



Indirect measurements of neutron-induced cross sections at storage rings

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and the NucAr collaboration

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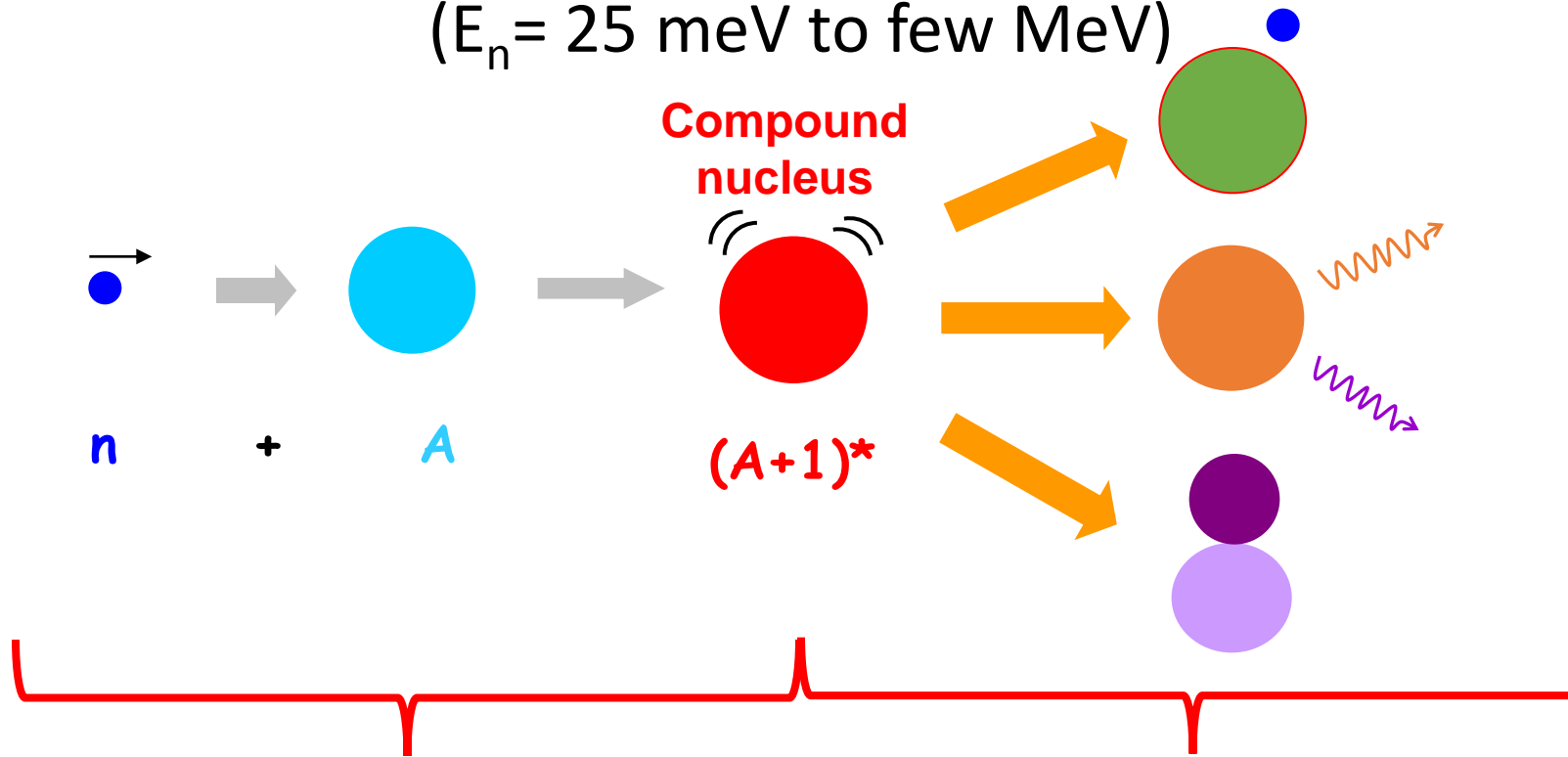
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5) CEA/DAM/DIF Bruyeres le Chatel, France

Neutron-induced reactions

($E_n = 25 \text{ meV}$ to few MeV)



