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Workshop on

# Nuclear Reaction Data and Nuclear Reactors: Physics, Design and Safety

13 March - 14 April 2000

*Miramare - Trieste, Italy*

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# NUCLEAR DATA AT HIGH ENERGY:

## Experiment, Theory and Applications

**Sylvie Leray**
**DAPNIA/SPhN CEA/Saclay**
**France**

# Nuclear Data at High Energy:

## Experiment, Theory and Applications

Sylvie LERAY
DAPNIA/SPhN CEA/Saclay

**New needs for High Energy Data (from 200 MeV to a few GeV) raised by new applications:**

- ➡spallation sources
- ➡accelerator driven systems
- ➡radioactive beams
- ➡radiation damage in space
- ➡astrophysics

# Outline

## 1. Importance of spallation reactions for applications

- Definition of spallation
- spallation sources and accelerator driven systems
- radioactive beams
- space and astrophysics

## 2. Models and codes at high energy

- Intra-nuclear cascade models
- Evaporation-fission models
- High Energy Transport Codes

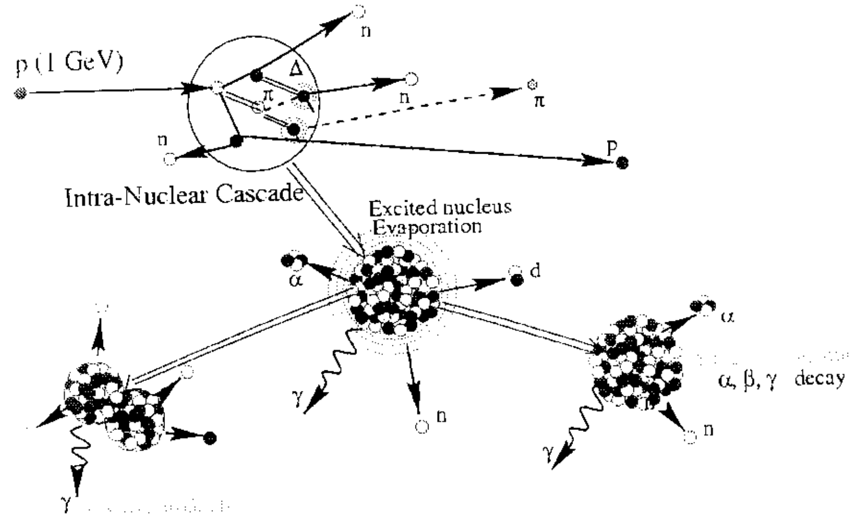
## 3. Measurements of microscopic high energy data

- Neutrons
- Charged particles
- Residues
- Coincidence measurements

## 4. Integral experiments and applications

- Neutrons
- Charged particles
- Residues

# Spallation reactions

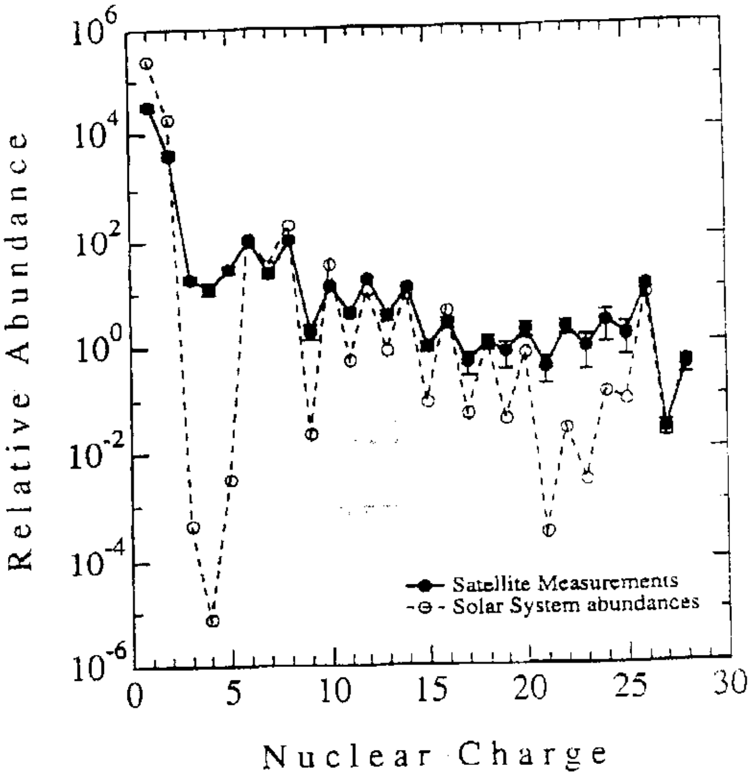


- **Definition:**

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

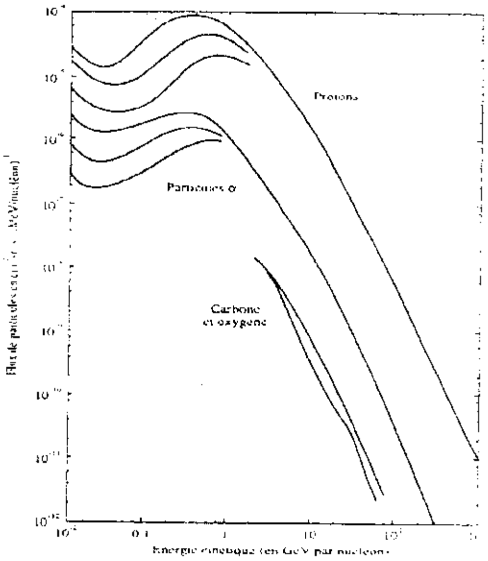
- **History:**
  - observation of particle cascades in cosmic rays interactions (G.Rossi, ZP82 (1933) 151)
  - secondary neutrons observed in n + U reactions at 90 MeV ( E.O.Lawrence, 1947)
  - Two step mechanism (Serber, PR72 (1947) 1114)

# Astrophysics



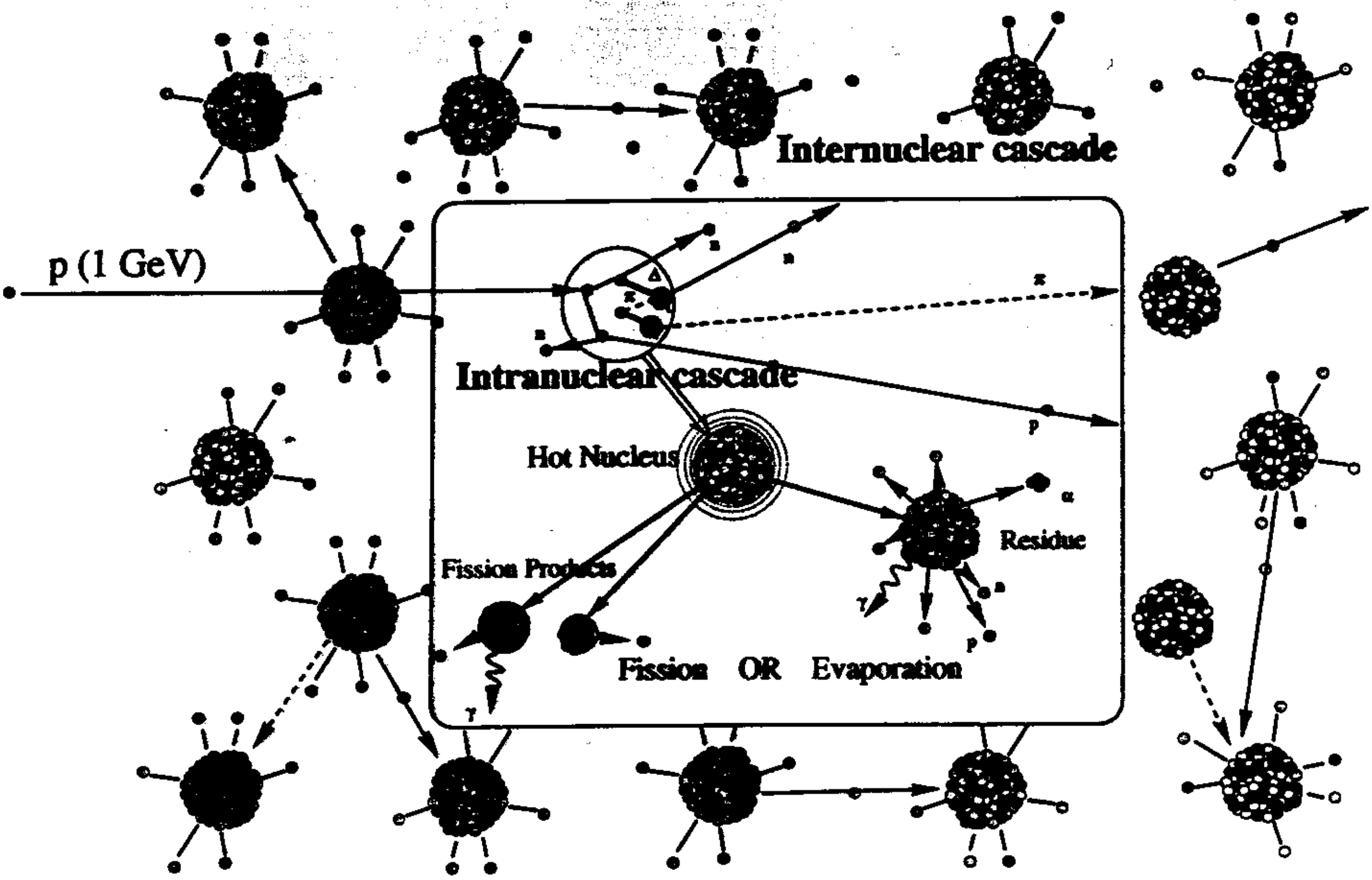
- Secondary reactions of cosmic rays in interstellar medium (90% of hydrogen)
  - ➥ explanation of abundance of isotopes
  - ➥ decide among models for galactic nucleosynthesis
  - ➥ origin of cosmic rays
- Composition of meteorites

# 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

[redacted]

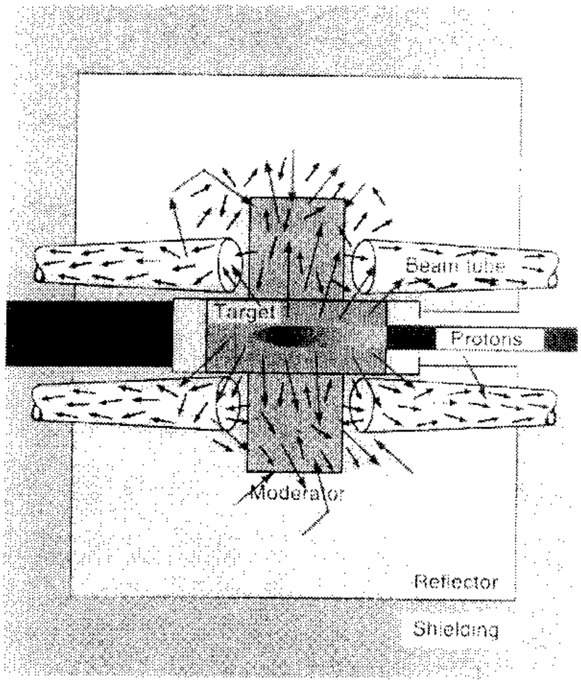


One proton on one target nucleus (Pb, Bi, W ...) produces by intranuclear **reaction:**

- several low energy evaporation neutrons
- a few high energy nucleons **which undergo** internuclear **reactions.**

**⇒ At the end, on a thick Pb target, one proton of 1 GeV produces around 25 neutrons**

# 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

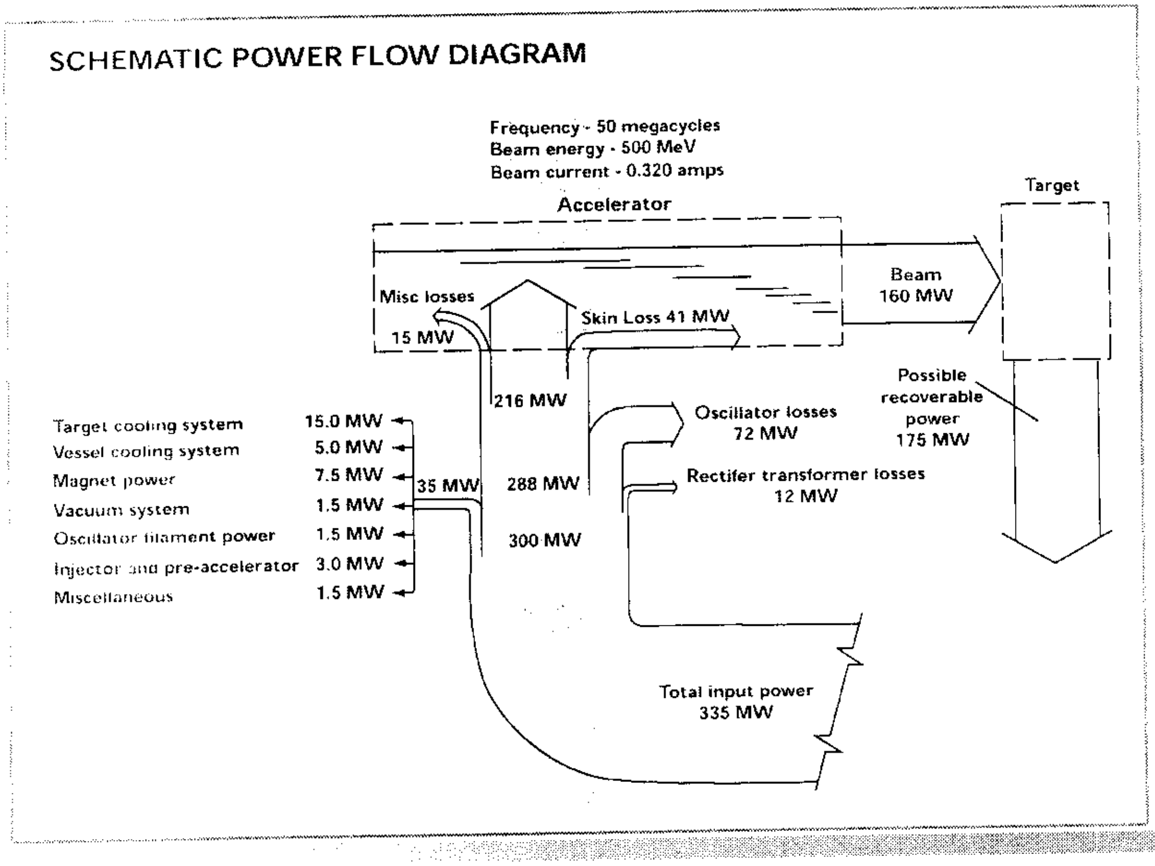
# The MTA project

## USA (1950-1954)

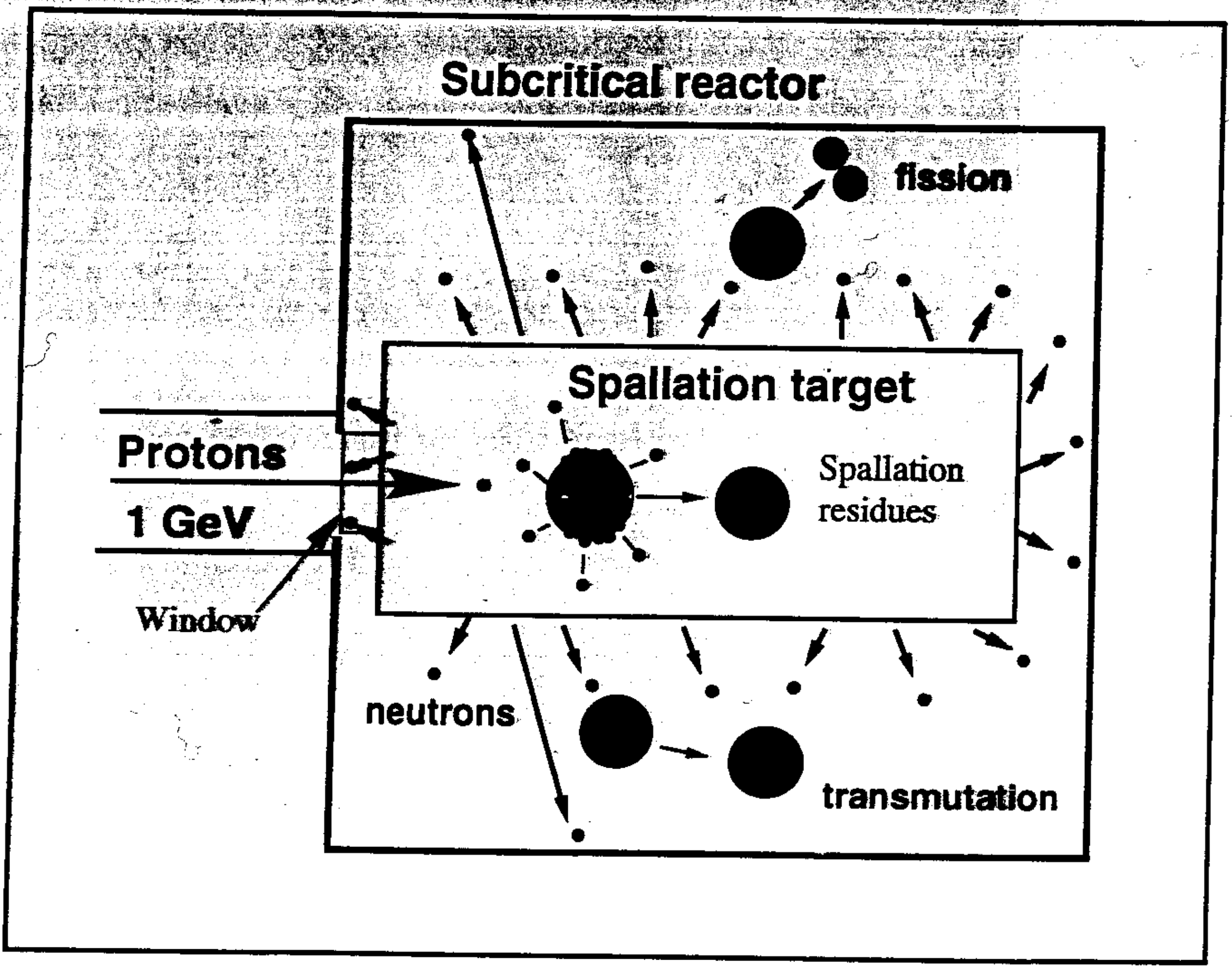
- **Objective:**

  to produce Pu from depleted uranium (or $^{233}U$ from $^{232}Th$) using a 500 MeV deuteron beam, a Be-U target and a sub-critical assembly

➡ abandoned when important amount of uranium ore was found in USA



[redacted]



- A high intensity accelerator (10 to 200 $mA$)

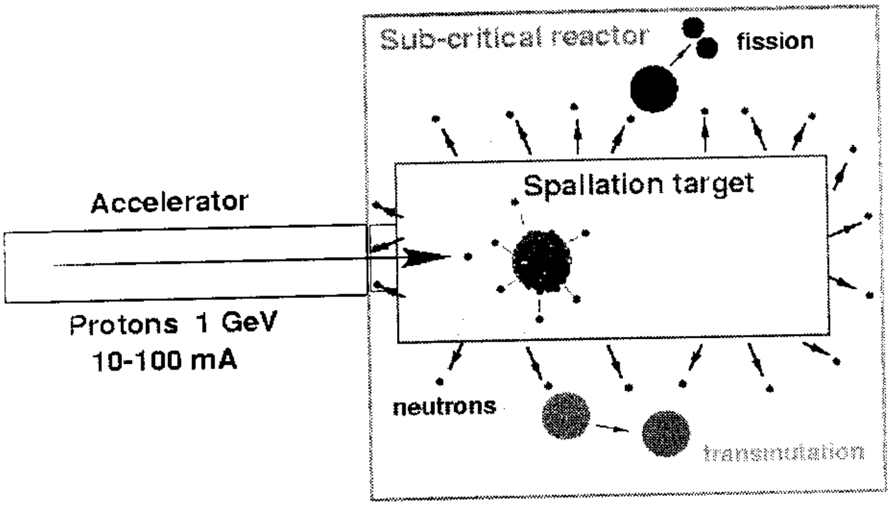
⇒ protons (around 1 $GeV$) that generate an intense neutron flux by spallation reactions

- A sub-critical blanket

⇒ driven by the spallation neutrons

⇒ where long-lived isotopes are transmuted by capture or fission reactions

# Data required for the design of spallation modules



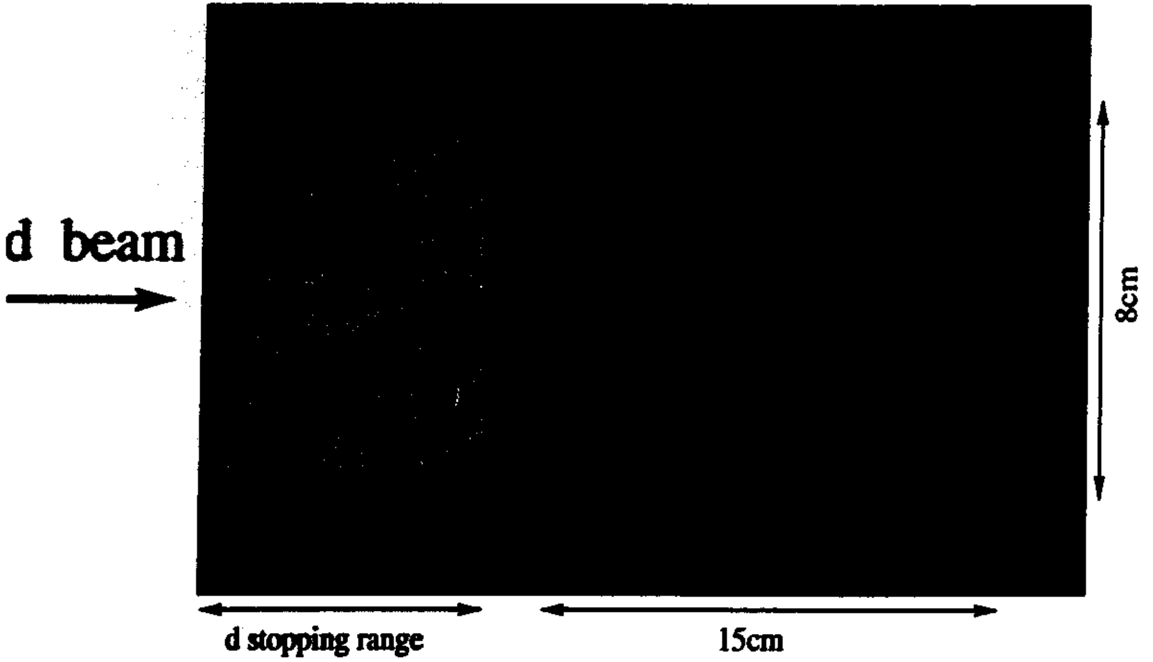
- Multiplicity and characteristics of the produced neutrons
  - ➡ performance of the target, damages, radioprotection
- Charged particle production
  - ➡ gas ($H_2$, He) production, DPA
- Residual nuclide production
  - ➡ radiotoxicity, corrosion, damages

## 5. production de RIBs: le projet SPIRAL Phase-II

**problème:** les cibles-sources limitées par puissance admissible (~20kW) par une cible

$$I = I_o \cdot \sigma \cdot N \cdot \epsilon = I' \cdot \epsilon$$

proposition: par groupe d'Argonne



**important:**

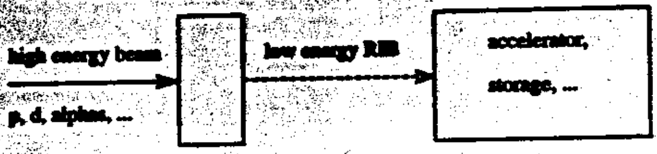
* la dissipation thermique par réactions "utiles"
* l'effet de l'énergie du faisceau primaire
* le volume (la masse) de la cible-source

la figure de *Ridikas, Mittig: Proc. of Int. Conf. ENAM (1998)*

# 5. production de RIBs: les méthodes directes

**1) ISOL**

(CERN,TISOL,LLN,...)



high energy beam

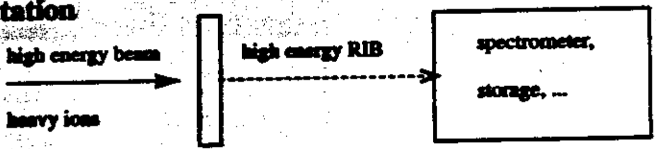
p, d, alphas, ...

low energy RIB

accelerator,
storage, ...

**2) Fragmentation**

(GANIL,MSU,GSI,...)



high energy beam

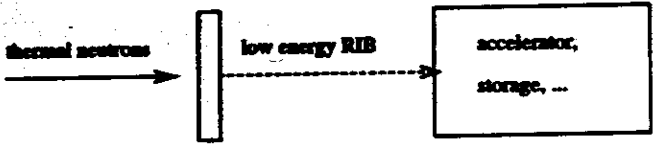
heavy ions

high energy RIB

spectrometer,
storage, ...

**3) Reactors**

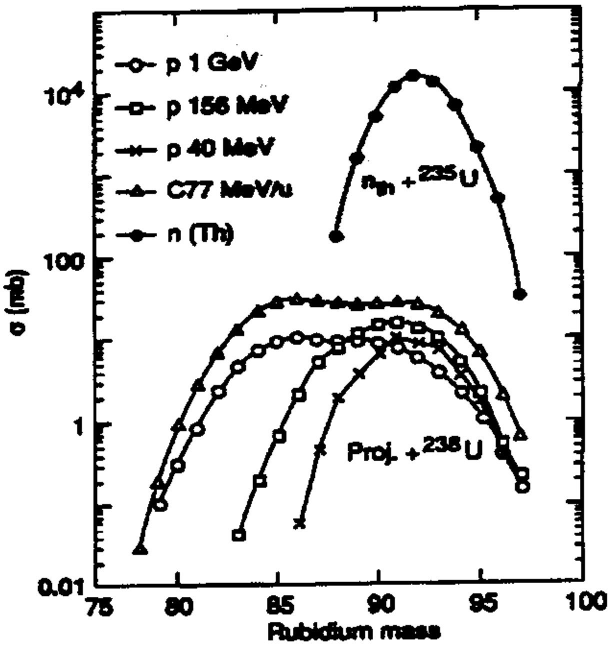
(MAFF)



thermal neutrons

low energy RIB

accelerator,
storage, ...



L'intensité finale des RIBs, $I$, dépendra des paramètres suivants:

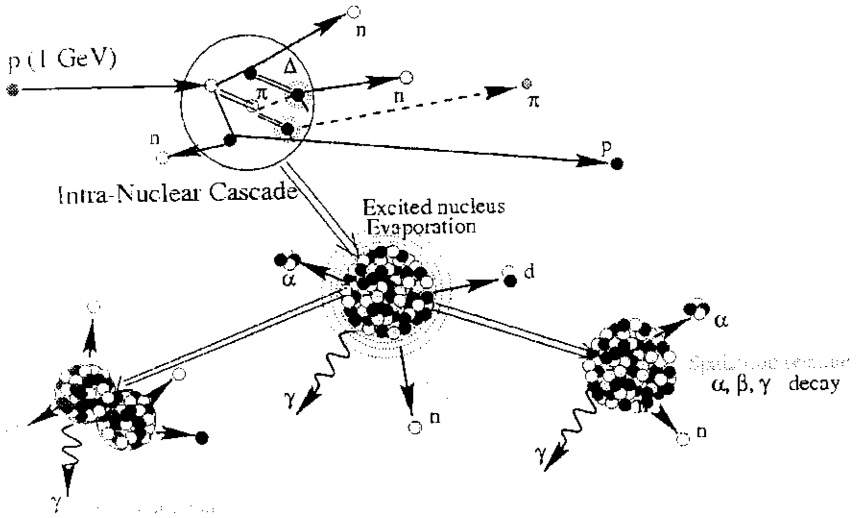
$$I = I_0 \cdot \sigma \cdot N \cdot \epsilon$$

# High energy nuclear data required for applications

- Secondary particle production (n, p, $\alpha$)
  - ➡ astrophysics
  - ➡ space
  - ➡ spallation sources
  - ➡ ADS
- Residual nuclide production
  - ➡ astrophysics
  - ➡ space
  - ➡ RIB
  - ➡ spallation sources
  - ➡ ADS

⇒ Both basic cross-sections and integral production

# 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)

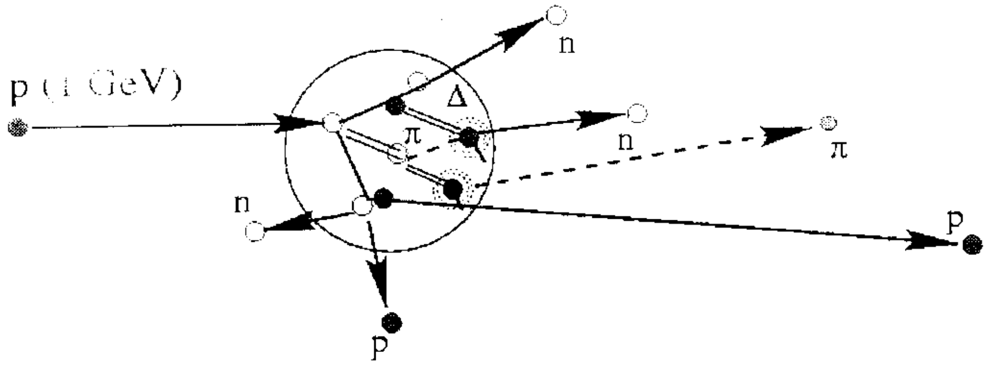
=> Heating of the nucleus - thermalisation

➡ De-excitation by evaporation or fission

statistical evaporation models

slow process ( hundreds of fm/c)

# Intra-Nuclear Cascade 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

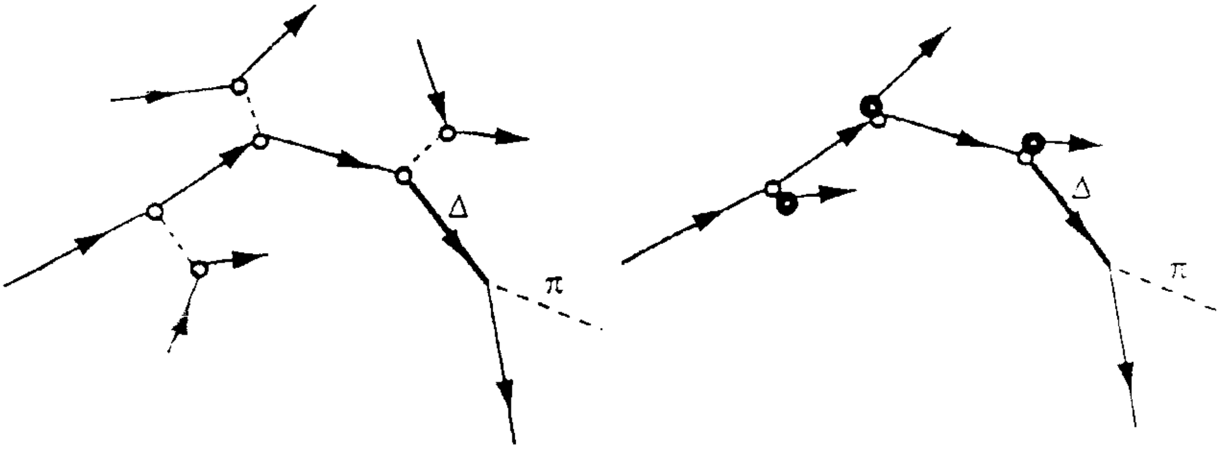
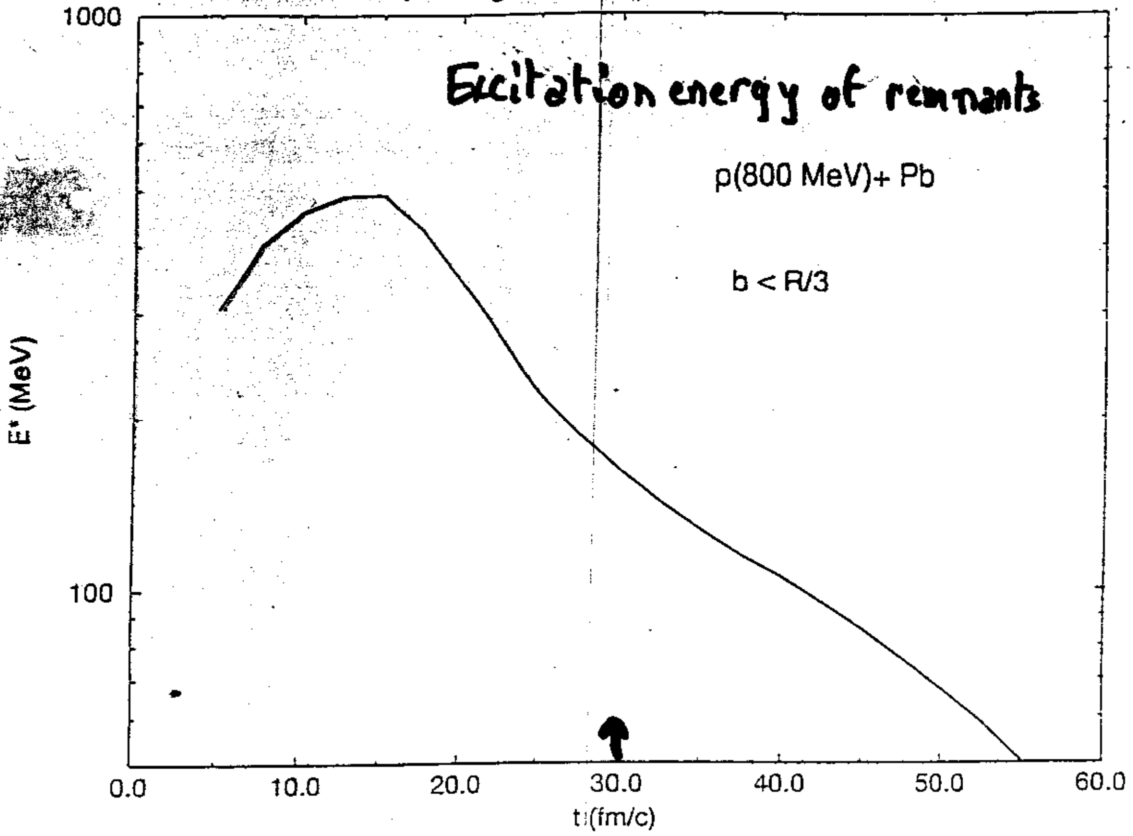
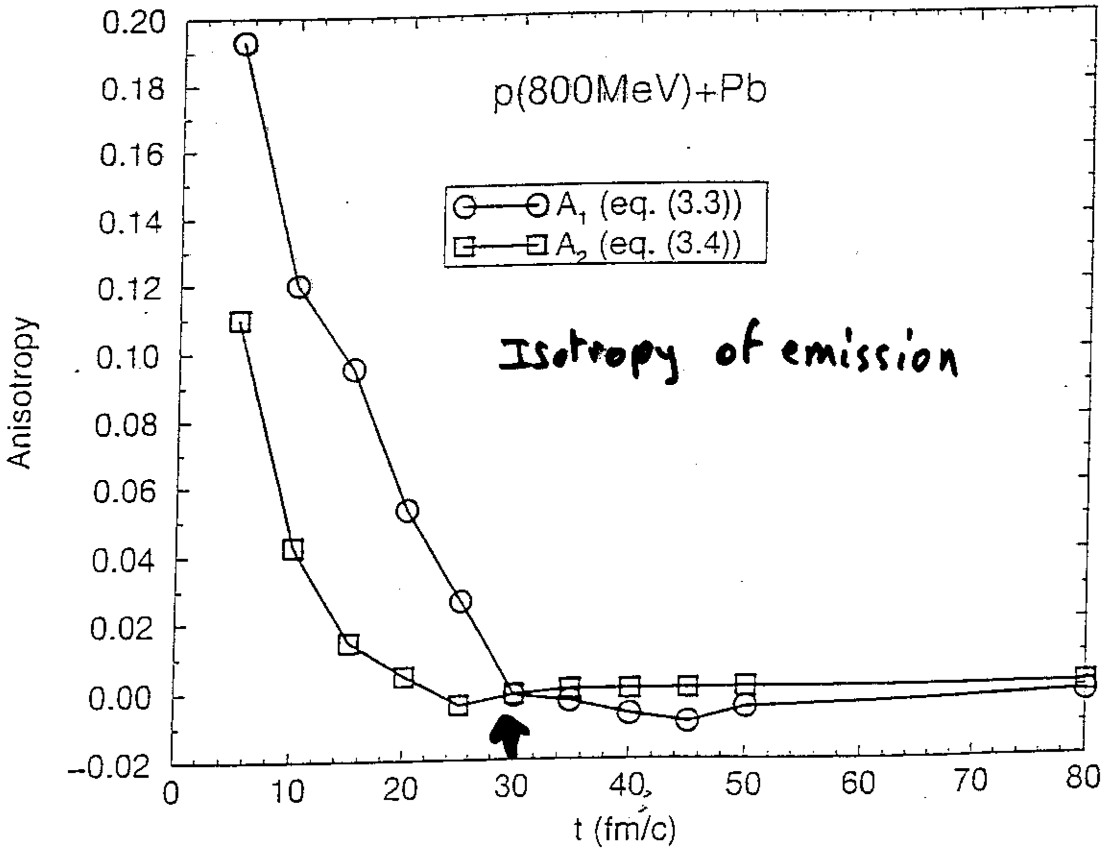


Fig. 3 : Schematic representation of the INC models of the first type (left) and of second type (right). In the latter case, nucleons promoted from the continuum are indicated by heavy dots.

