THE MODELING OF GAMMA EMISSION IN THE STATISTICAL DE-EXCITATION CODE ABLA07

Can we learn something from the even-odd effect in the yields of nuclear-reaction products?

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MOTIVATION

Hunting for the gamma strength

The experimental techniques suffer of some sever restrictions

Stable-nuclei targets
(partly overcome by surrogate method for nuclei close to the target)

We propose an idea for a method that could be:

independent of the target A,Z numbers

capable to scan a large continuous range in the chart of the nuclides
(possibility to investigate systematics and singularities)

based on the gamma emission from an excited nucleus

OUTLINE

Experimental evidence of even-odd staggering in the yields

GSI results: a powerful overview

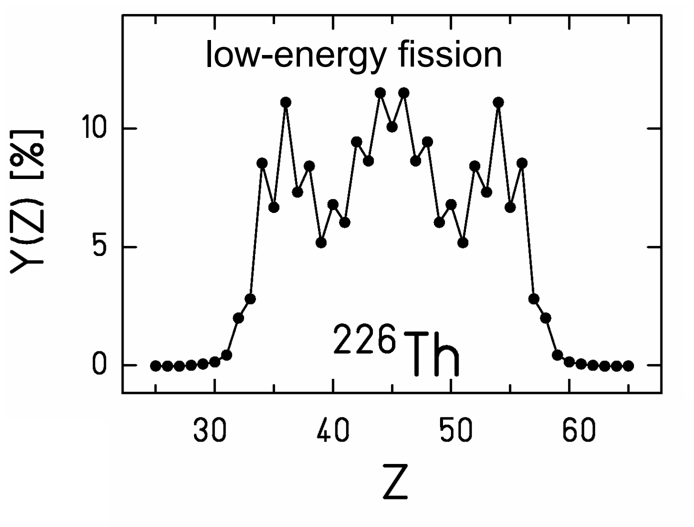
Understanding the even-odd staggering of light fragments
→ implication on our knowledge on level density

Understanding the even-odd staggering of heavy fragments
→ implication on our knowledge on radiative widths

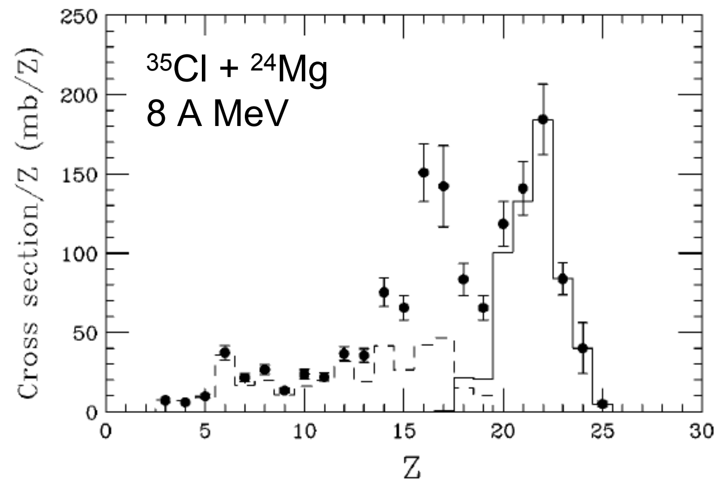
The possible new method for gamma strength measurements

Experimental evidence of even-odd staggering in the yields

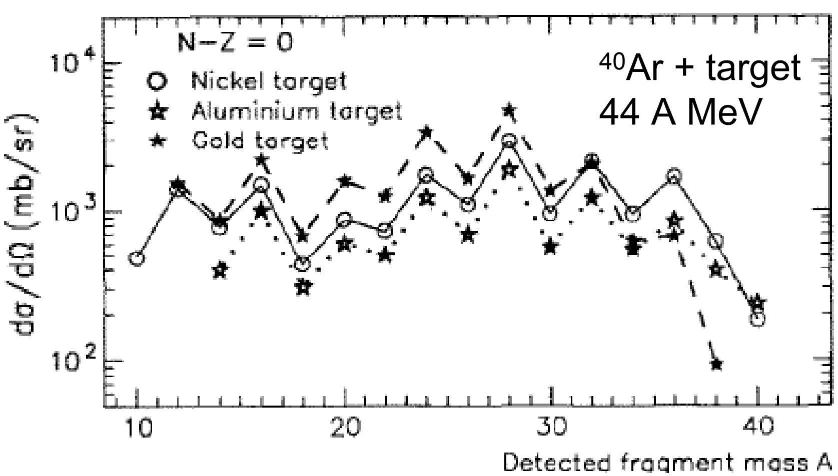
Steinhäuser et al., Nuc. Phys.A 634 (1998) 89



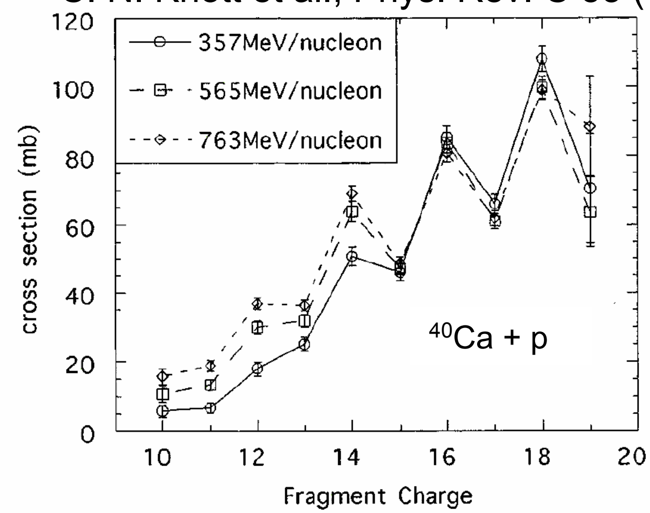
Sl. Cavallaro et al., Phys. Rev. C 57 (1998) 731



Ch. O. Bacri et al., Nucl. Phys. A 555 (1998) 477

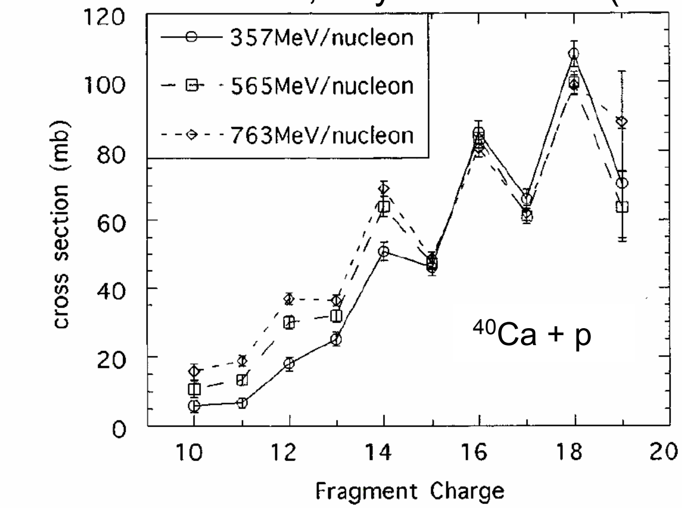


C. N. Knott et al., Phys. Rev. C 53 (1996) 347

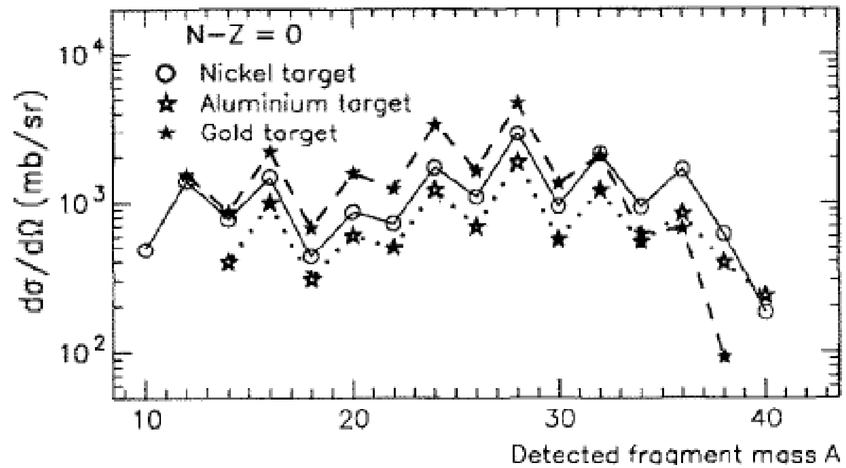


Evaporation residues:
Which are the characteristics of this type of final yields?

C. N. Knott et al., Phys. Rev. C 53 (1996) 347



Ch. O. Bacri et al., Nucl. Phys. A 555 (1998) 477



Yields of nuclei with **even Z** are enhanced

Yields of nuclides with **even N=Z** number are enhanced

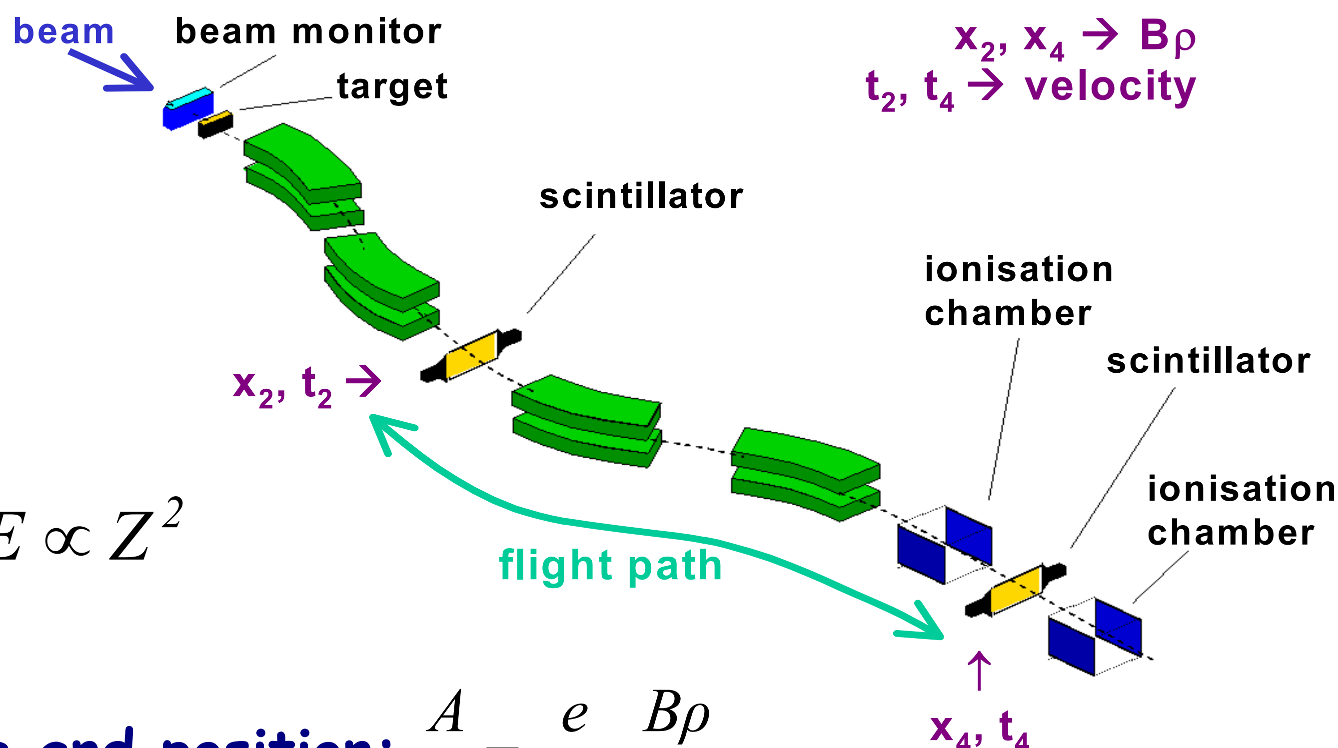
Nowadays we can tell much more...

