Probing T=0 proton-neutron pairing in the super-collective Z~60 and A~130 region

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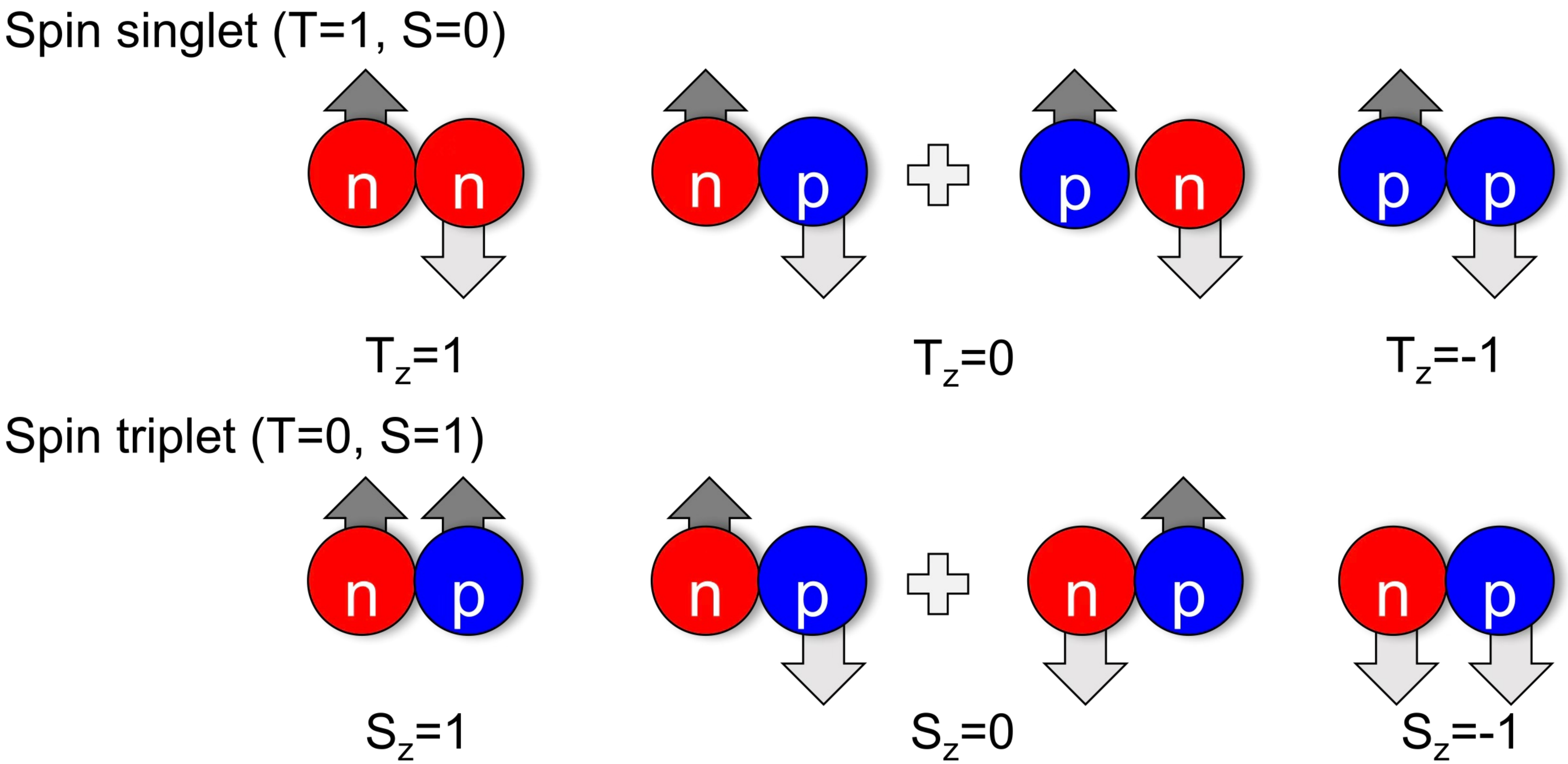
GRIT-AGATA-VAMOS Workshop, GANIL, 11-13/06/2025

Few words about proton-neutron pairing

- According to **Fermi statistics**, for two nucleons in the same spatial orbital, **T (isospin) + S (spin) = 1**



- We should be able to observe experimentally T=0 (n-p) and T=1 (n-n/n-p/p-p) pairing

Few words about proton-neutron pairing

➤ The existence of the deuteron implies spin-triplet pairing stronger than spin-singlet

➤ So why is spin-singlet pairing the most commonly observed across the nuclear chart?
➥ Because protons and neutrons usually occupy different shells.

➤ Can such a pairing phase be accessed experimentally in heavier N≈Z nuclei?

Few words about proton-neutron pairing

➤ Hints on p-n pairing effect in N=Z nuclei: **The binding energy anomaly in N=Z nuclei**

$$\Delta^2 B(Z,N) = -\frac{1}{4}[B(Z,N) - B(Z-2,N) - B(Z,N-2) + B(Z-2,N-2)]$$

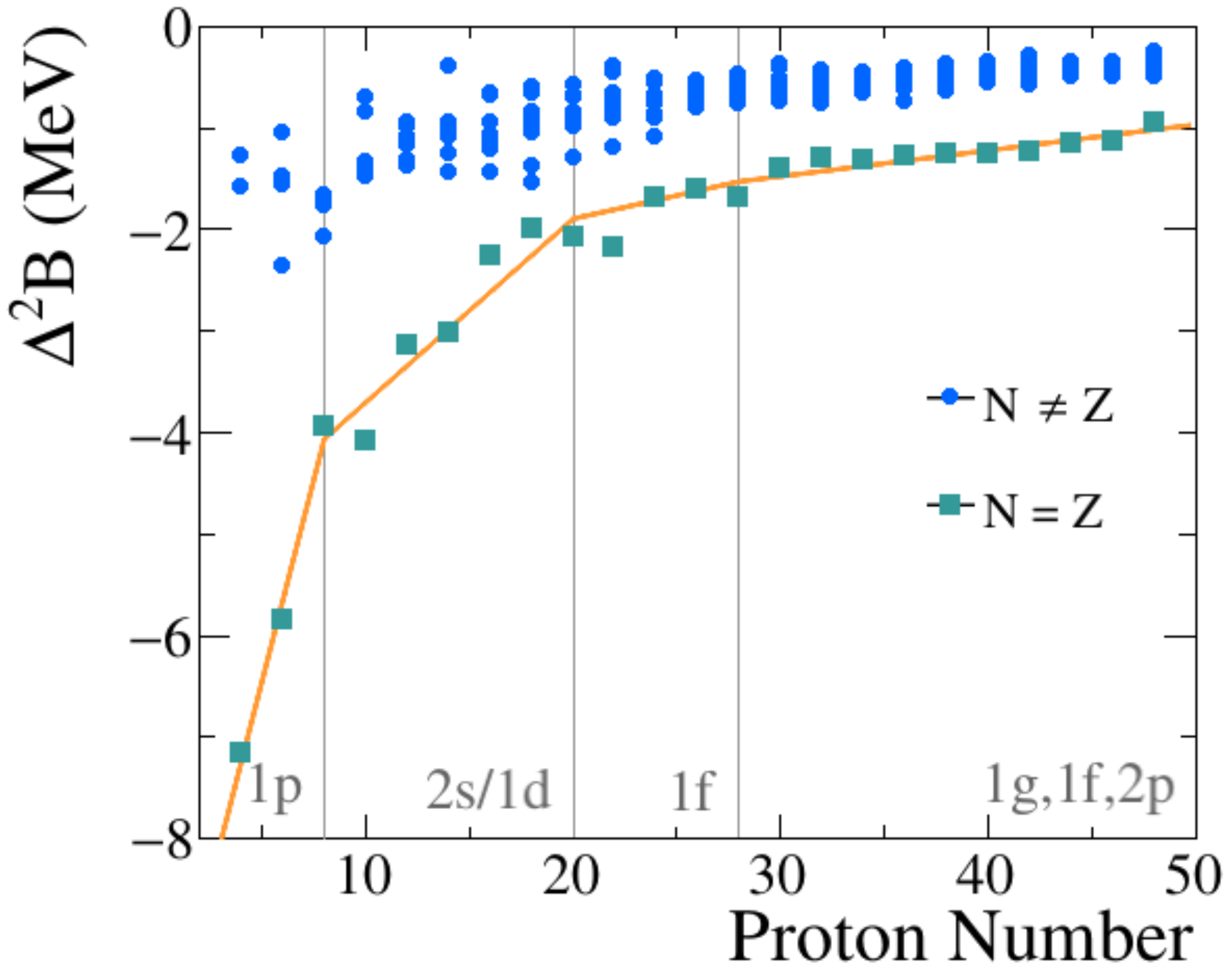


Figure from H. Jacob, data from ENSDF, produced with TkN.

➤ **N=Z nuclei systematically show an enhanced correlation energy**

Few words about proton-neutron pairing

N·H
ELSEVIER

2 July 1998

Physics Letters B 430 (1998) 203–208

PHYSICS LETTERS B

Pairing and the structure of the *pf*-shell $N \sim Z$ nuclei

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Editor: J.-P. Blaizot

➤ It has been suggested that the spin-orbit interaction suppresses spin-triplet pairing.

Spin-triplet pairing condensate in the rare-earth region

PHYSICAL REVIEW C **81**, 064320 (2010)