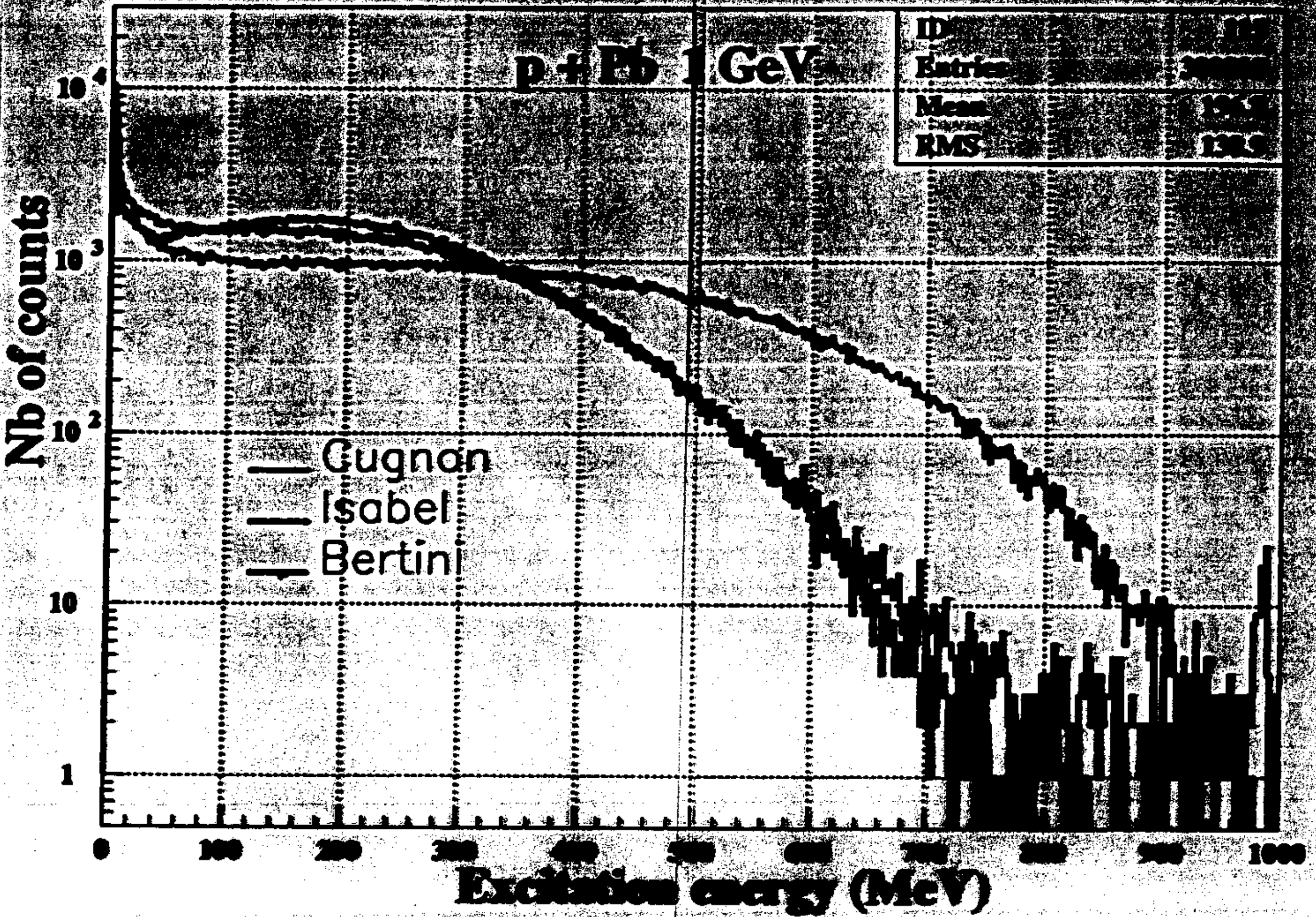
| | Bertini | Isabel | Cugnon |
|---|---|---|---|
| Medium | continuous | continuous | particles |
| Cascade propagation | collided particles | time steps | time steps |
| Collision criterium | mean free path | mean free path | minimum distance of approach |
| Stopping criterium | energy | energy | time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

