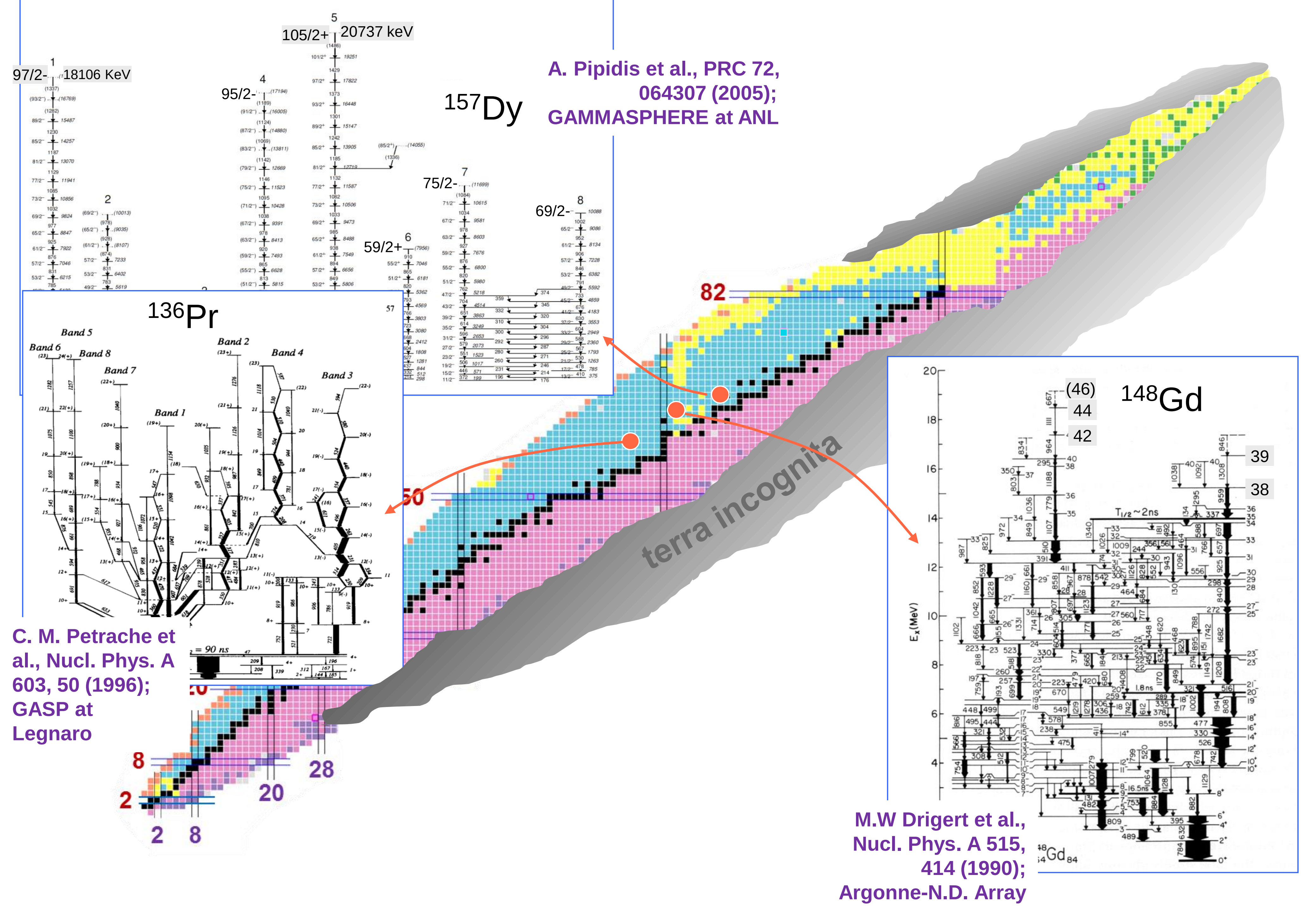
Prompt gamma-ray spectroscopy of neutron-rich nuclei

Bogdan Fornal

Institute of Nuclear Physics,
Polish Academy of Sciences
Krakow, Poland

Collaboration with: ANL Argonne (USA), INFN LNL Legnaro , Univ. Padova (Italy),
ANU Canberra (Australia), Univ. Surrey (UK), Univ. of Milan,
IPN Orsay

ECOS-EURISOL Joint Town Meeting
October 28-31, 2014 – IPN Orsay, France,



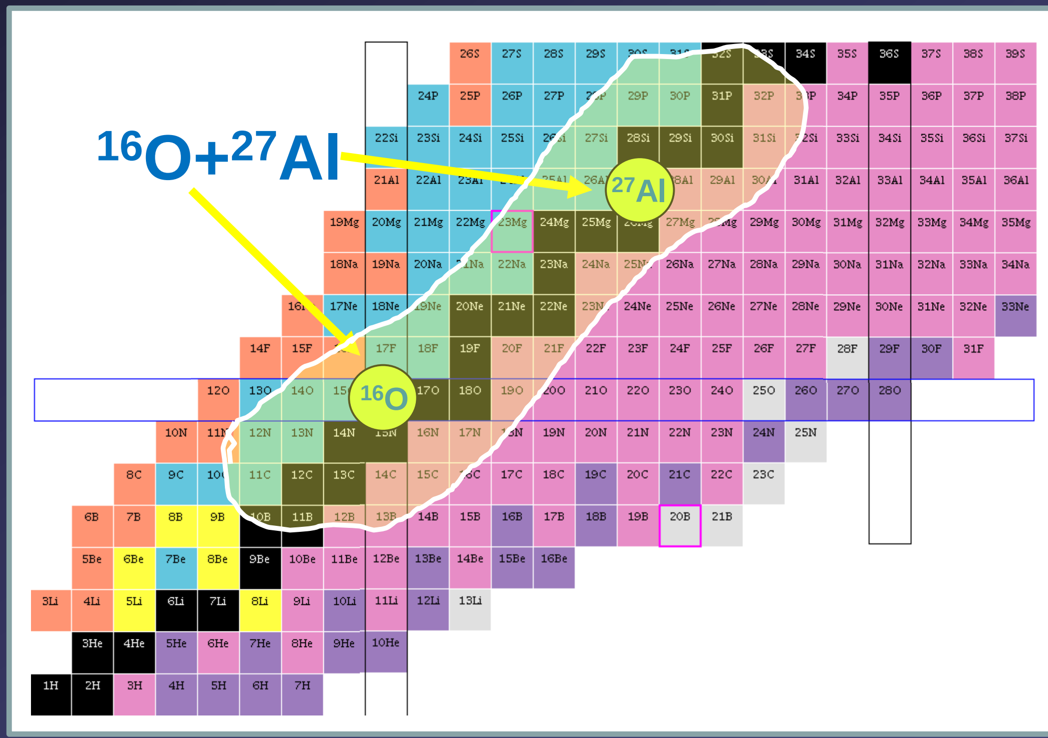
157Dy
A. Pipidis et al., PRC 72, 064307 (2005); GAMMASPHERE at ANL
105/2+ 20737 keV
97/2- 18106 KeV
95/2-
75/2-
69/2-
59/2+
136Pr
Band 1
Band 2
Band 3
Band 4
Band 5
Band 6
Band 7
Band 8
C. M. Petrache et al., Nucl. Phys. A 603, 50 (1996); GASP at Legnaro
148Gd
M.W Drigert et al., Nucl. Phys. A 515, 414 (1990); Argonne-N.D. Array
(46)
44
42
39
38
E_x (MeV)
$T_{1/2}$ ~ 2ns
terra incognita
82
50
28
20
8
2

VOLUME 3, NUMBER 5 PHYSICAL REVIEW LETTERS SEPTEMBER 1, 1959

COMPLEX NUCLEON TRANSFER REACTIONS OF HEAVY IONS*

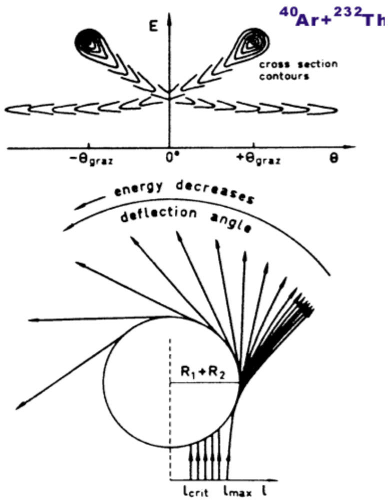
Richard Kaufmann† and Richard Wolfgang
Department of Chemistry, Yale University, New Haven, Connecticut
(Received August 12, 1959)

^{16}O (160 MeV) + ^{27}Al



In the 1970's, extensive experimental studies of the deep-inelastic reaction mechanism were carried out and theoretical concepts were developed.

Wilczynski Plot



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

V.V. Volkov, *Deep Inelastic Transfer Reactions – the New Type of Reactions Between Complex Nuclei*, Physics Reports 44, 93 (**1978**)

L.G. Moretto and R.P. Schmitt, *Deep inelastic reactions: a probe of the collective properties of nuclear matter*, Rep. Prog. Phys. Vol. 44 (**1981**)

A. Gobbi, *Different regimes of dissipative collisions* in Lecture Notes in Physics, Volume 168, **1982**, pp. 159-174.

W.U.Schroeder and J.R.Huizenga, *Dumped Nuclear Reactions* in Treatise on Heavy-Ion Science, Ed. D.A.Bromley. N.Y.; London. **1985**, pp 113-726.

VOLUME 38, NUMBER 7 PHYSICAL REVIEW LETTERS 14 FEBRUARY 1977

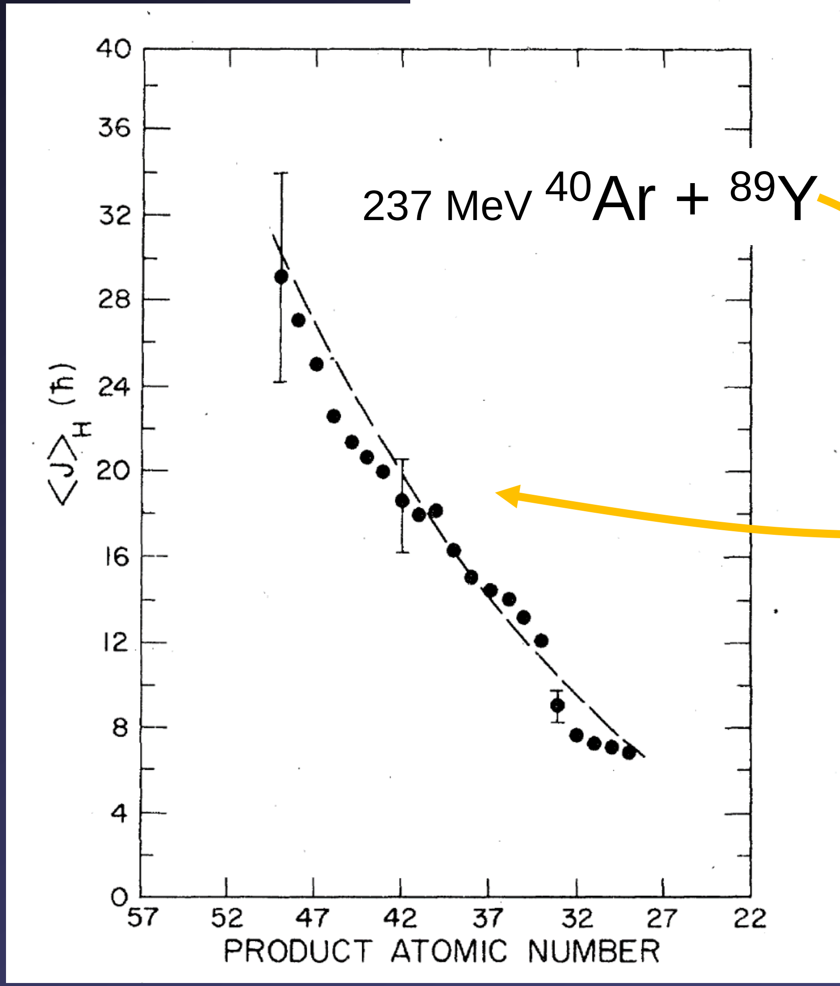
Angular-Momentum Transfer in Deep-Inelastic Processes

P. Glässel,* R. S. Simon,† R. M. Diamond, R. C. Jared, I. Y. Lee,
L. G. Moretto,‡ J. O. Newton,§ R. Schmitt, and F. S. Stephens
Department of Chemistry and Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 29 November 1976)

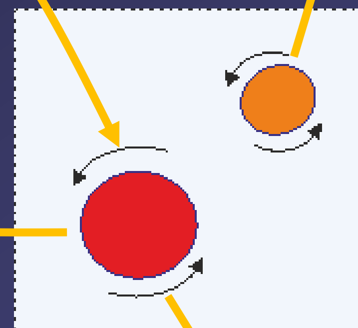
PHYSICAL REVIEW C VOLUME 20, NUMBER 3 SEPTEMBER 1979

Angular momentum transfer in the deep inelastic reactions of 237 MeV ^{40}Ar with ^{89}Y

M. N. Namboodiri, J. B. Natowitz, P. Kasiraj, R. Eggers,* L. Adler, P. Gonthier, C. Cerruti,† and S. Simon
Cyclotron Institute, Texas A & M University, College Station, Texas 77843
(Received 3 April 1979)



$$\vec{I}_1 = \frac{\mathfrak{I}_1 \vec{I}_{ini}}{\mathfrak{I}_1 + \mathfrak{I}_2 + \mathfrak{I}_{tot}}$$



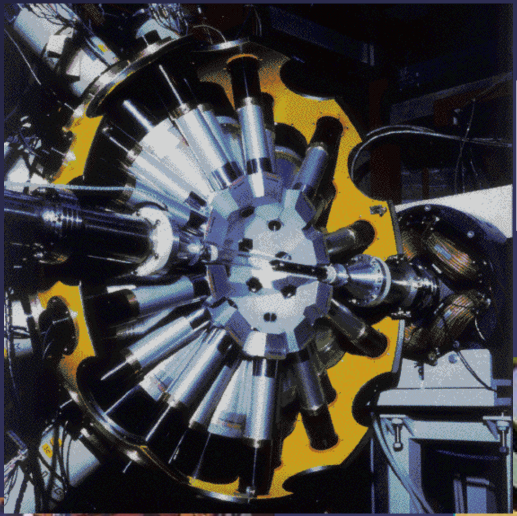
$$\vec{I}_2 = \frac{\mathfrak{I}_2 \vec{I}_{ini}}{\mathfrak{I}_1 + \mathfrak{I}_2 + \mathfrak{I}_{tot}}$$

To be able to resolve gamma rays from high-spin states in deep-inelastic reaction products one had to wait until the advent of the efficient germanium gamma-ray arrays.

