Yrast spectroscopy of neutron-rich nuclei –
present status and perspectives with high intensity stable beams

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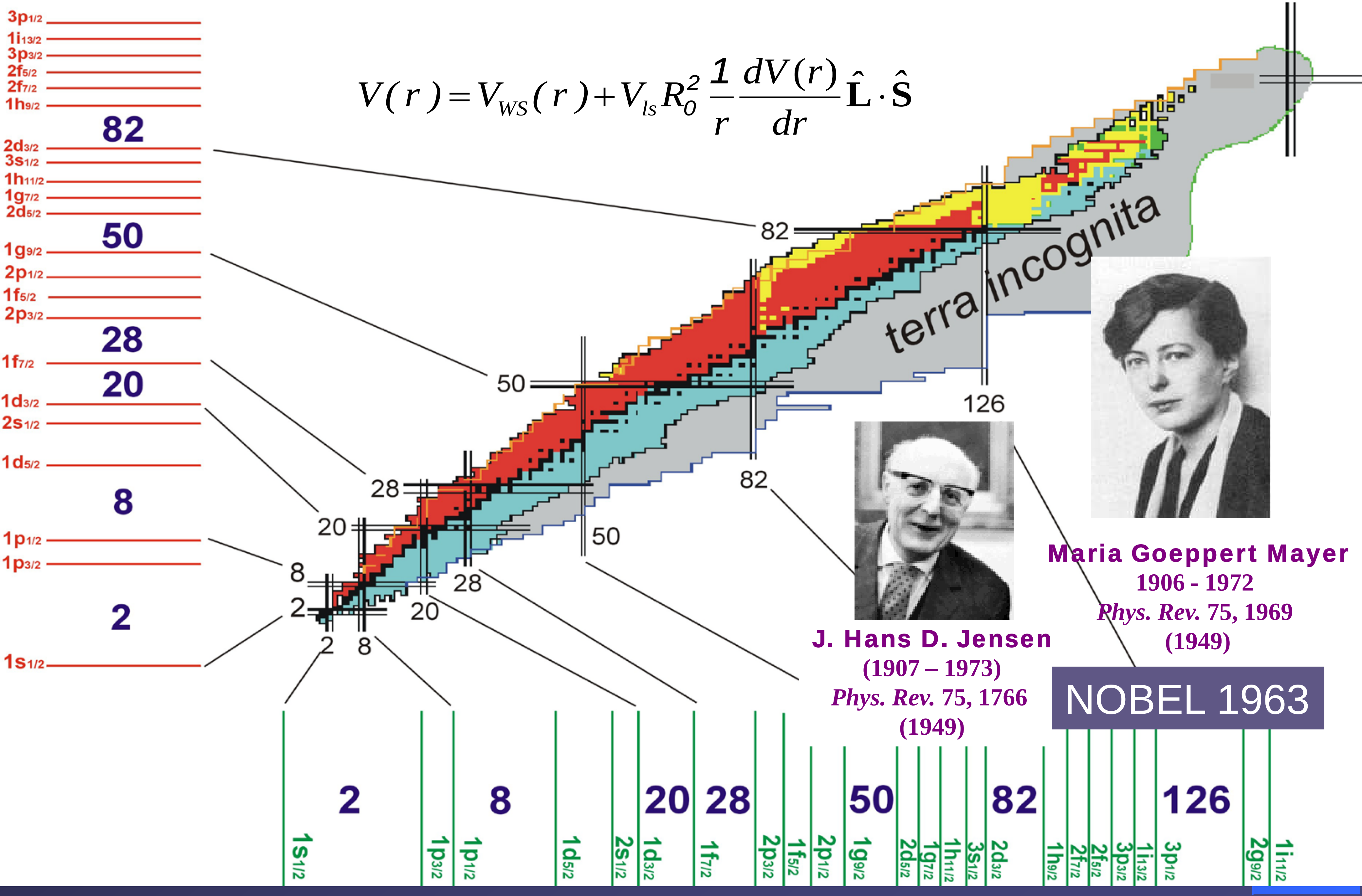
ECOS 2012: „*Advances and challenges in nuclear physics with high intensity stable beams*",
Villa Vigoni, Como Lake, Italy on June 18-21, 2012

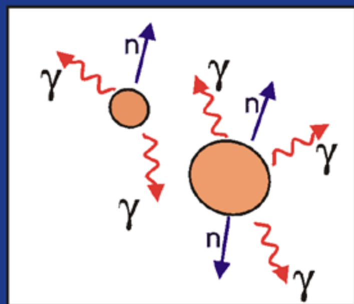
$$V(r) = V_{WS}(r) + V_{ls} R_0^2 \frac{1}{r} \frac{dV(r)}{dr} \hat{\mathbf{L}} \cdot \hat{\mathbf{S}}$$

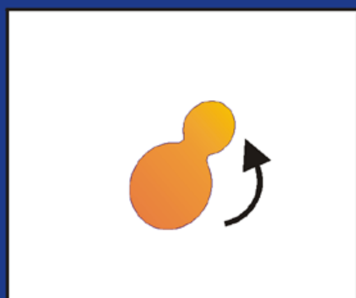


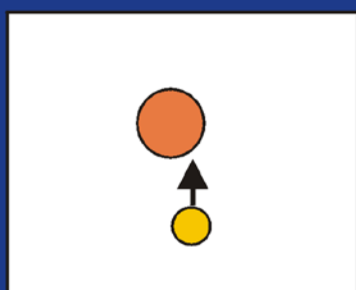
Outline

- **Deep-inelastic heavy-ion reactions**
  - **short history**
  - **product yield distribution assessed with different techniques**
- **Accessing yrast structures in neutron-rich nuclei around ^{48}Ca – successful combination of the thick-target and thin-target methods**
- **New yrast structures in nuclei located around ^{208}Pb**
- **Realistic V_{low-k} shell model calculations in the vicinity of ^{208}Pb and their predictive power**
- **Perspectives for discrete yrast gamma-ray spectroscopy „east” and „south-east” of ^{48}Ca or ^{208}Pb with high intensity stable beams**

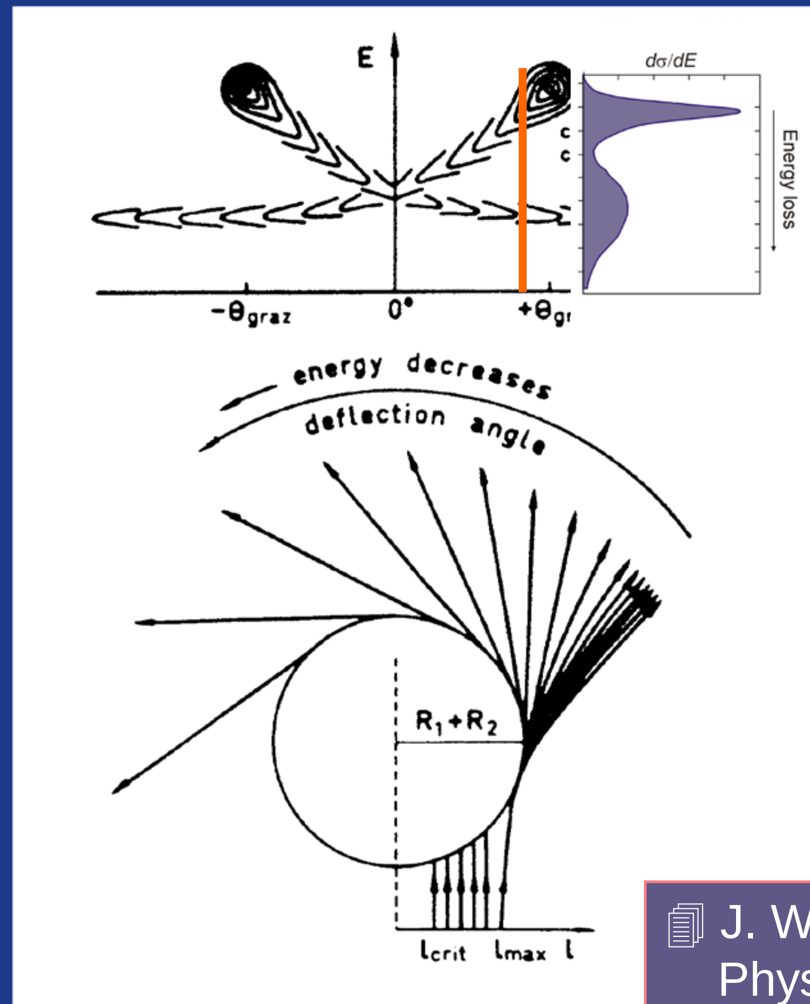
DEEP-INELASTIC HEAVY-ION COLLISIONS





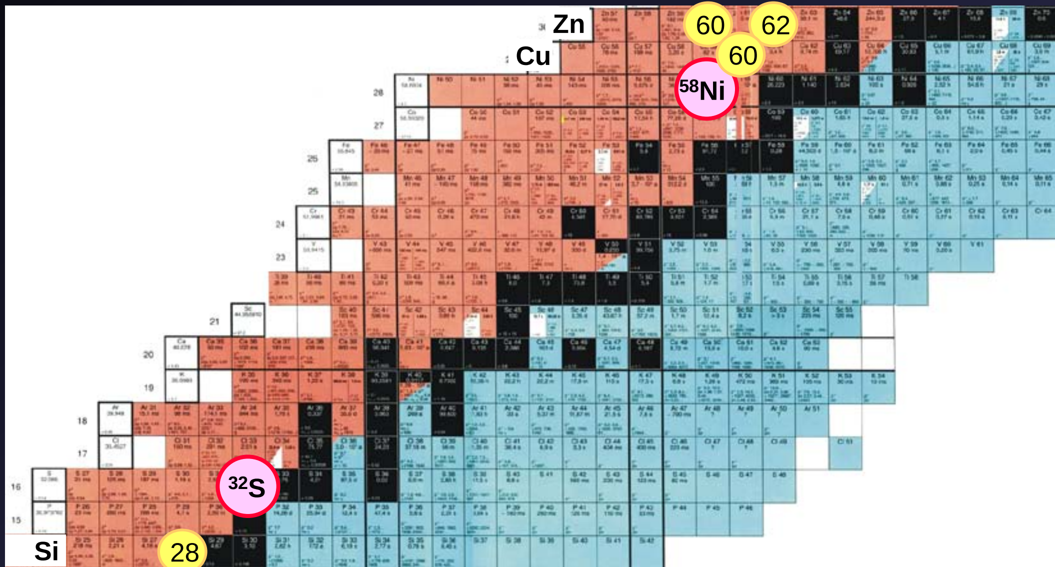


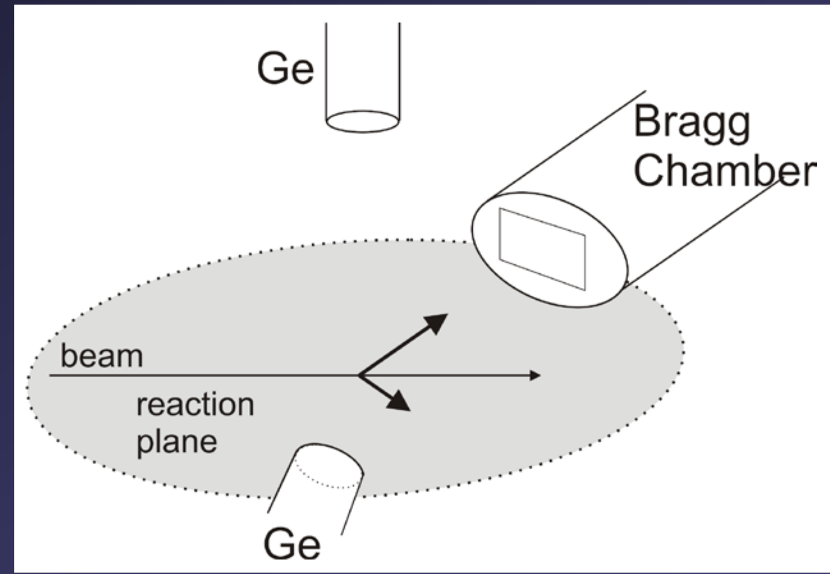
Wilczynski plot



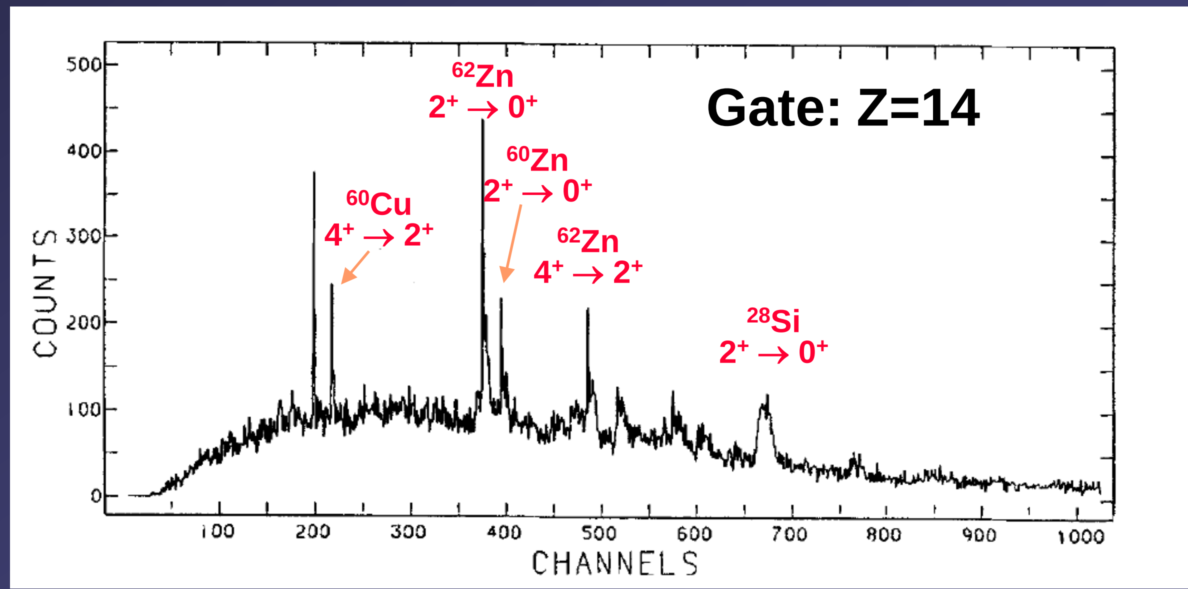
J. Wilczynski, Phys. Lett. B 47, 487 (1973)

