



Measurement of the $^{206}\text{Pb}(p, p'\gamma)$ Reaction to Constrain the $^{205}\text{Pb}(n, \gamma)^{206}\text{Pb}$ Cross Section Using the Surrogate Method

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On behalf of the collaboration





Presentation Outline

- What?
 - What is a surrogate method and how we can get $\sigma(n,y)$
- Why?
 - ^{205}Pb as a cosmochronometer
 - Pb data for new fission reactors
- How?
 - Experimental setup and technique





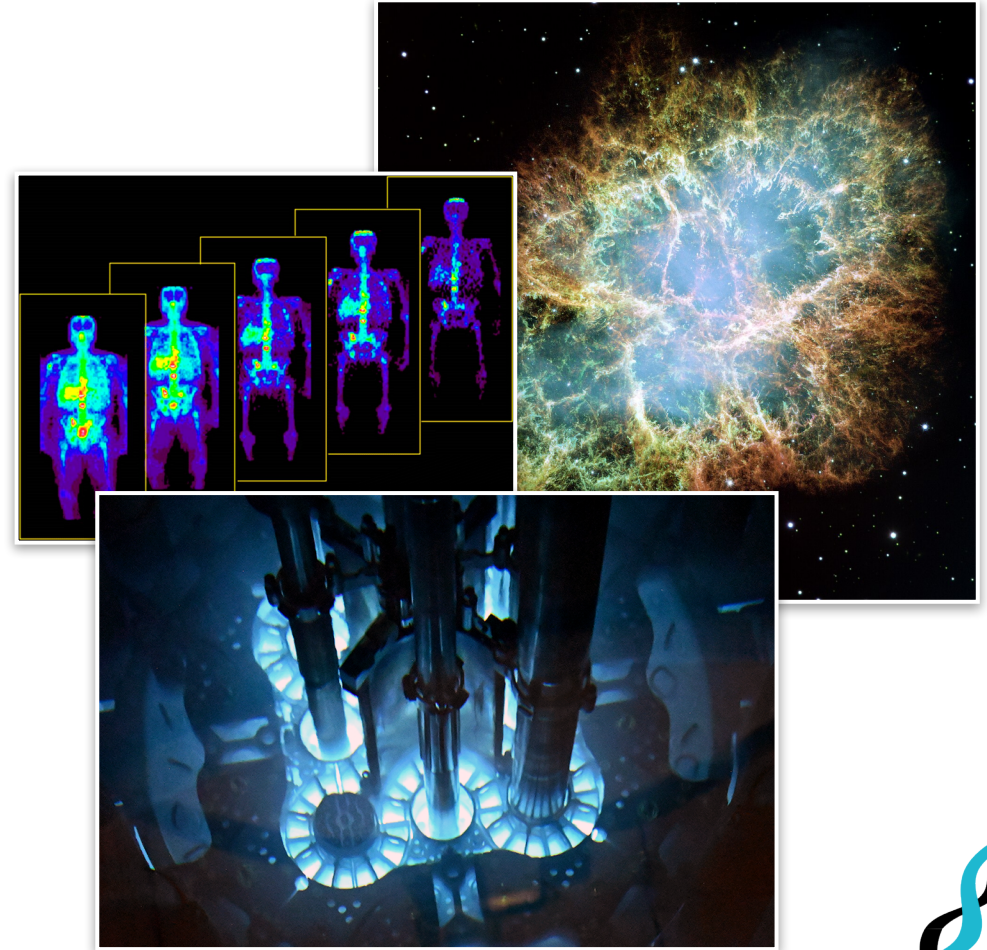
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Why we do surrogate reactions?

- Indirect way of determining cross sections for reactions that otherwise cannot be measured
 - Neutron capture cross sections of radioactive nuclei
- Neutron-induced reactions are some of the most interesting nuclear reactions
 - s , i and r process nucleosynthesis
 - Medical isotope production
 - Reactor cycles and waste management

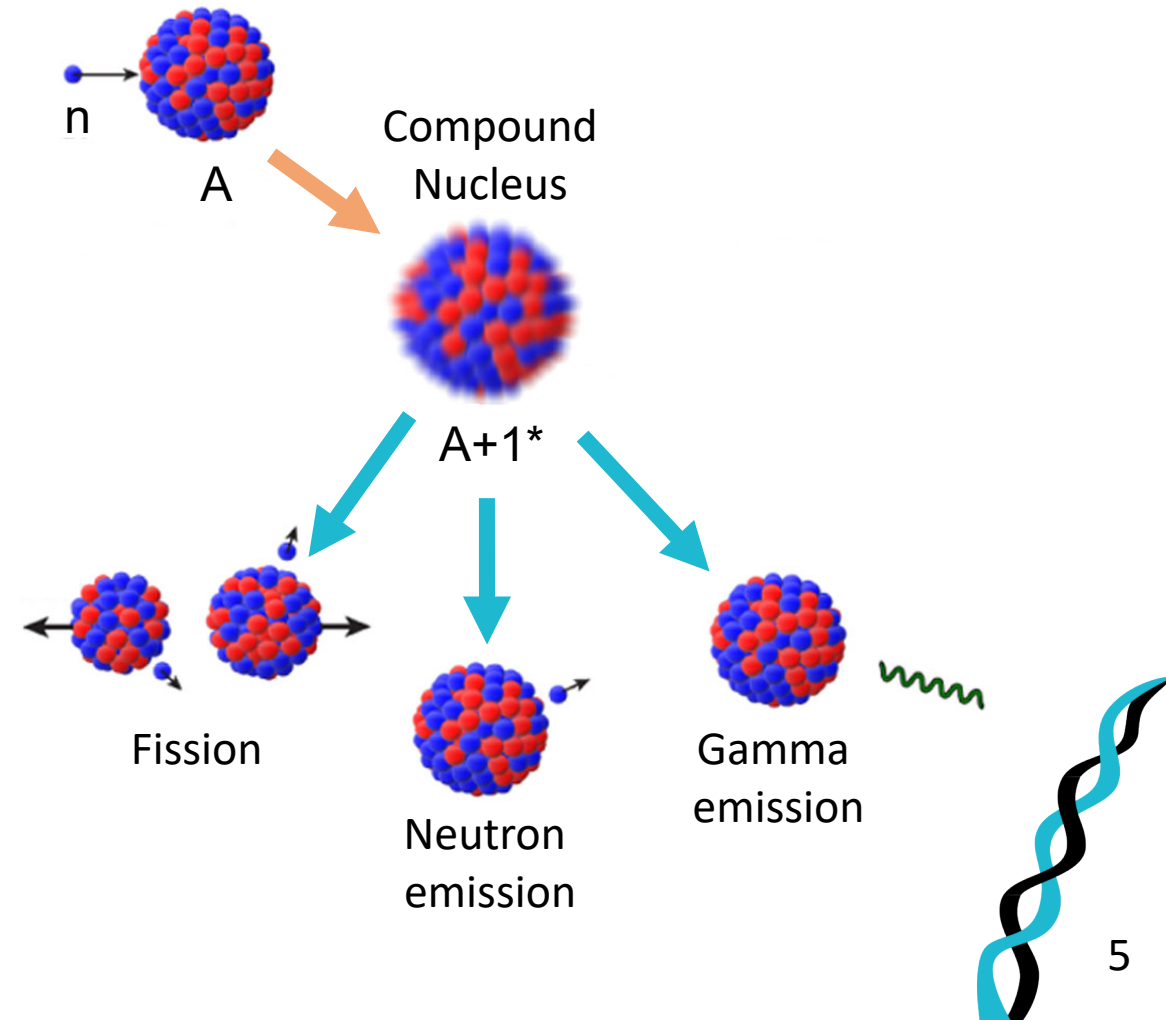




How to measure neutron cross sections?

- We shoot neutrons at the nuclei
 - Heavy nuclei and $E_n < \text{few MeV}$
- 2 step process:
 - Formation of compound nucleus (CN) $A+1$
 - CN decays via competing channels
- σ_x by measuring of decay modes

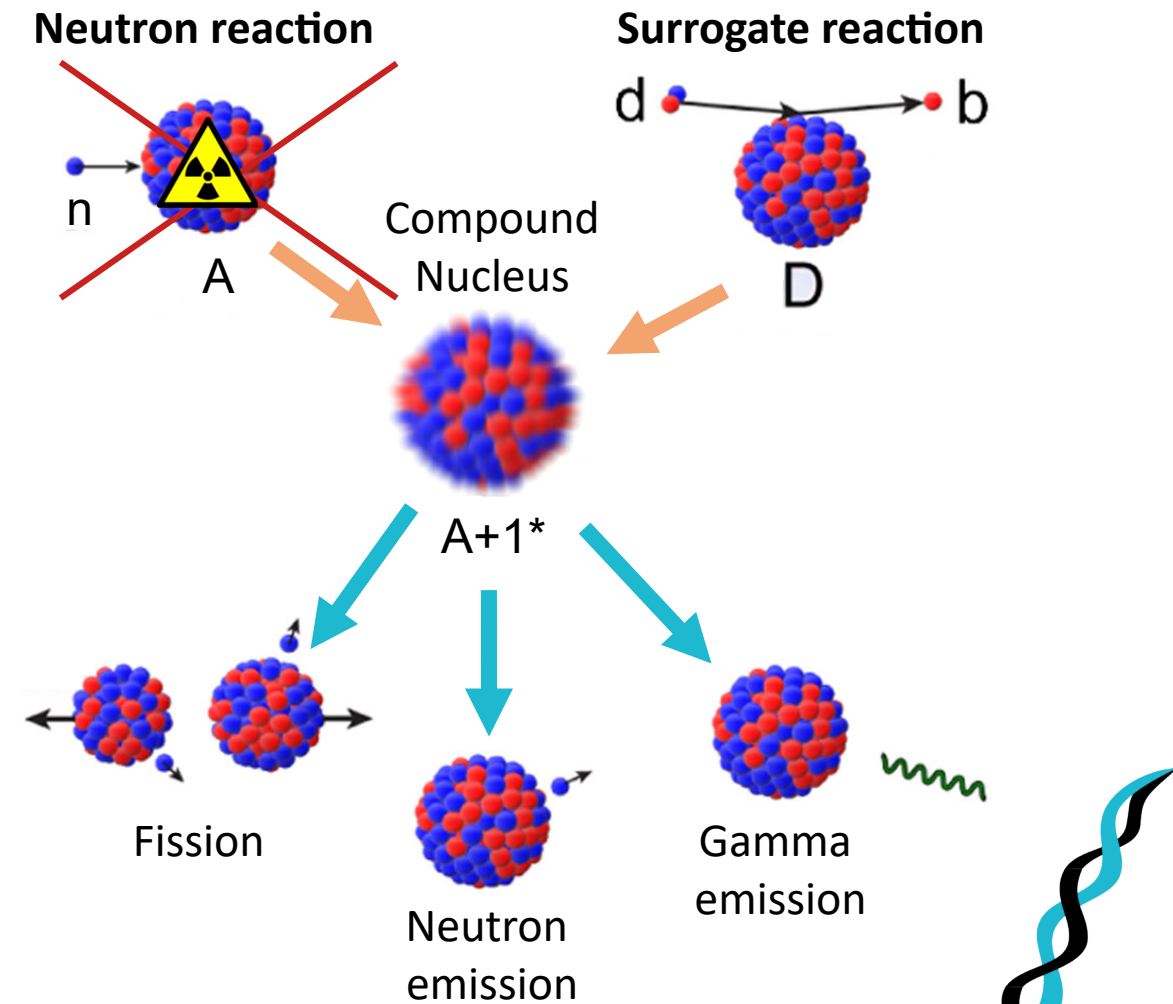
Neutron reaction





How to measure neutron cross sections?

- What if nuclei are radioactive?
 - Making or handling can be impossible
- Surrogate method
 - Different 2-body reaction that forms the same CN
 - Light residue used to calculate excitation energy
- We can measure probabilities:
 - Can be used as an input for theory to constrain cross section





Surrogate reaction method

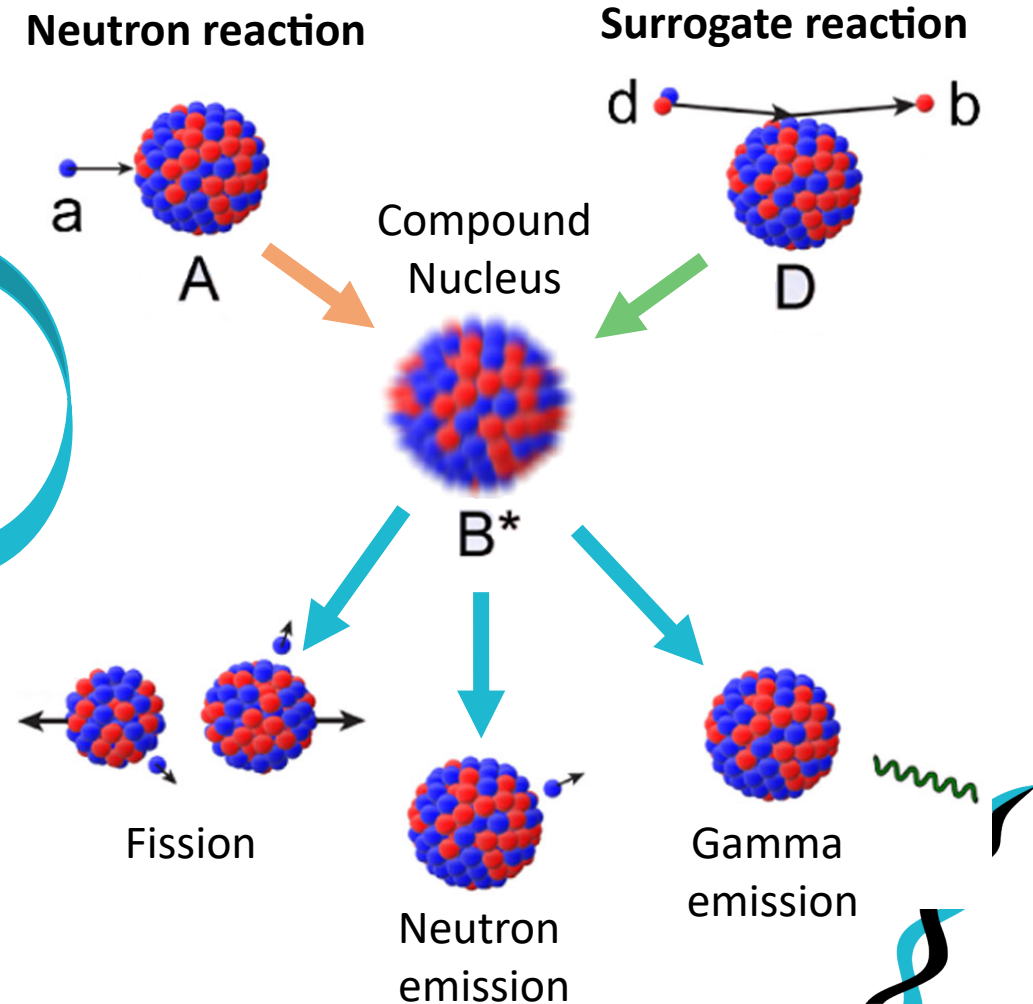
- Surrogate reaction forms the same CN to constrain **decay probabilities**:

$$P_{\chi}(E^*) = \sum_{J,\pi} F_{\delta}^{CN}(E^*, J, \pi) G_{\chi}^{CN}(E^*, J, \pi)$$

- Experimentally measured probabilities are then used for the cross section:

$$\sigma_{n\chi}(E_n) = \sum_{J,\pi} \sigma_n^{CN}(E^*, J, \pi) G_{\chi}^{CN}(E^*, J, \pi)$$

- Formation computed theoretically





De-excitation probabilities

- Probability for a given excitation E^* :

