# In-beam gamma-ray spectroscopy of exotic nuclei

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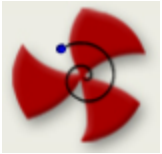
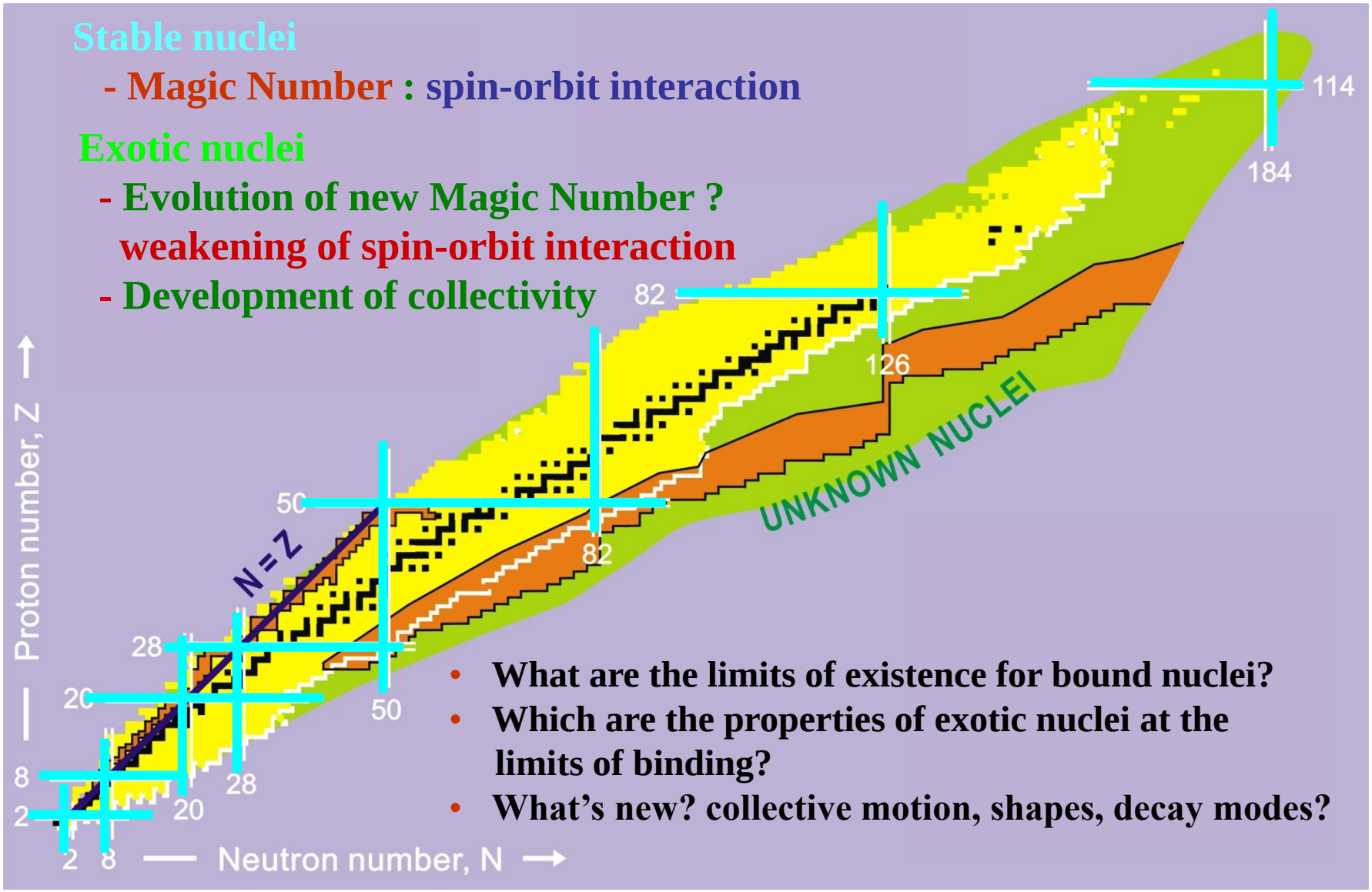
*Variable Energy Cyclotron Centre*
*Kolkata*



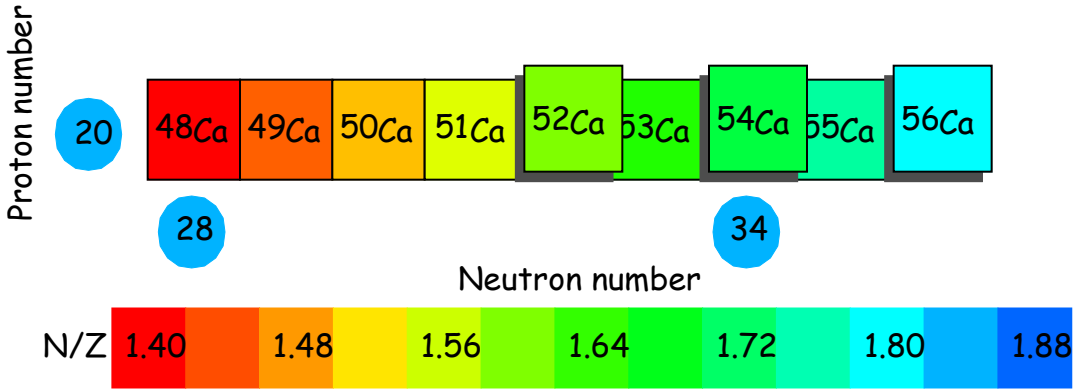
**Plan of the talk :**

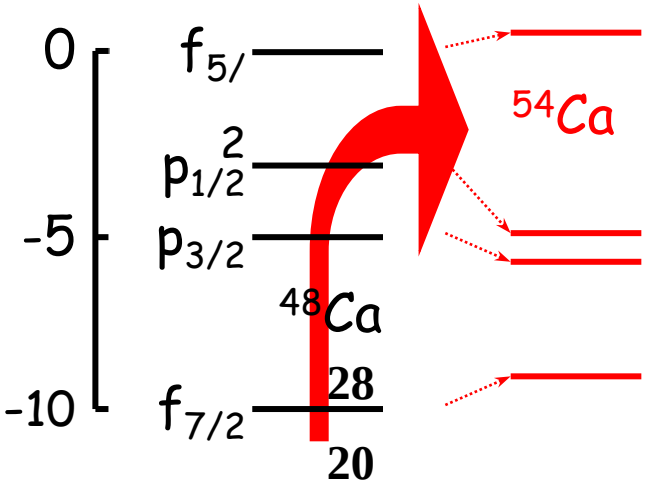
- Physics interest in exotic nuclei
- Neutron rich Ca and Ar isotopes beyond N=28
- Neutron rich nuclei around N=20
  - Deep-inelastic reaction with RIB
  - Transfer reactions with RIB after fragmentation
- Possibilities at ISOLDE

