Società Italiana di Fisica - 107° Congresso Nazionale
13 – 17 Settembre 2021

Recent Studies on Fission: Reaction Dynamics and Nuclear Structure

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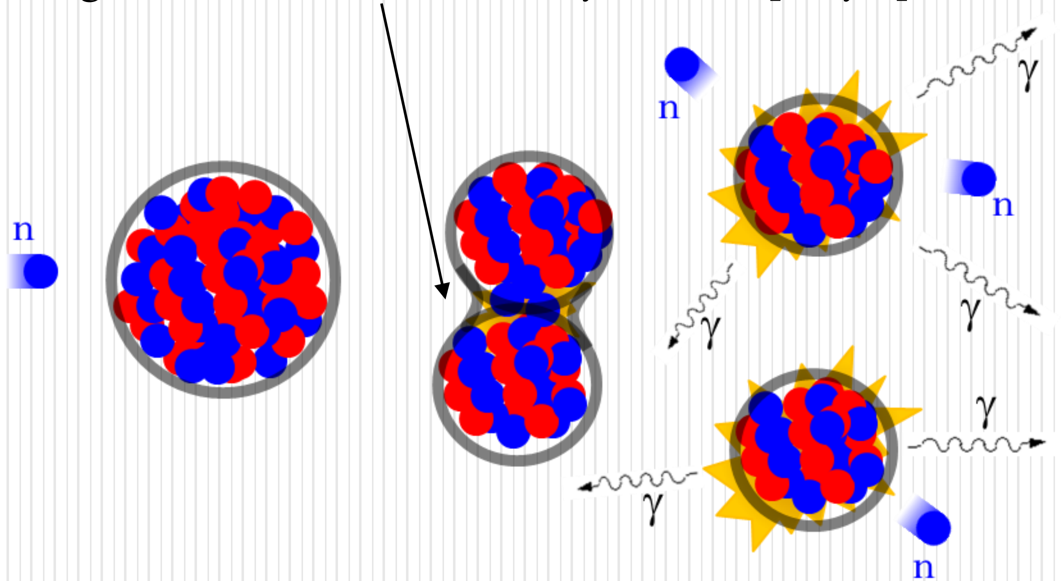
OUTLINE

- Introduction
  - *Experimental Technique: Gamma-ray Spectroscopy*
- Fission studies: Reaction dynamics (selected expample)
  - *Angular momentum generation*
- Fission studies: Nuclear Structure (selected expamples)
  - *Particle-core Excitations in the Nucleus ^{133}Sb*
  - *Onset of Shape Coexistence Before $N = 60$*
  - *Radioactive Ion Beams Facilities*
- Conclusions

Nuclear Fission

- Spontaneous or Induced (e.g. by neutron irradiation, beam induced)
- Competition between the surface energy and Coulomb energy can lead to an evolution in shape of a nucleus and finally to its scission
- The nascent fragments form a neck as they move rapidly apart, which quickly snaps

