Cosmic-ray propagation with a semi-analytical approach

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Qui-Nhon, July 24th, 2017
Annecy-Le-Vieux, FRANCE
Some results of this presentation are directly output from USINE

USINE by David Maurin
Public release in october !

USINE V3.3

USAGE:
./bin/usine_run -l => Local flux calculation, show only selected quantities
./bin/usine_run -m1 => List of fit-able parameters
./bin/usine_run -m2 => Chi2 minimisation on TOA fluxes (best chi2)
./bin/usine_run -t => Text-user interface (interactive run)
Precision era for CRs

Composition of cosmic rays:

|| Particle       | Fraction |
|-----------------|----------|
| protons         | 85%      |
| helium nuclei   | 12.5%    |
| heavier nuclei  | 1%       |
| Electrons       | 1.5%     |

⇒ Very small fraction of other things than proton and helium.

Precision era for CRs

Composition of cosmic rays:

<table>
<thead>
<tr>
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<tbody>
<tr>
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⇒ Very small fraction of other things than proton and helium.

⇒ 1 $e^+/10^3$ Protons, 1 $\bar{p}/10^4$ Protons!

Precision era for CRs

Composition of cosmic rays:

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⇒ Very small fraction of other things than proton and helium.

⇒ \(1 e^+/10^3\) Protons, \(1 \bar{p}/10^4\) Protons!

Indirect dark matter searches

The Principle:

\[ \chi \rightarrow \bar{p}, e^+, \ldots \]

\[ \chi \rightarrow \nu, \gamma, \ldots \]
Indirect dark matter searches

The Principle:

A fair evaluation of the astrophysical background is needed!
Example: the secondary antiprotons

Semi-analytical treatment agree...

Example: the secondary antiprotons

...with numerical treatment!

Introduction

Semi-analytical approach

Hints for a new propagation paradigm?

Conclusion & Prospects
Introduction

Semi-analytical approach

Hints for a new propagation paradigm?

Conclusion & Prospects
The propagation of CRs

CRs diffuse in the turbulent magnetic field..

..and undergo a large variety of processes
The propagation of CRs
The propagation equation

- Source term \( q_a \propto R^{-\alpha} \), \( \alpha \in [2, 2.5] \)

\[
\frac{\partial f_a}{\partial t} = q_a
\]
The propagation equation

- **Source term** \( q_a \propto R^{-\alpha}, \alpha \in [2, 2.5] \)
- **Diffusion in phase space** \( K = K_0 \beta R^\delta \)

\[
\frac{\partial f_a}{\partial t} - \nabla_x (K \nabla_x f_a) - \nabla_p (D \nabla_p f_a) = q_a
\]
The propagation equation

- **Source term** $q_a \propto R^{-\alpha}$, $\alpha \in [2, 2.5]$

- **Diffusion in phase space** $K = K_0 \beta R^\delta$

- **Convection**

\[
\frac{\partial f_a}{\partial t} - \nabla_x (K \nabla_x f_a) - \nabla_p (D \nabla_p f_a) + V_c \cdot \nabla_x f_a - \frac{1}{3} (\nabla_x V_c) p \frac{\partial f_a}{\partial p} = q_a
\]
The propagation equation

- **Source term** \( q_a \propto R^{-\alpha} \), \( \alpha \in [2, 2.5] \)
- **Diffusion in phase space** \( K = K_0 \beta R^\delta \)
- **Convection**
- **Interaction with the ISM**

\[
\frac{\partial f_a}{\partial t} - \nabla_x \cdot (K \nabla_x f_a) - \nabla_p \cdot (D \nabla_p f_a) + V_c \cdot \nabla_x f_a - \frac{1}{3} (\nabla_x \cdot V_c) p \frac{\partial f_a}{\partial p} + \nabla_p (b(p)f_a) + \sigma_a v_a n_{ISM} f_a = q_a + \sum_{Z_\beta > Z_a}^{Z_{max}} \sigma b \rightarrow a v_b n_{ISM} f_b
\]
The propagation equation

- **Source term** \( q_a \propto R^{-\alpha}, \ \alpha \in [2, 2.5] \)

- **Diffusion in phase space** \( K = K_0 \beta R^\delta \)

- **Convection**

- **Interaction with the ISM**

- **Radioactivity**

\[
\frac{\partial f_a}{\partial t} - \nabla_x( K \nabla_x f_a ) - \nabla_p(D \nabla_p f_a) + V_c \cdot \nabla_x f_a - \frac{1}{3} (\nabla_x V_c) p \frac{\partial f_a}{\partial p} + \nabla_p (b(p) f_a) + \sigma_a v_a n_{ISM} f_a + \frac{f_a}{\tau_a} = q_a + \sum_{Z_{\beta} \geq Z_a} \sigma_{\beta \rightarrow a} v_b n_{ISM} f_b + \frac{f_b}{\tau_b}
\]
Simplifications of the equation

Our motto.. Reduce the computing time without losing the physics!