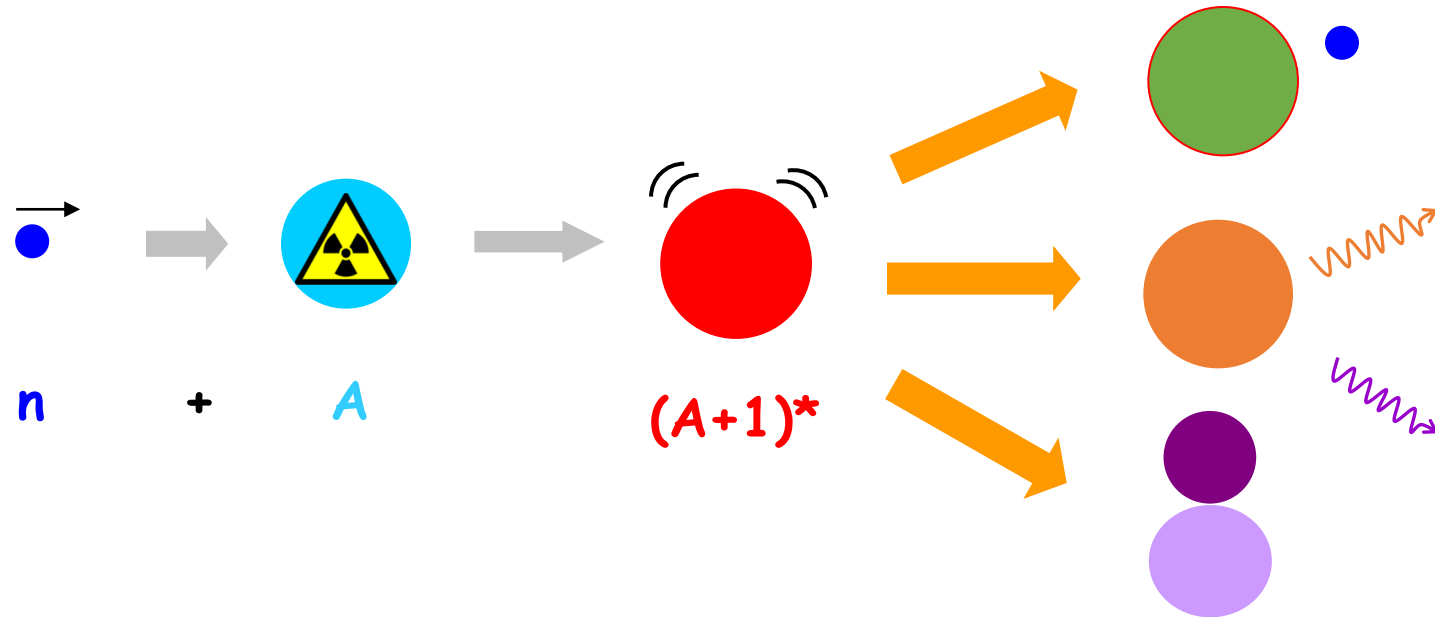
Step 1: Formation

Step 2: Decay

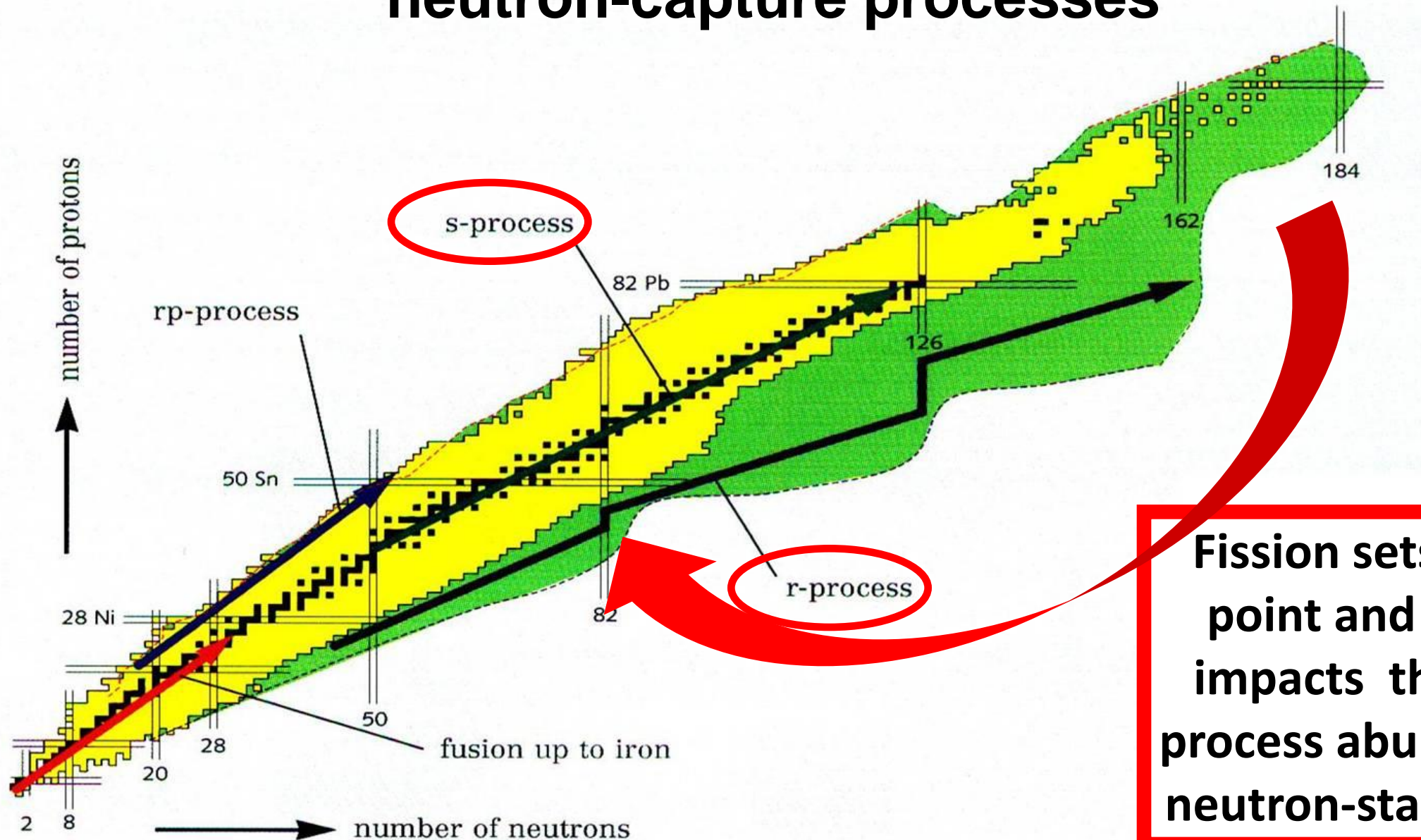
$$\sigma_{n,decay}^A(E_n) = \sigma_{formation}^{A+1}(E_n) \cdot P_{decay}^n(E_n)$$

$$\sigma_{n,\gamma}^A(E_n) = \sigma_{formation}^{A+1}(E_n) \cdot P_{\gamma}^n(E_n)$$

Need for neutron cross sections of short-lived nuclei



Synthesis of heavy elements: slow and rapid neutron-capture processes



Fission sets the end point and strongly impacts the final r-process abundances in neutron-star mergers!