^{32}S + ^{58}Ni, E_{beam}= 143 MeV, XTU Tandem at LNL Legnaro (1985)





G. Viesti, B. Fornal,
F. Gramegna, G. Prete *et al.*,
Z. Phys. A 324, 161 (1986)

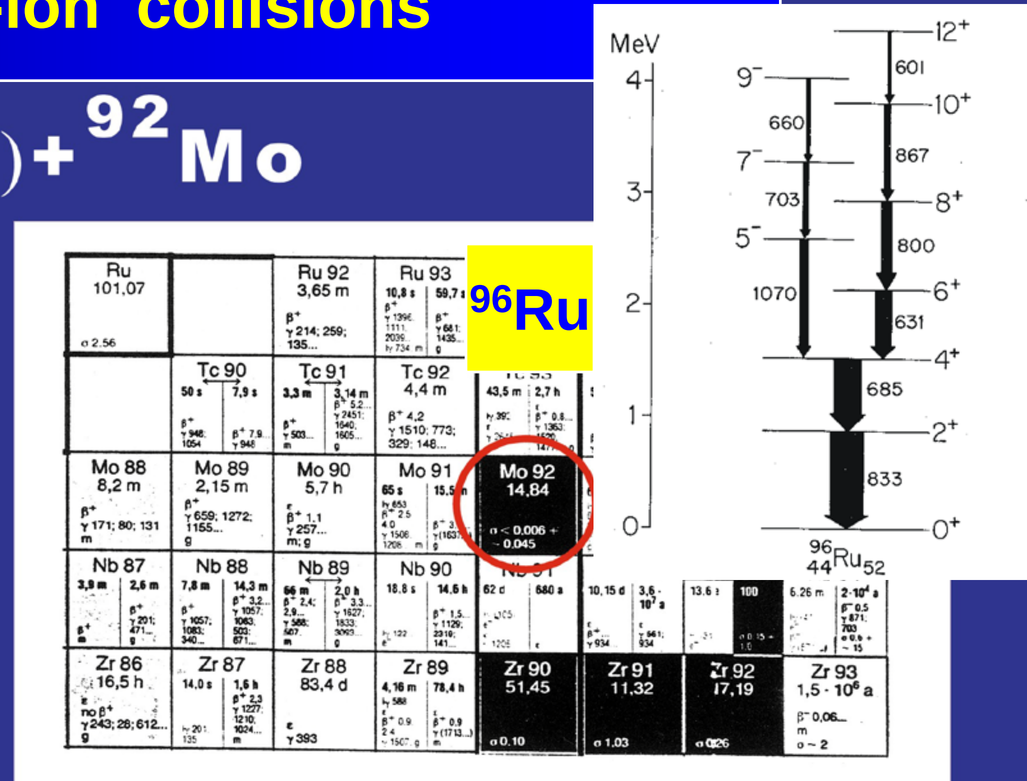


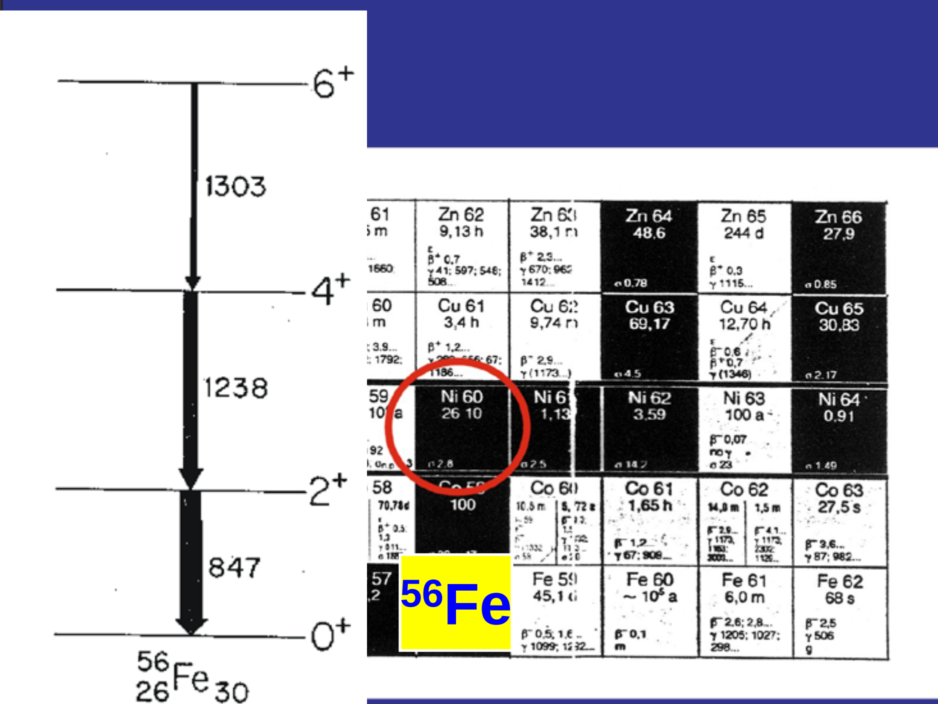
Gamma rays from deep-inelastic reaction products

Discrete gamma-ray spectroscopy with deep-inelastic heavy-ion collisions

^{60}Ni(255 MeV)+^{92}Mo

R. Broda *et al*.,
Phys. Lett. B 251, 245 (1990)





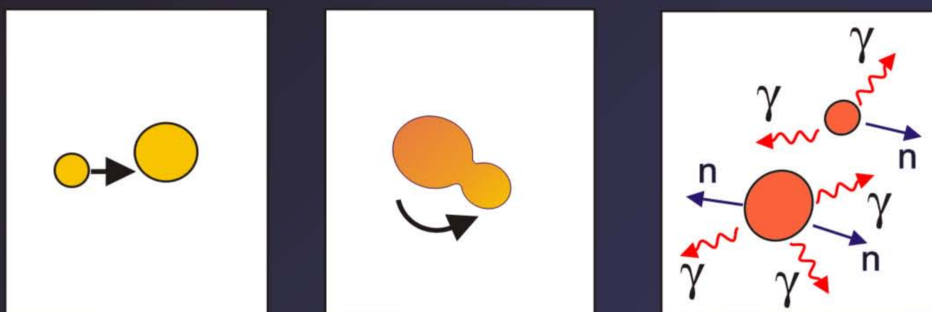
Argonne-Notre Dame Array
(16 HPGe+ 50 BGO)

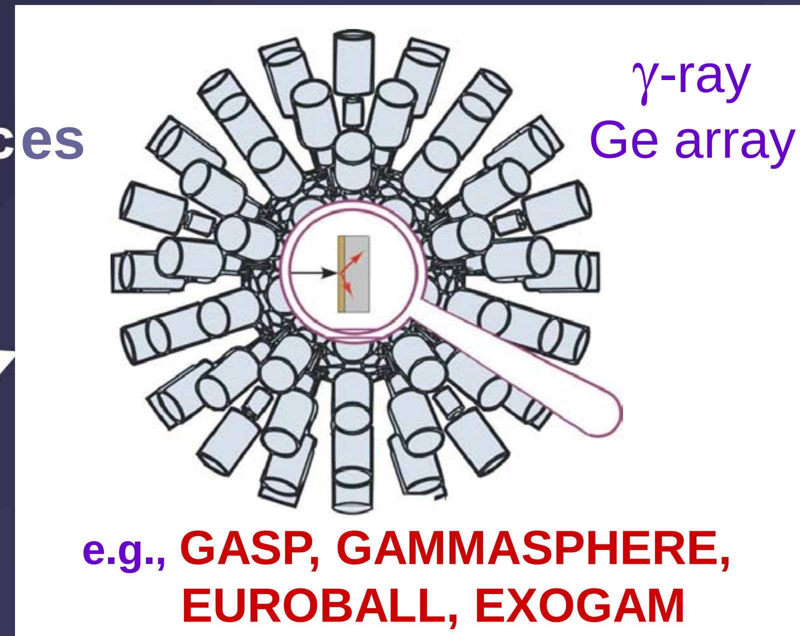
It was soon realized that deep-inelastic heavy-ion reactions could be an ideal tool to study the structure of neutron-rich nuclei

Deep-inelastic heavy-ion reactions – a tool for discrete gamma-ray spectroscopy of neutron-rich nuclei