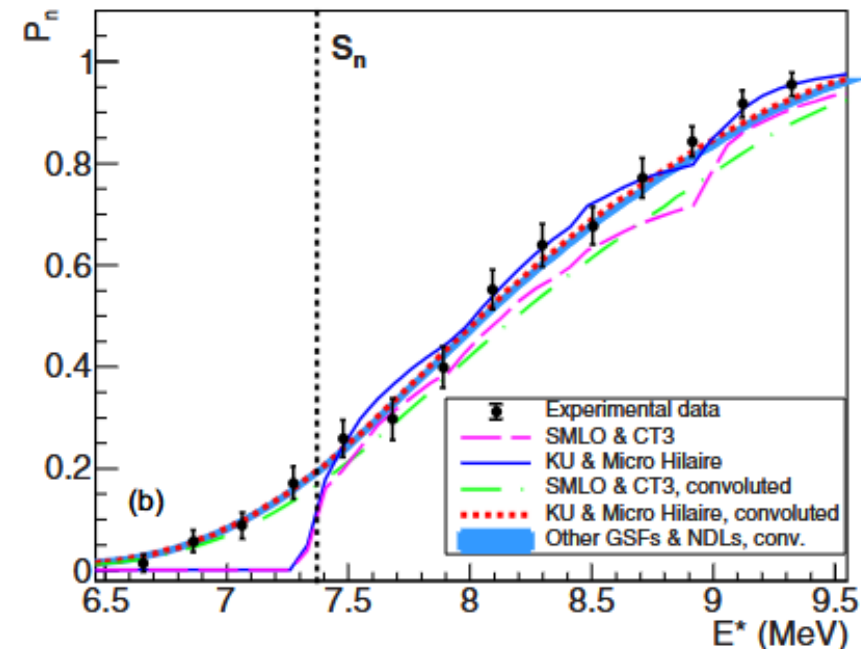
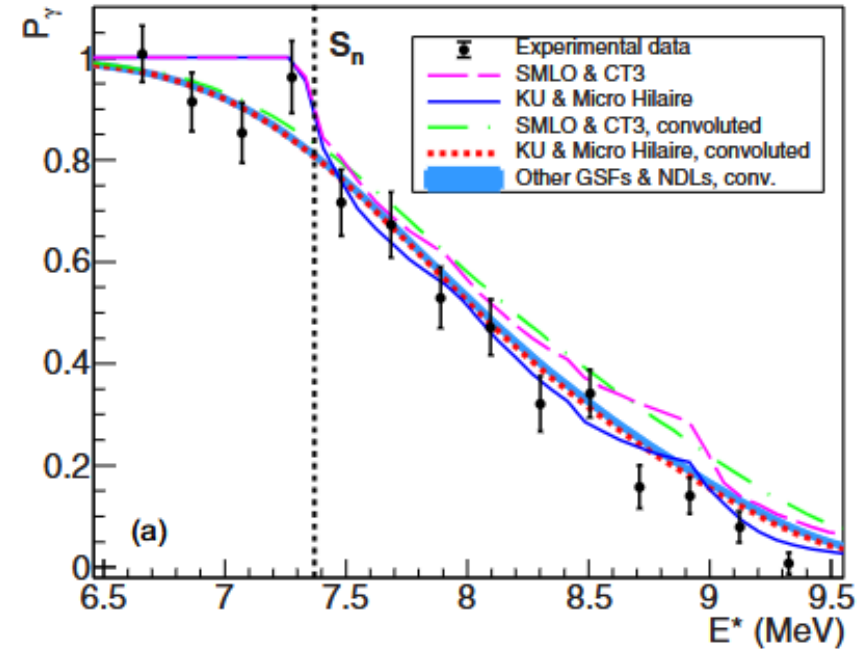
Number of coincidence events

$$P_{\gamma}(E^*) = \frac{N_{C,\gamma}(E^*)}{\epsilon_{\gamma}(E^*) \cdot N_S(E^*)}$$

