Investigating the surrogate method via the simultaneous measurement of fission and gamma probabilities

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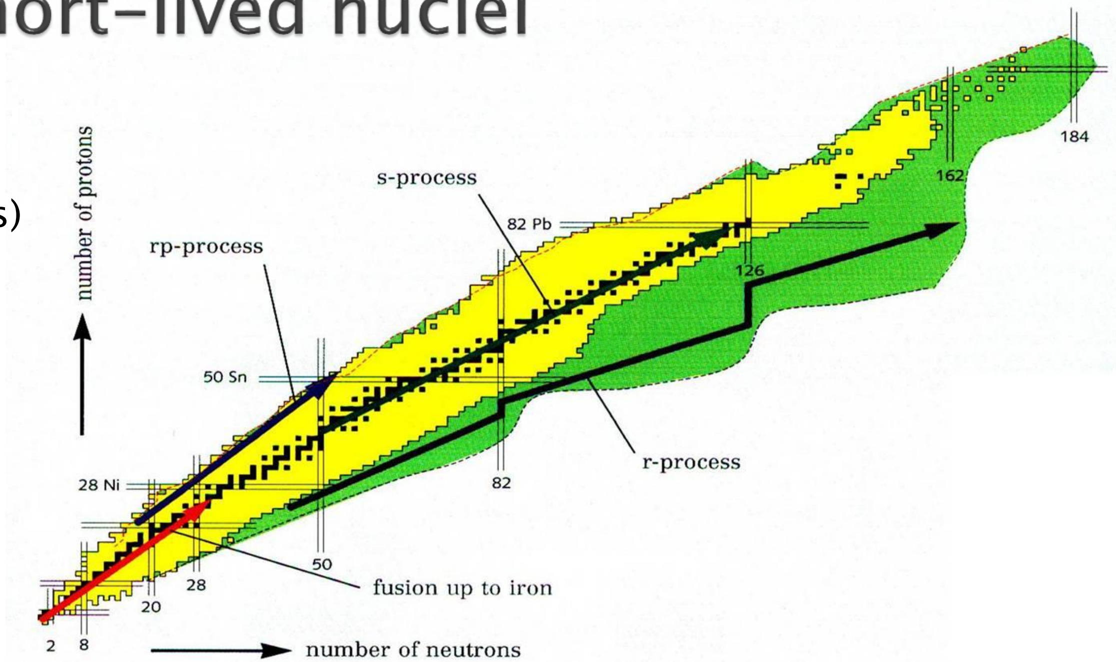
[6] EC-JRC, Geel, Belgium

Need for neutron induced cross sections of short-lived nuclei

- Astrophysical studies
  - Nucleosynthesis (r and s processes)
- Applications
  - Transmutation of nuclear wastes
  - New reactor design (Th/U cycle)



- Fundamental nuclear physics
  - Improvement of nuclear reaction models (level density, γ strength function, fission barriers…)

➢ **Difficulty : production and handling radioactive targets**
➢ **Alternative to neutron-induced reaction : the surrogate reaction method**

The surrogate-reaction method

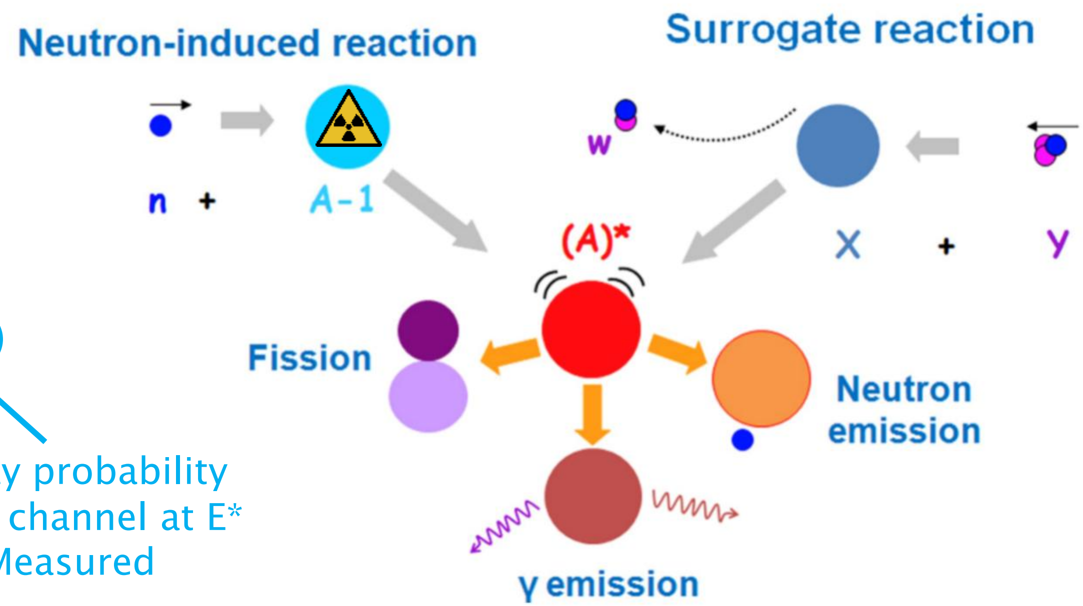
- Principe
  - Production of the same compound nucleus via an alternative reaction

χ (fission,γ,n) cross section :

$$\sigma_{\chi}^{A-1}(E_n) = \sigma_{CN}^{A}(E_n) P_{\chi}(E^*)$$

CN formation cross section
➢ Calculated

CN decay probability in the χ channel at E*
➢ Measured



➢ **Advantage : possibility to find a stable or weak radioactive target**
➢ **Validity of this method ?**

H. C. Cramer and J. D. Britt, Nucl. Sci. Eng. **41**, 177 (1970)

Validity of the surrogate-reaction method

- Formation of a compound nucleus (surrogate and the neutron reactions)

$$\sigma_\chi^{A-1}(E_n) = \sigma_{CN}^{A}(E_n) P_\chi(E^*) \quad \text{where : } \quad P_\chi(E^*) = \sum_{J^\pi} S(E^*, J^\pi) \mathcal{P}_\chi(E^*, J^\pi)$$

CN J and π distributions at E*
Difficult to calculate

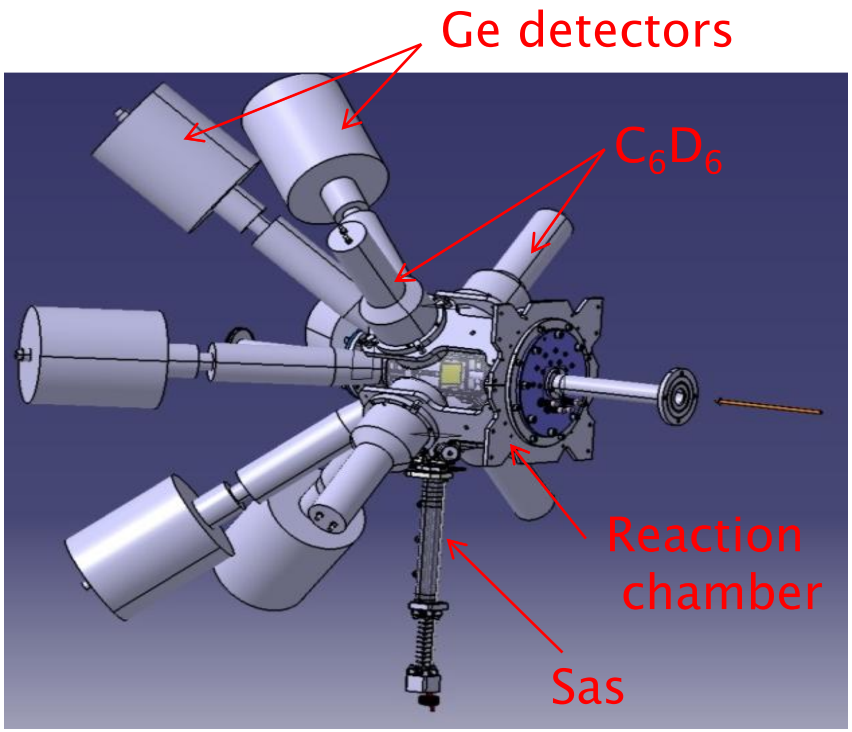
CN decay probability in a J^π state at E*

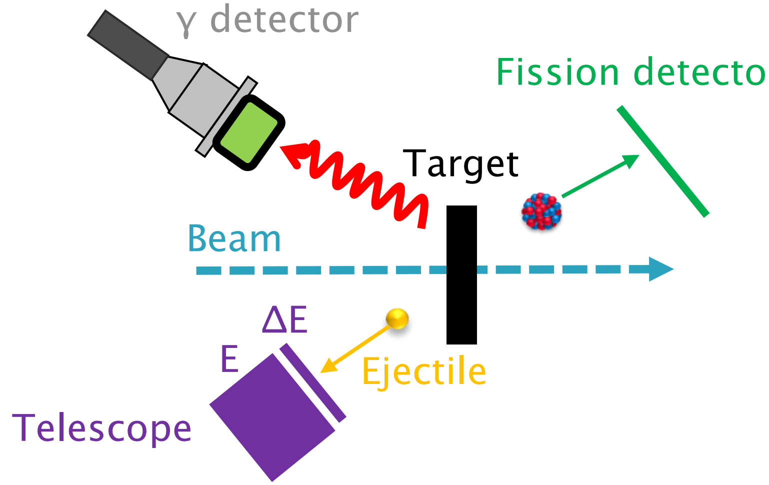
- Same decay probability in the surrogate and neutron-induced reactions
  → two extreme cases :
  - Same J and π distributions in the two reactions : $S_{\text{n-induced}}(E^*, J^\pi) = S_{\text{surrogate}}(E^*, J^\pi)$
  - Decay probability of the CN independent of the J and π distributions (Weisskopf-Ewing limit) : $\mathcal{P}_\chi(E^*, J^\pi) = \mathcal{P}_\chi(E^*)$

- Validity of the surrogate method determined *a posteriori*
  - Need neutron-induced data
  - Systematic studies must be performed

Experimental setup

- Measurement of the γ emission and fission probabilities simultaneously
  - Fission detectors : solar cells
  - γ detectors : C_6D_6, Ge
  - ΔE–E telescopes : SiLi





