Prospectives nationales 2020-2030

How to achieve a complete description of nuclear fission?

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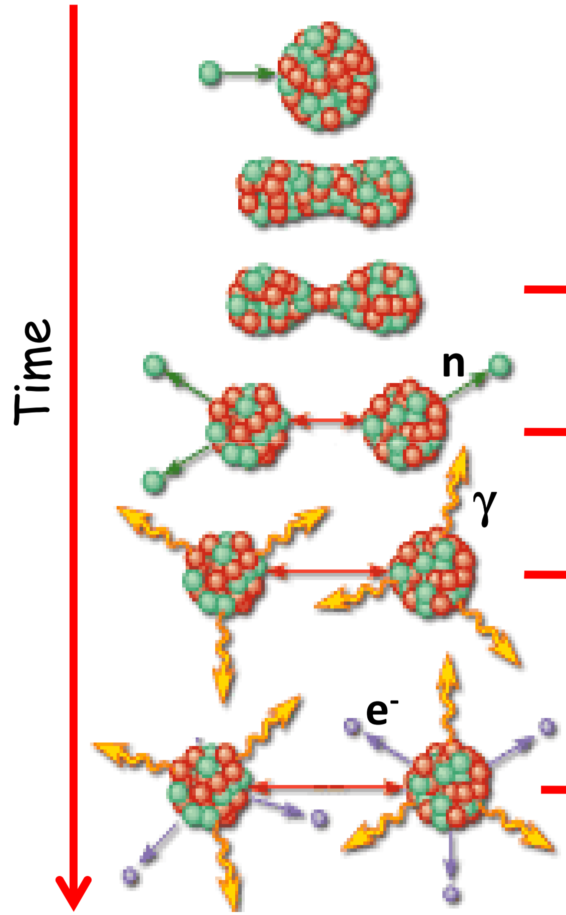
The fission process