Observable ? \( \psi (E, r, t) \)

At the Earth Now!

Simplifications by studying the time scales of the processes at stake

and / or

1st

Neglect terms in the equation

2nd

Geometrical assumptions based on the typical length probed by CRs

Both are energy dependent!
Timescales of propagation processes

$^7\text{Li} \quad - \quad ^{12}\text{C} \quad - \quad ^{56}\text{Fe}$
Timescales of propagation processes

\[ \text{\textsuperscript{7}Li} \quad \text{\textsuperscript{12}C} \quad \text{\textsuperscript{56}Fe} \]
Timescales of propagation processes

$^7\text{Li} - ^{12}\text{C} - ^{56}\text{Fe}$
1st Neglect terms in the equation

\[ ^7\text{Li} - ^{12}\text{C} - ^{56}\text{Fe} \]
1st Neglect terms in the equation

$^7\text{Li} - ^{12}\text{C} - ^{56}\text{Fe}$

![Graph showing timescales vs. kinetic energy per nucleon (GeV/nuc).](image)
Neglect terms in the equation

Limiting behavior for $\psi = 4\pi p E f_a$

($a$ stable)

Low Energy:

$$\partial_t \psi + \partial_E \{ b^{\text{loss}}(E) \psi - D(E) \partial_E \psi \} = Q$$

Intermediate Energy:

$$\partial_t \psi + \nabla_x (V_C \psi - K \nabla_x \psi) + \partial_E \{ b^{\text{loss}}(E) \psi - D(E) \partial_E \psi \} + \Gamma \psi = Q$$

High Energy:

$$\partial_t \psi + \nabla_x (K \nabla_x) \psi = Q$$
Sources and gas pinched inside the disk.
2nd Geometrical assumptions

Sources and gas pinched inside the disk.
2nd Geometrical assumptions

Typical length probed by CRs

@1GeV for $L \sim 10\text{kpc}$ the distance probed $\sim 2\text{kpc}$


**Typical assumptions → USINE**

**Standard approximations :**

- Continuous source term in space and time → steady state regime
- Homogeneous diffusion : $K(E, r)$
- Cylindrical symmetry of the diffusive halo :

$$\psi_a(E_{kn}, r, z) = \sum_{i} \psi_{a}^{i}(E_{kn}, z) J_0(\xi_{i} \frac{r}{R_{gal}})$$

- For a diffusive halosize $L < R_{Gal}$ → 1D approximation
- Source disk thickness $h \ll L$ the diffusive halo size :

$$n \rightarrow 2h\delta(z)n$$

$$b_{loss} \rightarrow 2h\delta(z)b_{loss}$$

**Assumptions required by the SA treatment :**

- The ISM density $n$ does not depend on the radius $r$
- Pinched reacceleration and galactic wind gradient :

$$K_{pp} \rightarrow 2h\delta(z)K_{pp}$$

$$\nabla_x.V_c \rightarrow 2h\delta(z)\nabla_x.V_c$$
Simplified equation and degeneracies

Example in the 1D case, the two variables are \((z, E)\):

\[
\partial_z (V_C \psi) - K \partial_z \psi + \partial_E \{ b^{loss}(E) \psi - D(E) \partial_E \psi \} + \Gamma \psi = Q
\]

This equation can be cast into the form,

\[
u + \alpha(x) \frac{d}{dx} \left[ \beta(x) u - \gamma(x) \frac{du}{dx} \right] = u^0,
\]

...and solved with a Crank Nicholson scheme.

Complete degeneracies for a stable nuclei \(a\):

- \(V_C, K_0, D\) are degenerated with \(n_{ISM}\)
- \(K_0\) and the halo size \(L\)
Summary about the SA approach

- Fast computing time (e.g. MCMC)
- Clear physical dependencies of the result

- A new solution for each model tested
- Lack of flexibility (e.g. homogeneous K)

Although..mathematical tricks can be used!

e.g. the pinching method presented by Mathieu

To compare the results of different analyses, consistency checks with numerical code should be performed!
Introduction

Semi-analytical approach

Hints for a new propagation paradigm?

