Complex nuclear-structure phenomena revealed from the nuclide production in fragmentation reactions

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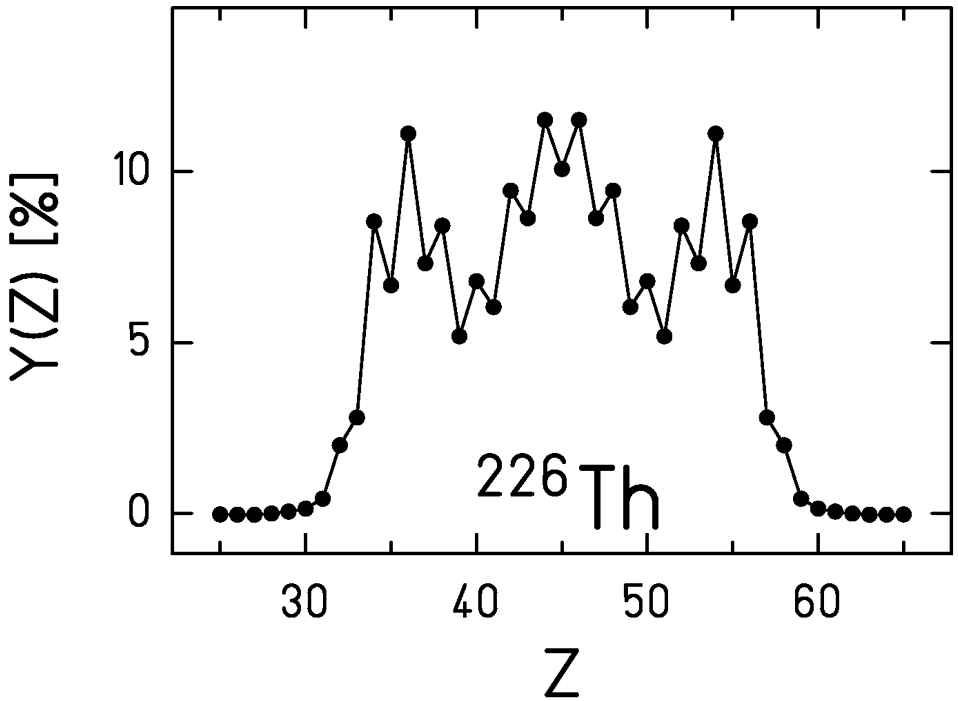
OUTLINE

- Structural effects observed in low energy reactions
- Experiment: $^{238}U \rightarrow Ti$ at 1 A·GeV at the FRS (GSI)
- Results: production cross sections of residual nuclides

  → Data reveal complex structural effects
- How to interpret the results
- Analysis of the results with statistical evaporation model
- The role of pairing and other possible effects
- Conclusions

Even-odd structure in low-energy fission

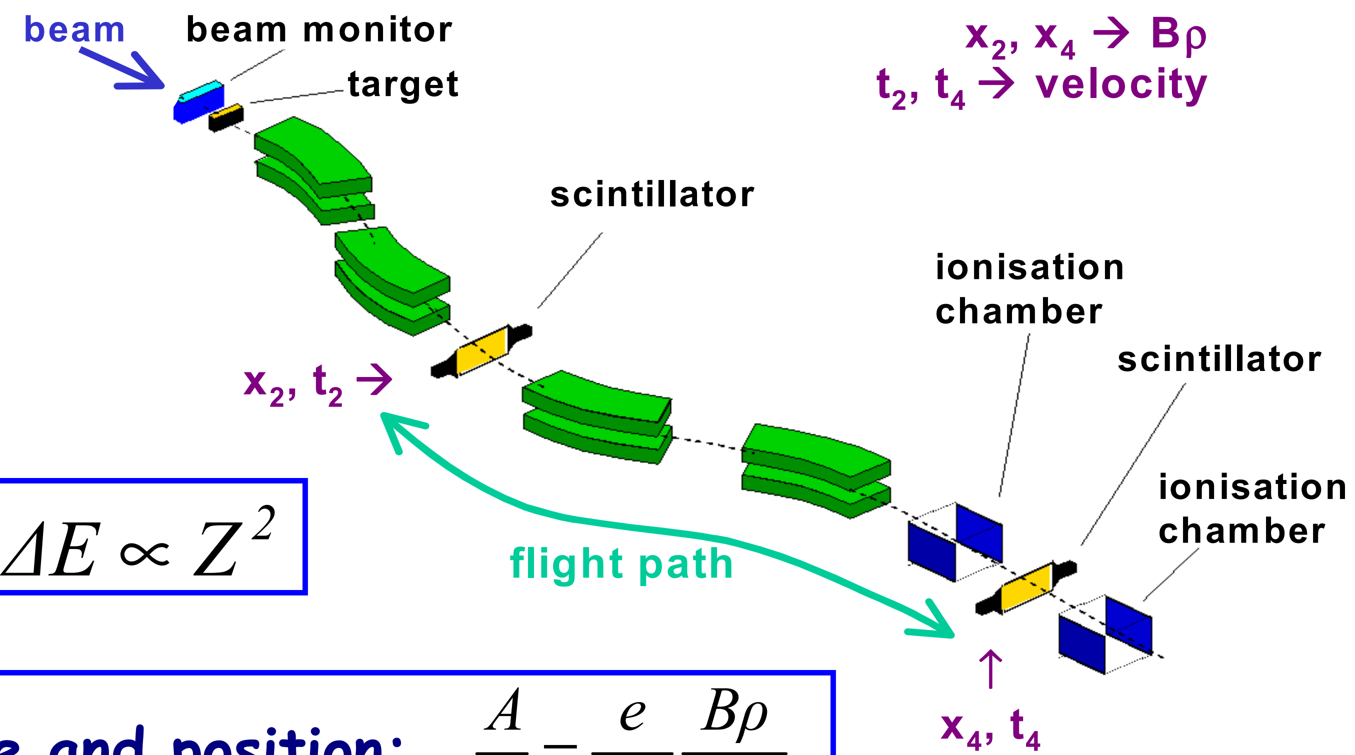


Results from e.m.-induced fission of 70 different secondary projectiles
(Steinhäuser et al., NPA634 89, 1998)

Structural properties survive at low energy
What does it happen at high energy?