A powerful overview: GSI data

Use of <u>high-resolution magnetic spectrometers</u> to measure production yields:

- full Z, A identification
- entire production range
- very precise measurement

Experimental set-up at the FRagment Separator (FRS), GSI



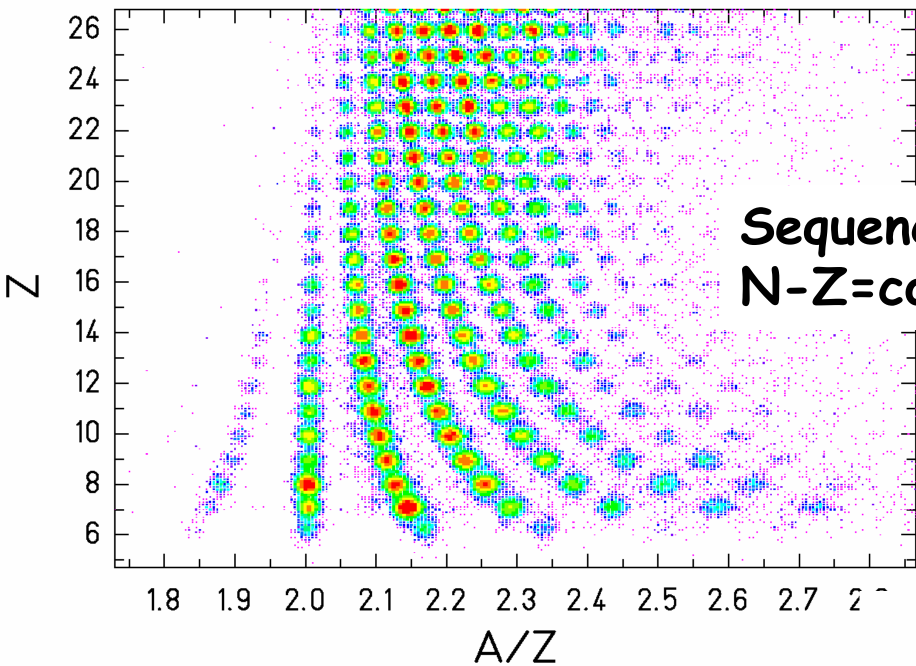
Z from IC: $\Delta E \propto Z^2$

A/Z from time and position: $\frac{A}{Z} = \frac{e}{m_0} \frac{B\rho}{c\beta\gamma}$

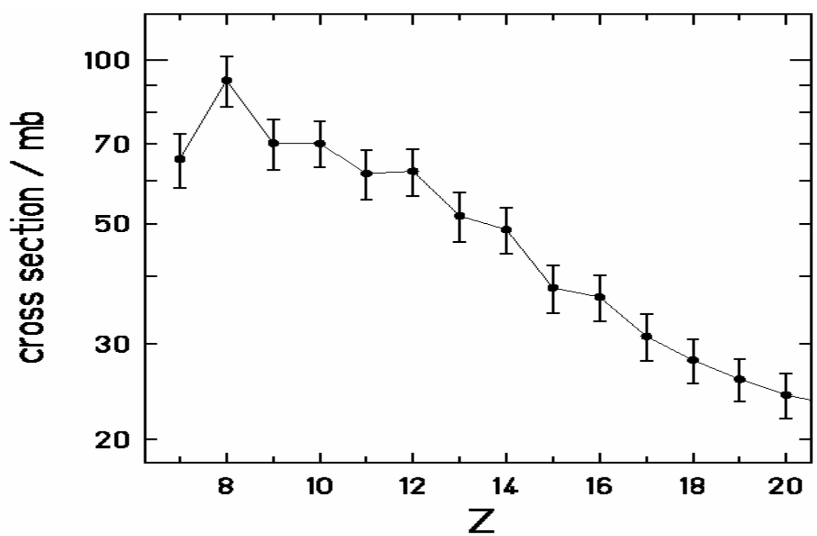
A powerful overview: GSI data

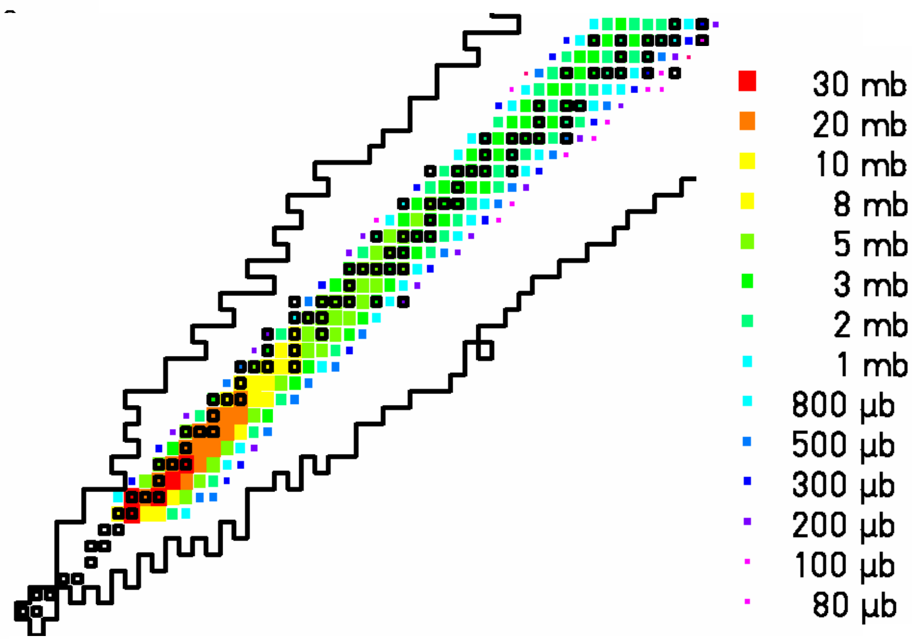
Fragmentation data:

1 *A* GeV ^{238}U on Ti

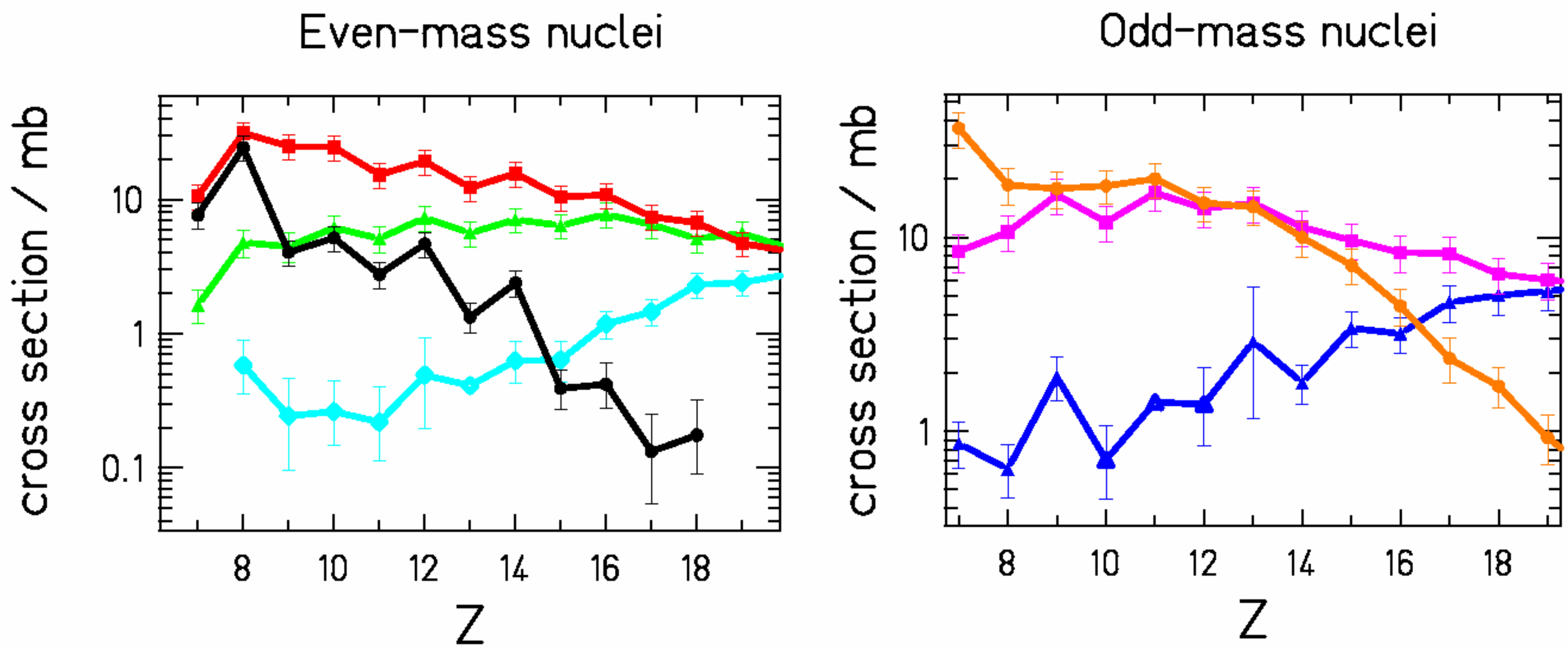


Sequence:
N-Z=constant





Experimental results for ^{238}U fragmentation



● N=Z ■ N=Z+2

▲N=Z+4 ♦N=Z+6

● N=Z+1 ■ N=Z+3

▲N=Z+5

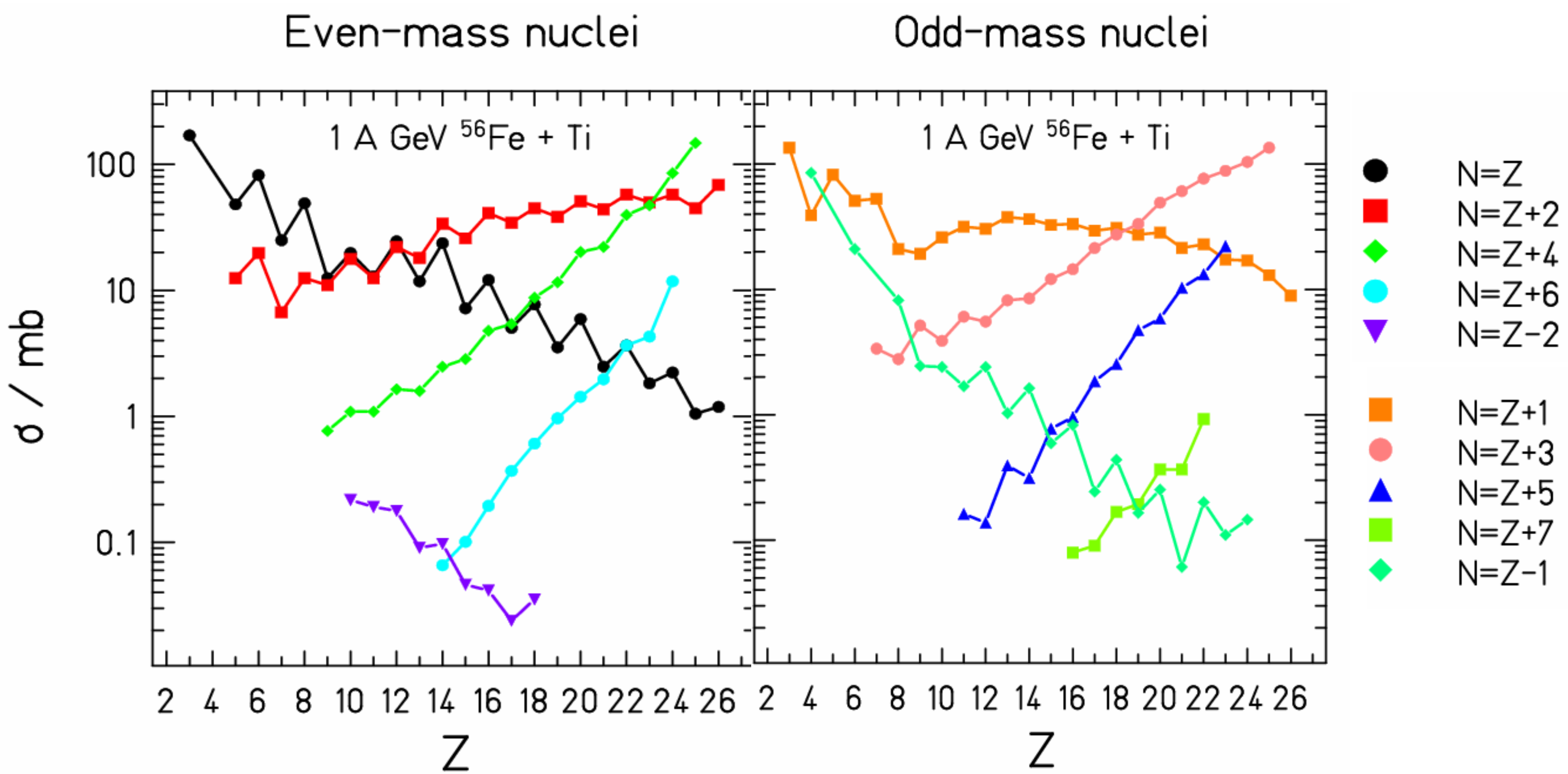
Data reveal complex structural effects!

