Cosmic-Ray Physics with NA61/SHINE – Status and Plans

M. Unger (KIT) for the NA61/SHINE Collaboration
Previous NA61/SHINE Results for Cosmic-Ray Physics

- **propagation in the Galaxy**
  - \( \bar{p} \)-production in \( p + p \) \[^1\]

- **ultrahigh-energy air showers**
  - \( \pi^{\pm} \)-production in \( \pi^- + C \) \[^2\] and \( p + C \) \[^3\]
  - \( \rho^0 \)-production in \( \pi^- + C \) \[^4\]
  - \( \bar{p} \)-production in \( \pi^- + C \) \[^5\]


Nuclear Fragmentation and Galactic Cosmic Rays

\[
\frac{\bar{p}}{p} \sim \Theta(p \rightarrow \bar{p}) \cdot S_{\text{ISM}}(x) \, dx
\]

Properties of elementary particle fluxes

Preliminary data, refer to upcoming AMS PRL publication
Nuclear Fragmentation and Galactic Cosmic Rays

\[ \frac{B}{C} \sim \int (C \rightarrow B) \cdot S_{\text{ISM}}(x) \, dx \]

[Graph showing \( B/C \) vs. \( R \) in GV with data points from PAMELA 2014 and AMS 2016]
Nuclear Fragmentation and Galactic Cosmic Rays

\[ \frac{B}{C} \sim \sigma(12C \rightarrow B) \cdot S_{\text{ISM}}(x) \, dx \]

\[ R \, [\text{GV}] \]

\[ E \, [\text{GeV/n}] \]

\[ \sigma(12C \rightarrow B) \, [\text{mb}] \]

CR sources \hspace{1cm} \text{interstellar matter (ISM)}

AMS 2016
PAMELA 2014
Evoli+2019
Nuclear Fragmentation and Galactic Cosmic Rays

\[ \frac{B}{C} \sim \sigma(C \rightarrow B) \cdot \frac{S_{\text{ISM}}(x) \, dx}{R \text{ [GV]}} \]

- **CR sources**
- **interstellar matter (ISM)**

**Graph 1:**
- Evoli+2019 in blue
- Cross section uncertainty

**Graph 2:**
- PAMELA 2014
- AMS 2016

**Graph 3:**
- \( \sigma(^{12}C \rightarrow B) \text{ [mb]} \)
- \( E \text{ [GeV/n]} \)
Nuclear Fragmentation and Galactic Cosmic Rays

\[ \frac{B}{C} \sim \Phi(C \rightarrow B) \cdot S_{1ms}(x) \, dx \]

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**Graph:**

- **Evoli+2019**
- **Cross section uncertainty**

**Axis:**
- **R [GV]**
- **B/C**

**Data Points:**
- **PAMELA 2014**
- **AMS 2016**
- **NA61/SHINE**

**Additional Graph:**

- **σ(^{12}C \rightarrow B) [mb]**
- **E [GeV/n]**

**Data Points:**
- **Korejwo**
- **Webber-2**
- **Webber-3**
- **Fontes-1**
- **Davids**
- **Olson**
- **Roche**

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**Images:**

- **CR sources**
- **Interstellar matter (ISM)**
- **AMS POCC**

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**Title:**

Nuclear Fragmentation and Galactic Cosmic Rays
Nuclear Fragmentation with SPS and NA61/SHINE

Pb \( \rightarrow \) Be

from SPS

\[ 4\text{He} \quad 12\text{C} \]

Pb fragments

H2 beamline

A/2 = 2

NA61/SHINE

P target

MB

12C fragments

SCNT

ToF + Z²
2018 Pilot Run on Nuclear Fragmentation

composition of secondary ion beam measured during data taking:

- primary Pb beam on Be target, rigidity selection in H2 beam line
- special H2 beamline optics (simulation and operation by N.Charitonidis)
- three days of data taking at 27 GV
- $1.1 \times 10^6$ beam trigger on $Z^2 = 36$
- offline selection: $3.6 \times 10^5$ $^{12}$C beam particles
- $20k (^{12}\text{C}+\text{CH}_2)$ and $17k (^{12}\text{C}+^{12}\text{C})$ interactions
2018 Pilot Run on Nuclear Fragmentation

"C+p = (C+CH₂) - (C+C) - OUT"

ToF(A to S1) + dE/dx(S1) → (A, Z²)_{beam}

Δ + dE/dx(MTPC) → (A, Z²)_{fragment}
12 C Beam Selection

triggered beam composition:

offline beam selection:

- 12 C purity: 99.2%
- B contamination: <0.1%
Identification of Isotopes Produced in Target (MTPC)

![Graph showing particle charge from dE/dx with B-selection indicated by red arrows.](image)

- Li fragments
- Be fragments
- B fragments
- C beam
- N beam
- Target in
- Target out