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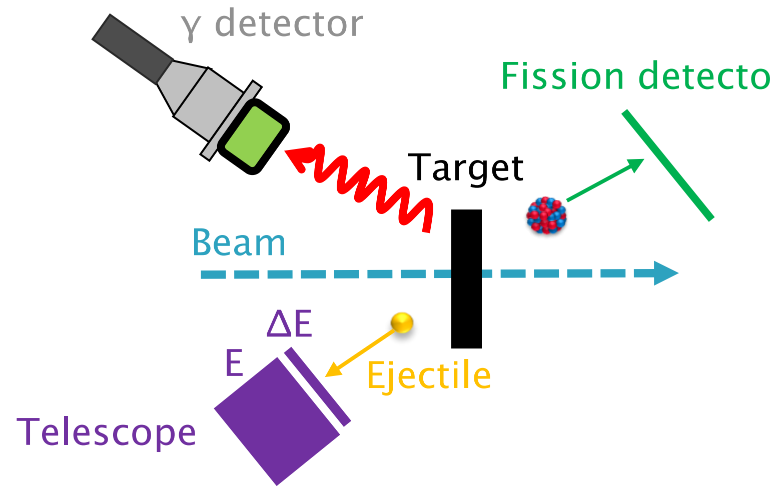
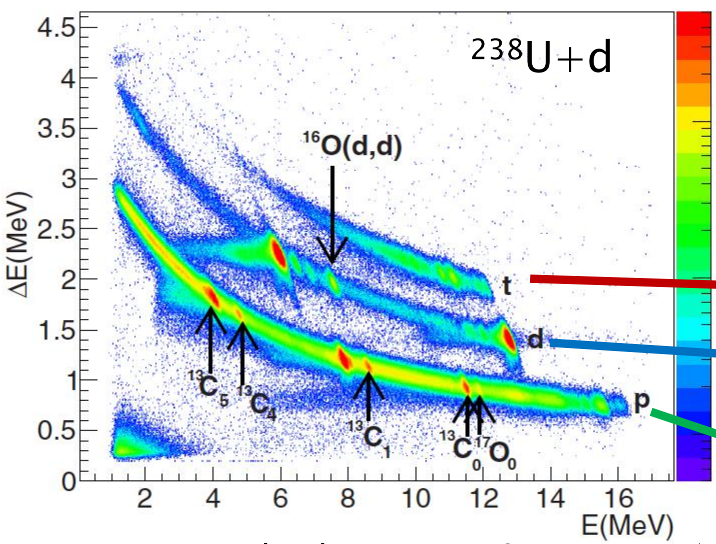


- Several surrogate reactions in one experiment
  - Identification of the reaction with the telescope



$^{238}U(d,t)^{237}U \Leftrightarrow n+^{236}U$

$^{238}U(d,d')^{238}U \Leftrightarrow n+^{237}U$

$^{238}U(d,p)^{239}U \Leftrightarrow n+^{238}U$

Q. Ducasse et al., Phys. Rev. C **94**, 024614 (2016)

- E* fully determined with the reaction kinematics

Validation of our experimental technique

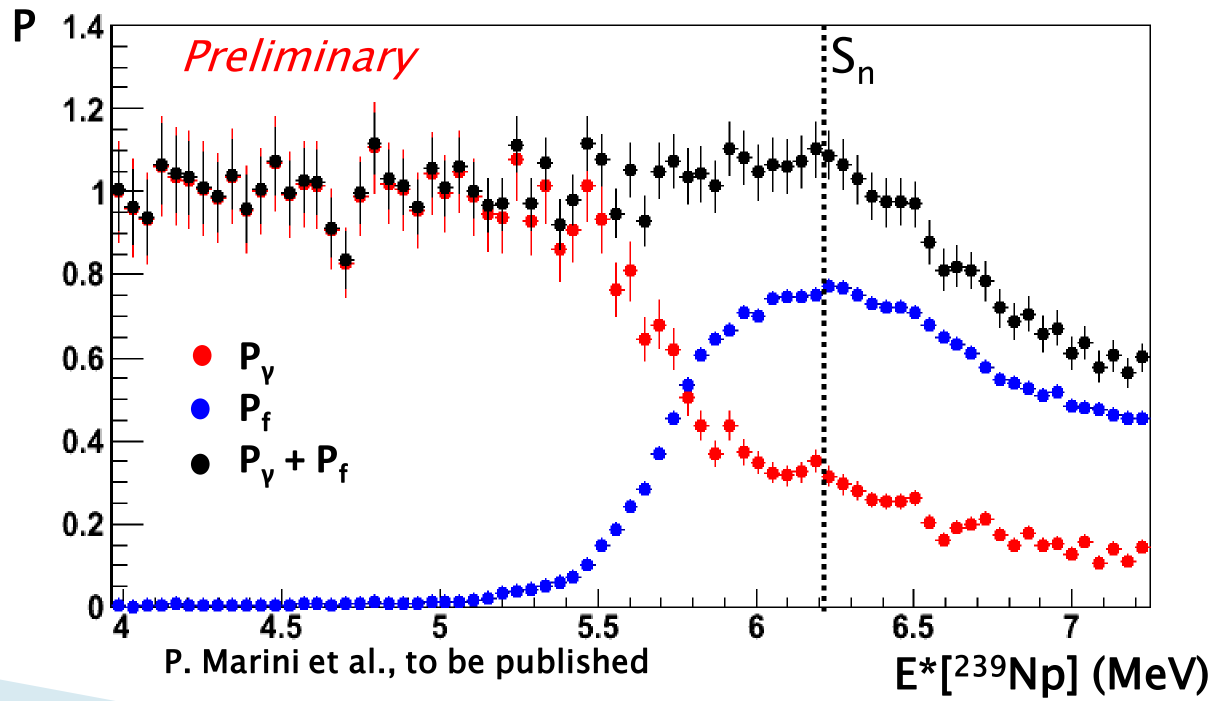
- Determination of the decay probability P_χ:

$$P_\chi(E^*) = \frac{N_\chi^{coinc}(E^*)}{N^{single}(E^*)\epsilon_\chi(E^*)}$$

Coincidence spectrum :
- Ejectile-γ for P_γ
- Ejectile-fission fragment for P_f

Single ejectile spectrum χ detection efficiency

- Check for a fissile nucleus : $^{238}U(^3He,d)^{239}Np \Leftrightarrow n + ^{238}Np$
  - $P_f + P_\gamma = 1$ for $E^* < S_n$



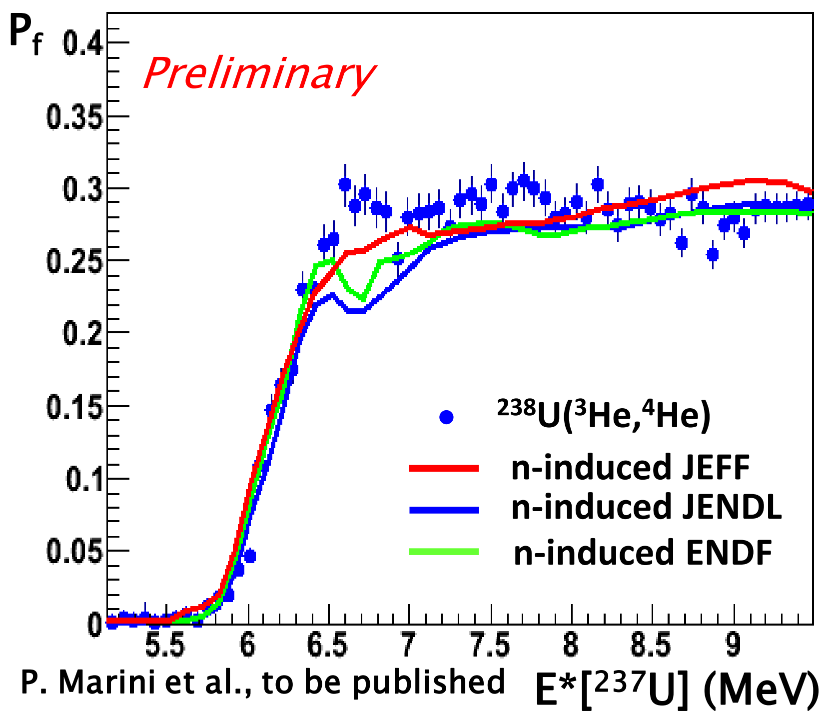
P. Marini et al., to be published

➢ Validity of the analysis method

Typical results

$^{238}U(^{3}He, ^{4}He)^{237}U \Leftrightarrow n + ^{236}U$

Fission



P. Marini et al., to be published

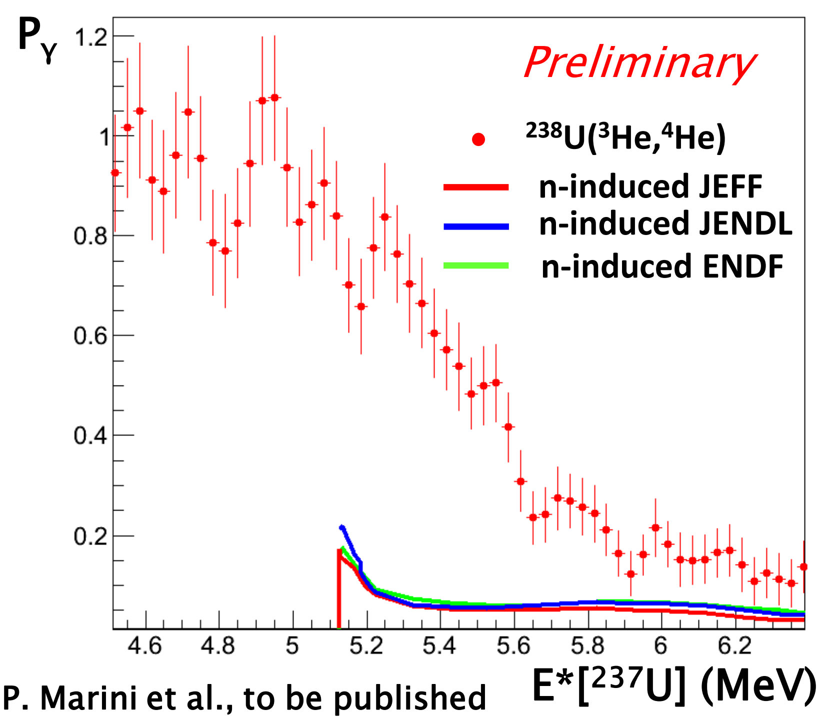
➢ Good agreement between surrogate and n-induced reactions

See also :

G. Kessedjian et al., Phys. Lett. B **692** 297 (2010)

G. Kessedjian et al., Phys. Rev. C **91** 044607 (2015)

γ emission



P. Marini et al., to be published

➢ Large discrepancies between surrogate and n-induced reactions

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G. Boutoux et al., Phys. Lett. B **712** (2012) 319

