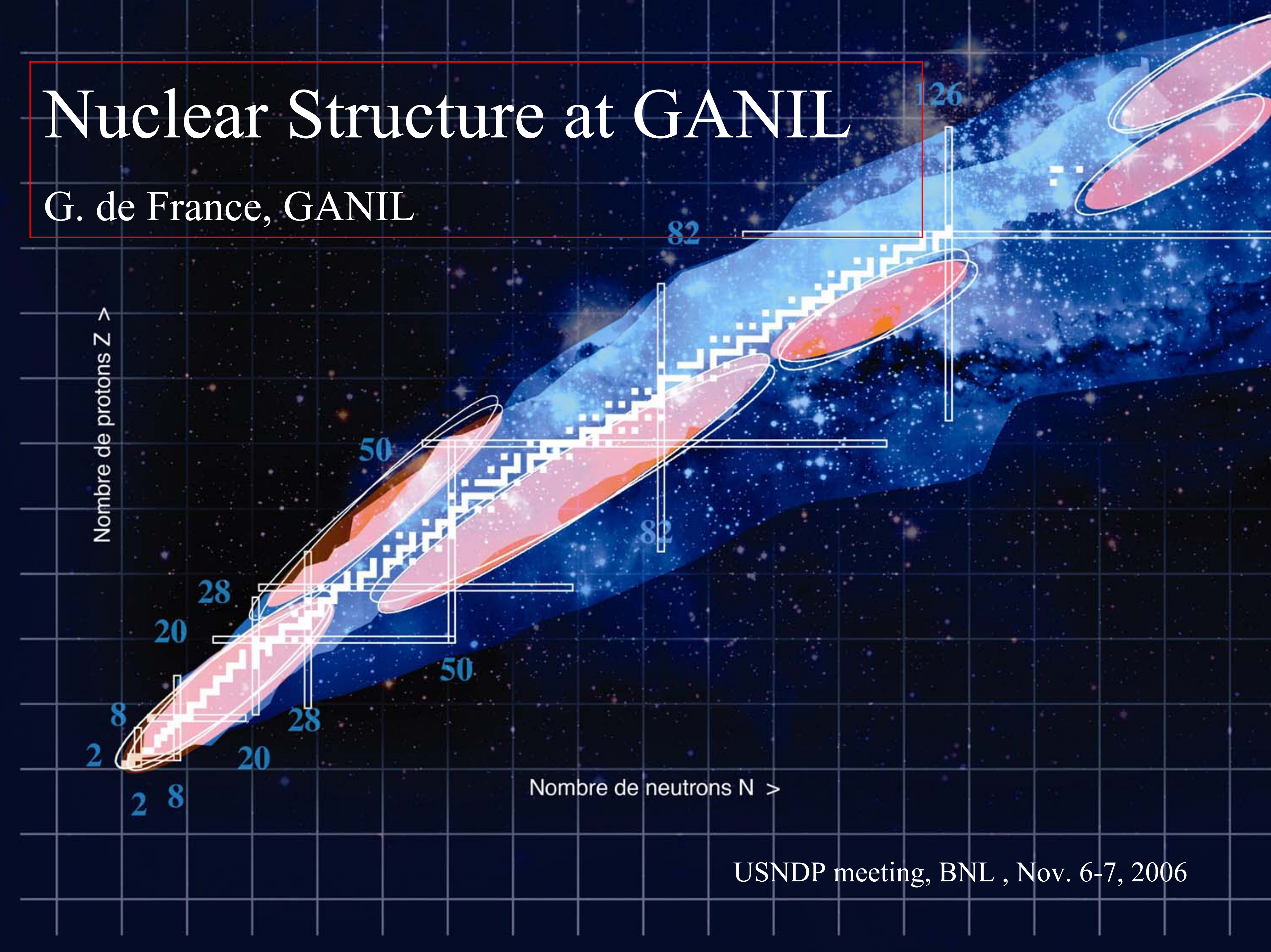
# Nuclear Structure at GANIL

G. de France, GANIL




USNDP meeting, BNL , Nov. 6-7, 2006

# Outline:

A. Introduction: the facility in brief

B. Nuclear structure at GANIL today

C. … and tomorrow

D. Conclusions

# A. Introduction: the facility in brief

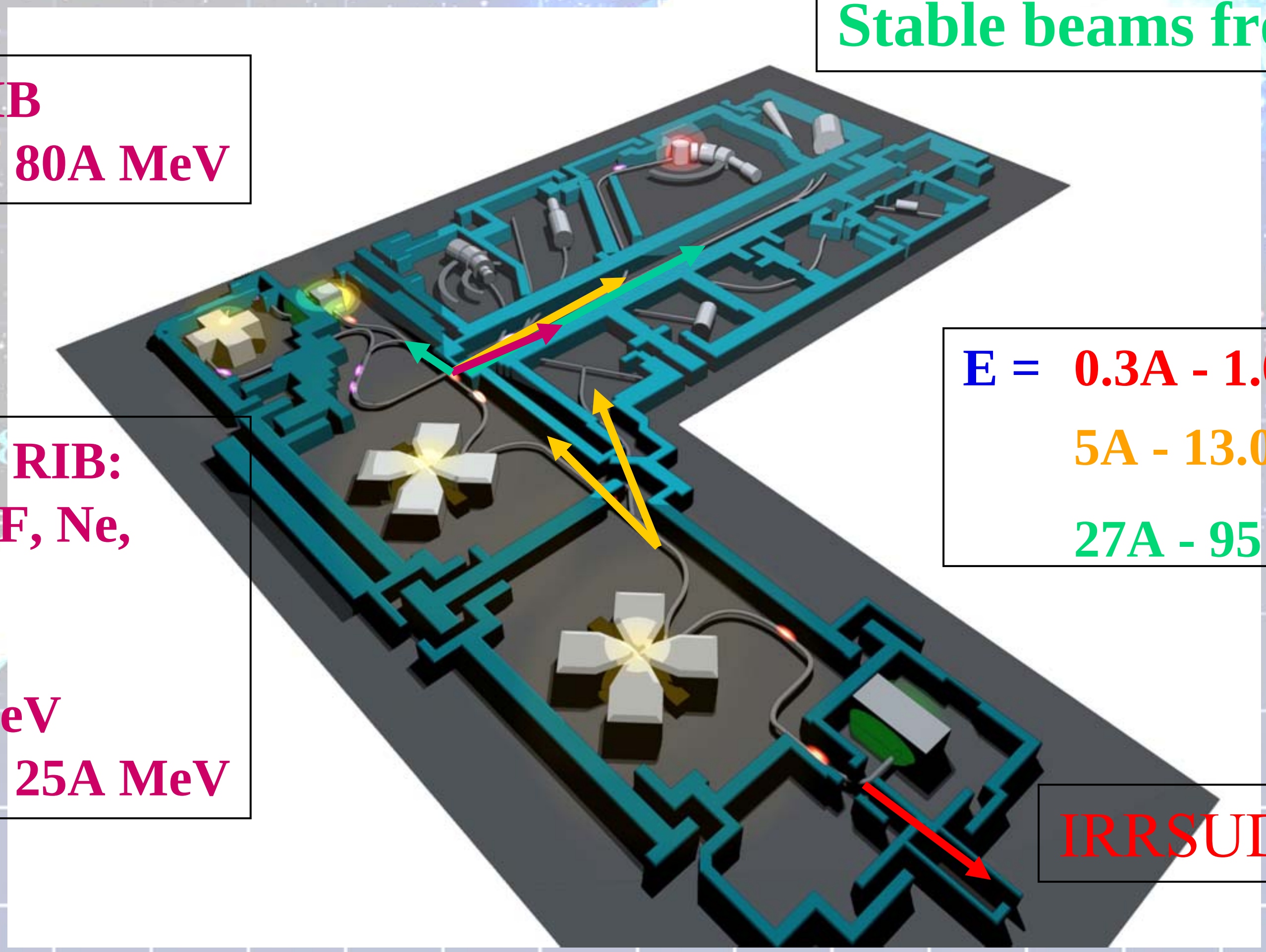
SISSI - RIB
E = 25A - 80A MeV

SPIRAL - RIB:
He, N, O, F, Ne,
Ar, Kr

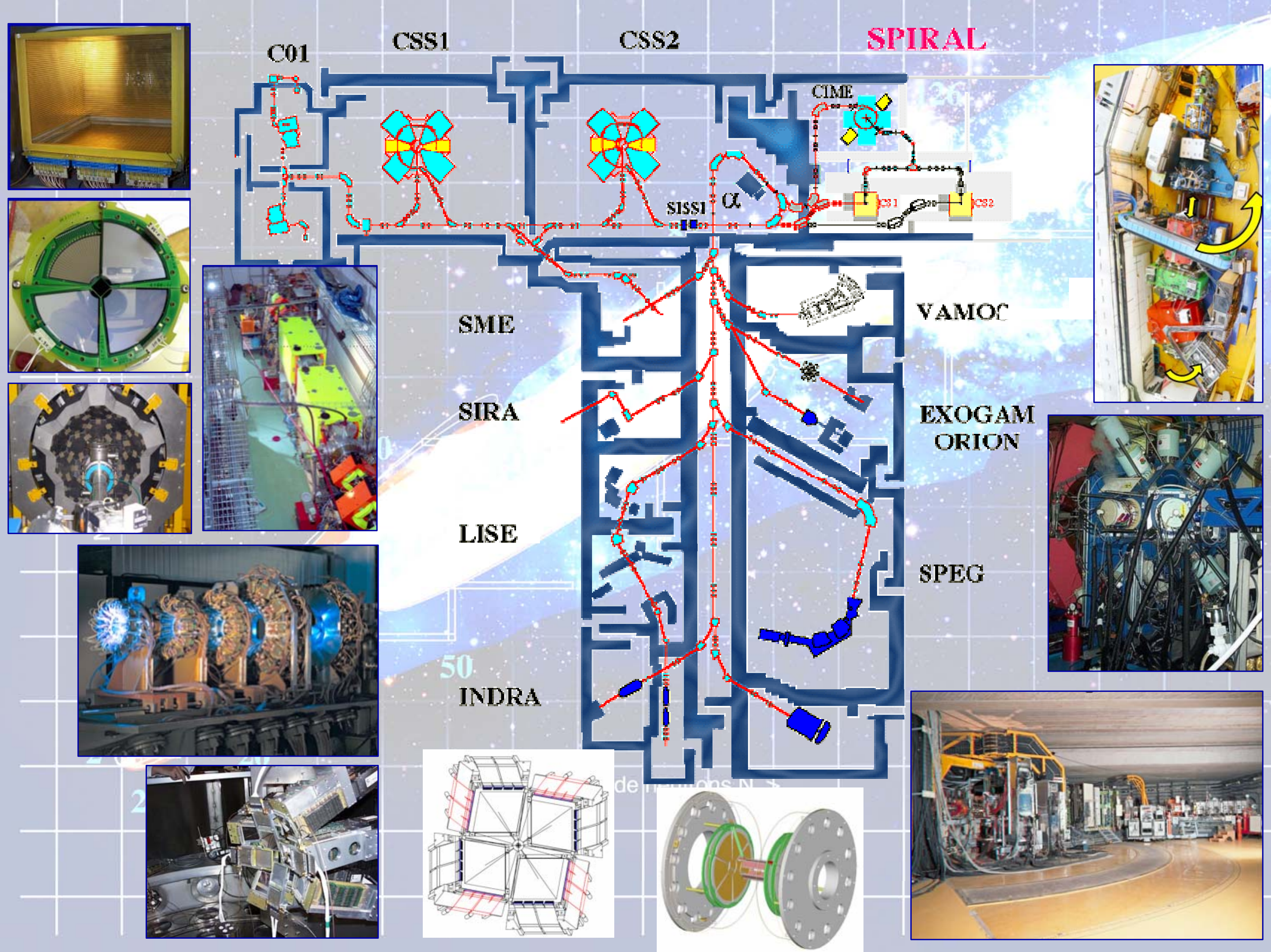
E < 20A keV
E = 1.7A - 25A MeV

Stable beams from C to U

E = 0.3A - 1.0A MeV
5A - 13.0A MeV
27A - 95 A MeV



IRRSUD


C01
CSS1
CSS2
SPIRAL
CIME
SISSI
α
CS1
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SIRA
LISE
INDRA
VAMO
EXOGAM
ORION
SPEG