Before scission, deformed nuclei in contact through the neck

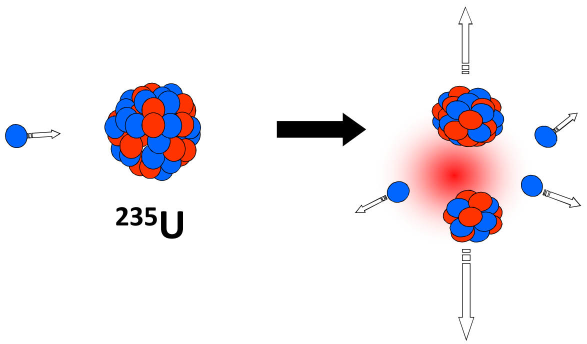
Fragments recover smaller deformation

E* release by prompt neutron emission

E* release by prompt gamma-ray emission

β decay

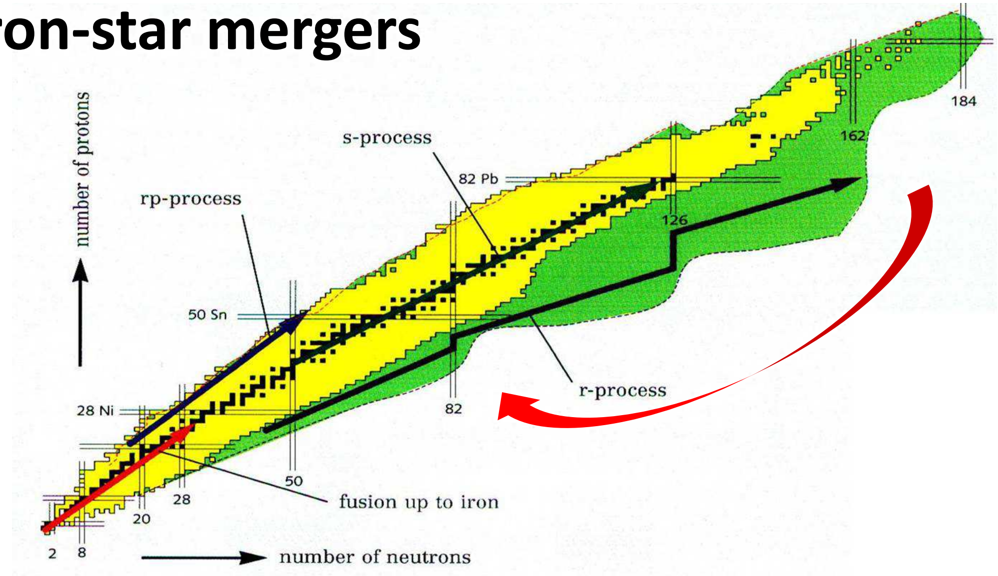
The importance of fission



Huge amount of energy released per fission event: ~ 200 MeV!
Few eV for combustion of a molecule of coal, gas or oil…

- Nuclear technology: production of electricity, of radio-isotopes for medecine, of RIBs

- Nuclear astrophysics, synthesis of elements via the r-process in neutron-star mergers

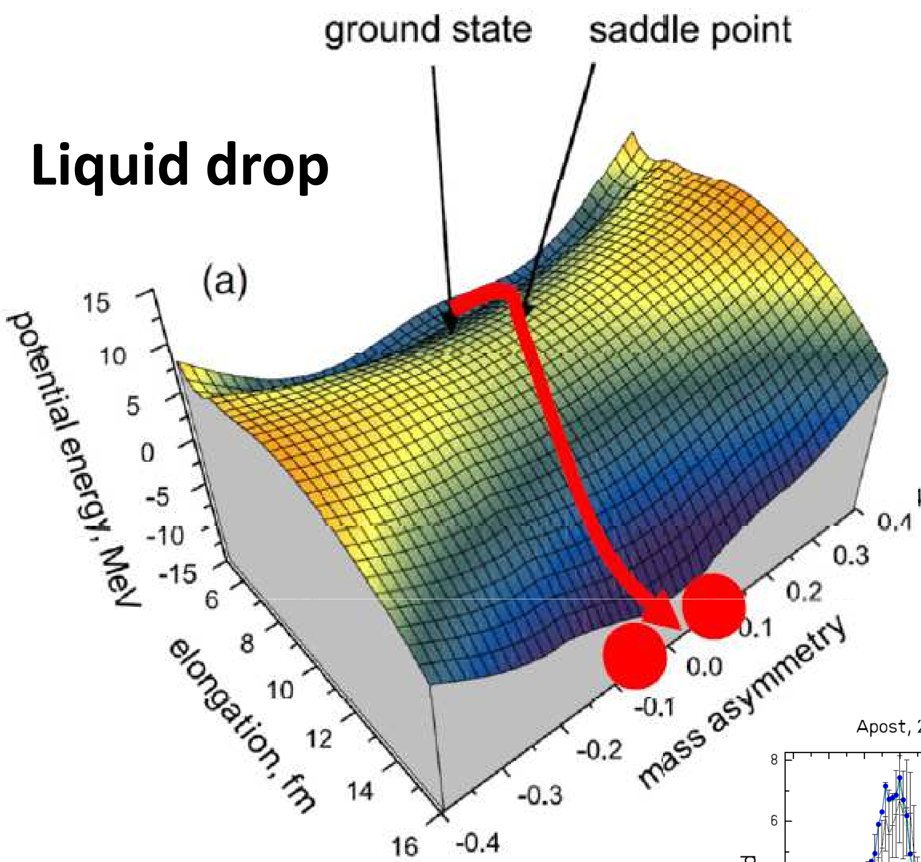


Fission sets the end point of the r-process and strongly influences the r-process abundances and light curves!