Conclusion & Prospects
Features in cosmic-ray spectra

http://www.physics.utah.edu/whanlon/spectrum.html
Most beautiful powerlaw in nature?

\[ \Psi \propto E^{-2.7+\Delta} \quad \Rightarrow \quad \Delta_{knee} \approx -0.3 \quad \Delta_{ankle} \approx +0.37 \]
Features in cosmic-ray spectra

\[ \Rightarrow \text{A universal kinck at } R \geq 200 \text{ GV} \ ? \ \Delta_{\text{kinck}} \approx 0.12 - 0.13 \]
Features in cosmic-ray spectra

Yang presentation, XSCR, march 2017

⇒ A universal kinck at $R \geq 200\text{GV}$? $\Delta_{kinck} \approx 0.12 - 0.13$
Origin of the break?

Standard expectation?
Origin of the break?

⇒ Explanation 1: break in the diffusion coefficient?

Origin of the break?

\[ \Phi(R) \propto \frac{q}{K} \propto R^{-\alpha} \propto R^{-\alpha+\Delta\alpha} \]

\[ K(R) \propto R^{\delta} \]

⇒ Explanation 2: break in the source spectrum?


Origin of the break?

$\Phi(R) \propto \frac{q}{K} = \propto R^{-\alpha}$

$K(R) \propto R^{\delta}$

$\Phi(R) \propto R^{-\alpha-\delta}$

$\Rightarrow \textbf{Explanation 3 : local source contribution?}$


Origin of the break?

⇒ **Explanation 3**: local source contribution?


⇒ **Explanation 1**: break in the diffusion coefficient?

*Indications for a high-rigidity break in the cosmic-ray diffusion coefficient, Preprint arxiv: 1706.09812*
Origin of the break?

⇒ Explanation 3: local source contribution?


⇒ Explanation 1: break in the diffusion coefficient?

Indications for a high-rigidity break in the cosmic-ray diffusion coefficient, Preprint arxiv: 1706.09812
Explanation 1: a break in the diffusion coefficient?
The break in secondary fluxes

\[ \Phi(R) \propto \frac{q}{K} = \]

\[ q(R) \propto R^{-\alpha} \quad \text{Primary flux} \]

\[ K(R) \propto R^\delta - \Delta \delta \]

\[ \Phi(R) \propto R^{-\alpha - \delta} \]

\[ \Phi(R) \propto R^{-\alpha - \delta + \Delta \delta} \]
The break in secondary fluxes

\[ \Phi(R) \propto \frac{q}{K} = \]

Primary flux

Secondary flux

\[ \propto R^{\delta - \Delta \delta} \]

\[ K(R) \]

\[ \propto R^{\delta} \]

\[ \Phi(R) \]

\[ \propto R^{-\alpha - \delta} \]

\[ \Phi^{\text{sec}}(R) \]

\[ \propto R^{-\alpha - \delta} \]

\[ K(R) \]

\[ \propto R^{\delta} \]

\[ \propto R^{\delta - \Delta \delta} \]
The break in the B/C ratio

Secondary flux = Primary flux

\( \Phi^\text{sec}(R) \propto R^{-\alpha - \delta} \)

\( \Phi(R) \propto R^{-\alpha - \delta + \Delta\delta} \)
The break in the B/C ratio

Secondary flux

Primary flux

\[ \phi_\text{sec}(R) \propto R^{-\alpha-\delta} \]

\[ \phi(R) \propto R^{-\alpha-\delta} \]

\[ \frac{\phi_\text{sec}(R)}{\phi(R)} \propto R^{-\delta} \]

\[ \phi_\text{sec}(R) / \phi(R) \propto R^{-\delta+\Delta\delta} \]
The break in the B/C ratio

⇒ One should observe a break in the B/C ratio!
Theoretical motivations?