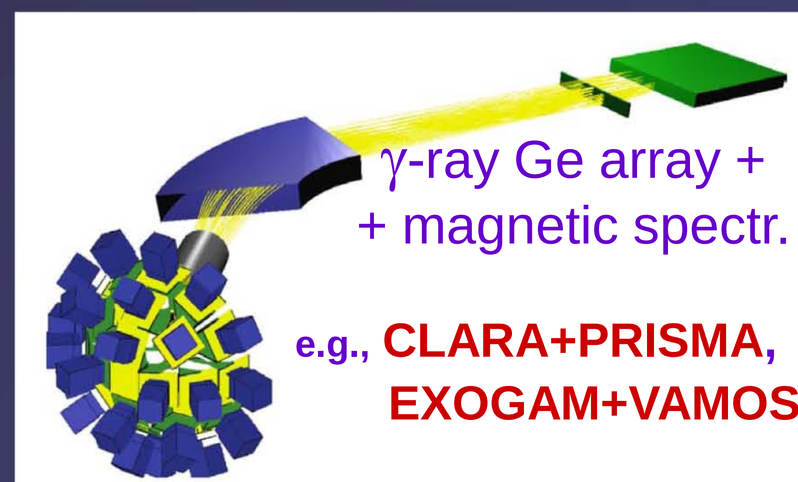
thick target

$\gamma-\gamma$ coincidences

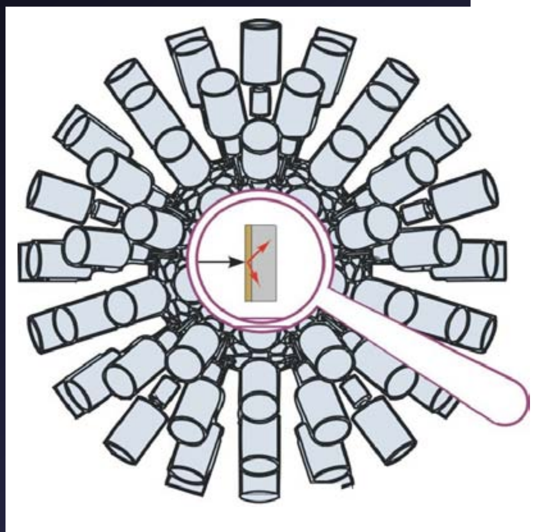


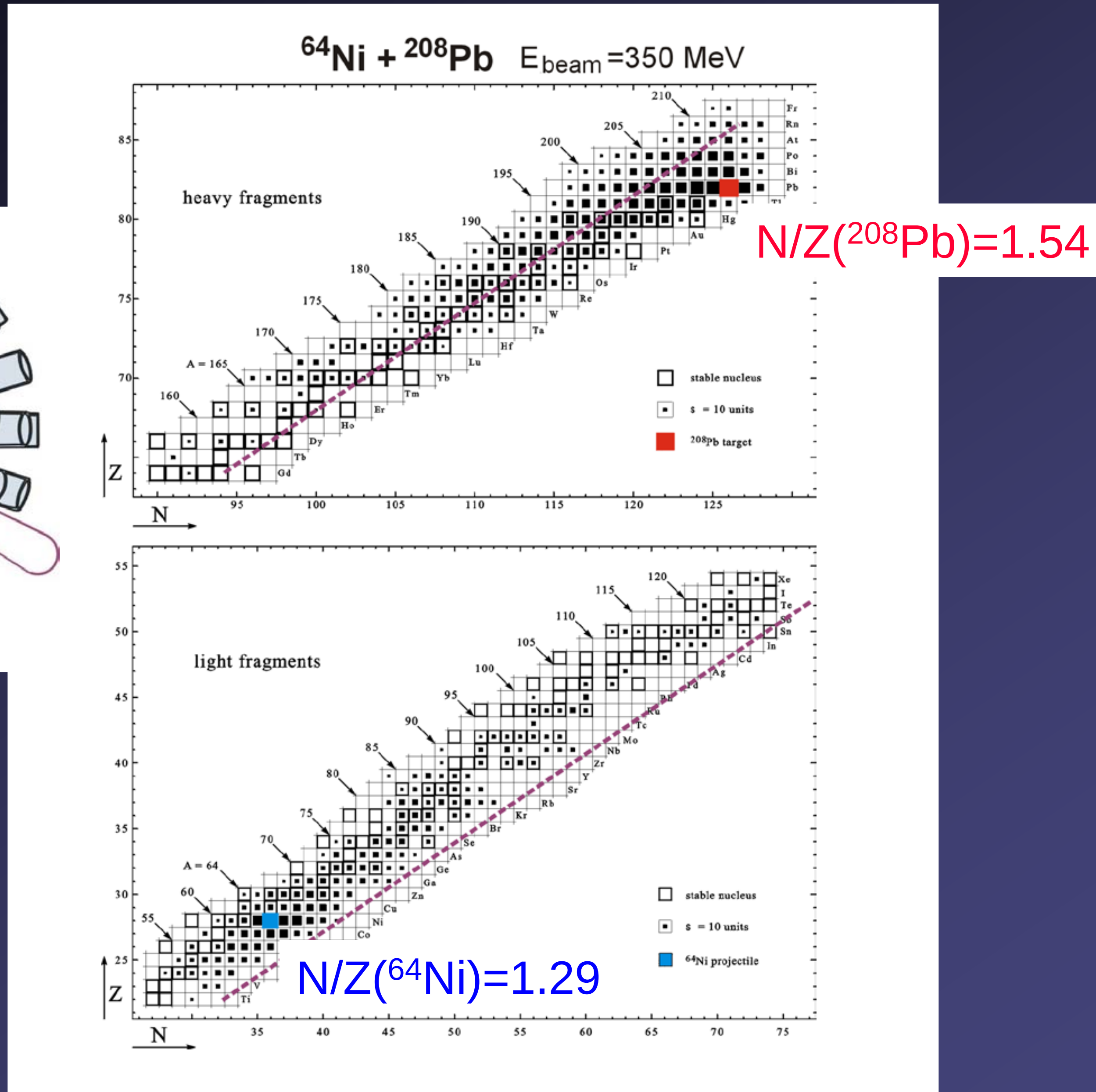


γ - reaction product coincidences



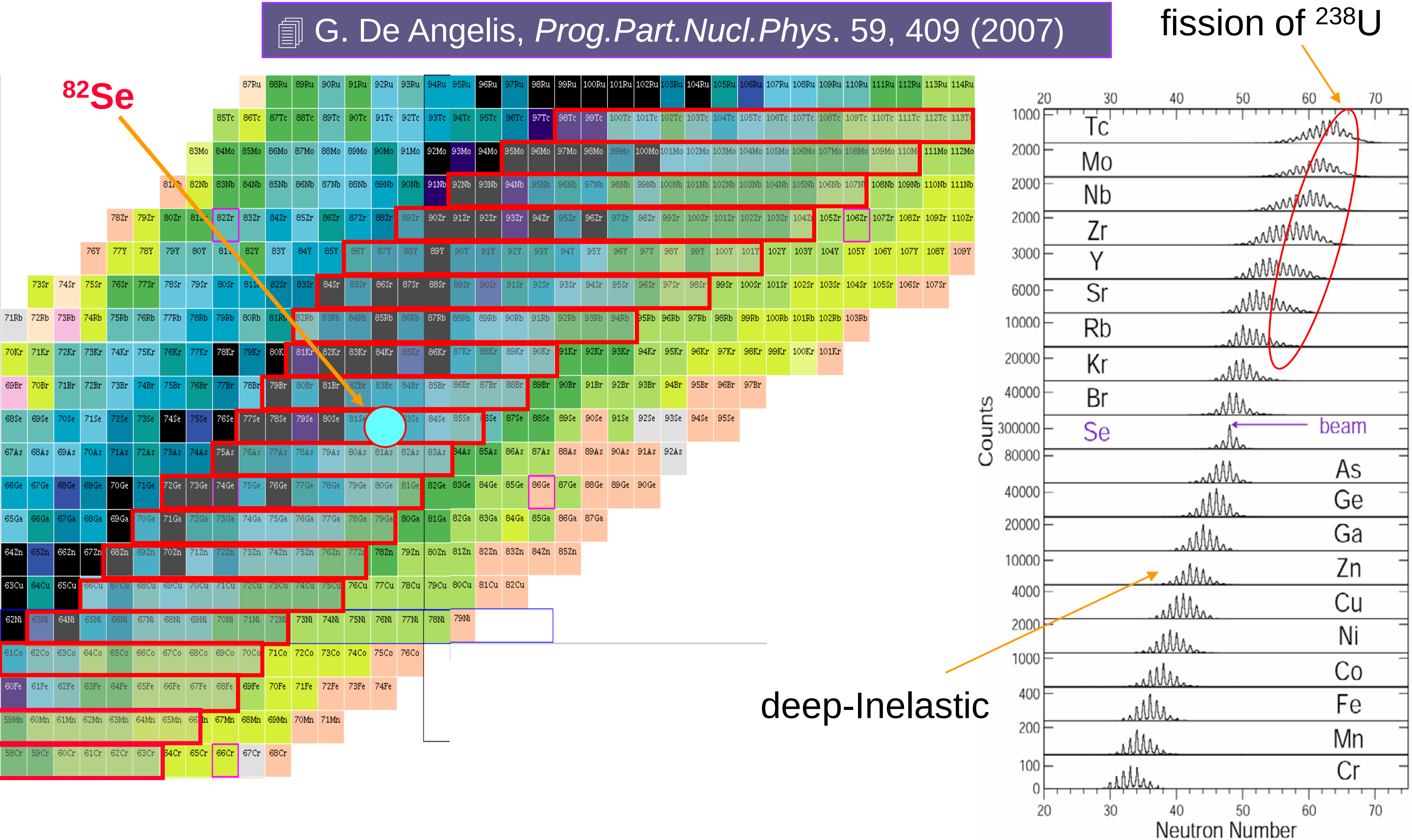
Detailed product yield distribution measured in deep-inelastic ^{64}Ni + ^{208}Pb reaction with the thick-target technique





Nuclei around ^{82}Se produced the reaction ^{82}Se (505 MeV) + ^{238}U and investigated with CLARA+PRISMA

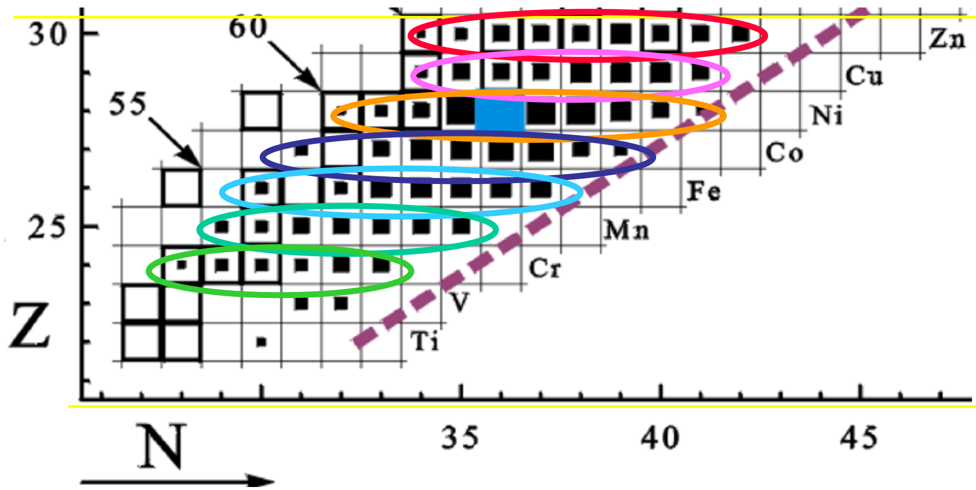
G. De Angelis, *Prog.Part.Nucl.Phys*. 59, 409 (2007)



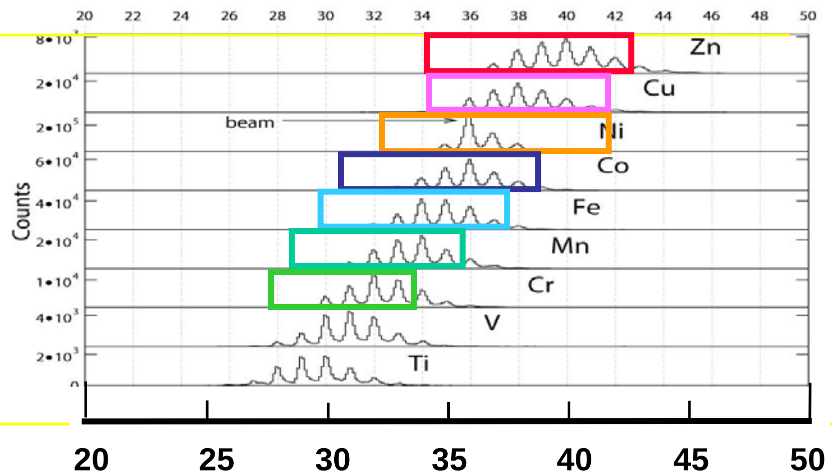
(courtesy of Giacomo de Angelis)

Comparison of product yield distributions around the projectile ^{64}Ni measured with thick target and thin target techniques

^{64}Ni (350 MeV) + ^{208}Pb
(thick taget)

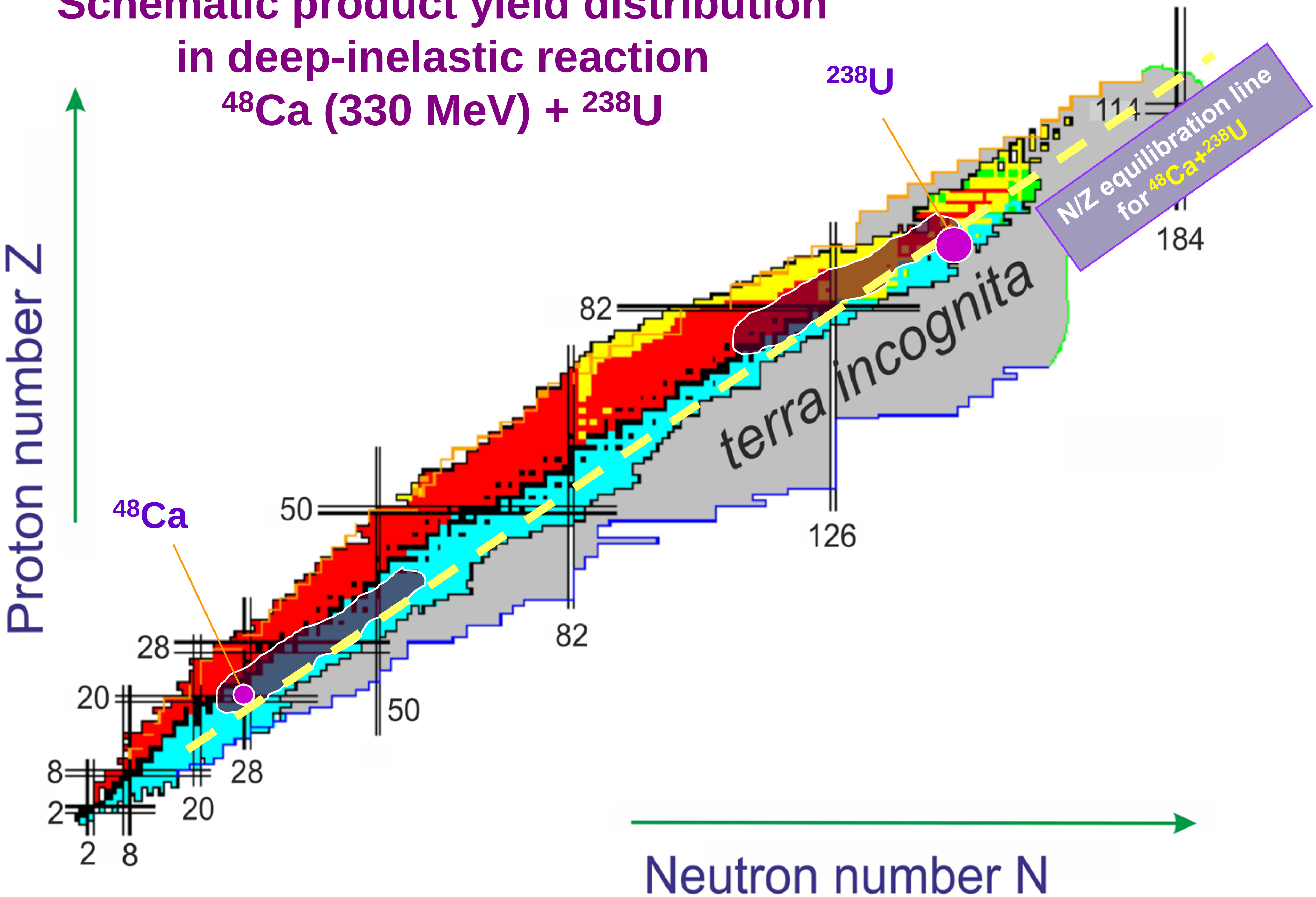


^{64}Ni (400 MeV) + ^{238}U
(thin taget – CLARA+PRISMA)

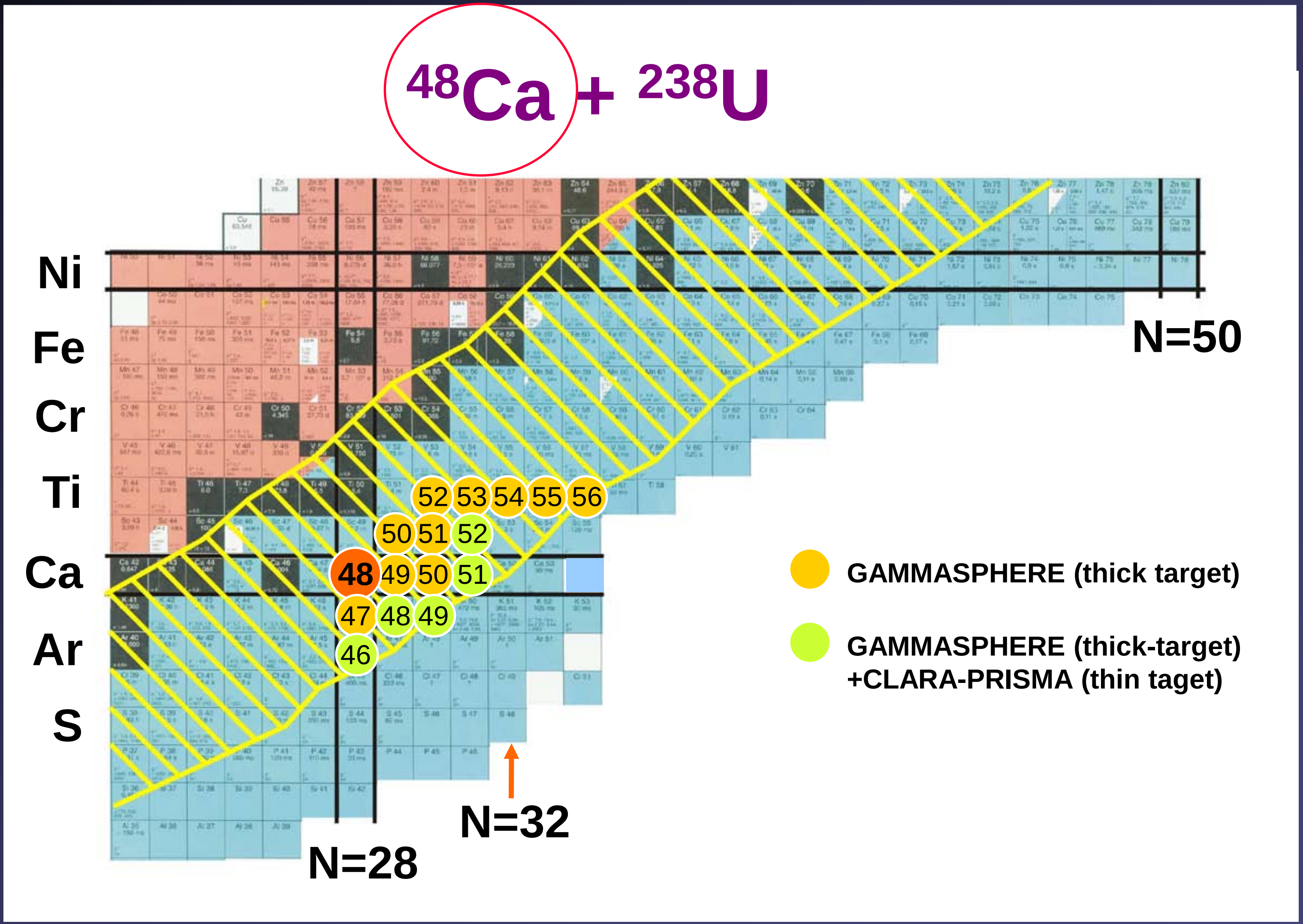


A. Gadea *et al*., J.Phys G31, S1443 (2005)

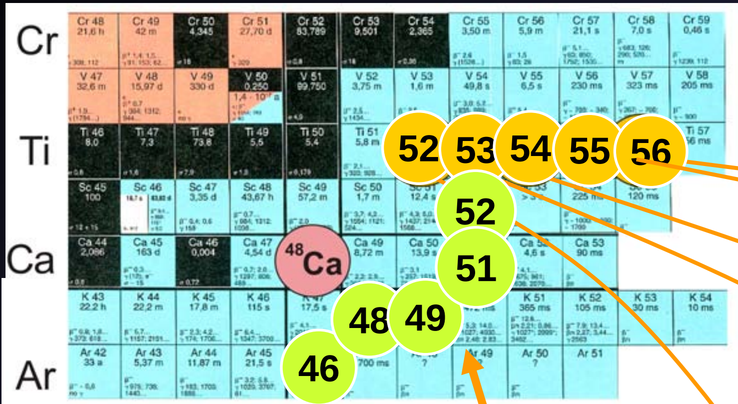
Schematic product yield distribution in deep-inelastic reaction ^{48}Ca (330 MeV) + ^{238}U