# What is happening away from stability ?

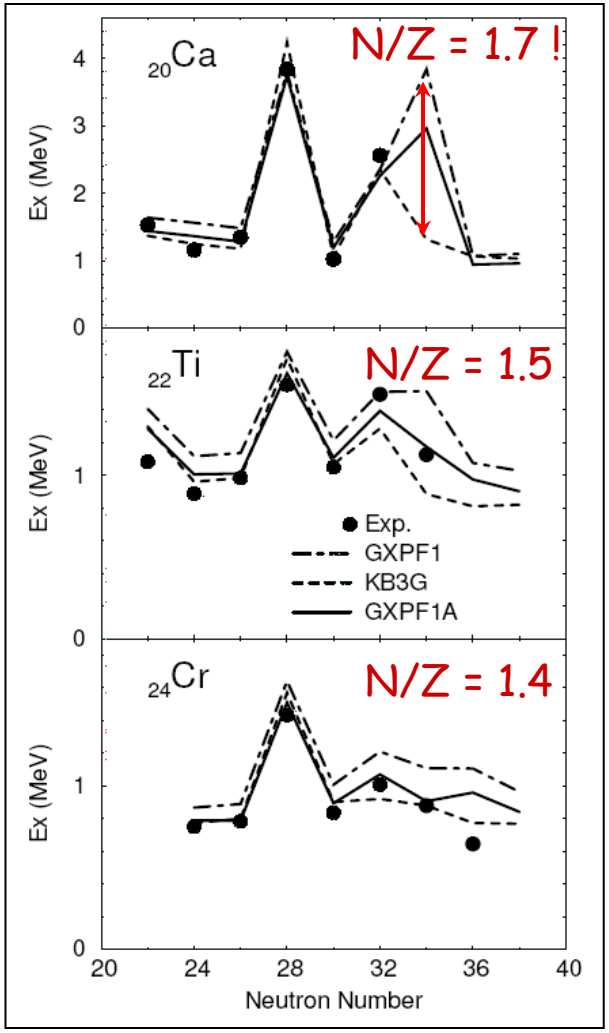


# Neutron rich Ca isotopes : question of N=34 gap



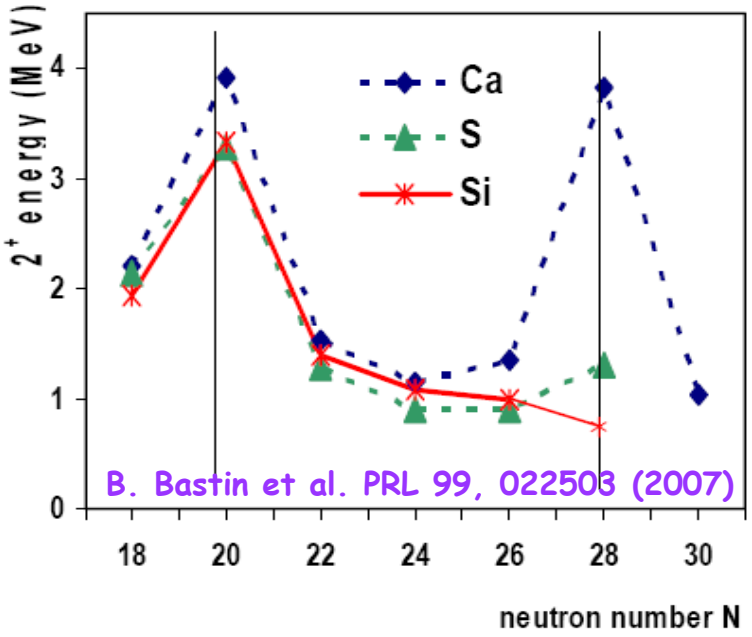

**Pronounced shell gap in $^{54}Ca$ ?**




*M. Honma et al, EPJ A25, 499, 2005.*

# New region of deformation near N=28

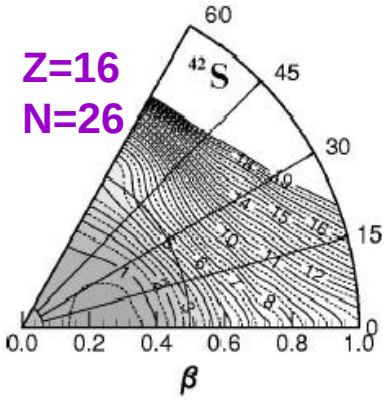
## Breakdown of N=28 shell gap at Z=14




→ high collectivity

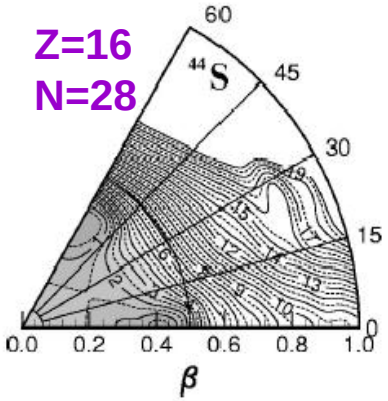
→ strong deformation (β=0.45)

→ no magicity




γ-soft

D. Sohler *et al.*
PRC 66, 054302 (2002)




Shape mixing in low energy states

Coexistence of 1p-1h and 2p-2h Configuration

D. Santiago-Gonzalez et al
PRC, 83, 061305(R) (2011)

Erosion of N=28 shell closure at Z=16

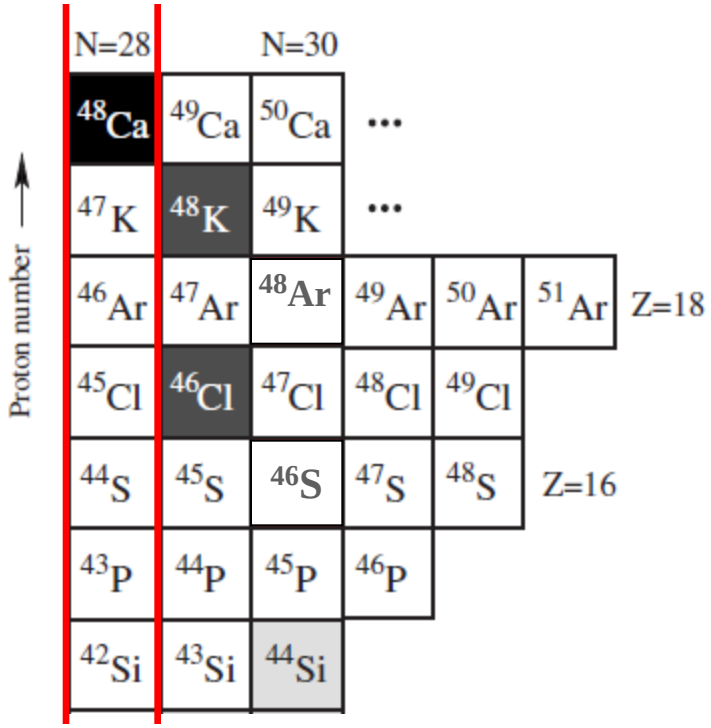
# Development of collectivity near N=28

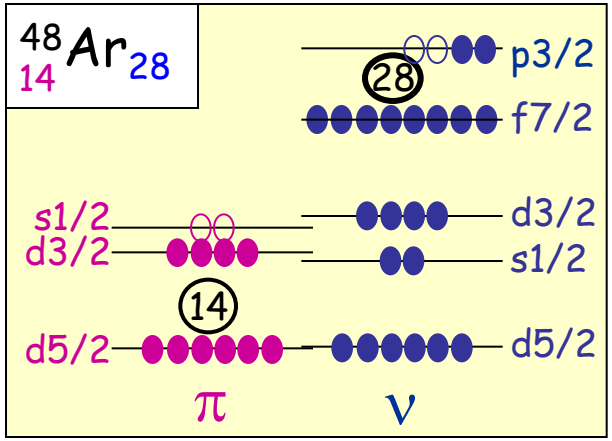
spherical

onset of deformation

shape coexistence

well deformed (axial)




- ✓ Strong presence of $N_{ph}$ excitations from $vf_{7/2}$ orbital
- ✓ Role of neutron proton correlation on collective motion
- ✓ Strong quadrupole interaction between Protons in sd and neutrons in pf
- ✓ Rapid development of collectivity

# Deep inelastic reaction with stable heavy beam @ GANIL
# Production of neutron-rich nuclei around Z=20

$^{238}U$ @ 5.5 MeV/u
(N/Z=1.58)
~ 12% above barrier

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

VAMOS
VARIABLE MODE SPECTROMETER

EXOGAM
- GANIL -

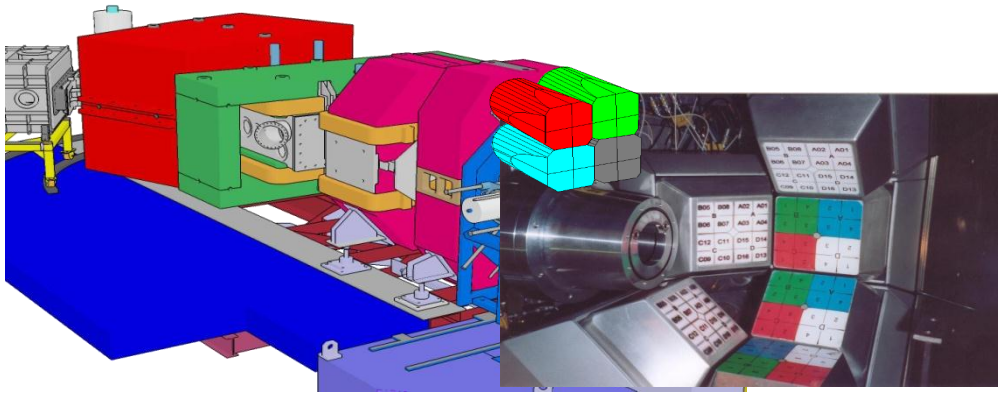
11 Nos. segmented Clover detectors
High v/c (~ 14%) of fragments

*Accurate Doppler correction is must !!*

Determination of Angle event by event

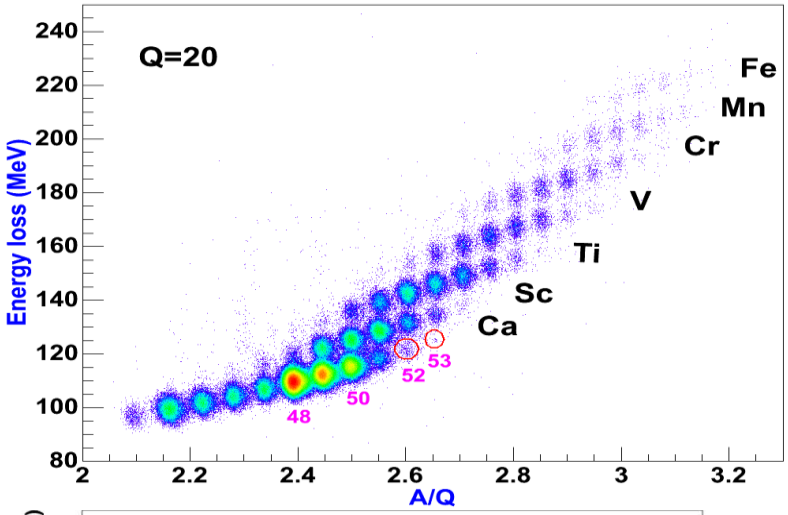
Velocity of fragment (VAMOS Reconstruction)

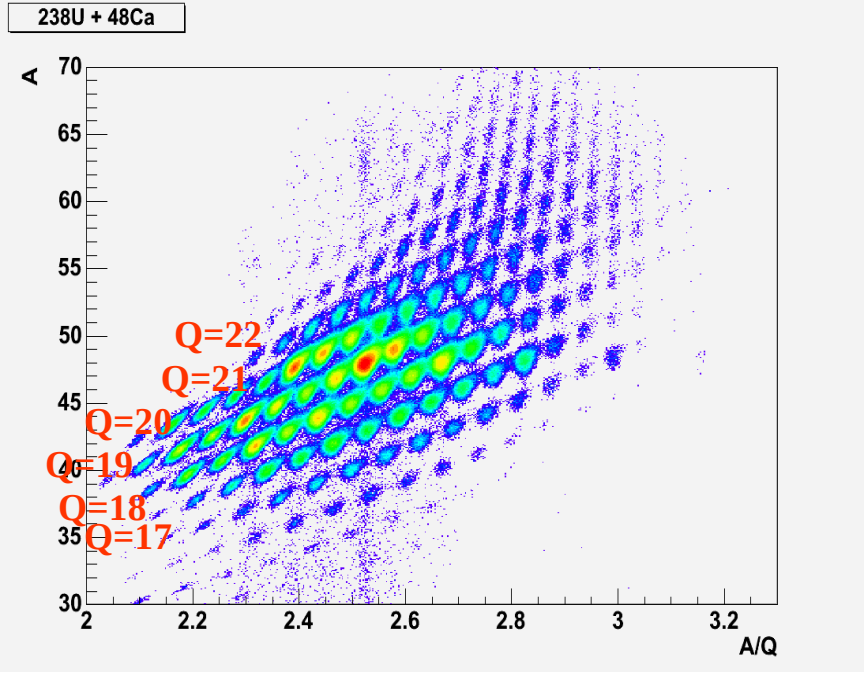
and segments of EXOGAM Clover

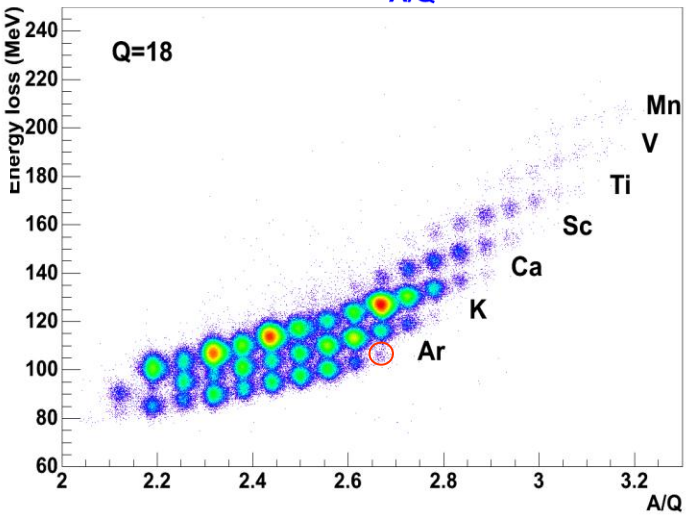



***Collaboration:***

*M. Rejmund, S. Bhattacharyya , A. Navin, W. Mittig, L. Gaudefroy, M. Gelin, G. Mukherjee, F. Rejmund, P. Roussel-Chomaz, (GANIL, France)*
*Ch. Theisen (CEA, Sacley, France)*
*E. Caurier, F. Nowacki,* M. Rousseau *(IPHC, Strasbourg)*
*A. Poves (IFT/CSIC, Universidad Autonoma de Madrid, Spain)*
A. Hodsdon, X. Liang, R. Chapman, D. O'Donnell, K.-M. Spohr *(Paisley, Scotland, UK)*

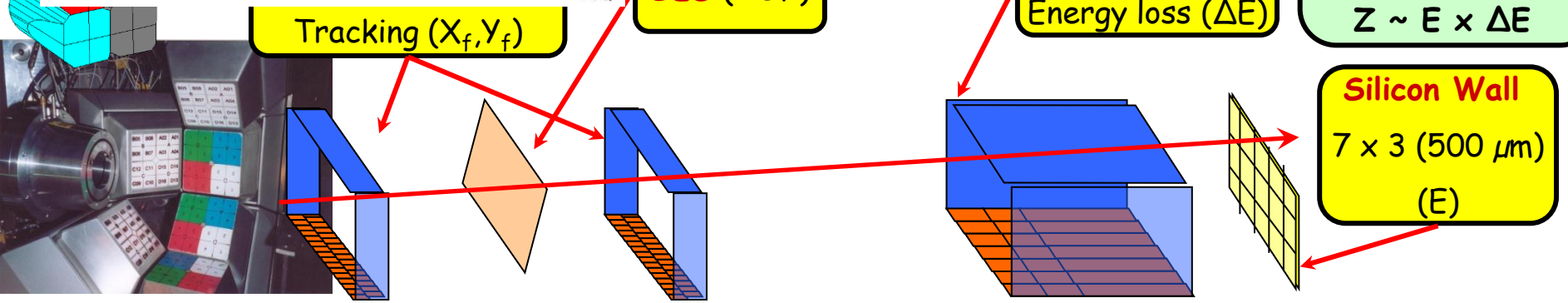


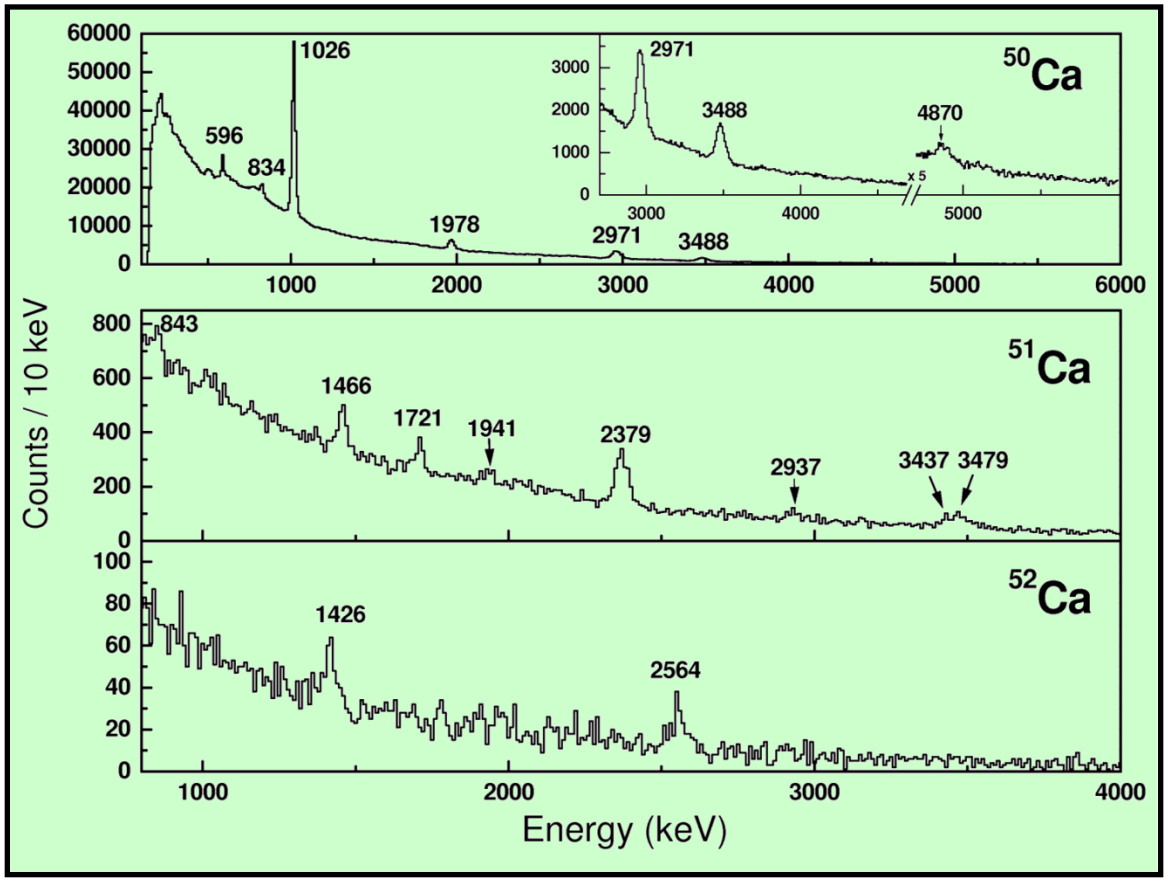




*-2p+2n* $^{48}Ar+^{238}Th$
*-1p+0n* $^{49}K+^{237}Np$
*0p+4n* $^{52}Ca+^{234}U$
*+1p+0n* $^{53}Sc+^{233}Pa$
*+2p+6n* $^{57}Ti+^{229}Pu$

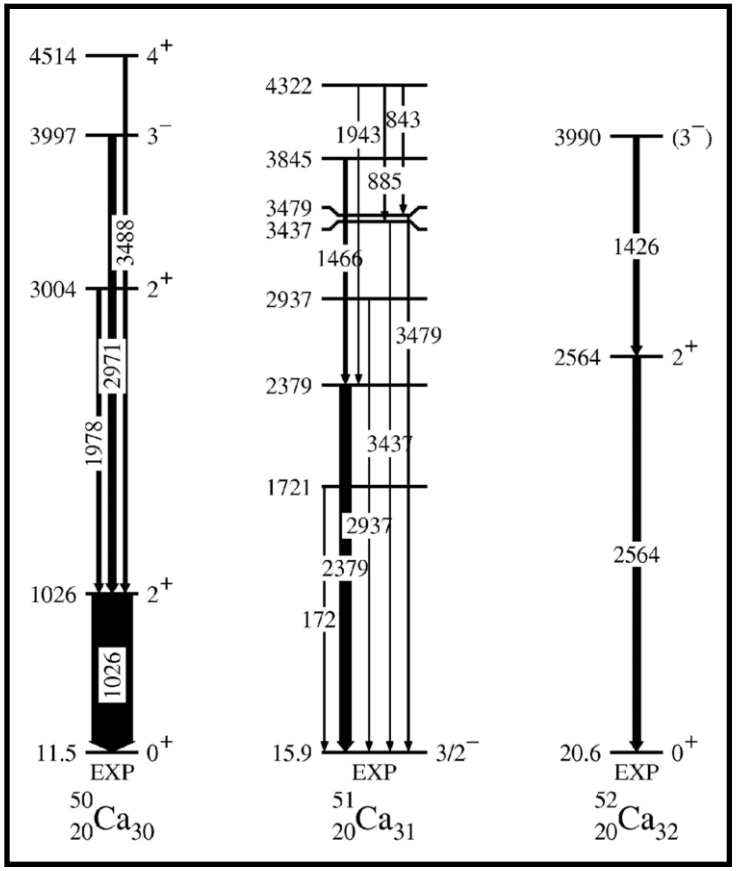
**Identification**
M/q ~ Bp x TOF
M ~ E x TOF²
Z ~ E x ΔE



# Neutron rich Calcium isotopes




M. Rejmund et al.,
PRC 76, 021304(R) (2007)

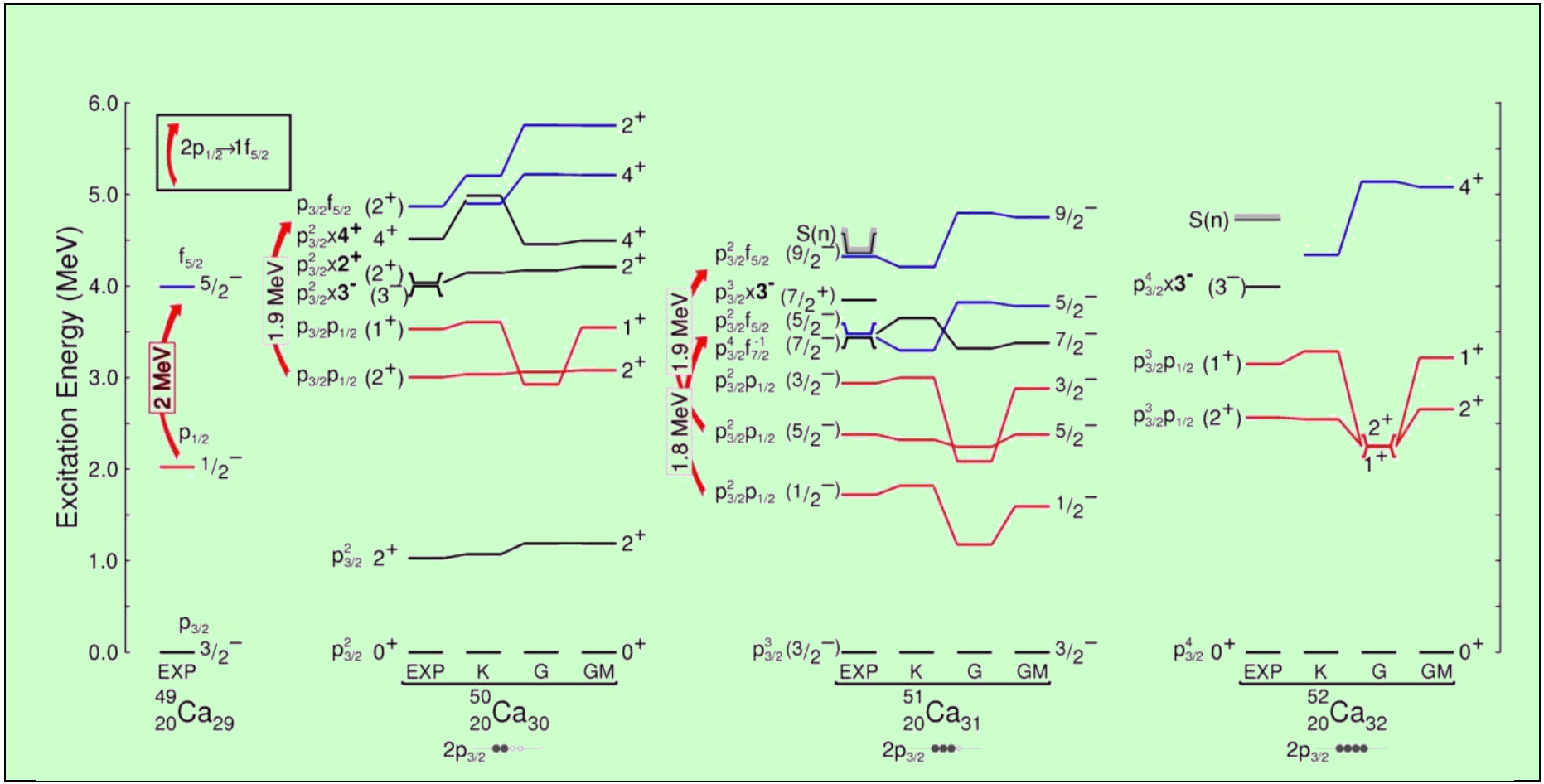



F. Perrot, PhD thesis, 2004

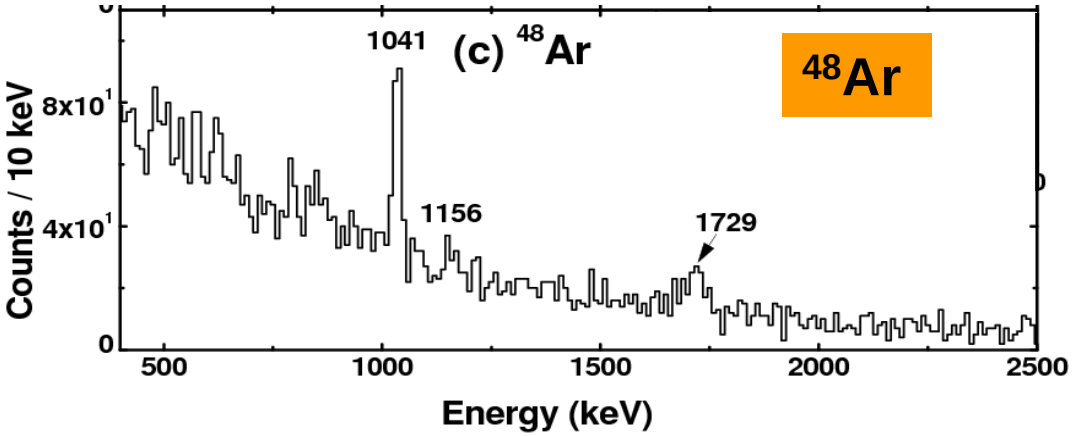
R. Broda et al., Acta Phys. Plolonica B36, 1343, 2005

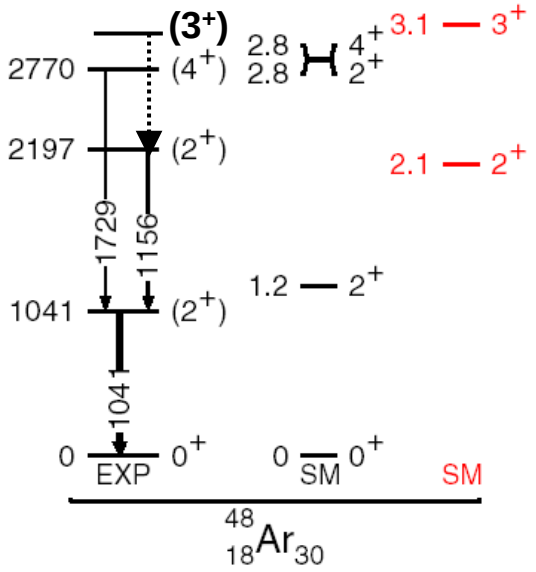
A. Gade et al., Phys. Rev. C, 021302(R), 2006

