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

- Subcritical system
  - Transmutation of long-lived nuclear waste

- Neutrino beam facility
  - Muon-decay neutrino factory
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Summary
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 ~< 550°C, 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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Summary
Proton induced spallation reactions

Fast stage \( \sim 10^{-22} \text{ s} \)

Intranuclear cascade

High-energy fission

Fission products

Evaporation

Evaporation product

Slow stage \( \sim 10^{-16} \text{ s} \)
Spallation products

- Neutrons: cascade, evaporation and fission neutrons
- Residues: heavy proton-rich and medium-mass residues
- Pions: $\pi^+$, $\pi^0$, $\pi^-$
- Light clusters: deuteron, tritium, alpha, etc.
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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 particles
  - Real fluctuations, two- and three- body potentials

- Percolation model
  - Fragment mass distributions
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Summary
The description of spallation reaction with INC model

Cross sections

<table>
<thead>
<tr>
<th>Cross section</th>
<th>Reaction</th>
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<td>Differential</td>
<td>π⁰–p</td>
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<tr>
<td>π⁻–p</td>
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<td>π⁰–p</td>
<td>Differential</td>
<td>π⁺–p</td>
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<tr>
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<td>Charge exchange</td>
<td>π⁰–p</td>
<td>Absorption</td>
</tr>
<tr>
<td>n–p</td>
<td>Single-pion production</td>
<td>n–p</td>
<td>Double-pion production</td>
</tr>
</tbody>
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Why microscopic cross sections instead of particle-nucleus cross sections?

\[
\frac{d^2\sigma_{\text{nonelastic}}}{dE \, d\Omega}(E_j, \Omega_j, h_i, E_i, A_k) \]

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

Pauli block

Phase space occupation probabilities:

\[
f_{\text{dyn}_{i(\theta)}} = \frac{1}{2} \frac{1}{V_r V_p} \sum_{k \neq i} \Theta (R_r - |\vec{r}_i - \vec{r}_k|) \Theta (R_p - |\vec{p}_i - \vec{p}_k|)
\]
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 from being well described and more precise knowledge is required by the spallation applications.
Thank you!
References: