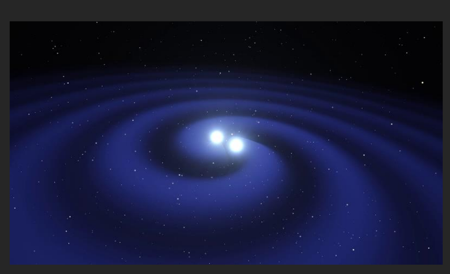
Nuclear fission at heavy-ion storage rings

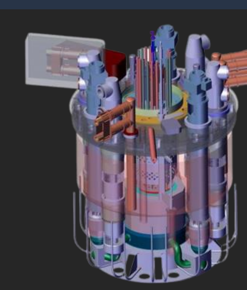
C. Berthelot, B. Jurado, J. Pibernat, M. Sguazzin, J. A. Swartz, B. Thomas, M. Grieser[1], J. Glorius[2], Yu. A. Litvinov[2],
P. Ascher, B. Blank, M. Gerbaux, J. Giovinazzo, S. Grévy, J. Michaud, S. Perard, M. Roche, M. Versteegen et B. Wloch
Laboratoire de Physique des Deux Infinis de Bordeaux, France

[1]Max-Planck Institut für Kernphysik, Heidelberg, Germany
[2]GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

Motivations

- Determine neutron-induced reaction cross sections of radioactive nuclei
- Use : understanding stellar nucleosynthesis, applications in medicine and nuclear technology


Artistic view of a neutron star merger. (*ESO/L. Calçada*)

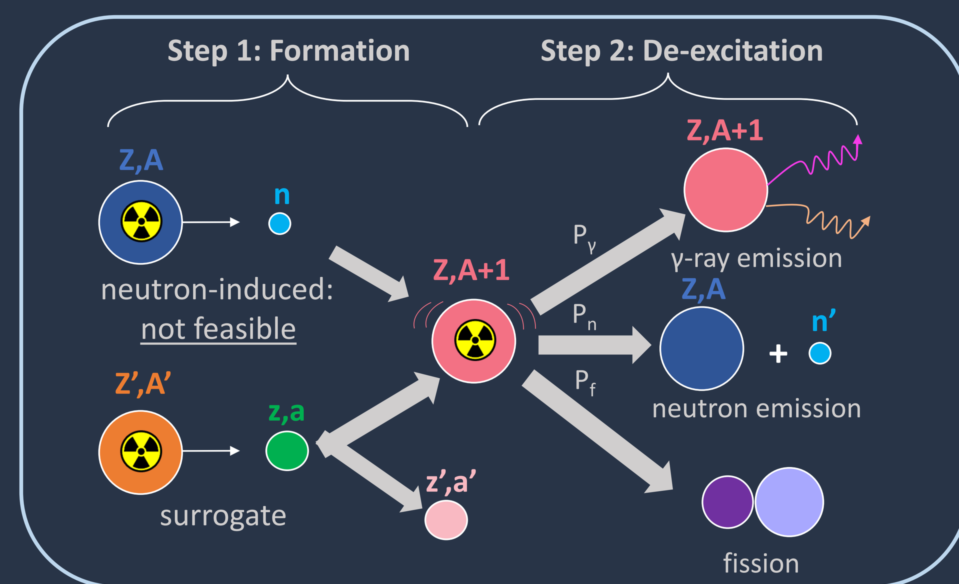

Design of a 4th generation nuclear reactor project. (*ASTRID, CEA*)

- These cross sections are challenging to measure due to the difficulty to produce and handle radioactive targets.

neutron beam → radioactive target : **difficult to produce** | radioactive beam → neutron target : **unavailable**

To solve the target problem, NECTAR uses the surrogate reaction method in inverse kinematics.

