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***Workshop on***

***Nuclear Data for Science & Technology: Accelerator Driven Waste Incineration***

**10 - 21 September 2001**

***Miramare - Trieste, Italy***

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# *Nuclear Reactions at High Energies*

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**France**

# Nuclear Reactions at High Energies

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## Design of spallation targets for ADS has raised needs for reliable numerical simulation codes

- ➪ Improvement of high energy nuclear reaction models (above 150-200 MeV)
- ➪ Validation on the bulk of newly available high energy data

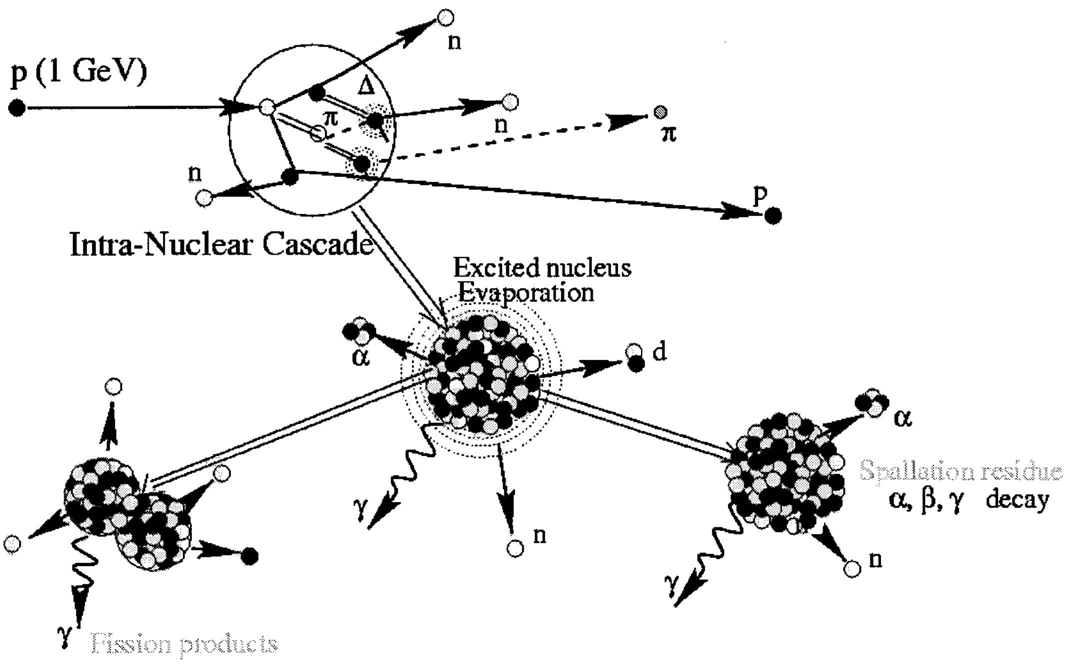
## Other applications:

- ✦ spallation neutron sources
- ✦ radioactive beams
- ✦ radiation damage in space
- ✦ astrophysics

# Outline

1. **Importance of spallation reactions for applications**
   - Definition of spallation
   - Data needed for Accelerator-Driven Systems
   - Other applications
2. **High energy nuclear models**
   - Models and codes for high energies
   - Intra-nuclear cascade models
   - The Liège INC model
3. **Comparison of models to available high energy data**
   - Neutrons
   - Charged particles
   - Residues
   - Coincidence measurements
4. **Conclusions**

# Spallation reactions

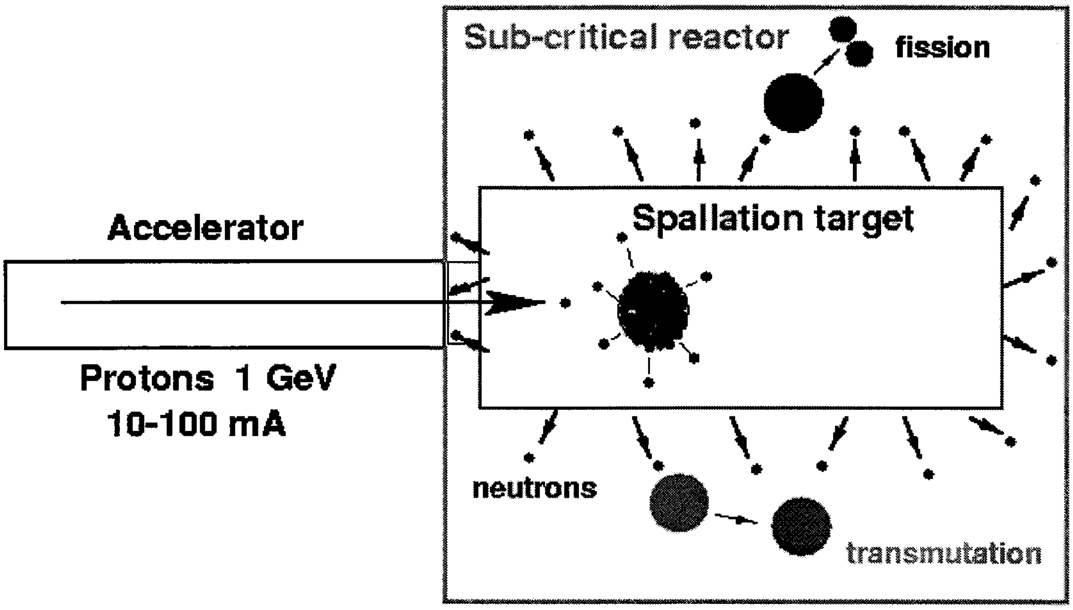



- **Definition:**

  **interaction of a high energy (> 100 MeV) light particle with a nucleus leading to emission of light particles and leaving a heavy residue.**

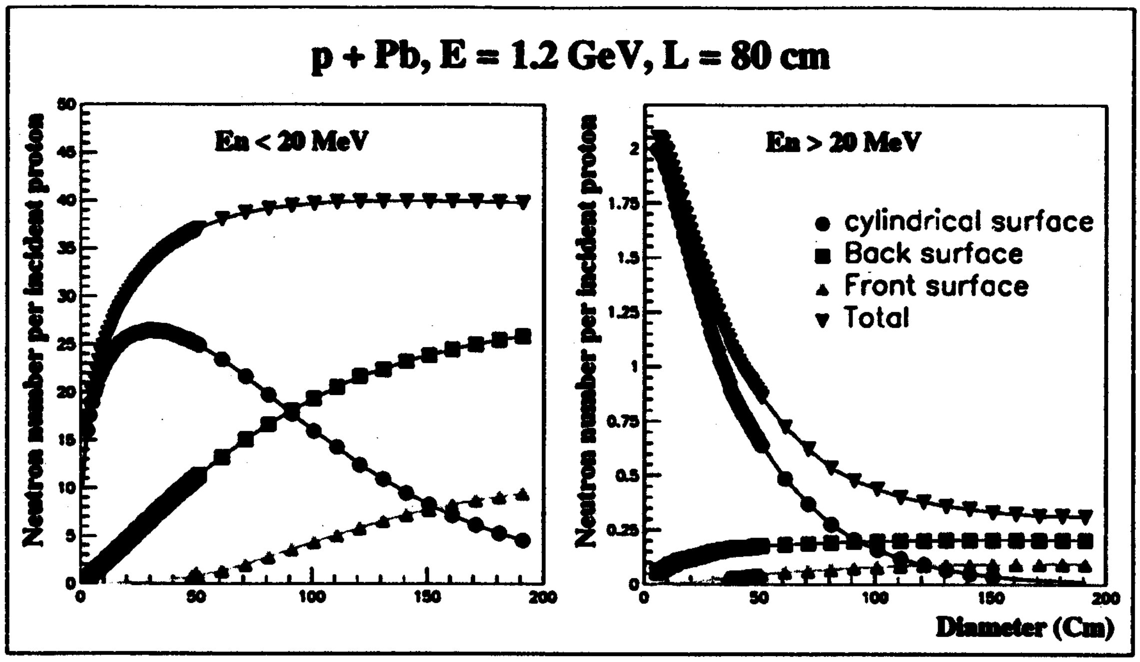
- **History:**
  - ➥ **observation of particle cascades in cosmic rays interactions** (G.Rossi, ZP82 (1933) 151)
  - ➥ **first accelerators: many nucleons emitted by the target nucleus** ( Cunningham, PR72 (1947) 739)
  - ➥ **Two step mechanism** (Serber, PR72 (1947) 1114)

# Data required for the design of spallation targets

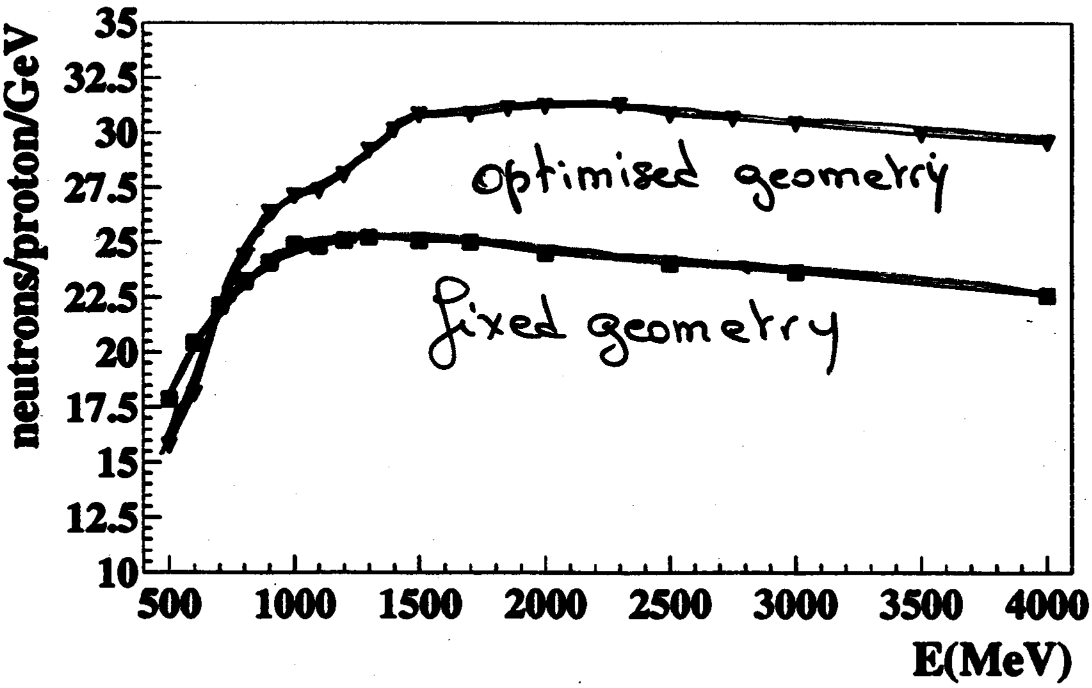



- **Neutron production**
  - ♦ number ➜ power of the system / needed accelerator intensity
  - ♦ energy, spatial distribution ➜ target optimisation, damage in window and structures
  - ♦ high energy neutrons ➜ shielding
- **Charged particle production**
  - ✦ gas ($H_2$, He) production ➜ embrittlement, swelling
  - ✦ energy ➜ DPA, energy deposition

# Shape optimisation of a spallation target



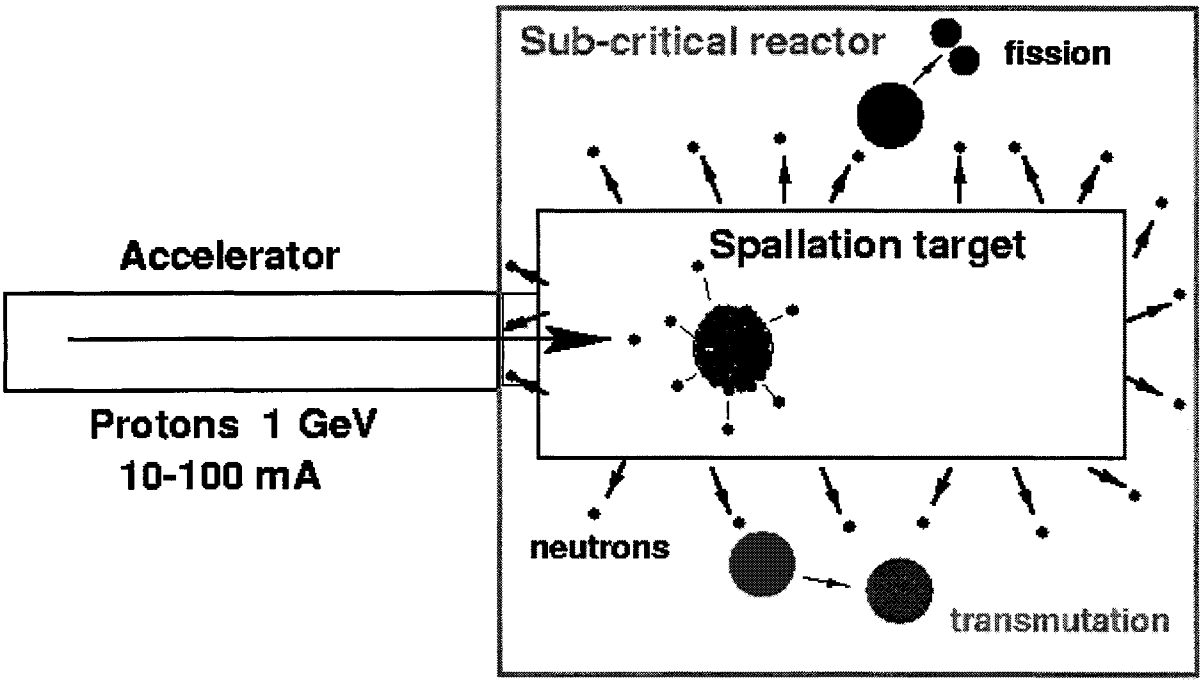

Number of low and high energy neutrons emitted through the different faces of a cylindrical lead target as a function of the target diameter.




