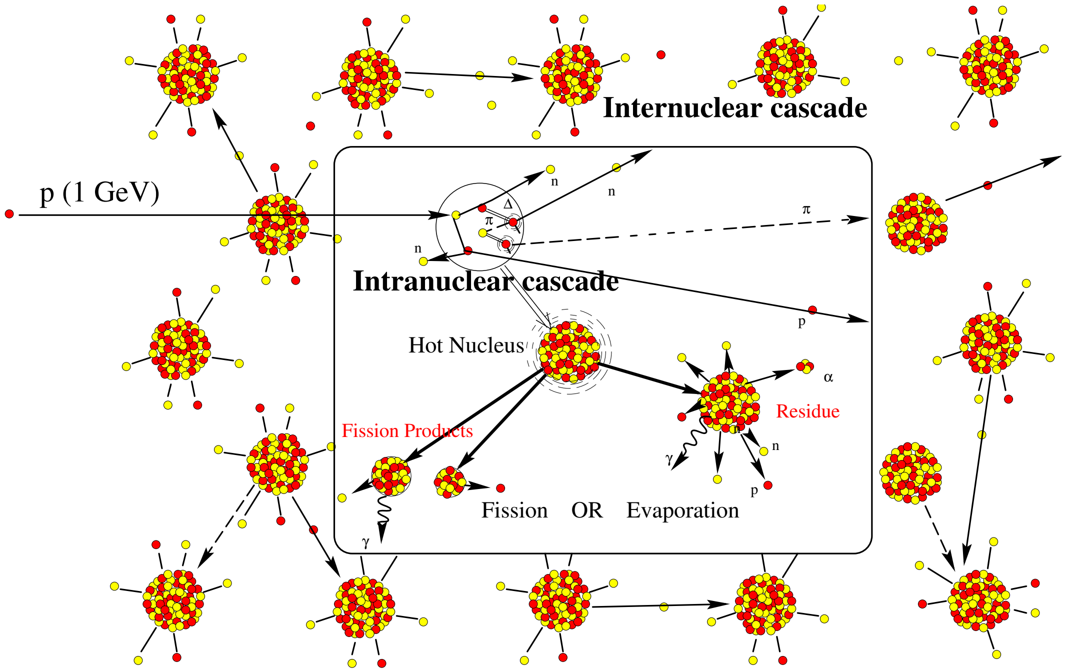
High-energy nuclear data for ADS

Sylvie LERAY

CEA/Saclay, IRFU/SPhN

Spallation neutron production

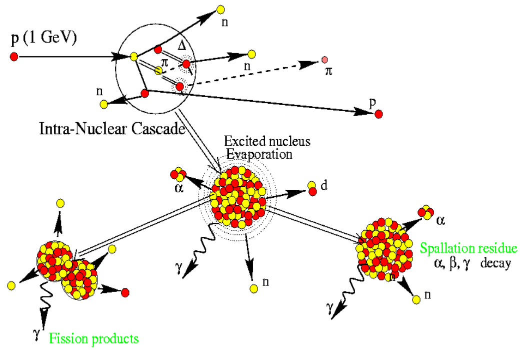


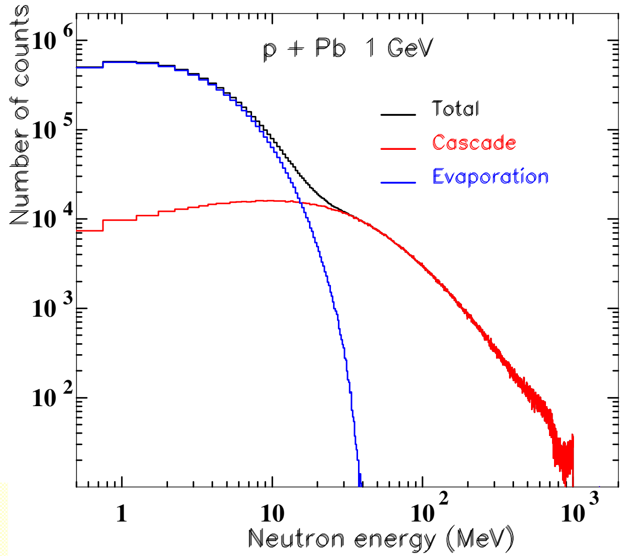
In a thick target: internuclear cascade

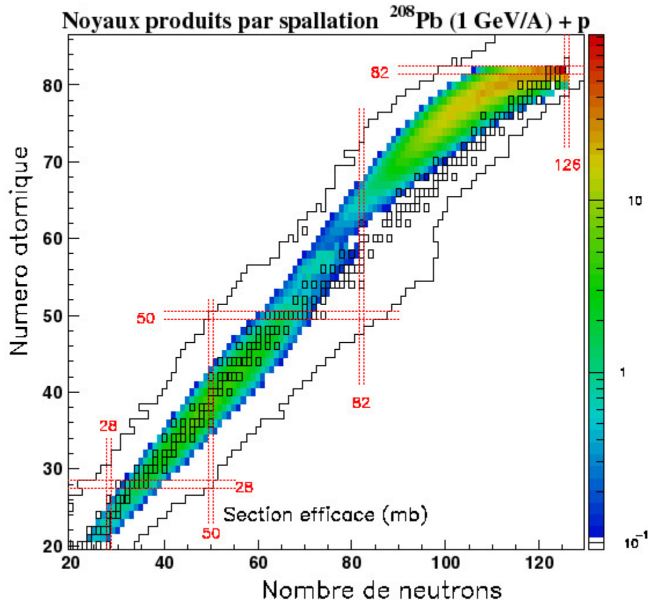
➔ large number of produced neutrons

- **In a heavy metal target (Pb, W, Ta, Pb-Bi) around 20 neutrons per incident proton and GeV**