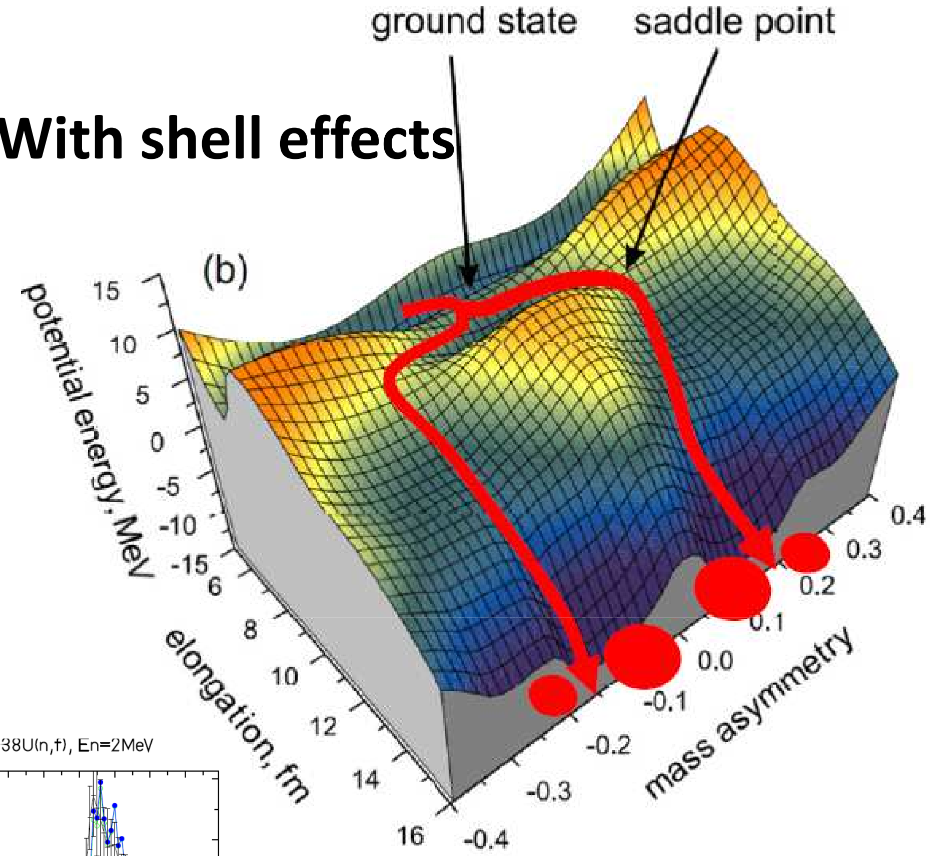
See talk by F. Hammache

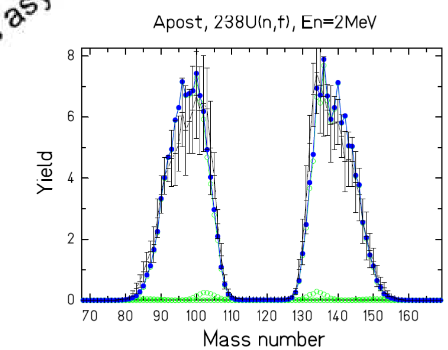
The importance of fission for fundamental nuclear physics