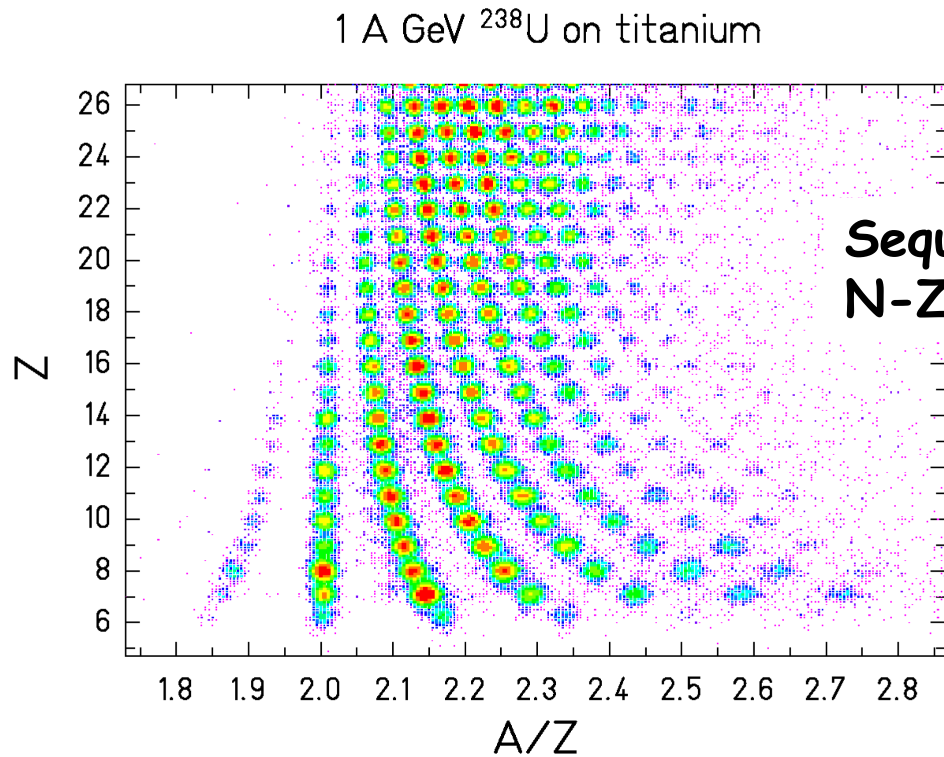
THE EXPERIMENT AT THE FRS AT GSI

1 A·GeV $^{238}U \rightarrow Ti$



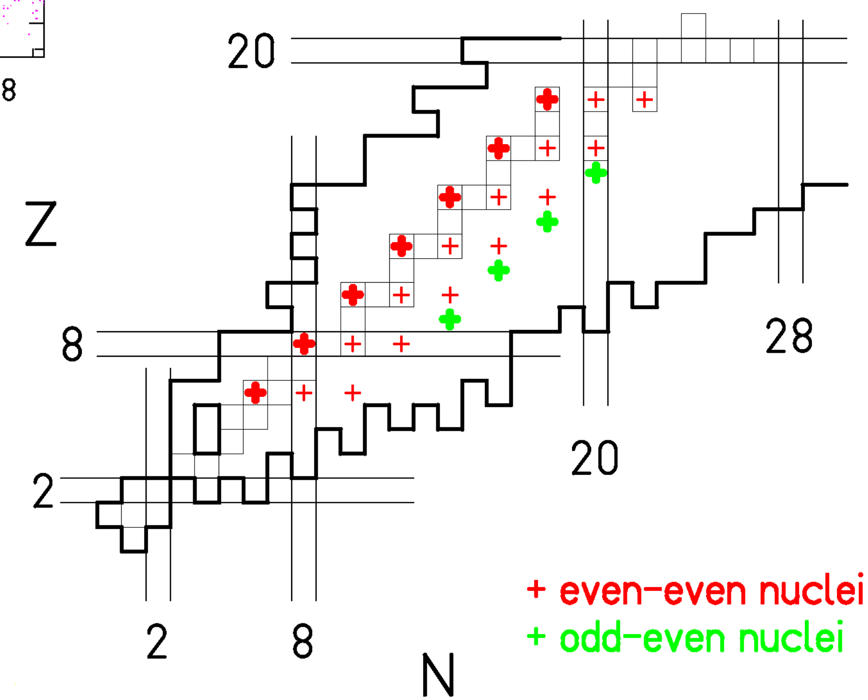
Z from IC: $\Delta E \propto Z^2$

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

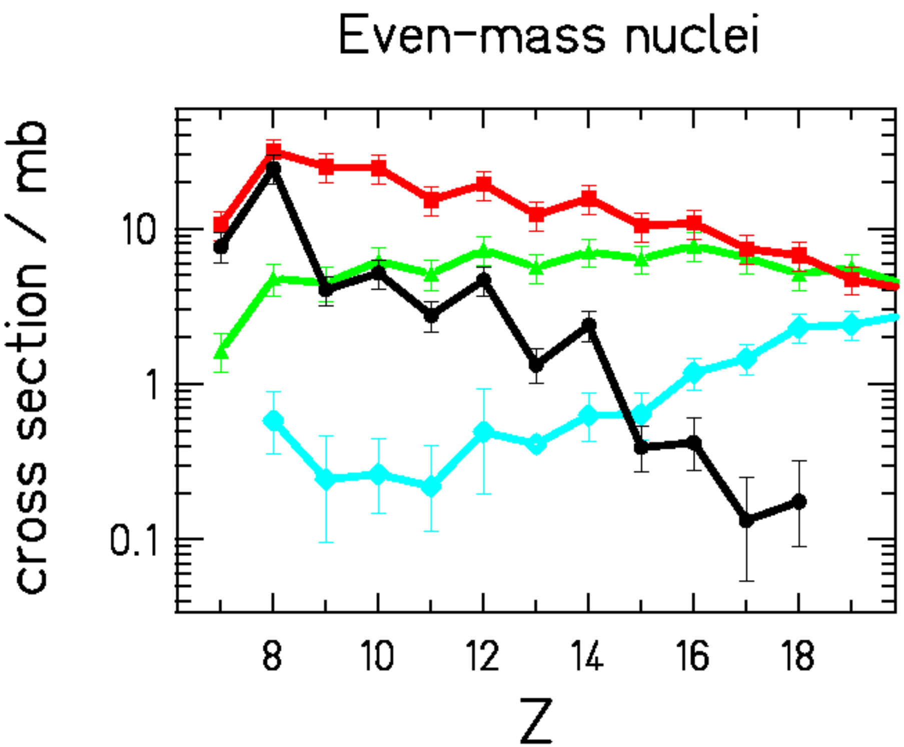


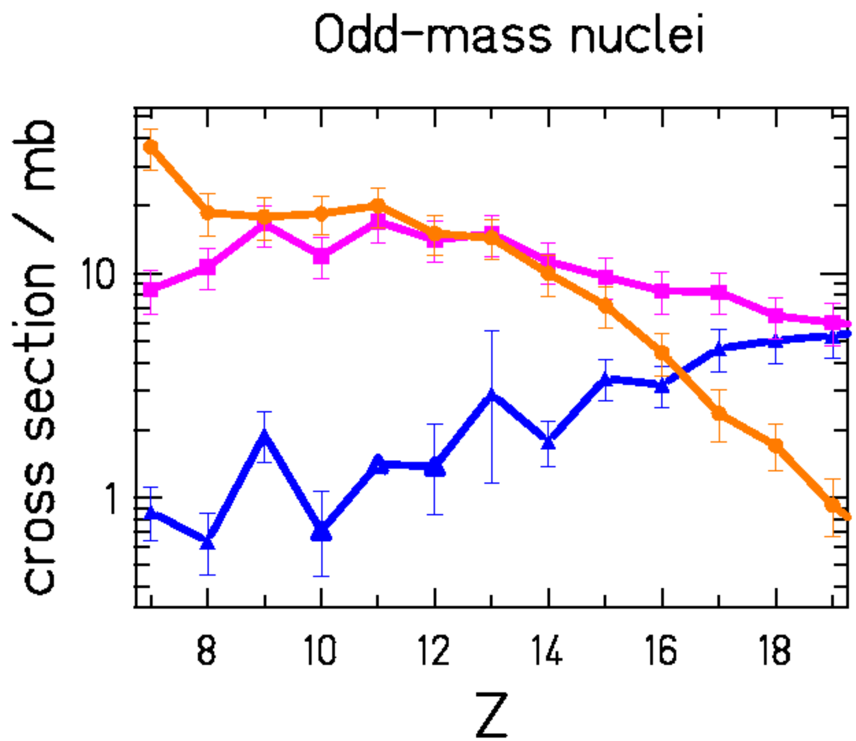
Sequence:
N-Z=constant

Nuclei with enhanced production



EXPERIMENTAL RESULTS





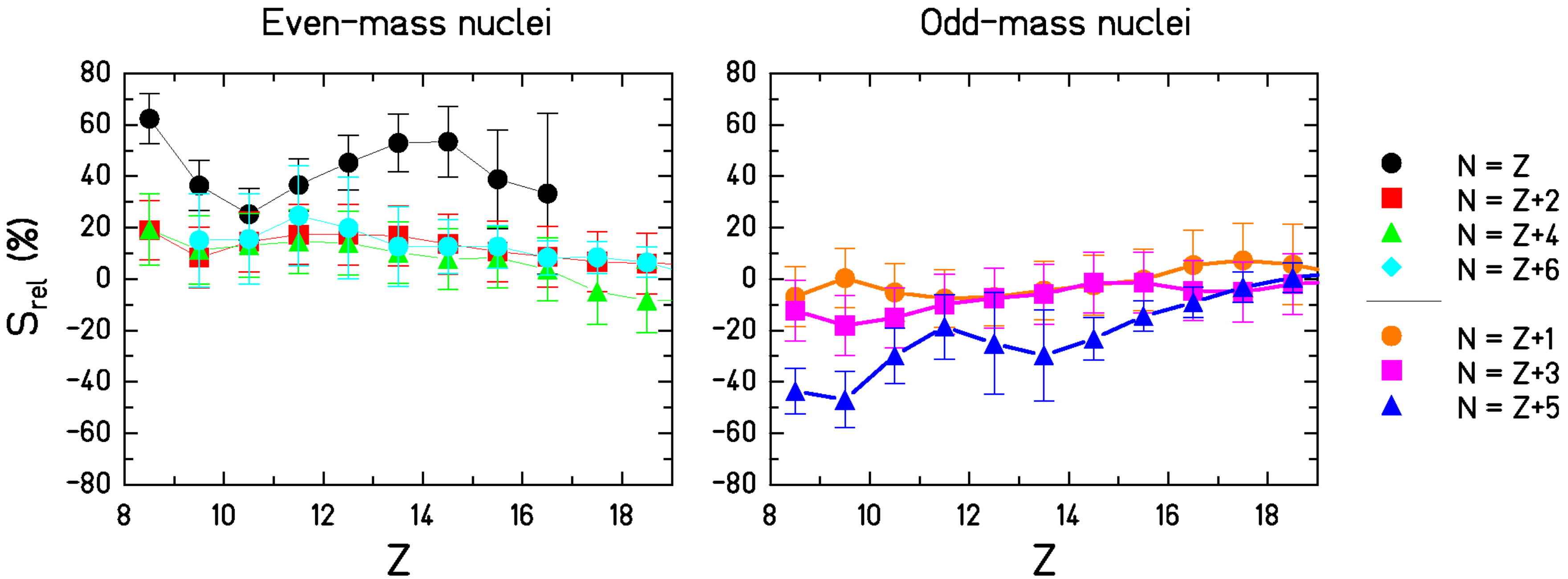
● N=Z ■ N=Z+2
▲N=Z+4 ♦N=Z+6

● N=Z+1 ■ N=Z+3
▲N=Z+5

the data reveal complex structural effects

STRENGHT OF THE STAGGERING - TRACY'S ANALYSIS

$$Srel(Z+3/2)=\frac{1}{8}(-1)^{Z+1}\left[ln\,Y(Z+3)-ln\,Y(Z)-3\left(ln\,Y(Z+2)-ln\,Y(Z+1)\right)\right]$$



S_{rel} = 0 means a smooth behaviour

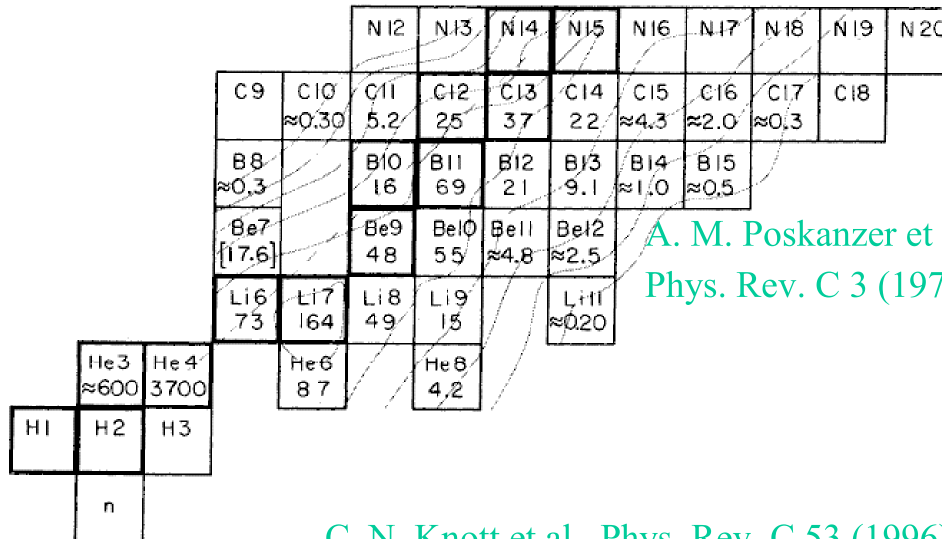
