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Proton induced spallation reaction and high power target station

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- **High power spallation target station**
  - Accelerator-Driven Spallation application
  - Challenges for high power target station
  - Design study on high power target station at IMP
- **Proton induced spallation reaction**
  - Brief introduction to spallation reaction
  - Basic theoretical models
  - The description of spallation reaction with INC model
- **Summary**

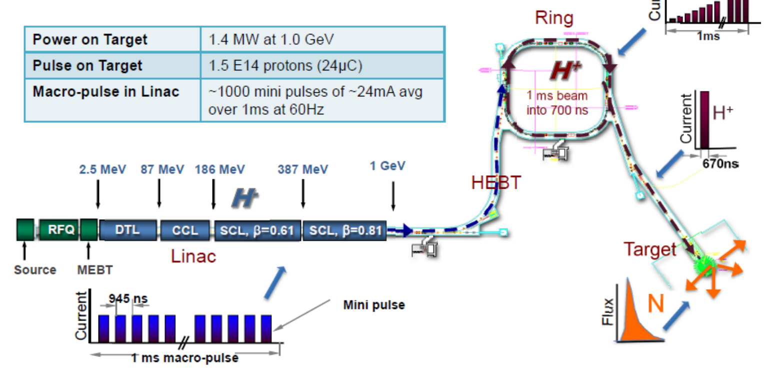
Accelerator-Driven Spallation application

➢ Spallation neutron source

- Material research
- Industry
- Medicine radiotherapy

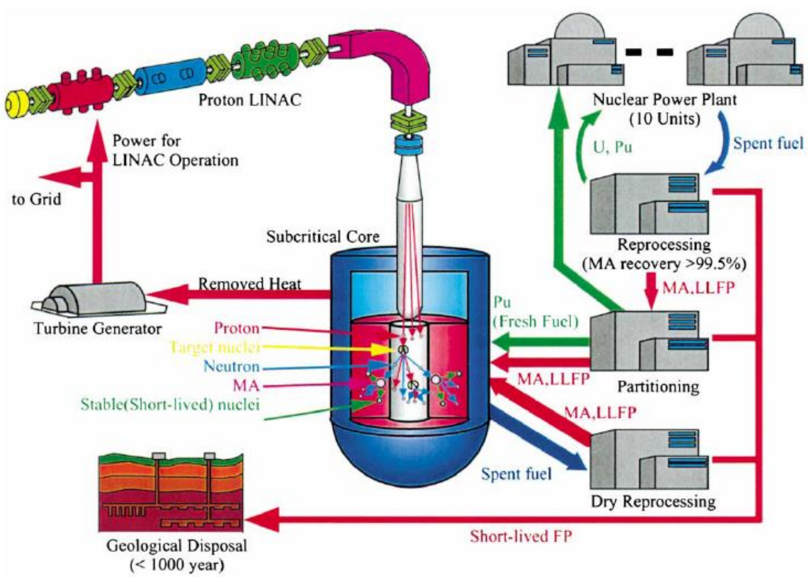
- Neutron scattering facility to research properties of materials
- 1 GeV Protons create neutrons through spallation in Hg target

Power on Target	1.4 MW at 1.0 GeV
Pulse on Target	1.5 E14 protons (24μC)
Macro-pulse in Linac	~1000 mini pulses of ~24mA avg over 1ms at 60Hz