Q. Ducasse et al., Phys. Rev. C **94**, 024614 (2016)

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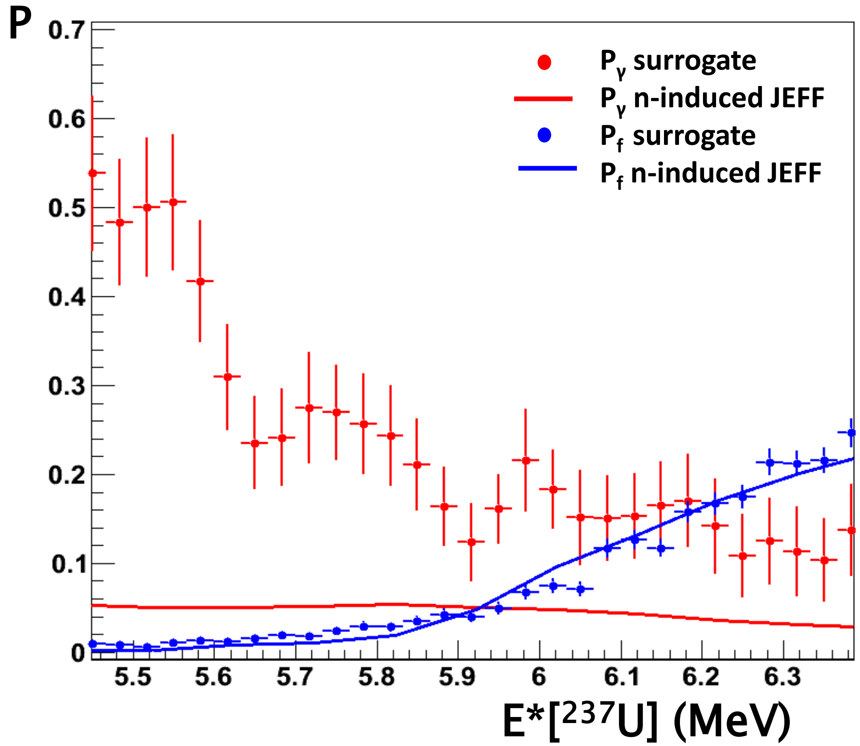

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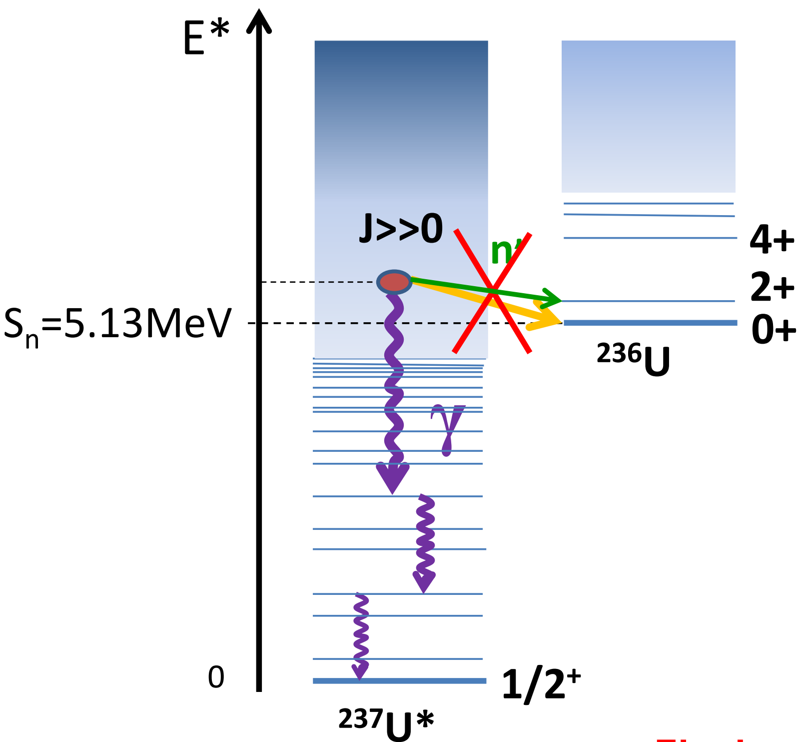
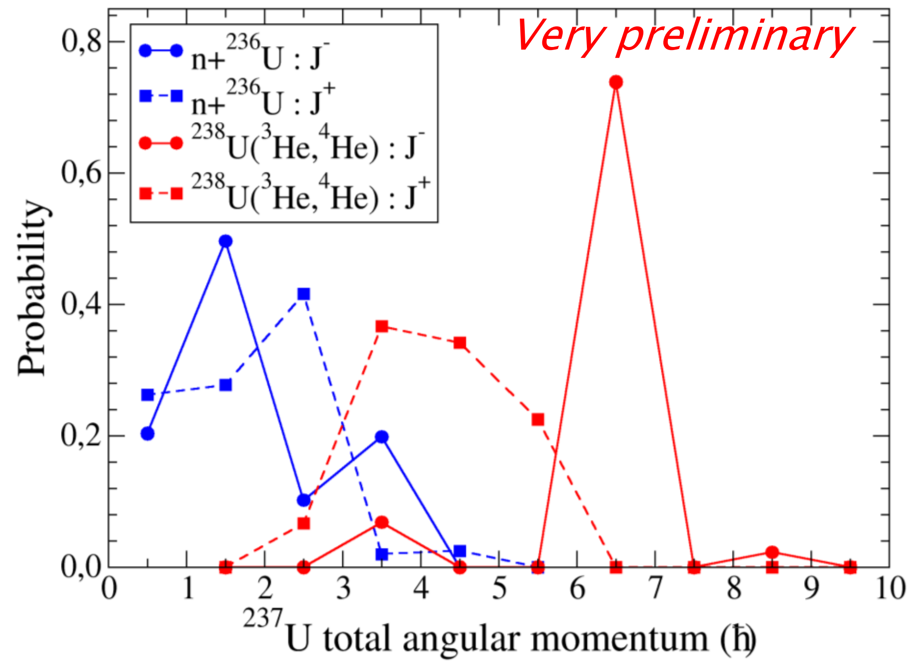
Spin and parity distribution calculations

- Difference between the spin distributions in surrogate and n-induced reactions
  - Surrogate reactions populate higher spins than n-induced ones
  - Neutron emission from high spins not possible
    - ➢ γ emission probability increases



DWBA calculations



I. Thompson, J. E. Escher, UCRL-TR-225984 (2006)

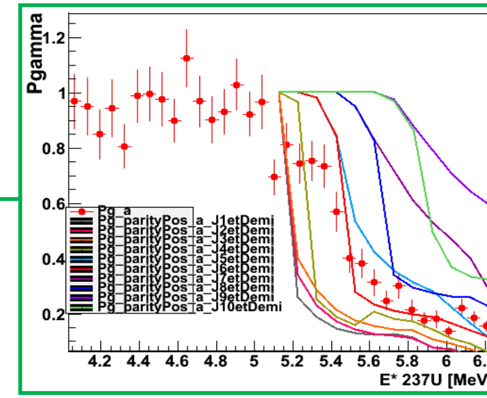
➢ **Fission seems not to be sensitive to the J^π distributions**

➢ **γ emission very sensitive to the J^π distributions**

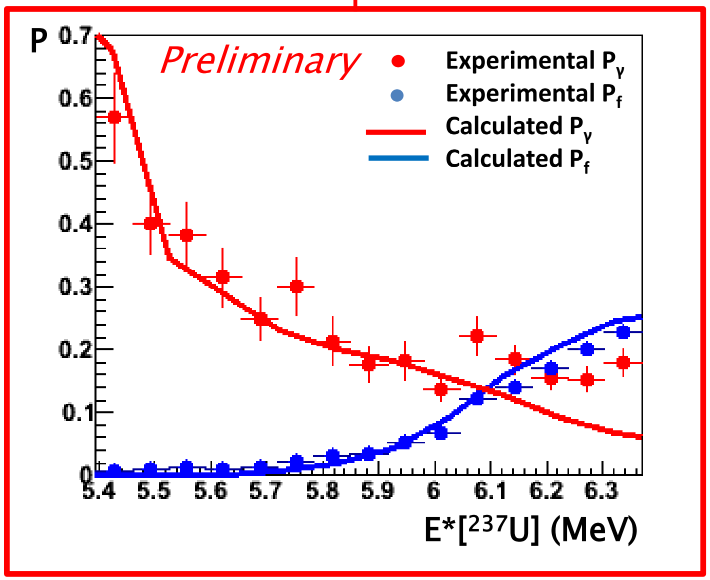
Theoretical interpretation of the $^{238}U(^{3}He,^{4}He)^{237}U$ reaction

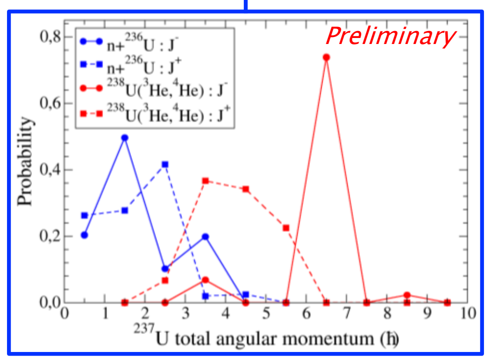
- γ and fission probabilities calculated with the statistical model
  - J^{π} distributions previously calculated are used as inputs in the Hauser-Feshbach calculations
  - Statistical model based on Extended R-Matrix theory (O. Bouland)
  - Model parameters adjusted on the n-induced cross section

$$P_{\chi}(E^*) = \sum_{J^{\pi}} S(E^*, J^{\pi}) \mathcal{P}_{\chi}(E^*, J^{\pi})$$



O. Bouland, contribution to ND2016
O. Bouland *et al.*, PRC **88**, 054612 (2013)





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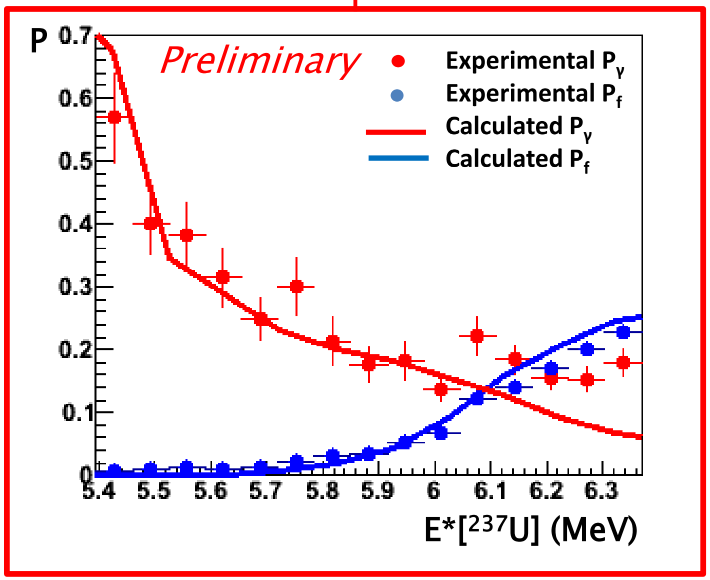

