Spectroscopic Studies of Neutron-Rich Nuclei with the CLARA-PRISMA Setup

E.Farnea

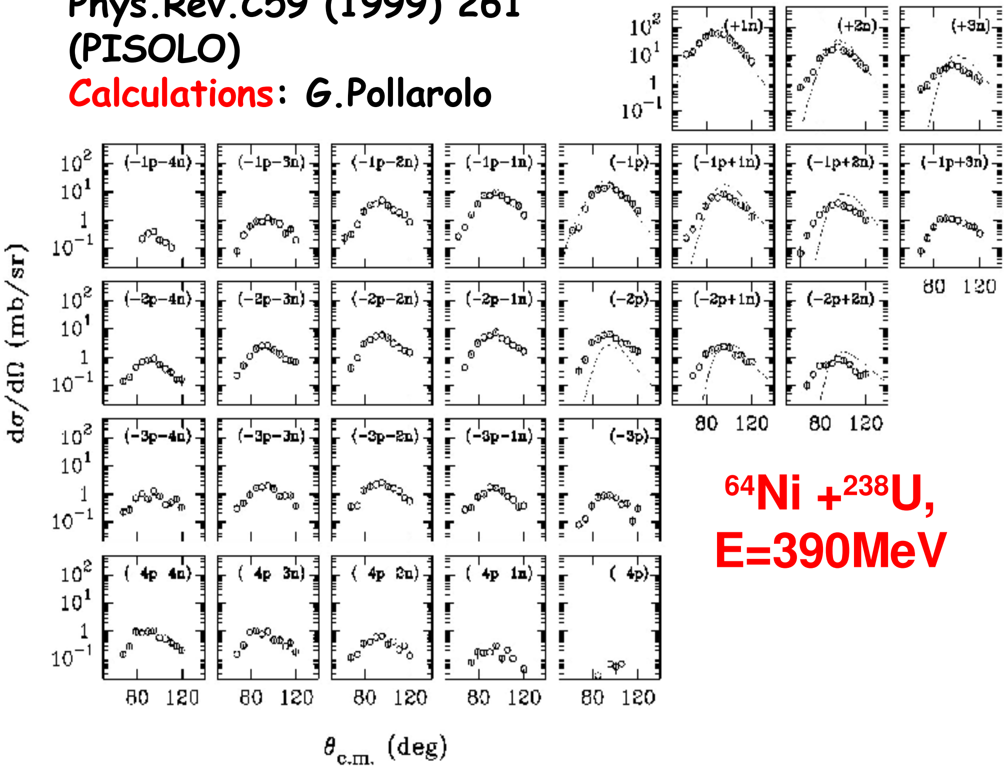
INFN Sezione di Padova

on behalf of the CLARA-PRISMA Collaboration

1) Gamma Spectroscopy with Multinucleon Transfer and Deep-Inelastic Reactions
2) PRISMA and CLARA
3) Results from the experimental campaign

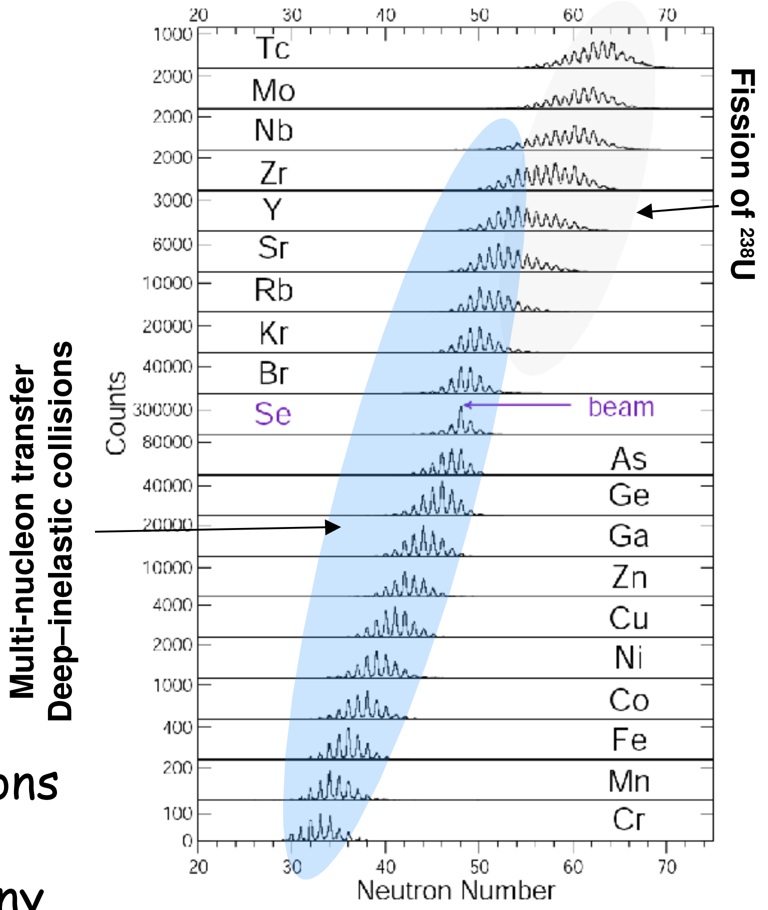
Grazing reactions as a tool to study n-rich nuclei

Exp. Data: L.Corradi et al.,
Phys.Rev.C59 (1999) 261
(PISOLO)
Calculations: G.Pollarolo



^{64}Ni +^{238}U, E=390MeV

^{82}Se + ^{238}U, E=505 MeV



Multinucleon transfer and deep inelastic reactions between stable nuclei at low and intermediate energy provide a convenient way to populate many nuclei far from stability which would be impossible to reach with fusion-evaporation reactions.

PRISMA Exp. Data
Inelastic channels only
(γs detected with CLARA)

G.de Angelis, G.Duchêne
Analysis: N.Mărginean

Grazing reactions as a tool to study n-rich nuclei

Exp. Data: L.Corradi et al.,
Phys.Rev.C59 (1999) 261
(PISOLO)
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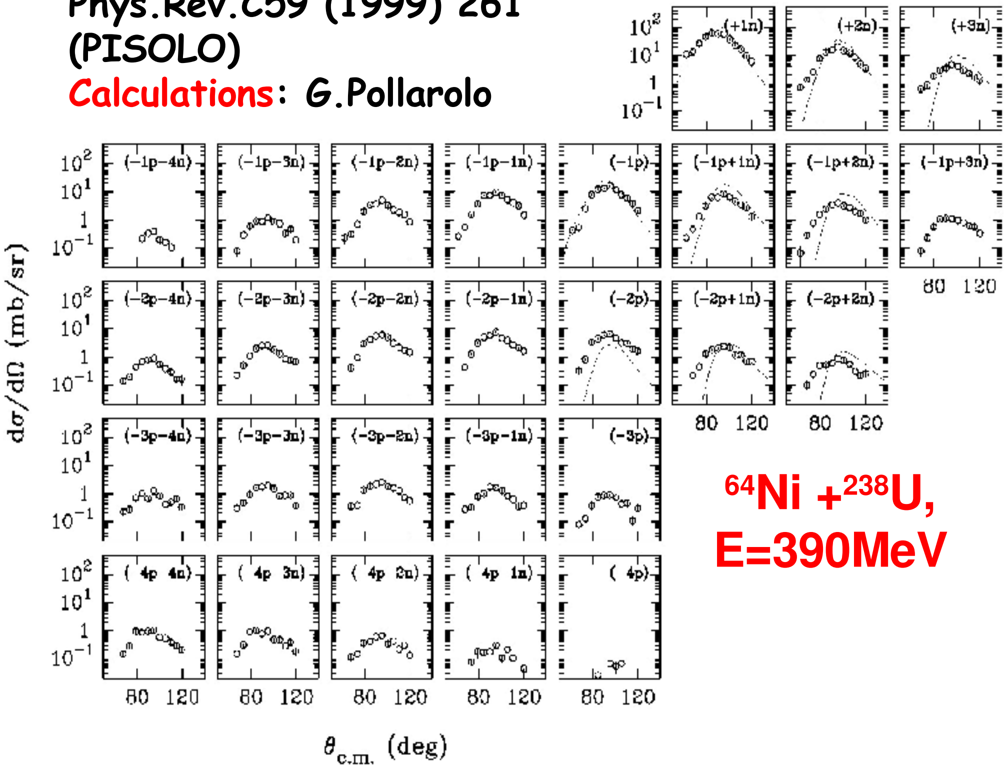

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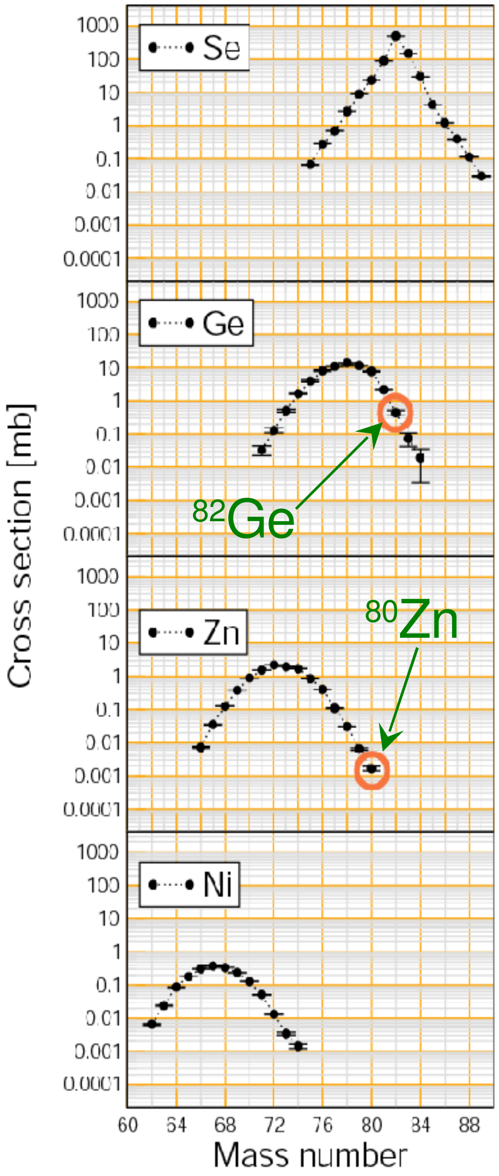
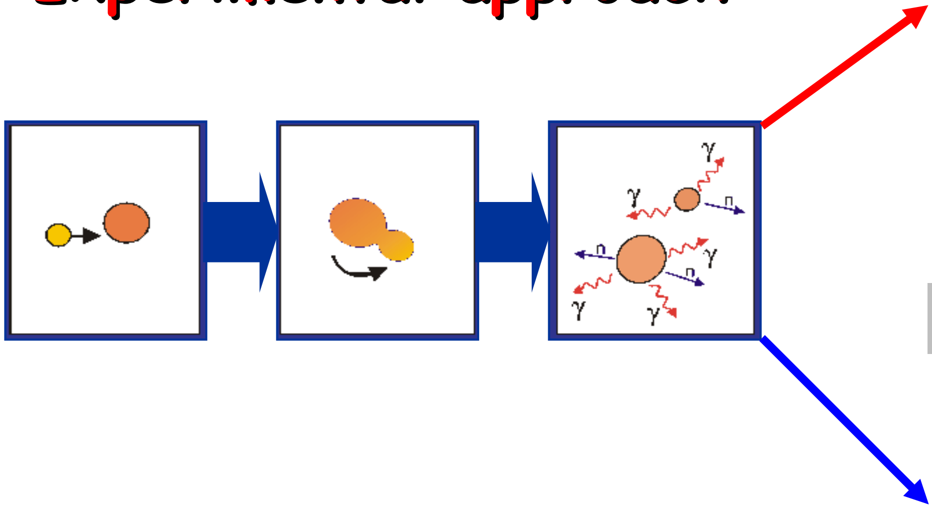


Multinucleon transfer and deep inelastic reactions between stable nuclei at low and intermediate energy provide a convenient way to populate many nuclei far from stability which would be impossible to reach with fusion-evaporation reactions.

In many cases, the production cross sections are not negligible.

γ-Ray Spectroscopy with Grazing reactions

Experimental approach



Thick target

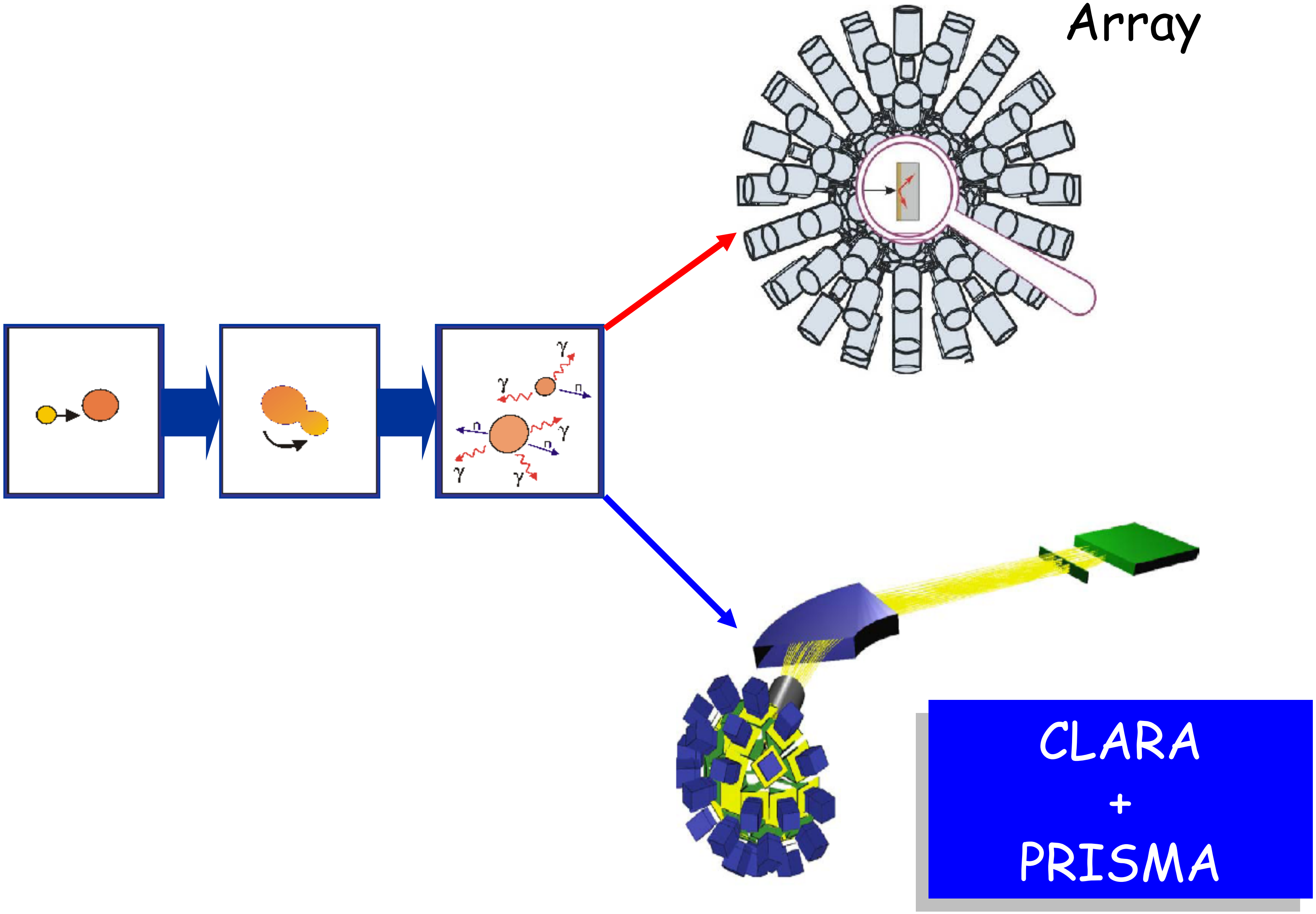
- Identification possible only when the „starting" transitions are known or when the cross-coincidences are available.
- Only gamma rays from states with cumulative half-life ≥1 ps visible.

*See e.g. Broda et al, PRL **74** (1995) 865*

Thin target

- detection of fast γ transitions
- *(A,Z)* identification and Doppler correction needed - isotopic assignment of γ transitions

