Pion production in proton induced spallation reactions in the energy range of few GeV order

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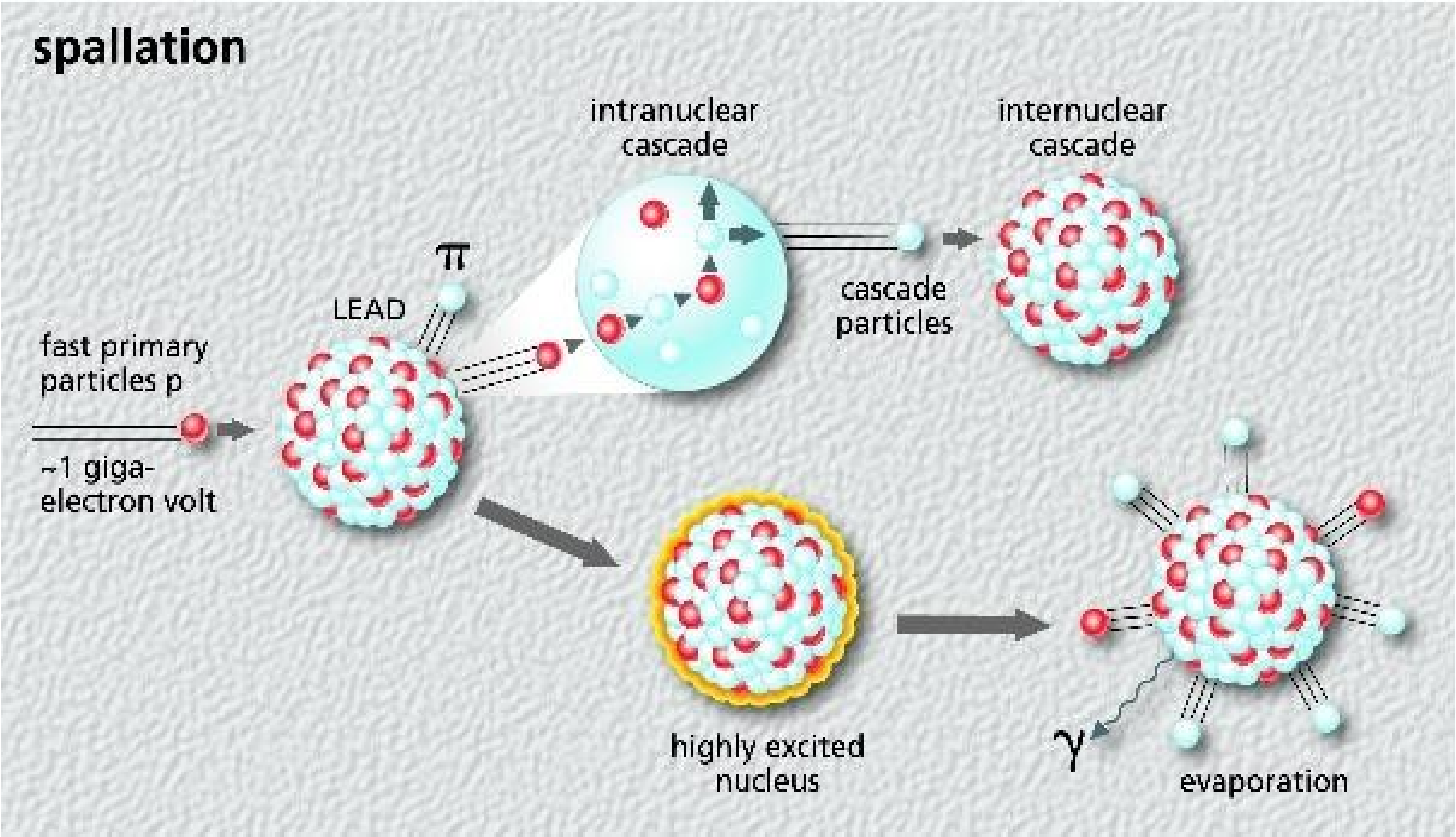
Spallation:



First stage:

$\sim 10^{-22}$ s

energy deposition

Second stage:

$\sim 10^{-18}\ 10^{-16}$ s

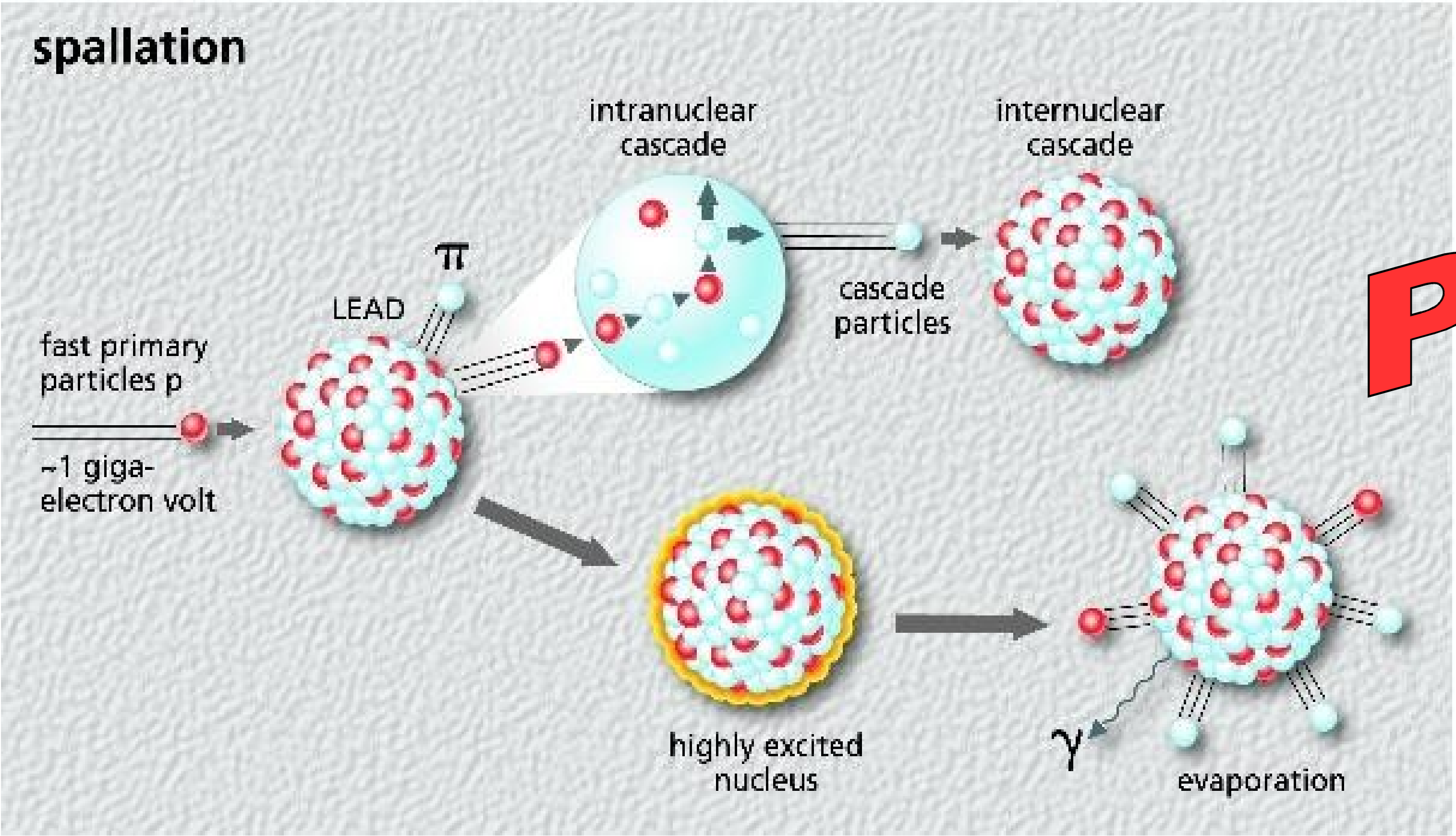
particles evaporation

Scenario used from 50's up to now !