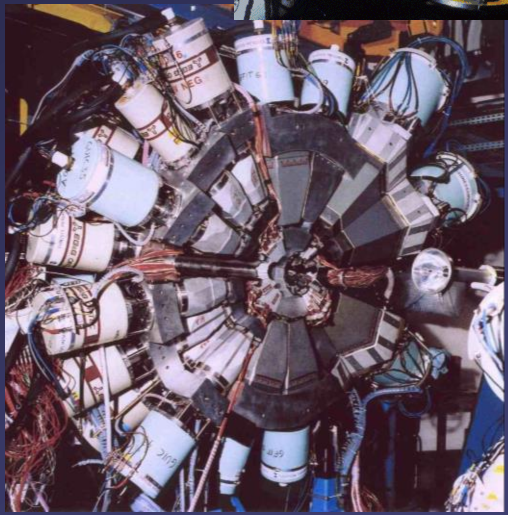
Gamma-ray arrays based on Compton supressed Ge detectors

Starting from the 80's:

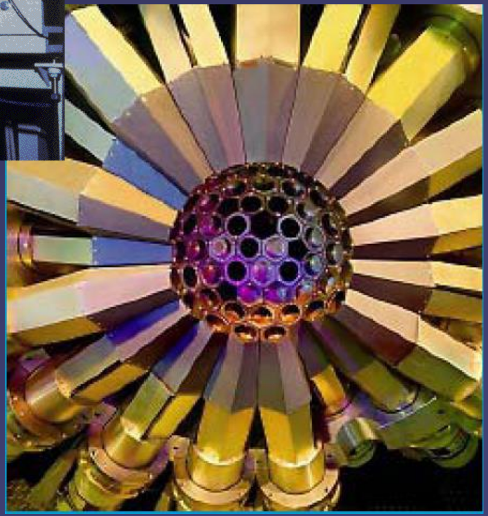
TESSA (Daresbury),
OSIRIS (Berlin),
ARGONNE-ND ARRAY (Argonne)
NORDBALL (Copenhagen),
JUROSPHERE (Jyvaskyla),
EUROGAM (Strasbourg),
CLARION (Oak Ridge)
GASP (Legnaro-Padova)
EUROBALL
GAMMASPHERE



GASP
Legnaro

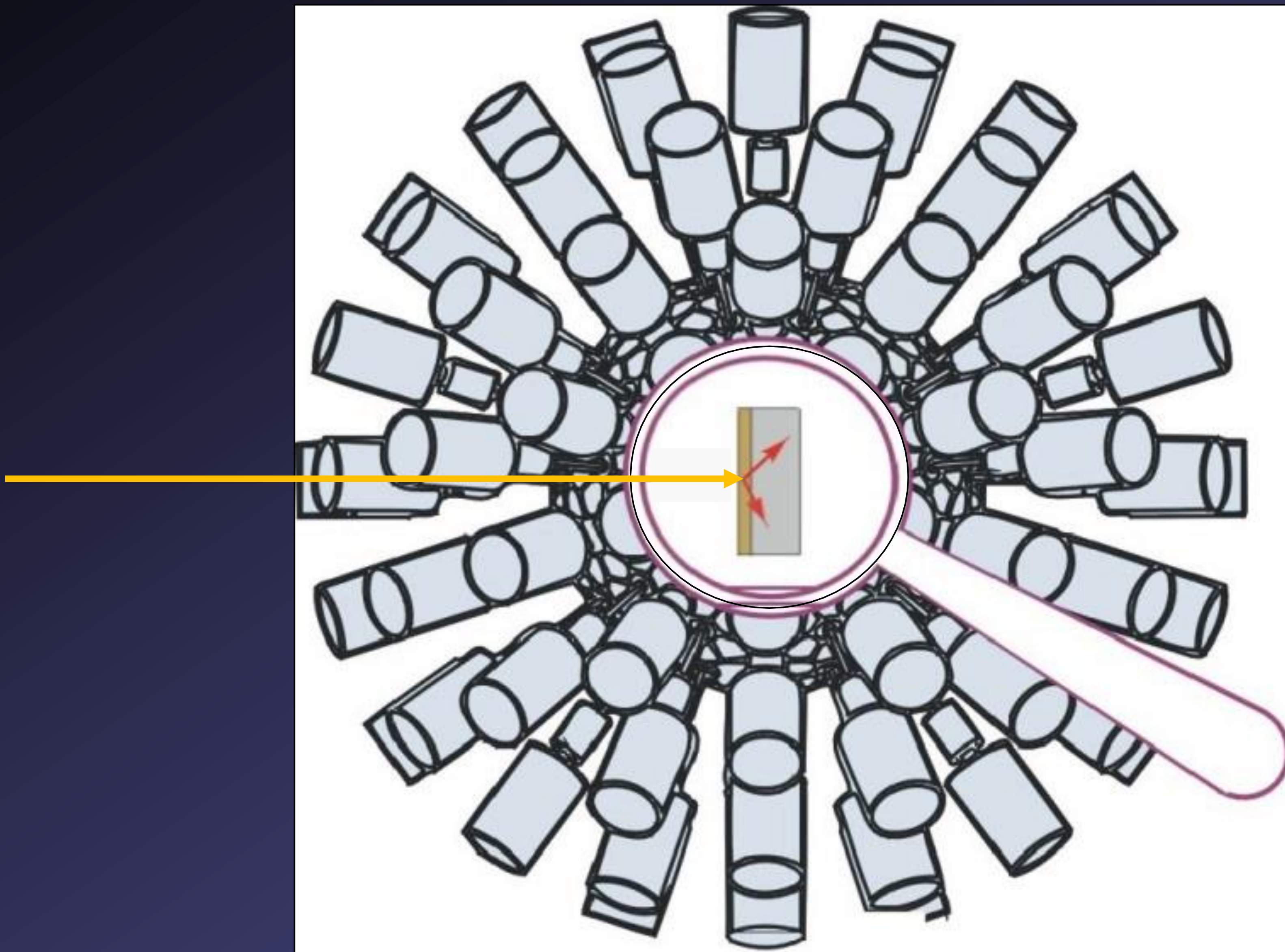


EUROBALL
Legnaro, Strasbourg



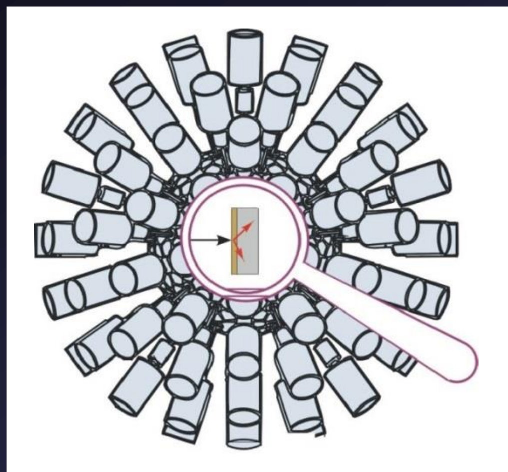
GAMMASPHERE
Argonne, Berkeley

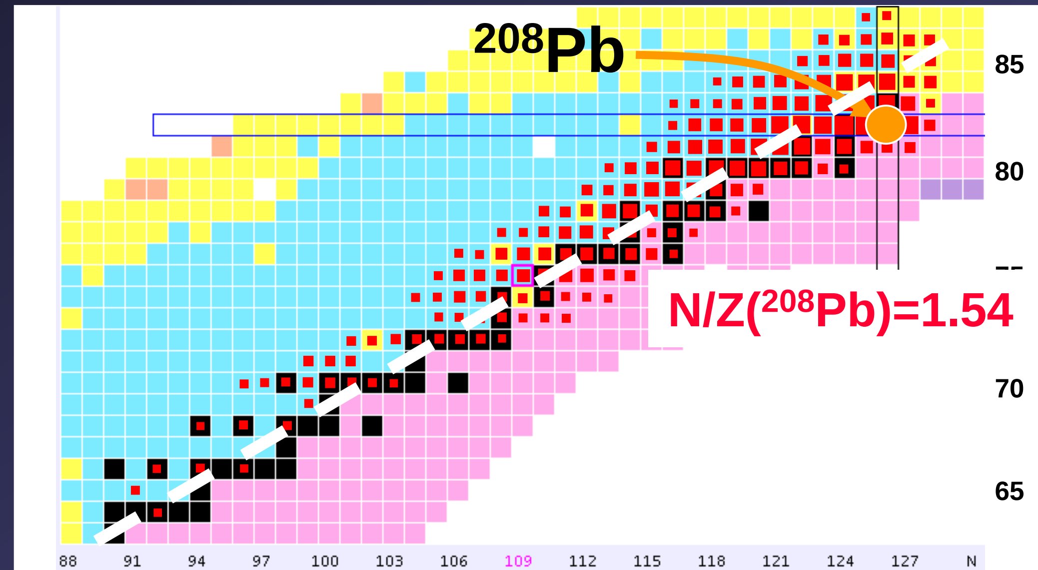
Measuring gamma rays from deep-inelastic reaction products by using the thick-target technique

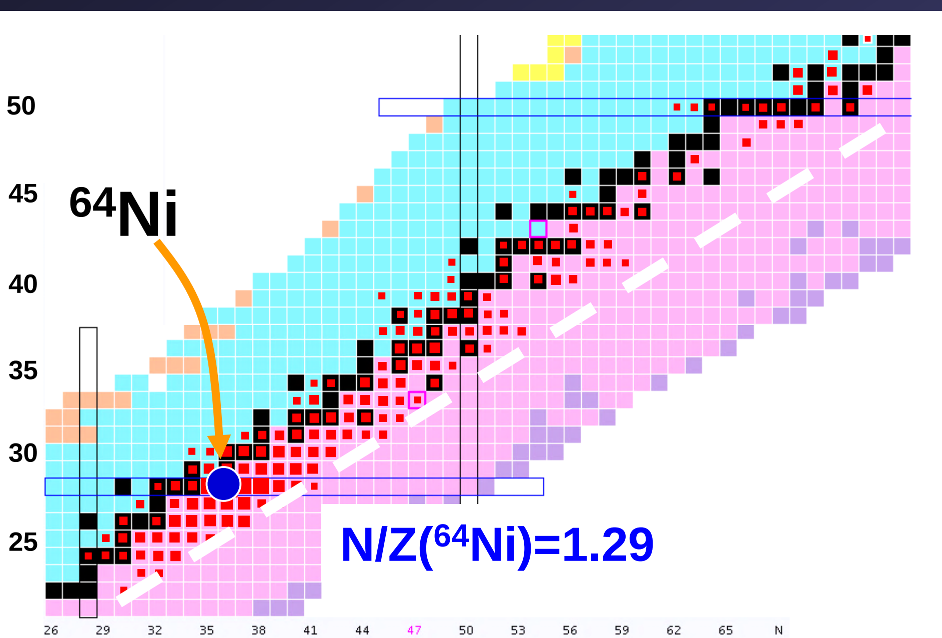


Detailed product yield distribution from gamma-gamma coincidence data measured with the thick-target technique for the system:

^{64}Ni + ^{208}Pb at 350 MeV



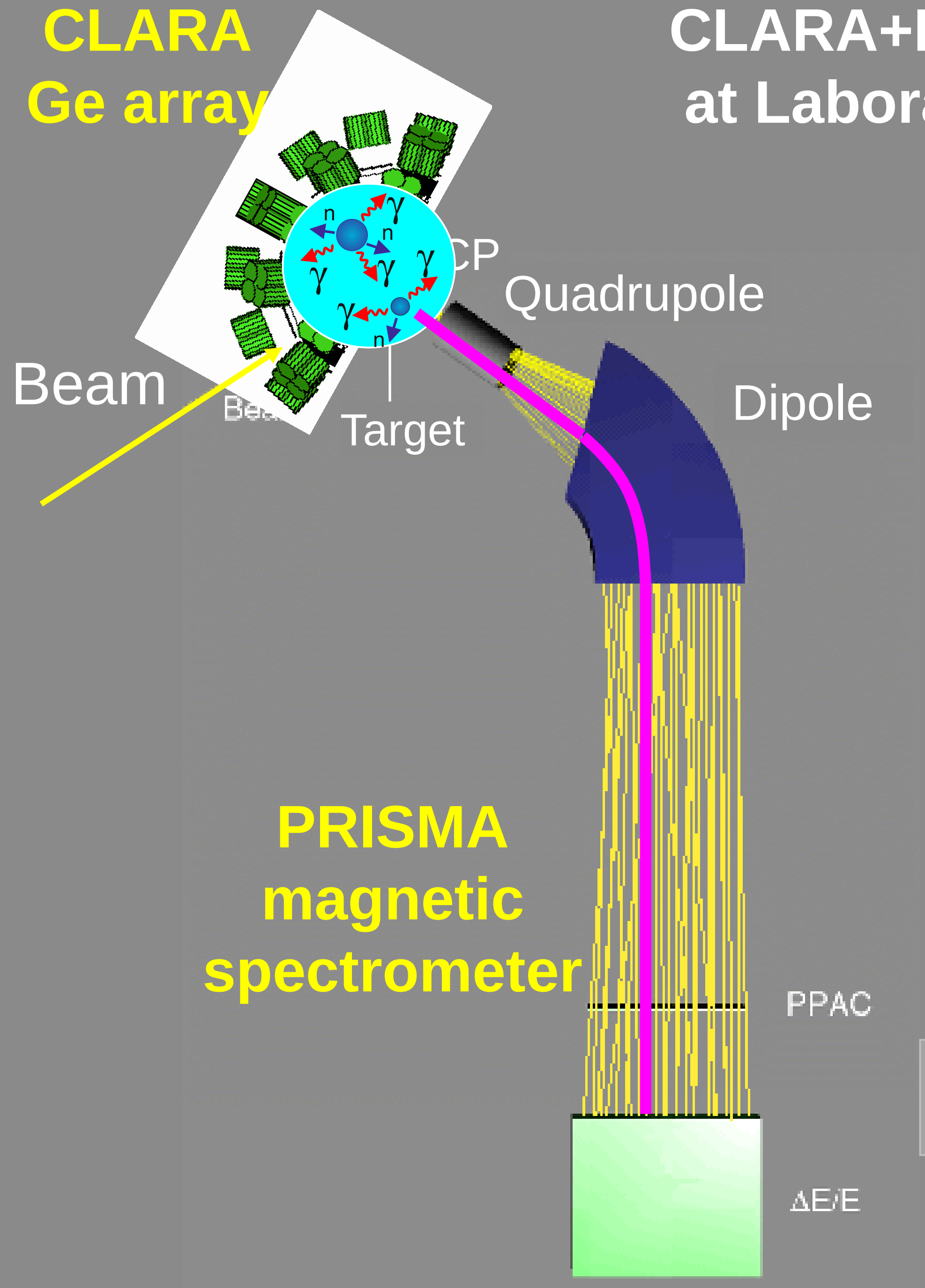


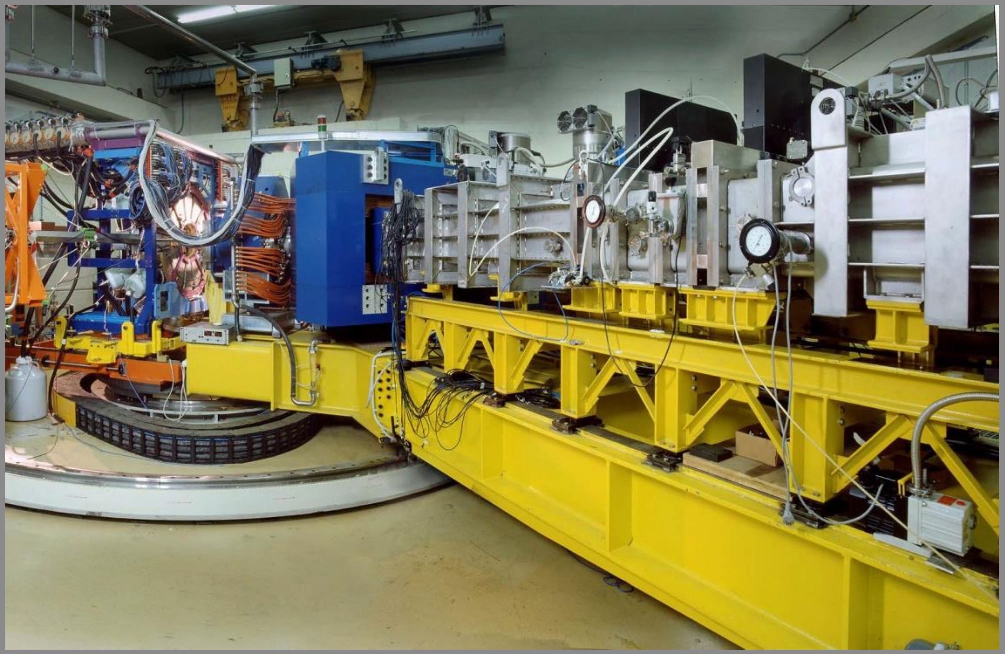


W. Krolas et al., Nucl. Phys. A724, (2003)

New developments in the gamma-ray spectroscopy of deep-inelastic reaction products: **magnetic spectrometers** coupled to **germanium arrays**