M. V. Ricciardi et al., Nucl. Phys. A 733 (2004) 299

Experimental results for ^{56}Fe fragmentation

^{56}Fe on Ti at 1000 *A* MeV

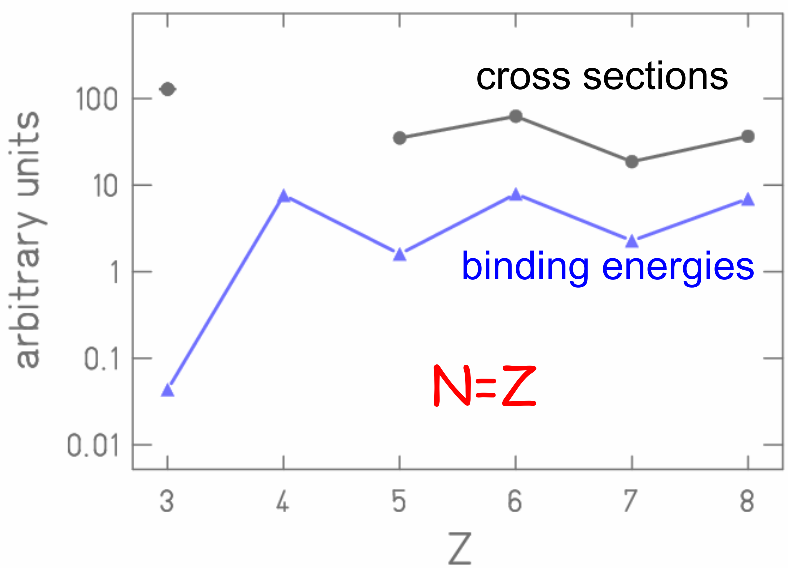
P. Napolitani et al., Phys. Rev. *C* 70 (2004) 054607

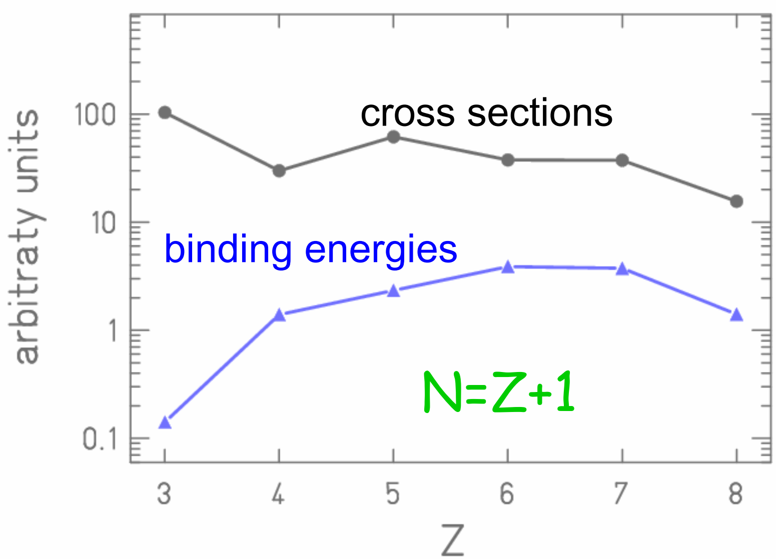


Same complex behavior observed in a large bulk of new data

Can we explain this complex behavior?

Let's test the idea that the staggering in evaporation residues correlates with the binding energy





Production cross sections (mb)
^{56}Fe on Ti at 1 *A* GeV

Staggering in binding energy (MeV)
(BE_{exp} from Audi Wapstra – BE_{calc} from pure LDM)

Overview on the staggering in the binding energy

Extra binding energy associated with the presence of congruent pairs:

$$\frac{3}{2}-\frac{|N-Z|}{A}-\frac{\delta}{A} \quad with \quad \delta = \begin{cases} 0 \quad for \ \ even-even \\ \frac{1}{2} \ for \ \ odd-even \\ 1 \ \ for \ \ odd-odd \\ 2 \ for \ \ N=Z=odd \end{cases}$$

most bound

↓

less bound

e	0	½	0	½	0	½	N=Z		N=Z+1	
o	½	1	½	1	½	1	½	2	½	1
e	0	½	0	½	0	½	0	½	0	½
o	½	1	½	1	½	2	½	1	½	1
e	0	½	0	½	0	½	0	½	0	½
o	½	1	½	2	½	1	½	1	½	1
e	0	½	0	½	0	½	0	½	0	½
o	½	2	½	1	½	1	½	1	½	1
	e	o	e	o	e	o	e	o	e	o

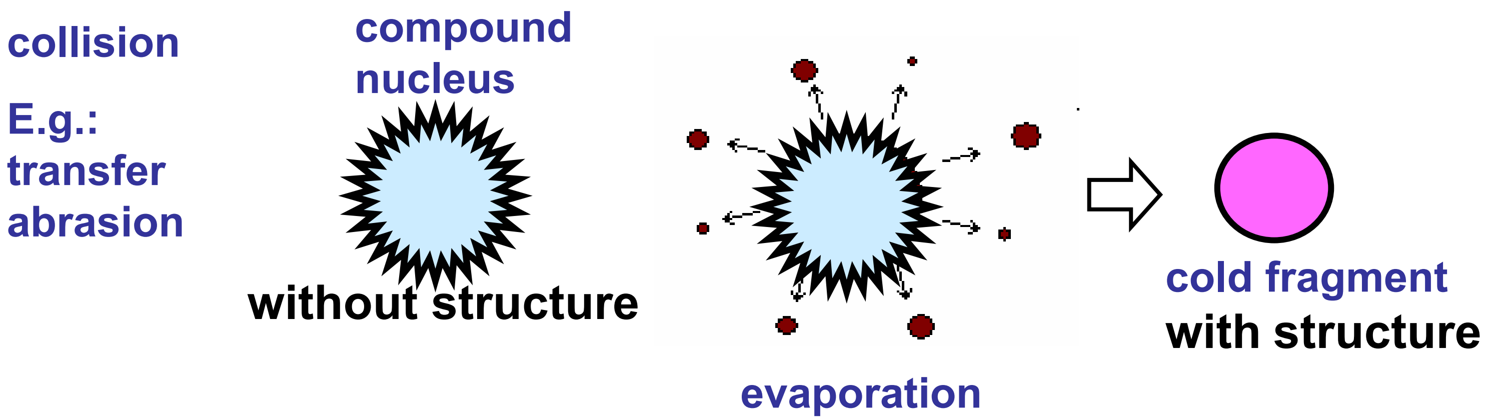
staggering in the ground-state energies

(Myers Swiatecki NPA 601, 1996, 141)

It is not the binding energy responsible for the staggering in the cross sections

Then, how can we explain this complex behavior?

We have this picture in mind:



The compound nucleus is hot and structureless

In each evaporation step the mass and excitation energy are reduced.
The new compound nucleus is still structureless.

Only below $E_{critical}$ (~10 MeV) structural effect can exist

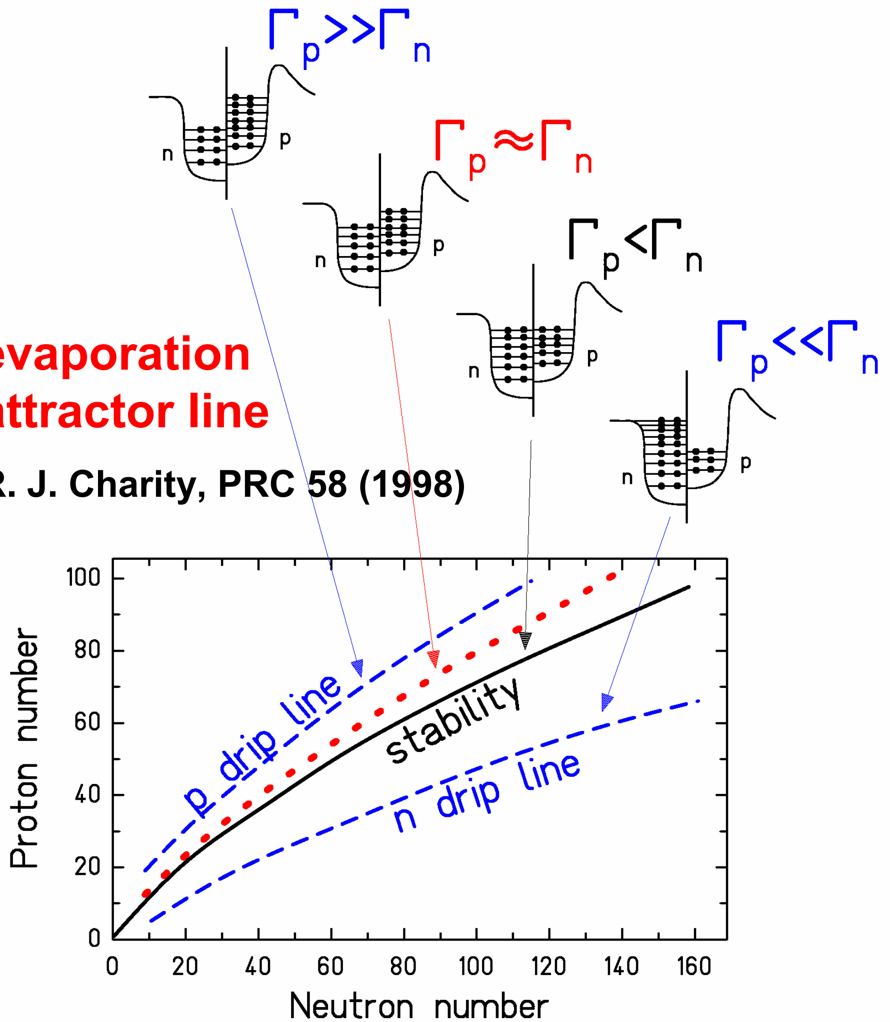
Below 10 MeV of excitation energy particle evaporation normally stops