# B. Nuclear structure at GANIL today

I. New shell gap at N=34 or not?

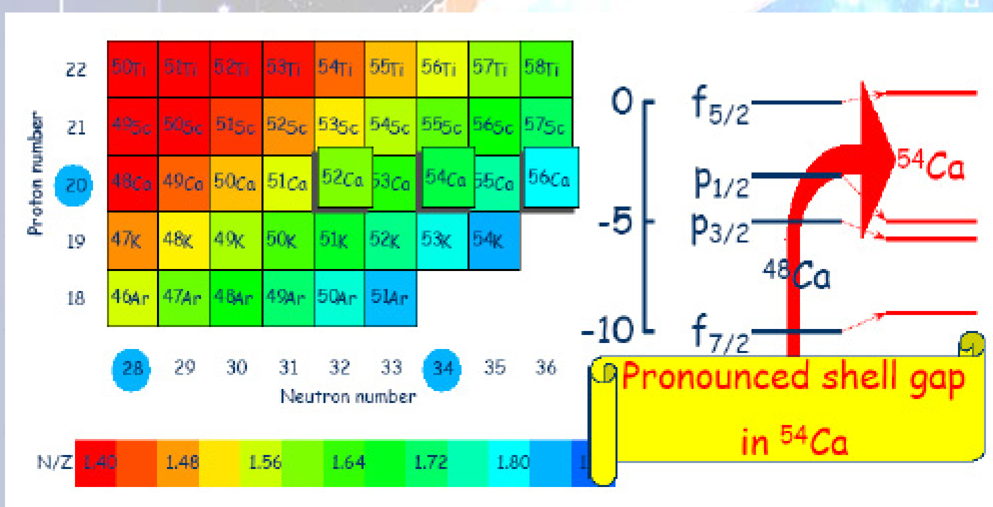
II. N and Z=20: the « island of inversion » and isospin symmetry.

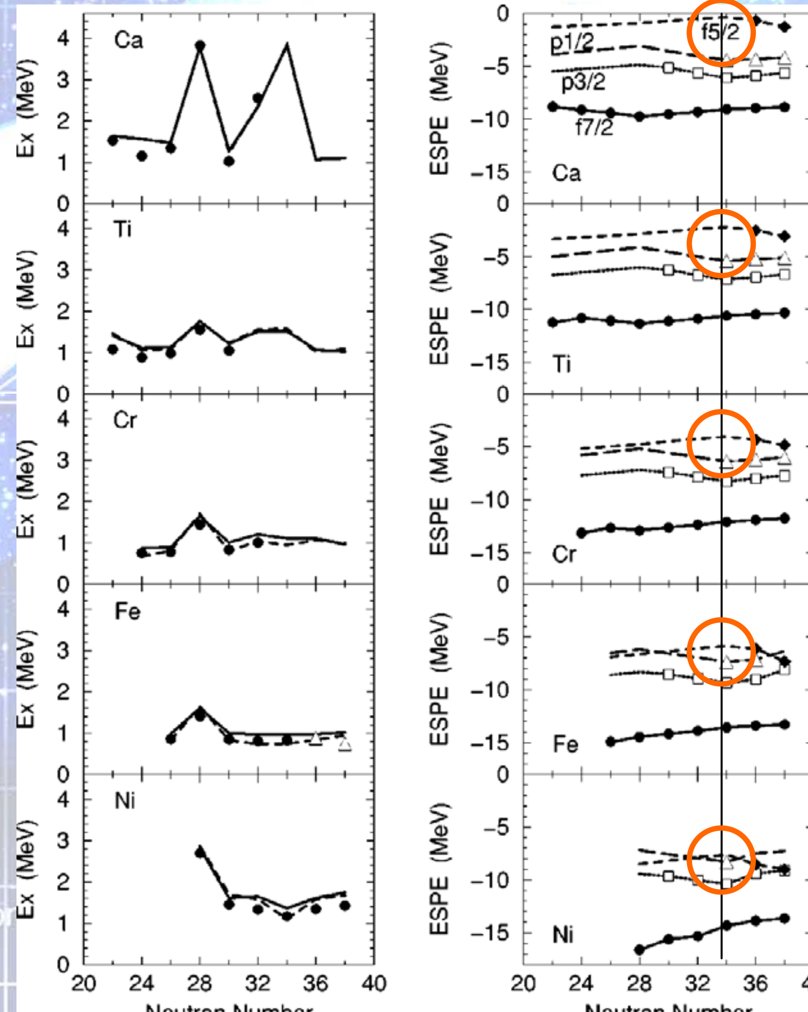
III. The N=28 shell gap.

IV. Summary of results from SPIRAL1.

# I. A new shell gap at N=34 or not?

- Ca ➔ Ni : fill the $\pi 1f_{7/2}$ level
- $(\pi 1f_{7/2}, \nu 1f_{5/2})$ pn monopole interaction binds $\nu 1f_{5/2}$ faster than others while filling it
- np spin-flip interaction generates the N=34 gap:



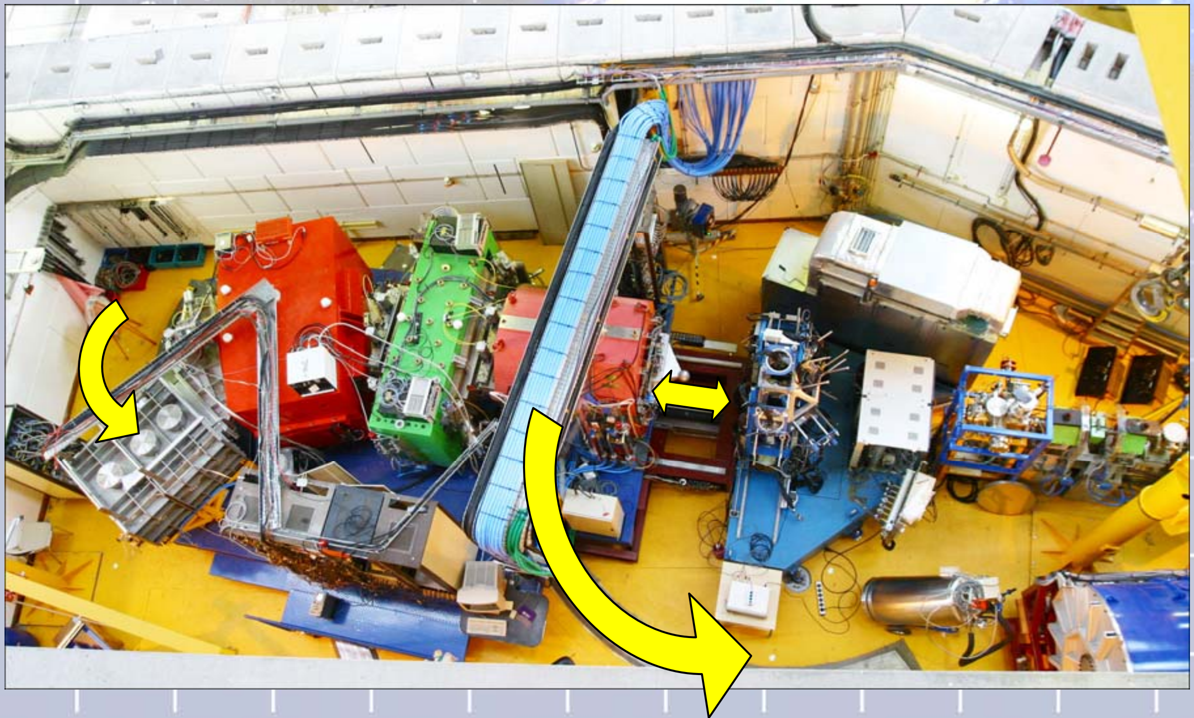




M.Honma et al., Phys. Rev. C 65, 061301.

# The experiment: deep inelastic reaction in inverse kinematics with thin target

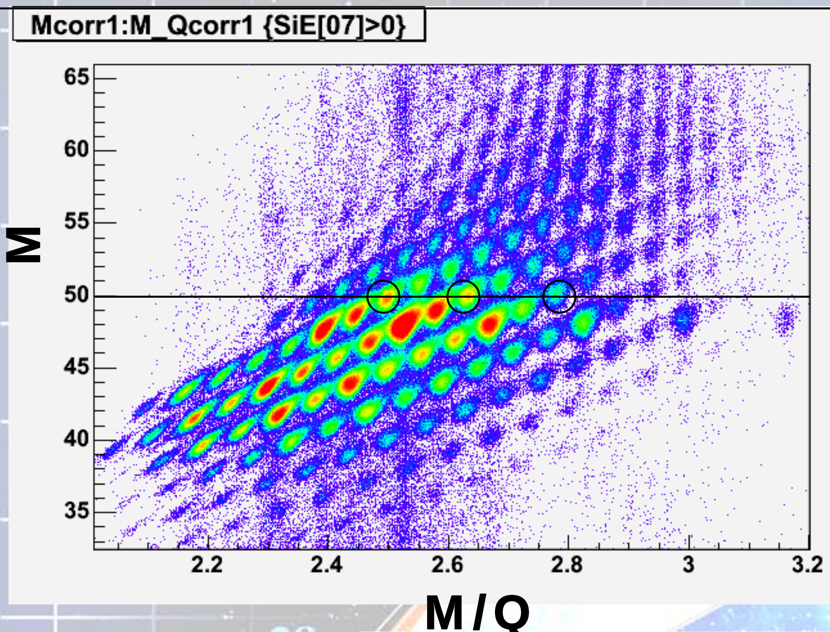
Beam : $^{238}U$ @ 5.5 MeV/u, (i ~ 2pnA)
(N/Z=1.58) ~ 12% above barrier

Target : $^{48}Ca$ (1 mg/cm$^2$)
(N/Z=1.4)