# Look for odd cases : does $^{51}$Ca has the answer ?



# Signature of triaxiality in $^{48}$Ar




**Signature of triaxiality :**

$E(2^+_2)/E(2^+_1) = 2.1$

$E(4^+_1)/E(2^+_1) = 2.6$

Agreement with
Davydov and Filipov

Appearance of a
low lying γ-band

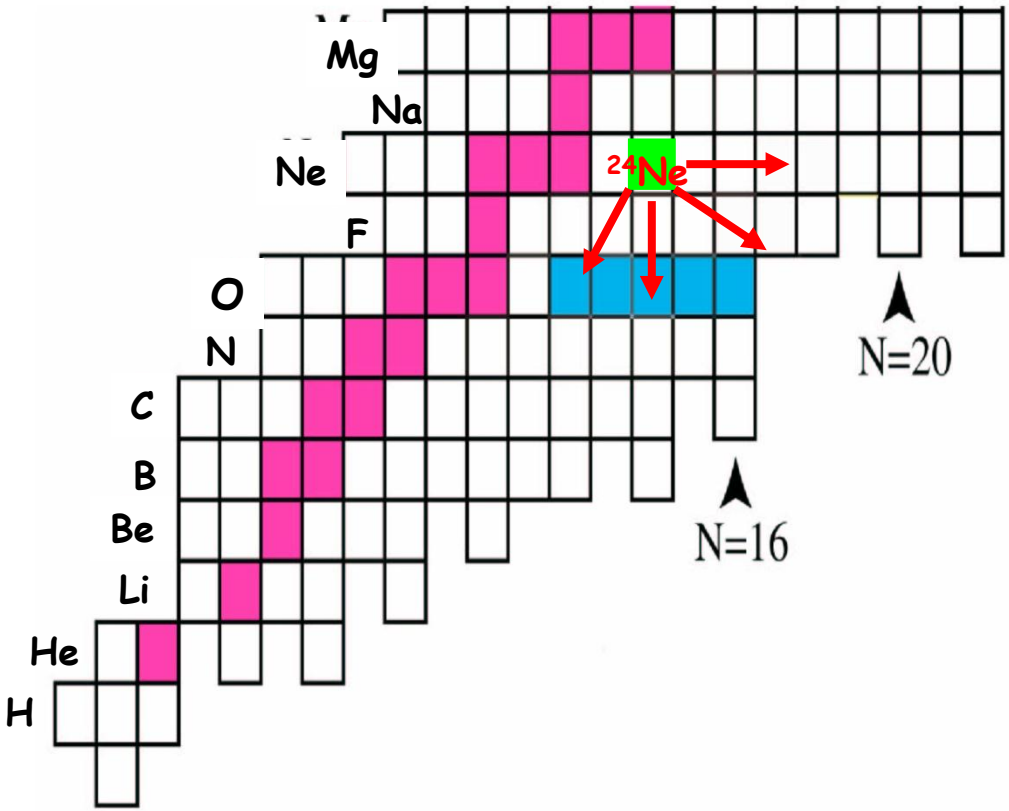
Deviation from axial symmetry

**β=0.25, γ=40°**

S. Bhattacharyya et al.,
PRL 101, 032501 (2008)

# Deep Inelastic Collisions using Radioactive Ion Beam
## $^{24}$Ne beam on $^{208}$Pb

- Nuclear structure of nuclei going towards the n drip line
- Probing the structure of neutron-rich O, F and Ne isotopes
- In-beam γ spectroscopy with deep-inelastic collision using RIB
- Cross section measurements

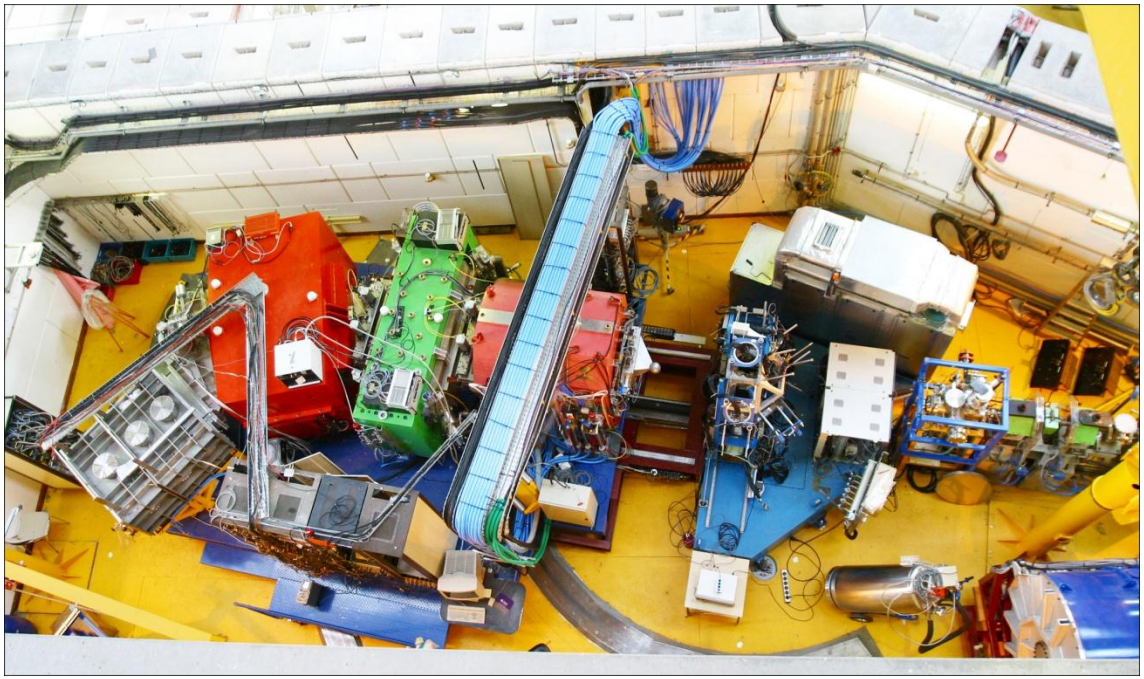




***Collaboration:***

*Università degli Studi and INFN sezione di Milano*
*LNL, Laboratori Nazionali di Legnaro*
*Università and INFN sezione di Padova*
*Università di Camerino and INFN Perugia*
*INFN sezione di Genova*
*The Niewodniczanski Institute, Krakow*
*Institut de Physique Nucleaire, Orsay*
*IRES Strasbourg*
*GANIL, Caen*
*IPN, Lyon*

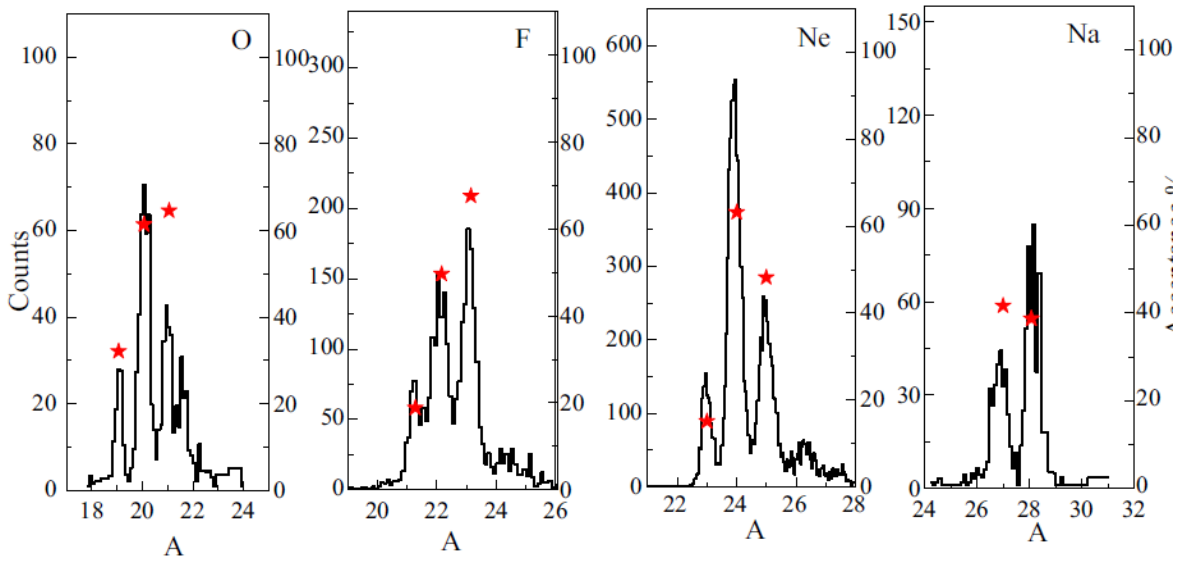
# Setup



- **Reaction:** $^{24}Ne$ @ 7.923 MeV/A + $^{208}Pb$
  $^{24}Ne^{5+}$ from SPIRAL-ISOL facility
  $I_{beam} \sim 1.5 \cdot 10^5$ pps

- **Setup:** VAMOS + EXOGAM
  VAMOS @ 45°
  EXOGAM 11 detectors

# Experimental mass distributions

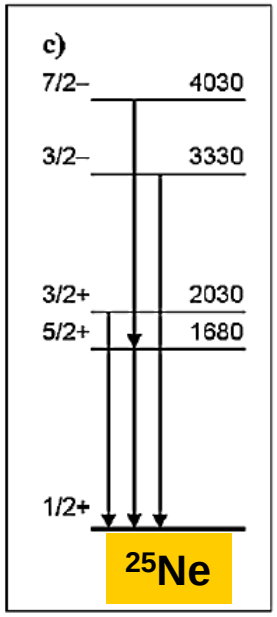


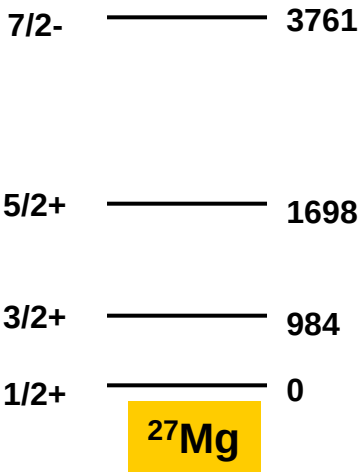

Measured experimental yields of the detected nuclei reported as percentage relative to $^{24}$Ne, compared to GRAZING predictions.

