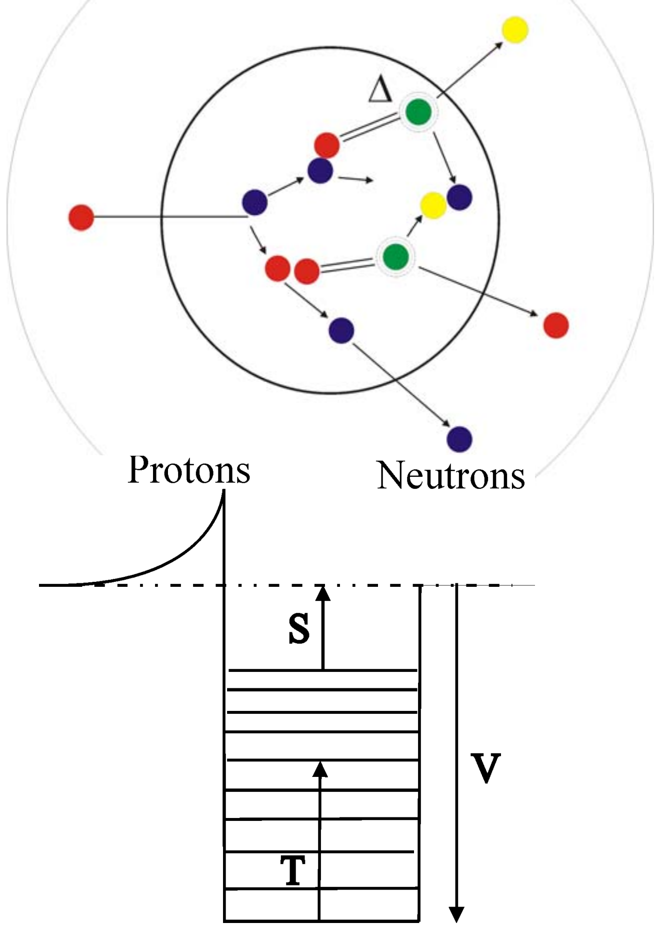
Extensions of the the INCL+ABLA reaction model and application to the study of the evolution of spallation targets

Th. Aoust[1,3], A. Boudard[2], J. Cugnon[3], S. Leray[2], Y. Yariv[2] and J. Wagemans[1]

[1]SCK CEN, Mol, Belgium
[2]CEA-Saclay, Gif-sur-Yvette Cedex, France
[3]Université de Liège, Belgium

IntraNuclear Cascade model of Liège

- Spallation reactions: high-energy (100 MeV- 1 GeV) particle hits a nucleus.
- Two steps: a fast step of N - N collisions (INC) + evaporation of the residual nucleus.



Initialisation:

a. Distributions of $N(\mathbf{r},\mathbf{p})$

b. Diffuse nuclear surface in INCL4.2

c. Nuclear mean field described by $V=T_F+S$

Collision:

a. Linear trajectory between collisions

b. Collisions fct of the distance of approach

c. free N-N cross sections

d. NN⇔NN

NN ⇔ NΔ

Δ ⇔ Nπ

d. Pauli blocking

e. Conservation laws:

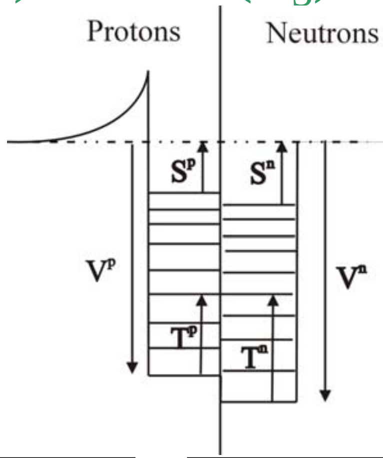
-baryon,

-charge,

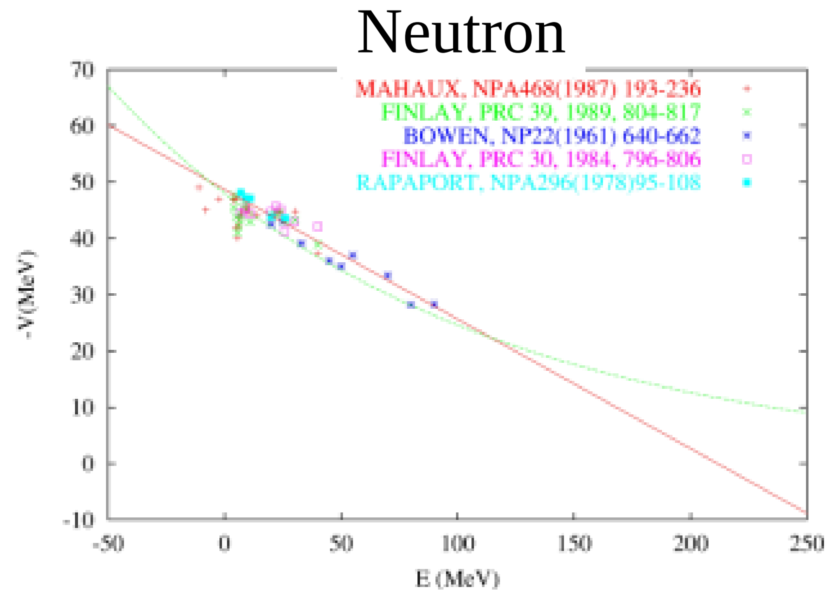
-energy.

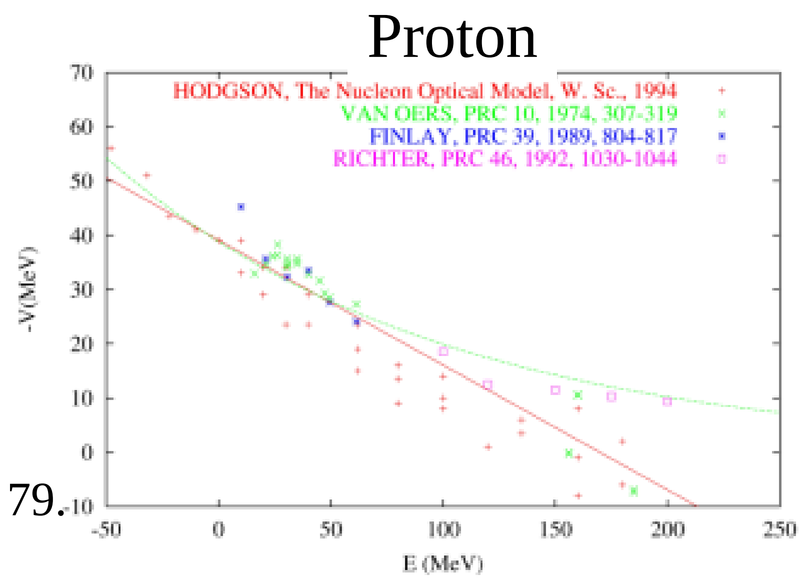
A. Boudard et al., Phys. Rev. C 66 (2002) 044615

1. $V^N(T_3,E)$ and $V^\Delta(T_3)$



	p_F^i (MeV/c)	V_0^i (MeV)
No isospin dep.	270.34	45.0
Isospin dep.		
$^{208}_{82}Pb$ protons	249.75	40.69
neutrons	288.20	50.27





More details in

- Th. Aoust and J. Cugnon, Eur. Phys. J. A **21** (2004) 79.

