



Indirect measurements of neutron-induced cross sections at storage rings

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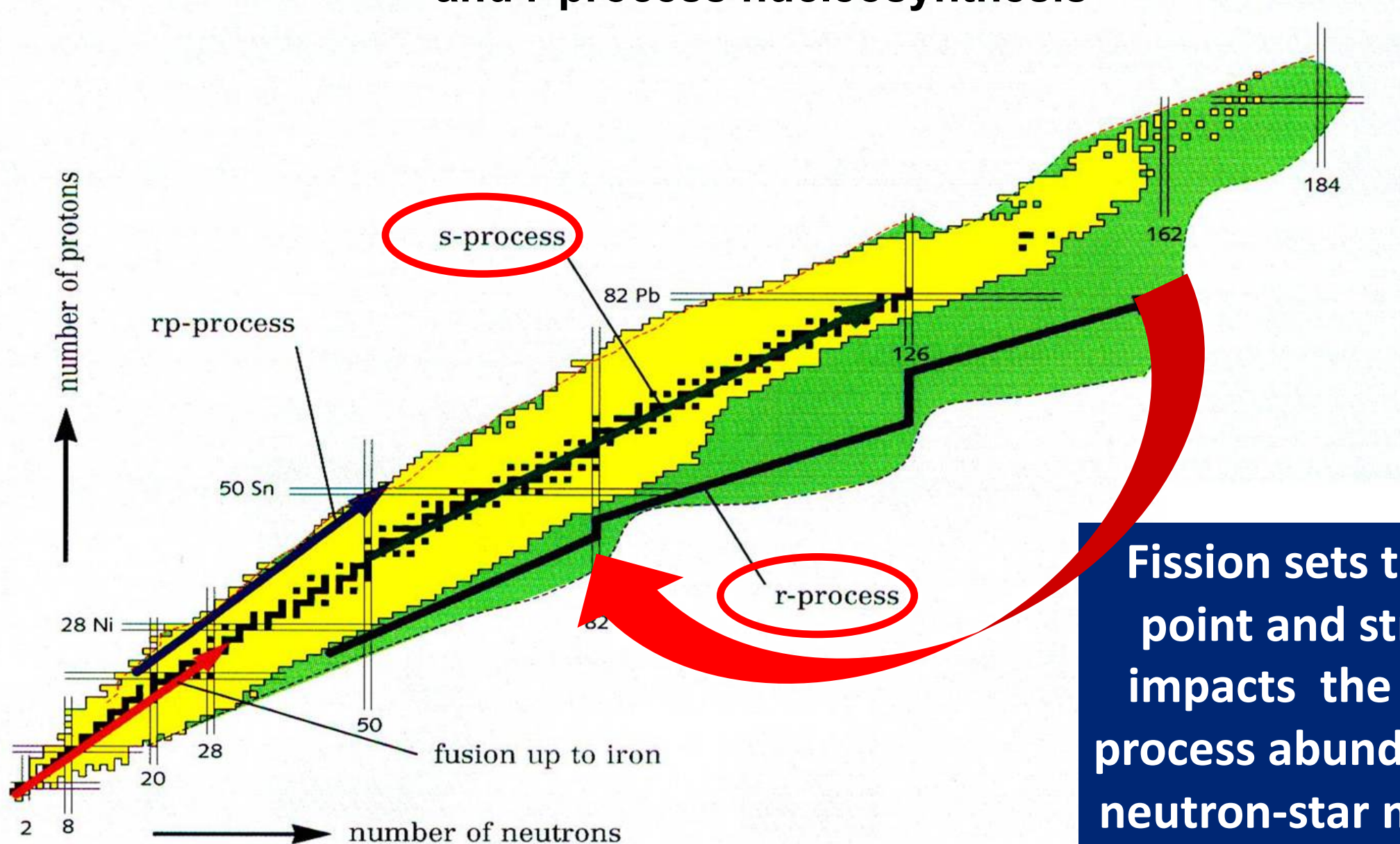
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Need for neutron-induced cross sections on short-lived nuclei : s- and r-process nucleosynthesis