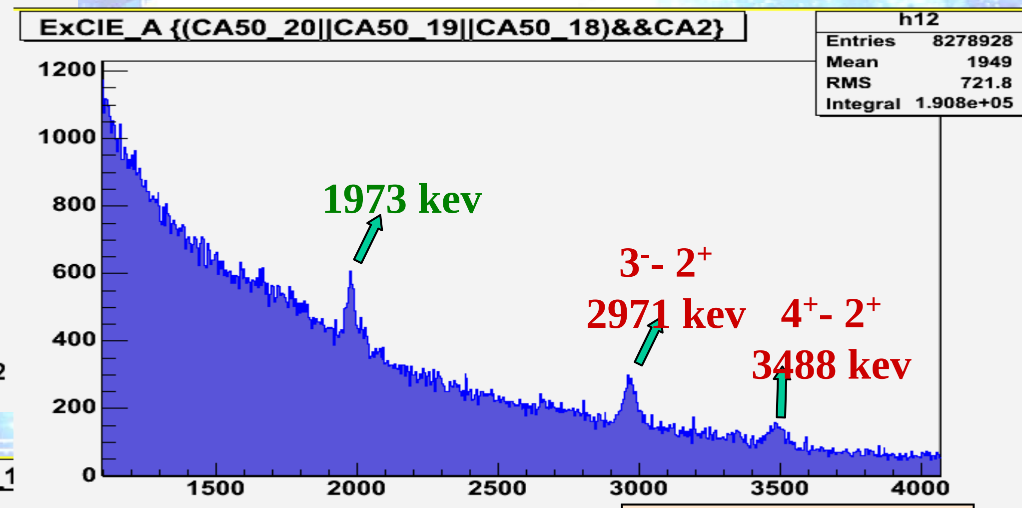


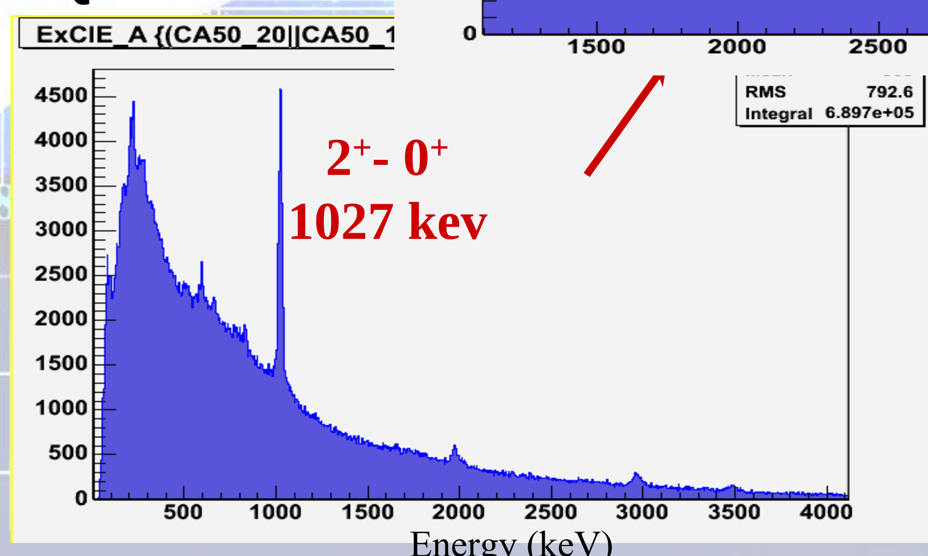
- Grazing angle (lab.) : scattered projectile ~ 11° Recoiling targetlike ~ 40°
- VAMOS + EXOGAM at 35° relative to beam - axis
- Detection of energetic targetlike residues at the focal plane

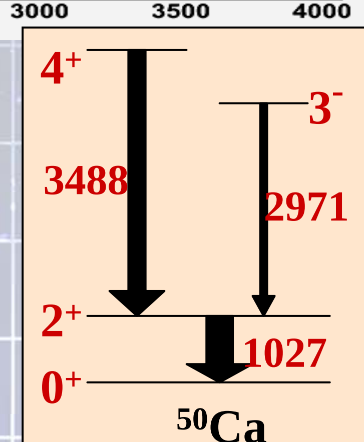
# « Typical » results: $^{50}Ca$




**Gamma-ray spectra gated by Z=20 and Mass=50 for Q=20⁺,19⁺,18⁺**



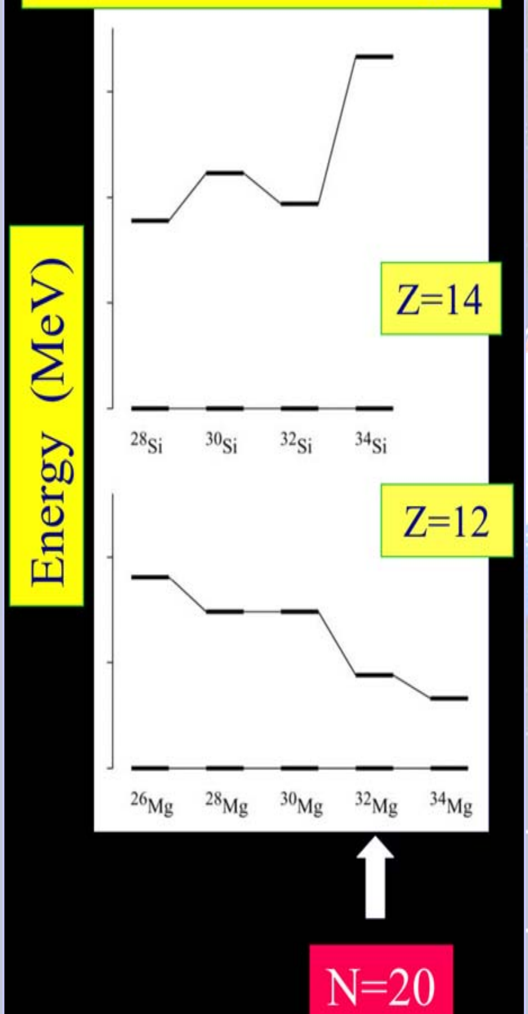

R. Broda et al., 2005

# Outcome:

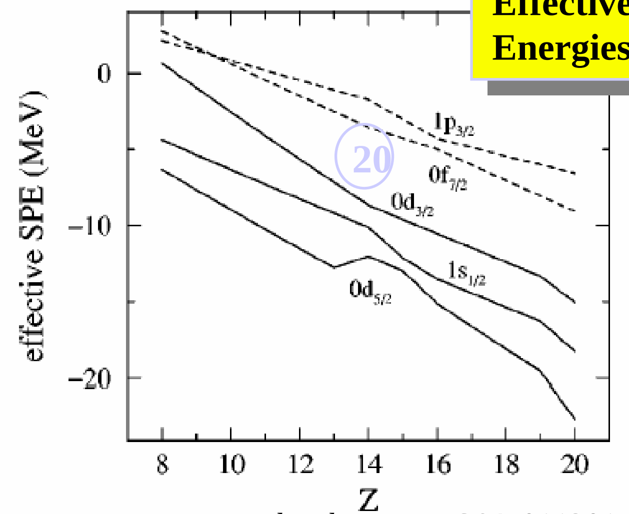
- Technique works very nicely: more γ-rays as compared to usual thick target experiment (γ-rays in $^{52}Ca$; $^{53}Ca$ observed)
- Some improvements envisaged
- But real breakthrouh from « intense » RIBs

# II. N and Z=20: the « island of inversion » and isospin symmetry

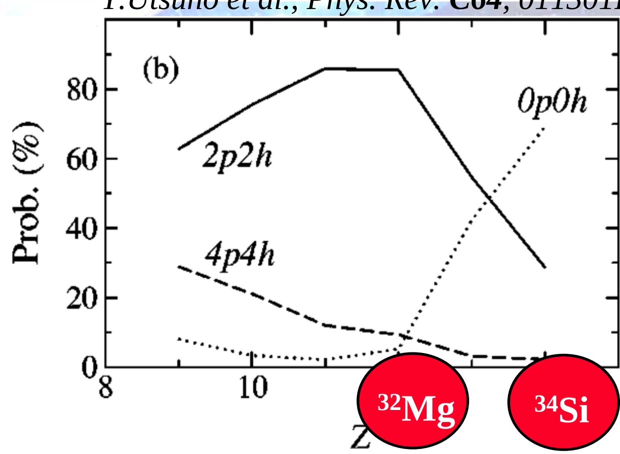
**2+ energies for heavy even-even Si and Mg**




**Effective single-particle Energies for N=20 isotones**

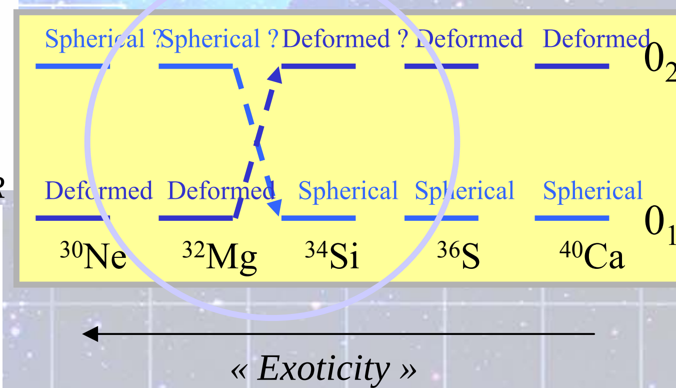



*Y.Utsuno et al., Phys. Rev.* ***C64****, 011301R*




**Probabilities of np-nh configurations for N=20 isotones**

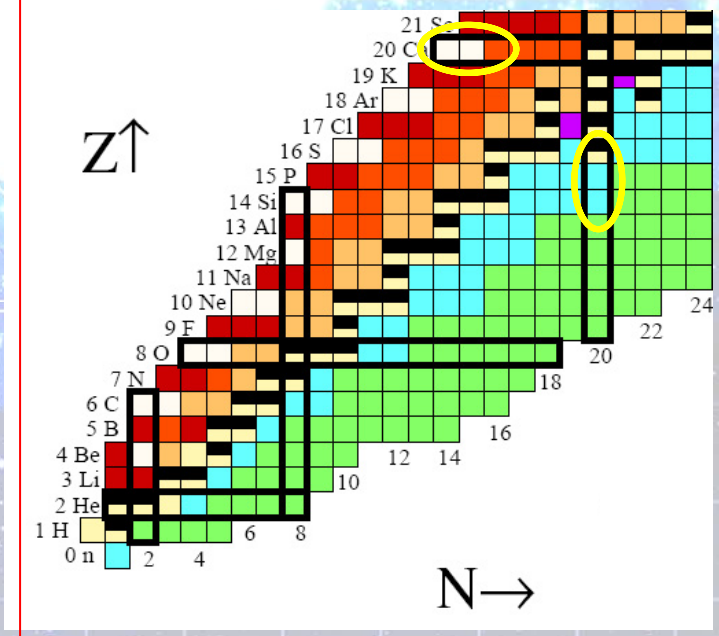
**Island of inversion**




- Mixing of 0p-0h, 2p-2h configurations

# Is there a Z=20 « island of inversion »?

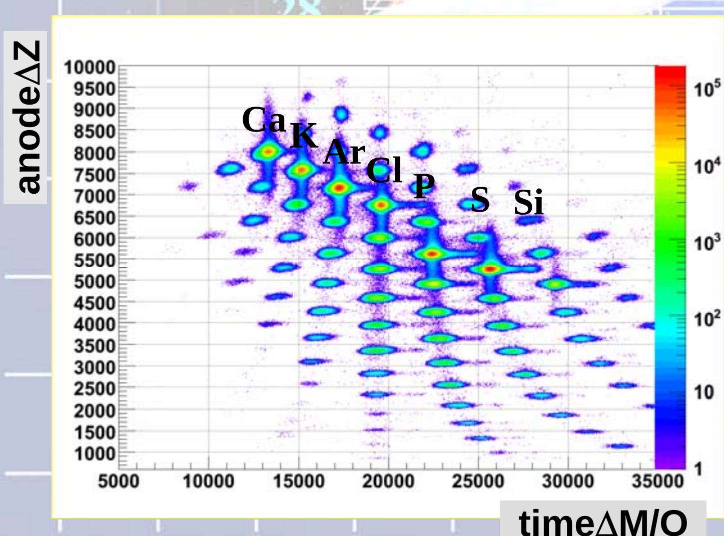
- « Island of inversion » established around N~20
  - Due to *np* interaction (πd5/2-νd3/2)
  - What are the frontiers?
  - What is the nature of the 2nd excited state: 3- or 4+?
- Is there an equivalent around Z~20?
  - The same orbitals are active => same effect?
  - But proton unbound…
  - ***However:*** the same *np* interaction makes $^{34}Si$ and $^{36}S$ « doubly magic »!

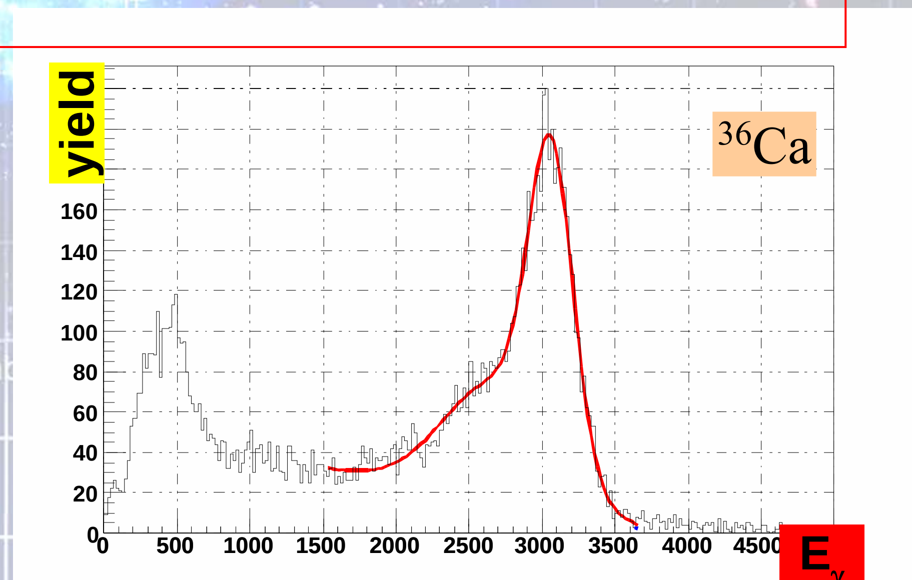



=> $^{34}Ca$ and $^{36}Ca$ should therefore also be « doubly magic »

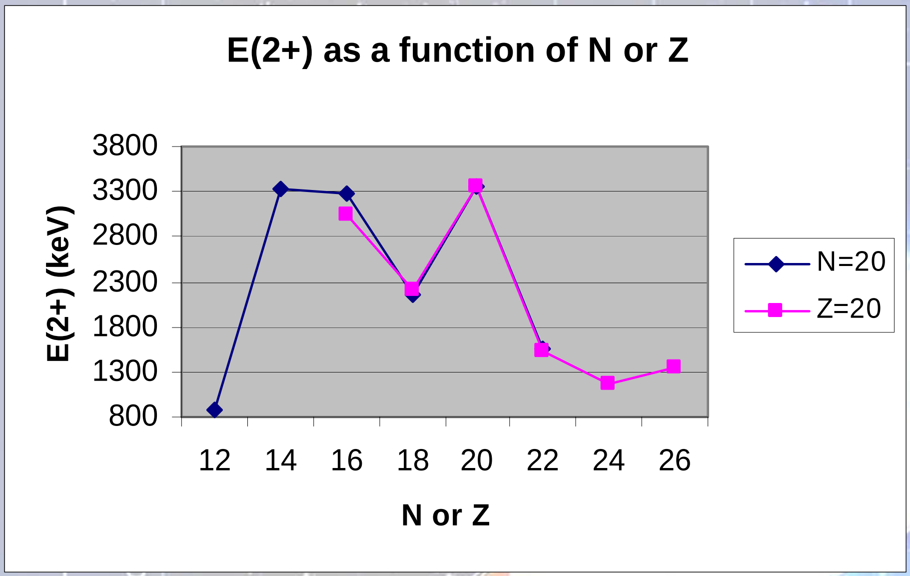
# Experimental technique: double step process

- In-beam γ-spectroscopy of $^{36}Ca$ with 1n removal reactions from $^{37}Ca$ beam:
  - 40Ca ➔ 37Ca ➔ 36Ca
- Search for $^{34}Ca$ using 2n removal reactions from $^{36}Ca$ beam:
  - 40Ca ➔ 36Ca ➔ 34Ca

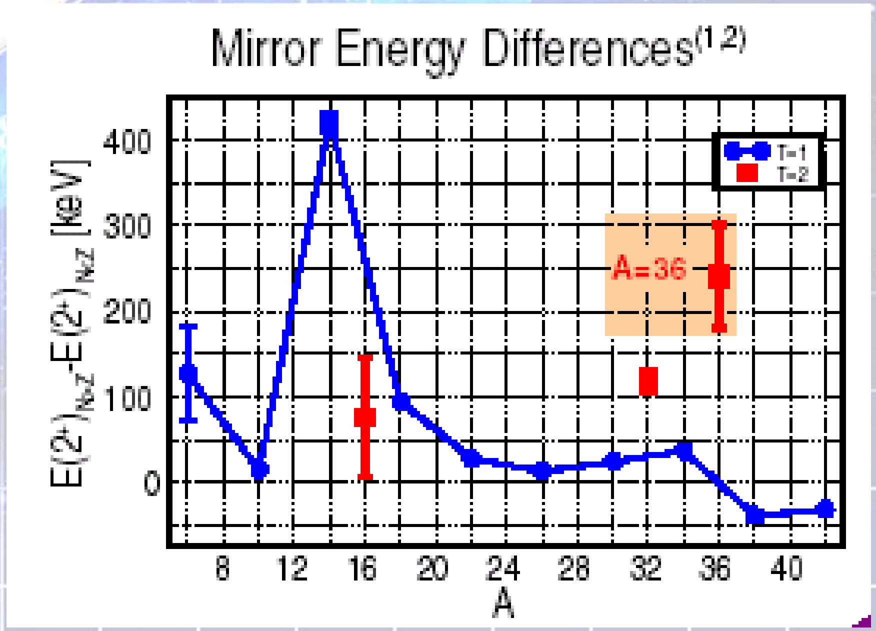


# E(2+) energies for N, Z=20 and MED




- E(2+)=3050(60) keV for $^{36}$Ca
- As magic as $^{36}$S
- E(2+) much lower than in mirror $^{36}$S (3291 keV)



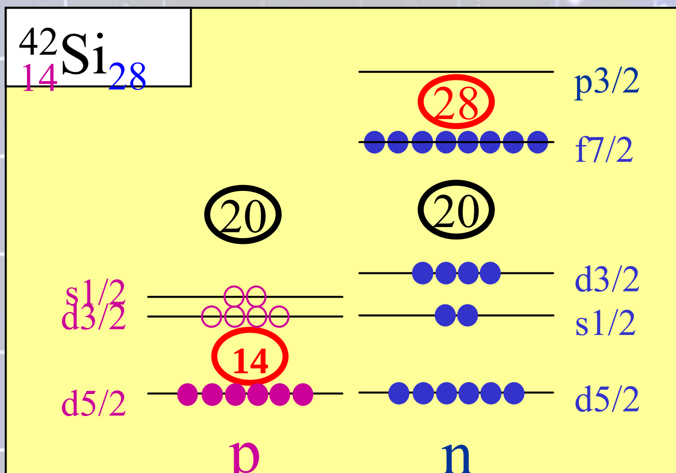
# On-line results

- 2+ state observed in 36Ca with E(2+) > Sp and S2p (~ 2.6 MeV)!
  - Z=20 shell closure very strong ➔ 2+ state is a neutron excitation ➔ decay via gamma
- E(2+) ~ 2.94 MeV i.e. 350 keV lower than its T=2 mirror nucleus $^{36}S$
  - Large MED (120 keV for $^{32}Ar/^{32}Si$) probably due to the pure n(p) configuration of the $2^+$ state in $^{36}Ca(^{36}S)$ and maybe reflecting better the isospin symmetry breaking of the nuclear interaction.

# III.$^{42}$Si: the N=28 shell gap

*S. Grévy et al.*

- Role of the Z=14 sub-shell gap on the proton configuration ?
- Is the gap N=28 robust / reduced / vanished ?



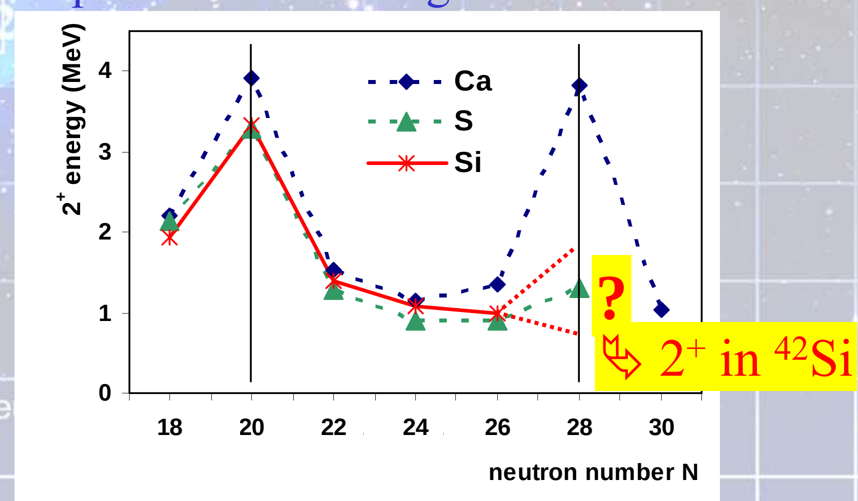

➢ Observation of the $^{43}$Si

*Notani et al. PLB542(2002)*

➢ Measurement of $t_{1/2}$ = 12.5 ±3.5 ms

*Grévy et al. PLB594(2004)*

➢ Experimental $2^+$ energies :




nature Vol 435|16 June 2005|doi:10.1038/nature03619

LETTERS

**'Magic' nucleus $^{42}$Si**

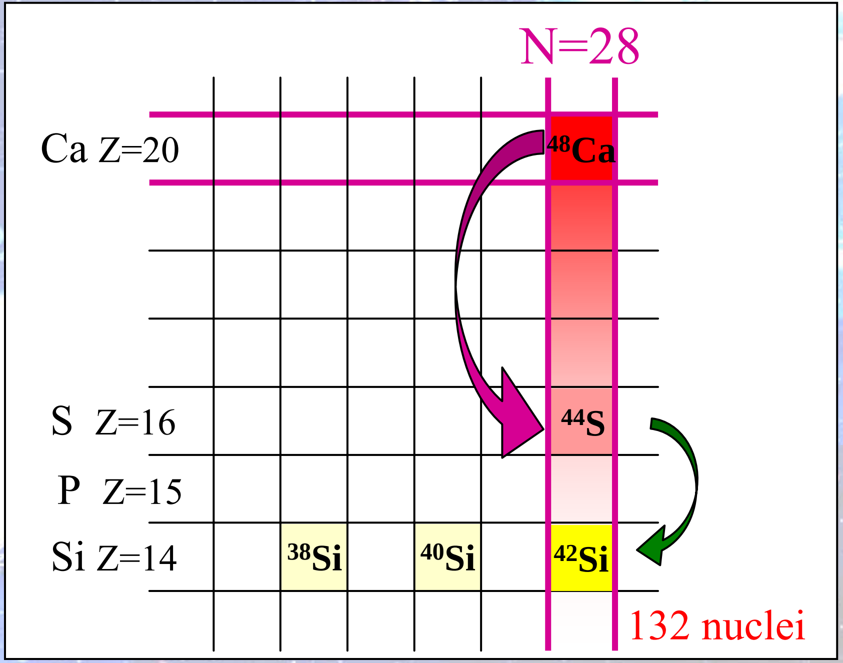
J. Fridmann[1], I. Wiedenhöver[1], A. Gade[2], L. T. Baby[1], D. Bazin[2], B. A. Brown[2], C. M. Campbell[2], J. M. Cook[2], P. D. Cottle[1], E. Diffenderfer[1], D.-C. Dinca[2], T. Glasmacher[2], P. G. Hansen[2], K. W. Kemper[1], J. L. Lecouey[2], W. F. Mueller[2], H. Olliver[2], E. Rodriguez-Vieitez[3], J. R. Terry[2], J. A. Tostevin[4] & K. Yoneda[2]

