Determining neutron-induced reaction cross sections through surrogate reactions at storage rings

J. A. Swartz

8 December 2021

1st Low Energy Nuclear Physics Meeting (PhyNuBE),

Centre Paul Langevin, Aussois, France

The NECTAR project - determine neutron-induced reaction cross sections

- Focus on short-lived nuclei, of interest to:

Nuclear astrophysics

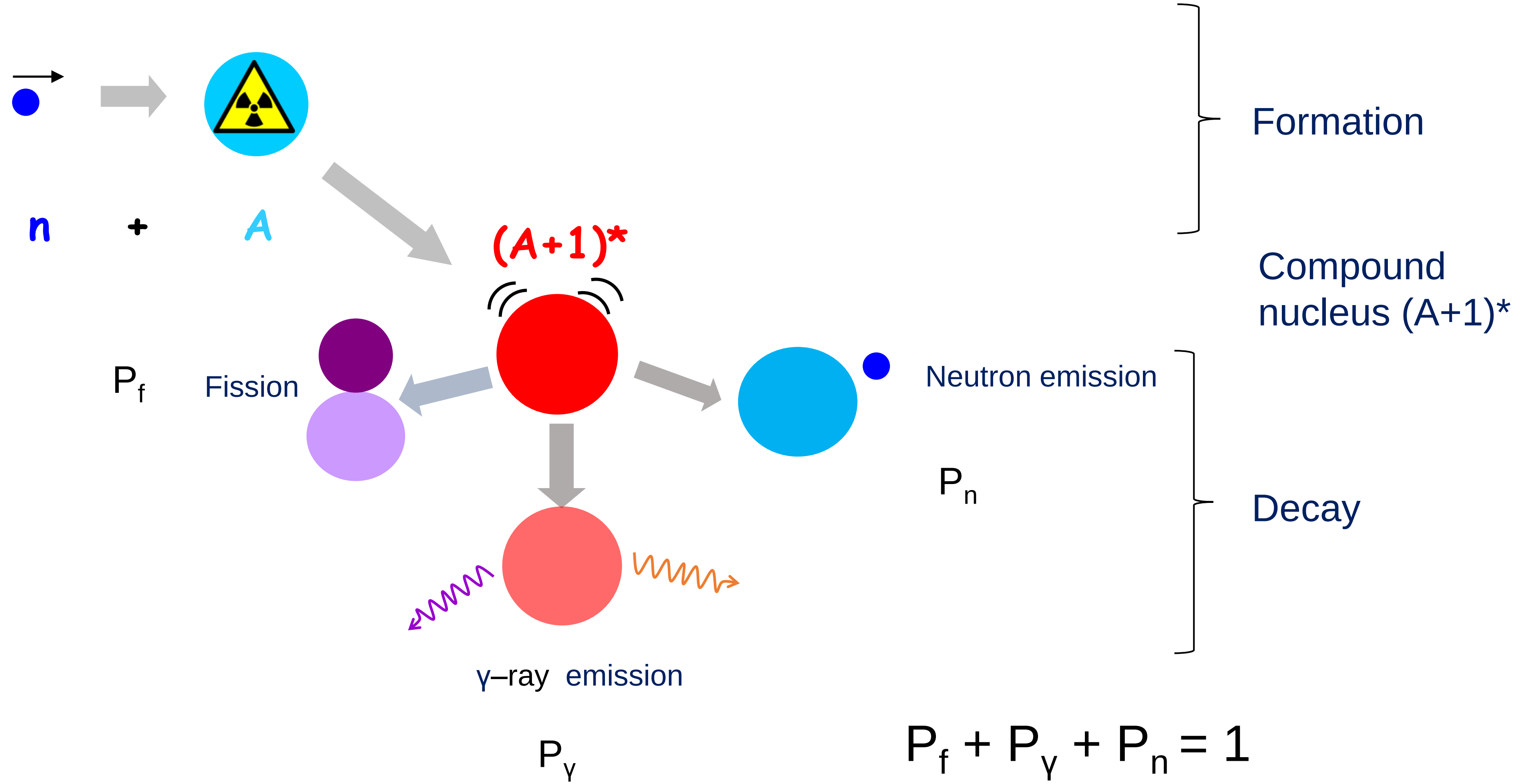
- Nuclear astrophysics
- Applications (e.g. nuclear energy, medicine)

Nuclear r
E
C
Tions
At storage
Rings

Nuclear medicine

Nuclear energy

→ One way: a neutron beam on a radioactive target:



$$P_f + P_\gamma + P_n = 1$$

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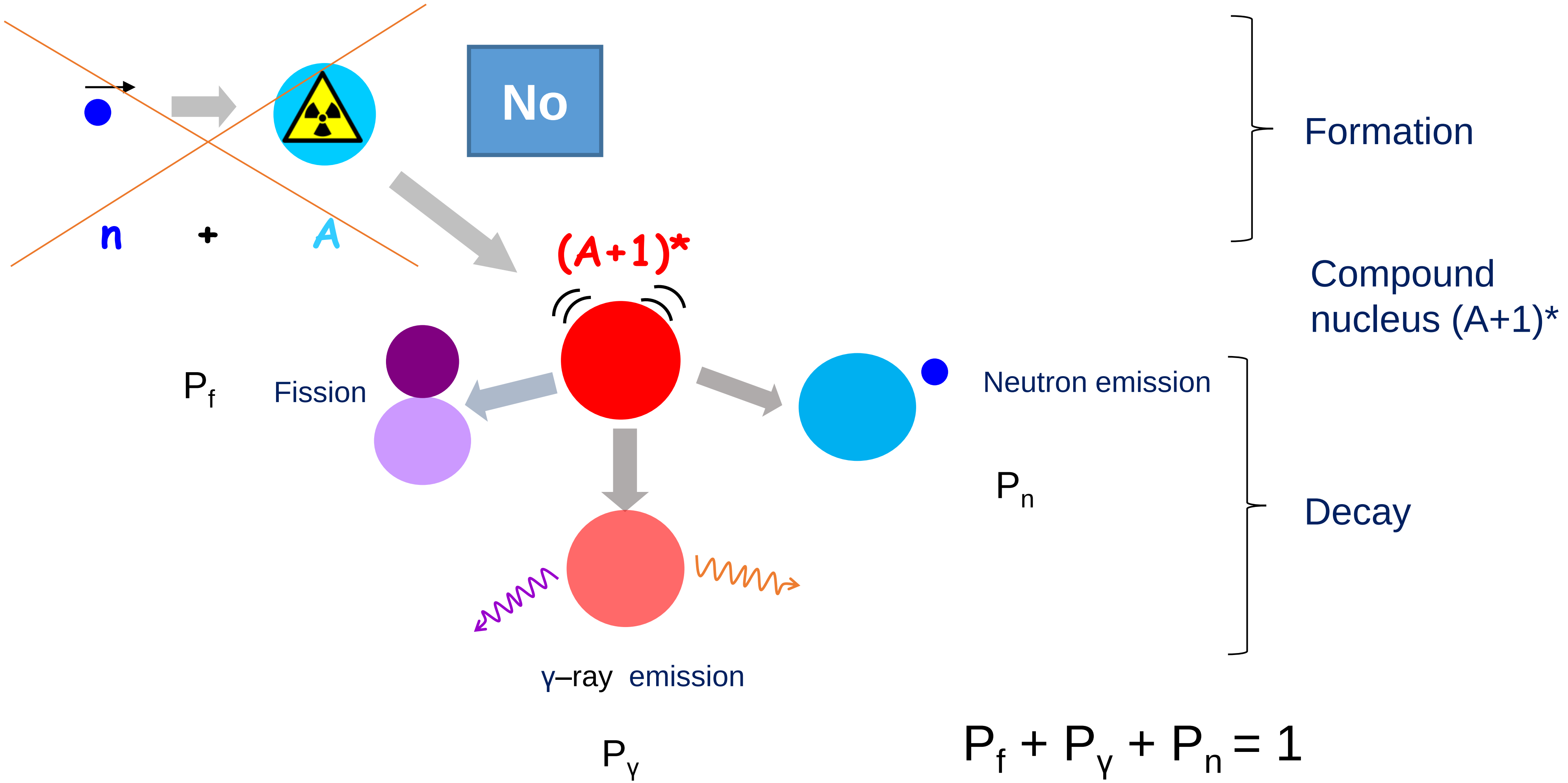
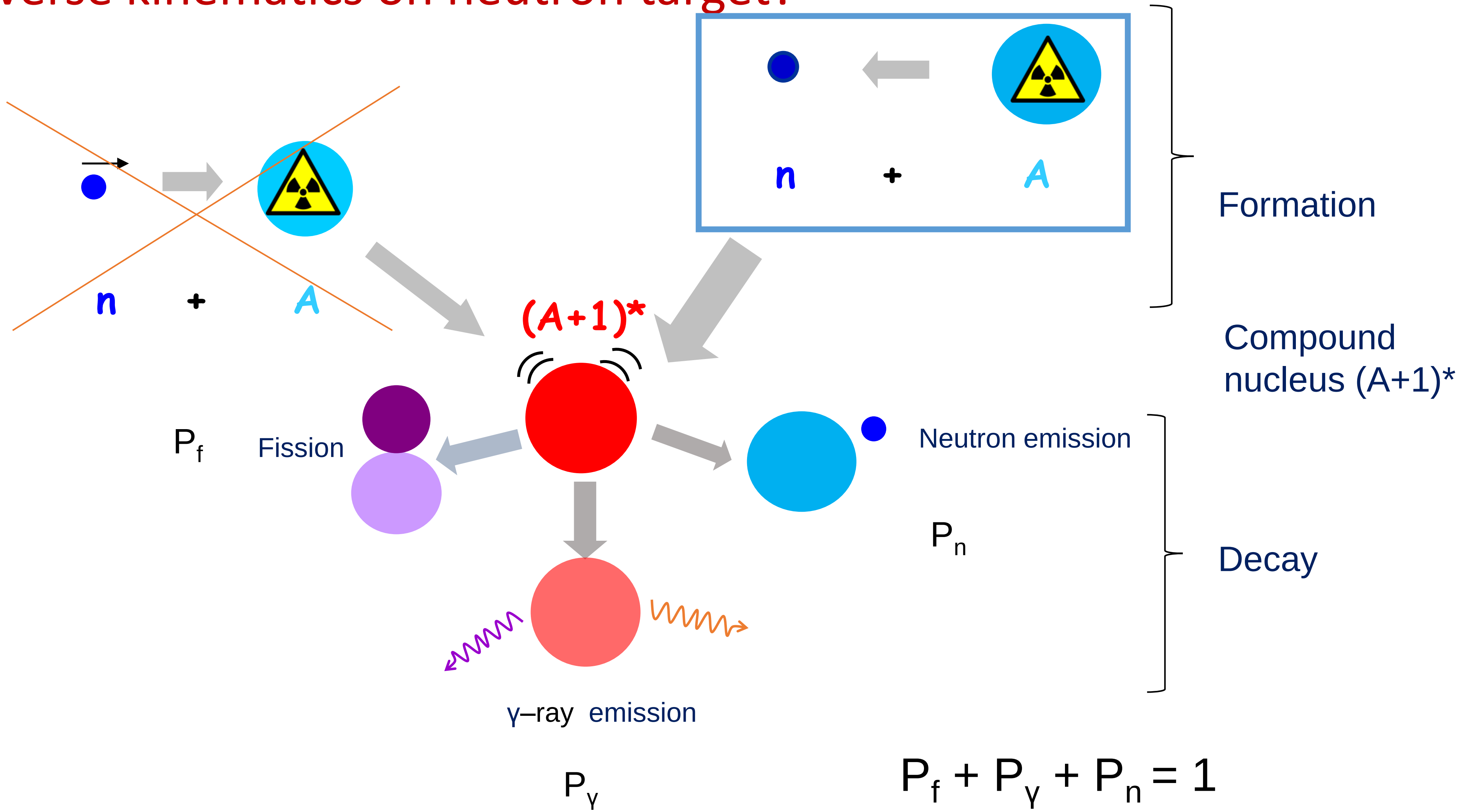


→ Then, in inverse kinematics on neutron target?



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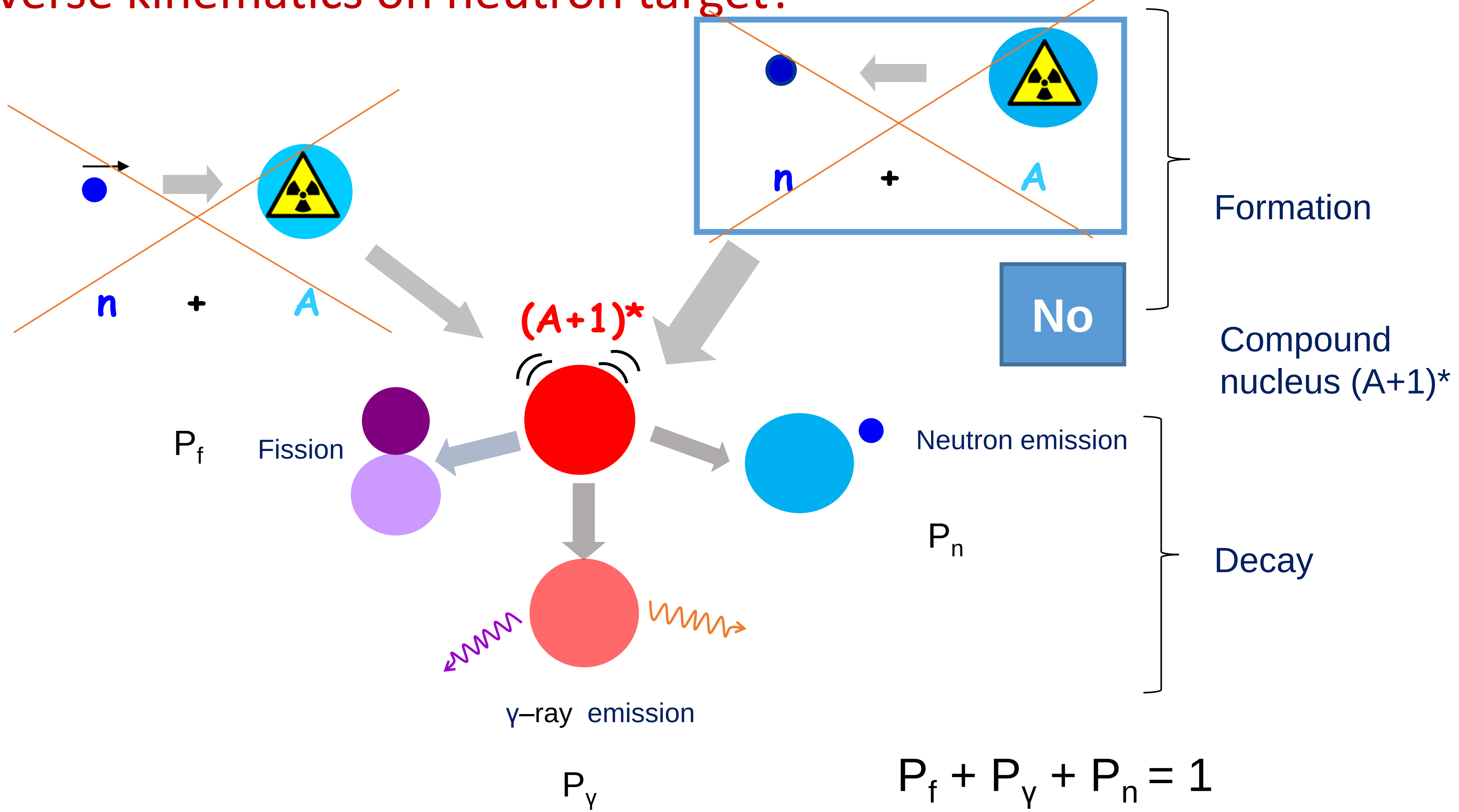
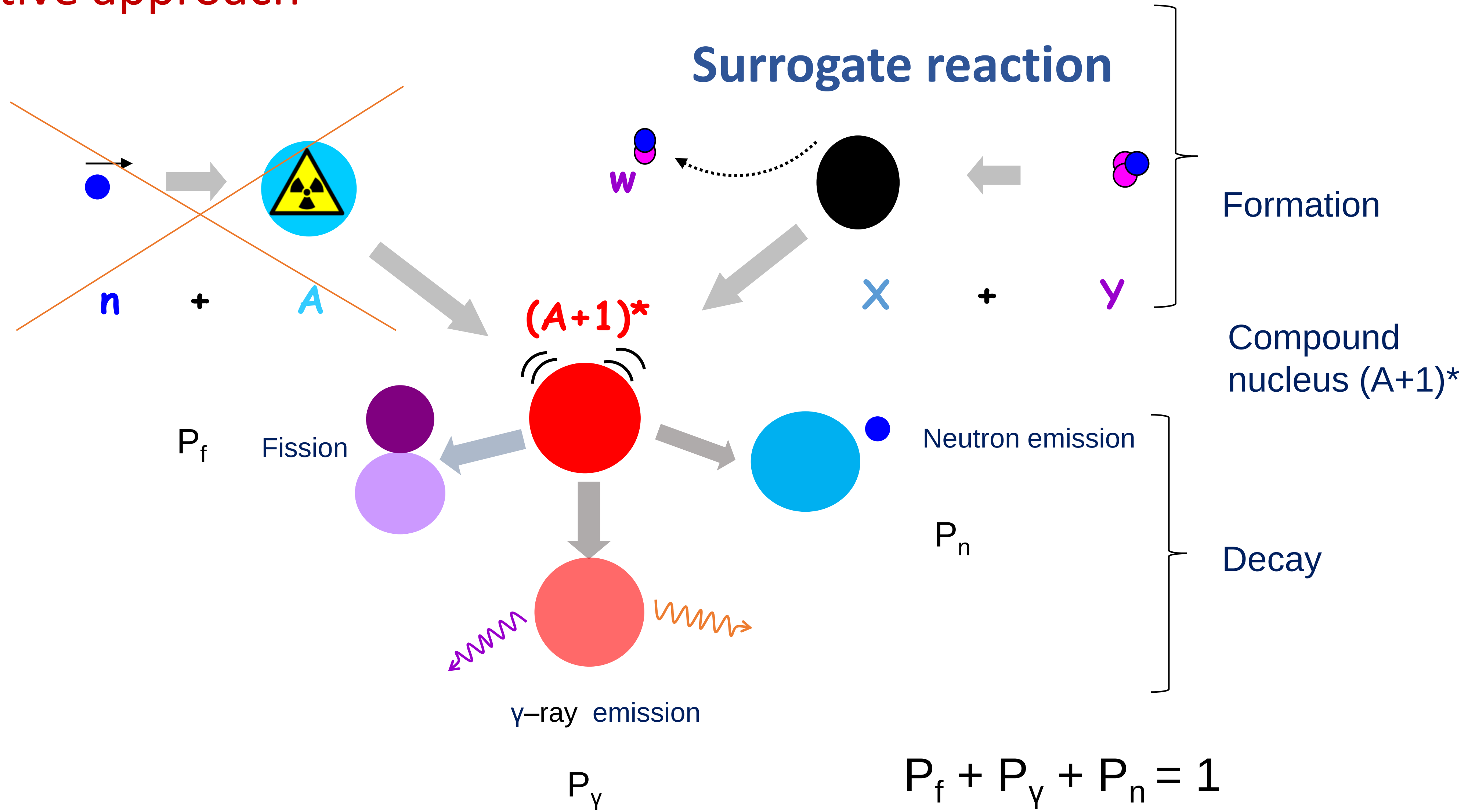