➢ Subcritical system

- Transmutation of long-lived nuclear waste



➢ Neutrino beam facility

- Muon-decay neutrino factory

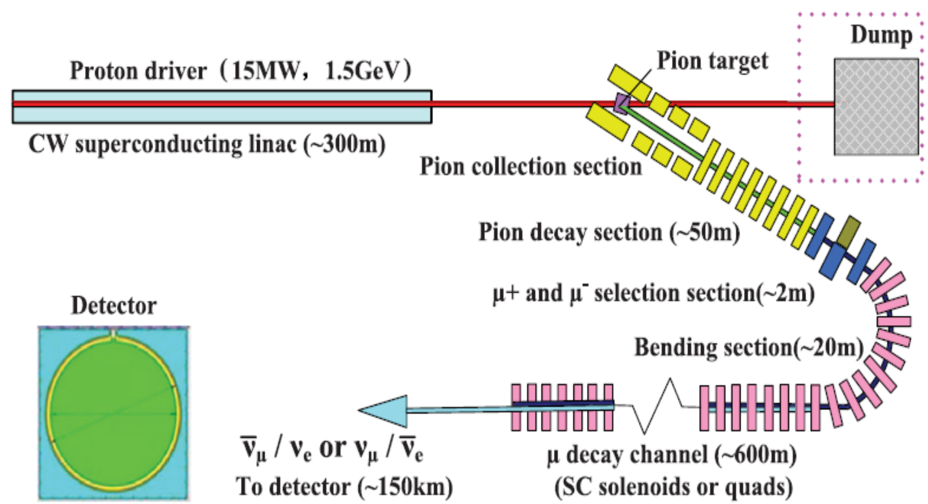


FIG. 2. Schematic layout of the MOMENT facility.

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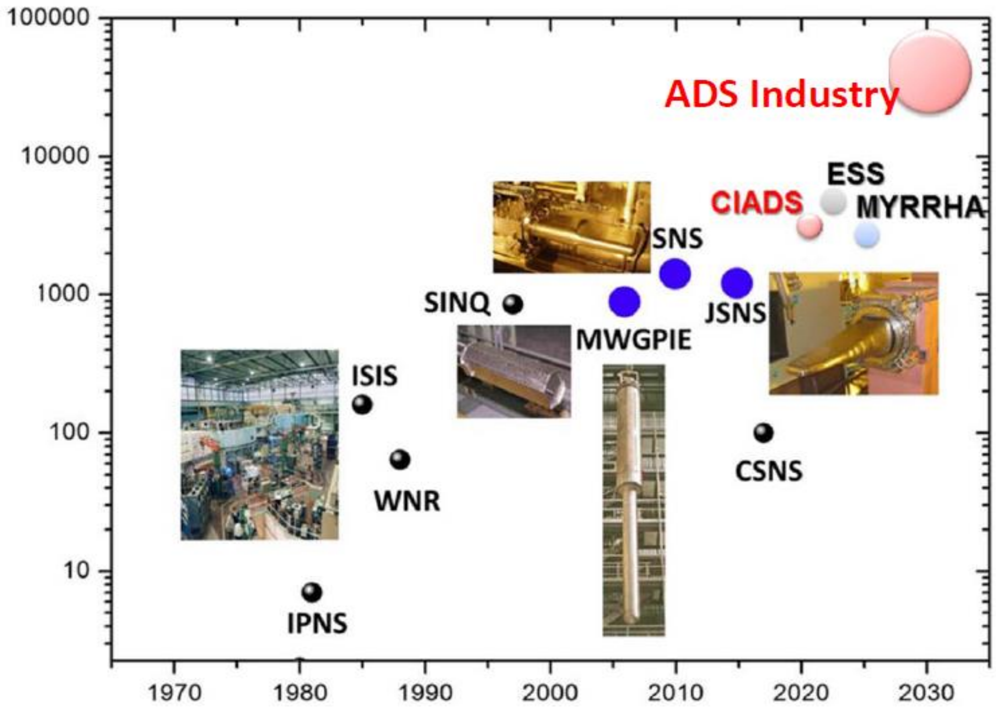
High Power Spallation target



- Solid target options
  Consist of a solid material in the form of rods, spheres, or plates to produce the neutrons, and coolant flowing between the elements for heat removal.
- Liquid target options
  Flowing liquid metal acts both as the source of neutrons and the heat removal media.