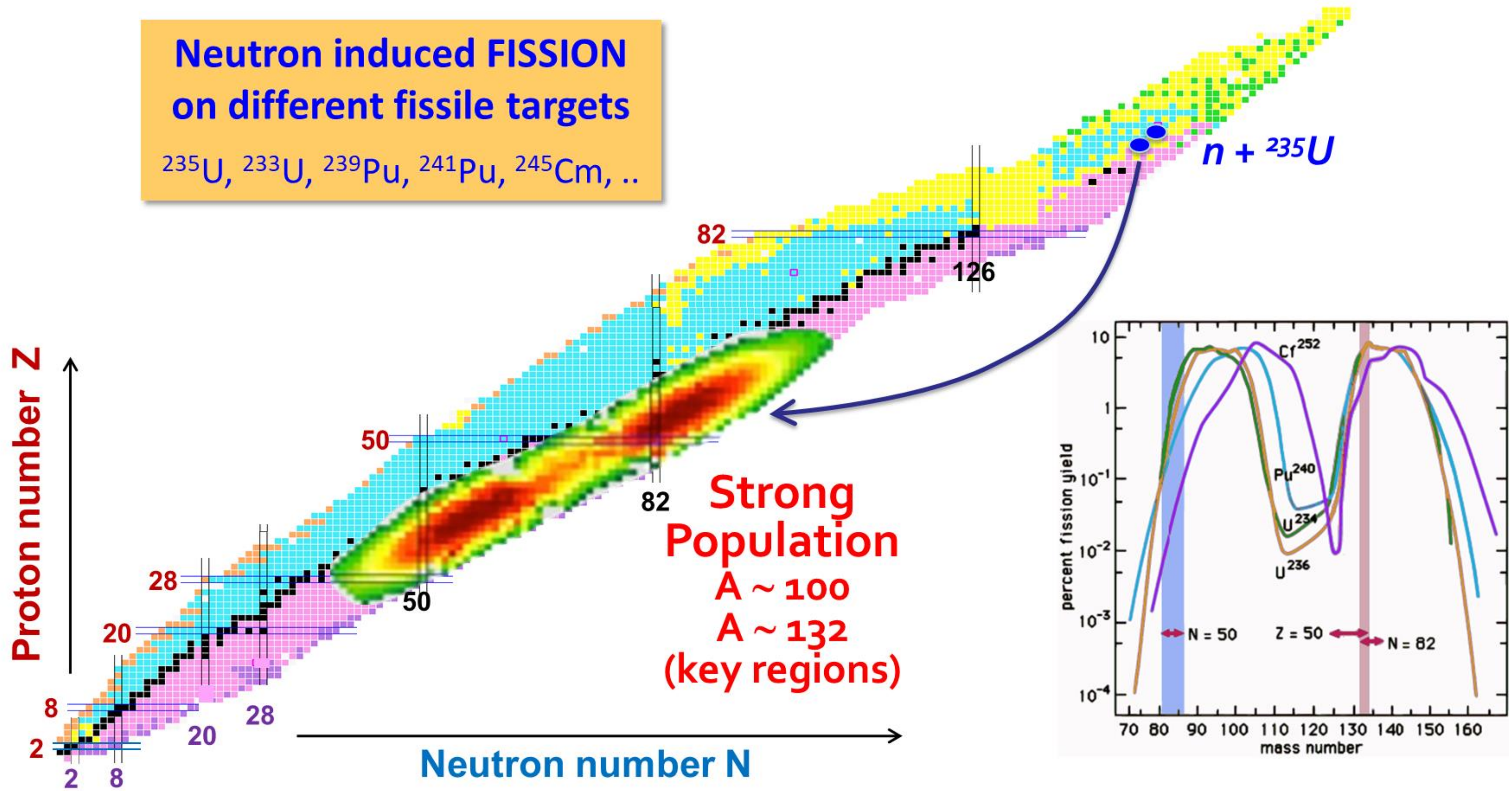


AFTER SCISSION→ decay of excited fragments:

- removal of excitation energy via emission of typically 0−2 neutrons and 1−3 high-energy **γ**-rays
- Subsequently, emission of several more **γ**-rays (carrying away the majority of the **angular momentum** and the remaining excitation energy)

➢ *Detection of* ***γ****-rays allow to extract important physical information!*

UNIQUE OPPORTUNITIES
For nuclear structure studies

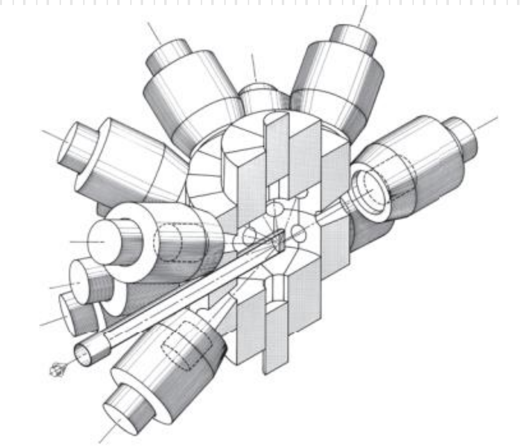


<u>Experimental Technique: γ-ray Spectroscopy</u>

➢ <u>Large arrays of semiconductor (HPGe) detectors</u> (*but also scintillators*)

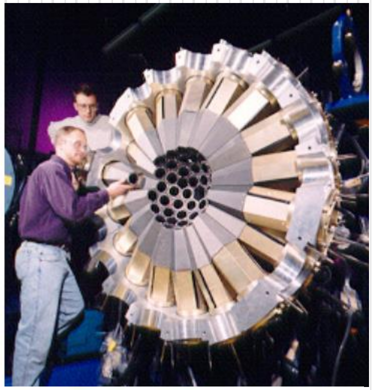
'…with the ingenious experimental approaches that are being developed, we may look forward with excitement to the detailed spectroscopic studies that will illuminate the behaviour of the spinning quantised nucleus' (A. Bohr and B. Mottelson, Nobel Prize in Physics 1975)

First generation arrays



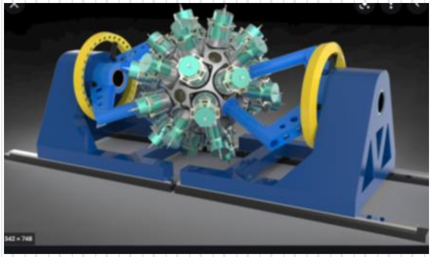
HERA 1981 LBNL USA

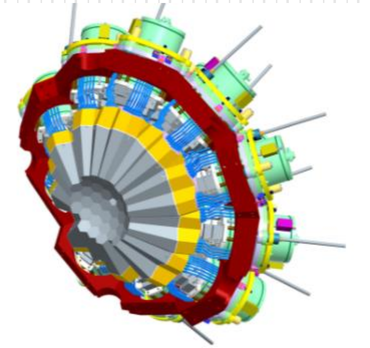
Second generation arrays



Gammashpere (USA), Euroball (EU)