Detection Efficiency

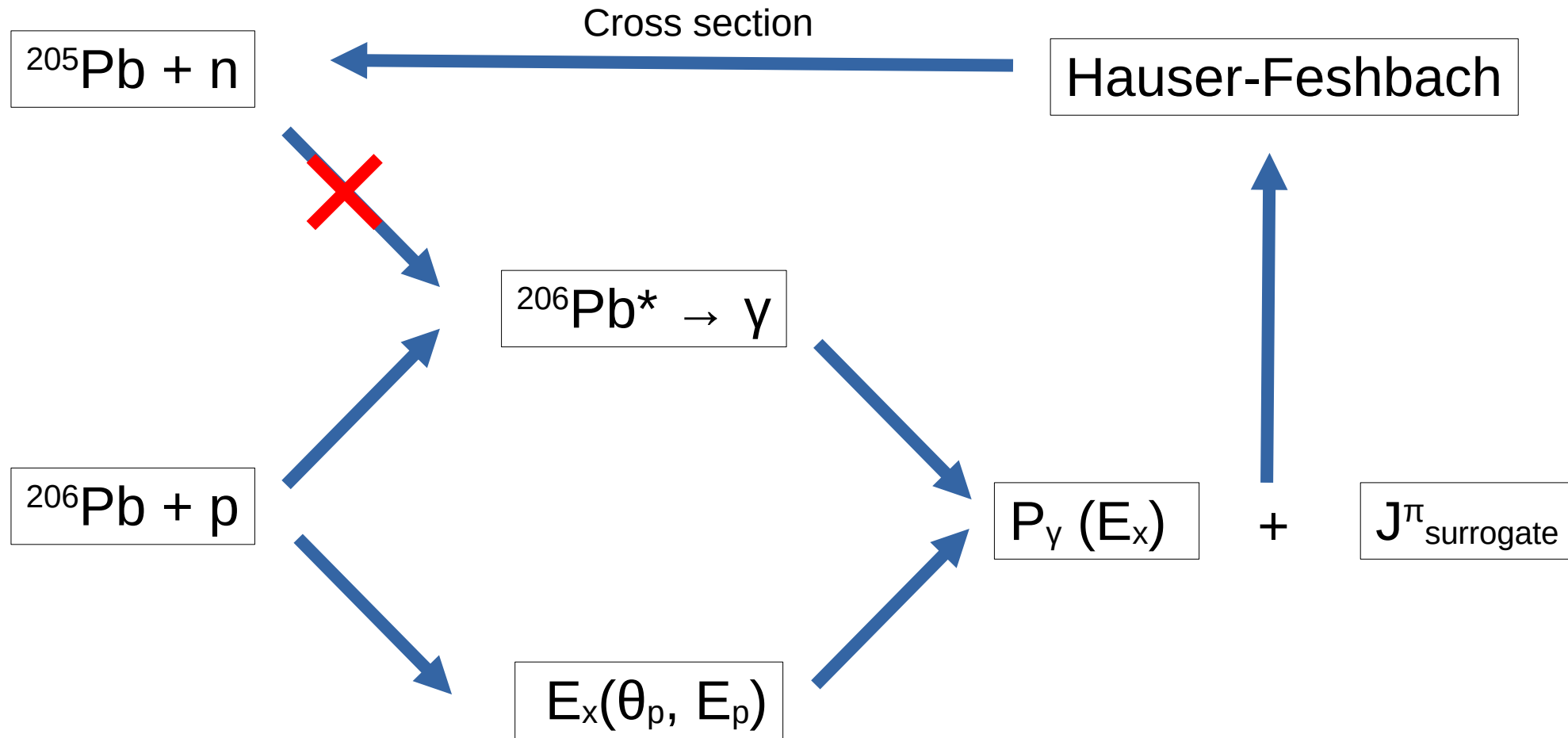
Number of singles in Telescope

- Comparison with Hauser-Feshbach (TALYS) calculations





The goal of this experiment





Presentation Outline

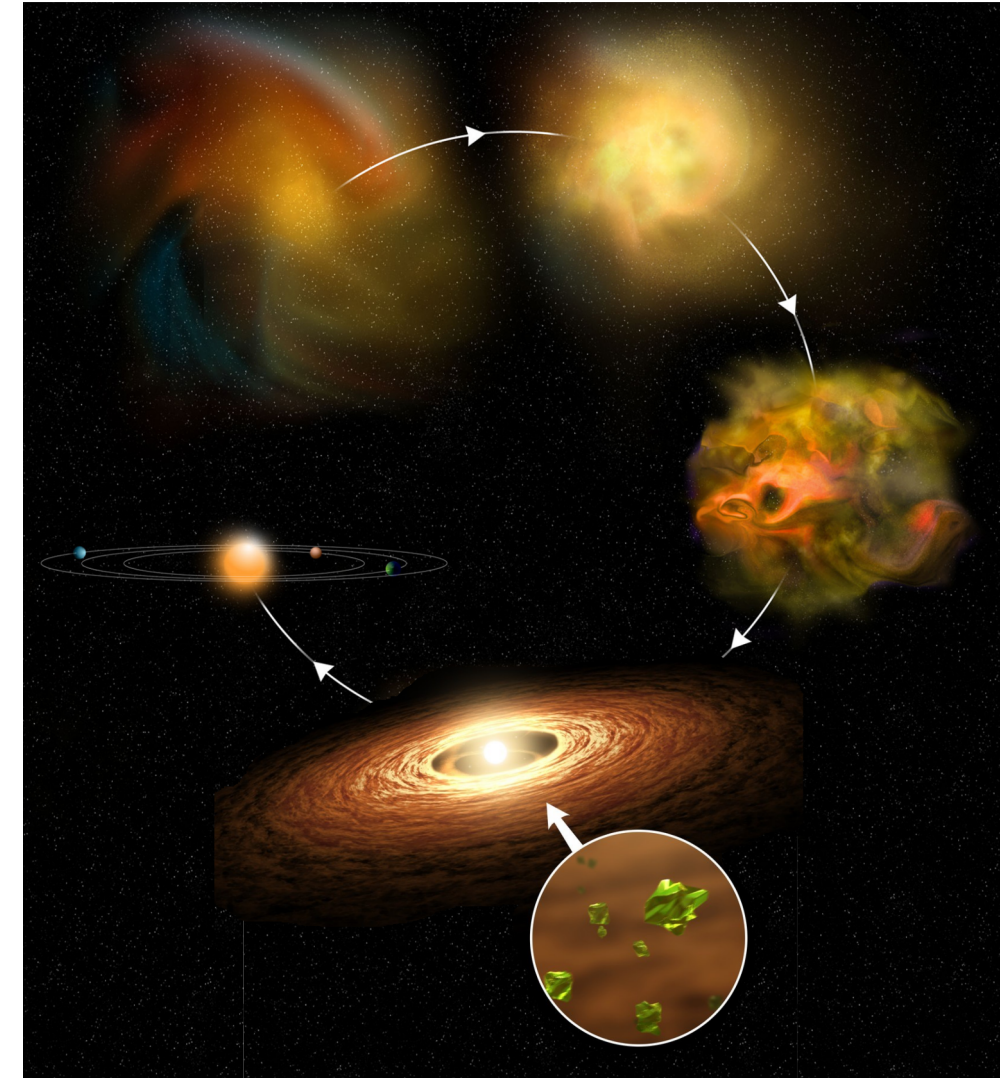
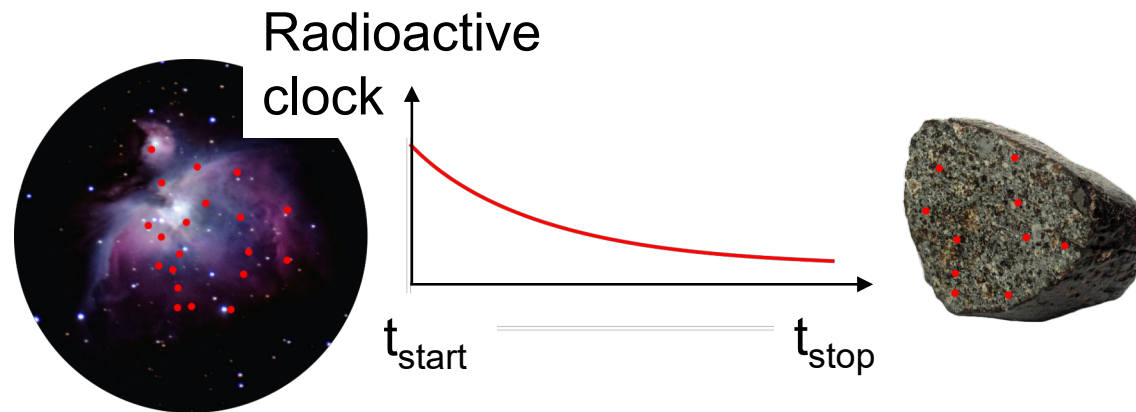
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^{205}Pb as a cosmochronometer