Spin-triplet pairing in large nuclei

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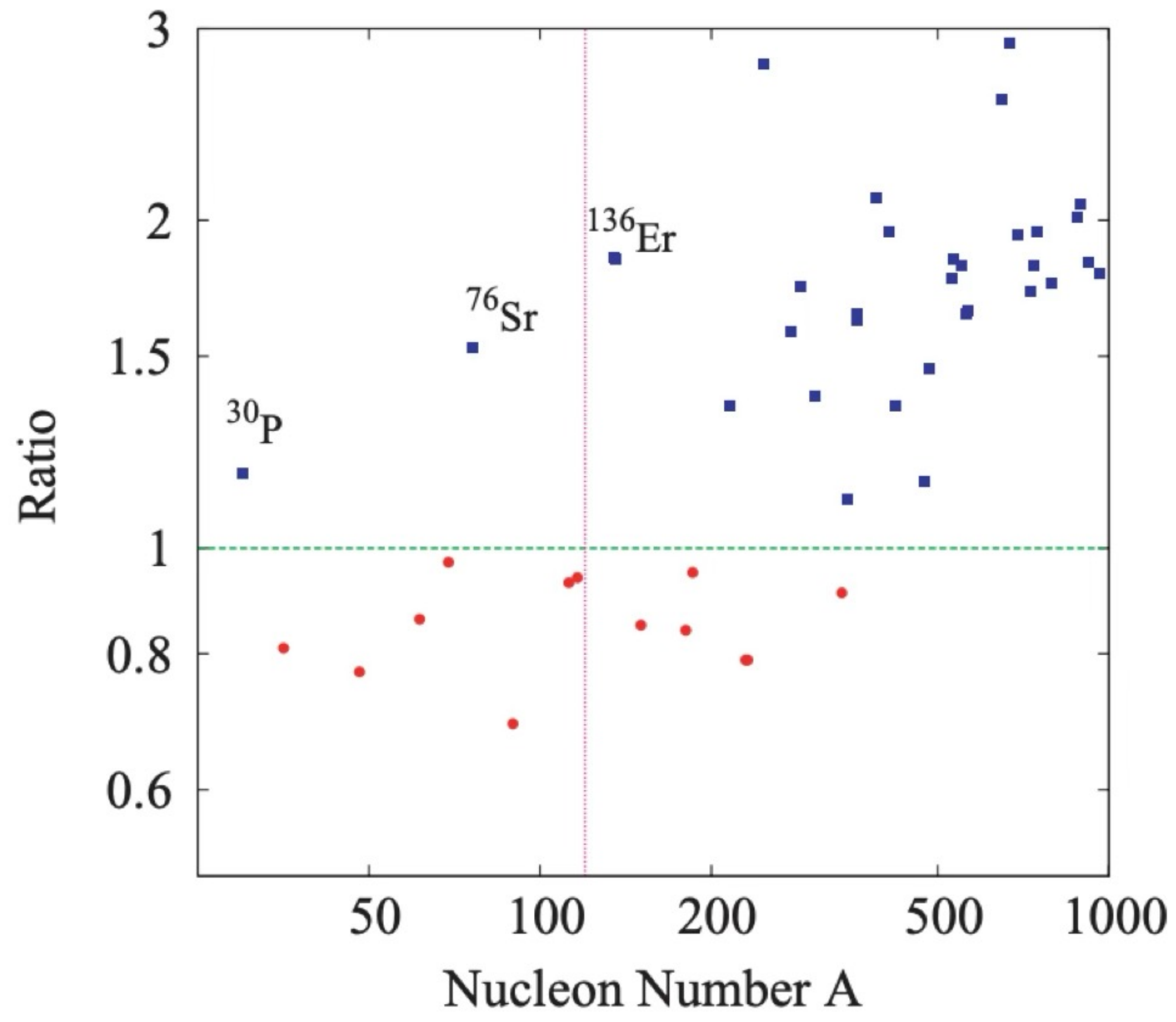
(Received 4 January 2010; published 23 June 2010)



- ➤ The spin-orbit field has a surface effect:
  - ➥ T=0 pairing will dominate when the surface-to-volume ratio is low

➥ **The lightest nuclei expected to host a well-developed spin-triplet condensate are for A ≈ 130–140.**

Spin-triplet pairing condensate in the rare-earth region

PRL **106,** 252502 (2011) PHYSICAL REVIEW LETTERS week ending 24 JUNE 2011

Mixed-Spin Pairing Condensates in Heavy Nuclei

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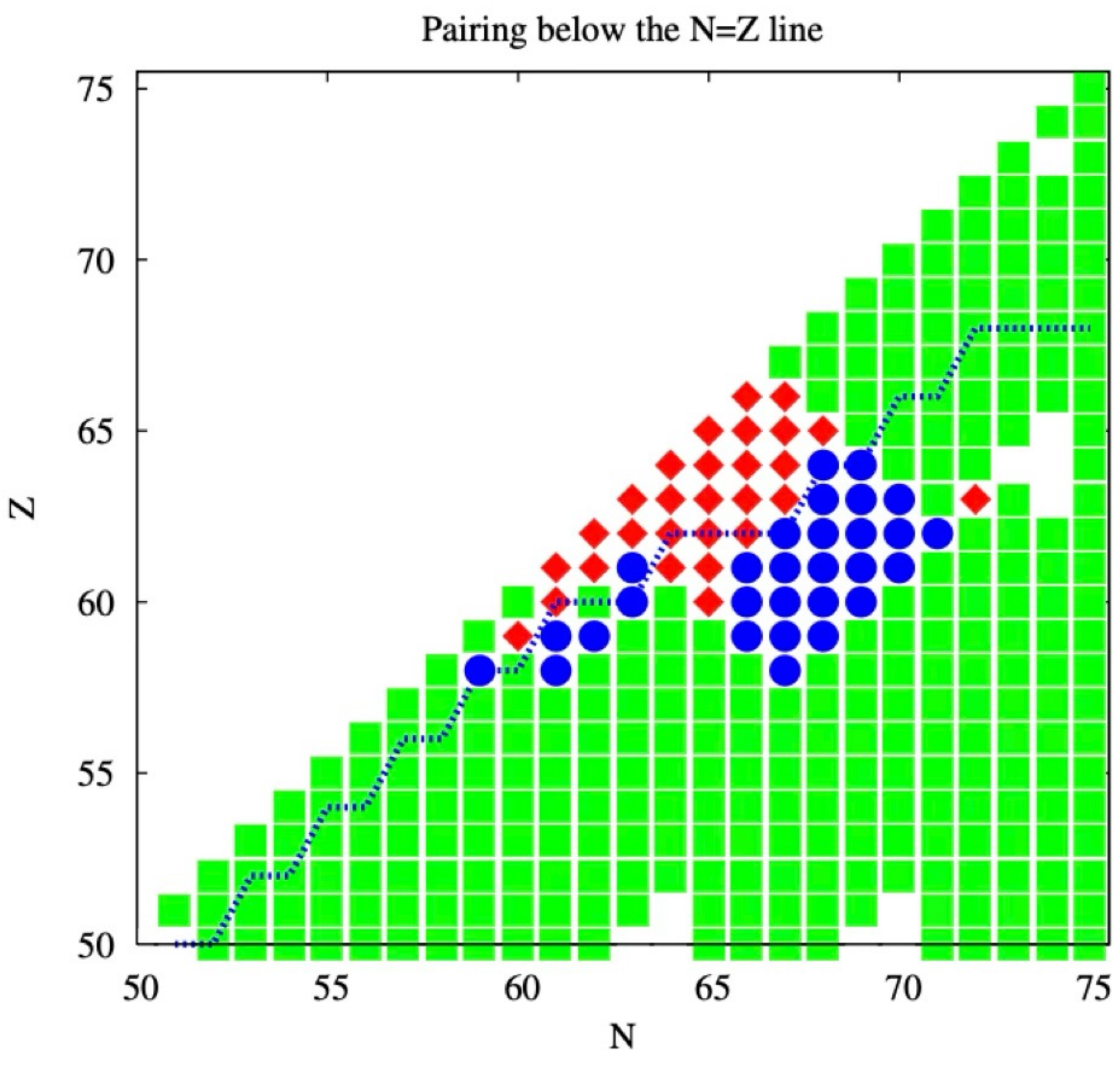
(Received 31 March 2011; published 23 June 2011)

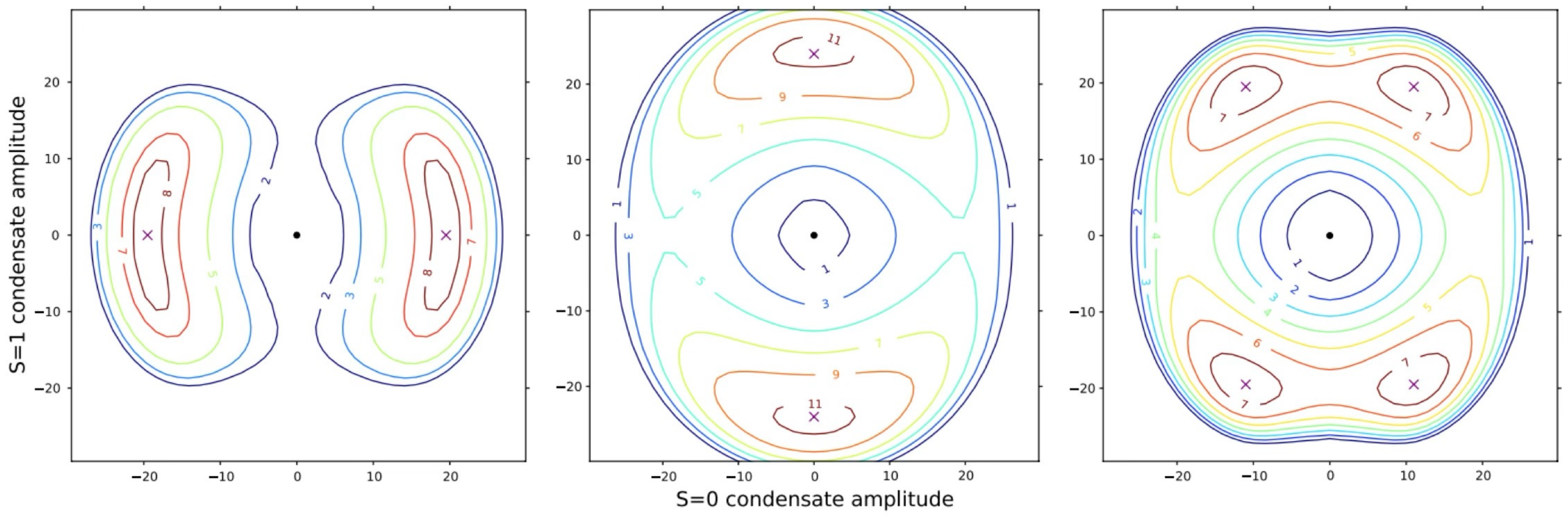


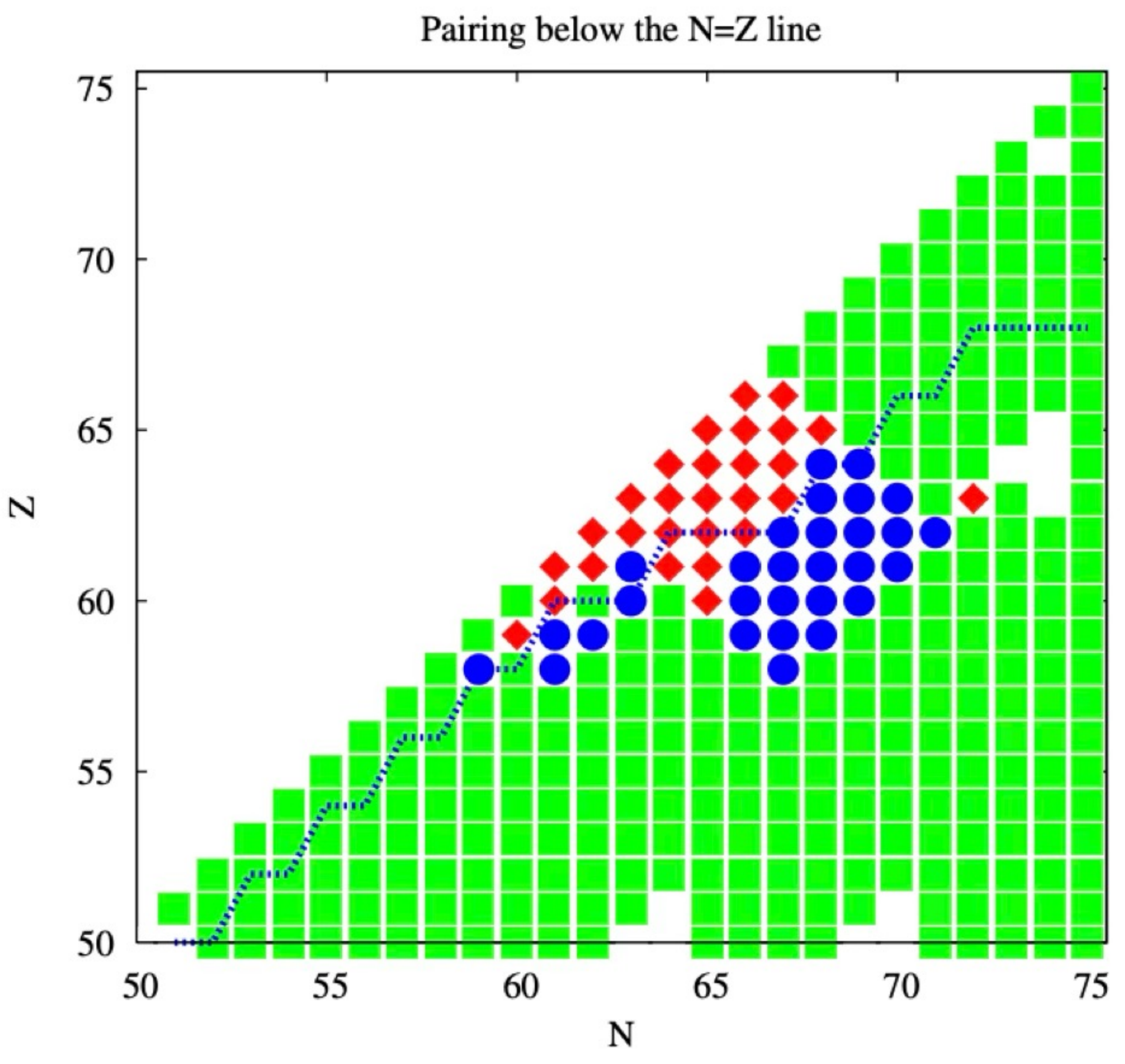
➤ Confirmation of an island of T=0 pairing nuclei, experimentally accessible