CLARA+PRISMA detection system at Laboratori Nazionali di Legnaro

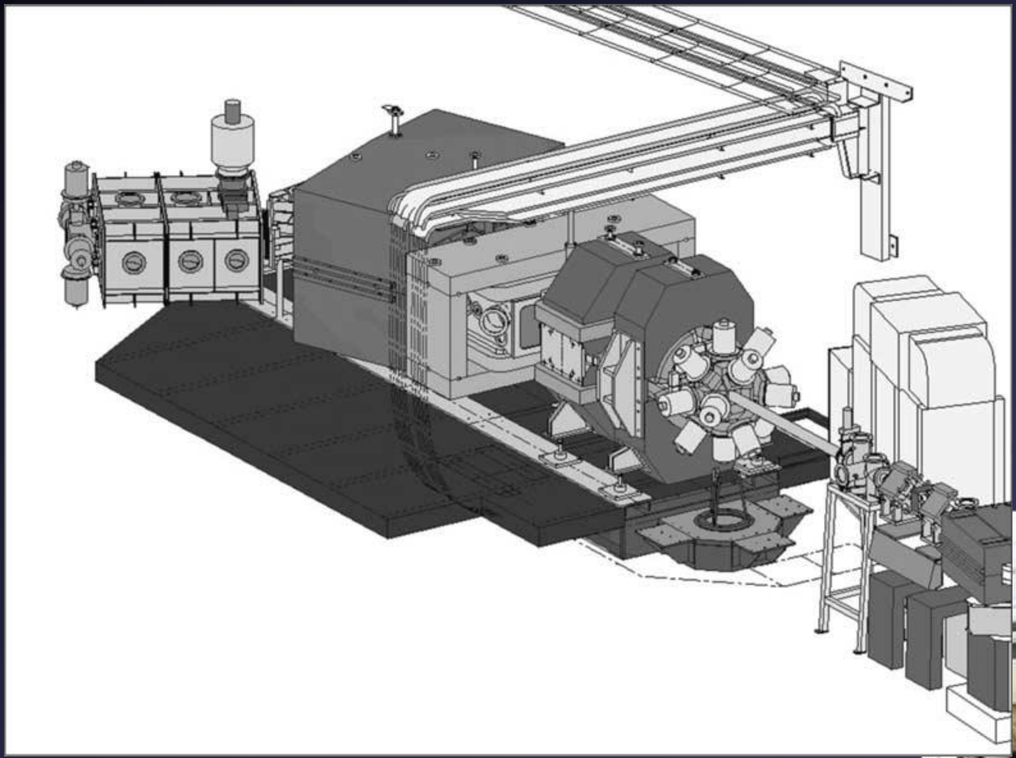




A. M. Stefanini et al., Nucl. Phys. A701, 217c (2002)

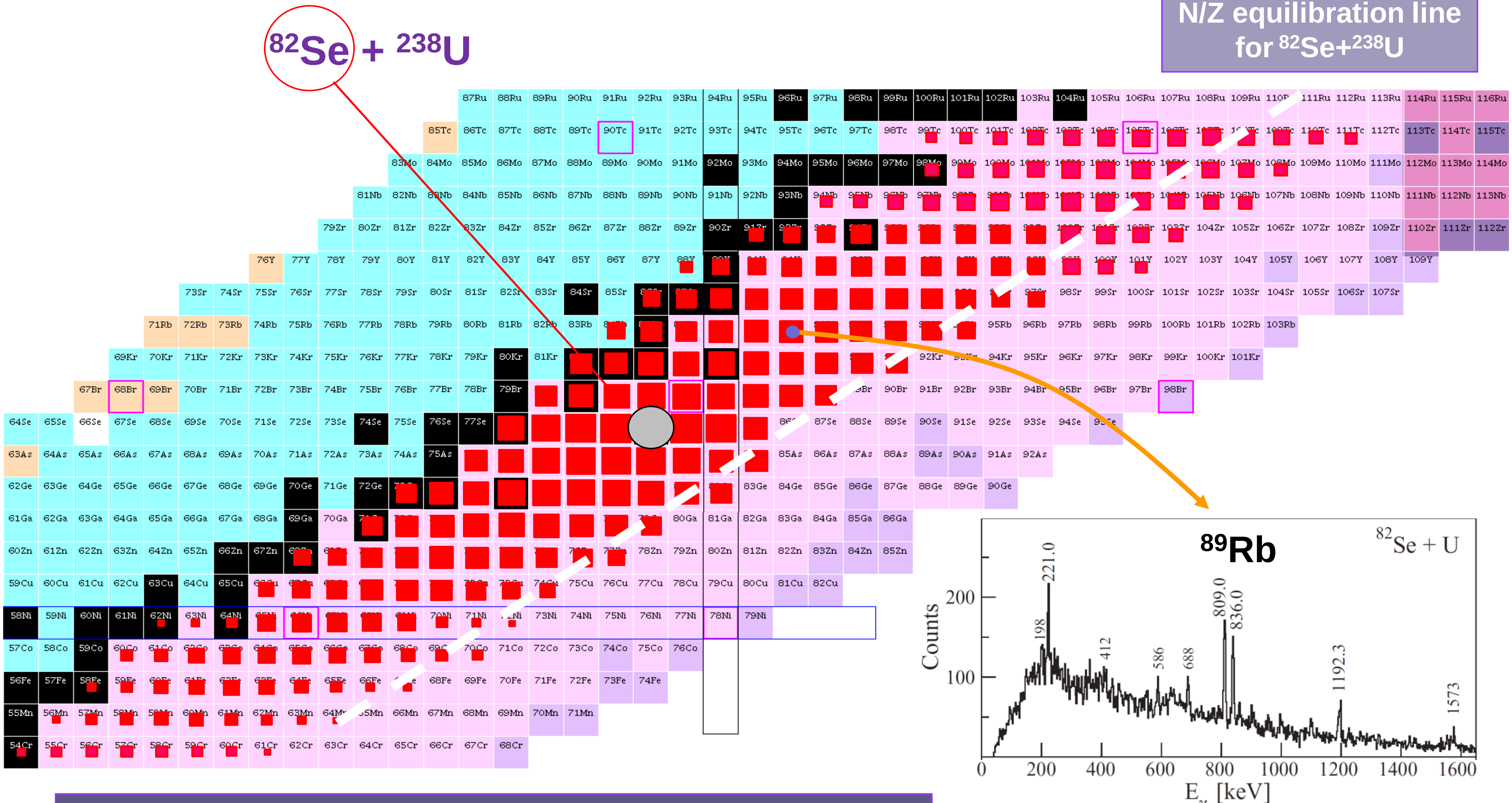
A. Gadea et al., Eur. Phys. J. A 20, 193 (2004).

Large-acceptance spectrometer VAMOS coupled to EXOGAM Ge array at GANIL, Caen (France)



H. Savajols, Nucl. Instr. and Meth. B 204 (2003) 146

The map of product yields for the reaction ^{82}Se (505 MeV) + ^{238}U investigated with CLARA+PRISMA at LNL Legnaro

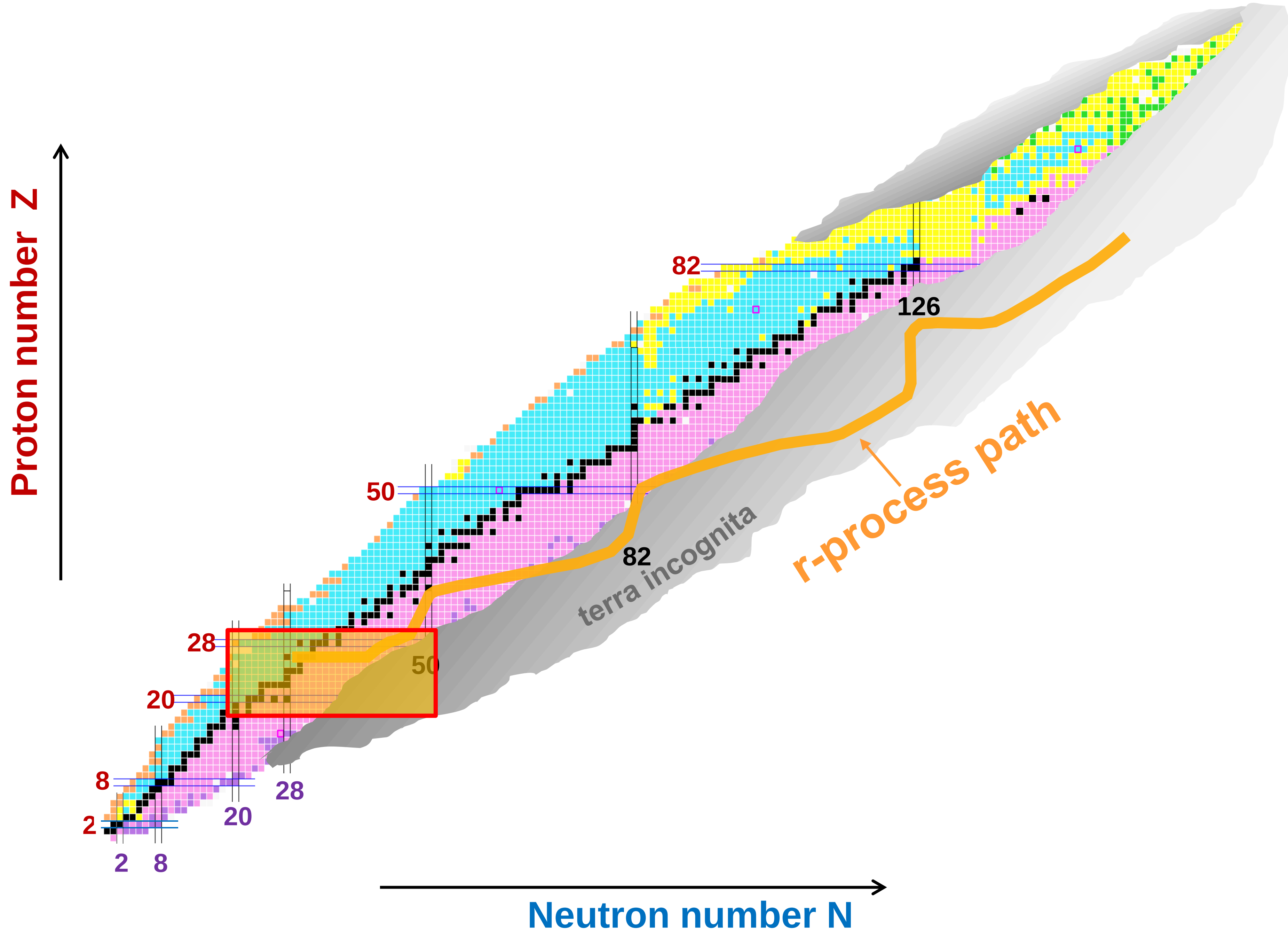


G. De Angelis, *Prog.Part.Nucl.Phys*. 59, 409 (2007)

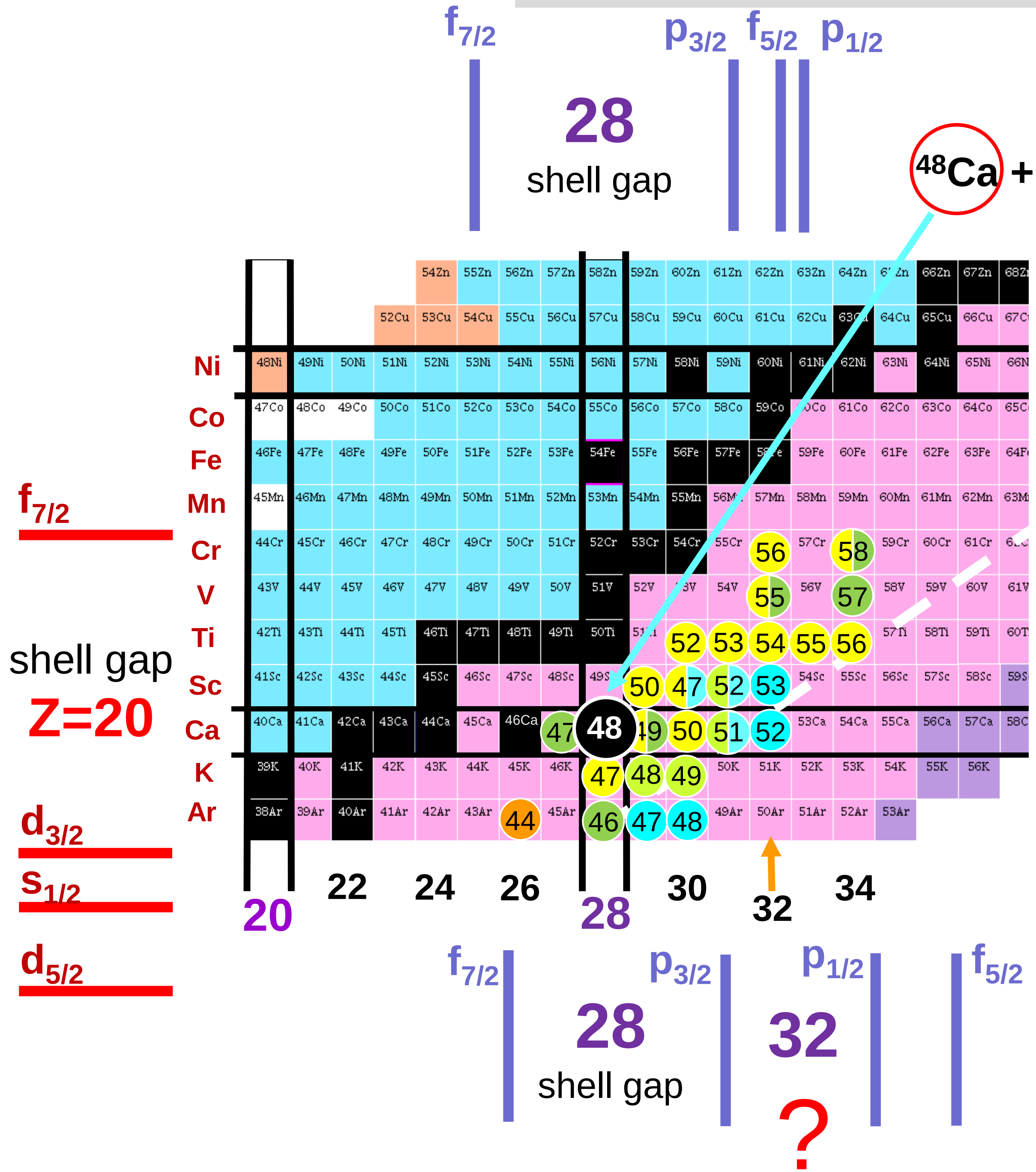
D. Bucurescu *et al.*, Phys. Rev. C 76 (2007)

We have the method that enables the studies of high-spin structures in neutron-rich nuclei – it relies on using deep-inelastic processes and two detection techniques:

a) thick-target technique with large germanium arrays
   or
b) thin target technique with magnetic spectrometers
   coupled to germanium arrays.


Proton number Z
Neutron number N
82
50
28
20
8
2
2
8
20
28
50
82
126
terra incognita
r-process path

Does the sub-shell closure occur at N=32 in neutron-rich nuclei?



N/Z equilibration line for $^{48}Ca+^{238}U$

GAMMASPHERE (thick target)

R.V.F. Janssens et al., Phys. Lett. B546, 55 (2002),
B.F. et al., Phys. Rev. C 70, 064304 (2004),
R. Broda et al., Acta Phys.Pol. B36, 1343 (2005).
B.F. et al., Phys. Rev. C 72, 044315 (2005),
S. Zhu et al., Phys.Rev.C 74, 064315 (2006),
S. Zhu et al., Phys. Lett. B 650, 135 (2007).

GAMMASPHERE (thick-target) +CLARA-PRISMA (thin taget)

B.F. et al., Phys. Rev. C 77, 014304 (2008),
R. Broda et al., Phys. Rev. C 82, 034319 (2010),
W. Krolas et al., Phys.Rev. C 84, 064301 (2011).