- **Applications:**
  - ↪ **ADS**
  - ↪ **Spallation neutron sources**
  - ↪ **Rare isotope beams (RIB)**

Interactions in a thin target



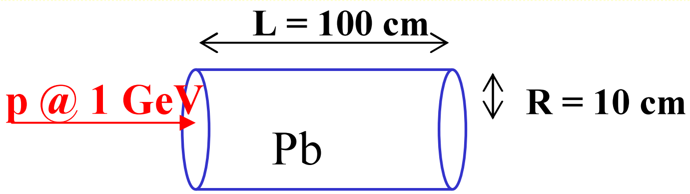


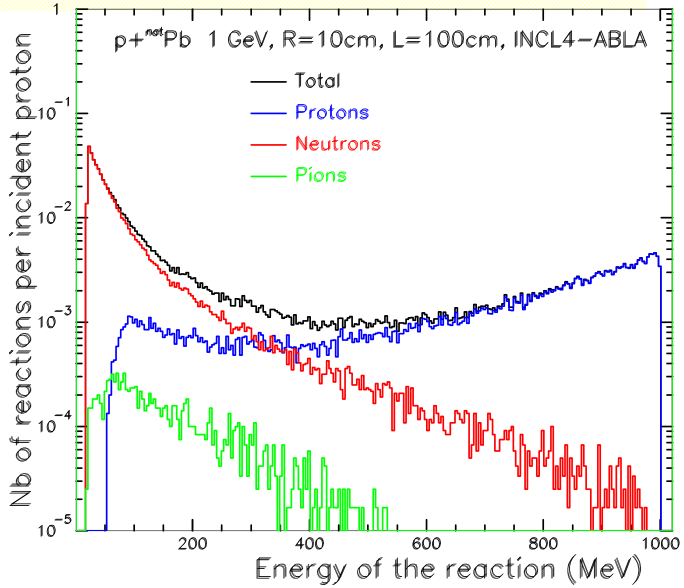


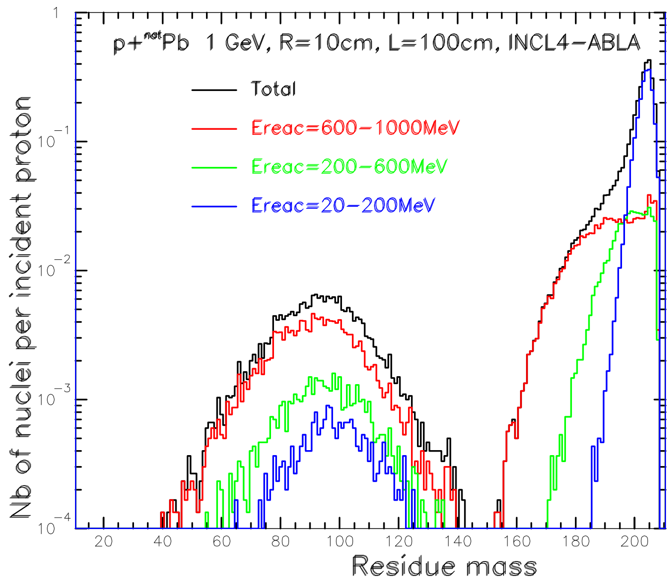
- ~2 neutrons with E>20 MeV (intra-nuclear cascade)
- ~15 neutrons with E<20MeV (evaporation)
- But energy carried out by cascade neutrons = 85% (95% for protons)