Applications in nuclear technology, reactor physics

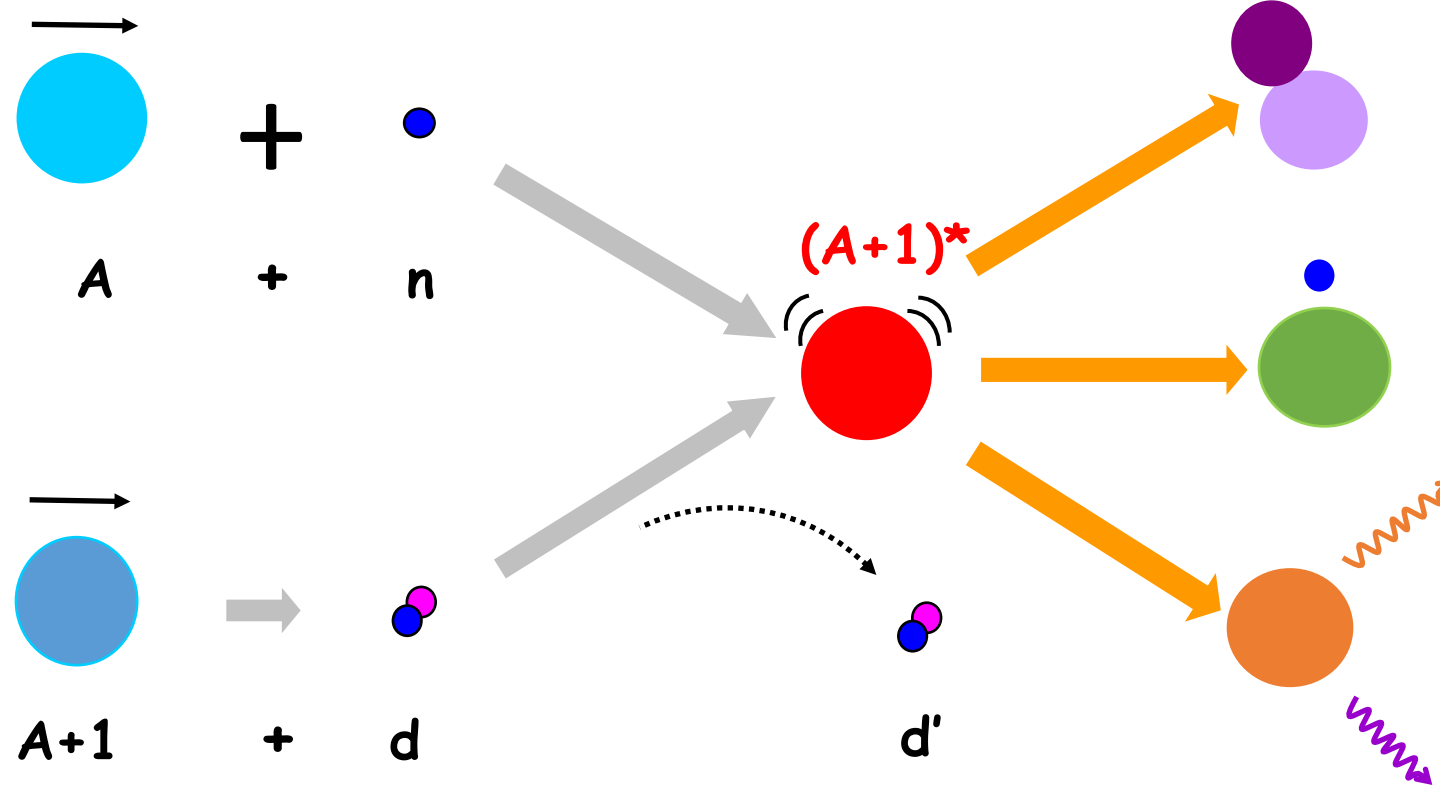
		Bk 238 144 s		Bk 240 5 m	Bk 241 4.6 m	Bk 242 7 m	Bk 243 4.5 h	Bk 244 4.35 h	Bk 245 4.90 d	Bk 246 1.80 d	Bk 247 1380 a	Bk 248 23.7 h	Bk 249 320 d
		€ βsf		€ βsf	€ γ 262; 152; 211	€ g	€ α 6.575; 6.543... γ 755; 946...	€ α 6.662; 6.620... γ 892; 218; 922...	€ α 5.888; 6.150... γ 253; 381... e ⁻	€ γ 799; 1081; 834; 1124... e ⁻	α 5.531; 5.710; 5.688... γ 84; 265... g	β ⁻ 0.9... α ? β ⁻ ? e ⁻ ?	β ⁻ 0.1; α 5.419; 5.391...; sf γ (327; 308...) σ 700; σ ₁ ~ 0.1
		Cm 237 ?	Cm 238 2.4 h	Cm 239 3 h	Cm 240 27 d	Cm 241 32.8 d	Cm 242 162.94 d	Cm 243 29.1 a	Cm 244 18.10 a	Cm 245 8500 a	Cm 246 4730 a	Cm 247 1.56 · 10 ⁷ a	Cm 248 3.40 · 10 ⁶ a
		α 6.656	€ α 6.558; 6.503 γ 55	€ γ 188... g	€ α 6.291; 6.248... sf g	€ α 5.939... γ 472; 431; 132... sf g	€ α 6.113; 6.069... sf g	€ α 5.785; 5.742... sf g	€ α 5.805; 5.762... sf g	€ α 5.361; 5.304... sf g	α 5.386; 5.343... sf g	α 4.870; 5.267... γ 402; 278... σ 1.2; σ ₁ 0.16	α 5.078; 5.035... sf; γ; e ⁻ ; g σ 2.6; σ ₁ 0.36
Am 234 2.32 m	Am 235 10.3 m	Am 236 2.9 m	Am 237 73.0 m	Am 238 1.63 h	Am 239 11.9 h	Am 240 50.8 h	Am 241 432.2 a	Am 242 141 a	Am 243 7370 a	Am 244 26 m	Am 245 2.05 h	Am 246 25 m	Am 247 22 m
€ βsf	€ α 6.457 γ 291; 224; 270; 739; 749...	€ α 6.15 ? γ 583; 654; 713	€ α 6.15 ? γ 719; 880; 320...	€ α 6.042... γ 280; 438; 474; 583; 909...	€ α 5.94 γ 963; 919; 561; 605...	€ α 5.774... γ 278; 228... g	€ α 5.486; 5.443... sf; γ 60; 26... e ⁻ ; g; σ 60 + 640 σ ₁ 3.15	€ α 5.498; 5.443... sf; γ (49...); e ⁻	€ α 5.275; 5.233... sf; γ 75; 44... σ 1700 σ ₁ 5900	€ β ⁻ 1.5... σ 0.4 γ 744; e ⁻ ; g	€ β ⁻ 0.9... γ 253; (241; 296...) e ⁻ ; g	€ β ⁻ 1.2... γ 253; 1079; 205; 799; 154; 1062... e ⁻ ; g	€ β ⁻ ... γ 285; 226 e ⁻
Pu 233 20.9 m	Pu 234 8.8 h	Pu 235 25.3 m	Pu 236 2.858 a	Pu 237 45.2 d	Pu 238 87.74 a	Pu 239 2.411 · 10 ⁴ a	Pu 240 6563 a	Pu 241 14.35 a	Pu 242 3.750 · 10 ⁵ a	Pu 243 4.956 h	Pu 244 8.00 · 10 ⁷ a	Pu 245 10.5 h	Pu 246 10.85 d
€ α 6.31 γ 235; 535...	€ α 6.202; 6.151... γ; e ⁻	€ α 5.85 γ 49; (756; 34...) e ⁻	€ α 5.768; 5.721... sf; Mg 28 γ (48; 109...); e ⁻	€ α 5.334... γ 60...; e ⁻	€ α 5.499; 5.456... sf; Si; Mg γ (43; 100...); e ⁻	€ α 5.157; 5.144... sf; γ 52... e ⁻ ; m σ 510; σ ₁ 752	€ α 5.168; 5.124... sf; γ (45...) e ⁻ ; g σ 290; σ ₁ ~ 0.058	€ β ⁻ 0.02; g α 4.896... γ (149...); e ⁻	€ α 4.901; 4.856... sf; γ (45...) e ⁻ ; g σ 19; σ ₁ < 0.2	€ β ⁻ 0.6... γ 64...; g σ < 100; σ ₁ 200	€ α 4.589; 4.546 e ⁻ σ 1.7	€ β ⁻ 0.9; 1.2... γ 327; 560; 308...; g σ 150	€ β ⁻ 0.2; 0.3 γ 44; 224; 180... m