→ An alternative approach



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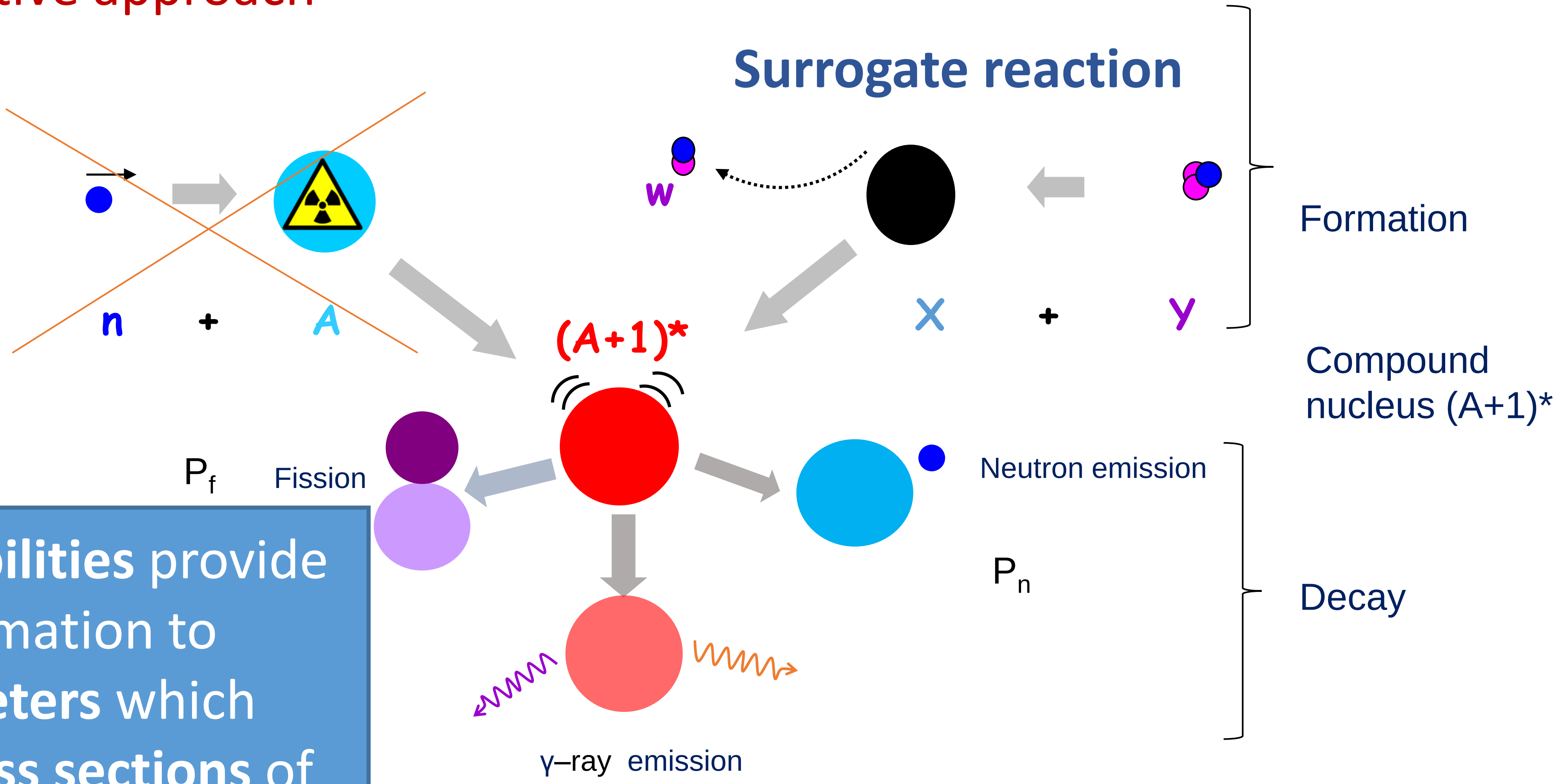
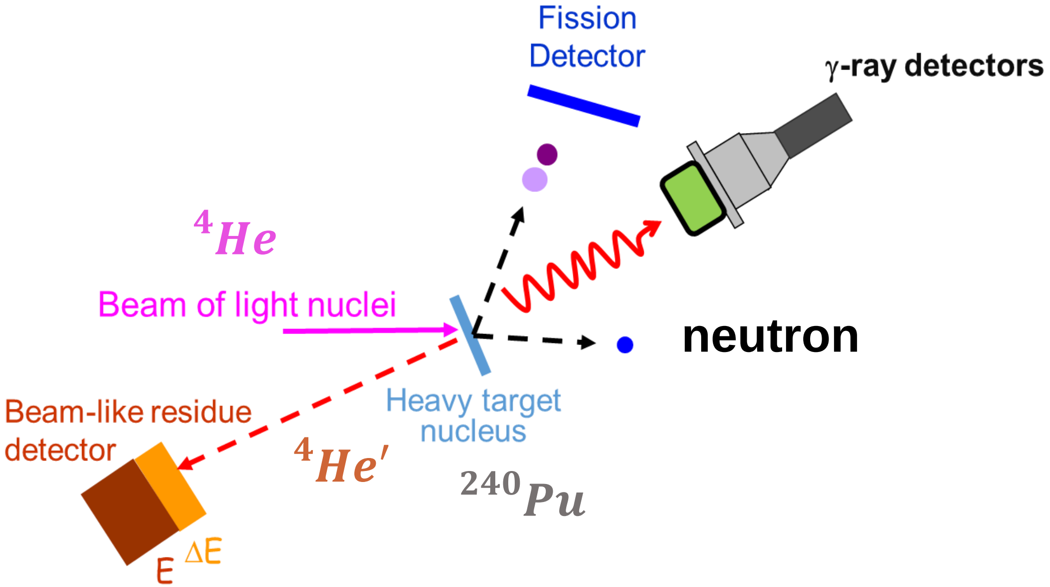


$$P_f + P_\gamma + P_n = 1$$

Decay probabilities provide key information to **Fix parameters** which constrain **cross sections** of neutron-induced reactions.

Surrogate reaction experiments, in direct kinematics



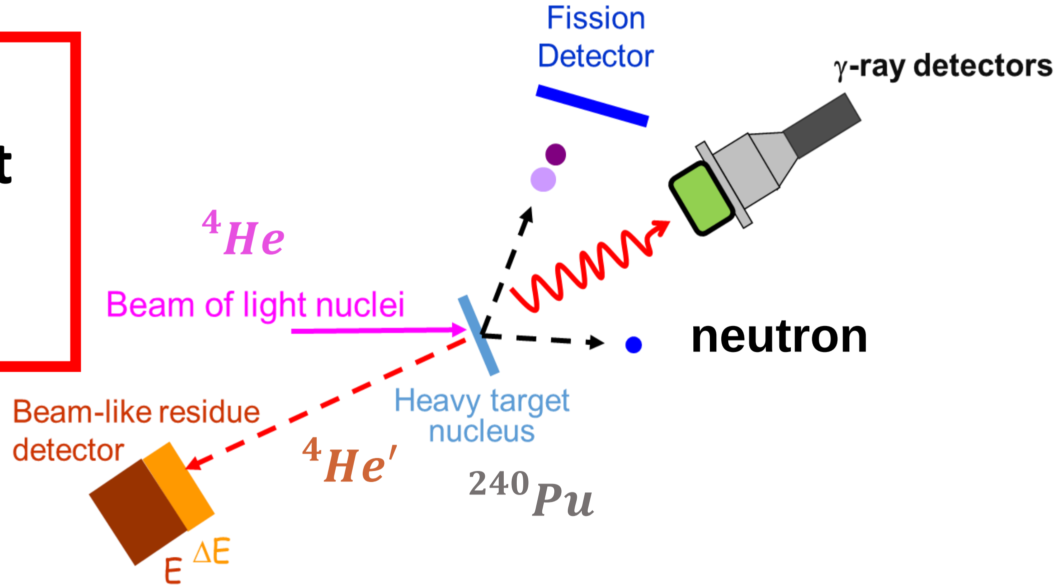
R. Perez Sánchez, B. Jurado et al., PRL 125, 122502 (2020)

^{240}Pu(^{4}He,^{4}He')^{240}Pu* as surrogate reaction for n+^{239}Pu → ^{240}Pu*

Surrogate reaction experiments, in direct kinematics

Limitations:

- **Target radioactivity, contaminants and target support**
- **P_γ efficiency**
- **P_n: low-energy neutrons and efficiency**



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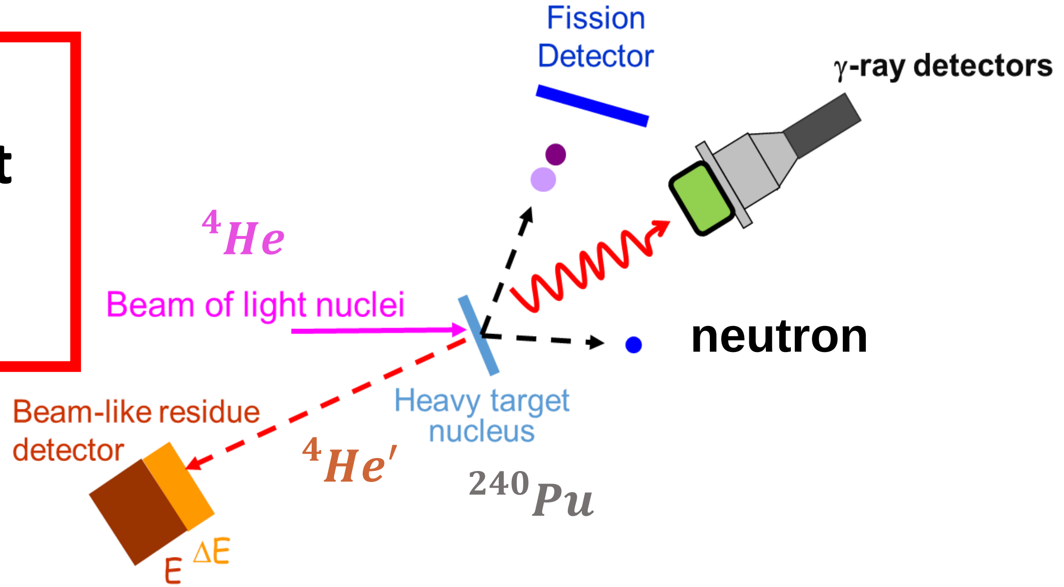
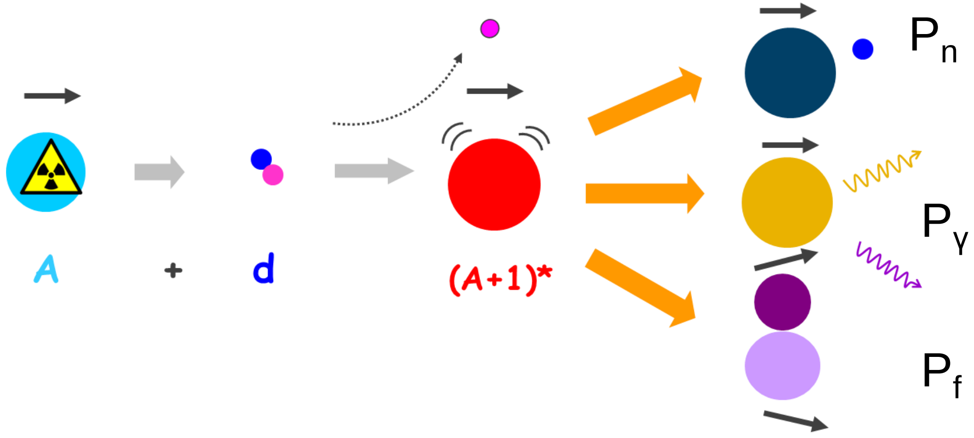


R. Perez Sánchez, B. Jurado et al., PRL 125, 122502 (2020)

..Surrogate reactions in inverse kinematics

Advantages:
- **Access to very short-lived nuclei**
- **Detection of heavy residues (high efficiency)**



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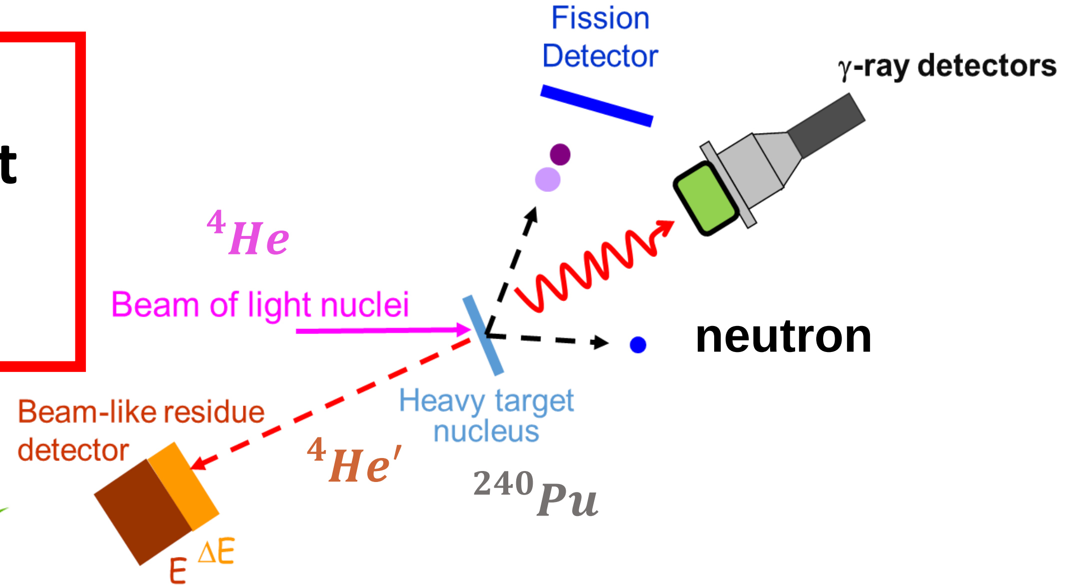

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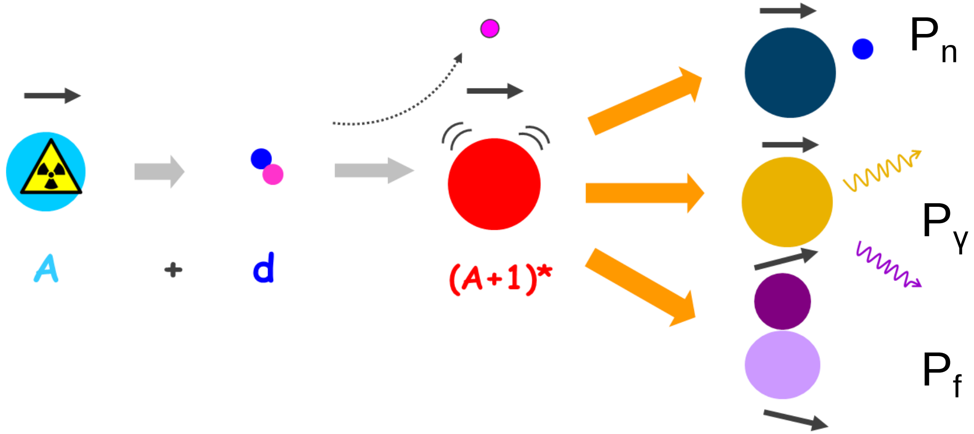

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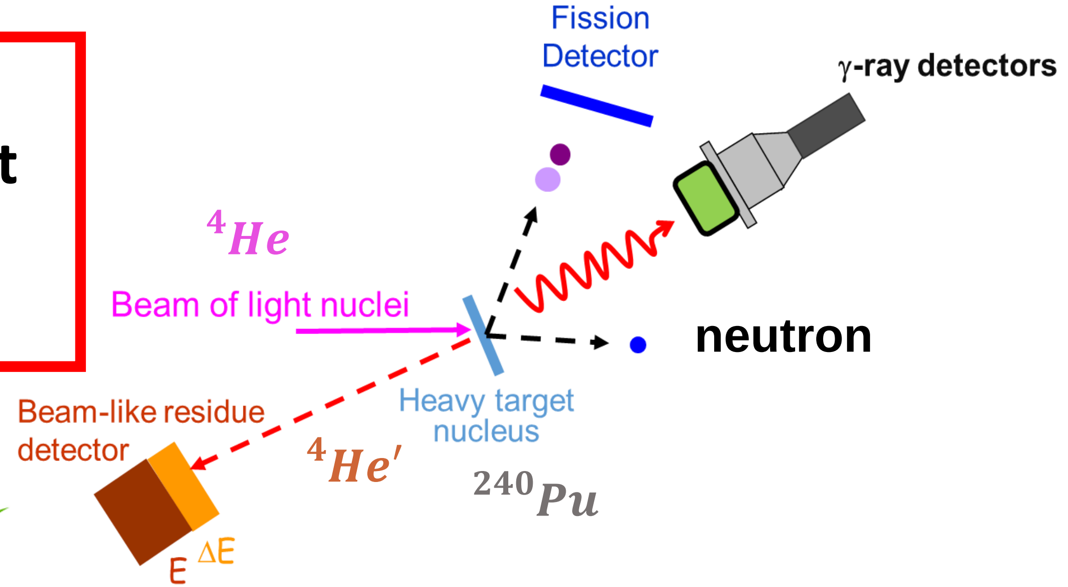

