Extension of the INCL model to incident energies between 2 and 15 GeV

Pion production aspects

S. Pedoux, J. Cugnon

Based on
Pedoux, S. and Cugnon, J., Nucl. Phys. A (submitted)

IFPA, AGO, University of Liège, Belgium

30 Years of strong interactions

Université de Liège

Outline

Spallation reactions

Main features

- Nuclear reactions between a high energy projectile and a target nucleus
- Produce a lot of neutrons

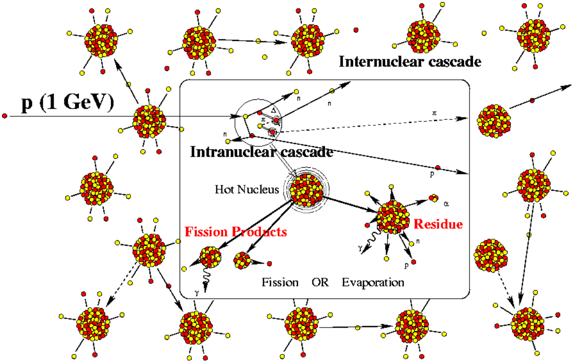
Applications

- Accelerator Driven System (e. g. MYRRHA)
- Radiation protection issue in space
- Hadrontherapy

Spallation reactions

2 stage description:

1. Intranuclear cascade $\Longrightarrow$ INCL4, ISABEL, etc.
2. Deexcitation $\Longrightarrow$ ABLA, GEM, etc.



Intranuclear cascade model of Liège

INCL 4.2

- Time-like Monte Carlo simulation,
- Describes spallation reactions,
- Developed and tested in the 40 MeV–2 GeV energy range,
- Included in Geant4 and MCNPX.

Complete description of the code:

A. Boudard, J. Cugnon, S. Leray and C. Volant, Phys. Rev. C **66** (2002), 044615

INCL is constantly under development:

- Light cluster emission,
- Light ion as projectile,
- Translation in C++

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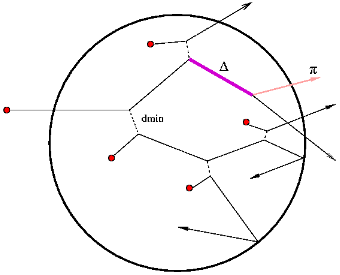
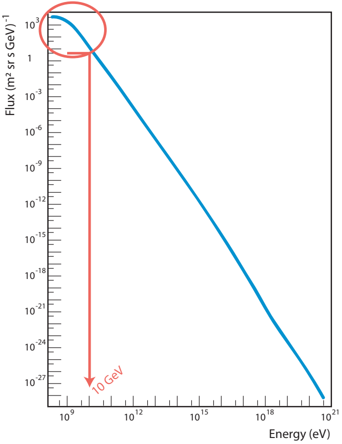
Collision treatment in INCL

1. Two particles reach their minimum distance of approach d_{min}
2. If σ_{Tot} is the total cross section for the two particles:
   if $\pi d_{min}^2 < \sigma_{tot}$ the two particles interact;
   if $\pi d_{min}^2 > \sigma_{tot}$ no interaction.
3. The outgoing channel is selected with a test based on Monte-Carlo methods and cross sections for the possible channels



INCL4+ABLA could be used for description of spallation in radiation protection against cosmic radiation



Energy spectrum for protons in galactic cosmic rays

- Mean energy $\sim$ 1 GeV
- $Max(Flux)$ around 0.6 GeV
- $Flux_{10\ GeV} \sim \frac{Flux_{Max}}{1000}$

Extension of INCL4 to incident kinetic energies up to $\approx$ 15 GeV

How to extend the model?

$\Rightarrow$ By addition of the opening inelastic NN and πN channels

Inelastic channels in INCL4.2

- $NN \Rightarrow N\Delta$
- $\Delta \Rightarrow \pi N$
- $\pi N \Rightarrow \Delta$

Nb: The only resonance in INCL4.2 is the Δ_{1232} resonance.

In the 2–15 GeV energy range:
Opening channels $\Rightarrow$ Resonances

Resonances

- 40+ resonances below 2.5 GeV,
- width from 100 to 500 MeV,
- overlap
- decay channels ⇒ mostly produce pions

In addition, we would need to describe resonances as objects with a definite mass, describe their propagation and their interaction with nucleons.

⇒ Alternative description:
Direct production of the nucleons and pions originating in the decay of the resonances

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Alternative description

Instead of considering all the resonances, we consider directly the asymptotically produced particles in NN and πN collisions.

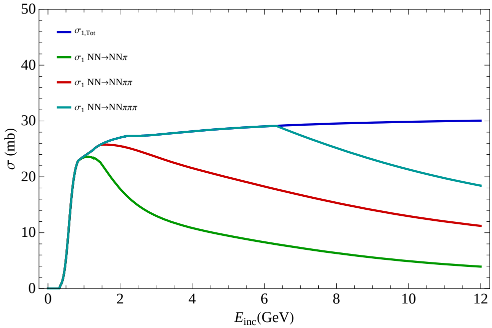
Ingredients

- Inelastic channel cross sections,
- Charge repartition model,
- Energy-momentum repartition model.