S_{rel} > 0 means enhanced production of even-*Z* nuclei

S_{rel} < 0 means enhanced production of odd-*Z* nuclei

COMPARISON WITH OTHER DATA

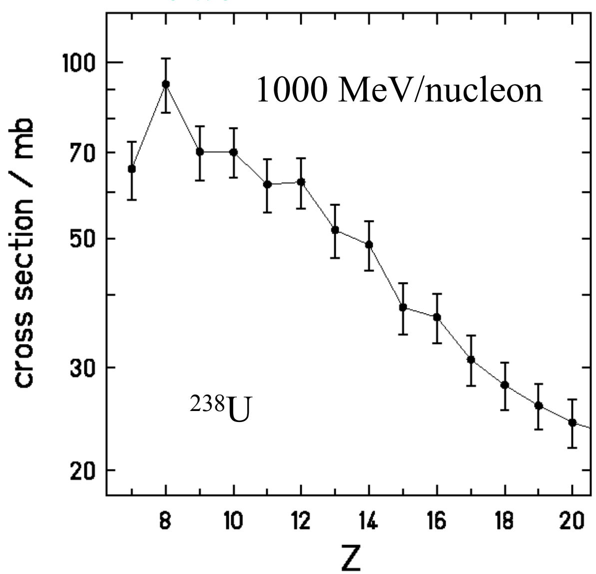
Reference	Reaction	Beam energy
B. Blank et al. [NIM A286 (1990)]	$^{40}Ar + ^{12}C$	403 A MeV
W. R: Webber et al. [PRC 41 (1990)]	$^{56}Fe + ^{12}C$	600 A MeV
Ch. O. Bacri et al. [NP A555 (1993)]	$^{40}Ar + Ni$	44 A MeV
C. N. Knott et al. [PRC 53 (1996)]	e.g. $^{32}Si + ^{1}H$	e.g. 571 A MeV
C. Zeitlin et al. [PRC 56 (1997)]	^{56}Fe + div.	1.05 A GeV
Sl. Cavallaro et al. [PRC 57 (1998)]	$^{35}Cl + ^{24}Mg$	8 A MeV
L. B. Yang et al. [PRC 60 (1999)]	$^{58}Fe + ^{58}Fe$ $^{58}Ni + ^{58}Ni$	45 to 105 A MeV
E. M Winchester et al. [PRC 63 (2001)]	$^{40}Ca + ^{58}Ni$ $^{40}Ar + ^{58}Fe$	25 A MeV

