Determining neutron-induced reaction cross sections with surrogate reactions in inverse kinematics at heavy-ion storage rings

C. Berthelot[1], B. Jurado[1], M. Sguazzin[5], B. Wloch[1], J. Pibernat[1], J. A. Swartz[13], M. Grieser[2], J. Glorius[3], Y. A. Litvinov[3], R. Reifarth[4], K. Blaum[2], P. Alfaurt[1], P. Ascher[1], L. Audouin[5], B. Blank[1], B. Bruckner[4], S. Dellmann[4], I. Dillmann[6], C. Domingo-Pardo[7], M. Dupuis[8], P. Erbacher[4], M. Flayol[1], O. Forstner[3], D. Freire-Fernandez[2], M. Gerbaux[1], J. Giovinazzo[1], S. Grevy[1], C. Griffin[6], A. Gumberidze[3], S. Heil[4], A. Heinz[9], D. Kurtulgil[4], G. Leckenby[6], S. Litvinov[3], B. Lorentz[3], V. Meot[8], J. Michaud[1], S. Perard[1], U. Popp[3], M. Roche[1], M.S. Sanjari[3], R.S. Sidhu[10], U. Spillmann[3], M. Steck[3], Th. Stöhlker[3], B. Thomas[1], L. Thulliez[8], M. Versteegen[1], L. Begue-Guillou[11], D. Ramos[11], A. Cobo[11], A. Francheteau[11], M. Fukutome[12], A. Henriques[13], I. Jangid[11], A. Kalinin[3], W. Korten[8], T. Yamaguchi[12]

[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
[11]-GANIL, France
[12]-University of Osaka, Japan
[13]-FRIB, USA

Motivations

- Neutron-induced reaction cross sections of short-lived nuclei - $\sigma_{n,\gamma}$ $\sigma_{n,n'}$ $\sigma_{n,f}$
  - → applications in nuclear technology and medicine
  - → understanding the r and s processes

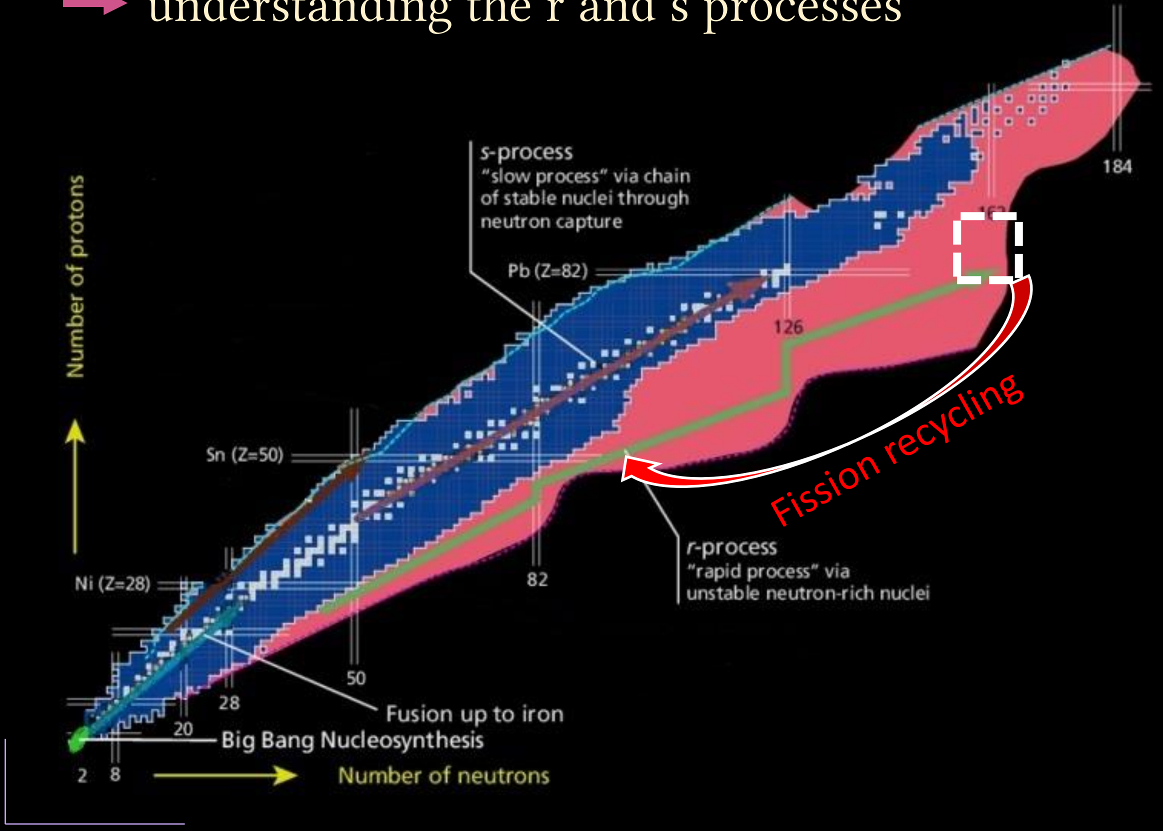
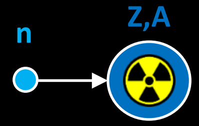
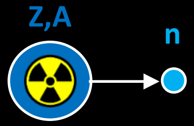