γ-Ray Spectroscopy with Grazing reactions

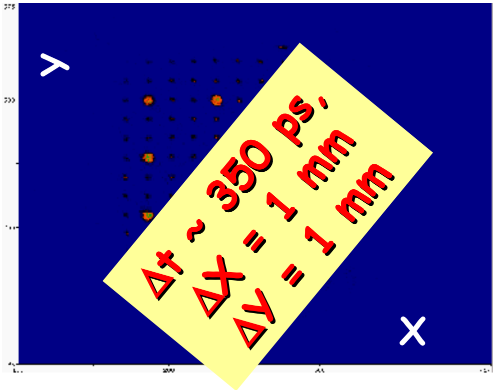


CLARA
+
PRISMA

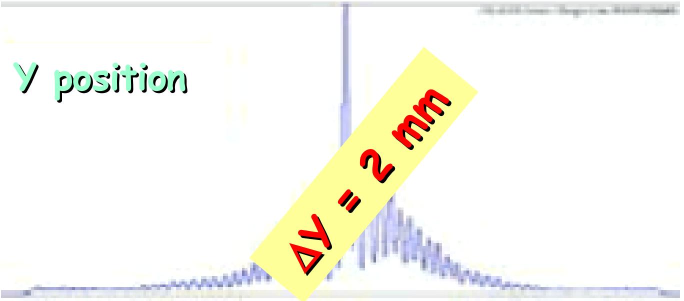
Thick target

Thin target

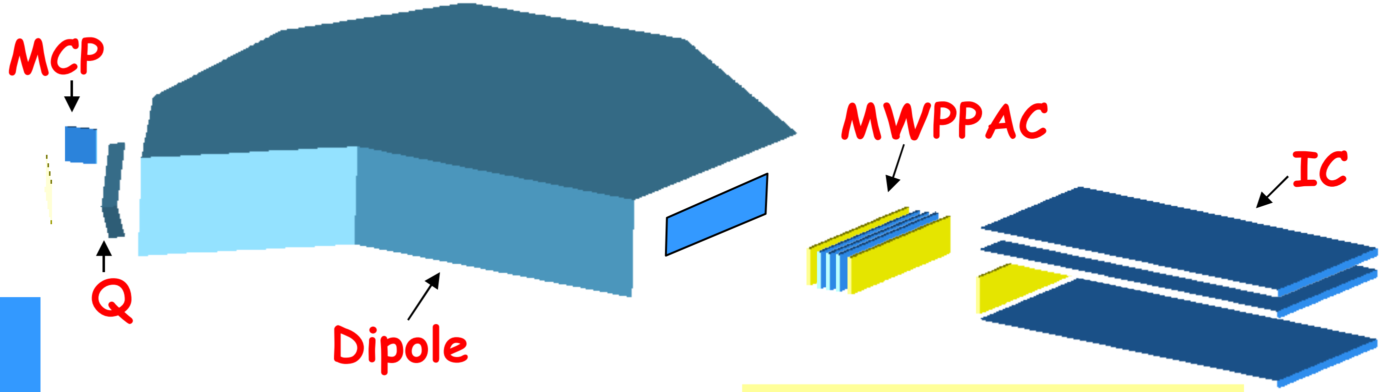
The PRISMA Magnetic Spectrometer



$\Delta t \sim 350$ ps,
$\Delta X = 1$ mm
$\Delta Y = 1$ mm

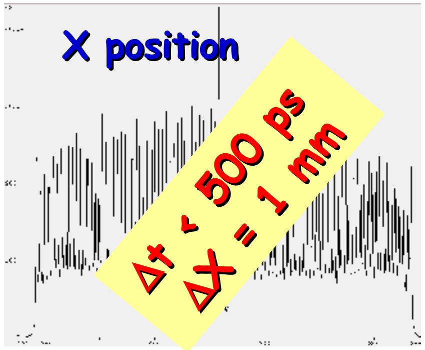


$\Delta Y = 2$ mm



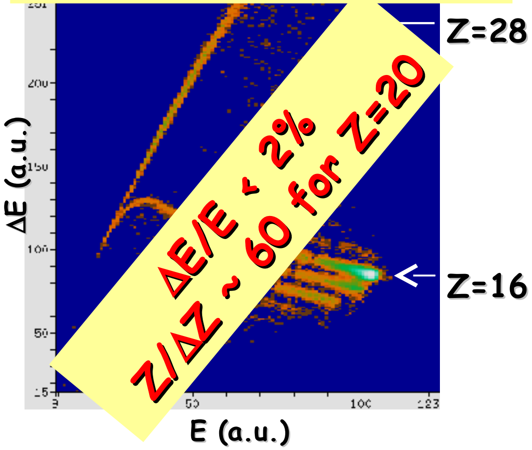
$\Delta\Omega = 80$ msr

$\Delta Z/Z \approx 1/60$
$\Delta A/A \approx 1/190$
ΔE ±20%
$B\rho = 1.2$ T.m



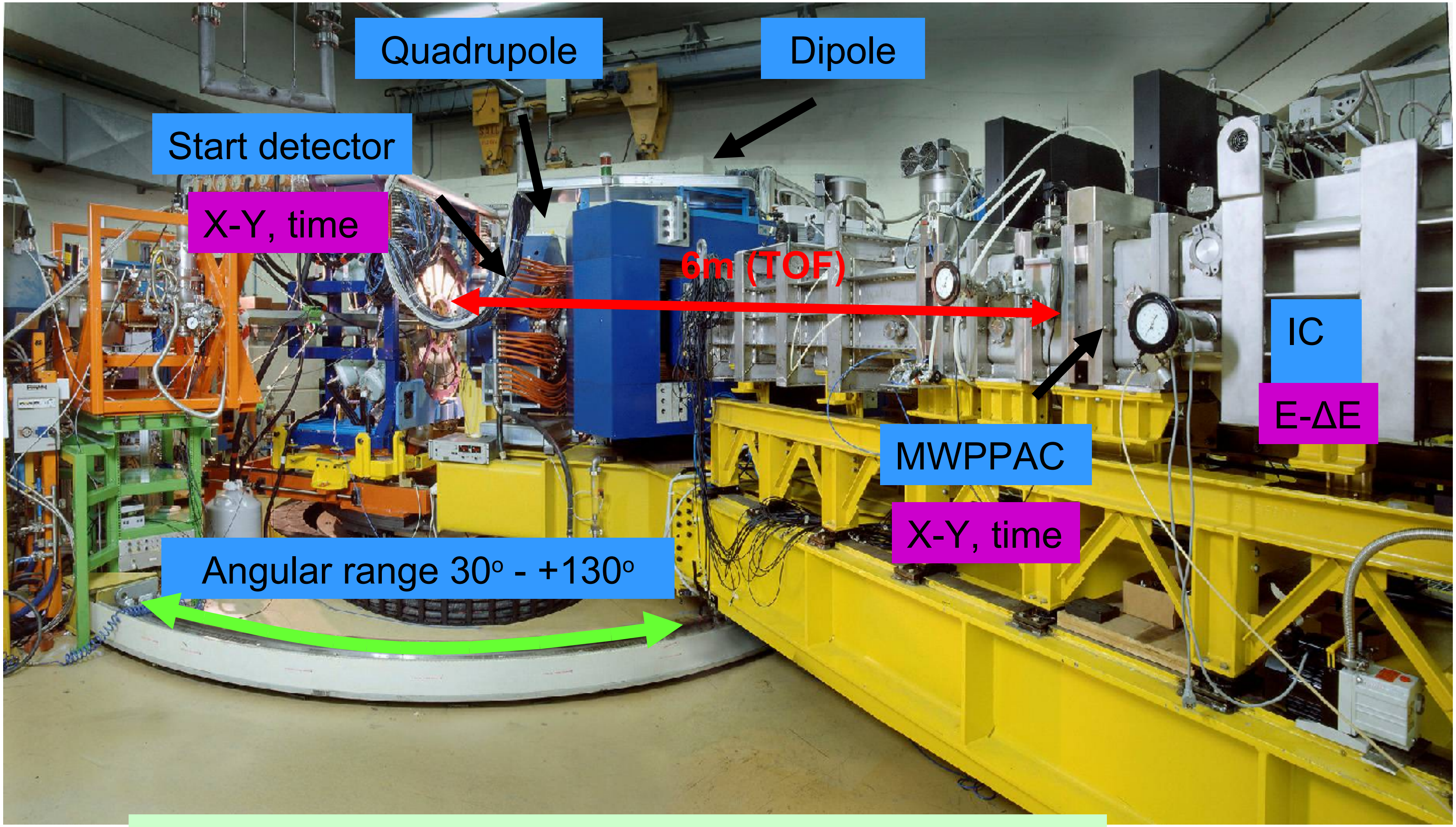
$\Delta t < 500$ ps
$\Delta X = 1$ mm

195 MeV $^{36}S + ^{208}Pb$, $\theta_{lab} = 80^{o}$



$\Delta E/E < 2\%$
$Z/\Delta Z \sim 60$ for $Z=20$

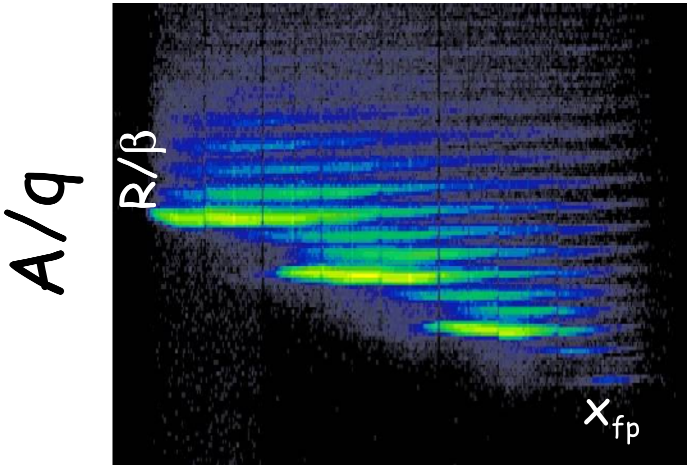
The CLARA-PRISMA setup

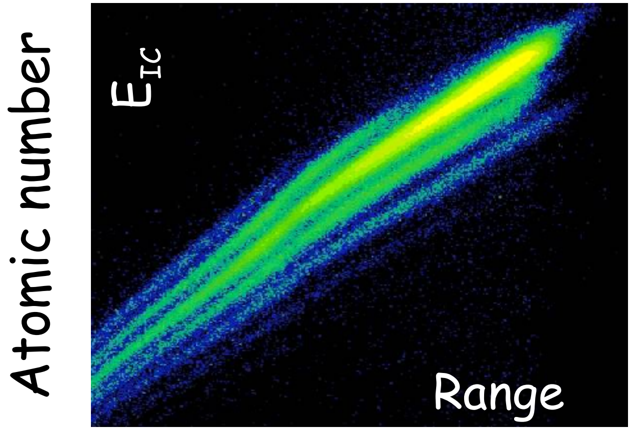


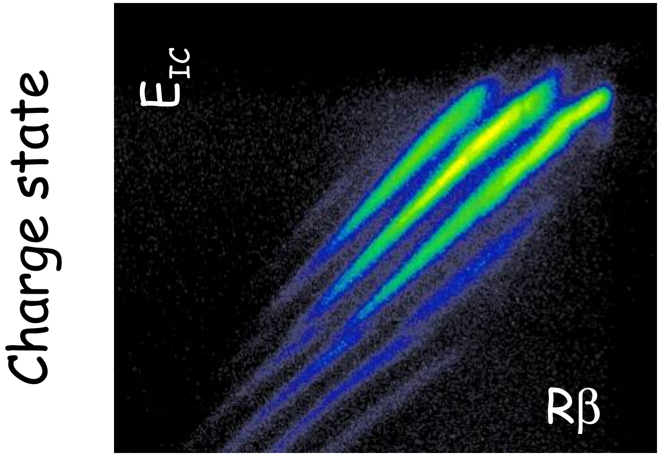
Laboratori Nazionali di Legnaro (INFN), Italy

The PRISMA Magnetic Spectrometer

Trajectories reconstructed through iterative procedure depending only on ratio of fields in dipole and quadrupole and providing trajectory length and curvature radius



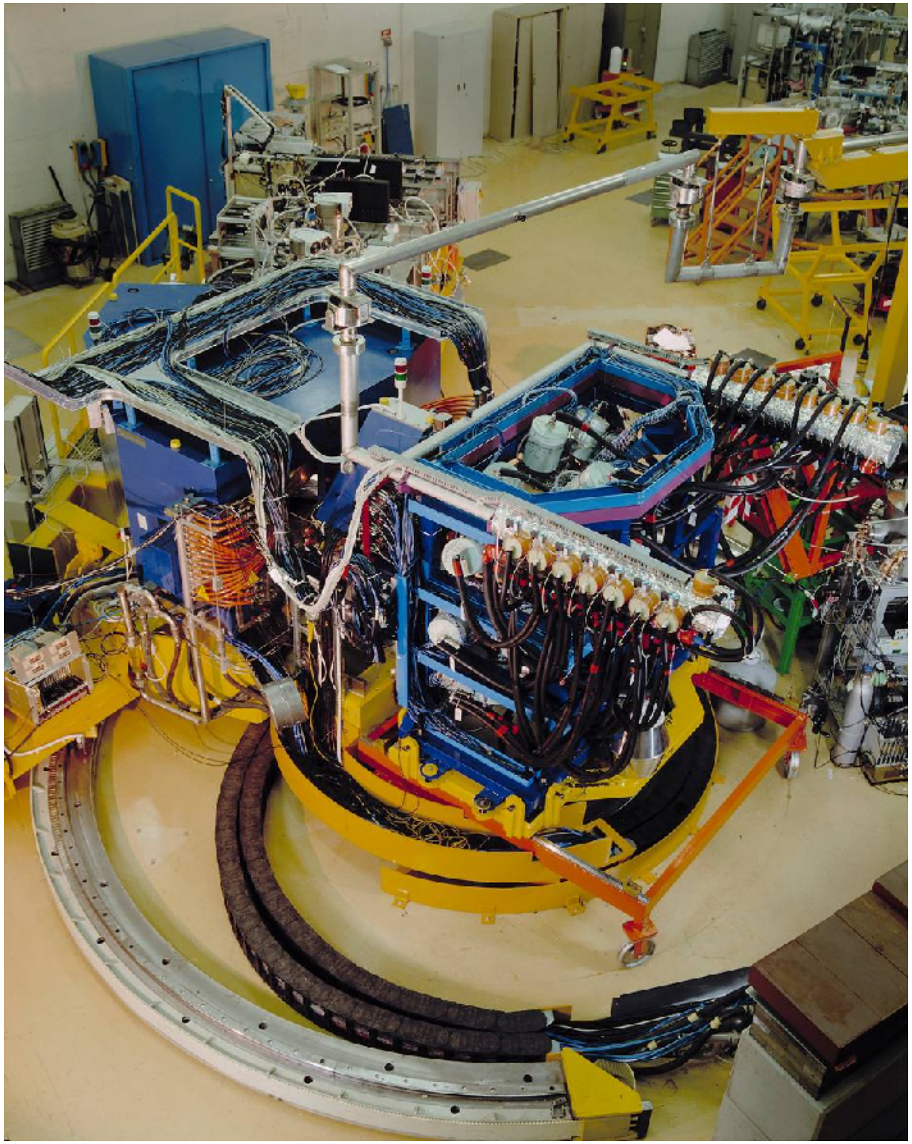


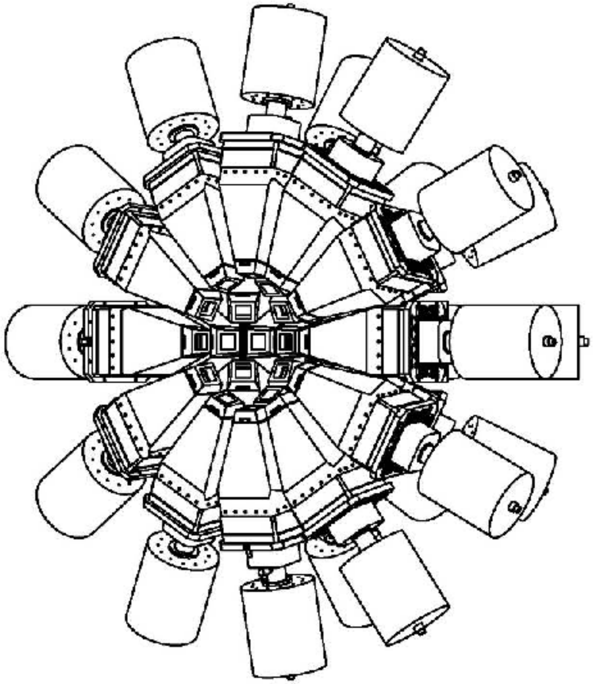


Full Z, A selection

Vector velocity of recoils (direction from start detector, β from TOF and trajectory length)

CLARA: Clover Detector array





Up to 25 Euroball Clover detectors (from the EU GammaPool)

For Eγ= 1.3MeV:

Efficiency ~ 3 %

Peak/Total ~ 45 %

FWHM < 10 keV (at v/c = 10 %)

The CLARA-PRISMA collaboration

- France

IPHC (IReS) Strasbourg
GANIL Caen

- U.K.

University of Manchester
Daresbury Laboratory
University of Surrey
University of Paisley

- Germany

HMI Berlin
GSI Darmstadt

- Poland

IFJ-PAN Kraków

- Croatia

Ruder Boskovic Institute, Zagreb

- Italy

INFN LNL-Legnaro
INFN and University Padova
INFN and University Milano INFN and University Genova INFN and University Torino INFN and University Napoli INFN and University Firenze University of Camerino

- Spain

University of Salamanca

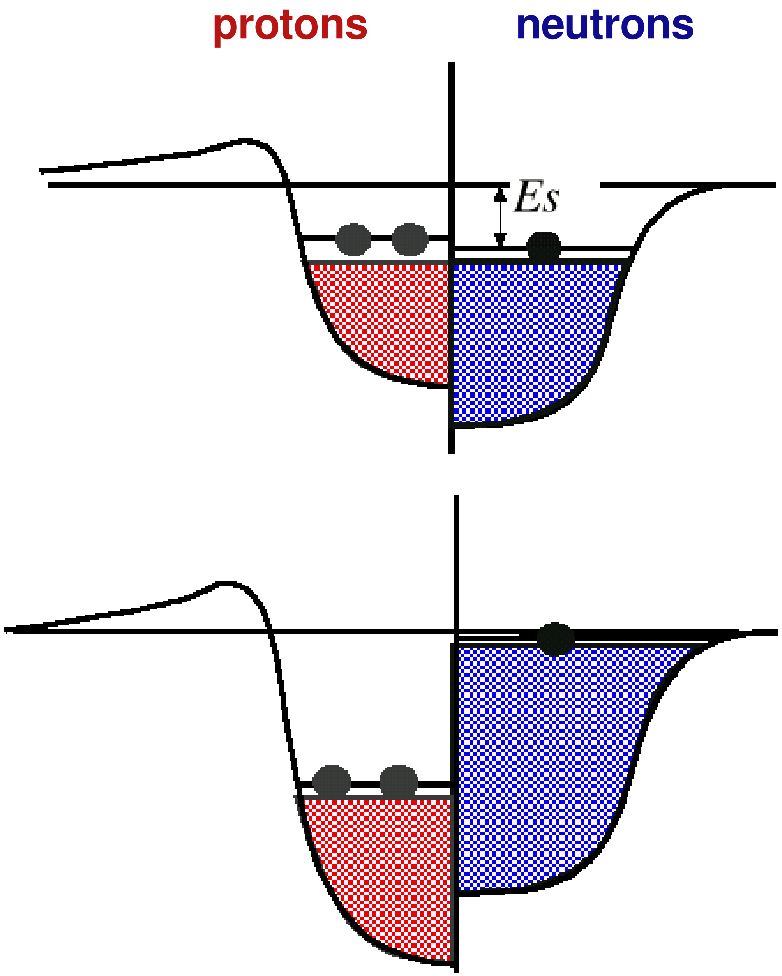
- Romania

Horia Hulubei NIPNE Bucharest

Summary of the campaign

- 24 experiments (2004-2008)
- 16 papers (so far)
- Over 40 presentations at international conferences/workshops
- 6 theses (diploma, PhD, …)

Qualitative Difference Near the Neutron-Dripline



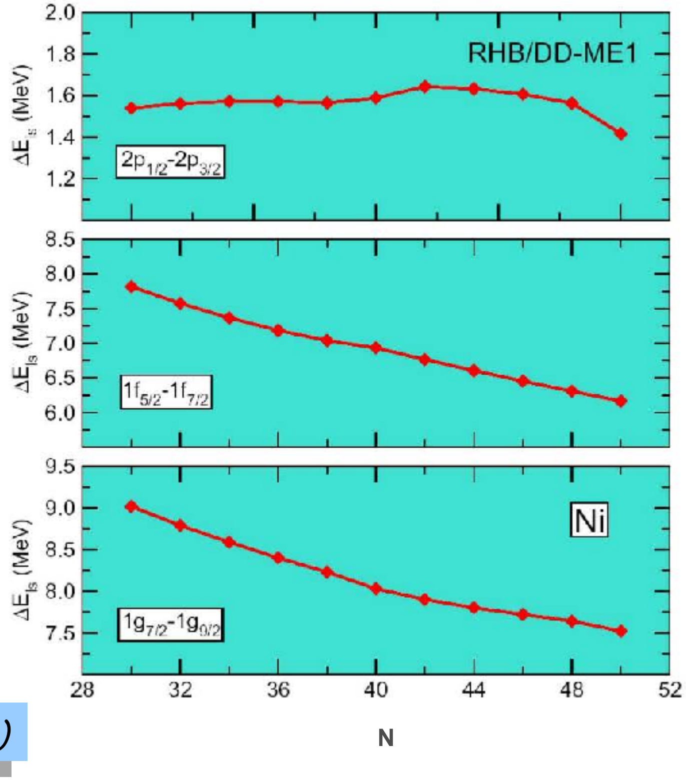
Reduction of spin-orbit potential

$$V_{s.o.} \approx \frac{1}{r}\frac{\partial}{\partial r}V_{ls}(r)$$

$$V_{ls} = \frac{m}{m_{eff}}(V - S)$$

reduced energy spacings between spin-orbit partners

$$\Delta E_{ls} = E_{n,l,j=l-1/2} - E_{n,l,j=l+1/2}$$

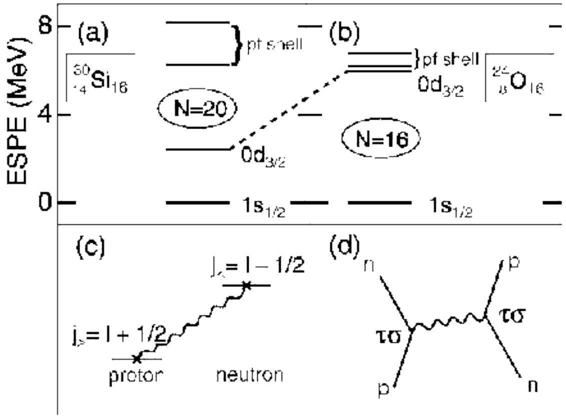


Phys. Lett. B 418, 7 (98)

Orbital migrations

Proton-neutron spin-flip interaction

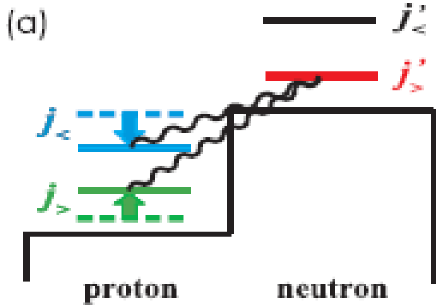
$$V_{\tau\sigma} = \tau \cdot \tau\sigma \cdot \sigma f_{\tau\sigma}(r).$$



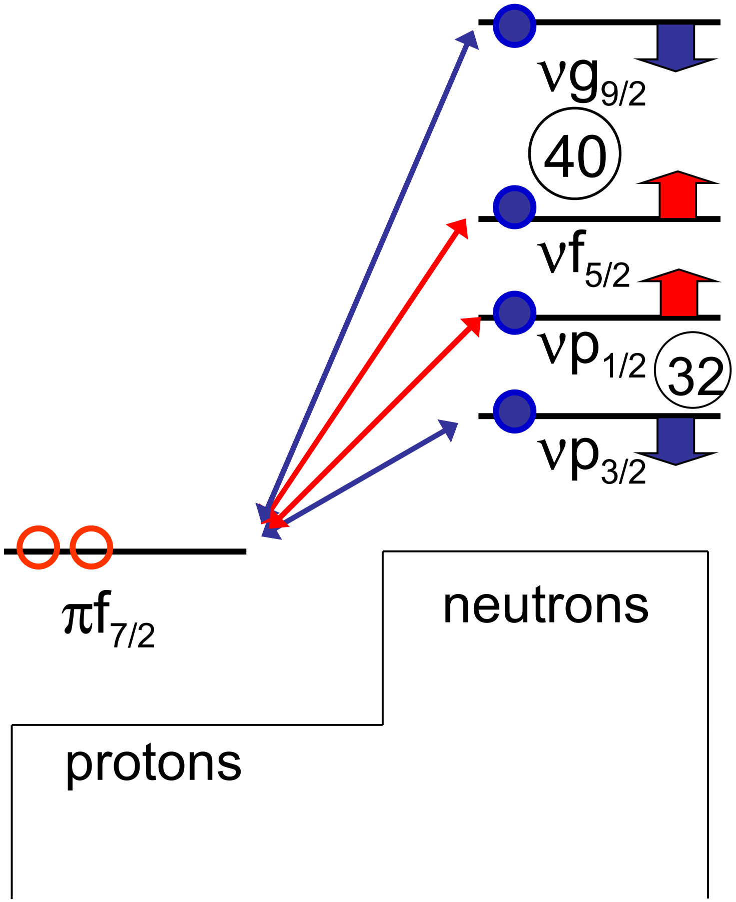
T. Otsuka et al., PRL87, 082502 (2001)

Tensor force

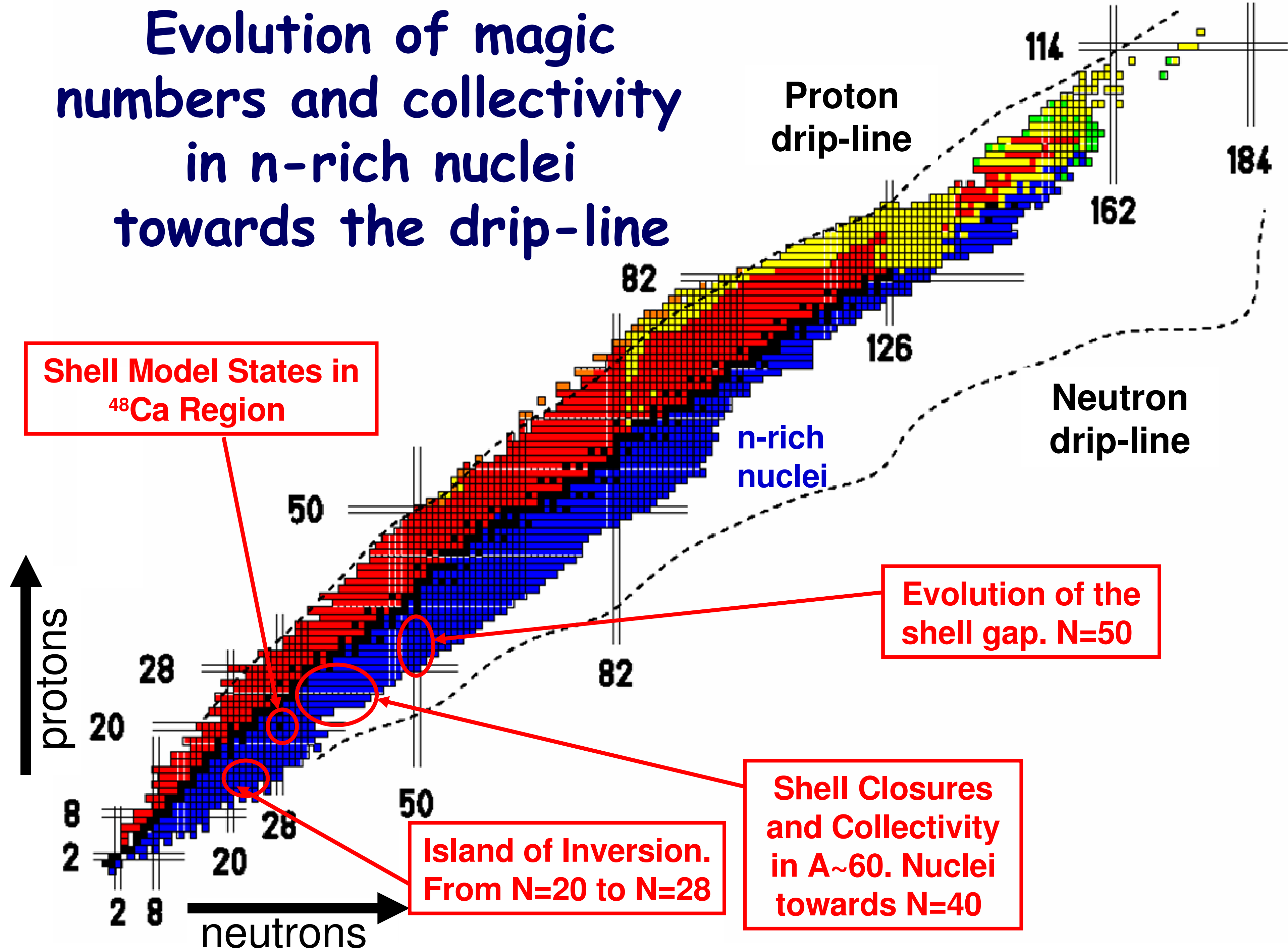
$$V_T = (\vec{\tau}_1 \cdot \vec{\tau}_2)([\vec{s}_1\, \vec{s}_2]^{(2)} \cdot Y^{(2)}) f(r),$$