N. Metropolis et al., Phys. Rev. 110(1958)185

I. Dostrovsky et al., Phys. Rev. 111(1958)1658

Spallation:



First stage:

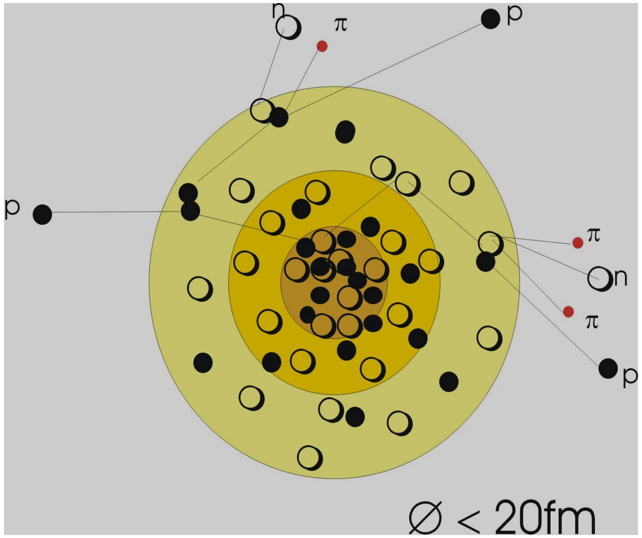
Pions

Second stage:

- ***The most abundantly produced mesons***
- ***Locally available amount of four-momentum large enough***

Boltzmann-Uehling-Uhlenbeck (BUU) model:

- *Classical Boltzmann transport equation complemented with Pauli blocking factors*
- *p + A collision described as cascade of N + N collisions*
- *Time evolution (between collisions nucleons move in mean field – function of nuclear density)*
- *the equation solved with Monte Carlo method, (positions and momentum of particles generated in successive time steps)*



K. Niita, W. Cassing and U. Mosel, Nucl. Phys. A 504(1989)391
G. F. Bertsch and S. Das Gupta, Phys. Rep. 160(1988)189

The transport equation:

$$\{\frac{\partial}{\partial t} + (\frac{\vec{p}_1}{m_1} + \frac{\partial \boxed{U(\vec{r},\vec{p}_1,t)}}{\partial \vec{p}_1})\frac{\partial}{\partial \vec{r}} - \frac{\partial \boxed{U(\vec{r},\vec{p}_1,t)}}{\partial \vec{r}}\frac{\partial}{\partial \vec{p}_1}\} f(\vec{r},\vec{p}_1,t) =$$

$$\frac{4}{(2\pi)^3}\int d^3p_2\, d^3p_3\, d\Omega\, v_{12} \frac{d\sigma_{12}}{d\Omega}\delta^3(\vec{p}_1+\vec{p}_2-\vec{p}_3-\vec{p}_4)\cdot[f_3 f_4 \overline{f}_1 \overline{f}_2 - f_1 f_2 \overline{f}_3 \overline{f}_4]$$

- $f_i \equiv f(\vec{r},\vec{p}_i,t)$ – one-body phase-space distribution
- $\overline{f}_i \equiv 1 - f(\vec{r},\vec{p}_i,t)$ – Pauli blocking factors
- v_{12} – relative velocity of colliding particles 1 and 2
- Ω – angle between momenta of outgoing particles: $\vec{p}_3$ and $\vec{p}_4$
- $\frac{d\sigma_{12}}{d\Omega}$ – differential cross section of the reaction

- $\boxed{U(\vec{r},\vec{p}_1,t)}$ – mean-field potential, dynamically changing, calculated as a function of local density:

$$U(\vec{r}) = \frac{3}{4}t_0\rho(\vec{r}) + \frac{7}{8}t_3\rho(\vec{r})^{4/3} + V_0\int d^3\vec{r}'\frac{exp(-\mu|\vec{r}-\vec{r}'|)}{\mu|\vec{r}-\vec{r}'|}\rho(\vec{r}') + V_{Coul}$$