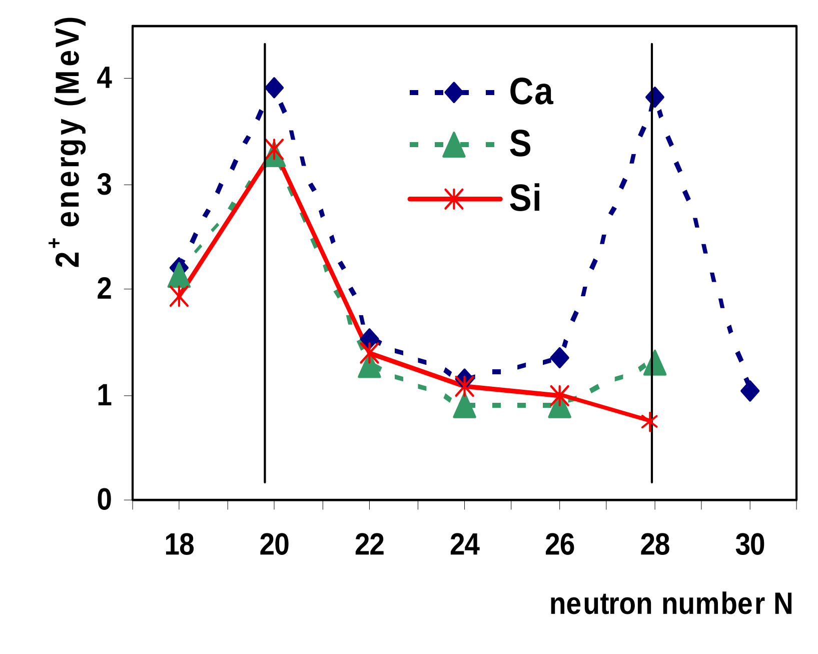
2p-removal cross section: $^{44}S \rightarrow ^{42}Si$

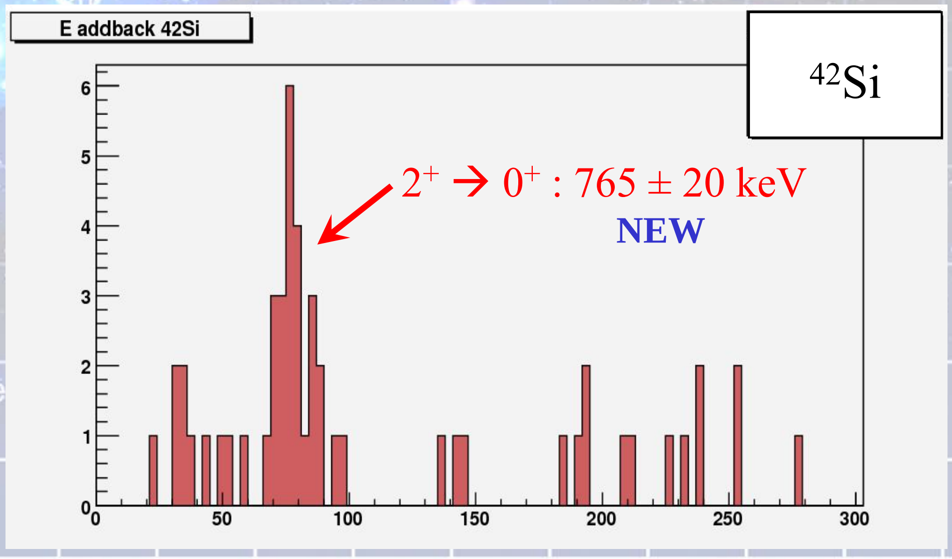
$S_{2p}$=120±20 μb → 'Magic' nucleus $^{42}$Si

# Experimental technique: double step process

$^{48}Ca$ (>$10^{12}$ pps) → $^{44}S$ (100-150 pps) → $^{42}Si^*$ (8/day) → $^{42}Si + \gamma$




**PRELIMINARY** - S. Grévy et al. - GANIL, december 2004

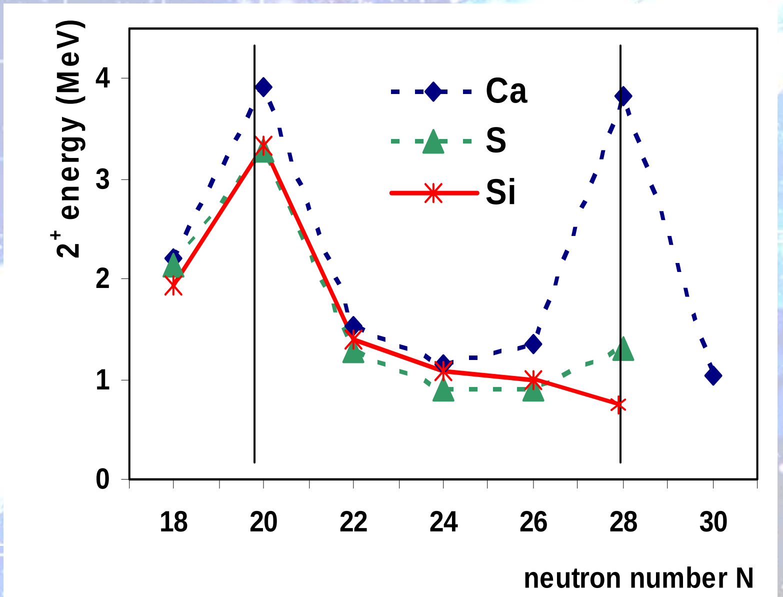
# $^{42}$Si: the N=28 shell gap

- $^{42}$Si observations :
  - $T_{1/2}$ short
  - Very low $2^+$ gamma-ray energy (765 keV)

    → high collectivity

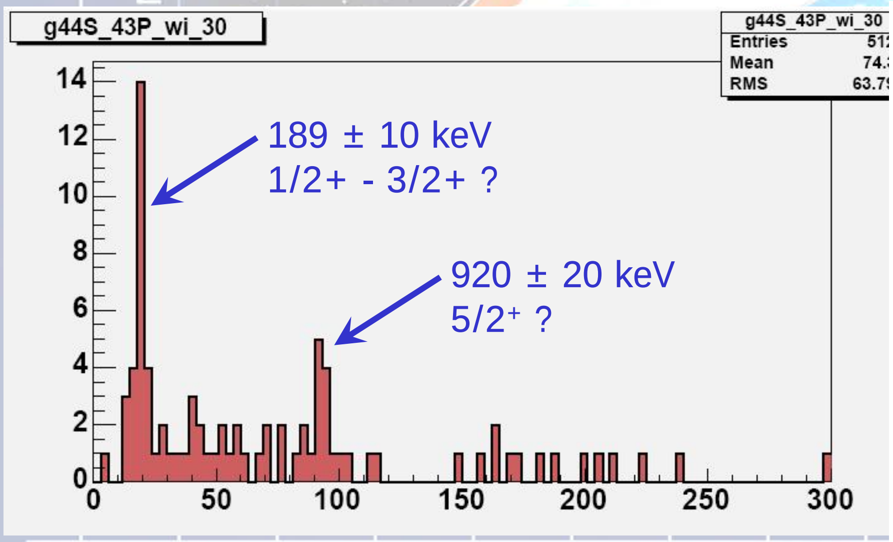
    → deformation

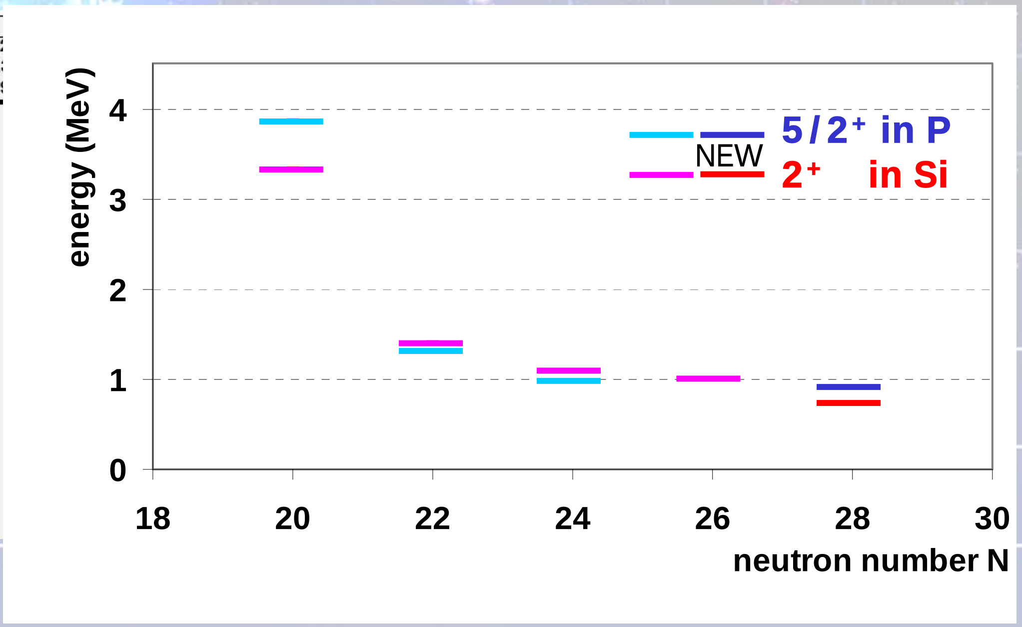
    → no magicity
  - $\sigma_{2p}$ ($^{44}$S->$^{42}$Si) = 81 ± 19 μb




- Same trend observed for 5/2+ in neighboring nucleus $^{43}$P :

$\sigma_{1p}$ ($^{44}$S->$^{43}$P) = 4 ± 1 mb



# $^{42}$Si: SM calculations

Modifications of the interaction to fit the data:

- pairing reduced by 300 keV to reproduce exp. 2+ in $^{36}$Si
- $d_{5/2}$-fp shell monopole reduced to obtain Z=14 gap at 5.8 MeV

With this interaction:

- all Si isotopes OK
- $5/2^+$ in $^{35}$P OK
- $2^+$($^{42}$Si): 810 keV
- the $2^+$ in $^{42}$Si is a mixing of nh-np exitations for both p and n
- $\beta_2 \sim - 0.4$

# IV- Topics studied with SPIRAL beams

## -I- Beams of Borromean nuclei

- Full p-shell and a new excited state in $^{8}He$
- s-p inversion in $^{9}He$
- No signal from 4n
- Super heavy hydrogen : $^{7}H$
- Reaction with halo nuclei

## -II- Magicity and interaction

- Shells around N=14 from $^{24}Ne(d,p)^{25}Ne$
- Shells around N=16 from $^{26}Ne(d,p)^{27}Ne$
- Shells around N=28 from $^{46}Ar(d,p)^{47}Ar$