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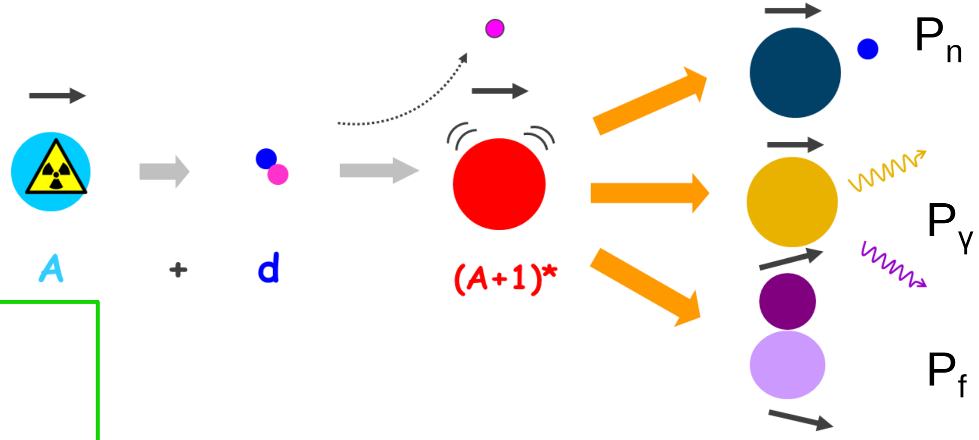


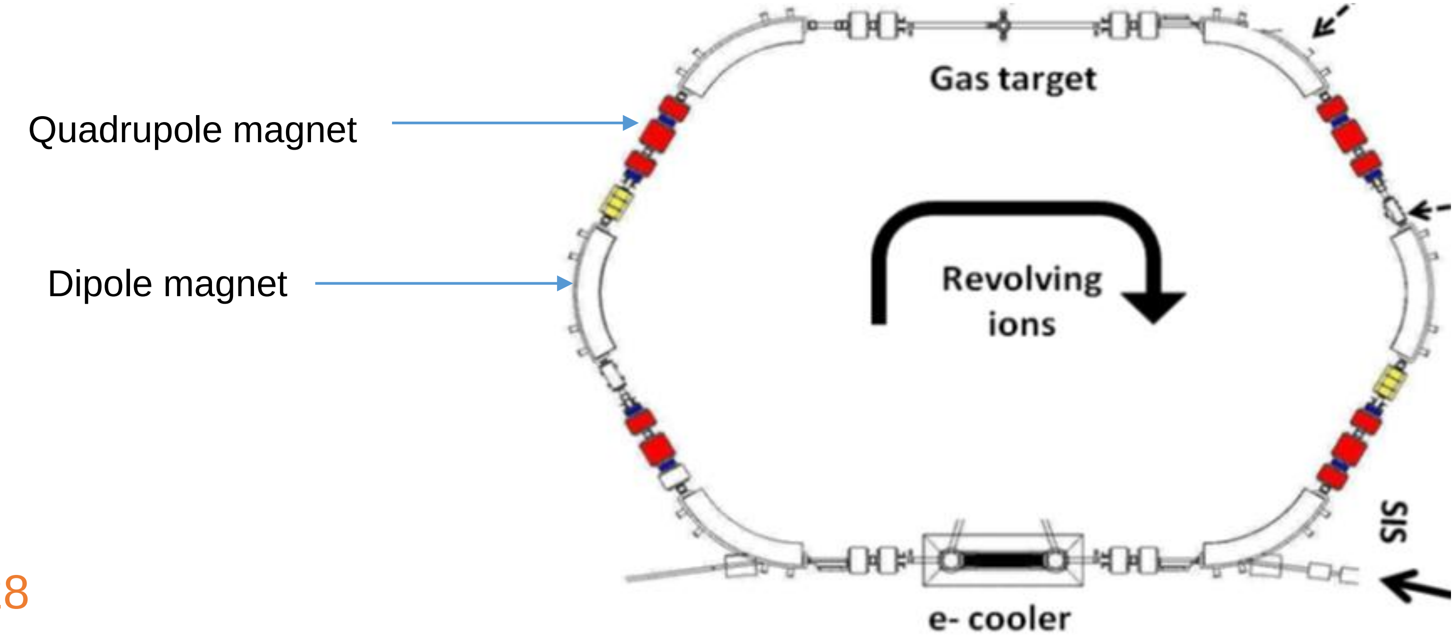
But how do we reach the energy resolution required? E*~ few 100 keV

Experiments at storage rings of GSI/FAIR

Advantages:

- Excellent excitation energy resolution possible through low-density gas jet target and electron cooling.
- Frequency compensates for thin target.
- No target contaminants or window.

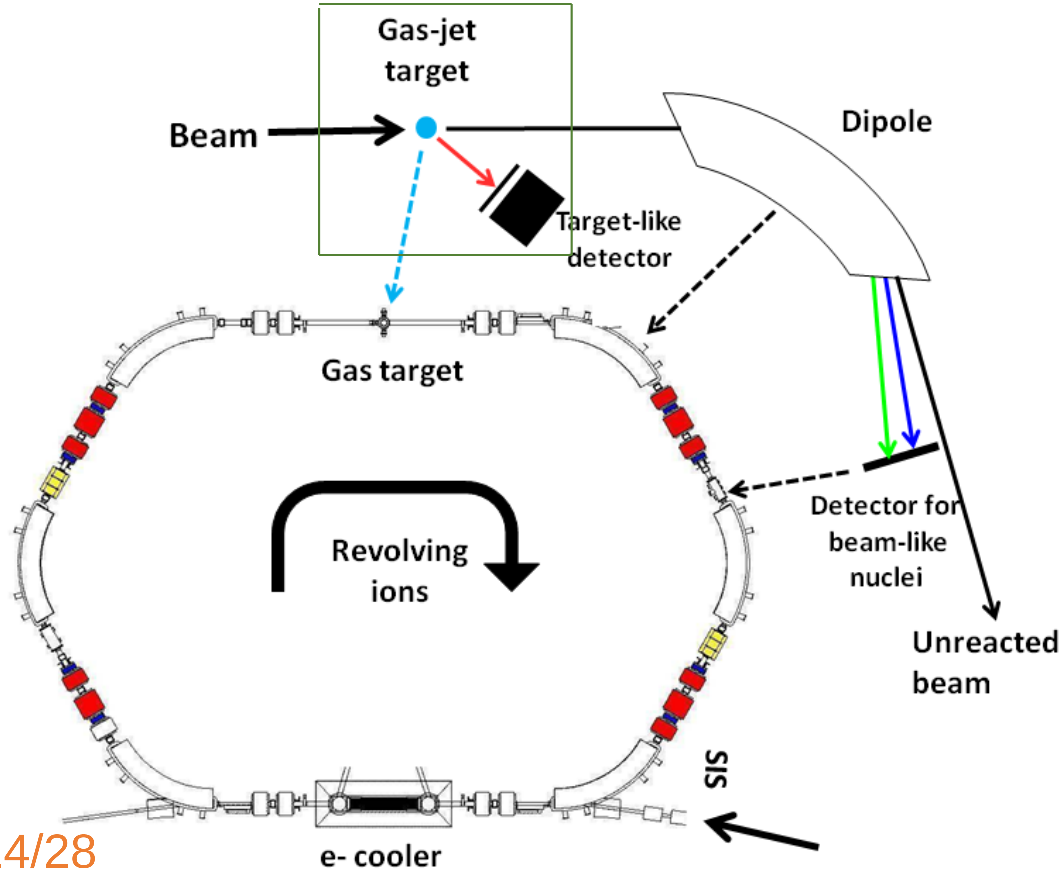
➢ Challenge: UHV of the ring (P ~ 10^{-11} – 10^{-12} mbar)



The ESR storage ring at GSI

NECTAR Proof-of-Principle (PoP) experiment – June 2022

- Beam of ^{208}Pb at E_{beam} = 30 AMeV on ^{1}H gas jet target
- $^{208}Pb(p,p')^{208}Pb^*$ reaction as surrogate for $n+^{207}Pb \rightarrow {}^{208}Pb^*$



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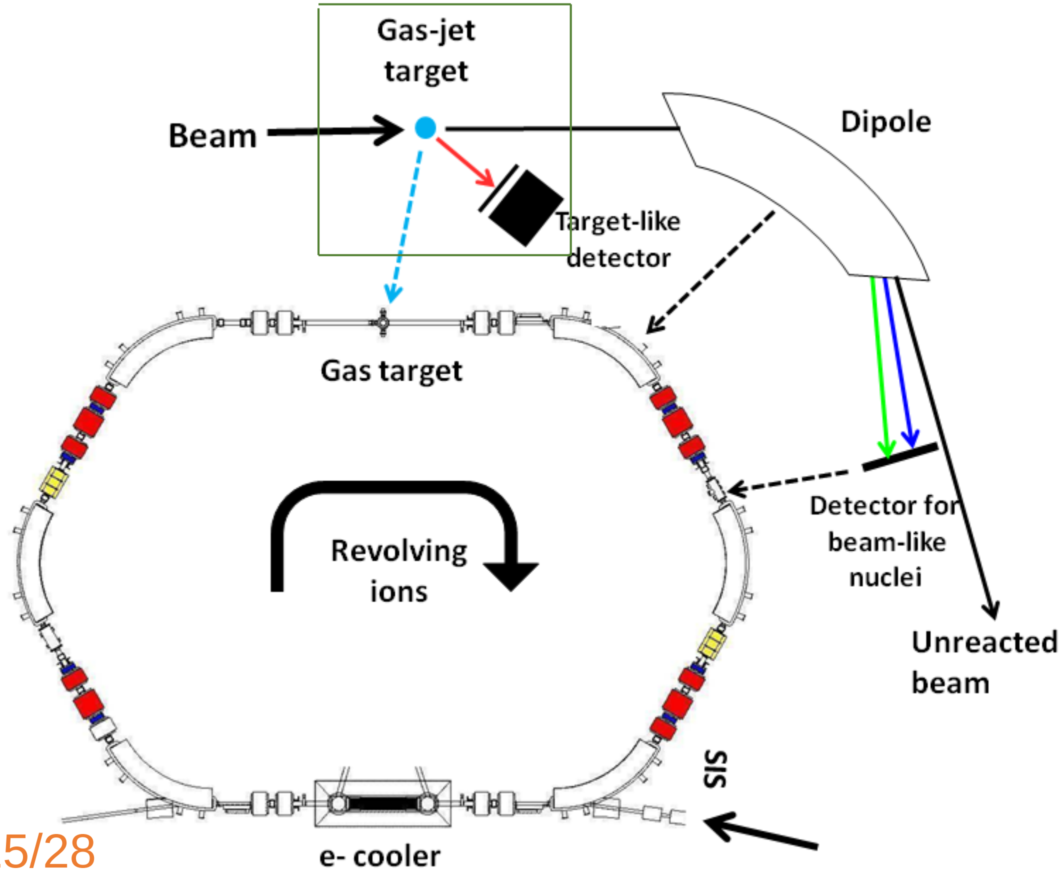

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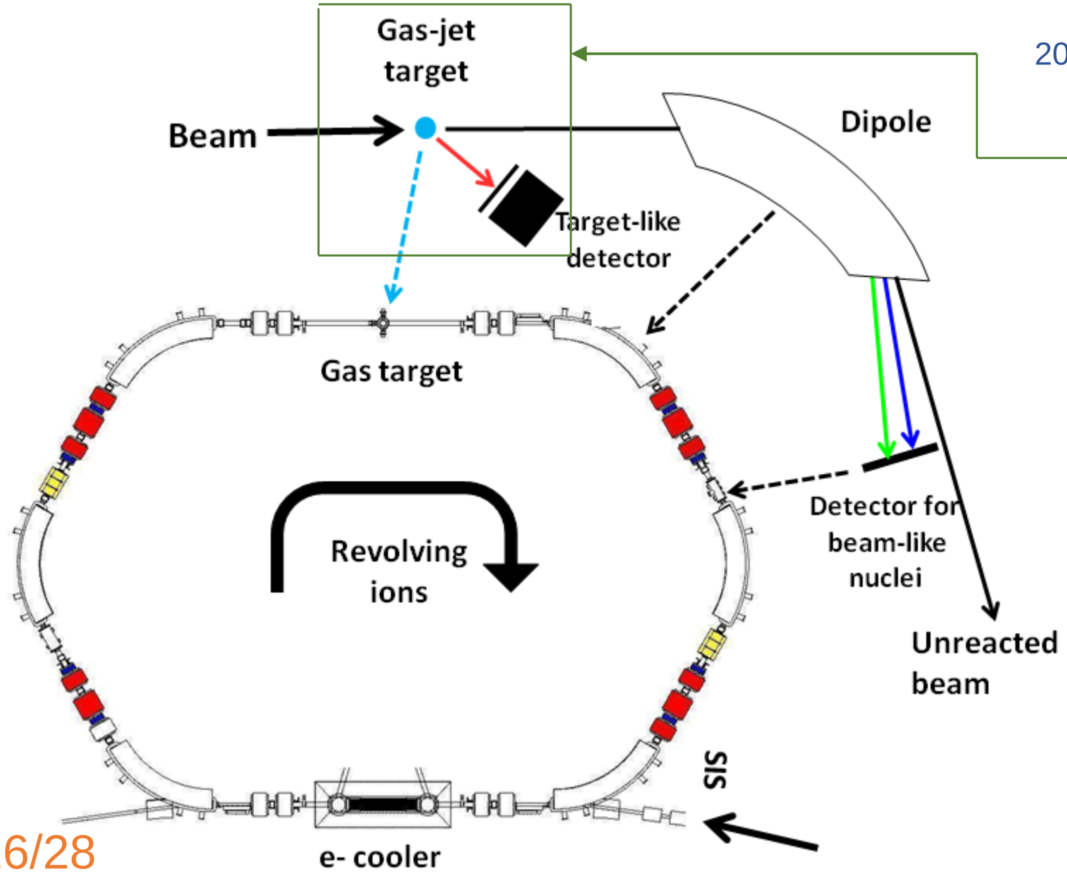