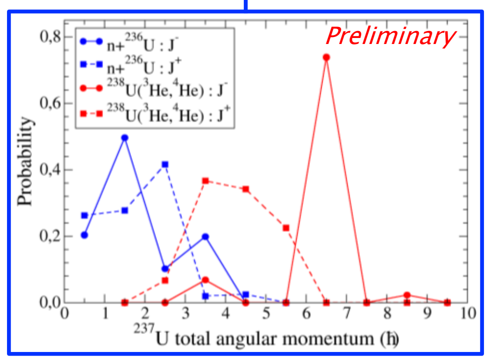

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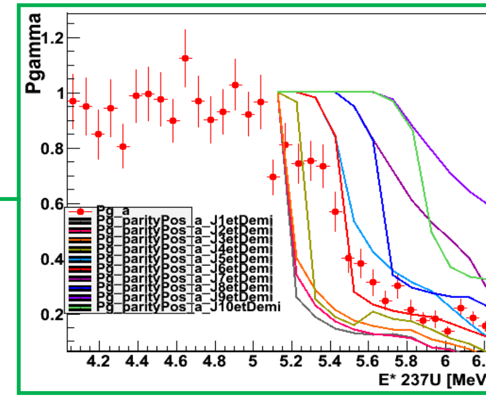


O. Bouland, contribution to ND2016

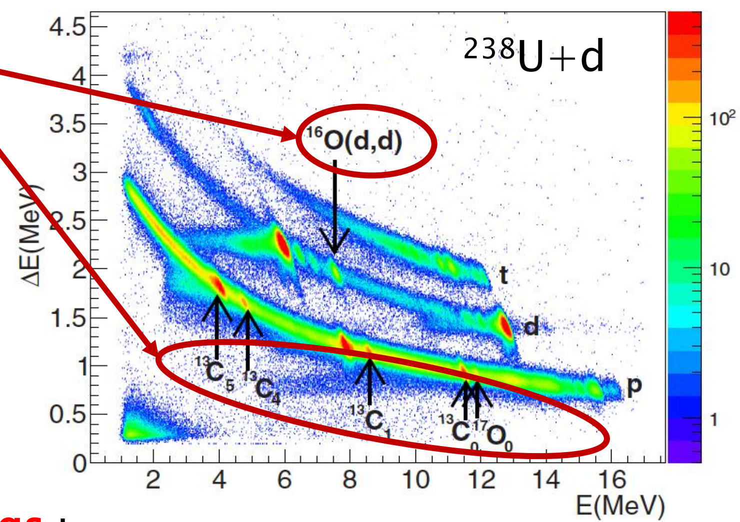
O. Bouland *et al.*, PRC **88**, 054612 (2013)

➢ **Common theoretical framework which reproduces fission and γ emission for n-induced and surrogate reactions**

➢ **Possibility to use surrogate data to tune model parameters**
→ calculations of n-induced cross sections

Surrogate reactions inside storage rings ?

- Limitation of the surrogate reaction in direct kinematics
  - Availability of targets
  - Background from target contaminants and backing
  - Heavy decay residues not measured

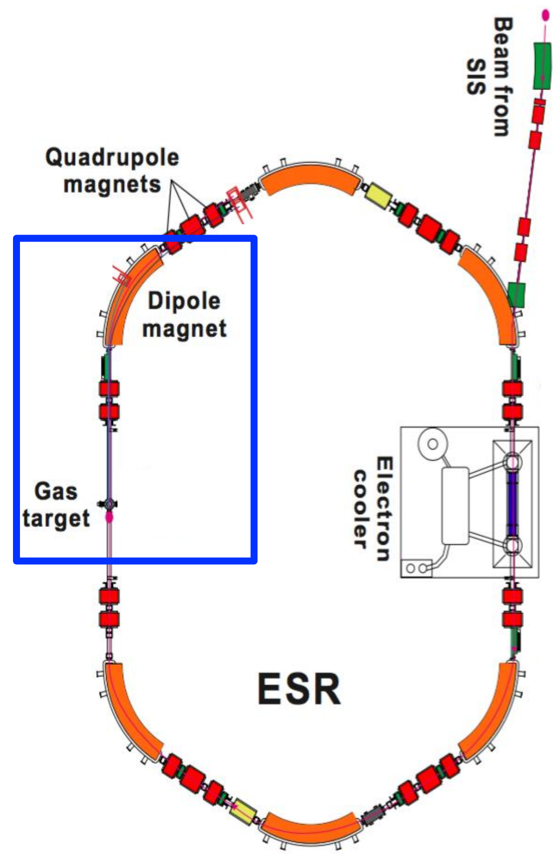


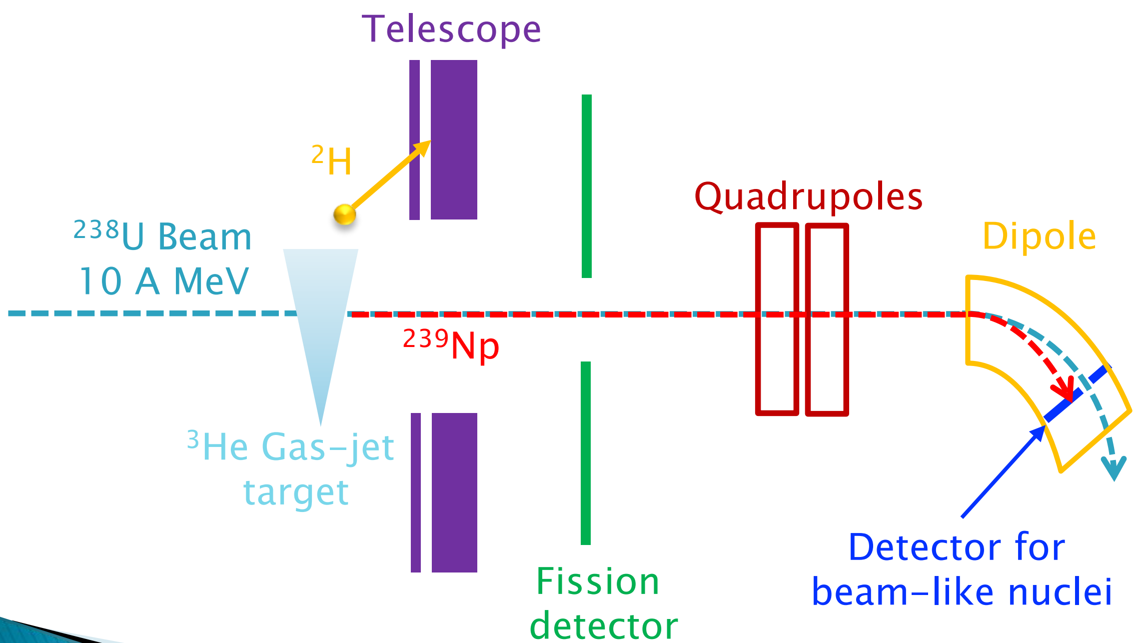
- Advantages of inverse kinematics :
  - Access to short-lived nuclei
  - Detection the heavy decay residues
  - Better fission fragment detection efficiency (forward angle focusing)

- Advantages of inverse kinematics **inside storage rings** :
  - Good beam energy definition and resolution (a few 100 keV at 10 A MeV)
  - Good beam spatial resolution (~1 mm)
  - Measurement with gas-jet target (H, D, ^{3}He, ^{4}He)
    - Pure target : no window, no backing, no contaminant
    - Low density target (10^{14} atoms/cm^2) but counterbalanced by the revolution frequency (1 MHz)
  - Production of isomeric beams : study the impact of J^π on nuclear reaction models

Experimental setup inside a storage ring

- Experiment inside a storage ring (ESR, CRYRING,…)
  - Inverse kinematics
  - Ultrahigh vacuum (UHV) : 10^{-11} mbar
- Benchmark reaction : $^{238}U+^{3}He \rightarrow ^{239}Np+^{2}H \Leftrightarrow n+^{238}Np$
  - γ emission : coincidence telescope $^{2}H/^{239}Np$ in the dipole