Number of low energy neutrons emitted from the lateral face of a cylindrical lead target for fixed or an optimised geometry.

From F. Lavaud, stage DEA, CEA/SPhN (1998)

# Data required for the design of spallation targets




- **Residual nuclide production**
  - ✦ element distribution → corrosion, change in metallurgical properties
  - ✦ isotope distribution → activity (short lived isotopes), radiotoxicity (short lived isotopes), decay heat
  - ✦ recoil energies → DPA in window and structures, energy deposition

Activity in Pb and Pb/Bi targets after 1 year irradiation

E = 0.8 GeV

I = 30mA

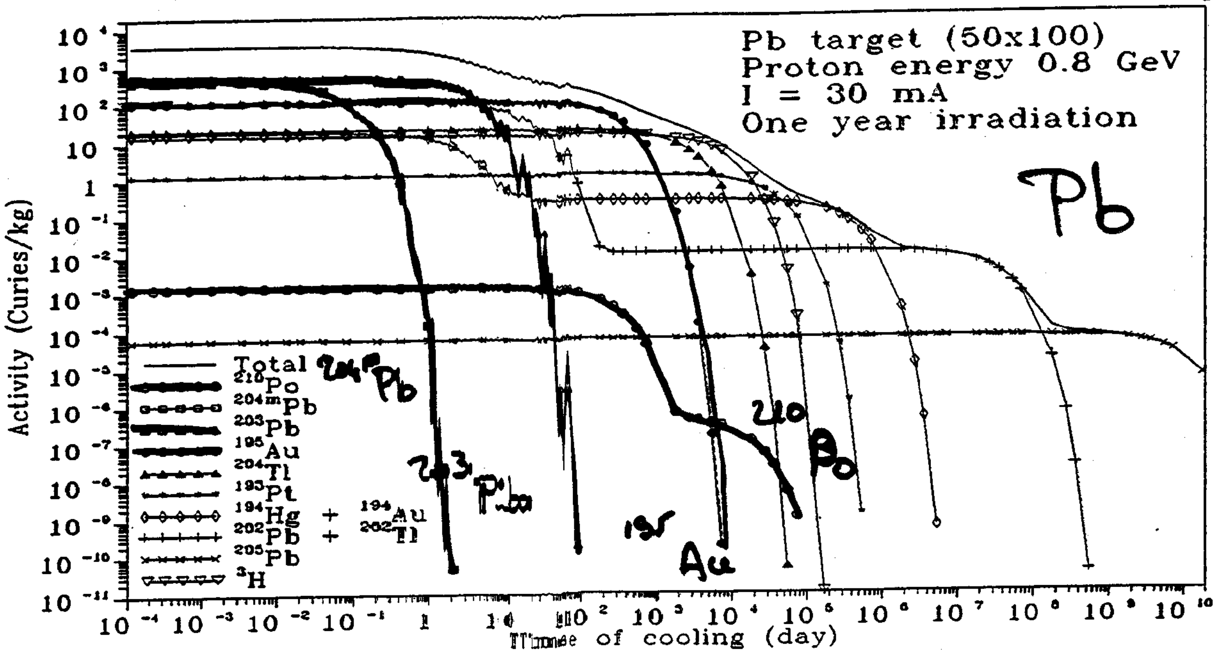



Fig. 4. Total and partial activities of lead target as a function of cooling time.

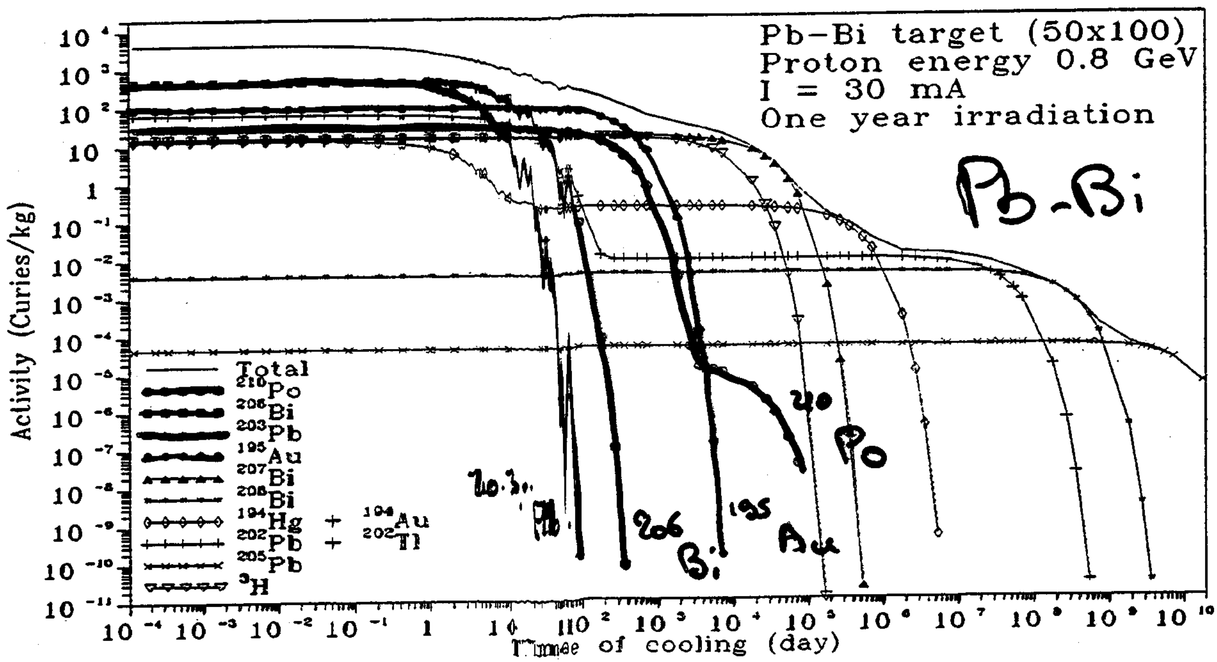
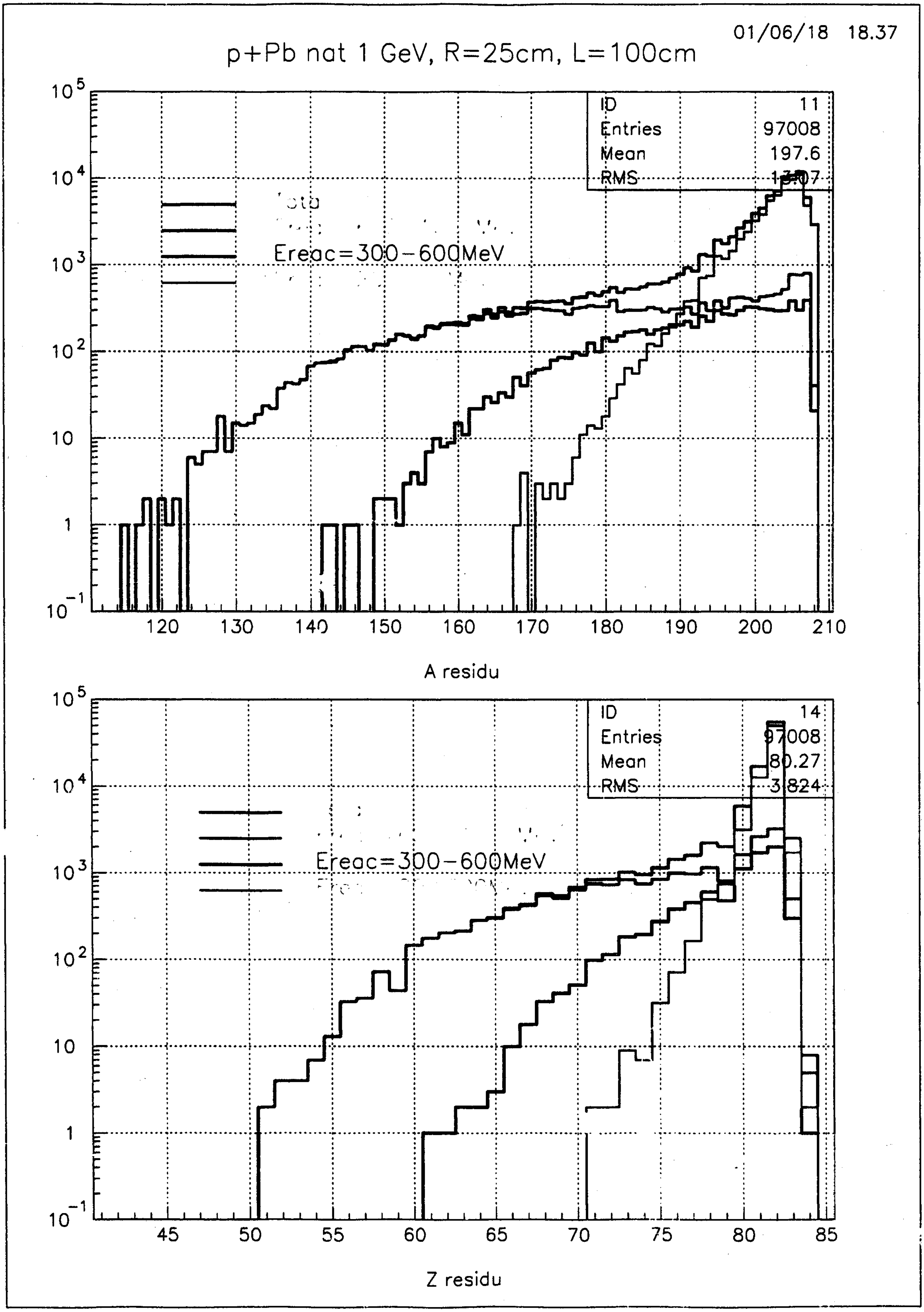
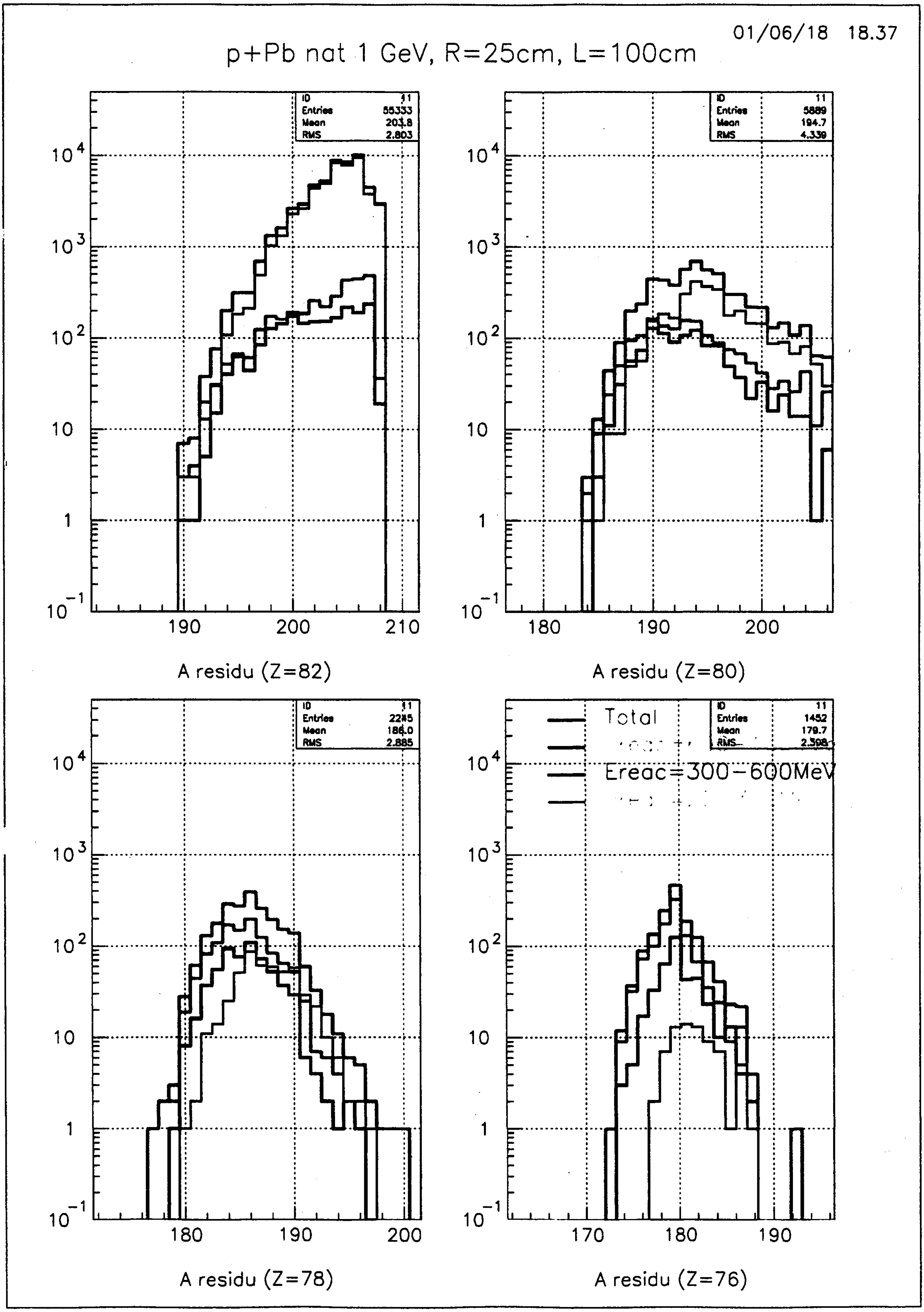



Fig. 5. The same as in Fig. 3 for lead-bismuth target.