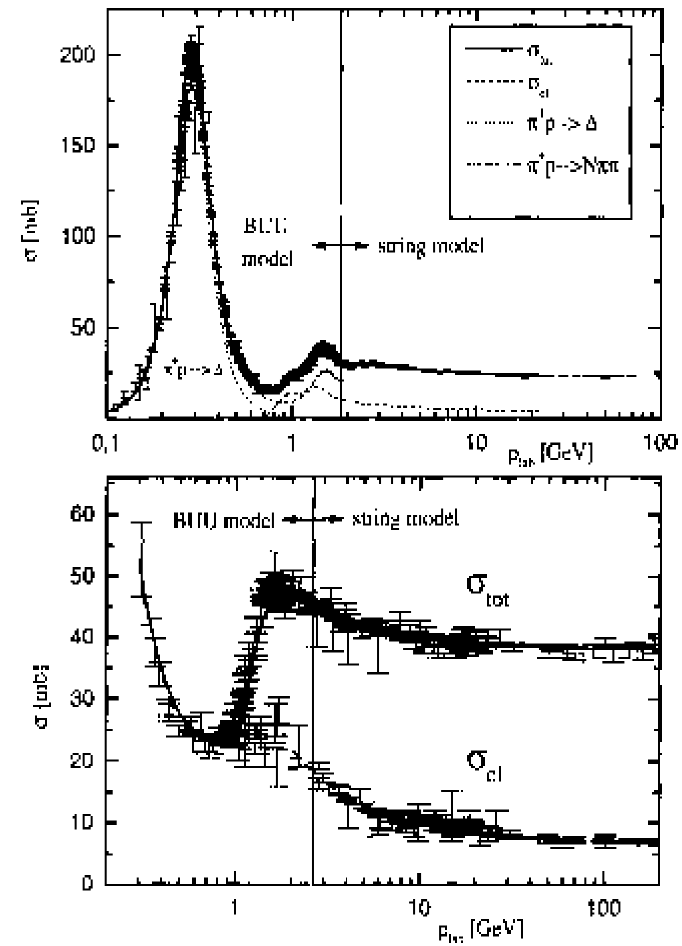
where:

t_0=-1124 MeV·fm^3; t_3=2037 MeV·fm^4; V_0=-378 MeV; μ=2.175 fm^{-1}.

Elementary cross sections:

- **NN → NN (elastic)**
- **NN → NNπ**
- **NN → NR → NπN**
- **NN → RR → NπNπ**
- **πN → πR → π Nπ**
- **NR → NN (delta absorption)**
- **πN → πN (elastic, charge exchange)**
- **production and propagation of other baryons (Λ, Σ, $\Sigma*$, Ξ, Ω), corresponding antibaryons and mesons (K, η, η', ρ, ω, ϕ, K$*$, a1)**

R = Δ, N(1440),N(1535)



PDG, Phys. Rev. D 50(1994)1173

A. Kowalczyk, arXiv: nucl-th/0801.0700

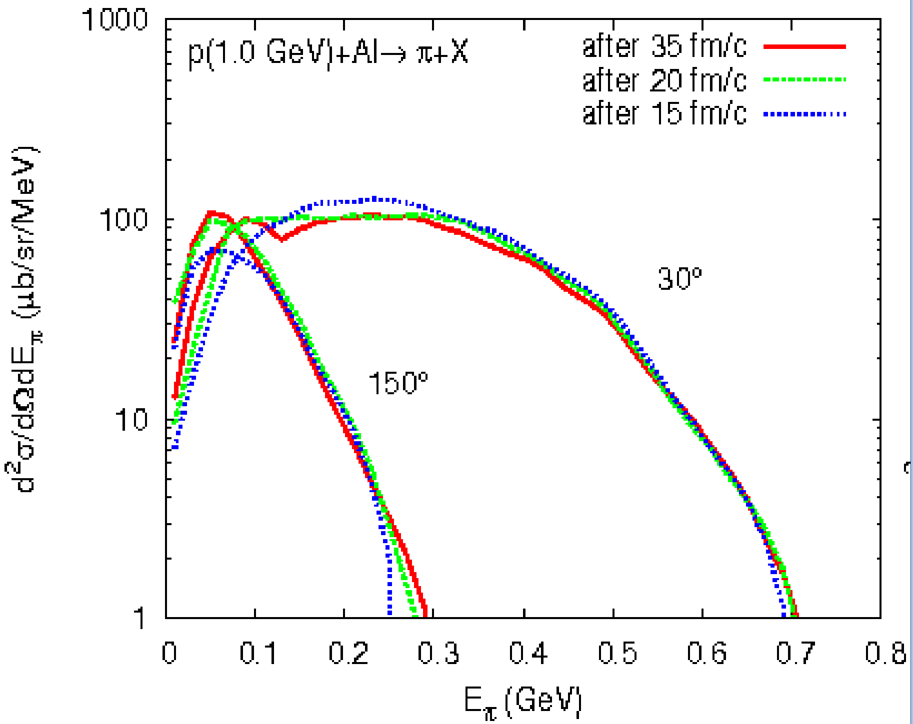
J. Geiss, W. Cassing, C. Greiner, Nucl. Phys. A 644(1998)107