Reactor physics: fast reactors, transmutation, new fuel cycles

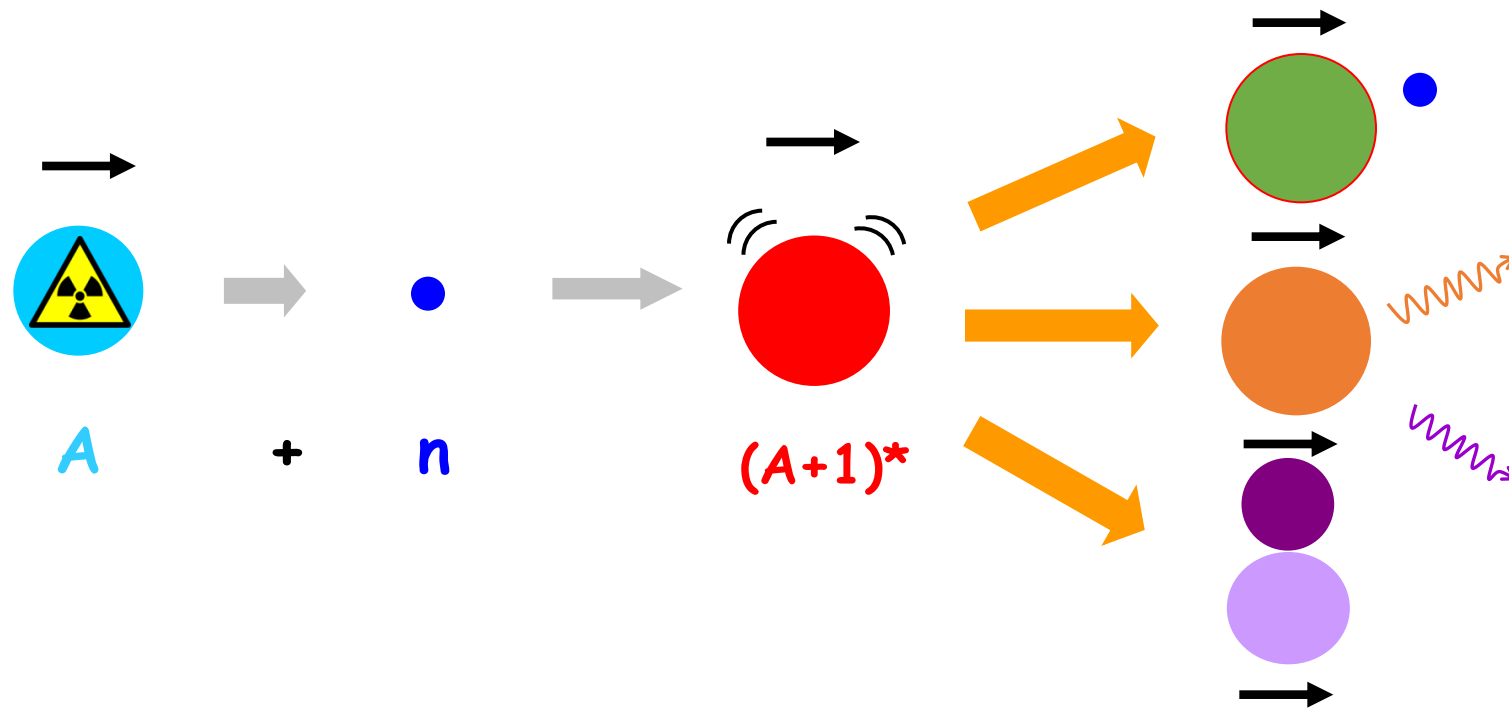
		Bk 238 144 s		Bk 240 5 m	Bk 241 4.6 m	Bk 242 7 m	Bk 243 4.5 h	Bk 244 4.35 h	Bk 245 4.90 d	Bk 246 1.80 d	Bk 247 1380 a	Bk 248 237 h > 9 a	Bk 249 320 d
		€ βsf		€ βsf	€ γ 262; 152; 211	€ g	€ α 6.575; 6.543... γ 755; 946...	€ α 6.662; 6.620... γ 892; 218; 922...	€ α 5.888; 6.150... γ 253; 381... e ⁻	€ γ 799; 1081; 834; 1124... e ⁻	α 5.531; 5.710; 5.688... γ 84; 265... g	β ⁻ 0.9... α ? γ 551... 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...	€ α 6.291; 6.248... sf g	€ α 5.939... sf γ 472; 431; 132... e ⁻	€ α 6.113; 6.069... sf g	€ α 5.785; 5.742... sf γ (44...); e ⁻	€ α 5.805; 5.762... sf γ (43...); e ⁻	€ α 5.361; 5.304... sf γ 175; 133... σ 350; σ ₁ 2100	α 5.386; 5.343... sf γ (45); e ⁻	α 4.870; 5.267... γ 402; 278... σ 60; σ ₁ 82	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 3.6 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 16 h	Am 243 7370 a	Am 244 26 m 10.1 h	Am 245 2.05 h	Am 246 25 m 39 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; 860; 320...	€ α 6.042... γ 280; 438; 474; 909...	€ α 5.94 γ 963; 919; 561; 605...	€ α 5.774... γ 278; 228...	€ α 5.378... γ 988; 889...	€ α 5.486; 5.443... sf; γ 60; 26... e ⁻ ; g; σ 60 + 840 σ ₁ 3.15	€ α 5.275; 5.233... sf; γ 75; 44... σ 75 + 5 σ ₁ 0.079	€ β ⁻ 1.5... σ 19; σ ₁ <0.2	€ β ⁻ 0.9... γ 253; (241; 296...) e ⁻ ; g	€ β ⁻ 1.2... σ 100; σ ₁ 200	β ⁻ 1.2; 2.2... γ 679; 1079; 205; 799; 1062... 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 26 γ (46; 109...); e ⁻	€ α 5.334... γ 60...; e ⁻	€ α 5.499; 5.456... sf; Mg γ (43; 100...); e ⁻	€ α 5.157; 5.144... sf; γ (52...) e ⁻ ; m	€ α 5.168; 5.124... sf; γ (45...) e ⁻ ; g	€ β ⁻ 0.02; g γ (149...); e ⁻	€ α 4.901; 4.856... sf; γ (45...) e ⁻ ; g	€ β ⁻ 0.6... γ 84...; e ⁻ σ <100; σ ₁ 200	€ α 4.589; 4.546... sf e ⁻ ; g	€ β ⁻ 0.9; 1.2... γ 327; 560; 308...; g σ 150	β ⁻ 0.2; 0.3 γ 44; 224; 180... m ₁
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 1.54 · 10 ⁵ a	Np 237 2.144 · 10 ⁶ a	Np 238 2.117 d	Np 239 2.355 d	Np 240 7.22 m 65 m	Np 241 13.9 m	Np 242 2.2 m 5.5 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	€; α 5.025; 5.007... γ (26; 84...); e ⁻ g; σ 160 + ?	€; β ⁺ 0.5... γ (842...); e ⁻ σ 290; σ ₁ 2700	€ α 4.790; 4.774... γ 29; 87...; e ⁻ σ 170; σ ₁ 0.020	β ⁻ 1.2... γ 984; 1029; 1026; 924...; e ⁻ σ 32 + 19; σ ₁ <1	β ⁻ 0.4; 0.7... γ 106; 278; 228...; e ⁻ ; g σ 32 + 19; σ ₁ <1	β ⁻ 2.2... γ 555; 566; 597...; g h...; g	β ⁻ 1.3... γ 175; (133...) g	β ⁻ 2.7... γ 736; 780; 945; 1473... g	β ⁻ 2.8... g	β ⁻ 2.17; 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 236 120 ns 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... Mg 28; Ne; γ (53; 121...) e ⁻ ; σ 96; σ ₁ 0.07	α 4.398... Ne; γ 186... e ⁻ ; σ 95; σ ₁ 58	α 4.494; 4.445... γ 1283; sf; γ (49...) 113... e ⁻ ; σ 5	β ⁻ 0.2... γ 60; 208... e ⁻ σ ~100; σ ₁ <0.35	α 4.198... 190... e ⁻ ; σ 27; σ ₁ 164	β ⁻ 1.2; 1.3... γ 75; 44... σ 22; σ ₁ 15	β ⁻ 0.4... γ 44; (190...) m		β ⁻ 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 1.17 m 6.70 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; 4.952; 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 ⁻ 2.3... γ 1001; 12... 767...; γ 131; 881; h ₁ (74...); e ⁻ σ <500; σ ₁ <5000	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 ⁻ 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 ⁻	β ⁻ 1.2... γ 87; 29... 459...; e ⁻ σ 1.8; σ ₁ <0.01	β ⁻ 0.2... γ 63; 92; 93... e ⁻ ; m	β ⁻ 1.4... γ 417; 727; 196... g	β ⁻ 1.0... γ 111; (647; 196... g						

152

150

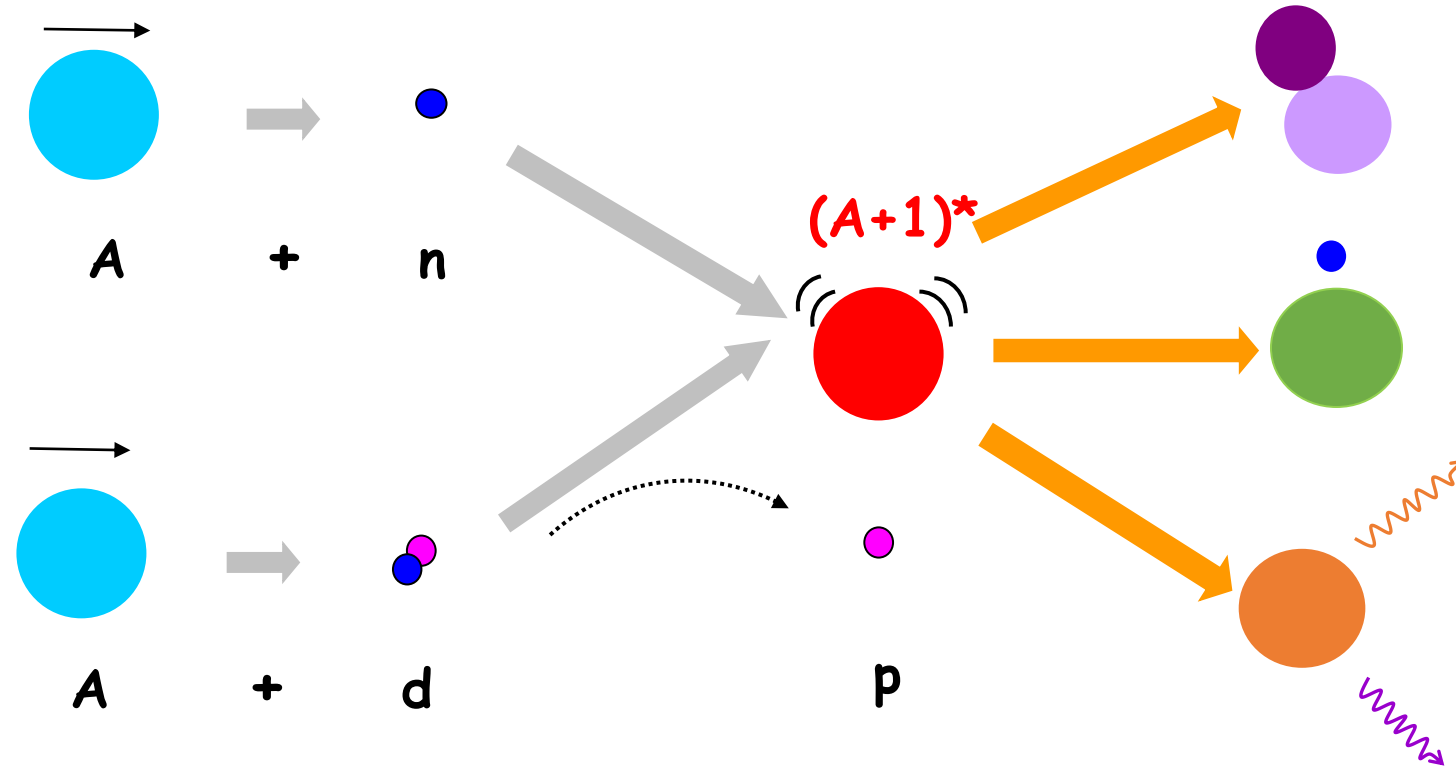
Very difficult or even impossible to measure with standard techniques → difficulty to produce and handle the needed targets!