*Analysis of the Contributions of the Proton and Neutron Spectral Components to the Accumulating Activity*

From Y.N. Shubin et al., Proc. ADTTA 96, Kalmar, Sweden, June 1996 p 953

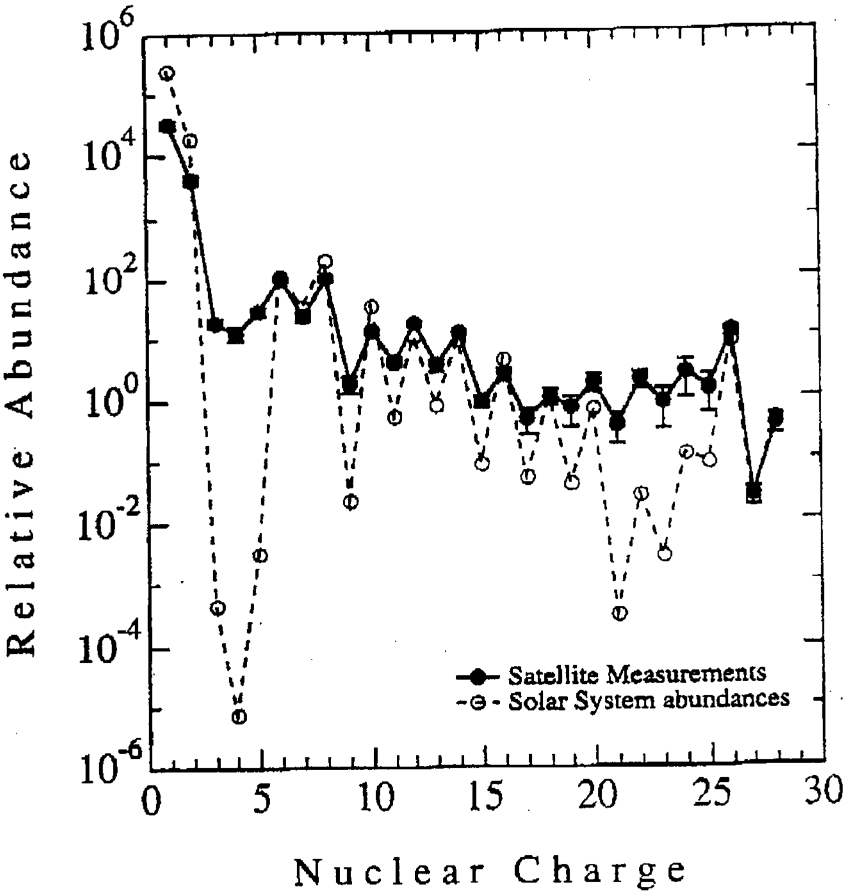

01/06/18 18.37
p+Pb nat 1 GeV, R=25cm, L=100cm
ID 11
Entries 97008
Mean 197.6
RMS 13.07
Ereac=300-600MeV
A residu
ID 14
Entries 97008
Mean 80.27
RMS 3.824
Ereac=300-600MeV
Z residu



01/06/18 18.37
p+Pb nat 1 GeV, R=25cm, L=100cm
ID 11
Entries 55333
Mean 203.8
RMS 2.803
A residu (Z=82)
ID 11
Entries 5889
Mean 194.7
RMS 4.339
A residu (Z=80)
ID 11
Entries 2245
Mean 186.0
RMS 2.885
A residu (Z=78)
Total
Ereac=300-600MeV
ID 11
Entries 1452
Mean 179.7
RMS 2.398
A residu (Z=76)

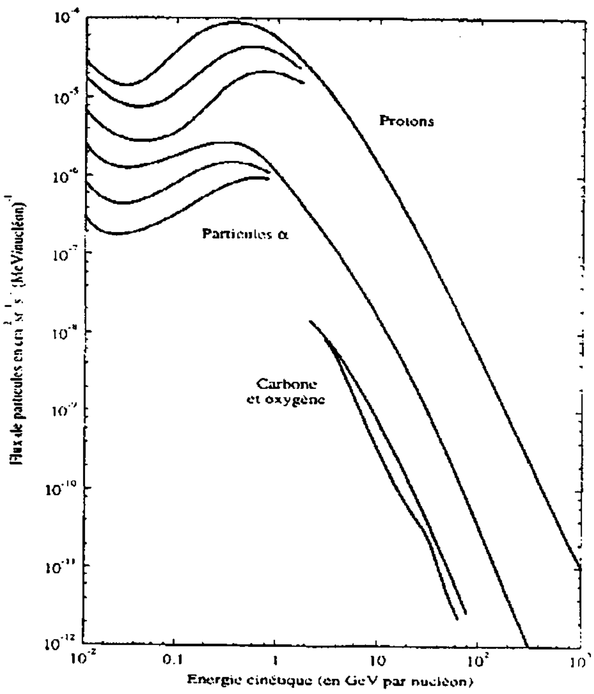

9

# Astrophysics




- **Secondary reactions of cosmic rays in interstellar medium (90% of hydrogen)**
  - ➥ **explanation of abundance of isotopes**
  - ➥ **decide among models for galactic nucleosynthesis**
  - ➥ **origin of cosmic rays**
- **Composition of meteorites**

# Spallation reactions in space instruments

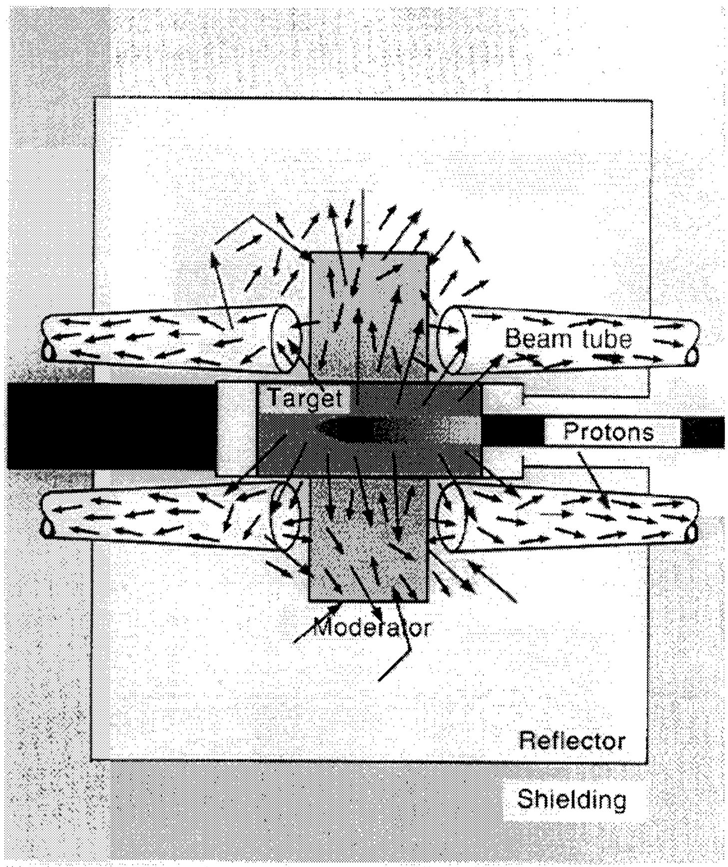



- **Cosmic ray bombardment of the spacecraft and instruments**
  - ➥ **Noise due to secondary gammas, neutrons and spallation residues**
  - ➥ **ex: spectrometer of the INTEGRAL mission devoted to high resolution γ - ray astronomy**
    - ⇨ **determination of the flux of secondary particles**
    - ⇨ **background due to radioactive residues**

# Rare isotope production

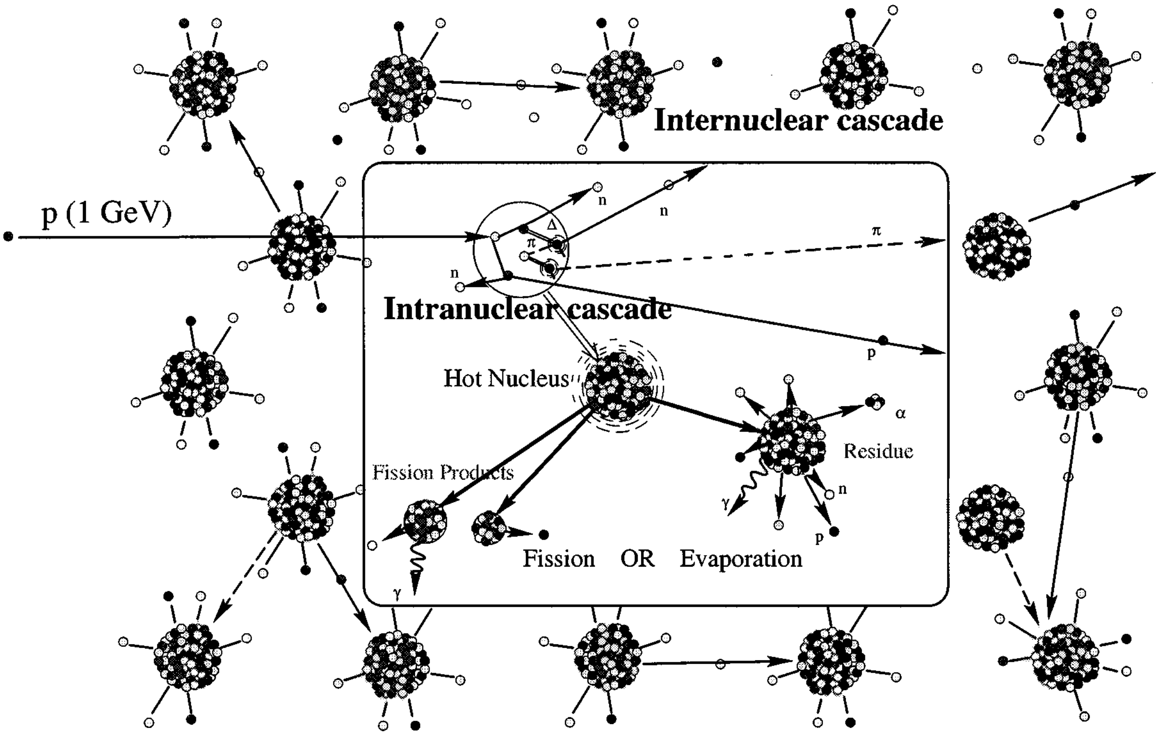
- **Direct methods**
  - ➥ ISOL p (1 GeV) + A ⇛ low energy RIB
  - ➥ fragmentation of GeV/A heavy ions ⇛ high energy RIB
- **Converter methods**
  - ➥ use of moderated spallation neutrons to induce fission

# Spallation neutron sources




- **Moderation of spallation neutrons in (heavy) water**
- **Reflectors to direct escaping neutrons into beam tubes**
  - ➥ **pulsed sources: well-defined time structure, high peak flux ⇨ tof experiments**
  - ➥ **continuous sources: high neutron flux in a large volume ⇨ irradiation experiments**