Pion angular & energy distribution:

2 components:

- ***high energy anisotropic part:***
  pions emitted in first chance NN collisions, dominantly in forward direction

- ***isotropic part:***
  low energy thermal pions (Maxwell distribution)

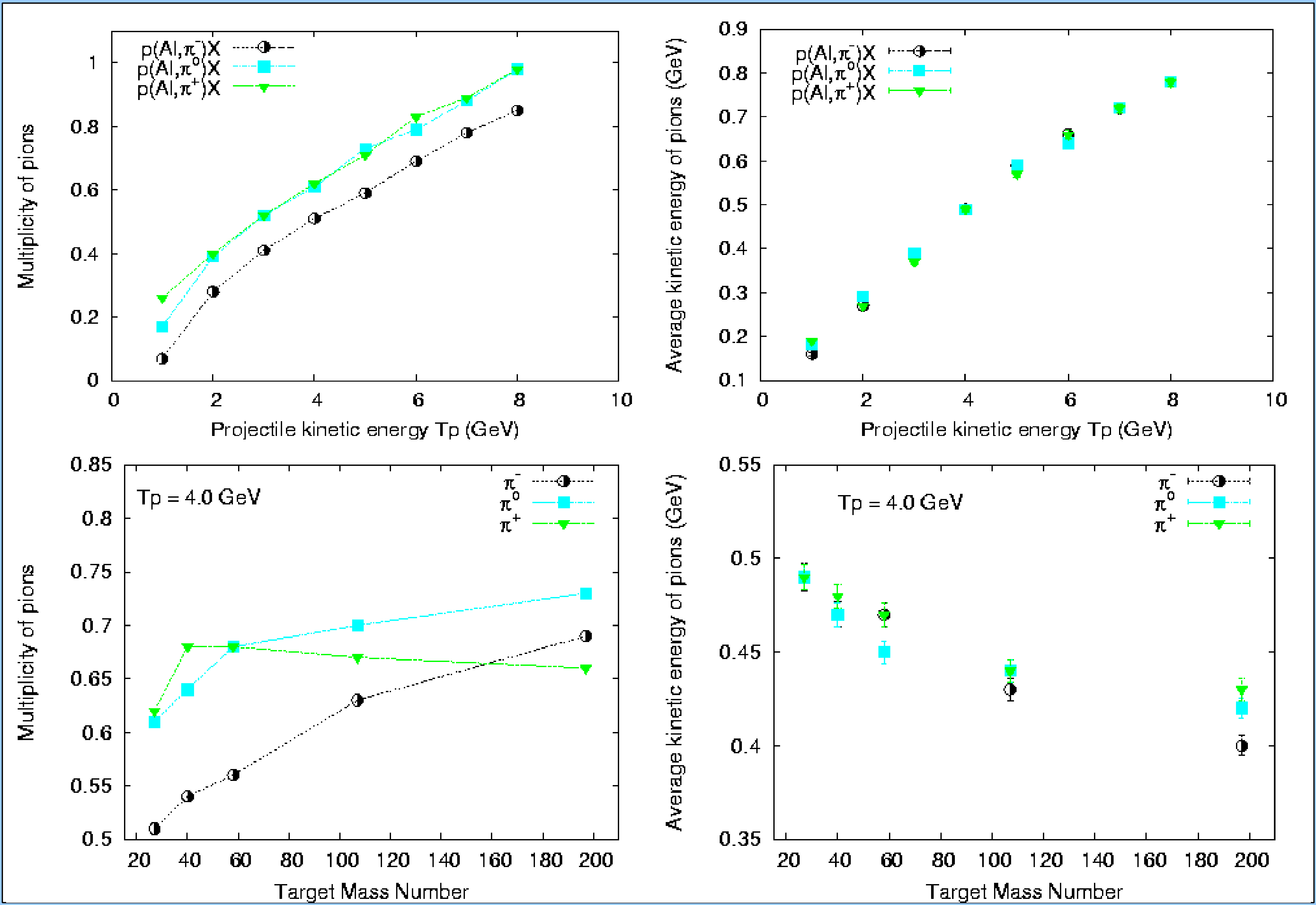


- ***production and absorbtion - several times during reaction***
- ***low production threshold***
- ***Mean free path ~ 1.0 – 1.5 fm***

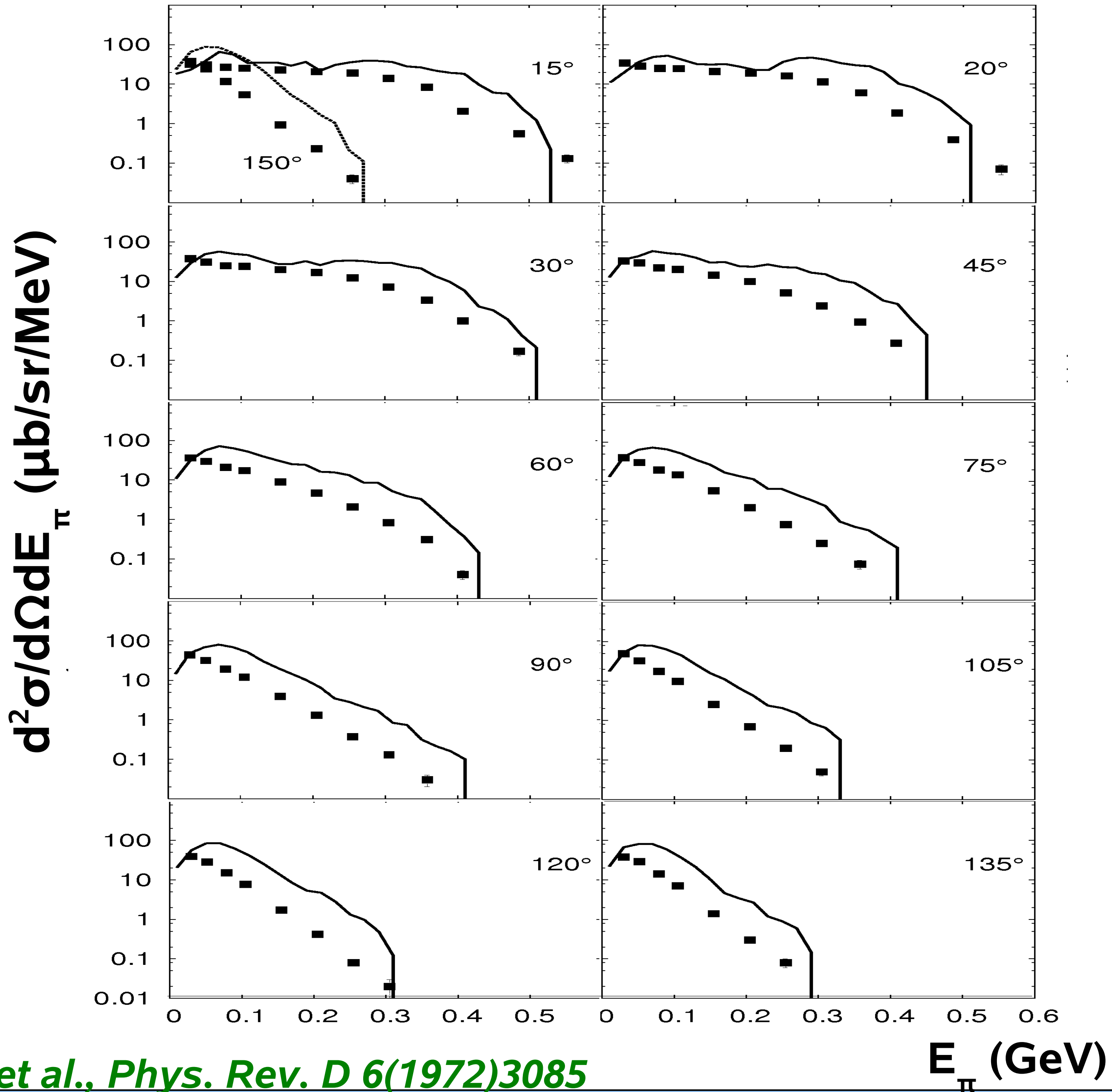
free N-N collision: 289 MeV

inside nucleus: 141 MeV

(Fermi motion)


p(Al,π⁻)X
p(Al,π⁰)X
p(Al,π⁺)X
Multiplicity of pions
Projectile kinetic energy Tp (GeV)
Average kinetic energy of pions (GeV)
Tp = 4.0 GeV
π⁻
π⁰
π⁺
Target Mass Number