Liquid drop



With shell effects

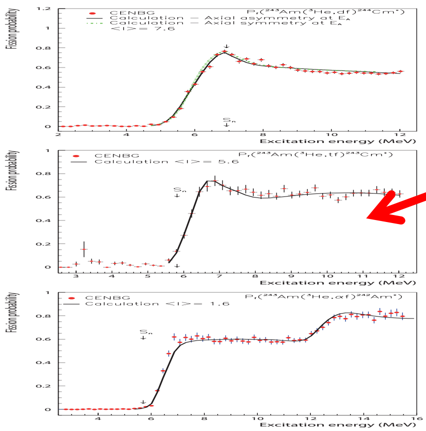


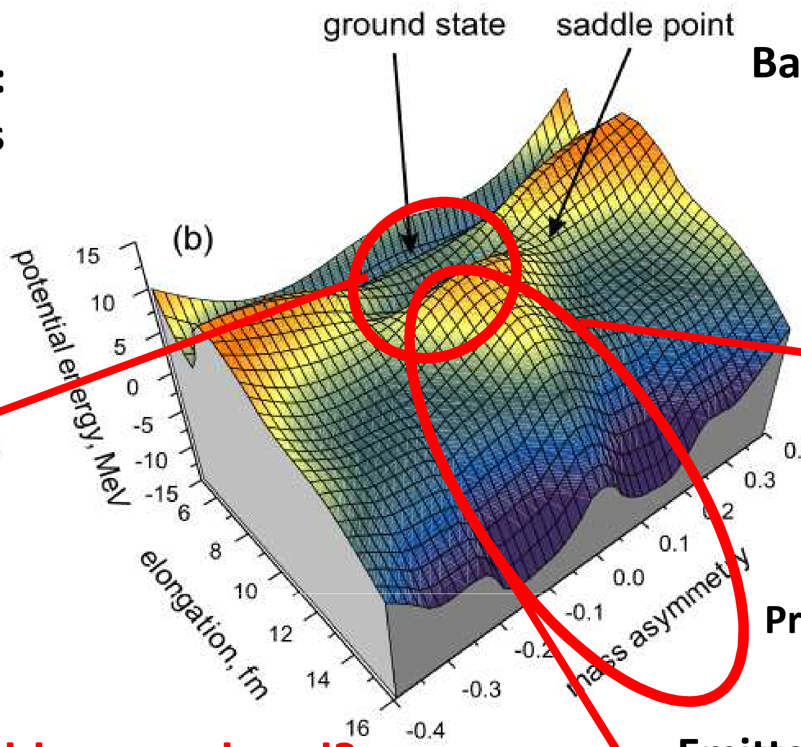


Fission is a complete laboratory for studying nuclei at extreme deformation under the influence of shell effects, correlations and dynamics!

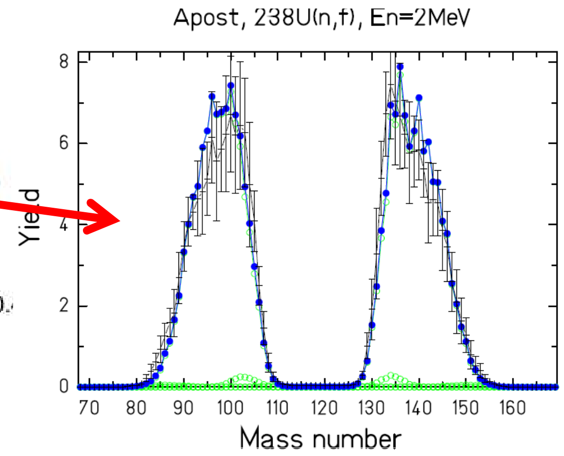
The richness of fission observables

Ground-state to barrier : Fission probability, cross sections



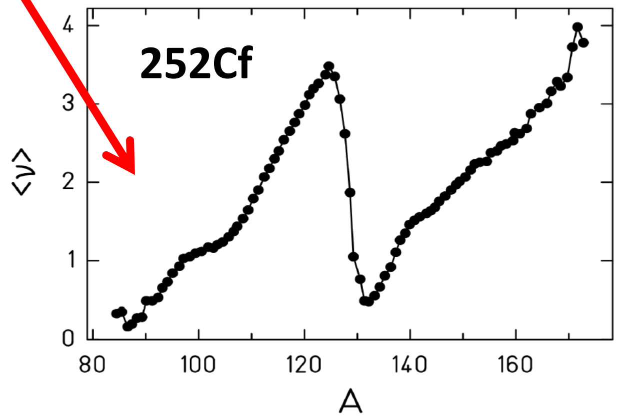


Barrier to well after scission: Fission fragment yields



Prompt neutrons & gammas, etc.