# Spallation target modelling



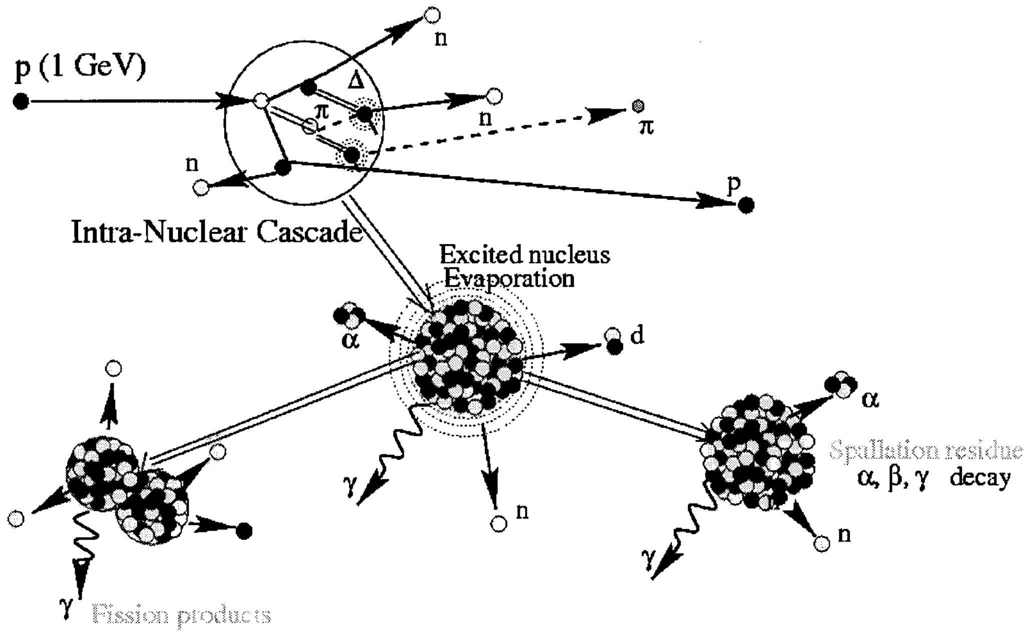

- **Monte-Carlo transport codes**
  - ➥ **propagation of all particles created in elementary interactions (HETC + MCNP type)**
- **Nuclear physics models (above 150-200 MeV**
  - ➥ **generating cross-sections (Intra-Nuclear Cascade followed by evaporation-fission)**
- **Evaluated data files (below 150-200 MeV)**
  - ➥ **providing all reaction channels**

# What is needed above 150-200 MeV for ADS and other applications

## Objective: to reliably predict production rates of all produced nuclei with their energy and angular distributions

- Elementary cross-sections measu-rements
  - ➥ to test the physics models
- Improvement of models and/or development of new ones
  - ➥ validation on experimental data
- Integral measurements
  - ➥ test and validation of transport codes

# Models for spallation reactions




**Two step mechanism (Serber 1947):**

➥ **Intra-Nuclear Cascade**

**sequence of independent *N-N* collisions**

$\Lambda_{\text{de Broglie}} = hc/p \ll \lambda = 1/\rho\sigma_{NN}$ **mean free path**

**fast process ( ≈ 30 fm/c)**

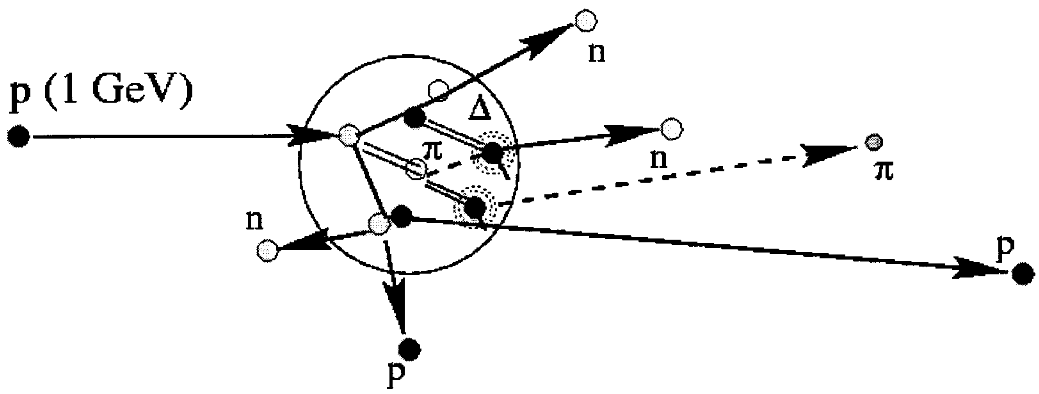
**=> Heating of the nucleus - thermalisation**

➥ **De-excitation by evaporation or fission**

**statistical evaporation models**

**slow process ( hundreds of fm/c)**

# Intra-Nuclear Cascade




**Determines the number and direction of the high energy particles**

- ➥ shielding against energetic neutrons
- ➥ inter-nuclear cascade propagation

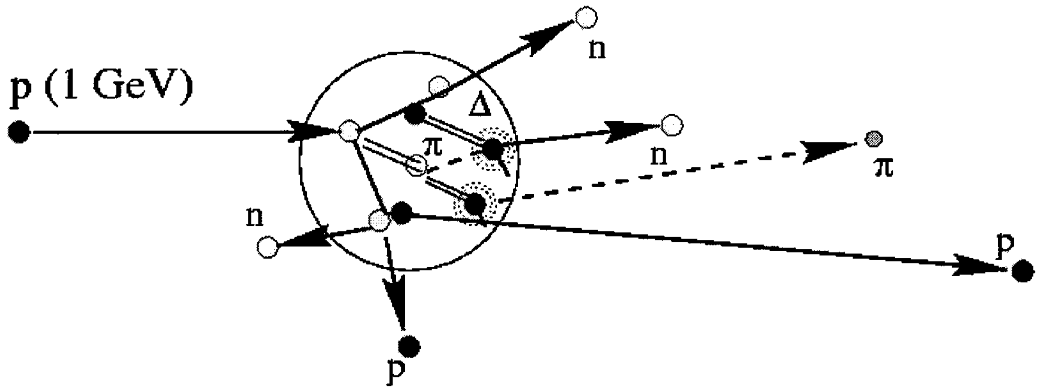
  for lead INC neutrons = 15% total nb

  but carry 80% of the energy

**Determines initial conditions for evaporation-fission**

- Excitation energy
- Z, A of the pre-fragment
- Angular momentum

# Intra-Nuclear Cascade models




## Common features

- ➥ linear trajectory between collisions
- ➥ nuclear potentiel
- ➥ free *N-N* cross-sections
- ➥ inelastic collisions $N+N \rightarrow N+\Delta \rightarrow N+N+\pi$
- ➥ Pauli blocking

## Main available INC models

- **Bertini** (Phys. Rev. 131 (1963) 1801)
- **Isabel** (Yariv and Frankel, Phys. Rev. C20 (1979) 2227)
- **Cugnon** (Cugnon et al., Nucl. Phys. A620 (1997) 457)

# Differences between the different INC models

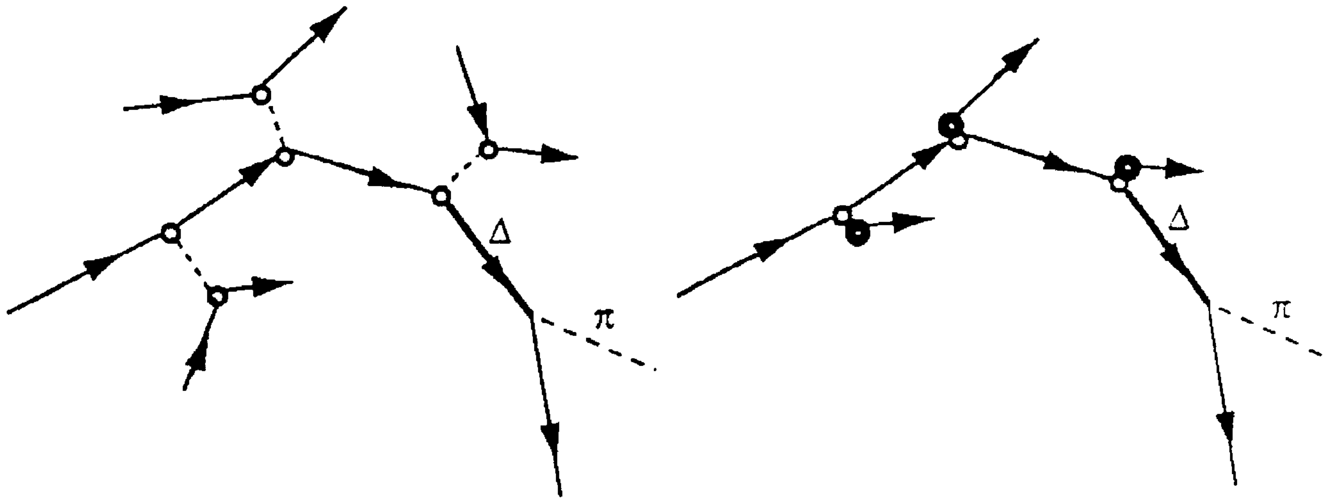



Fig. 3 : Schematic representation of the INC models of the first type (left) and of second type (right). In the latter case, nucleons promoted from the continuum are indicated by heavy dots.

| | Bertini | Isabel | Cugnon |
|---|---|---|---|
| Medium | continuous | continuous | particles |
| Cascade propagation | collided particles | time steps | time steps |
| Collision criterium | mean free path | mean free path | minimum distance of approach |
| Stopping criterium | energy | energy | time |
| Surface | diffuse (3 density regions) | diffuse | sharp |
| Pauli blocking | strict | not fully strict | statistics |

# The Liège INC model (INCL)

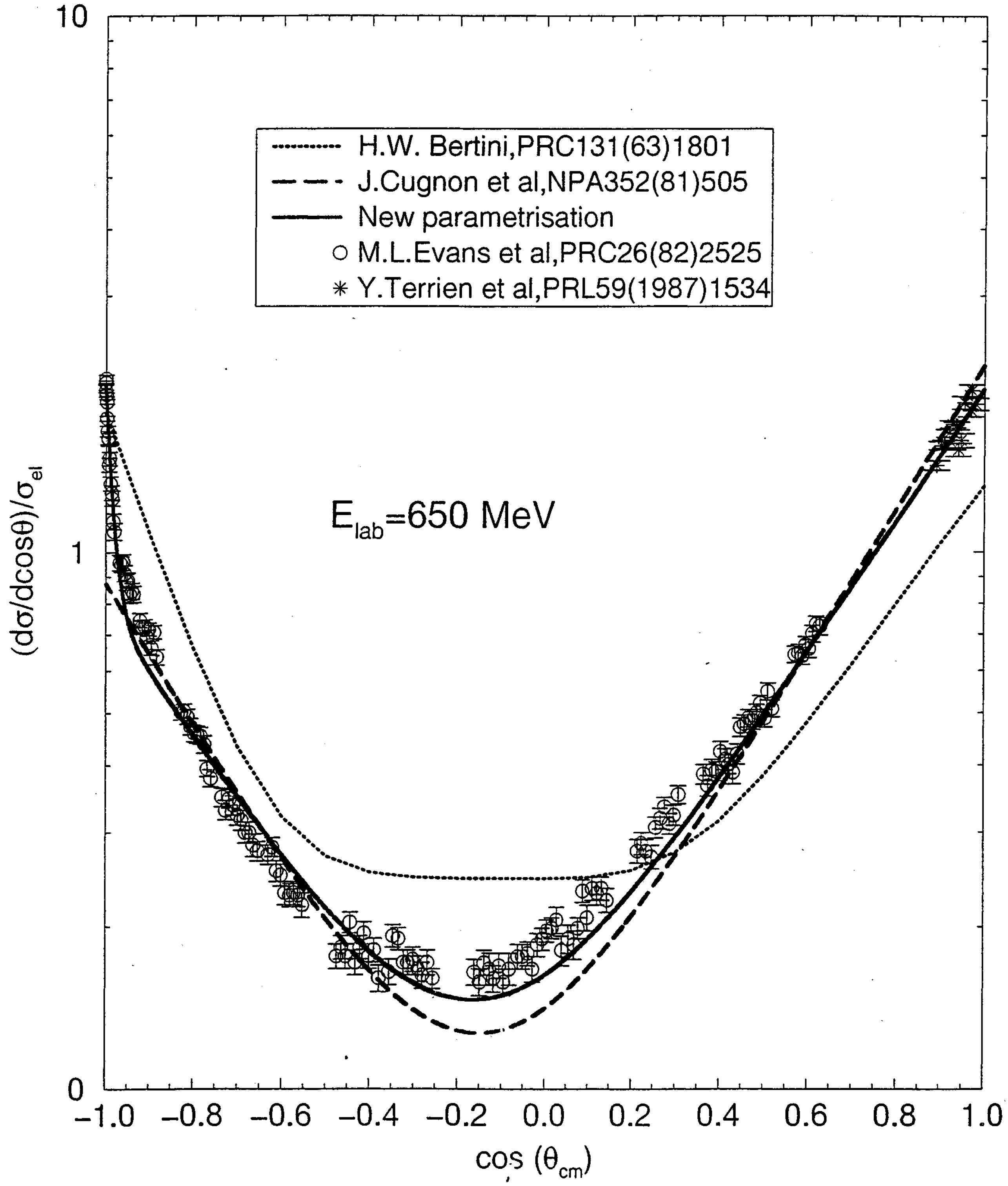
- **First developed for heavy ion collisions** (Cugnon et al., Nucl. Phys. A352 (1981) 505) **then applied to proton induced reactions** (Cugnon, Nucl. Phys. A462 (1987) 751)

