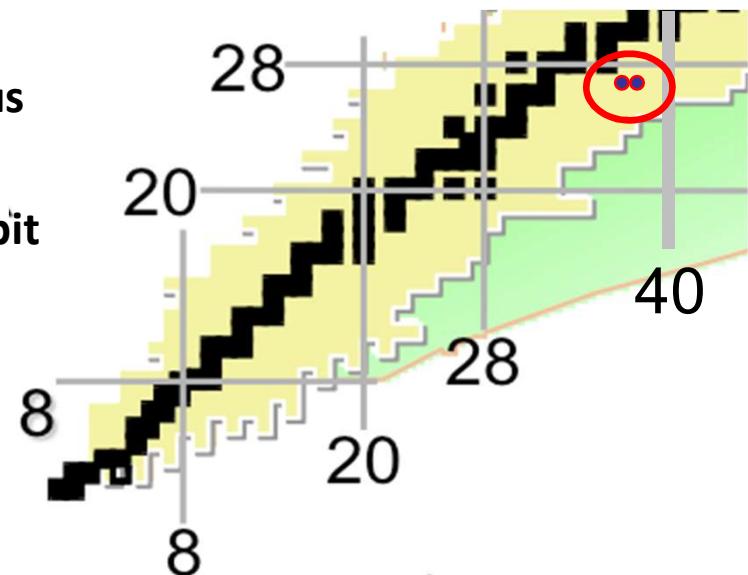
□ Experiment

- $^{70}\text{Zn}^{29+}$ @ 63 AMeV, $2 \cdot 10^{11}$ pps
-> $6 - 3 \cdot 10^3$ pps, ~50% purity for $^{64-65}\text{Co}$

□ Results

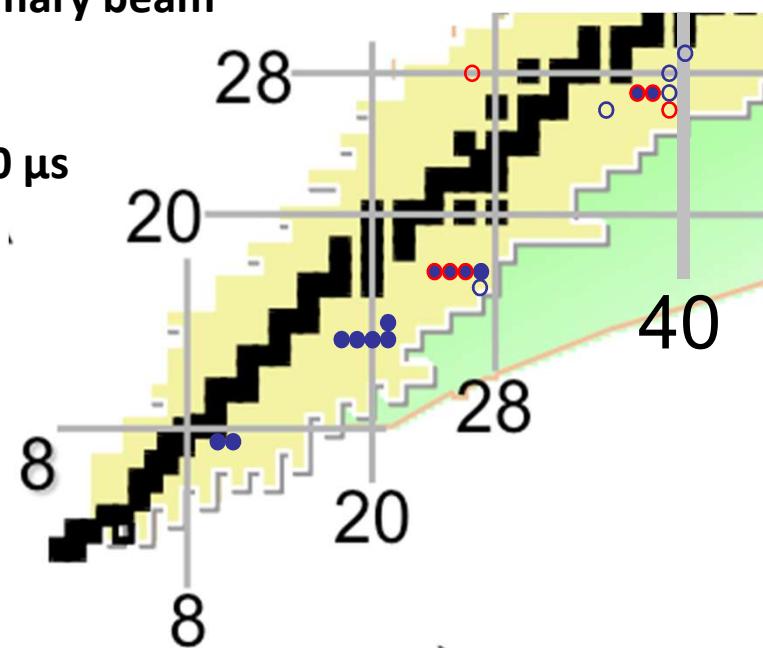
- No resonance found within the g-factor scan ranges
-> relaxation issue? NaCl, Si and Al_2O_3 hosts tested
-> β -decay from contaminants?
=> No reference case to test the setup

H. Heylen, PhD thesis, IKS Leuven, 2016



□ Conclusion

- GANIL/LISE well suited to the g-factor measurement of fragments:
 - With yields $\geq 10^3$ pps, i.e. $\sigma \geq 10^{-2}$ mb (e.g. $-4\pi/-1\nu$)
 - Fully stripped, i.e. $Z_f \leq 32$ (^{76}Ge)
 - With $> 30\%$ purity, i.e. preferably on the n-rich side and rather exotic
 - Ideally, reference case available with the same primary beam
- Lifetime ranges:
 - TDPAD technique appropriate for $200\text{ ns} < T_{1/2} < 10\text{ }\mu\text{s}$
 - NMR for $1\text{ ms} < T_{1/2} < 10\text{ s}$ (host cooling)
 - HVTF for $1\text{ ps} < T_{1/2} < 1\text{ ns}$



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□ Perspectives

- TDPAD: ^{71m}Cu , ^{69m}Ni , $^{66-67m}\text{Co}$, ^{66m}Cu
- NMR: $^{65-67}\text{Co}$, $^{57,58}\text{Ni}$, ^{23}F
- HVTF: ^{56}Cr , $^{74,76}\text{Kr}$

But:

- Deeper theoretical support (and motivation) needed
- Test/preparation needed = beam time -> quite difficult at GANIL in coming years