Np 232 14.7 m	Np 233 36.2 m	Np 234 4.4 d	Np 235 396.1 d	Np 236 22.5 h	Np 237 2.144 · 10 ⁶ a	Np 238 2.117 d	Np 239 2.355 d	Np 240 7.22 m	Np 241 13.9 m	Np 242 2.2 m	Np 243 1.85 m	Np 244 2.29 m	
€ γ 327; 820; 867; 864; 282... e ⁻	€ α 5.54 γ (312; 299; 547...)	€; β ⁺ ... γ 1559; 1528; 1602... σ ₁ ~ 900	€; β ⁻ ... γ (26; 84...); e ⁻ g; σ 160 + ?	€; β ⁻ 0.5... γ (642; 160; 688...); e ⁻	€; β ⁻ 1.2... γ 984; 1029; 1026; 924...; e ⁻ g; σ 2600	€ β ⁻ 1.2... γ 984; 1029; 1026; 924...; e ⁻ g; σ 2600	€ β ⁻ 0.4; 0.7... γ 106; 278; 228...; e ⁻ ; g σ 32 + 19; σ ₁ < 1	€ β ⁻ 2.2... γ 555; 567... e ⁻ ; g	€ β ⁻ 1.3... γ 175; (133...) g	€ β ⁻ 2.7... γ 736; 780; 1473... g	€ β ⁻ ... γ 288 g	€ β ⁻ ... γ 217; 681; 163; 111... g	
U 231 4.2 d	U 232 68.9 a	U 233 1.592 · 10 ⁵ a	U 234 0.0054	U 235 0.7204	U 236 2.342 · 10 ⁷ a	U 237 6.75 d	U 238 99.2742	U 239 23.5 m	U 240 14.1 h		U 242 16.8 m		
€; α 5.456; 5.471; 5.404 γ 26; 84; 102... e ⁻ ; σ ₁ ~ 250	α 5.320; 5.262... Ne 24; γ (58; 129...); e ⁻ σ 73; σ ₁ 74	α 4.824; 4.783... Ne 25; γ (42; 97...); e ⁻ σ 47; σ ₁ 530	α 4.775; 4.723...; sf Mg 28; Ne; γ (53; 121...) e ⁻ ; σ 96; σ ₁ 0.07	α 4.398...; sf Ne; γ 186... e ⁻ ; σ 95; σ ₁ 581	α 4.494; 4.445... γ 238; sf; γ (49...) e ⁻ ; σ 5	€ β ⁻ 0.2... γ 60; 208... e ⁻ σ ~ 100; σ ₁ < 0.35	€ β ⁻ 1.2; 1.3... γ 75; 44... σ 22; σ ₁ 15	€ β ⁻ 1.2; 1.3... γ 75; 44... σ 22; σ ₁ 15	€ β ⁻ 0.4... γ 44; (190...) e ⁻ m		€ β ⁻ ... γ 68; 58; 585; 573... m		
Pa 230 17.4 d	Pa 231 3.276 · 10 ⁴ a	Pa 232 1.31 d	Pa 233 27.0 d	Pa 234 27.0 h	Pa 235 24.2 m	Pa 236 9.1 m	Pa 237 8.7 m	Pa 238 2.3 m	Pa 239 1.8 h				
€; β ⁻ 0.5... α 5.345; 5.326... γ 952; 919; 455; 899; 444...; σ ₁ 1500	α 5.014; 4.962; 5.028...; Ne 24; F 237 γ 27; 300; 303...; e ⁻ σ 200; σ ₁ 0.020	β ⁻ 0.3; 1.3...; € γ 969; 894; 150...; e ⁻ σ 460; σ ₁ 1500	β ⁻ 0.3; 0.6... γ 312; 300; 341...; e ⁻ σ 20 + 19; σ ₁ < 0.1	β ⁻ 0.5... γ (1001; 767...); h (74...); e ⁻ σ < 500	β ⁻ 1.4... γ 128 - 659 m	β ⁻ 2.0; 3.1... γ 642; 687; 1763...; g βsf ?	β ⁻ 1.4; 2.3... γ 854; 865; 529; 541... g	β ⁻ 1.7; 2.9... γ 1015; 635; 448; 680... g	β ⁻ ... γ 522 - 681				
Th 229 7880 a	Th 230 7.54 · 10 ⁴ a	Th 231 25.5 h	Th 232 100	Th 233 22.3 m	Th 234 24.10 d	Th 235 7.1 m	Th 236 37.5 m	Th 237 5.0 m	Th 238 9.4 m				
α 4.845; 4.901; 4.815...; γ 194; 211; 86; 31...; e ⁻ σ ~ 60; σ ₁ 30	α 4.687; 4.621... γ (68; 144...); e ⁻ Ne 24; σ 23.4 σ < 0.0005	β ⁻ 0.3; 0.4... γ 26; 84... e ⁻	α 4.013; 3.950...; sf γ (64...); e ⁻ σ 7.37; σ ₁ 0.000000	β ⁻ 1.2... γ 87; 29; 459...; e ⁻ σ 1500; σ ₁ 15	β ⁻ 0.2... γ 63; 92; 93... e ⁻ ; m σ 1.8; σ ₁ < 0.01	β ⁻ 1.4... γ 417; 727; 696... g	β ⁻ 1.0... γ 111; (647; 196...) g	β ⁻ ... γ 89					