Surrogate reaction method



- Competition of the 3 different de-excitation modes → determination of $P_\gamma(E^*)$, $P_n(E^*)$ and $P_f(E^*)$.
- These probabilities are very useful to constrain model parameters and provide much more precise predictions of the n-induced cross sections [1].
- To measure the rapid evolution of the $P_f(E^*)$, an E* resolution of a few hundred keV is needed (difficult to obtain due to energy loss and straggling effects in target).
- Inverse kinematics : detection of heavy products with much higher efficiency than in direct kinematics.

ESR heavy-ion storage ring

▶ What ESR storage ring allows:

High quality gas jet target:
- windowless, pure and thin target,
- ultra-low density (10^{13} to 10^{14} atoms/cm^2),
- yet the revolving frequency of the beam (10^6 Hz) induces a target effective thickness of a million times larger.

High quality (radioactive) beam:
- use of electron cooling technology,
- beam energy and quality are restored after each passing of the target.

The combination of gas jet and electron cooling allows to neglect energy loss and straggling effect in the target.

▶ What ESR storage ring requires:

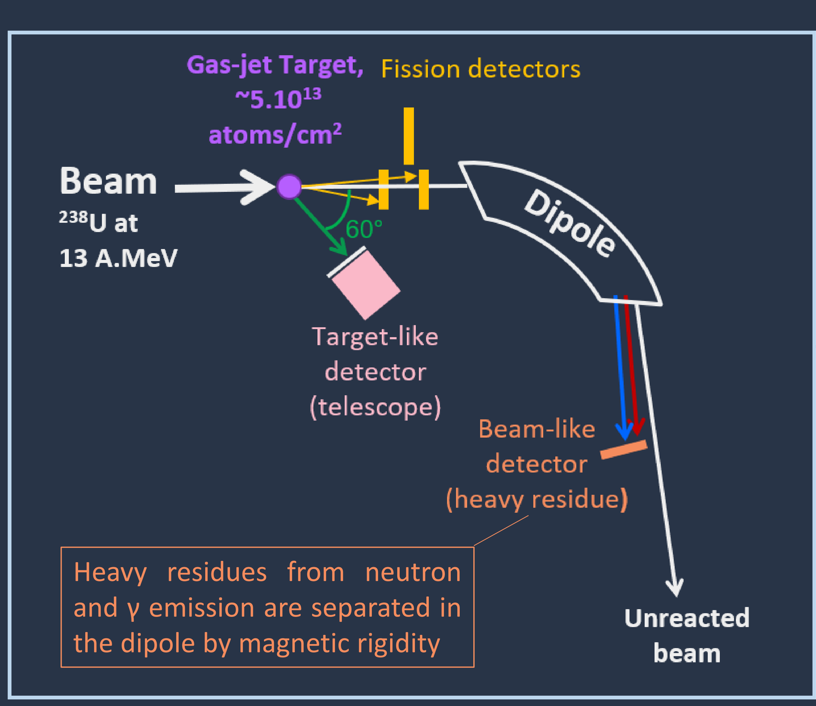
Ultra-high vacuum:

The detection systems have to be compatible with very low pressure levels (10^{-10} to 10^{-12} mbar).