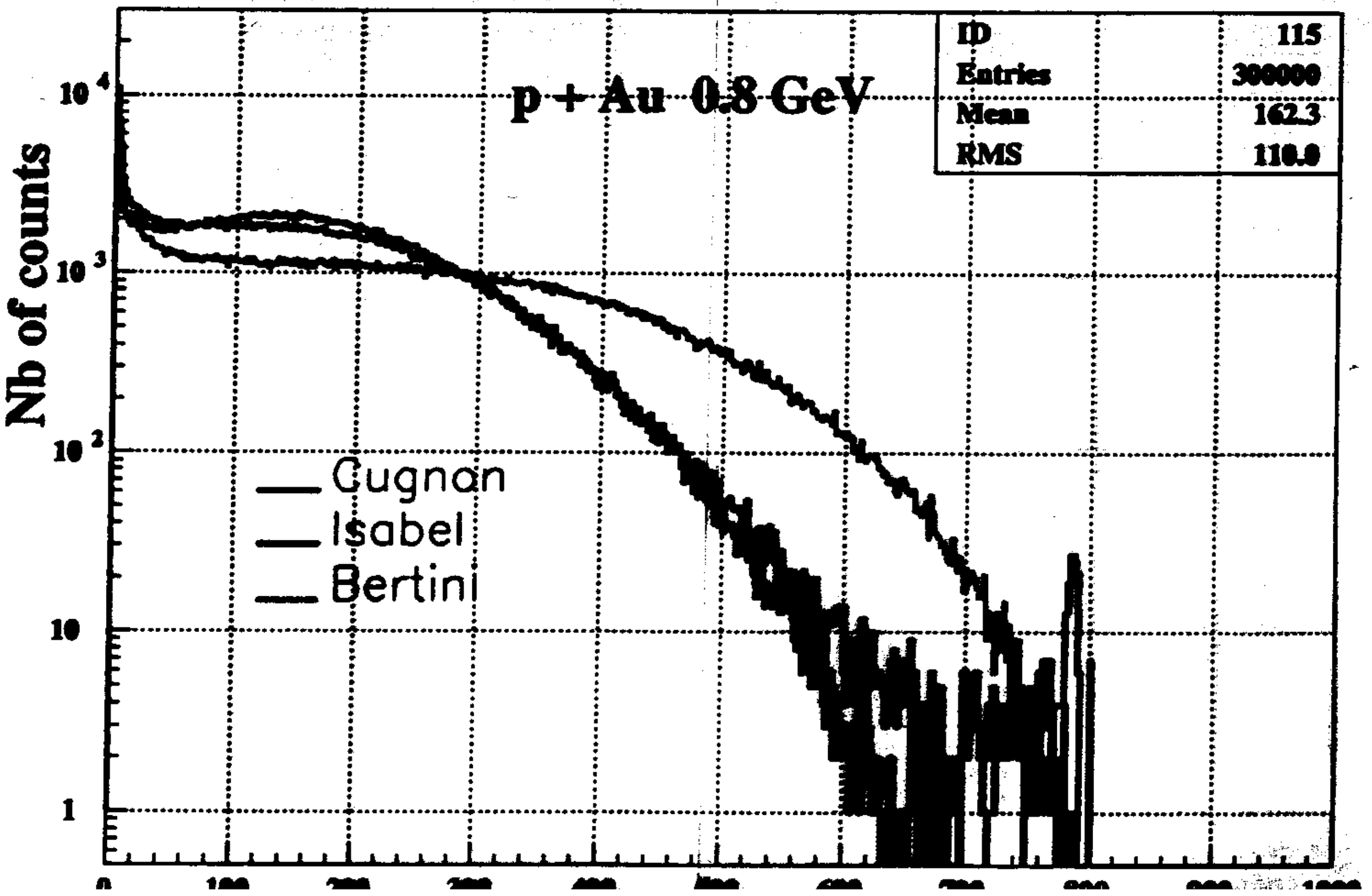
# Choice of stopping time of INC

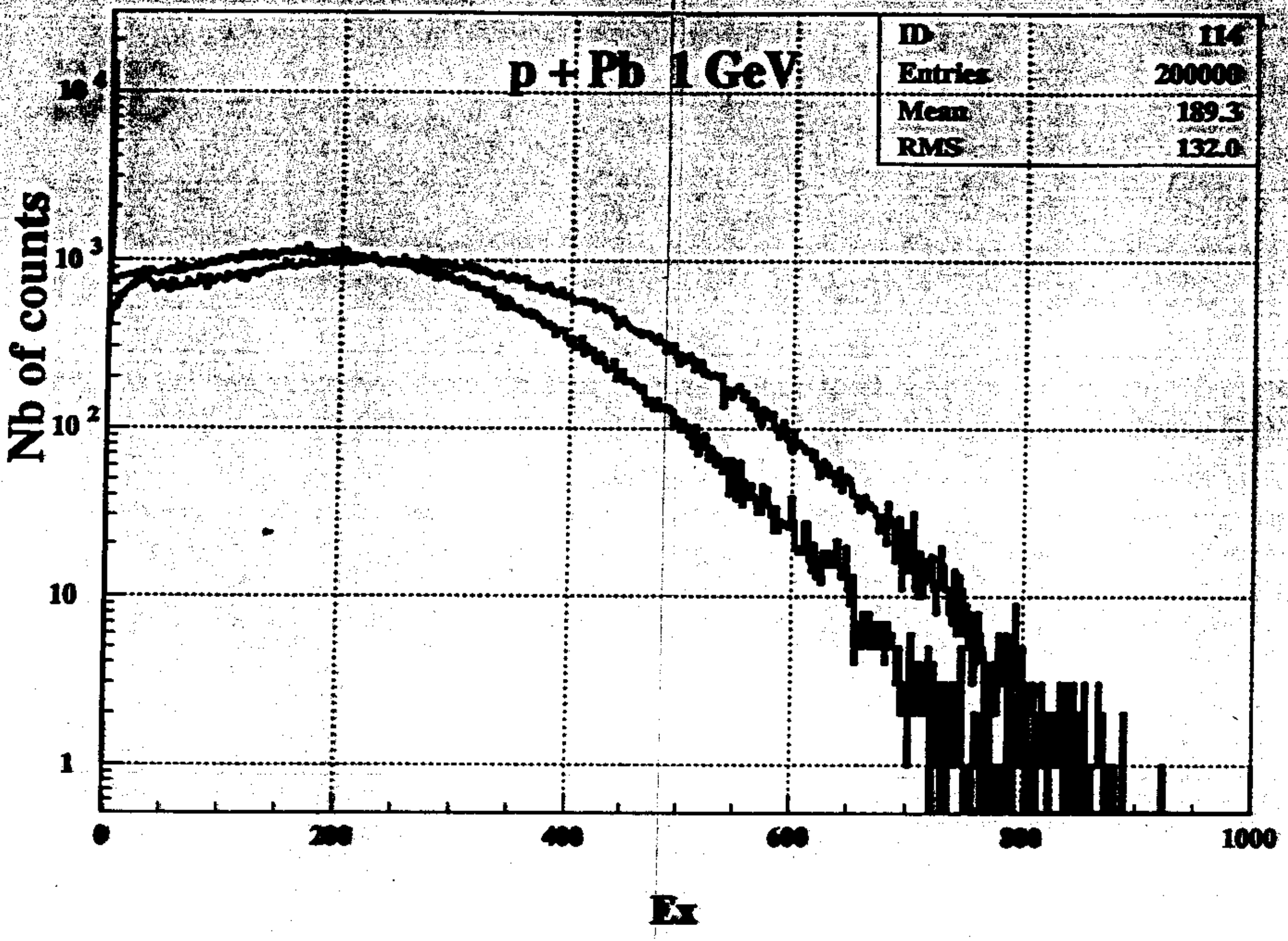


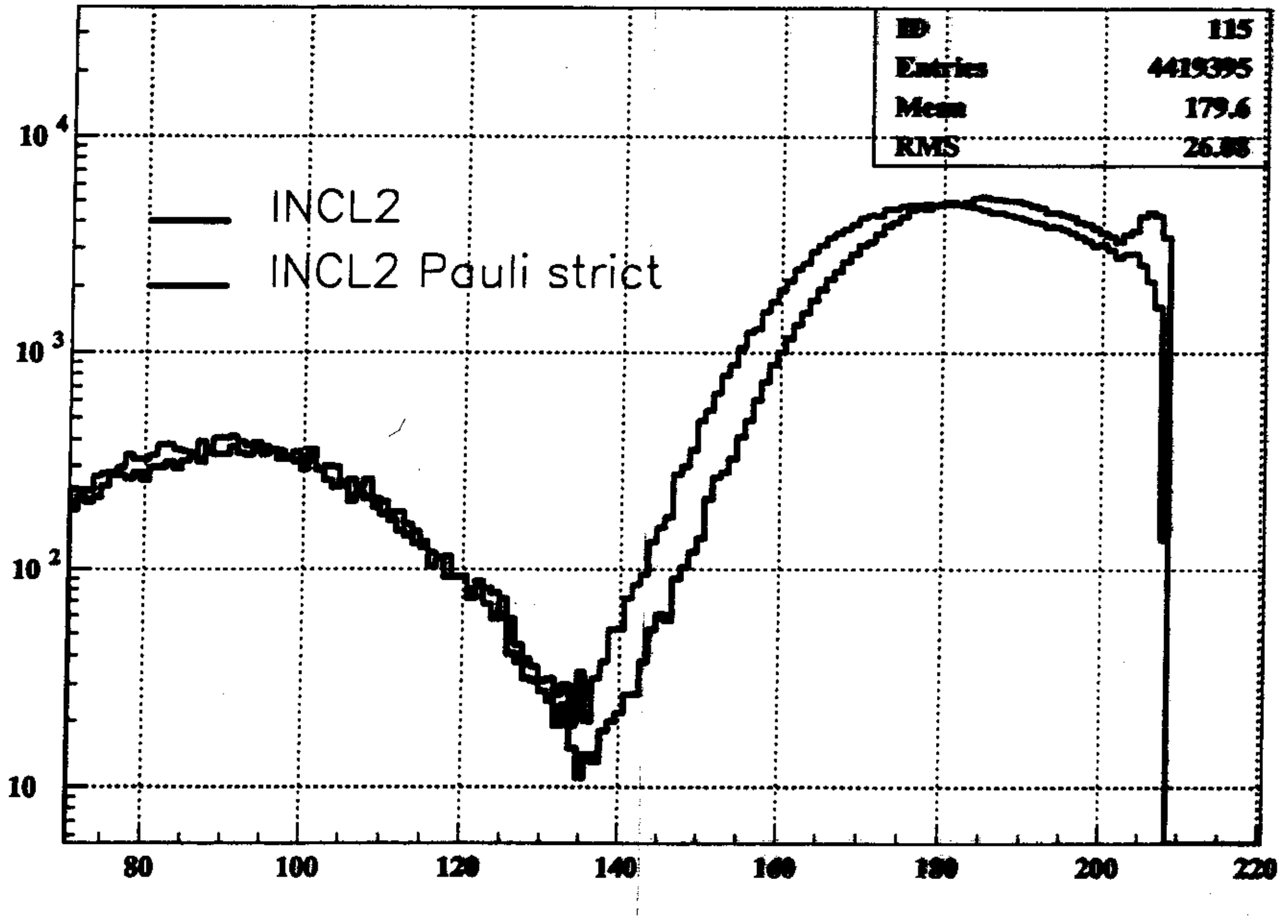


$f(E_i, A, b)$


p + Pb 1 GeV
ID
Entries
Mean
RMS
Nb of counts
10^4
10^3
10^2
10
1
Cugnon
Isabel
Bertini
0
100
200
300
400
500
600
700
800
900
1000
Excitation energy (MeV)


p + Au 0.8 GeV
ID 115
Entries 300000
Mean 162.3
RMS 110.0
Nb of counts
10^4
10^3
10^2
10
1
Cugnon
Isabel
Bertini
0
100
200
300
400
500
600
700
800
900
1000

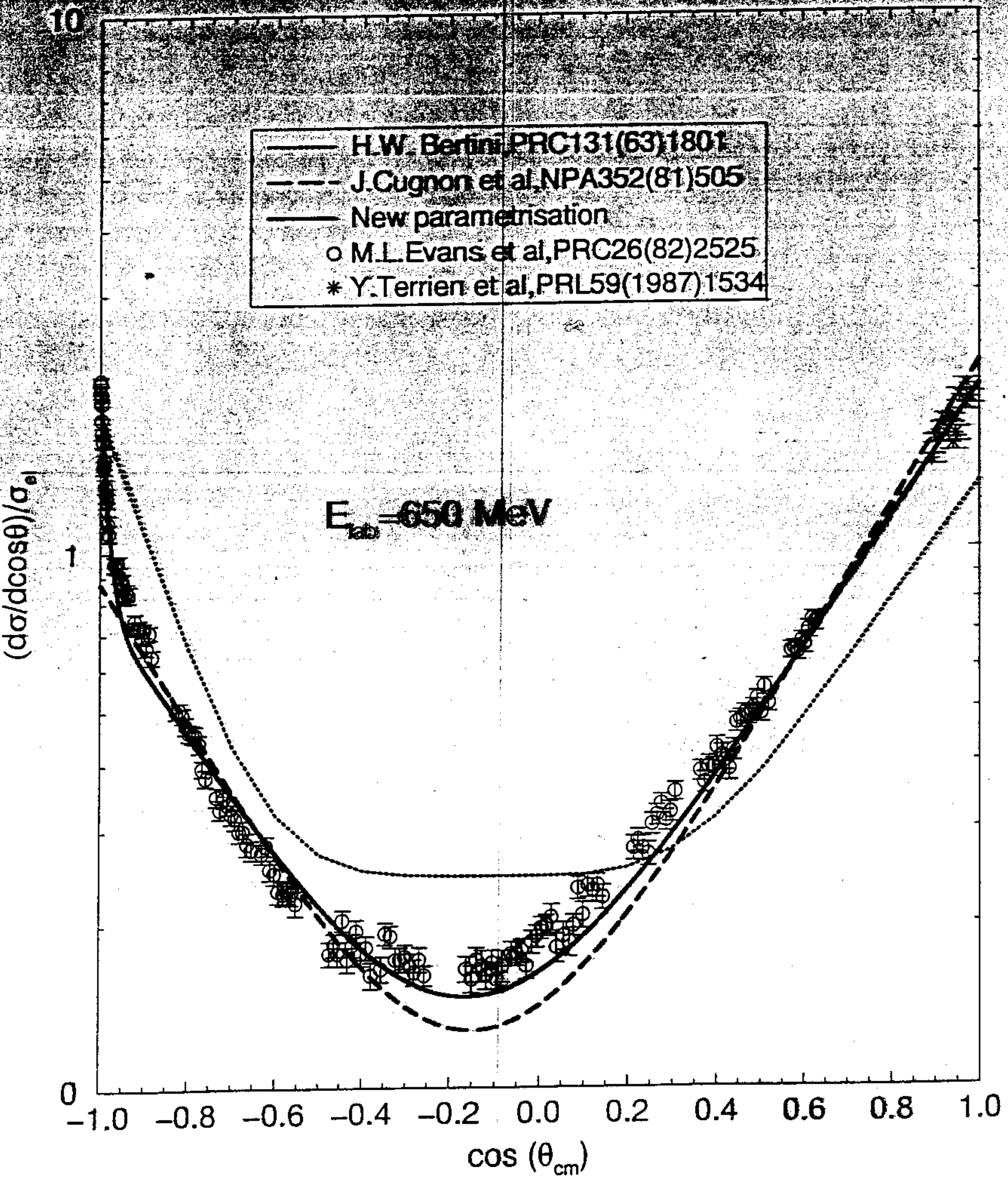

p + Pb 1 GeV
ID 114
Entries 200000
Mean 189.3
RMS 132.0
Nb of counts
10^4
10^3
10^2
10
1
0
200
400
600
800
1000
Ex


ID 115
Entries 4419395
Mean 179.6
RMS 26.88
INCL2
INCL2 Pauli strict
10^4
10^3
10^2
10
80
100
120
140
160
180
200
220

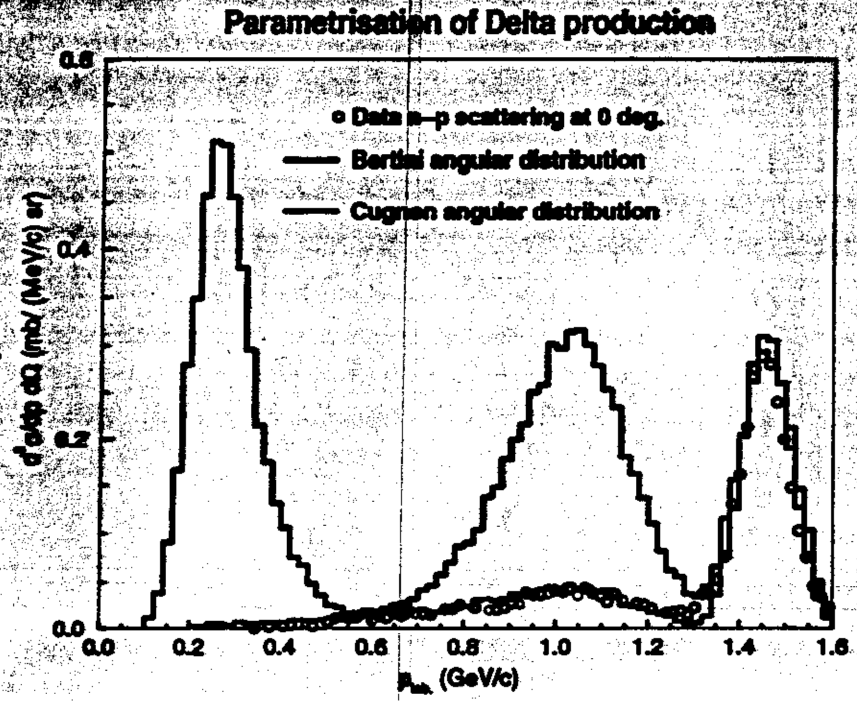
np angular distributions

→ rise at backward angle (charged pion exchange)

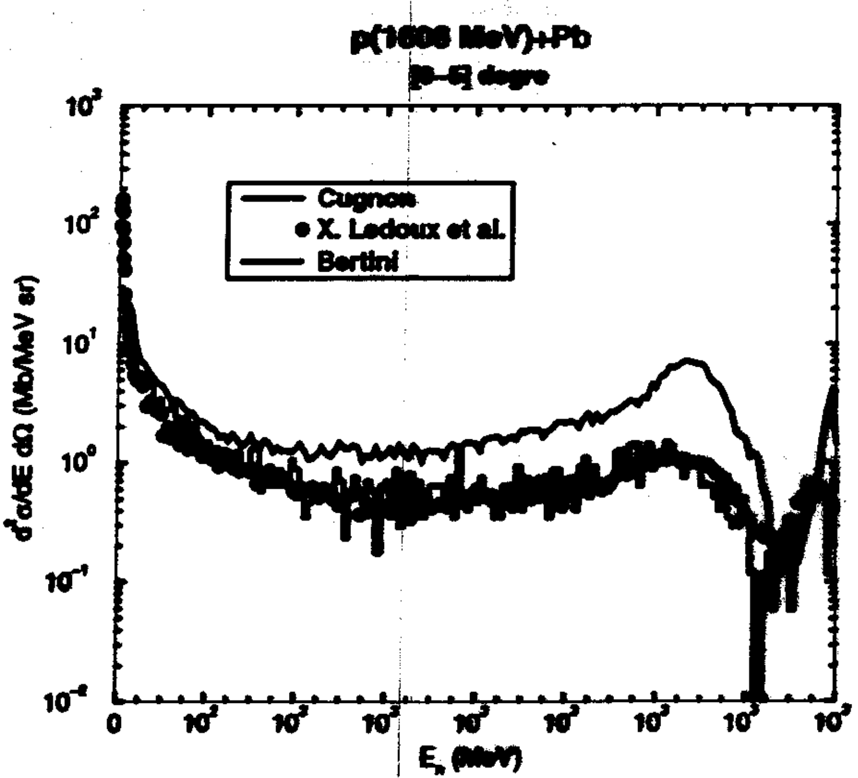
mainly affect 0° in (p,xn)