«Tracking» generation arrays



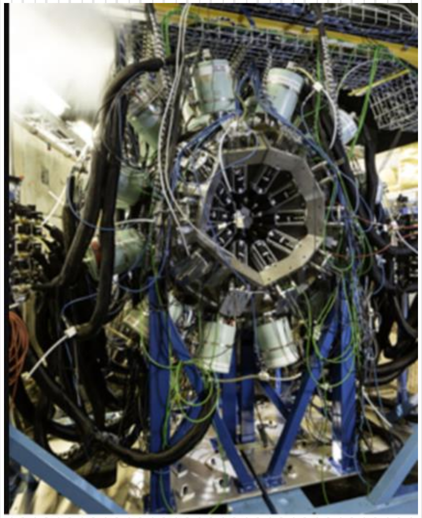


GRETA (USA), AGATA (EU)

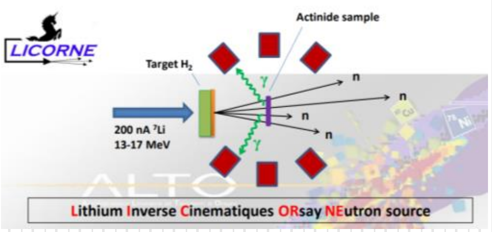
Experimental Technique: γ-ray Spectroscopy

➢ Arrays used for the SELECTED EXAMPLES cases

J.N. Wilson et al., Nature volume 590, pages 566–570 (2021)



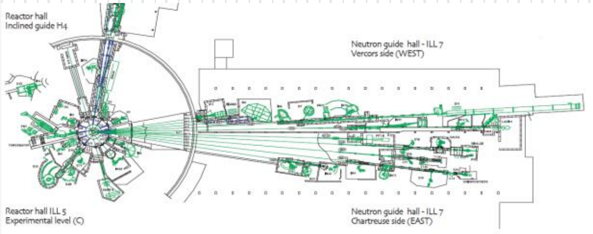
ν-Ball γ-ray spectrometer at IPN Orsay, France



FIPPS γ-ray spectrometer at ILL Grenoble, France

Worldwide highest continous neutron flux

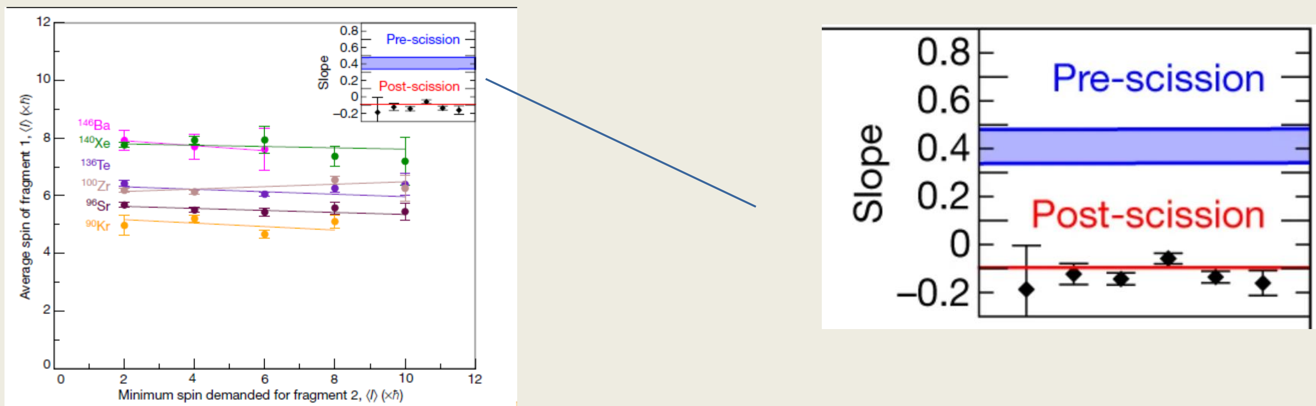
NEUTRONS FOR SOCIETY



"Angular momentum generation in nuclear fission"

*J.N.Wilson et al., [Nature](#) **volume 590**, pages 566–570 (2021)*

- Fission Fragments are Observed to Emerge **Spinning …*How can this happen?***
  - *Long-standing problem in nuclear physics: currently no experimental observation enables decisive discrimination between the many competing theories for the mechanism that generates the angular momentum*
- Consensus **was** that excitation of collective vibrational modes generates the intrinsic spin *before* the nucleus splits (**Pre-scission**), the present work *[J.N.Wilson, Nature (2021)]* showed that this can happen **Post-scission**
→ **GREAT INTEREST and PROMPTED NEW PUBLICATIONS**