## ➥The standard INCL2 model

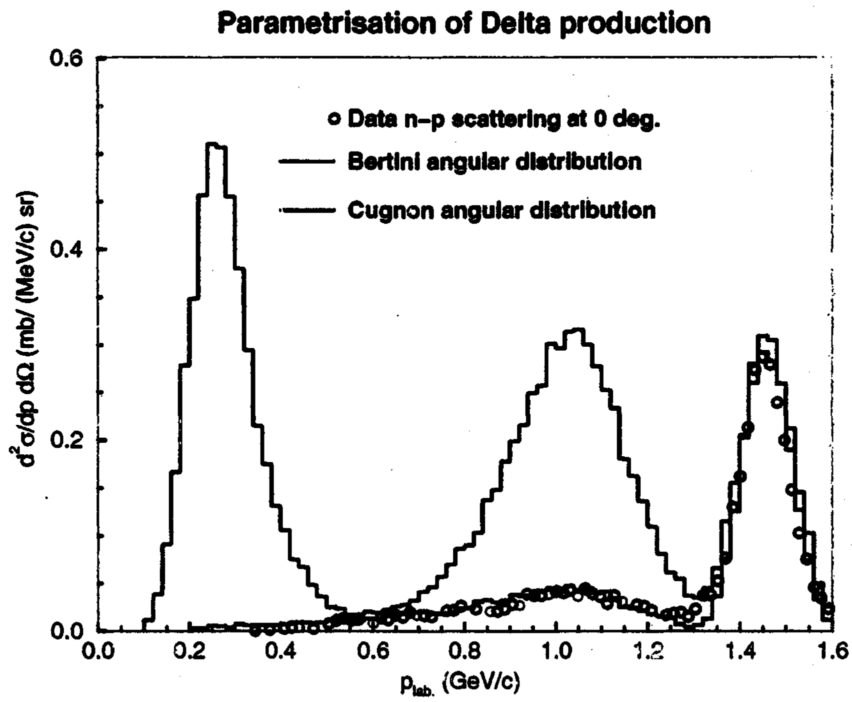
(Cugnon et al., Nucl. Phys. A620 (1997) 457)

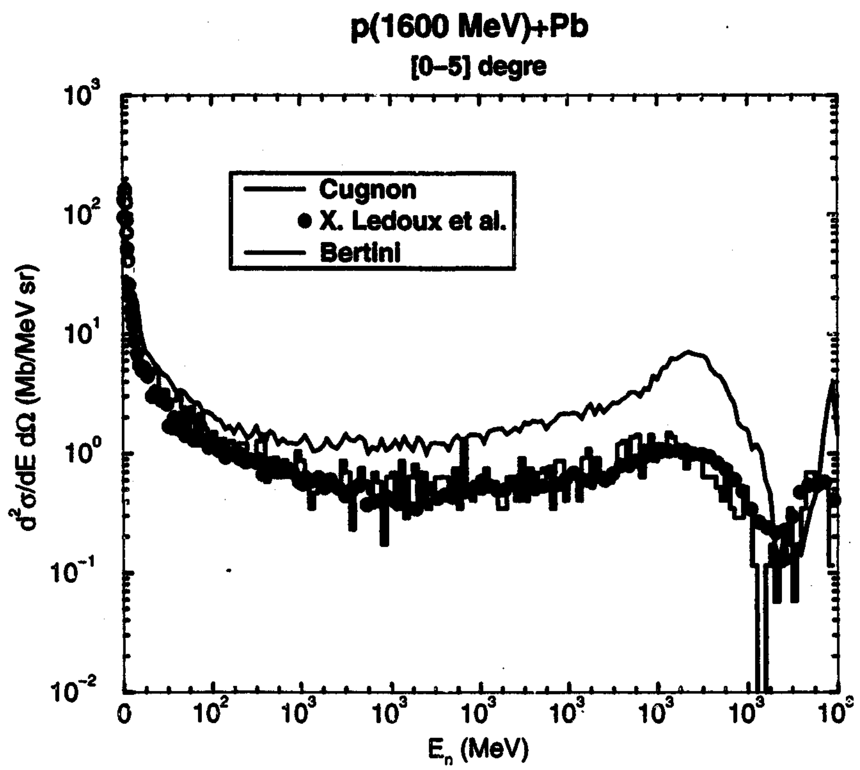
- succession of binary collisions well separated in space and time
- generation of initial positions of target nucleons at random inside a sharp surface sphere
- stochastical generation of initial momenta of target nucleons inside a Fermi sphere
- straight line trajectories until minimum distance of approach or hitting of the wall of the potential
- statistical Pauli blocking
- inelastic collisions, pion production and absorption: $N+N \leftrightarrow N+\Delta$ , $\Delta \leftrightarrow N+\pi$
- isospin degree of freedom
- improved parameterisation of NN cross-sections
- self-consistent determination of the stopping time

np angular distributions
→ rise at backward angle (charged pion exchange)
mainly affect 0° in (p, xn)



# Parametrisation of the ▲ production cross-section




J. Cugnon et al., Phy. Rev. C56 (1997) 2431

# The Liège INC model (INCL)

## ➥ The new INCL4 version

(Boudard et al., to be published)

- **diffuseness of the nuclear surface:**

Wood-Saxon distribution with parameters in accordance with experimental values

→ good total reaction cross-sections

→ better prediction of peripheral collisions

- **consistent dynamical Pauli blocking:**

phase space occupation probability evaluated

collisions leading to energy $\sum \varepsilon_i > E_{GS}(A_R)$ forbidden

→ no more negative excitation energies

- **collisions between spectators forbidden**

→ no spurious nucleon evaporation

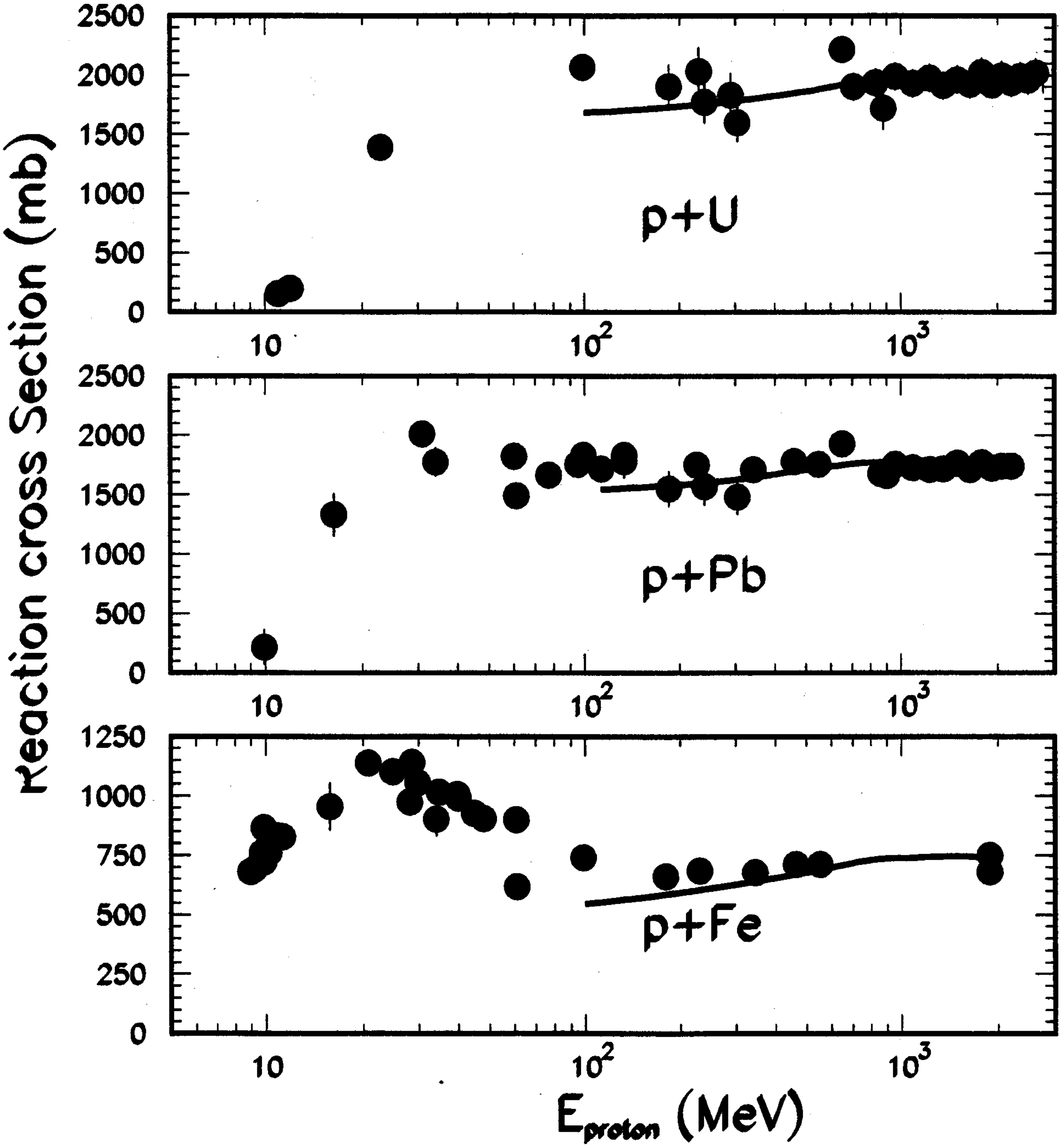
→ dynamical evolution of the phase space preserved

- **angular momentum of the remnant calculated**

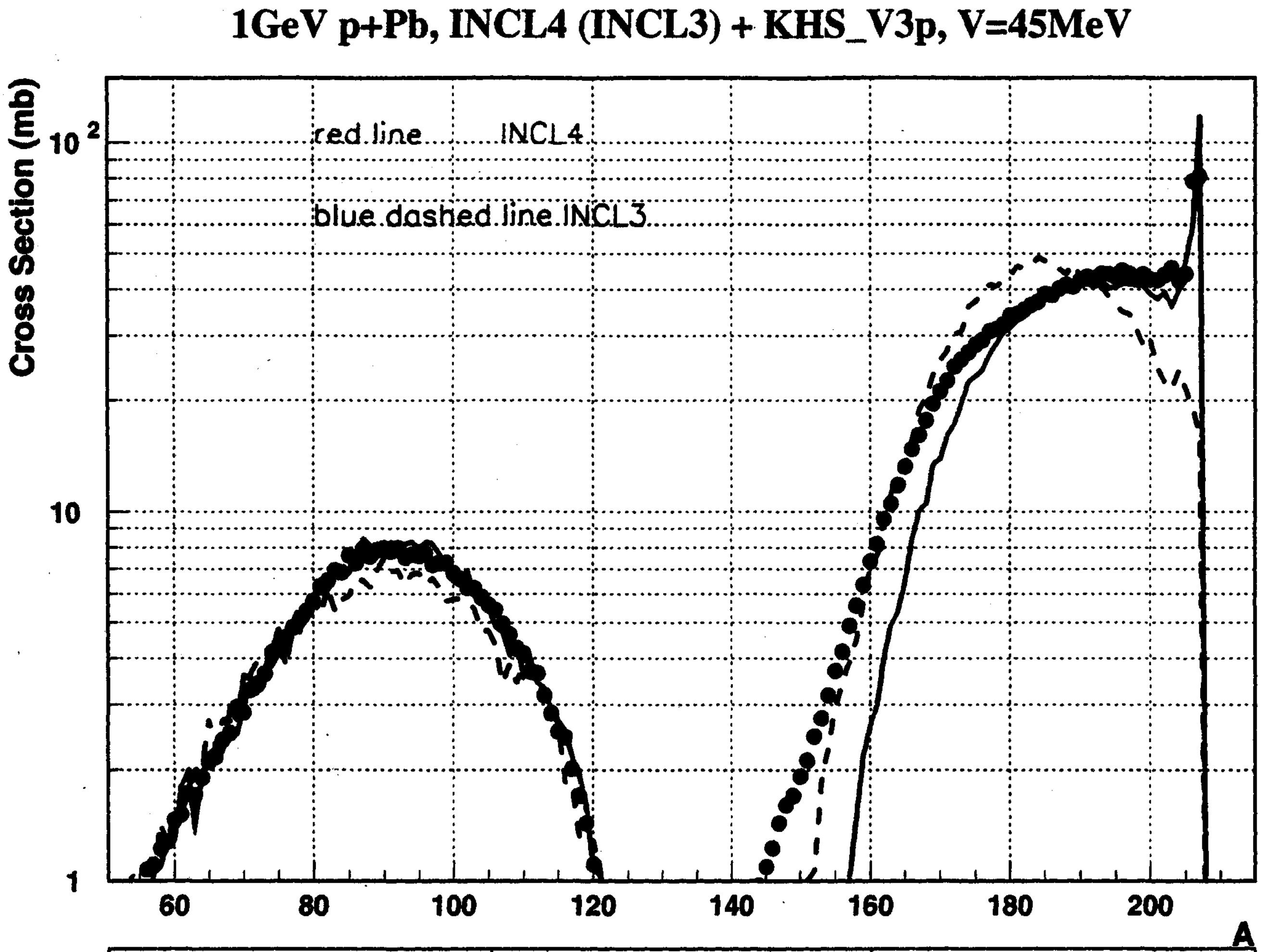
→ important for input in evaporation-fission