# [illegible] in [illegible] Δ production cross-section



Parametrisation of Delta production

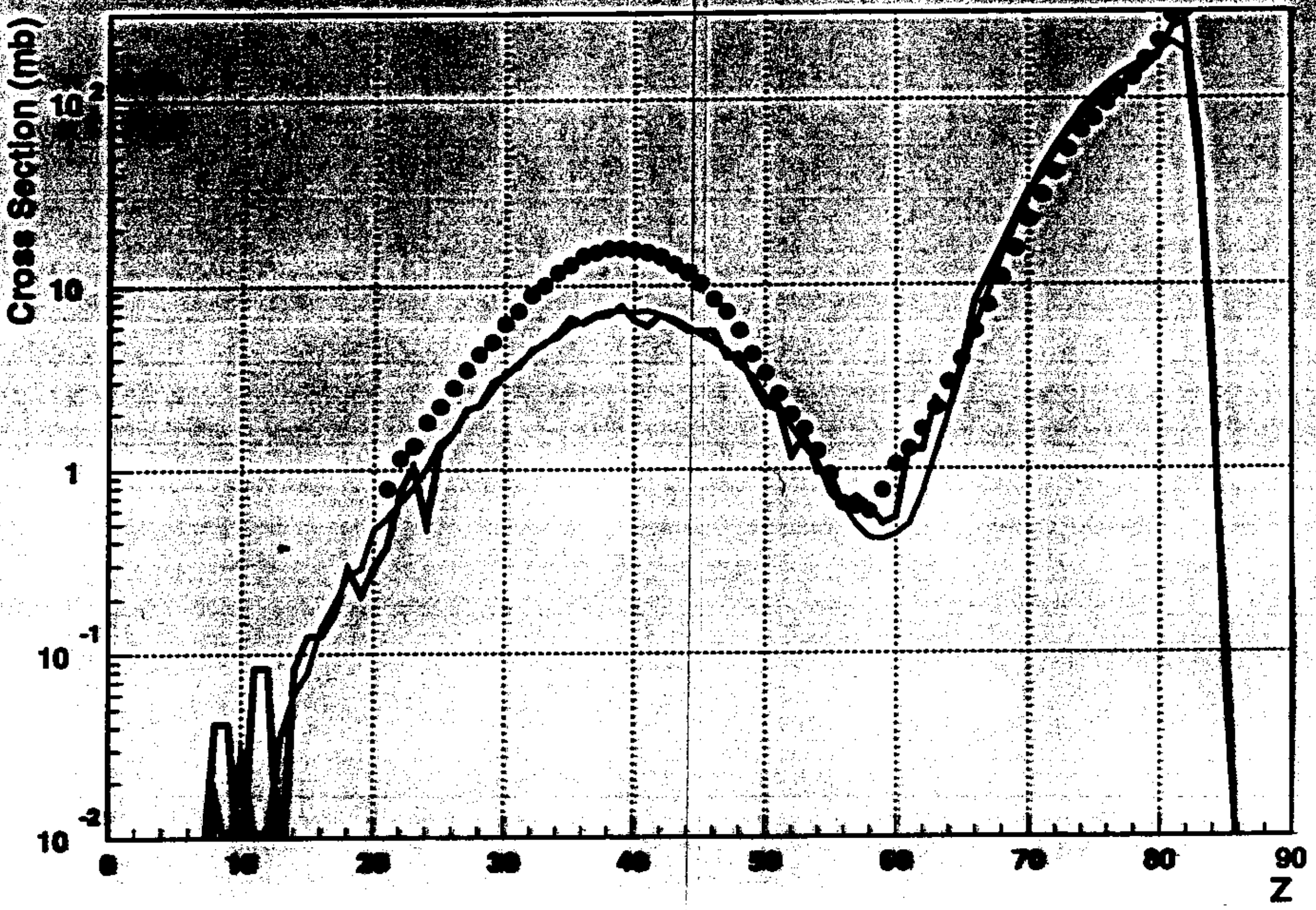


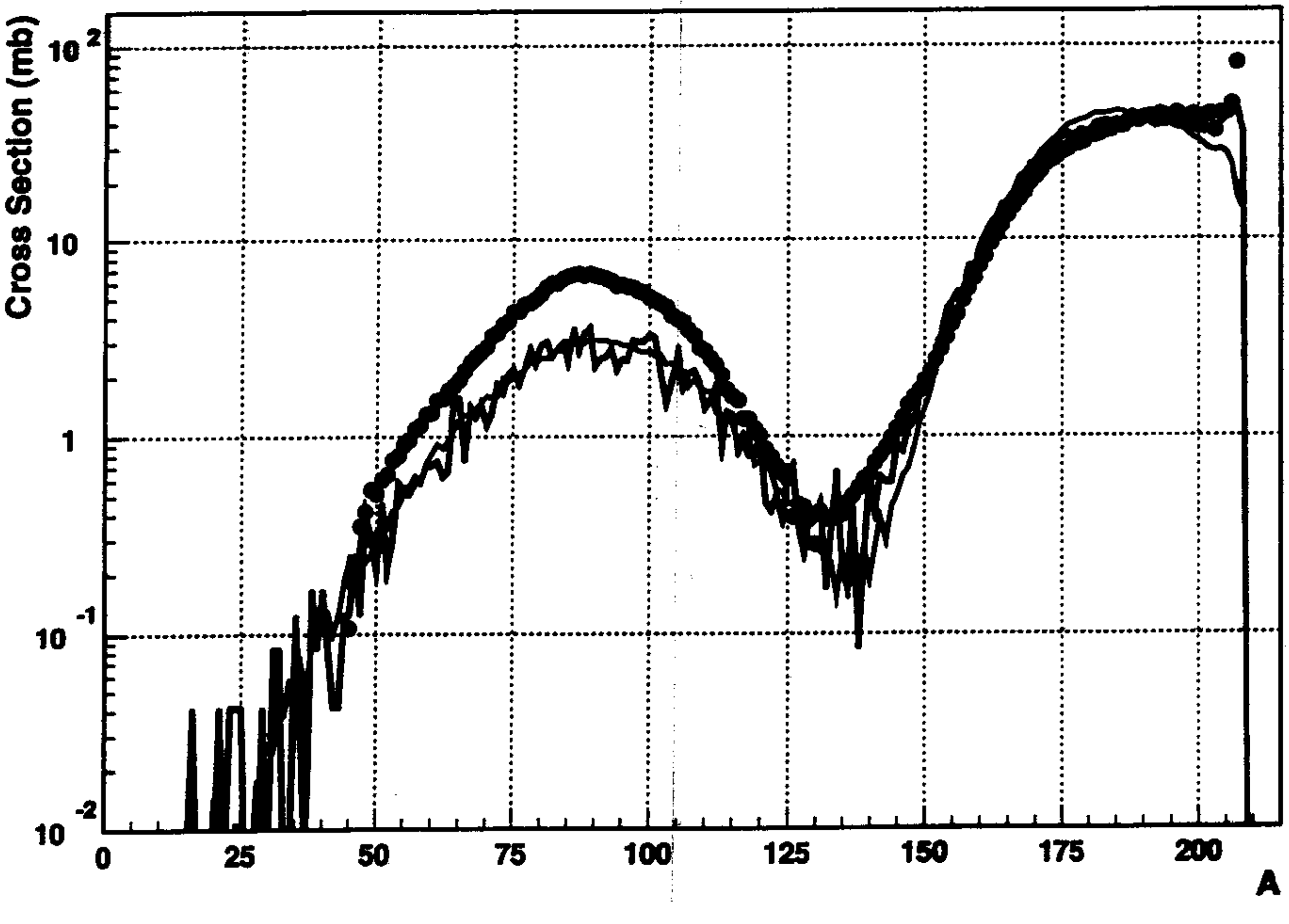
p(1600 MeV)+Pb

[0–5] degre

00/03/14 10.31

1 GeV Pb+p,cugnon_3 (trapeze vuillier, z OK) + KHS_V3, V=45MeV, t0/0.85





# Models for the de-excitation

## Evaporation: two classes of models

- ➡ Weisskopf-Ewing formalism
  - detailed balance principle
  - Dresner, ORNL-TM-196 (1962)
- ➡ Transition state method
  - transition probability at the barrier
  - GEMINI, Moretto et al., NP A247 (1975) 211

Main ingredients:

- level density parameters
- barriers
- inverse cross-sections

## Fission: Bohr-Wheeler formalism

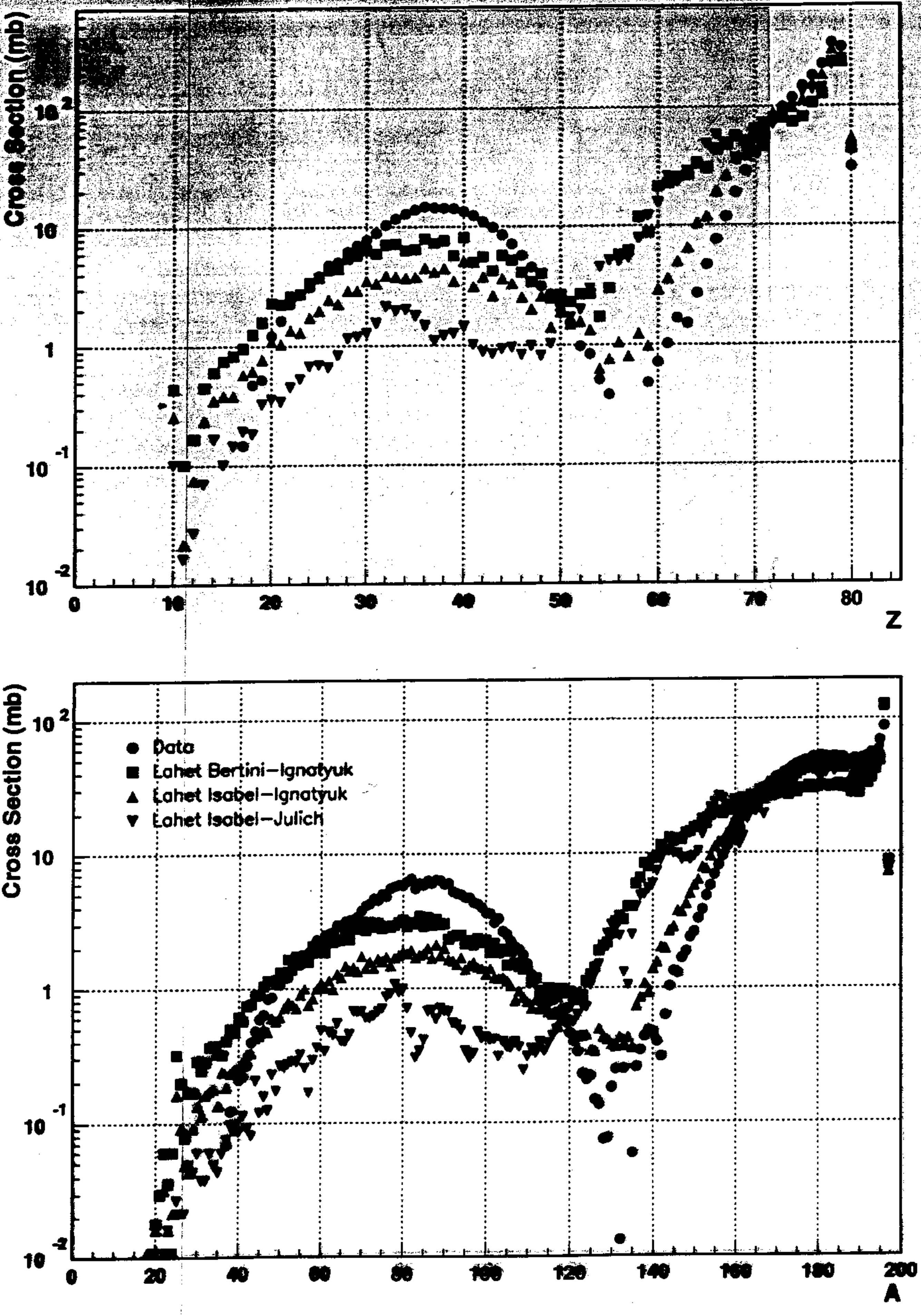
- ➡ phenomenological parameterisation of barriers
- ➡ ORNL, Z>91 (Alsmiller, ORNL-7528 (1981))
- ➡ RAL, Z>70 (Atchison, KFA Julich conf-34 (1981))