Extensions of the INCL4 model

3. Pion-nucleon cross section above the Δ-resonance

4. Pion mean field

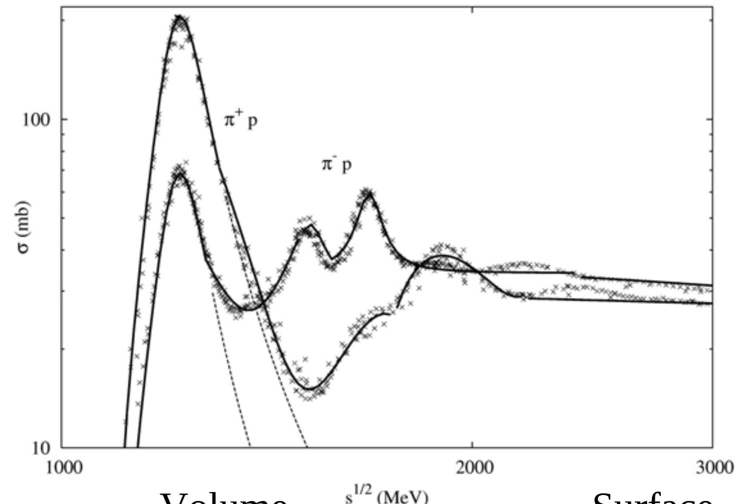
-badly determined (in the interior at least).

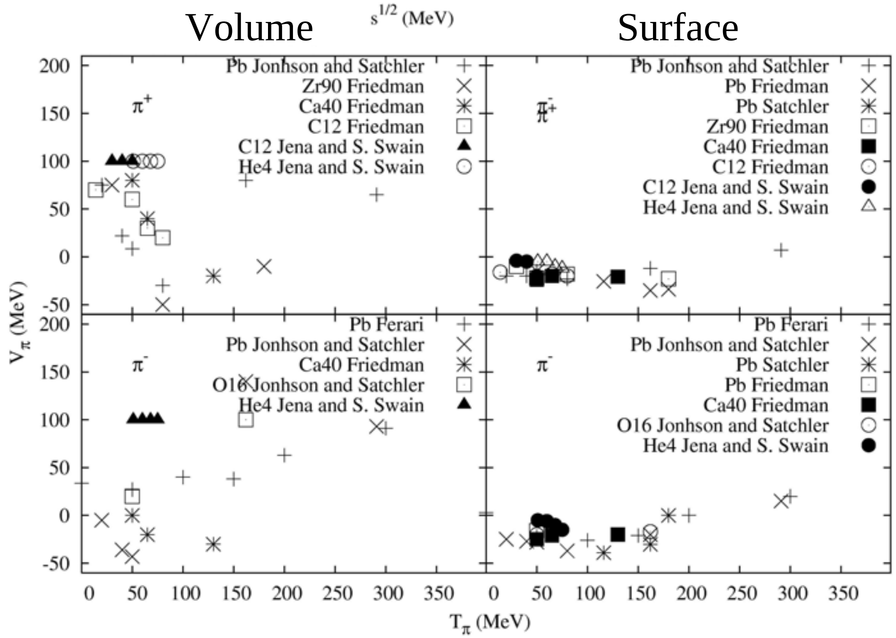
-Pion Potential determine by global fit

- $V_{\pi}(T_3) = -30.6 + 71.0\, T_3 \varsigma + V_C$ (MeV)

More details in

-Th. Aoust and J. Cugnon,
Phys. Rev. C **74** (2006) 064607





Extensions of the INCL4 model

4. Pauli blocking:
   Assessment of the validity of the INCL model down to incident energies of a few tens of MeV using a refined implementation of the Pauli blocking : new statistical approach and strict Pauli blocking for the first collision.

   (J. Cugnon and P. Henrotte, Eur. Phys. J. A **16** (2003) 393)
5. d, t, He3 and He4 emission at high energy:
   Development of a surface coalescence model for the production of composites in the cascade stage.

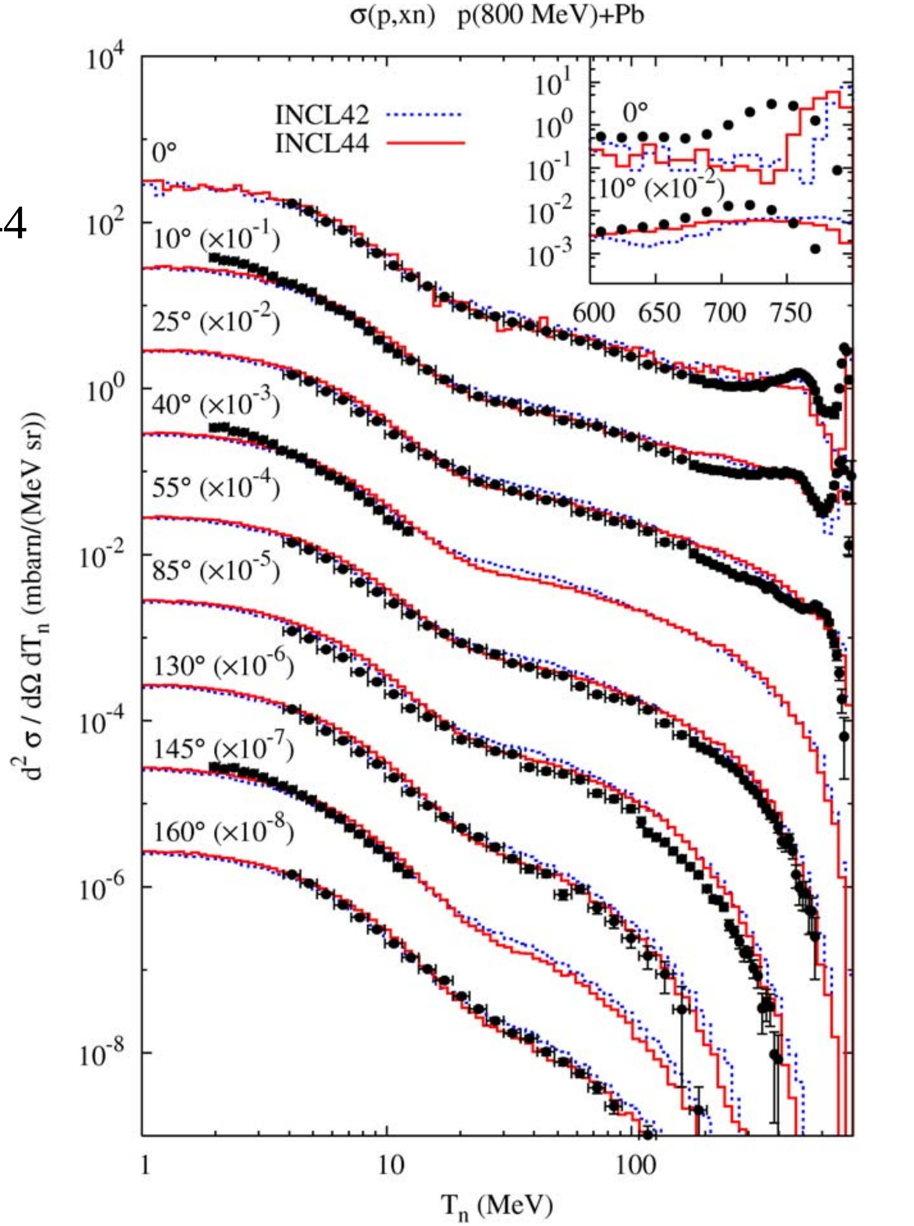
   (A. Boudard et al., Nucl. Phys. A **740** (2006) 195)
6. Assessment of low-energy nucleon-nucleon collision and “local” energy to improve low-energy proton-nucleus reaction