Solution: measurements in inverse kinematics...



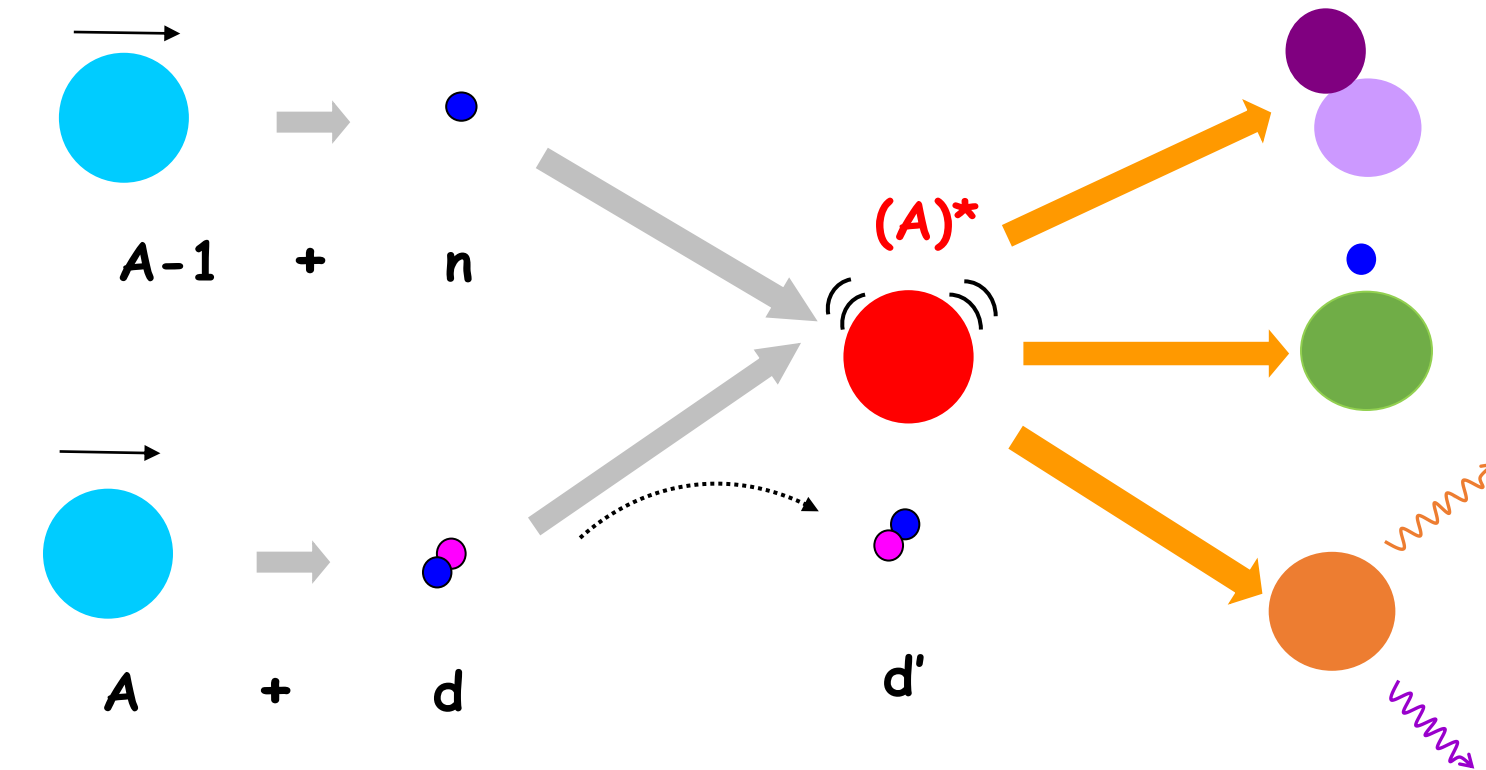
...but free-neutron targets are not yet available!

Surrogate-reaction method in inverse kinematics



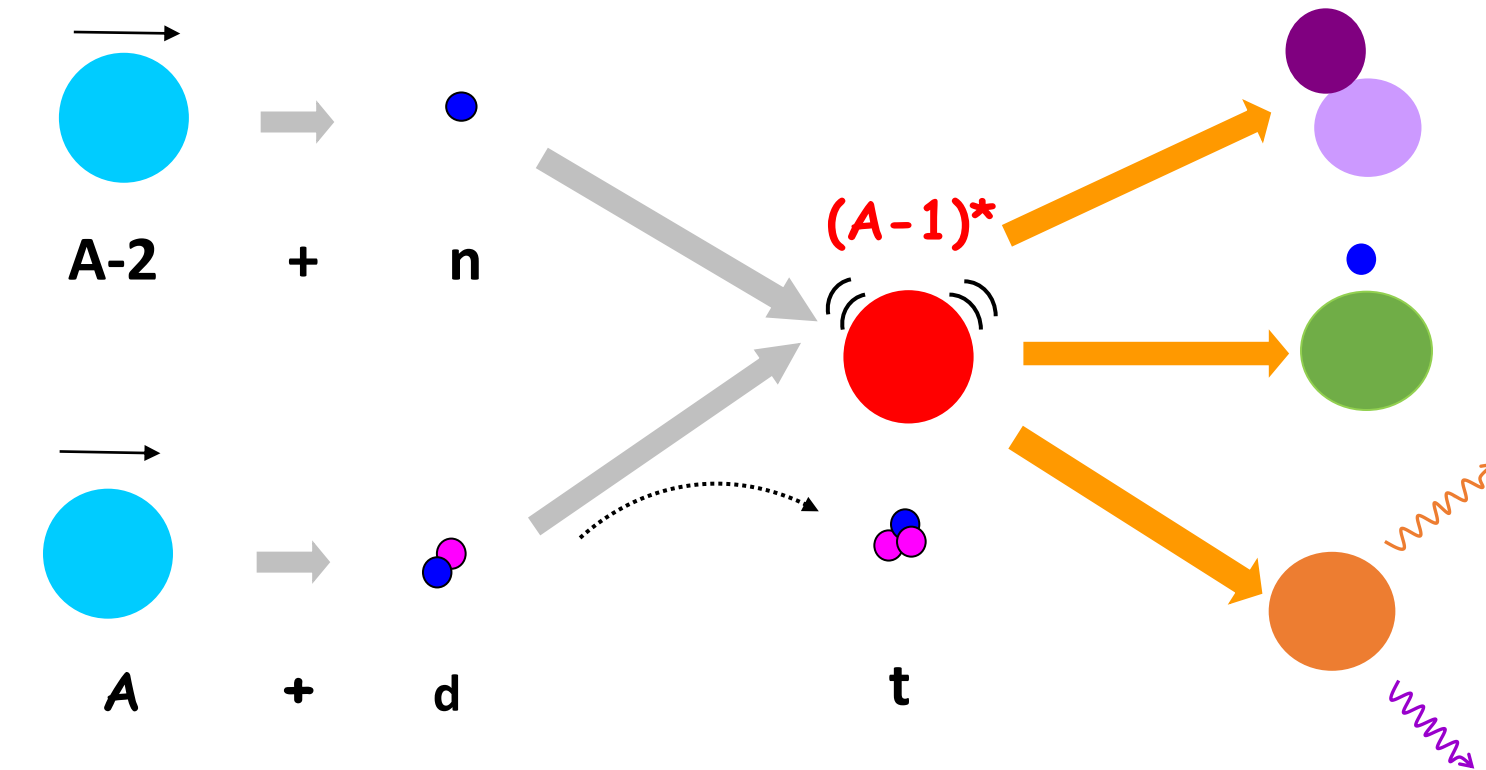
$$\sigma_{n,decay}^A(E^*) = \underbrace{\sigma_{formation}^{A+1}(E^*)}_{\text{Theory}} \cdot \underbrace{P_{decay}^{surro}(E^*)}_{\text{Experiment}}$$

Several reactions can be studied in the same experiment!