5500 MeV protons on ^{238}U

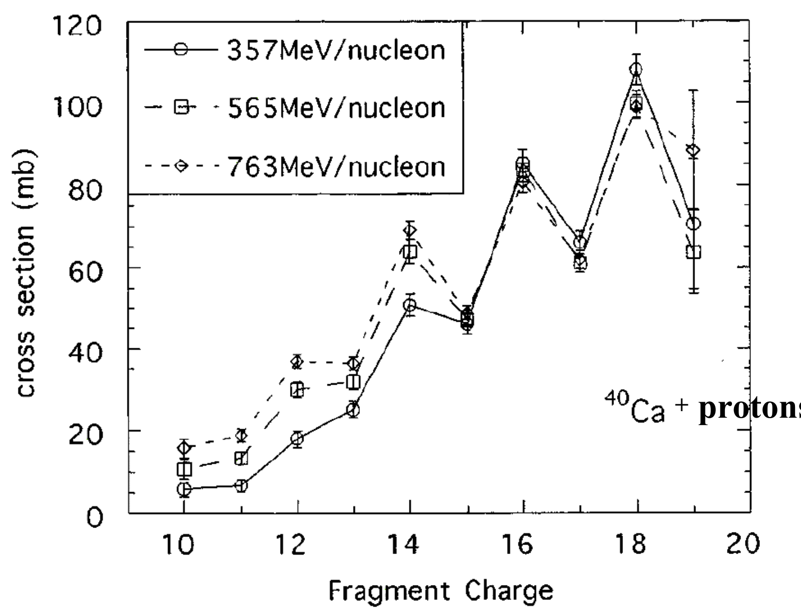


A. M. Poskanzer et al., Phys. Rev. C 3 (1971) 882

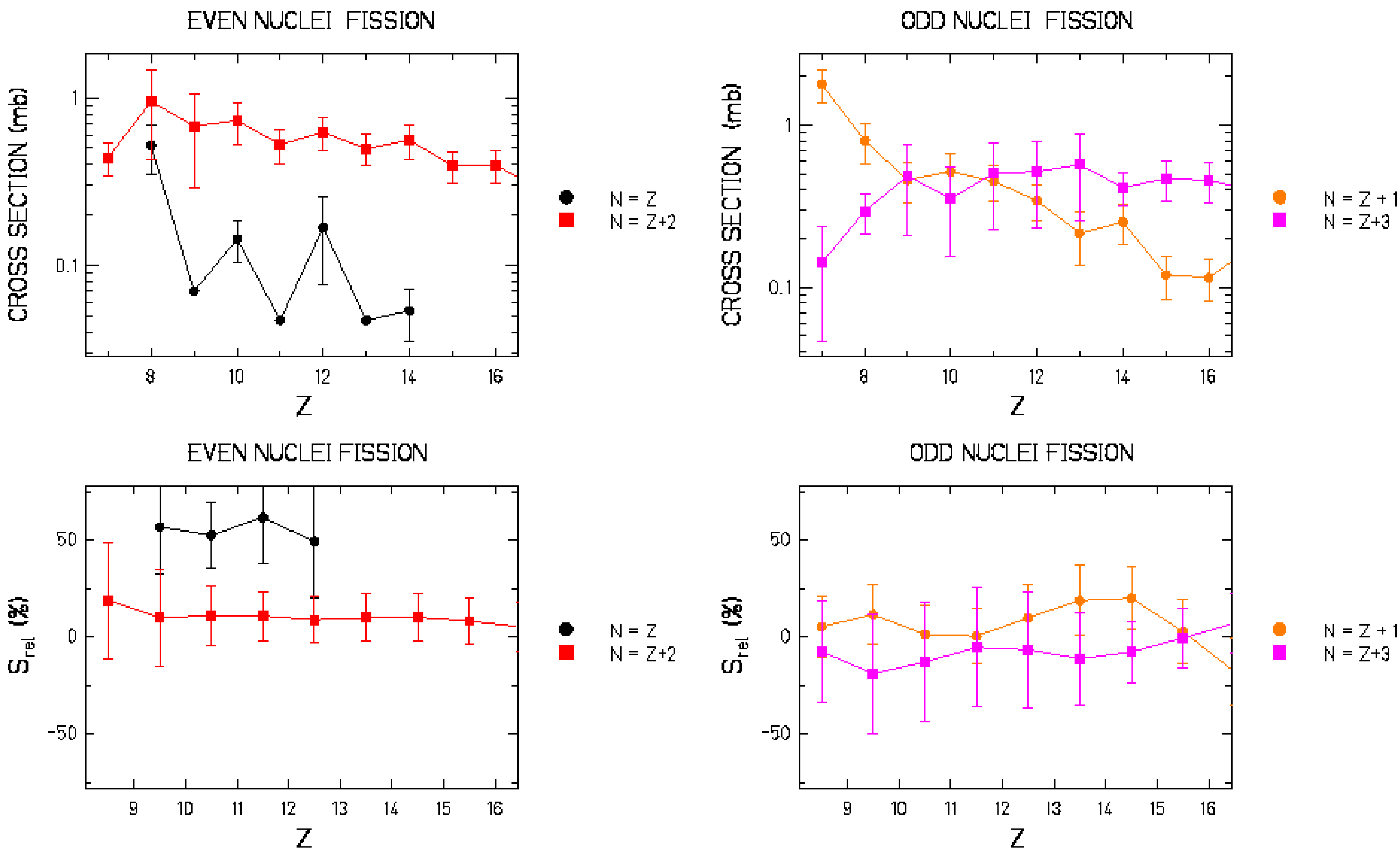
this work



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



Fission products from ^{238}U on protons at 1A GeV (this work)



HOW TO INTERPRET THE RESULTS

Nuclear structure manifests itself in:

- Ground-state properties (binding energy, half-life, radius, deformation)
- All production yields in specific nuclear reactions at low energies (low-energy fission, transfer reactions)

but also in:

- Light production yields in specific nuclear reactions at high energies (fragmentation, deep inelastic, high-energy fission)

This experimental results can have a two-fold interpretation:

either part of the high-energies reactions, by some unknown reason, pass by very low excitation energies

or nuclear structure can manifest itself also in the end-products of very hot nuclei ← we test this hypothesis

ANALYSIS WITH THE STATISTICAL MODEL

The available phase space for the final residue determines its yield
(T. Ericson (1960))