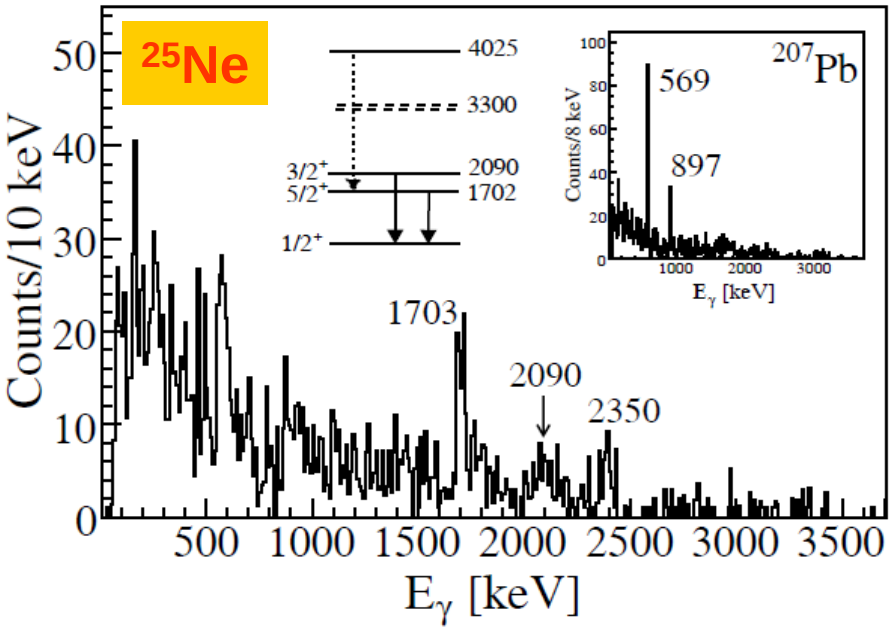
G. Benzoni et al
EPJ A 45, 287 (2010).

| Nucleus | Channel | Experimental relative yield | GRAZING relative yield |
|---|---|---|---|
| $^{24}$Ne | 0p0n | 100 (0.54) | 100 |
| $^{24}$Ne (inelastic) | | 2.85 (0.09) | |
| $^{23}$Ne | −1n | 0.19 (0.02) | 1.48 |
| $^{25}$Ne | +1n | 3.3 (0.10) | 3.07 |
| $^{23}$F | −1p | 0.65 (0.04) | 0.4 |
| $^{22}$F | −1p-1n | 0.55 (0.04) | 0.003 |
| $^{21}$F | −1p-2n | 0.13 (0.02) | 0.002 |
| $^{21}$O | −2p-1n | 0.16 (0.02) | 0.006 |
| $^{20}$O | −2p-2n | 0.21 (0.03) | 0.006 |
| $^{19}$O | −2p-3n | 0.07 (0.01) | 0.006 |
| $^{27}$Na | +1p+2n | 0.17 (0.02) | $3 * 10^{-4}$ |
| $^{28}$Na | +1p+3n | 0.25 (0.02) | $3 * 10^{-5}$ |

# Excited states in $^{25}$Ne




$d(^{24}Ne,p\gamma)^{25}Ne$ $^{26}Mg(d,p)^{27}Mg$

Raising in energy of $0d_{3/2}$ orbital in neutron-rich nuclei

Monopole shift in the effective $0d_{3/2}$ single particle energy
→ opens N=16 gap

W.N. Catford et al
PRL 104, 192501 (2010).

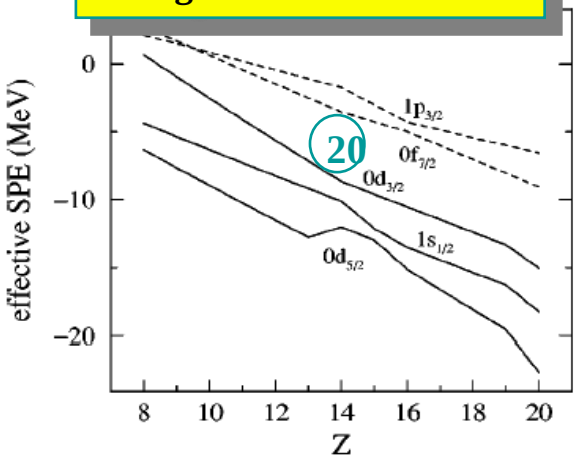
F. Meurders et al
NPA 230, 317 (1974)

# γ-ray spectroscopy of neutron-rich nuclei around N=20

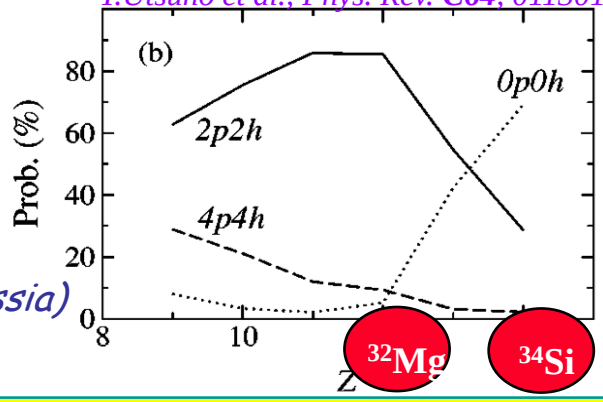
## N=20 shell closure

- To study the excited states of neutron-rich nuclei around N=20
- Focus on: $^{34}$Si, $^{32}$Mg & odd-A nuclei
- Cocktail radioactive beam around $^{34}$Si & $^{32}$Mg on a $CD_2$ target

**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**


***Collaboration:***

*H. Savajols, W. Mittig, P. Roussel-Chomaz, M. Rejmund, M. Gelin, G. Mukherjee, G. De France, S. Bhattacharyya, A. Navin (GANIL)*
*A. Gillibert, A. Obertelli, Ch. Thiesen (DAPNIA/SPhN Saclay)*
*S. Lukyanov, V. Maslov, Y.E. Penionzhkevich (FLNR,JINR Dubna, Russia)*
*D. Baiborodin, Z. Dlouhy (NPI, Czech Republic)*
*M. Caamano (Universidade de Santiago de Compostella, Spain)*

# Experiment with RIB via Fragmentation

* Inelastic scattering / transfer reaction with cocktail RIB:
  - Populates excited states in a number of nuclei.
  - $3^-$ states are strongly populated.

* $\gamma$–$\gamma$ coincidence measurement:
  - Search for the $0_2^+$ in $^{34}$Si
  - Spectroscopy of odd-*A* nuclei

Population of the excited states:
Target: $CD_2$ (30 mg/cm$^2$)
Mechanism: Reactions like
(d,d′), (d,$^3$He), (d,t) …etc.

* Angular distribution of the $\gamma$-ray transitions
  - To determine the multipolarity.

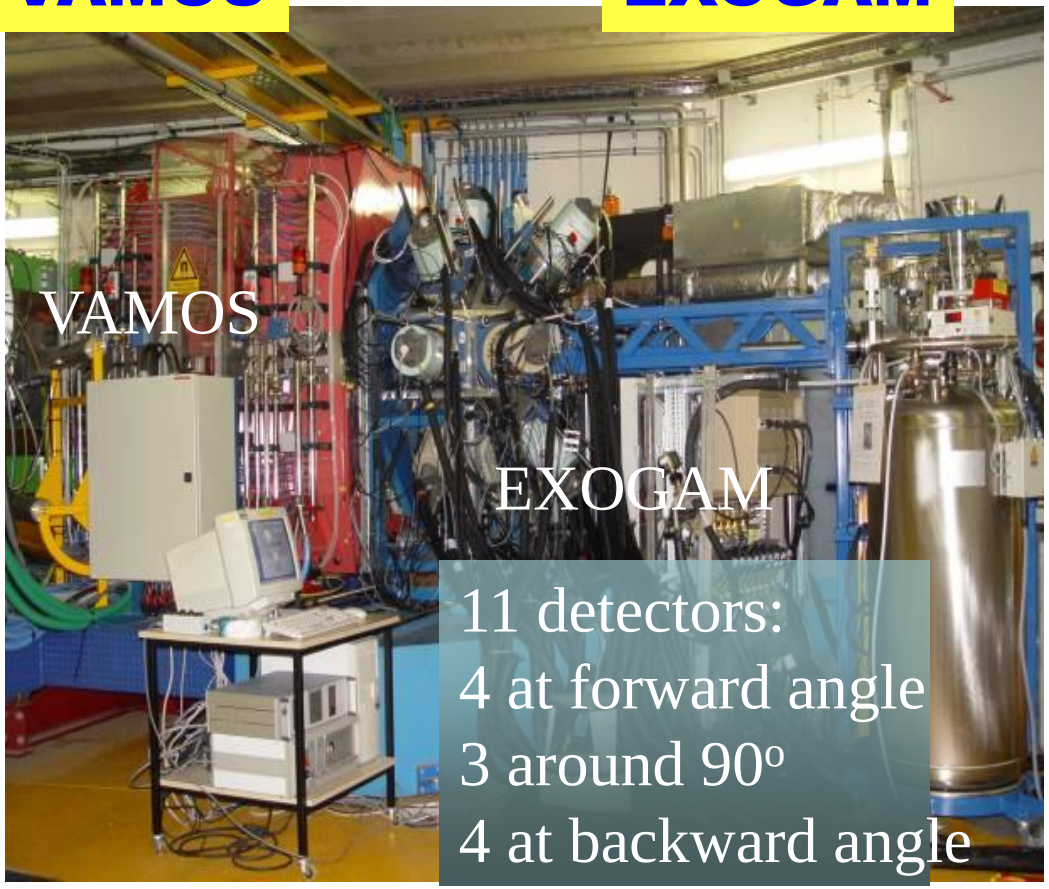
**Production of RIB around $^{34}$Si and $^{32}$Mg:**
Primary beam: $^{36}$S (77 MeV/A)
Primary Target: ~ 1gm/cm$^2$ Ta (SISSI)
Selection: $\alpha$- spectrometer
Energy: ~ 30 MeV/A