Challenges for high power target

- **The heat removal (Solid target/beam window) will be limited by the heat conduction of the target material and convection-cooling.**
- **The life time of the target will be limited by the radiation damage, heat shock, et al..**
- **Safety, operation, complexity, decommissioning, et al..**

The system of Liquid target will be complex: the challenges of techniques.

- Hydrodynamic instability: Cavitations, Shock waves, Splashing, etc.

- Corrosion and erosion of material: high speed ML
  - corrosion and erosion of material (for LBE now, temperature ~< 550C, velocity ~< 2m/s). Structure material will be a limitation for the beam power increase

- Vapor environment: vacuum, temperature
  - For example: Hg -> 10^5 (Rt-> 200 C); Li boiling T -> 10^1 (10^-9 Pa)

- Chemical-toxicity: HLW / LLW

- Radio-toxicity: HLW (Operation, Safety, Cleanup chemistry, Decommissioning
  - For example: the production of α-radioactive 210Po having 138 days half-life undergoes α-decay, 210Po is volatile
  - For example: Operation: the leakage from the cover gas poses some hazard to operate.

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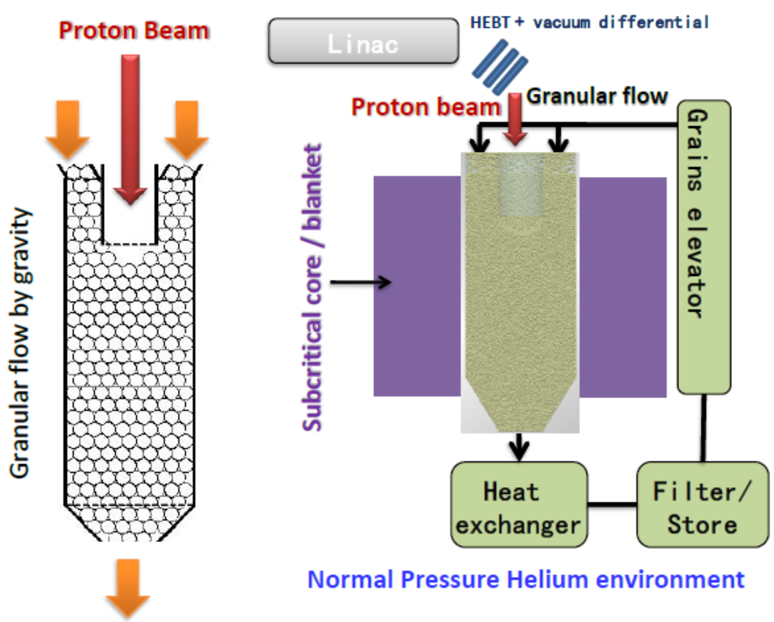
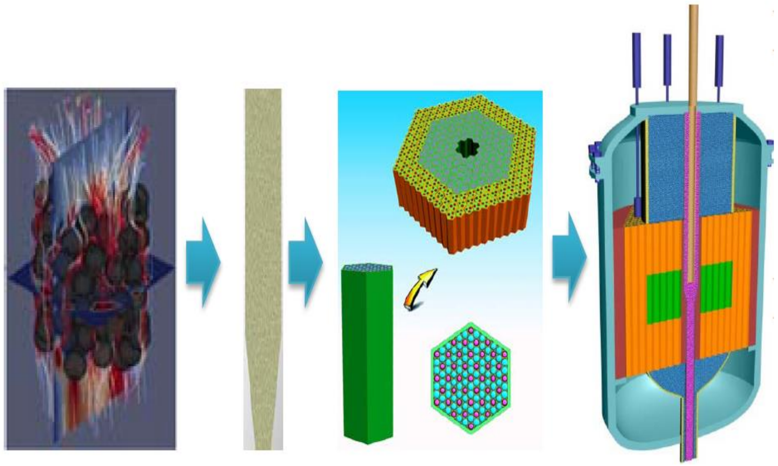
Design study on high power target station at IMP