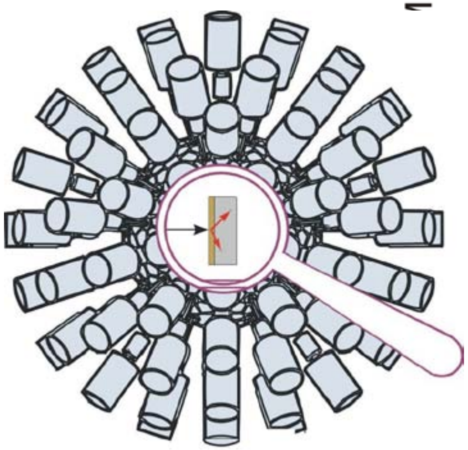
The nuclei around ^{48}Ca produced in deep-inelastic reactions of ^{48}Ca (330 MeV) on ^{238}U and investigated with GAMMASPHERE and CLARA+PRISMA



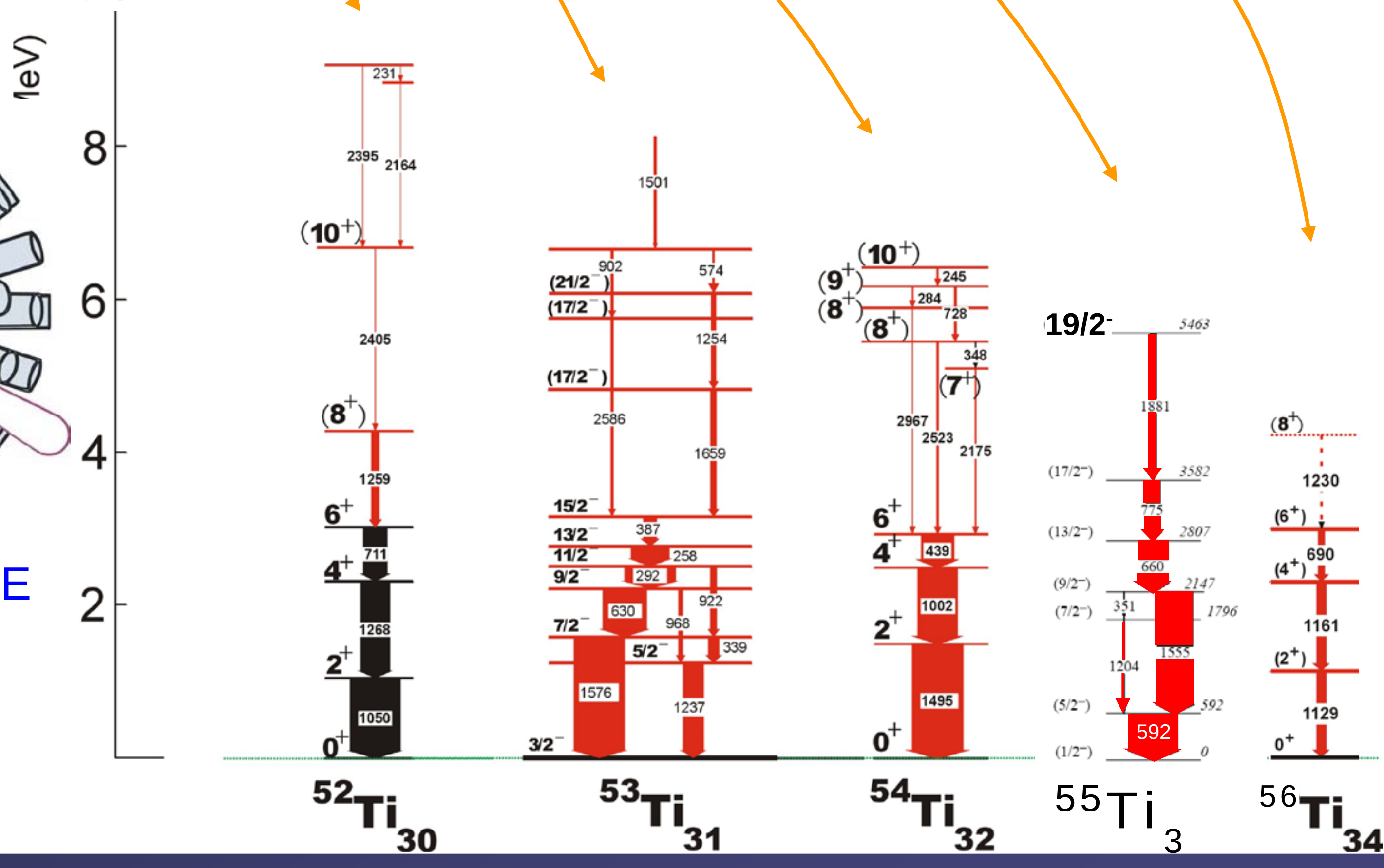
Results on the neutron-rich Ti isotopes from the ^{48}Ca (330 MeV) + ^{238}U reaction studied with GAMMASPHERE in a thick target experiment



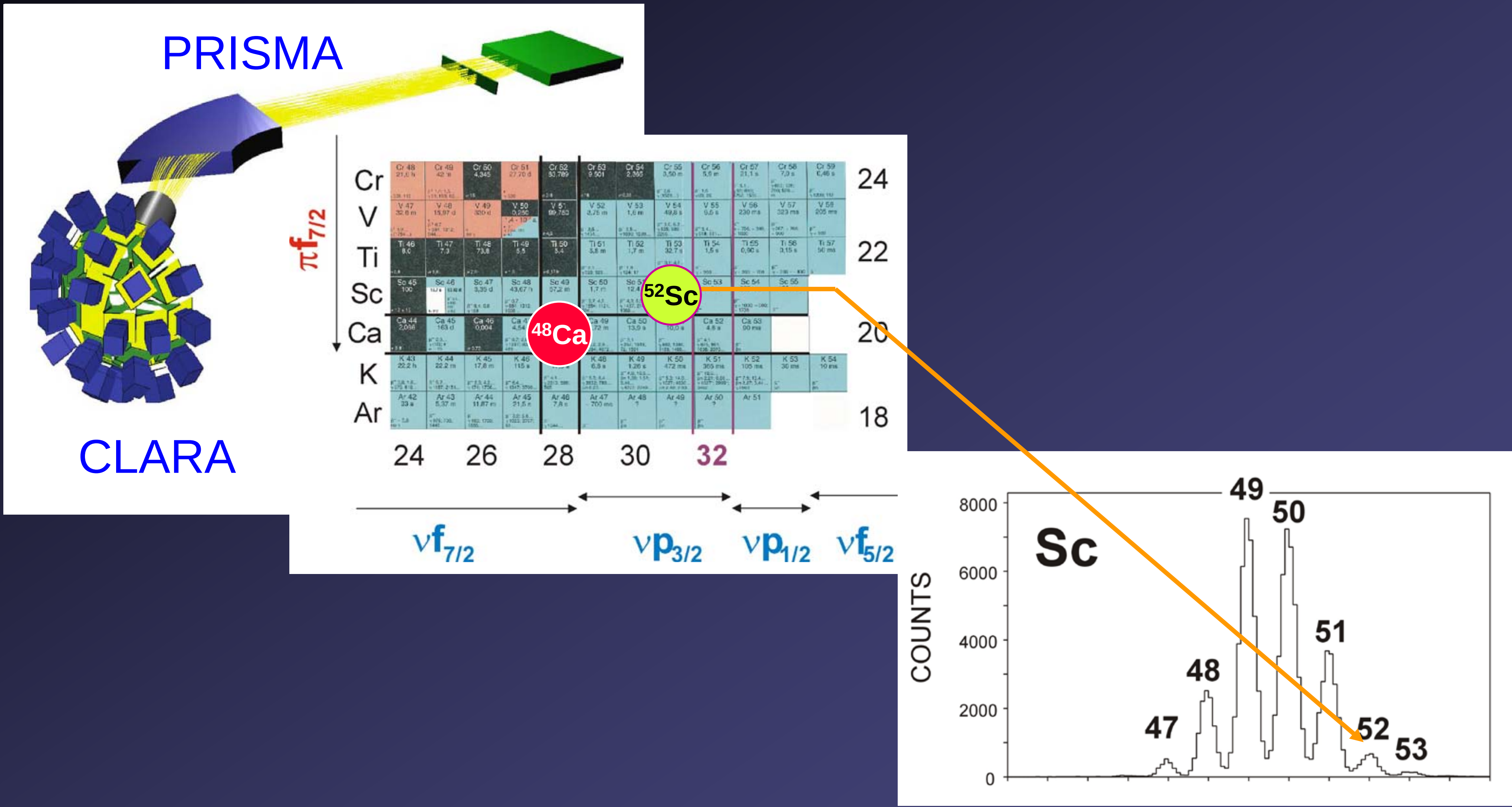
no „starting points”