Cross sections

Following the procedure of Bystricky *et al.*[*] we use experimental data to reconstruct the cross section σ_T, with total isospin T:

- $\sigma_T(NN \to NNa\pi)$ with $a = 1,\ 2,\ 3$ or 4, and $T = 0$ or 1
- $\sigma_T(\pi N \to Na\pi)$ with $a = 2,\ 3$ or 4, and $T = \frac{1}{2}$ or $\frac{3}{2}$



[*] J. Bystricky *et al.*, J. Physique **48** (1987), 1901-1924.

Charge repartition model

Based on isospin symmetry and Clebsch-Gordan coefficients
Assumption: produced pions are in the lowest angular momentum state

Nucleon-Nucleon collision

1 and 2 pion(s) production: uniquely determined
3 and 4 pions production: charge repartition connected to the 2 pion production probabilities:

- $P(pp \rightarrow nn\pi^+\pi^+\pi^0) = P(pp \rightarrow nn\pi^+\pi^+)$
- $P(pp \rightarrow np\pi^+\pi^0\pi^0) = \frac{1}{3}P(pp \rightarrow np\pi^+\pi^0)$
  $P(pp \rightarrow np\pi^+\pi^+\pi^-) = \frac{2}{3}P(pp \rightarrow np\pi^+\pi^0)$

The factors 1/3 and 2/3 are proportional to the degeneracy of the neutral components

$\pi - N$ collisions: same procedure is applied

Energy-momentum repartition model

Uniform phase space distribution

Energy-momentum repartition model

Modified phase space distribution

$\Rightarrow$ Bias on the first emitted nucleon:

$$\frac{dP}{dt} \propto e^{Bt}$$

where t is the squared momentum transfer of the nucleon
B is a constant determined from phenomenology:

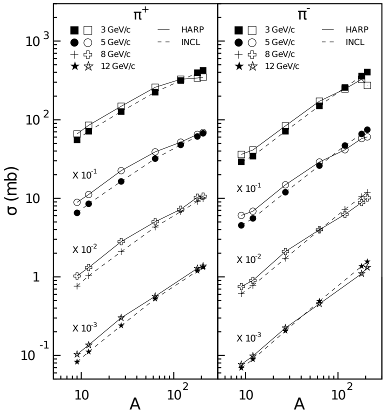
- $N - N$: $B = 6 \ GeV^{-2}$
- $\pi - N$: $B = 15 \ GeV^{-2}$

Total pion yield

Comparison between INCL HE and HARP data

Total cross sections

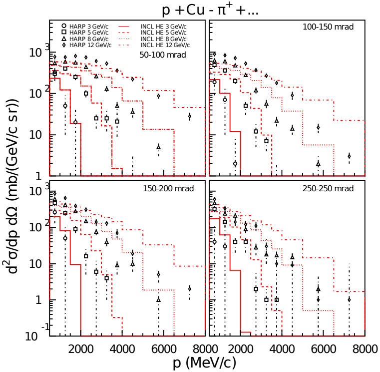
- **Projectile** p
- **Target** Be, C, Al, Cu, Sn, Ta, Pb
- **Energy** 3, 5, 8 and 12 GeV/c
- **Ejectiles** π^+ (left), π^- (right)
- **Angular domain** 350 to 2150 mrad
- **Energy domain** 150 to 400-750 MeV/c (depending upon the angles)



Double-differential cross sections

Double-differential cross sections

- **Projectile** p
- **Target** Cu
- **Energy** 3, 5, 8 and 12 GeV/c
- **Ejectiles** π^+
- **Angular domain** 150 to 250 mrad and 350-2150 mrad
- **Energy domain** 0 to 8000 MeV/c and 150 to 400-750 MeV/c (depending upon the angles)



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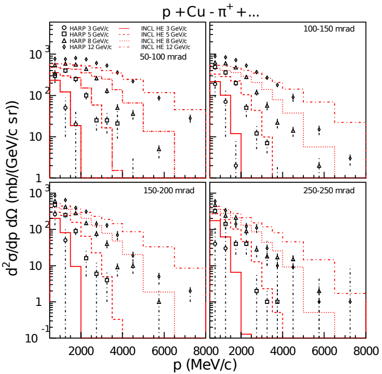

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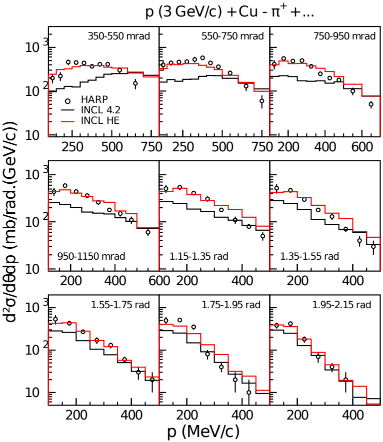