152

150

Very difficult or even impossible to measure with standard techniques → difficulty to produce and handle the needed targets!

Surrogate-reaction method in inverse kinematics



Other reactions possible: (d,p), (d,t)...

$$\sigma_{n,decay}^A(E^*) = \underbrace{\sigma_{CN}^{A+1}(E^*)}_{\text{Theory}} \cdot \underbrace{P_{decay}^{surro}(E^*)}_{\text{Experiment}}$$

Validity of the surrogate-reaction method

$$\sigma_{n,decay}^A(E^*) = \sigma_{CN}^{A+1}(E^*) \cdot P_{decay}^{surro}(E^*)$$

Neutron-induced and surrogate reaction must lead to the formation of a compound nucleus :

Decay only depends on E^* , J and π !!

$$P_{decay}^{surro}(E^*) = P_{decay}^n(E^*)$$

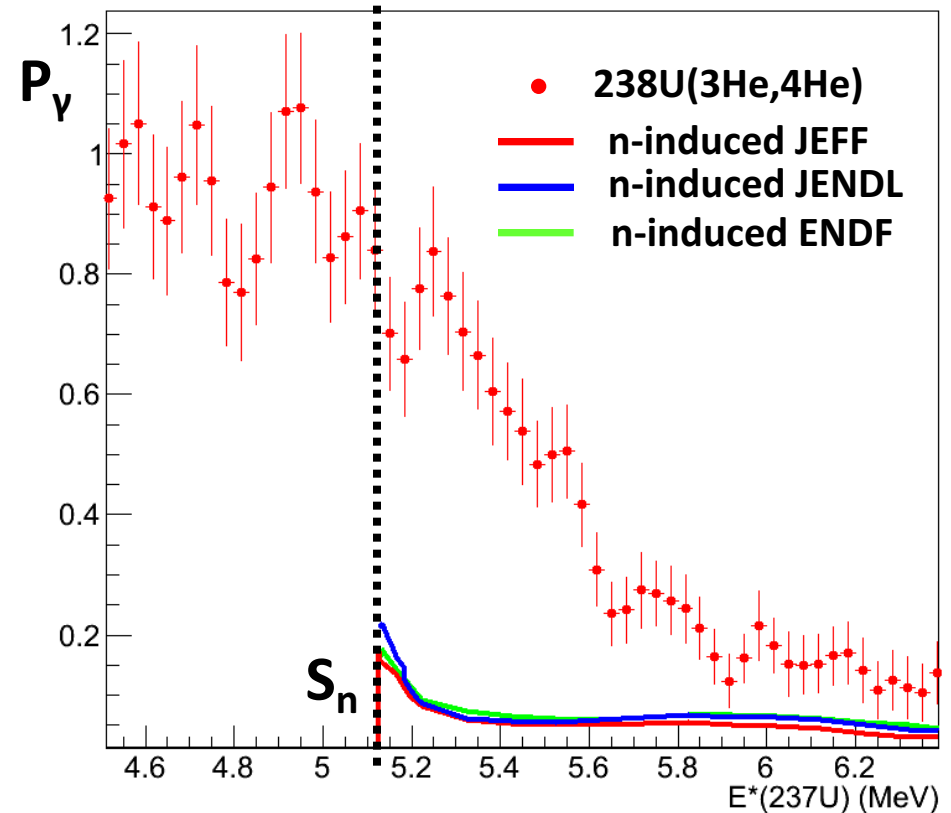
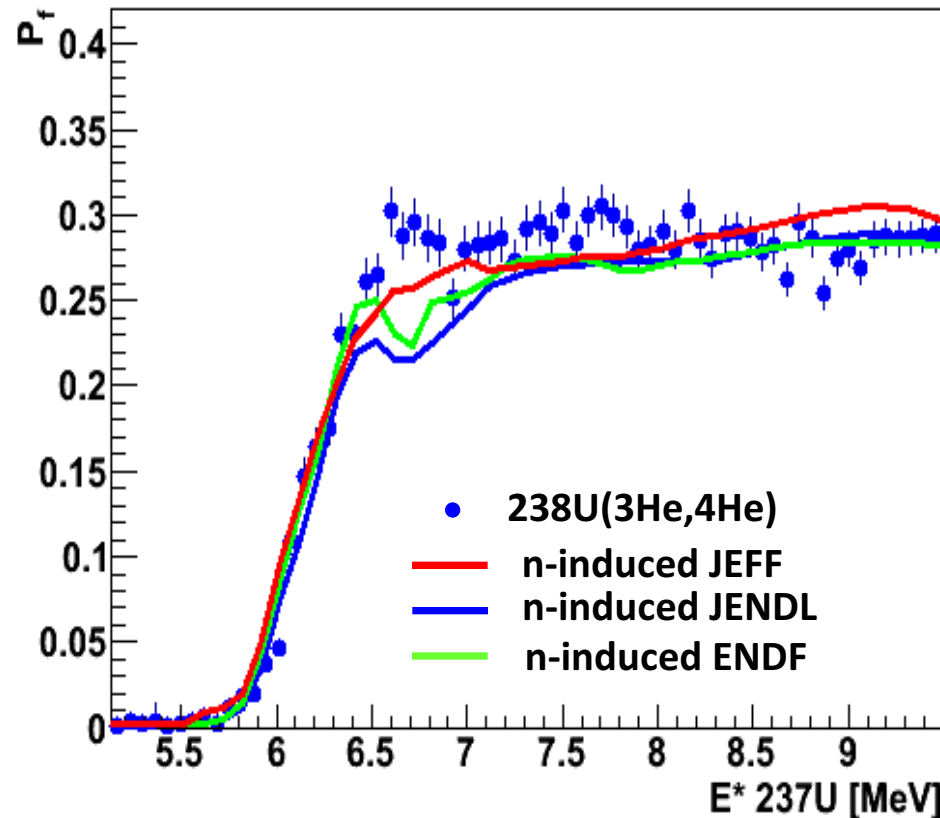
Populated J and π distributions
are equal

OR

Decay independent of J and π
(Only valid at high E^* in
the Weisskopf-Ewing limit)

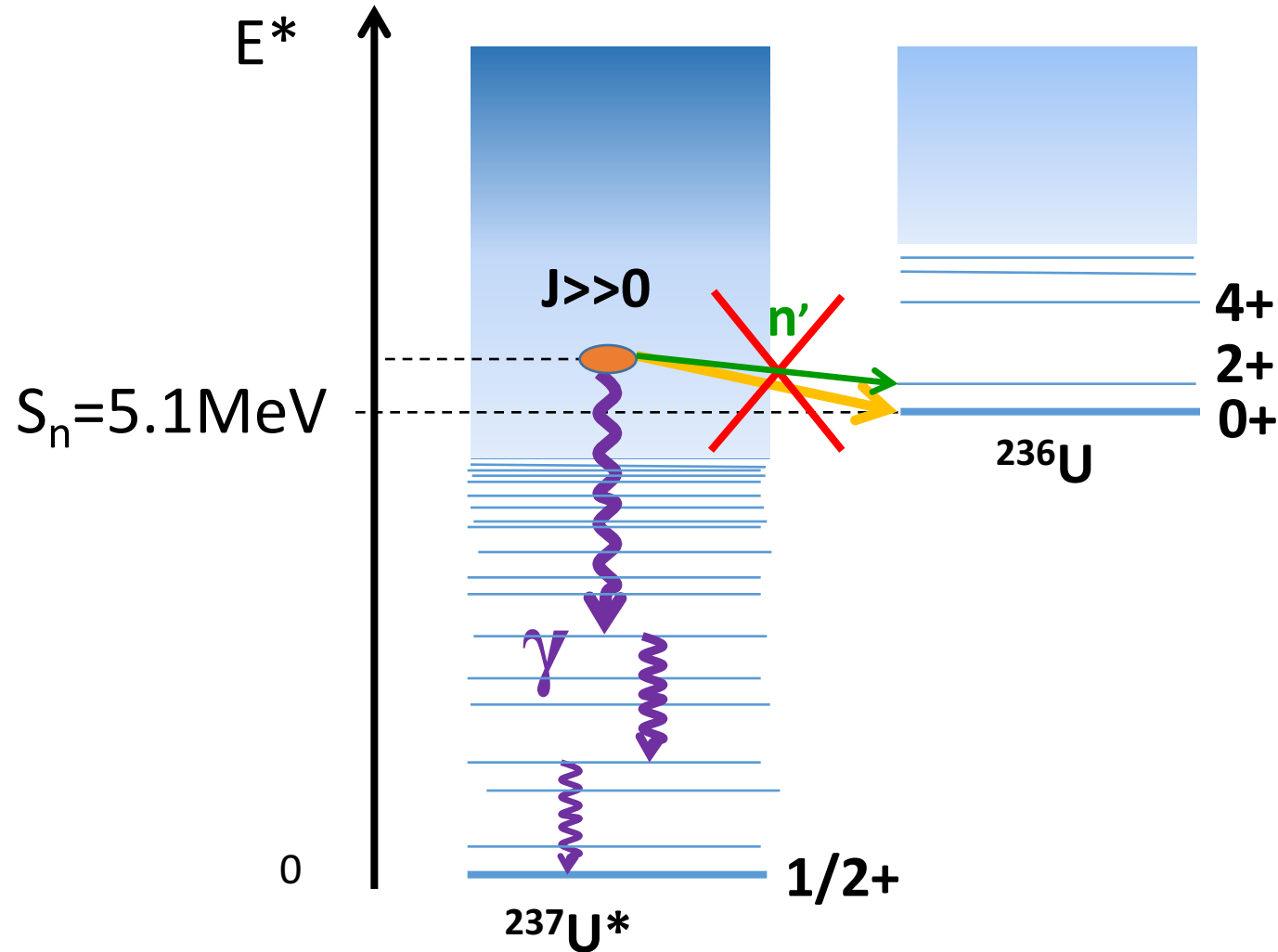
**Not possible to say a priori if a reaction meets these conditions.
Data obtained with the surrogate method need
to be compared to neutron-induced data!**