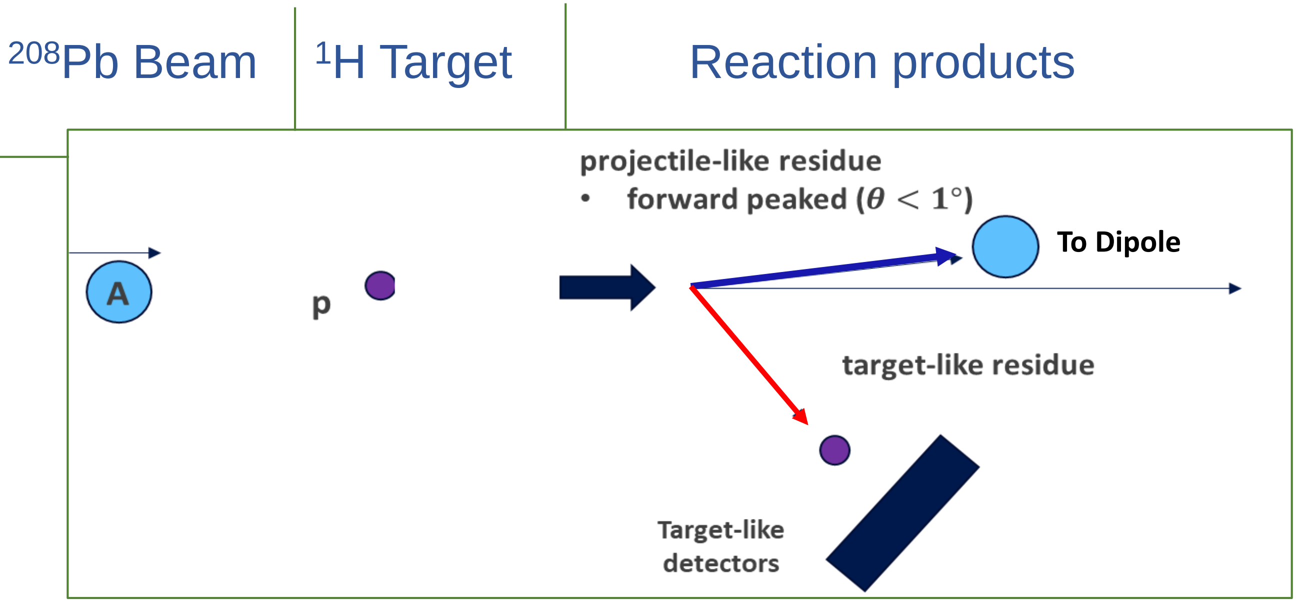

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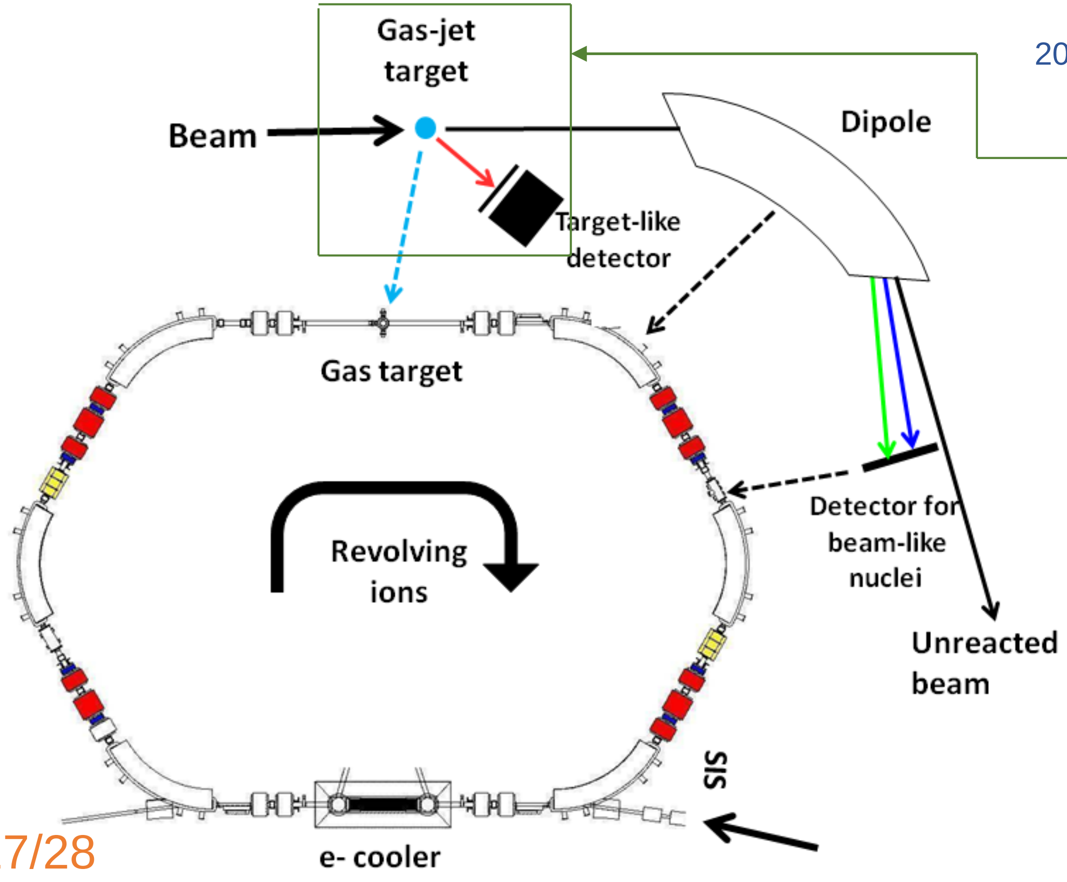
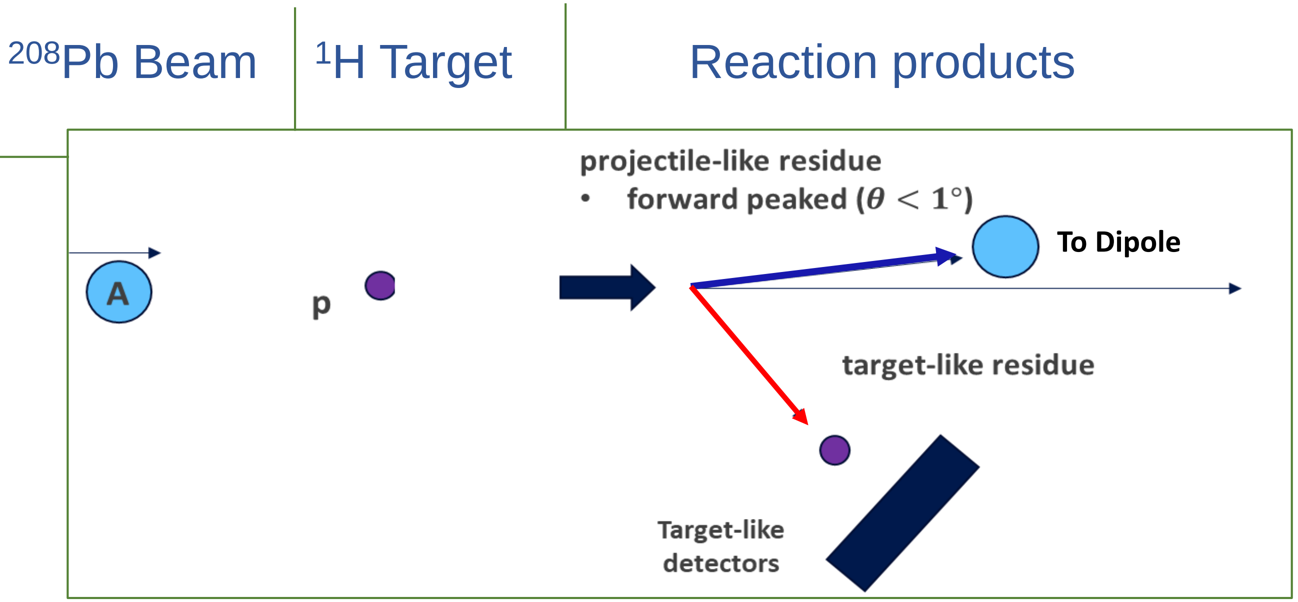




$$P_\gamma(E^*) = \frac{N_\gamma(E^*)}{N_p(E^*).\varepsilon(E^*)}$$

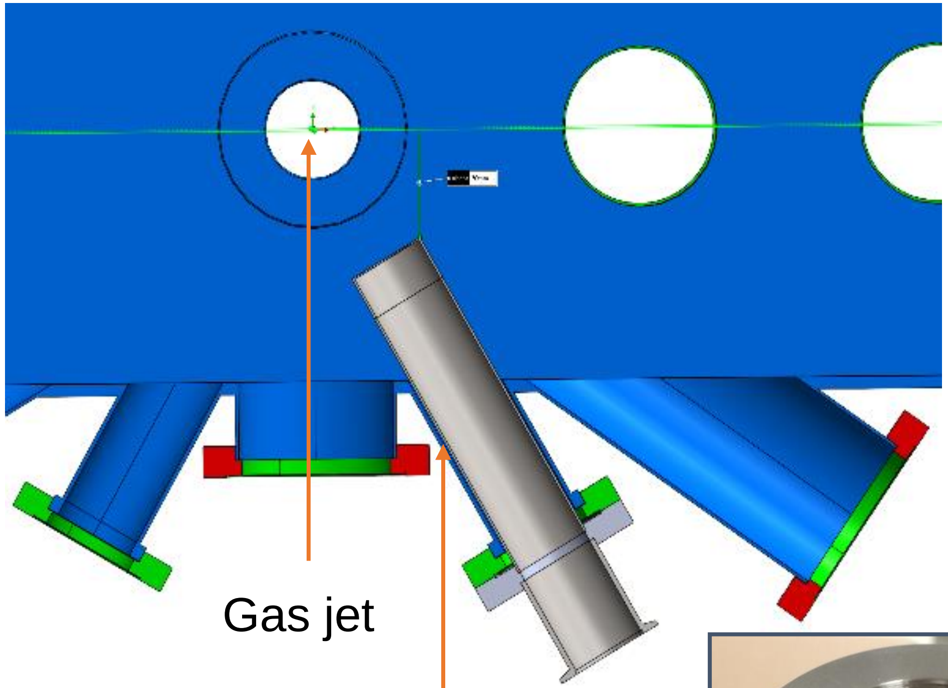
$$P_\gamma + P_n = 1$$

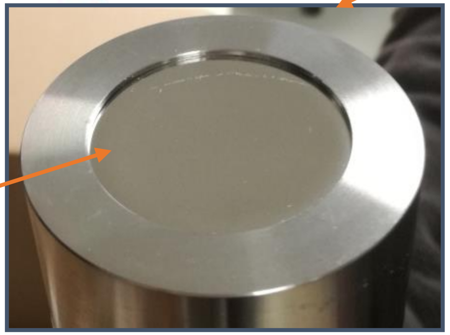
NECTAR PoP experiment

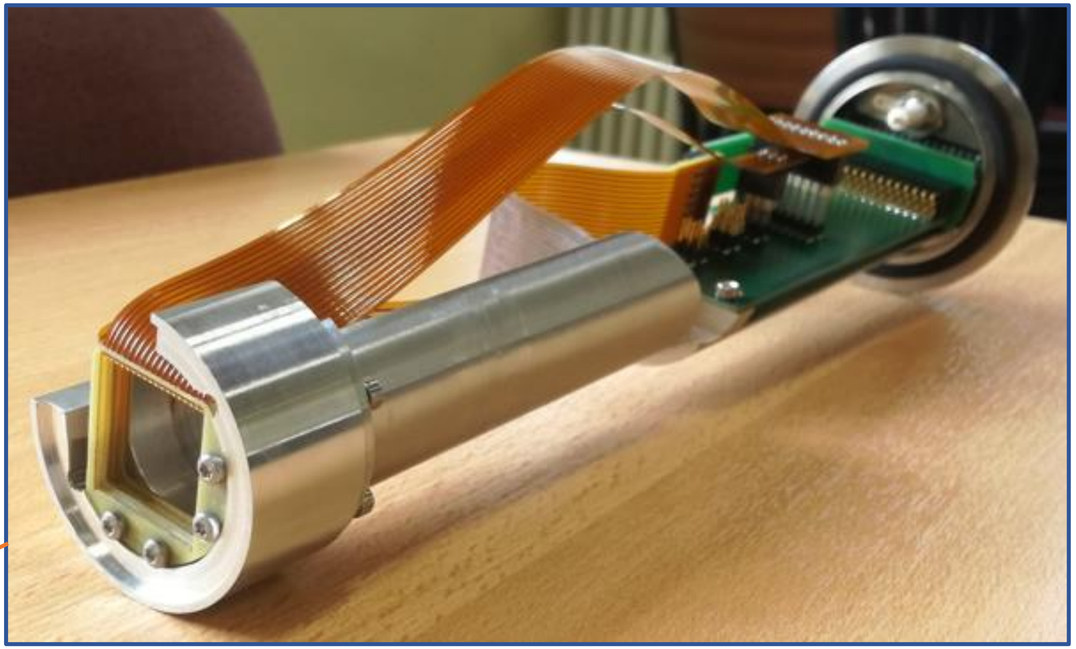
Target residue detectors:

- 20×20 mm^2 DSSSDs (16×16 strips) + 6*1.5 mm Si detectors.

Top-view diagram of reaction chamber

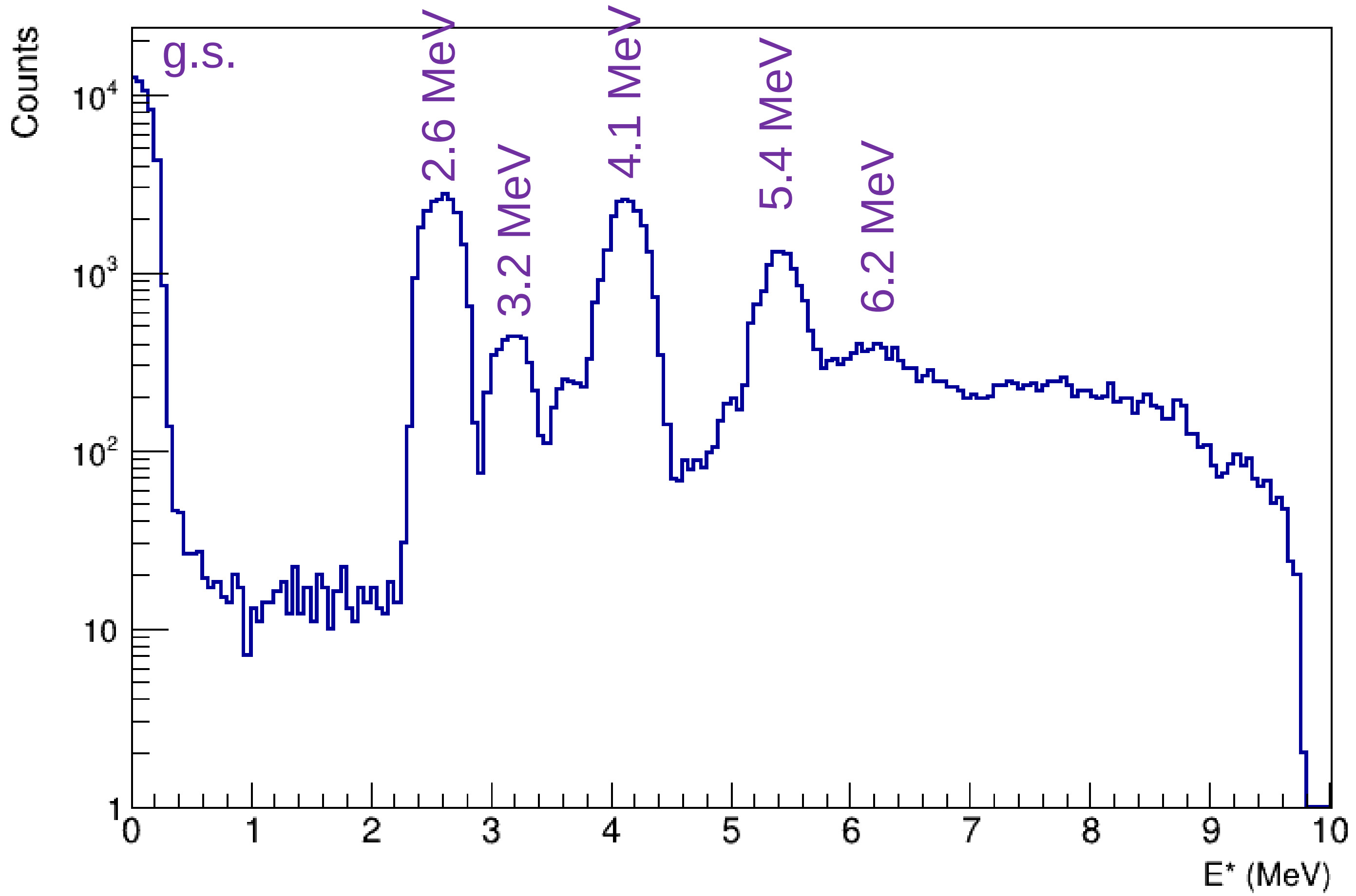






Frame for telescope detector in pocket

NECTAR PoP Simulations



^{208}Pb excitation energy

Target residue detectors:

- σ(E*) = 200 keV at E* = 2.6 MeV,

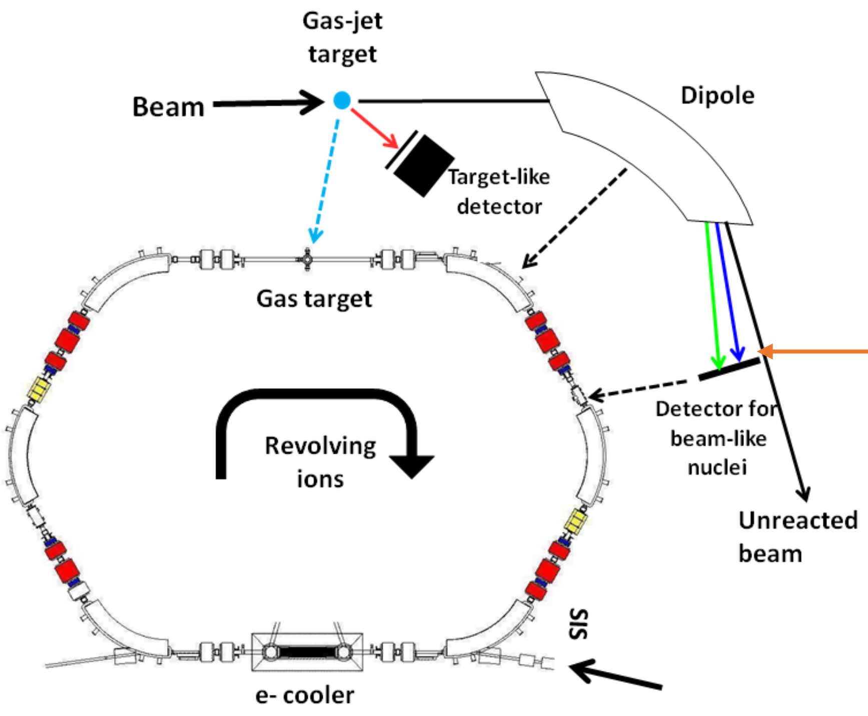
for target radius = 0.5 mm,

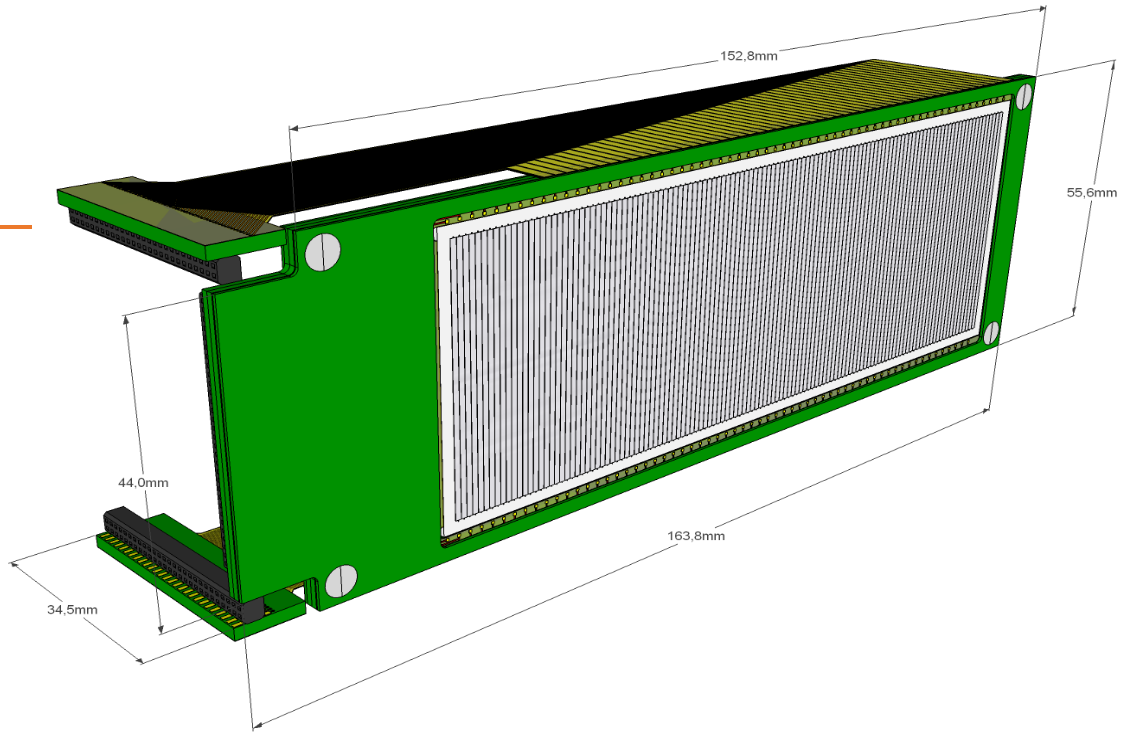
Beam emittance = 0.05 mm.rad

NECTAR PoP experiment

Heavy residue detectors:

- 122×40 mm^2 DSSSDs





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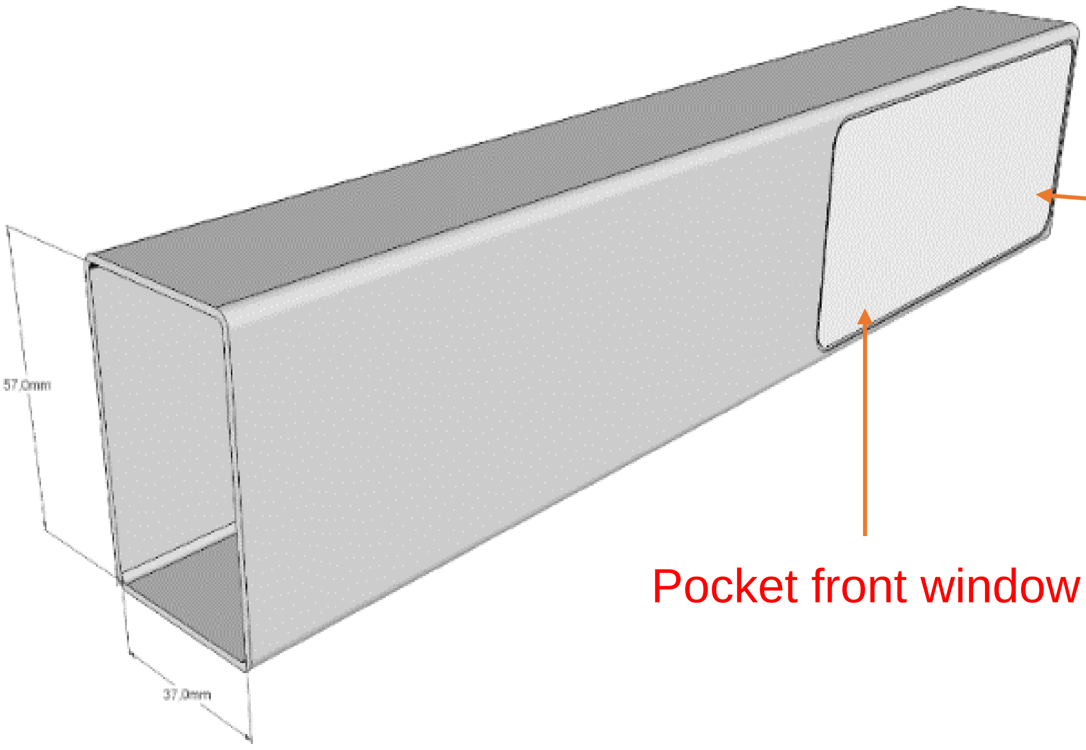
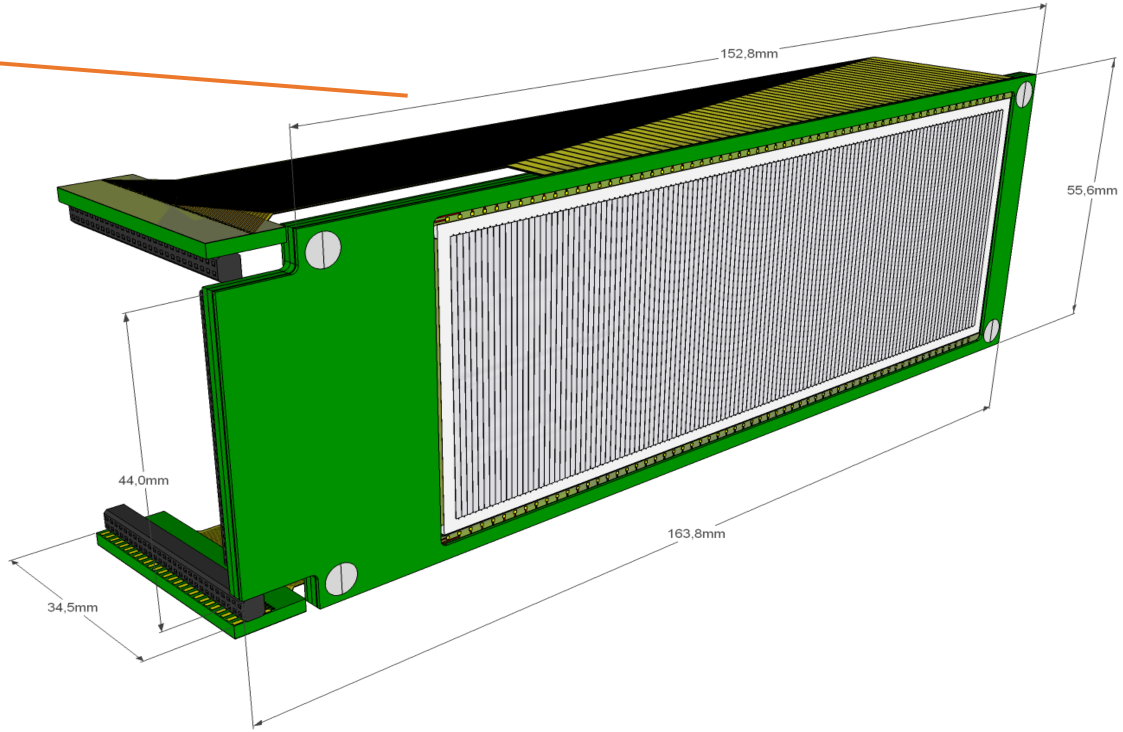
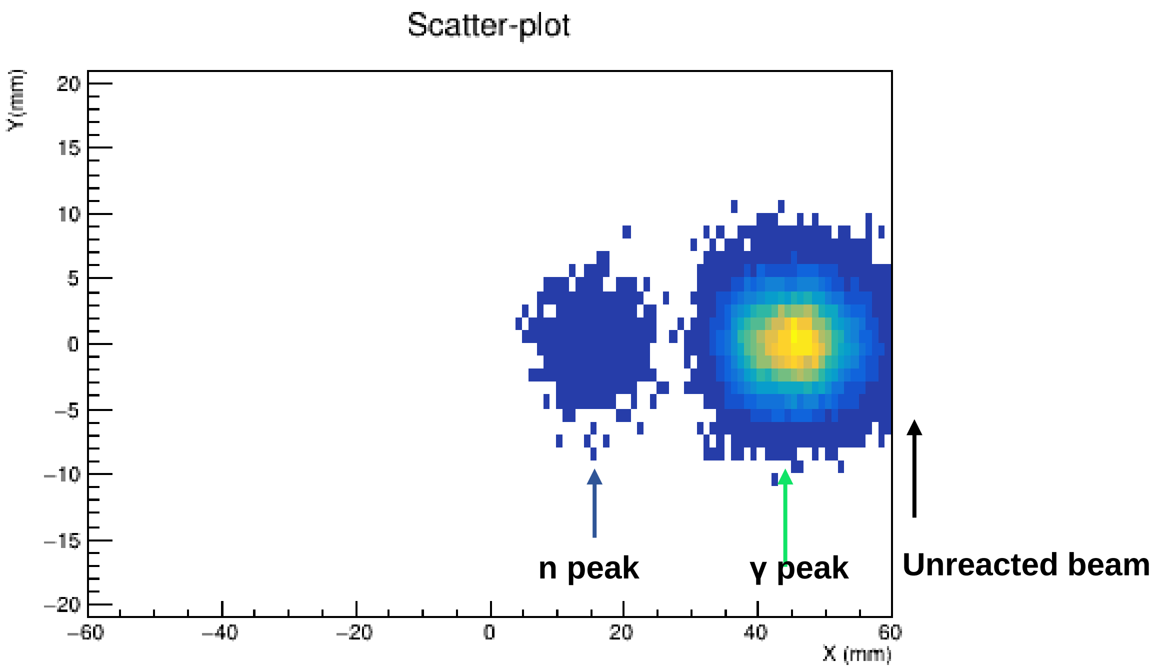




NECTAR PoP Simulations

Heavy residue detectors:

- Simulations indicate n + ^{207}Pb and γ + ^{208}Pb peaks to be well separated.
- Over 99% transmission efficiency!

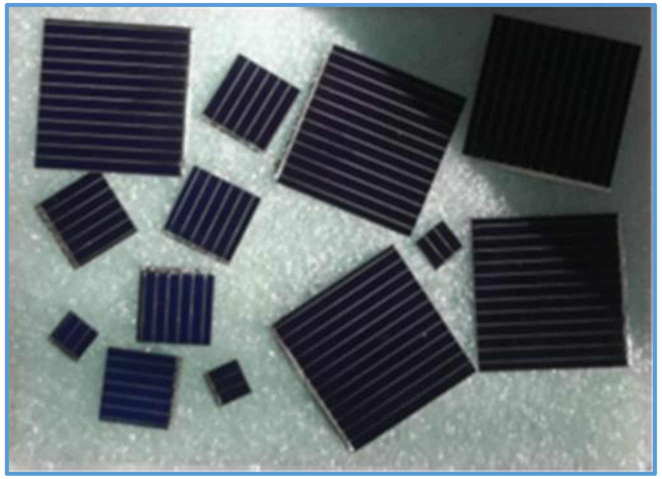


NECTAR PoP experiment

Future possibility:

May use **solar cells** here.

- See talk from M. Sguazzin



Ge solar cells

Heavy residue detectors:

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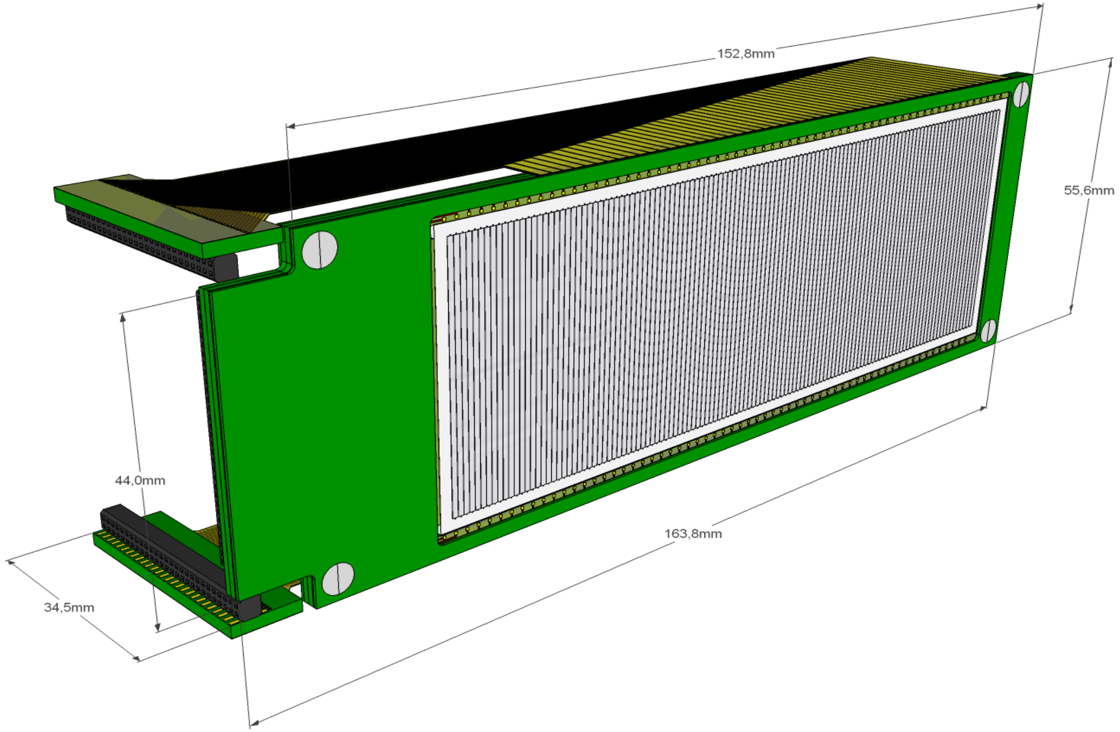
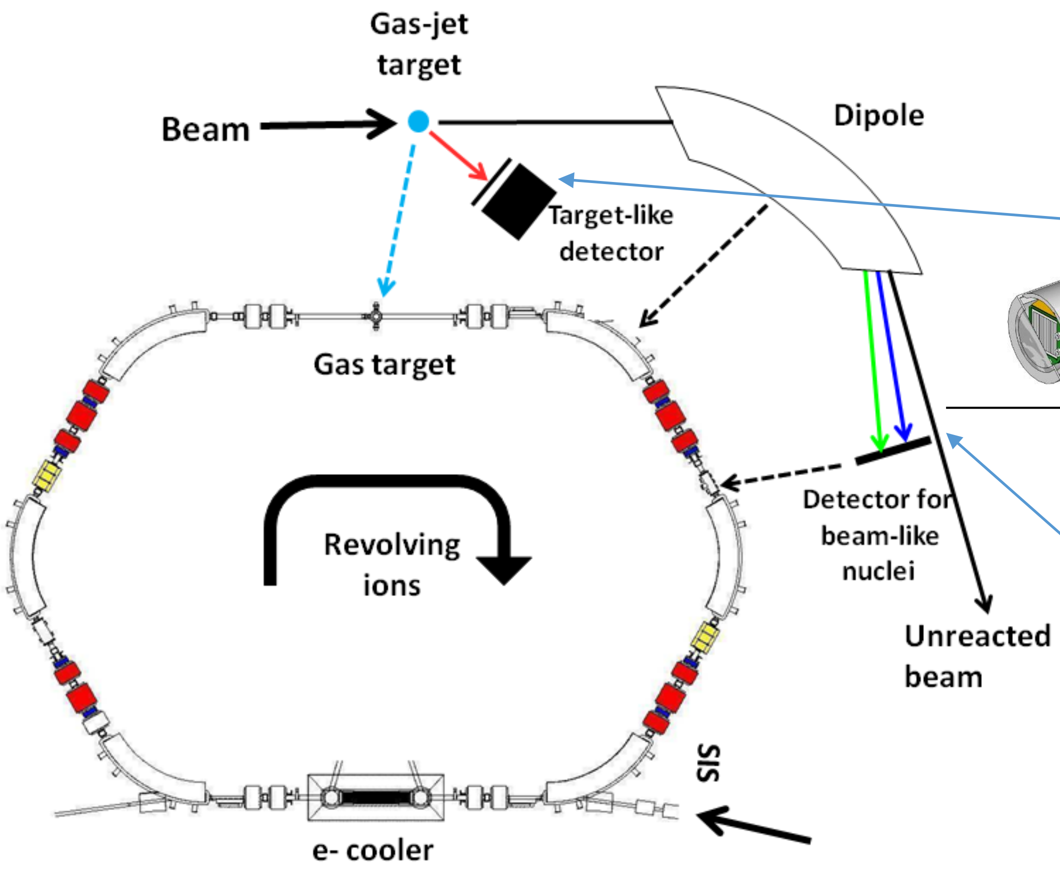
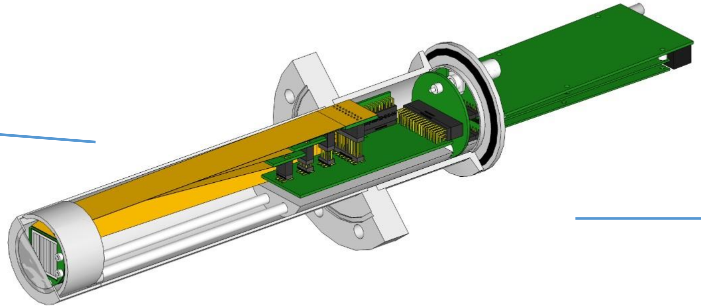
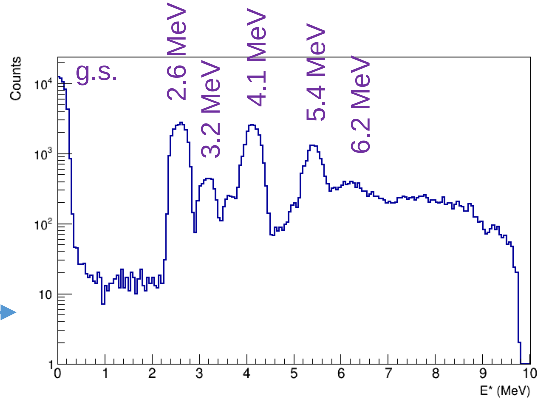