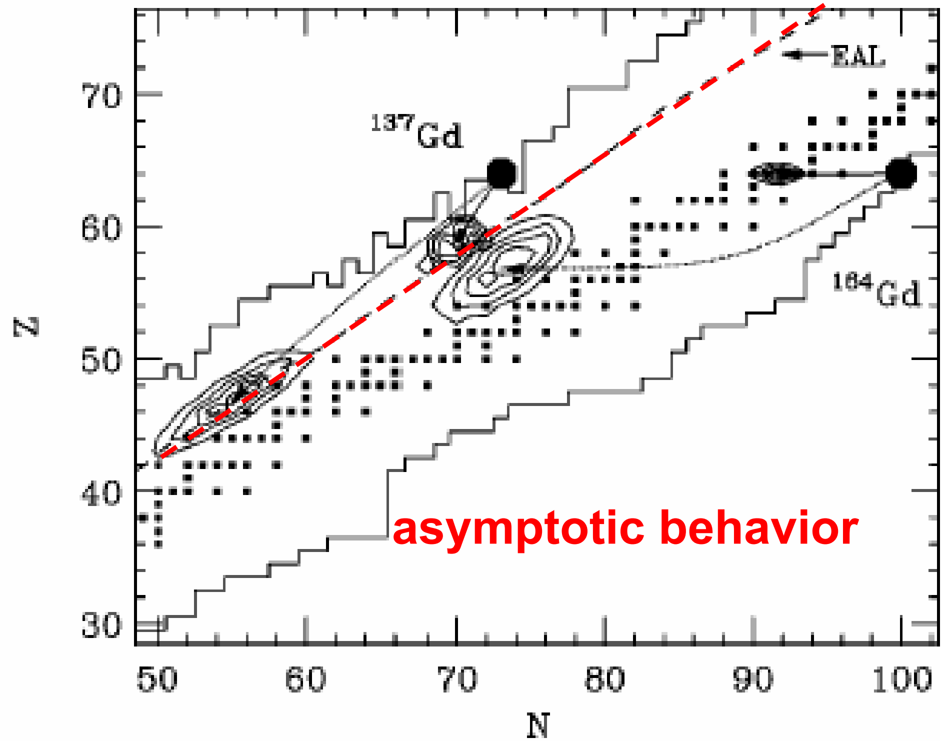
→ we test the idea that pairing is restored in the last evaporation step, i.e. the even-odd effect in the yields is determined in the <u>last evaporation step</u>

Main features of fragmentation reactions

evaporation attractor line

R. J. Charity, PRC 58 (1998)

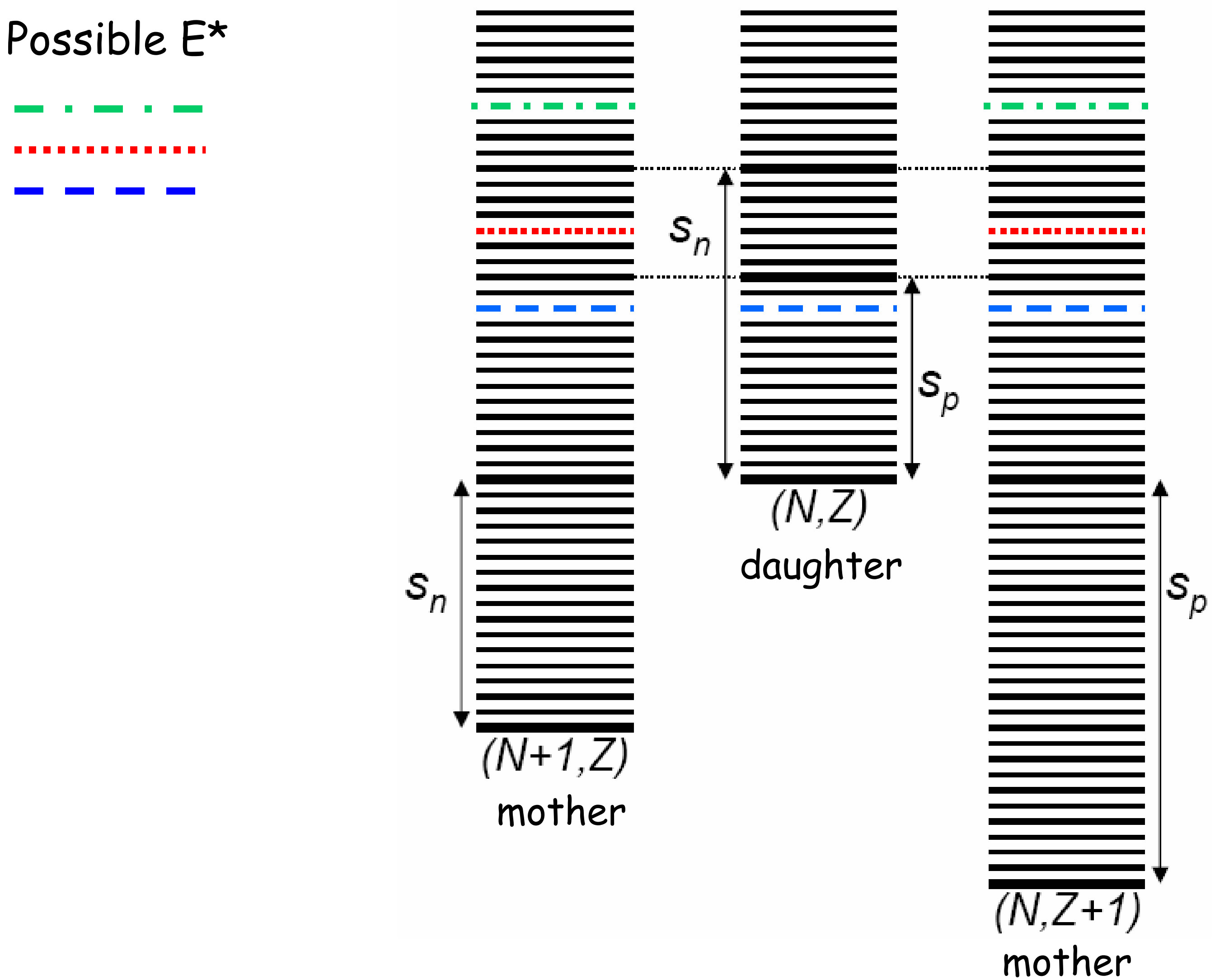




The dominant particle-decays in the last evaporation step are n and p emission

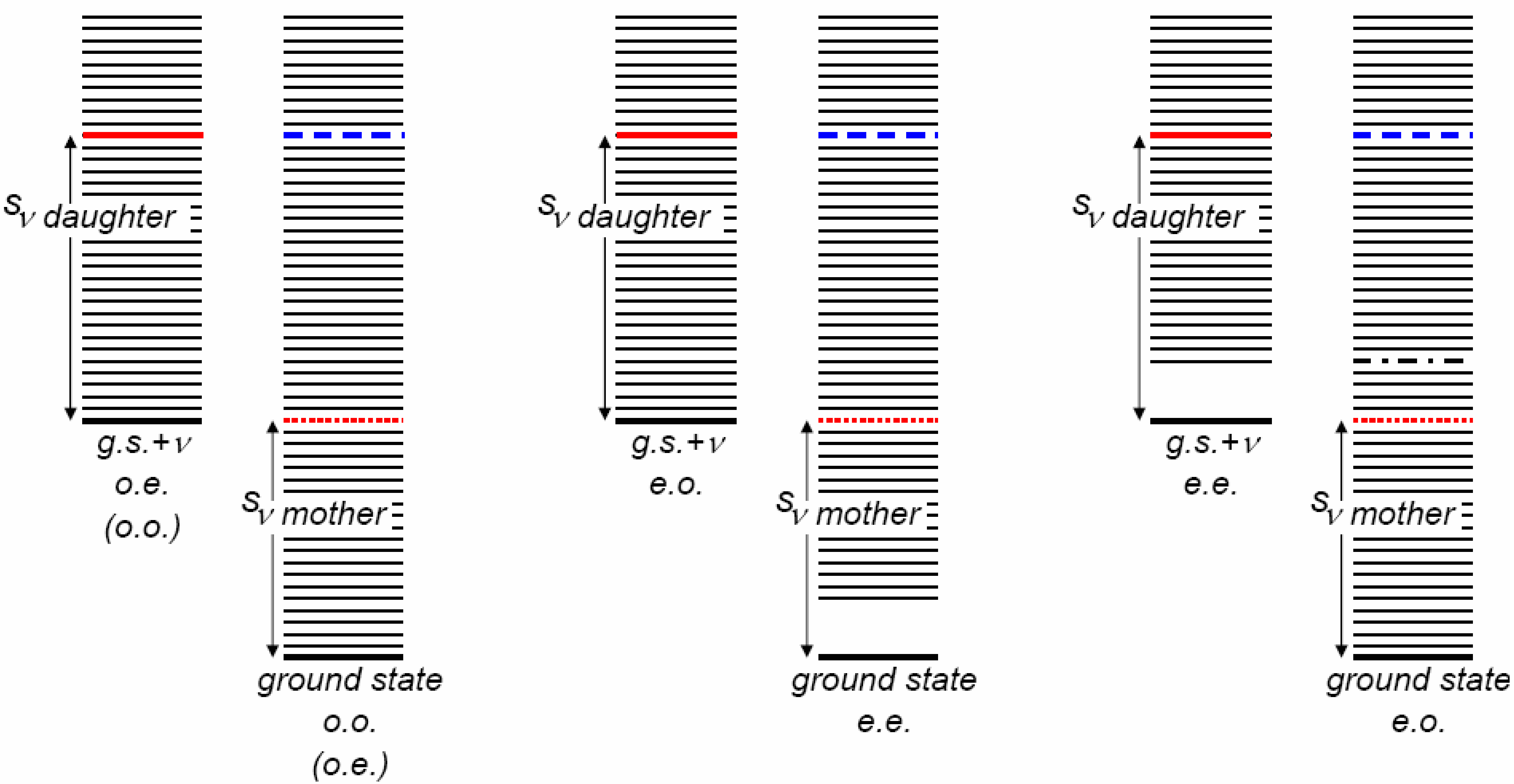
Understanding the staggering in the yields

Last step in the evaporation cascade
(assuming only n and p evaporation)



Understanding the staggering in the yields

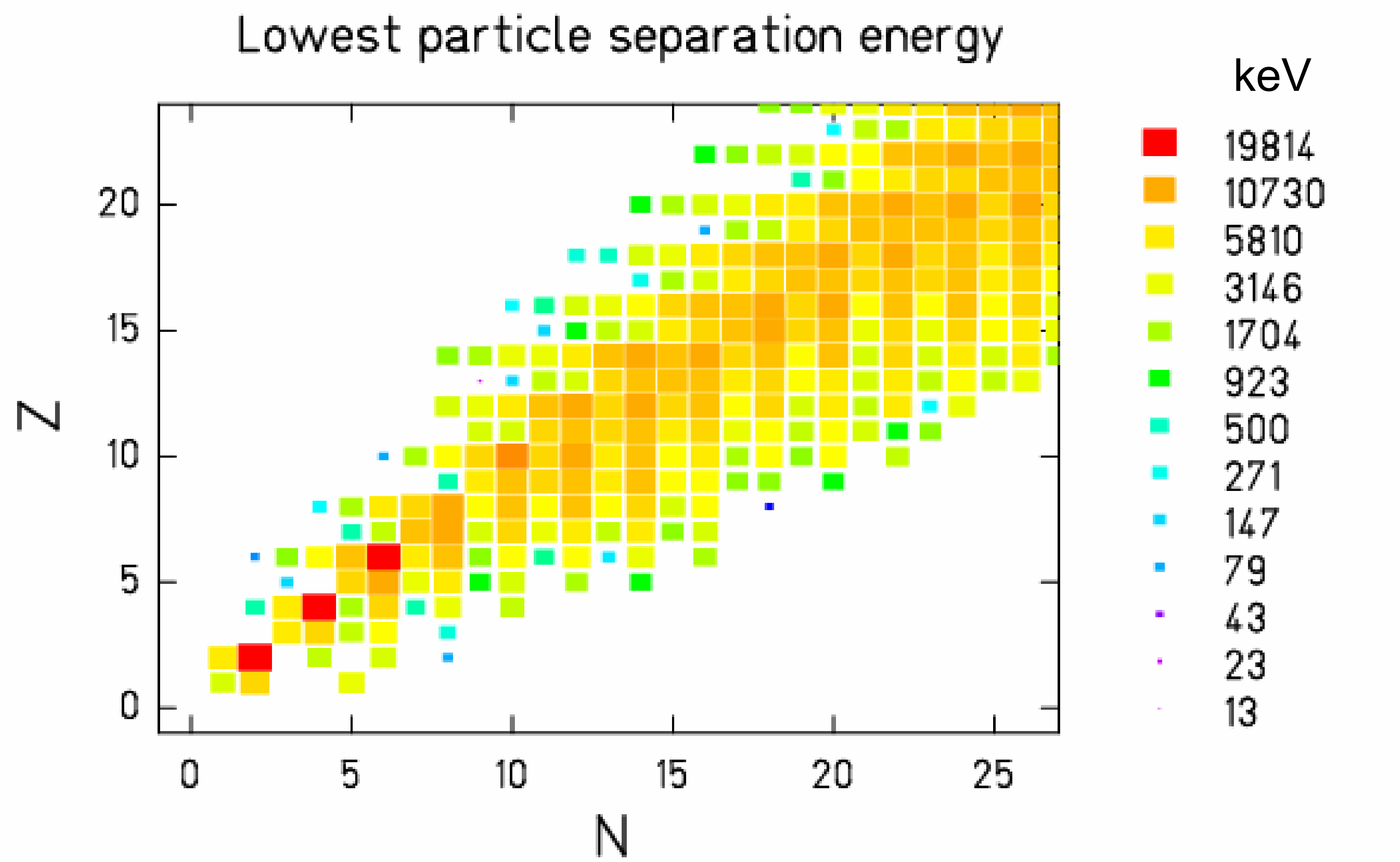
Last step in the evaporation cascade
(assuming only n and p evaporation)



The lowest particle separation energy is the key quantity!