- a lot of light charged particles produced (including helium and tritium)
- Hundreds of different residues produced

Interactions in a thick target



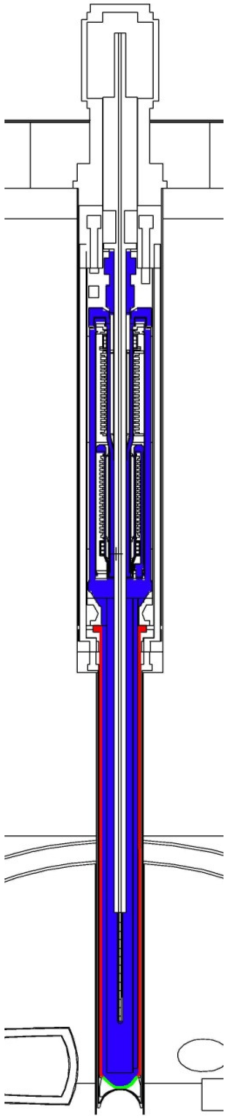


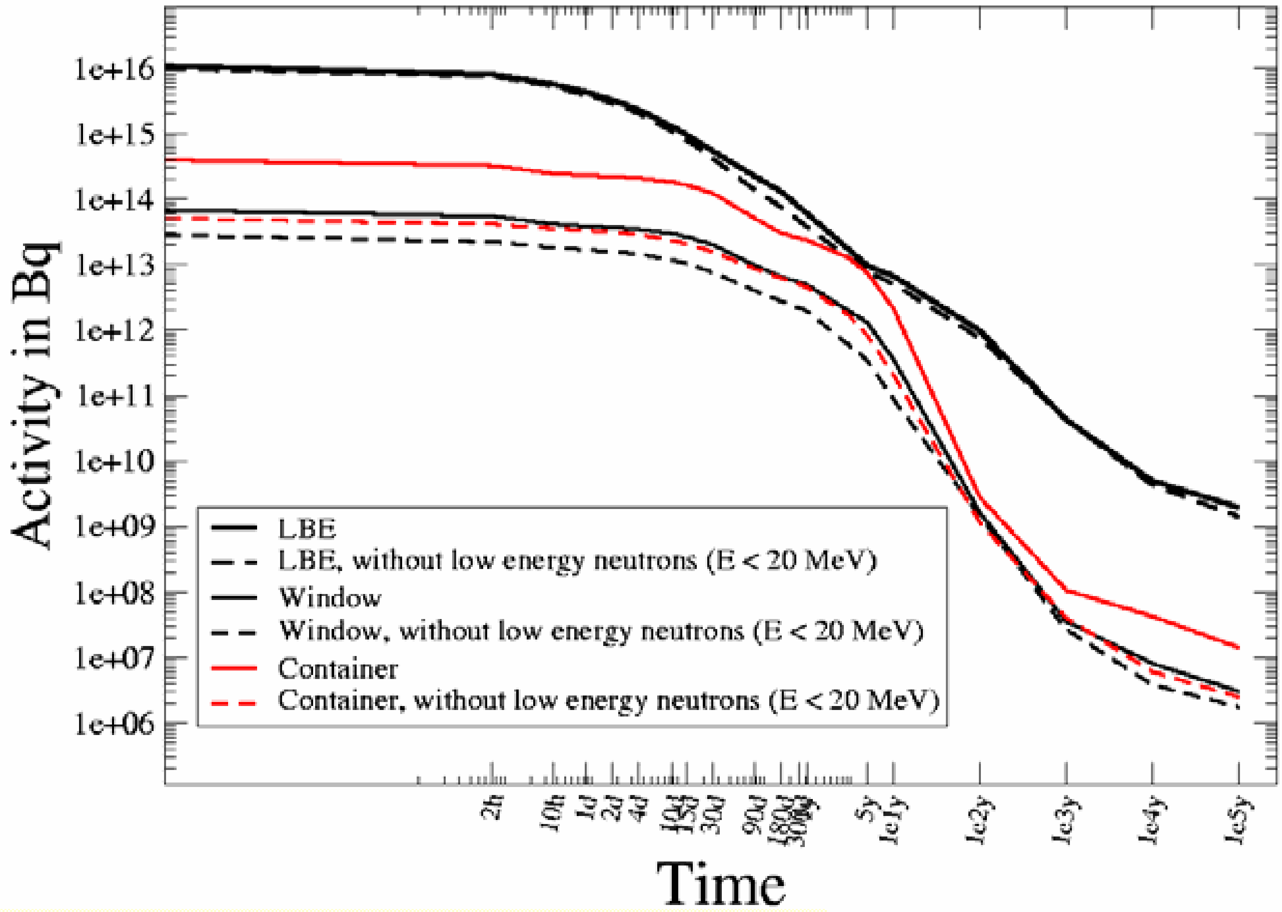


- Protons interact before slowing down
- Large number of secondary neutron interactions
- 3.6 residues per incident protons (not taking into account E<20 MeV)
- Highest mass residue coming mostly from low-energy interactions
- Light evaporation residues, fission fragments from high-energy reactions