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

Several reactions can be studied in the same experiment!



$$\sigma_{n,decay}^{A-2}(E^*) = \underbrace{\sigma_{formation}^{A-1}(E^*)}_{\text{Theory}} \cdot \underbrace{P_{decay}^{surro}(E^*)}_{\text{Experiment}}$$

Validity of the surrogate-reaction method

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

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

Decay only depends on E^* , J and π !

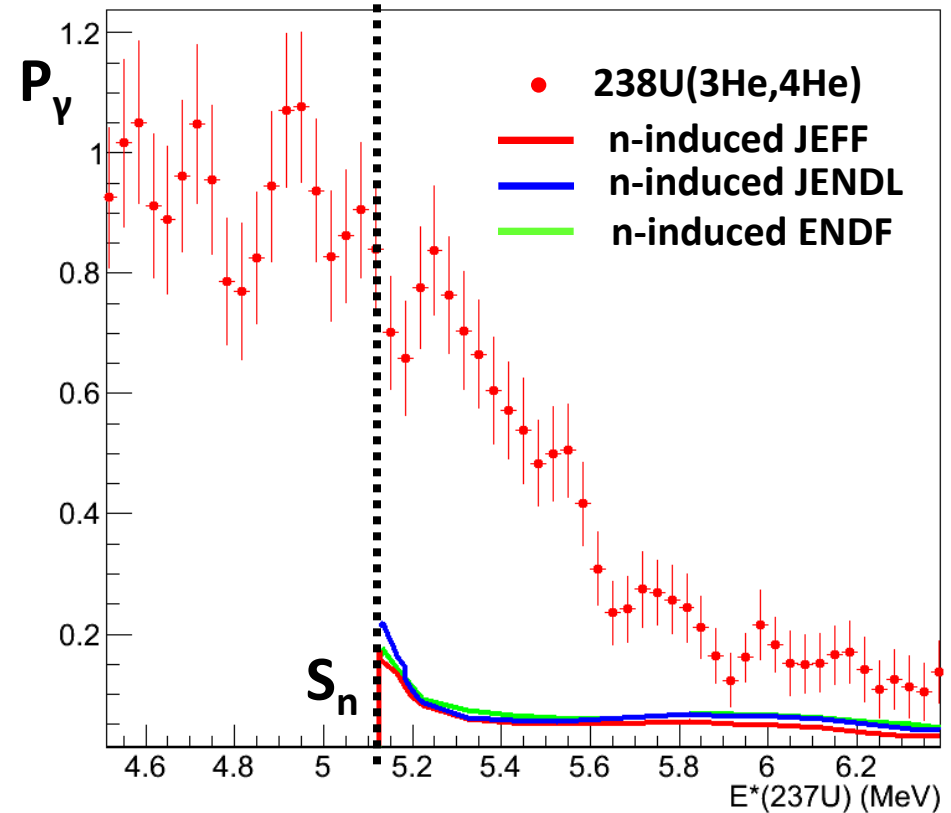
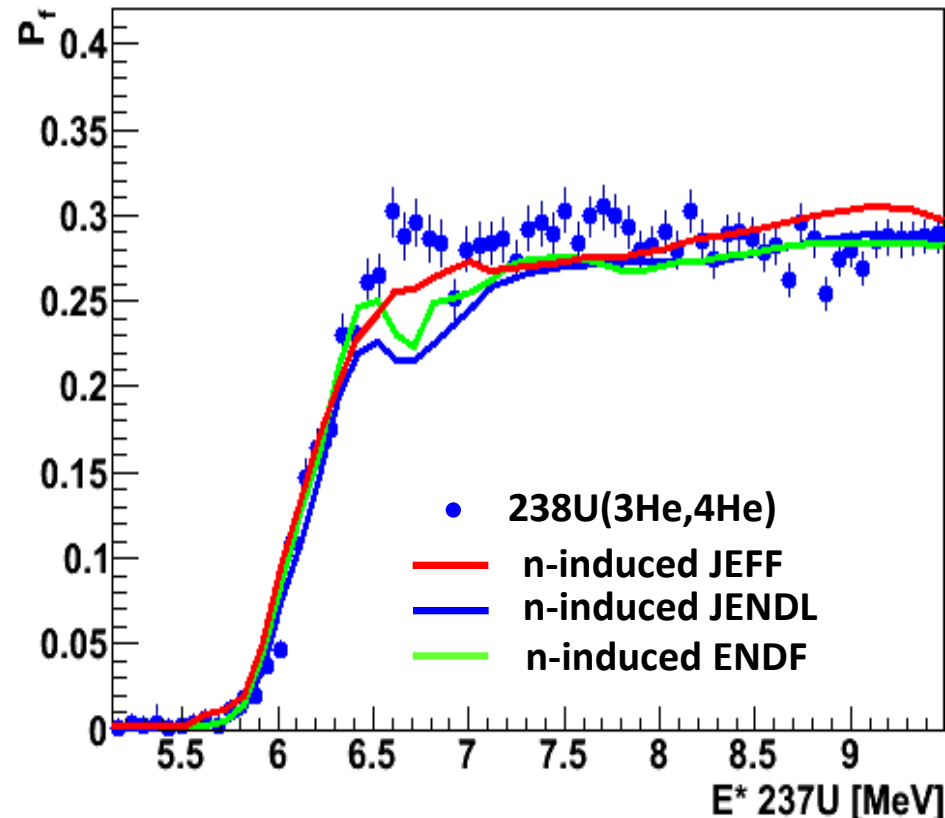
2. $P_{decay}^{surro}(E^*) = P_{decay}^n(E^*)$

But P_{decay} can depend on J and π , and the populated J and π can be different for the n-induced and surrogate reactions

Not possible to say a priori if a reaction meets these conditions.

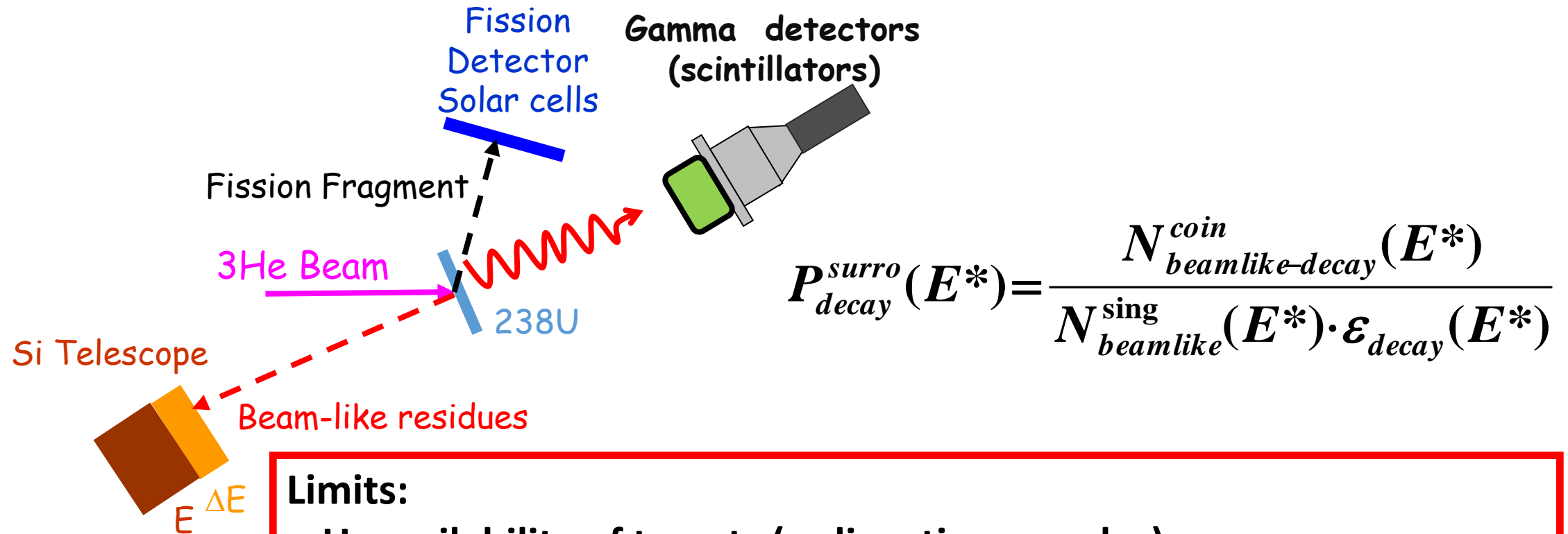
Data obtained with the surrogate method need
to be compared to neutron-induced data!