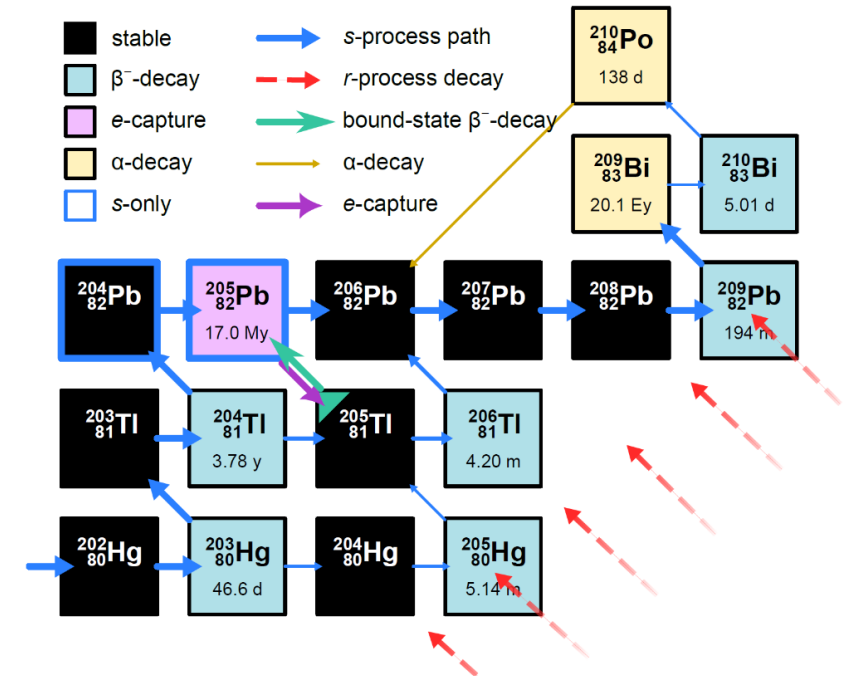
- Solar system condensed from molecular cloud
- Meteorites preserve isotopic ratios
- Short lived Radionuclei ($t_{1/2} \sim \text{Ma}-100\text{Ma}$) can be used as a clock





^{205}Pb as a cosmochronometer

- ^{205}Pb ideal candidate, the s-only SLR
- Produced by AGB stars, steady state in the interstellar medium
- ^{204}Pb as a reference
- ^{205}Tl bound state β -decay measured
- Only $^{205}\text{Pb}(n,y)$ remains uncertain



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High-temperature ^{205}Tl decay clarifies ^{205}Pb dating in early Solar System

Guy Leckenby , Ragandeep Singh Sidhu, Rui Jiu Chen , Riccardo Mancino, Balázs Szányi, Mei Bai, Umberto Battino, Klaus Blaum, Carsten Brandau, Sergio Cristallo, Timo Dickel, Iris Dillmann, Dmytro Dmytriyev, Thomas Faestermann, Oliver Forstner, Bernhard Franczak, Hans Geissel, Roman Gernhäuser, Jan Glorius, Chris Griffin, Alexandre Gumberidze, Emma Haettner, Pierre-Michel Hillenbrand, Amanda Karakas, ... [Jianwei Zhao](#)  [+ Show authors](#)

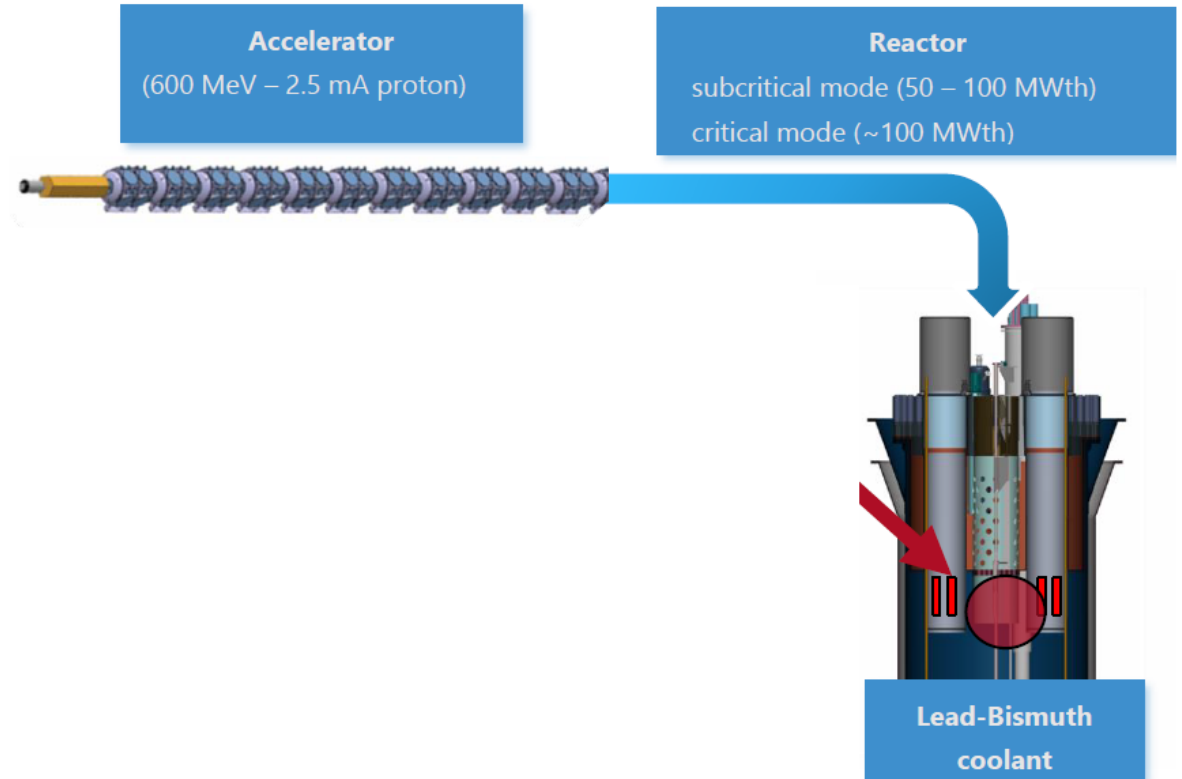
Nature **635**, 321–326 (2024) | [Cite this article](#)