   (A. Boudard et al., Radioactive Nuclear Beams conference, Cortina d’ampezzo, 2006)
7. Extension of INCL until 20 GeV

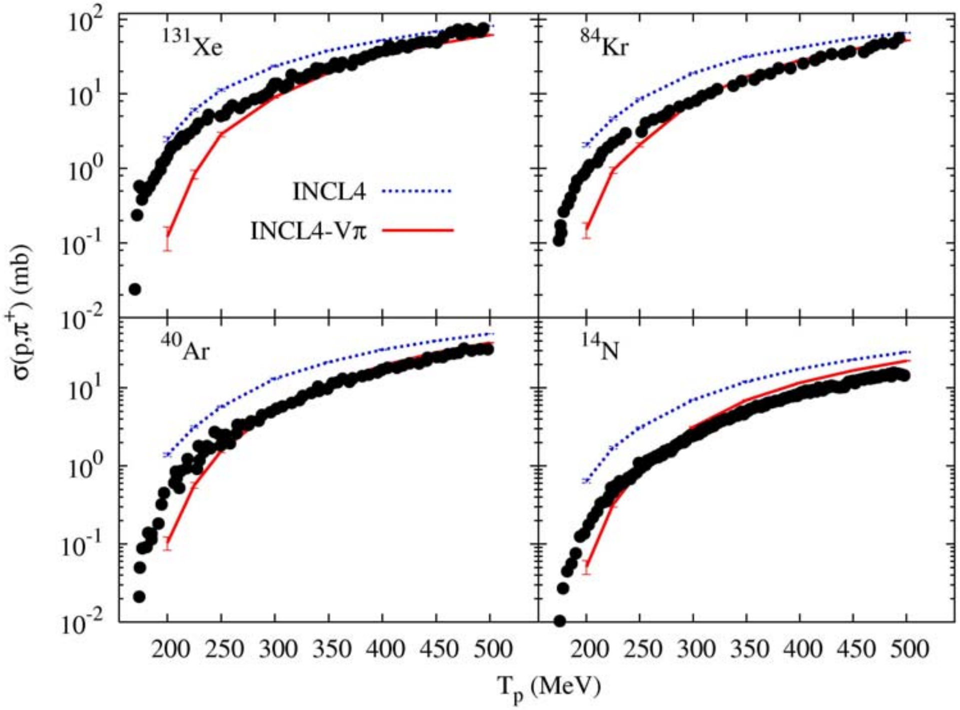
   (J. Cugnon and S. Pedoux, ND2007, Nice, 2007)
8. Extension of INCL to accomodate α … ^{12}C induced reaction

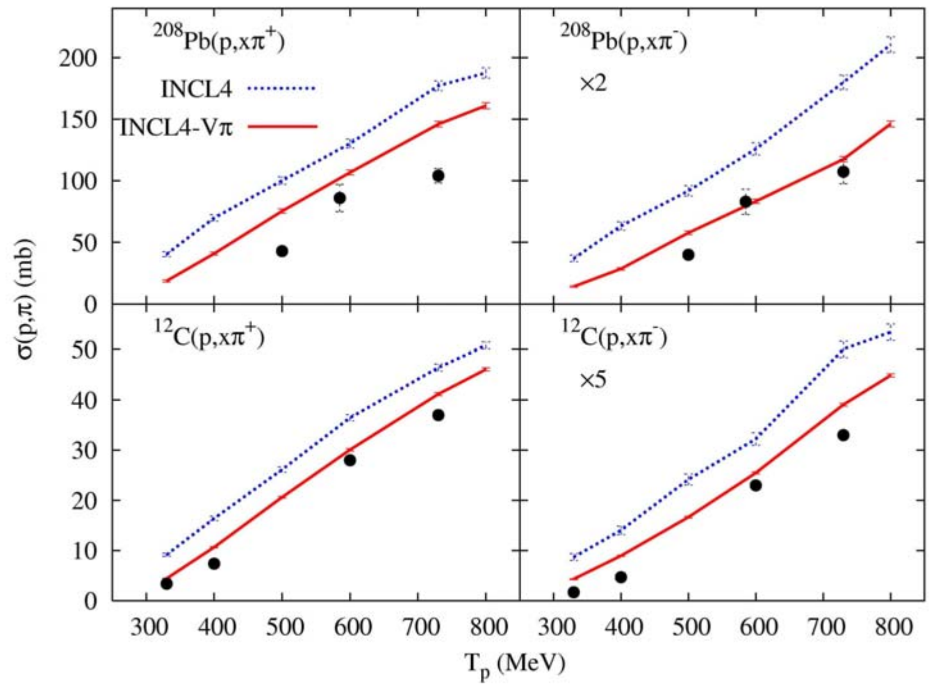
Production of particles

	EXP	INCL42	INCL44
n > 20 MeV	1.9	2.5	2.2
20 MeV > n > 2 MeV	6.5	6.8	7.6
E* (MeV)		120	141