T. Otsuka et al., PRL 95, 232502 (2005)



Evolution of magic numbers and collectivity in n-rich nuclei towards the drip-line



Shell Model States in ^{48}Ca Region

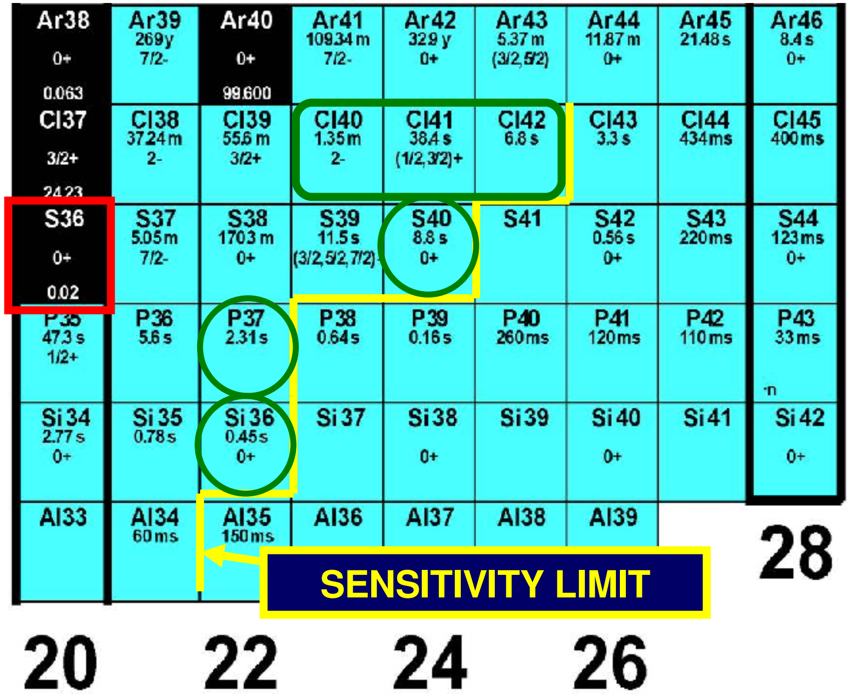
Evolution of the shell gap. N=50

Shell Closures and Collectivity in A~60. Nuclei towards N=40

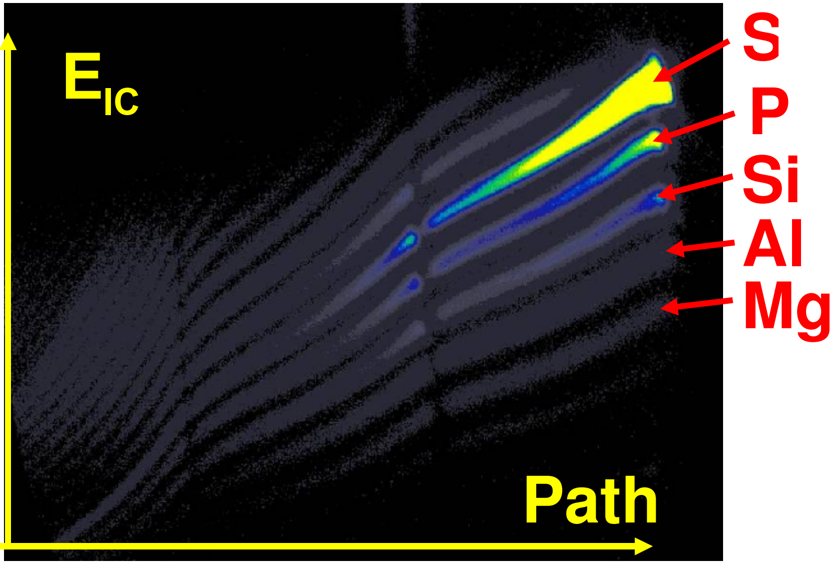
Island of Inversion. From N=20 to N=28

From N=20 to N=28

R.Chapman, X.Liang (Manchester), M.Stanoiu, F.Azaiez (IPN Orsay)



Ar38 0+ 0.063	Ar39 269y 7/2-	Ar40 0+ 99.600	Ar41 109.34 m 7/2-	Ar42 32.9 y 0+	Ar43 5.37 m (3/2,5/2)	Ar44 11.87 m 0+	Ar45 21.48 s	Ar46 8.4 s 0+
Cl37 3/2+ 24.23	Cl38 37.24 m 2-	Cl39 55.6 m 3/2+	Cl40 1.35 m 2-	Cl41 38.4 s (1/2,3/2)+	Cl42 6.8 s	Cl43 3.3 s	Cl44 434 ms	Cl45 400 ms
S36 0+ 0.02	S37 5.05 m 7/2-	S38 170.3 m 0+	S39 11.5 s (3/2,5/2,7/2)-	S40 8.8 s 0+	S41	S42 0.56 s 0+	S43 220 ms	S44 123 ms 0+
P35 47.3 s 1/2+	P36 5.6 s	P37 2.31 s	P38 0.64 s	P39 0.16 s	P40 260 ms	P41 120 ms	P42 110 ms	P43 33 ms -n
Si34 2.77 s 0+	Si35 0.78 s	Si36 0.45 s 0+	Si37	Si38 0+	Si39	Si40 0+	Si41	Si42 0+
Al33	Al34 60 ms	Al35 150 ms	Al36	Al37	Al38	Al39		
20		22		24		26		28

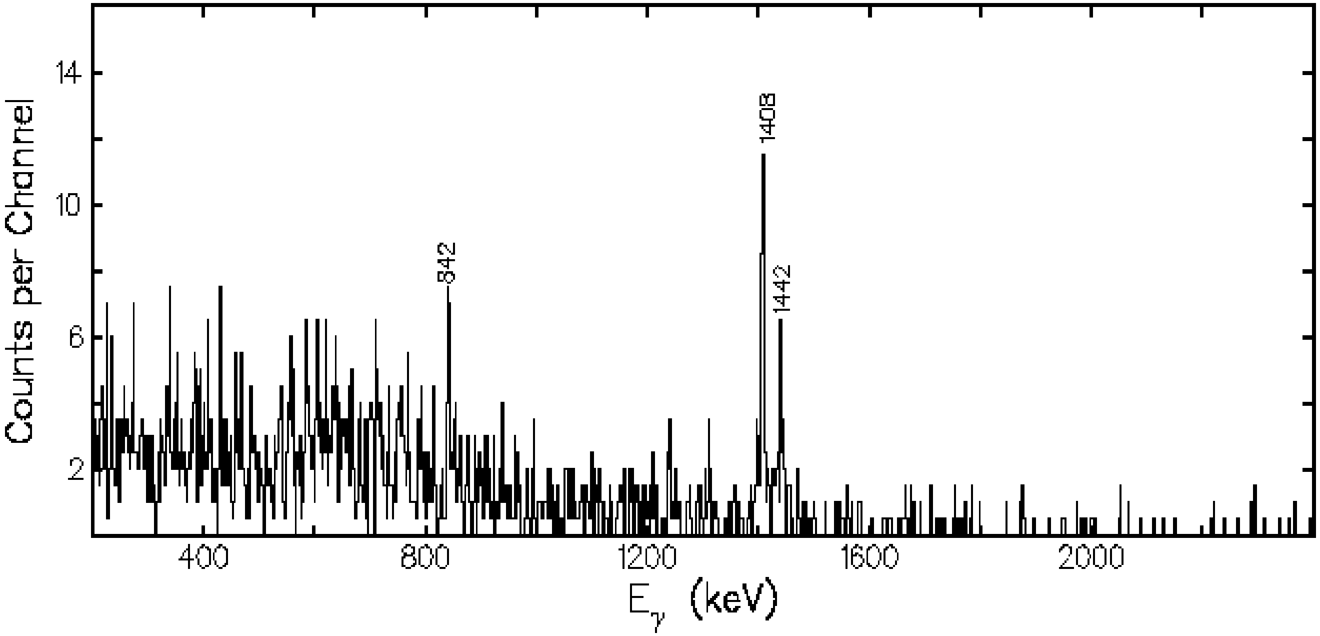


^{36}S(230 MeV) + ^{208}Pb

Effect of the occupancy of the $\nu 1f_{7/2}$ orbital on the $\pi d_{3/2}$ and $\pi s_{1/2}$ single particle energy separation.

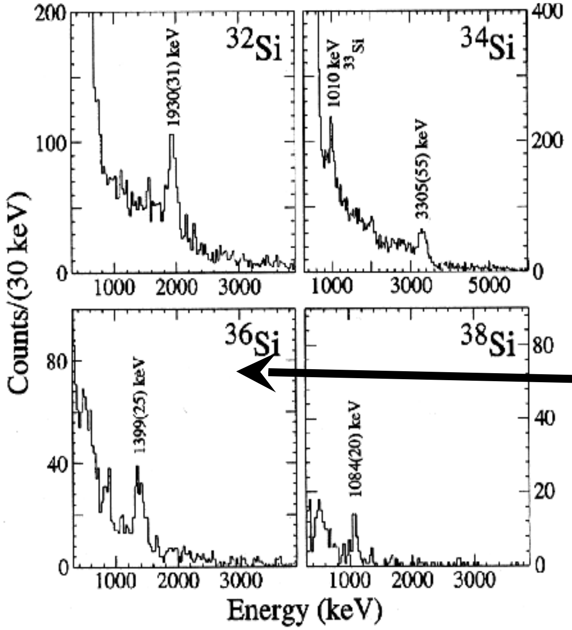
"Pseudo-SU(3)" symmetry and quadrupole deformation in n-rich S (N=24,26) isotopes

215MeV ^{36}S + ^{208}Pb CLARA + PRISMA



^{36}Si

6 neutrons
from
stability



In-beam Coulomb excitation following projectile fragmentation (MSU)

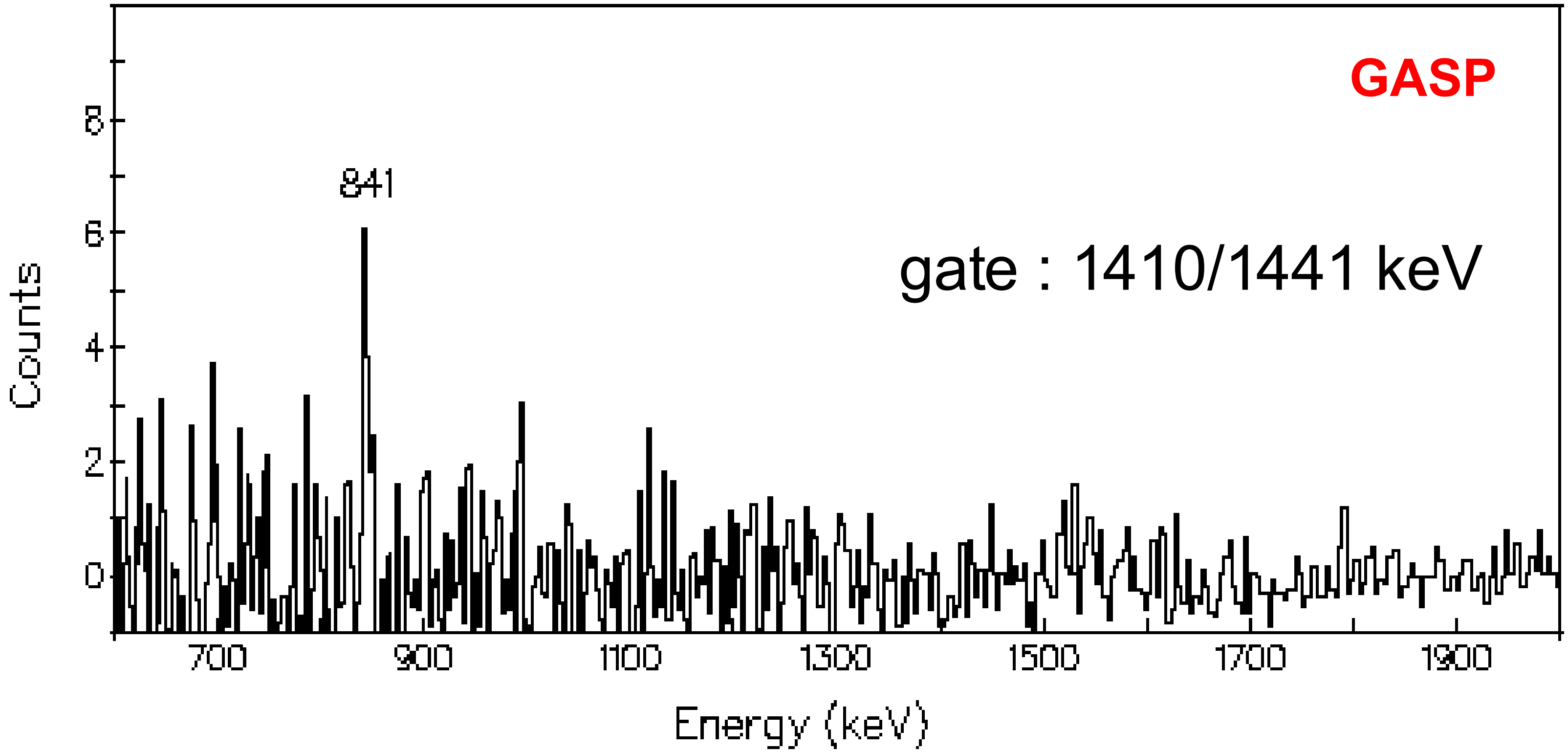
Array of 39 NaI(Tl) detectors

70MeV/A ^{48}Ca + ^{9}Be

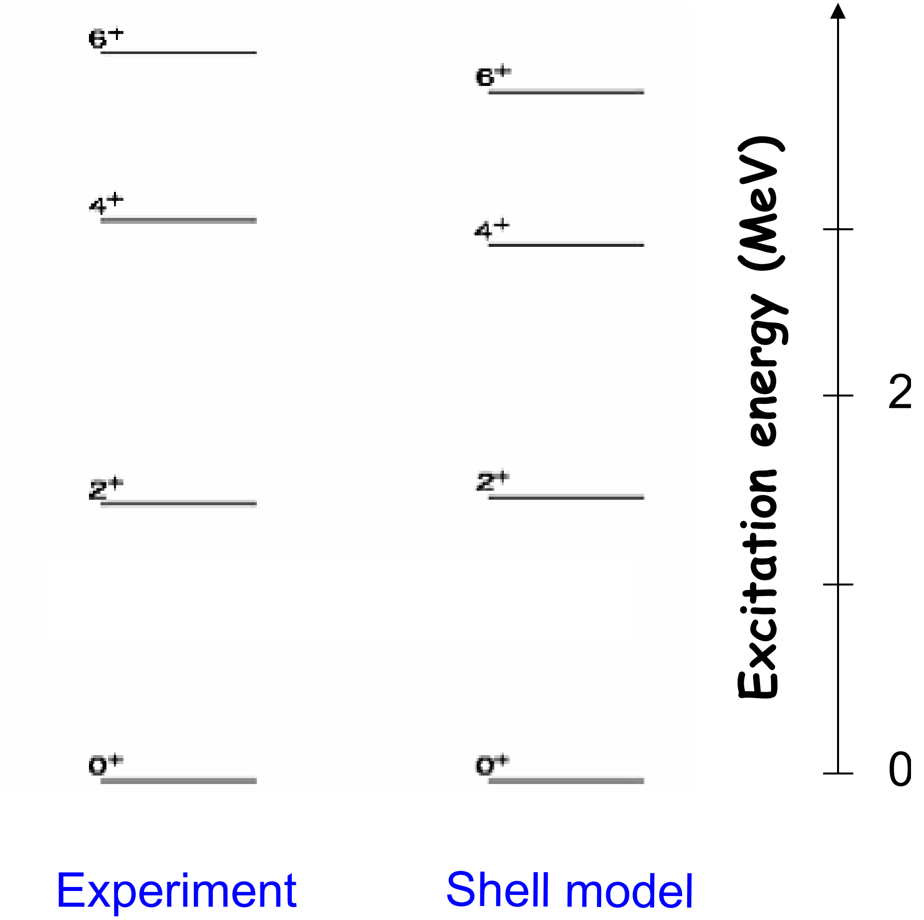
R.W. Ibbotson et al., Phys. Rev. Lett. **80**(1998)2081

Double gated ^{36}Si spectrum from data obtained in thick target 230MeV ^{36}S + ^{208}Pb experiment

J. Ollier, PhD thesis University of Paisley (2004) unpublished



^{36}Si



Strasbourg shell-model calculation

modified SDPF-NR interaction

π sd-shell

ν fp-shell

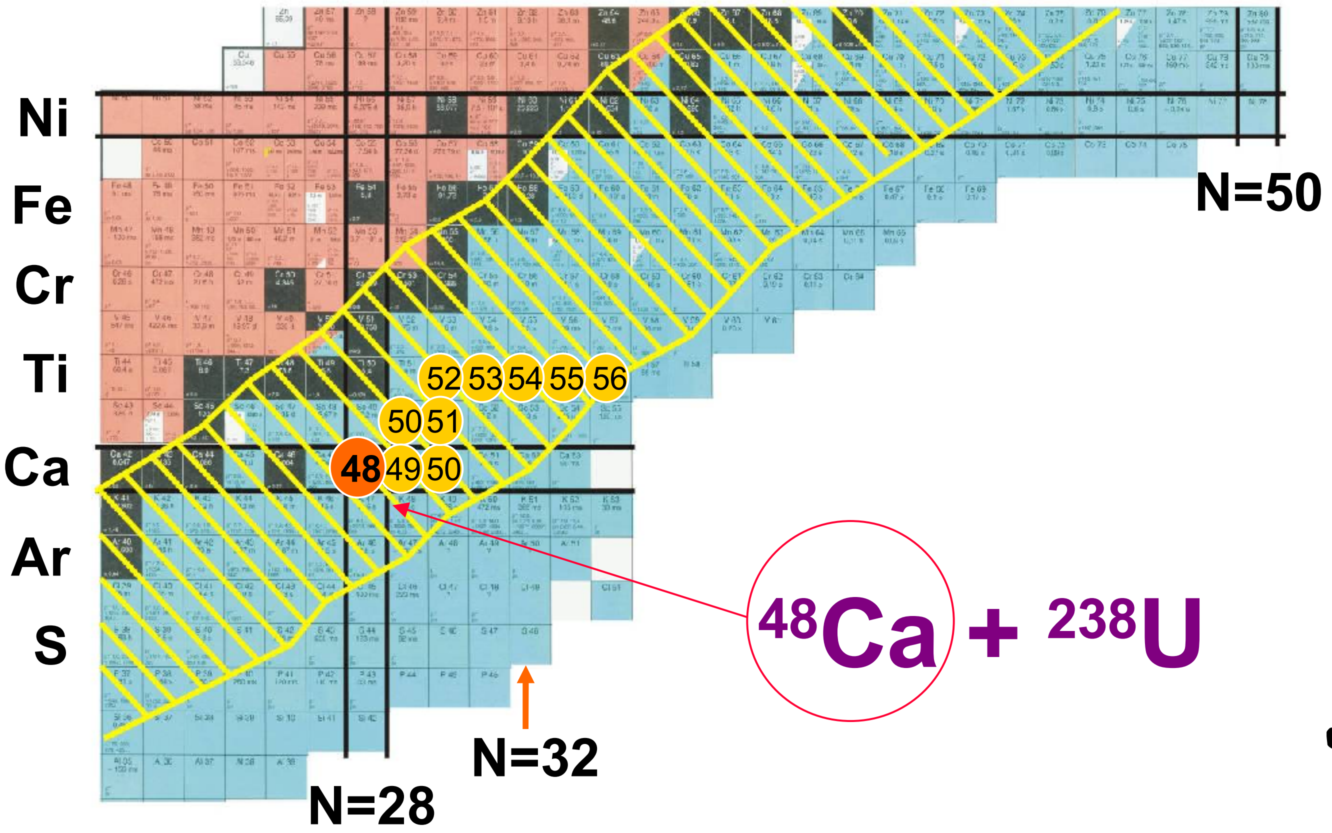
pf shell pairing reduced by 200keV to reproduce E_{2+}

$2p_{3/2}$ orbital energy decreased by 1MeV, otherwise higher spin levels too compressed.