*there is **no significant correlation between the spins of the fragment partners**, which leads to conclude that angular momentum in fission is actually generated after the nucleus splits (post-scission)*

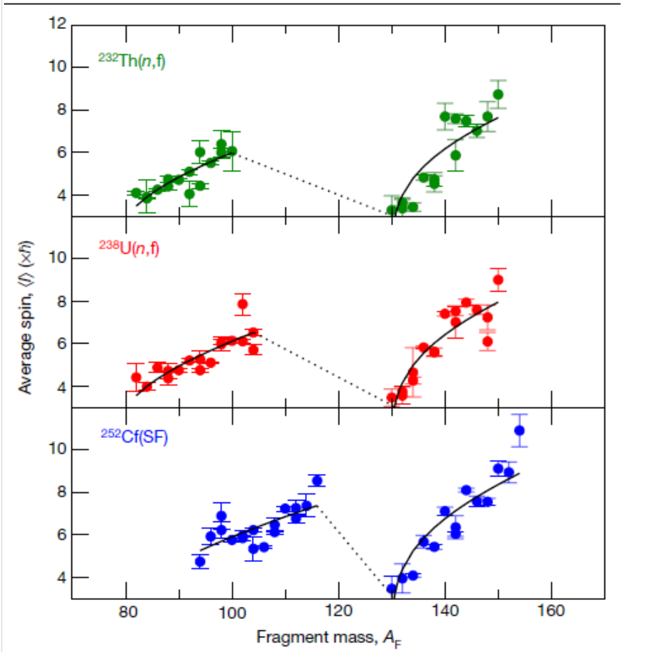
ALTO facility of the IJC Laboratory in Orsay, France, with LICORNE
fast-neutron-induced fission of $_{232}$Th and $_{238}$U, and the spontaneous fission of $_{252}$Cf with the addition of an ionization chamber
Collaboration with the Italian INFN/UNIMI GAMMA group

Recent Studies on Fission (Reaction Dynamics)

"Angular momentum generation in nuclear fission"

J.N.Wilson et al., Nature ***volume 590****, pages 566–570 (2021)*

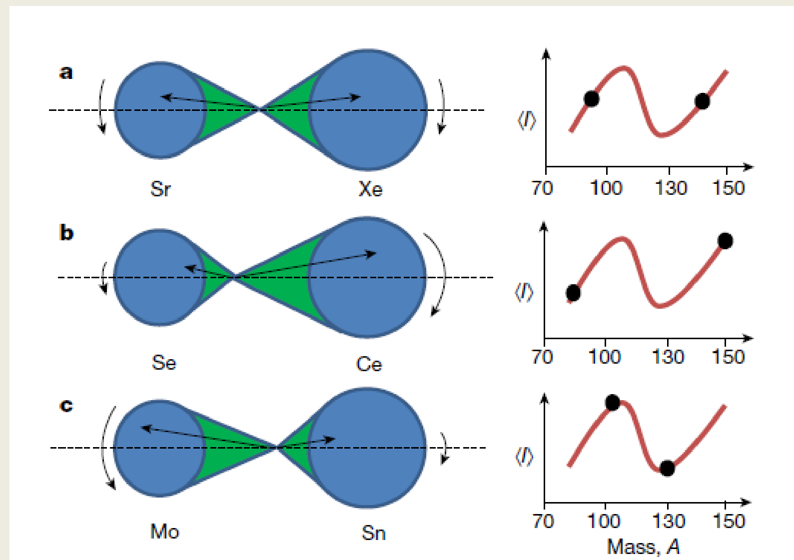
The data show that the average spin is strongly mass-dependent, varying in saw-tooth distributions



Proposed explanation of the new results:

- The collective motion of nucleons in the ruptured neck of the fissioning system generates two independent torques: (macroscopically) **analogous to the snapping of an elastic band**

Schematic model



Recent Studies on Fission (Nuclear Structure)