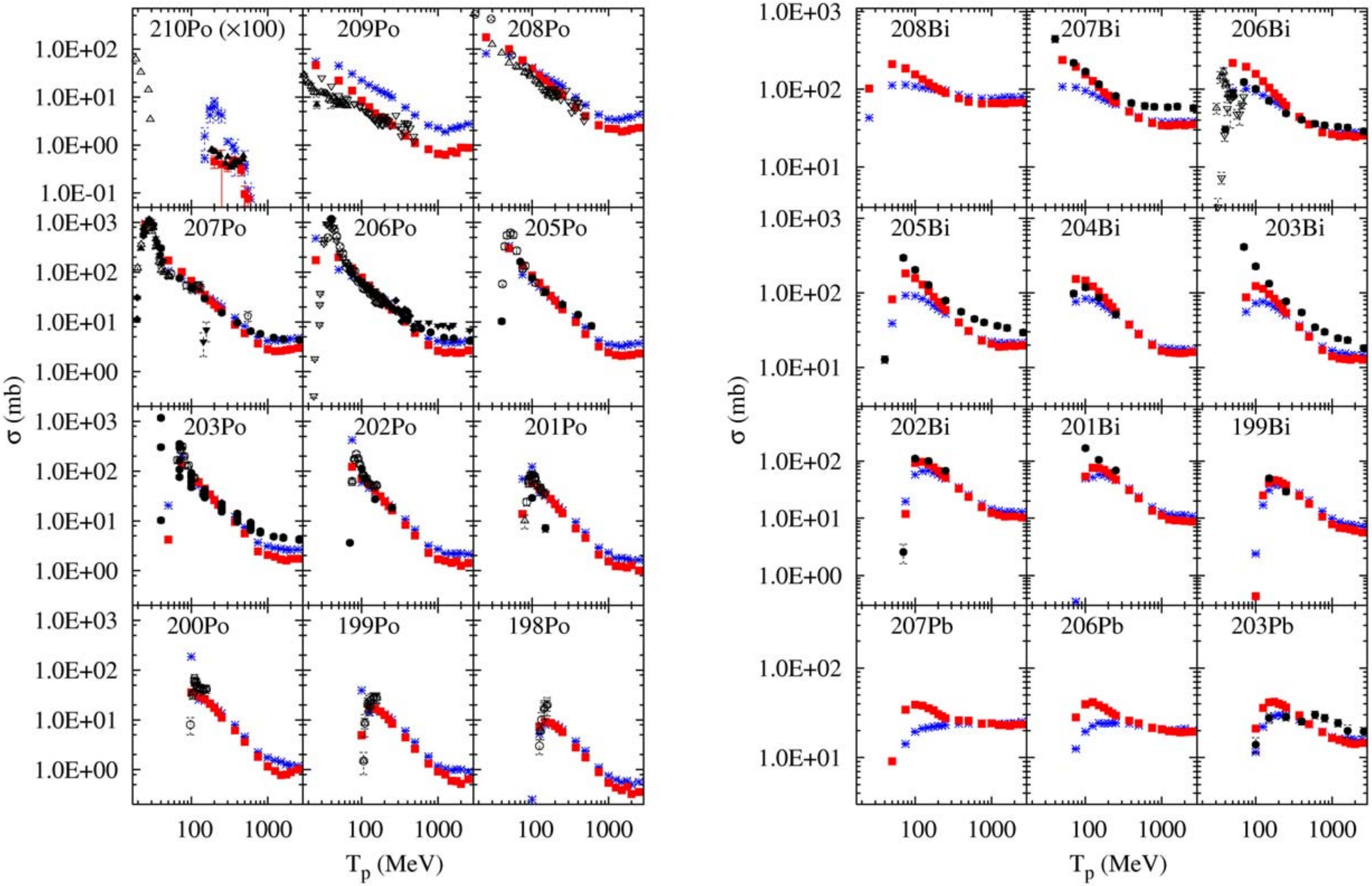
π production in p-induced reaction



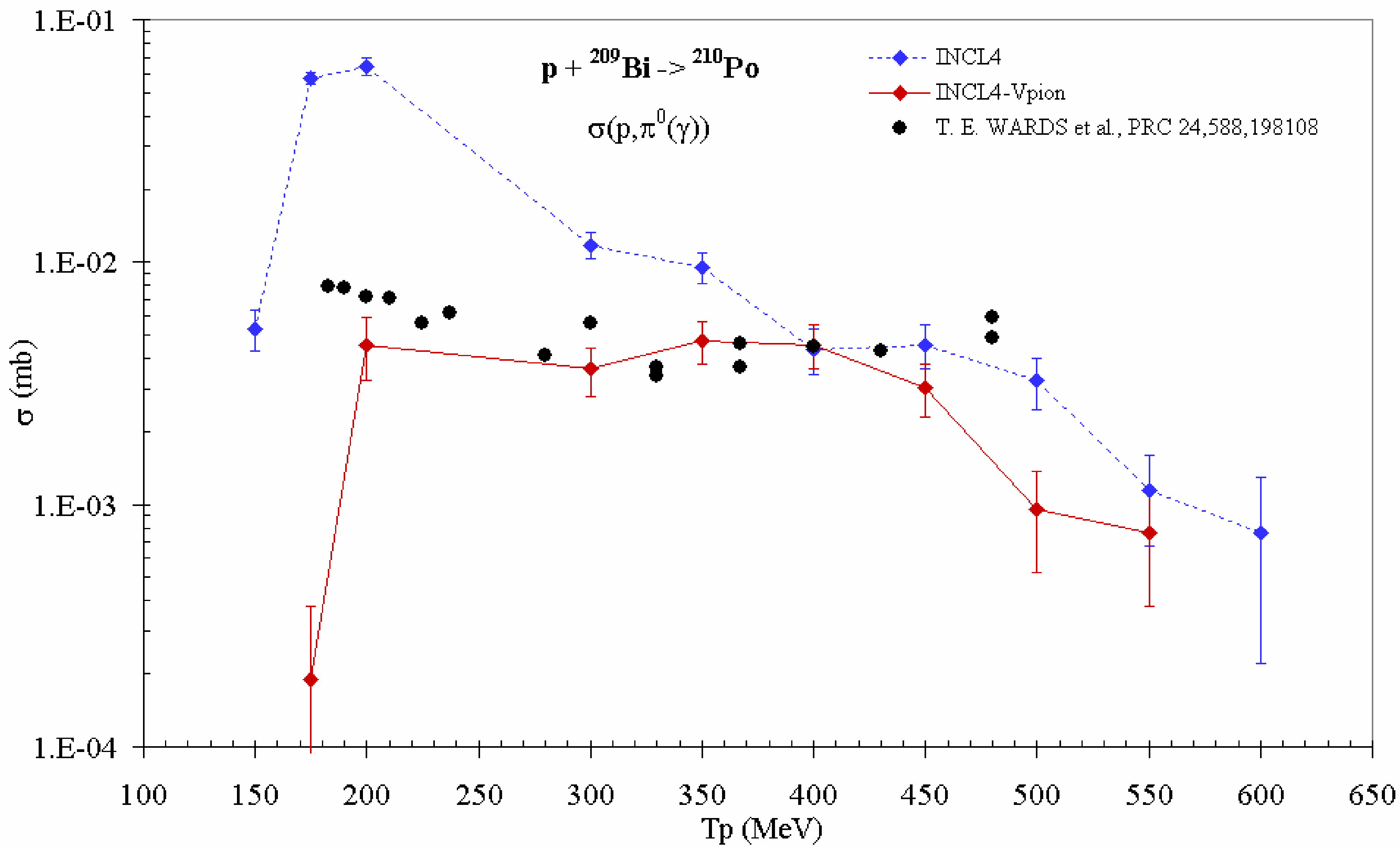


Production of residues

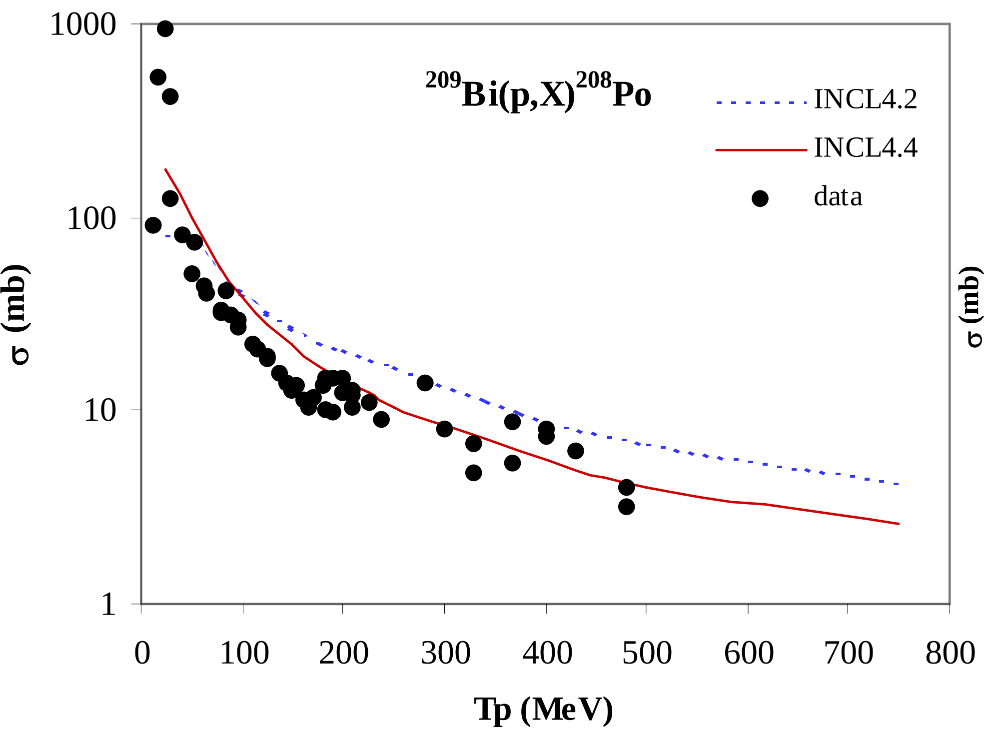
p + ^{209}Bi

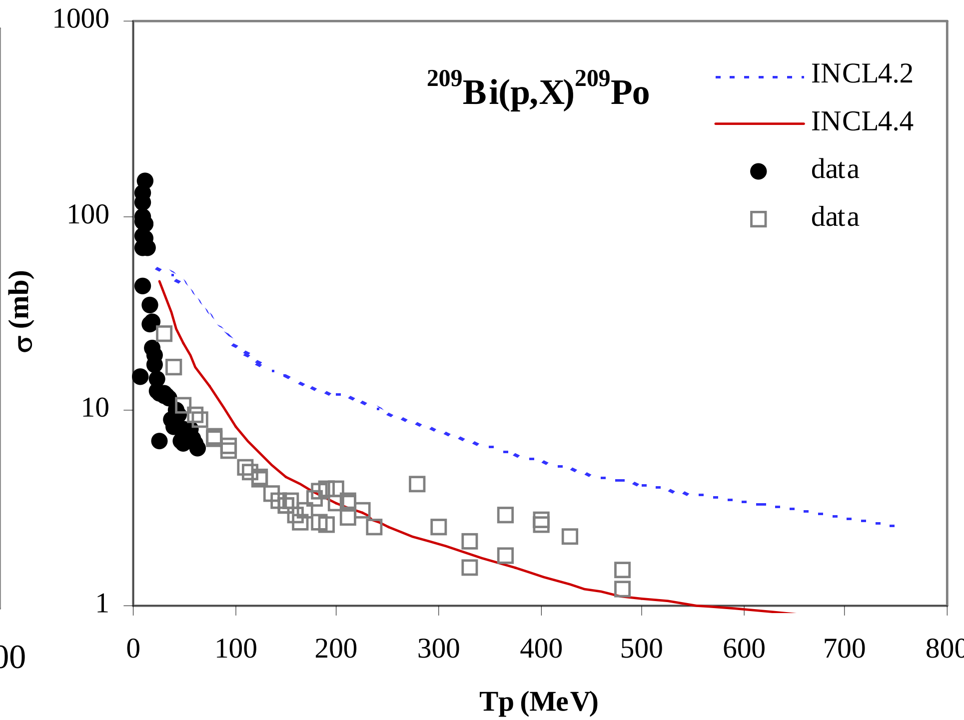