X. Liang et al., Phys. Rev. C 74, 014311 (2006)

E. Caurier et al., Rev. Mod. Phys. 77, 427 (2005)

Deep-inelastic reaction products around ^{48}Ca previously studied in thick target experiment



^{48}Ca + ^{238}U

^{52,53,54,56}Ti:

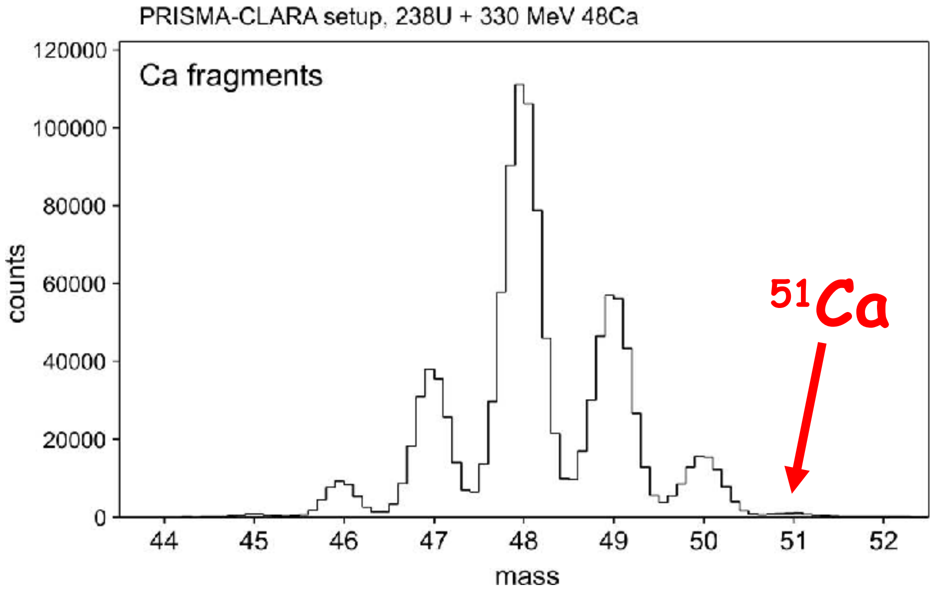
- ✔ R.V.F. Janssens et al., PLB 546, 55 (2002)
- ✔ B. Fornal et al., PRC 72, 044315 (2005), PRC 70, 064304 (2004)
- ✔ S. Zhu et al., PLB 650, 135 (2007)

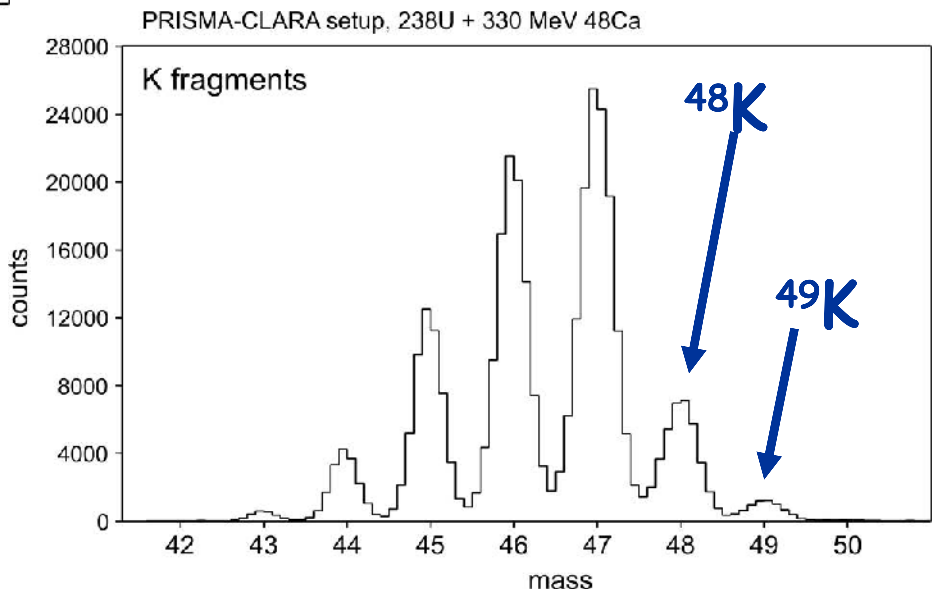
^{49,50}Ca, ^{51}Sc:

- ✔ R. Broda at al., APPB 36, 1343 (2005)

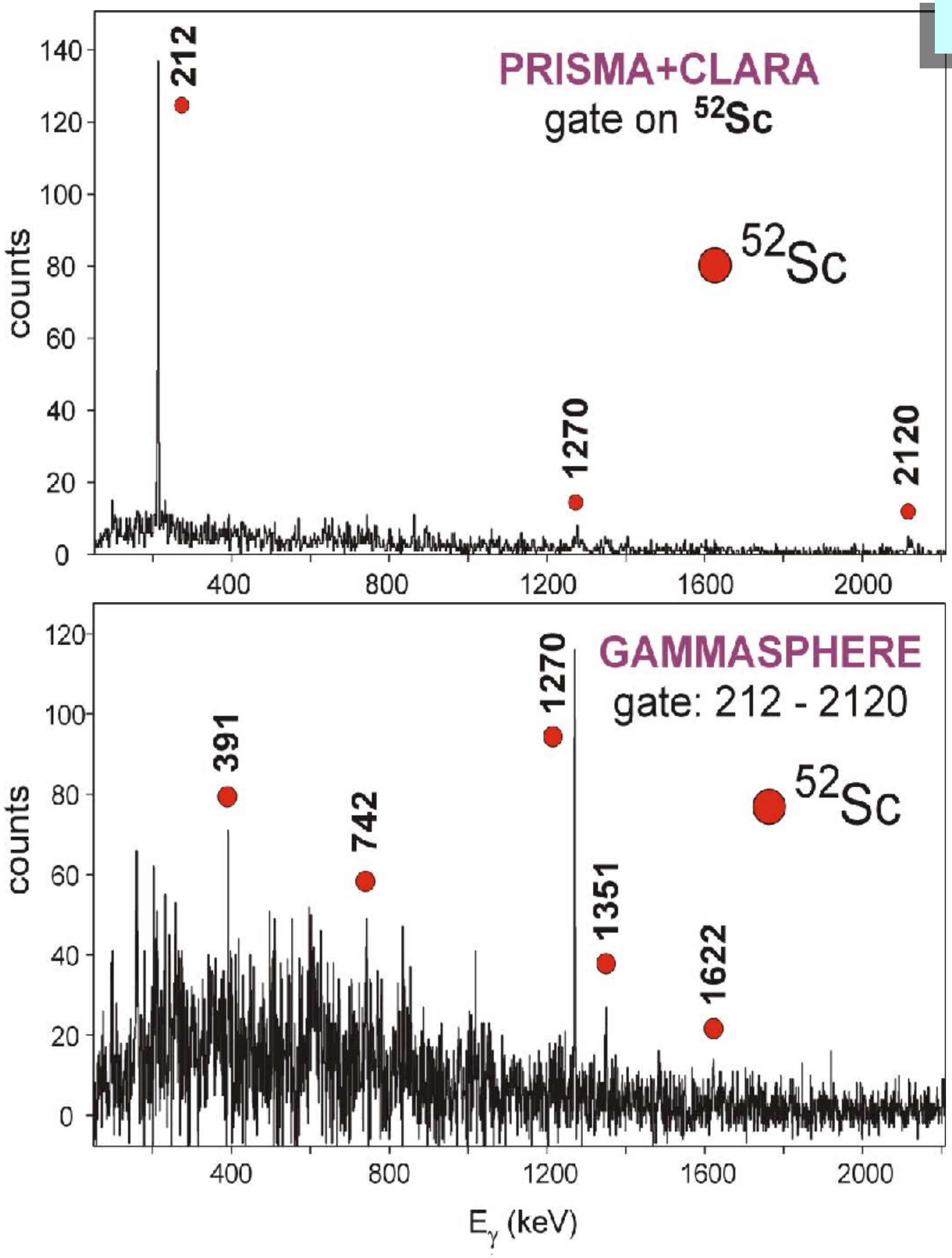
B.Fornal, R.Broda

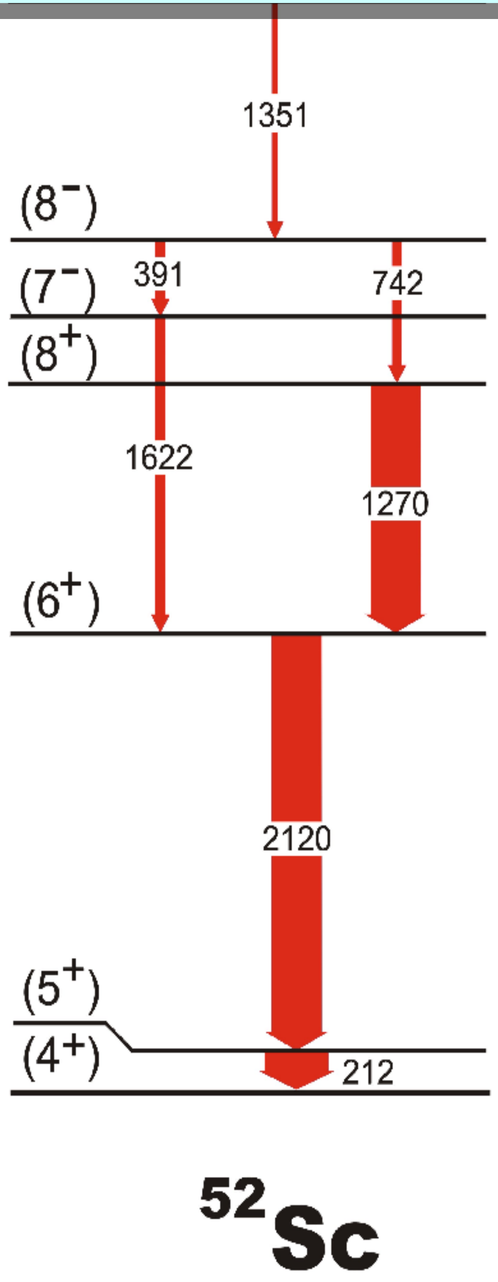
Sample mass spectra

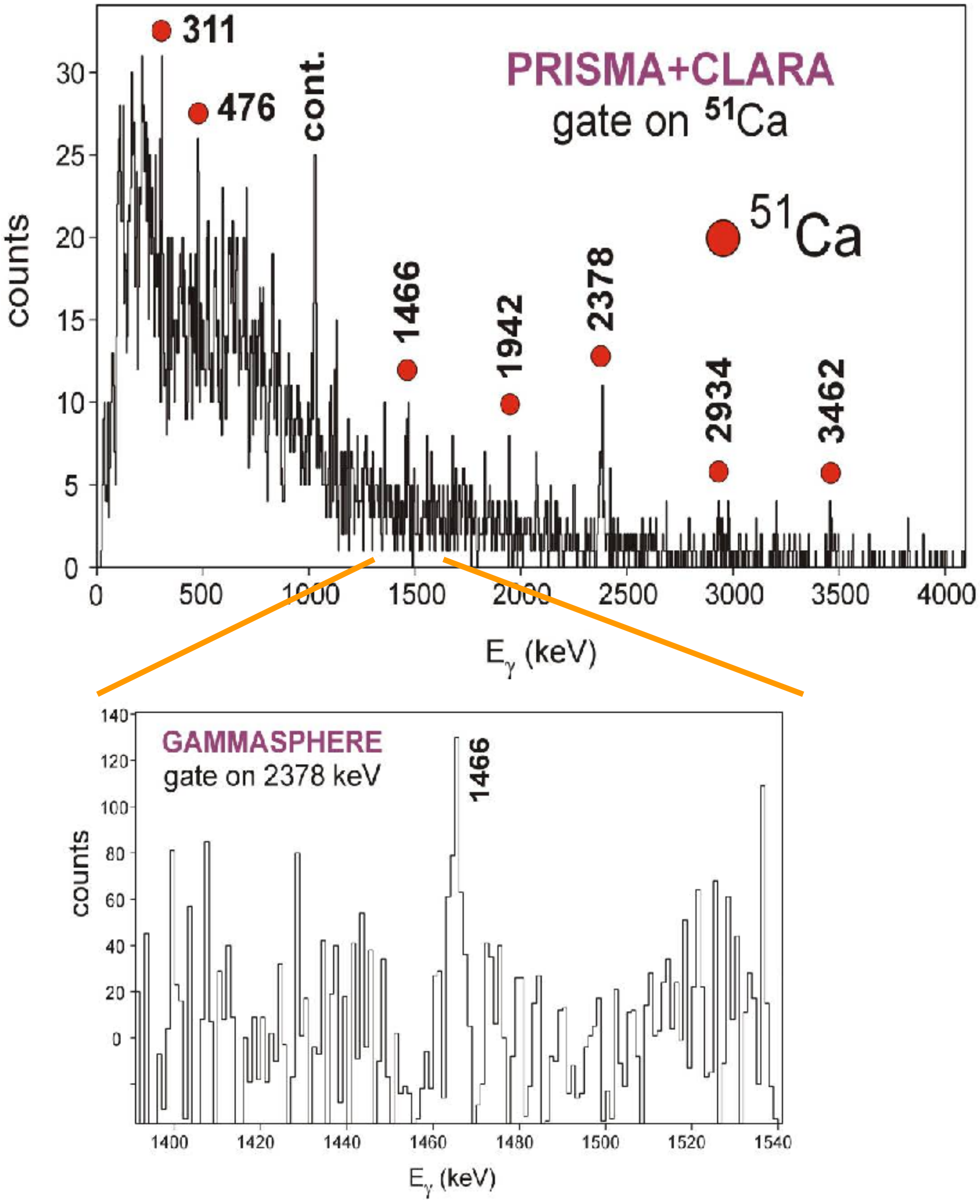

PRISMA-CLARA setup, 238U + 330 MeV 48Ca

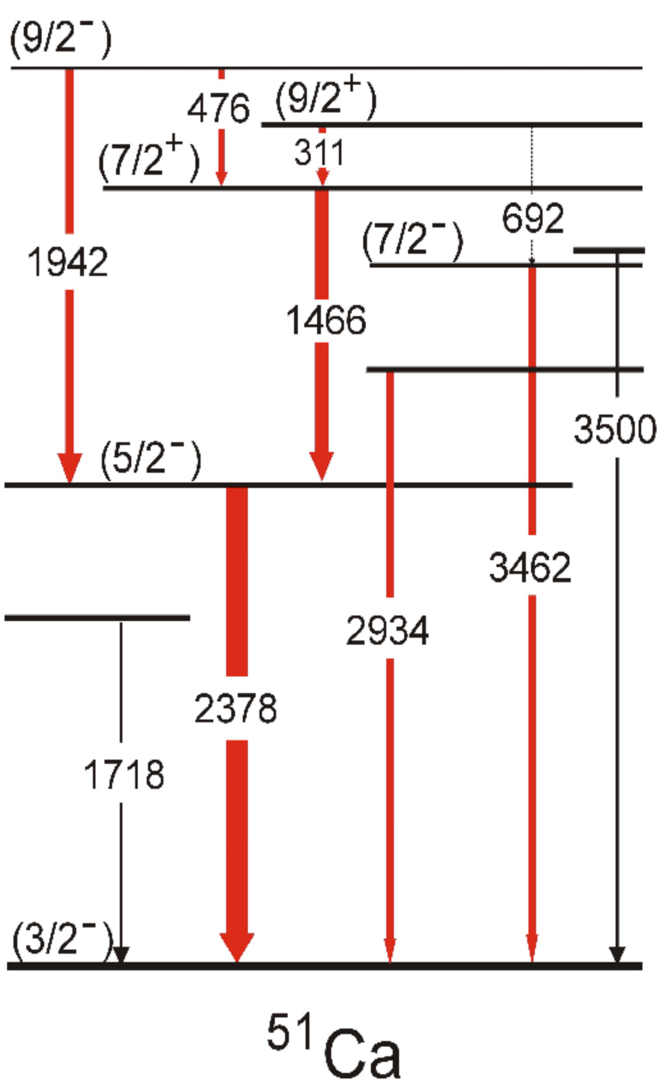

PRISMA-CLARA setup, 238U + 330 MeV 48Ca

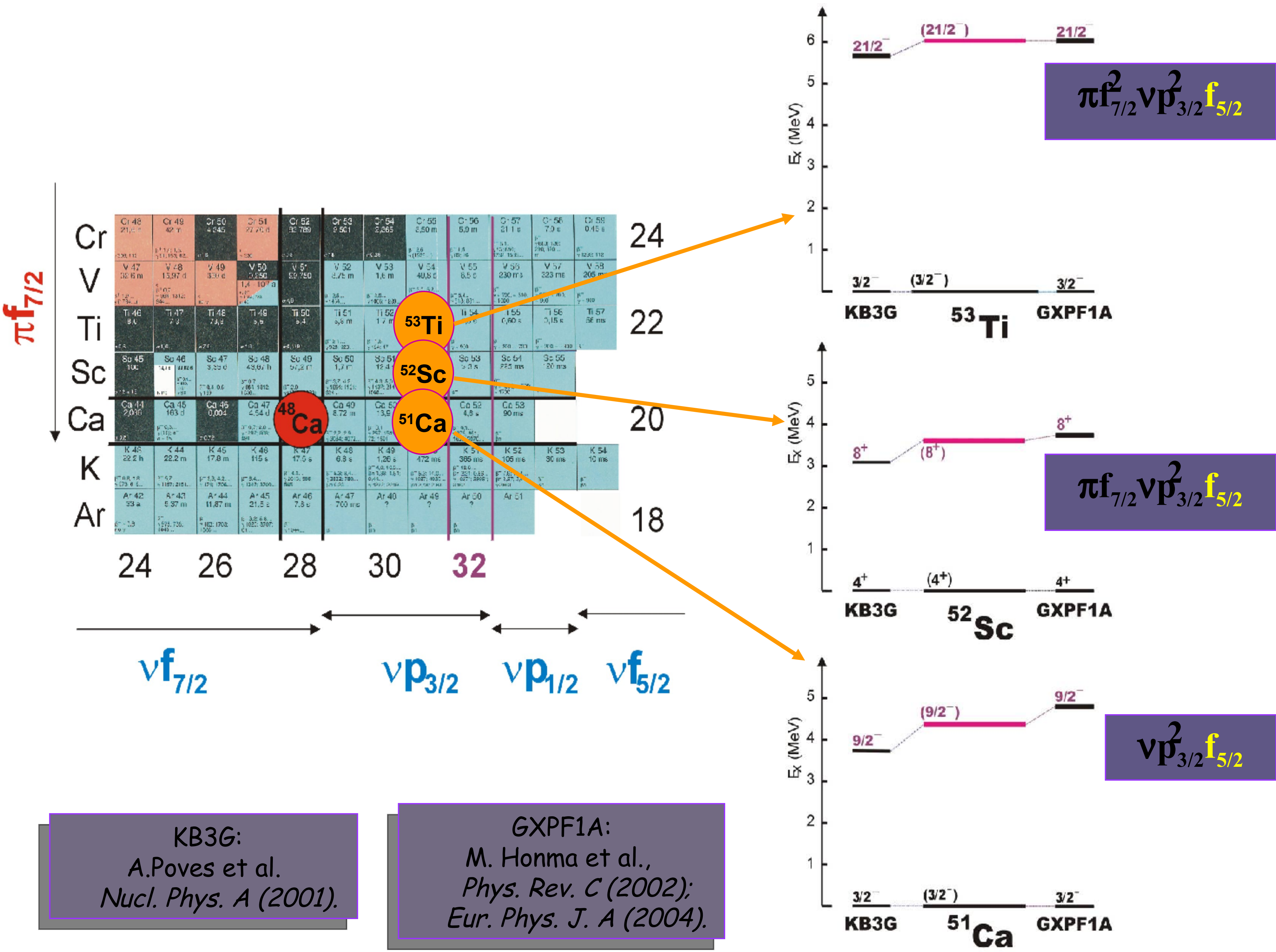
B.Fornal et al., PRC77, 014304 (2008)






PRISMA+CLARA
gate on ^{51}Ca
^{51}Ca
311
476
cont.
1466
1942
2378
2934
3462
counts
0
5
10
15
20
25
30
0
500
1000
1500
2000
2500
3000
3500
4000
E_γ (keV)
GAMMASPHERE
gate on 2378 keV
1466
counts
0
20
40
60
80
100
120
140
1400
1420
1440
1460
1480
1500
1520
1540
E_γ (keV)


(9/2⁻)
476
(9/2⁺)
(7/2⁺)
311
692
(7/2⁻)
1942
1466
3500
(5/2⁻)
3462
2934
2378
1718
(3/2⁻)
^{51}Ca