Representative results



Good agreement for fission probabilities but strong disagreement for γ -emission probabilities. Not understood, need systematic studies involving nuclei with different nuclear structure and different reactions to define how to use surrogate reactions when no neutron data exist.

Measurement of fission and gamma-emission probabilities in direct kinematics

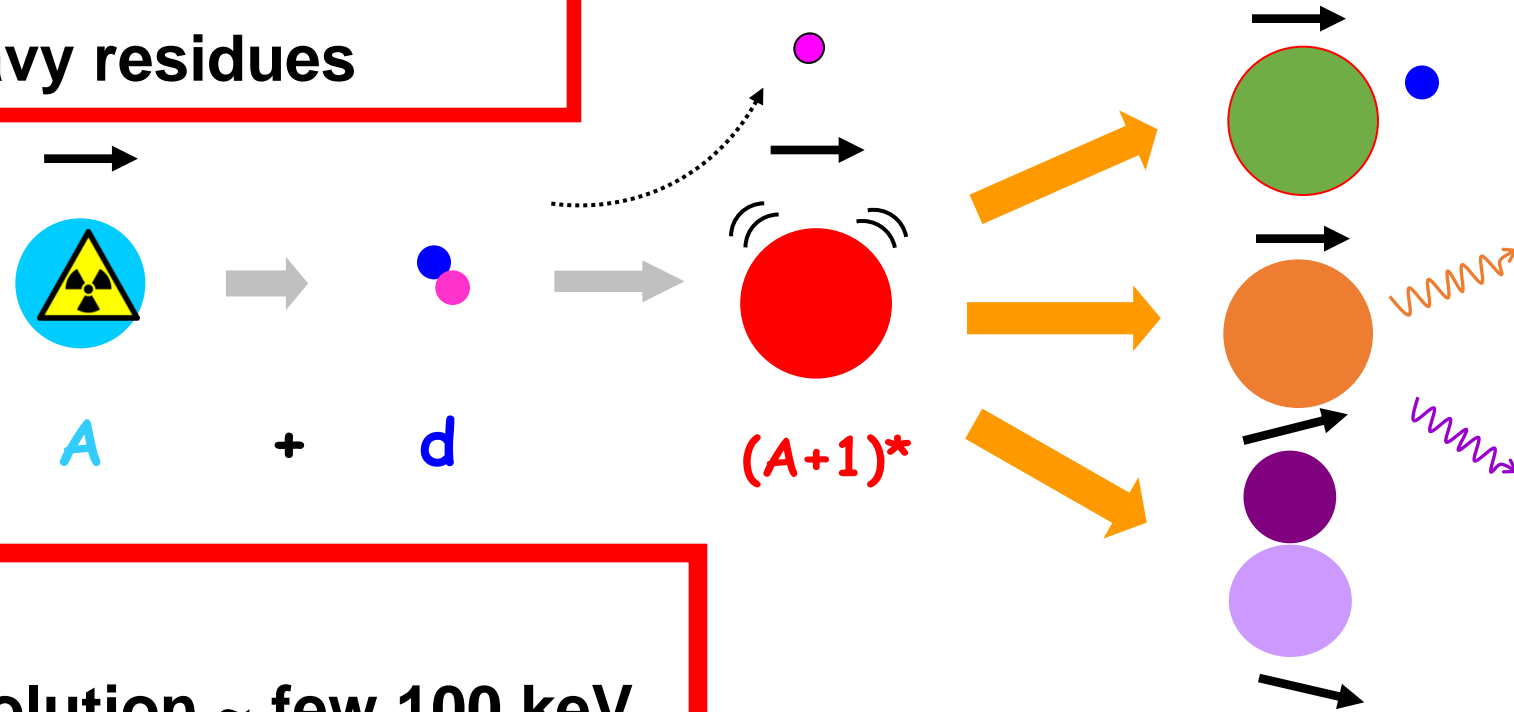


Limits:

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

Advantages of Inverse kinematics:

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



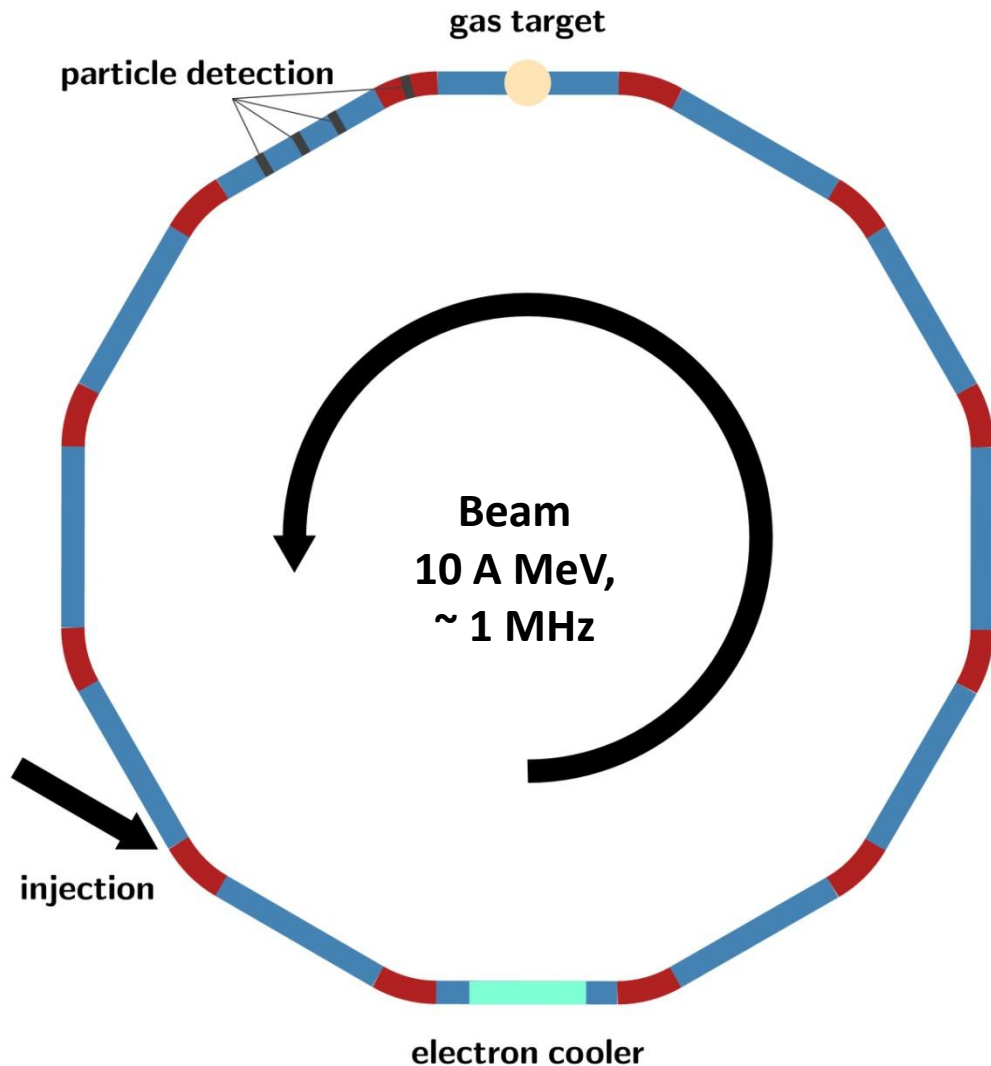
BUT!