^{210}Po production p-induced reaction



$^{208,\,209}$Po production p-induced reaction

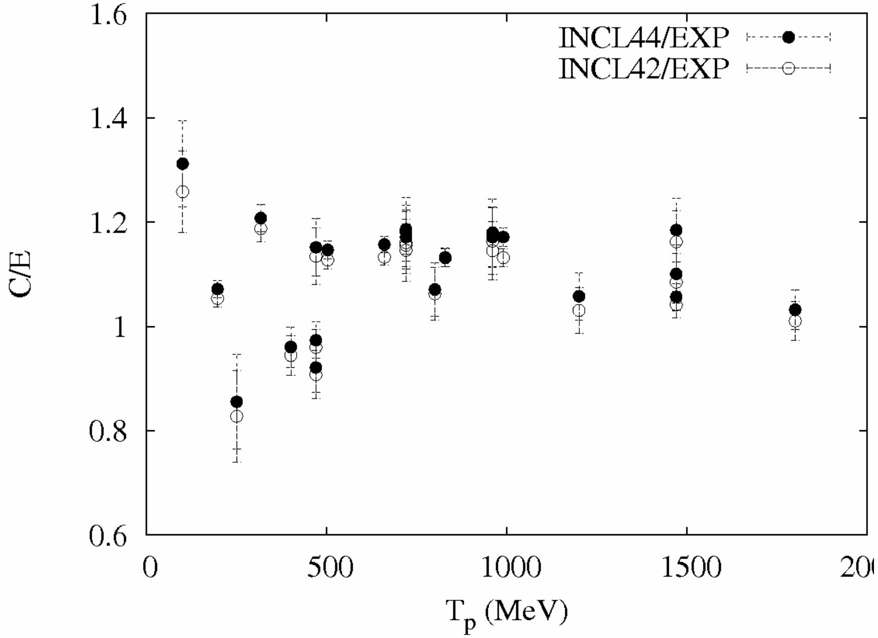


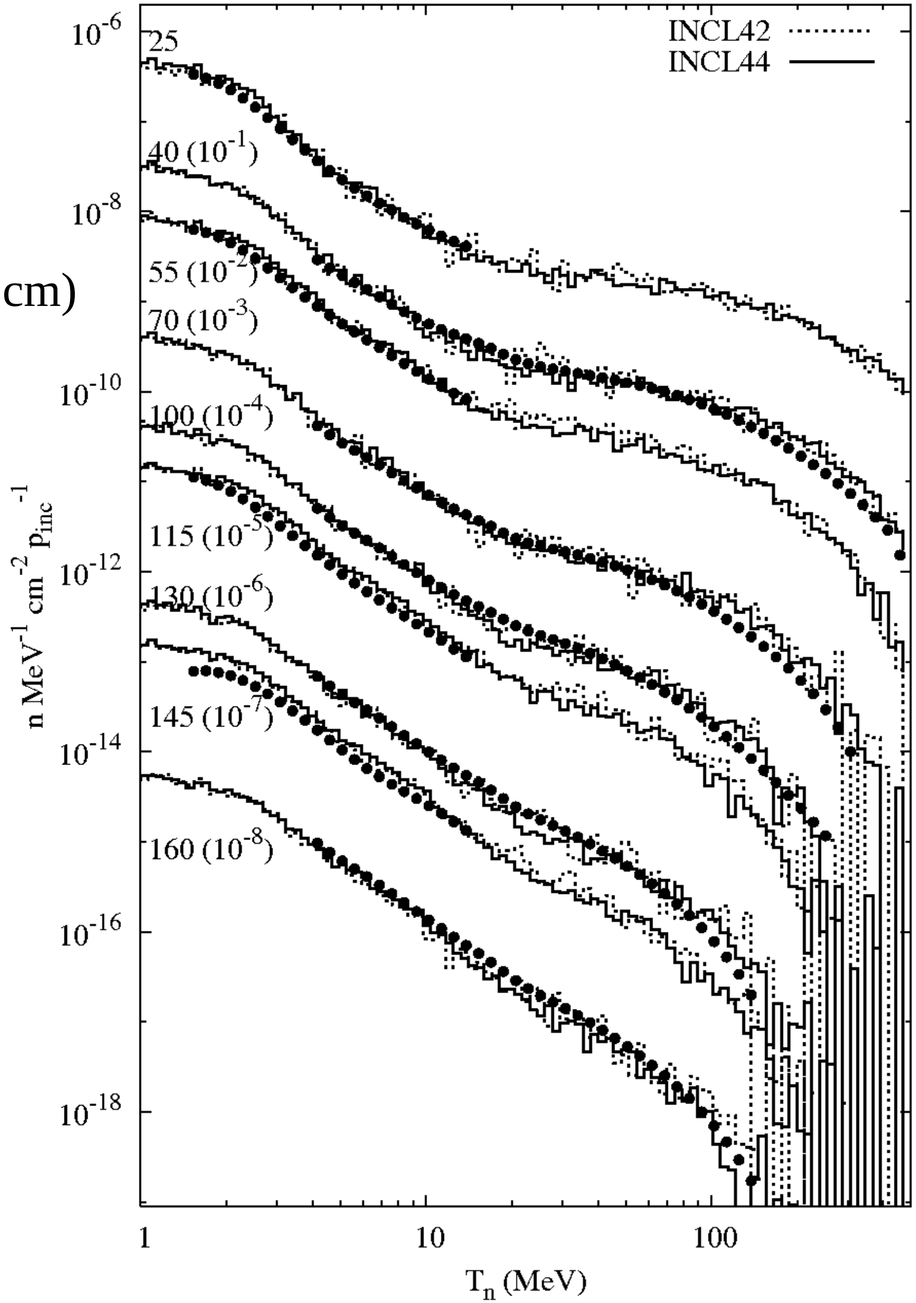


Production of neutrons in thick target

INCL of MCNPX was updated

p (800 MeV) + Pb (r=10 cm ; L=65 cm)