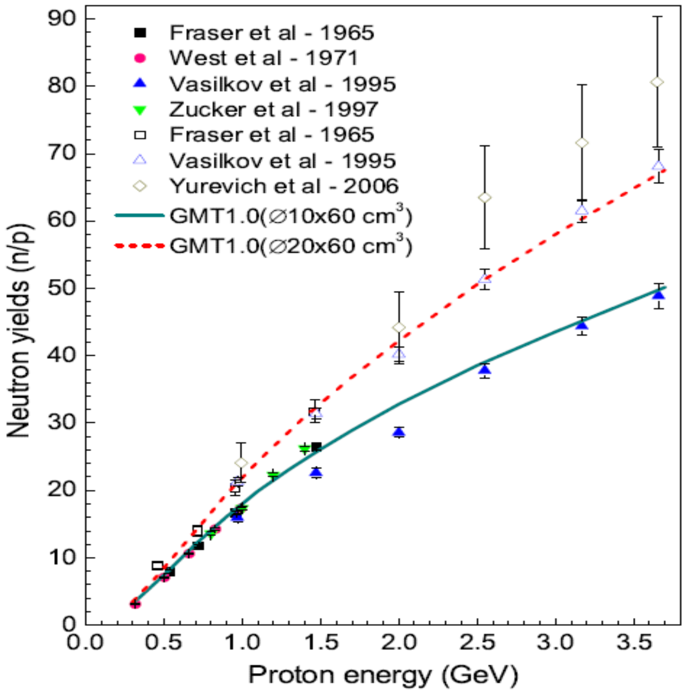
- **Granular target concept:**
  - Gravity driven dense granular flow
  - Granular flow heat exchange + Helium cooled
  - Windowless

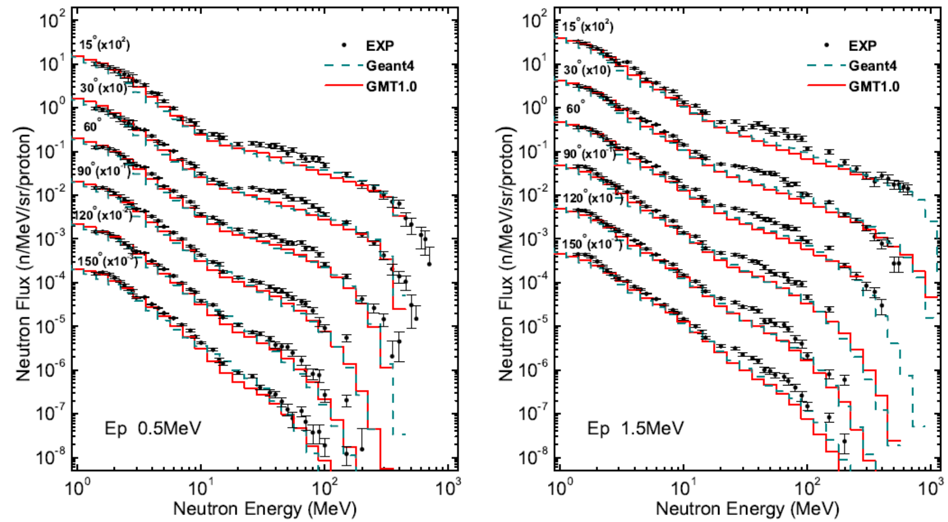
- **Mass parallel simulation method (GPU) for granular target**
  - Granular flow simulations and thermal-hydraulic analysis.
  - Simulation of stochastic granular target: neutronic characteristics analysis, heat deposit, spallation products, etc.

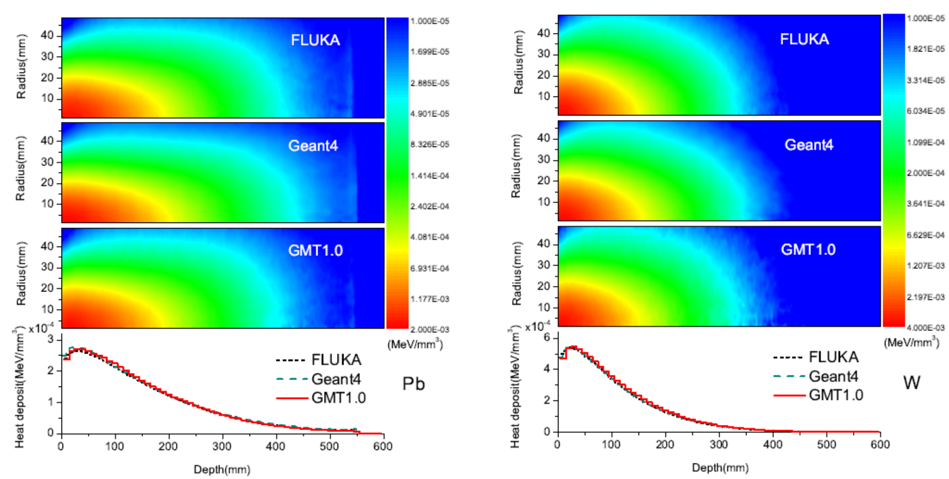
Coupled computations



GMT: Code development for the design study of the target station of China-ADS







- Monte Carlo transport module
- INCL + ABLA model for spallation reactions
- Functional modules: data processing module, burnup calculation module, etc.