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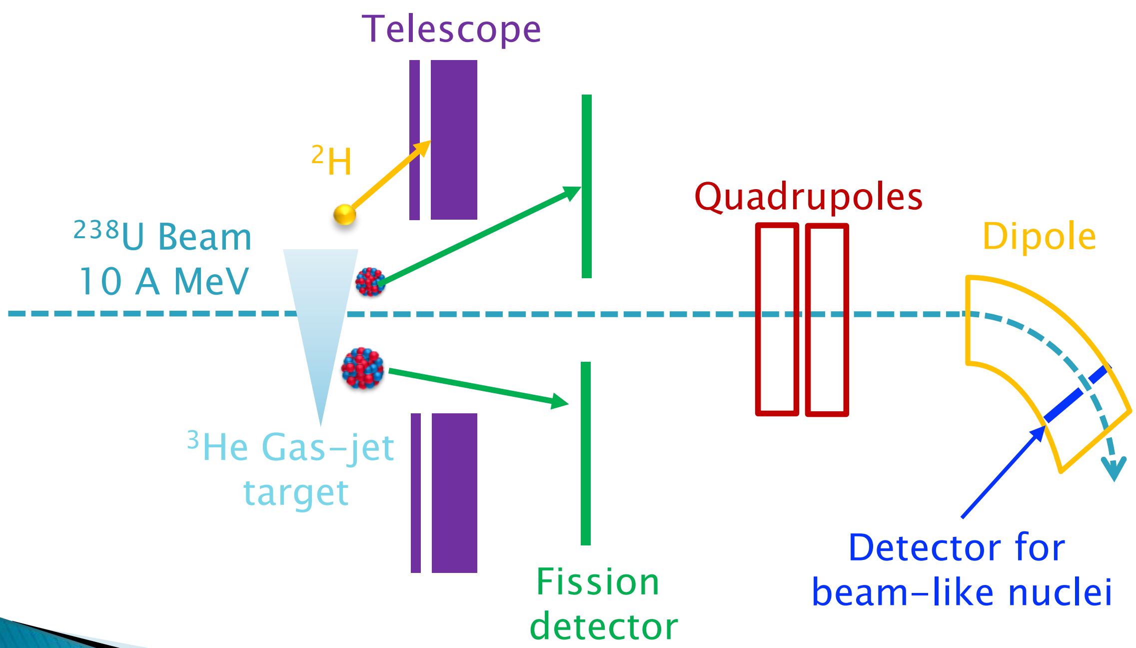
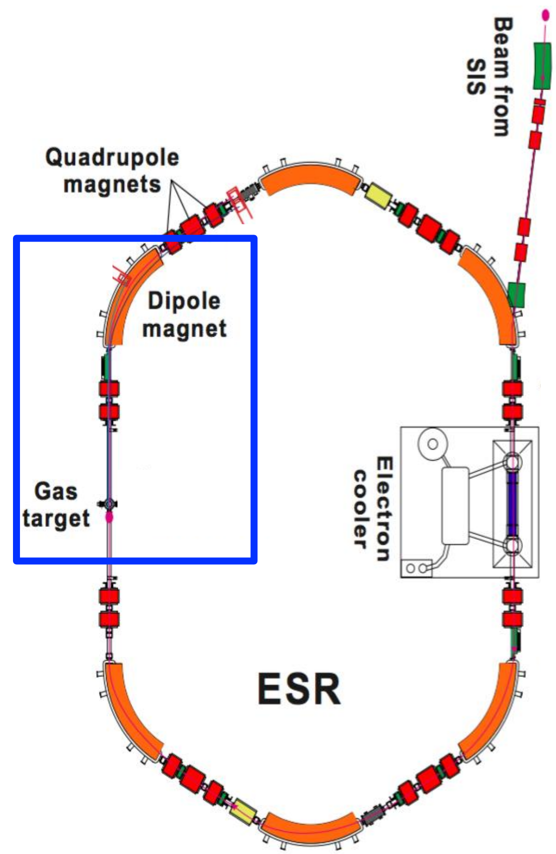
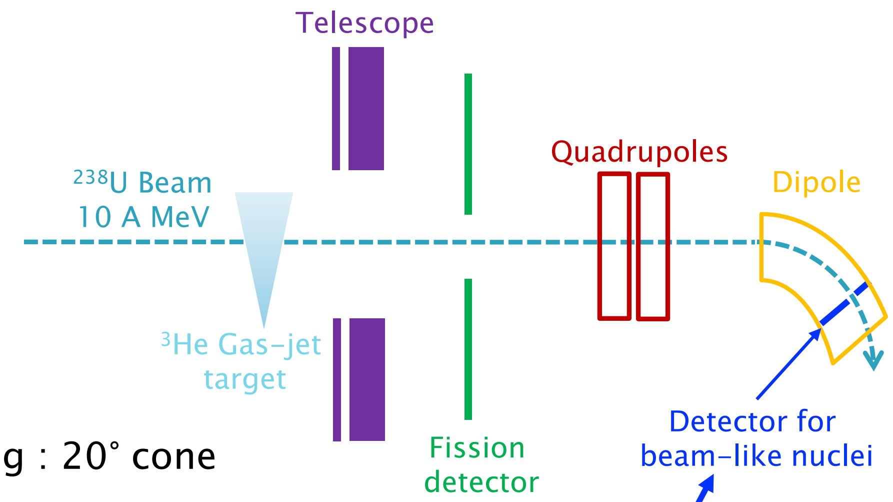
  - Fission : coincidence telescope ^{2}H/fission detector

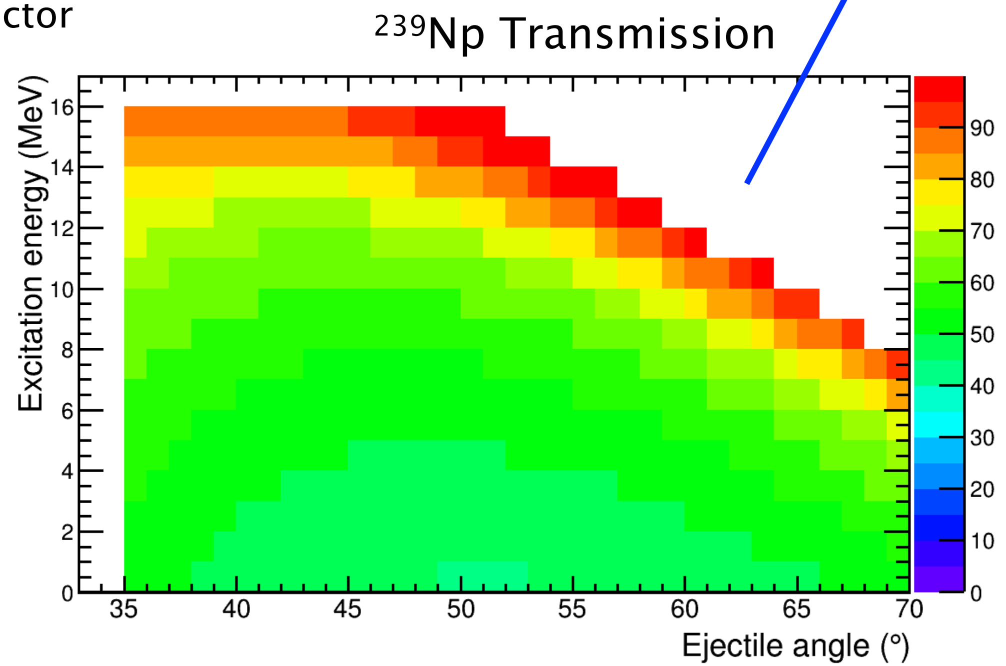




Feasibility studies inside storage rings

- Telescopes
  - High angular resolution needed to obtain a well energy resolution
  - 4 Si 6.2x6.2 cm, 128x128 strips
  - θ from 35° to 70° with Δθ from 0.03° to 0.3°
- Fission fragment detector
  - High detection efficiency due to forward focusing : 20° cone
  - Efficiency : ~94% at 35 cm
  - Solar cells if UHV compatible or Si detector
- Beam-like nucleus detector
  - Si detector in a specific arm: feasibility demonstrated
  - Transmission higher than 40%
  - ➢ High detection efficiency (~6% in direct kinematics)





Conclusion

- Surrogate reactions: alternative to neutron induced reactions
  - Good agreement between surrogate and n-induced reaction for fission …
  - … but large discrepancies for γ emission
    - ➢ **More investigations required to understand this phenomenon and the role of the spin/parity distributions**
    - ➢ Last experiment in Orsay (April 2017) : $^{240}Pu(^{3}He,^{4}He)$, $^{240}Pu(^{3}He,^{3}He')$, $^{240}Pu(^{4}He,^{4}He')$

- Surrogate reactions in direct kinematics: limitations
  - Target availability (even if easier than for n-induced reactions)
  - Target contaminants
  - No heavy residue detection
  - ➢ **Experiment in inverse kinematics inside storage rings ?**

- Surrogate reaction inside storage rings
  - Pure target
  - High beam quality: energy and spatial resolution
  - High detection efficiencies: fission fragments, beam residues
  - Isomeric beams
    - ➢ **Studies in progress…**

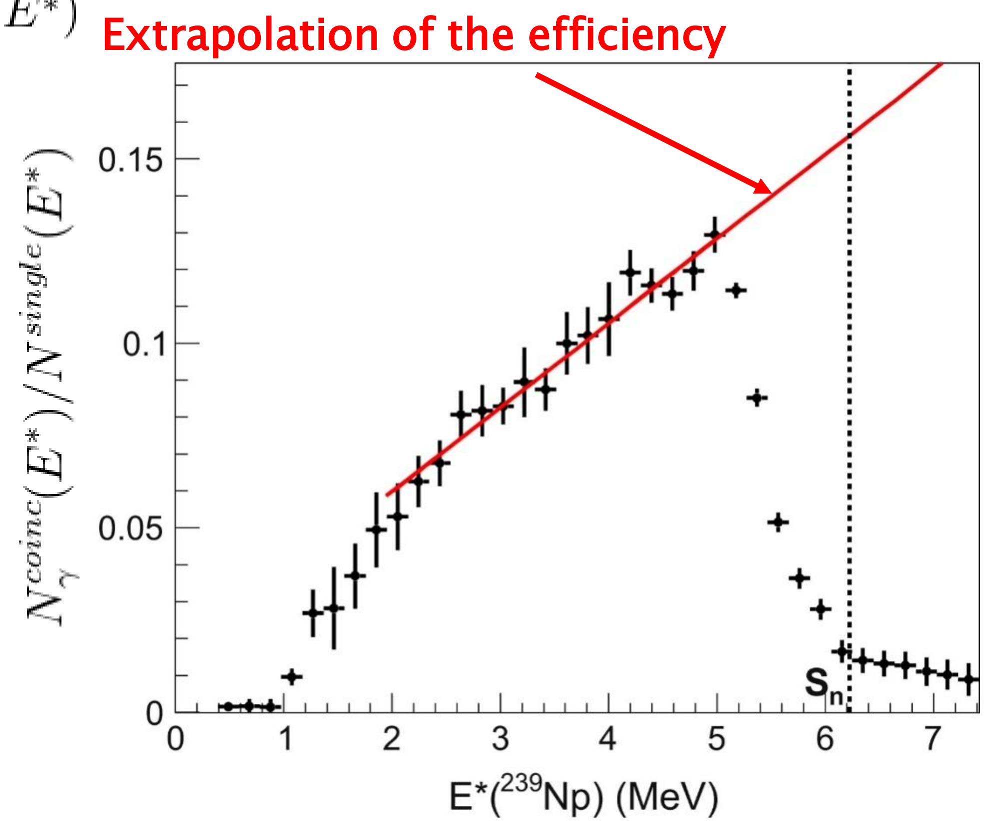
Thank you for your attention

The EXtrapolated Efficiency Method (EXEM)