Comparison with experimental data: $p(0.73\ GeV) + Pb \rightarrow \pi^- + X$



D.F.R. Cochran et al., Phys. Rev. D 6(1972)3085

Pion production – mainly Δ(1232) resonance decay:

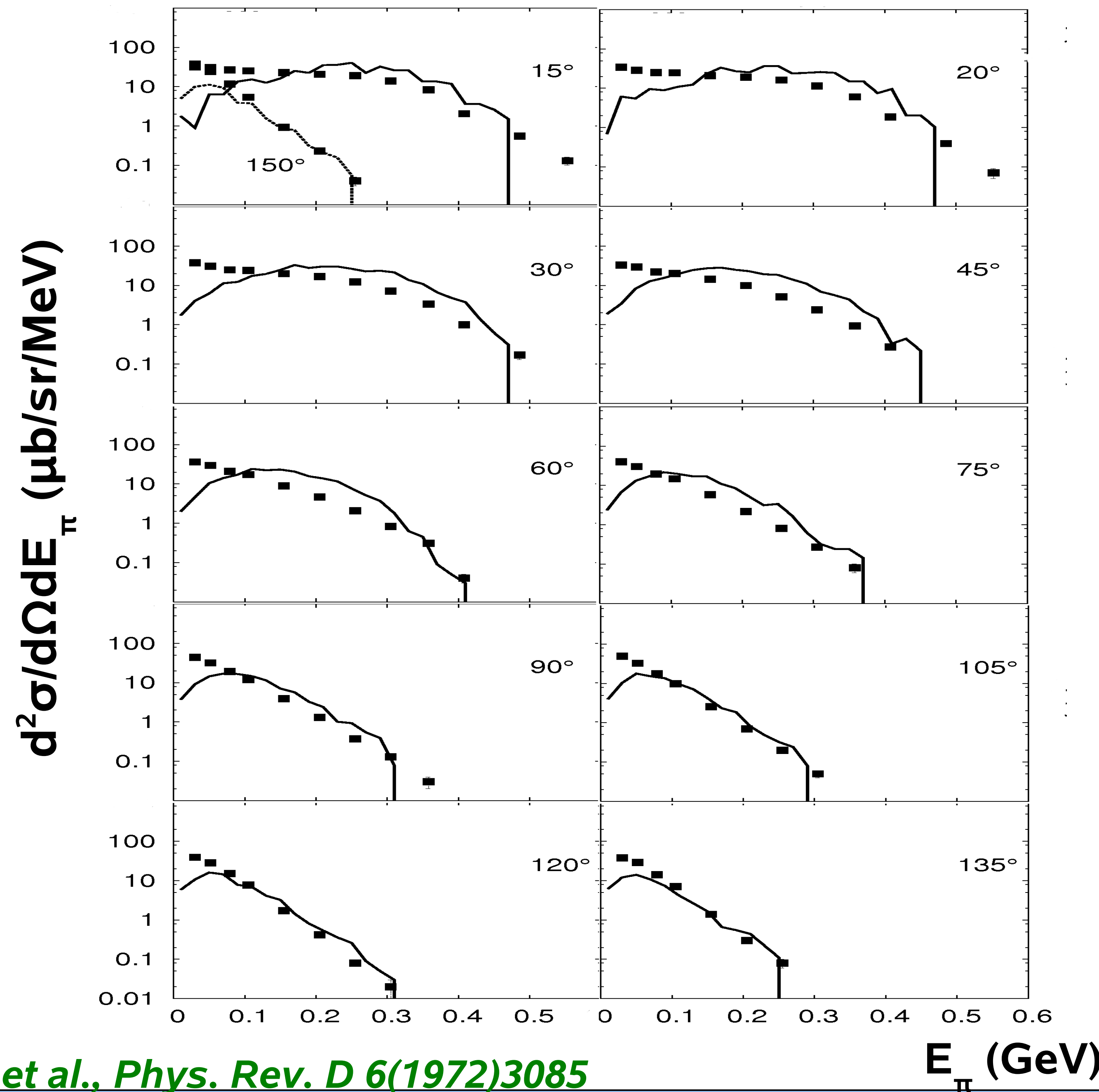
$$NN \rightarrow N\,\Delta$$
$$\rightarrow \pi\,N$$