➡ **The evolution from triplet to singlet pairing may proceed through a mixed-spin condensate configuration.**

Spin-triplet pairing condensate in the rare-earth region

^{132}Nd: spin-singlet | ^{132}Dy: spin-triplet | ^{132}Gd: mixed-spin





➤ Confirmation of an island of T=0 pairing nuclei, experimentally accessible

➥ **The evolution from triplet to singlet pairing may proceed through a mixed-spin condensate configuration.**

Spin-triplet pairing condensate in the rare-earth region

PHYSICAL REVIEW LETTERS **134,** 032501 (2025)

Spin-Triplet Pairing in Heavy Nuclei Is Stable against Deformation

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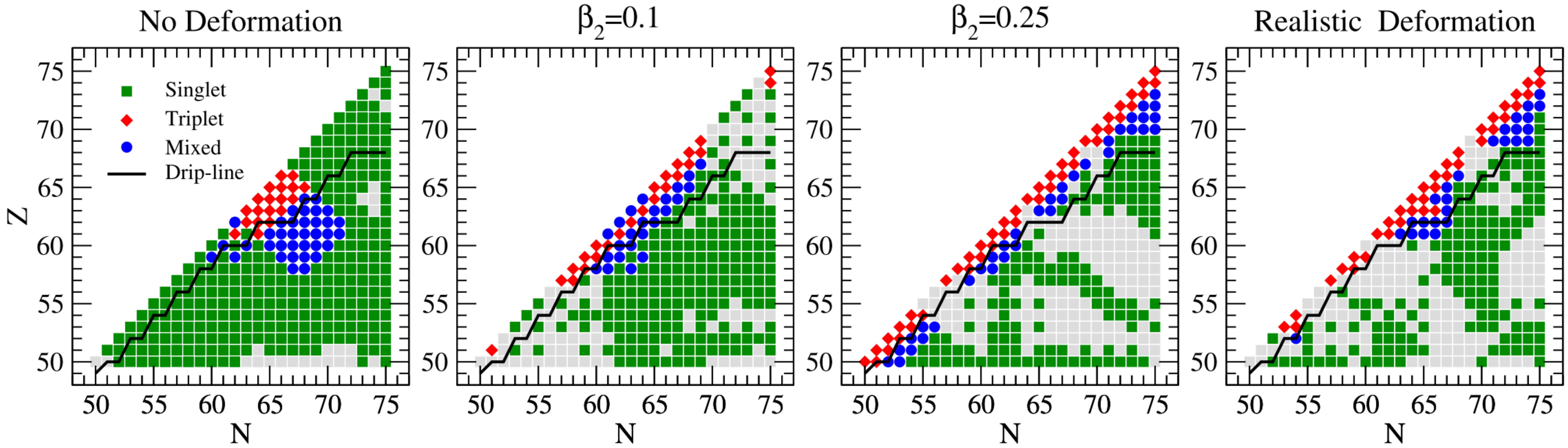
(Received 22 February 2024; accepted 4 December 2024; published 23 January 2025)

➤ Very recent studies introduce for the first time deformation in the spin-triplet pairing predictions

➡ **Deformation reduces p-n correlations, but more spin-singlet than spin-triplet**
➡ **Spin-triplet superfluidity still exists below the proton drip line**

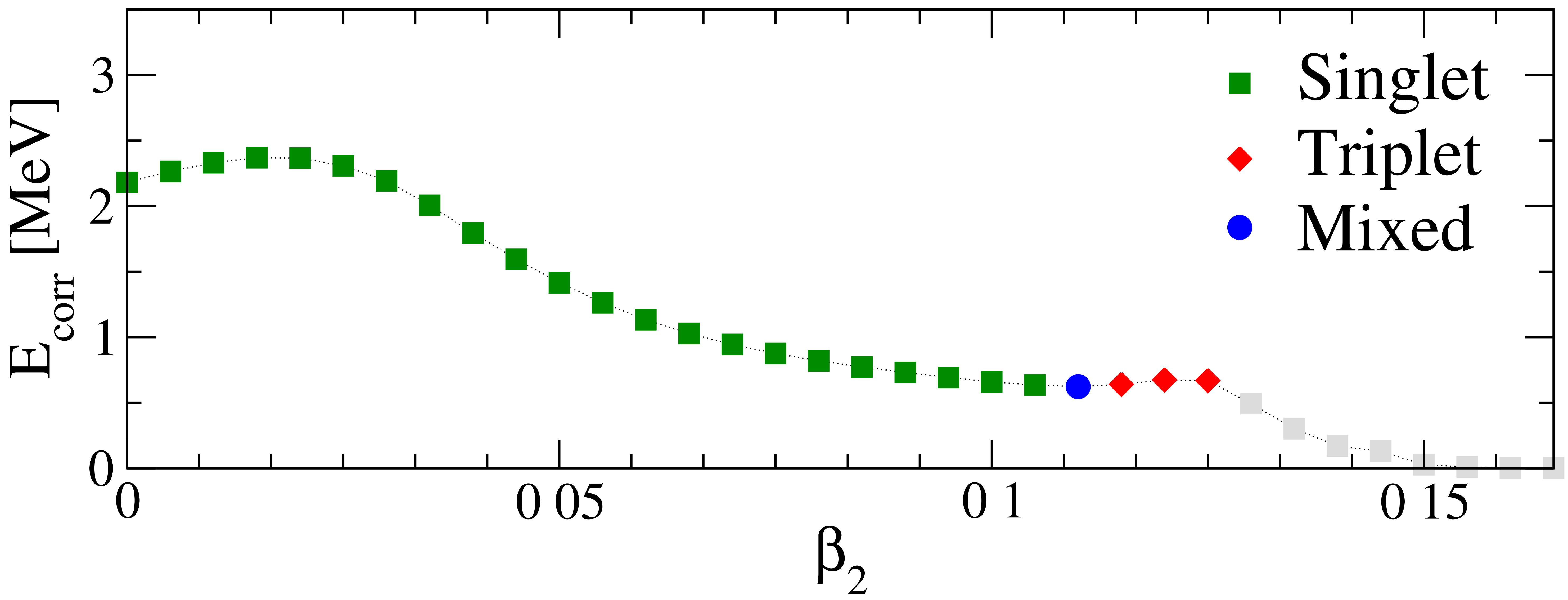
Spin-triplet pairing condensate in the rare-earth region



- ➤ Very recent studies introduce for the first time deformation in the spin-triplet pairing predictions
  - ➥ **Deformation is found to reduce p-n correlations, especially for spin-singlet pairing**