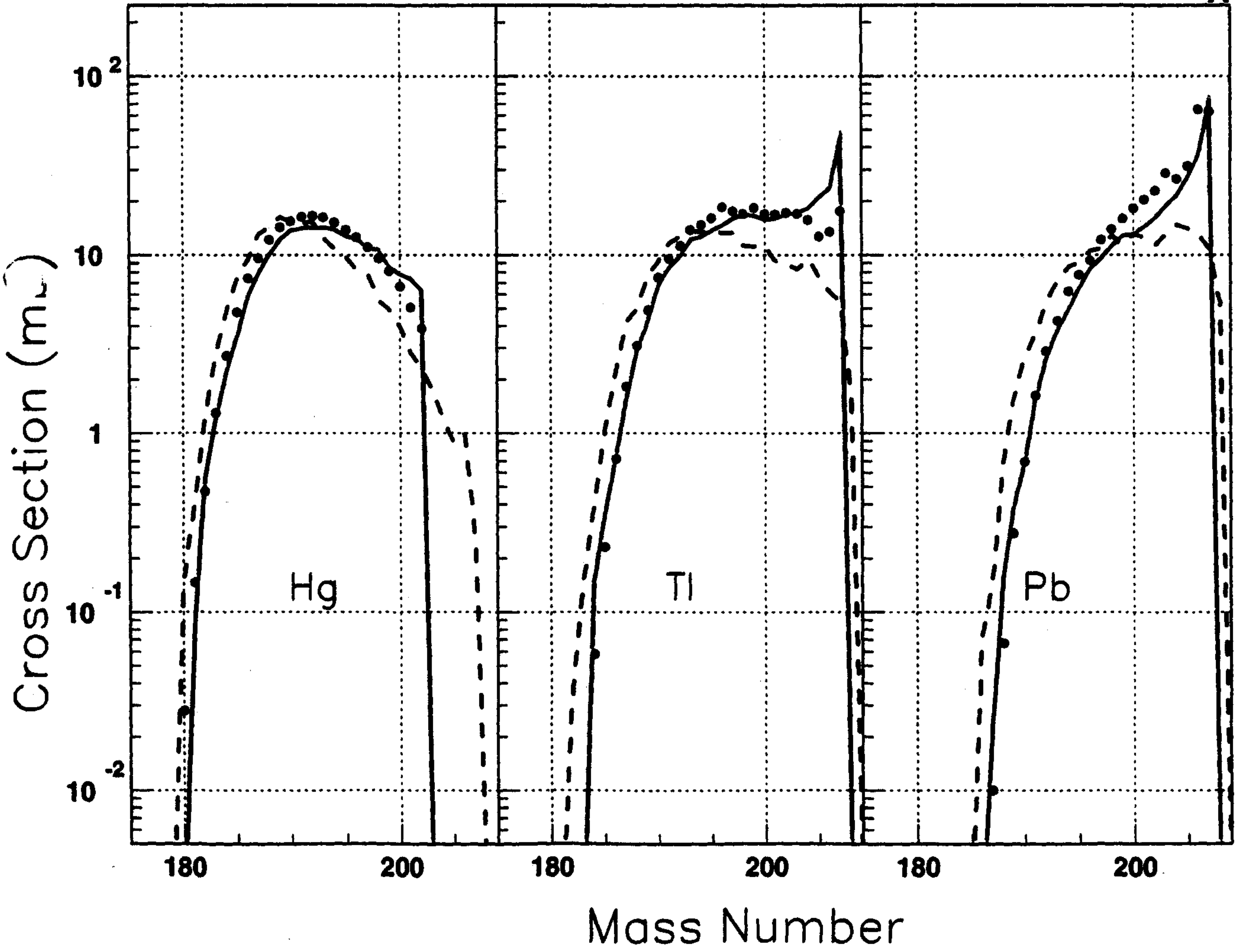
- **possibility of composite incident particles**

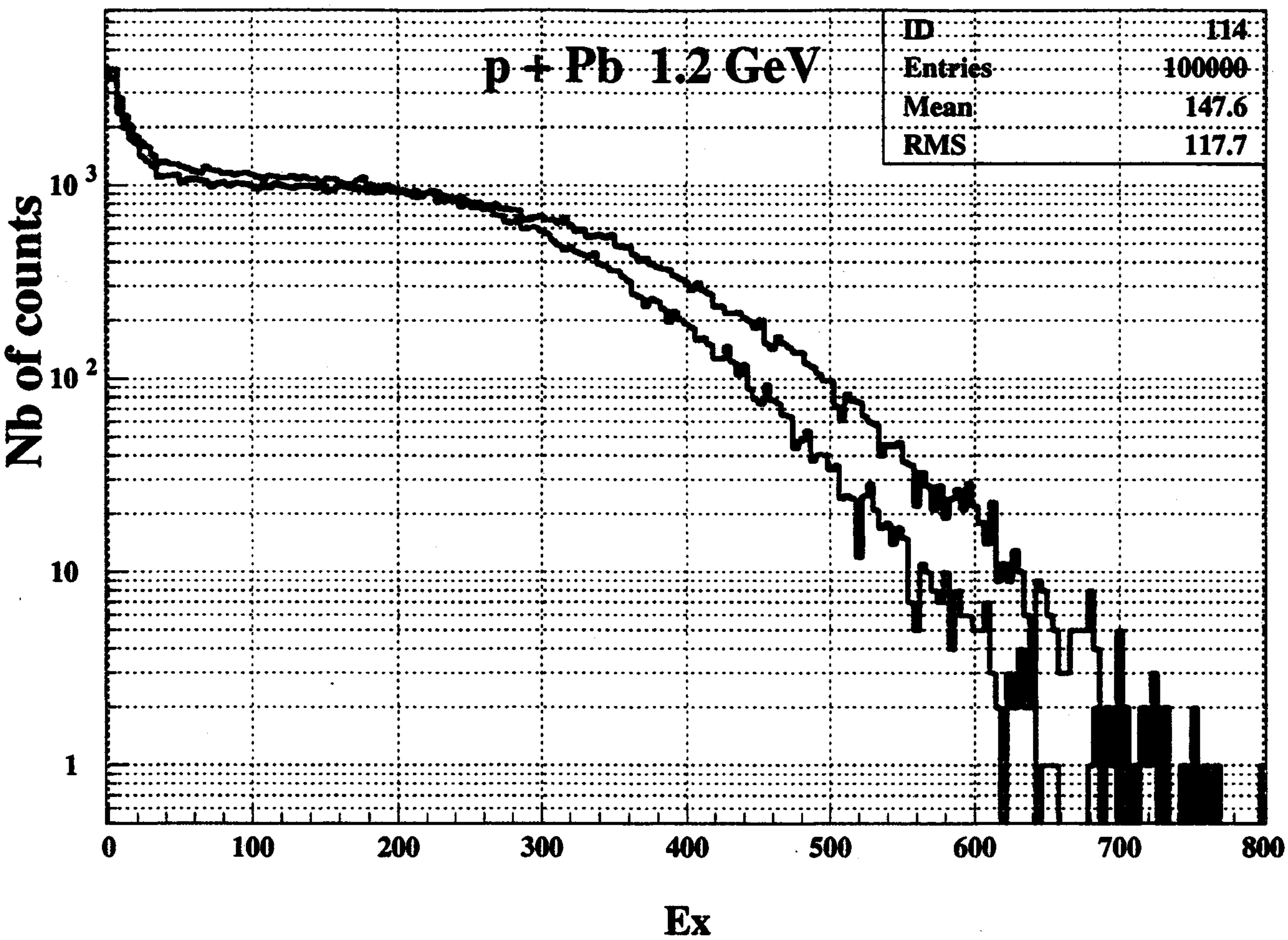
with realistic momentum distribution

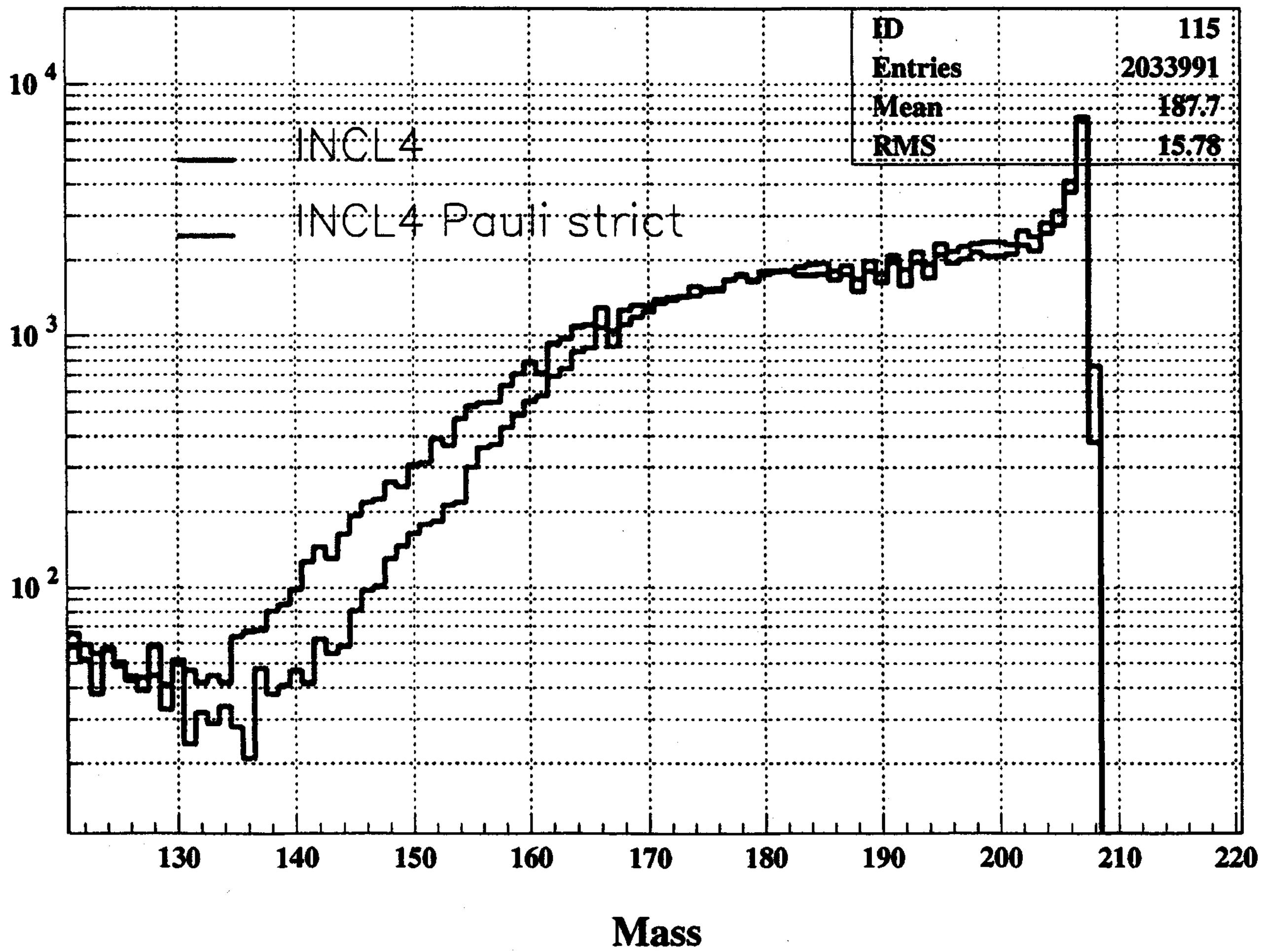


Reaction cross Section (mb)
p+U
p+Pb
p+Fe
$E_{proton}$ (MeV)


1GeV p+Pb, INCL4 (INCL3) + KHS_V3p, V=45MeV
Cross Section (mb)
red line INCL4
blue dashed line INCL3
10²
10
1
60
80
100
120
140
160
180
200
A