- Required E^* resolution \sim few 100 keV,
 $E^* = f(E_{\text{beam}}, E_{\text{target_like}}, \theta)$
- Target contaminants and target windows have to be avoided

STORAGE RINGS!

Advantages of heavy-ion storage rings

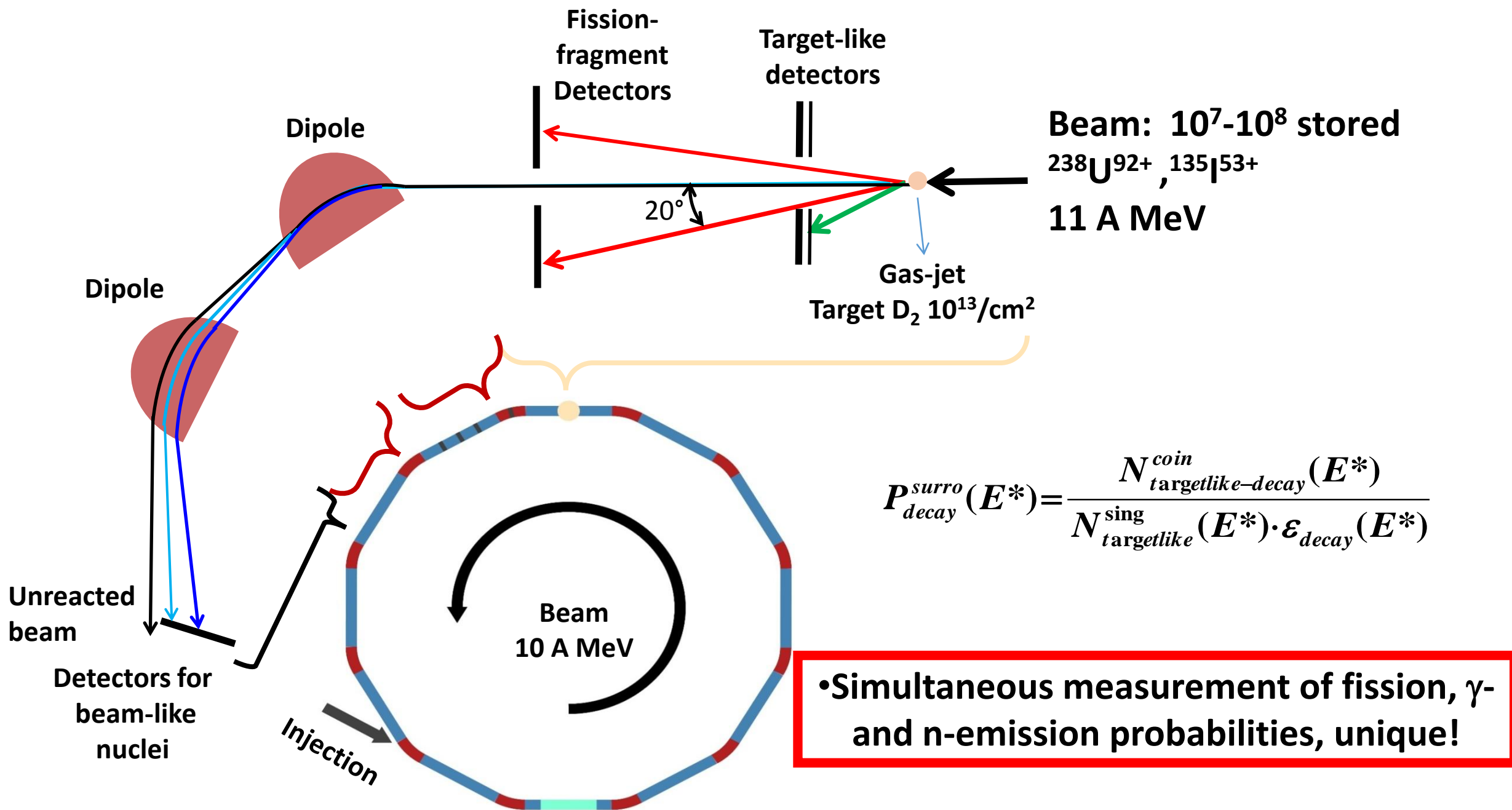
The CRYRING at GSI/FAIR



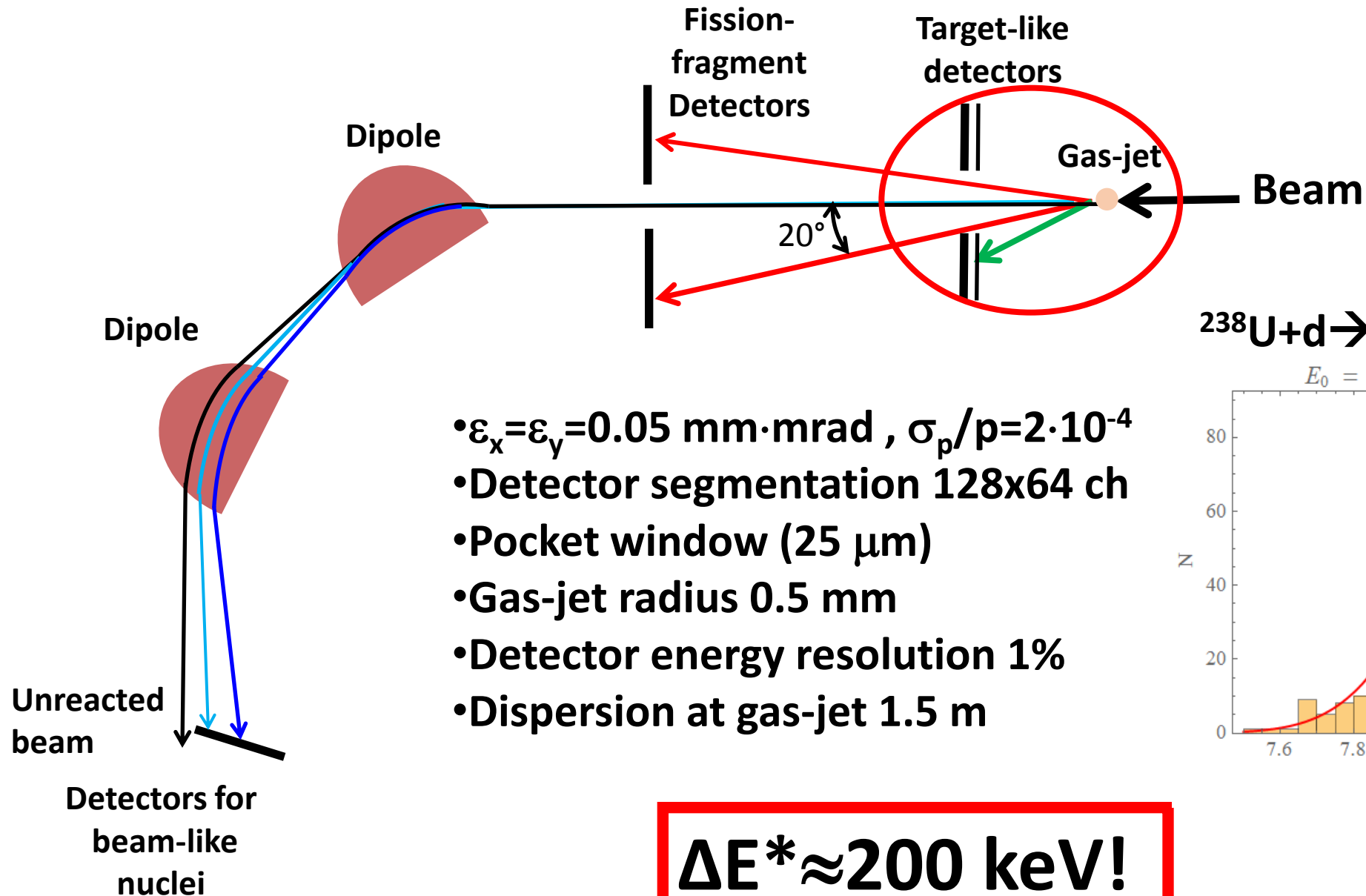
- Beam cooling → Excellent energy and position resolution of the beam, restored after each passage through the target, negligible straggling effects and energy-loss effects
- Use of ultra-thin in-ring gas-jet targets $\sim 10^{13}/\text{cm}^2$. Effective target thickness increased by $\sim 10^6$ due to revolution frequency (at 10 A MeV)
- Pure targets, pure beams, (no backing, no contaminants)