CLARA+PRISMA (thin taget)

N. Marginean et al., Phys. Lett. B 633, 696 (2006),
D. Napoli et al., J. Phys.: Conf. Ser. 49, 91 (2006),
J. Valiente-Dobon et al., PRL. 102, 242502 (2009),
D. Mengoni et al., Phys.Rev. C 82, 024308 (2010),
D. Montanari et al., Phys.Lett. B 697, 288 (2011),
D. Montanari et al., Phys.Rev. C 85, 044301 (2012).

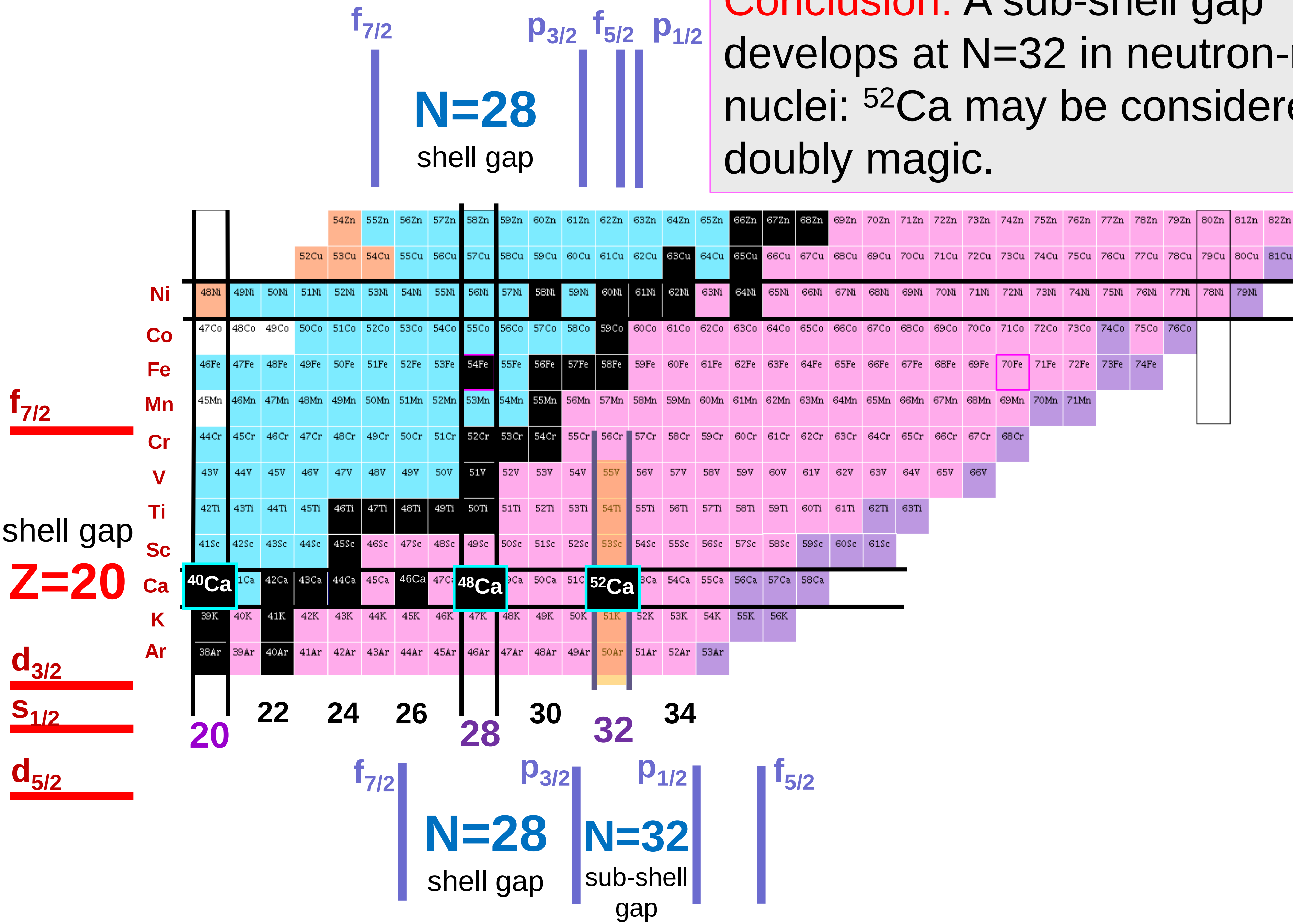
EUROBALL (thick target)

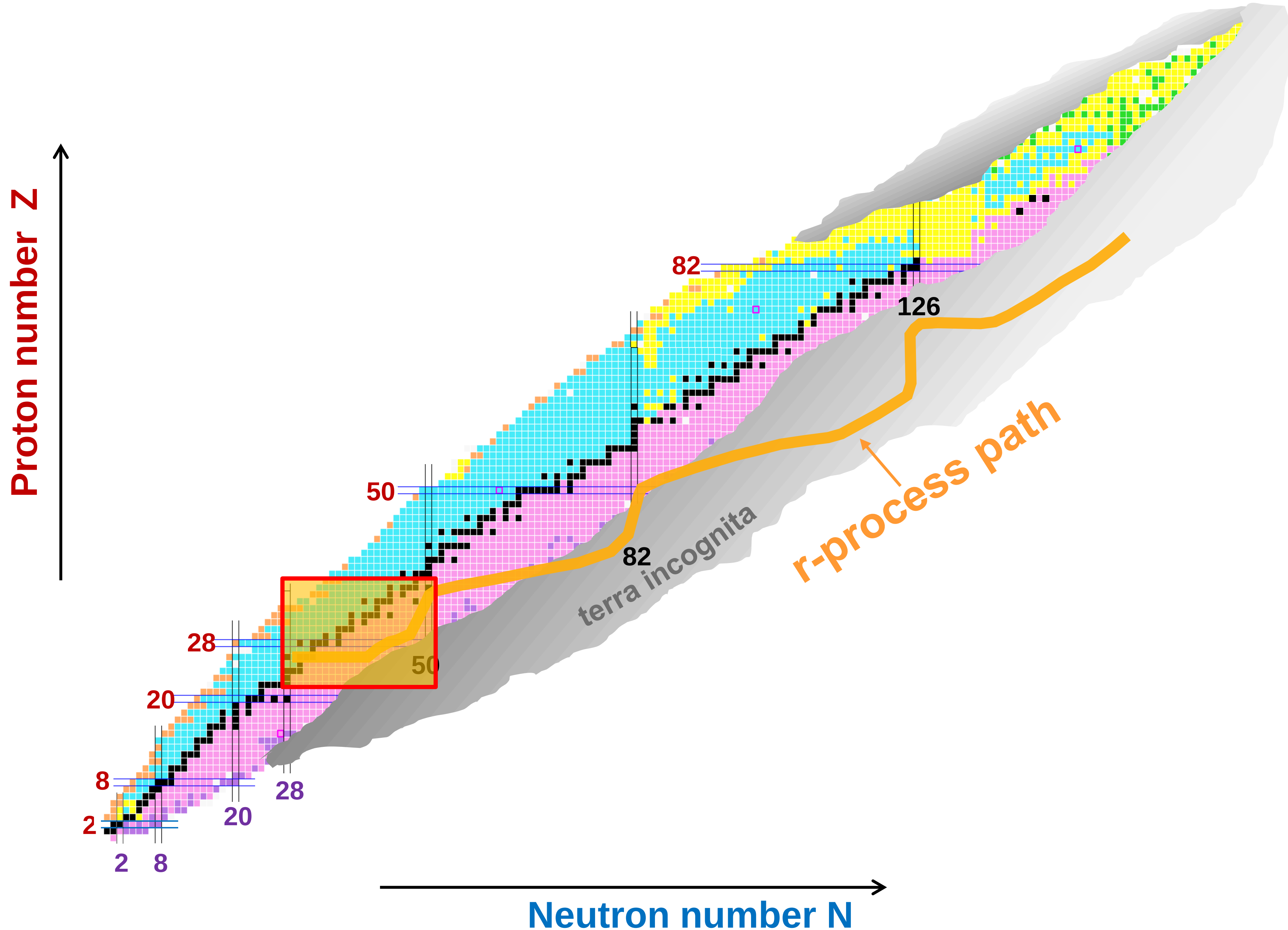
B.F. et al., Eur. Phys. J. A 7, 147 (2000).

EXOGAM+VAMOS (thin taget)

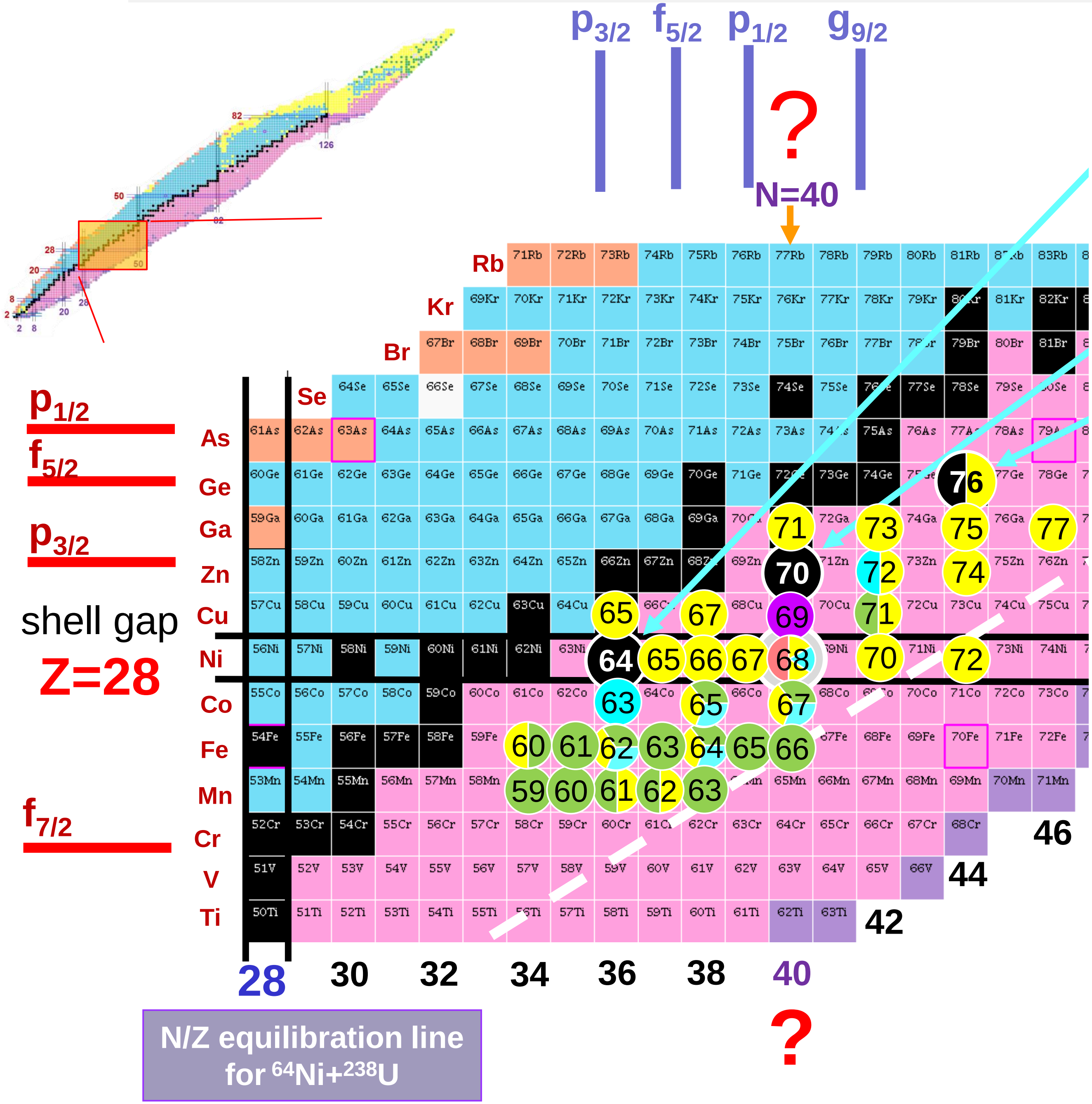
M. Rejmund et al., Phys. Rev. C 76, 021304(R) (2007),
S. Bhattacharyya et al., PRL 101, 032501 (2008),
S. Bhattacharyya et al., Phys.Rev. C 79, 014313 (2009)

Conclusion: A sub-shell gap develops at N=32 in neutron-rich nuclei: ^{52}Ca may be considered doubly magic.




Proton number Z
Neutron number N
r-process path
terra incognita
82
50
28
20
8
2
126
82
50
28
20
8
2

Does there exist a sizable energy gap at N = 40 in neutron-rich nuclei?



GASP (thick target)
R. Broda et al., PRL 74, 868 (1995),

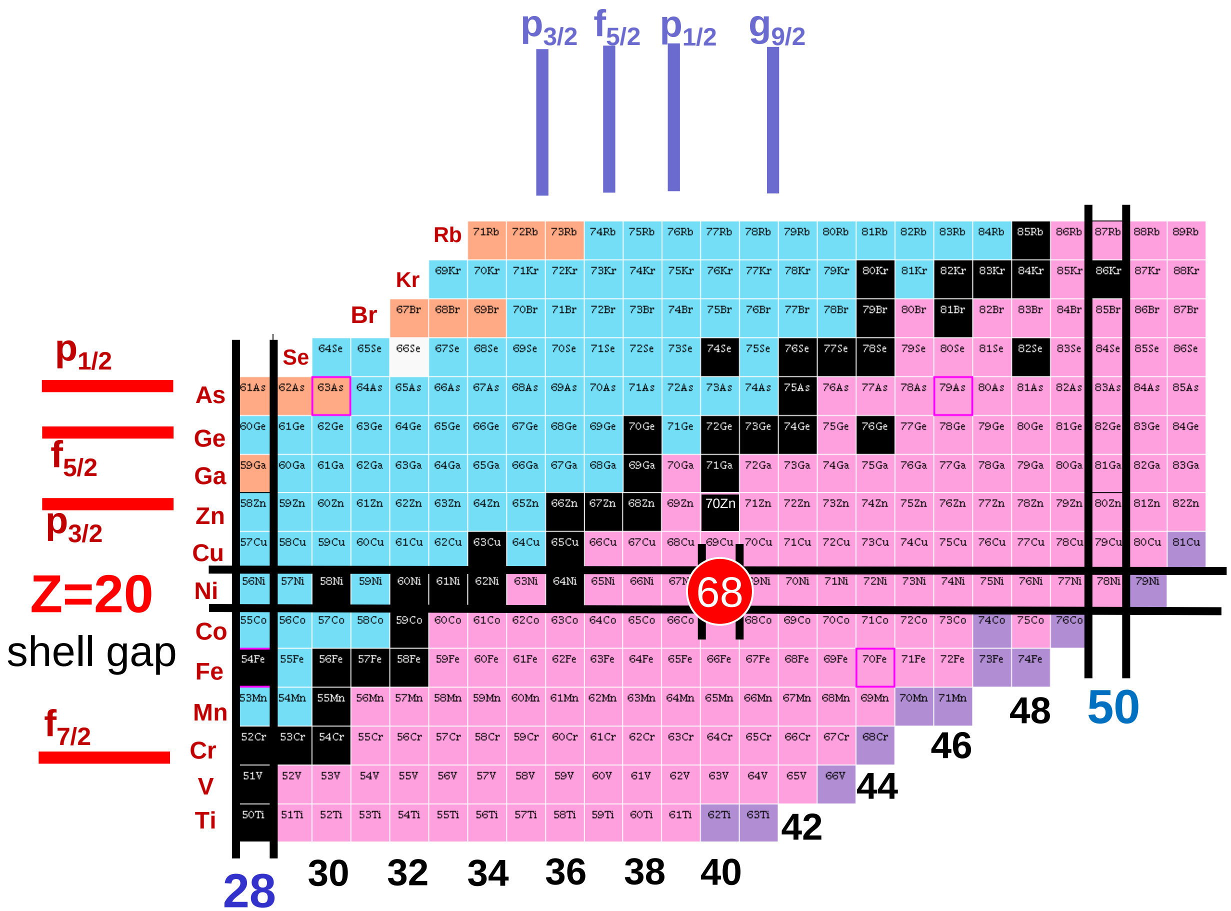
GAMMASPHERE (thick target)
I. Stefanescu et al., PRC C 79, 064302 (2009),
C.J. Chiara et al., PRC 82, 054313 (2010),
N. Hotelinket al., PRC 82, 044305 (2010).
C.J. Chiara et al., PRC 84, 037304 (2011),
C.J. Chiara et al., PRC 85, 024309 (2012),
C.J. Chiara et al., PRC 86, 041304 (2012),
S. Zhu et al., PRC 85, 034336 (2012).,
C.J. Chiara et al., PRC C 86, 041304 (2012),