**Two zones model:**


\[
K(z, \rho) = \begin{cases} 
  k_0 \beta \rho^\delta \sim 0.3 & \text{for } |z| < \xi L \text{ (inner halo)} \\
  k_0 \beta \rho^\delta + \Delta \sim 0.8 & \text{for } |z| > \xi L \text{ (outer halo)} 
\end{cases}
\]

Turbulence is different between the halo (SNRs) and the disk (CR-driven)

**Damping of CRs on self generated plasma waves:**


Coupled system of equations:

\[
\begin{align*}
  \frac{\partial}{\partial k} \left[ D_{kk} \frac{\partial W}{\partial k} \right] + \Gamma_{CR} W &= q_W(k), \\
  -\frac{\partial}{\partial z} \left[ D \frac{\partial f}{\partial z} \right] + v_A \frac{\partial f}{\partial z} - \frac{dv_A}{dz} \frac{\partial f}{\partial p} &= q_{CR}(z, p)
\end{align*}
\]
The break in the B/C ratio

The break in the B/C ratio

Fit: $B/C = k R^{-\delta}$
$R > 65 \text{ GV}$

$\delta = 0.333 \pm 0.014(\text{fit}) \pm 0.005(\text{syst})$

The break in the B/C ratio

Featureless B/C ratio?

Fit: \( B/C = kR^{-\delta} \)
\( R > 65 \text{ GV} \)

\( \delta = 0.333 \pm 0.014(\text{fit}) \pm 0.005(\text{syst}) \)

Not related to \( \delta \) of \( K(R) \propto R^\delta \)

Spallation processes are still at stake!

Test of the break hypothesis

We compare the two cases:

\[
K(R) = K_0 \beta (R/GV)^\delta \quad \text{or} \quad K_0 \beta \frac{(R/GV)^\delta}{\left\{1 + (R/R_b)^{\Delta \delta/s}\right\}^s}
\]

Methodology:

- Semi analytical code **USINE** used.
- High-energy fit of the B/C, above \( R_{min} = 15 \) GV.
- Fixed number of free parameters: only \( \delta \) and \( K_0 \).
- \( V_a, V_c, R_b, \Delta \delta, s \) are treated as nuisance parameters.
- Fit quality comparison: w/ and w/o the break.
- Study of the robustness of the result.

⇒ Our goal is not to provide benchmark parameters over the all energy range.
First step: fix the break

⇒ Combined fit of AMS-02 proton and helium fluxes

\[ \Phi_{H/He} = C_{H/He} \left( \frac{R}{45 \text{ GV}} \right)^\gamma \left\{ 1 + \left( \frac{R}{R_b} \right)^{\Delta \delta/s} \right\}^s \]

This fixes the break parameters in:

\[ K(R) = K_0 \beta \left( \frac{R}{\text{GV}} \right)^\delta \left\{ \frac{1}{1+(R/R_b)^{\Delta \delta/s}} \right\}^s \]
Second step: fit of the B/C ratio

- **H1** (without):
  \[ \chi^2 = 62 \]
  \[ \delta = 0.52 \]
  \[ K_0 = 7.4 \times 10^2 \text{kpc}^2 \text{Myr}^{-1} \]

- **H2** (with):
  \[ \chi^2 = 50 \]
  \[ \delta = 0.53 \]
  \[ K_0 = 7.1 \times 10^2 \text{kpc}^2 \text{Myr}^{-1} \]

- \[ \Delta \chi^2 = 12 \]
  *decisive evidence!*
  (in Bayesian terms)

*H. Jeffreys (1961).*
Third step: robustness of the result

1st effect which can mimic a break: E-dependent XS


Usually taken flat above $\sim 5\text{GeV/nuc}$

Enhancement observed in:
- $pp$ collisions
- Air showers experiments
- Increasing interaction range


\[
\frac{J_B(E_k)}{J_C} = \text{H.E.} \sum_{Z_b \geq Z_C} \sigma_{b \rightarrow B} \frac{J_b}{J_C} / \{ \sigma_{\text{diff}} + \sigma_B \}
\]

$\Rightarrow$ We calibrate this enhancement on $\sigma_{pp}^{\text{tot}}$

Third step: robustness of the result

E-dependent XS

- **H1 (without)**:
  \[ \chi^2 = 59 \]
  \[ \delta = 0.52 \]
  \[ K_0 = 7.4 \times 10^2 \text{kpc}^2 \cdot \text{Myr}^{-1} \]

- **H2 (with)**:
  \[ \chi^2 = 48 \]
  \[ \delta = 0.53 \]
  \[ K_0 = 7.1 \times 10^2 \text{kpc}^2 \cdot \text{Myr}^{-1} \]

- \[ \Delta \chi^2 = 11 \]
  
  *decisive evidence!*  
  (in Bayesian terms)  
  
  *H. Jeffreys (1961).*
Example of the boron to carbon ratio

2\textsuperscript{nd} effect which can mimic a break: **primary boron**

The boron may not be a pure secondary species.

