Proton induced spallation reactions
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Wide range of applications

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Many applications…
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Many applications…

Therefore, the **realistic** and **reliable** models which enable us to predict the **cross sections** (probability of reactions) are necessary.
THE MOST IMPORTANT TASK IS
THE MOST IMPORTANT TASK IS TO UNDERSTAND THE REACTION MECHANISM
Two stages of reaction

1st stage of reaction
Two stages of reaction

1st stage of reaction

Intra-nuclear cascade of NN collisions

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RANKING OF SPALLATION MODELS
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Heavy
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2\textsuperscript{nd} STAGE OF REACTION

Equilibrated Heavy Residua

De-excitations
De-excitations

2nd STAGE OF REACTION

Equilibrated Heavy Residua

Evaporation

Two stages of reaction
De-excitation

2nd STAGE OF REACTION

Equilibrated Heavy Residua

Evaporation

Fragmentation

Two stages of reaction

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2nd STAGE OF REACTION

Equilibrated Heavy Residua

Evaporation
Fragmentation
Fission

De-excitation
Two stages of reaction

De-excitation processes:
- Equilibrated Heavy Residua
- Evaporation
- Fragmentation
- Fission
- Multi-fragmentation
Theoretical Models

1\textsuperscript{ST} STAGE OF REACTION
1ST STAGE OF REACTION

INCL4.6

A. Boudard, D. Mancusi, J.-C. David, J. Cugnon, S. Leray:
CEA-irfu, Saclay, France
University of Liege, Belgium
Theoretical Models

1st STAGE OF REACTION

2nd STAGE OF REACTION

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CEA-irfu, Saclay, France
University of Liege, Belgium

2ND STAGE OF REACTION

ABLA07
A. Kelic, M. V. Ricardi & K. Schmidt
GSI Darmstadt, Germany

SMM
A. Botvina
GSI Darmstadt, Germany

GEMINI++
Robert Charity
Washington University in St. Louis
USA

GEM2
S. Furihata
Mitsubishi Research Int., Japan

Theoretical Models
The goal:

to validate different spallation models
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- to validate different spallation models
- by comparing predictions of various models with measured data qualitatively and quantitatively
- for different targets and proton beam energies.
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Outline:
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to validate different spallation models
by comparing predictions of various models with measured data
qualitatively and quantitatively
for different targets and proton beam energies.

Outline:

- Angular asymmetry of fragments emission
  (results of the analysis for Au+p at 1 and 3 GeV)
Angular asymmetry

- **F** = total probability to observe products of the reaction emitted in the **FORWARD** direction (in respect to the direction of impinging proton), i.e. for angles smaller than 90 degree.

- **B** = total probability to observe products of the reaction emitted in the **BACKWARD** direction, i.e. angles larger than 90 degree.

- The asymmetry is equal to the ratio of F/B - it measures anisotropy of the angular distribution of the reaction products.
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F/B asymmetry at 1 GeV

Data:
S.B Kaufmann et al.,
Phys. Rev. C 18,
1349(1978)

Lines = model predictions:
INCL4.6+ABLA07
INCL4.6+SMM
INCL4.6+GEMINI++
INCL4.6+GEM2
Shape and magnitude of mass dependence of F/B asymmetry is BEST reproduced by GEMINI++. 


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F/B asymmetry at 1 GeV


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INCL4.6+SMM  
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INCL4.6+GEM2

- Shape and magnitude of mass dependence of F/B asymmetry is BEST reproduced by GEMINI++.
- The magnitude of F/B asymmetry of HEAVY products significantly OVERESTIMATED by GEM2 and SMM.
**INTRODUCTION**

**SPALLATION MODELS**

**F/B ASYMMETRY FOR Au+p**

**RANKING OF SPALLATION MODELS**

**SUMMARY**

Data:
GEMINI++ and ABLA07 are competing with each other in describing the exp. data.

Data:
**F/B asymmetry at 3 GeV**

- **GEMINI++** and **ABLA07** are competing with each other in describing the exp. data.
- **GEM2** overestimates the F/B ratio for the fragment A=139.

Data:
Need for statistical factors or tests?

- The **qualitative** agreement between the data and model calculations allows to conclude about general applicability of the models.

- However, it does not allow to judge in **objective** manner about quality of different model descriptions i.e. for the ranking of models.

- One has to use some **quantitative** measures of (dis)agreement of the data and theoretical cross sections.
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H- Test: (Like Chi-square )

$$H = \left( \frac{1}{N} \sum_{i=1}^{N} \frac{\sigma_i^{\text{exp}} - \sigma_i^{\text{calc}}}{\Delta \sigma_i^{\text{exp}}} \right)^{1/2}$$

M- Test: (Modulus test)

$$M = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{\sigma_i^{\text{exp}} - \sigma_i^{\text{calc}}}{\Delta \sigma_i^{\text{exp}}} \right|$$
Average of H and M test over 1GeV and 3GeV
### Average of H and M test over 1GeV and 3GeV

#### RANKS

<table>
<thead>
<tr>
<th>Model</th>
<th>H-Test</th>
<th>M-Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>INCL4.6 + ABLA07</td>
<td>4.74</td>
<td>3.99</td>
</tr>
<tr>
<td>INCL4.6 + GEMINI++</td>
<td>5.02</td>
<td>3.95</td>
</tr>
<tr>
<td>INCL4.6 + SMM</td>
<td>6.99</td>
<td>6.15</td>
</tr>
<tr>
<td>INCL4.6 + GEM2</td>
<td>7.18</td>
<td>6.16</td>
</tr>
</tbody>
</table>
The INCL4.6 model coupled to GEMINI++, SMM, ABLA07 and GEM2 models without any free parameters is able to reproduce the shape of the mass number dependence of the F/B asymmetry.
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The INCL4.6 model coupled to GEMINI++, SMM, ABLA07 and GEM2 models without any free parameters is able to reproduce the shape of the mass number dependence of the F/B asymmetry. The model predictions also agree with the beam energy dependence of the F/B asymmetry.

Ranking of Models:

INCL4.6 plus:

✓ 1st ABLA07, GEMINI++
✓ 2nd SMM, GEM2