NΔ → NN and Δ - lifetime influence <u>pion multiplicity</u>:

Δ - lifetime enlarged
<u>number of pions</u> emitted in backward direction – reduced

NΔ → NN cross section enlarged
<u>number of pions</u> emitted in forward direction – reduced

Comparison with experimental data: $p(0.73\ GeV) + Pb \rightarrow \pi^- + X$



D.F.R. Cochran et al., Phys. Rev. D 6(1972)3085

Summary:

- *Not satisfactory agreement between calculations and data – not too surprising pion production in p-A collision – complicated process*

elementary cross sections for pions production in free NN interactions – well known
in-medium problem appears
(in-medium effects in BUU model: Pauli principle and Δ absorption)

- *Other tests: pion production mechanism – sensitive to π and Δ dynamics:*

modifications of Δ parameters, density dependent width of Δ resonance (increasing with density), pion potential, anisotropic Δ decay into πN channel, etc.

Th. Aoust and J. Cugnon, Phys. Rev. C 74(2006)064607
A. Engel et al., Nucl. Phys. A 572(1994)657

results still not satisfactory

- *Modelling of pions production and dynamics in p-A reaction cannot be verified – experimental data scarce, especially in projectile energy range of a few GeV order !*

arXiv: nucl-th/0801.0700

SOLUTION: TEST PARTICLE METHOD

Represent the one-body phase-space distribution by discretized test particles:

$$f(\vec{r},\vec{p},t) = \frac{1}{N}\sum_{i=1}^{N\cdot A(t)} \delta^3(\vec{r}-\vec{r}_i(t))\ \delta^3(\vec{p}-\vec{p}_i(t))$$

N – number of test particles
$A(t)$ – number of real particles at time t

The test particles propagate between collisions according to classical Hamilton equations of motion:

$$\dot{\vec{p}_i} = -\frac{\partial U(\vec{r}_i,\vec{p}_i,t)}{\partial \vec{r}_i}$$

$$\dot{\vec{r}_i} = \vec{p}_i/\sqrt{m^2+p^2} + \frac{\partial U(\vec{r}_i,\vec{p}_i,t)}{\partial \vec{p}_i}$$

<u>Literature</u>:

K.Niita, W.Cassing, U.Mosel, Nucl.Phys.A 504(1989)391
G.F.Bertsch,S.Das Gupta, Phys.Rep. 160(1988)189
J.Geiss, W.Cassing, C.Greiner, Nucl.Phys.A 644(1998)107
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