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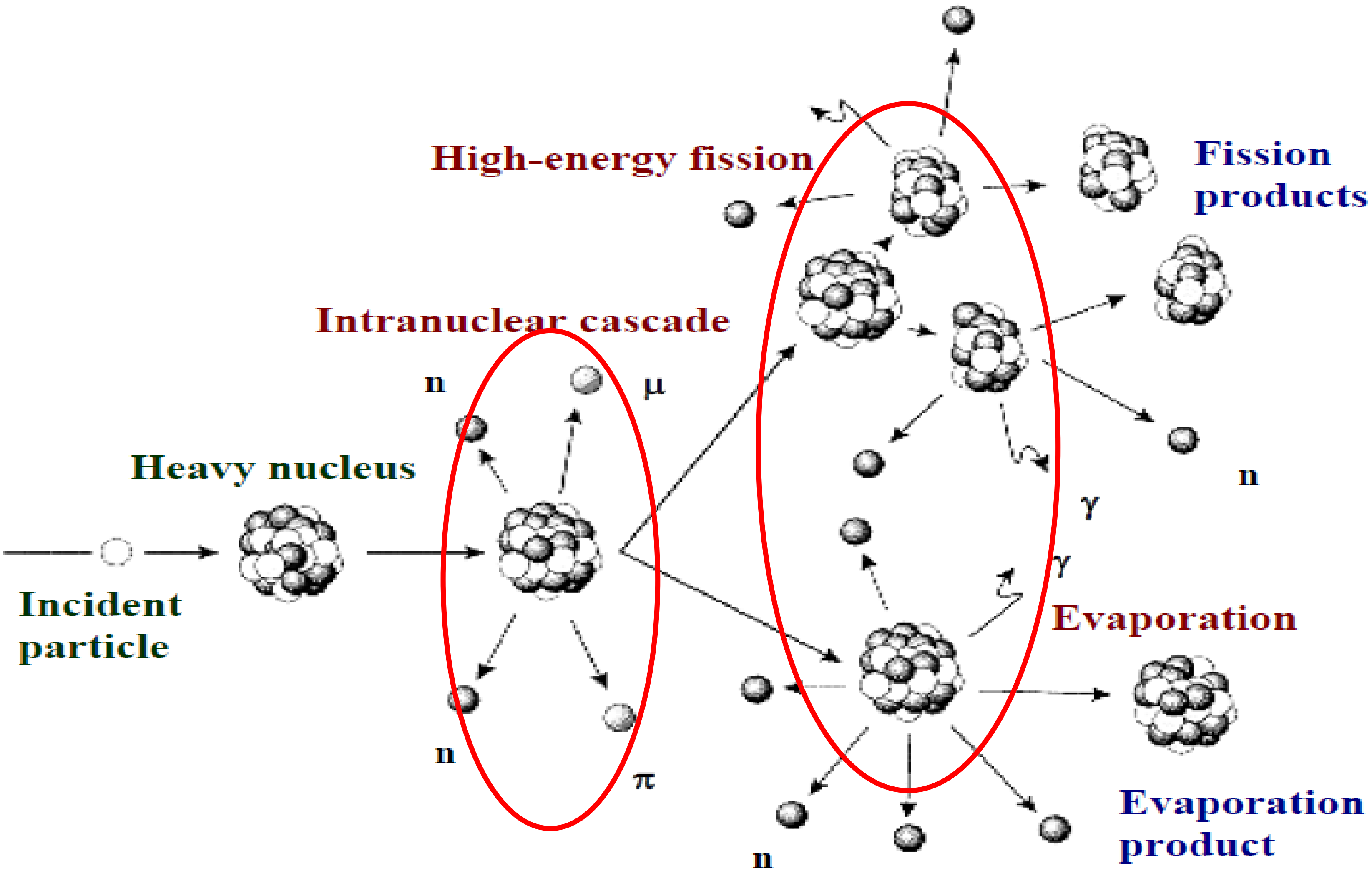
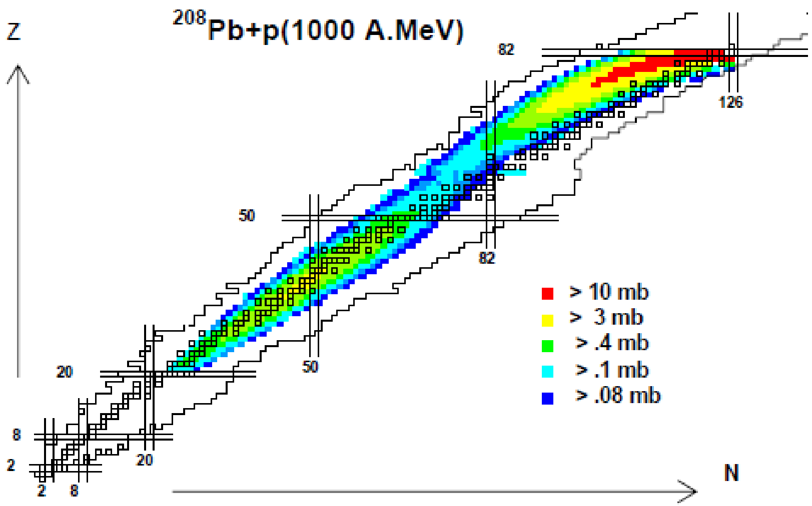
Proton induced spallation reactions