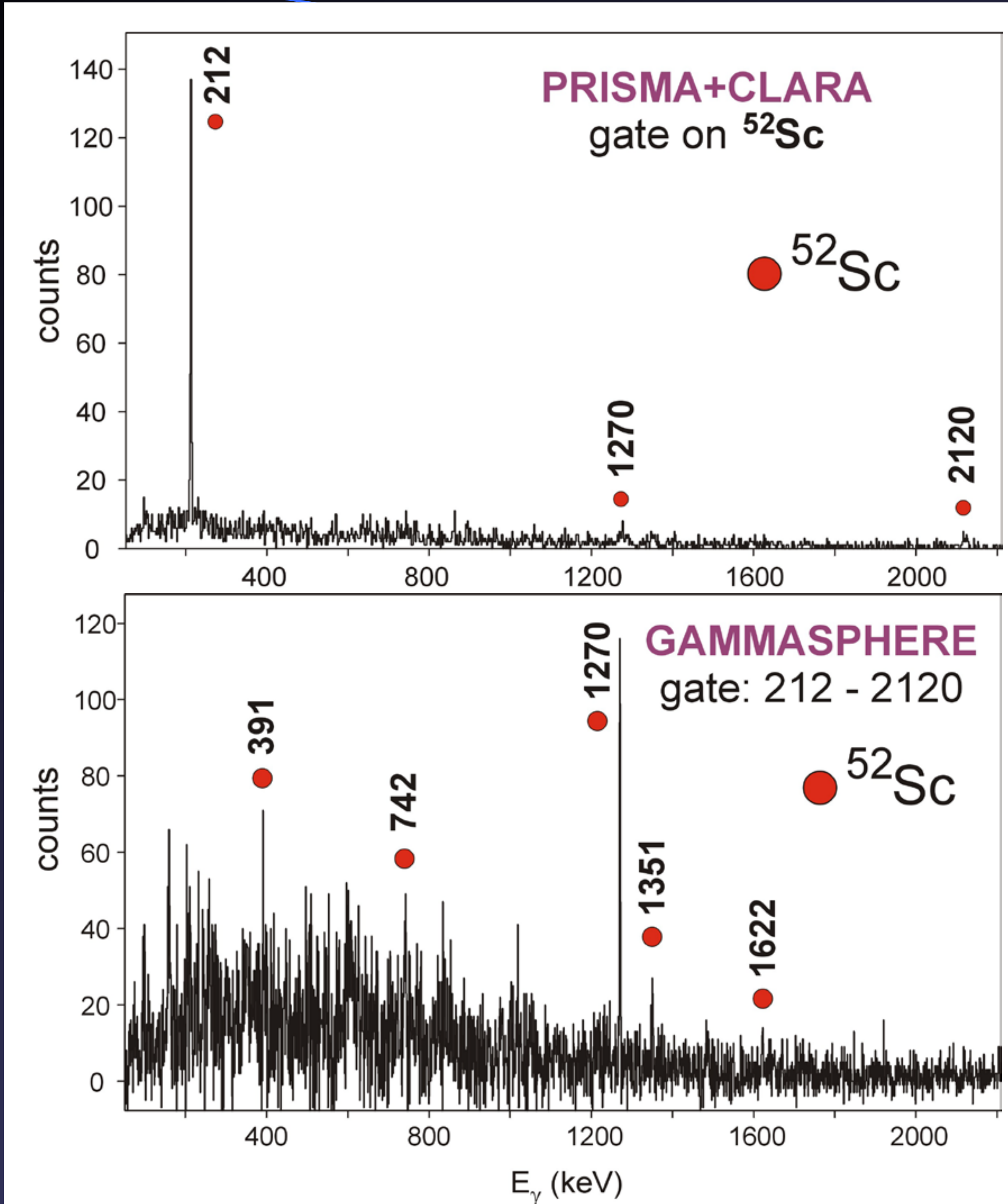


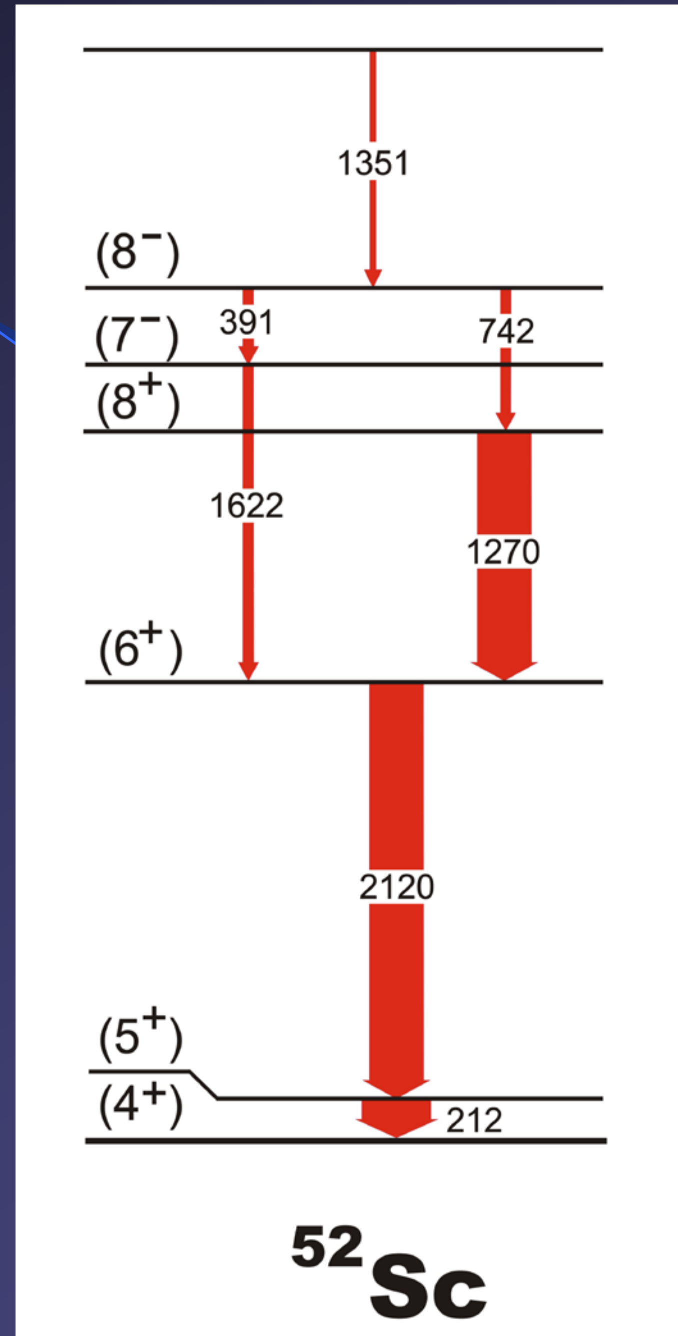
GAMMASPHERE

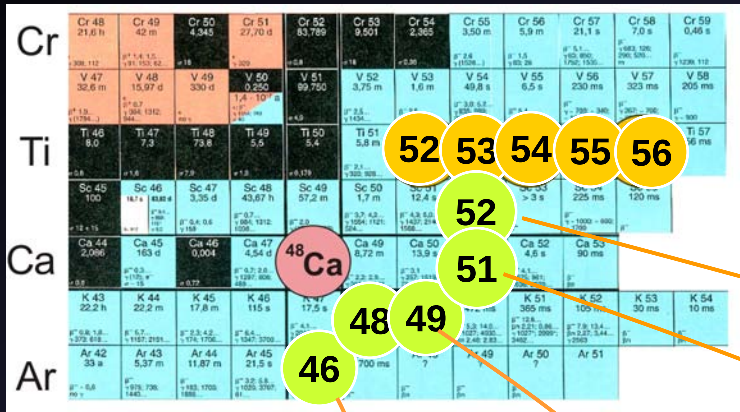


^{48}Ca (330 MeV) + ^{238}U at LNL Legnaro with **PRISMA+CLARA**

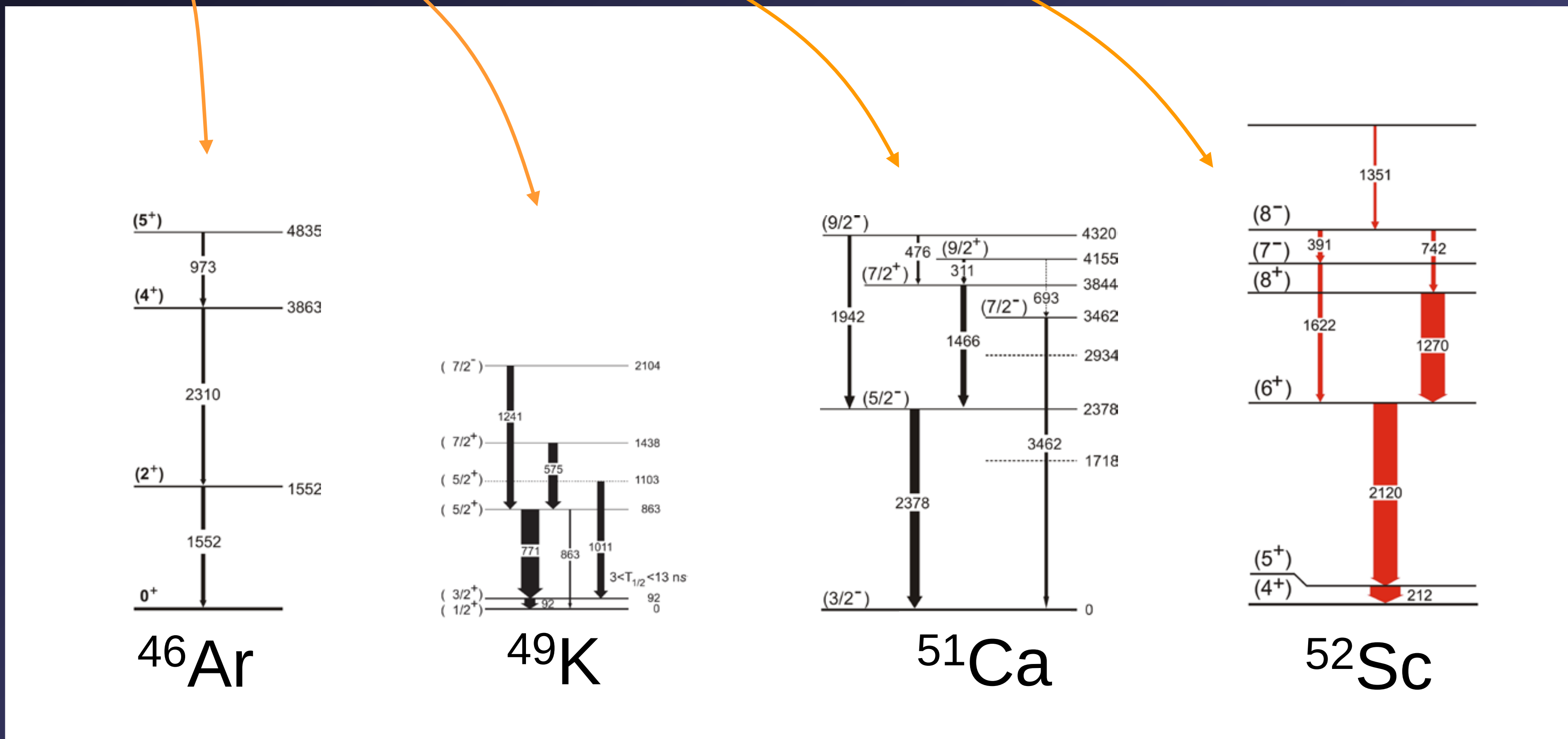



PRISMA+CLARA
gate on 52Sc
52Sc
212
1270
2120
counts
140
120
100
80
60
40
20
0
400
800
1200
1600
2000
GAMMASPHERE
gate: 212 - 2120
52Sc
391
742
1270
1351
1622
counts
120
100
80
60
40
20
0
400
800
1200
1600
2000
Eγ (keV)


1351
(8−)
391
742
(7−)
(8+)
1622
1270
(6+)
2120
(5+)
(4+)
212
52Sc

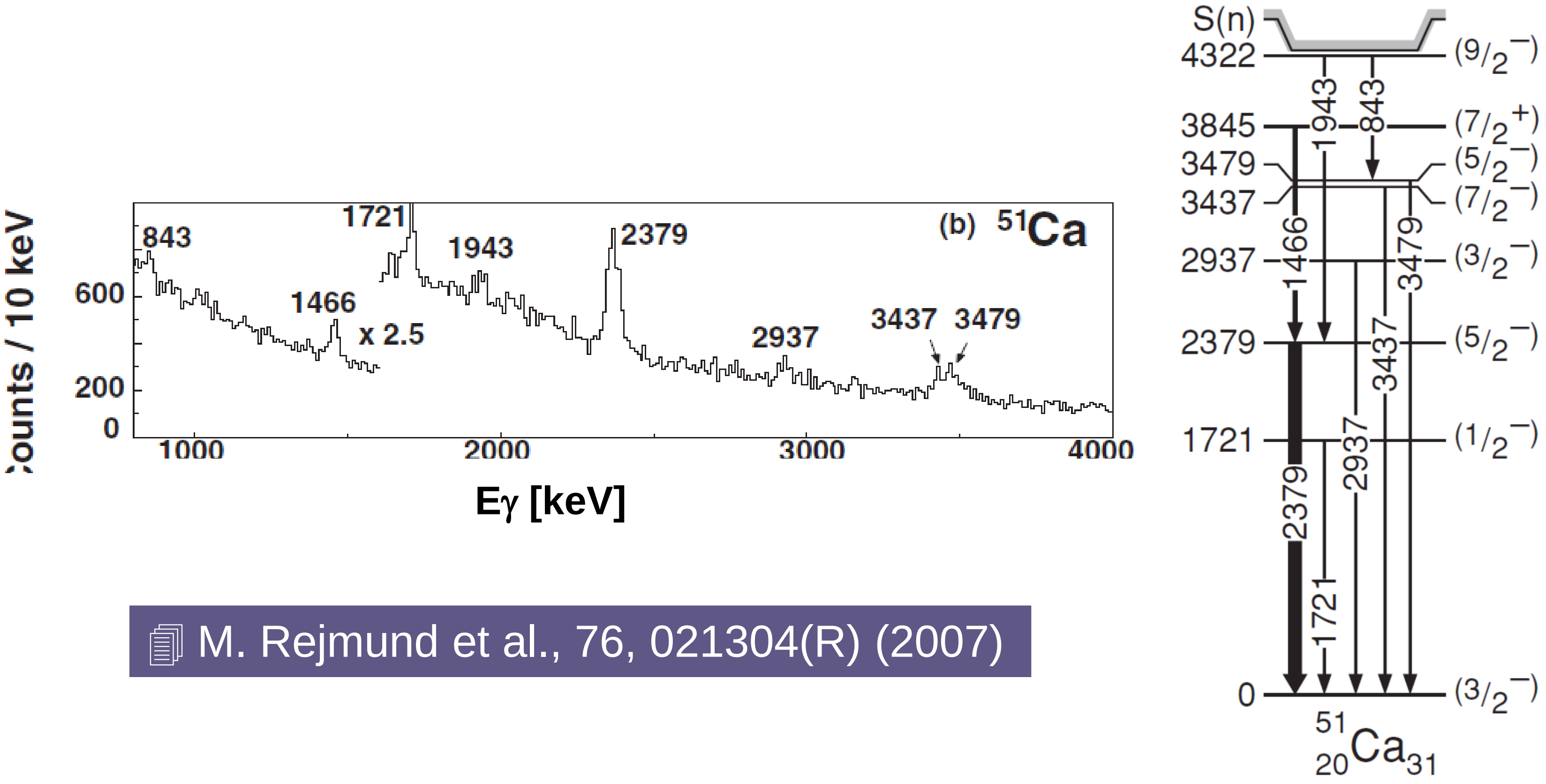


Results on the most neutron-rich nuclei from the ^{48}Ca (330 MeV) + ^{238}U reaction studied with GAMMASPHERE and CLARA+PRISMA