Preliminary results!



**General finding : Good agreement for fission probabilities
but strong disagreement for γ -emission probabilities**

Why do we obtain such discrepancies?

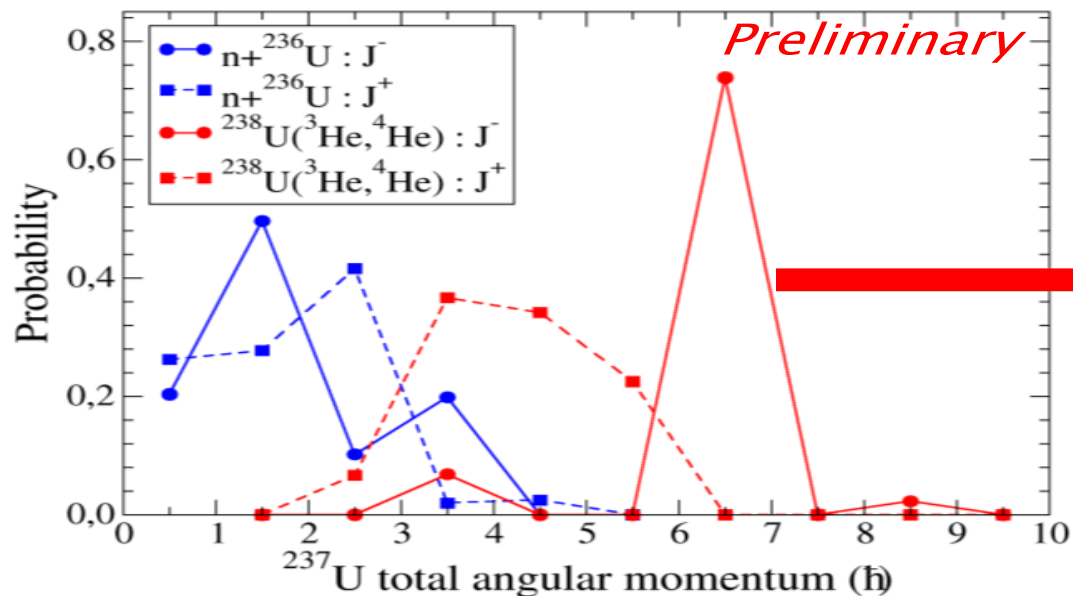


Strong sensitivity of neutron emission to $J\pi$!

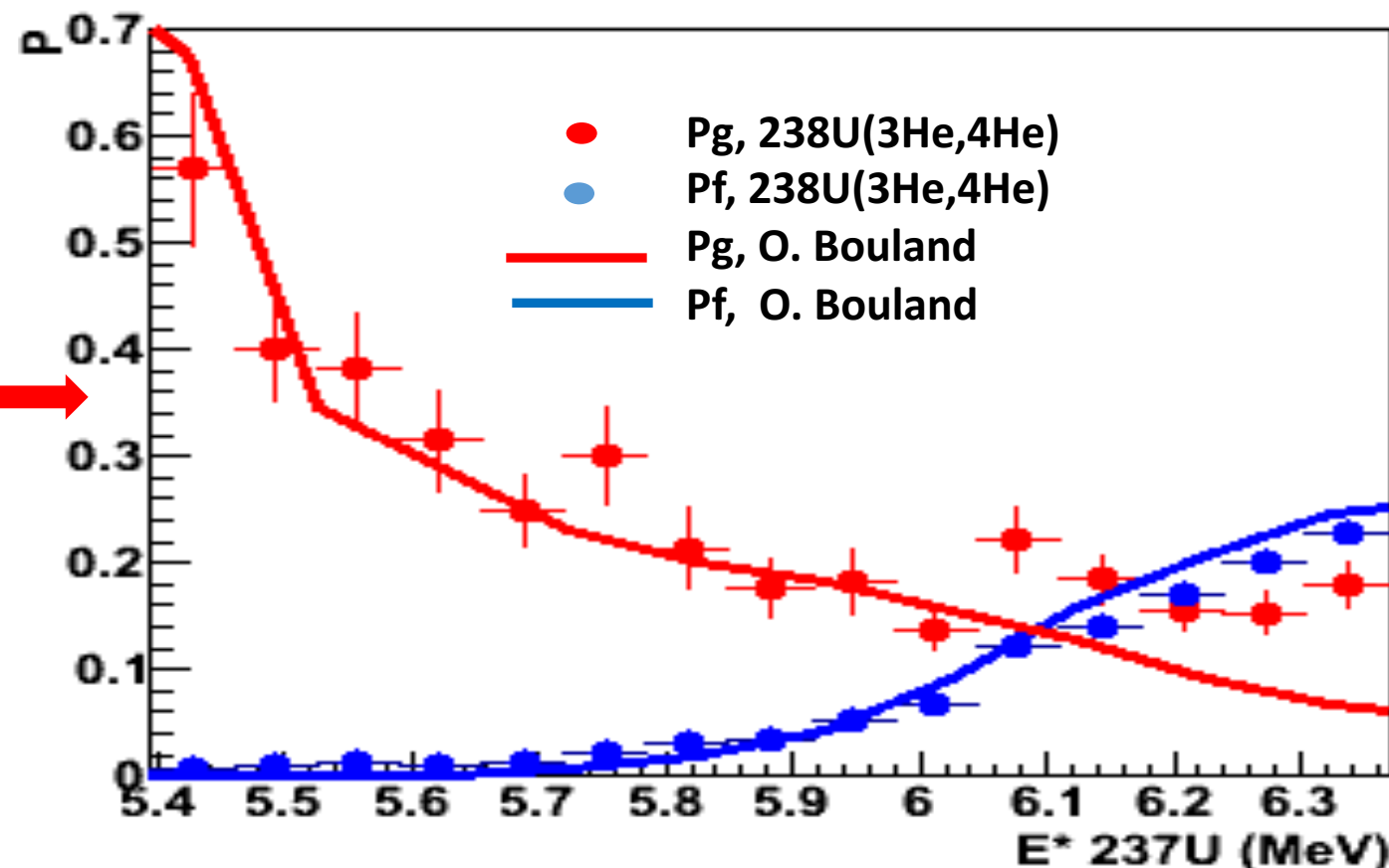
Preliminary results!