Chart of nuclei and the paths followed by the different nucleosynthesis processes.
2014 J. Phys.: Conf. Ser. 503 012038

Challenging to measure:

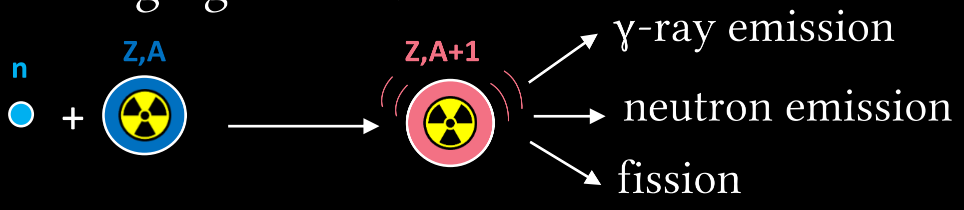


Radioactive targets : difficult to make and handle



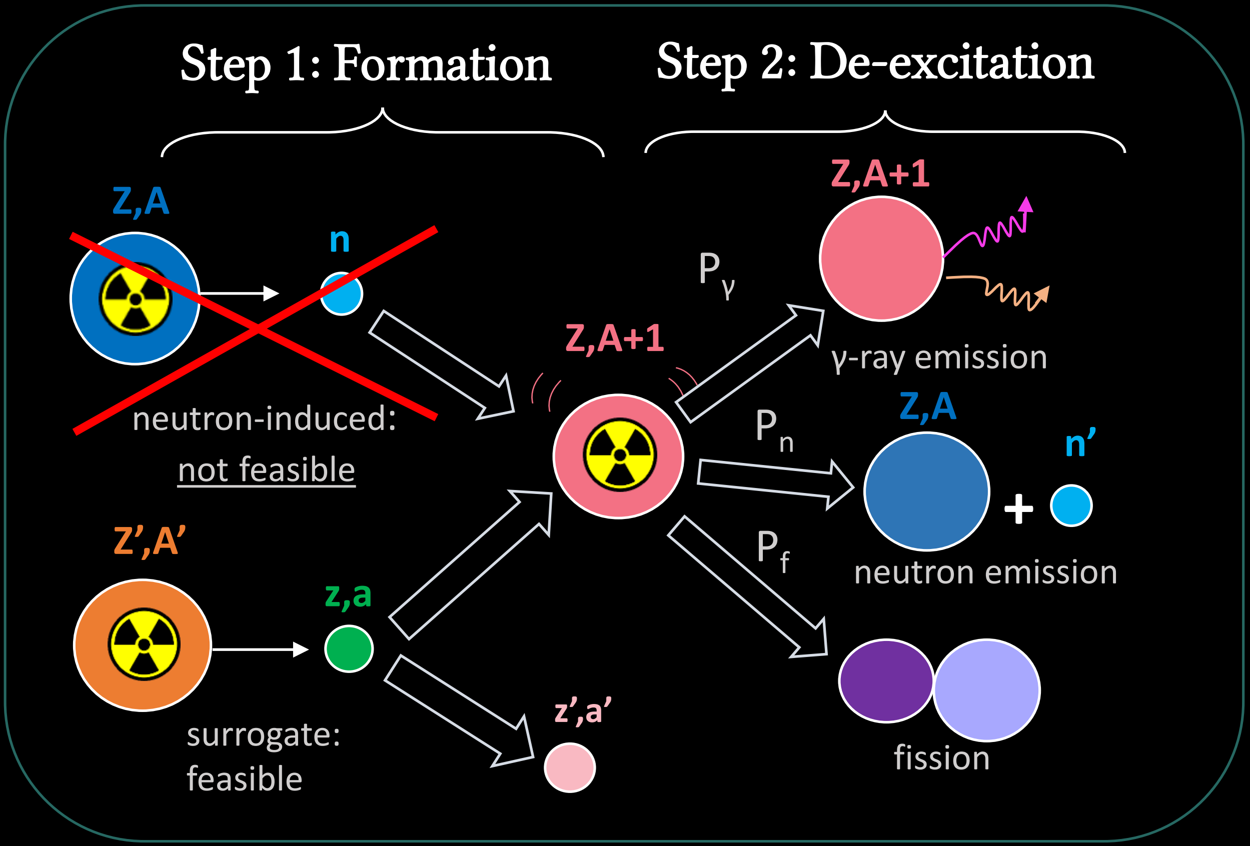
Free neutron targets : not available

Challenging to calculate:



De-excitation calculations need fundamental quantities: **NLD, B_f, γSF,…**

The surrogate reaction method



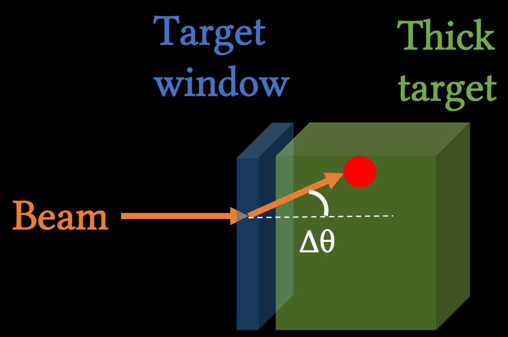
determination of $P_\gamma(E^*)$, $P_n(E^*)$ and $P_f(E^*)$.

Probabilities $P_x(E^*)$ → Model parameters NLD, B_f, γSF,… → Constrain models → Cross-sections $\sigma_{n,X}$

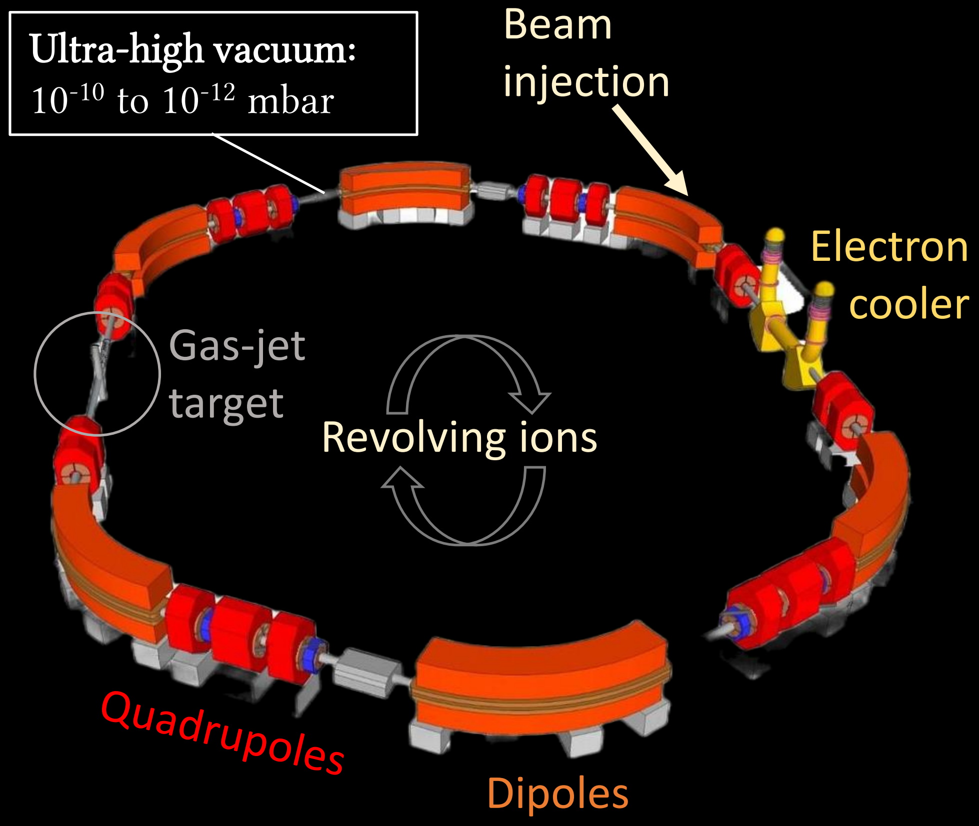
→ E* energy resolution needed ~ a few 100 keV

$$E^* = f(E_{beam}, E_{ejectile}, \theta_{ejectile})$$

→ Difficult to achieve in inverse kinematics



Heavy-ion storage rings



Gas jet target:

- windowless, pure and thin target

High quality beam:

- electron cooling technology: beam energy spread and size are restored after each passing in the target.