CLARA(AGATA) + PRISMA (thin taget)
S. Lunardi et al., PRC 76, 034303 (2007)
J.J. Valiente-Dobon et al., PRC 78, (2008)
F. Recchia et al., PRC 85, 064305 (2012)
M. Doncel et al., APP B44, 505 (2013)

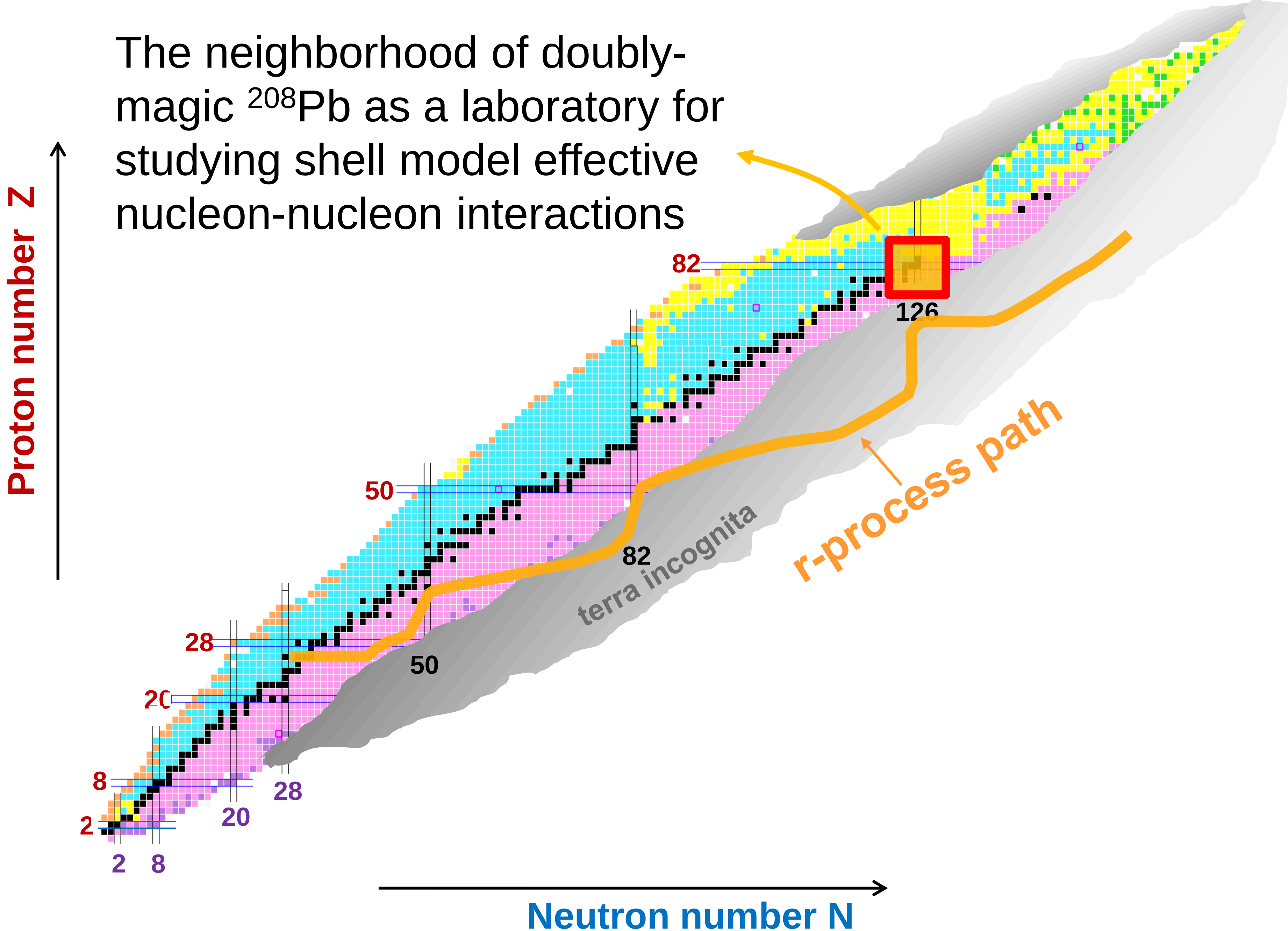
EXOGAM+VAMOS (thin taget)
J.Ljungvall et al., PRC 81, 061301 (2010)
A. Dijon et al., PRC 83, 064321 (2011)
I. Celikovic et al., APP B44, 375 (2013)

Isomer-scope – RIKEN (thin taget)
T.Ishi et al., NIM A 395 (1997)

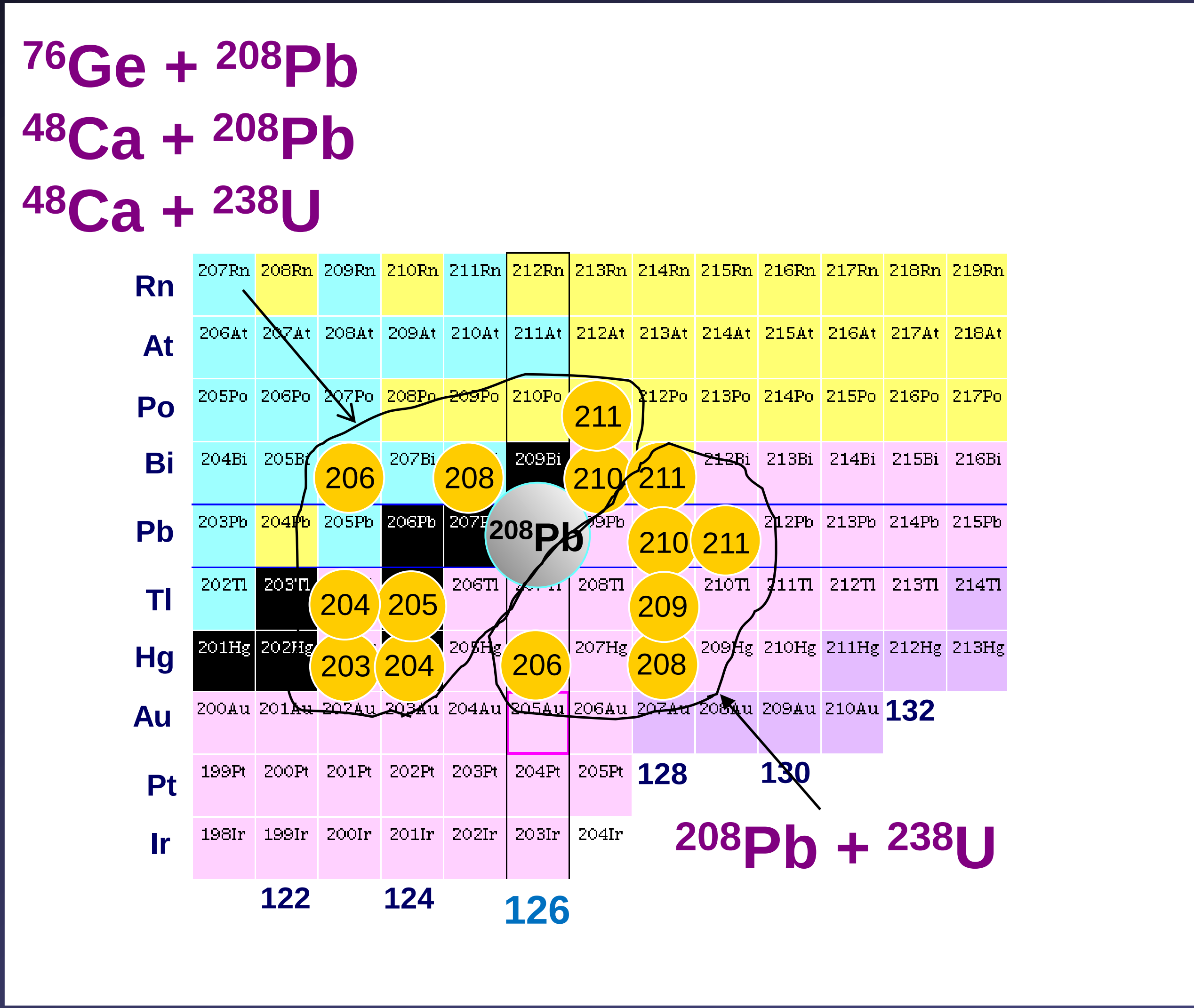
Conclusion: The sub-shell closure at N=40 occurs in Ni nuclei, making the ^{68}Ni nucleus „almost” doubly magic.
This closure, however, is rather weak and restricted to the close proximity of ^{68}Ni.



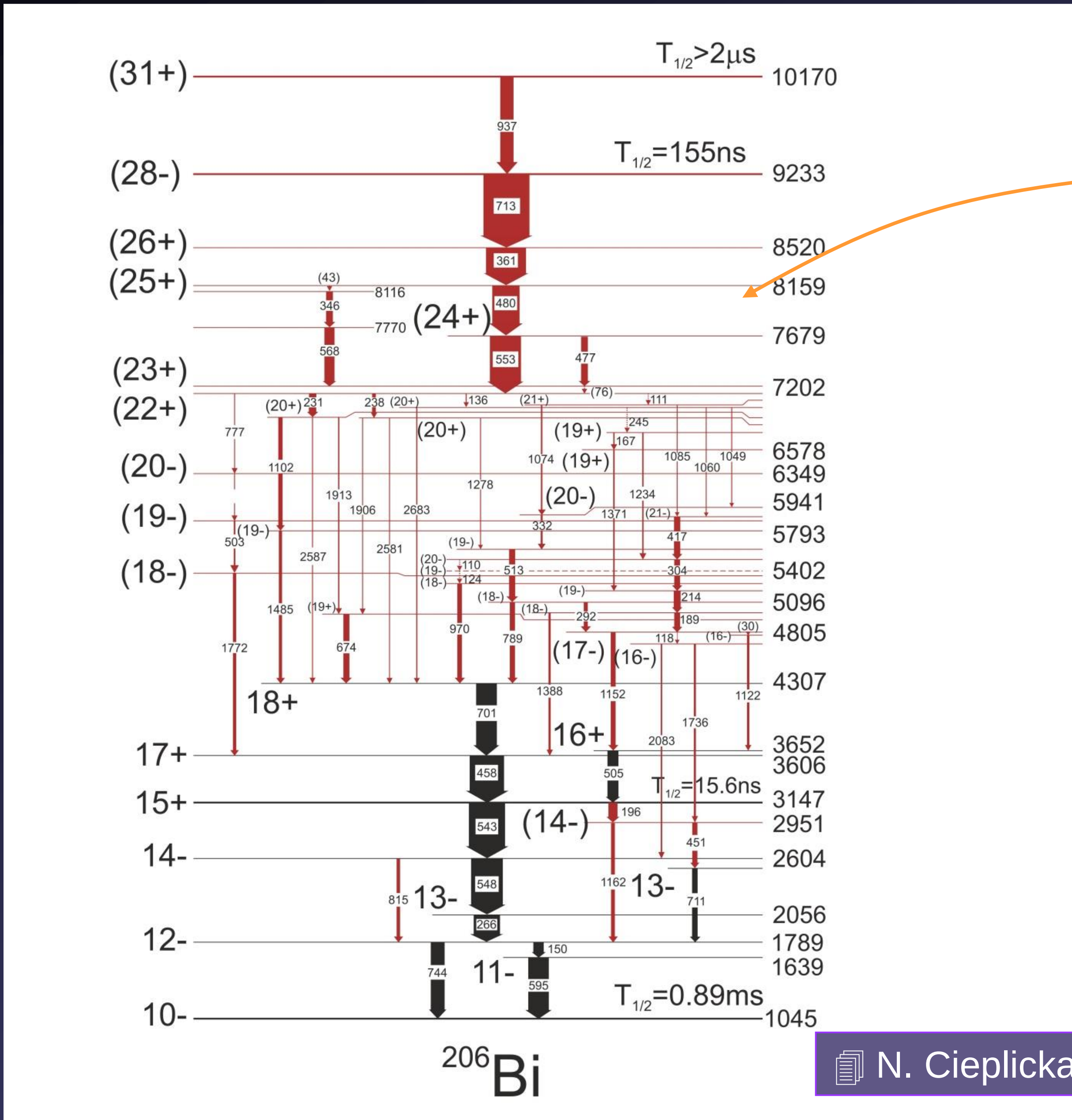
The neighborhood of doubly-magic ^{208}Pb as a laboratory for studying shell model effective nucleon-nucleon interactions

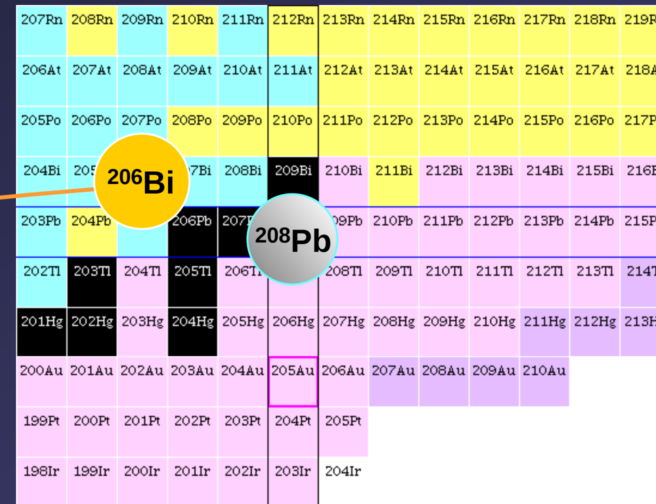


Investigations in the region of doubly-magic ^{208}Pb by employing deep-inelastic reactions and the γ–γ–γ coincidence thick-target technique



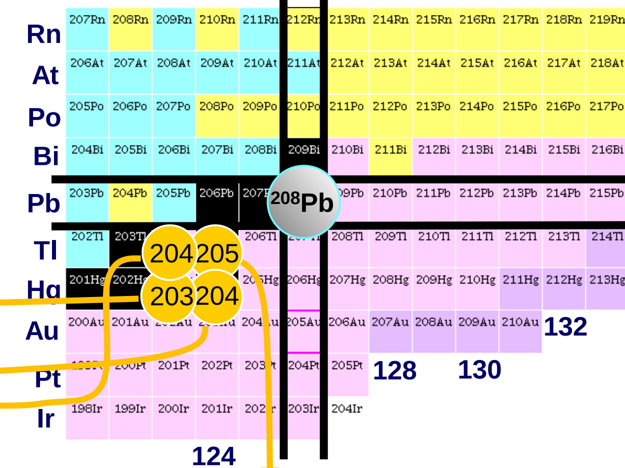
Yrast structure of ^{206}Bi studied by using the ^{76}Ge+^{208}Pb reaction and gamma-coincidence thick target technique (GAMMASPHERE at ANL).