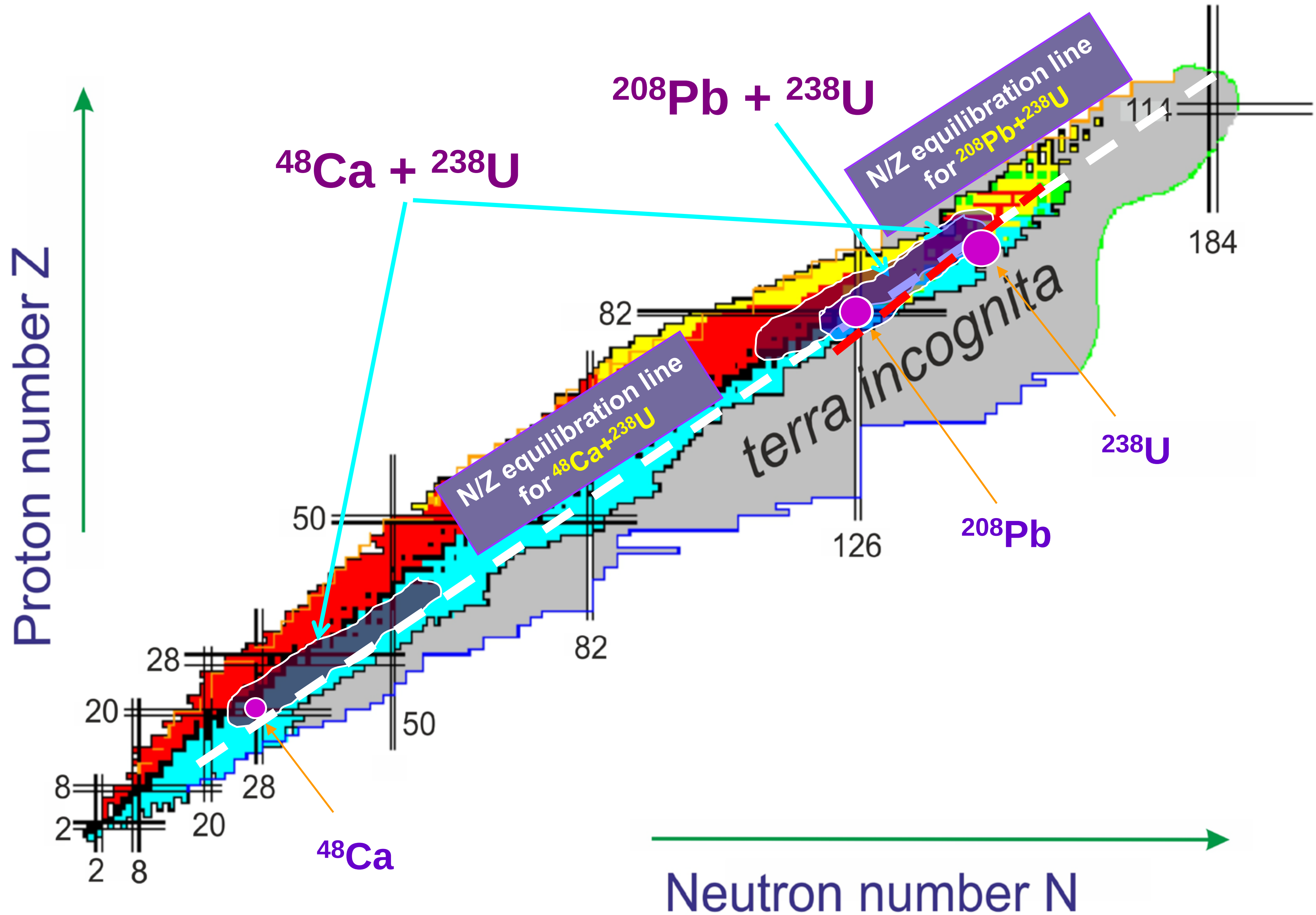


Data on ^{51}Ca from EXOGAM+VAMOS at GANIL

^{238}U (1310 MeV) + ^{48}Ca

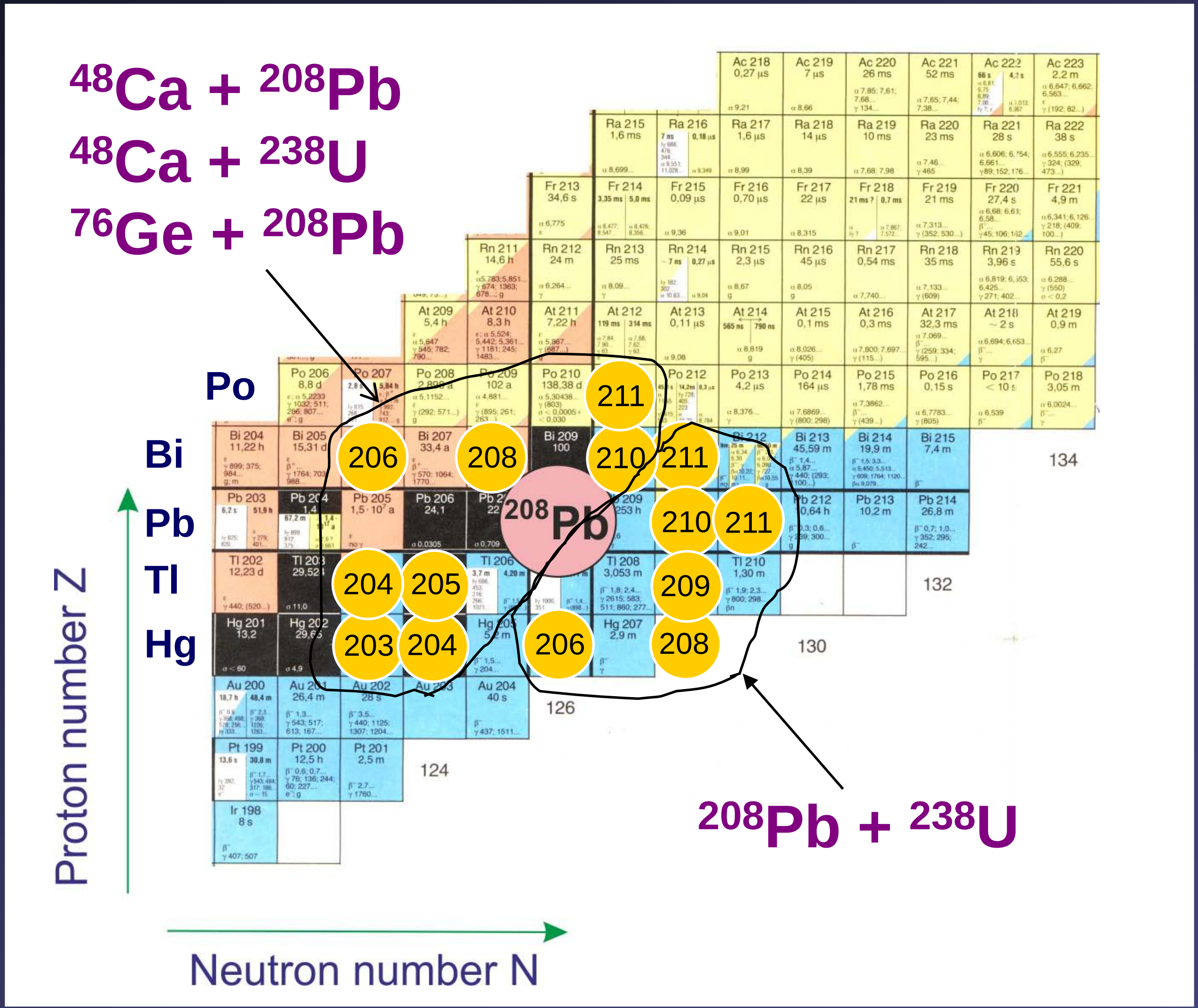


M. Rejmund et al., 76, 021304(R) (2007)

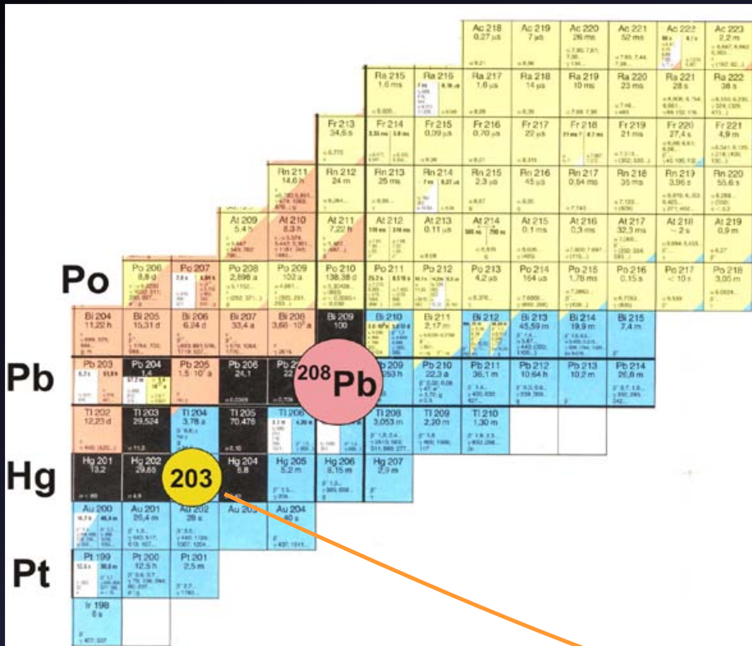


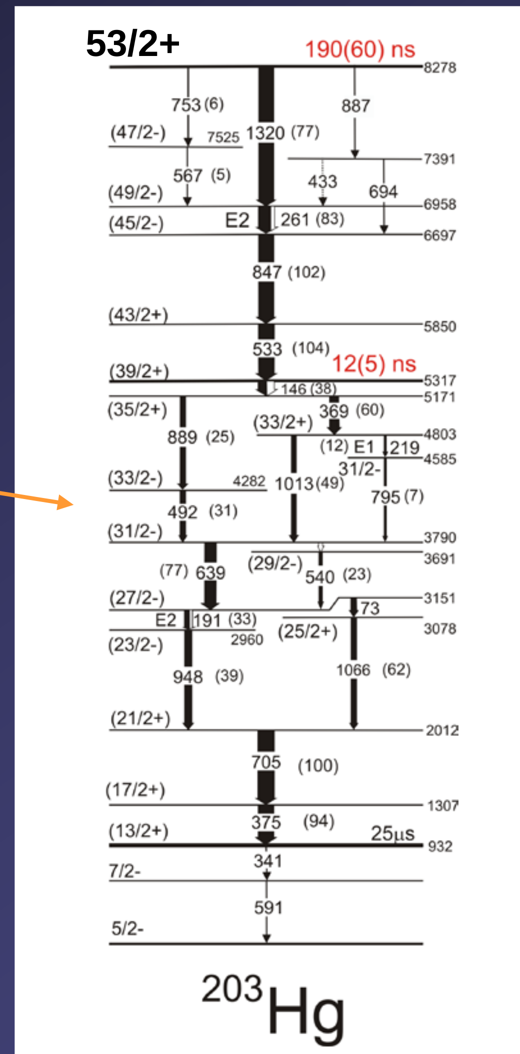
Proton number Z
Neutron number N
^{48}Ca + ^{238}U
^{208}Pb + ^{238}U
N/Z equilibration line for ^{48}Ca+^{238}U
N/Z equilibration line for ^{208}Pb+^{238}U
terra incognita
^{48}Ca
^{208}Pb
^{238}U
2
8
20
28
50
82
114
2
8
20
28
50
82
126
184

The nuclei around ^{208}Pb, produced in deep-inelastic reactions in which we have identified yrast structures by using γ–γ–γ coincidence thick-target technique with GAMMASPHERE



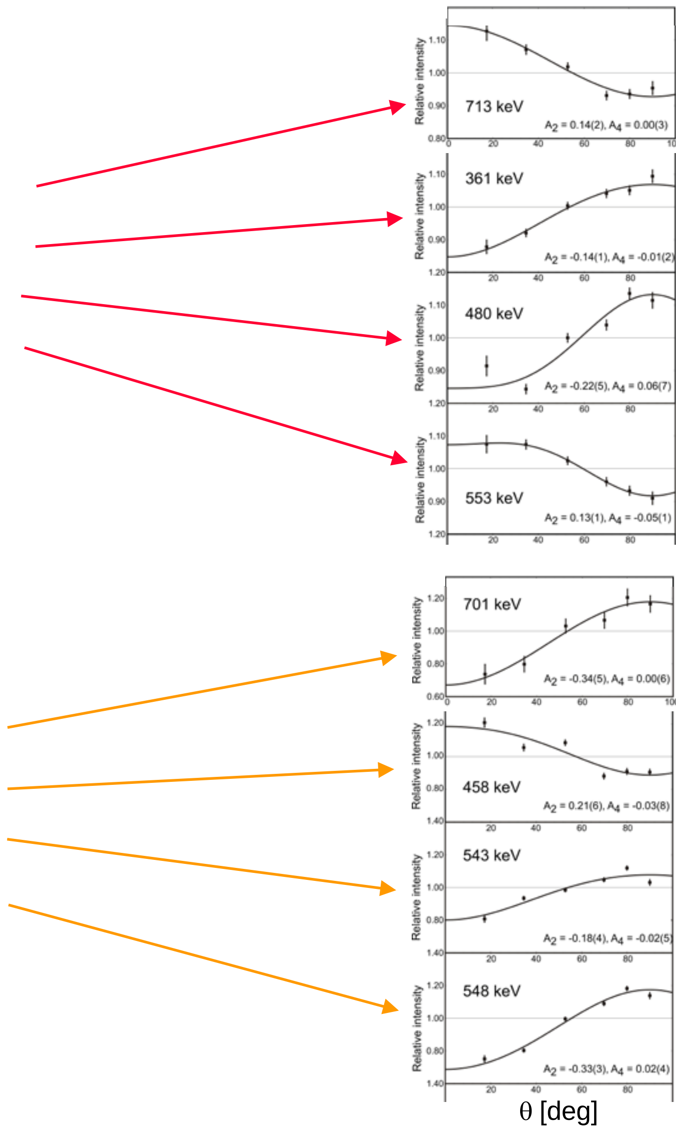
Yrast structure of ^{203}Hg identified by using the ^{48}Ca+^{238}U reaction and gamma-coincidence thick target technique with GAMMASPHERE

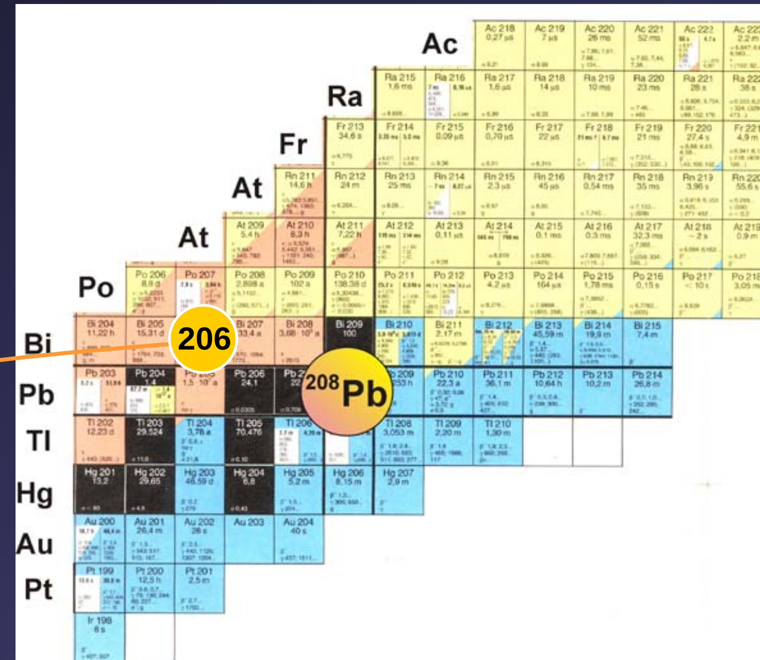




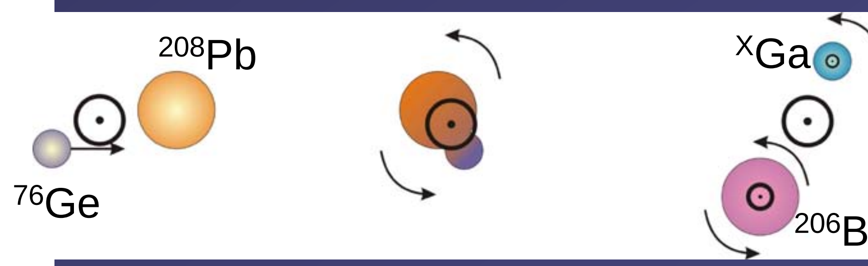
Yrast structure of ^{206}Bi identified by using the ^{76}Ge+^{208}Pb reaction and gamma-coincidence thick target technique with GAMMASPHERE