PoP experiment – coming to ESR@GSI June 2022

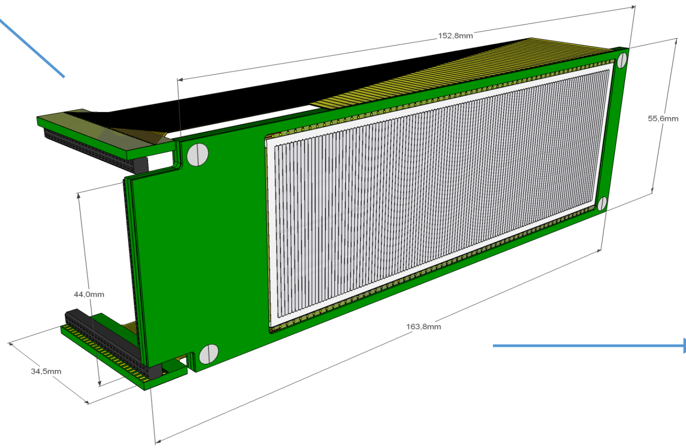


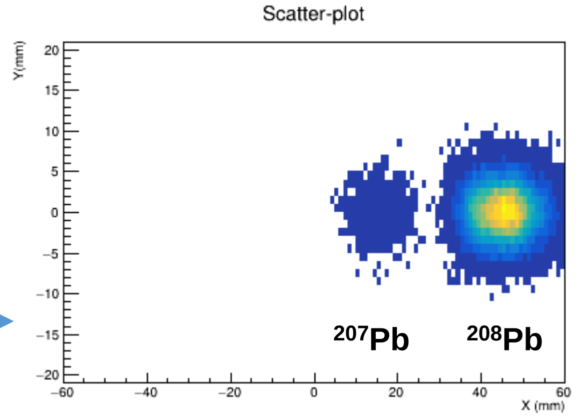
Target residue detection





Heavy residue detection



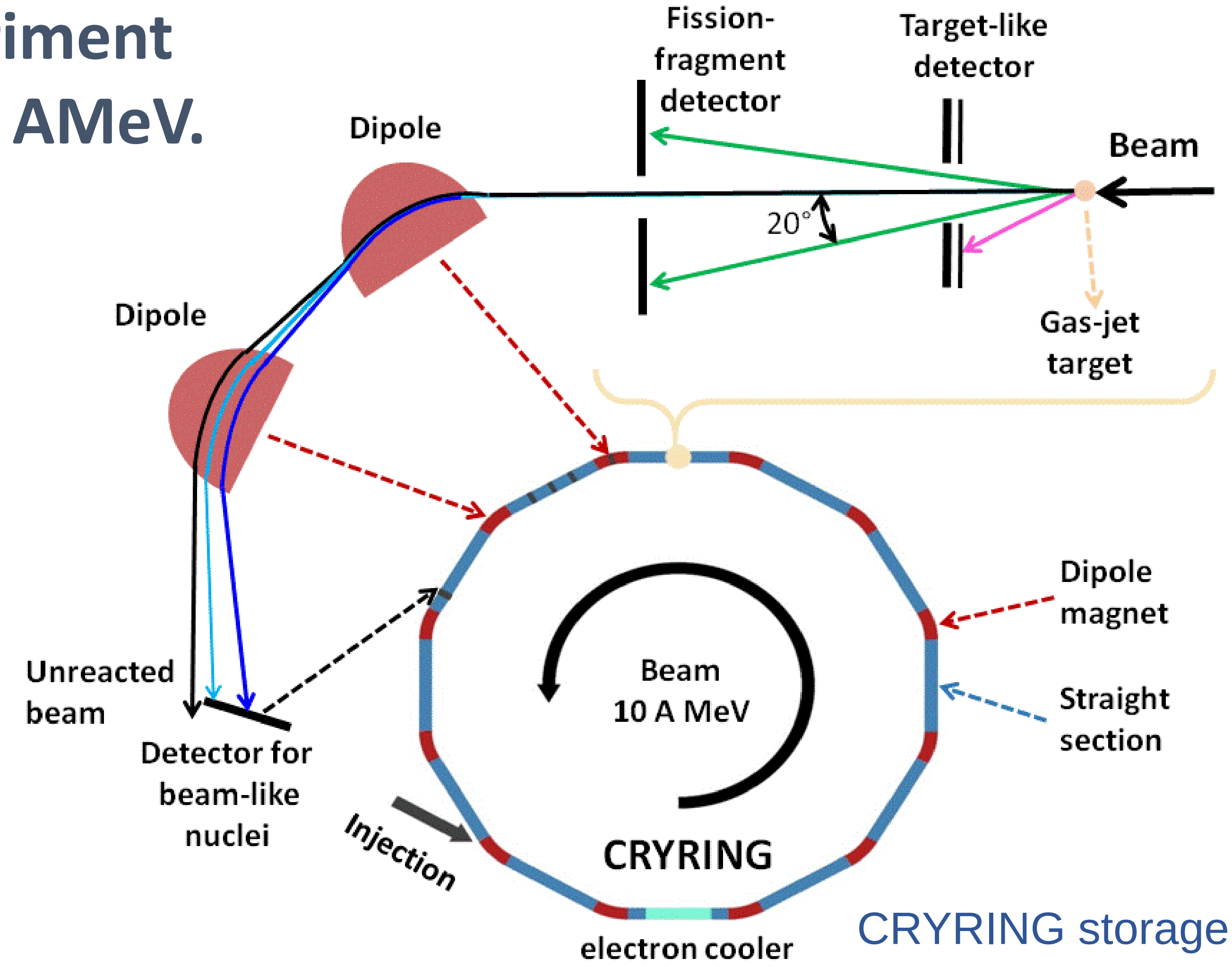


Outlook:

- NECTAR PoP experiment – coming to ESR@GSI June 2022
- NECTAR experiments featuring fission detection coming ca. 2024 at GSI/FAIR

- 1st full experiment

$^{238}U + d$ at E = 10 AMeV.



CRYRING storage ring at GSI/FAIR

Outlook:

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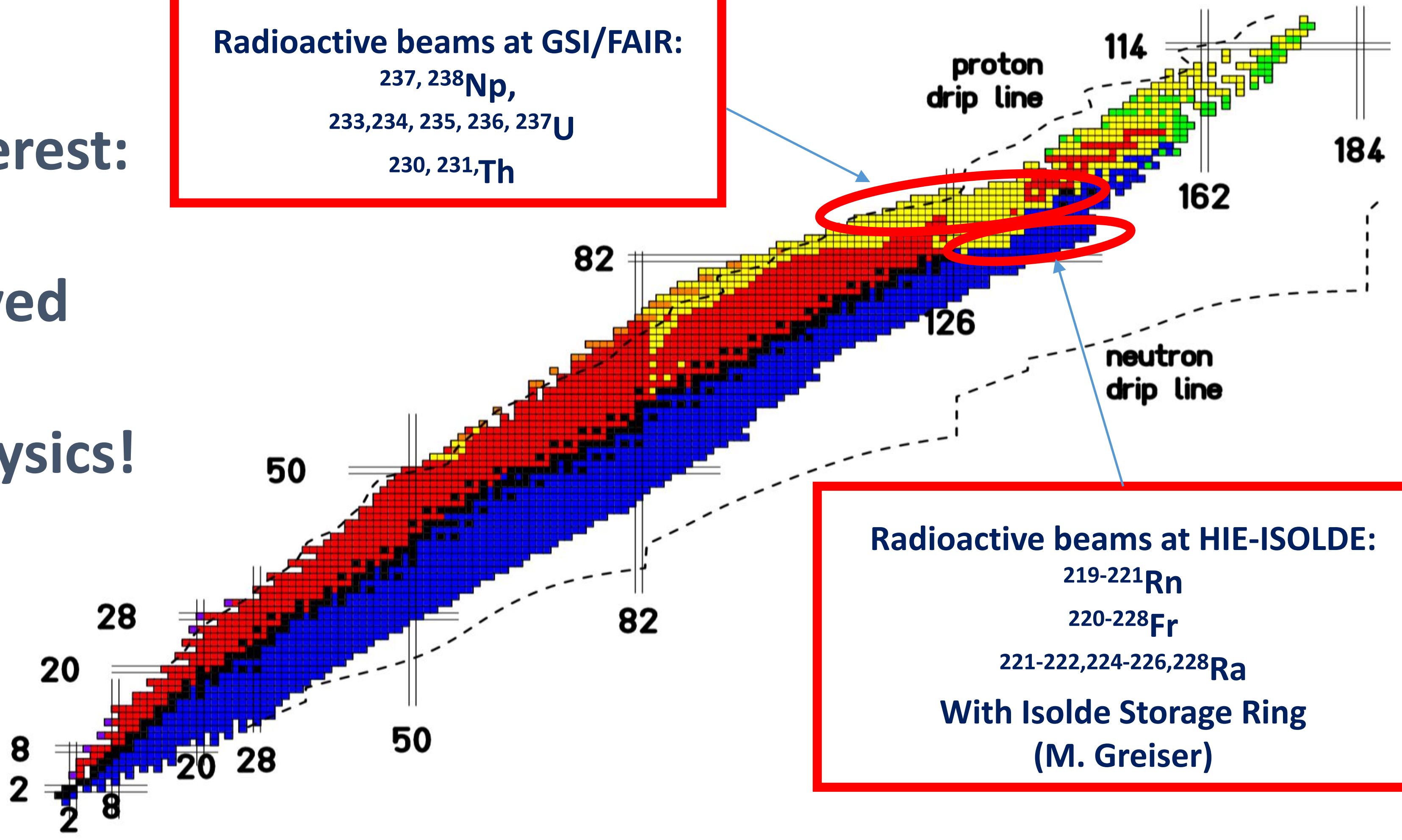
^{238}U + d at E = 10 AMeV.

- Isotopic chains of interest:
- U, Th, Np etc.
- Multitude of short-lived nuclei
- Years and years of physics!

Radioactive beams at GSI/FAIR:
$^{237,\,238}$Np,
$^{233,234,\,235,\,236,\,237}$U
$^{230,\,231,}$Th



Radioactive beams at HIE-ISOLDE:
$^{219\text{-}221}$Rn
$^{220\text{-}228}$Fr
$^{221\text{-}222,224\text{-}226,228}$Ra
With Isolde Storage Ring
(M. Greiser)

Acknowledgement of support

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The NECTAR Collaboration

CENBG (Bordeaux)

B. Jurado (PI)
J. Pibernat (technical lead)
J.A. Swartz
M. Sguazzin
B. Thomas
M. Roche
P. Alfaurt
J. Giovinazzo
J. Michaud
B. Blank
M. Gerbaux
S. Grevy
T. Kurtukian

MPIK Heidelberg

M. Grieser
K. Blaum

GSI/FAIR Darmstadt

J. Glorius
Y. Litvinov

CEA/DAM

M. Dupuis
L. Gaudefroy
V. Méot
O. Roig

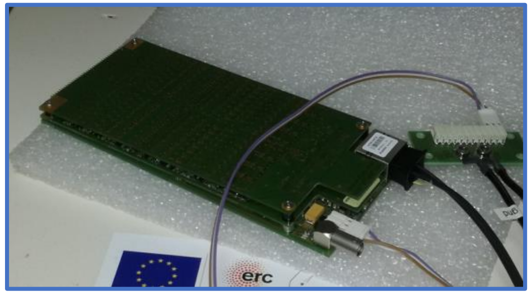
University of Frankfurt

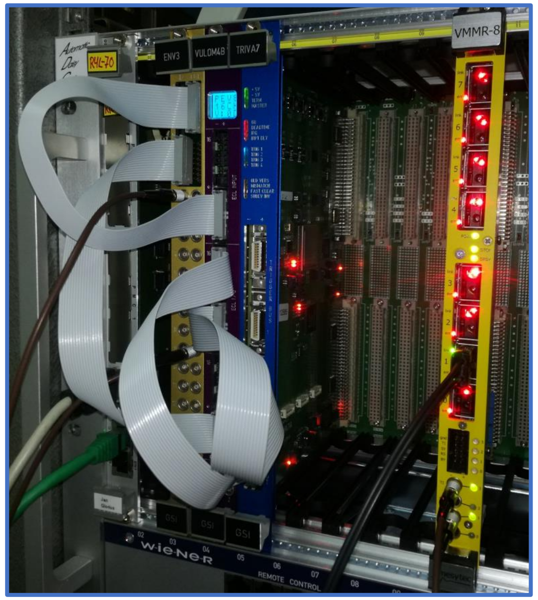
R. Reifarth

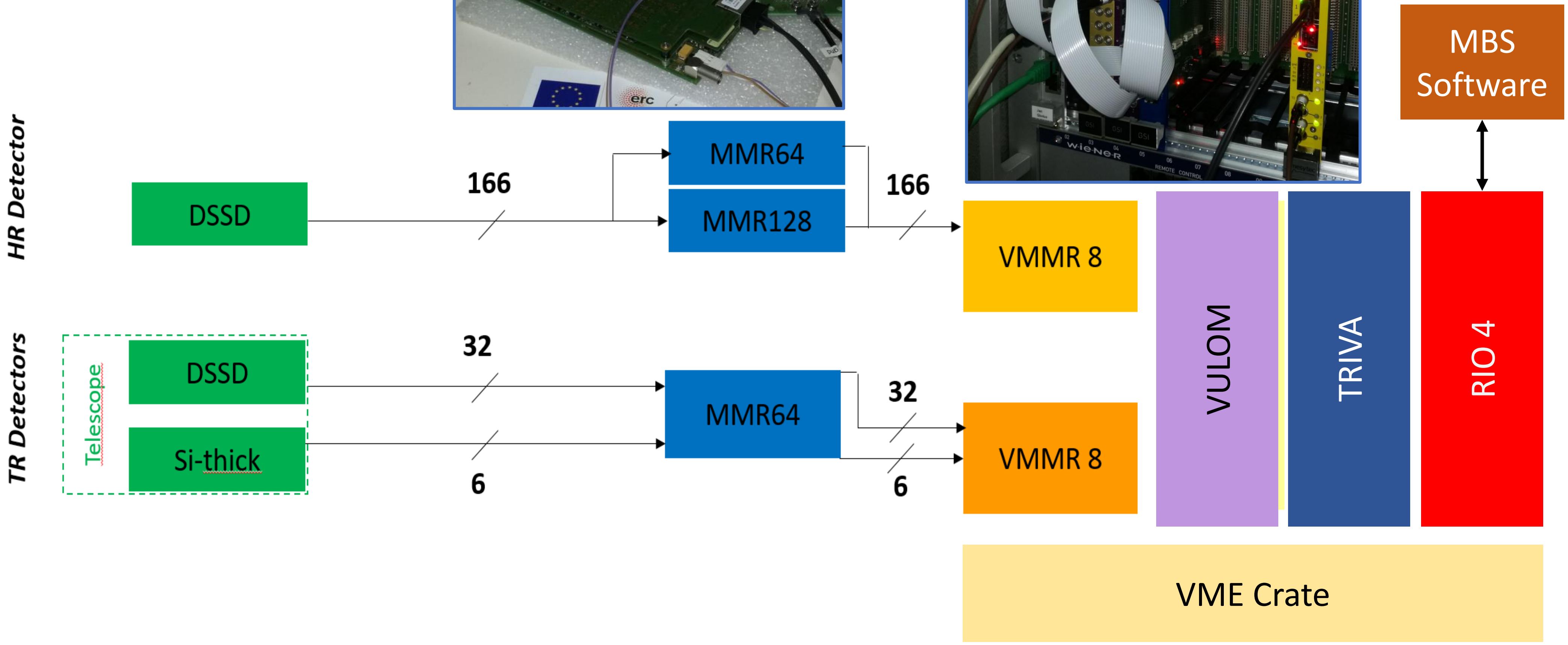
Thank you for listening! To be continued..

Backup slides

MBS DAQ system with electronic modules from GSI and Mesytec







NECTAR PoP experiment electronics & DAQ

MMR64

Link 1

optical cable

Link 4

VMMR 8

Ch. 9

To

TI

Ch. 1 in

ENV3

Ch. 9 out

Ch. 9-16 in

Ch. 1-8 out

ECL out (1-8)

ECL in (1-8)

VULOM

ECL I/O (9-16)

ECL I/O (1-8)

ECL out

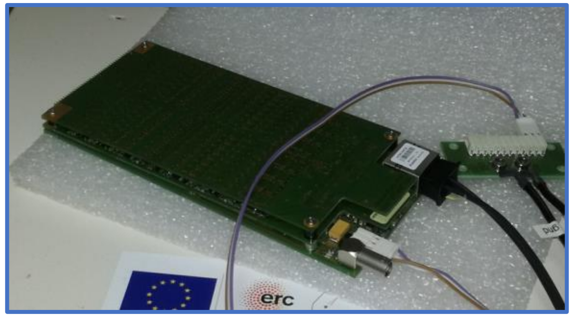
ECL in

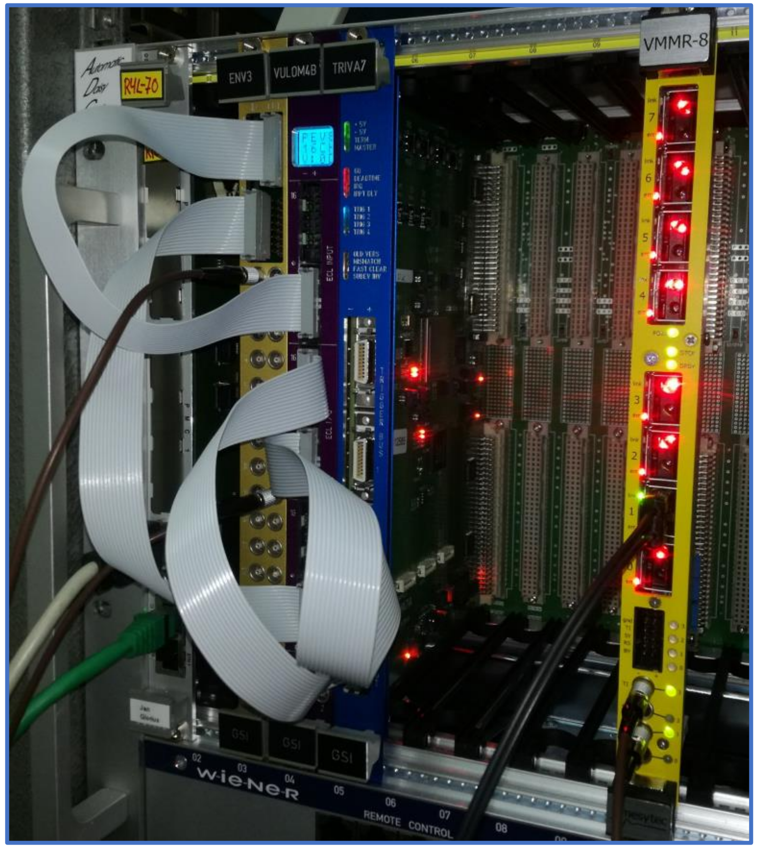
TRIVA

MBS Software

RIO4

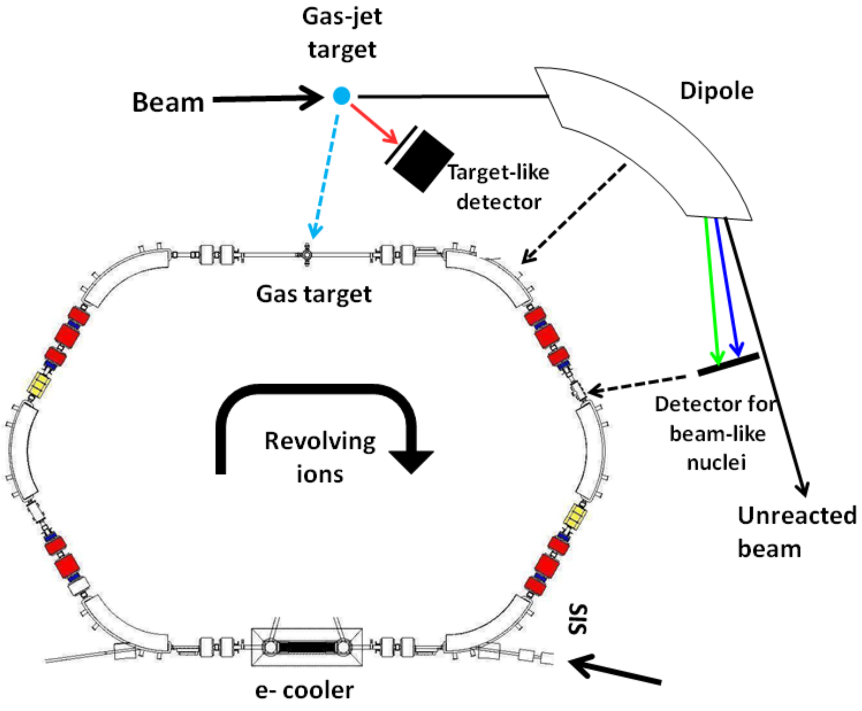
Ethernet





NECTAR PoP experiment

- Beam: ^{208}Pb at 30 MeV/u
- Target: ^{1}H



PoP preparation status summary:

- Detector pockets manufactured
- Final detector specifications and manufacturing
- Testing electronics and data acquisition system at CENBG
- Refining simulations

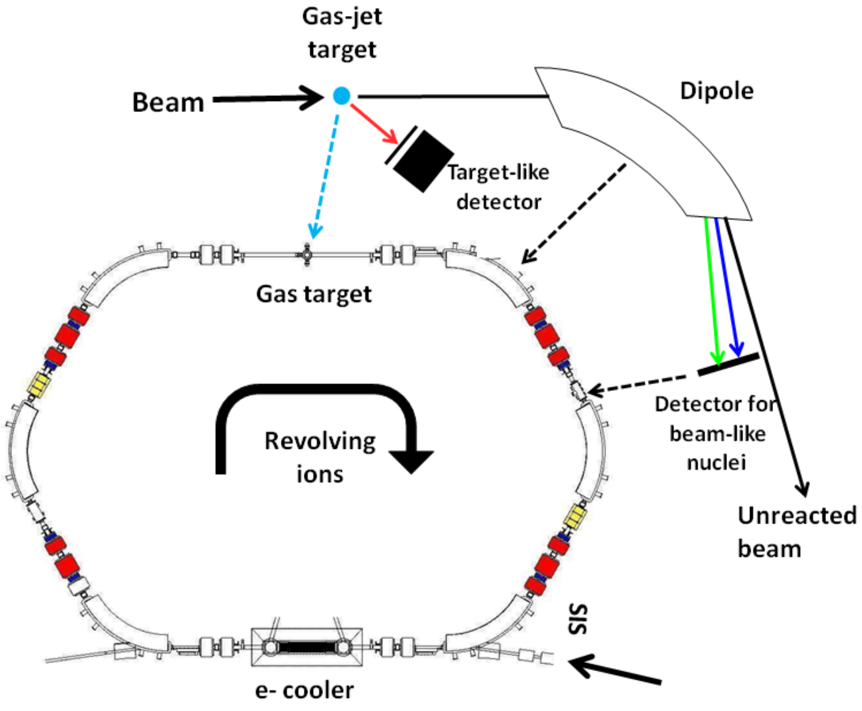
NECTAR PoP experiment – coming to ESR@GSI June 2022

- Master electronics and DAQ system, and test with detectors.
- Move detectors and electronics to GSI to commence testing there.
- Final setup and execution of experiment in June 2022

NECTAR PoP experiment

- Measure P_γ, P_n

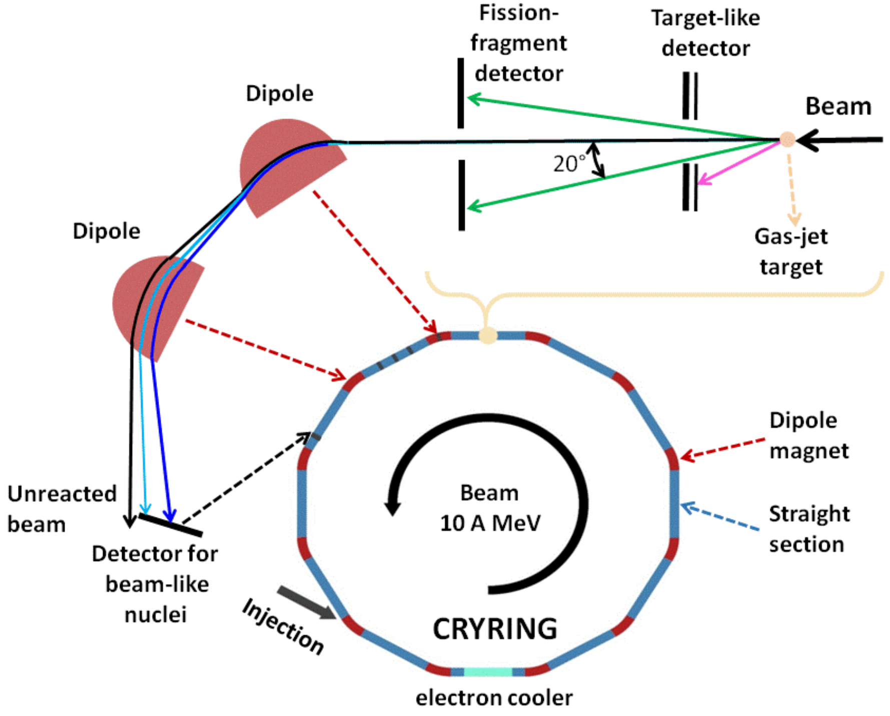
Beamtime **20 – 25 June 2022**



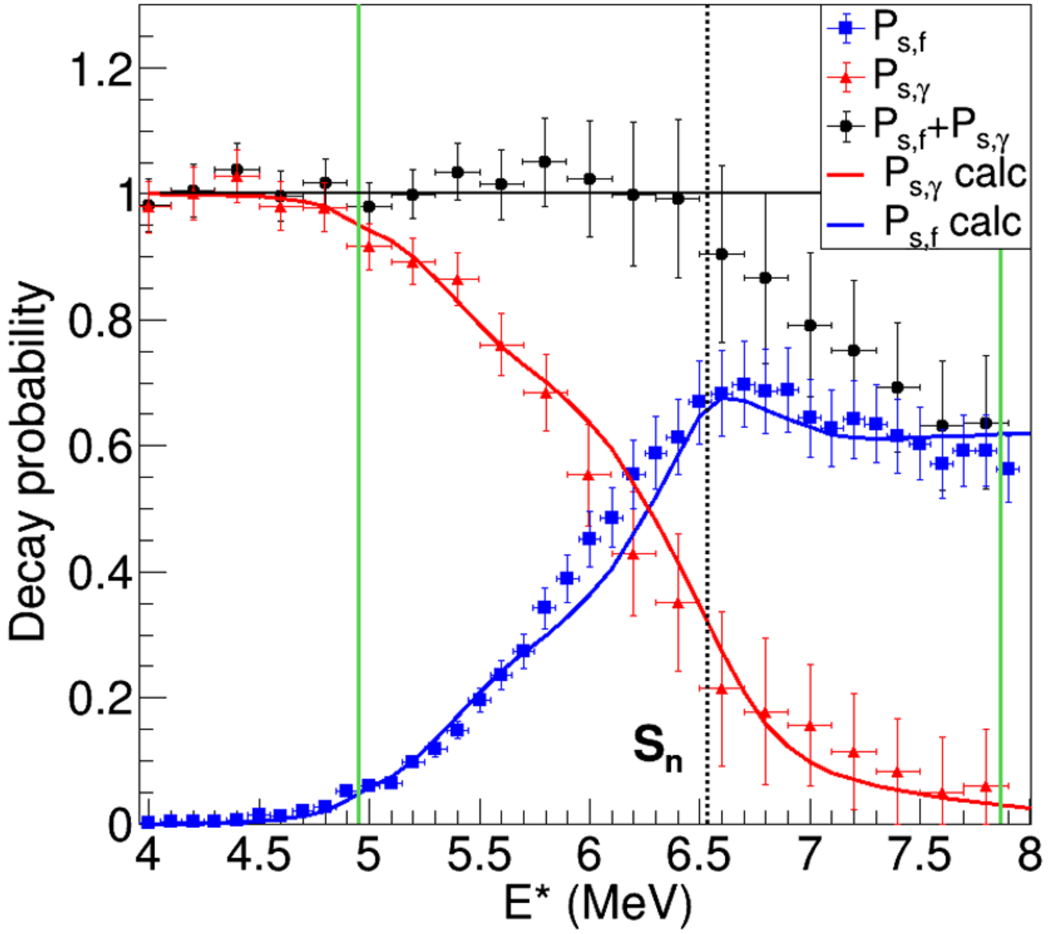
NECTAR final setup:

- Measure P_γ, P_n, P_f (with solar cells)

Not yet scheduled, TDR being submitted to GSI/FAIR ECE + GPAC



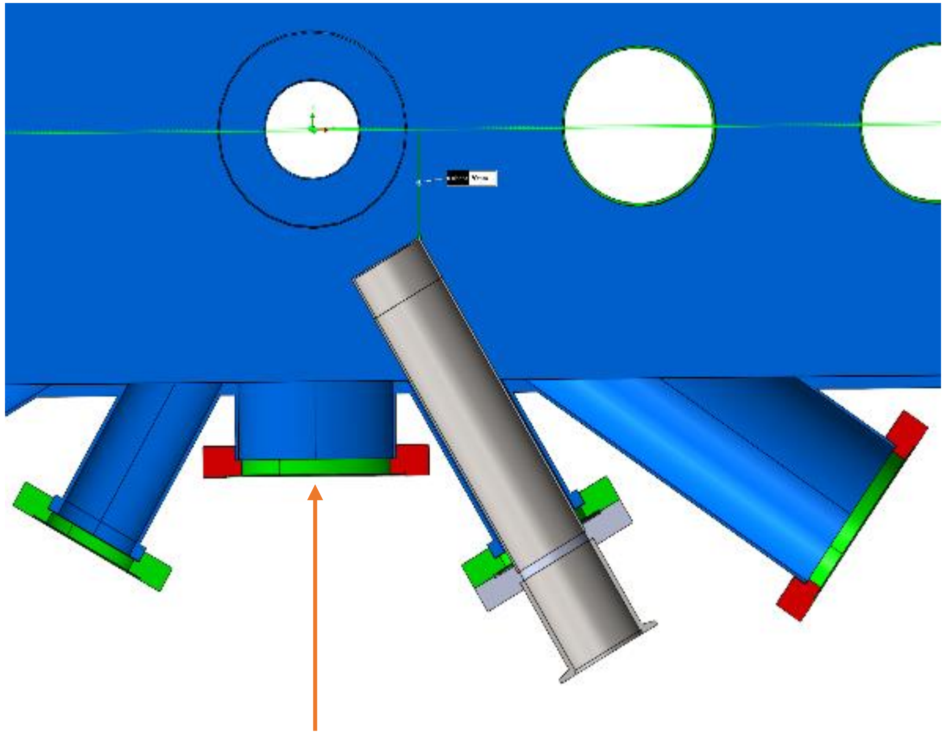
Decay probabilities for fission (blue squares) and γ emission (red triangles) measured for the $^{240}Pu(^{4}He,^{4}He')^{240}Pu$ reaction as a function of the excitation energy E of ^{240}Pu. The sum of the two probabilities is given by the black circles.



R. Perez Sánchez, B. Jurado et al., PRL 125, 122502 (2020)

NECTAR PoP experiment

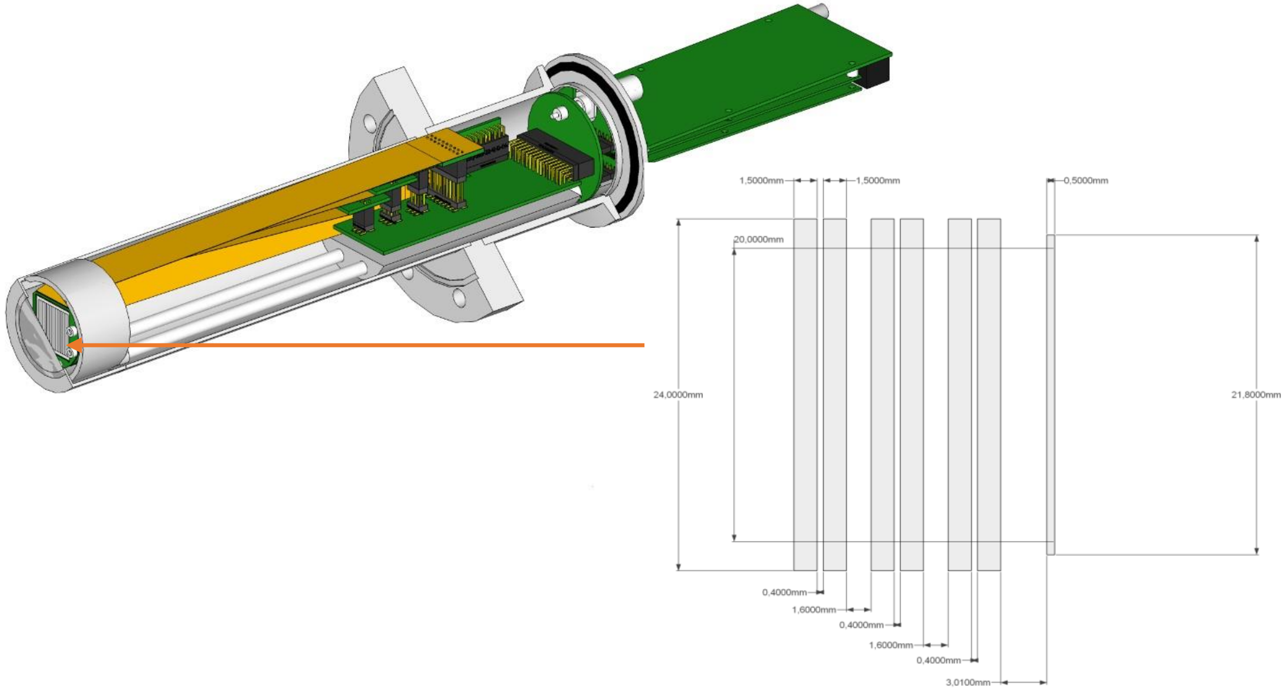
Top-view diagram of reaction chamber



- X-ray measurements with HPGe detectors of GSI.

Target residue detectors:

- 20×20 mm^2 DSSSDs (16×16 strips) + 6*1.5 mm Si detectors.



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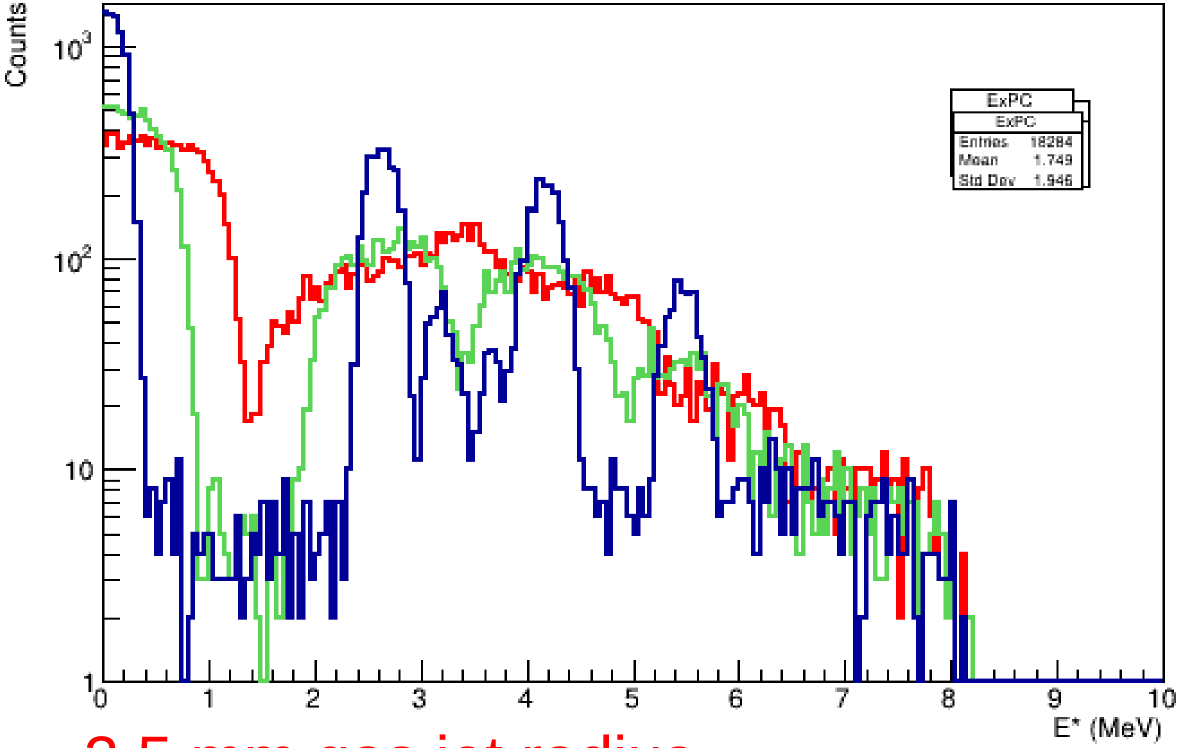


2.5 mm gas jet radius

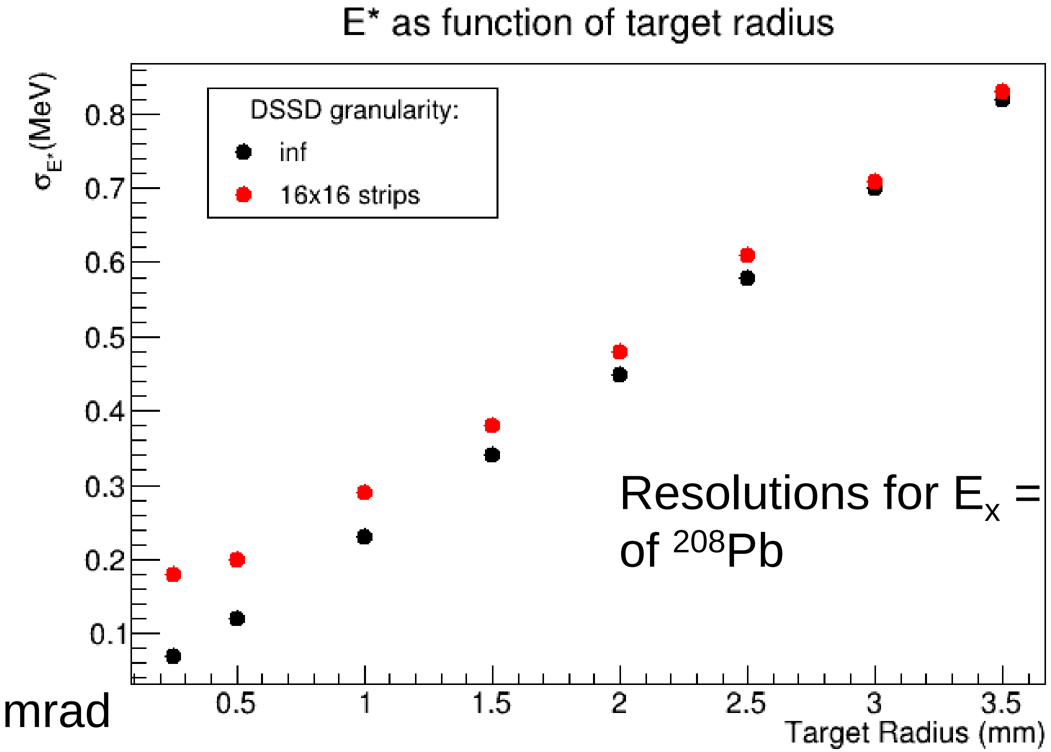
1.5 mm gas jet radius

0.5 mm gas jet radius

Emittance = 0.05 mm.mrad

Target residue detectors:

- E resolution improves with smaller gas jet.
- Smaller pixel size may help at low radius.



$$\sigma_{n,\chi}(E_n) \cong \sigma_{\mathrm{CN}}(E_n) P_{s,\chi}(E^*)$$

n-induced CS — CS for CN formation — Probability

$$E_n = \frac{A+1}{A}(E^* - S_n)$$

Why don't we simply use a neutron beam on a radioactive target?