## -III- Shapes and coexistence

- Coulomb excitation of $^{74}Kr$

## -IV- Spectroscopic studies for astrophysics

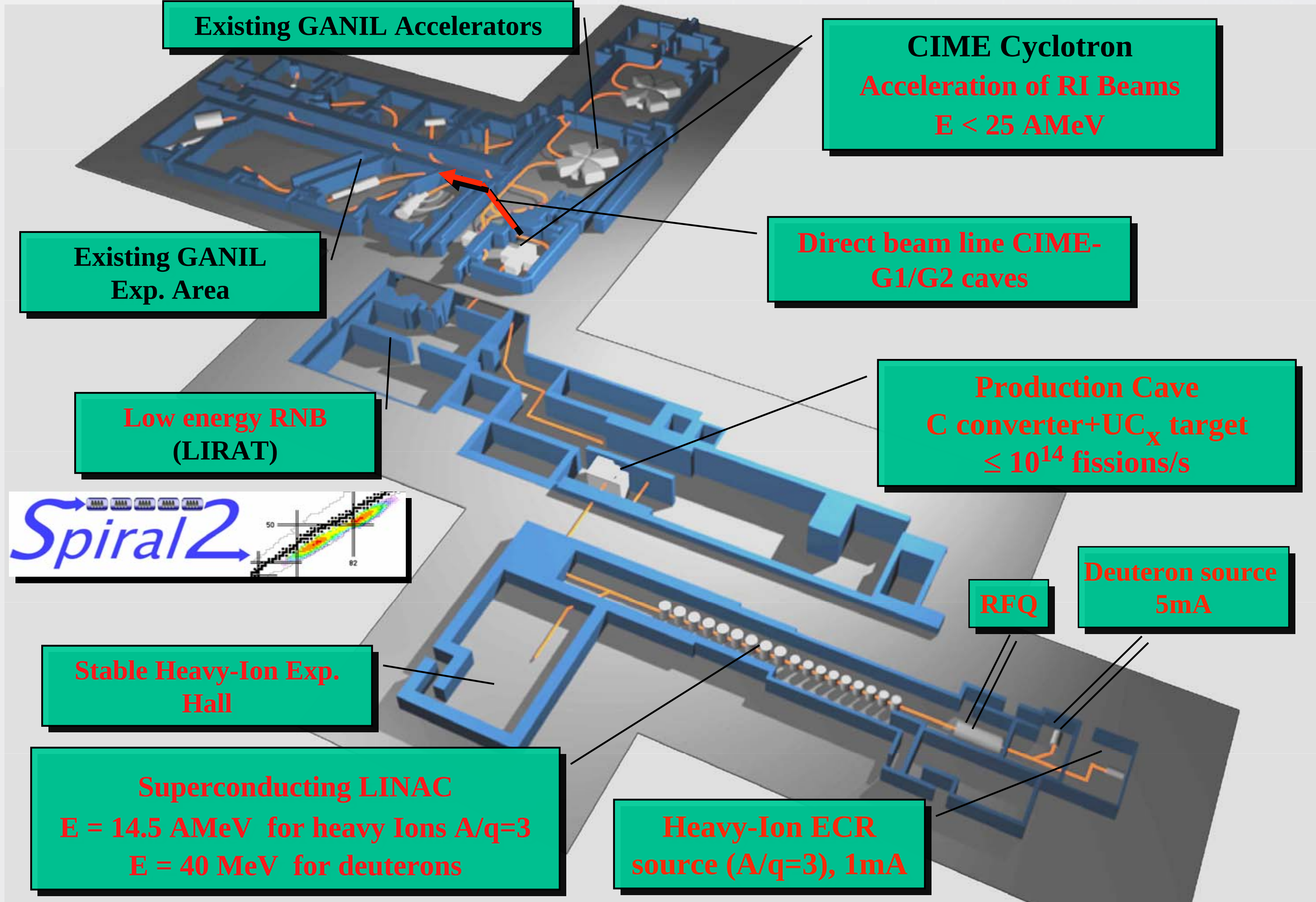
- Resonant scattering in $^{18}Ne+p \Rightarrow {}^{19}Na$ and $^{15}O+\alpha \Rightarrow {}^{19}Ne$
- Resonant scattering $^{15}O+ p \Rightarrow {}^{16}F$

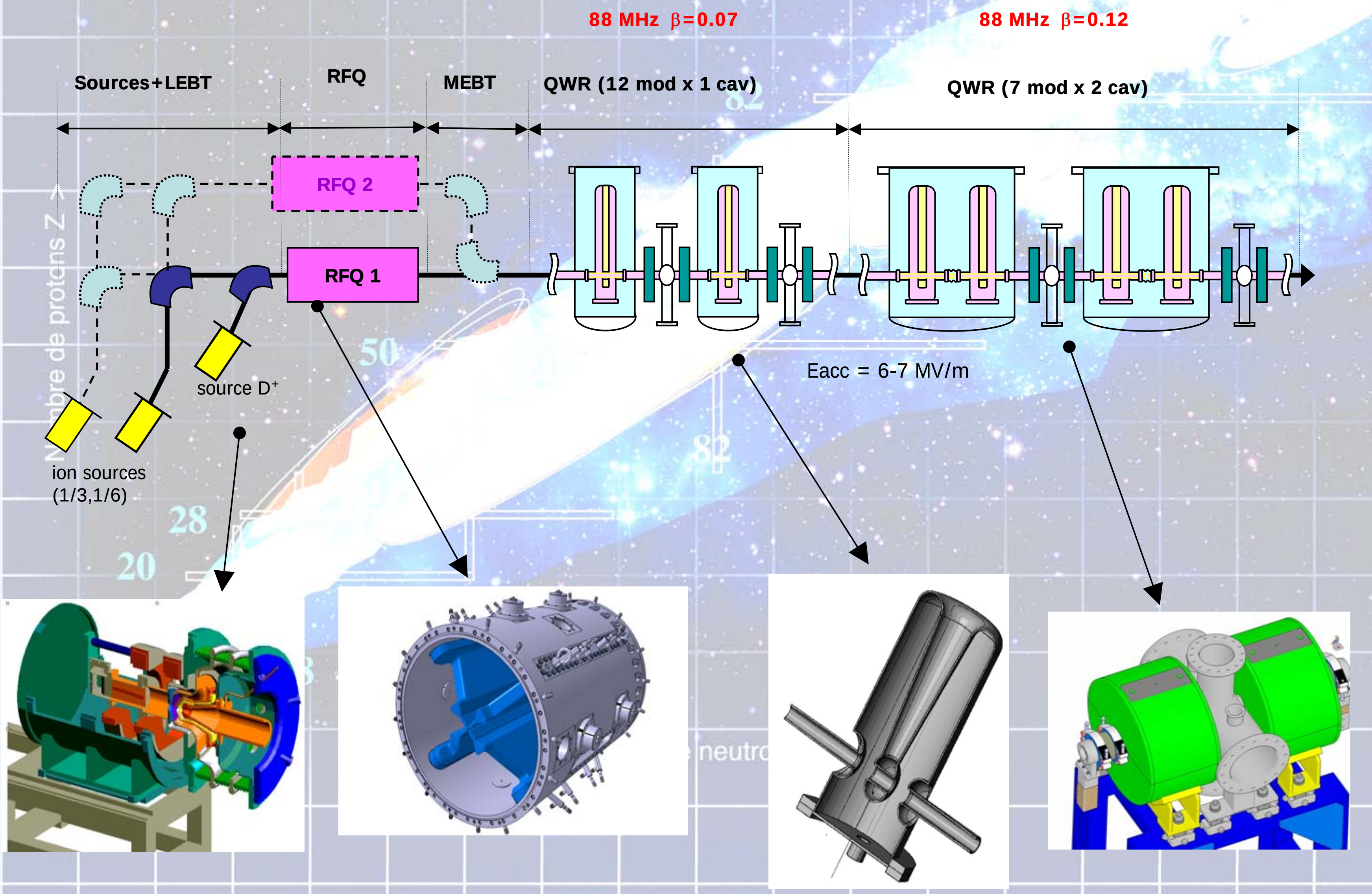
## -V- Fundamental interaction

- First measure of β - nucleus (β - ν) correlation in a trap

# C. Nuclear structure at GANIL tomorrow : the SPIRAL2 project


http://www.ganil.fr/


Existing GANIL Accelerators
CIME Cyclotron
Acceleration of RI Beams
E < 25 AMeV
Existing GANIL Exp. Area
Direct beam line CIME-G1/G2 caves
Low energy RNB (LIRAT)
Production Cave
C converter+UCx target
≤ 10^14 fissions/s
Spiral2
Deuteron source 5mA
RFQ
Stable Heavy-Ion Exp. Hall
Superconducting LINAC
E = 14.5 AMeV for heavy Ions A/q=3
E = 40 MeV for deuterons
Heavy-Ion ECR source (A/q=3), 1mA



88 MHz β=0.07
88 MHz β=0.12
Sources+LEBT
RFQ
MEBT
QWR (12 mod x 1 cav)
QWR (7 mod x 2 cav)
RFQ 2
RFQ 1
source D+
ion sources
(1/3,1/6)
Eacc = 6-7 MV/m

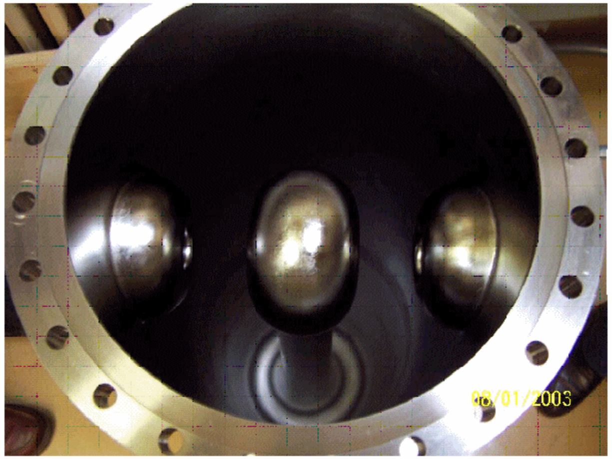
# Linac Accelerator

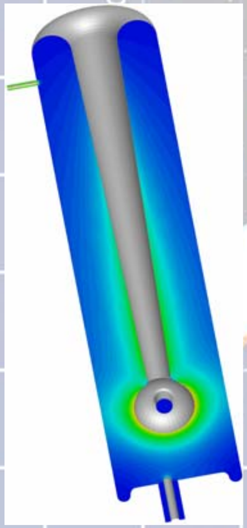
## -Accelerator design: sources, RFQ, superconducting linac

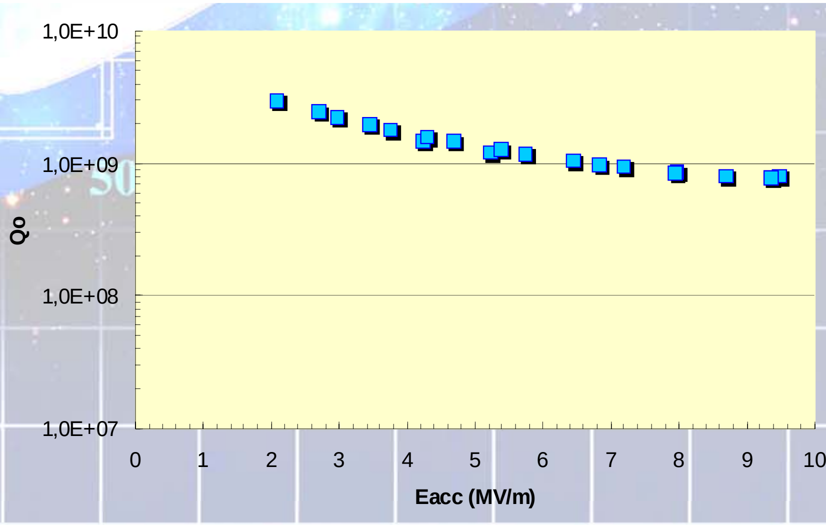
## RF systems

Quarter-wave resonators
2 cavity prototypes were constructed and tested in Nov.2004-Feb.2005