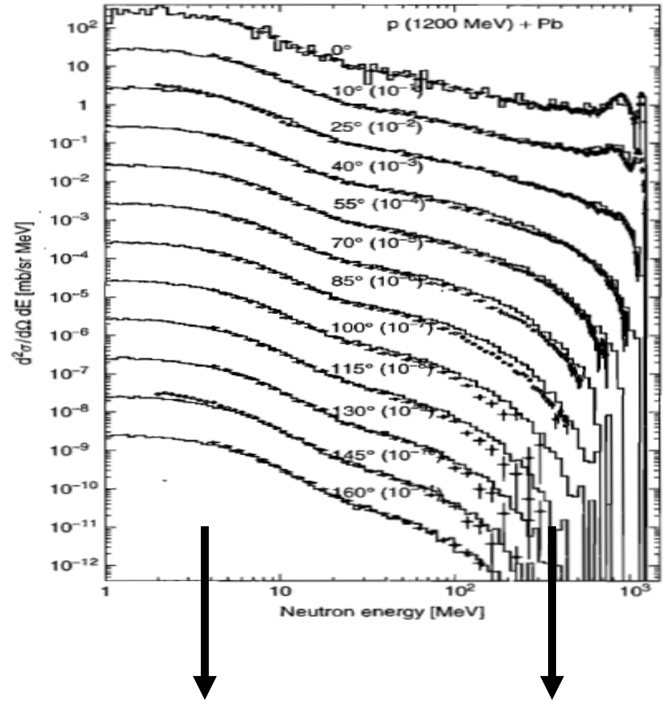


fast stage ~ 10^{-22} s **slow stage ~ 10^{-16} s**

Spallation products

- Neutrons: cascade, evaporation and fission neutrons
- Residues: heavy proton-rich and medium-mass residues





Isotropic emission

Anisotropic emission

- Pions: pi+, pi0, pi-.
- Light clusters: deuteron, tritium, alpha, etc.

	p(1.0 GeV)+Al			p(2.5 GeV)+Al		
	π^-	π^0	π^+	π^-	π^0	π^+
15 fm/c:	0.067	0.18	0.29	0.38	0.51	0.50
20 fm/c:	0.071	0.18	0.29	0.37	0.47	0.47
35 fm/c:	0.069	0.17	0.26	0.37	0.47	0.46
	p(1.0 GeV)+Au			**p(2.5 GeV)+Au**		
	π^-	π^0	π^+	π^-	π^0	π^+
15 fm/c:	0.010	0.045	0.060	0.35	0.46	0.41
20 fm/c:	0.085	0.19	0.26	0.53	0.60	0.52
35 fm/c:	0.11	0.17	0.23	0.49	0.53	0.46

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Basic theoretical models

- Intra-Nuclear Cascade (INC) model
  - Binary nucleon - nucleon collisions
  - Constant static potential

- Boltzmann-Uehling-Uhlenbeck (BUU) model
  - One-body phase-space distribution
  - Dynamically changing field, minimal fluctuations

- Quantum Molecular Dynamics model
  - Time evolution of correlations between partices
  - Real fluctuations, two- and three- body potentials

- Percolation model
  - Fragment mass distributions

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The description of spallation reaction with INC model

- Cross sections

Cross section	Reaction	Cross section	Reaction
n–p	Differential	n–p	Elastic
p–p	Differential	p–p	Elastic
π^+–p	Differential	π^-–p	Elastic
π^-–p	Differential	π^0–p	Elastic
π^-–p	Differential charge exchange	π^0–n	elastic
π^0–p	Differential	π^+–p	Absorption
π^-–p	Charge exchange	π^0–p	Absorption
p–p	Single-pion production	p–p	Double-pion production
n–p	Single-pion production	n–p	Double-pion production
π^+–p	Single-pion production	π^0–p	Single-pion production
π^-–p	Single pion production	π^0–n	Single pion production

Why microscopic cross sections instead of particle-nucleus cross sections?

$$\frac{d^2\sigma_{\text{nonelastic}}}{dE\, d\Omega}(E_j, \vec{\Omega}_j, h_i, E_i, A_k)$$

10^7 input values are needed for the model! No way!