Spin-triplet pairing condensate in the rare-earth region

^{108}Xe correlation energy as a function of quadrupole deformation



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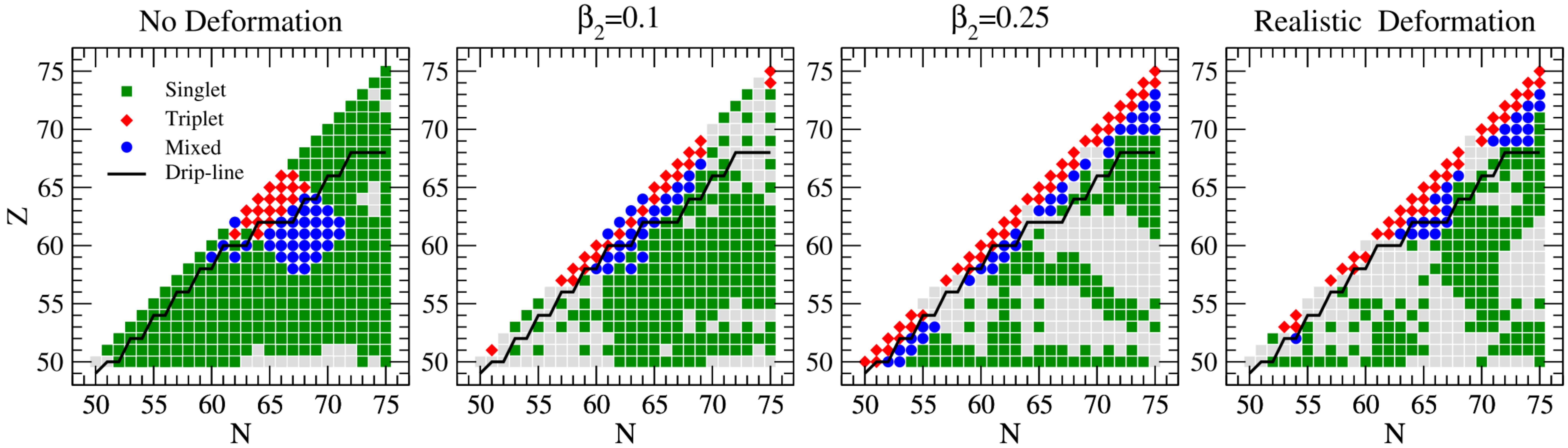
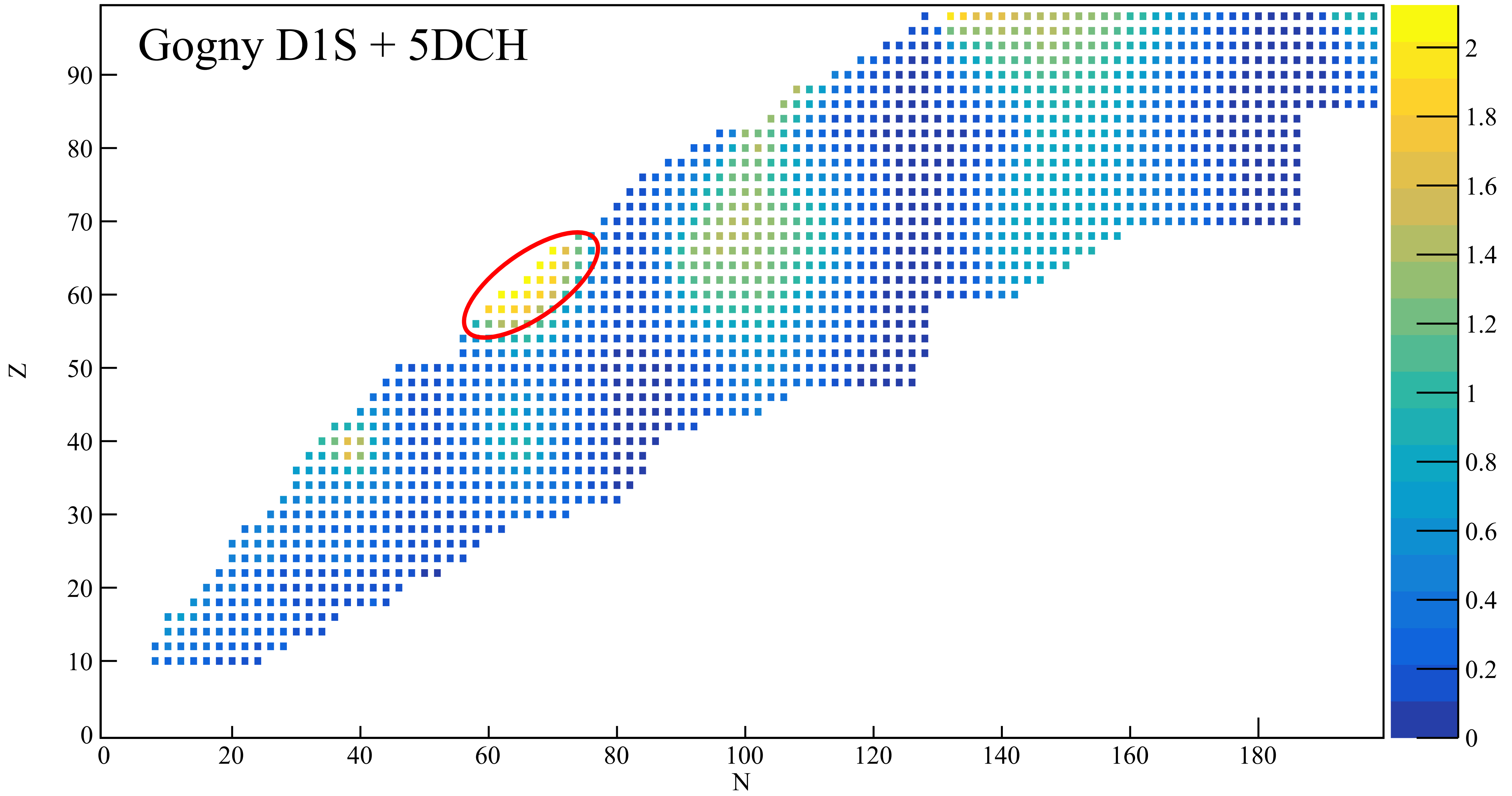
Spin-triplet pairing condensate in the rare-earth region



- Very recent studies introduce for the first time deformation in the spin-triplet pairing predictions
  - ➡ **Deformation is found to reduce p-n correlations, especially for spin-singlet pairing**
  - ➡ **Spin-triplet superfluidity still exists below the proton drip line, for $^{125, 126, 127}$Pm**

What about deformation in this region

- ➤ **B(E2): $2^+ \rightarrow 0^+$:** mostly used indicator of collectivity
- ➥ **Weisskopf unit:** rough estimate of the number of nucleons involved in the transition based on a single-particle transition model.

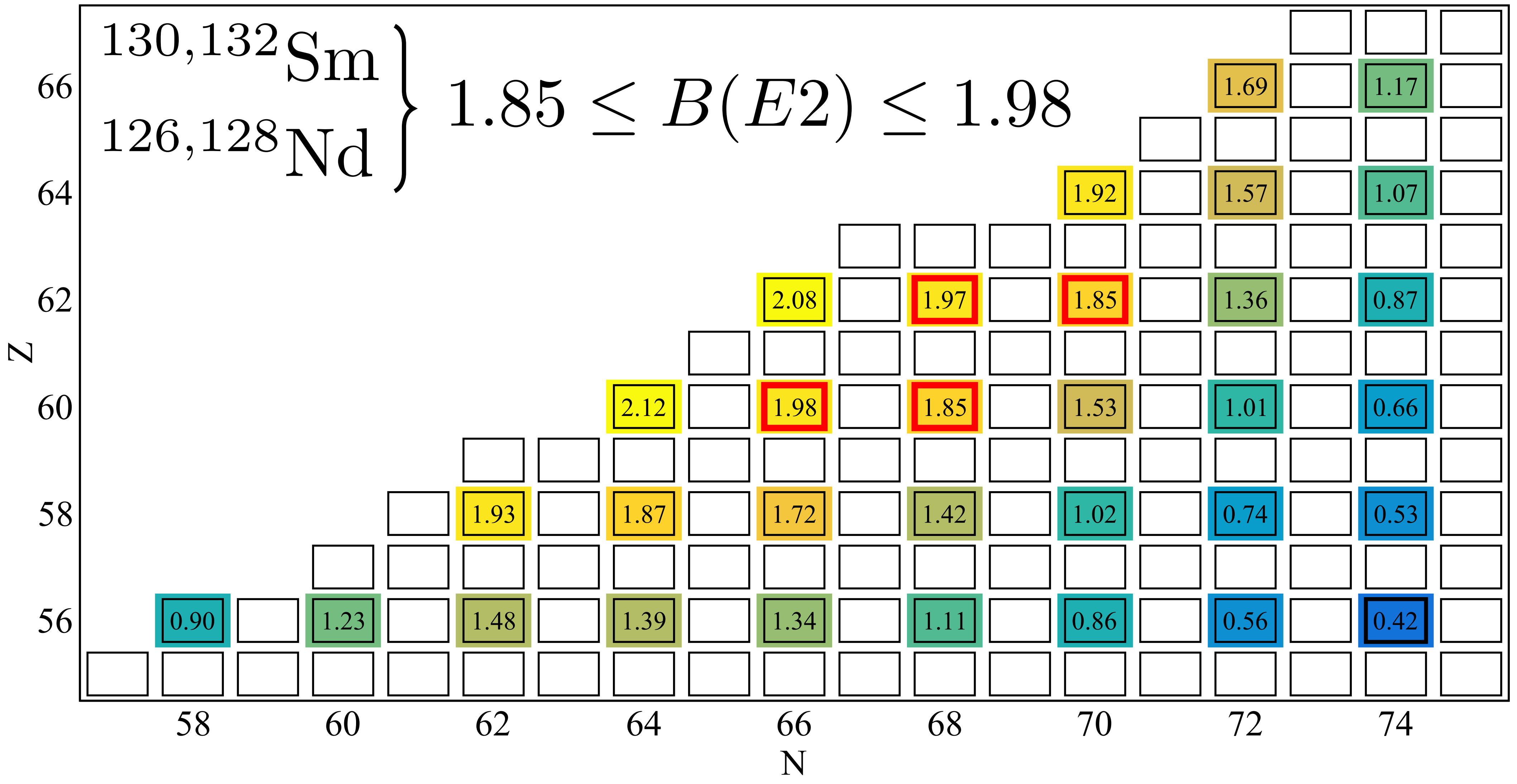


- ➤ The rare-earth region is predicted to be the place of the highest collective modes of the nuclear chart in the ground state configuration with values up to **B(E2)/A ~ 2 W.u**
- ➥ **single-particle model not valid → fully collective motion of the nucleons**