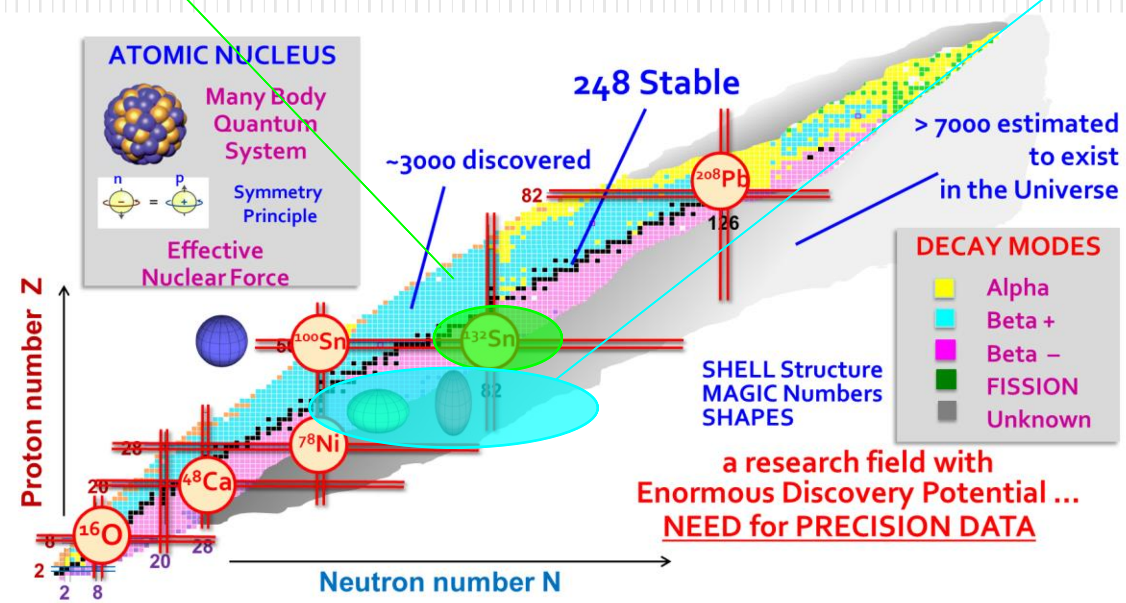
- *Fission is also a way to produce a variety of neutron rich nuclear systems, allowing to study their structure*

➢ Nuclear structure studies with neutron-induced fission reactions at the **ILL** (*Grenoble*)

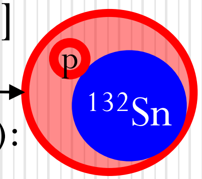
- ➢ *neutron induced fission of ^{233}U, ^{235}U and ^{241}Pu targets (in some cases also diluted in a scintillator)*
- ➢ *high resolution gamma ray spectrometers* (**EXILL, FIPPS**)

1) *"The mutable nature of particle-core excitations with spin in the one-valence-proton nucleus ^{133}Sb"*
[G. Bocchi et al., PLB 760(2016)273–278]

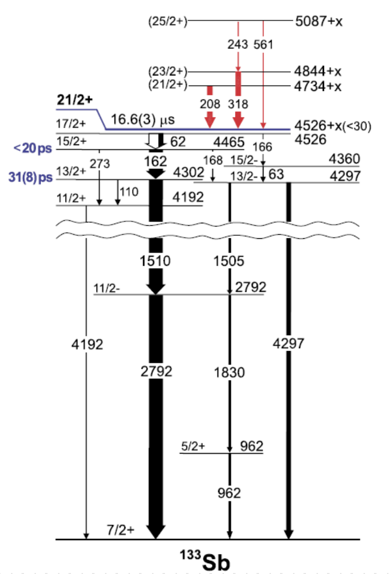
2) *"γ spectroscopy of the ^{96}Y isotope: Searching for the onset of shape coexistence before N = 60"*
[L. Iskra et al., PRC 102, 054324 (2020)]

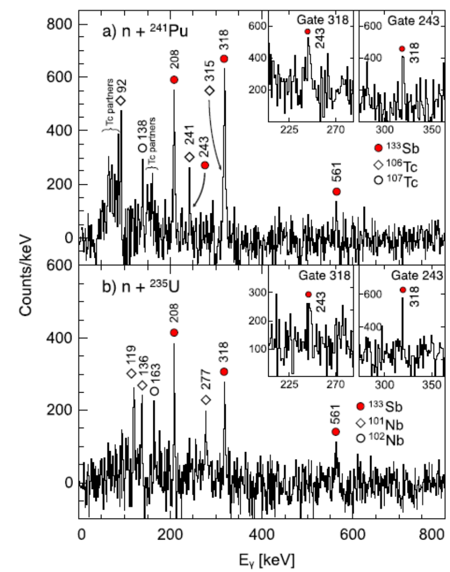


- *"The mutable nature of particle-core excitations with spin in the one-valence-proton nucleus ^{133}Sb"*
  [G. Bocchi et al., PLB 760(2016)273–278, Università degli Studi di Milano / INFN and IFJ PAN Krakow]



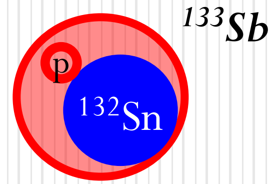
- **γ-ray decay of excited states** has been studied in ^{133}**Sb** (*one-valence proton nucleus*):
  - 132 nucleons wrapped up in a stable core (^{132}Sn core, "*doubly magic*") and one "*alone*" proton
  - Ideal system to study the interplay between collective vibrations of the core and the single particle excitations (such hybridization phenomena are well known also in others branches of physics)
  - *Essential synergy between theoretical and experimental physicists*