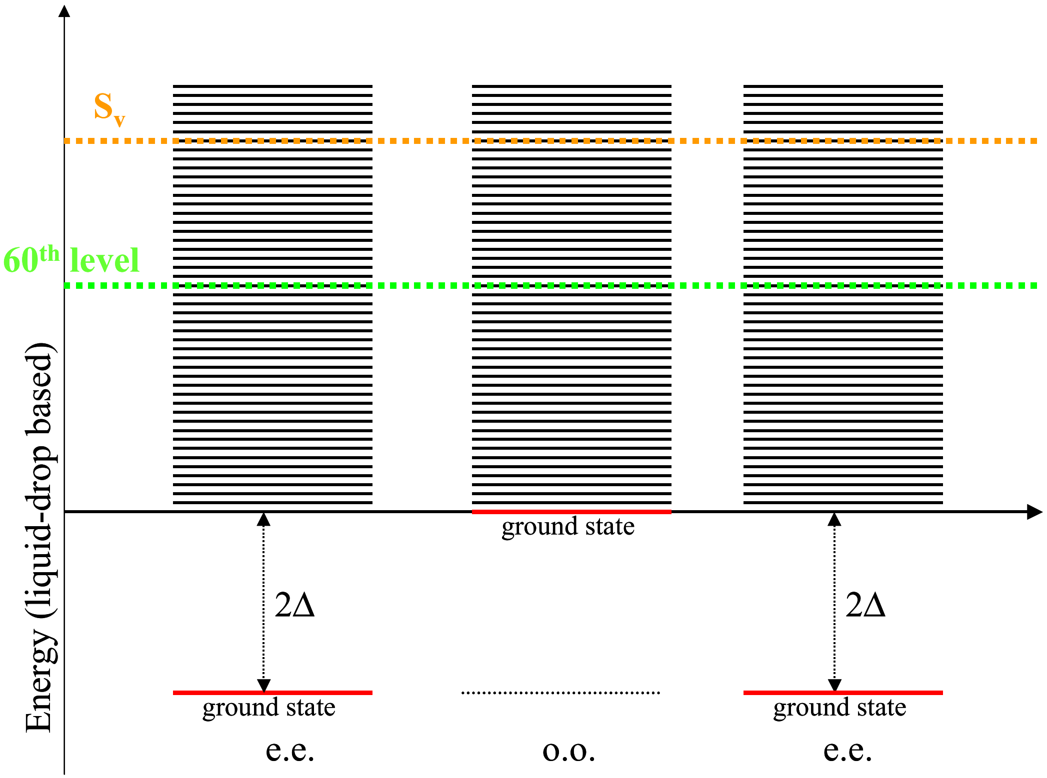
available phase space = number of possible final states = number of bound states

The number of particle bound states is determined by number of energy levels available between ground state and particle separation energy:

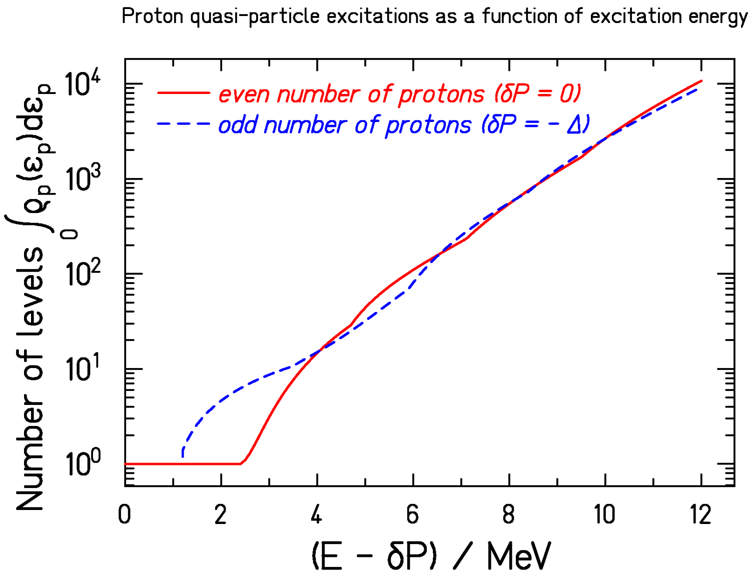
$$\int_{gs}^{S_\nu} \rho(E)\,dE = \int_{gs}^{S_\nu} \frac{\sqrt{\pi}}{12} \frac{exp\left(2\sqrt{a(E-\delta)}\right)}{a^{1/4}(E-\delta)^{5/4}}\,dE$$

$$\begin{cases} \delta_{oo} = 0 \\ \delta_{oe} = \delta_{eo} = \Delta \\ \delta_{ee} = 2\Delta \end{cases} \qquad \Delta = \frac{12}{\sqrt{A}}$$

$$S_\nu = m_\nu + M_{X-\nu} - M_X \qquad M = M_{LD} - \delta$$



V. M. Strutinsky (1958)

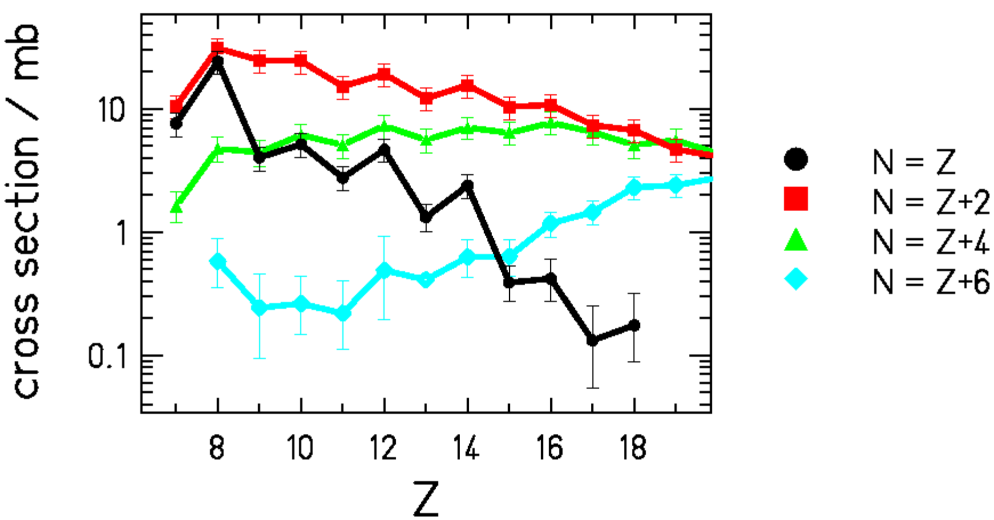


"The combined pairing effects in binding energies and level densities cancel in such a way that evaporation <u>cross sections</u> become approximately <u>independent of pairing effects</u>"