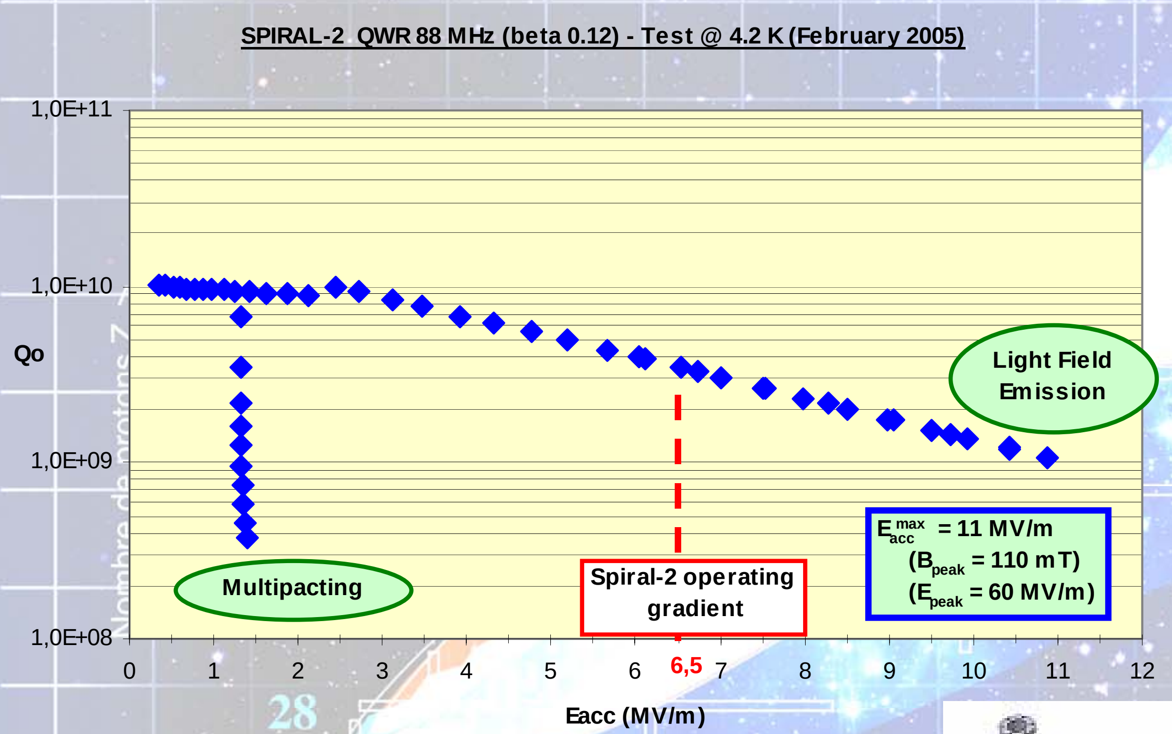

β 0.07 cavity prototype

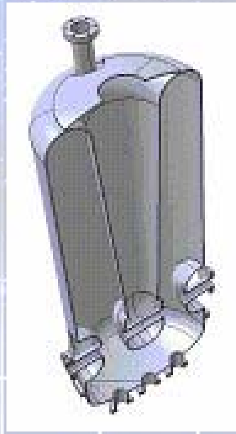




# Linac Accelerator



High beta cavity

# Production target development

## Carbon converter

-Receives a 200 kW 20 A.MeV $D^+$ beam

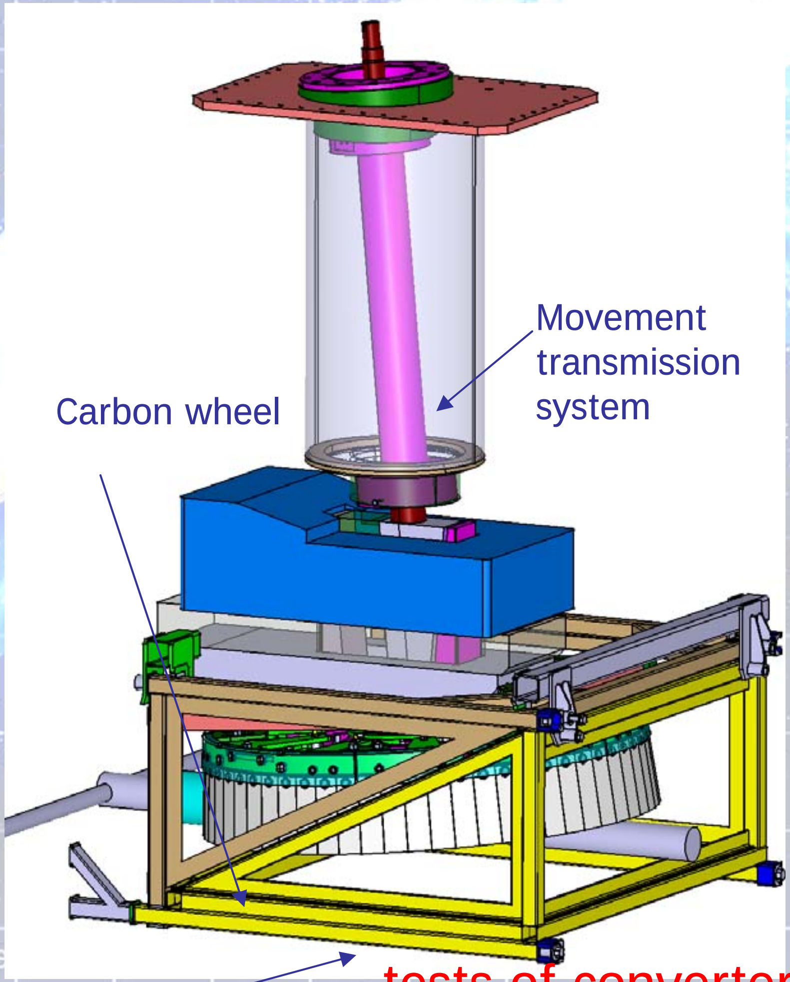
-set of graphite pieces
 fixed together around a 1m diameter structure

-rotation speed: 200 to 400 r.p.m

-T°:1700°C

| | SPIRAL2 | PSI |
|---|---|---|
| Pmax | 200 kW | 60 kW |
| Diameter | 1 m | 0.45 m |
| Pradiation | 53 W/cm$^2$ | 35 W/cm$^2$ |
| T max | 1750°C | 1527°C |

