





Nuclear fission at storage rings

B. Jurado¹, J. Pibernat¹, M. Sguazzin¹, J. A. Swartz¹, M. Grieser², J. Glorius³, Y. A. Litvinov³, R. Reifarth⁴, K. Blaum², P. Alfaurt¹, P. Ascher¹, D. Atanasov¹, L. Audouin⁵, C. Berthelot¹, B. Blank¹, B. Bruckner⁴, S. Dellmann⁴, I. Dillmann⁶, C. Domingo-Pardo⁷, M. Dupuis⁸, P. Erbacher⁴, M. Flayol¹, O. Forstner³, D. Freire-Fernandez², M. Gerbaux¹, J. Giovinazzo¹, S. Grevy¹, C. Griffin⁶, A. Gumberidze³, S. Heil⁴, A. Heinz⁹, W. Korten⁸, D. Kurtulgil⁴, G. Leckenby⁶, S. Litvinov³, B. Lorentz³, V. Meot⁸, J. Michaud¹, S. Perard¹, U. Popp³, M. Roche¹, M.S. Sanjari³, R.S. Sidhu¹⁰, U. Spillmann³, M. Steck³, Th. Stöhlker³, B. Thomas¹, L. Thulliez⁸, M. Versteegen¹

1- LP2I (ex-CENBG), Bordeaux, France
2- MPIK, Heidelberg, Germany
3-GSI, Darmstadt, Germany
4-University of Frankfurt, Germany
5-IJCLAB, Orsay, France
6-Triumf, Vancouver, Canada
7-IFIC, Valencia, Spain
8-CEA, France
9-University of Chalmers, Sweden
10-University of Edinburgh, UK

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

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...

•Production of electricity, of radio-isotopes for medecine, of RIBs, of neutrinos...

•Nuclear astrophysics, synthesis of elements via the r-process



Fission sets the end point of the r-process, fission recycling. Fission strongly influences the r-process abundances and light curves.

The importance of fission for fundamental nuclear physics



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

Exploring the fission barrier region via decay-probability measurements

4He+240Pu→4He'+240Pu*



First simultaneous measurement of P_f and P_v!

Stringent test of experimental method!

Only way to access the fission threshold of fissile nuclei!

R. Perez Sanchez, BJ et al., Phys. Rev .Lett. 125 (2020) 122502



First simultaneous determination of neutron-induced fission and capture cross sections n+239Pu→240Pu*



R. Perez Sanchez, BJ et al., Phys. Rev .Lett. 125 (2020) 122502

Setup for the measurement of fission and gamma-emission probabilities in direct kinematics





Advantages of heavy-ion storage rings

The ESR at GSI/FAIR



e- cooler

Beam cooling → Excellent energy and position resolution of the beam, maintained after each passage through the target, negligible, E-loss & straggling effects

Use of ultra-thin in-ring gas-jet targets ~10¹³/cm².
 Effective target thickness increased by ~10⁶ due to revolution frequency (at 10 A MeV)

 High-quality, pure, fully-stripped beams and pure, ultra-thin, windowless targets → unique!

Challenge: Detectors in Ultra-High Vacuum (10⁻¹¹-10⁻¹² mbar)!

First proof of principle experiment at the ESR (Pgamma, Pn), 20-27 June 2022



Preliminary results, excitation energy resolution



Preliminary results, detection of beam-like residues



PhD Thesis of Michele Sguazzin

Preliminary results, detection of beam-like residues



PhD Thesis of Michele Sguazzin

Entries 579 Mean x 29.05 Mean y -16.2 Std Dev x 15.12 Std Dev y 2.27

X{mm}

Perspectives: measure simultaneously fission, neutron and gamma-emission probabilities



- Add fission detectors. First time that fission is studied in a storage ring!
- Demonstrate feasibility for measuring simultaneously P_f, P_γ and P_n!
- Experiment accepted, to be probably conducted in 2024!
- After, produce dedicated reaction chamber to increase target-residue and fission detection efficiencies!

Longer term perspectives: radioactive beams & other observables...



Conclusions...

-Storage rings offer the ideal conditions to precisely measure decay probabilities and explore the fission threshold in a unique way!

-First proof of principle experiment succesfully conducted at the ESR in June 2022

 $\rightarrow \Delta E^* \approx 600 \text{ keV}$ in accordance with expectations

→ Full separation and 70-100% detection efficiency for beam-like residues

 \rightarrow Validation of new methodology for simultaneous measurement of P_y and P_n

...Perspectives

-Add a fission detector to measure simultaneously P_{γ} , P_n and P_f with 238 U & target radius 0.5-1 mm.

-Build a dedicated reaction chamber to significantly increase efficiency for target residues and fission.

-Measurements with radioactive beams!

Acknowledgements



This work is supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (ERC-Advanced grant NECTAR, grant agreement No 884715). NECTAR: Nuclear rEaCTions At storage Rings



Prime 80 program from CNRS, PhD thesis of M. Sguazzin