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^{205}Pb in Accelerator Driven Nuclear reactors

- Next-gen subcritical reactor
- Spallation target, cooling etc. all use lead
- Understanding $^{205}\text{Pb}(n,\gamma)$, $^{205}\text{Pb}(n,n')$ and $^{205}\text{Pb}(n,2n)$ crucial for neutron flux and waste production



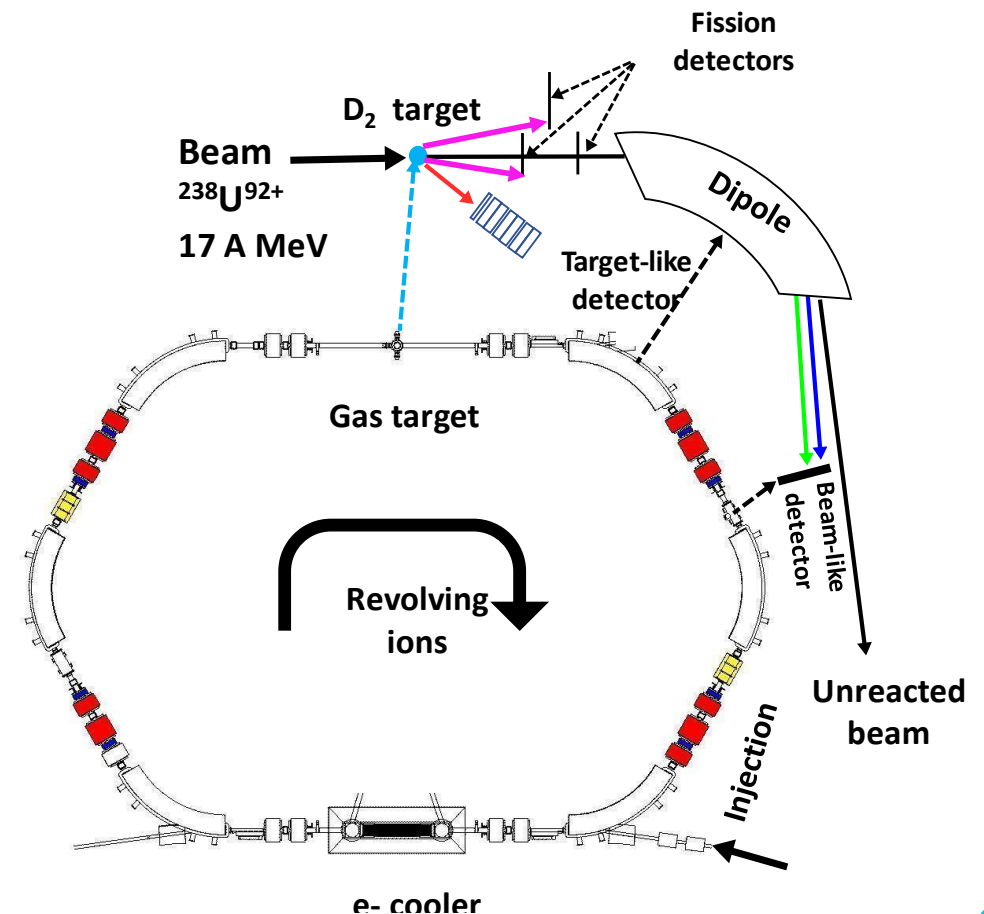
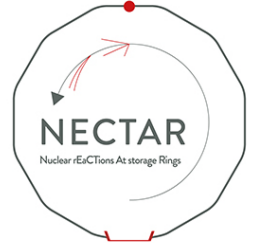
MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) [1] Abderrahim *et al.* (2021) Sustainability 13:12643

Complementary approach within surrogate program

- ERC NECTAR (Bordeaux/GSI group)
- Storage-ring surrogate measurements in inverse kinematics
- Two experiments so far, $^{208}\text{Pb}+p$ and $^{238}\text{U}+d$
- CCB - proton-induced, direct kinematics on stable target
- The CCB measurement complements the existing storage-ring program and provides an independent benchmark of surrogate reactions in the heavy-mass region