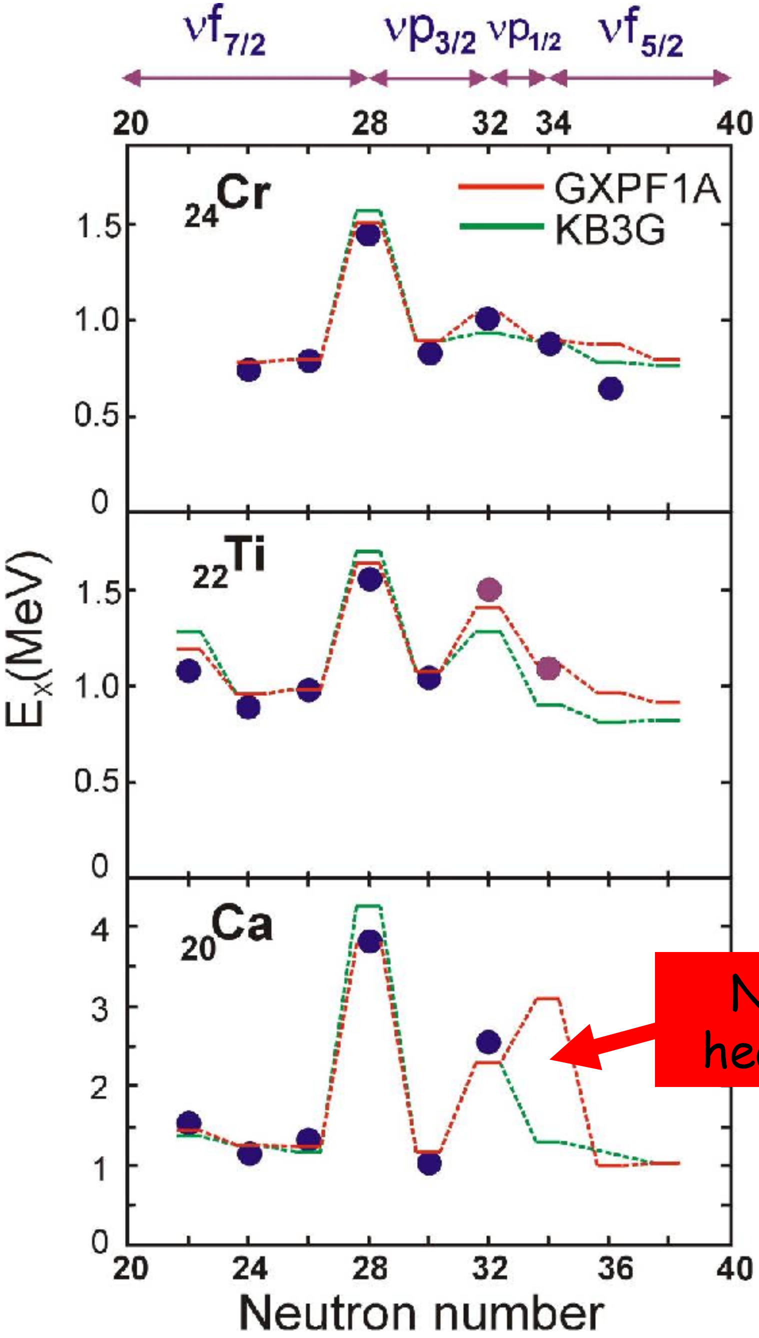
$\pi f^2_{7/2} \nu p^2_{3/2} f_{5/2}$

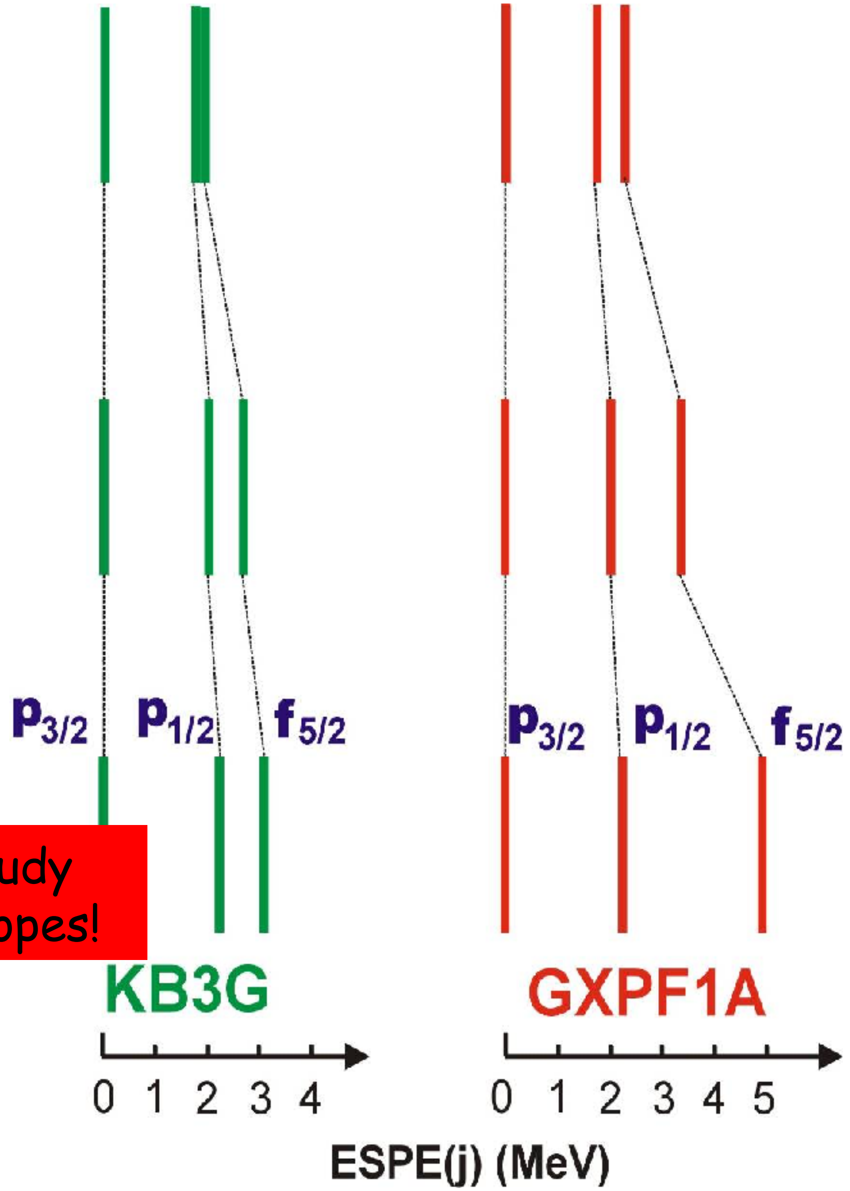
$\pi f_{7/2} \nu p^2_{3/2} f_{5/2}$

$\nu p^2_{3/2} f_{5/2}$

KB3G:
A.Poves et al.
Nucl. Phys. A (2001).

GXPF1A:
M. Honma et al.,
Phys. Rev. C (2002);
Eur. Phys. J. A (2004).

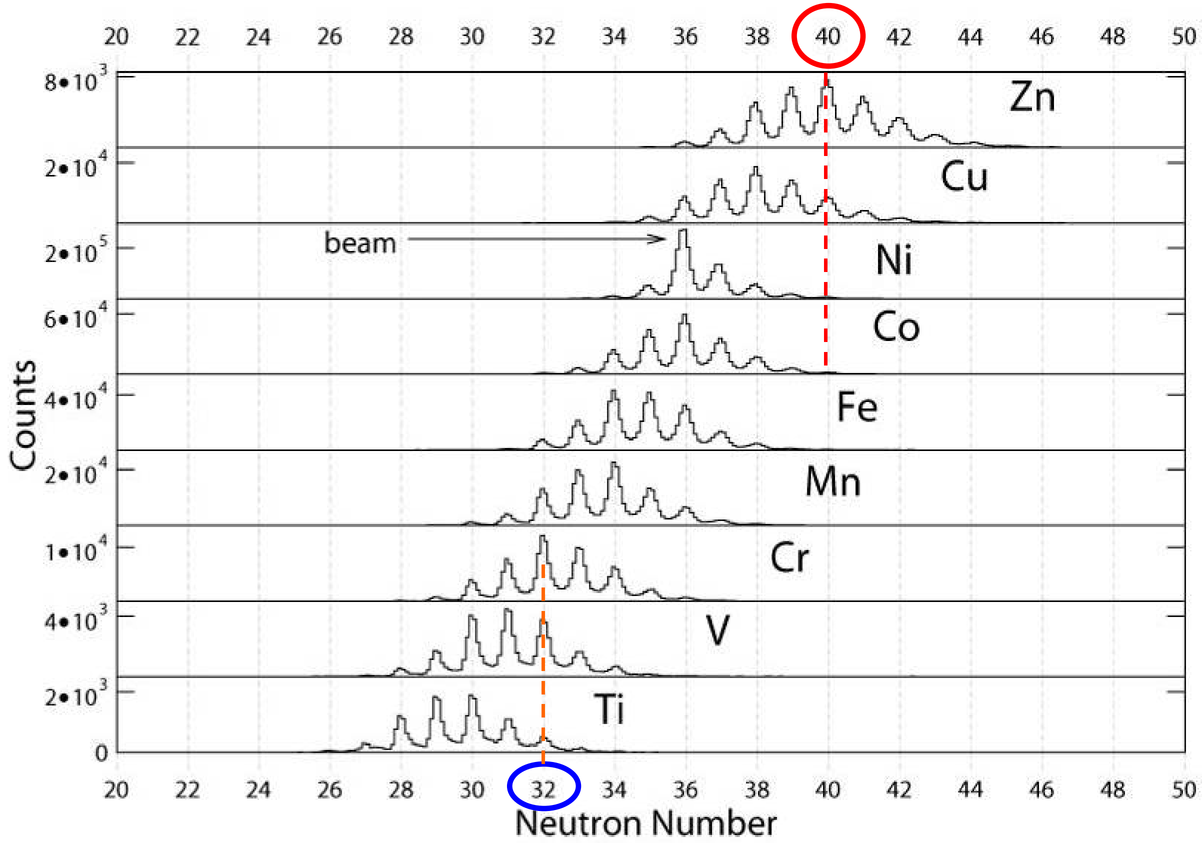




Need to study heavier isotopes!

Shell closures and collectivity in n-Rich A≈50-60 Nuclei

- Possible shell closures at N=32 and N=34
- Onset of collective behaviour in heavier isotopes

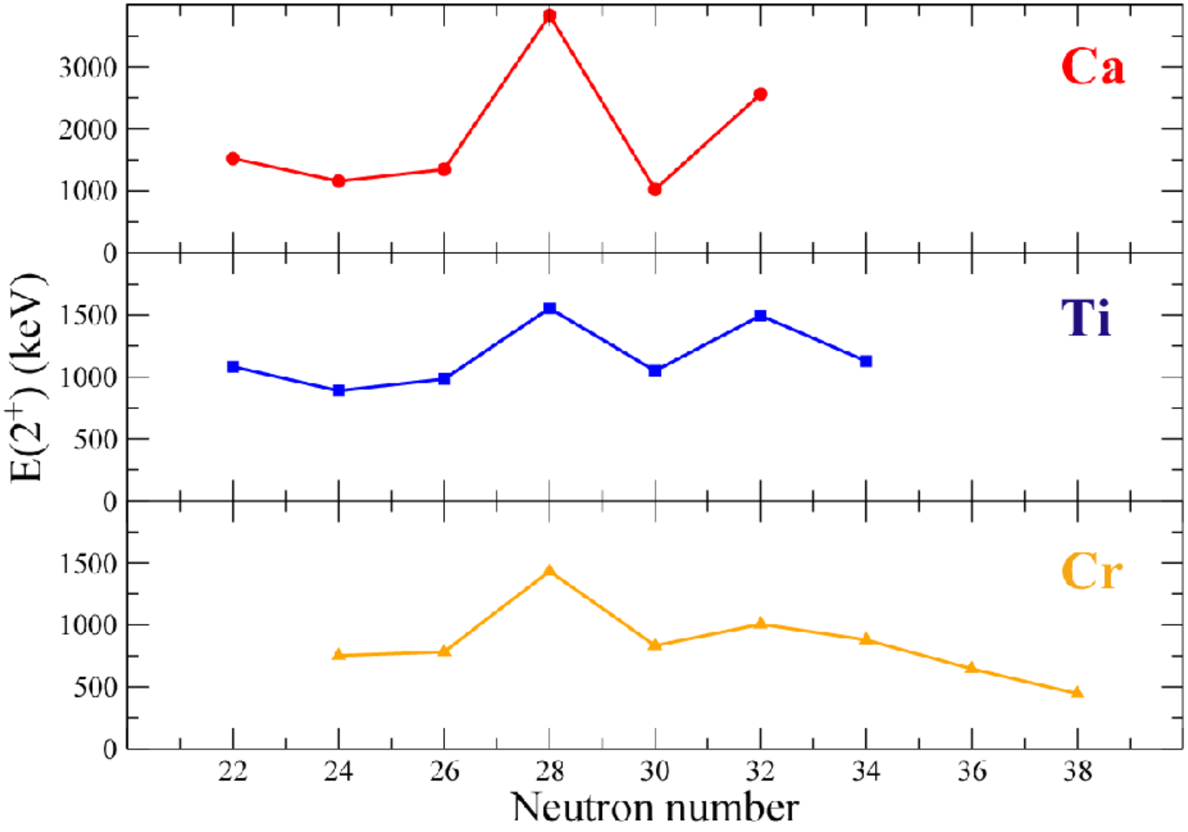


400 MeV ^{64}Ni on ^{238}U

S.M.Lenzi, S.Lunardi

Shell closures and collectivity in n-Rich A≈50-60 Nuclei

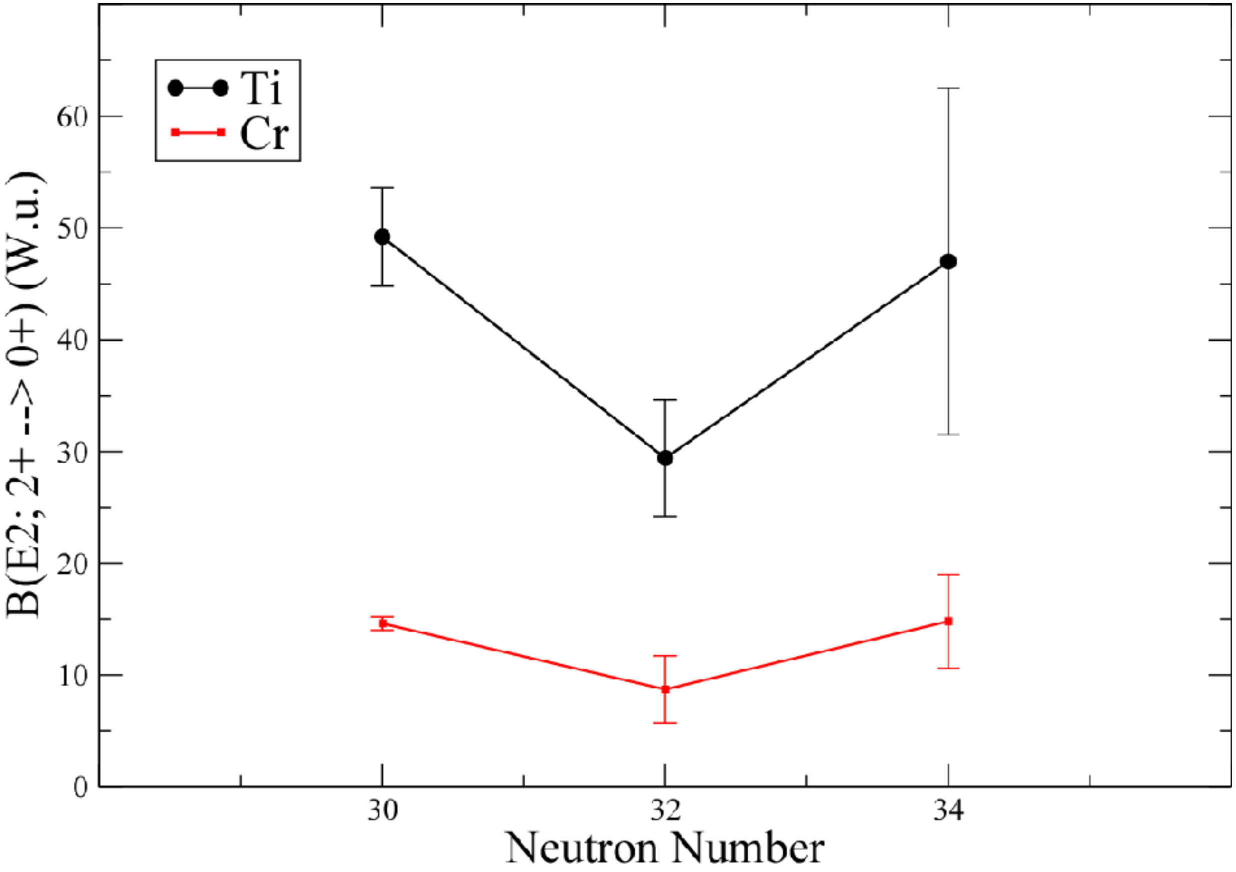
Systematics of the 2^+ energy in the Ca and Ti even-even isotopes suggests that *N=32* might be a good (sub)shell closure. The same systematics for the Cr isotopes points to quite a collective behaviour for the heavier isotopes.



This trend is well reproduced by shell-model calculations in a ***pf*** space

Shell closures and collectivity in n-Rich A≈50-60 Nuclei

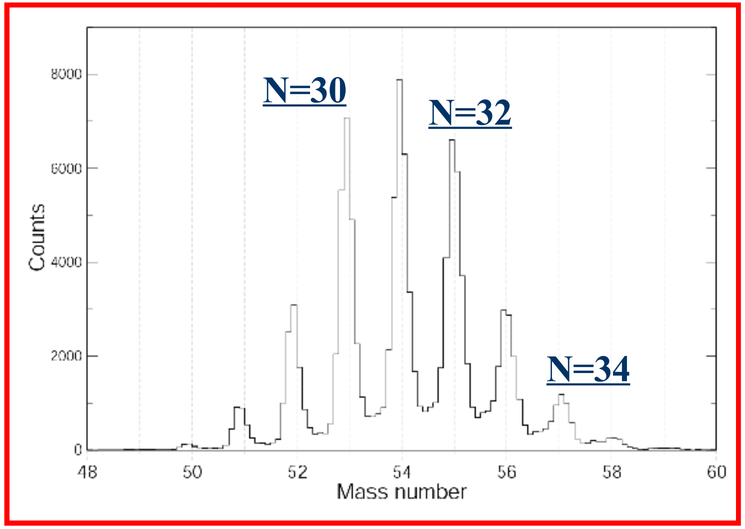
Transition probability data from RISING and MSU are consistent with a sub-shell closure at N=32. The spectroscopic information for the heavy Cr isotopes, prior to this measurement, was mostly limited to the energy of the first 2^+ state, identified from β-decay experiments.



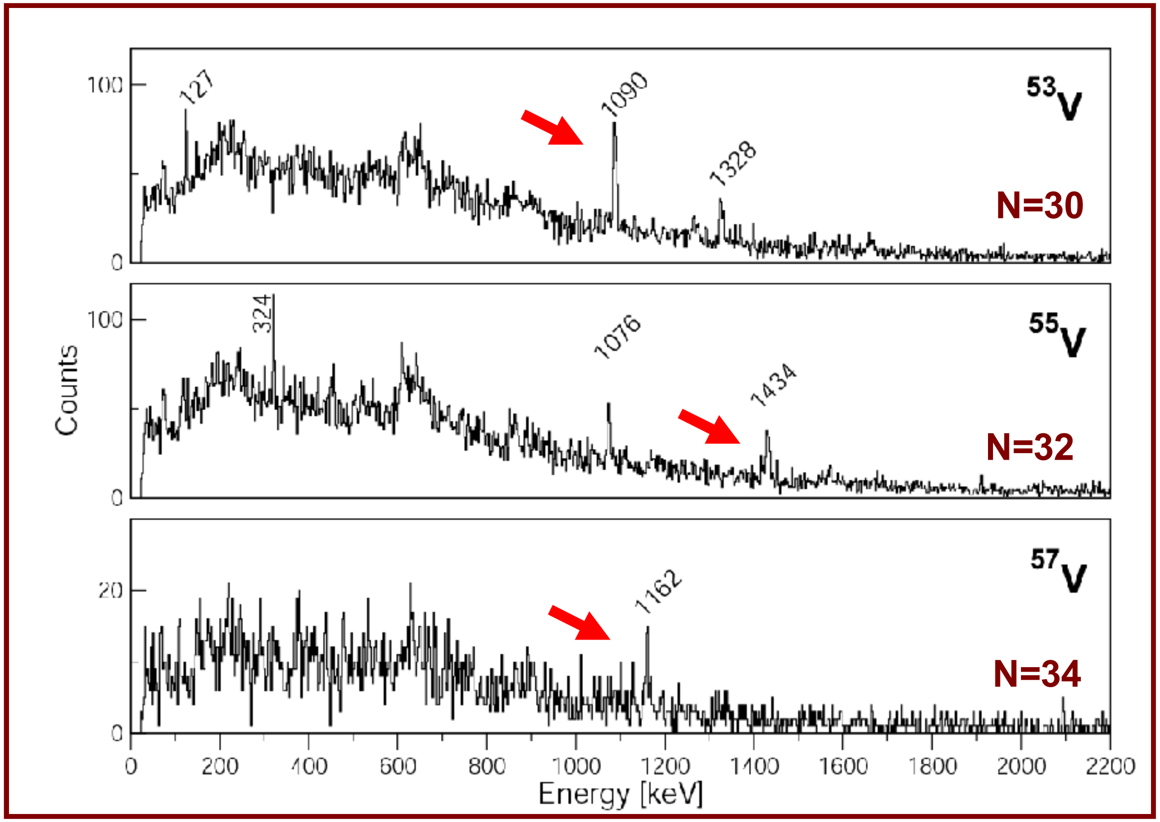
A.Bürger et al,
*PLB **622**, 29 (2005)*
D.-C.Dinca et al,
*PRC **71**, 041302(R) (2005)*
J.I.Prisciandaro et al,
*PLB **510**, 17 (2001)*
O.Sorlin et al,
*EPJA **16**, 55 (2003)*

Spectroscopy around the N=32 shell closure

V isotopes



First identification of yrast states in heavy odd-A Vanadium isotopes ^{55}V and ^{57}V