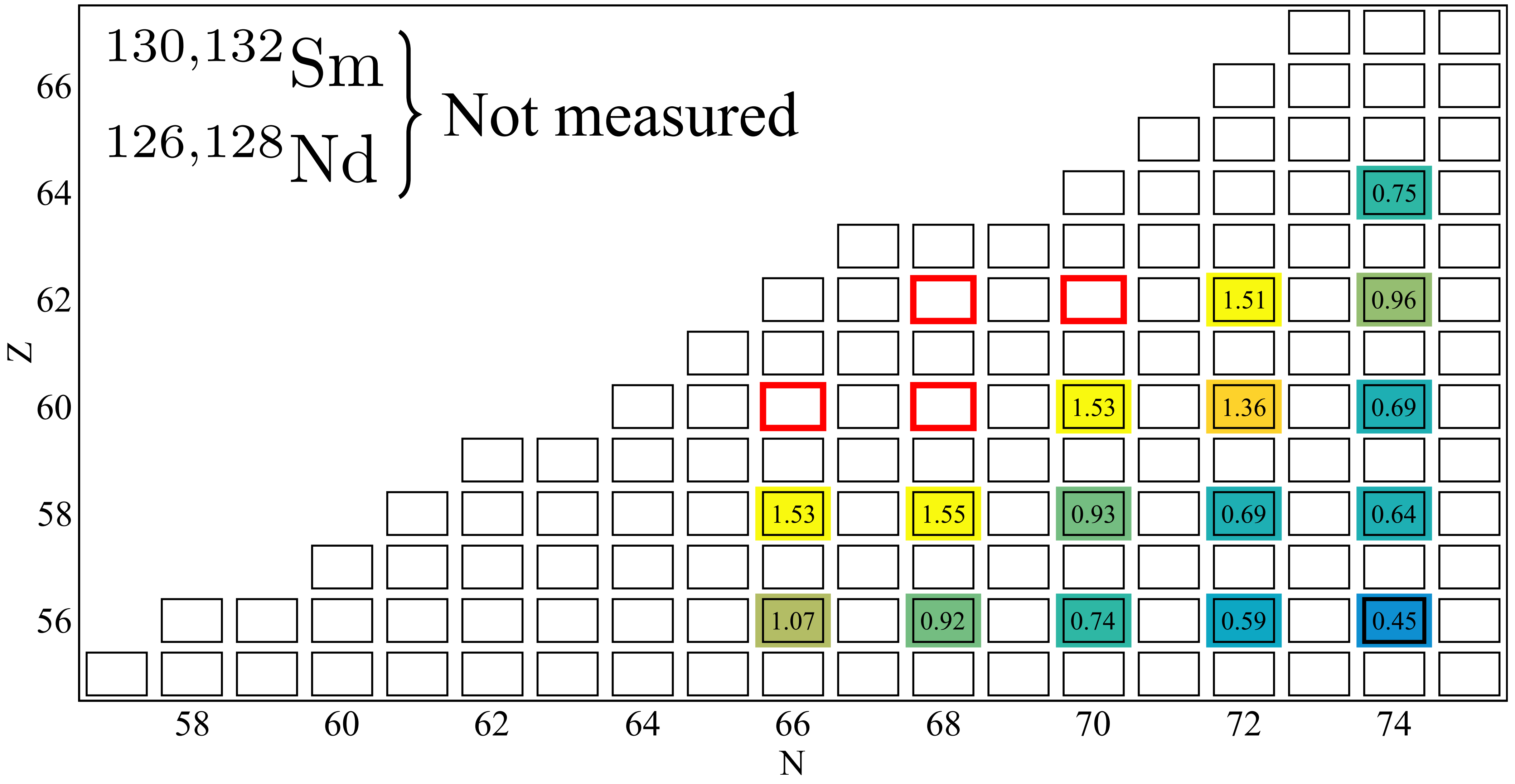
What about deformation in this region

$$B(E2;2_1^+ \rightarrow 0_1^+)\ (\mathrm{W.u})/A$$

Calculated values



Measured values

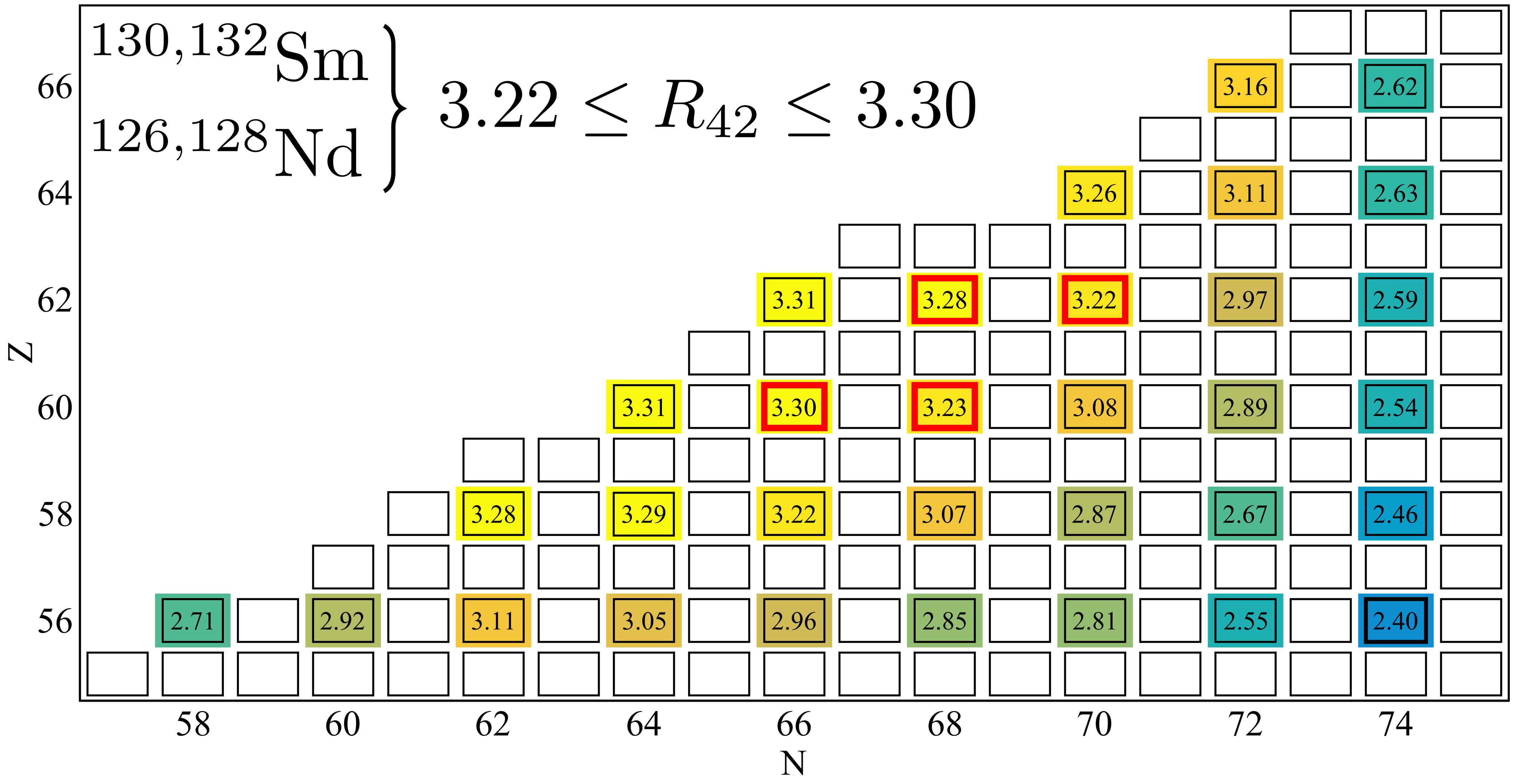


- ➤ The most proton-rich nuclei measured so far in this region have already values up to 1.5, and are in reasonable agreement with the theoretical values.

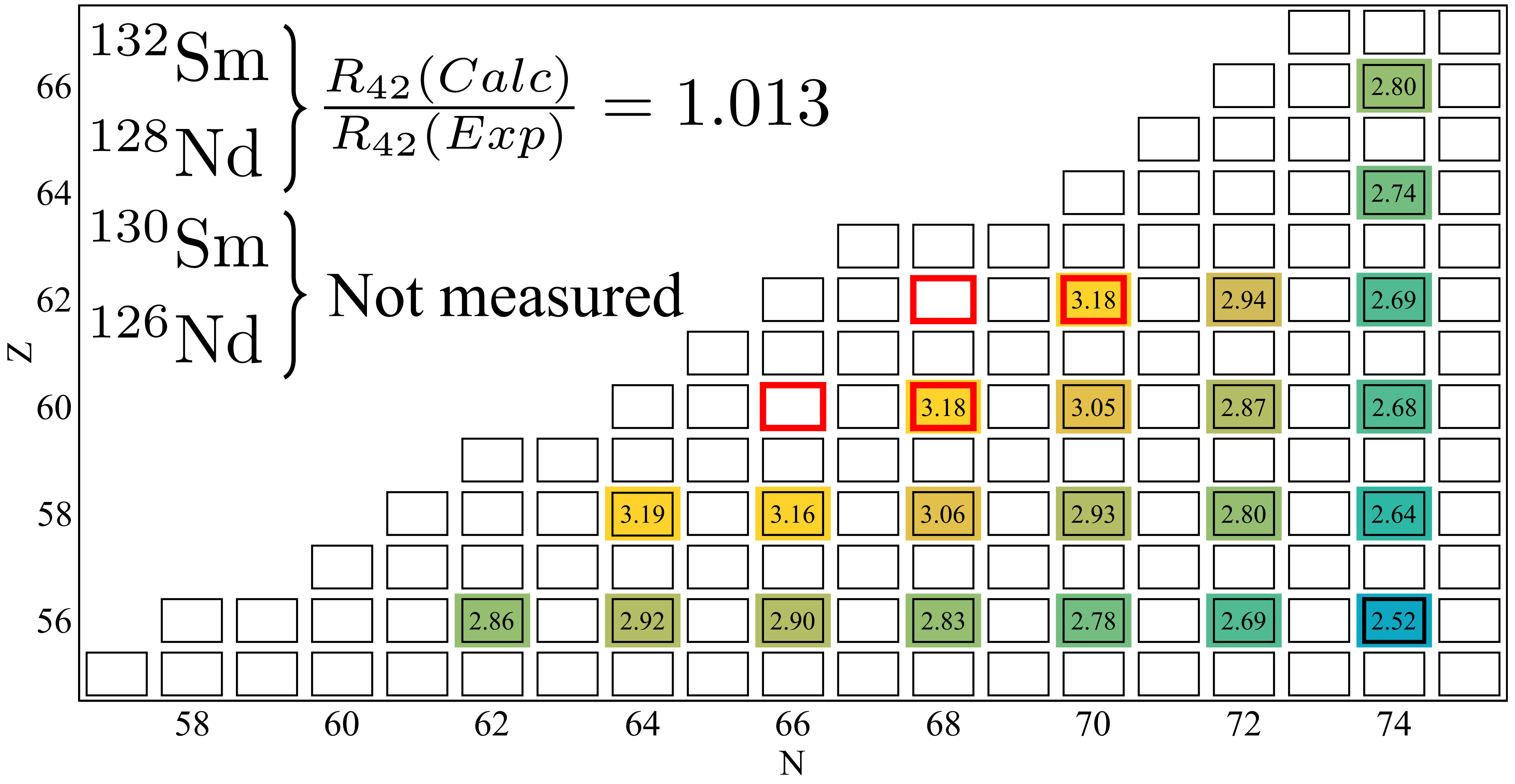
What about deformation in this region

$$R_{4/2} = E(4^+)/E(2^+)$$

Calculated values

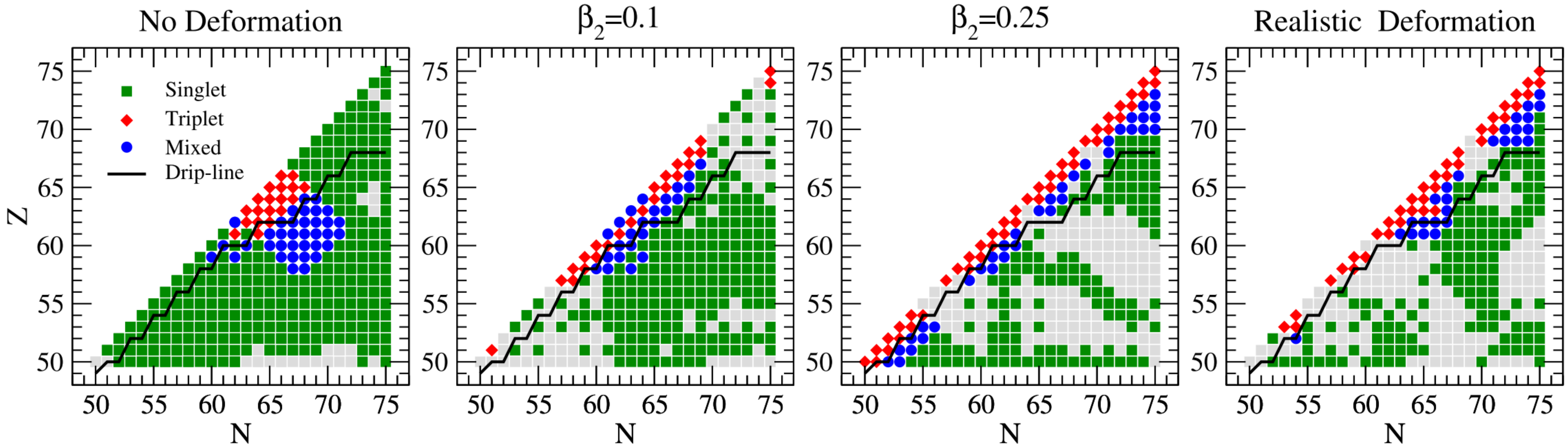


Measured values



➤ The same applies for $R_{4/2}$, with values approaching the rigid rotor limit of 3.3

Spin-triplet pairing condensate in the rare-earth region



- The rare-earth region is:
  - ➡ **the unique chance to have signs of a proton-neutron mixed-spin pairing**
  - ➡ **the place of the highest predicted deformations in ground state configuration**
- And both seem to be correlated !