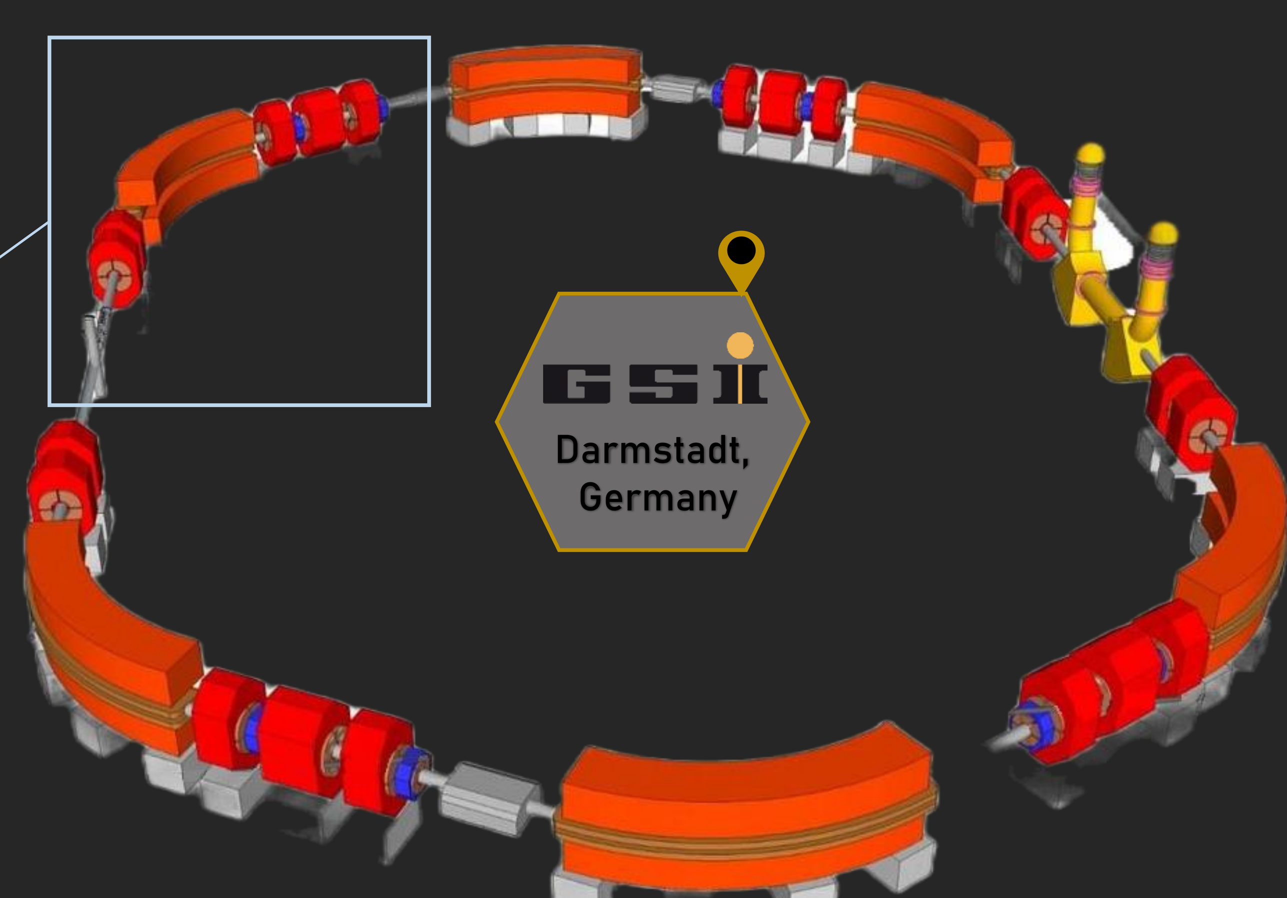

Picture of the TREVO test bench for detector UHV compatibility.

Experimental setup

After a first proof of principle (PoP) experiment in June 2022 where we succeeded to validate the experimental method by determining $P_\gamma(E^*)$ and $P_n(E^*)$ for ^{208}Pb [3], we plan a second experiment in June 2024 with ^{238}U to measure also $P_f(E^*)$.



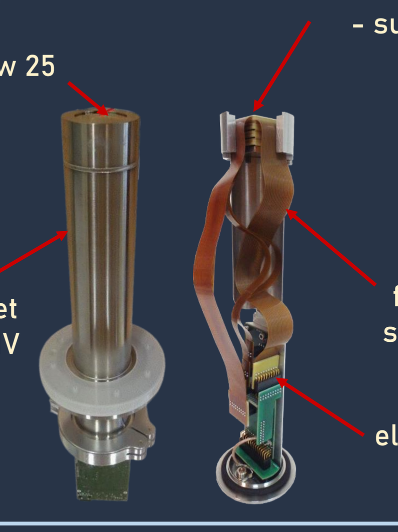
Heavy residues (HR) and fission fragments are detected in coincidence with a target-like residue in the telescope.