(31+)

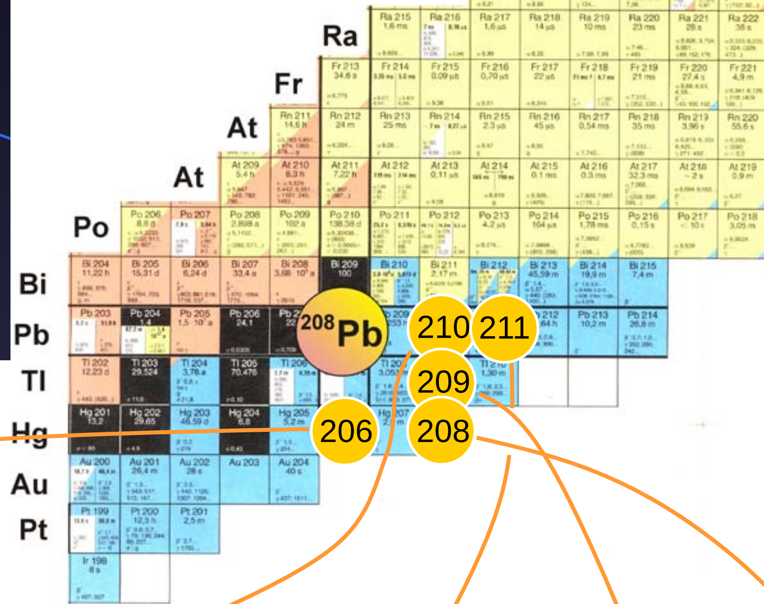


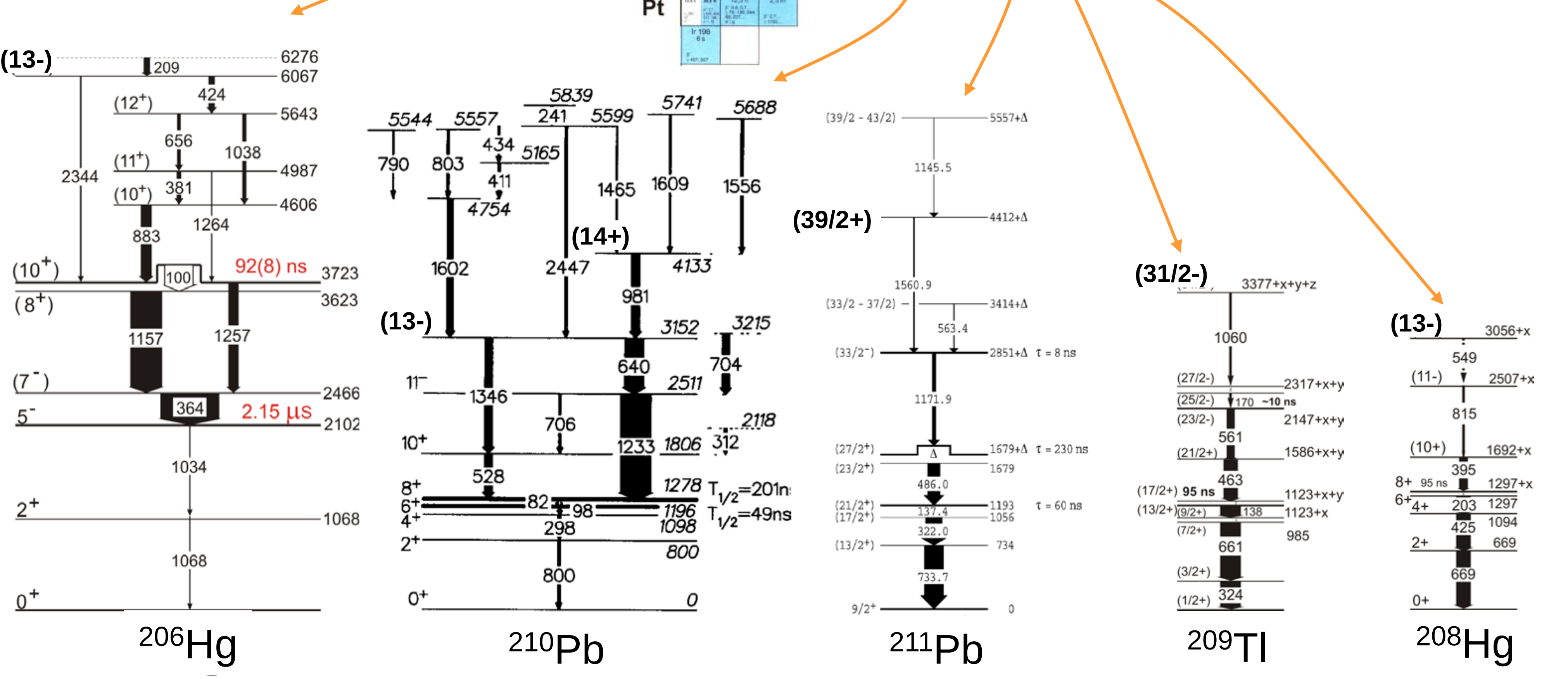


Angular distribution of gamma rays fom the ^{206}Bi product



Results on the most neutron-rich nuclei around ^{208}Pb produced in the ^{208}Pb + ^{238}U reaction and studied by using the γ–γ–γ coincidence thick-target technique with GAMMASPHERE





Realistic shell model calculations
of YRAST STATES using the $V_{low\text{-}k}$ approach –
residual n-n interaction derived
from the free nucleon–nucleon potential

To get the $V_{low\text{-}k}$ effective interaction we used:

Computational Environment for Nuclear Structure (CENS)

CD-Bonn potential, $\Lambda=2.2\ fm^{-1}$,

model spaces: (Z=50-82, N=82-126) , (Z=50-82, N=126-184)

For shell-model calculations we used:
computer code **OXBASH,**

s.p.s. energies from experiment;

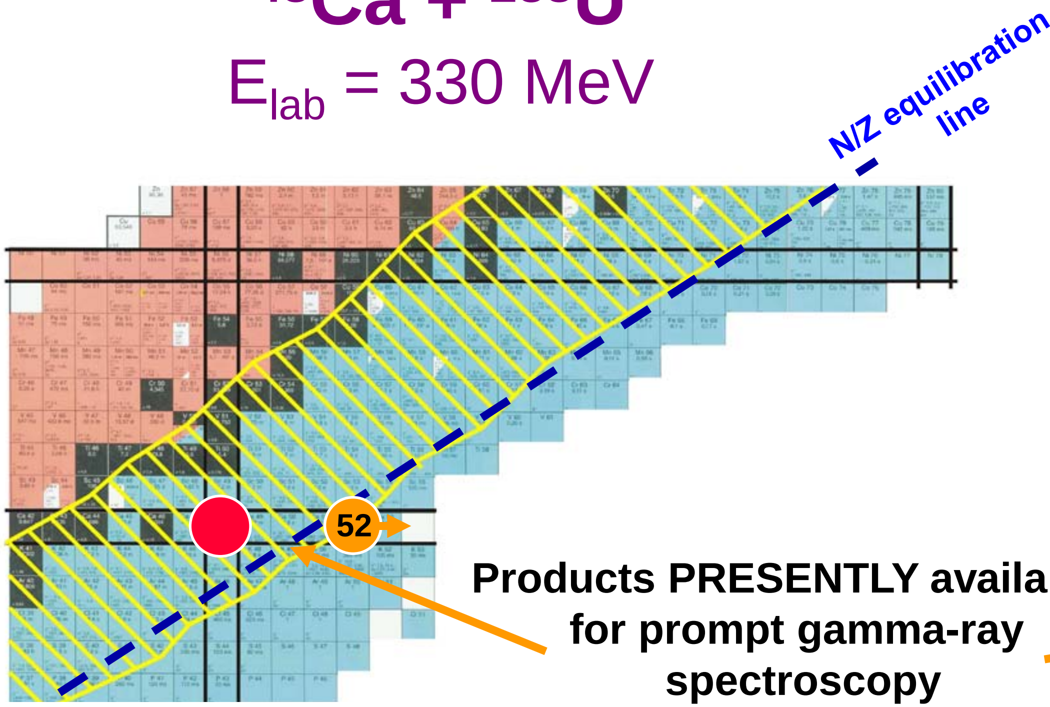
^{208}Pb

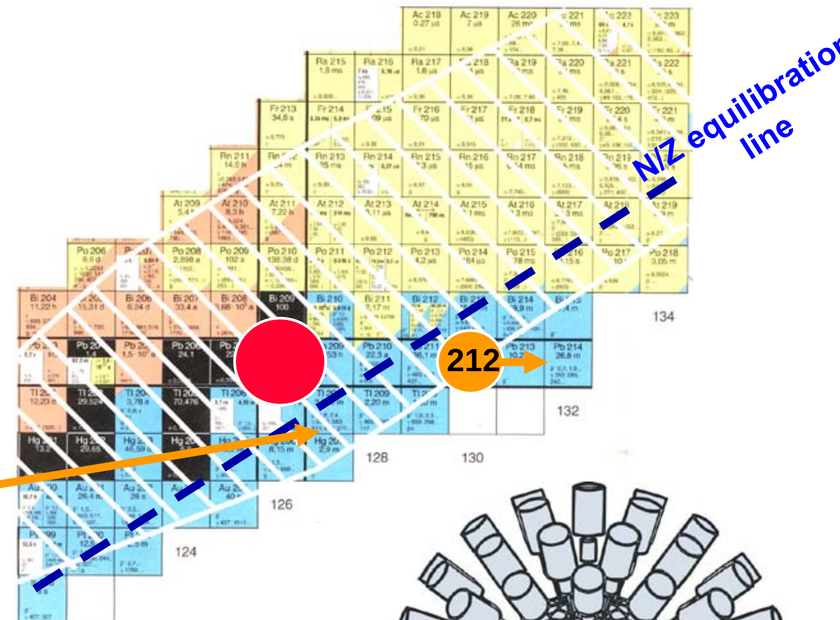
$^{48}Ca + ^{238}U$

$E_{lab} = 330$ MeV

$^{208}Pb + ^{238}U$

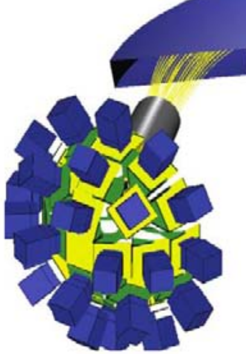
$E_{lab} = 1760$ MeV



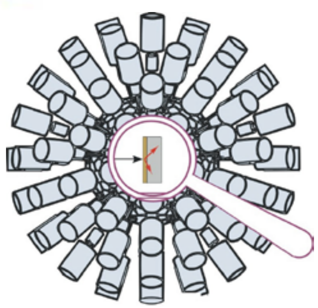


Products PRESENTLY availaible for prompt gamma-ray spectroscopy

PRISMA



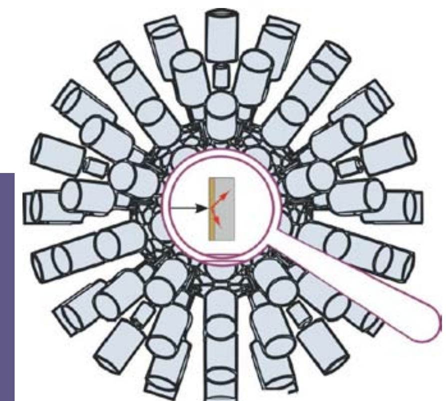
AND



CLARA

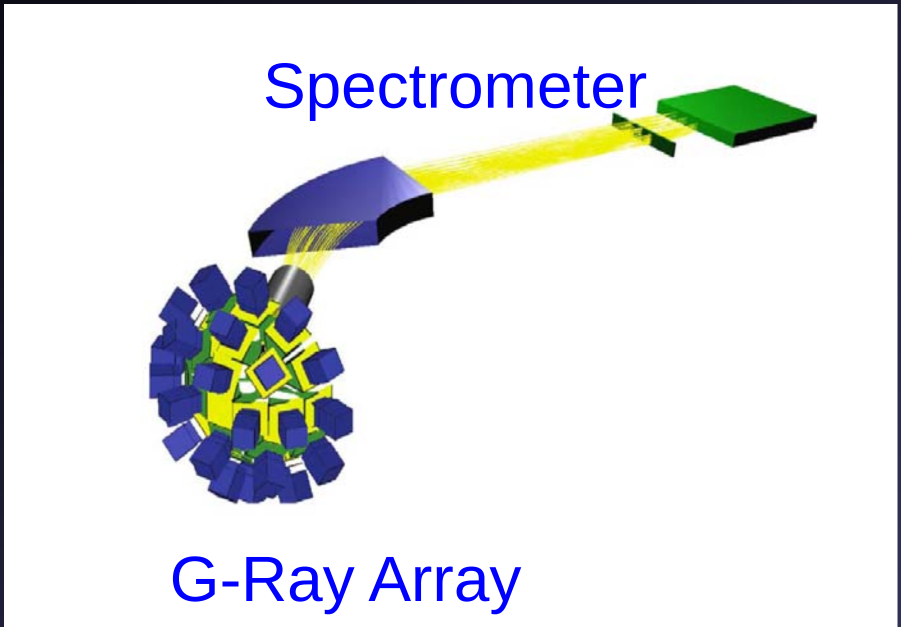
GAMMASPHERE

At the edge of the yield distributions, with increasing isotope mass by 1 unit the cross section decreases by a factor of approx. 5