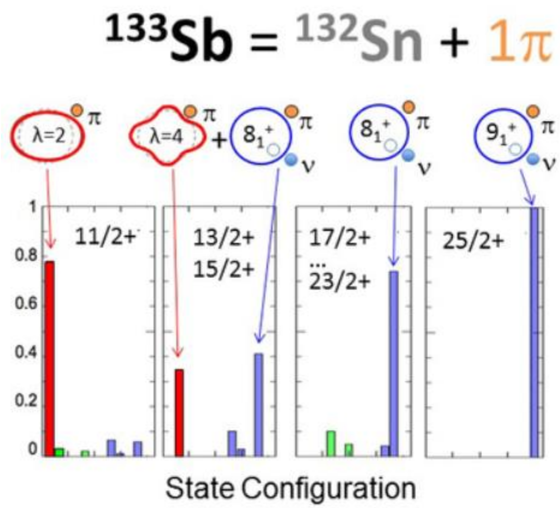


Recent Studies on Fission (Nuclear Structure) A≈132

- *"The mutable nature of particle-core excitations with spin in the one-valence-proton nucleus ^{133}Sb"* [G. Bocchi et al., PLB 760(2016)273–278, Università degli Studi di Milano / INFN and IFJ PAN Krakow]



Complex nature of the excitations of ^{133}Sb*: experimental result cannot be described in the framework of "pure shell model" configurations and points to a* *<u>hybrid nature of excitations</u>**, where couplings between the valence proton and excitations of the ^{132}Sn core, of both genuine phonon type (red components) and less collective character (blue and green components), coexist (illustrated by the histograms and by the cartoons on top of the figure)*



- *(G. Colò, P. F. Bortignon, …Università degli Studi di Milano/INFN)*

Recent Studies on Fission (Nuclear Structure) A≈100

❑ *"γ spectroscopy of the ^{96}Y isotope: Searching for the onset of shape coexistence before N = 60"*
[L. Iskra et al., PRC 102, 054324 (2020) IFJ PAN Krakow and Università degli Studi di Milano / INFN]

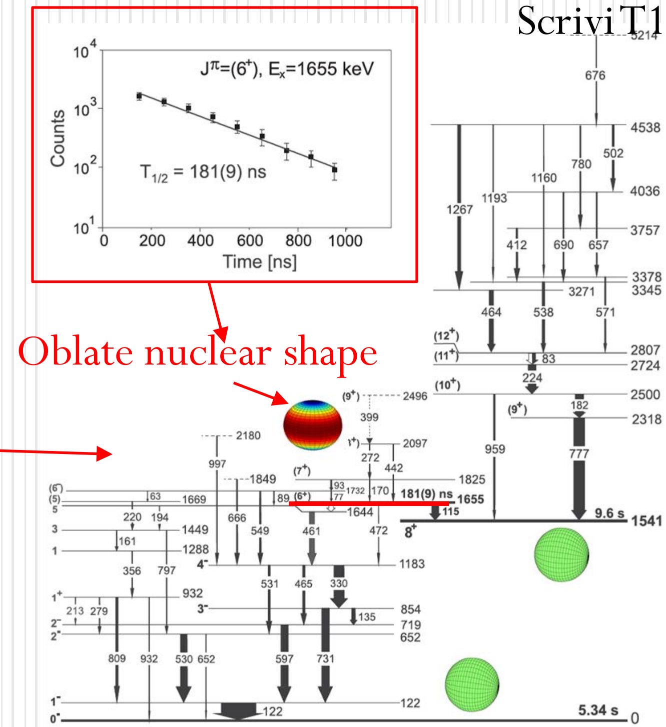
- **γ-ray decay of excited states** has been studied in ^{96}Y

(*nucleus in the* ***shape-coexistence*** *region near Z = 40 and N = 60*):

➢ «shape coexistence» phenomenon: *remarkable feature of some nuclei possessing different geometrical configurations, which are energetically similar, yet have very different surface shapes.*

- A **complex level scheme**, extending up to 5.2 MeV was investigated, and firm spin and parity assignments were given to a number of states, on the basis of angular correlation analysis and considerations on the γ–decay patterns.