The key role of the separation energy

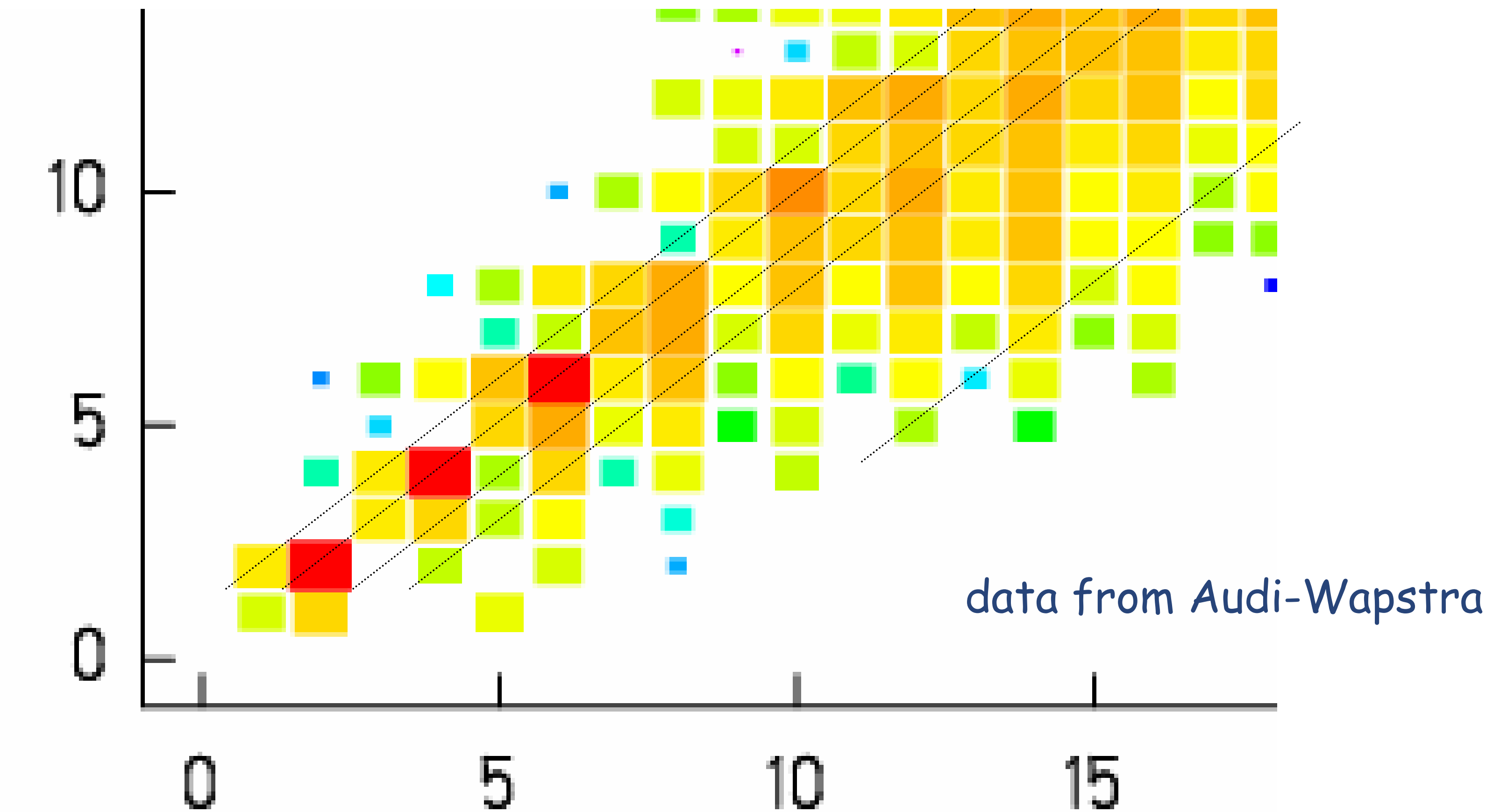
"Energy range" = "Particle threshold" = min(Sn, Sp)



data from Audi-Wapstra

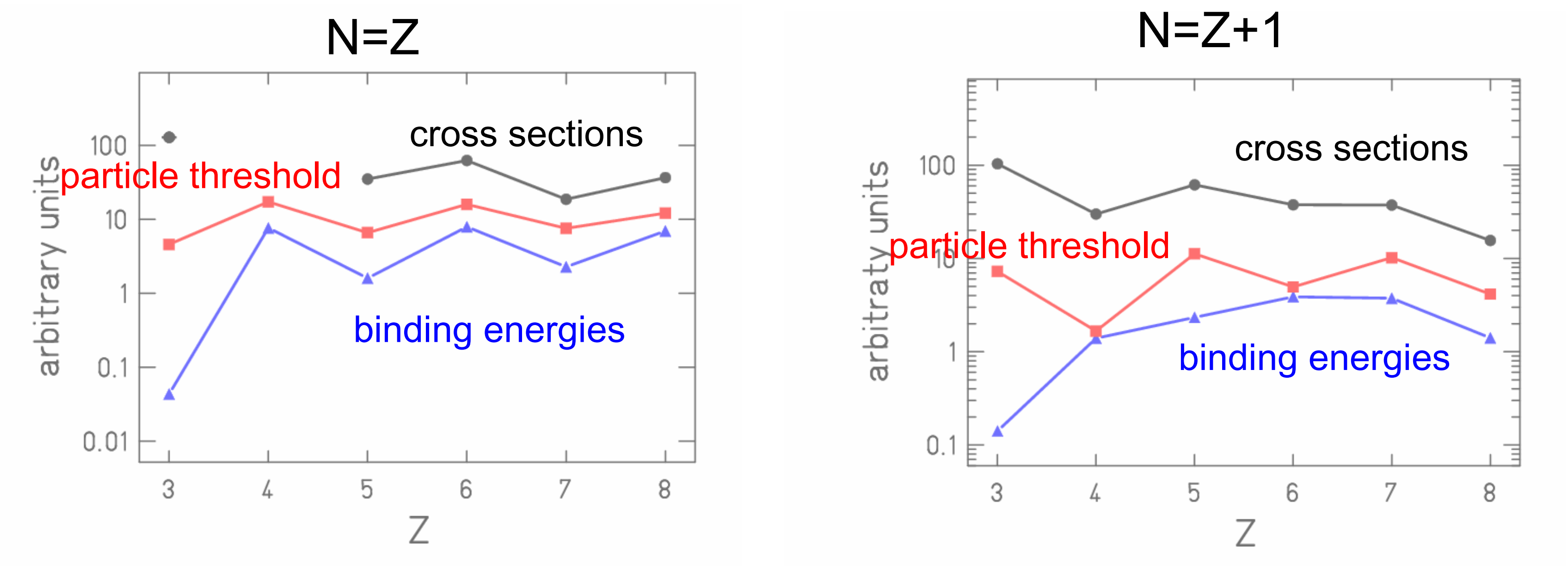
The key role of the separation energy

"Energy range" = "Particle threshold" = min(Sn, Sp)



The complex features of the even-odd staggering are reproduced in this **fishbone pattern**!

Staggering in yields vs. min(Sn,Sp)



Production cross sections (mb)

Staggering in binding energy (MeV)

Particle threshold = lowest particle separation energy (MeV)

The lowest particle separation energy reproduces perfectly the staggering

Conclusions concerning the even-odd staggering in light evaporation residues

The even-odd staggering of final nuclei which have experienced a particle-decay de-excitation process (**evaporation**) is determined in the last evaporation step

in other words:

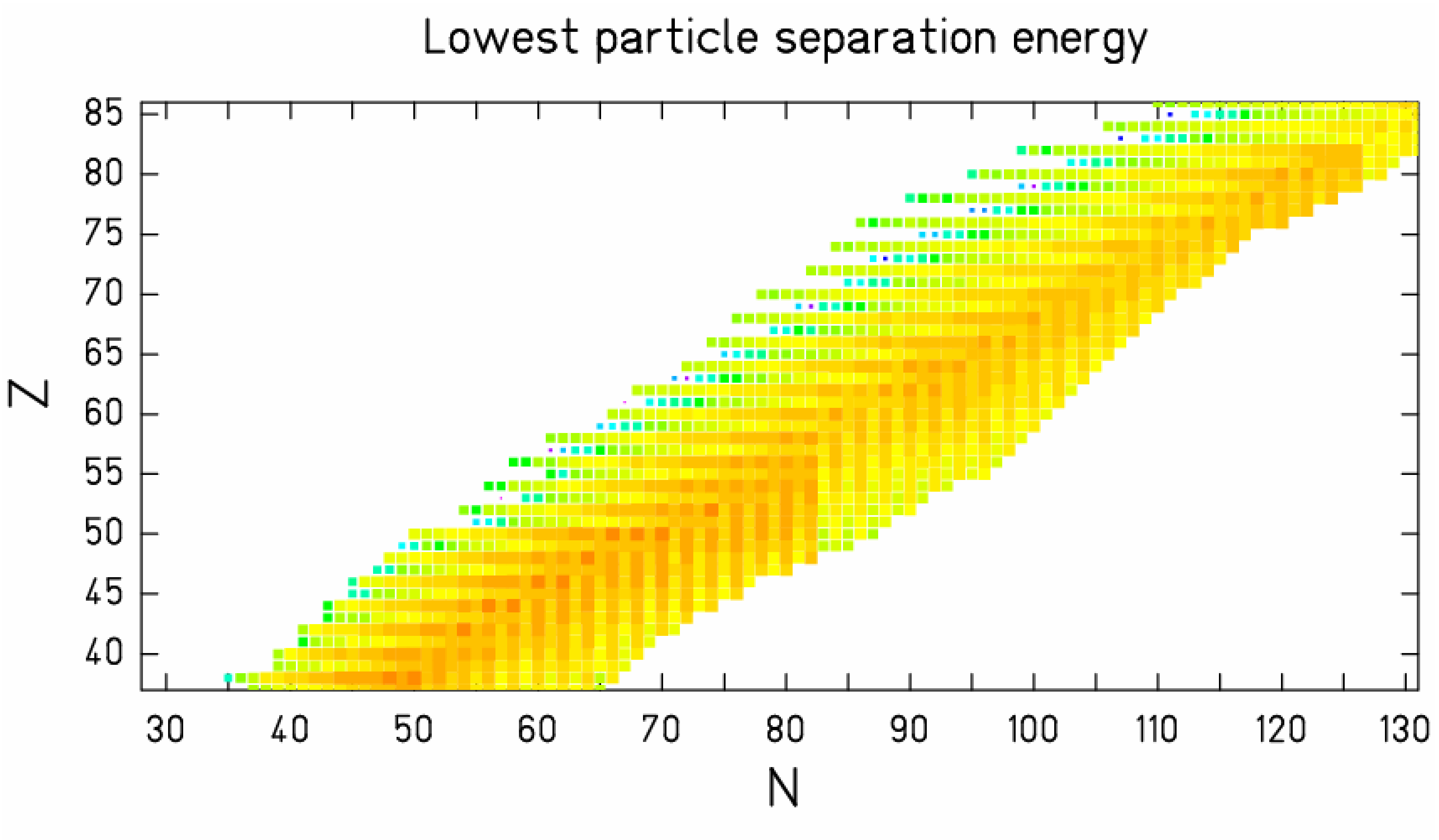
Structural properties do not survive in excited nuclei, but the pairing interaction is **restored** once the nucleus falls below the critical energy

The characteristics of the staggering correlate strongly with the **lowest n p particle separation energy** of the final experimentally observed nuclei.