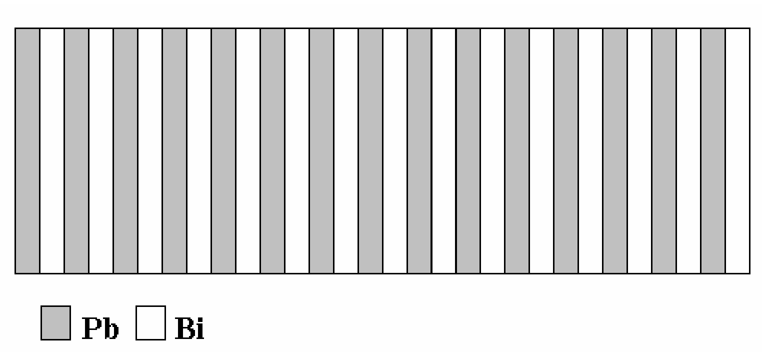


Production of residue in Thick Target

- PSI: Irradiation of a stack of 30 Pb anb Bi disks by protons of 590 MeV

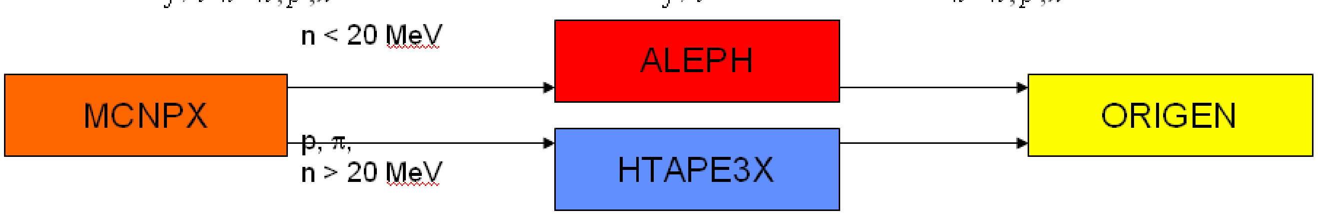
  (K. Van der Meer et al. NIMB **217** (2004) 202)

P (590 MeV)