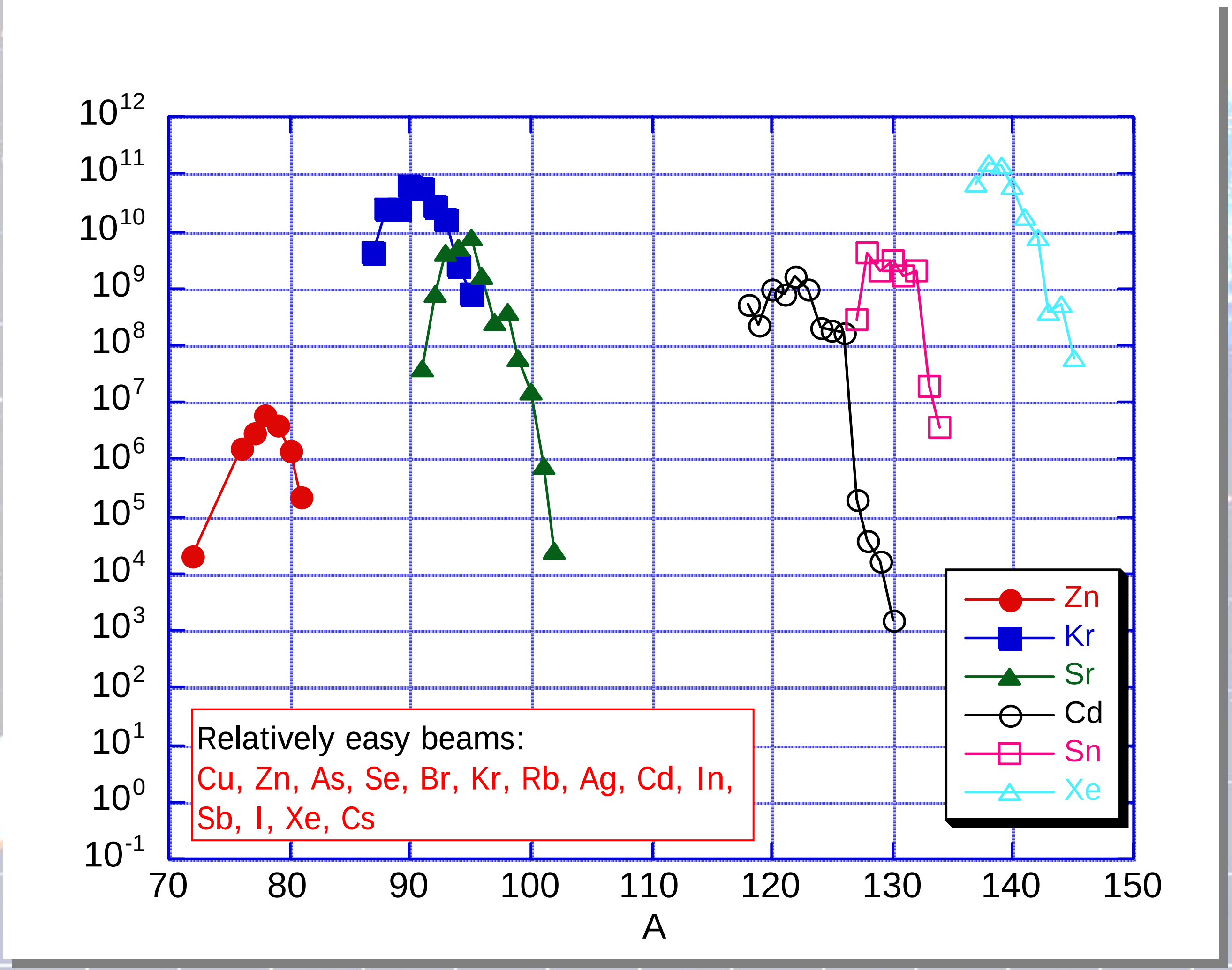
to limit the C evaporation




- tests of converter ball-bearings to be done

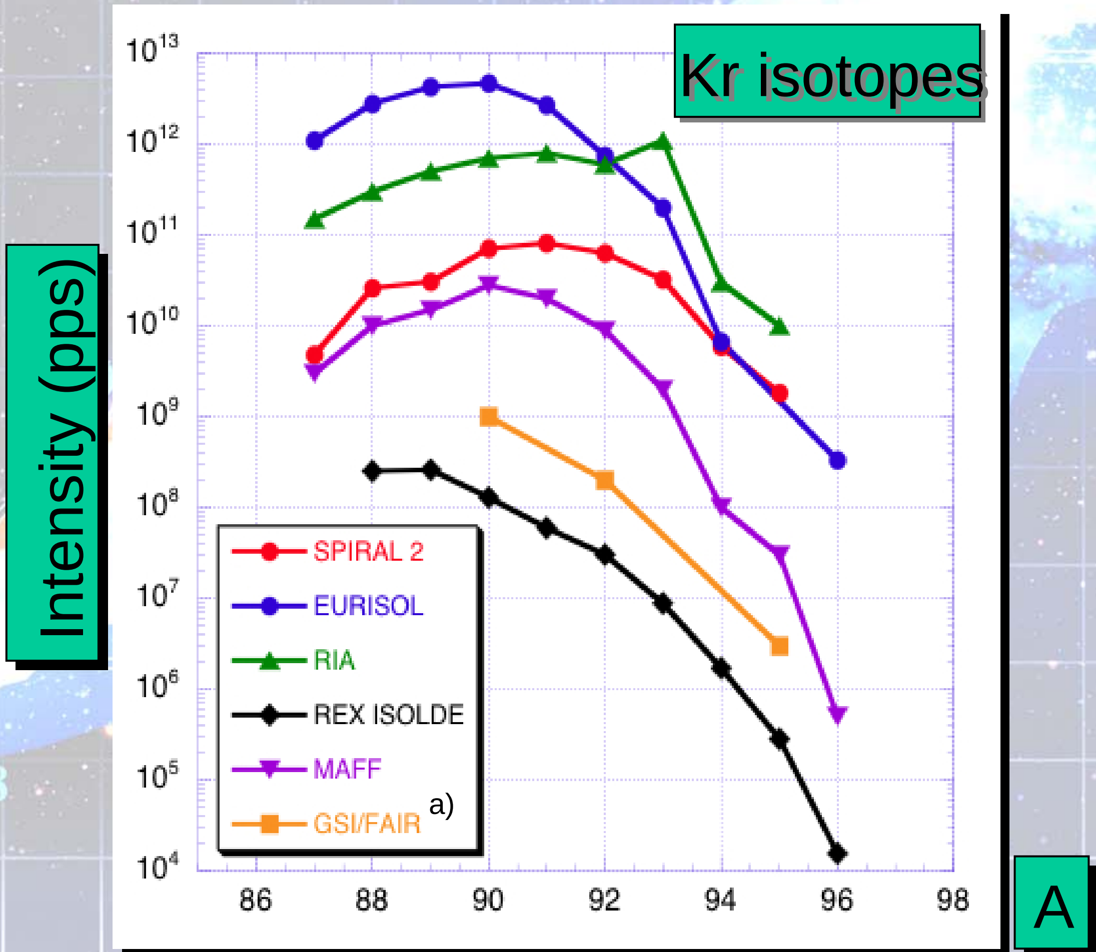
## Performances:

## Accelerated FF beam intensities (pps) - Examples



# Performances:

## SPIRAL 2 yields for $10^{14}$ fissions/s after acceleration compared to other RNB facilities (best numbers for all)




a) Yield for in-flight production of fission fragments at relativistic energy

Performances:

Other possible RNB production mode

## Production of N=Z, light and heavy nuclei

p,d,HI → Thick target

Fusion-evaporation and transfer reactions

Residues produced by thick target method (like GSI mass separator)

Example: $^{100}Sn^{1+}$

HI → Recoil Separator

Fusion-evaporation residues produced by thin target method (In-flight)

Ex: $^{24}Mg(25p\mu A)+^{58}Ni \rightarrow ^{80}Zr^{1+}$ $3x10^4/s$

***But also:***

$^{134}Sn + ^{48}Ca \rightarrow ^{182}Yb$ $^{130}In + ^{48}Ca \rightarrow ^{178}Tm$

# Performances

## Light High Intensity RIB

Halo Nuclei

| Isotope | A/Z | $T_{1/2}$, s | Production reaction |
|---|---|---|---|
| **$^{6}$He** | **3** | **0.81** | **$^{9}$Be(n,$\alpha$)$^{6}$He** |
| **$^{8}$He** | **4** | **0.12** | **$^{9}$Be($^{13}$C,$^{14}$O)$^{8}$He** |
| $^{8}$Li | 2.7 | 0.84 | $^{11}$B(n,$\alpha$)$^{8}$Li or $^{9}$Be(d,$^{3}$He)$^{8}$Li |
| $^{9}$Li | 3 | 0.18 | $^{11}$B(n,$^{3}$He)$^{9}$Li or $^{9}$Be($^{7}$Li,$^{7}$Be)$^{9}$Li |
| **$^{11}$Be** | **2.8** | **13.8** | **$^{11}$B(n,p) $^{11}$Be** |
| $^{15}$C | 2.5 | 2.45 | $^{9}$Be($^{7}$Li,p)$^{15}$C |
| $^{16}$N | 2.3 | 7.13 | $^{16}$O(n,p)$^{16}$N or $^{10}$B($^{7}$Li,p)$^{16}$N |
| $^{18}$N | 2.6 | 0.62 | $^{18}$O(n,p)$^{18}$N |
| $^{19}$O | 2.4 | 26.9 | $^{19}$F(n,p)$^{19}$O |
| $^{20}$O | 2.5 | 13.5 | $^{19}$F(n,$\gamma$)$^{20}$O or $^{19}$F(d,n)$^{20}$O |
| $^{23}$Ne | 2.3 | 37.2 | $^{19}$F($^{6}$Li,2p)$^{23}$Ne or $^{24}$Mg(n,2p)$^{23}$Ne |
| $^{25}$Ne | 2.5 | 0.6 | $^{26}$Mg($^{13}$C,$^{14}$O)$^{25}$Ne or $^{26}$Mg(n,2p)$^{25}$Ne |
| $^{27}$Si | 1.9 | 4.16 | $^{27}$Al(d,2n)$^{27}$Si |

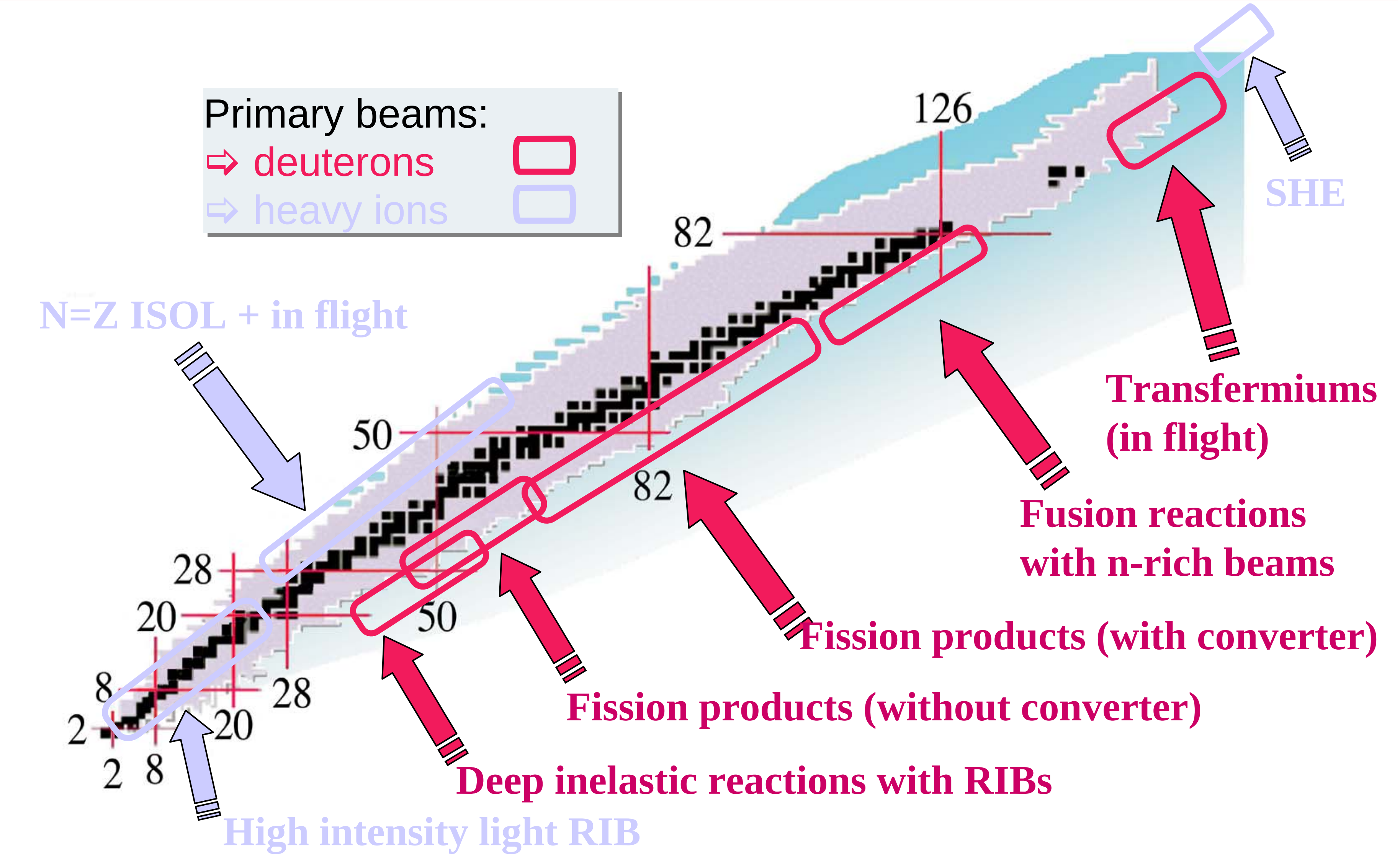
| Isotope | A/Z | $T_{1/2}$, s | Production reaction |
|---|---|---|---|
| $^{8}$B | 1.6 | 0.77 | $^{12}$C(p,$\alpha$n)$^{8}$B |
| $^{10}$C | 1.7 | 19.3 | $^{11}$B(p,2n)$^{10}$C |
| $^{11}$C | 1.8 | 1224 | $^{11}$B(p,n)$^{11}$C or $^{14}$N(p,$\alpha$)$^{11}$C |
| $^{13}$N | 1.9 | 598 | $^{12}$C(d,n)$^{13}$N or $^{13}$C(p,n)$^{13}$N |
| $^{14}$O | 1.8 | 70.6 | $^{14}$N(d,2n)$^{14}$O or $^{14}$N(p,n)$^{14}$O |
| $^{15}$O | 1.9 | 122 | $^{14}$N(d,n)$^{15}$O or $^{15}$N(p,n)$^{15}$O |
| $^{17}$F | 1.9 | 64.5 | $^{16}$O(d,n)$^{17}$F or $^{14}$N($\alpha$,n)$^{17}$F |
| $^{18}$Ne | 1.8 | 1.67 | $^{19}$F(p,2n)$^{18}$Ne |
| $^{19}$Ne | 1.9 | 17.3 | $^{19}$F(p,n)$^{19}$Ne |
| $^{21}$Na | 1.9 | 22.4 | $^{19}$F($^{3}$He,n)$^{21}$Na |
| $^{25}$Na | 2.3 | 59.1 | $^{25}$Mg($^{12}$C,$^{12}$N)$^{25}$Na or $^{25}$Mg(n,p)$^{25}$Na |
| $^{26}$Na | 2.4 | 1.08 | $^{26}$Mg(d,$^{2}$He)$^{26}$Na or $^{26}$Mg(n,p)$^{26}$Na |
| $^{35}$Ar | 1.9 | 1.77 | $^{35}$Cl(p,n)$^{35}$Ar |

In-target (1liter volume) production yields:

$^{9}$Be(n,$\alpha$)$^{6}$He ~ $10^{13}$ pps

$^{14}$N(d,n)$^{15}$O ~ $10^{12}$ pps

# Regions of interest accessible with SPIRAL2 beams




See white paper at http://www.ganil.fr/

# Some tentative key dates:

- Reference solution: November ’06
- Delivery of draft safety document: September ’07
- Test accelerator July ’11
- Test production July ‘12

## Total cost: 135 M€

# Conclusions:

- Many new results on the structure of exotic nuclei which renew the field

-SPIRAL facility is reliable, gave and will give a lot of new results. Beam development to bridge first SPIRAL2.

-SPIRAL 2 is on the way