Activity in a thick target

Comparison of activity from spallation and activation





S. Lemaire et al., ND2007, Nice

Results obtained during the last years

- **Large amount of high quality data collected**

  ➥ **Neutron and light charged particle production, isotopic residue distributions, excitation functions**

- **Improvement of nuclear models**

  ➥ **INCL4/ABLA tested against all the available data with the same set of parameters** (A.Boudard et al., PR C66 (2002) 044615)

  ➥ **but also FLUKA and CEM**

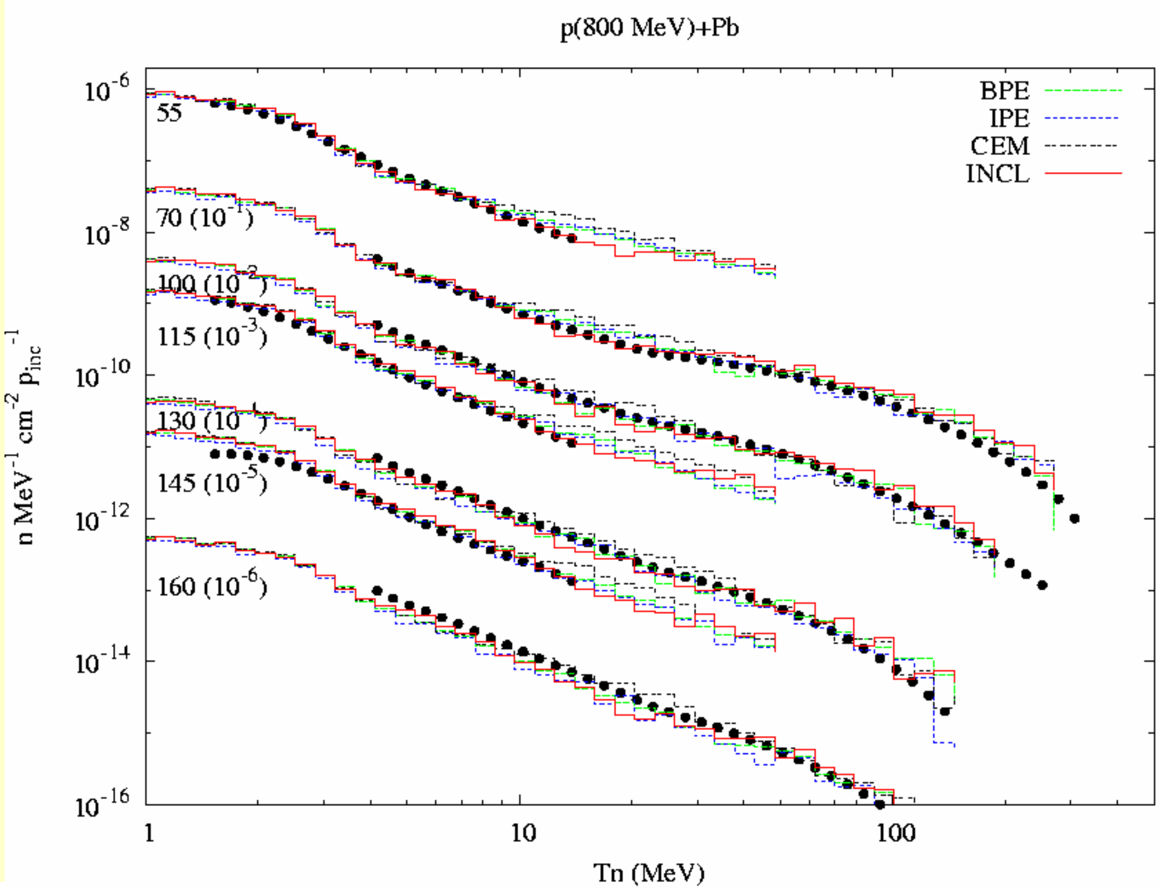
- **Implementation of INCL4/ABLA and CEM into MCNPX, INCL4/ABLA now in GEANT4**