The phase-space, which is related to **the level density**, **is not the relevant quantity anymore in the last evaporation step**: It is the **separation energy**, which gives the range of excitation energy, which "catches" the evaporation flux in particle-stable states.

M. V. Ricciardi et al., submitted to PRC, arXiv:1007.0386

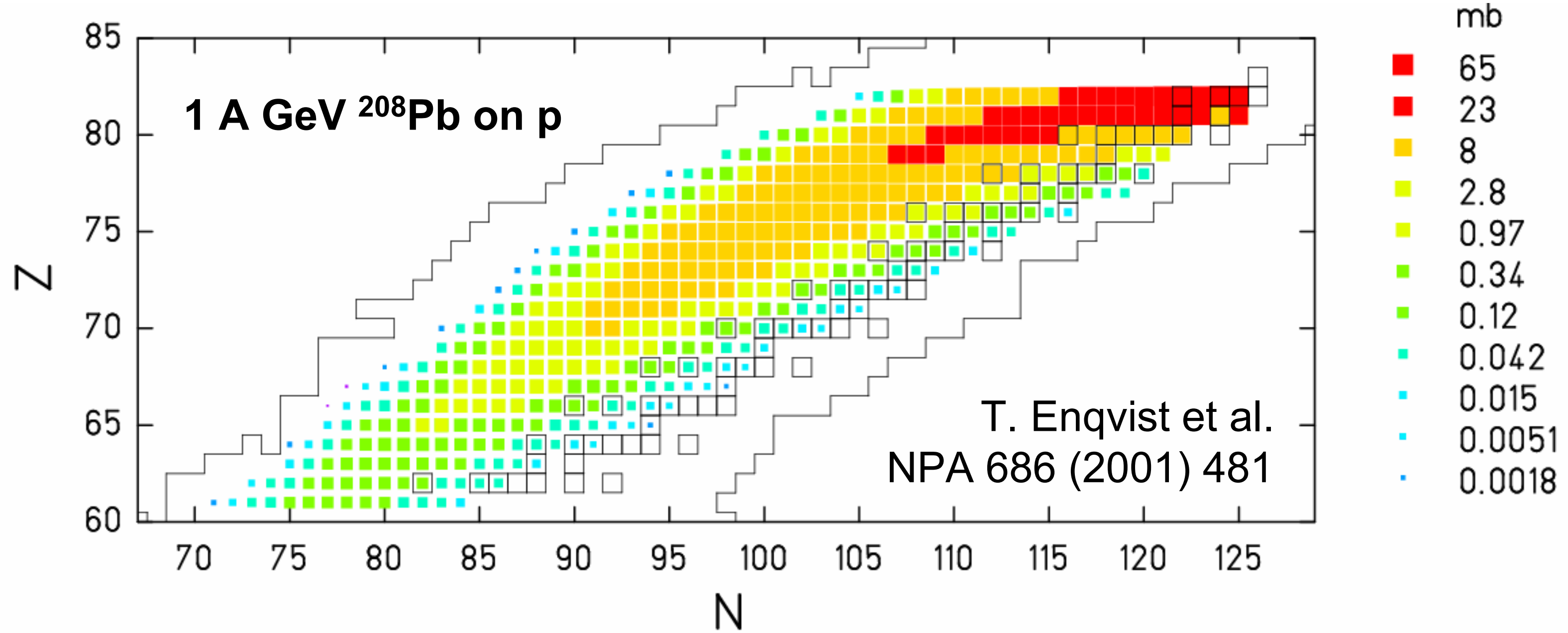
What happens to heavy evaporation residues?

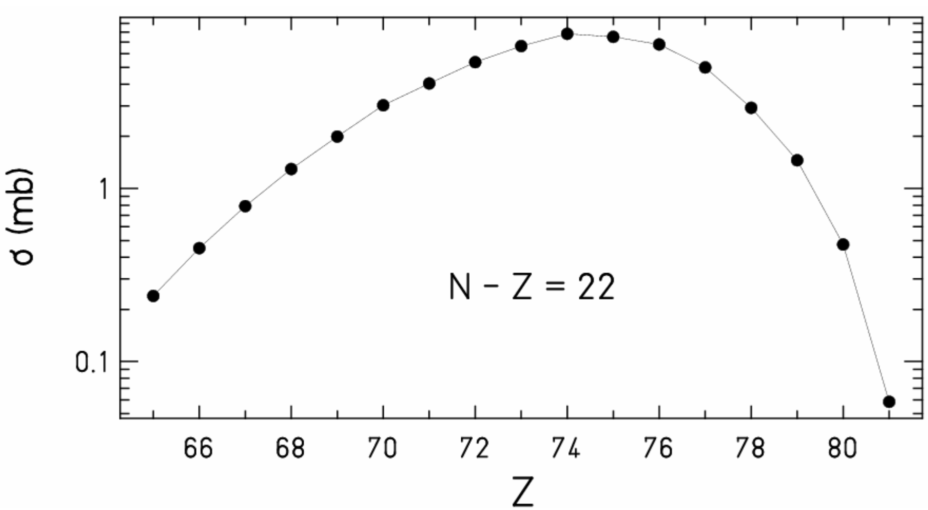


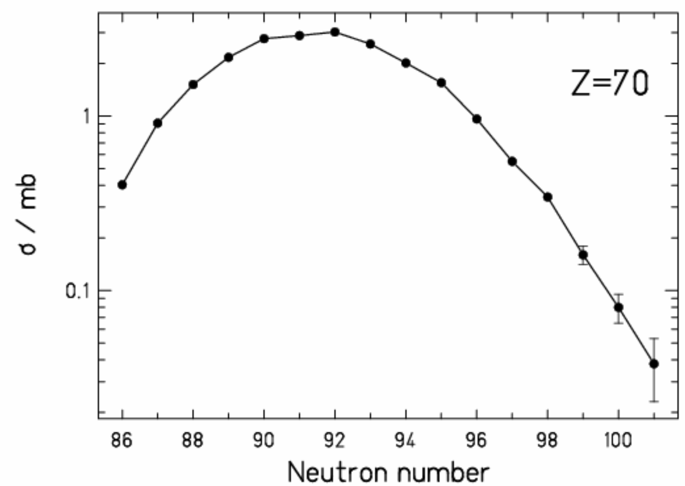
we expect to observe a strong even-odd staggering

Heavy evaporation residues: Experimental data

We do not see the expected even-odd staggering!







The even-odd effect for heavy residues: why does it disappear?

$\Delta = \frac{12}{\sqrt{A}}$ makes the even-odd staggering reduce but not disappear

Angular momentum?

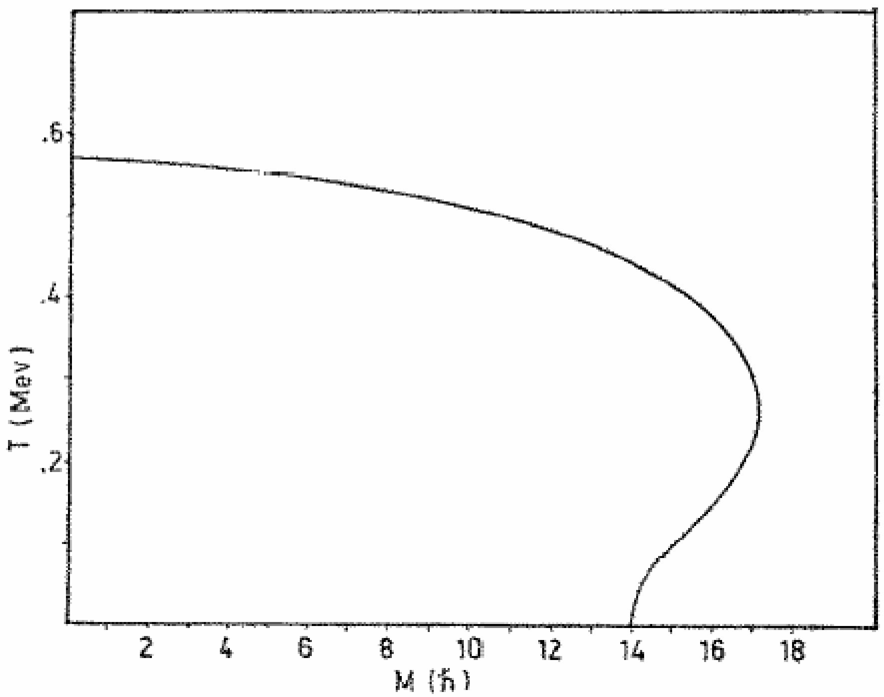
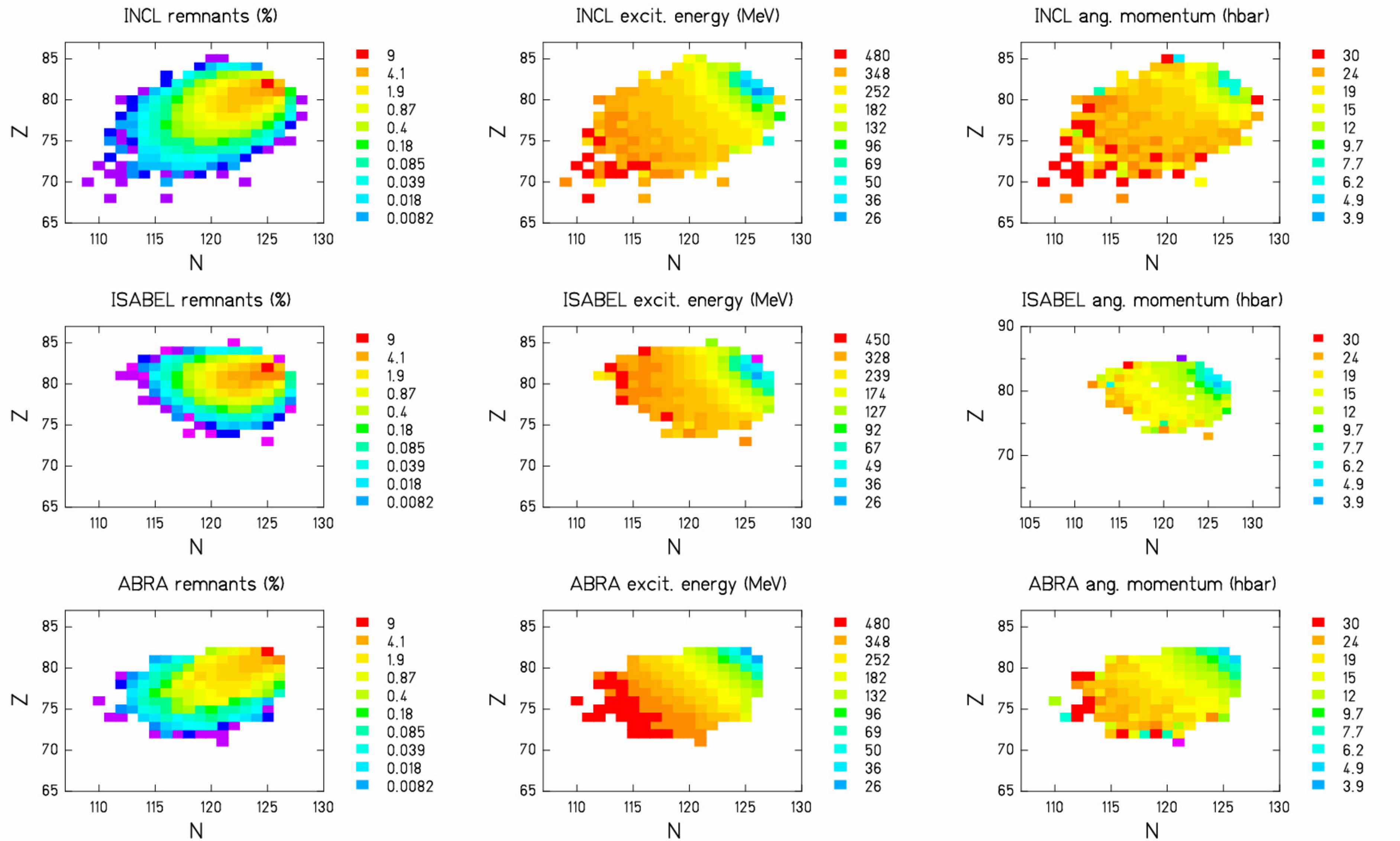


Fig. 5. Dependence of the critical temperature upon angular momentum. The parameters are the same as in fig. 4.