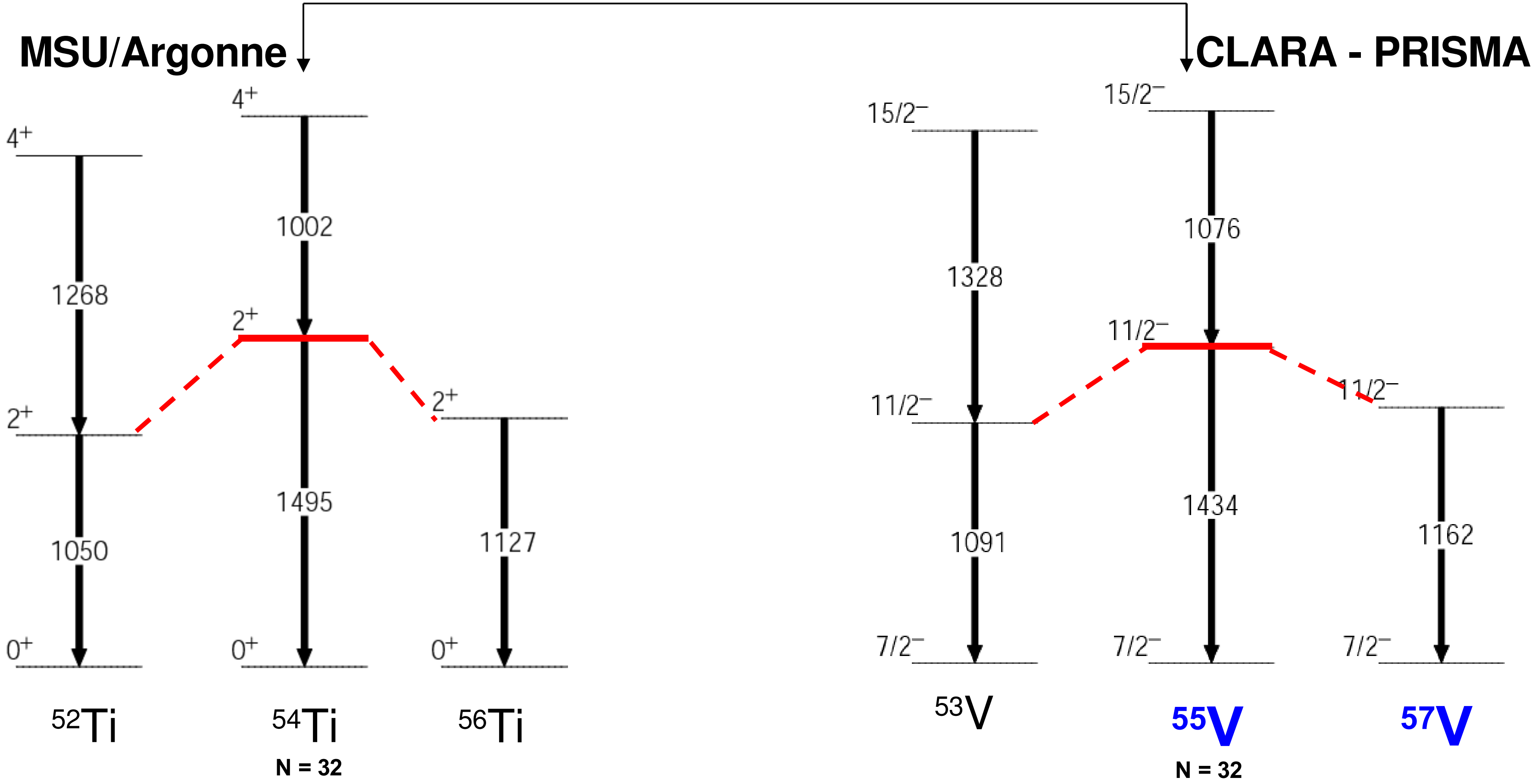


^{64}Ni(400 MeV) + ^{238}U

N=32 shell closure previously observed in ^{54}Ti and ^{56}Cr

D.R. Napoli et al., Jour. of Phys. Conf. S. 49, 91 (2006)

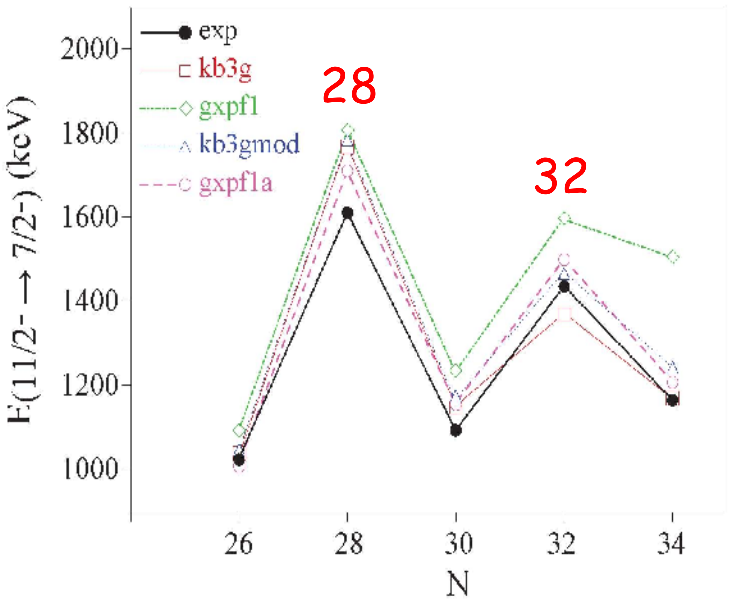
Shell closure at N=32



- First experimental observation of the $1\pi f_{7/2}$ band in ^{55,57}V

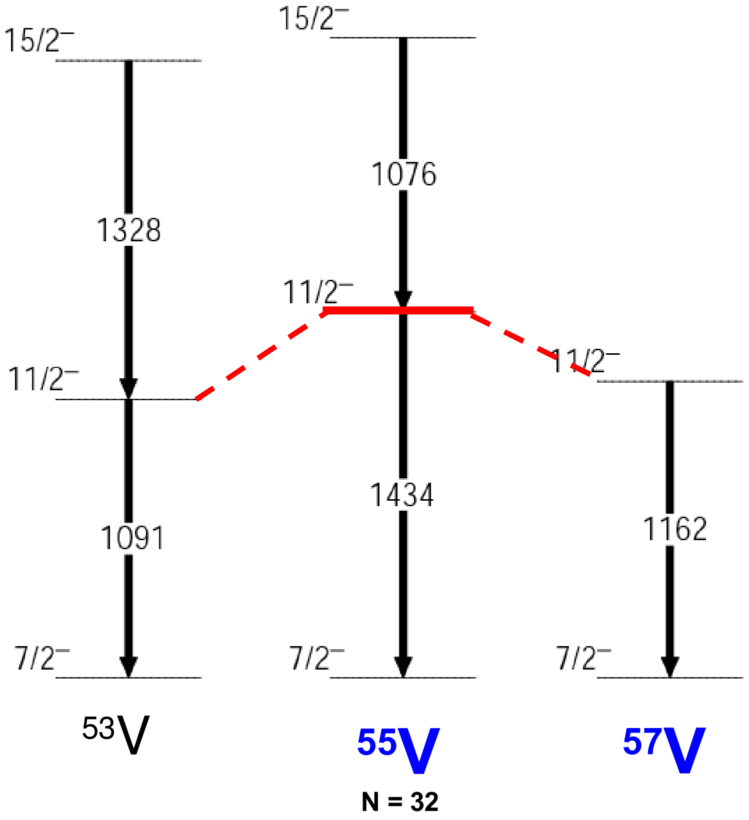
Shell closure at N=32

Shell model Calculations
for Vanadium isotopes



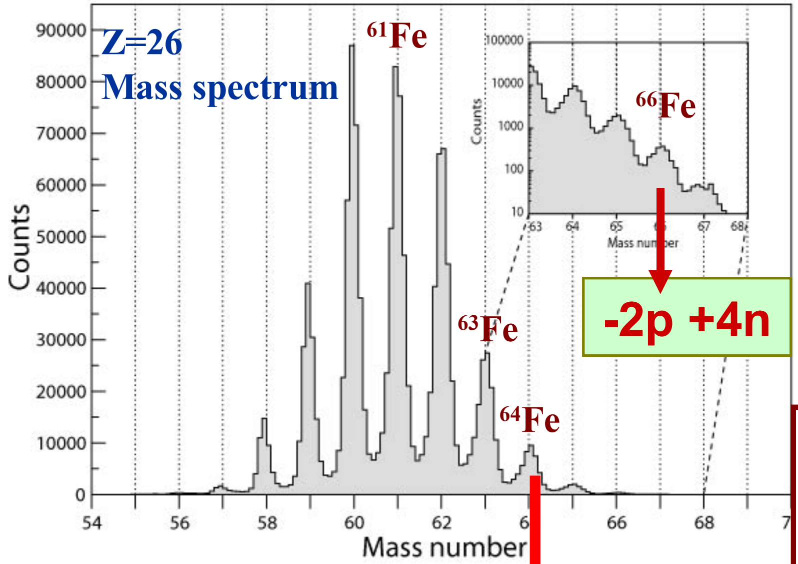
kb3g: A.Poves et al
gxfp1: M.Honma et al.

CLARA - PRISMA

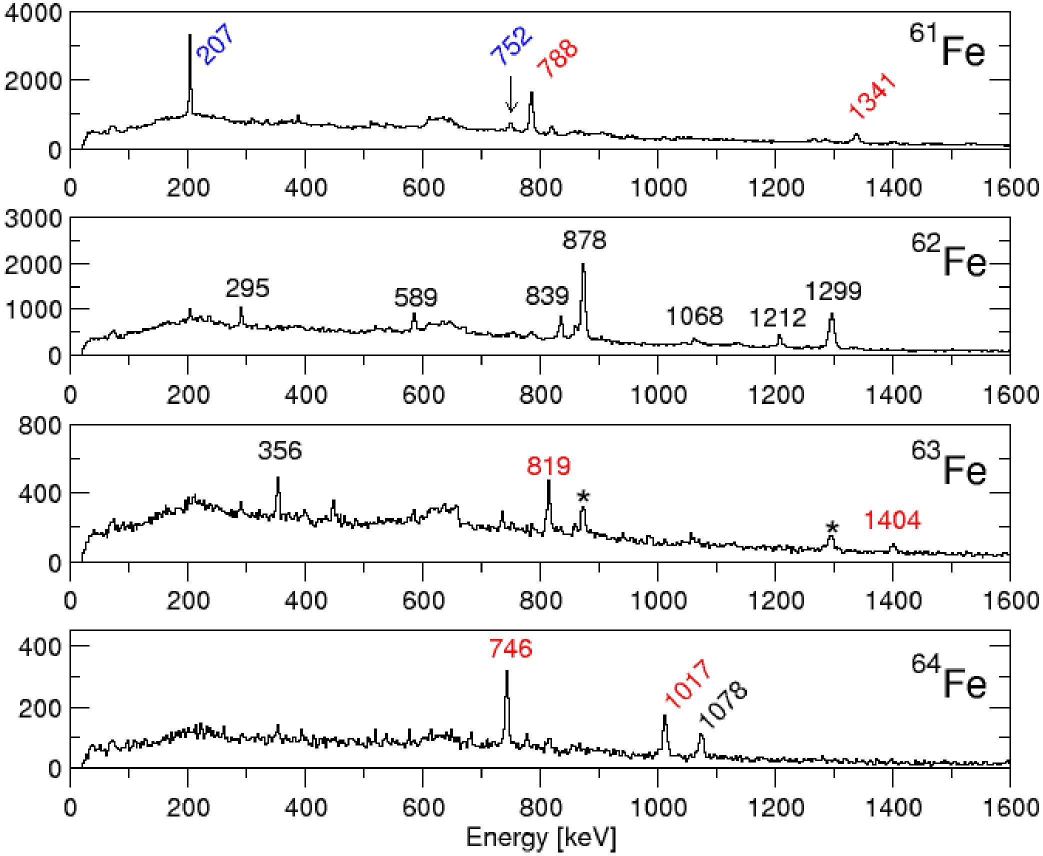


- First experimental observation of the $1\pi f_{7/2}$ band in ^{55,57}V
- The shell closure predicted at N=34 in some calculations is not confirmed by experimental data