Detectors

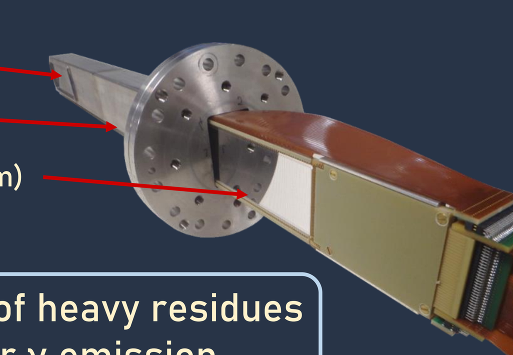
Detector stack:
- ΔE position-sensitive Si (300 µm)
- E stack of Si thick detectors (9 mm)
- surface 20*20 mm²

Telescope:



Measures position and energy of target-like residue → E* of compound nucleus.

Heavy residue detector:

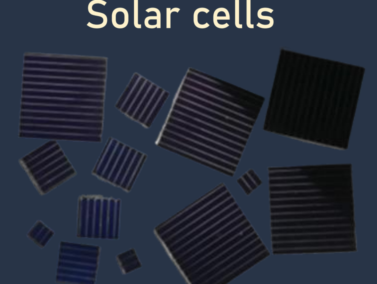


Measures position of heavy residues after neutron or γ emission.

Fission fragment detection

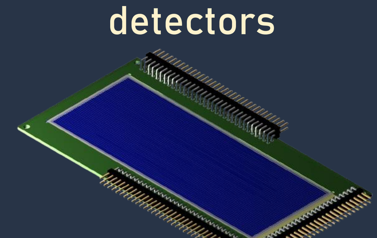
Detector type

Solar cells



- low cost
- high radiation resistance
- in development

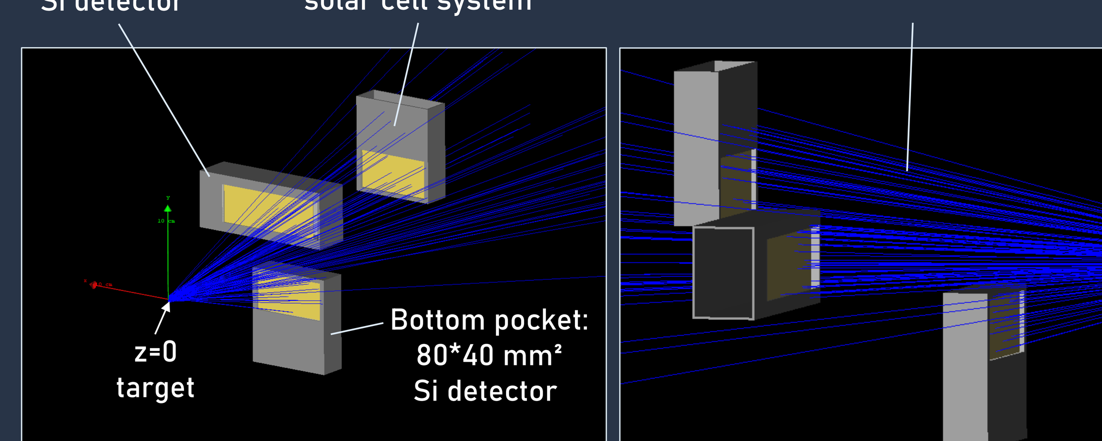
Silicon strip detectors



- worked successfully to detect heavy residues in the first experiment

Simulations

The three fission fragment detectors are placed in pockets. The side pocket is fixed to a movable drive to get closer to the beam after injection.