Probability of a carbon nuclei to interact during acceleration:

\[ r \sigma_{B \rightarrow C} n_{ISM} \tau \sim 1\% \]

We expect an effective source term

\[ Q_B / Q_C \approx 1\% \]
Third step: robustness of the result

**Primary B (1%)**

- **H1** (without):
  
  \[ \chi^2 = 52 \]
  \[ \delta = 0.54 \]
  \[ K_0 = 7.2 \times 10^2 \text{kpc}^2 \text{Myr}^{-1} \]

- **H2** (with):
  
  \[ \chi^2 = 42 \]
  \[ \delta = 0.55 \]
  \[ K_0 = 6.9 \times 10^2 \text{kpc}^2 \text{Myr}^{-1} \]

\[ \Delta \chi^2 = 10 \]  
*decisive evidence!*

(in Bayesian terms)

*H. Jeffreys (1961).*
Third step: robustness of the result

Uncertainties in the inputs:

- Spallation XS
- GALPROP (GAL) Webber 2003 (W03)

Data uncertainties:

- Total Statistical
- $\sigma_{\text{tot}}$
- $\sigma_{\text{stat}}$

$\Rightarrow$ In all cases the decisive evidence is confirmed.
Discussion...

⇒ Indication for a diffusive explanation of the spectral breaks

⇒ The spectral shape of B/C can be completely explained by $\frac{Q_B}{Q_C} \sim 5\%$ but:

i) We lose the common explanation for the breaks

ii) Lead to $\delta \sim 0.8$ in tension with antiprotons and anisotropy.

⇒ Direct consequences for DM indirect searches

⇒ Enlarge data set in needed (Li, B, Be, C, N, O, ..) @ $\sim 100\text{GeV}$-$1\text{TeV}$.

⇒ Further data from AMS-02, CALET, DAMPE, ISS-CREAM are eagerly awaited!
Introduction

Semi-analytical approach

Hints for a new propagation paradigm?

Conclusion & Prospects
Conclusion & Prospects

Claims for DM discovery from CRs only have to wait!

⇒ Propagation processes are not yet under control!
  ⇒ This is partly due to dramatic low quality XS data

⇒ More advance scenarios of propagation should be tested
  ⇒ anisotropic, inhomogeneous..

⇒ Till now the semi-analytical approach has proven very usefull!
  ⇒ Gives a first order understanding of CR fluxes
  ⇒ Learns us the physics through toy models and simplifications
  ⇒ Completely complementary with the numerical approach

Public version of USINE in october!
Questions
BACKUP
Primary boron

1st This determination is model dependent..

Example: boron may not be a pure secondary species.

Well motivated in literature:


⇒ Used to explain anti particle excess!
Primary boron

Parametric study in:


⇒ Scan over $\frac{N_B}{N_C}$ with preliminary AMS02 data.
⇒ Few percent of contamination of primary boron $\rightarrow$ 30% uncertainty on delta!
**XS problem**

This determination relies on very unprecise data.

\[
\frac{J_B}{J_C}(E_k) = \sum_{Z_b \geq Z_C} Z_{max} \sigma_{b \to B} \frac{J_b}{J_C} / \left\{ \sigma_{\text{diff}} + \sigma_B \right\}
\]


Summary of the evidence in all cases

<table>
<thead>
<tr>
<th>Fit cases</th>
<th>Fiducial</th>
<th>Cross section enhanced</th>
<th>Primary boron $Q_B/Q_C = 1%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error</td>
<td>w/o break</td>
<td>w/ break</td>
<td>w/o break</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\rm stat}$</td>
<td>$K_0$ $\delta$ $\chi^2$</td>
<td>$K_0$ $\delta$ $\chi^2$</td>
</tr>
<tr>
<td>W03</td>
<td></td>
<td>2.7 0.67 197</td>
<td>2.7 0.68 164</td>
</tr>
<tr>
<td>GAL</td>
<td></td>
<td>4.3 0.62 160</td>
<td>4.3 0.62 131</td>
</tr>
<tr>
<td>$\sigma_{\rm tot}$</td>
<td>W03</td>
<td>4.5 0.58 84</td>
<td>4.3 0.59 68</td>
</tr>
<tr>
<td></td>
<td>GAL</td>
<td>7.4 0.52 62</td>
<td>7.1 0.53 50</td>
</tr>
</tbody>
</table>