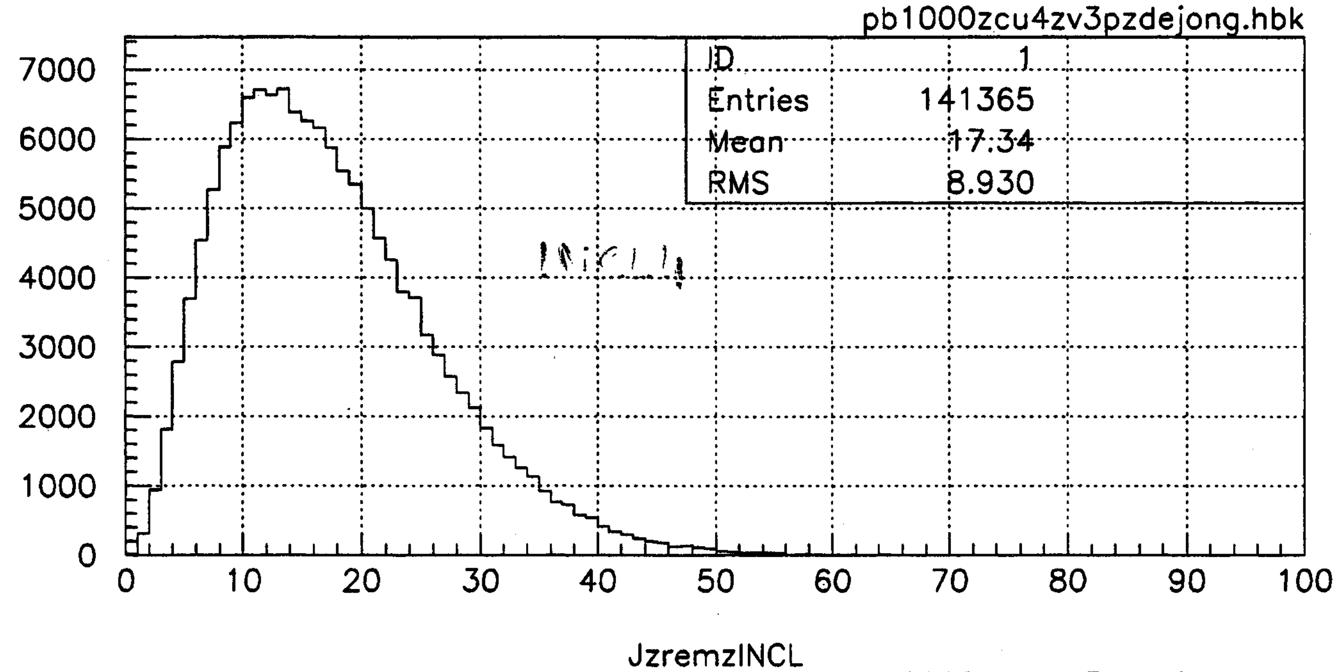

Cross Section (mb)
10²
10
1
10⁻¹
10⁻²
Hg
Tl
Pb
180
200
Mass Number

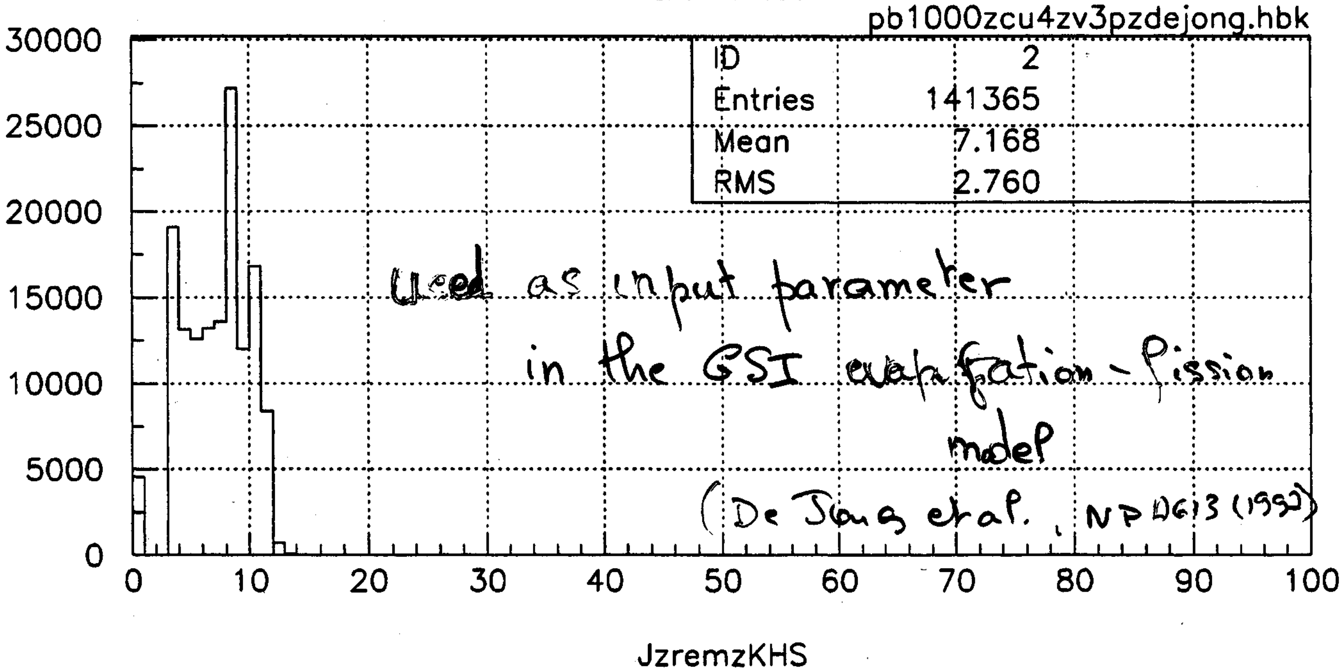

p + Pb 1.2 GeV
ID 114
Entries 100000
Mean 147.6
RMS 117.7
Nb of counts
10 3
10 2
10
1
0
100
200
300
400
500
600
700
800
Ex


ID 115
Entries 2033991
Mean 187.7
RMS 15.78
INCL4
INCL4 Pauli strict
10 4
10 3
10 2
130
140
150
160
170
180
190
200
210
220
Mass

Angular momentum destribution

2001/09/07 15.13



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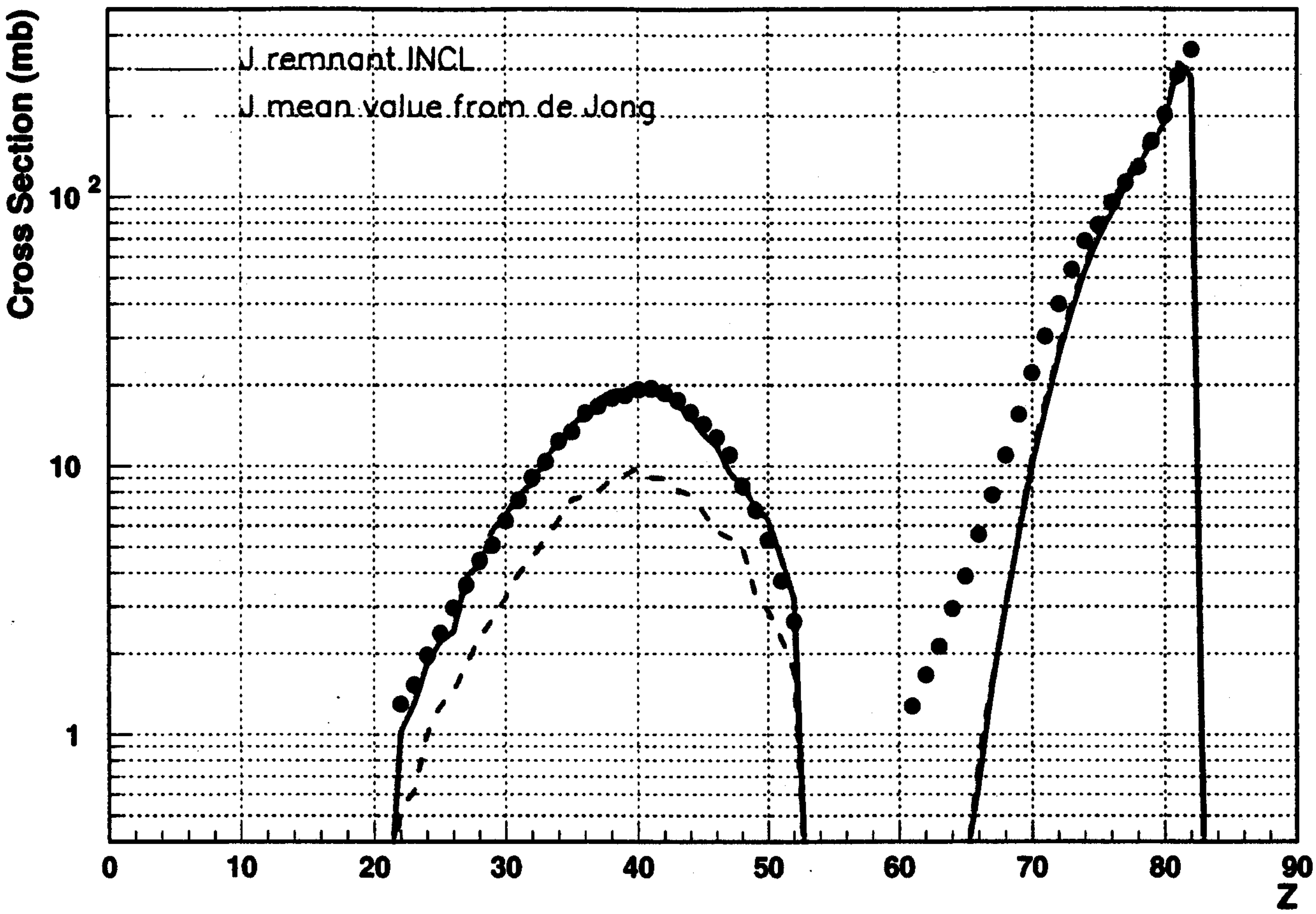
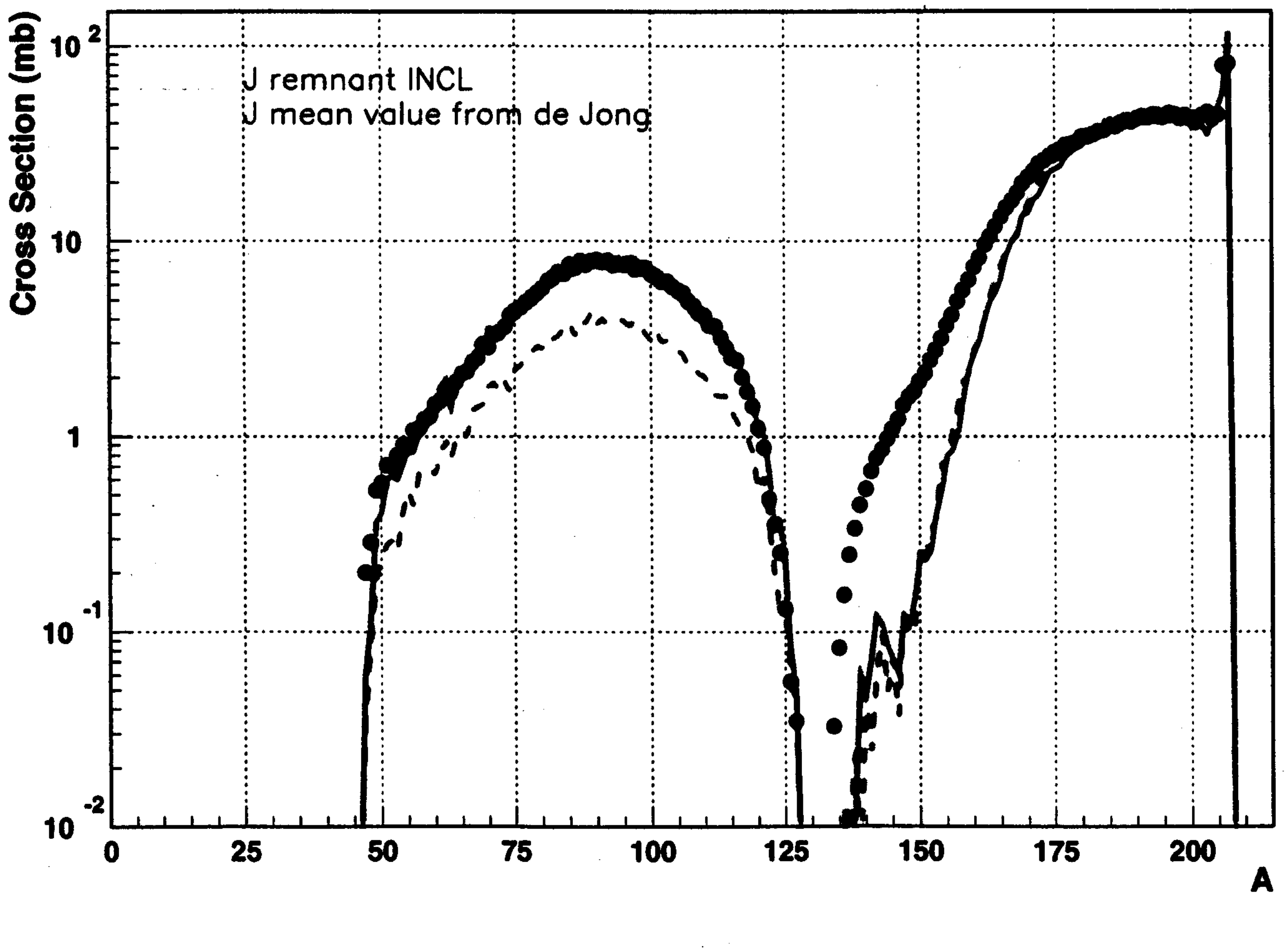
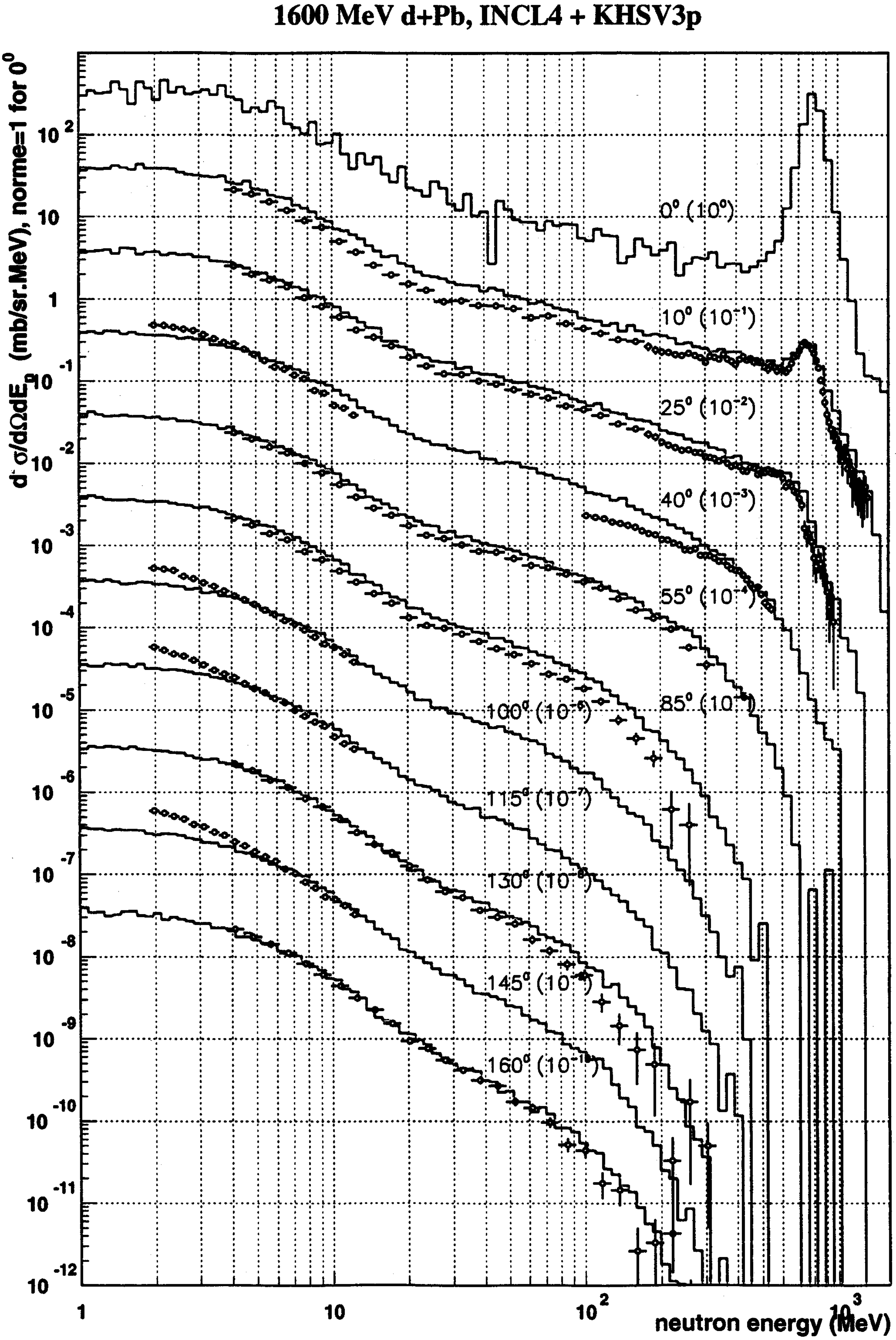
# 1GeV Pb+p, INCL4 + KHSV3p (J mean deJong)