B-selection indicated by red arrows
Direct $^{10}\text{B} + ^{11}\text{B}$ Production (NA61/SHINE preliminary at ICRC19)

$$\sigma(^{12}\text{C} + p \rightarrow ^{10}\text{B} + X) + \sigma(^{12}\text{C} + p \rightarrow ^{11}\text{B} + X) = 47.7 \pm 3.0 \text{ (stat.)} \pm 2.3 \text{ (syst.)} \text{ mb}$$

**Graph**

- Red: World $^{10}\text{B}$
- Blue: World $^{11}\text{B}$
- Black: World $^{10}\text{B} + ^{11}\text{B}$
- Red filled circle: NA61/SHINE $^{10}\text{B} + ^{11}\text{B}$ preliminary

Fit: Evoli+19, Data: Korejwo+02, Korejwo+99, Webber+98, Webber90, Olson+83, Fontes+77
Summary

2018 Pilot Run on Nuclear Fragmentation:

- demonstrated unique capabilities of NA61/SHINE + SPS for nuclear fragmentation measurements
- preliminary results presented at ICRC2019
- test data already useful to constrain asymptotic $\sigma(^{12}\text{C} + p \rightarrow B + X)$

Future Plans:

- precise reaction data base for Galactic cosmic-ray studies

Many thanks to the CERN PH, BE and EN Departments for the strong support of NA61/SHINE!
Additional Material
Charge-Changing $^{12}\text{C} + ^{12}\text{C}$ and $^{12}\text{C} + \text{CH}_2$ Cross Section

$^{12}\text{C} + ^{12}\text{C} \rightarrow (Z<6) + X$

$^{12}\text{C} + \text{CH}_2 \rightarrow (Z<6) + X$

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<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\sigma$ [mb]</th>
<th>stat. [mb]</th>
<th>sys. [mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C + CH$_2 \rightarrow (Z &lt; 6) + X$</td>
<td>1179</td>
<td>$\pm 24$</td>
<td>$\pm 1$</td>
</tr>
<tr>
<td>C + C → (Z &lt; 6) + X</td>
<td>755</td>
<td>$\pm 16$</td>
<td>$\pm 3$</td>
</tr>
<tr>
<td>C + p → (Z &lt; 6) + X</td>
<td>217</td>
<td>$\pm 9$</td>
<td>$\pm 2$</td>
</tr>
</tbody>
</table>
Upstream $^{12}$C Selection (logarithmic scale)

fractional impurity $f(i) = N_i/N_{tot}$ of selected beam:

$f(^{11}\text{C}) = 0.0035$
$f(\text{N}) = 0.0016$
$f(^{13}\text{C}) = 0.0018$
$f(\text{B}) = 0.0007$
$f(^{14}\text{C}) = 0.0000$

$f(\text{tot}) = 0.0076$
Corrections and Systematics

Corrections (B)

- beam impurity \( \leq 0.01 \text{ mb}^1 \)
- B reinteraction in target +1.4 \text{ mb}^{1,2} 
- B reinteraction in detector +3.9 \text{ mb}^1 
- MTPC B cut +0.08 \text{ mb}^1 
- \(^{12}\text{C}\) interaction in detector -0.2 \text{ mb}^1 

Systematics (B)

- target thickness 0.2 \text{ mb} 
- beam impurity 0.01 \text{ mb} 
- B reinteraction in target 0.3 \text{ mb} 
- B reinteraction in detector 1.4 \text{ mb} 
- MTPC B cut 0.08 \text{ mb} 
- \(^{11}\text{B}/^{10}\text{B}\) reinter difference 0.03 \text{ mb} 
- undetermined measurement equation 1.8 \text{ mb} 

\(^1\) from data, \(^2\) model
## Measured Interaction Probabilities

<table>
<thead>
<tr>
<th>Target</th>
<th>(N_{\text{beam}})</th>
<th>(N_{^{12}\text{C}})</th>
<th>(N_B)</th>
<th>(P_{C \rightarrow (Z&lt;6)})</th>
<th>(P_{C \rightarrow B})</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH(_2)</td>
<td>171399</td>
<td>151871</td>
<td>2259</td>
<td>0.1139 ± 0.0008</td>
<td>0.0132 ± 0.0003</td>
</tr>
<tr>
<td>C</td>
<td>147692</td>
<td>131172</td>
<td>1530</td>
<td>0.1119 ± 0.0008</td>
<td>0.0104 ± 0.0003</td>
</tr>
<tr>
<td>OUT</td>
<td>37926</td>
<td>36111</td>
<td>174</td>
<td>0.0479 ± 0.0011</td>
<td>0.0046 ± 0.0004</td>
</tr>
</tbody>
</table>
Interactions in Detector Volume

Tracks of Fragments (13 A GeV/c, Magn. Field Scale Factor: 70%, VTPC-1 only)

- $^{10}$B
- $^{11}$B
- $^{10}$C
- $^{11}$C

Run Settings

2018 V0 Vertices
Interactions in Detector Volume
Cut on G/VTPC dE/dx:

⇒ $P_{\text{OUT}}(C \rightarrow B) = 0.8\% \rightarrow 0.5\%$