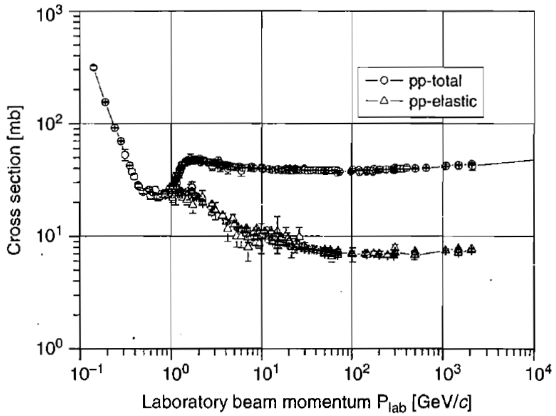
- Pauli block

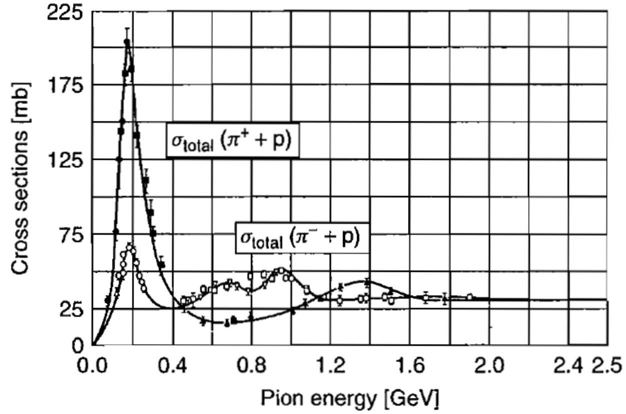
Phase space occupation probalities:

$$f_{\text{dyn}_{i(j)}} = \frac{1}{2}\frac{1}{V_r V_p}\sum_{k \neq i} \Theta\left(R_r - |\vec{r}_i - \vec{r}_k|\right)\Theta\left(R_p - |\vec{p}_i - \vec{p}_k|\right)$$

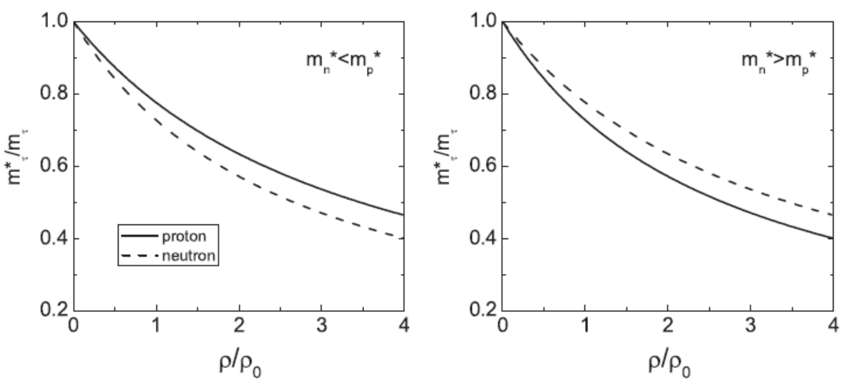
Nuclear in-medium effects

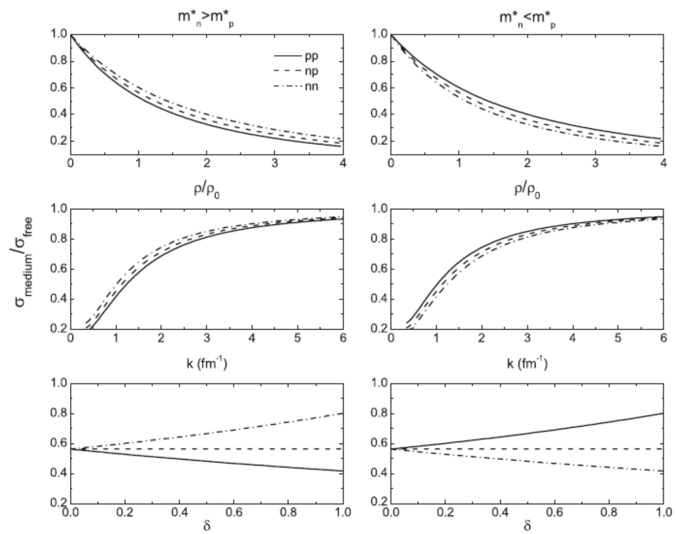
➢ Free space cross sections: well known from experimental data





➢ In-medium nucleon-nucleon cross section





More precise knowledge about the in-medium NNCS is required.

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summary

- High power spallation target is the most innovative component in Accelerator-Driven Systems and is challenging at the same time.
- Spallation reaction is far away form being well described and more precise knowledge is required by the spallation applications.

Thank you！

References:

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4. Z.Q. Feng, Phys. Rev. C, 85 (2012)