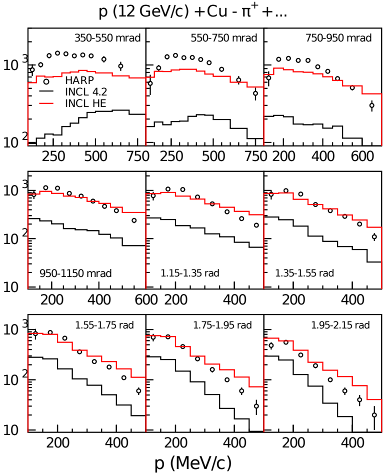

Double-differential cross sections

Double-differential cross sections

- **Projectile** p
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- **Energy** 3, 5, 8 and 12 GeV/c
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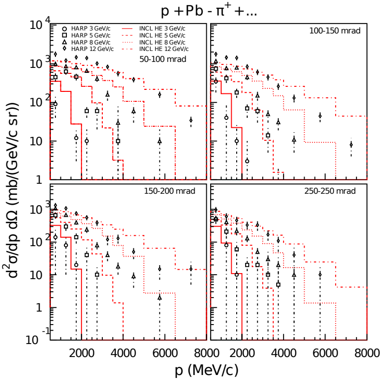

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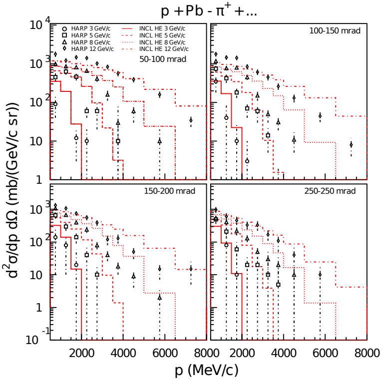

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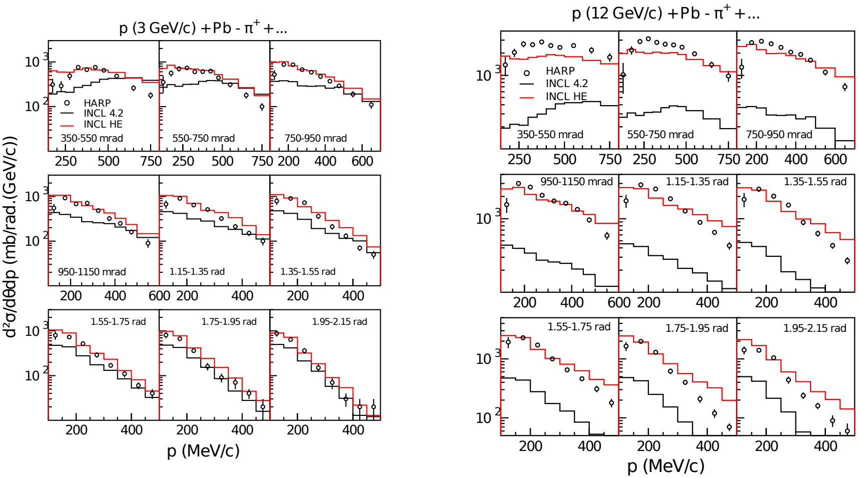
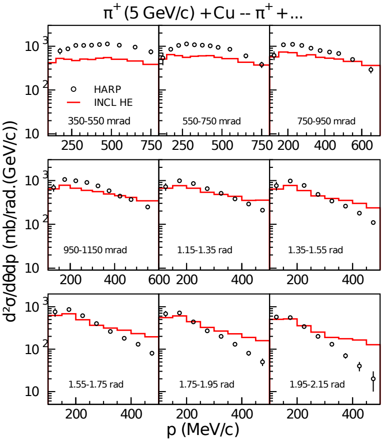


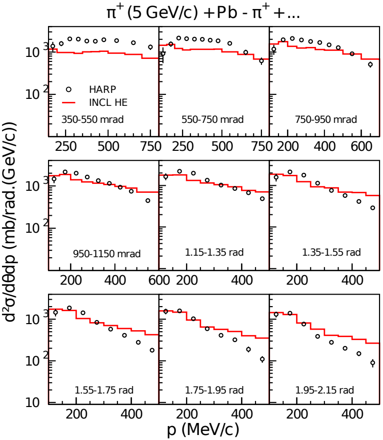
Double-differential cross sections

Double-differential cross sections

- **Projectile** π^+
- **Target** Cu, Pb
- **Energy** 5 GeV/c
- **Ejectiles** π^+
- **Angular domain** 350-2150 mrad
- **Energy domain** 150 to 400-750 MeV/c (depending upon the angles)

Double-differential cross sections





Conclusion

- Extension of the domain of validity of INCL4.2
  - Cross sections parametrization
  - Model for the charge repartition
  - Model for the energy-momentum repartition
- Comparison with a large set of data
  $\Rightarrow$ Rather good agreement despite the simplicity of the model

Direct production approximation is valid

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Direct production approximation is valid

Future work

- Refinement of the phase space distribution
- Inclusion of strange particle production channels

Cugnon, Patron Saint of Intranuclear Cascade