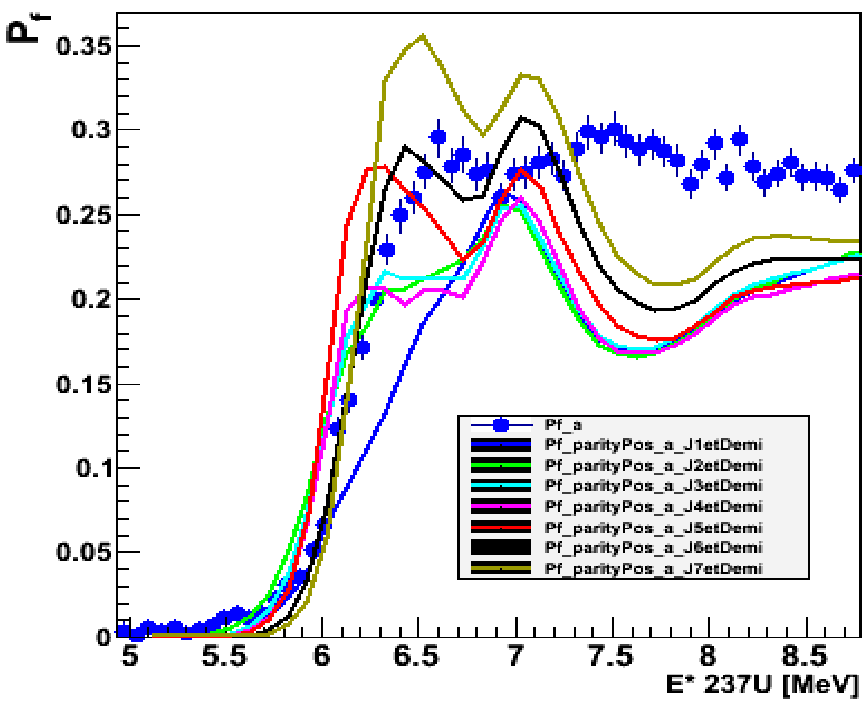
γ emission probability : $P_\gamma(E^*) = \dfrac{N_\gamma^{coinc}(E^*)}{N^{single}(E^*)\epsilon_\gamma(E^*)}$

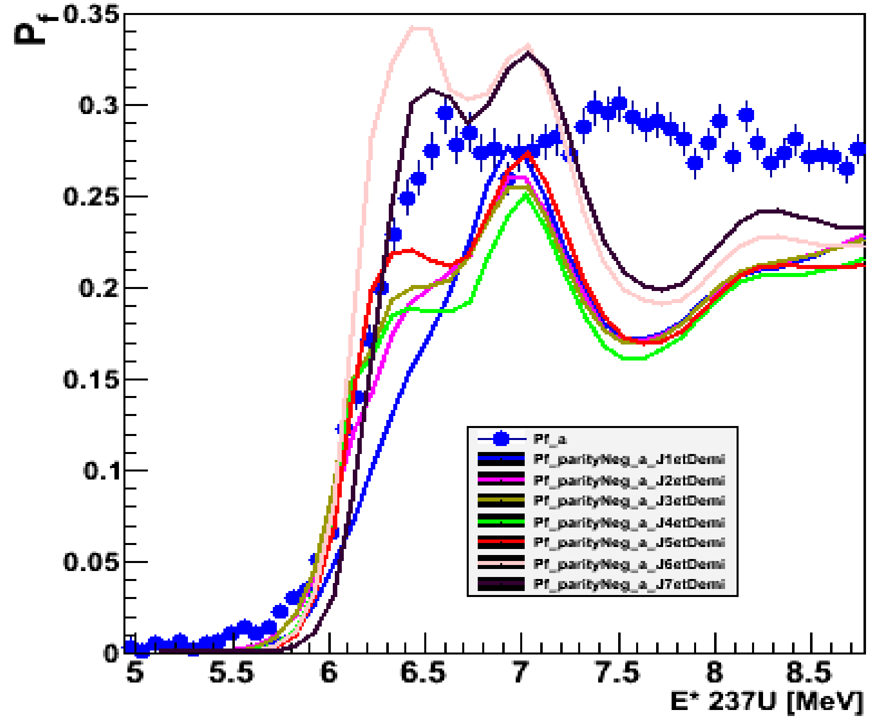
For E* where only the emission is possible (E*<S_n,fission threshold) : $P_\gamma(E^*) = 1$

$$P_\gamma(E^*) = 1 \Rightarrow \epsilon_\gamma(E^*) = \frac{N_\gamma^{coinc}(E^*)}{N^{single}(E^*)}$$



Fission probabilities as function of J^{π}





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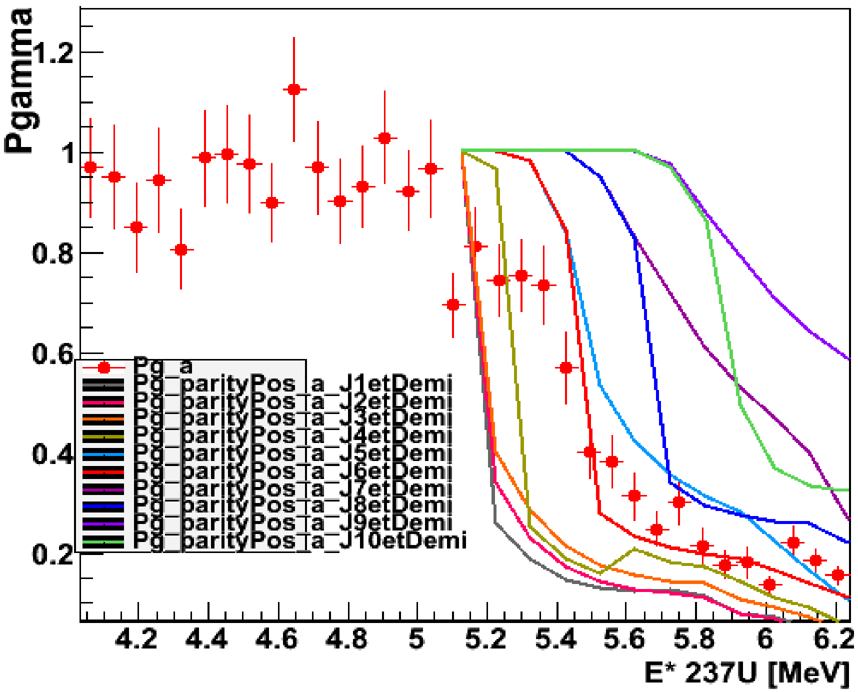
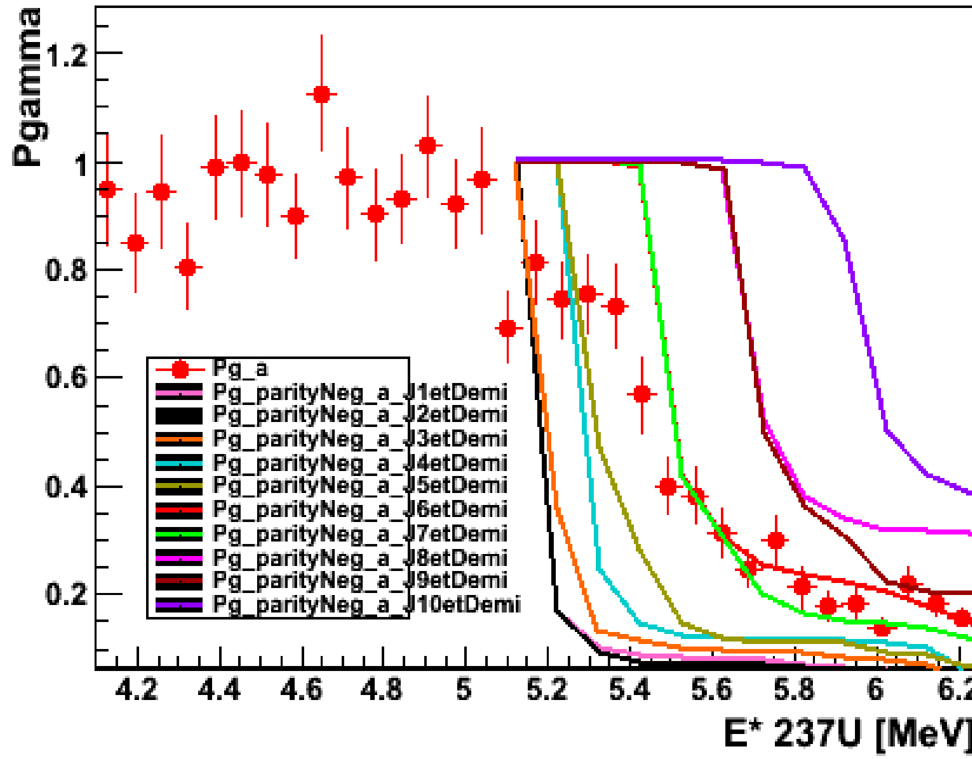
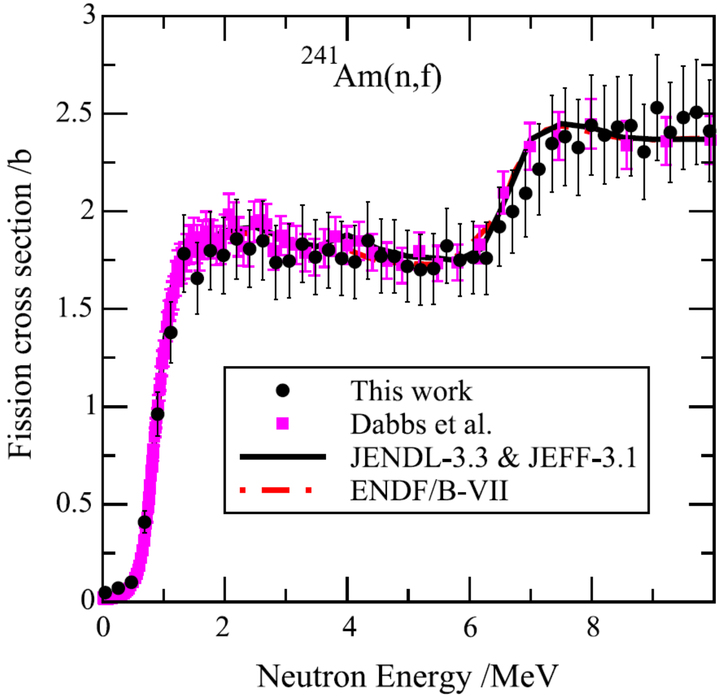