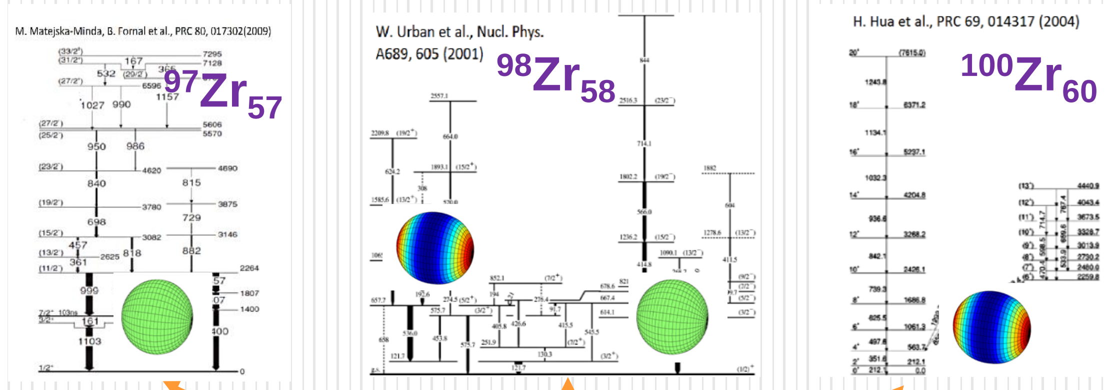
Scrivi T1/2

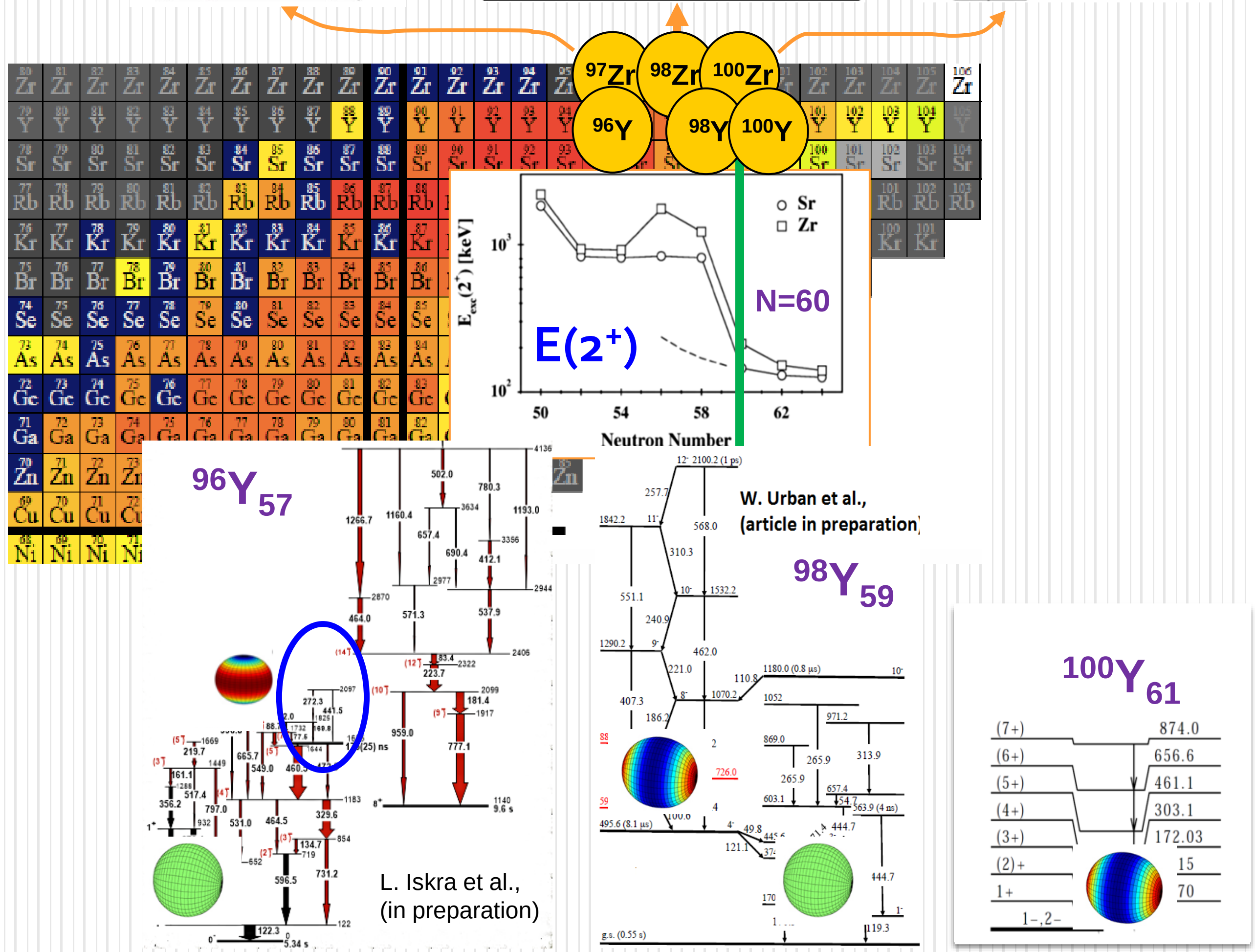


$^{96}Y_{57}$

L. Iskra et al., PRC102, 054324 (2020)
n+^{235}U, FIPPS

The region of most dramatic changes





Recent Studies on Fission (Nuclear Structure) A≈100

- "*γ spectroscopy of the ^{96}Y isotope: Searching for the onset of shape coexistence before $N = 60$*"
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- **γ-ray decay of excited states** has been studied in ^{96}Y