Emitted prompt neutron yields



- **How are fission observables correlated?**
- **How do fission observables and their correlations depend on the fissioning nucleus, excitation energy and angular momentum?**
- **Fission is far from being fully understood!**
- **Exclusive, high-precision fission experiments and microscopic fission models are a great challenge!**

Experimental projects

From the ground state to the fission barrier

Direct kinematics

Neutron-induced cross sections

- CENBG@**AIFIRA**, **CEA-DAM** or **JRC-Geel,** En=0.1-1 MeV, flux (n,p), Pu targets
- **NFS-GANIL**, En=1 -40 MeV, flux (n,p) , ^{238}U, ^{232}Th
- IPNO@**n-TOF-CERN**, En=1 ev-GeV, targets ^{231}Pa, ^{239,240,242}Pu
- CEA-DAM@**LANSCE**-Los Alamos NL, En=1-800 MeV, targets ^{239,240,241,242}Pu

Strongly motivated by applications, **challenge: uncertainties of a few %!**

Fission and **gamma emission probabilities** induced by light-charged particles

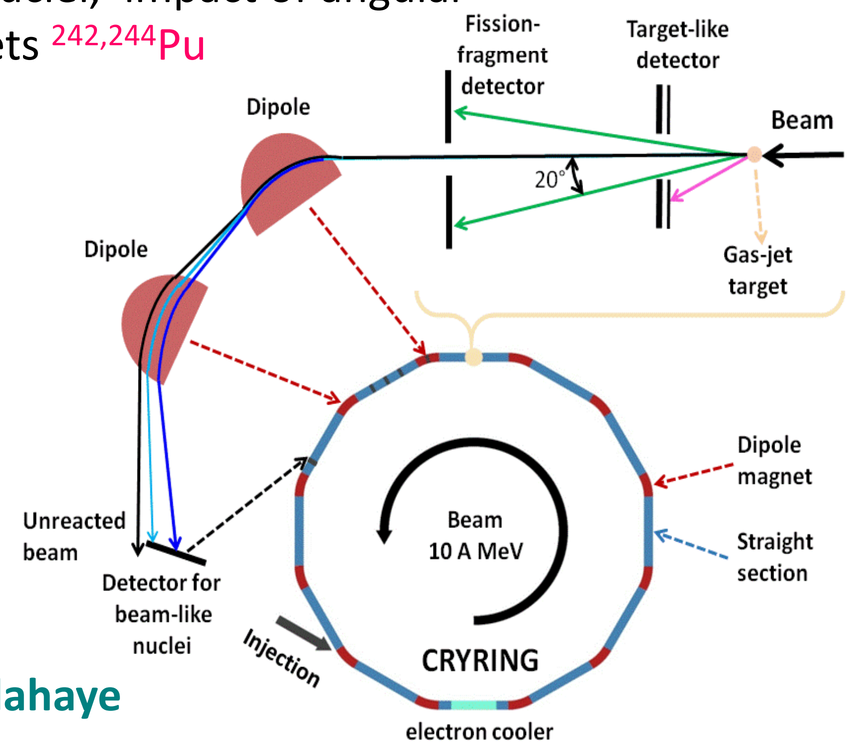
- CENBG@Tandem-**ALTO**, access to E*<Sn, fissile and very radioactive nuclei, impact of angular momentum, targets ^{242,244}Pu

Inverse kinematics

Heavy-ion storage rings:
High-quality RIBs +
ultra-thin, pure, window-less light targets

High-precision simultaneous measurement of **fission, gamma- and neutron-emission probabilities** of numerous unstable nucleii around N=126

- CENBG@**GSI-FAIR** (**HIE-ISOLDE** , **GANIL**?)



See talk by P. Delahaye

From the fission barrier to scission and de-excitation of fragments

Direct kinematics

Spontaneous fission

Fragments A, E_{k}, prompt neutrons and gammas → IPNO@Nu-ball2-PARIS-**ALTO**, ^{252}Cf, ^{248}Cm
Multiplicity and angular distribution of **prompt neutrons**→**IPHC** with DEMON and IC CODIS, ^{252}Cf