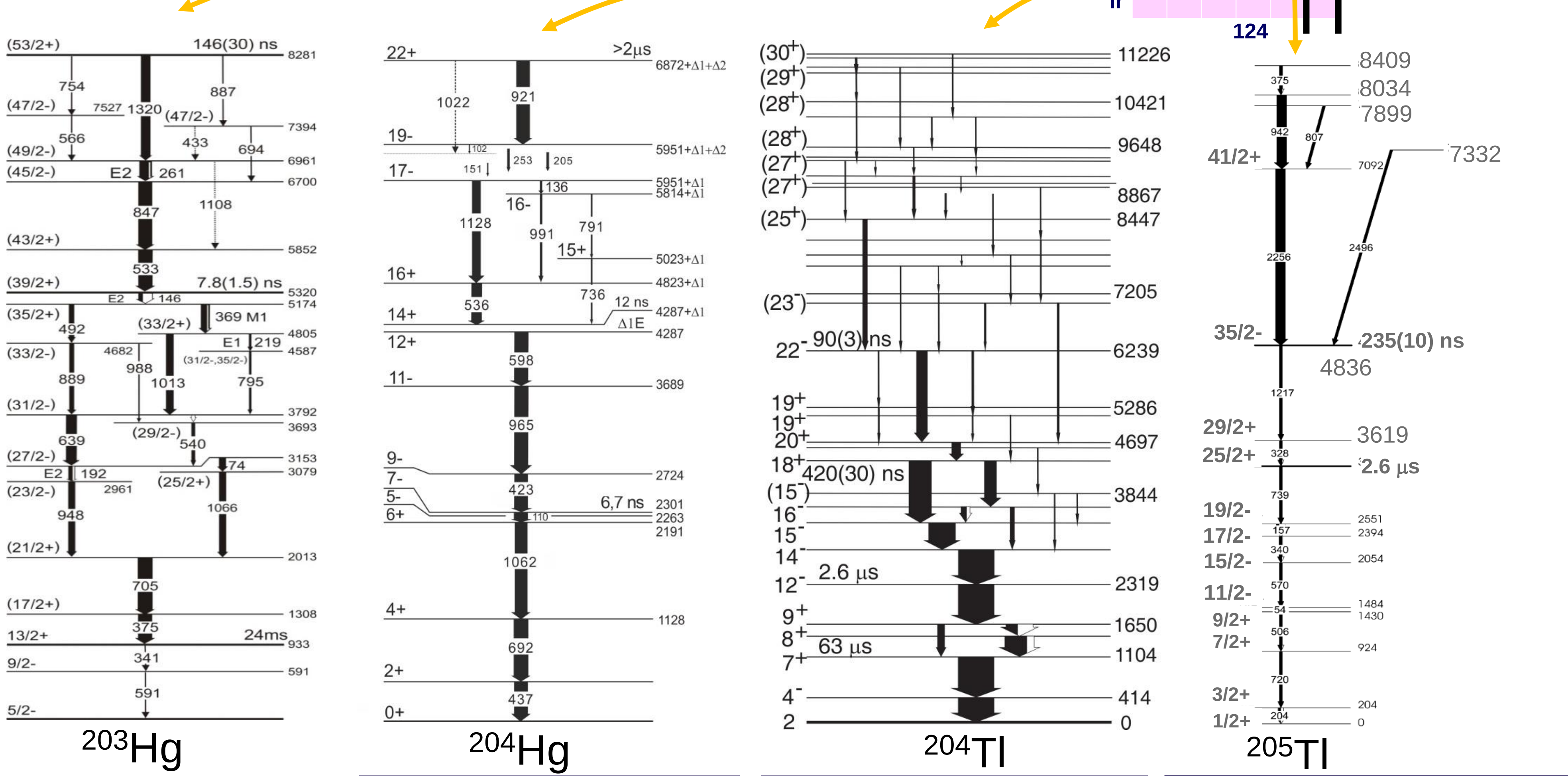




N. Cieplicka et al., PRC 86, 054322 (2012)

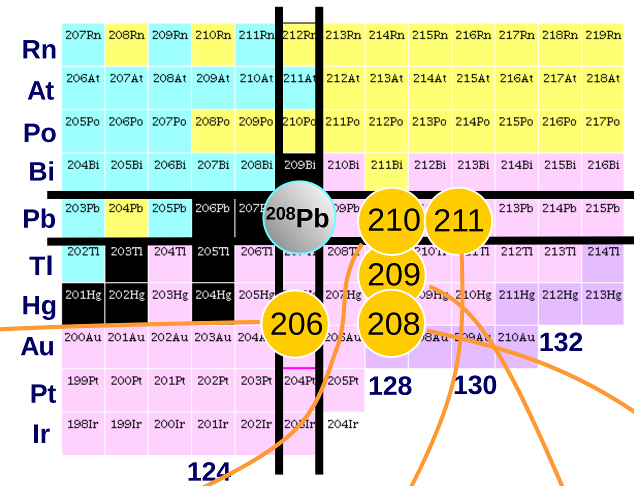
Identification of high-spin structures in nuclei located „south-west"of ^{208}Pb from the γ–γ–γ coincidence thick-target experiments

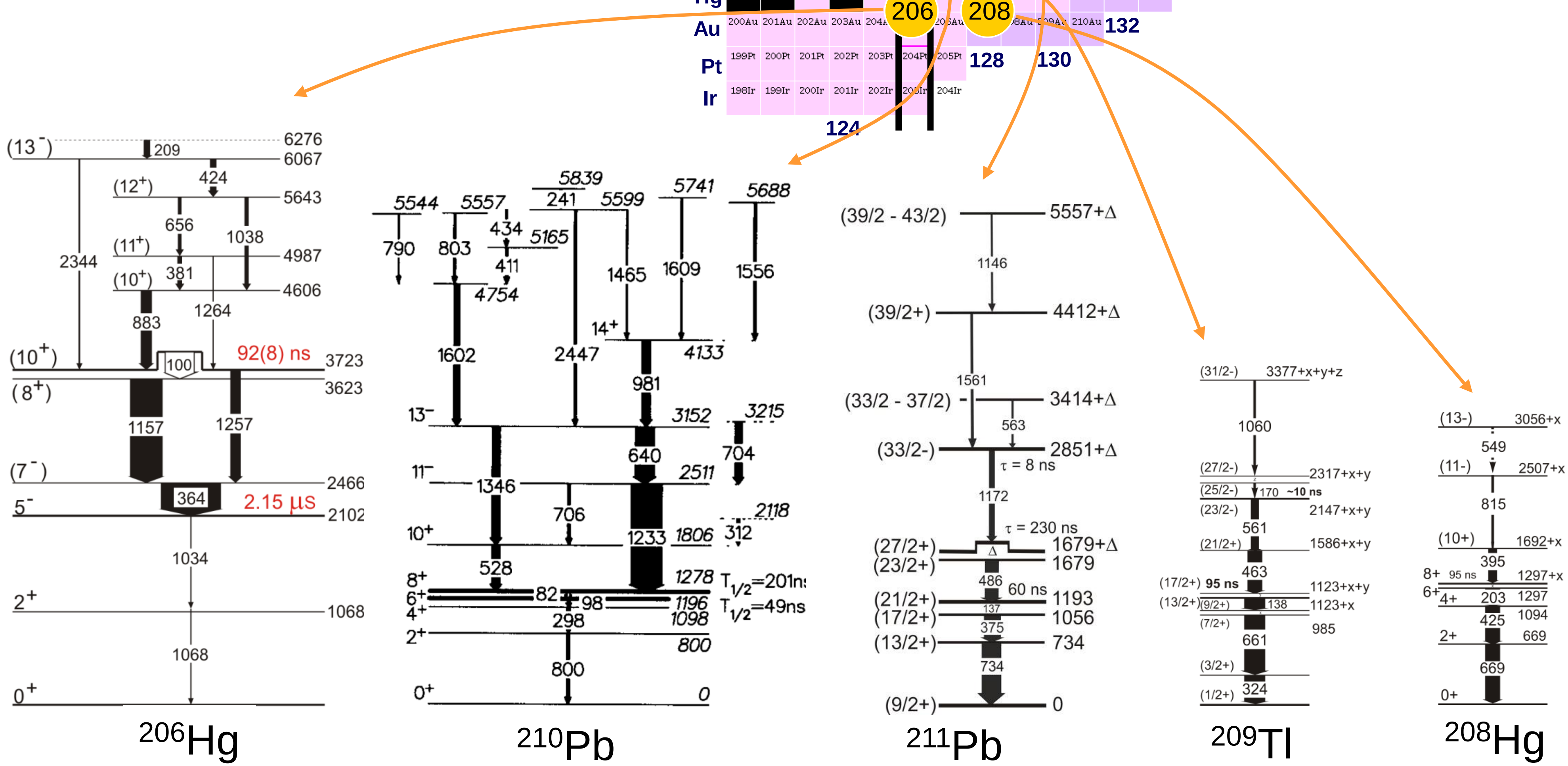




B. Szpak et al., PRC 83, 064315 (2011) | G. Lane et al., to be published | R. Broda et al., PRC 84, 014330 (2011) | J. Wrzesinski et al., Eur. Phys. J 20 (2004)

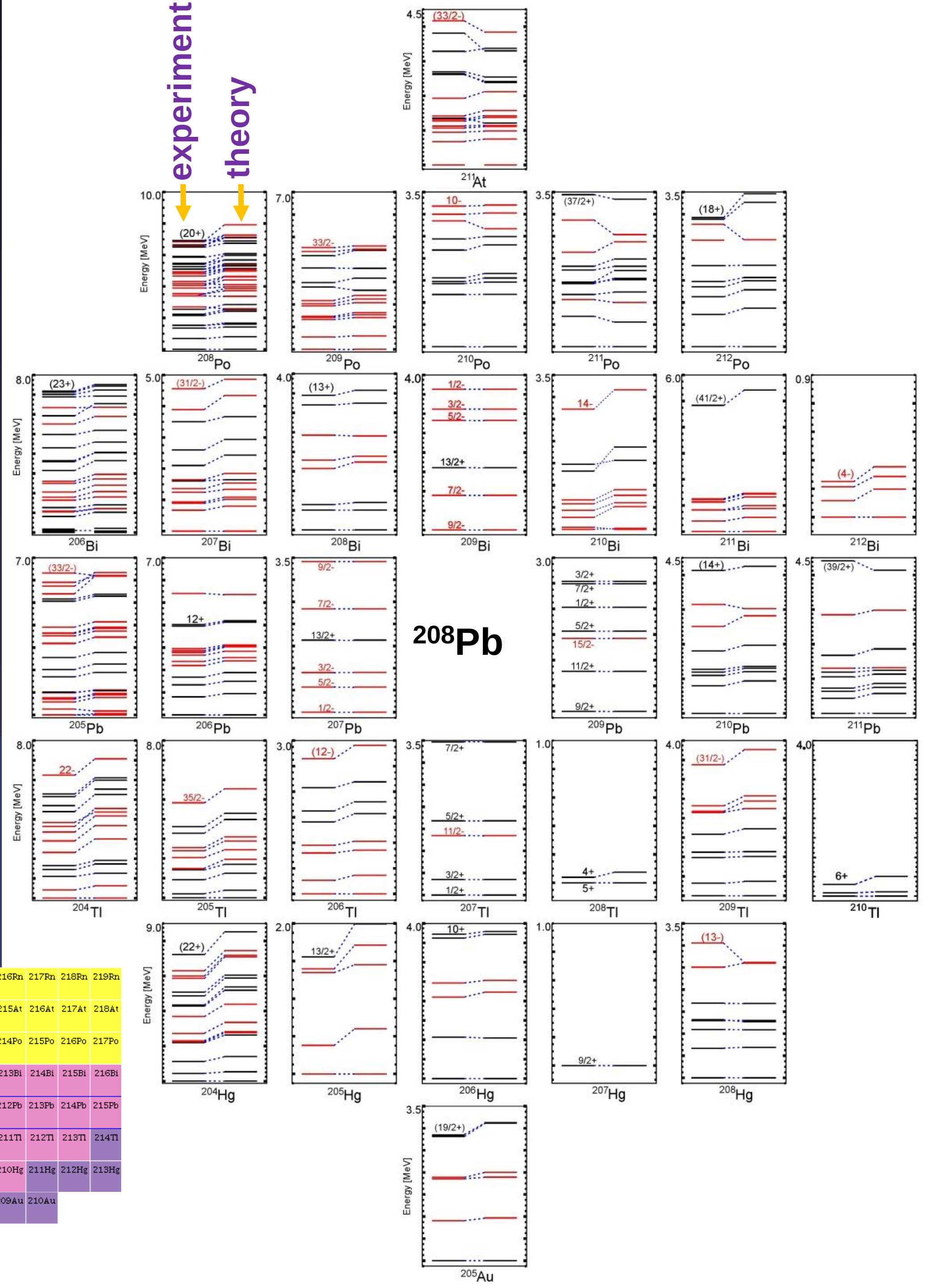
Identification of high-spin structures in nuclei located „south-east”of ^{208}Pb from the γ–γ–γ coincidence thick-target experiments (GAMMASPHERE at ANL)



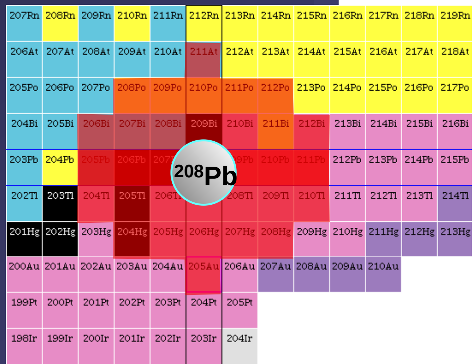


B. F. et al., Phys. Rev. Lett. 87 (2001) | G. Lane et al., Nucl. Phys. A682 (2001) | G. Lane et al., Phys. Lett. B 606 (2005) | B. F. et al., Proc. Vietri Conf. (2010)

Comparison of high-spin structures around ^{208}Pb with results of shell-model calculations using realistic, effective $V_{low\text{-}k}$ interaction

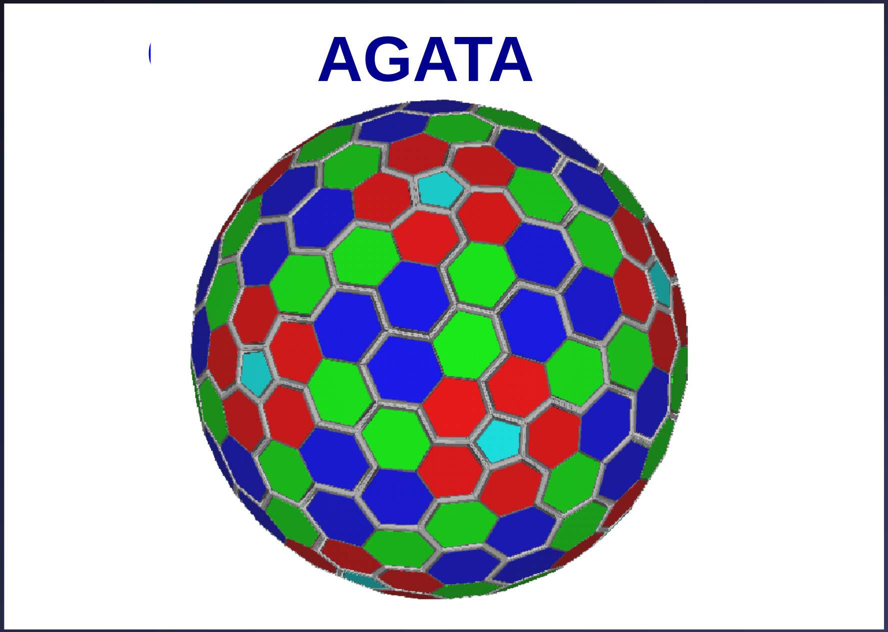


B. Szpak, R.V.F Janssens, B.F., (to be published)

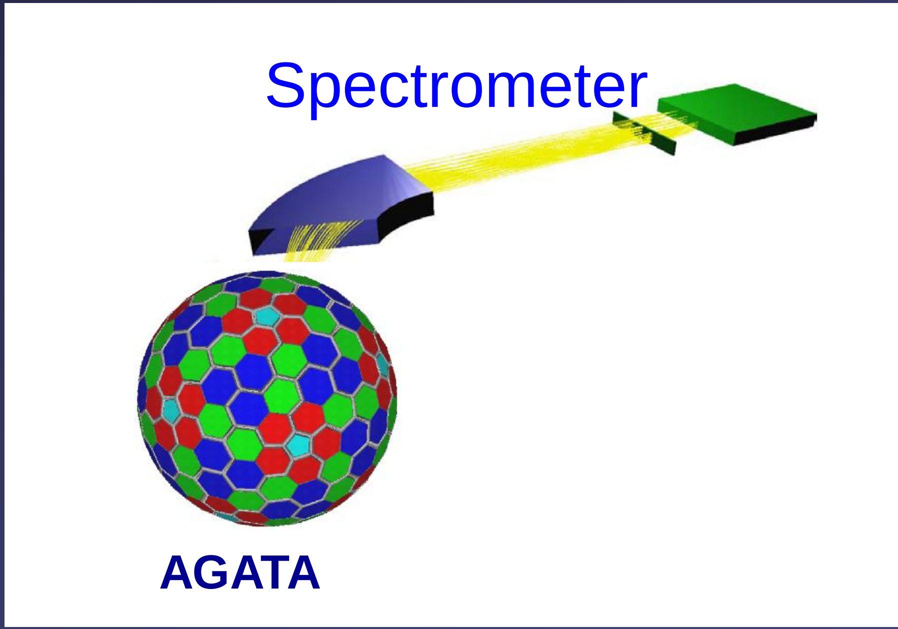


Can high-intensity heavy-ion beams be of advantage for doing prompt, discrete gamma-ray spectroscopy with deep-inelastic processes?