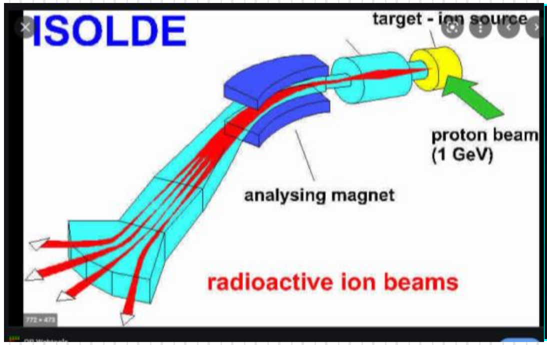
(*nucleus in the **shape-coexistence** region near Z = 40 and N = 60*):

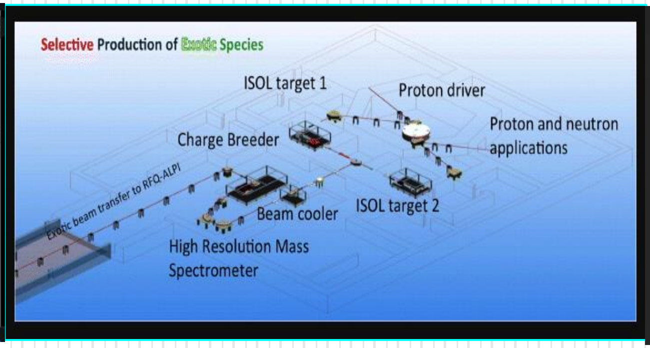
- Structures built on the 0^- ground state and the 8^+ isomer show irregular patterns typical for **spherical shapes**
- the (6^+) isomeric state at 1655 keV and the rotational band built are consistent with an **oblate deformation**
- 115-keV transition connects the (6^+) isomeric state to the 9.6-s β-decaying 8^+ spherical isomer. The latter can now be firmly placed at 1541 keV excitation energy, which has to be taken into account in *calculations of electron and antineutrino spectra from fission of actinides, for which ^{96}Y is a prominent product.*

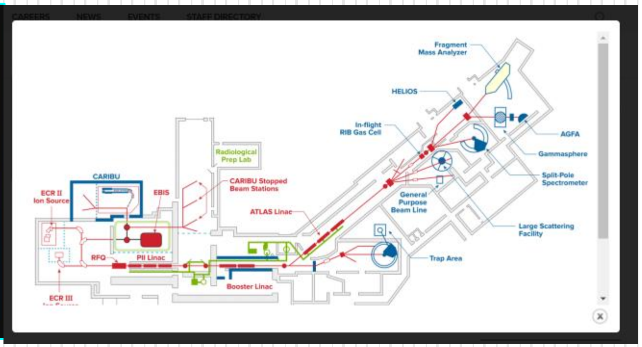
Recent Studies on Fission (Nuclear Structure)

- ***Fission is also a way to produce a variety of neutron rich nuclear systems, allowing to study their structure***
- *Radioactive isotopes building up the nuclear chart are essential for fundamental nuclear physics research and for many applications in various fields of science.*
- *Developments over the last decades for the production and study of radioactive ion beams (RIBs) have resulted in mature techniques that allow to explore the properties of isotopes that have a proton-to-neutron ratio very different from the stable isotopes in an unprecedented way.*
- *SPES is a new ISOL facility dedicated to the production of neutron-rich beams. A proton beam of 40 MeV and 200 μA, delivered by the cyclotron, will impinge on a uranium carbide target and neutron rich isotopes will be produced **as fission fragments***
- *The neutron rich products will be extracted and mass separated to be reaccelerated.*

Examples: ISOLDE at CERN and SPES at LNL-INFN, CARIBU at ANL (USA) …







Conclusions

- **Fission** is a physical phenomenon that has still fascinating unknown aspects to be revealed
- **Gamma spectroscopy** technique provides important physical information, illuminating aspects of nuclear physics:
  - *Angular momentum generation in nuclear fission*
  - ***Other scientific implications**, examples:*
    - *Structure of neutron-rich isotopes (spontaneous fission, induced fission)*
    - *Radioactive Ion Beam Facilities*
    - *Synthesis and stability of super-heavy elements*
- **Social implications** (as happened historically with other topics in nuclear physics), examples:
  - *Consequences for the γ-ray heating problem in nuclear reactors*
- Fission is (also) a **natural phenomenon**!
  - *1 example only in the world: Natural nuclear fission reactor (Oklo, Gabon)*