→ **neglect energy loss and straggling effect in the target**

$$E^* = f(E_{beam}, E_{ejectile}, \theta_{ejectile})$$

ultra-low density target (10^{11} to 10^{14} atoms/cm^2)

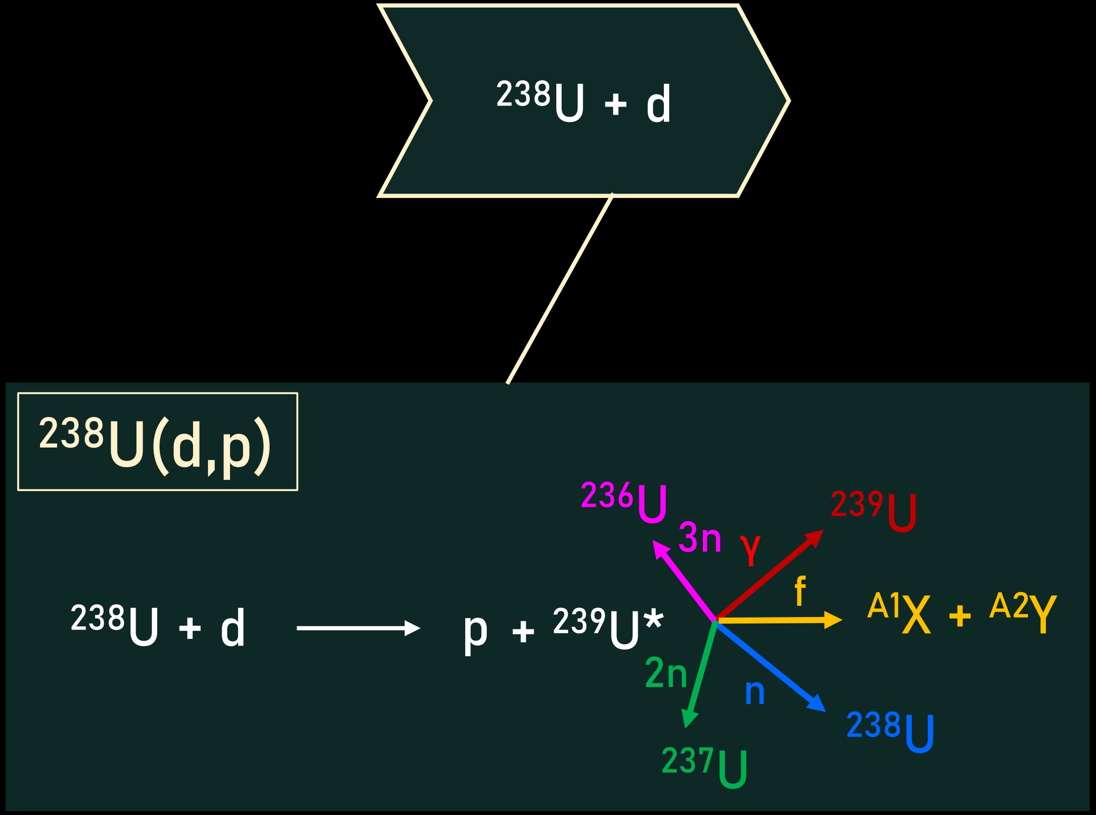
\+

revolving frequency of the beam (10^6 Hz)