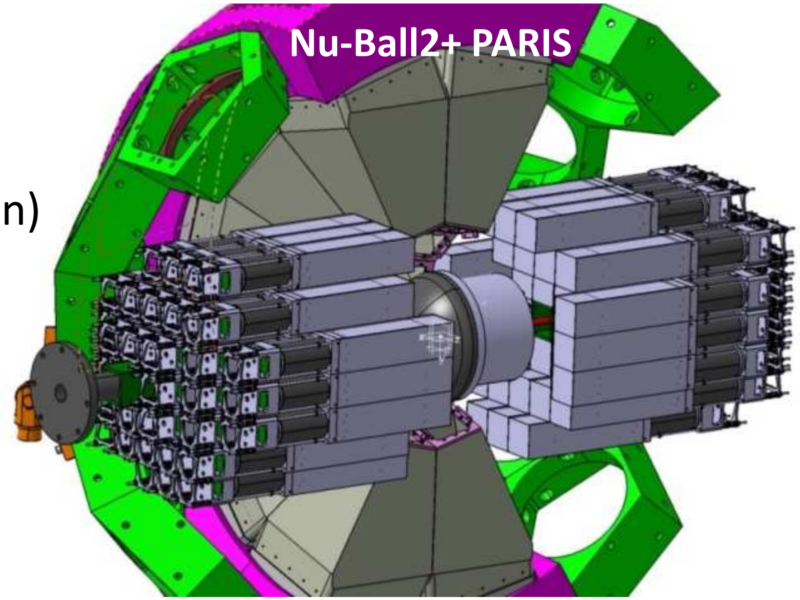
Neutron-induced fission

Fragment E_{k}, isomeric ratios→LPSC@**LOHENGRIN-ILL**, En thermal
Energy spectrum and multiplicities of **prompt neutrons**→ CEA-DAM@**LANSCE**, ^{240,241,242}Pu
Fragments A, E_{k} and prompt-neutrons →FALSTAFF@**NFS**
Fragments A, E_{k}, prompt neutrons and gammas → IPNO@Nu-ball2-PARIS-Licorne-**ALTO**, ^{238}U

Fusion-fission

Fragments E_{k} , prompt neutrons and gammas →
IPHC@PARIS-**ALTO**, ^{12}C + ^{204}Pb ,^{40}Ca + ^{144}Sm (quasi-fission)

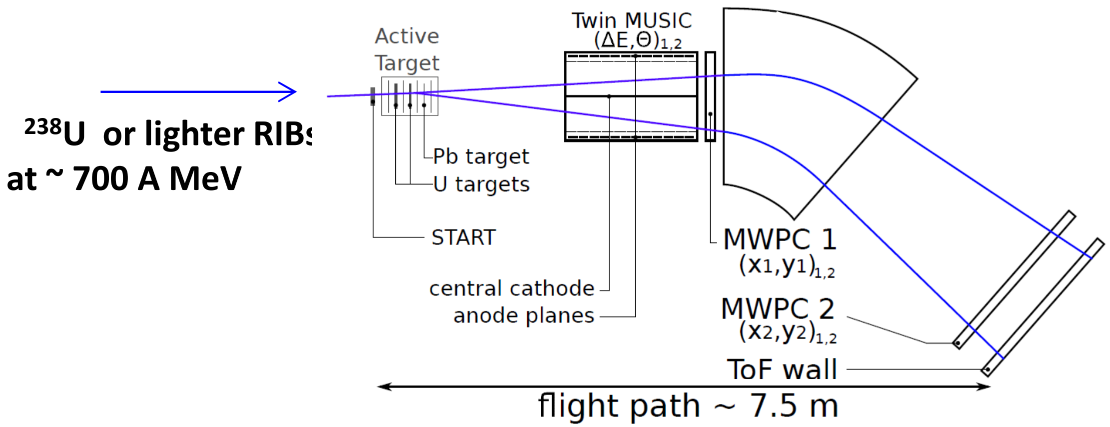
Different fissioning nuclei under different conditions and more and more observables will be simultaneously measured!