- Target handling safety.
- Background from target radioactivity.
- Scattering of beam neutrons.

Why don't we work in direct kinematics?

- Nuclei of interest are radioactive/unavailable.
- Competing reactions in target contaminants and backing.
- Heavy decay products of compound nucleus are stopped in the target.

Hence, we will use surrogate reactions in inverse kinematics,
with heavy nuclei in the beam and light nuclei in a **gas jet target**.

NECTAR – **N**uclear r**E**a**CT**ions **A**t storage **R**ings

Light targets (e.g. ^{1}H, ^{2}H) to be put in gas jet targets
- Would this provide enough areal density of target?

- Not in a single-pass experiment.
- But this is a storage ring experiment!

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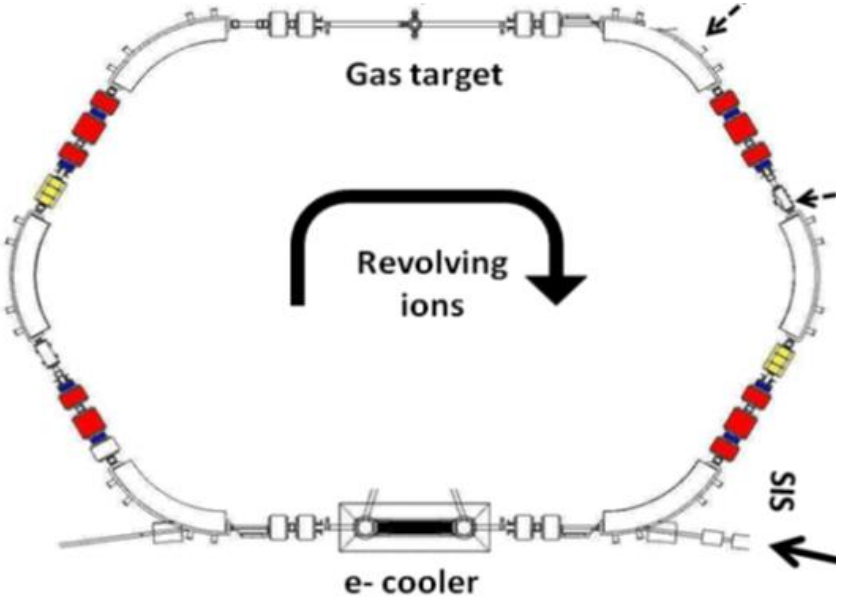
Experiments at storage rings of GSI/FAIR

Light targets (e.g. ^{1}H, ^{2}H) to be put in gas jet targets

- Would this provide enough areal density of target?

- Not in a <u>single-pass experiment</u>.
- But this is a **storage ring experiment**! => **UHV**



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Light targets (e.g. ^{1}H, ^{2}H) to be put in gas jet targets
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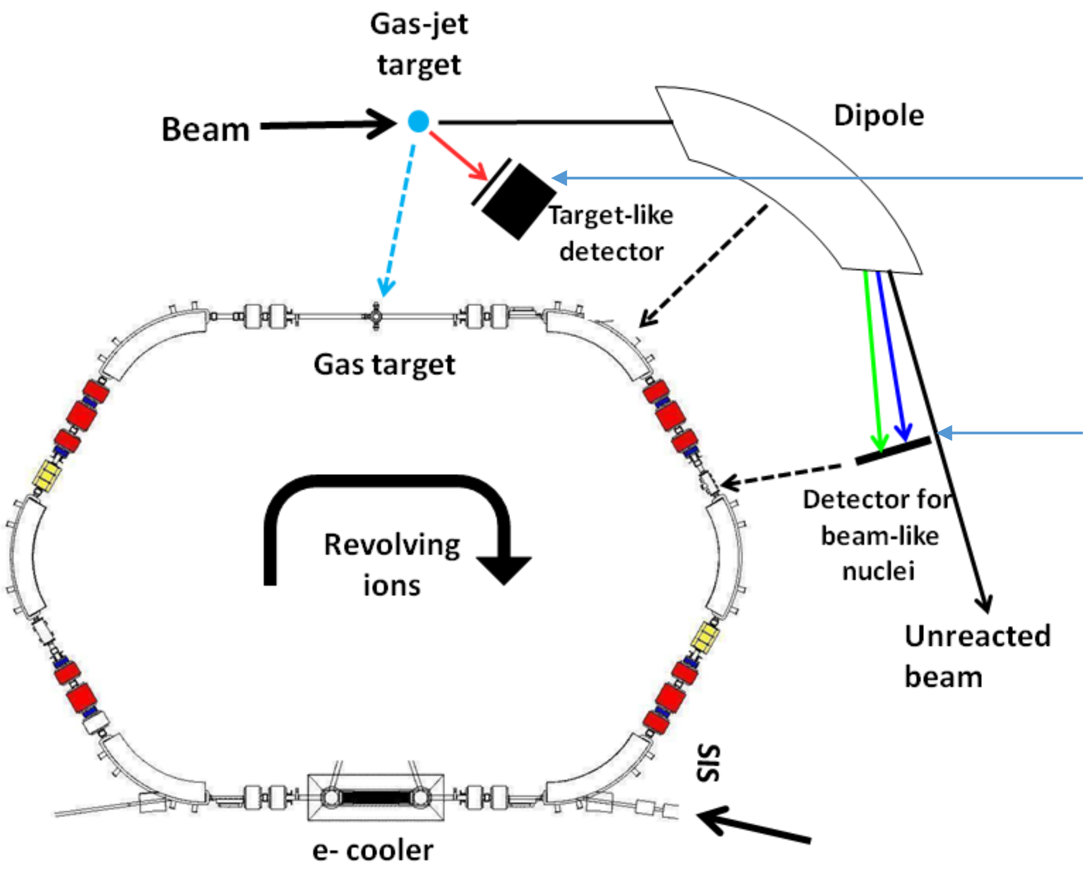
What about e^{-} capture and emission?

- Storage rings => Ultra High Vacuum (UHV) where P ~ 10^{-11} – 10^{-12} mbar,
- and we have fully stripped ions.

NECTAR Proof-of-Principle (PoP) experiment – June 2022

- Beam of ^{208}Pb at E_{beam} = 30 AMeV on ^{1}H gas jet target
- Measure P_γ and P_n from ^{208}Pb



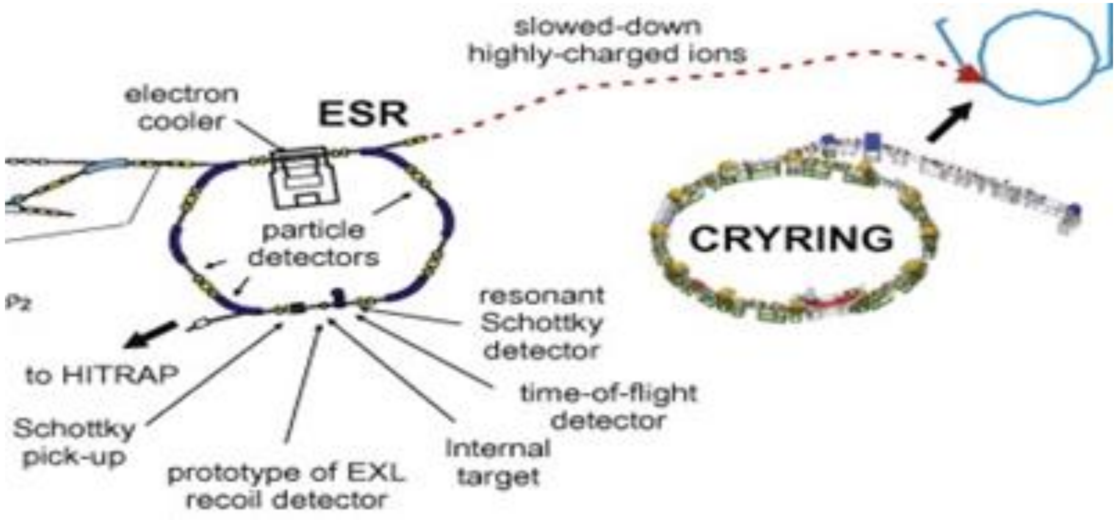
Target residues (p) measured here.

Heavy residues (^{207,208}Pb) measured here.

No fission detection in PoP experiment, but see the talk from M. Sguazzin.

NECTAR

- First PoP experiment at ESR 20 – 25 June 2022.
- CRYRING experiments planned for the future.



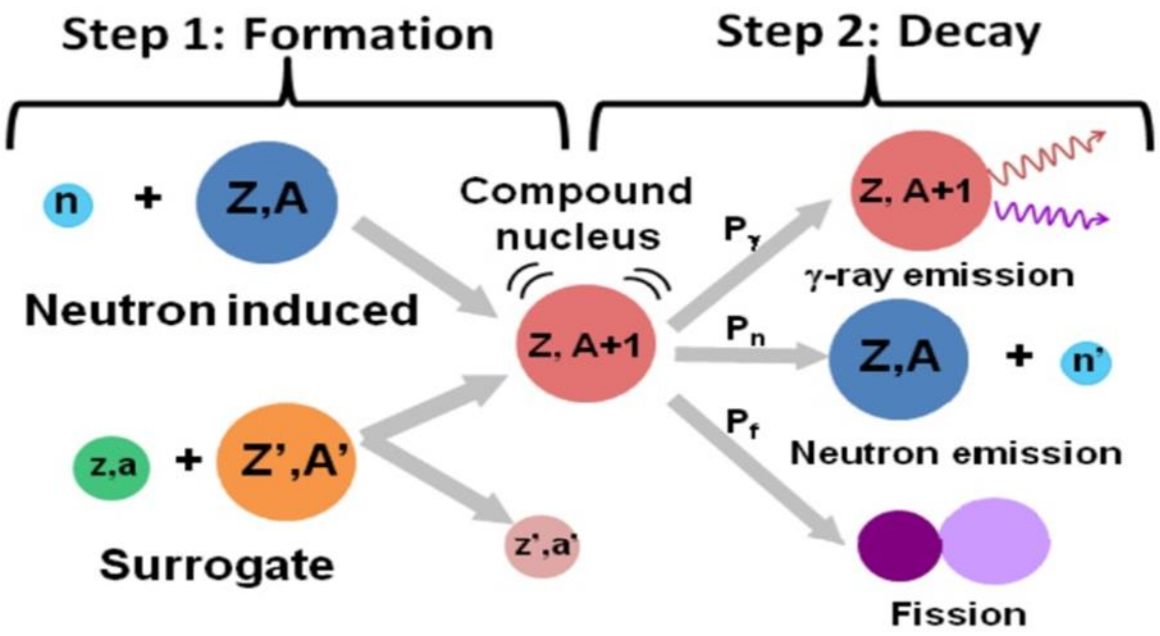
In HF formalism, with i=s or i=n

$$P_{i,\chi}(E^*) = \sum_{J^\pi} F_i(E^*, J^\pi) G_\chi(E^*, J^\pi)$$

Probability

Formation

Decay probability of CN



In HF model, where i=s or i=n

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Decay probability

Formation

Decay probability of CN

At high E*, *Gχ* becomes independent of J^π

=> $P_{s,\chi} \approx P_{n,\chi}$ and

$$\sigma_{n,\chi}(E_n) \cong \sigma_{\text{CN}}(E_n) P_{s,\chi}(E^*)$$

n-induced CS

CS for CN formation

Decay proba

$$E_n = \frac{A+1}{A}(E^* - S_n)$$

In HF formalism, with i=s or i=n

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Probability — Formation — Decay

At high E*, G_χ becomes independent of J^π
=> $P_{s,\chi} \approx P_{n,\chi}$ and

$$\sigma_{n,\chi}(E_n) \cong \sigma_{CN}(E_n) P_{s,\chi}(E^*)$$

n-induced CS — CS for CN formation — Probability

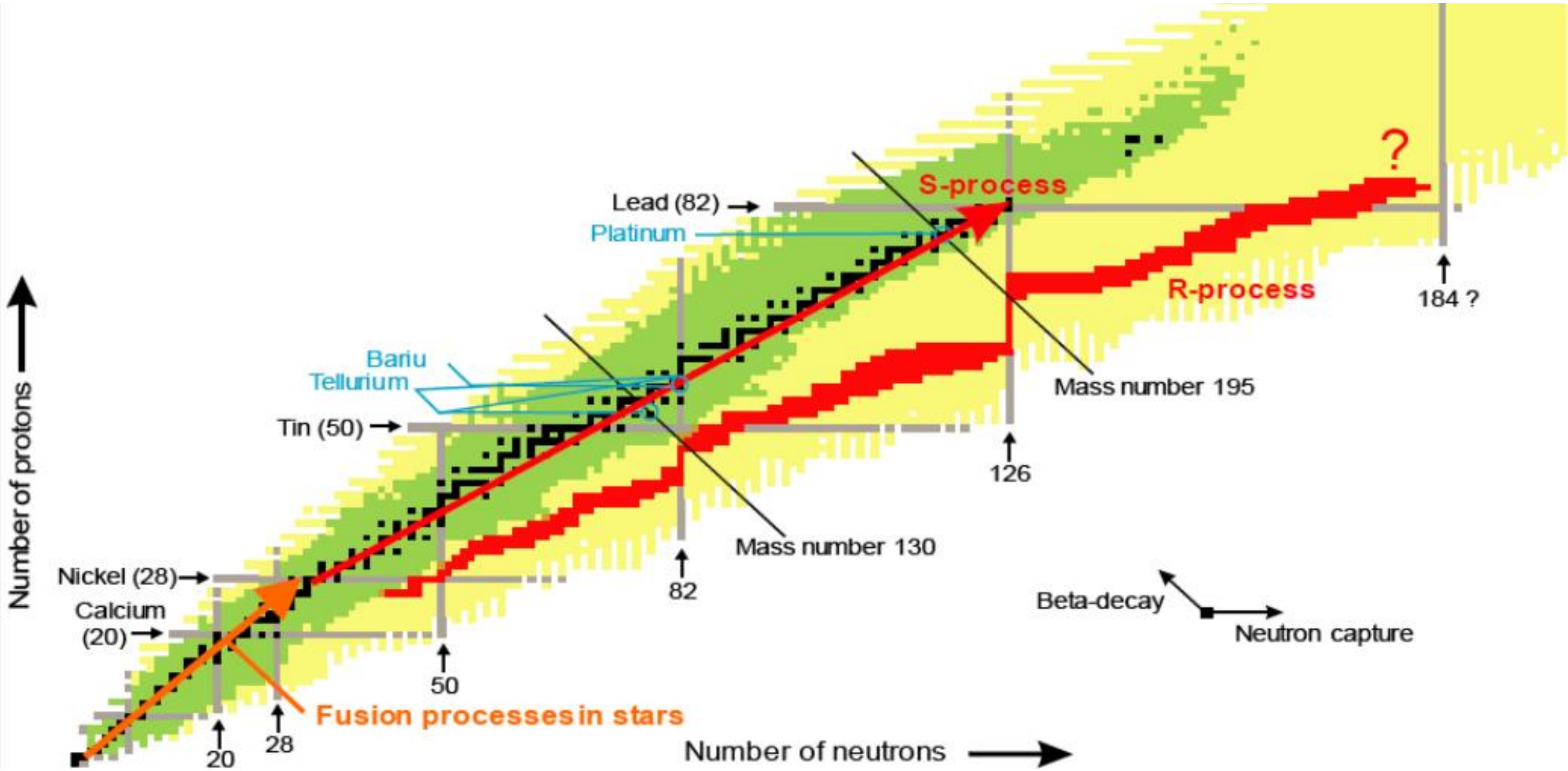
$$E_n = \frac{A+1}{A}(E^* - S_n)$$

- **This approach is not valid in all cases.**
- **One can always constrain level densities, fission barrier though.**

Probabilities in Step 2 identical for n vs surrogate at Step 1, according to Bohr Independence Formalism.

But, spin-parity at Step 1 still has an effect.

- This cancels out at high energies with high density of states.
- At low energies it does not, but we can measure observables (level density, fission barrier) which constrain this CS.



Number of protons
Lead (82)
Platinum
S-process
?
R-process
184 ?
Bariu
Tellurium
Mass number 195
Tin (50)
126
Mass number 130
Nickel (28)
82
Beta-decay
Calcium
(20)
Neutron capture
50
Fusion processes in stars
20
28
Number of neutrons