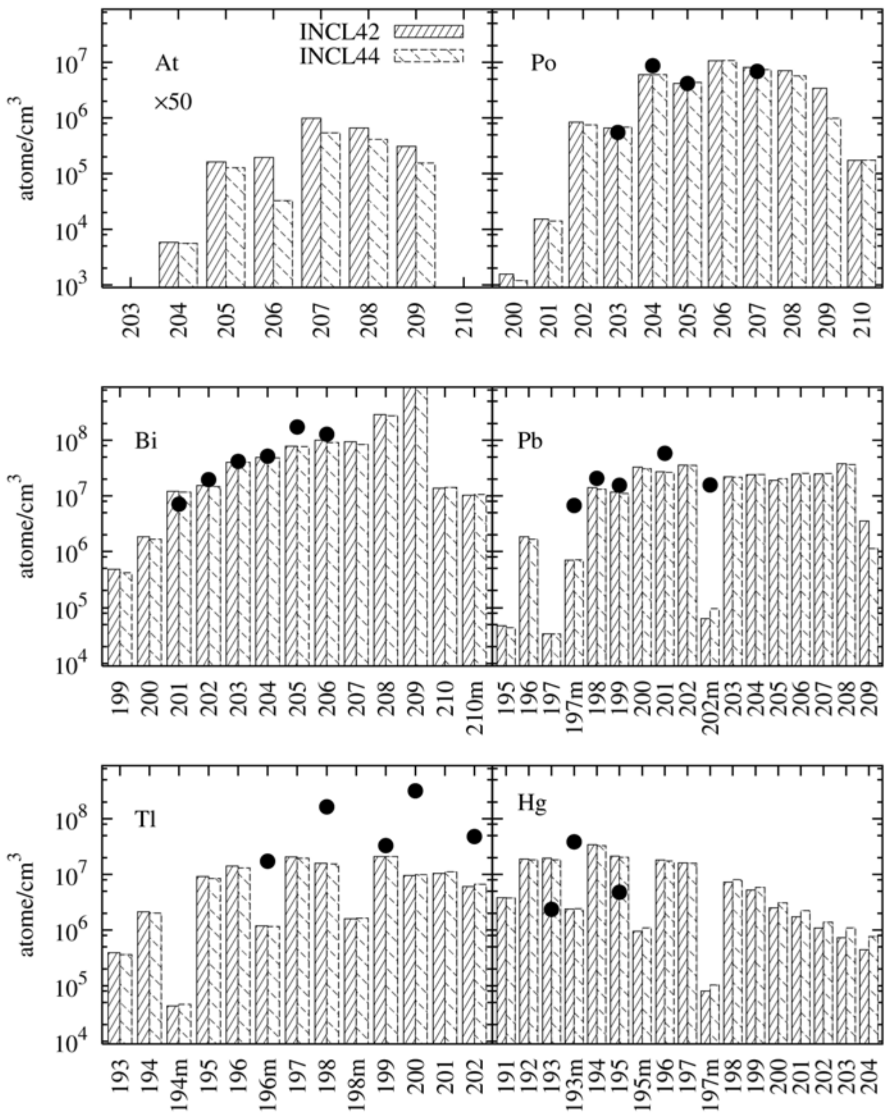


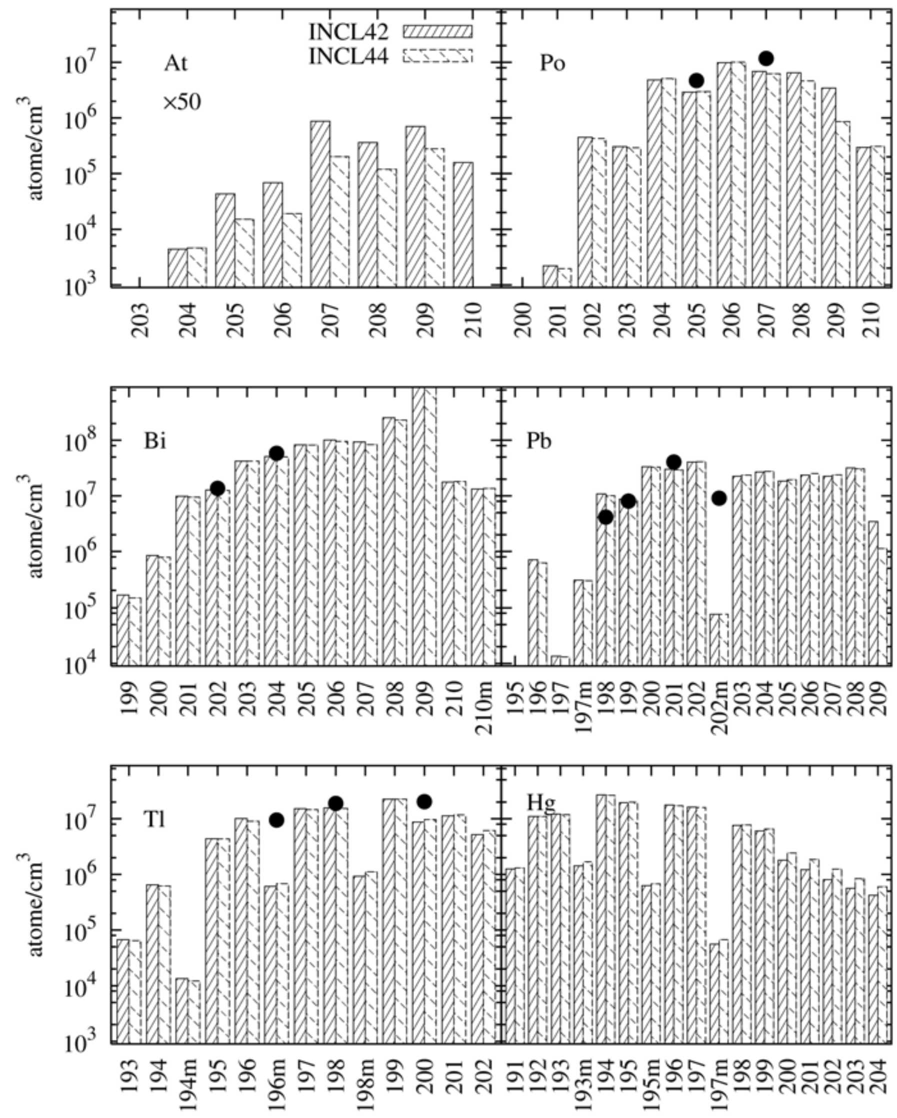
- Measurements of neutron multiplicities (integral and differential) and the determination of the distributions of residual radio-nuclides by γ-ray spectroscopy.
- INCL of MCNPX was updated and coupled to ORIGEN using ALEPH*

$$\frac{dN_i}{dt} = \sum_{j\neq i}\sum_{k=n,p,\pi}\alpha_{j,k,i}\sigma_{j,k}\phi_k N_j + \sum_{j\neq i}\beta_{j,i}\lambda_j N_j - \sum_{k=n,p,\pi}\sigma_{i,k}\phi_k N_i - \lambda_i N_i$$