## Fermi-Break-up

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

98/12/01 12,16

# Au+p 800 MeV/A (evapo Dresner)



SPhN/CEA/Saclay

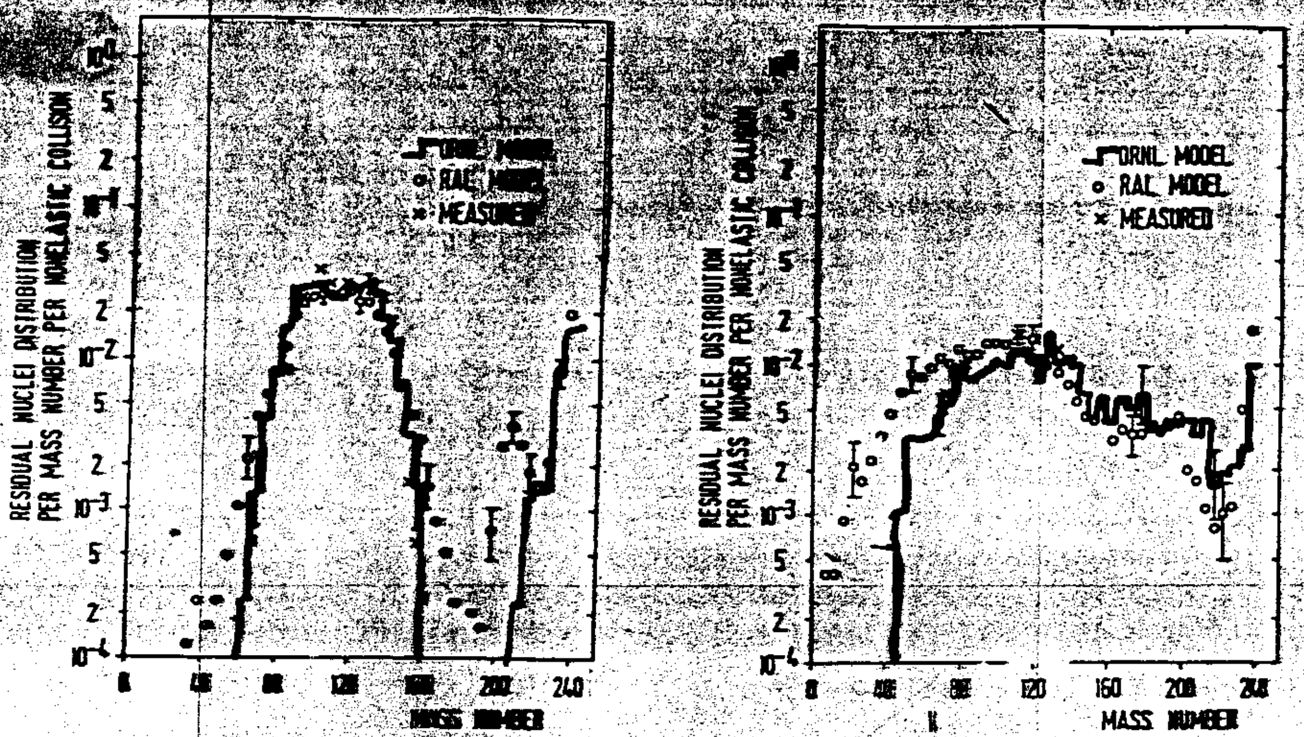


Figure 4.2: Comparaison des distributions de masse calculées à l'aide des modèles de fission RAL et ORNL dans le cas de protons de 380 et 2900 $MeV$ bombardant une cible mince de $^{238}U$.

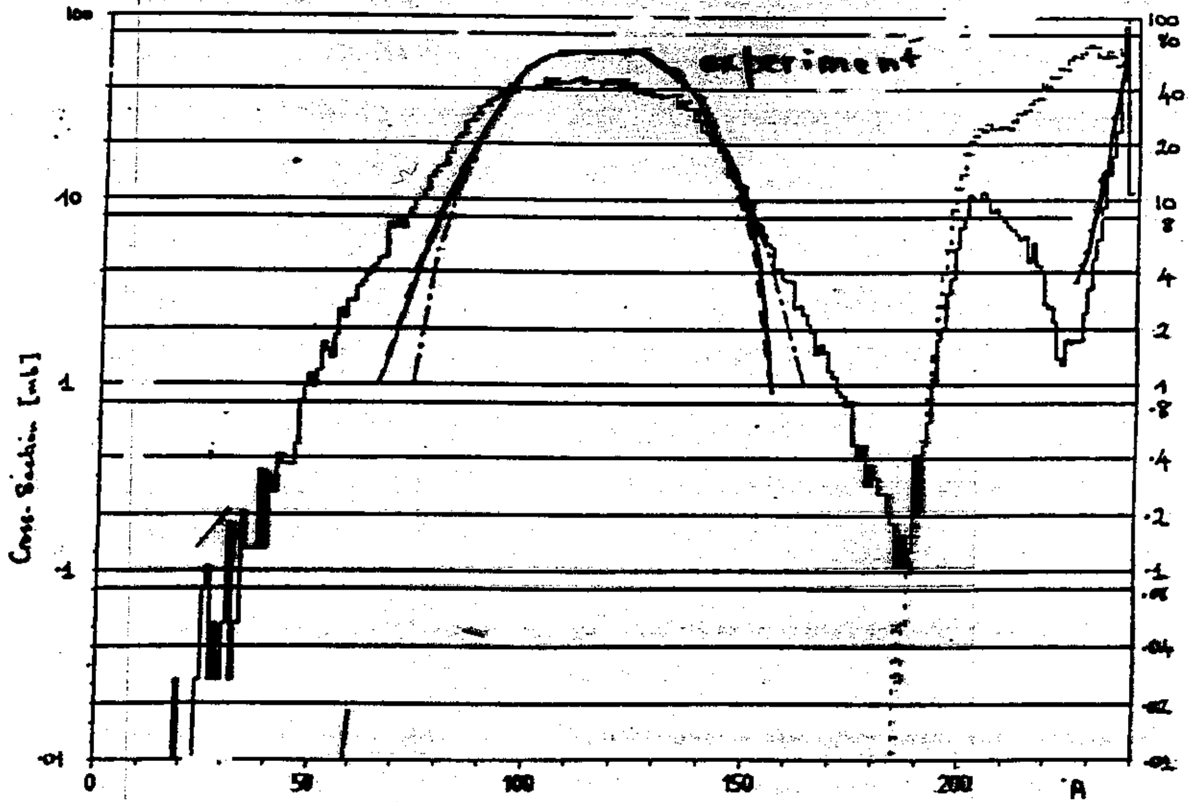


Figure 4.3: Distribution de masse résultant du bombardement d'une cible mince $^{238}U$ par des protons de 340 $MeV$.

# Further possible improvements

## in INC

- ➡ medium effect on *N-N* cross-sections
- ➡ emission of composite particles (d, t, $\alpha$, IMF)
- ➡ treatment of the first collision (quasi-elastic reactions)
- ➡ energy dependence of the potential

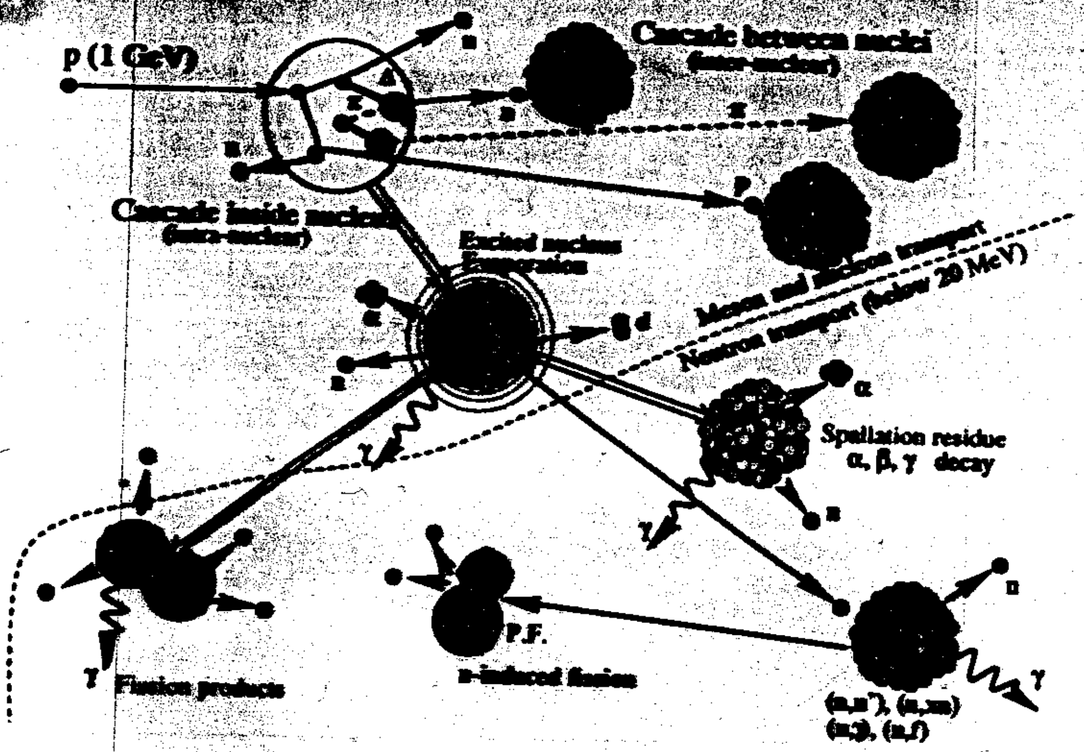
## in Evaporation-fission

- ➡ better level density parameters (cf. S.Hilaire)
- ➡ fission models

## Other models

- pre-equilibrium stage between INC and de-excitation
- QMD models

# Simulation codes: Monte-Carlo transport codes



- Above 20 (150) MeV: Physics models to generate cross-sections (HETC, FLUKA, ...)

⇒ **Intra Nuclear Cascade models** (Bertini, Isabel, Cugnon....)