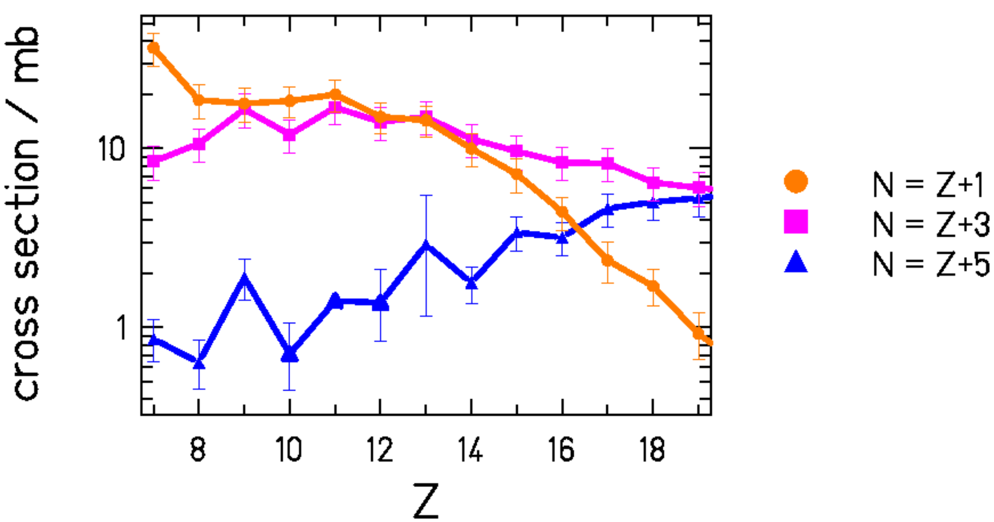
(T. Ericson, Advances in Physics 9 (1960) page 471)

experiment

Even-mass nuclei

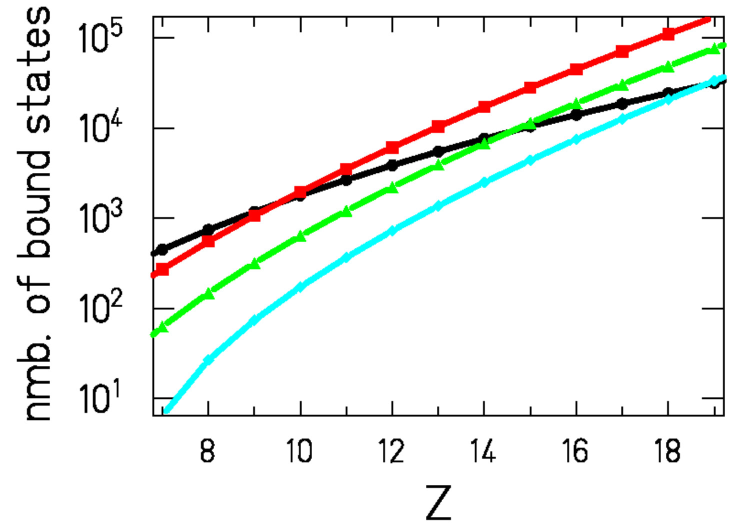


Odd-mass nuclei

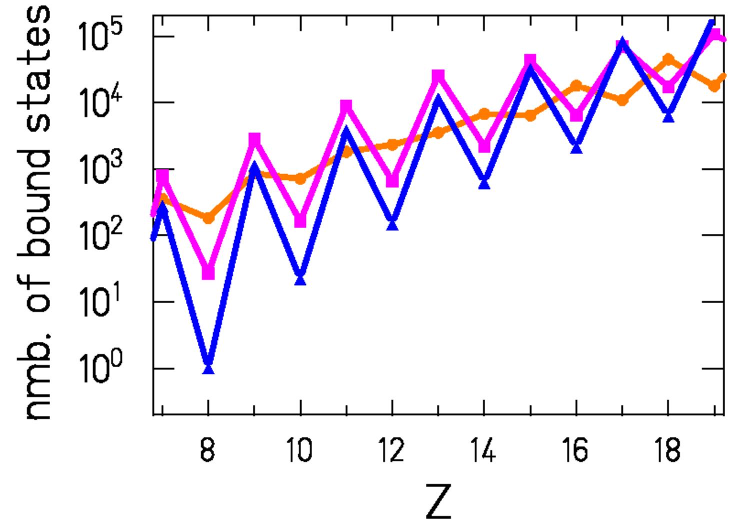


calculation "Ericson"

Even-mass nuclei

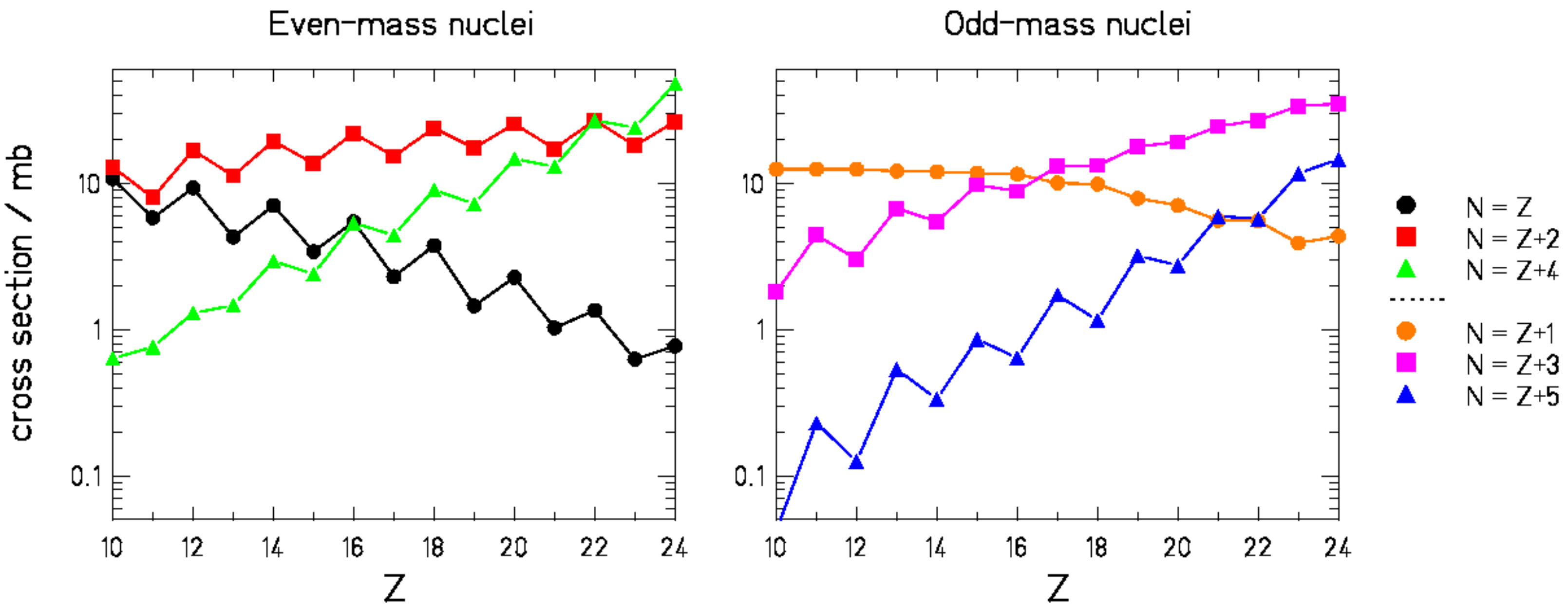


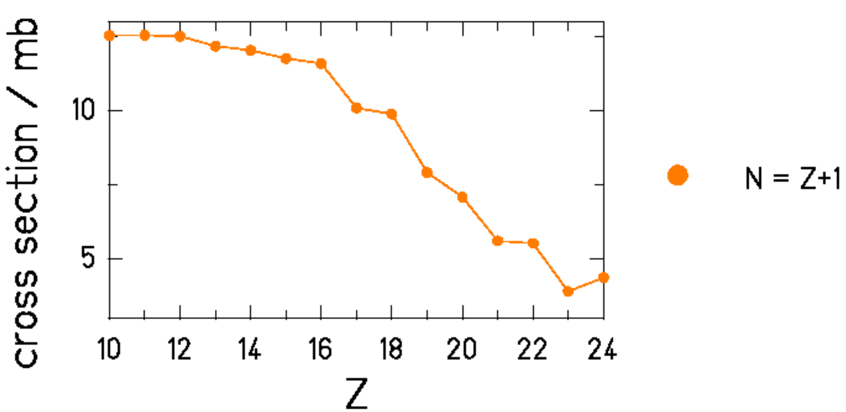
Odd-mass nuclei



ANALYSIS WITH AN EVAPORATION CODE (ABRABLA)