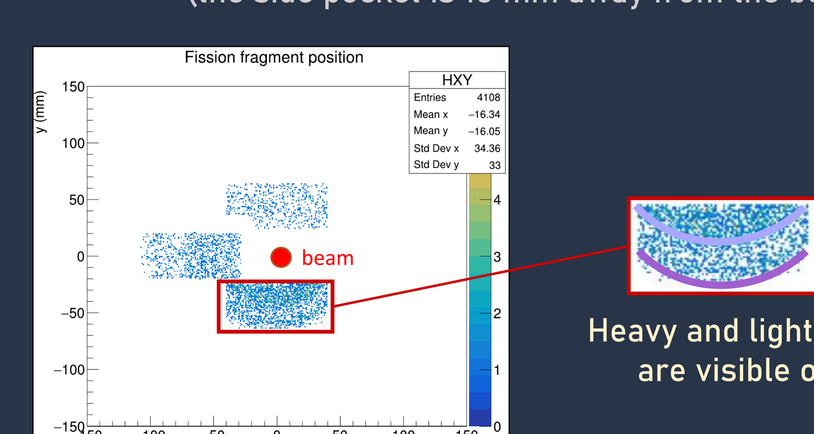


Simulation visualization made with G4beamline.

As we determine de-excitation probabilities, we estimate the fission event detection efficiency (only 1 fission fragment counted if 2 are detected).

Detector	Top	Bottom	Side
Detection efficiency	10%	38%	17%
Total	65%		

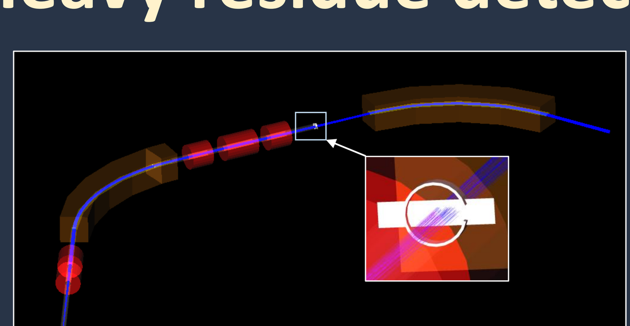
Fission event detection efficiency (the side pocket is 18 mm away from the beam).



Heavy and light fragment angle limits are visible on bottom detector.

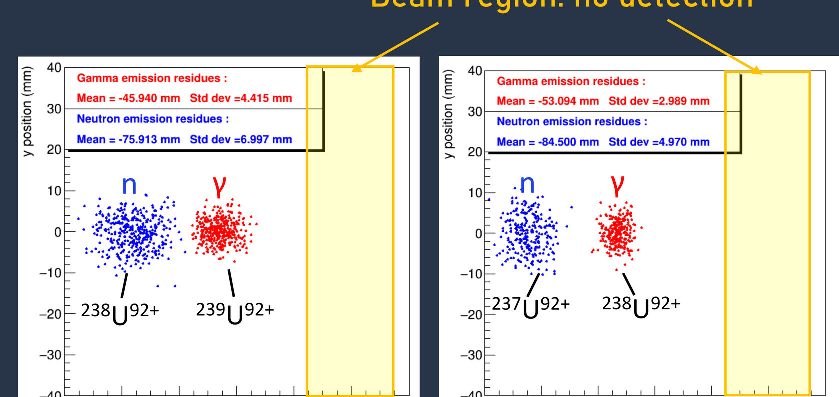
Fission fragment positions (x,y) plotted in planes perpendicular to the beam axis.

Heavy residue detection



Very few residues are lost in the beam region : HR detection efficiency is above 99%.

Beam region: no detection



Heavy residue positions (x,y) on detector: simulated for (d,p) reaction (right) and (d,d') reaction (left) at 7 MeV E* for both.

Timeline and collaboration

2019 - 2022	June 2022	2022 - 2024	June 2024	
PoP1 development	PoP1 : ^{208}Pb	PoP2 development	PoP2 : ^{238}U	NECTAR@ESR Radioactive beams

[1] *R. Pérez Sánchez et al., Phys. Rev. Lett.* **125**, *122502 (2020)* - [2] *M. Sguazzin et al., EPJ Web of Conferences* **284**, *01008 (2023)* - [3] *K.H. Schmidt, B. Jurado, GEF – A General Description of Fission Observables, http://www.khs-erzhausen.de/GEF.html*