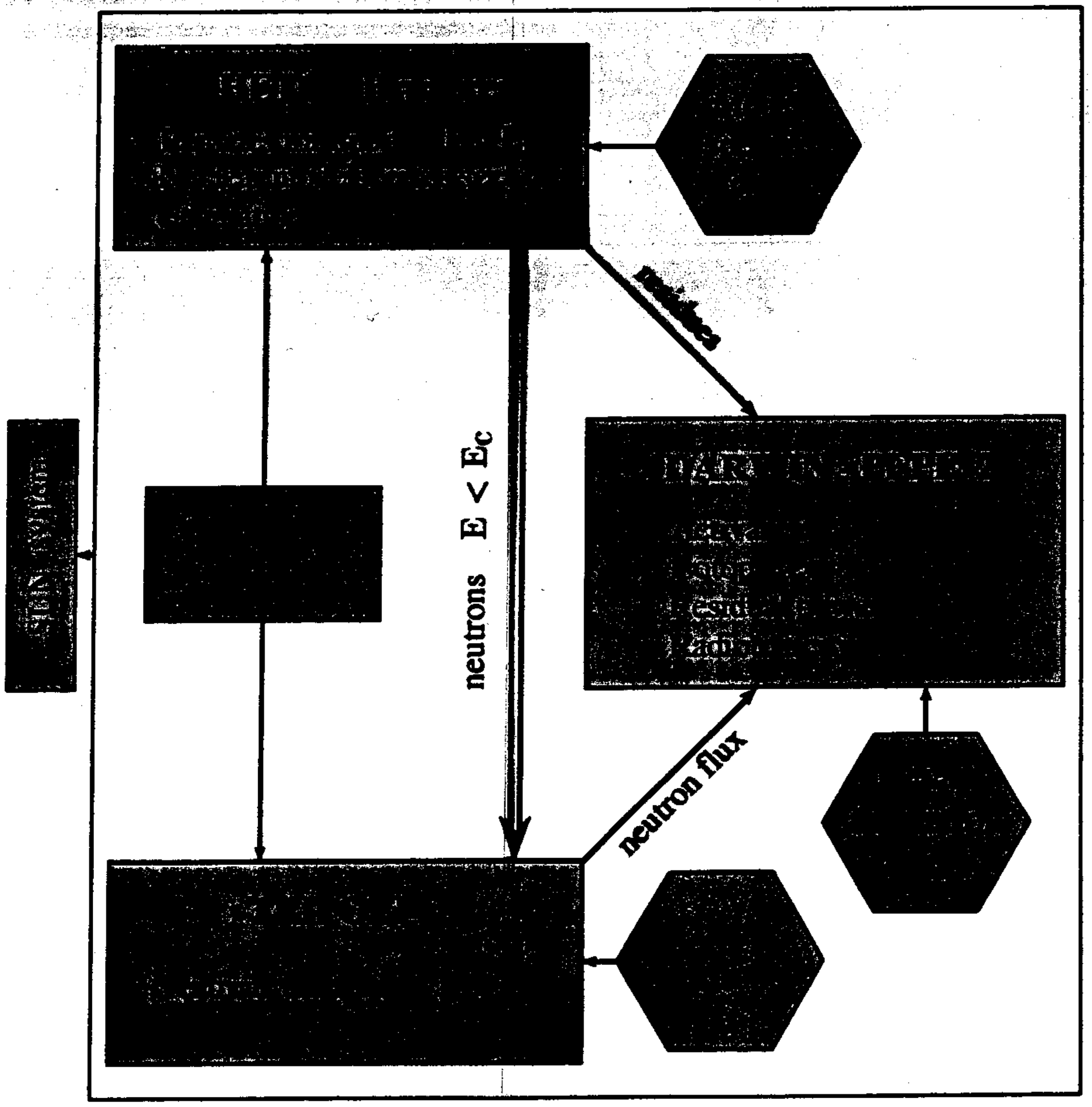
⇒ (**Preequilibrium** (Isabel, FLUKA, Mashnik...))

⇒ **Evaporation/fission** (Dresner-Atchison, Gemini....)

- Below 20 (150) MeV: Data base read by neutron transport code (MCNP, MORSE, TRIPOLI ...)

⇒ **Capture, fission, (n,xn)....**

# Modelisation of the spallation
# Projet SPARTE from the CEA



Non elastic cross-sections

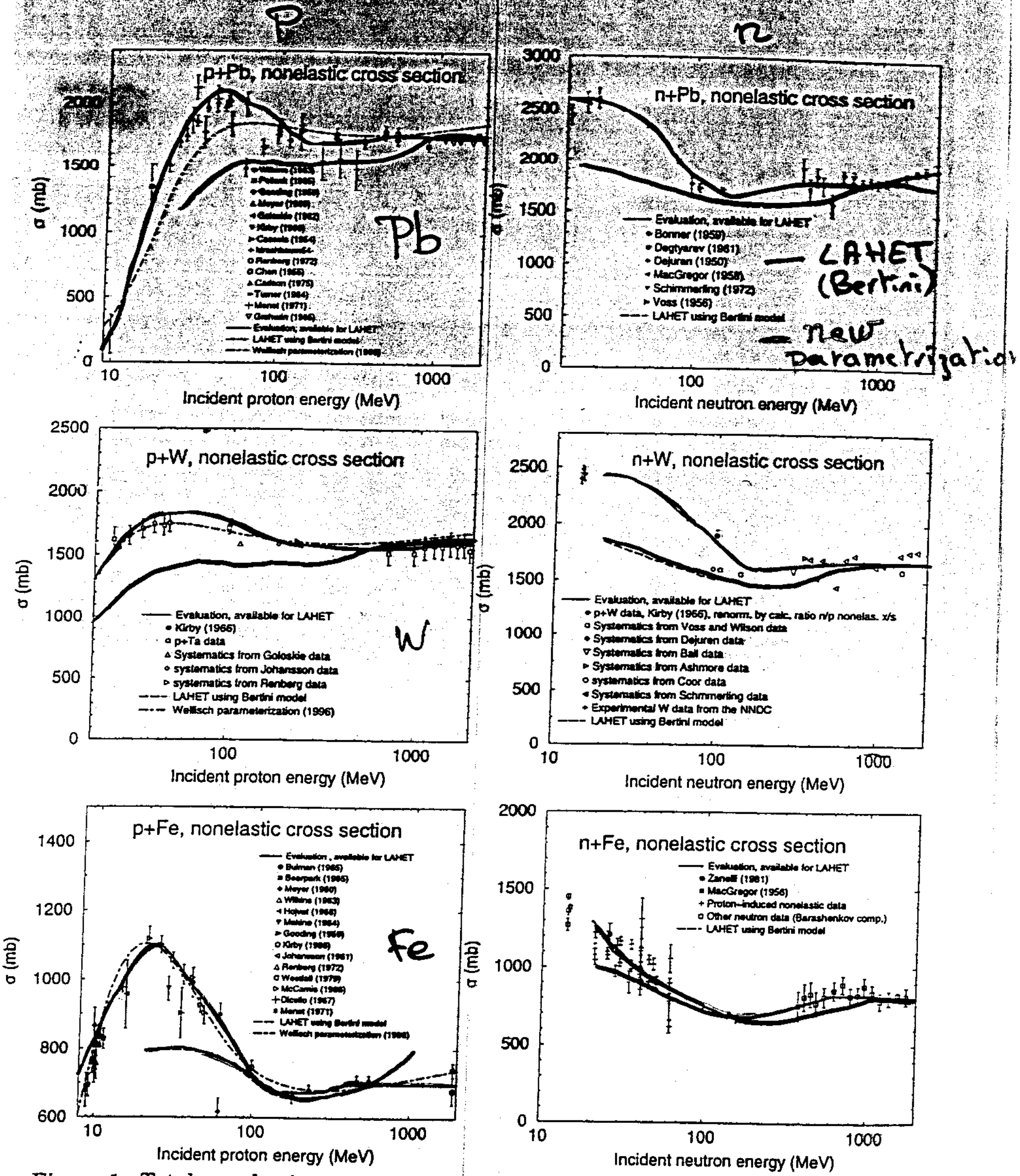


Figure 1: Total nonelastic cross section compared with measurements.

LAHET and MCNP are trademarks of the Regents of the University of California and the Los Alamos National Laboratory.

D. Filges et al. OECD thick target benchmark, Report NSC/DOC (95) 2 (1995)

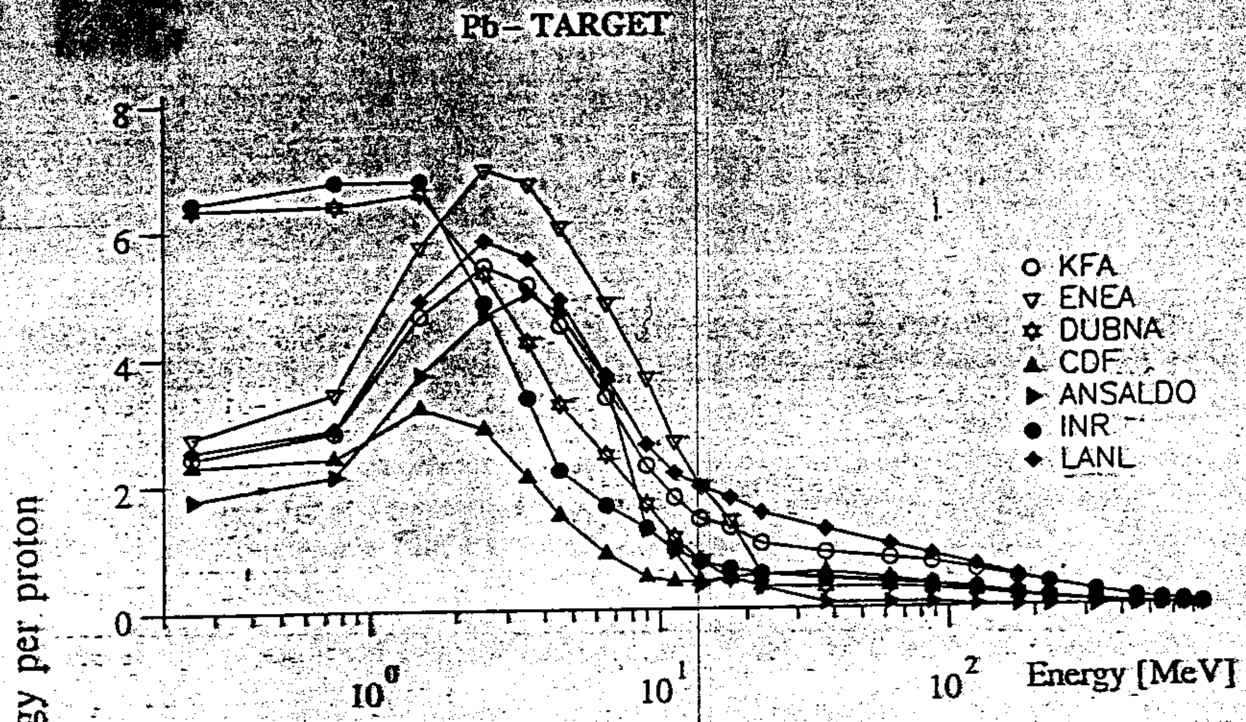


FIG.IV.1.1.b Neutron yield over whole energy range

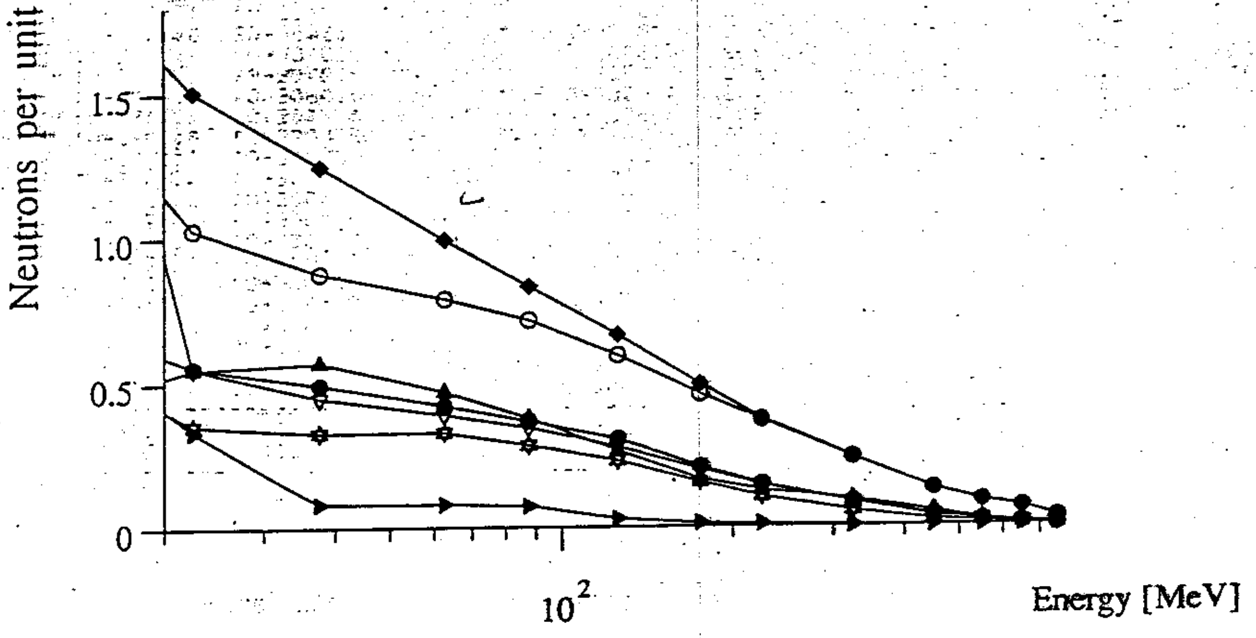


FIG.IV.1.2.b Neutron yield above 20 MeV

R. Michel

# International Model and Code Intercomparison on Intermediate Energy Activation Yiel
organized by NEA/OECD (R. Michel & P. Nagel, 1996)