Same principle: in each step the probability of a certain decay channel is essentially determined by the number of possible final bound states

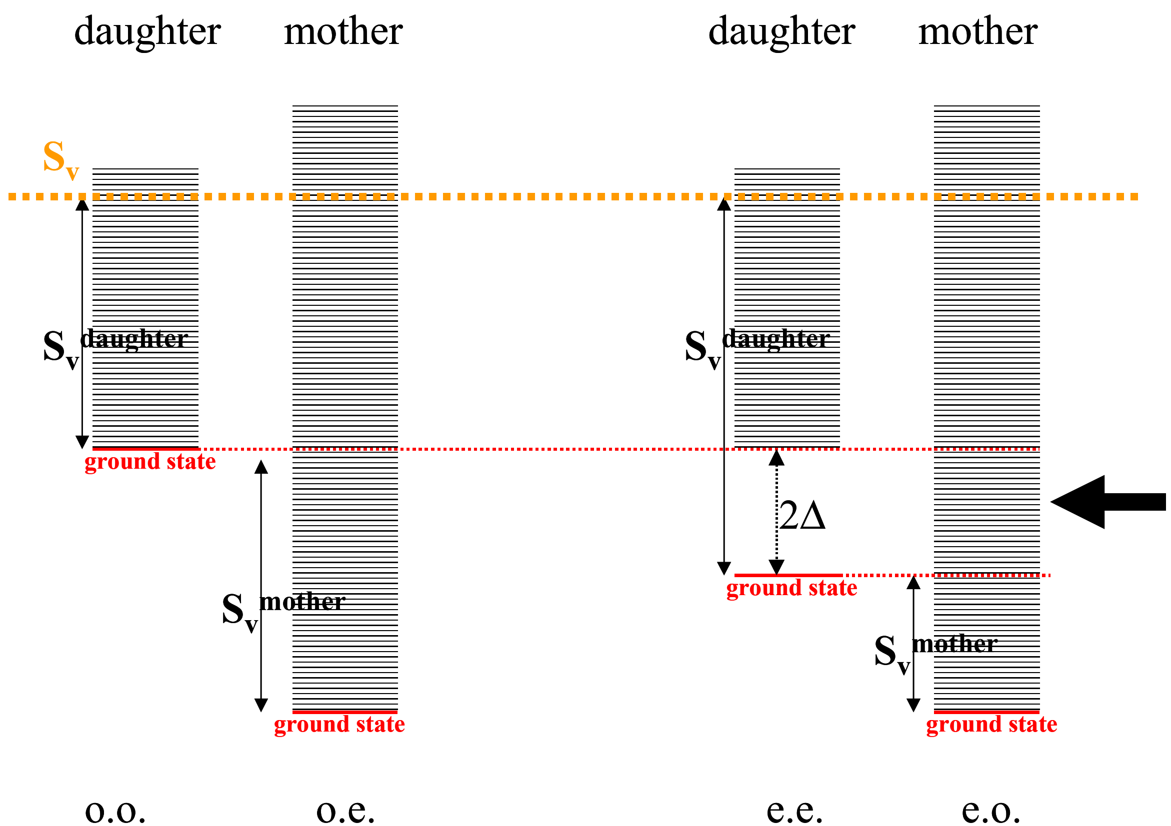




WHY THIS?

In each step the probability of a certain decay channel is essentially determined by the number of possible final bound states…

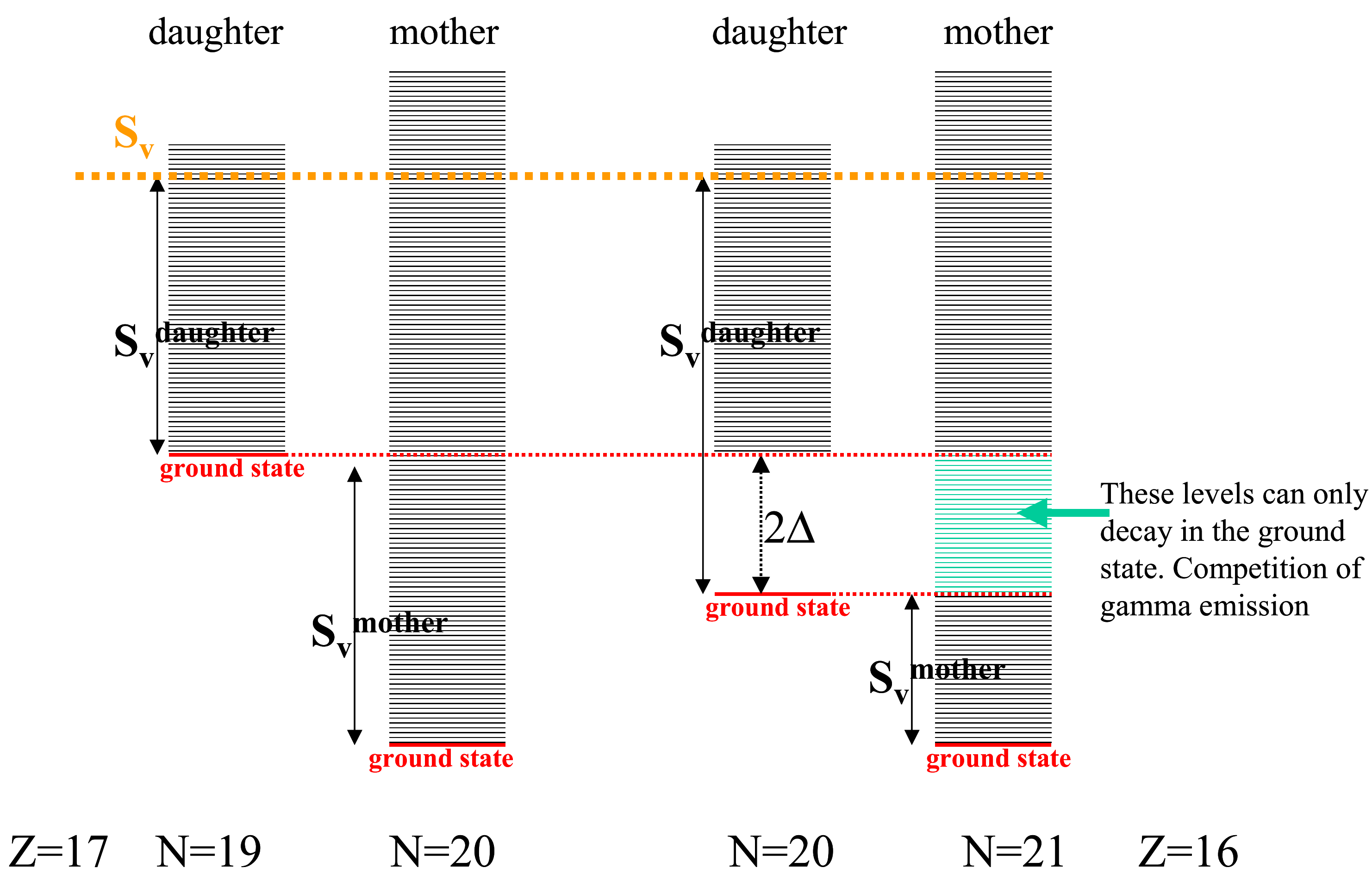
… but also by the number of possible excited levels in which the mother nucleus can sit before entering the decay channel