→ high enough effective thickness

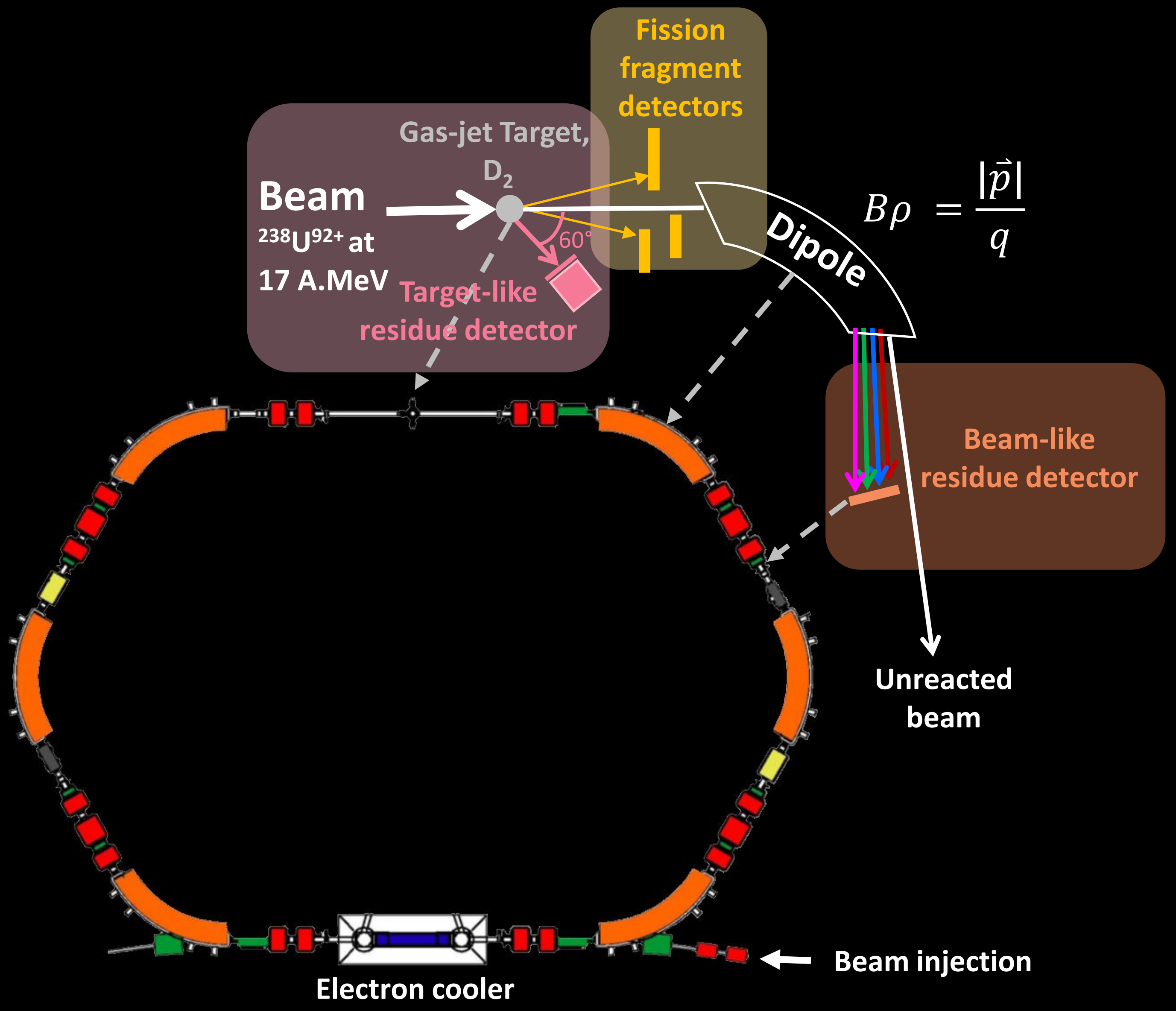
NECTAR experiments at the ESR

June 2024

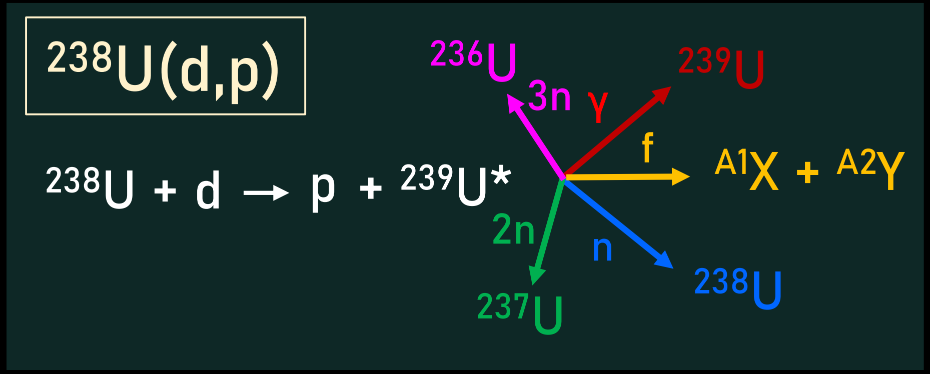


Simultaneous measurement of **neutron**, **gamma-ray**, **fission**, **two-neutron** and even **three-neutron** emission probabilities as a function of the excitation energies E* of ^{238}U and ^{239}U.