Standalone gamma-ray array
γ–γ–γ coincidences



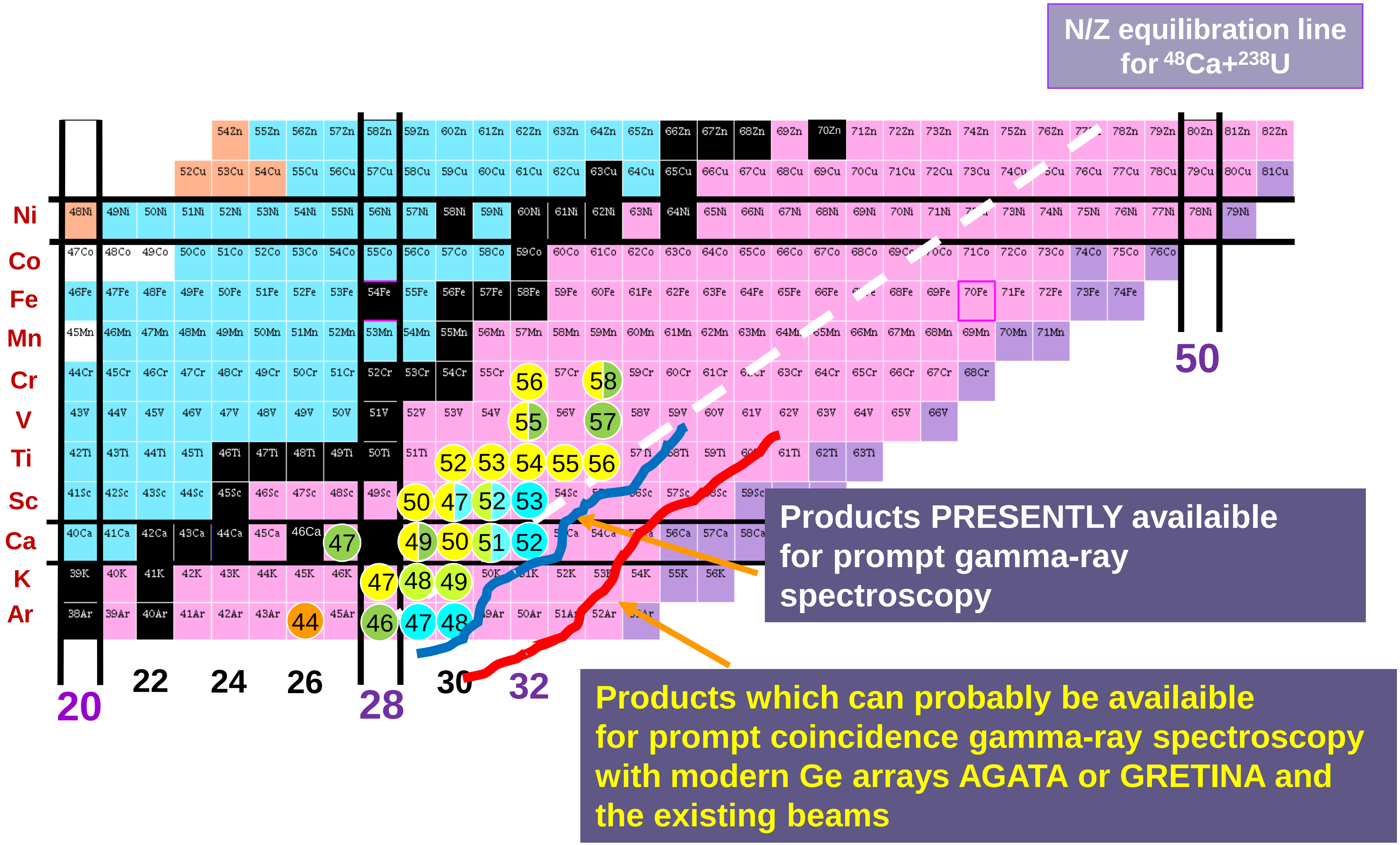
Gamma-ray array coupled to a magnetic spectrometer: γ-product coincidences



Limitation is given by the high counting rate limit of individual Ge detectors.
With digital electronics one can run with a beam current of **a few pnA.**

Limitation here is the spectrometr: can work with a beam current of **a few tens of pnA**

Products around doubly magic ^{48}Ca investigated with prompt gamma-ray spectroscopy by using deep-inelastic reactions



Can high-intensity heavy-ion beams make available even more exotic n-r species for the prompt, discrete gamma-ray spectroscopy with deep-inelastic reactions?

In 2008, a research program aimed
at prompt gamma-ray spectroscopy with S^3
was introduced by Faical Azaiez under the title:
"In-beam gamma spectroscopy of neutron-rich nuclei
studied with EXOGAM and PARIS
at the intermediate focal plane of S^3 "

The idea relies on studying prompt gamma rays in the
products of two-step deep-inelastic ractions:
secondary reaction would be induced by DI reaction
products emitted around 0 degree in the first reaction.

Let's see how it might work!

The idea of Faical Azaiez on employing „two-step DI reaction”

$^{18}O + ^{238}U$ —(primary DI reaction)→ $X + ^{238}U$ (e.g. ^{18}C) —(secondary DI reaction)→ Y (e.g.^{20}C) + U-like partner

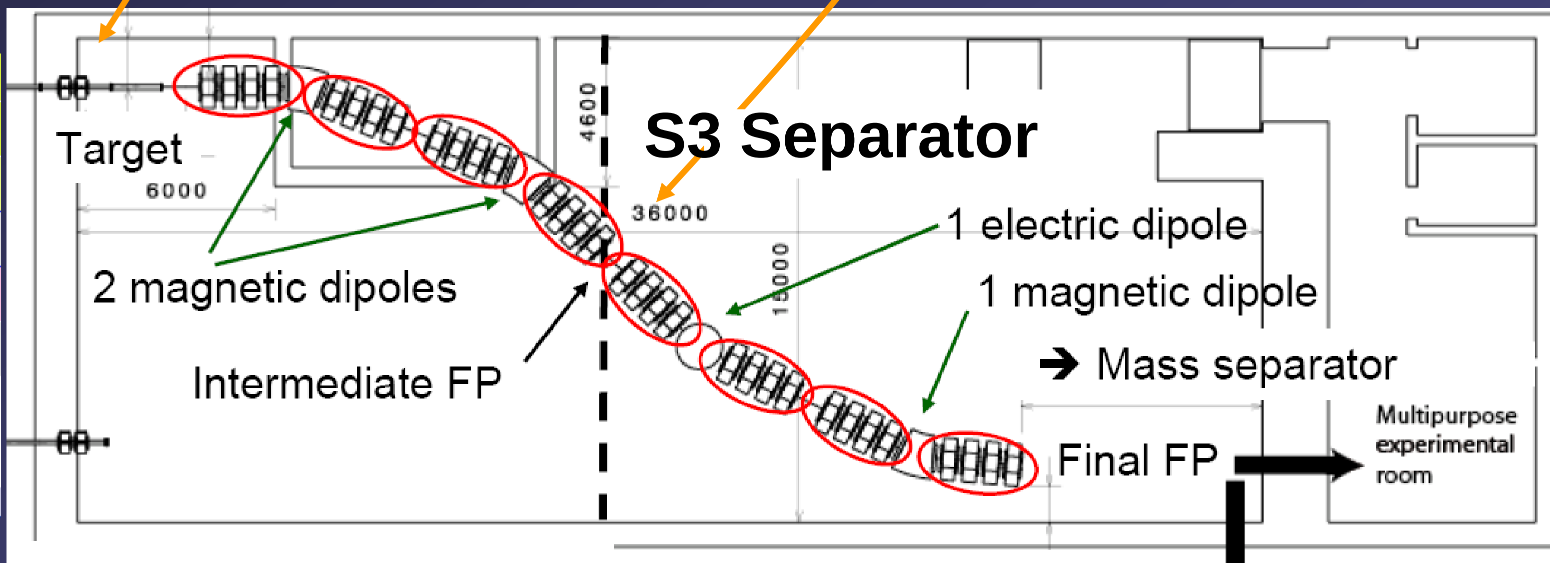
high intensity beam (~10 AMeV, ~ 30 000 pnA) from LINAC

high power rotating target

separation of deep-inelastic secondary beams

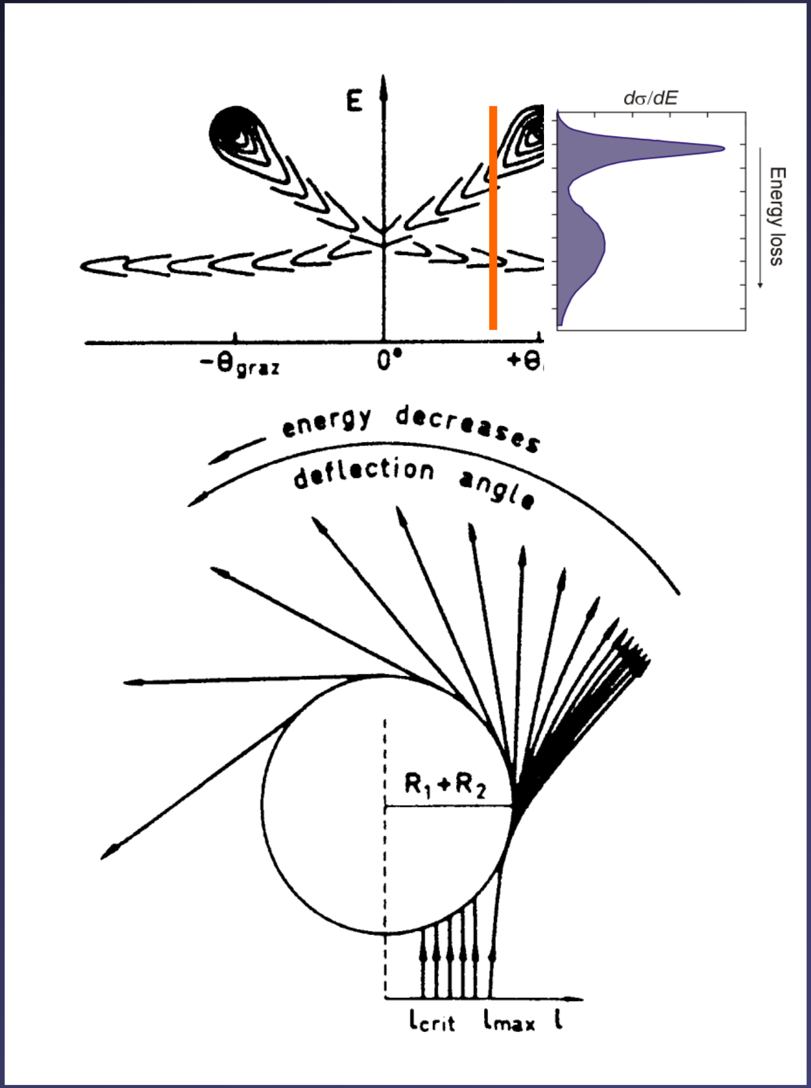
in-beam gamma spectroscopy of ^{20}C (EXOGAM, PARIS)

19Na	20Na	21Na	22Na	23Na	24Na	25Na	26Na	27Na
18Ne	19Ne	20Ne	21Ne	22Ne	23Ne	24Ne	25Ne	26Ne
17F	18F	19F	20F	21F	22F	23F	24F	25F
16O	17O	18O	19O	20O	21O	22O	23O	24O
15N	16N	17N	18N	19N	20N	21N	22N	23N
14C	15C	16C	17C	18C	19C	20C	21C	22C
13B	14B	15B	16B	17B	18B	19B	20B	21B
12Be	13Be	14Be	15Be	16Be				
8		10		12		14		16