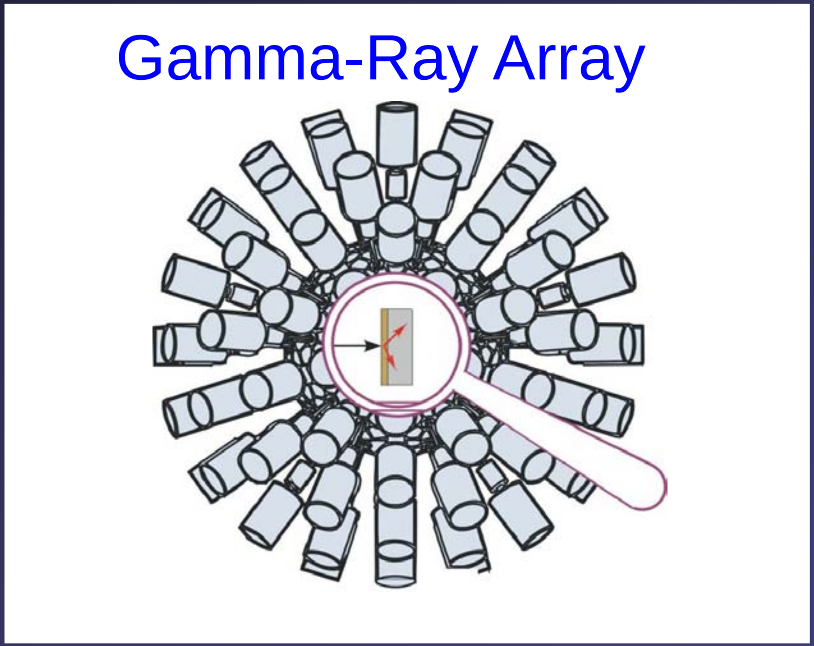
GAMMASPHERE

Gamma-ray array coupled to a magnetic spectrometer: γ-product coincidences



Assuming that an individual Ge detector of a new Ge ARRAY covers the same solid angle as in CLARA,
for **thin-target** experiments with such Ge ARRAY (digital electronics) coupled to a SPECTROMETER the beam intensity can be increased by **~50**

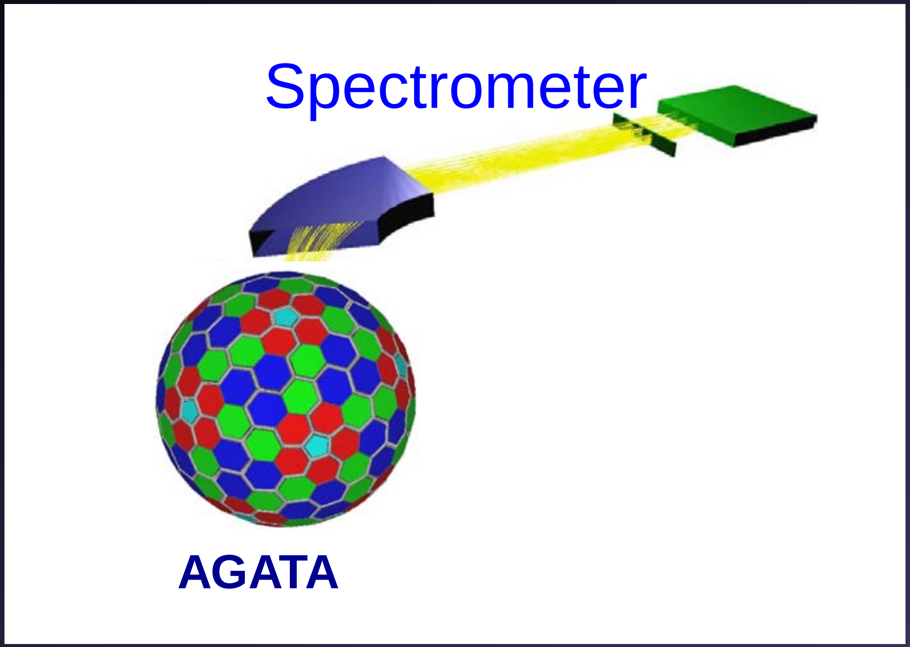
Standalone gamma-ray array γ–γ–γ coincidences

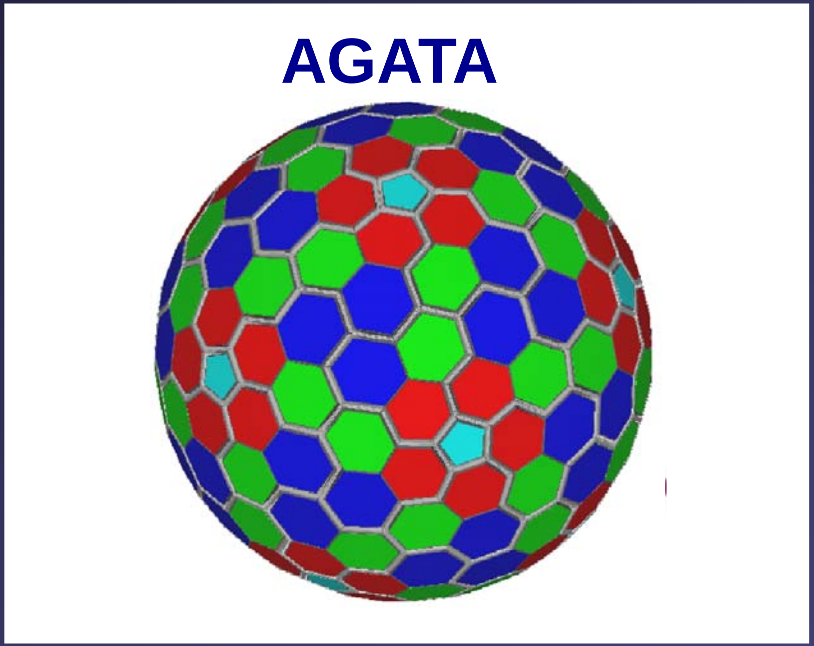


Assuming that an individual Ge detector of a new Ge ARRAY covers the same solid angle as in GAMMASPHERE,
in **thick-target** experiments with such Ge ARRAY (digital electronics) the beam intensity can be increased by **~5**

Gamma-ray array coupled to a magnetic spectrometer: γ-product coincidences

Standalone gamma-ray array γ–γ–γ coincidences





Gain from the increased beam intensity **~50**

Gain (for singles) from the increased AGATA efficiency **~10**

Overall improvement for γ-p **~500**

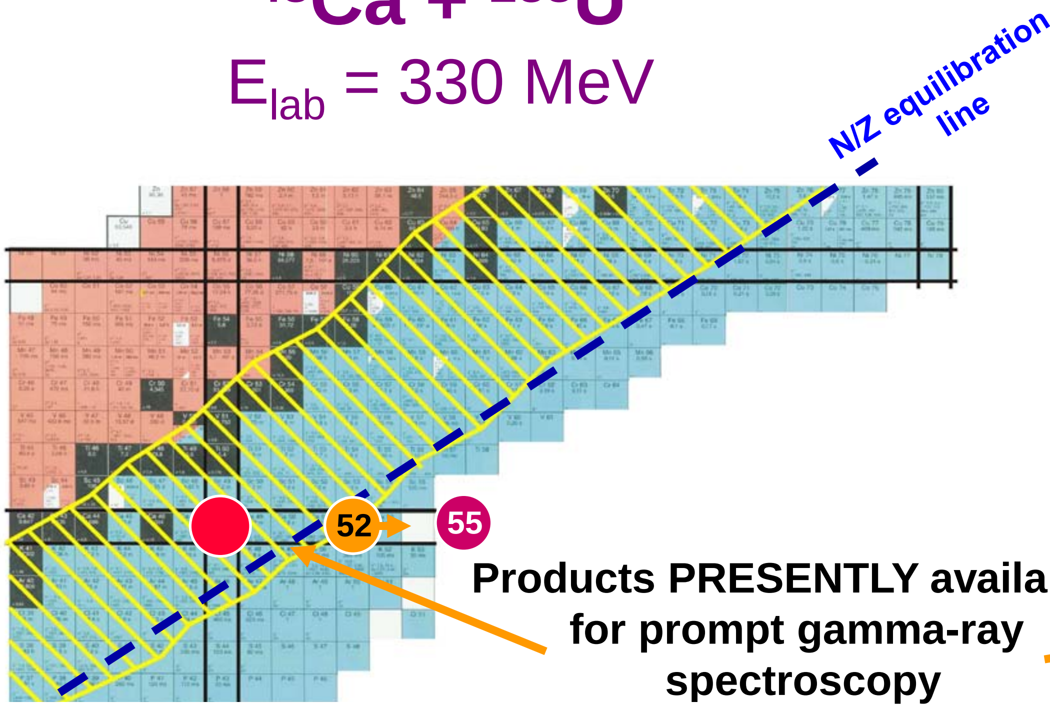
Gain from the increased beam intensity **~5**

Gain (for triple γ coincidences) from the increased AGATA efficiency **~64**

Overall improvement for γ–γ–γ **~320**

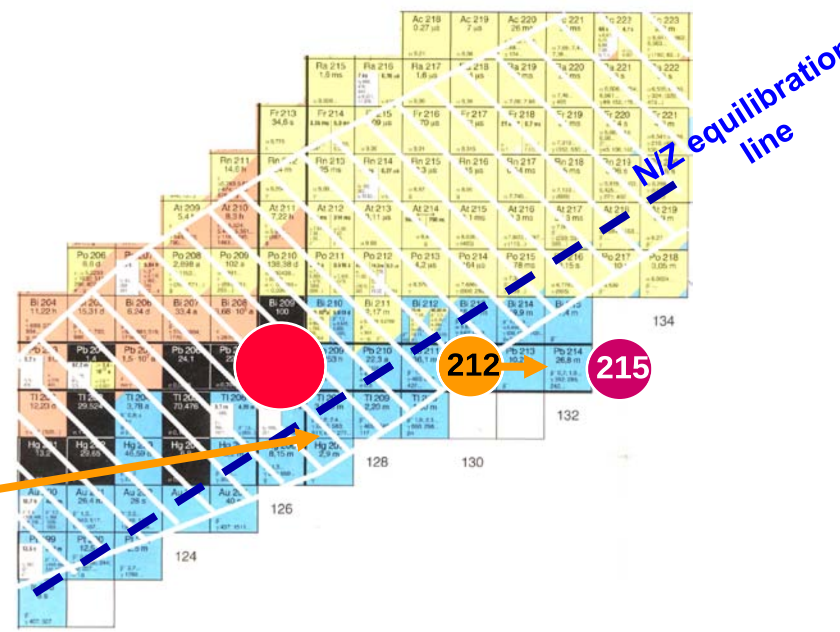
$^{48}Ca + ^{238}U$

$E_{lab} = 330$ MeV

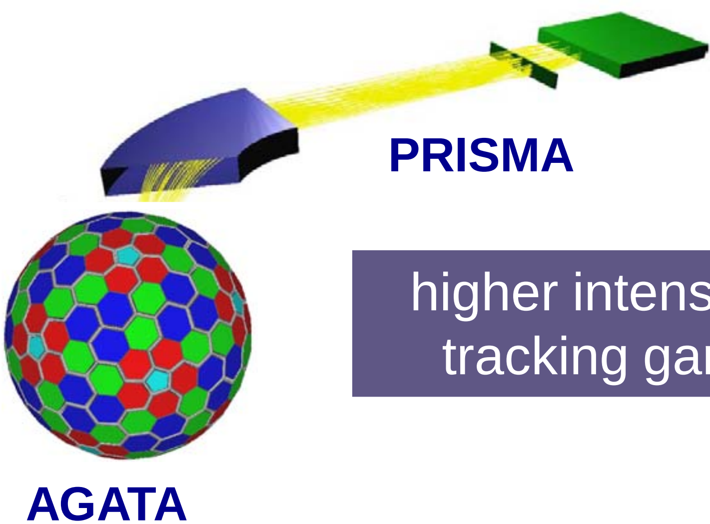


$^{208}Pb + ^{238}U$

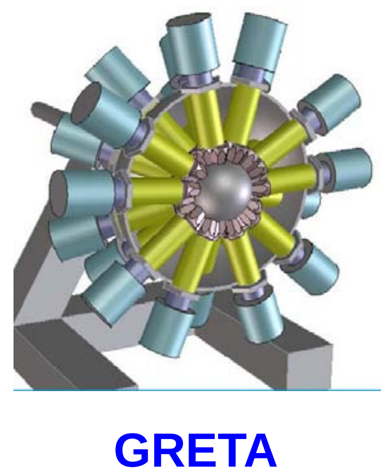
$E_{lab} = 1760$ MeV

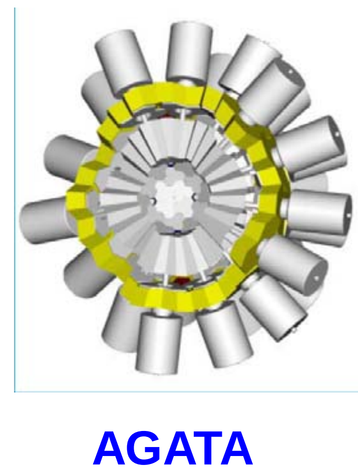


Products PRESENTLY availaible for prompt gamma-ray spectroscopy



higher intensity beams + tracking gamma array





Conclusions and Outlook

- Discrete in-beam gamma-ray spectroscopy with deep-inelastic reactions turned out to be efficient in elucidating yrast structures in many neutron-rich nuclei.

- Combination of thick-taget (standalone γ-ray array: GASP, EUROBALL, GAMMAPSHERE) and thin-target (γ-ray array coupled to a magnetic spectrometer: CLARA+PRISMA, EXOGAM+VAMOS) techniques were particularly successful in identifying yrast structures in weakly populated neutron-rich species .

- Discrete in-beam gamma-ray spectroscopy of deep-inelastic reactions products will benefit from high intensity beams, although only beams with moderately higher intensity will be of use.

  Experiments using these higher intensity beams and modern tracking germanium arrays should extend the in-beam spectroscopy toward more neutro-rich nuclei by at least 3 mass units.

Collaborators

R. Broda, N. Cieplicka, W. Krolas, K.H. Maier, T. Pawlat, B. Szpak, J. Wrzesinski, B. Fornal	*IFJ PAN Krakow, Poland*
R.V.F. Janssens, S. Zhu, M.P. Carpenter, D. Seweryniak et al.	*ANL Argonne, USA*
G. Lane, G. Dracoulis et al.	*ANU Canberra, Australia*
P. Mantica, A. Gade, D.-C. Dinca, B.A. Brown et al.	*MSU East Lensing, USA*
M. Honma	*University of Aizu, Japan*
T. Otsuka	*University of Tokyo, Japan*
L. Corradi, G. de Angelis, A. Gadea, E. Farnea, S. Lenzi, S.Lunardi, N. Marginean, J. J. Valiente-Dobon, C. Ur et al.	*PRISMA-CLARA group, Legnaro-Padova*