L. G. MORETTO

Nuclear Physics **A185** (1972) 145—165

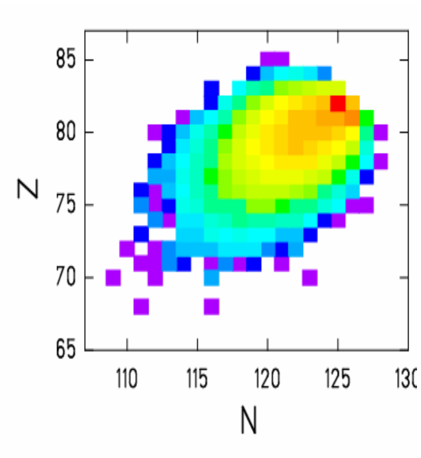
1 GeV p + ^{208}Pb



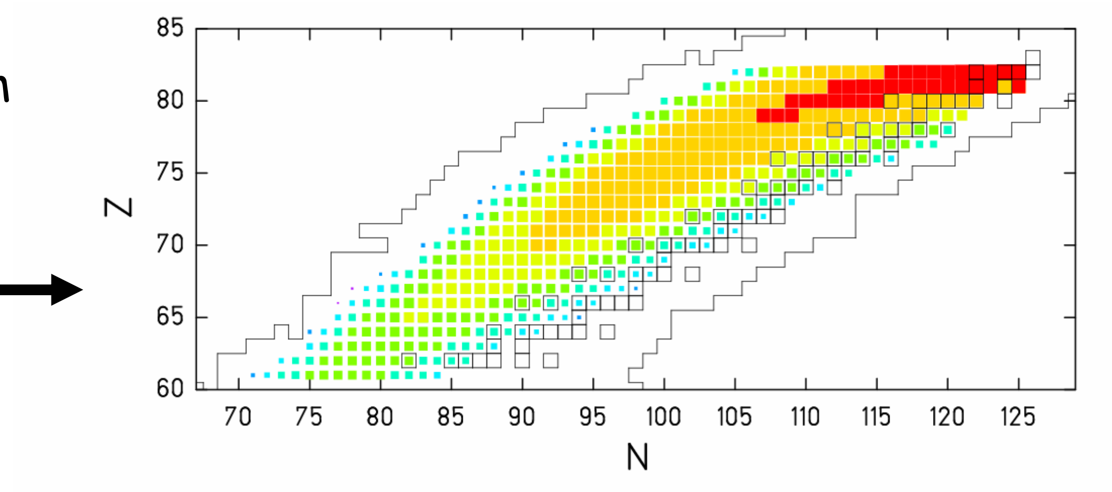
Angular momentum: rather low for most pre-fragments

In Fe+Ti: similar or higher angular momentum → strong e.o. staggering!

Could be gamma emission responsible for the disappearing of the even-odd staggering?



we go from here to there



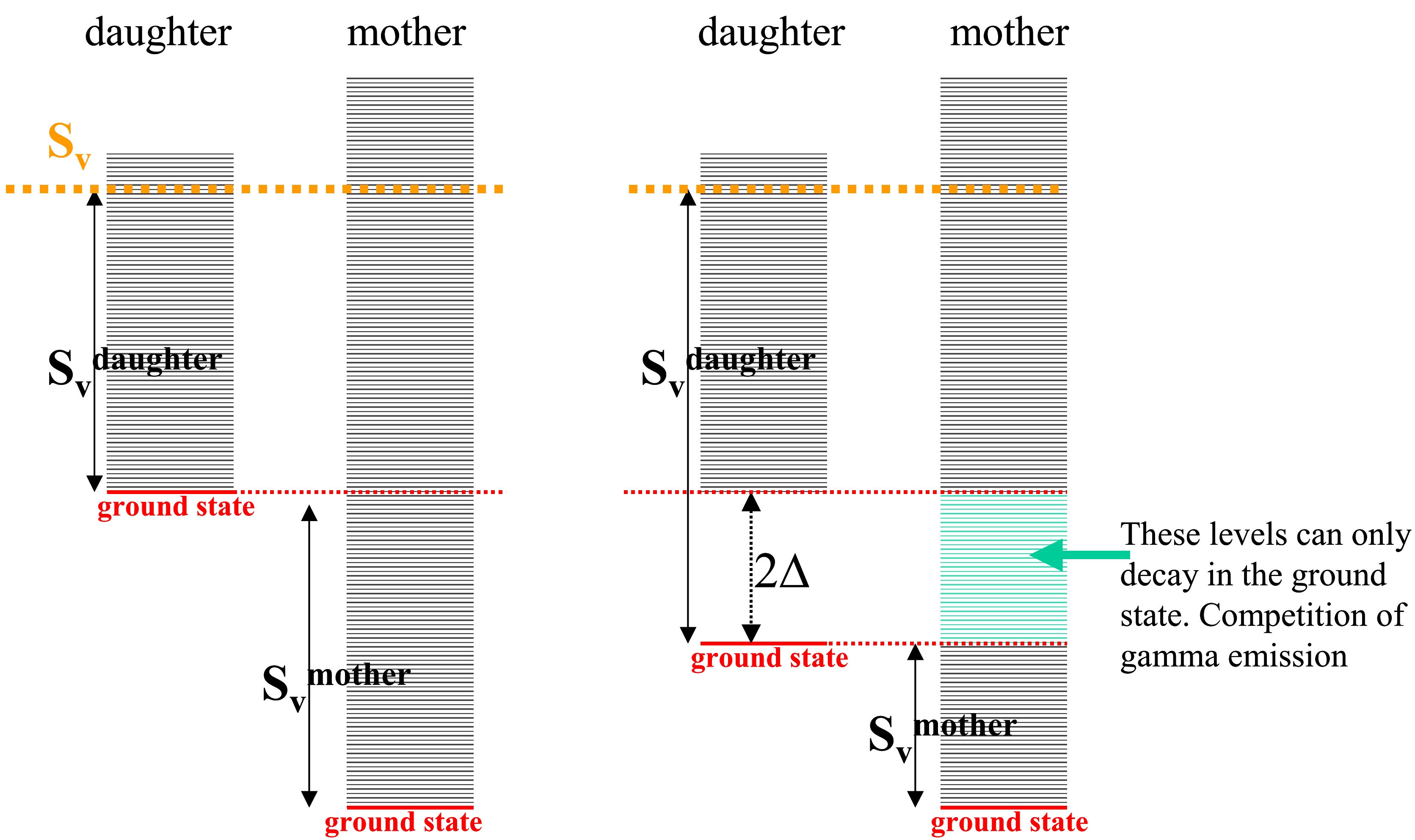
The population of pre-fragments will remain always smooth as long as the excitation energy remains above the pairing critical energy

Only when the excitation energy drops eventually below the pairing critical energy (typically in the last evaporation step) pairing correlations are established and even-odd structures may appear

The population of parent nuclei in the last evaporation step is still smooth.

We test the idea that parent nuclei in certain conditions do not further decay by particle emission but cool down by gamma decay

The competition with gamma decay



ABLA07

http://www-nds.iaea.org/reports-new/indc-reports/indc-nds/indc-nds-0530.pdf

mostly Aleksandra Keliċ-Heil, Karl-Heinz Schmidt - GSI

$$\Gamma_\nu(E_i) = \frac{2 \cdot s_\nu + 1}{2 \cdot \pi \cdot \rho_i(E_i)} \cdot \frac{2 \cdot m_\nu}{\pi \cdot \hbar^2} \cdot \int_0^{E_i - S_\nu - B_\nu} \sigma_c(\varepsilon_\nu) \cdot \rho_f(E_f) \cdot (\varepsilon_\nu - B_\nu) \mathrm{d}E_f$$

$$\rho_{in}(E) = \frac{\sqrt{\pi}}{12} \frac{\exp(S)}{\tilde{a}^{1/4} E_{eff}^{5/4}}$$

$E_{eff} = E$	odd Z – odd N
$E_{eff} = E - \Delta$	odd A
$E_{eff} = E - 2\Delta$	even Z – even N.

$$\Delta = 12 / \sqrt{A}$$

$$S = 2 \cdot \sqrt{\tilde{a} \cdot E_{corr}} = 2 \cdot \sqrt{\tilde{a} \cdot \left(E_{eff} + \delta U \cdot k(E_{eff}) + \delta P \cdot h(E_{eff})\right)}$$

$$\tilde{a} = 0.073 \cdot A + 0.095 \cdot B_S \cdot A^{2/3}$$

$$\delta P = -\frac{1}{4} \cdot \Delta^2 \cdot g + 2 \cdot \Delta \qquad g = 6 \cdot \tilde{a} / \pi^2$$

δU is the shell-correction energy

$$k(E_{eff}) = 1 - \exp(-\gamma E_{eff})$$

$$h(E_{eff}) = \begin{cases} 1 - \left(1 - \dfrac{E_{eff}}{E_{crit}}\right)^2, & E_{eff} < E_{crit} \\ 1, & E_{eff} > E_{crit} \end{cases}$$

ABLA07 (continue)

contribution of collective excitations to the level density

$$\rho(E) = \rho_{in}(E) \cdot K_{vib}(E) \cdot K_{rot}(E)$$

vibrational and rotational enhancement factors.

In order to calculate the intrinsic level density at very low excitation energies, we switch from the Fermi-gas level density to the constant-temperature level density [35]. The calculation is based on the work performed in Ref. [36], where the values of the parameters of the constant-temperature level density approach were obtained from the simultaneous analysis of the neutron resonances and the low-lying levels in the framework of the Gilbert-Cameron approach [35].