EVEN-ODD EFFECT FOR HEAVY RESIDUES

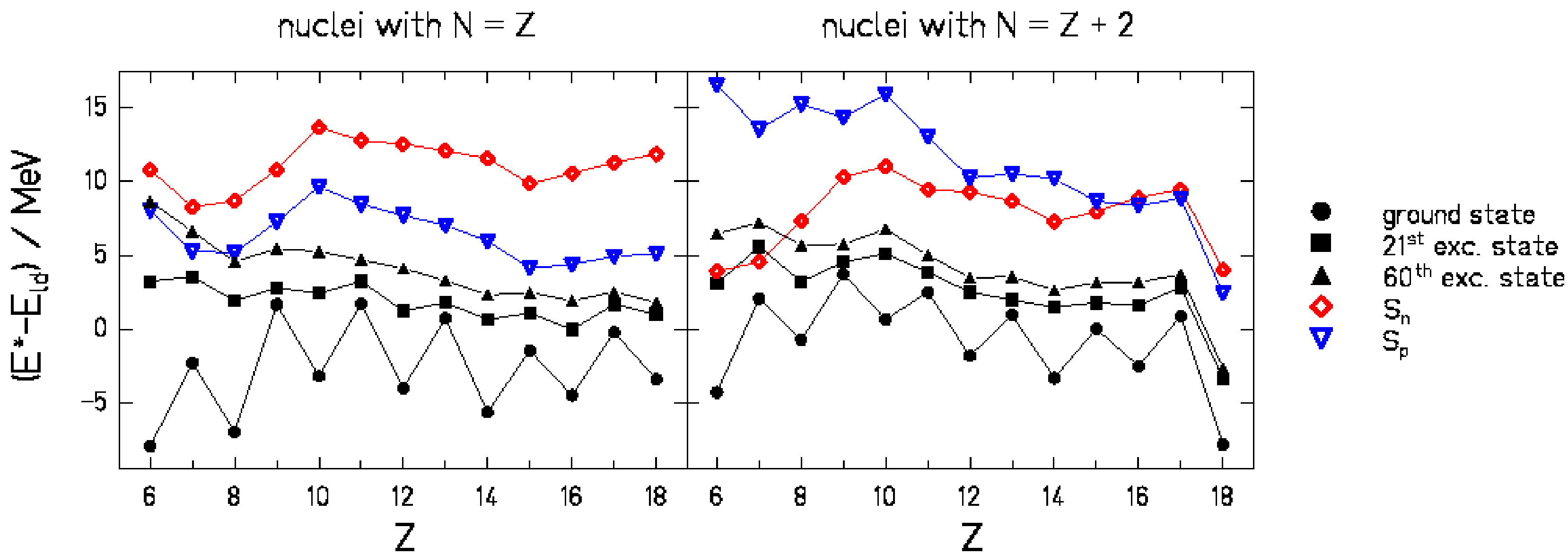
No staggering is found in the production yield of heavy residues

$$\Delta = \frac{12}{\sqrt{A}}$$ and gamma-emission are responsible for its disappearing

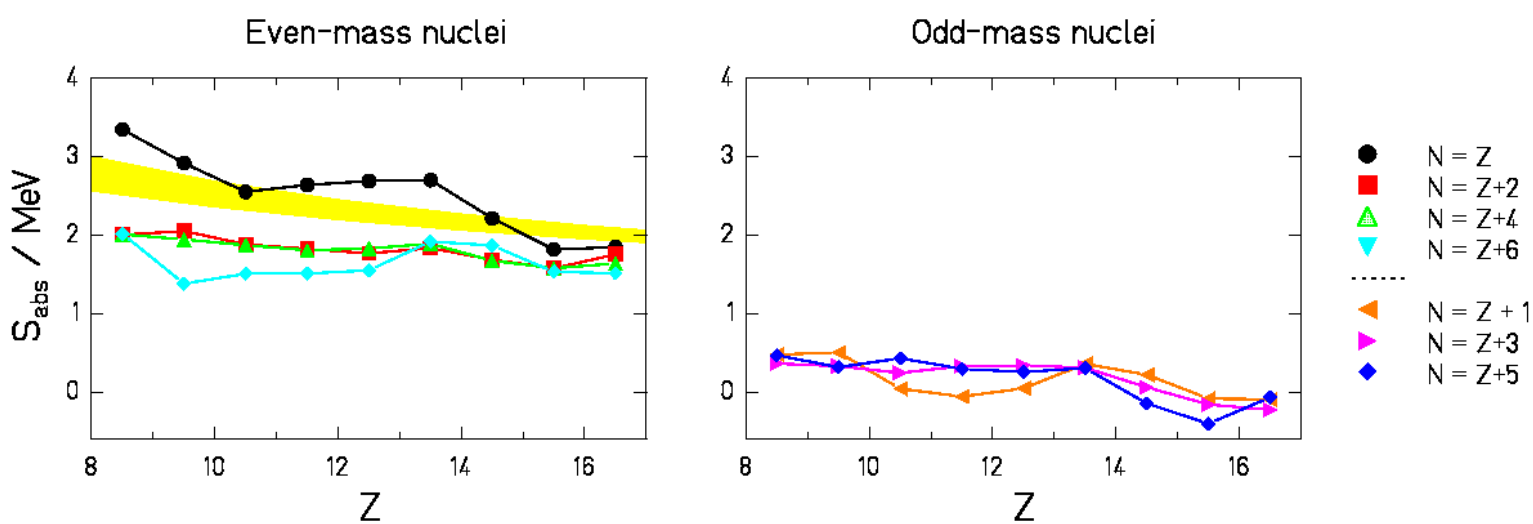


A closer view on ….

Measured excited levels



Measured binding energies



Facts and ideas

Statistical evaporation model:
→no enhanced staggering for N=Z nuclei with respect to other even-A residues

Measured binding energies and excited states
→more complex behavior than what described

Possible complex phenomena that could be responsible for the strong even-odd structure in N=Z residues:

- ***Mean-field contributions to pairing effects***
- ***Alpha clustering***
- ***Neutron-proton pairing***

Conclusions

Previous observations:

- Structural effects survive in the yields of all final products of low-energy fission, transfer reactions
- Structural effects are observed in the yields of light final products of fragmentation reactions, high-energy fission, deep inelastic reactions

Our experimental results: light nuclides of 1A·GeV ^{238}U+Ti :

- FRS allows full identification → formation cross section for every isotope. The complex structure of nuclei produced in rather violent collisions could be for the 1st time systematically investigated with an appropriate filter

Conclusions

- A statistical evaporation code can reproduce the main characteristics of the staggering: The the main characteristics of the staggering are a manifestation of the blocking effect of pairing
- Structural effects are restored in the end products of hot decaying nuclei, regardless of the first-stage of the reaction mechanism
- The strength of the staggering in the cross sections, the experimental masses and energy levels of nuclei suggest that more complex phenomena have to be introduced in the description. In particular, these complex phenomena could be responsible for the strong even-odd structure observed in the yields of the N=Z residues

yields from highly excited nuclei are a rich source of information on nuclear structure