From the fission barrier to scission and de-excitation of fragments

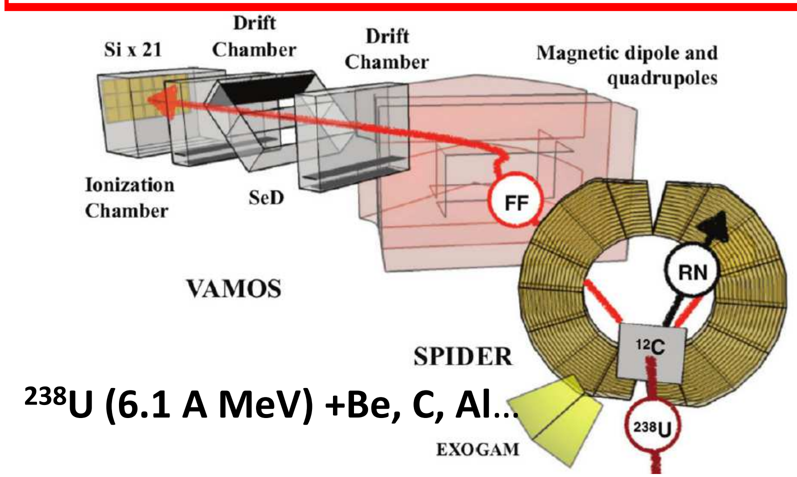
Inverse kinematics

SOFIA@GSI/FAIR, CEA-DAM, IJCLab, CENBG, Coulomb excitation



- Study of region of neutron deficient nuclei around Pb
- Feasibility of (p,2p) reaction
- **Z and A and neutron multiplicity of two fragments** with NeuLAND
- Access to unexplored region of neutron-rich Th, Ac
- Development of a ^{242}Pu beam

VAMOS@GANIL, transfer-induced fission, fusion



- **Z and A of two fragments**
- **Prompt gammas and neutrons** with PARIS
- Coupling with the GRIT detector to improve the detection of the target –like residues
- ^{232}Th beam and neutron-deficient nuclei around Pb
- Discrimination between fusion-fission and quasi-fission

Access to short-lived nuclei, A and Z of fragments with high resolution and neutrons & gammas!

Theoretical projects

Modeling of the full fission process

Microscopic models: quantum-mechanical framework with mean-field approximation

-Time-Dependent Generator-Coordinate Method(TDGCM)→CEA-DAM (N. Dubray, N. Pillet et al.) **Quantum fluctuations but no dissipation**

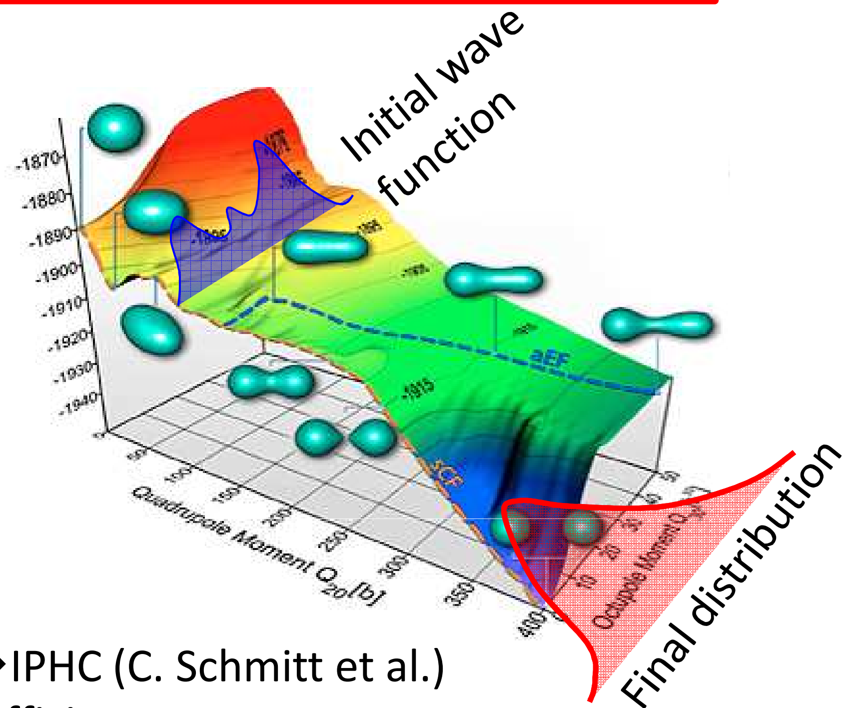
-Time-Dependent Hartree-Fock-Bogoliuvov(TDHFB)→ IJCLab (D. Lacroix et al.)