# Setup

**Recoil detection/identification** ⟵ **γ-ray detection** ⟵ **Beam identification**

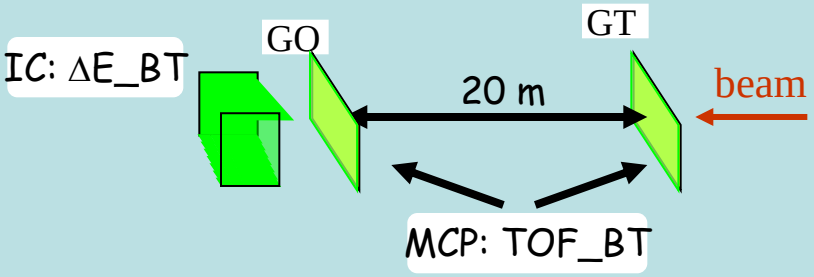
## VAMOS

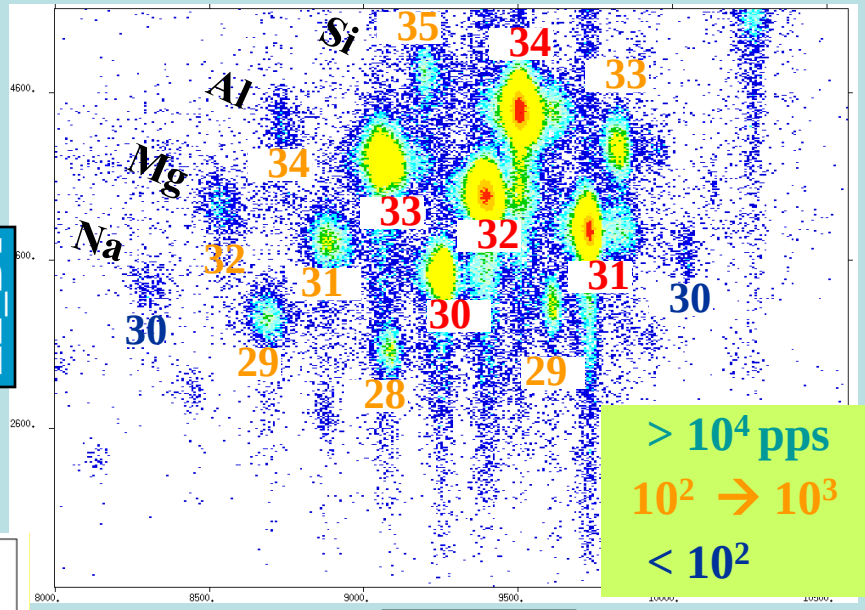
## EXOGAM




DE-TOF technique:
Ionization Chamber and
MCP Before the target

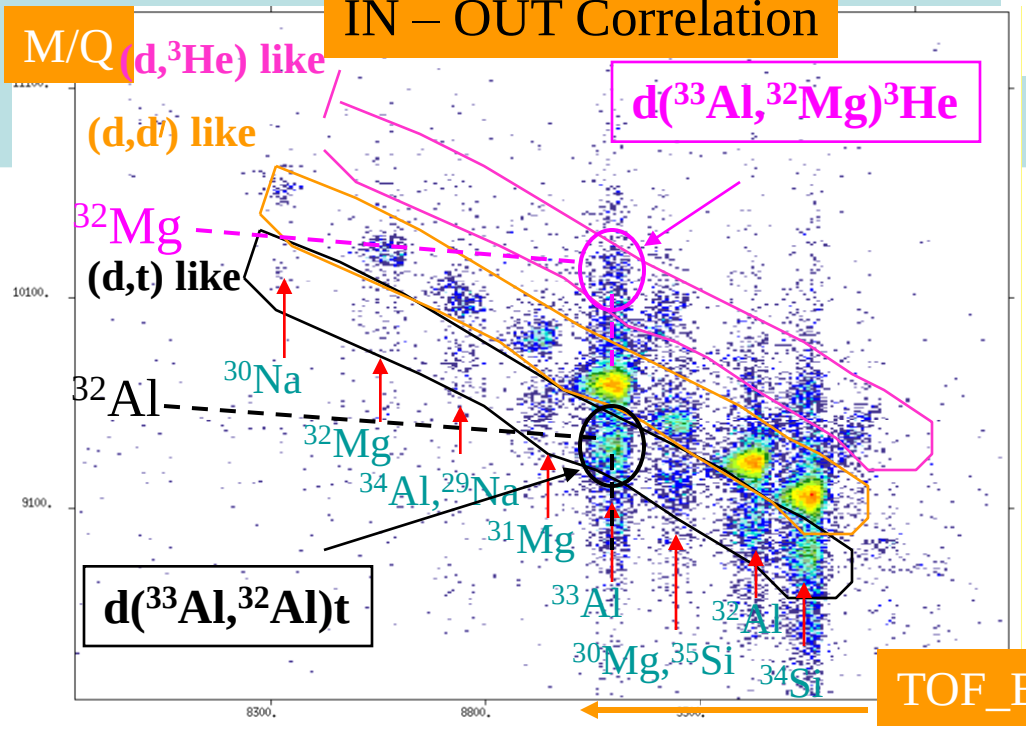
# Identification



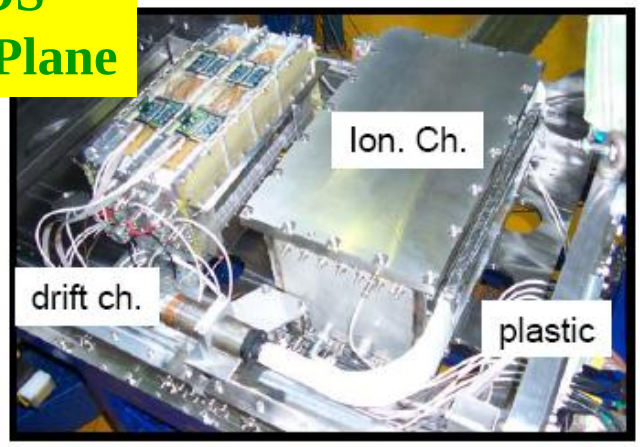




> $10^4$ pps
$10^2$ → $10^3$
< $10^2$

IN – OUT Correlation




**VAMOS Focal Plane**

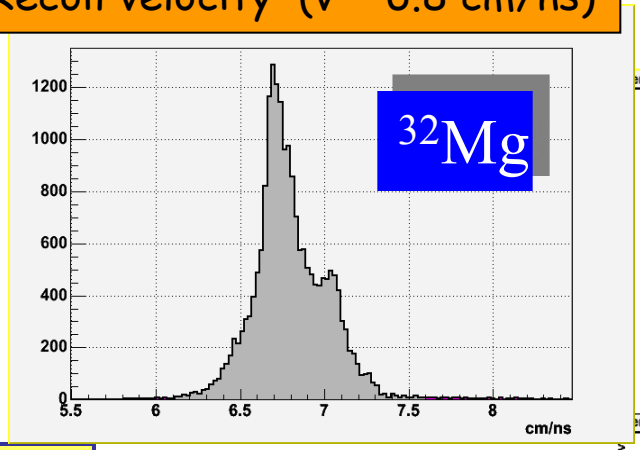


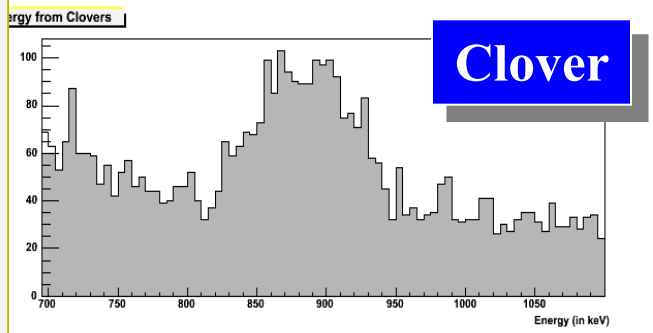
# Gamma detection

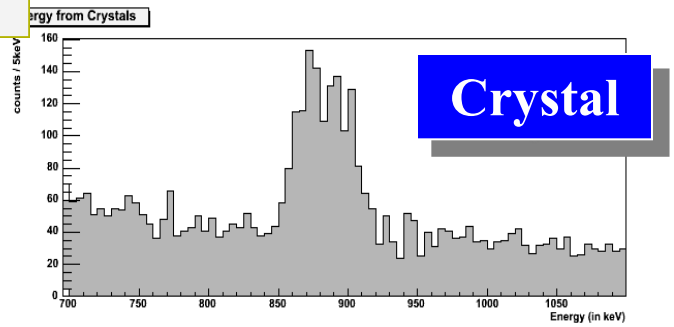
VAMOS :
➲ Recoil velocity (v ~ 6.8 cm/ns)