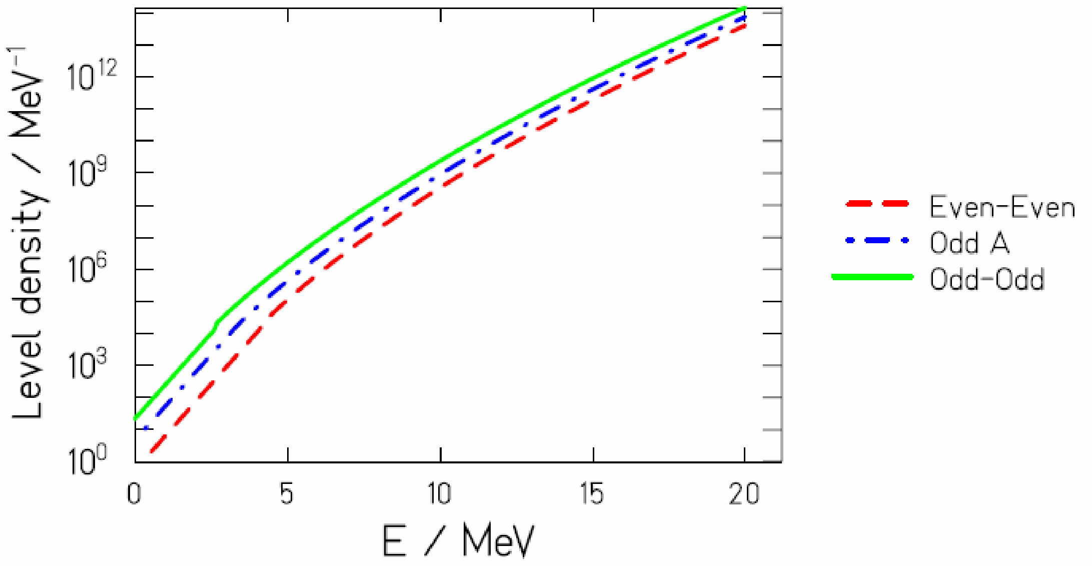


Figure 1: Intrinsic level density $\rho_{in}(E)$ for three nuclei – ^{242}Cf, ^{241}Bk and ^{240}Bk – calculated in ABLA07 using combined Fermi-gas – constant-temperature level density approach.

Modeling of Γ_γ in ABLA07

To test the possible competition of gamma decay we calculated the gamma decay width with a simple parameterisation of A.V. Ignatyuk (Proceed. Bologna 2000)

2 Systematics of Total Radiative Widths

For many nuclei beside the neutron resonance spacing the total radiative widths are determined too [1, 10]. The total radiative widths connected with the level densities by the relation

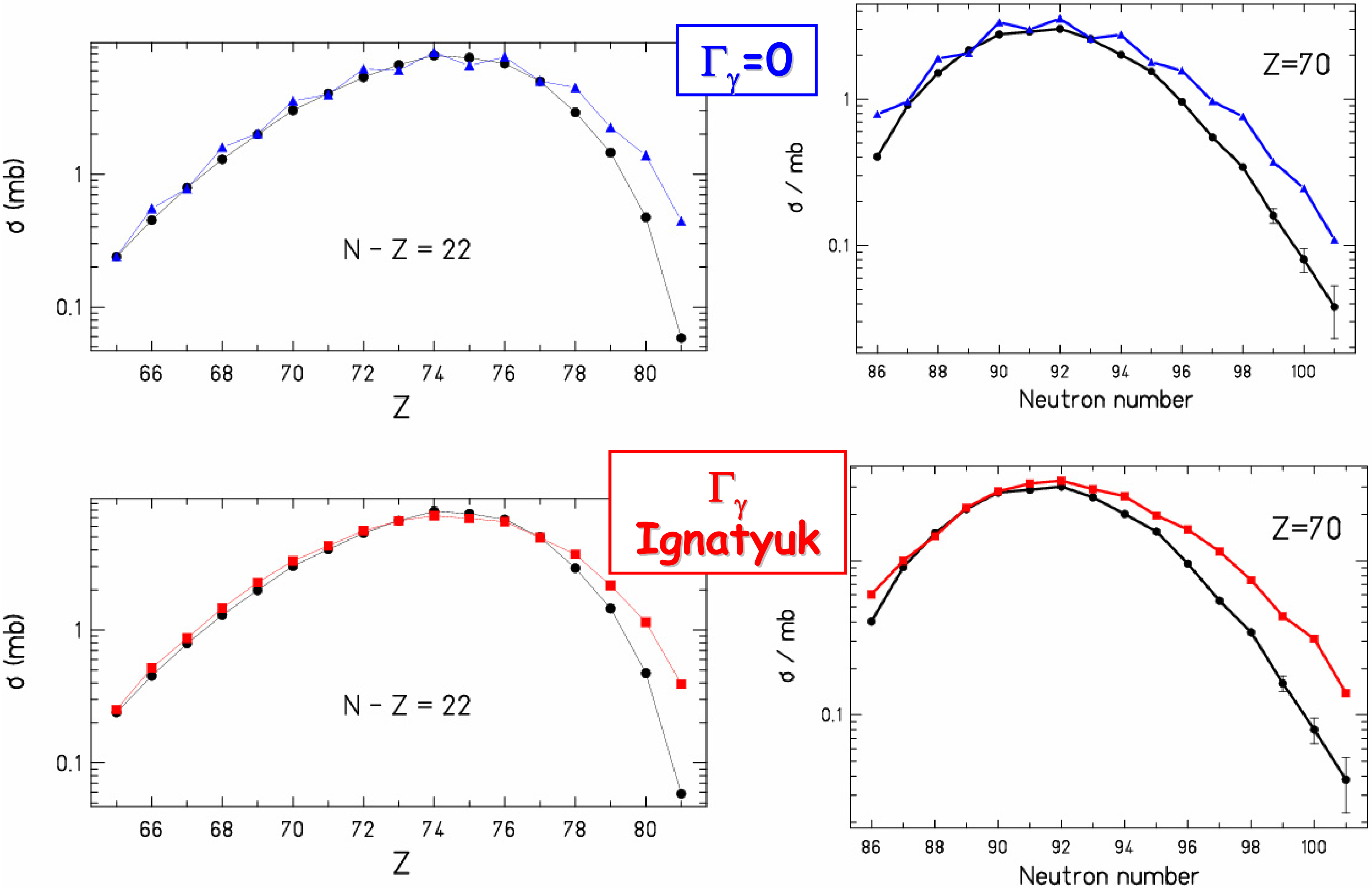
$$\Gamma_\gamma^{tot}(B_n, J) = \sum_\lambda \sum_{I=|J-1|}^{J+1} \int_0^{B_n} \varepsilon_\gamma^3 k_{E(M)\lambda}(\varepsilon_\gamma) \frac{\rho(B_n - \varepsilon_\gamma, I)}{\rho(B_n, J)} d\varepsilon_\gamma \qquad (5)$$

where $k_{E\lambda}(\varepsilon_\gamma)$ is the radiative strength function for the corresponding electric $E\lambda$ or magnetic $M\lambda$ gamma-transitions. As a rule, the dipol electric transitions with energies of 2-3 MeV dominate into the integrant of Eq. (5). Using the power approximations for the radiative strength functions [11] and the constant temperature model, Eq. (5) can be transformed to the very simple form

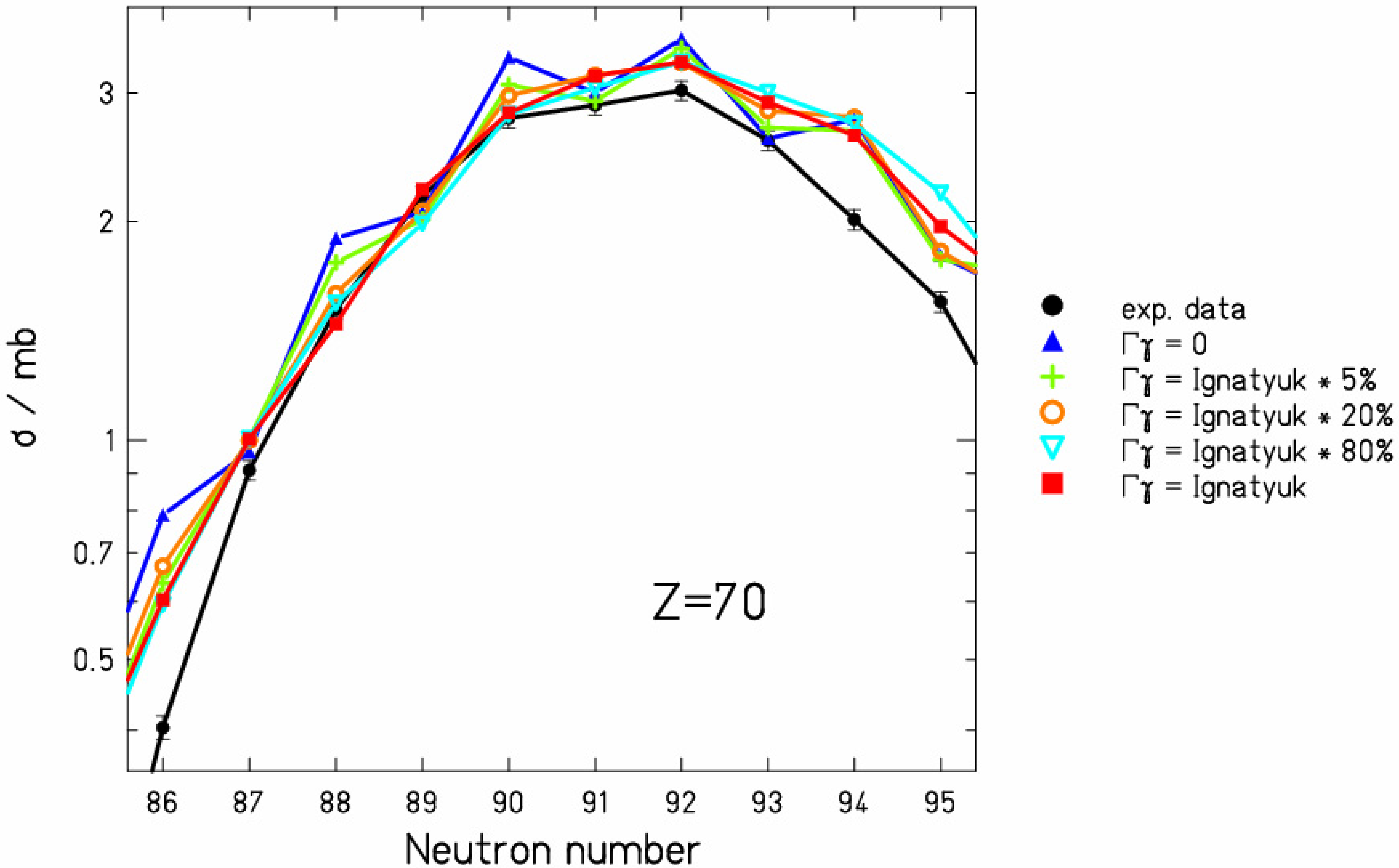
$$\Gamma_\gamma = .624 A^{1.60} T^5 \quad , \qquad T = 17.60 / A^{.699} \sqrt{1 + \gamma \delta E_0} \qquad (6)$$

where the numerical coefficient corresponds to the widths expressed in eV. Relations similar to (5) were analyzed by many authors [10, 12, 13].

Results



The ratio $\Gamma_{particle}/\Gamma_{\gamma}$ is sensitive to the strength of even-odd staggering!



σ / mb
3
2
1
0.7
0.5
86
87
88
89
90
91
92
93
94
95
Neutron number
Z=70
exp. data
Γγ = 0
Γγ = Ignatyuk * 5%
Γγ = Ignatyuk * 20%
Γγ = Ignatyuk * 80%
Γγ = Ignatyuk

The ratio $\Gamma_{particle}/\Gamma_\gamma$ is sensitive to the strength of even-odd staggering!

Potentially a powerful method because:

- not limited to the stability of a target
- in principle usable also to investigate extremely exotic nuclei
- investigates gamma emission from an excited nucleus (astrophysics)
- could lead to study systematic tendencies along the chart of the nuclides
- could lead to find out peculiarities of some specific nuclide deviating from systematic

Things to be considered:

- one must fix the contribution of angular momentum (benchmark on light fragments)
- it requires knowledge on the first excited states (the knowledge exists)
- it could require very precise measurement of production cross sections (question of beam time)
- more...

CONCLUSIONS

Experimental study of even-odd staggering in the yields bring interesting information on our understanding of the last evaporation step

The phase-space, which is related to the level density, is not the relevant quantity anymore in the last evaporation step: It is the separation energy, which gives the range of excitation energy, which "catches" the evaporation flux in particle-stable states.

In heavy fragments, the competition between gamma and particle decay becomes relevant in the last evaporation step

The strength of the even-odd staggering in the data is sensitive to the ratio between gamma and particle decay width

The strength of the even-odd staggering in the data could lead to a possible new method for the investigation the total radiative widths

Thank you!

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