Experimental setup - a bit of history

- The E404aS experiment performed in 2004 at GANIL:
  - ➡ **^{76}Kr @ 4.3 MeV/A (5x10^{5} pps) + ^{58}Ni target in fusion evaporation**
  - ➡ **11 EXOGAM clovers**
  - ➡ **VAMOS spectrometer (almost not used due to technical issues)**
  - ➡ **DIAMANT CsI detector system for tagging light charged particles**
  - ➡ **7 days of beam time (but only 4 of effective data taking)**

E404aS **Identification of gamma rays in nuclei around the dripline nucleus ^{130}Sm: probing the maximally deformed light rare-earth region**

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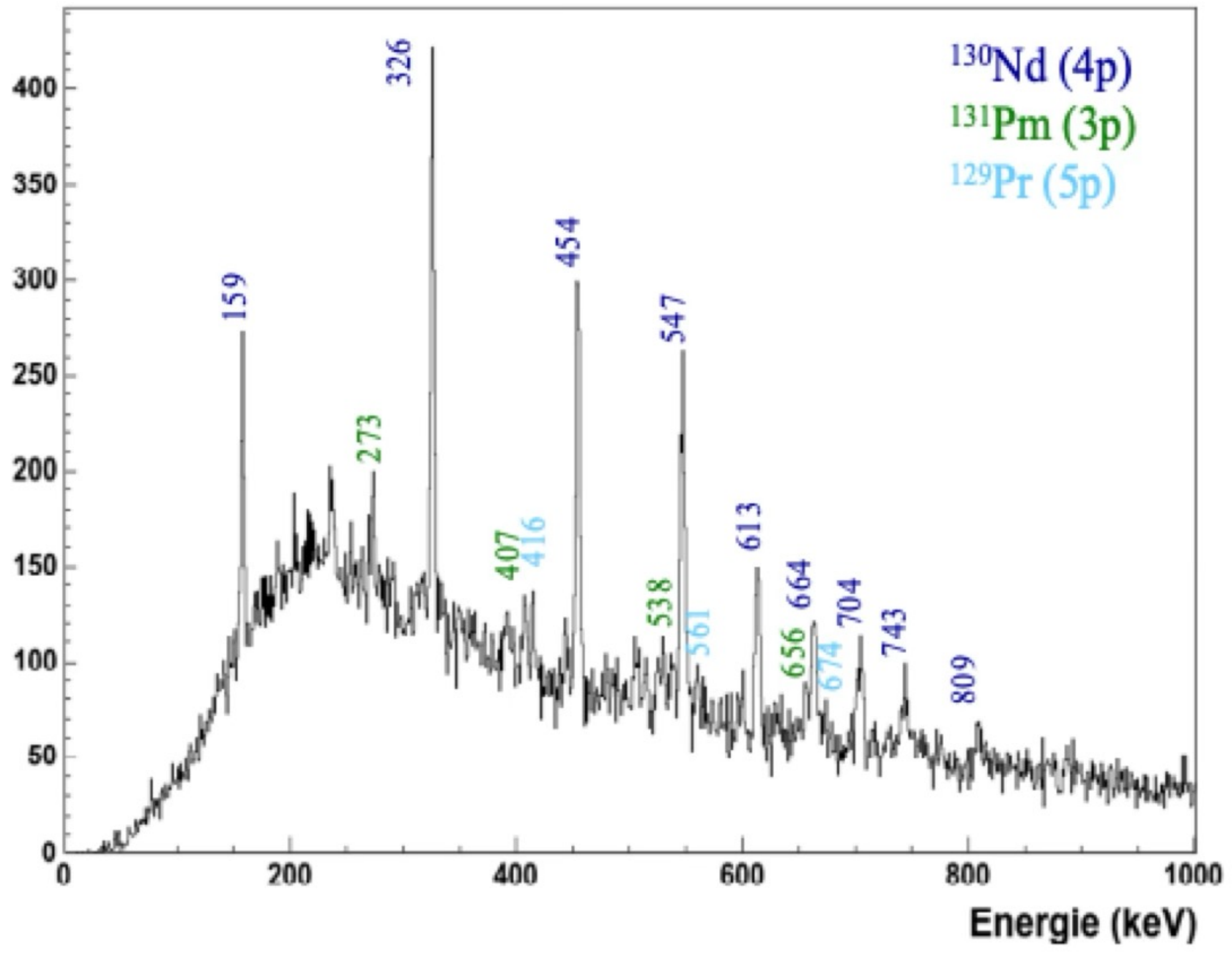
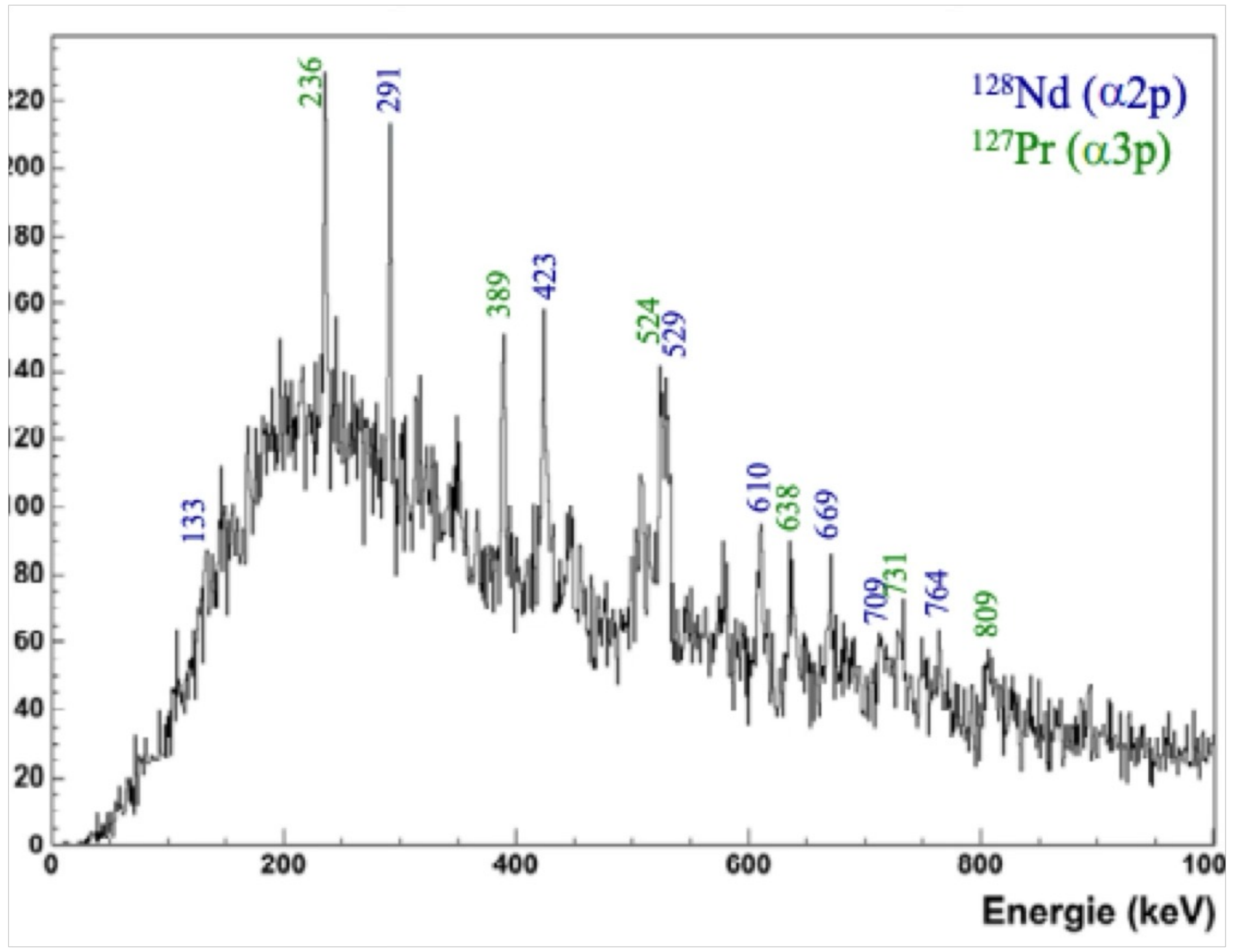
N. Redon, D. Guinet, Ph. Lautesse, M. Meyer, B. Rossé, Ch. Schmitt, O. Stézowski[2]
G. De France, S. Bhattachasyya, G. Mukherjee, F. Rejmund, M. Rejmund, H. Savajols[3]
J.N. Scheurer3
A. Astier[4]
I. Deloncle, A. Prévost[5]
B.M. Nyakó, J. Gál, J. Molnár, J. Timár, L. Zolnai[6]
K. Juhász[7]
V.F.E. Pucknell[8]
R. Wadsworth, P. Joshi[9]
G. La Rana, R. Moro, M. Trotta, E. Vardaci[10]
G. Ball, G. Hackman[11]

Experimental setup - a bit of history

- Similar experiment performed in 2004: the E404aS experiment:
  - ➥ **^{76}Kr @ 4.3 MeV/A (5x10^5 pps) + ^{58}Ni target in fusion evaporation**



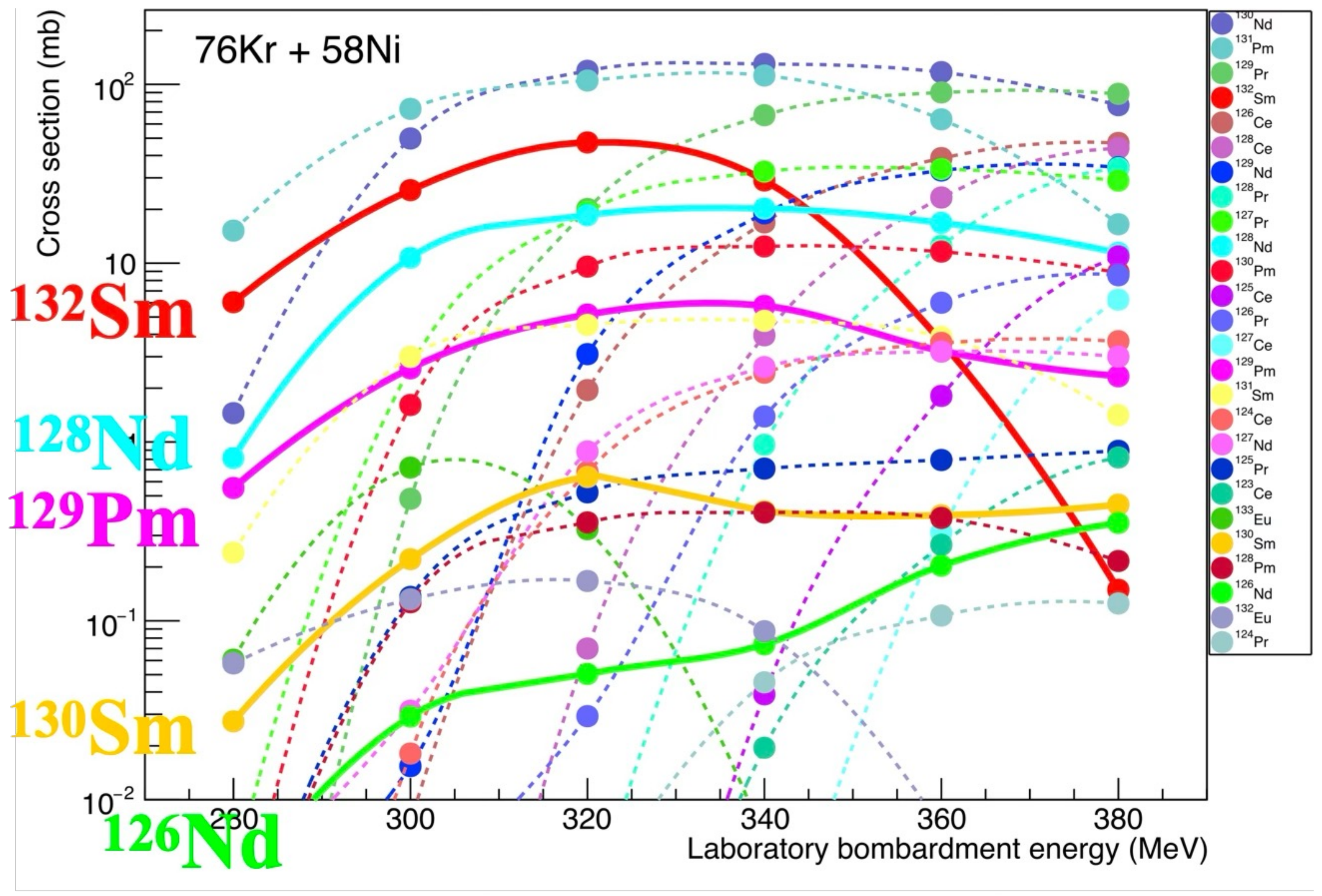


- Only DIAMANT could be used to tag the reaction
- Spectroscopy up to ^{128}Nd and ^{130}Pm, not proton-rich enough for the mixed-spin pairing studies