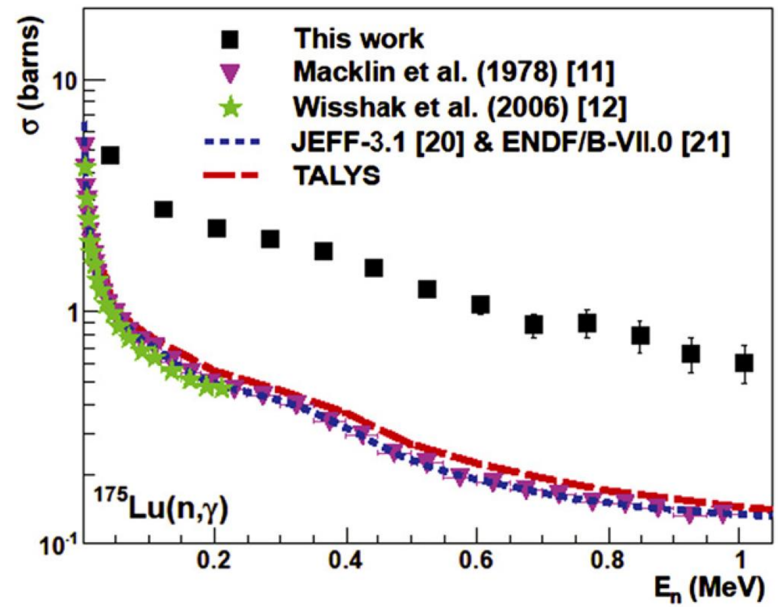
Typical results

$^{243}Am(^{3}He, ^{4}He)^{242}Am \Leftrightarrow n + ^{241}Am$

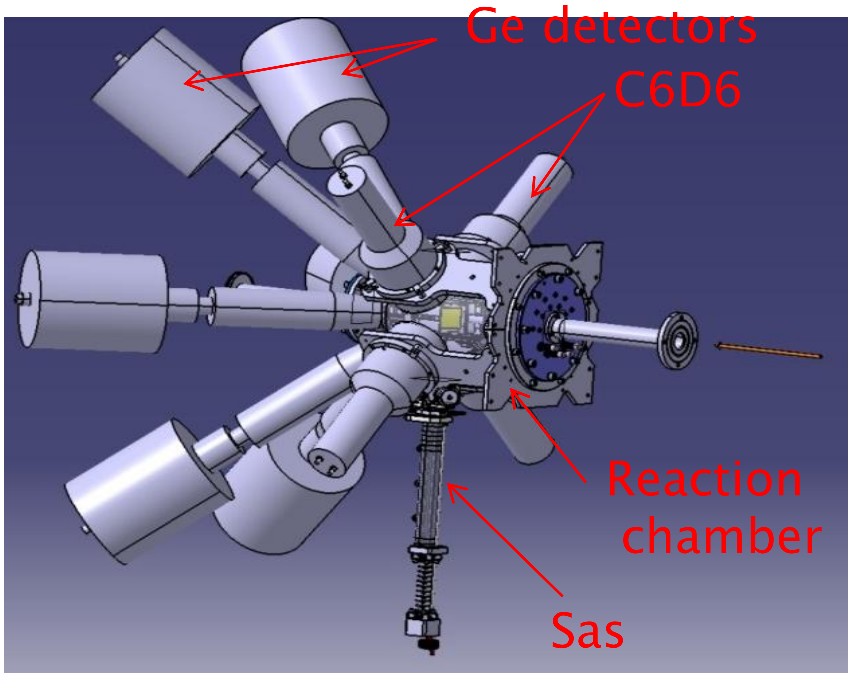


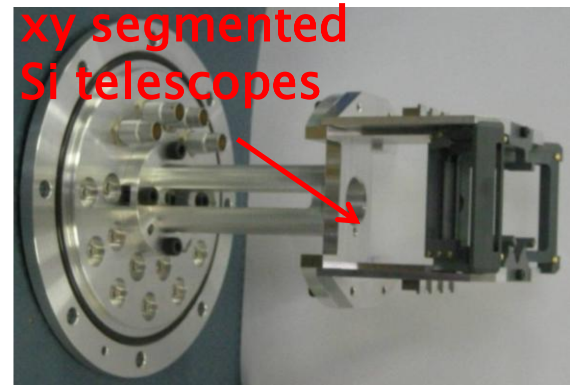
G. Kessedjian et al., Phys. Lett. B **692** 297 (2010)

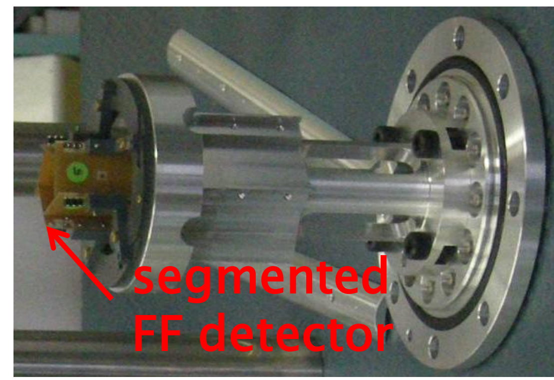
$^{174}Yb(^{3}He,p)^{176}Lu \Leftrightarrow n + ^{175}Lu$