TABLE I: Best fit values for $K_0$ (in units of $10^2$ kpc$^2$.Myr$^{-1}$) and $\delta$, using AMS-02 B/C data above $R_{\min} = 15$ GV. The number of degrees of freedom is $46 - 2 = 44$. For each cases described in the paper, we compare the best $\chi^2$ with and without the break. Two different spallation cross-section (Spal. XS) datasets are tested, i.e., GALPROP (GAL) and Webber (W03), as well as different choices for the data uncertainties.
Correlations of the break parameters:

- $1/R_b$ (GV)
- $\delta$
- $\Delta$
- $s$

Graphs showing distributions and correlations with axes and data points.
Scan on $R_{\text{min}}$

$\Delta \chi^2 = \chi^2_{\text{w/o break}} - \chi^2_{\text{w/ break}}$

$\sigma_{\text{stat}}$

$\sigma_{\text{tot}}$

$W_{03}$

GAL

$W_{03}$

GAL

Rigidity $R_{\text{min}}$ [GV]
Status of antiprotons

**NEWS** : Two PRLs pointing toward an excess around $\sim 20\text{-}80$ GeV consistent with the *Galactic center gamma-ray excess.*


$\Rightarrow$ Compatibility numerical vs analytical codes?

$\Rightarrow$ tertiary contribution under control?

Refinement of this prediction includes:

$\rightarrow$ Refreshing XS measurement *Donato et al arXiv:1704.03663.*

$\rightarrow$ Recalibrating the propagation parameters from i.e. B/C

$\rightarrow$ Better understanding of the solar modulation
Main channels contributing to boron

XS dataset: **Webber 2003**  **Usine output!**

<table>
<thead>
<tr>
<th>Energy</th>
<th>1 GeV/nuc</th>
<th>10 GeV/nuc</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 step</td>
<td>74.6%</td>
<td>80.6%</td>
</tr>
<tr>
<td>2 steps</td>
<td>19.4%</td>
<td>15.9%</td>
</tr>
<tr>
<td>&gt;2 steps</td>
<td>6%</td>
<td>3.5%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy</th>
<th># of reactions</th>
<th>Total</th>
<th># of reactions</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;1%</td>
<td>28</td>
<td>7.2%</td>
<td>28</td>
<td>8.8%</td>
</tr>
<tr>
<td>[0.1%, 1%]</td>
<td>89</td>
<td>3.3%</td>
<td>90</td>
<td>3.5%</td>
</tr>
<tr>
<td>[0.01%, 0.1%]</td>
<td>276</td>
<td>0.7%</td>
<td>277</td>
<td>0.7%</td>
</tr>
<tr>
<td>&lt; 0.01%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reaction</th>
<th>11B ←12C</th>
<th>11B ←16O</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>33%</td>
<td>32.4%</td>
</tr>
<tr>
<td>11B ←16O</td>
<td>15.9%</td>
<td>18.8%</td>
</tr>
<tr>
<td>10B ←12C</td>
<td>10.3%</td>
<td>10.4%</td>
</tr>
<tr>
<td>10B ←16O</td>
<td>7.4%</td>
<td>9.0%</td>
</tr>
<tr>
<td>10B ←11B</td>
<td>2.3%</td>
<td>2.3%</td>
</tr>
<tr>
<td>10B ←15N</td>
<td>2.2%</td>
<td>1.7%</td>
</tr>
<tr>
<td>10B ←11B</td>
<td>1.5%</td>
<td>1.5%</td>
</tr>
<tr>
<td>11B ←24Mg</td>
<td>1.4%</td>
<td>1.4%</td>
</tr>
<tr>
<td>11B ←14N</td>
<td>1.3%</td>
<td>1.4%</td>
</tr>
<tr>
<td>11B ←14N</td>
<td>1.2%</td>
<td></td>
</tr>
<tr>
<td>11B ←13C</td>
<td>1.1%</td>
<td></td>
</tr>
<tr>
<td>11B ←20Ne</td>
<td>1.1%</td>
<td></td>
</tr>
<tr>
<td>11B ←28Si</td>
<td>1.0%</td>
<td></td>
</tr>
</tbody>
</table>
XS Precision measurements

⇒ Production XS are a limiting factor to reach the percent accuracy in modelling

► A few key channels should be measured with high accuracy (contribute to 50%)

► A huge number of individually-low-level contributions can make up up to 10%

⇒ Dominant production channels do not depend too much on the level of accuracy we presently have on the XS

In preparation: tables with channels ranking to define priorities of future nuclei XS measurements

In collaboration with David Maurin, Igor Moskalenko, Leslie M. Kerby