2001/07/16 11.59

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# The Liège INC model (INCL)

## ➥ The new INCL4 version

- **no really free parameters:**

stopping time fixed by consideration on the variation rate of several observables

→ results insensitive to a variation of ± 5fm/c

Potential = 45 MeV ($E_F$+S)

→ could be slightly varied

- **Further possible improvements**

➥realistic momentum density

➥medium effect on *N-N* cross-sections

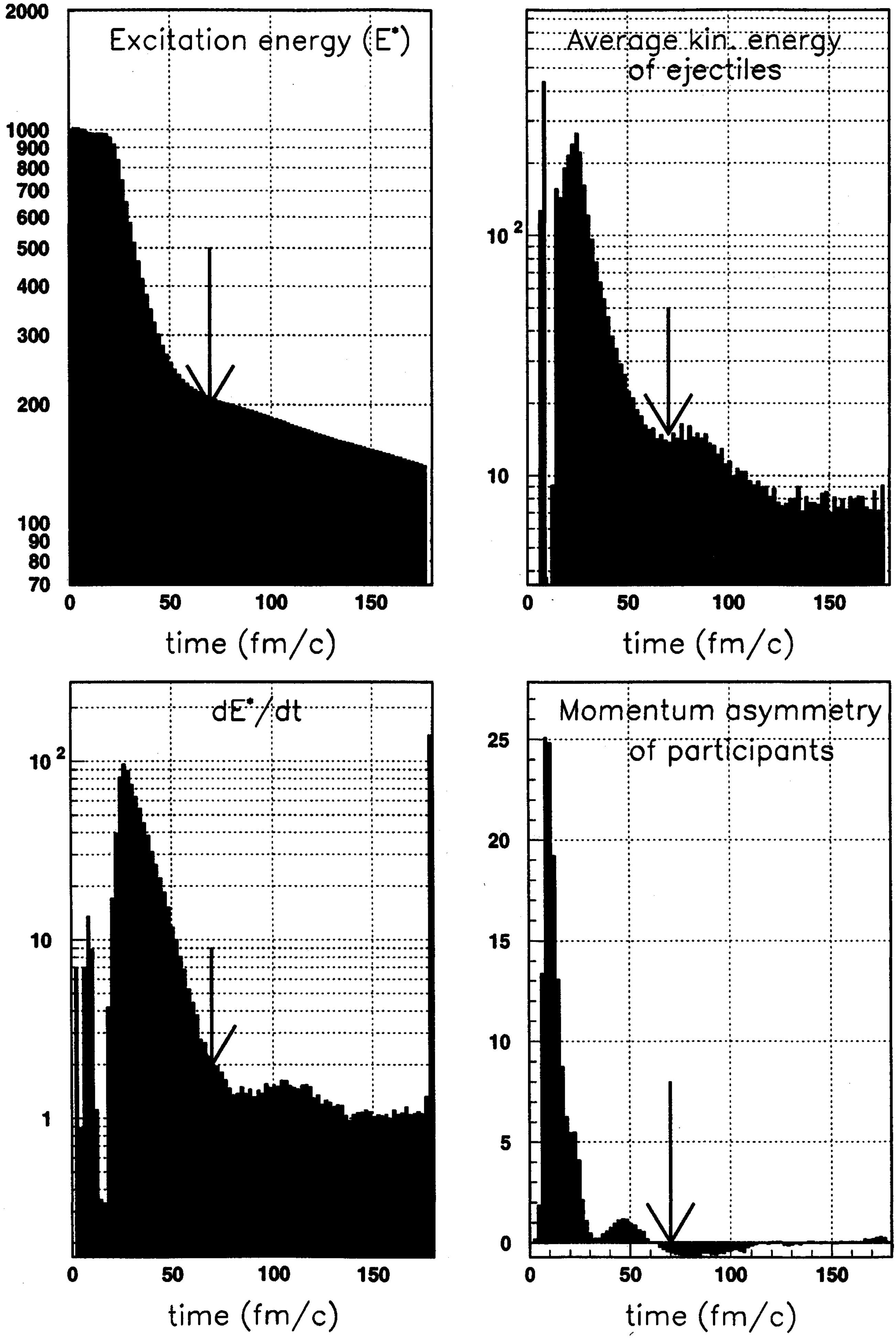
➥emission of composite particles (d, t, α, IMF)

➥special treatment of the first collision (quasi-elastic reactions)

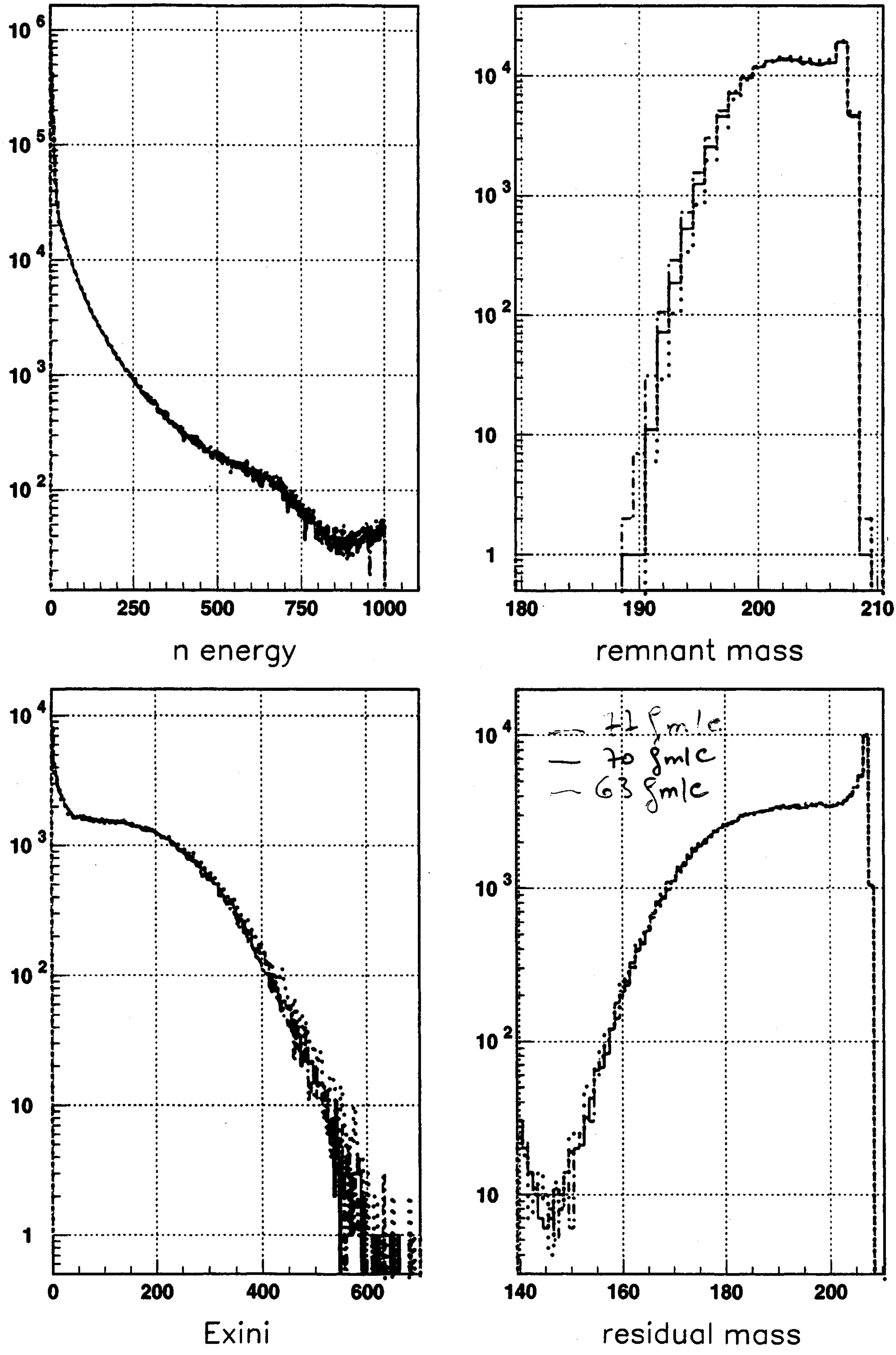
➥energy dependence of the potential

➥improvement of pion dynamics

- **Implementation in LAHET3 in progress** p+Pb ($T_p$=1.0 GeV), b=4 fm



# 1000 MeV p+Pb, INCL4 + KHSV3p, t=63, 70, 77 fm/c



# Models for the de-excitation

✦ **Evaporation: statistical models**

**Emission probability of one particle governed by**

- ➥ **inverse capture cross-section (detailed balance principle)**
- ➥ **Coulomb barriers**
- ➥ **density of available states**

✚ **Most widely used model : Dresner (ORNL-TM-196 (1962))**

- ➥ **Weisskopf-Ewing formalism**
- ➥ **all types of LCP evaporation**
- ➥ **GCC-Ignatyuk level density parameter ($\rightarrow$ A/8)**
- ➥ **Coulomb barriers lowering with E***

✚ **GSI (K.H.Schmidt) model (Nucl. Phys. A629 (1998) 635)**

- ➥ **Weisskopf-Ewing formalism**
- ➥ **only n,p,$\alpha$ evaporation**
- ➥ **Level density parameter $\rightarrow \sim$ A/12**
- ➥ **realistic Coulomb barriers**

✦ **Fermi-Break-up**

- ➥ **For A < 22**
- ➥ **break-up probabilities from available phase space**

# Models for the de-excitation

## ✦ Fission:

### ✚ Models used in high-energy transport codes

- ➥ Bohr-Wheeler formalism
- ➥ phenomenological parameterisation of barriers
- ➥ phenomenological parameterisation of Z and A distribution of fission fragments
- ➥ only n/fission competition
- ⇨ ORNL, Z>91 (Alsmiller, ORNL-7528 (1981))
- ⇨ RAL, Z>70 (Atchison, KFA Julich conf-34 (1981))

### ✚ GSI model

- ➥ friction introduced through a delay time
- ➥ full particle/fission competition
- ➥ Z and A distribution of fission fragments based on potential energy surface at saddle
- ➥ ~~GCC-Ignatyuk level density parameter (→ A/8)~~
- ➥ ~~Coulomb barriers lowering with E*~~

### ✚ GEMINI model (Moretto et al., NP A247 (1975) 211)

- ➥ Transition state method
- ➥ particle, IMF and fission treated on an equal footing