Populated spin/parity distributions



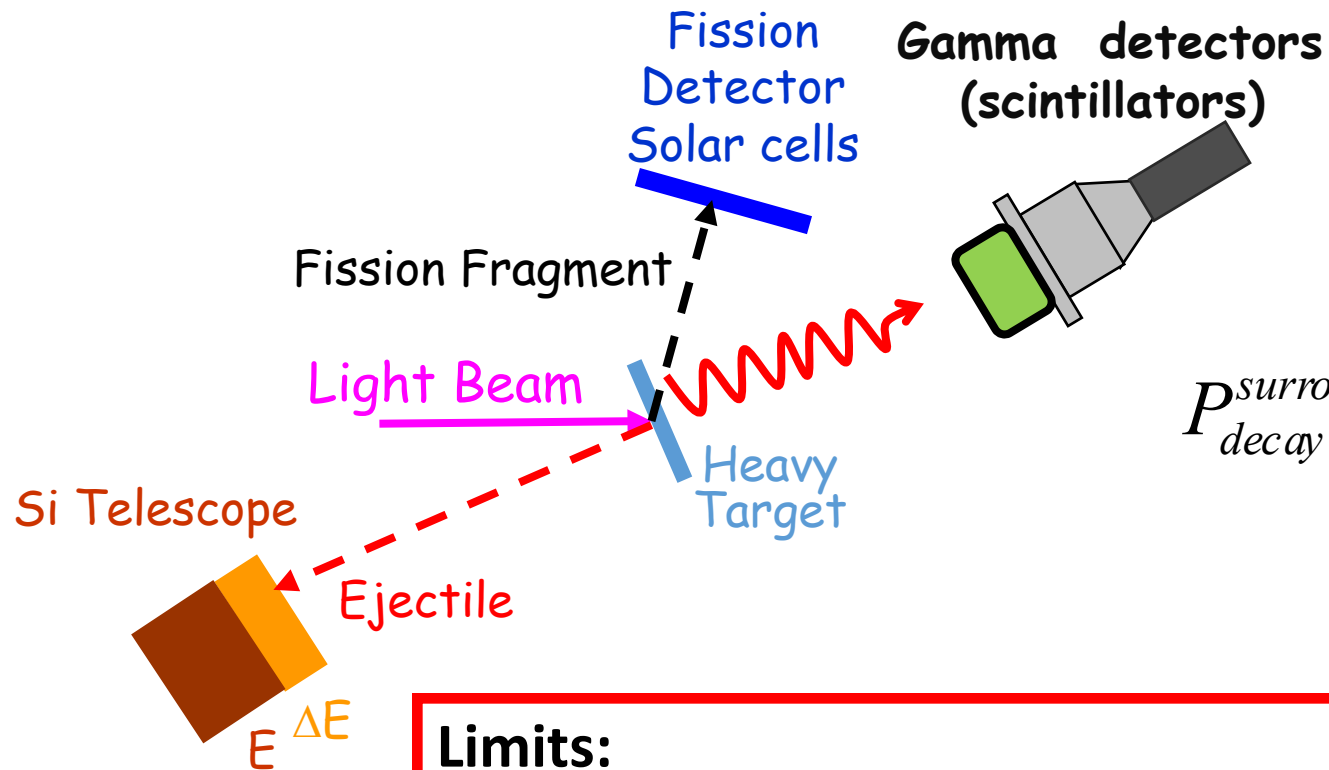
I. Thompson, J. E. Escher,
UCRL-TR-225984 (2006)



O. Bouland & B. Jurado, contribution to ND2016

P_γ is much more sensitive to J^π than P_f but it is possible to correct for J^π effects

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



$$P_{decay}^{surro}(E^*) = \frac{N_{eject-decay}^{coin}(E^*)}{N_{eject}^{sing}(E^*) \cdot \varepsilon_{decay}(E^*)}$$

Limits:

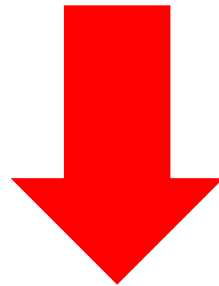
- Unavailability of targets (radioactive samples)
- Target contaminants and backing
- P_γ : discrimination of γ 's from fission fragments
- P_n : measurement of low-energy neutrons and neutron efficiency

Advantages of Inverse kinematics:

- Access to very short-lived nuclei**
- Detection of heavy residues**

BUT

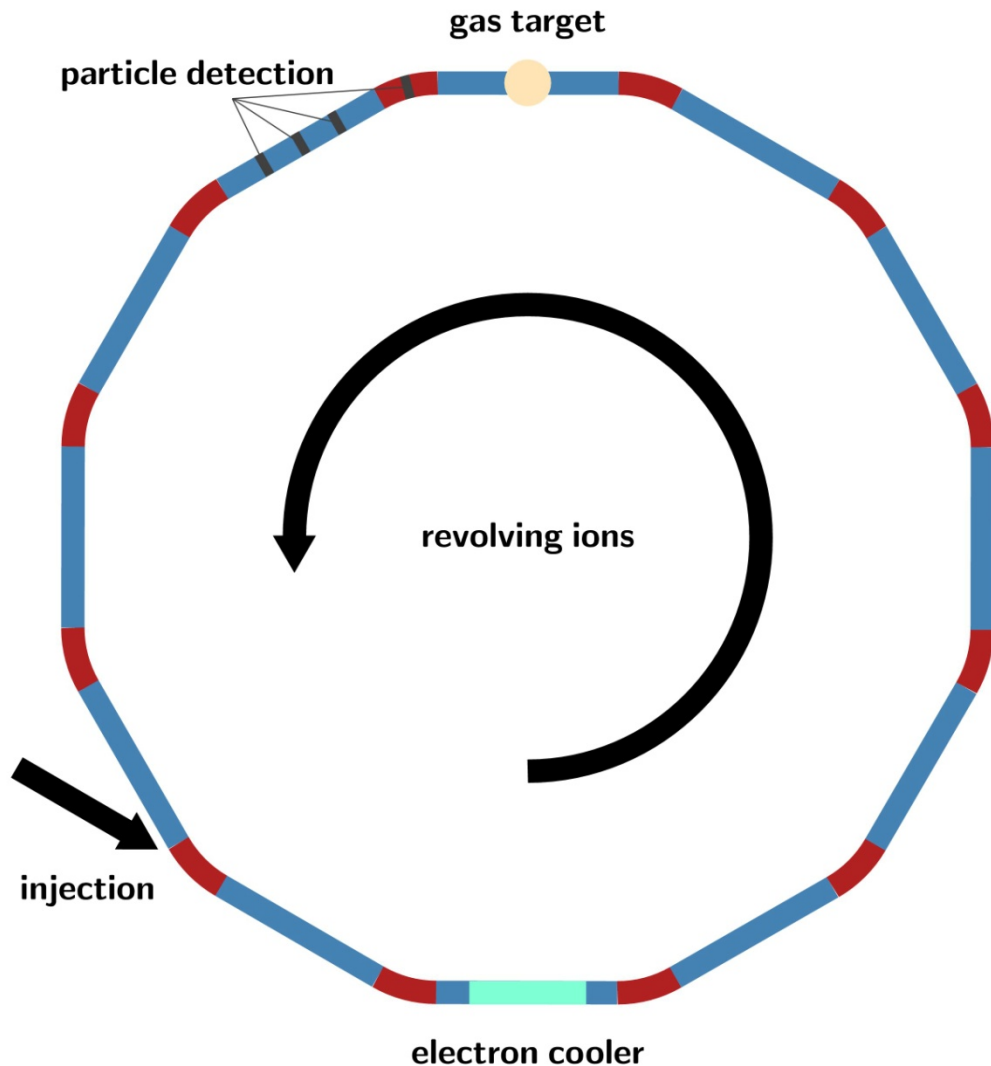
- Required E^* resolution ≤ 100 keV**
- Target contaminants and target windows have to be avoided**



STORAGE RINGS!

Advantages of heavy-ion storage rings

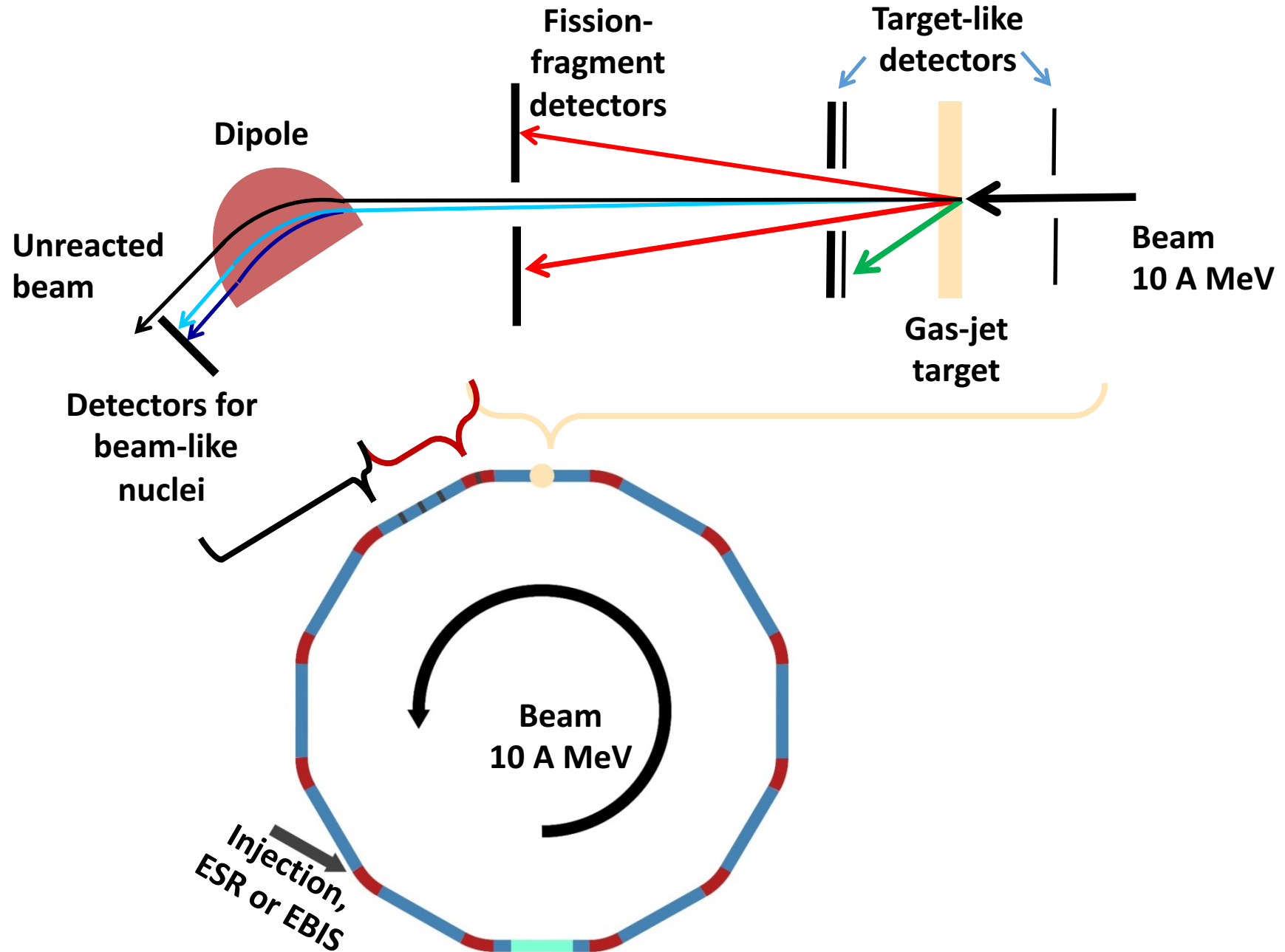
The CRYRING at GSI/FAIR



- Beam energies ~ 10 A MeV
- Beam cooling \rightarrow Excellent energy and position resolution of the beam
- Use of ultra-thin in-ring gas-jet targets $\sim 10^{13}/\text{cm}^2$. Effective target thickness increased by $\sim 10^6$ due to revolution frequency
- Pure targets, pure beams, (no backing, no contaminants)
- Pure isomeric beams!