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

Set-up at the CRYRING

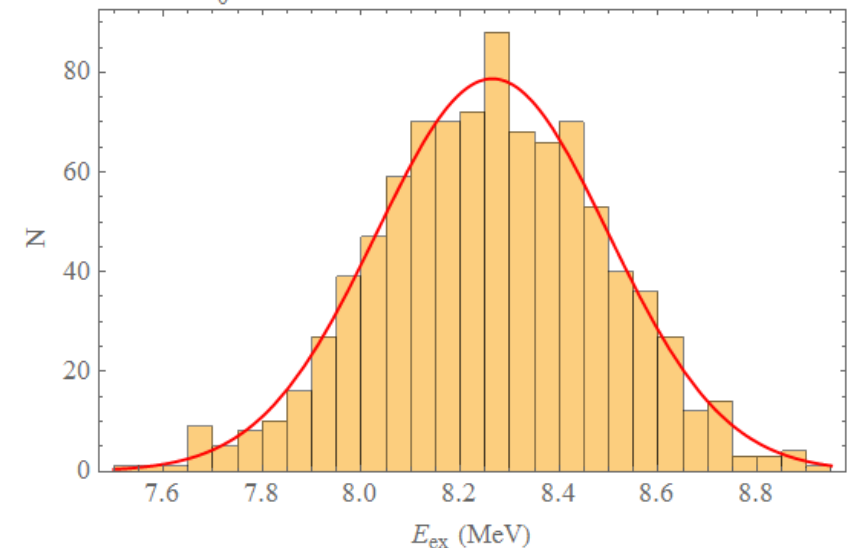


Detailed Geant 4 simulations: excitation-energy resolution



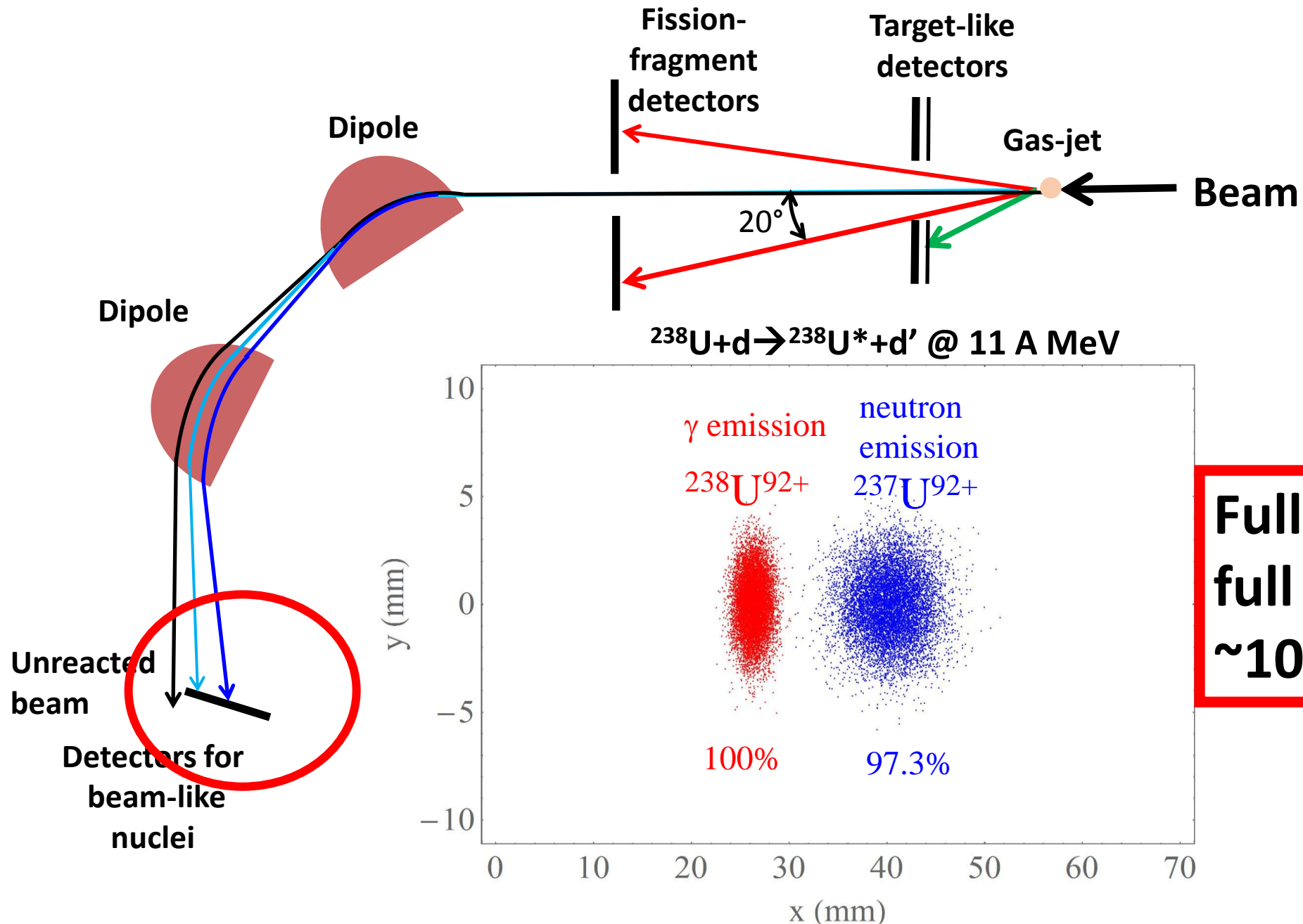
$^{238}\text{U} + d \rightarrow ^{238}\text{U}^* + d' @ 11 \text{ A MeV}$

$E_0 = 8.26486 \text{ MeV}$ $\sigma = 0.23413 \text{ MeV}$



$\Delta E^* \approx 200 \text{ keV!}$

Detailed Geant 4 simulations: separation of beam-like residues



**Full separation and
full transmission:
~100% efficiency!**

Conclusions

- Surrogate reactions in inverse kinematics are the most promising indirect method to infer neutron cross sections of short-lived nuclei which are crucial for nuclear astrophysics and applications in nuclear technology.
- CRYRING is the ideal place to carry out high-resolution surrogate reaction studies in inverse kinematics:
 - E^* resolution of few 100 keV
 - No target contaminants or backing, pure beams
 - Simultaneous measurement of all decay probabilities with $\sim 100\%$ efficiency
- Numerous measurements with stable and radioactive beams will be possible
- Applications for funding submitted, TDR will be prepared for end 2019, submission of proposal to next PAC