Dissipation but no quantum fluctuations

•Include dissipation in TDGCM

•Provide codes to be used by the community

•Combine TDGCM and TDHFB



Stochastic models: classical dynamics

Langevin equation, Brownian shape-motion model→IPHC (C. Schmitt et al.)

•Microscopic calculation of inertia and dissipation coefficients

•Apply to fusion-fission and extend to quasi-fission

Semi-empirical model

General Fission Model (GEF)→ K.H. Schmidt, B. Jurado, C. Schmitt, M. Estienne, M. Fallot

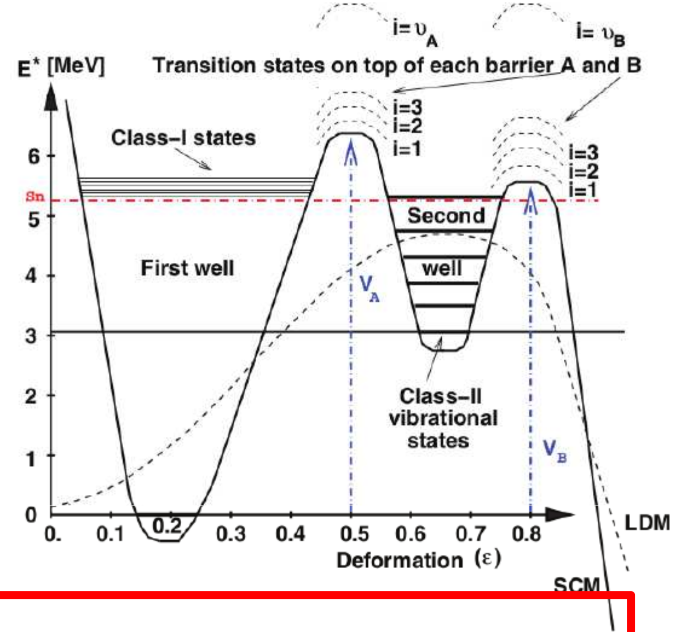
•Improve the model by using new available data

•Microscopic interpretation of observed regularities and parameter values

Modeling of specific parts of the fission process

From ground-state to the barrier: Fission cross sections and probabilties

R-matrix + statistical model→
CEA-Cadarache (O. Bouland et al.**)**
•Include more degrees of freedom in the description of the fission barrier
•Calculate the single-particle and collective states on top of the barriers with **self consistent mean-field with pairing + collective model →** CENBG (L. Bonneau et al.)
•Compare with new data on neutron cross sections and decay probabilities.



Precise modeling of the de-excitation of fission fragments

FIFRELIN→CEA-Cadarache (O. Serot et al.)
•Improve the model for the properties of the fission fragments before de-excitation
•Use a microscopic description of level densities and gamma-ray strength functions
•Compare with new data on prompt neutrons and gammas and iisomeric ratios

All the 5 types of models are mutually enriching and require high-quality experimental data for comparison and improvement!

Conclusions

•Fission is an important, very complex process and there is no complete understanding yet!
•France is world leader in the investigation of fission!
•France has fully competitive and unique experimental facilities to study fission!
•French groups foresee future experiments to investigate more fissioning nuclei under different conditions and to measure more and more observables simultaneously with increasing precision
•All types of models, from microscopic to semi-empirical , will be further developed profiting from synergies between them and the new high-quality experimental data

Needed technical developments
-Storage ring set-up at GSI/FAIR
-PARIS
-Second arm at VAMOS
-PARIS@ VAMOS
-GRIT@VAMOS

Synergies
GT2:
-Theory (talks by M. Grasso, M. Bender)
-Nuclear structure (talk by G. Duchene)
-Super-heavy nuclei (talk by A. Lopez Martens)
-Nucleosynthesis (talk by F. Hammache)
-Future facilities (talk by P. Delahaye)
GT 11: Nuclear energy
GT7: Instrumentation, targets
GT6: Neutrino physics