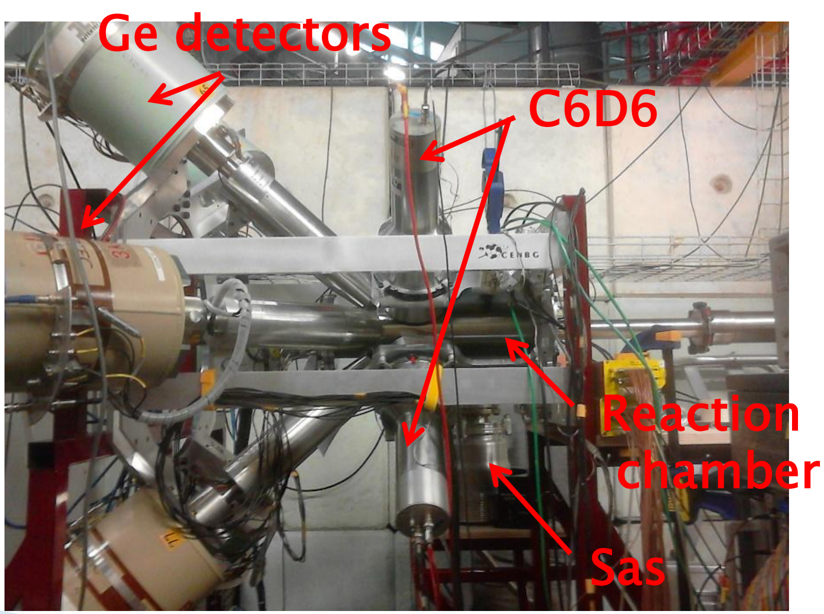


G. Boutoux et al., Phys. Lett. B **712** (2012) 319


Ge detectors
C6D6
Reaction chamber
Sas

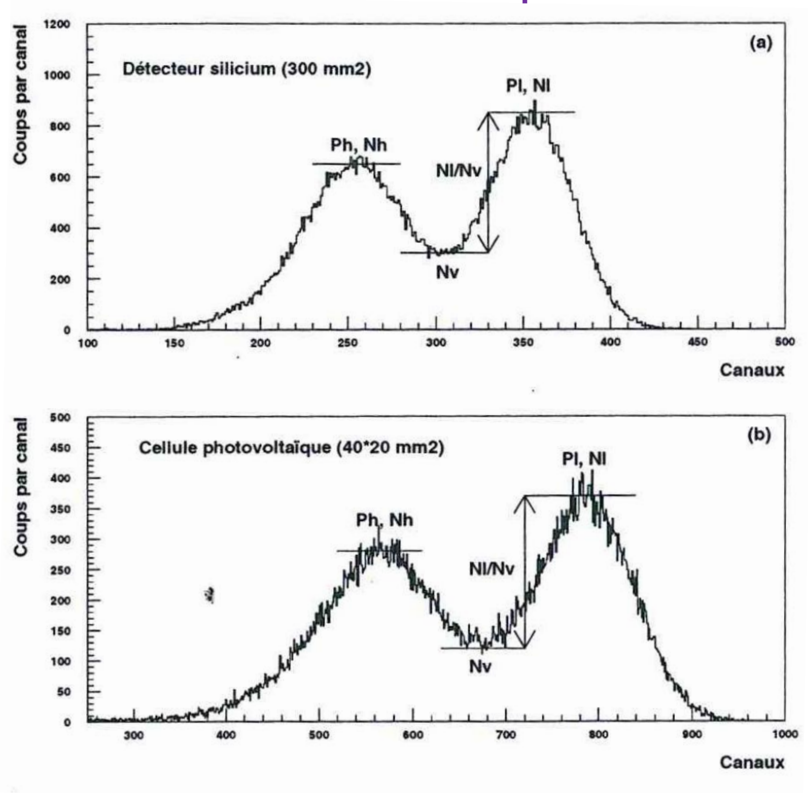

xy segmented
Si telescopes


segmented
FF detector

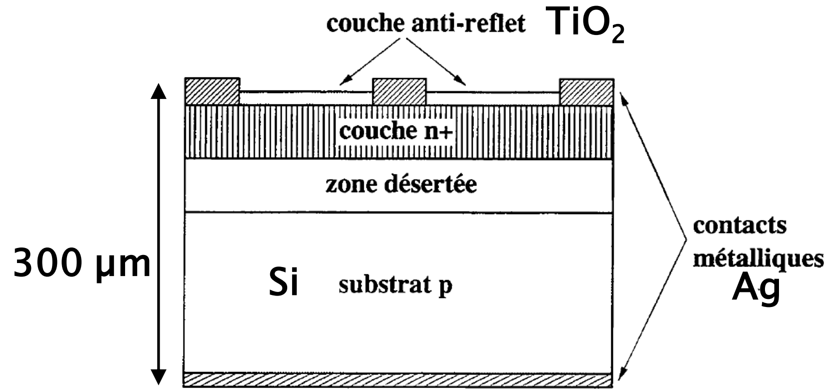

Ge detectors
C6D6
Reaction chamber
Sas

Solar cell

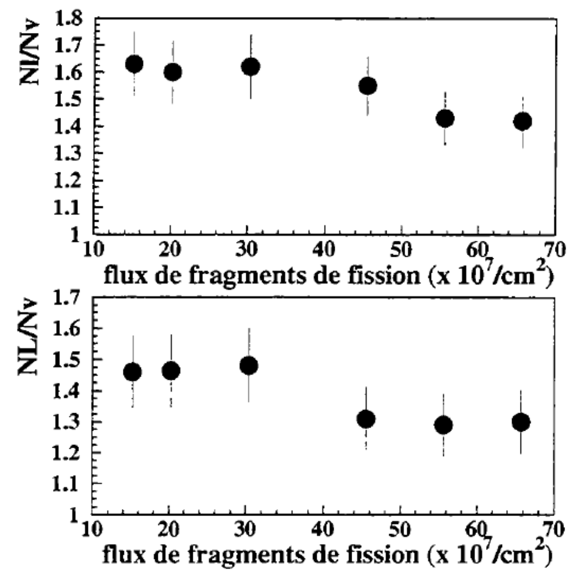
Si-Solar cell comparison



Composition

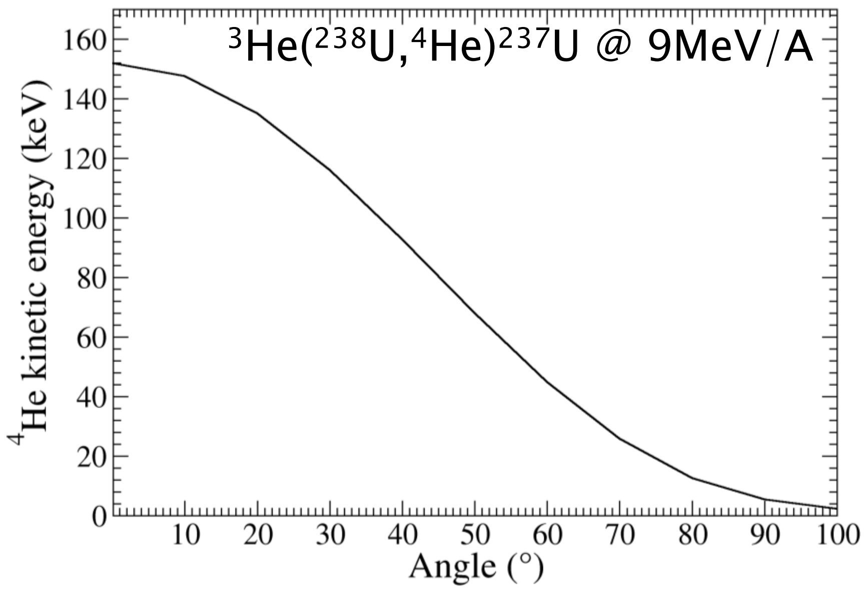


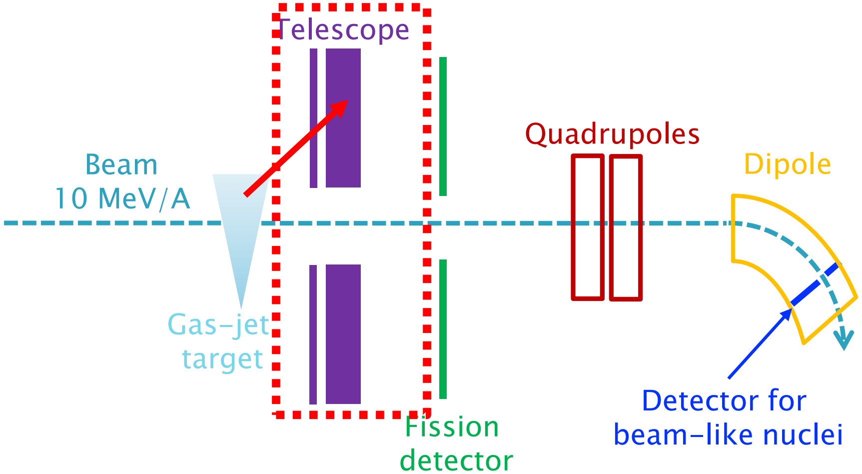
Impact of the FF flux



Telescope

- Inverse kinematics: strong dependence of kinetic energy of target-like nuclei with angle
  - Need a high angular resolution to obtain a suitable energy resolution : $\Delta\theta \sim 0.1°$





  - Possible design: annular Si detector like SPIDER (GANIL)

➢ **High pixelisation required**
➢ **Need a reaction chamber (at ESR)**

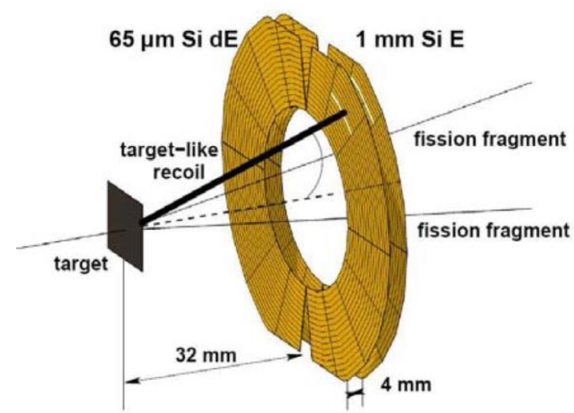
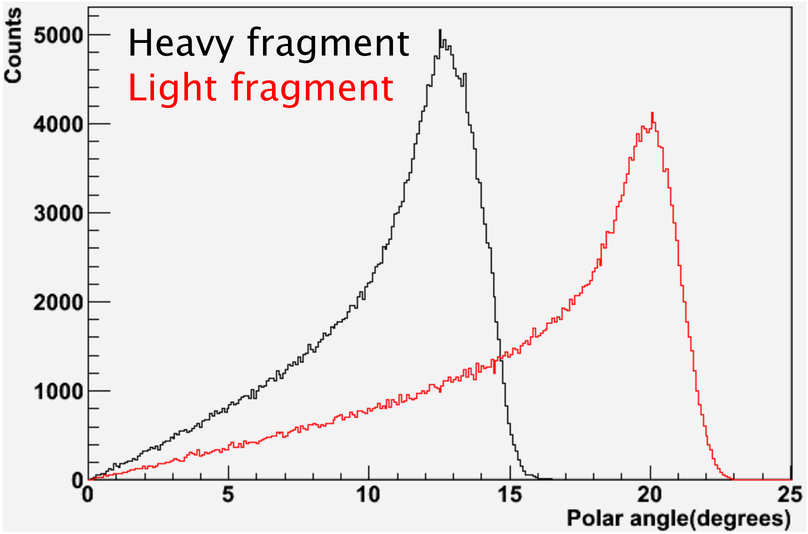


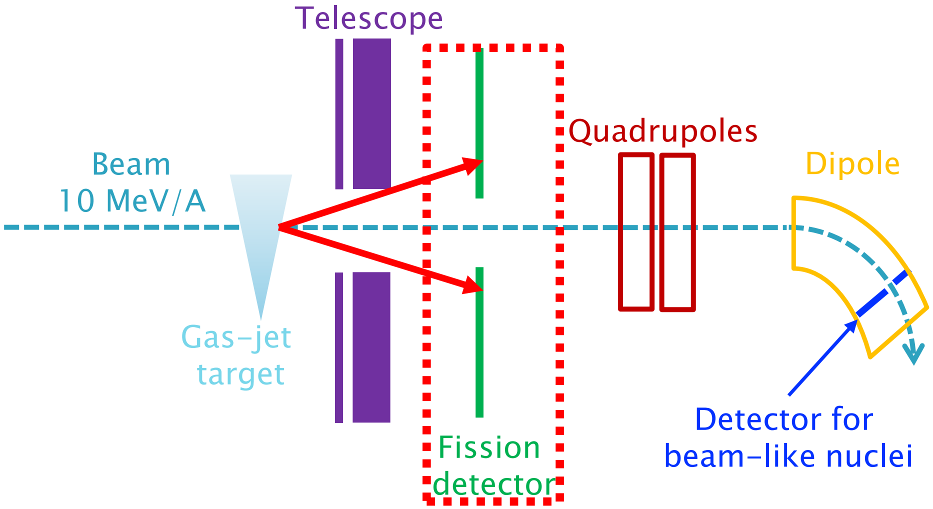
Fig. 1. Scheme of the annular telescope SPIDER

X. Derkx *et al.*, EPJ web of Conf. **2**, 07001 (2010)

Fission detector

- Inverse kinematics: fission fragments focused at forward angle
  - Higher detection efficiency : ~94% at 35 cm





^{231}Th fission at E*=10 MeV and 8.7 MeV/A
Kinetic energy calculated with the GEF code. Isotropic angular distribution in the CM for the fragments.
B. Jurado, HDR, Université de Bordeaux (2015)

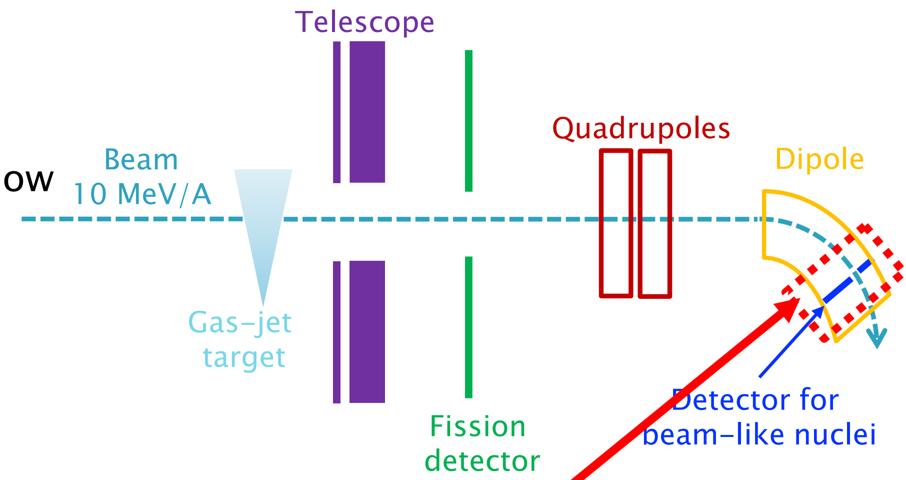
- Solar cells
  - Access to the fragment kinetic energy
  - In UHV : no energy loss in an entrance window

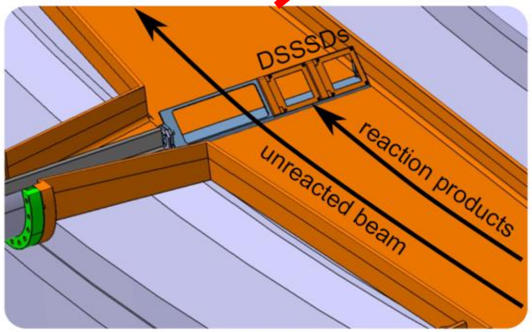
➢ **FF properties as a function of E***
➢ **Can we use solar cell in UHV ?**

Beam-like nuclei detector

- Feasibility of nuclear reaction measurement demonstrated
  - Double-Side Silicon Strip Detector (DSSSD) used to measure beam-like nuclei
- Recent developments:
  - DSSSD directly in UHV without an entrance window
- Coincidence with the telescopes
  - No background
- Use solar cells instead of Si
  - Same response
  - Cheaper
- Transmission efficiency
  - Geant4/Mocadi simulations are in progress

B. Mei *et al.*, Phys. Rev. C, **92** 035803 (2015)





J. Glorius *et al.*, PoS **NIC XIII**, 096 (2014)