NECTAR experiments at the ESR



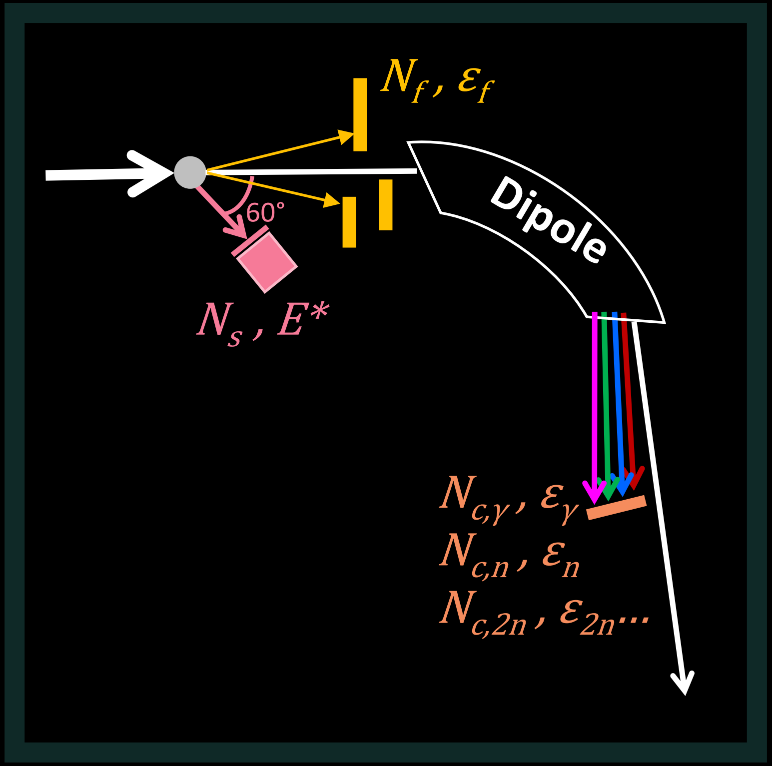
$$B\rho = \frac{|\vec{p}|}{q}$$



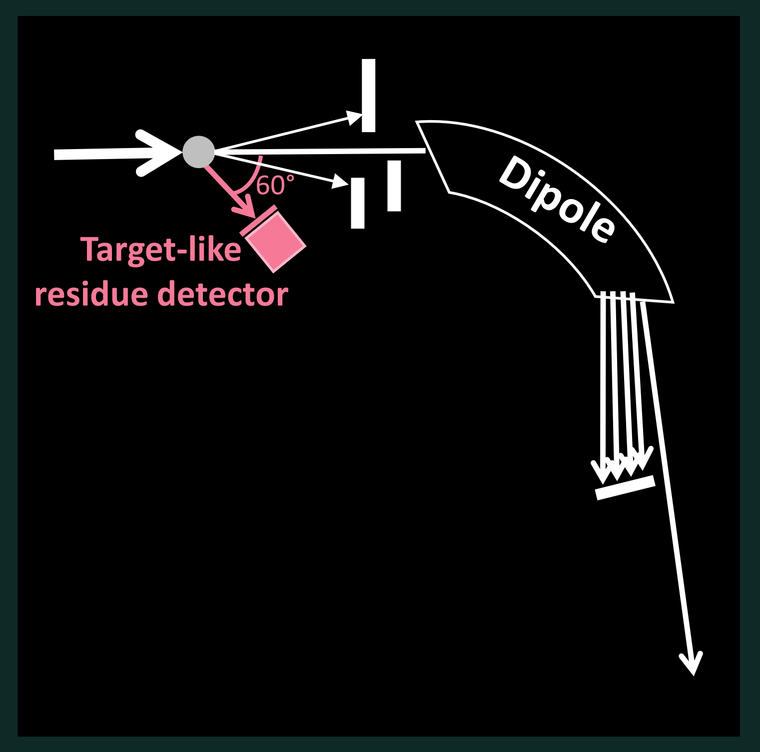
Determining probabilities

For a given decay mode χ :