Challenge: Detectors in Ultra-High Vacuum (10^{-11} - 10^{-12} mbar)!

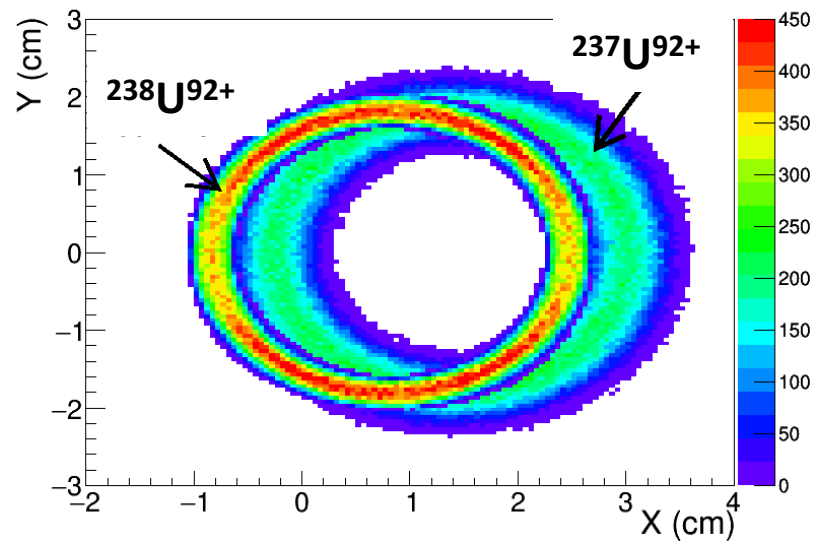
Set-up for decay-probability measurements at storage rings



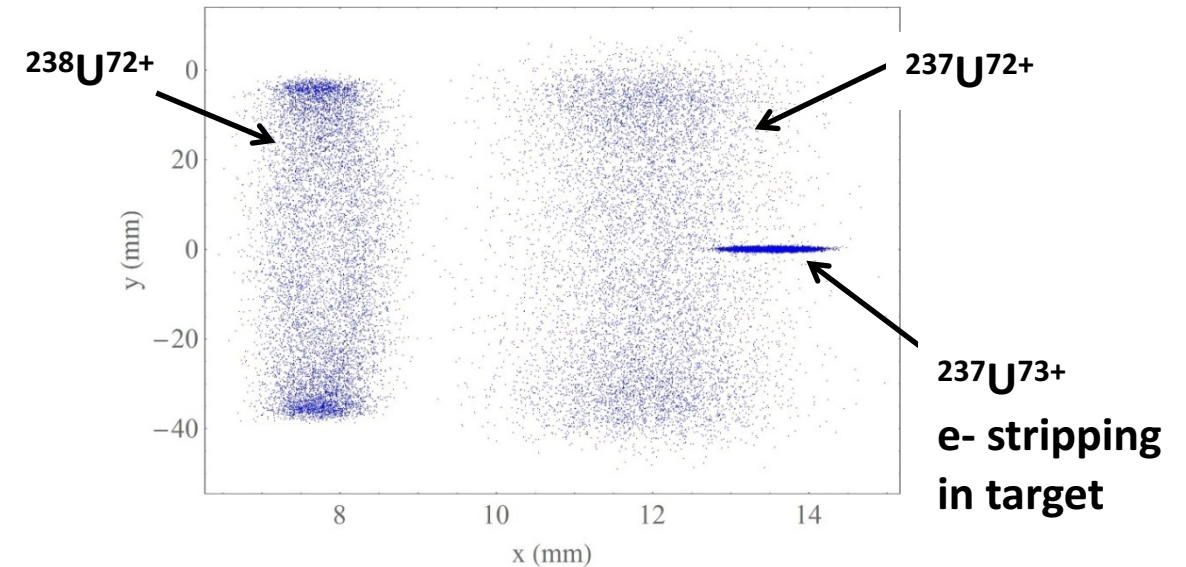
Results of feasibility studies

- Ultra-thin gas-jet target + cooled beams + highly segmented target-like detectors (128X128 ch) → E^* resolution ~ 100 keV!
- Fission detection efficiency up to 95 %!
- Possible to separate heavy residues produced after γ and neutron emission

MOCADI Simulation for CRYRING, $^{238}\text{U}(d,d')$



G4beamline simulation for the ISR, $^{238}\text{U}(d,d')$



Simulation by Manfred Grieser!

- Detection efficiencies of heavy residues: 30 -90%!

Decay probabilities for ALL open channels can be measured simultaneously with good E^* resolution, unique!

First measurements with stable beams

- **Validate the technology by comparing with decay probabilities measured in direct kinematics:**
 - $^{181}\text{Ta}(d,d')$
 - $^{238}\text{U}(d,d')$
- **Study of the (d,p) reaction in several regions by comparing with well known neutron cross sections**
 - $^{181}\text{Ta}(d,p)$
 - $^{197}\text{Au}(d,p)$
 - $^{208}\text{Pb}(d,p)$
 - $^{238}\text{U}(d,p)$
- **Study of the (d,d') reaction in the Zr region**
 - $^{94}\text{Zr}(d,d') \Leftrightarrow n+^{93}\text{Zr}$, deduce $^{93}\text{Zr}(n,\gamma)$ and compare with available data
 - $^{96}\text{Zr}(d,d') \Leftrightarrow n+^{95}\text{Zr}$ ($T_{1/2}=64$ d), deduce $^{95}\text{Zr}(n,\gamma)$, which is unknown and very important for the s-process!

Conclusions

Storage rings are the ideal devices to carry out high resolution surrogate reaction studies in inverse kinematics:

- No target contaminants or backing, pure (isomeric) beams**
- E^* resolution ~ 100 keV**
- Simultaneous measurement of all decay probabilities with very large efficiencies**