Neutron-rich Fe nuclei populated in the ^{64}Ni + ^{238}U reaction at 400 MeV

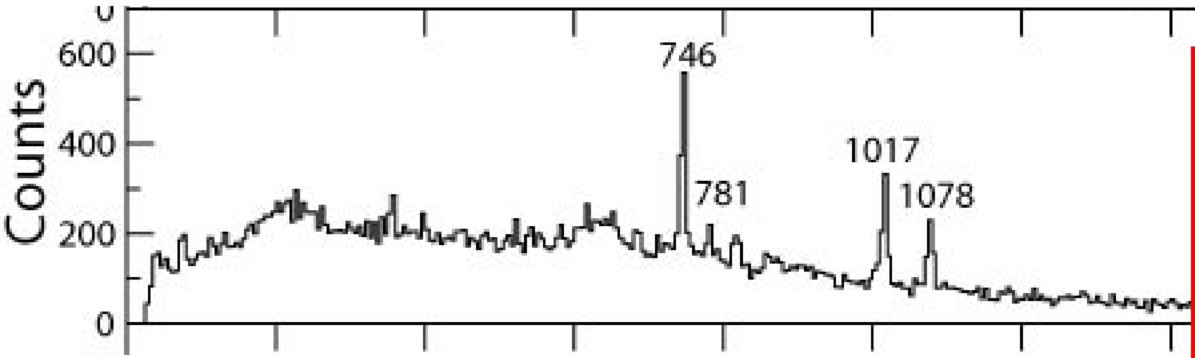


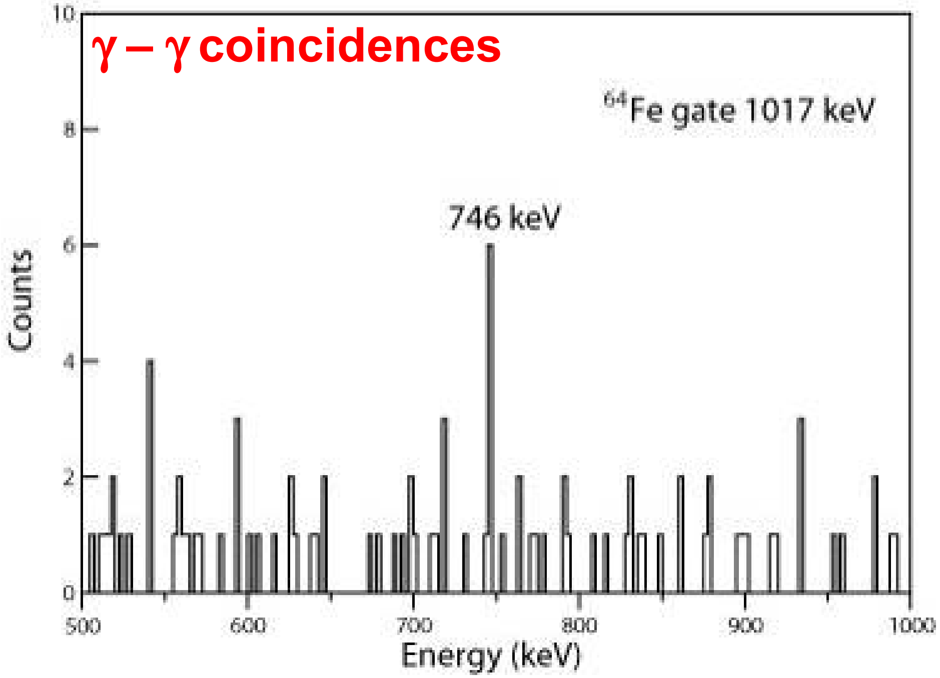
CLARA-PRISMA coincidences

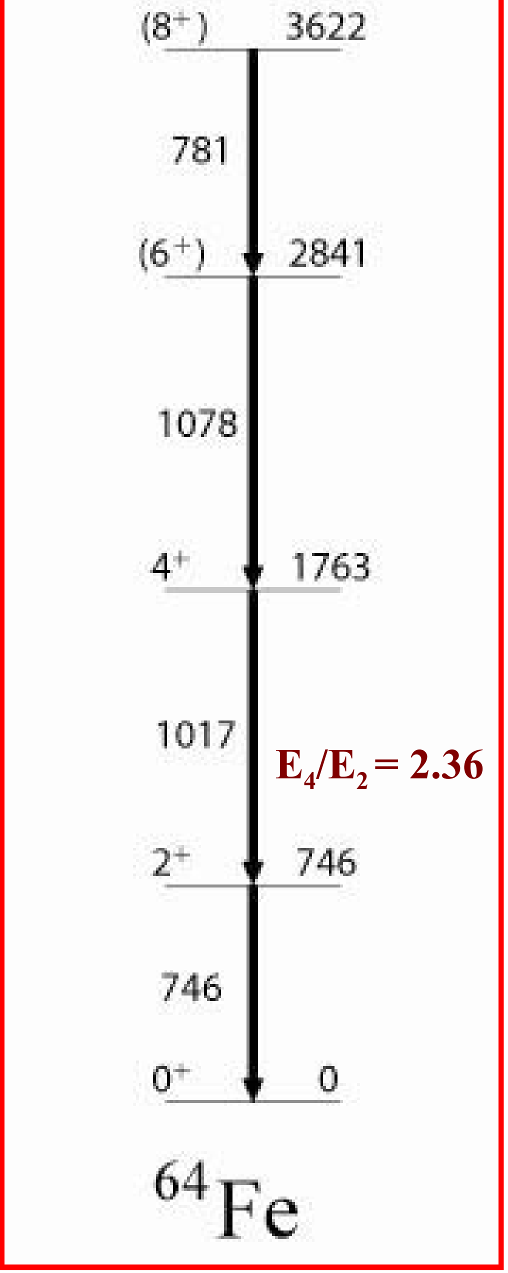


S. Lunardi *et al.* PRC76, 034303 (2007)

^{64}Fe

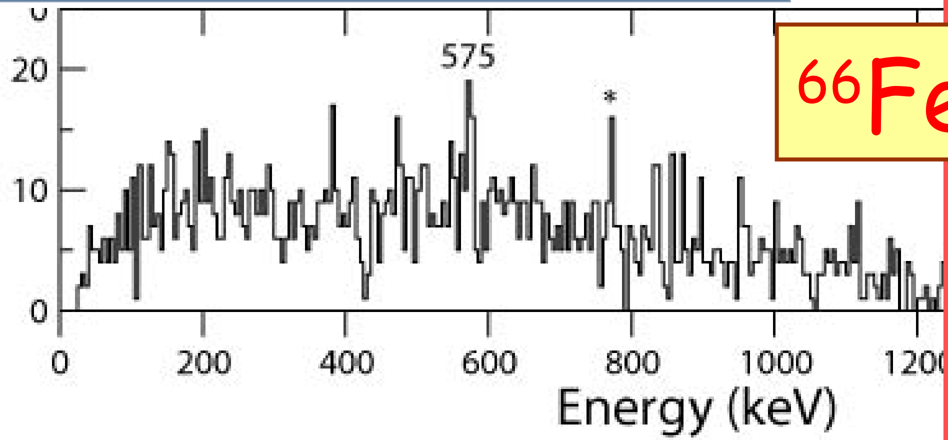



γ – γ coincidences

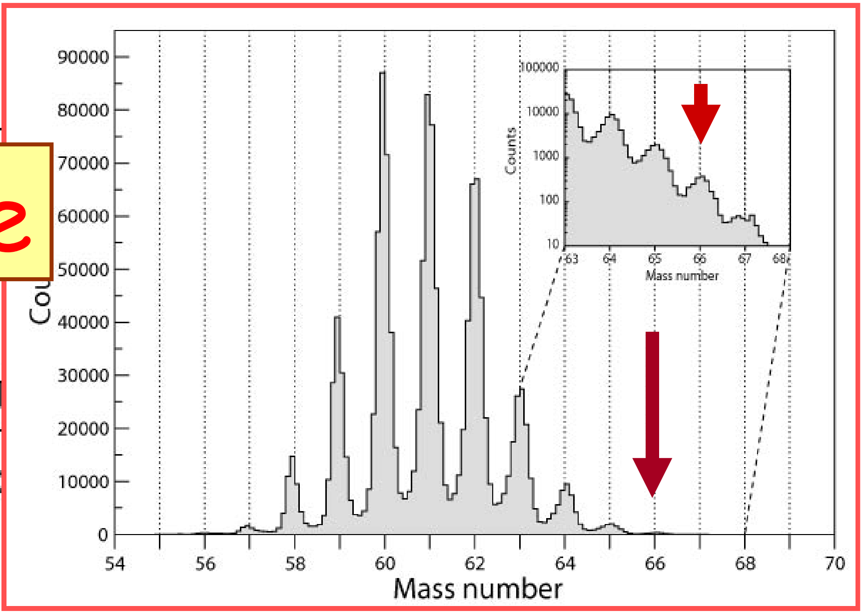


$E_4/E_2 = 2.36$

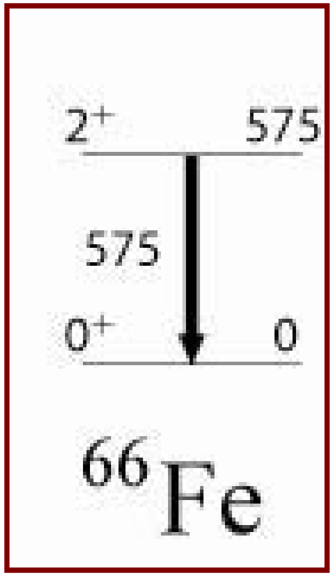
^{64}Ni+^{238}U at 400 MeV



^{66}Fe

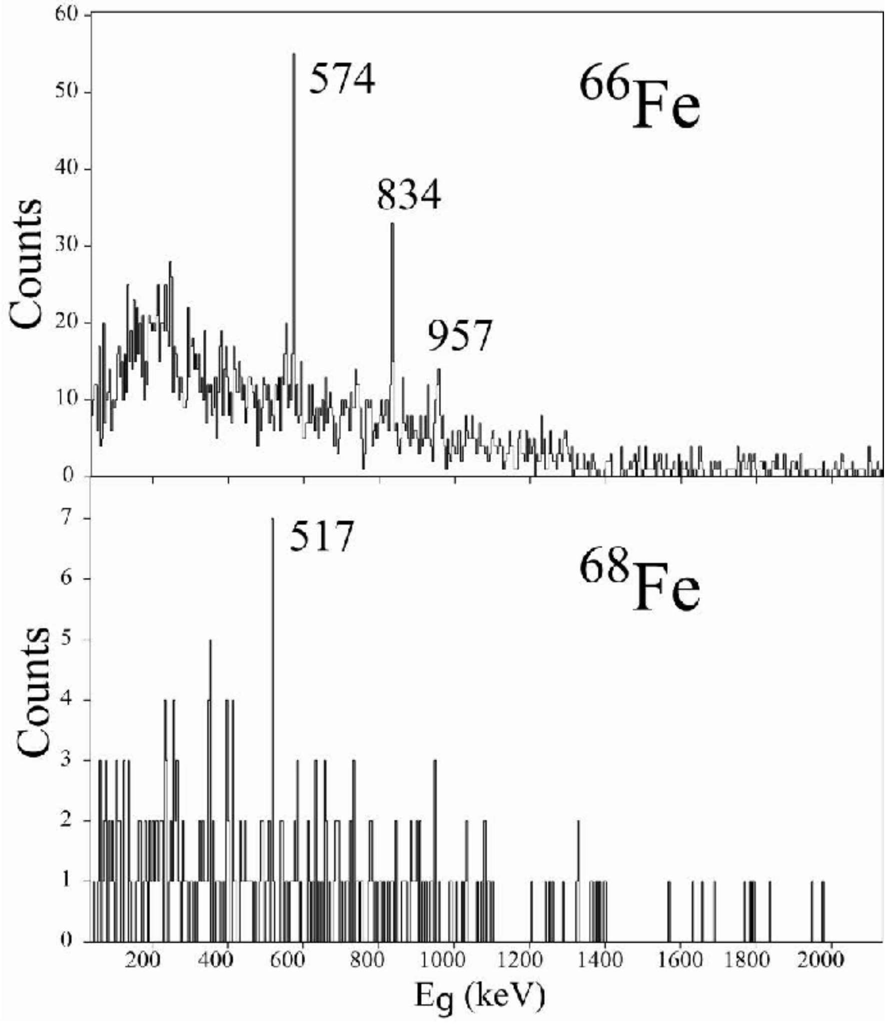


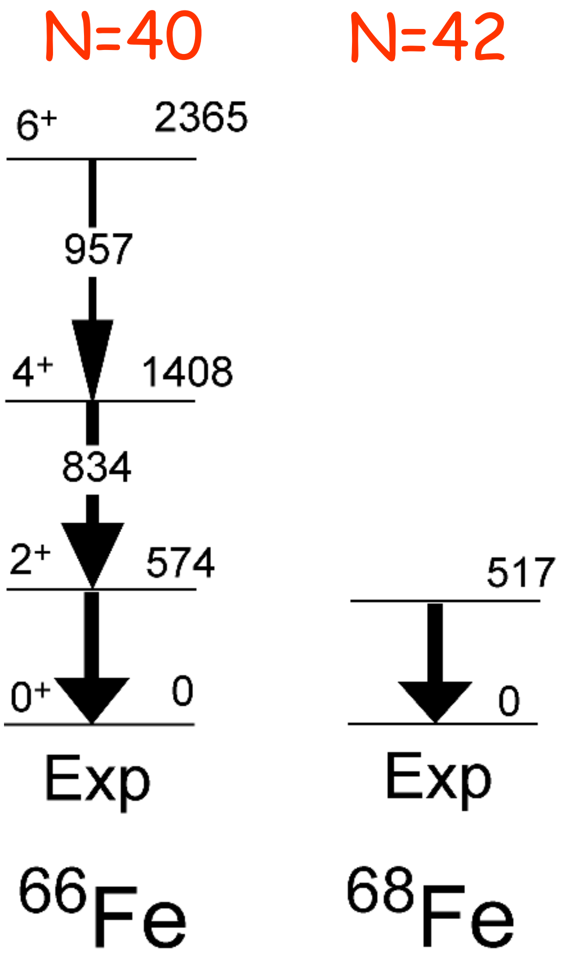
-2p + 4n channel



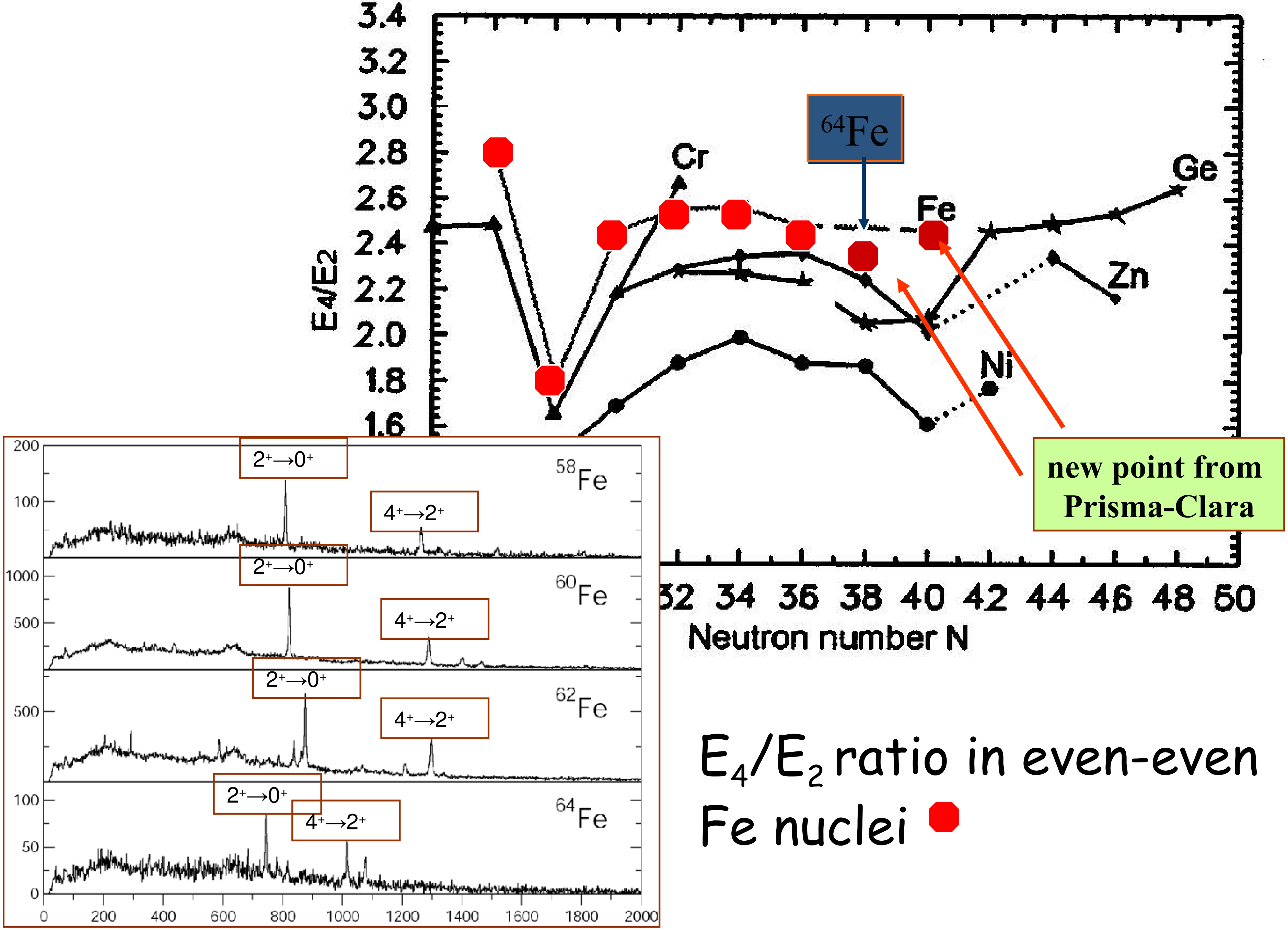
Beyond N=40

^{70}Zn on ^{238}U at 460 MeV





S.M. Lenzi et al., LNL Annual Report 2007 and to be published



new point from Prisma-Clara

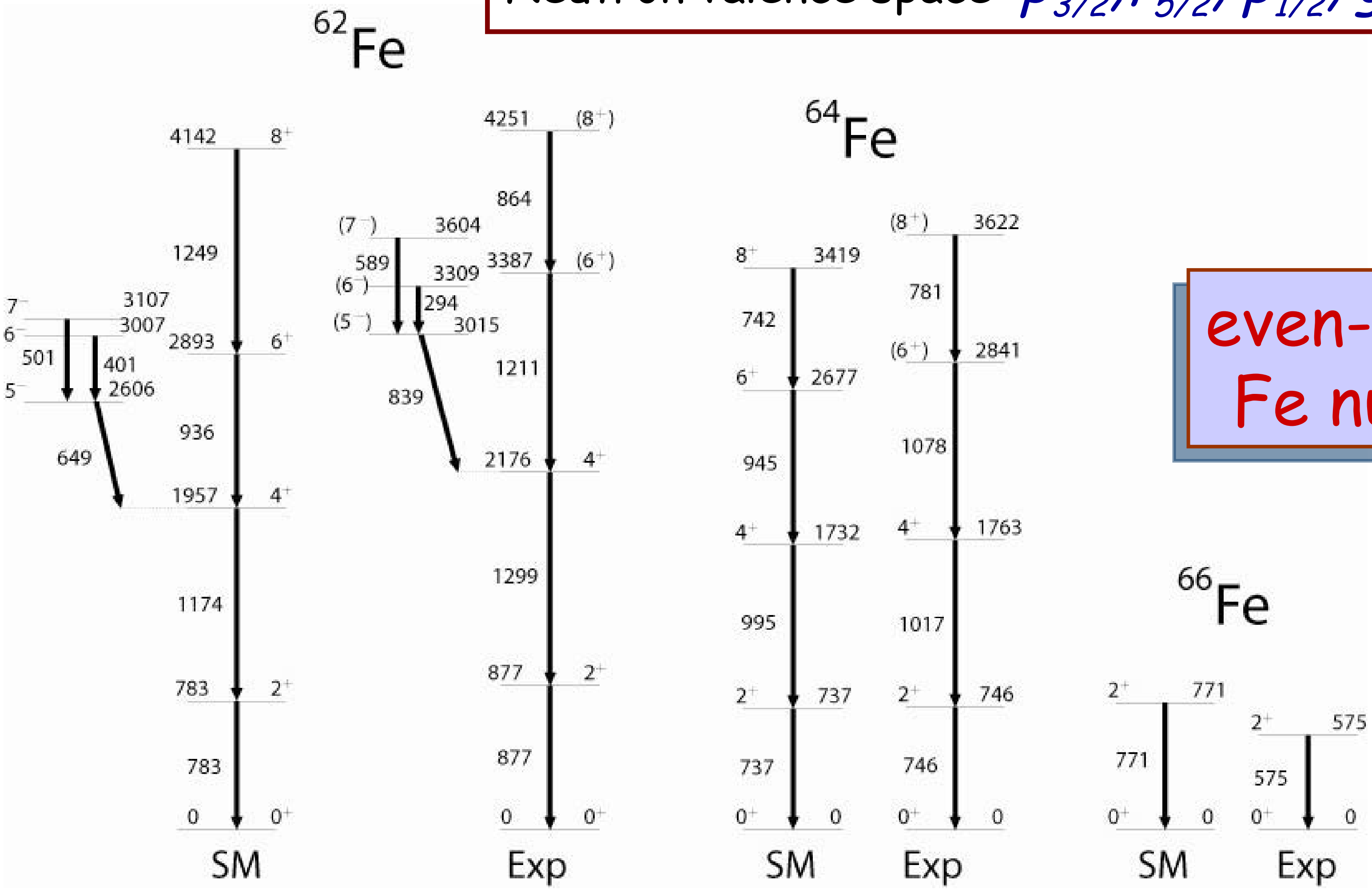
E_4/E_2 ratio in even-even Fe nuclei ●

Shell model calculations for Fe nuclei

Core ^{48}Ca, fpg effective interaction

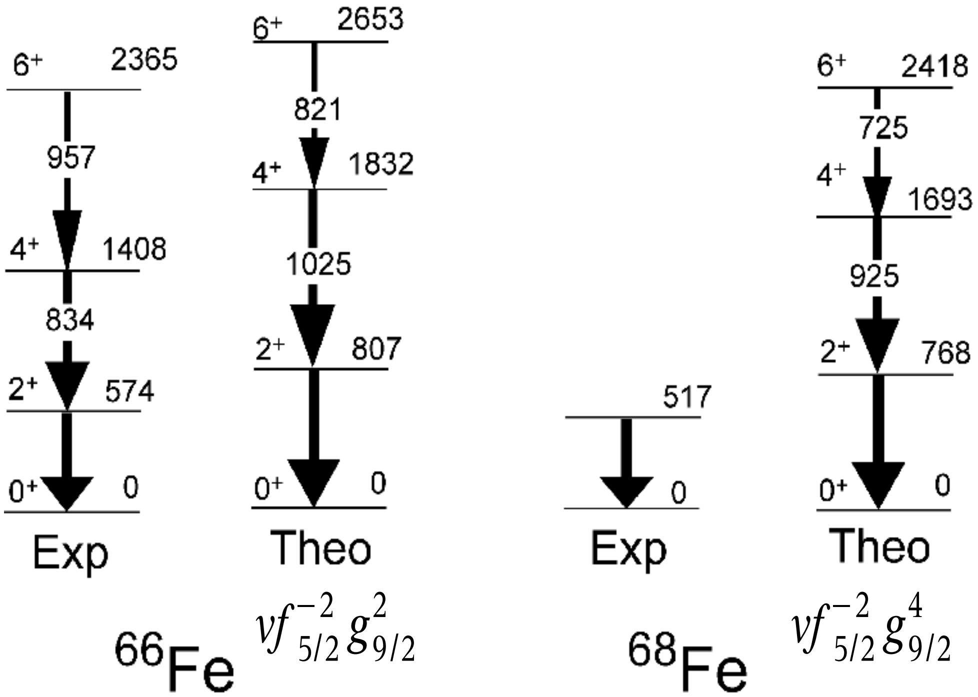
Proton valence space: *fp* orbitals

Neutron valence space: $p_{3/2}, f_{5/2}, p_{1/2}, g_{9/2}$



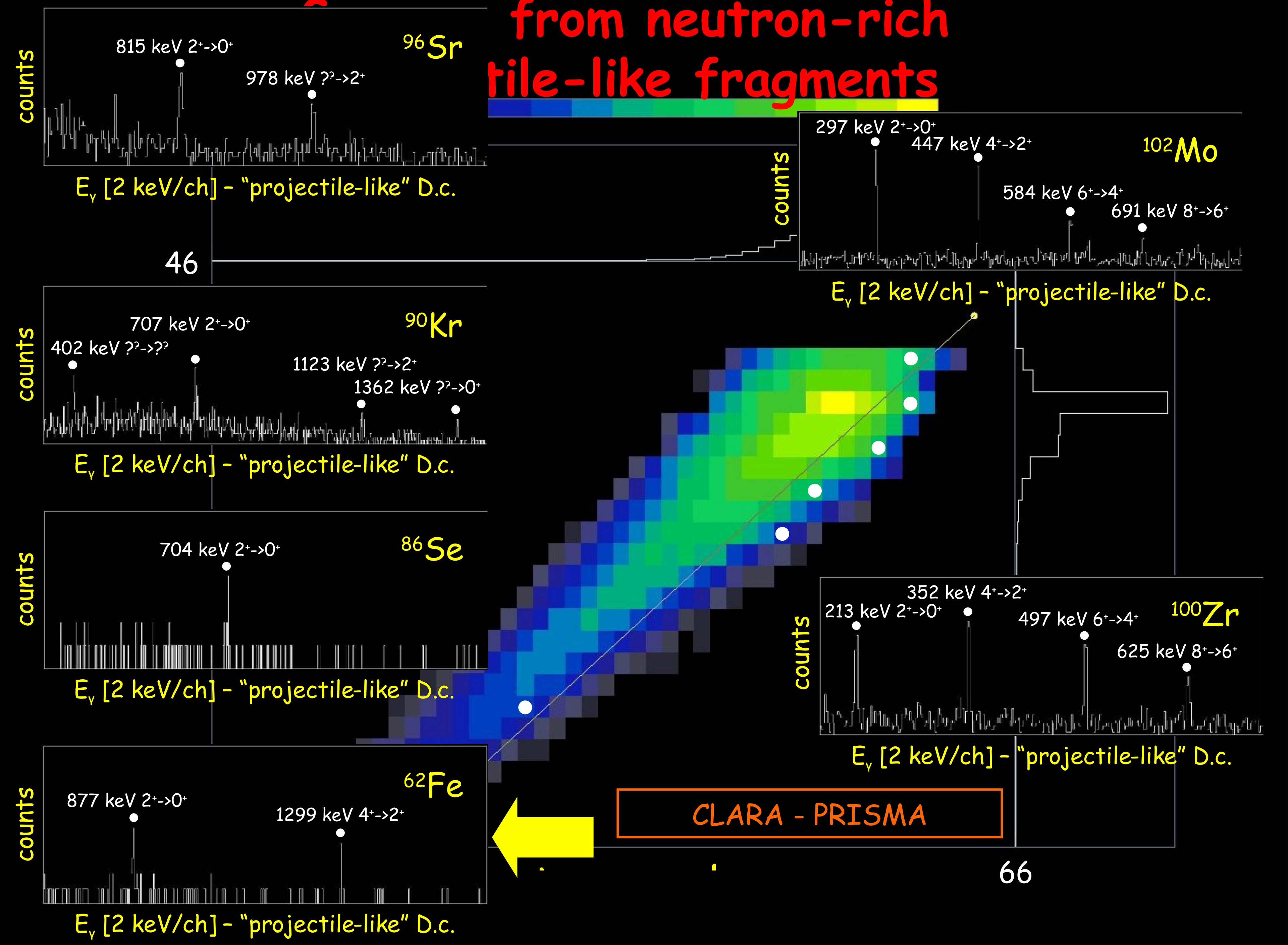
even-even Fe nuclei

Comparison with shell model



The experimental level schemes seem to be more quadrupole-collective than the calculated ones.
This quadrupole collectivity can be produced by including the $d_{5/2}$ shell in the model space (pseudo-SU(3), see A.P.Zuker et al., PRC, 2005)

from neutron-rich
tile-like fragments



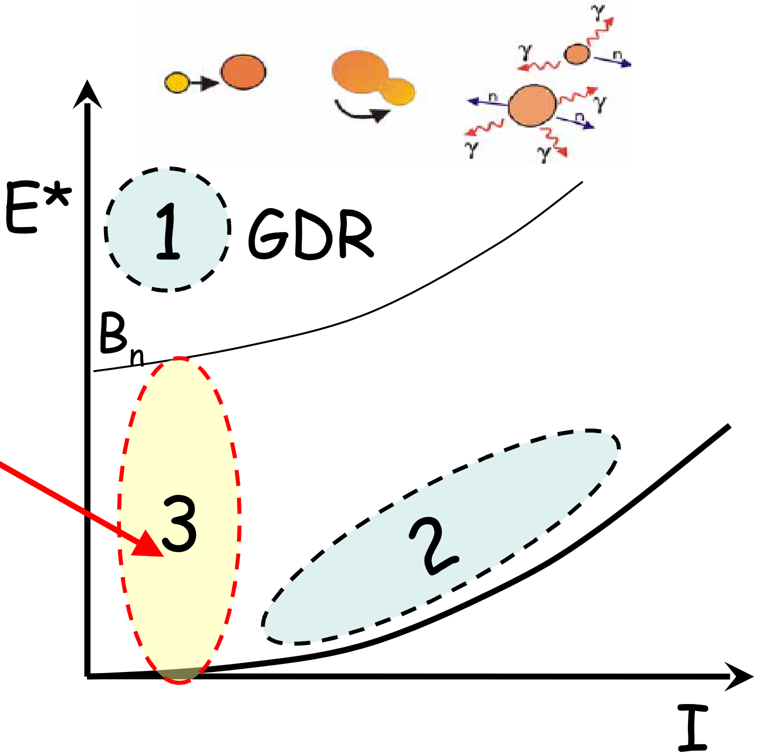
CLARA - PRISMA

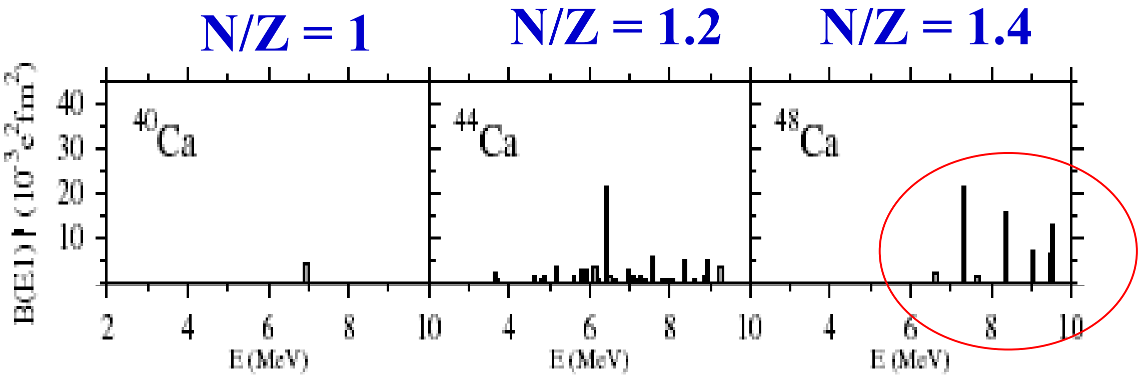
$^{48}Ca+^{64}Ni$ @ 300 MeV

S.Leoni et al.