$$P_\chi(E^*) = \frac{N_{c,\chi}(E^*)}{N_S(E^*) \cdot \varepsilon_\chi(E^*)}$$

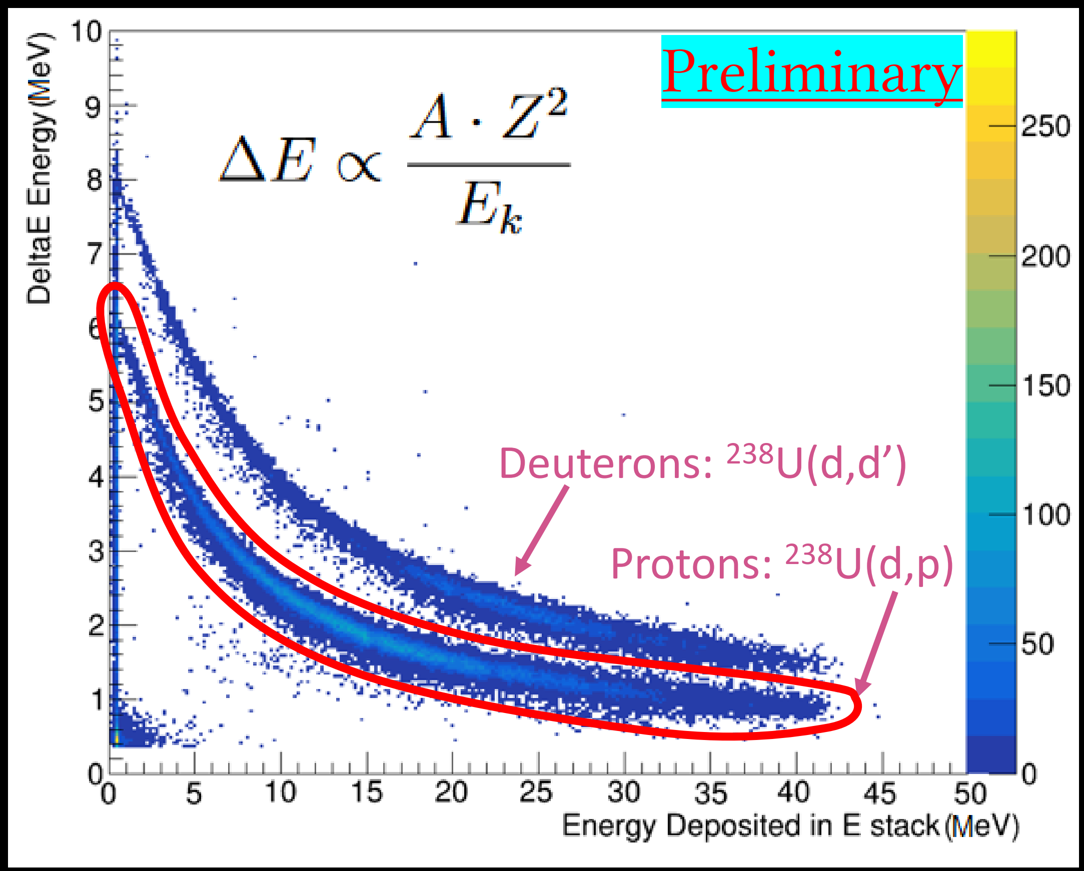


Results

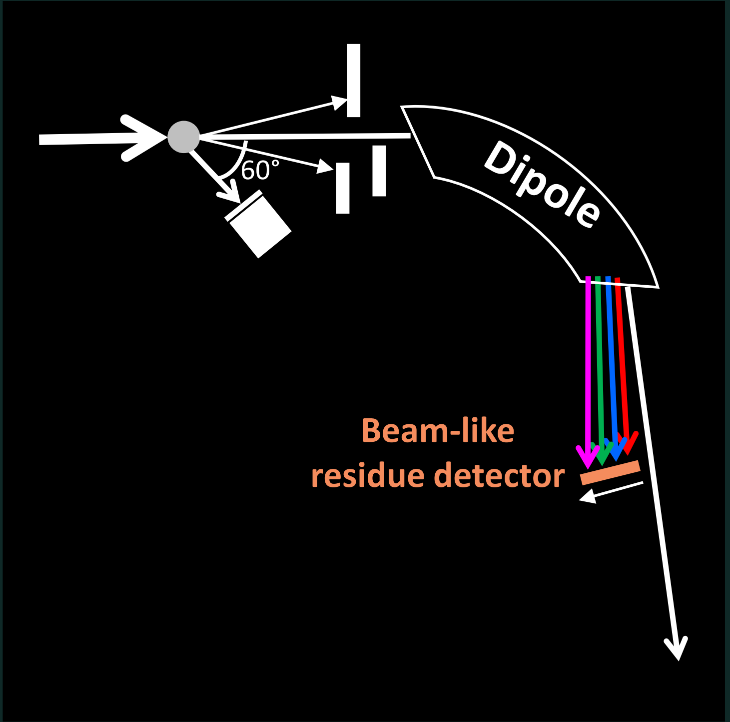


$$P_X(E^*) = \frac{N_X(E^*)}{N_S(E^*) \cdot \varepsilon_X(E^*)}$$

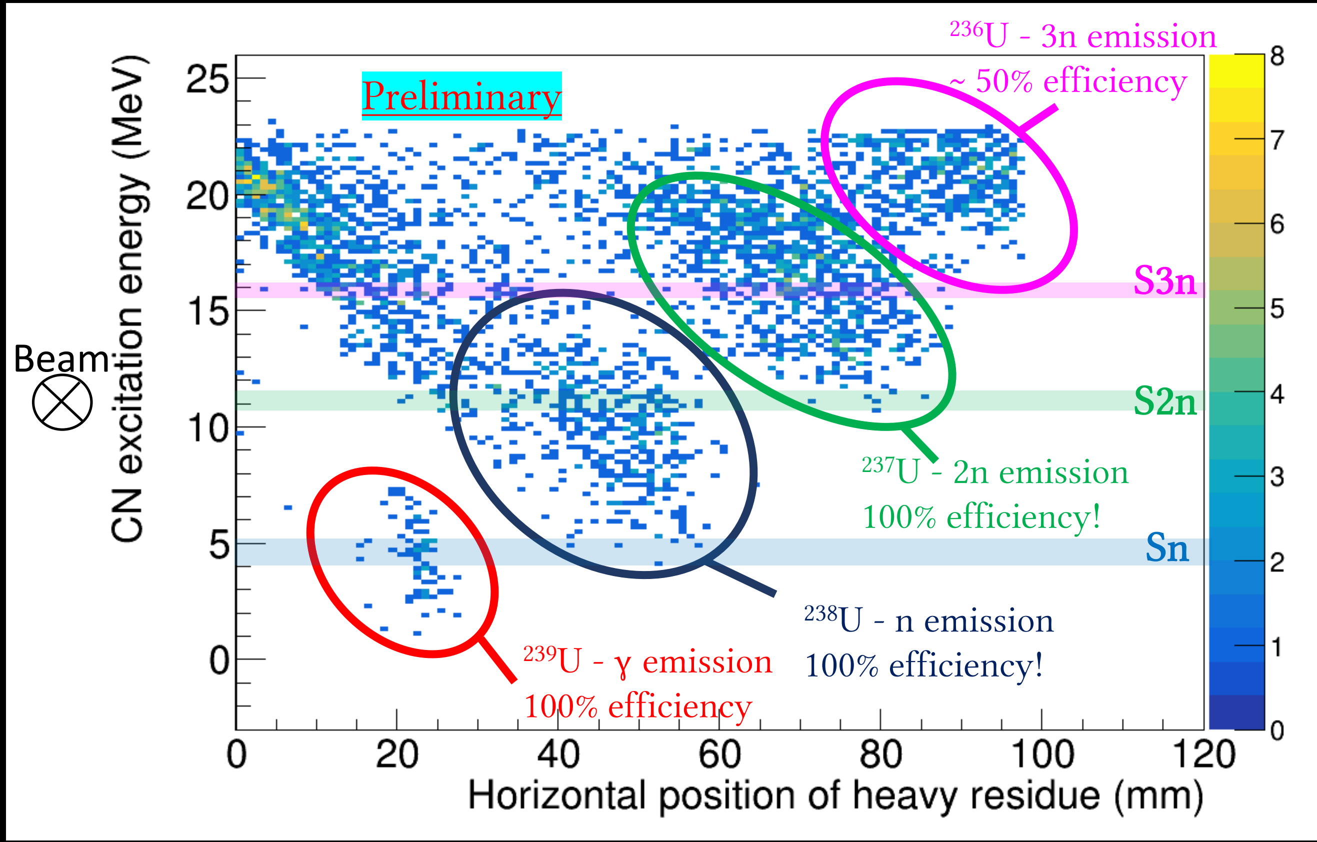
Target-like residue identification plot



Results



$$P_f(E^*) = \frac{N_{\gamma,\,n,\,2n,\,3n}(E^*)}{N_S(E^*) \cdot \varepsilon_{\gamma,\,n,\,2n,\,3n}(E^*)}$$



$^{238}U(d,p)$

E^*_{max} = 26 MeV

Results

Preliminary probabilities

First measurement of P_{2n} and P_{3n}
First simultaneous measurement of all decay channels up to $E^* = 25$ MeV

$^{238}U(d,p)$

$E^*_{max} = 26$ MeV

Preliminary

Conclusion and perspectives

- Surrogate reaction method → obtain σ_n indirectly with experimentally feasible reactions

- Heavy-ion storage rings provide outstanding efficiencies and high precision data

Short and long-term perspectives:

- Cross section calculations

- Next experiment scheduled in 2027 to study ^{205}Pb and ^{206}Pb at the ESR with a dedicated reaction chamber

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.

Accord de collaboration 19-80 GSI/IN2P3.

The results presented here are based on the experiment G-22-00028-1.1-E, which was performed at the GSI Helmholtzzentrum fuer Schwerionenforschung, Darmstadt (Germany) in the context of FAIR Phase-0.

This project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No 101057511.