Experimental setup - a bit of history

- Similar experiment performed in 2004: the E404aS experiment:
  - ➥ **^{76}Kr @ 4.3 MeV/A (5x10^{5} pps) + ^{58}Ni target in fusion evaporation**

HIVAP calculations



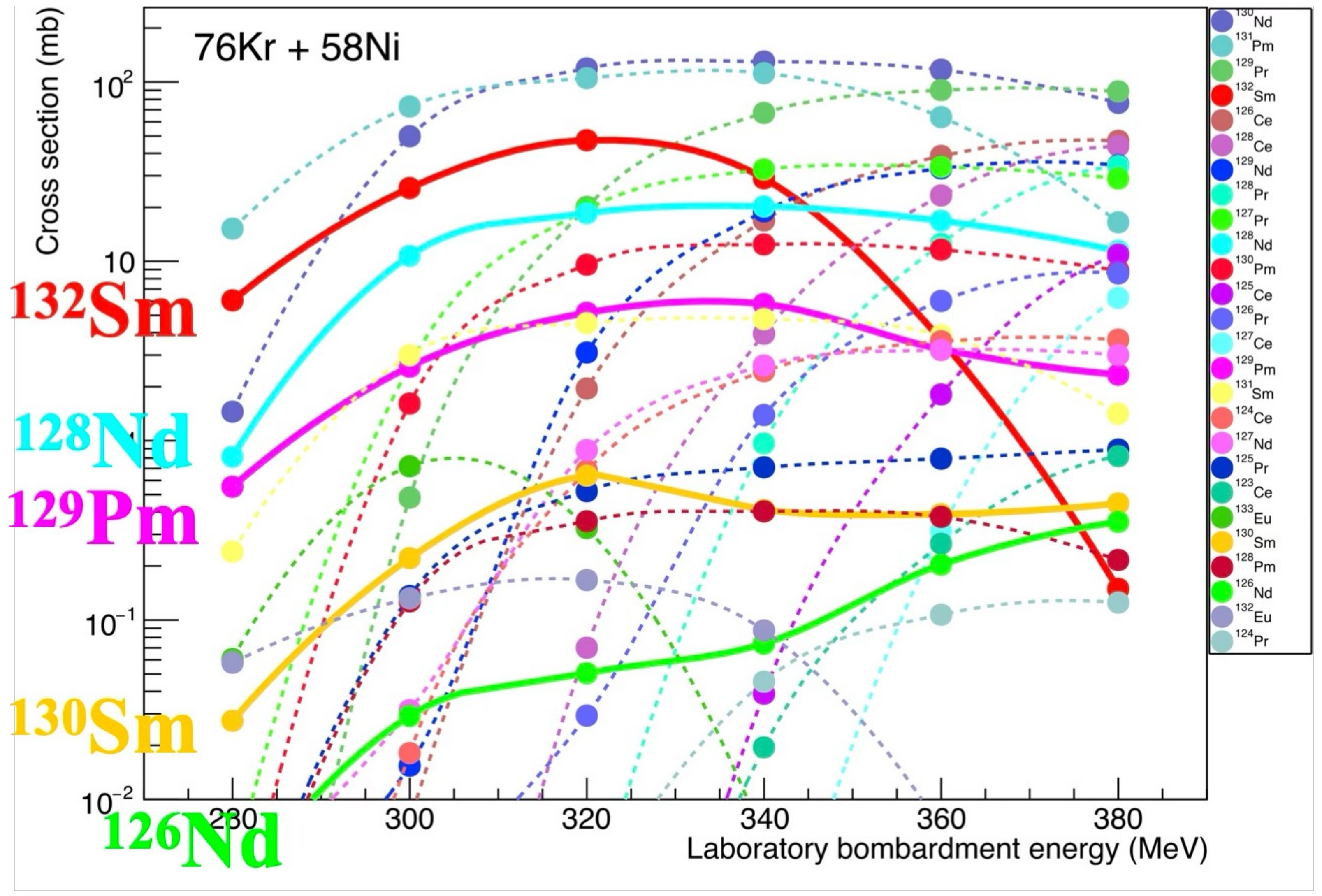
- The reaction leads to a broad distribution of evaporation channels.
- The nuclei of interest were difficult to isolate from the background.

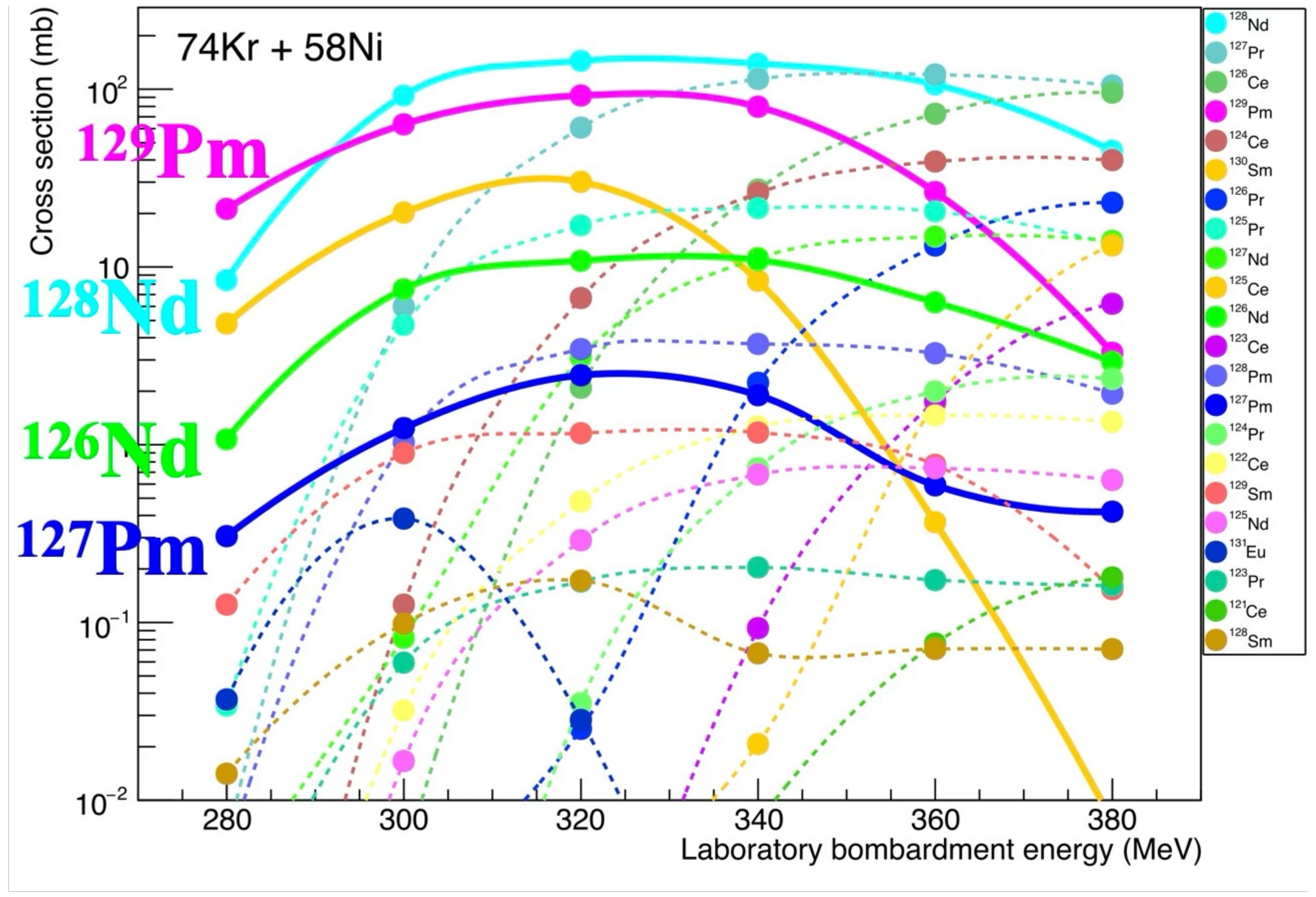
Experimental setup - could we use a ^{74}Kr beam ?

➤ From the GANIL web site: ^{74}Kr @ 4.3 MeV/A at 3x10^4 pps (1x10^4 in practice, **possible beam dev to 1x10^5**)