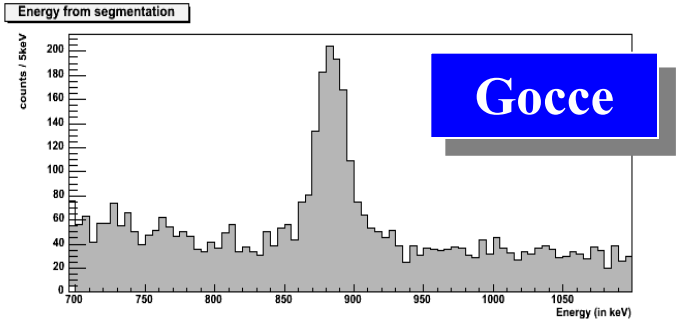
Doppler correction for 885 keV γ-ray in $^{32}$Mg

- Energy from crystal
- Angle from GOCCE
  - * Doppler correction
  - *Angular distribution



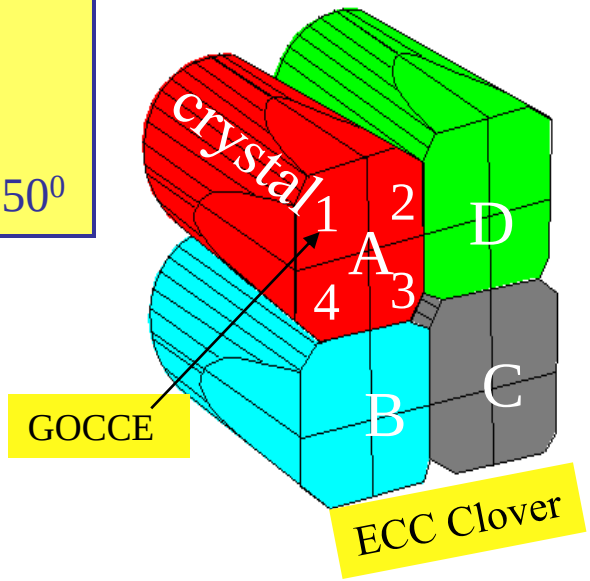



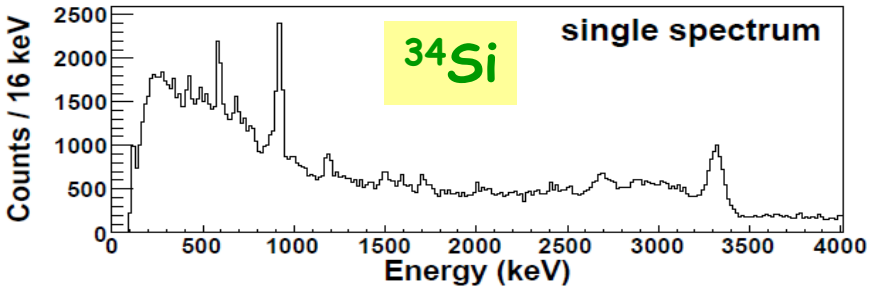



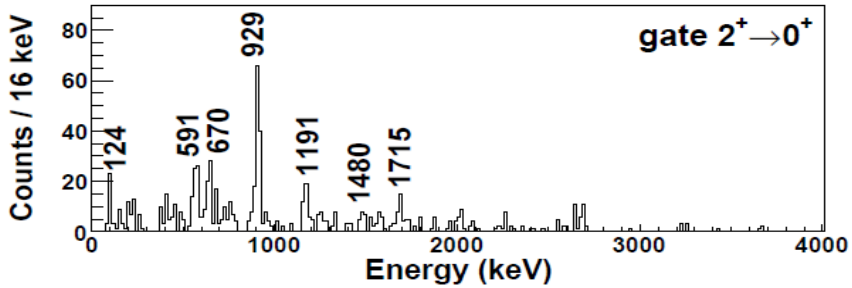

12 GOCCE rings:
Forward: $30^0$, $40^0$, $50^0$, $60^0$
Middle: $75^0$, $85^0$, $95^0$, $105^0$
Backward: $120^0$, $130^0$,$140^0$,$150^0$

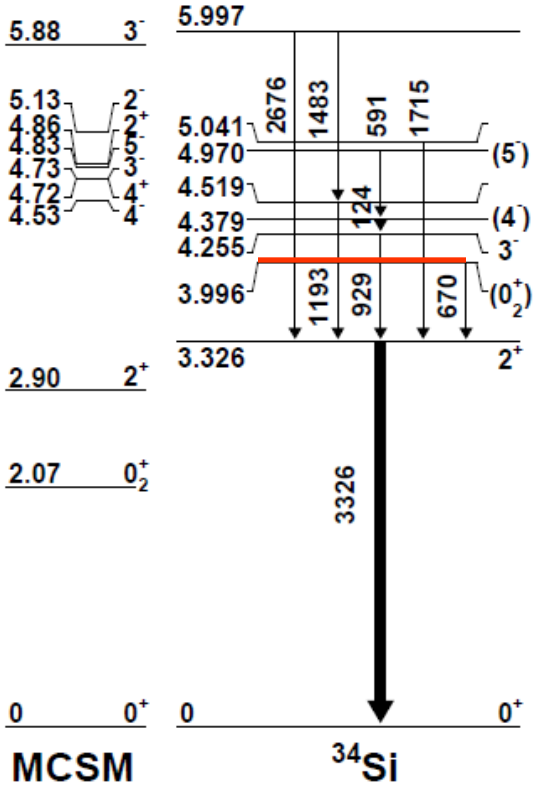
6 Crystal rings:
Forward: $36^0$,$56^0$
Middle: $80^0$, $100^0$
Backward: $124^0$, $144^0$



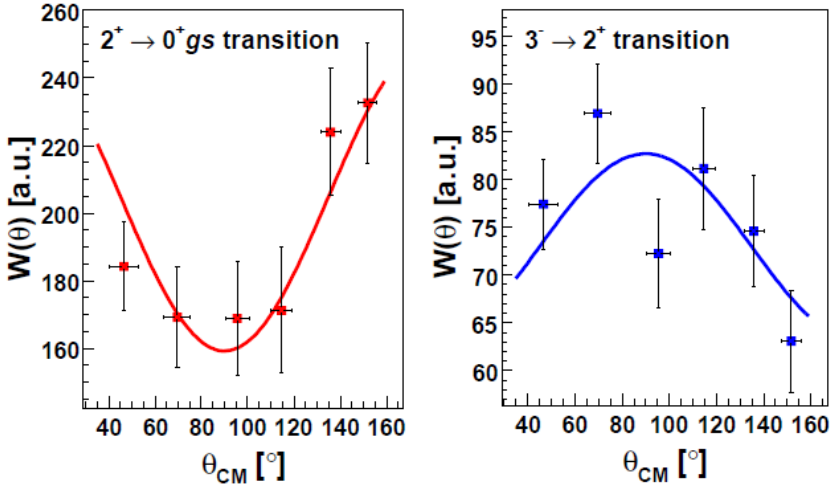
# Spectroscopy of $^{34}$Si




## γ-ray Angular distribution using EXOGAM segments




State at 3996 keV :
Possible candidate for intruder 0$^+$ state

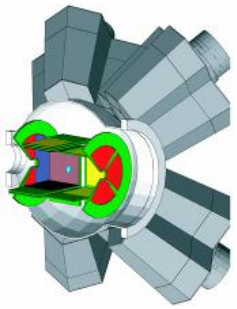
M. Gelin et al., Ph.D. thesis,
Universite´ de Caen, 2007.

# Complimentary experiments around 'island of inversion' @ REX-ISOLDE

## Measure B(E2) : Coulomb Excitation

$^{31}$Mg M. Scidlitz *et al.* PLB 700, 181 (2011)

$^{30}$Mg O. Niedermaier *et al.* PRL 94, 172501 (2005)



## Transfer Reactions

K. Wimmer *et al.* PRL 105, 252501 (2010)

Discovery of the Shape Coexisting $0^+$ State in $^{32}$Mg

- Two Neutron Transfer Reaction in inverse kinematics

## Moment measurements

Magnetic moment of $^{31}$Mg $^{33}$Mg

D. T. Yordanov et . al.
PRL 99, 292501 (2007)

- hyperfine structure and nuclear magnetic resonance
- spin and magnetic moment
- both $^{31}$Mg and $^{33}$Mg belong to 'island of inversion'

## Possible complimentary experiments @ REX-ISOLDE / HIE-ISOLDE

- Coulomb excitation and moment measurements around Z=20
- Deep-inelastic transfer reactions with MINIBALL + SPECTROMETER (?)

# Summary

- ✓ Neutron rich nuclei around Z=20
  - Deep-inelastic multi-nucleon transfer
  - Direct tagging of exotic nuclei
- ✓ Neutron rich Ca isotopes : question of a new shell closure
- ✓ Development of collectivity near N=28
- ✓ Deep-inelastic reaction with radioactive beam from ISOL-SPIRAL
  - excited states of $^{25}$Ne
- ✓ Neutron rich nuclei around N=20 island of inversion
  - transfer reaction with RIB via fragmentation
- ✓ Complimentary experiments at ISOLDE