DEEP-INELASTIC HEAVY-ION COLLISIONS

Wilczynski Plot

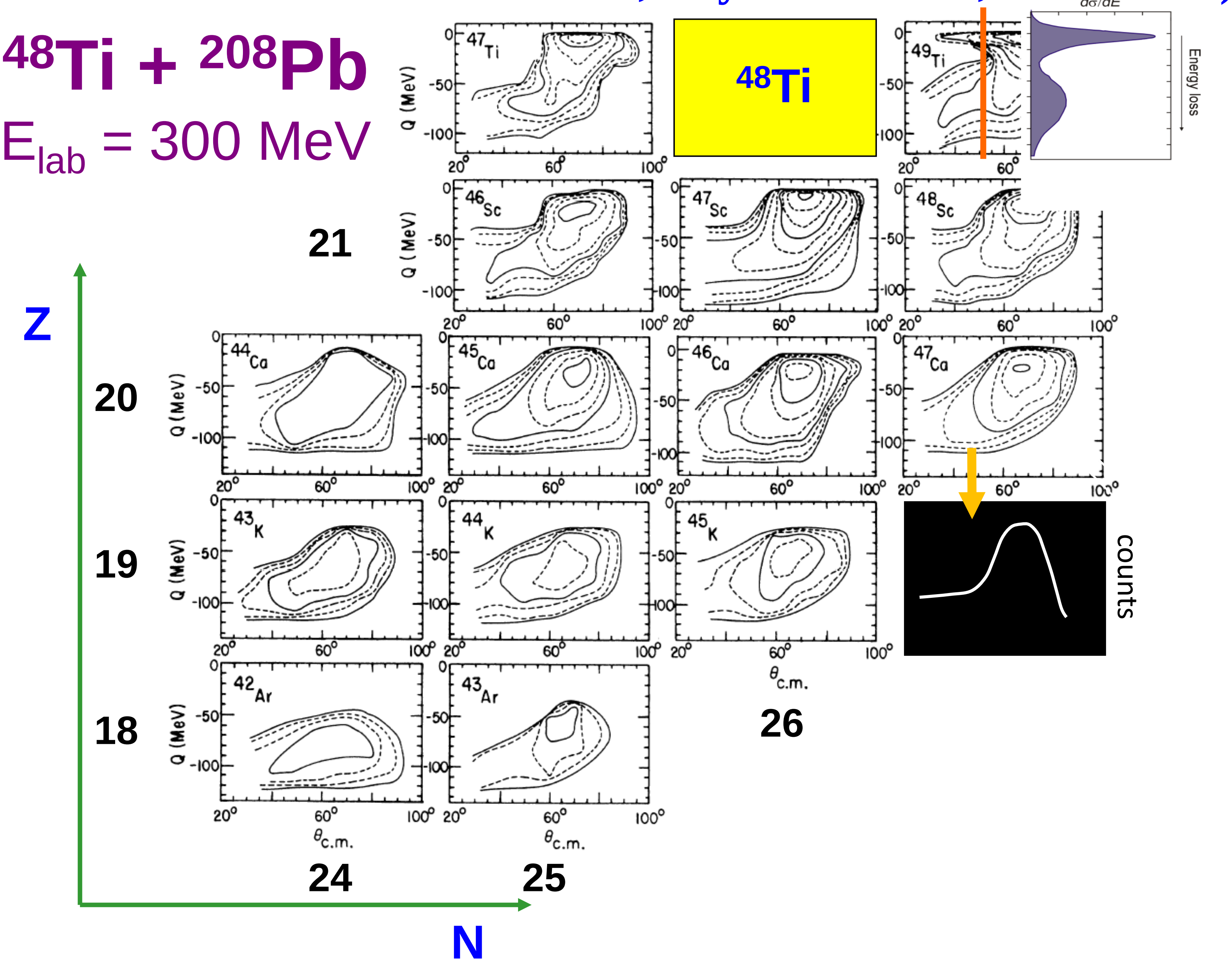


J. Wilczynski, Phys. Lett. B 47, 487 (1973)

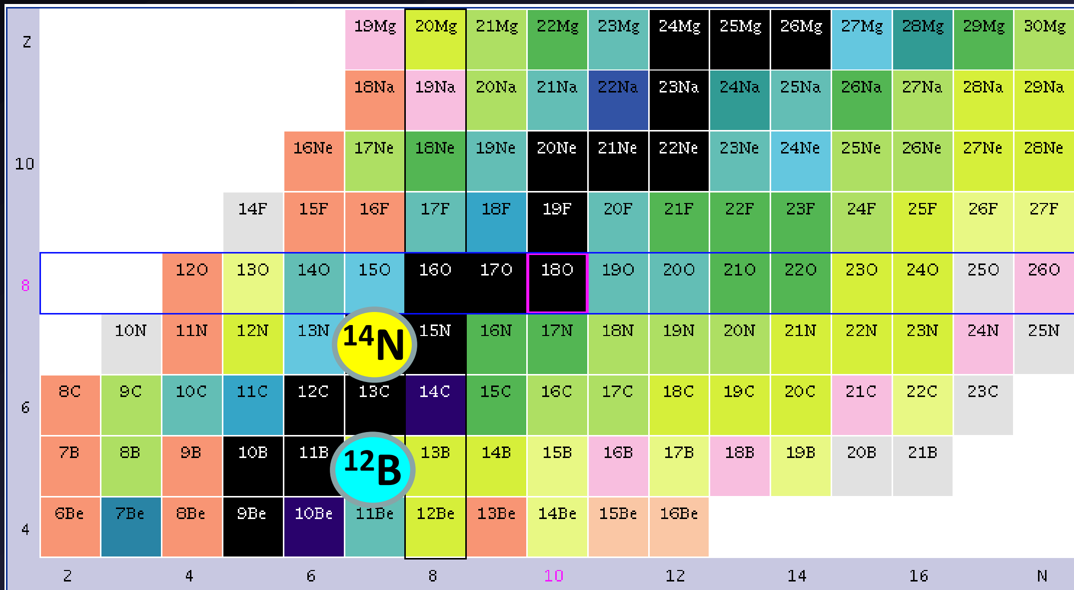
N. E. Rehm *et. al.*, Phys. Rev. C37, 2 … 8)

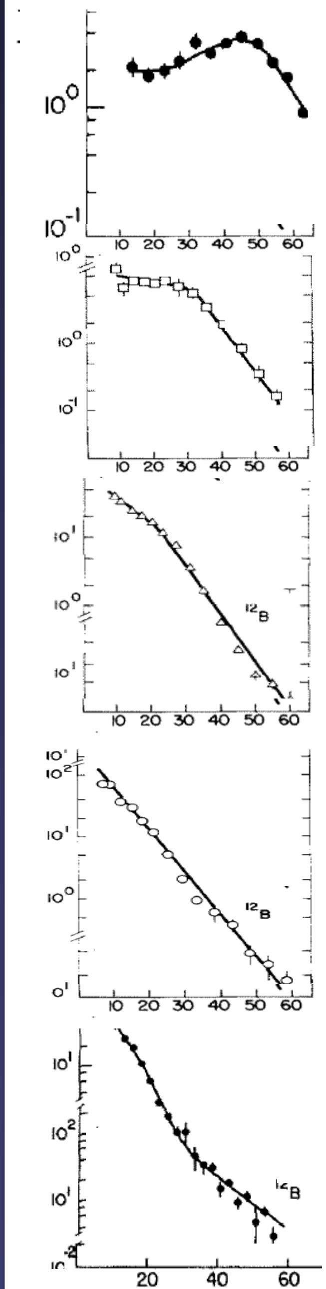
^{48}Ti + ^{208}Pb

E_{lab} = 300 MeV



Angular distributions →





^{12}B

6.6 MeV/A

8 MeV/A

10 MeV/A

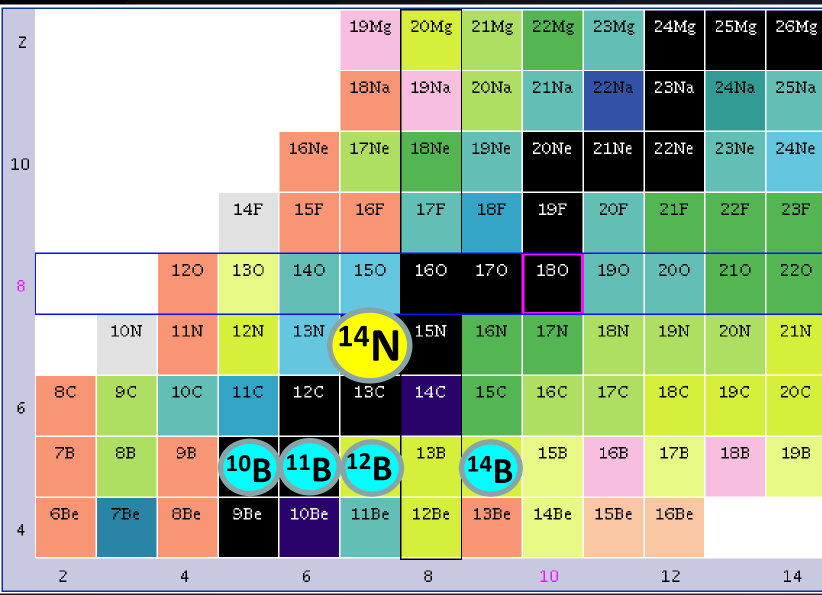
12 MeV/A

17 MeV/A

Reaction

$^{14}N + ^{159}Tb$

G.H. Balster et al., Nucl. Phys. A 468, 97 (1987)



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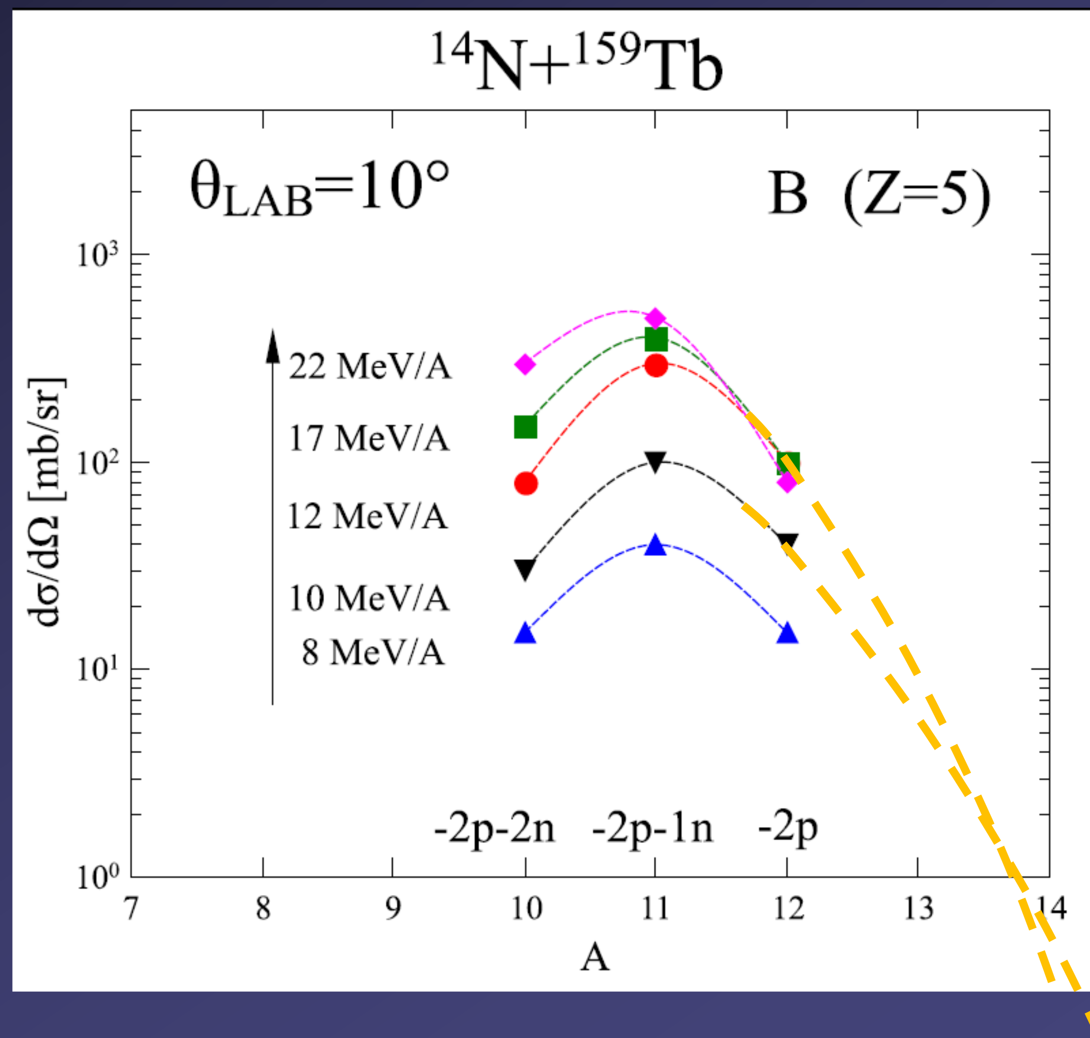
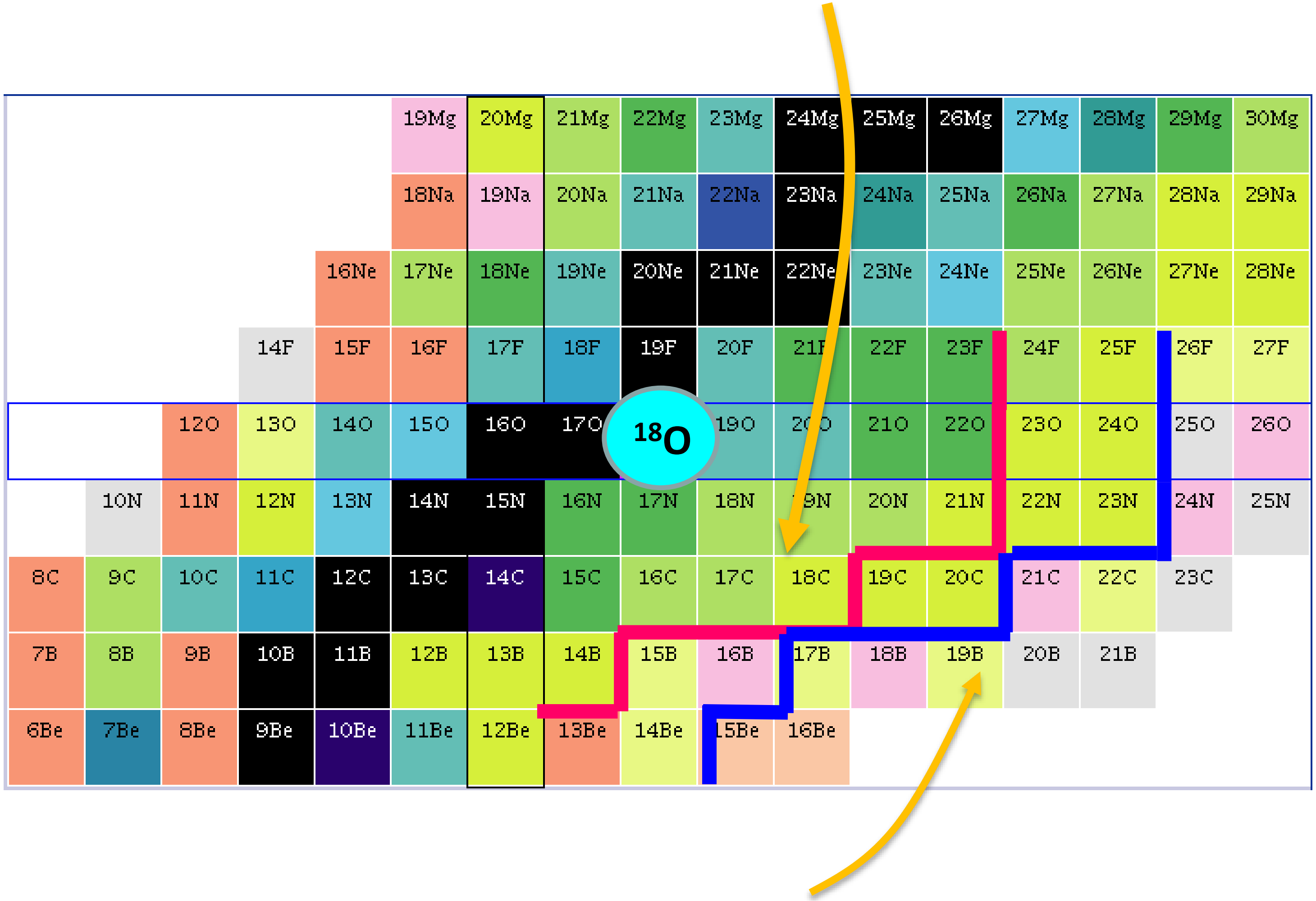


Nuclei available for in-beam discrete gamma-ray spectroscopy in single-step deep-inelastic reactions of ^{18}O on ^{238}U measured with AGATA+PARIS+VAMOS



Nuclei available for in-beam discrete gamma-ray spectroscopy in two-step deep-inelastic reactions induced by ^{18}O beam on ^{238}U targets measured with S^3+EXOGAM+PARIS

Letters of Intent for S^3

- Exploring exotic excited nuclei decay modes with correlation measurement (with two-step multinucleon transfer reactions induced by a ^{36}S beam)

  P. Marini, I. Stefan, F. Azaiez

- γ-spectroscopy of neutron-rich C, N, O and F nuclei around A=20 produced in two-step multi-nucleon transfer reactions with S^3

  B. Fornal, S. Leoni, I. Stefan, A. Maj
  for the PARIS, EXOGAM and S3 Collaborations

Conclusions and Outlook

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

- Discrete in-beam prompt gamma-ray spectroscopy of high-spin structures in products of deep-inelastic reactions might benefit from high intensity beams by applying the two-step reaction technique.

Collaborators

R. Broda, M. Ciemała, N. Cieplicka, W. Krolas,
K.H. Maier, A. Maj, T. Pawlat, B. Szpak,
J. Wrzesinski, B. F. — *IFJ PAN Krakow, Poland*

R.V.F. Janssens, S. Zhu, M.P. Carpenter,
D. Seweryniak et al. — *ANL Argonne, USA*

D. Bazzacco, L. Corradi, G. de Angelis, E. Farnea,
A. Gadea, S. Lenzi, S.Lunardi, N. Marginean,
R. Menegazzo, G. Montagnoli, F. Recchia, C. Rossi-Alvarez, A. Stefanini, S. Szilner,, J. J. Valiente-Dobon, C. Ur et al. — *GASP and PRISMA-CLARA group, Legnaro-Padova*

G. Dracoulis , G. Lane et al. — *ANU Canberra, Australia*

Z. Podolyak, E. Wilson, P.H. Regan, P. Walker et al., — *University of Surrey, UK*

S. Leoni et al., — *Univ. of Milano and Sez. INFN, Italy*

F. Azaiez, I. Stefan et al., — *IPN Orsay, France*

A quote from Maria Sklodowska-Curie:

A scientist in his laboratory is also a child confronting natural phenomena that impress him as though they were fairy tales.

Maria Skłodowska-Curie
1867-1934
Nobel Prizes:
1903 – physics
1911 – chemistry