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Experimental requirement

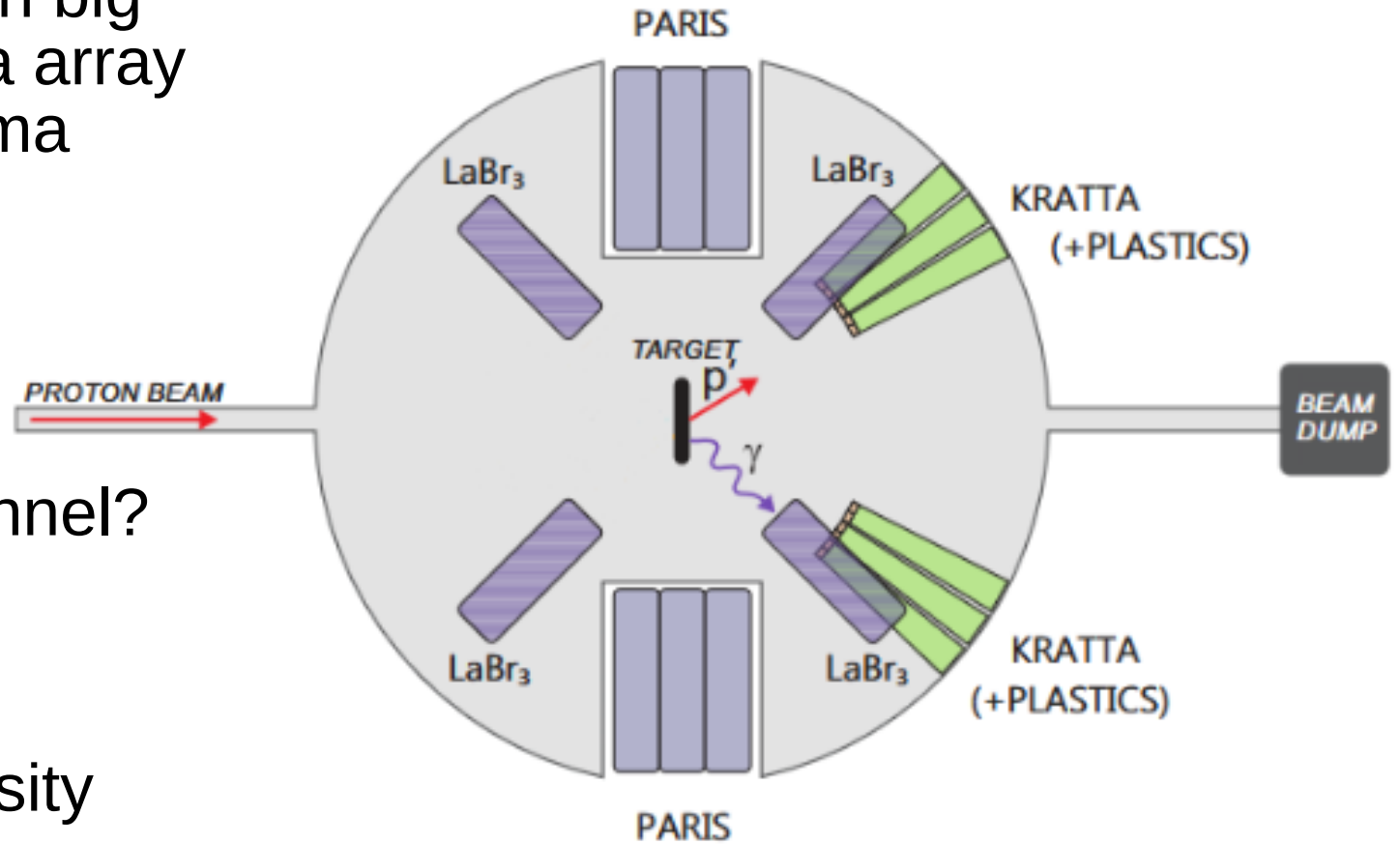
- $p + {}^{206}\text{Pb} \rightarrow p' + {}^{206}\text{Pb}^* \rightarrow \gamma$
- Beam energy $\sim 100\text{-}150$ MeV
- Particle detection and identification (KRATTA)
- Gamma ray detectors (LaBr_3 and PARIS)
- Proton-gamma coincidences
- ${}^{206}\text{Pb}$ and ${}^{208}\text{Pb}$ for Target (M. Ciemała)





Experimental setup

- Standard CCB setup with big Vacuum chamber, Kratta array and LaBr₃ / PARIS gamma detectors
- DSSD for (p,d) (p,t) channel?
- Faraday cup and pico amperometer for luminosity monitoring





How do we control the surrogate reaction?

- In general $J_{\text{surrogate}}^{\pi} \neq J_{n,\gamma}^{\pi}$
- J^{π} depends on the θ_p , E_p but can be calculate using DWBA/CC
- By measuring over broad θ_p we can cross-check theoretical calculation
- Kratta modules well suited for that





Why ^{208}Pb ? A built-in benchmark

- Since $^{207}\text{Pb}(n,\gamma)^{208}\text{Pb}$ is known and $^{208}\text{Pb}(p,p')$ surrogate has been studied - we can cross-check our method

- Surrogate reaction method
$$R(E_x) = \frac{P_{\gamma}^{206}(E_x)}{P_{\gamma}^{208}(E_x)}$$
 - Same setup, same energy, common systematical effects reduced
 - Can also constrain
$$\sigma_{^{205}\text{Pb}(n,\gamma)}(E_n) \approx R(E_x) \sigma_{^{207}\text{Pb}(n,\gamma)}(E_n)$$



- What
 - Surrogate method provide access to n,y cross section through the decay probabilities of the same compound nucleus.
- Why
 - $^{205}\text{Pb}(n,y)$ is a key remaining uncertainty for the ^{205}Pb - ^{205}Tl cosmochronometer and is also relevant for Pb nuclear data
- How
 - Measure $^{206}\text{Pb}(p,p'y)$ at CCB, use angular coverage to investigate J^π effects and benchmark the method with $^{208}\text{Pb}(p,p'y)$





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