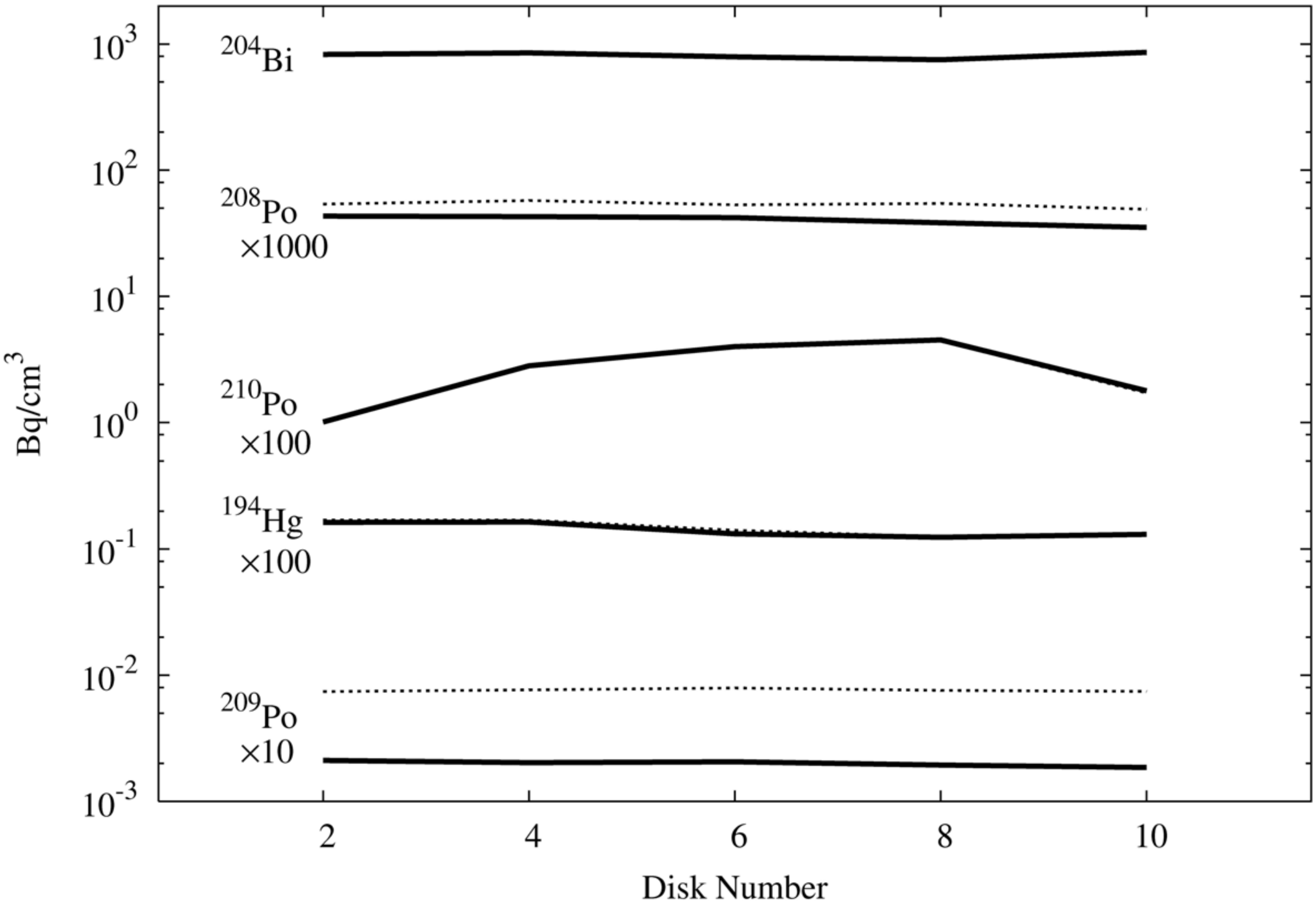


Results disks 2 and 10 (Bi)

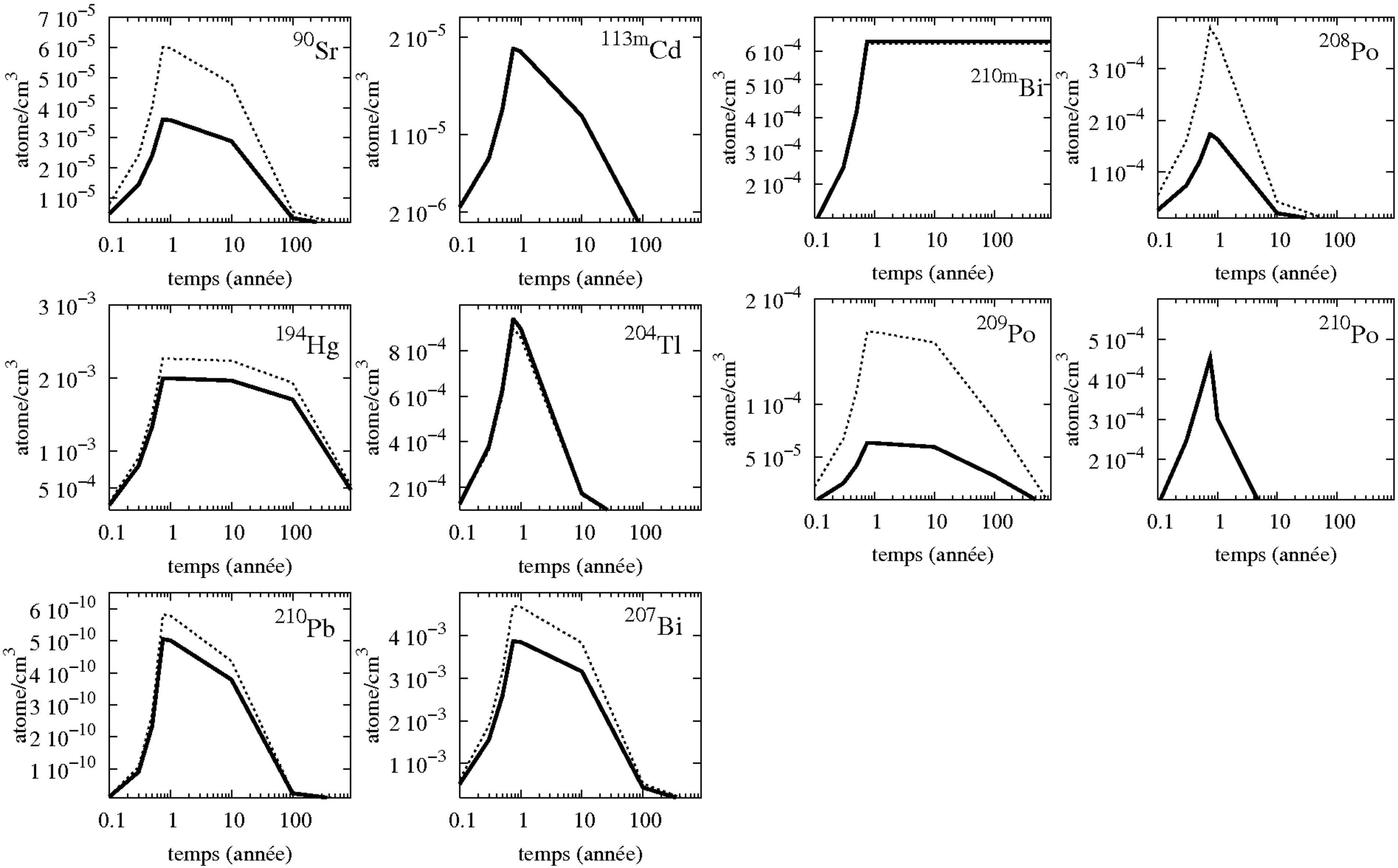




Activity radiotoxic isotopes in Bi disks



Activity radiotoxic isotopes in XT-ADS target



Conclusion

INCL4.2 is improved by

- $V^N(T_3,E)$ and $V^\Delta(T_3)$
- Pion Physics: $V^\pi(T_3)$, $\sigma_{\pi N}$
- Pauli blocking

- Low-energy and High energy extensions
- Composite's production

Effects of these modifications :

a. Thin target:

- reduce the production of π, **now close to experiments**
- reduce also n during INC, **now close to experiments**
- increase E* and n during evaporation, **go away from experiments**
- Reduce the production of Bi, Po which is **now close to experiments**

b. Thick target:

- Slight increase of n/p (2%)
- Spectrum remains unchanged

Conclusion

Evolution of spallation targets

- Update of MCNPX2.6.a and adaptation of ALEPH code
- Stack of Pb and Bi disks bombarded with 590 MeV protons at PSI
  - INCL4.2 and INCL4.4 remain close to the experiments

    The production of 209Po and 208Po are strongly reduced
  - ^{210}Po ^{210m}Bi in the bismuth disks are no influenced by our modif.
  - Use of an old version of PHTLIB => underestimation of isomeric
- XT-ADS,
  - Same tendencies as before
  - Sub-critical core increases the n,γ reaction rates

    => production rates of ^{210}Po and ^{210m}Bi is higher.