➥ **A factor of 50 (or 5 with beam dev) lower than the ^{76}Kr beam**

HIVAP calculations

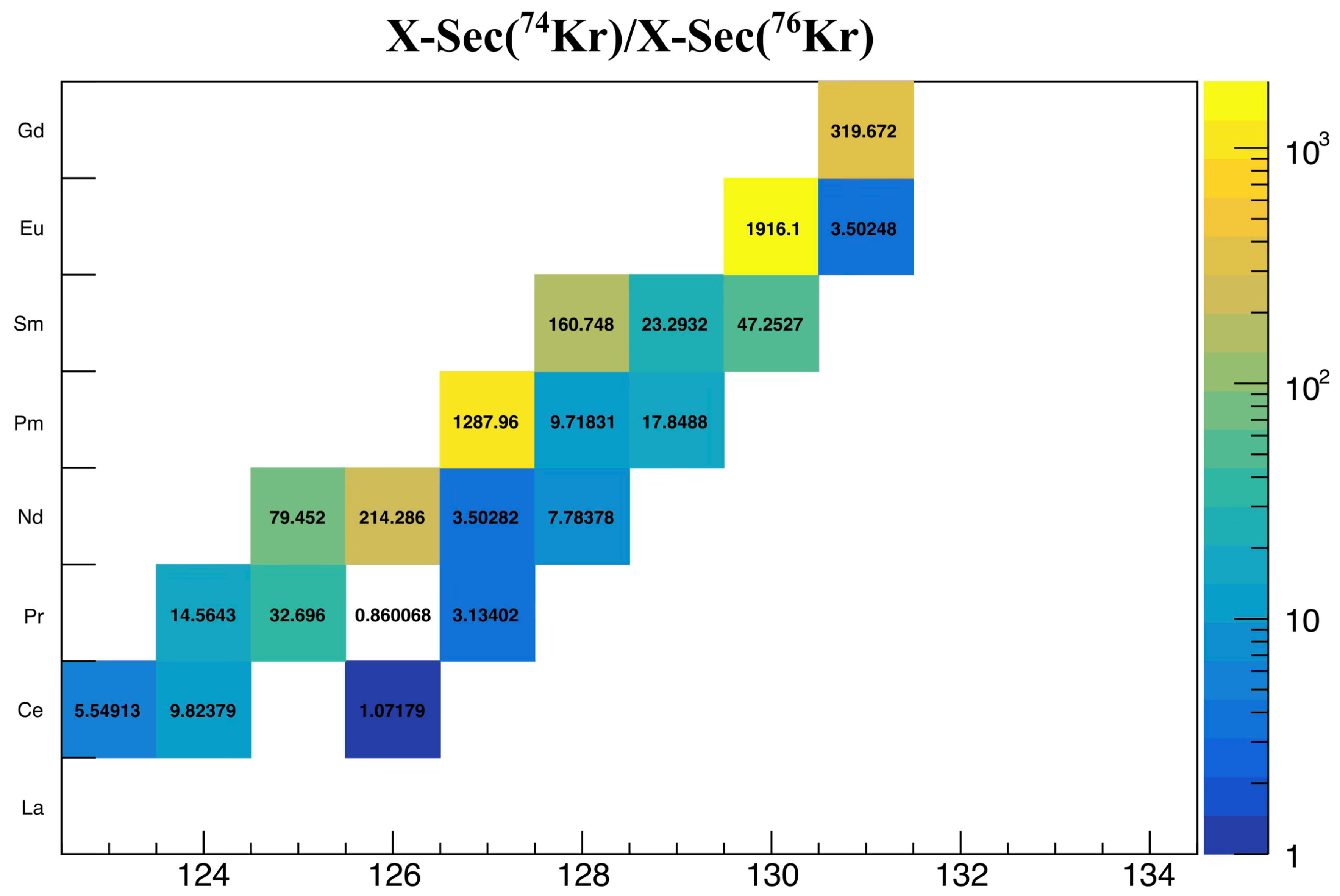




➤ However, the channels of interest are the most strongly populated !

Experimental setup - could we use a ^{74}Kr beam ?

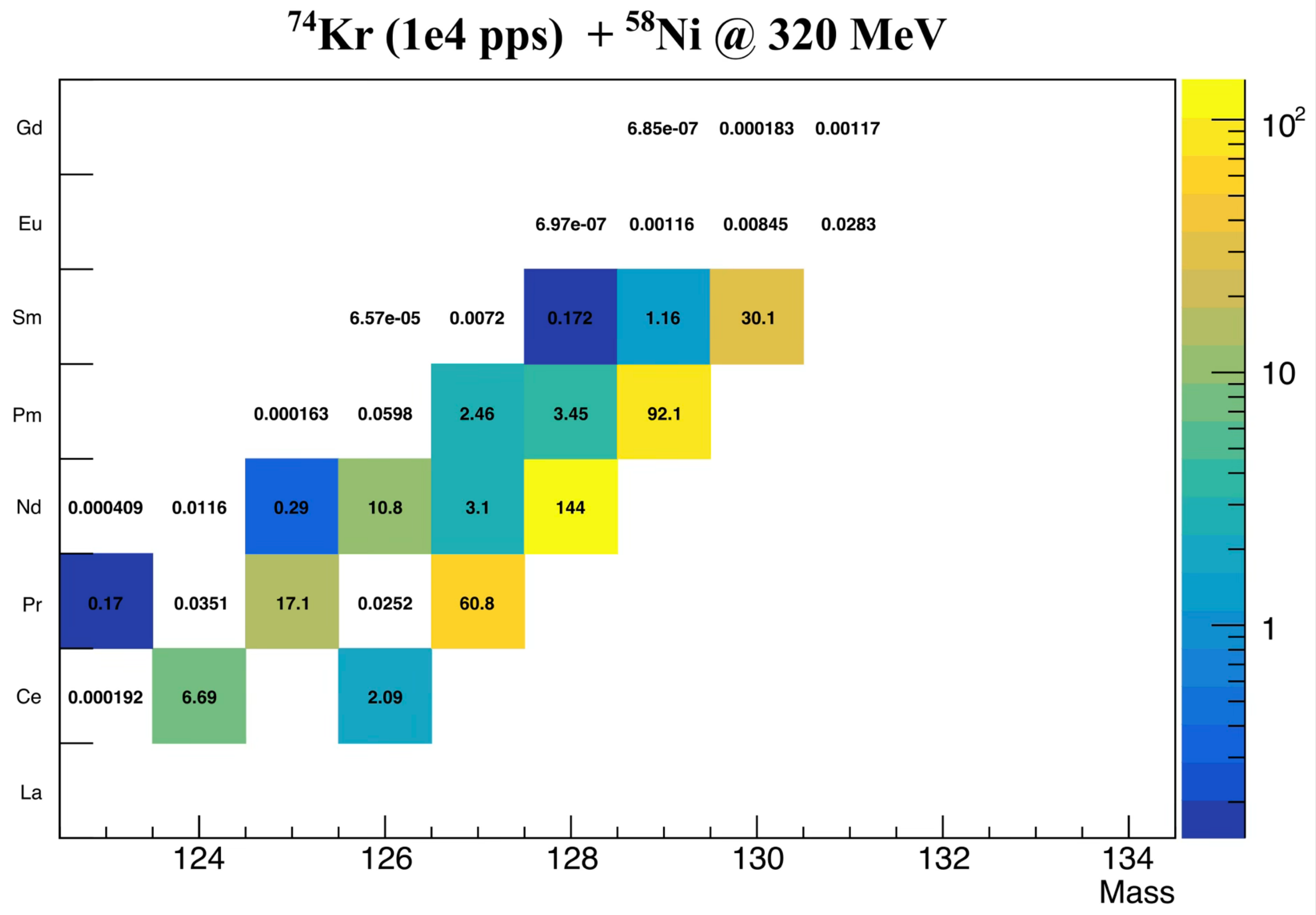
- From the GANIL web site: ^{74}Kr @ 4.3 MeV/A is given at $3x10^4$ pps ($1x10^4$ in practice)
  - ➥ **A factor of 50 lower than the ^{76}Kr beam**

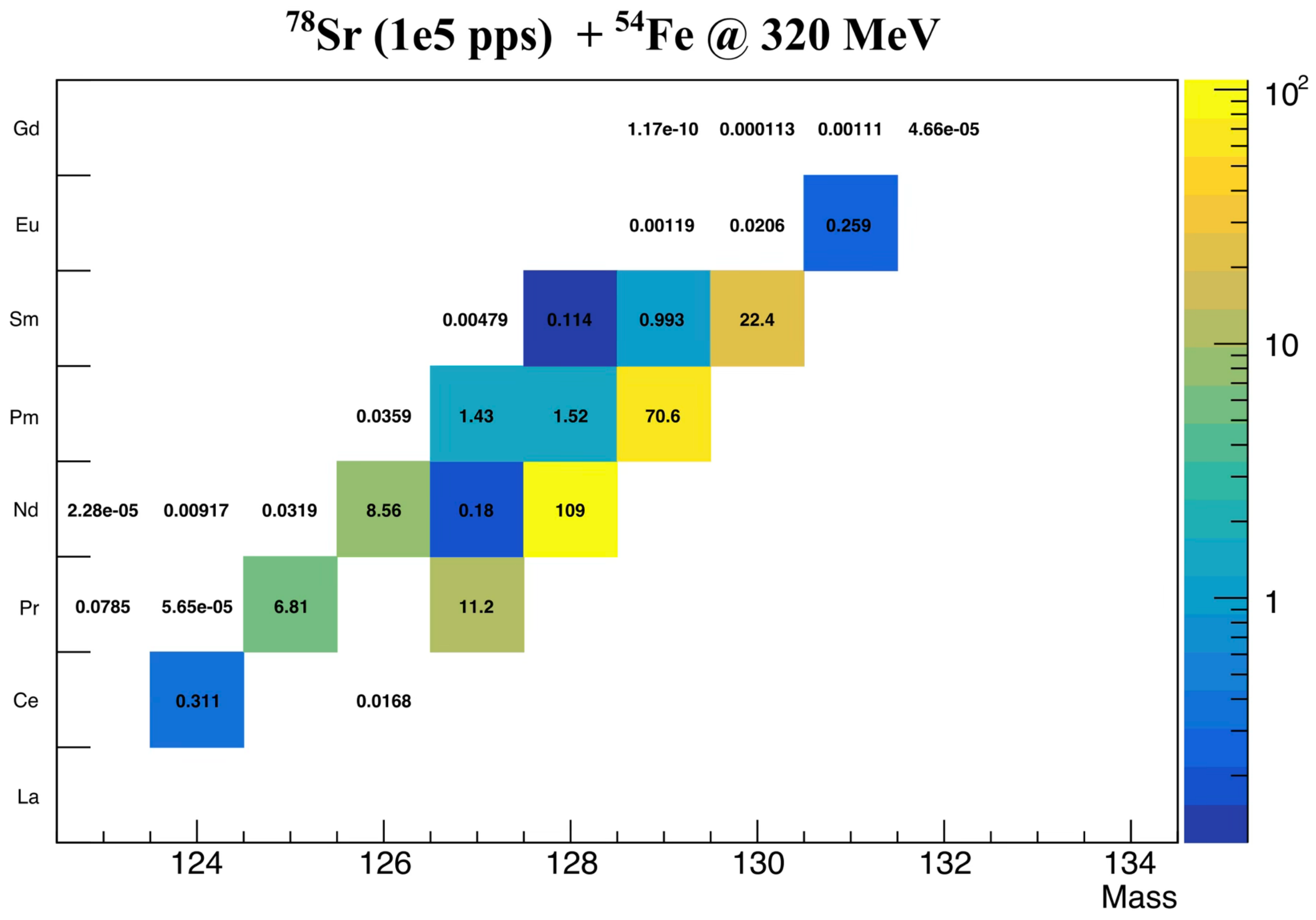


- But the channels of interest are the most produced one !
- And the cross sections are increased by a factor ranging from 10 to 1000, depending on the channel

Experimental setup - could we use a ^{78}Sr beam ?

- From the GANIL web site: ^{78}Sr is possible at $1x10^5$ pps with required target development
  - ➥ **It then requires a ^{54}Fe target (not the easiest one to produce)**





- Same compound nucleus (^{132}Gd), but cross sections a bit lower (but beam current 10 times more)

Experimental setup proposed

- Beam: ^{74}Kr @ 4.3 MeV/A, 1x10^{4} pps (are 3x10^{4} pps feasible ?)
- Target: ^{58}Ni (1mg/cm^{-2})
- Detection:
  - ➥ **AGATA: measuring gamma-rays**
  - ➥ **VAMOS++: Identification of the fusion-evaporation channel**
  - ➥ **GRIT: A/Z identification of evaporated light charged particles**
  - ➥ **A lifetime measurement system for ~ns decay range (LaBr^{3} ?)**
- Experiment length: 7 days

Merci !