Investigation of the potentiality of deep inelastic reactions to get access to excited bound states (~ up to 6-8 MeV above yrast)

- beam energy ≈ 7 MeV/A
- E_{cm} ≈ 2.5 x Coulomb Barrier
- $\theta_{grazing}$ ~ 20°

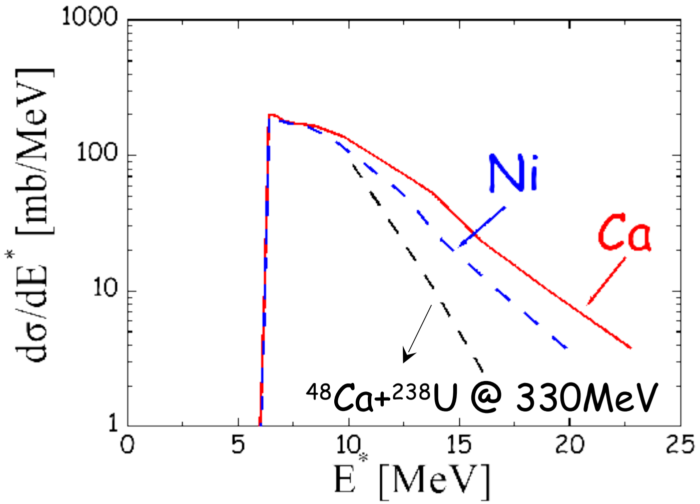




(γ,γ') experiments on stable Ca isotopes

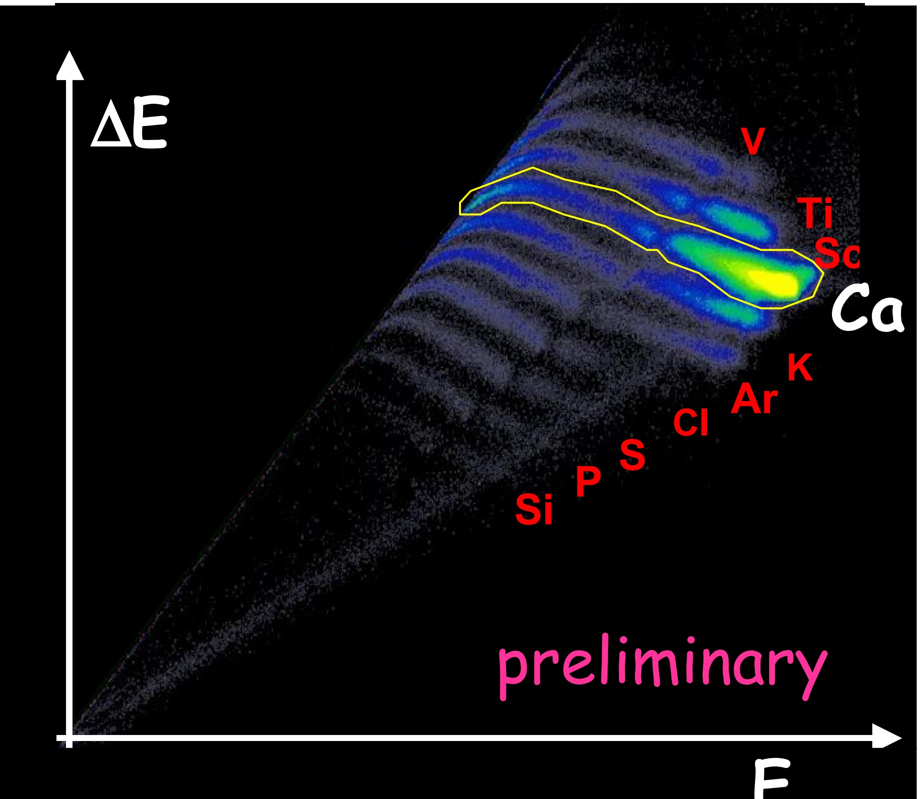
T. Hartmann PRL85(2000)274

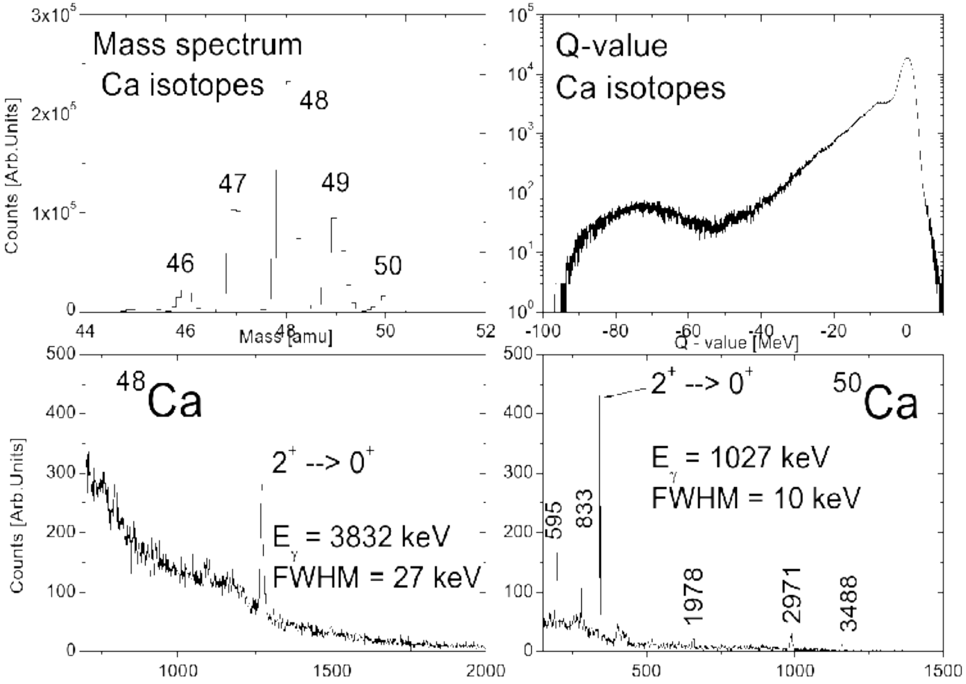
^{48}Ca+^{64}Ni @ 300 MeV



[Cross section calculation GRAZING code (Pollarolo et al.)]()

the nuclei of interest (^{48}Ca)
should have sufficient **internal energy**
to populate
highly excited/pygmy states



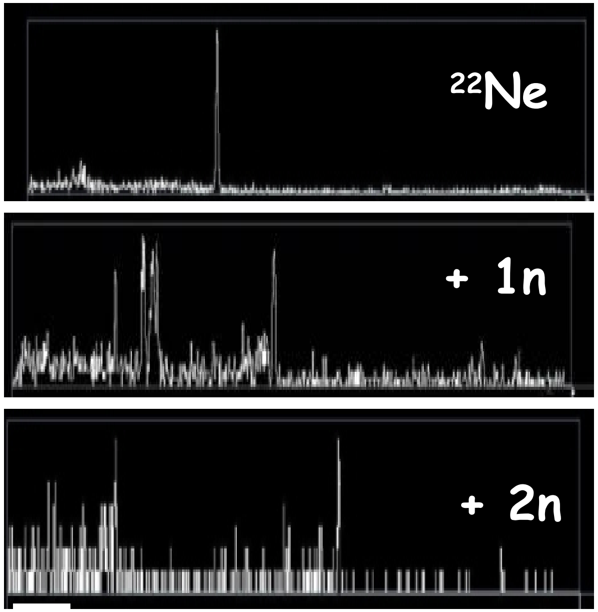


Work in progress:
Calibration & add-back of **BGO**'s to improve statistics of high-energy γ's

In-beam γ spectroscopy using DIC with stable and radioactive Ne beams

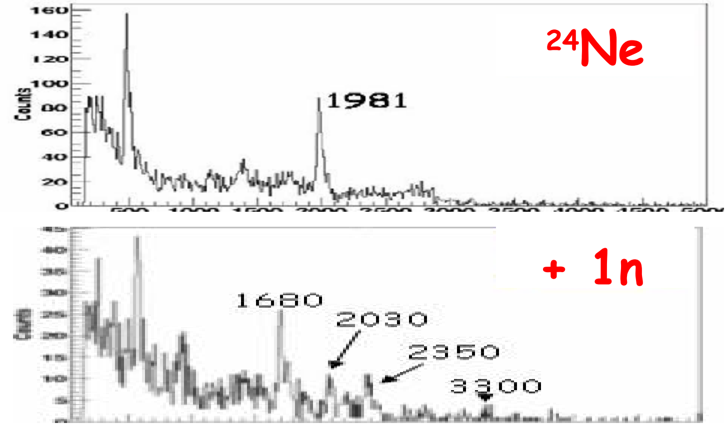
^{22}Ne+^{208}Pb @ 300 MeV

CLARA - PRISMA



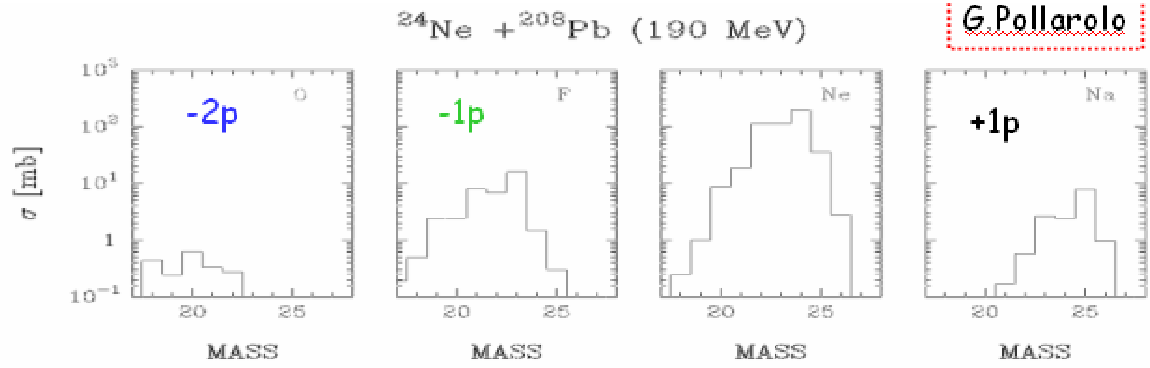
^{24}Ne+^{208}Pb @ 190 MeV

Vamos+EXOGAM



Comparative study:

- γ-spectroscopy
- cross sections

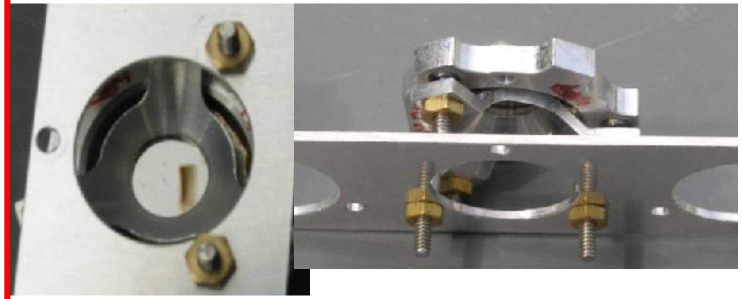


G.Pollarolo

G.Benzoni et al.

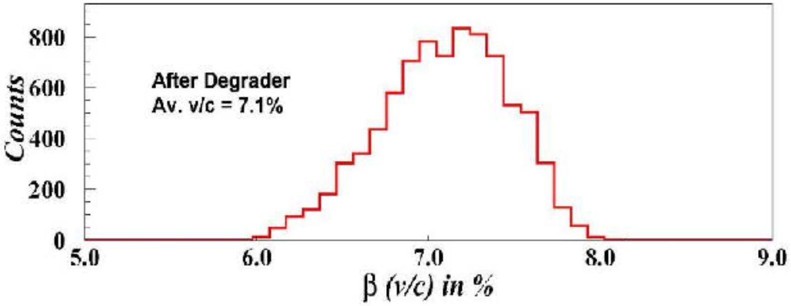
Differential RDDS Measurements with CLARA-PRISMA

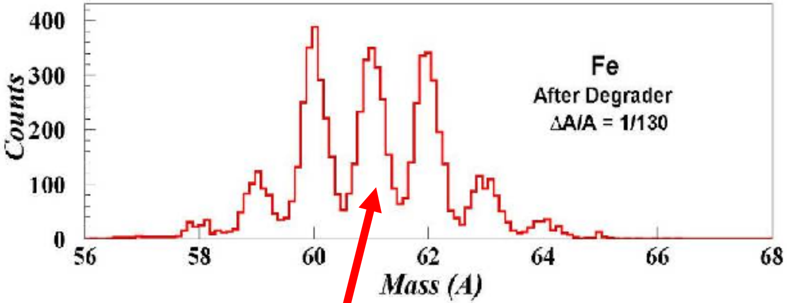
Basic idea: use the "wrong" value to perform Doppler correction
→ differential plunger (target+degrader)

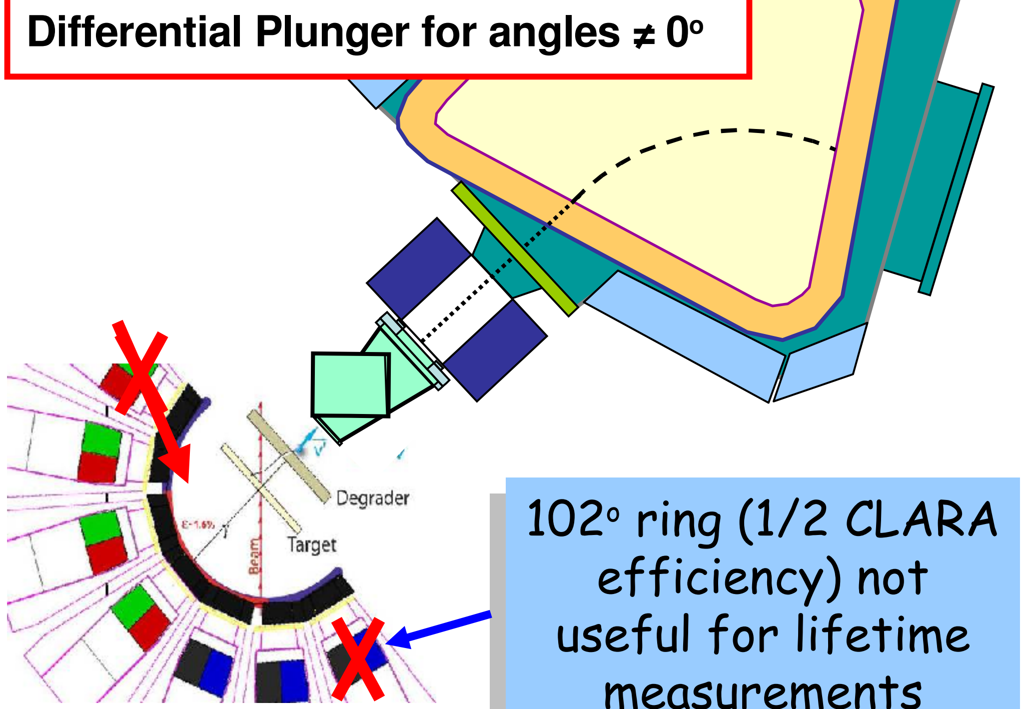


Differential Plunger for angles ≠ 0°

A.Dewald, A.Gadea, N.Mărginean







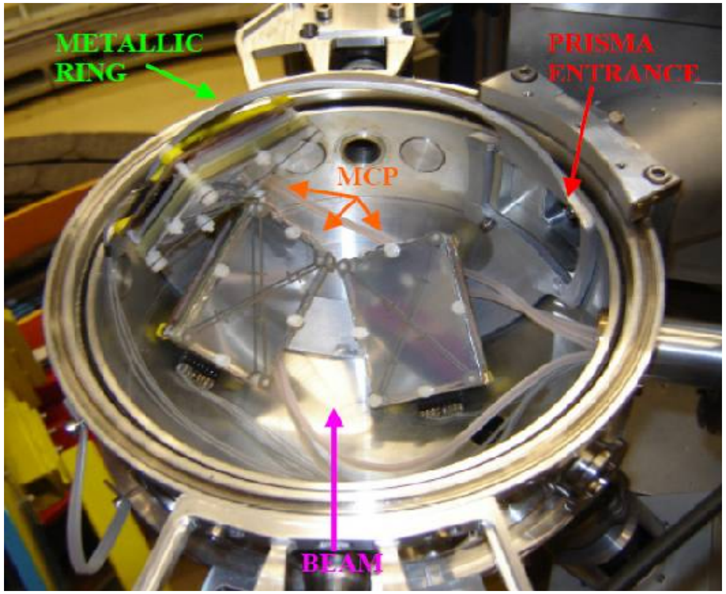
102° ring (1/2 CLARA efficiency) not useful for lifetime measurements

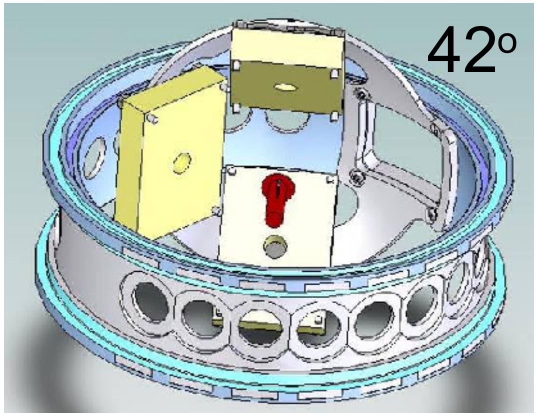
PRISMA mass resolution after degrader is preserved

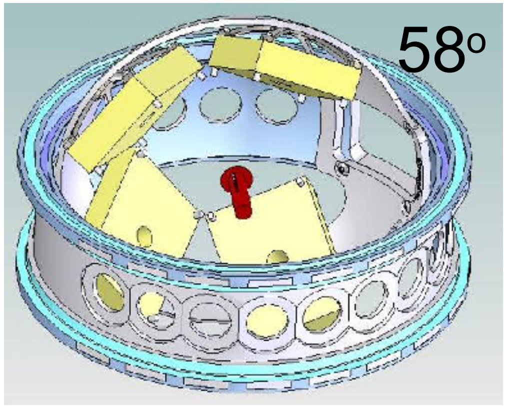
The DANTE MCP Array

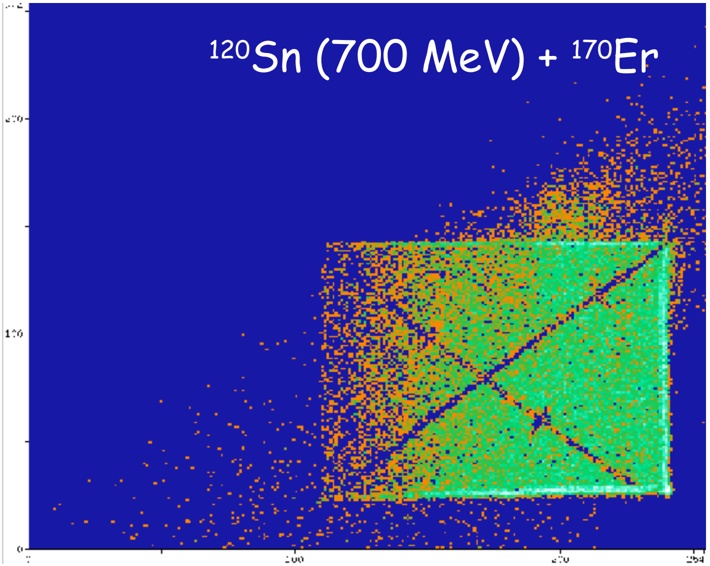
Detector Array for multi Nucleon Transfer Ejectiles

DANTE is a highly efficient array of position-sensitive MCP detectors, developed in collaboration with FLNR Dubna. It can be used in different configurations depending on the grazing angle of the reaction.



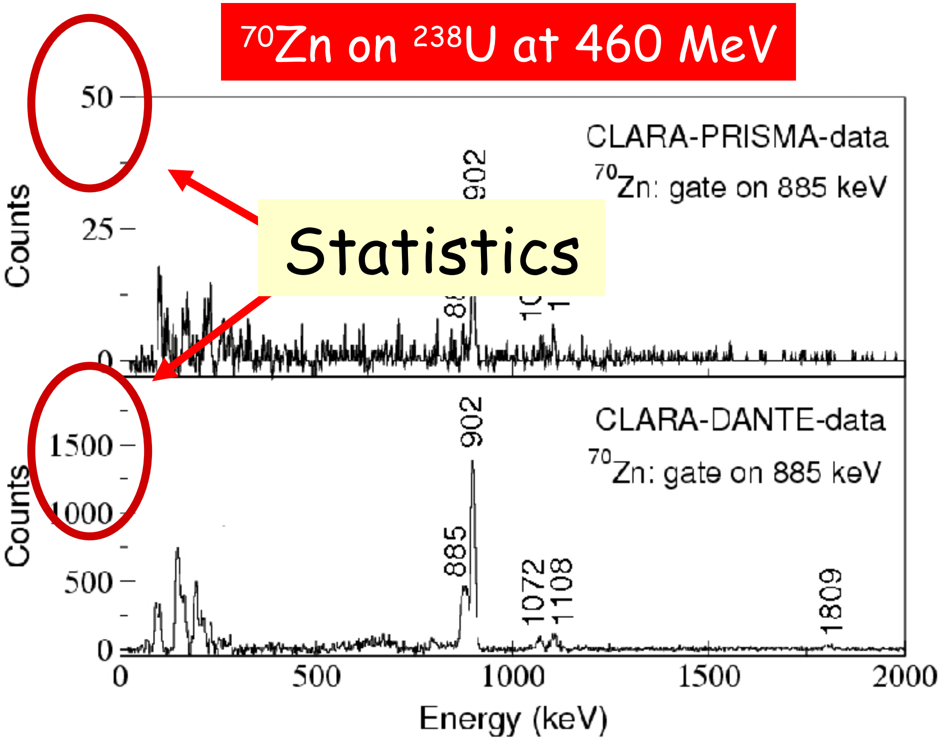





^{120}Sn (700 MeV) + ^{170}Er

Performance of DANTE

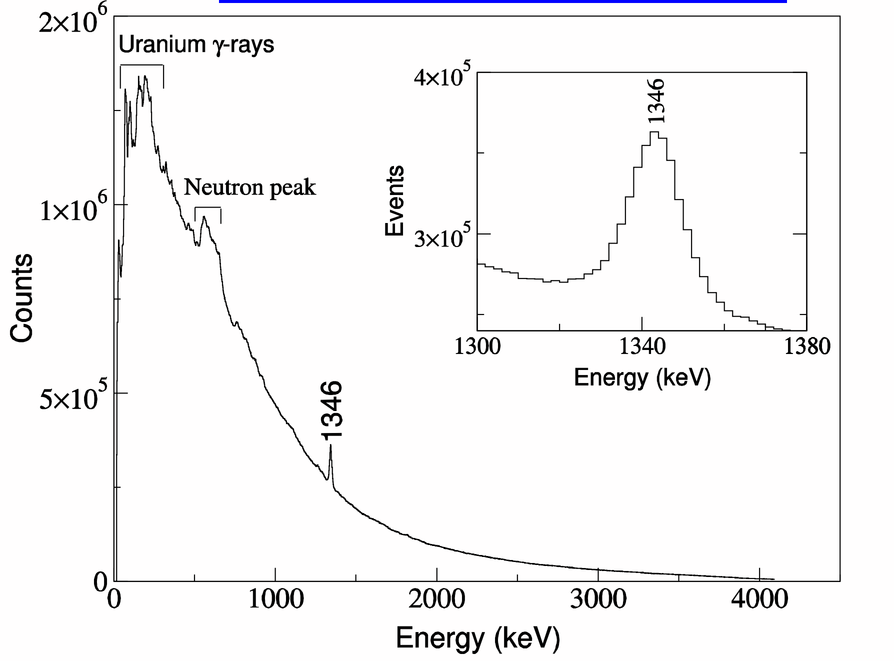
^{70}Zn on ^{238}U at 460 MeV



Statistics

Energy resolution 1.2%

^{64}Ni on ^{238}U at 440 MeV



Problems with fission background! Need kinematical coincidences to clean up data and access weaker channels

Summary

- Valuable information on moderately n-rich nuclei has been collected using multinucleon transfer and deep inelastic collisions with stable beams at the CLARA - PRISMA setup
- The analysis of the most recent experiments is still in progress, so we expect interesting results to be shown at the next Gammapool workshop!

Thanks!

- To the colleagues who enjoyed beam times in Legnaro
- To the colleagues who took hard effort in analysing data
- To the colleagues who made my life easier providing excellent slides
- To the colleagues who took hard effort in keeping CLARA and PRISMA working properly
- To the GammaPool and to the UE (under contract RII3-CT-2004-506065)
- To all of you for your attention!