≈ **HINDAS FP5 and EUROTRANS/NUDATRA FP6 projects**

Neutron production

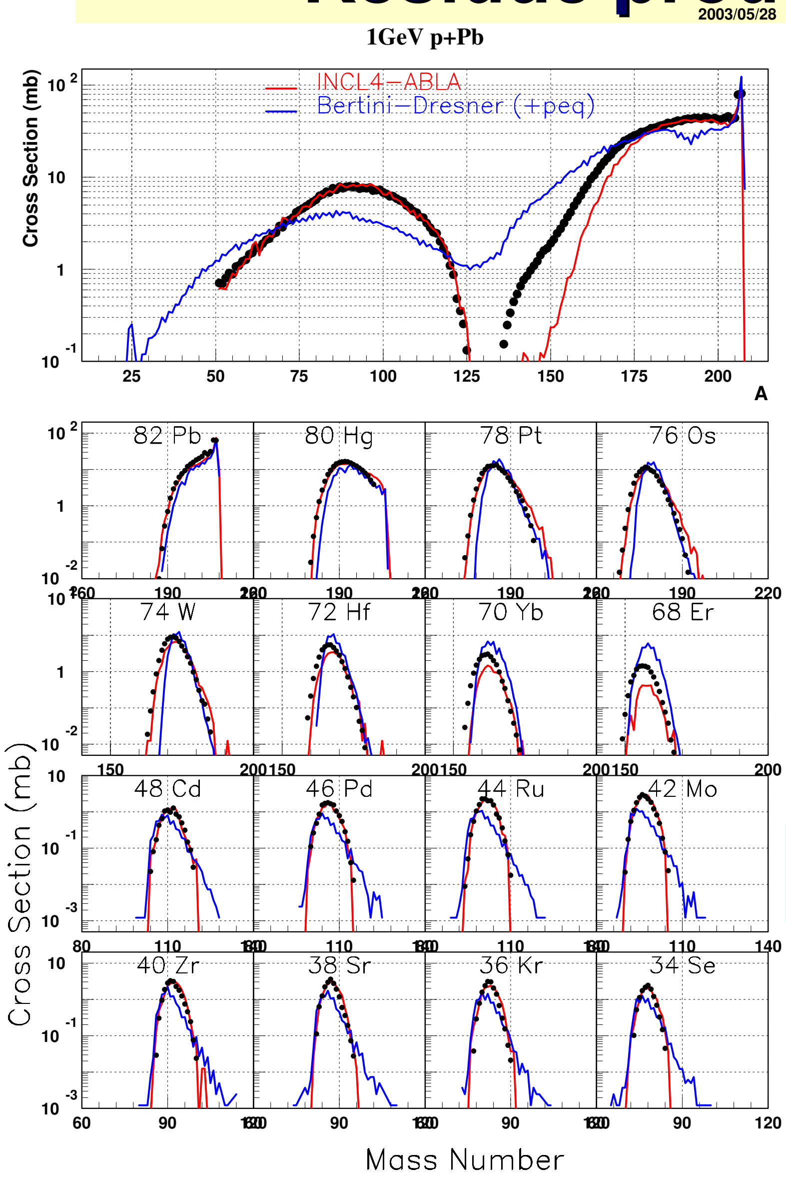
- **Total production, energy and angular distribution : general trends well understood**

Differential spectra from a thick Pb target (SATURNE data)



From T. Aoust et al., ND2004, Santa Fe

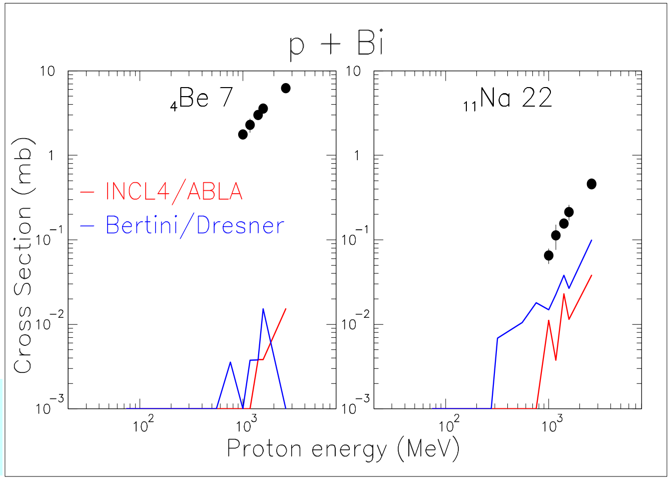
Residue production: heavy systems



- **Models behave differently especially for fission fragments, light evaporation residues and isotopic distribution shape**
- **Generally intermediate mass fragments badly predicted**

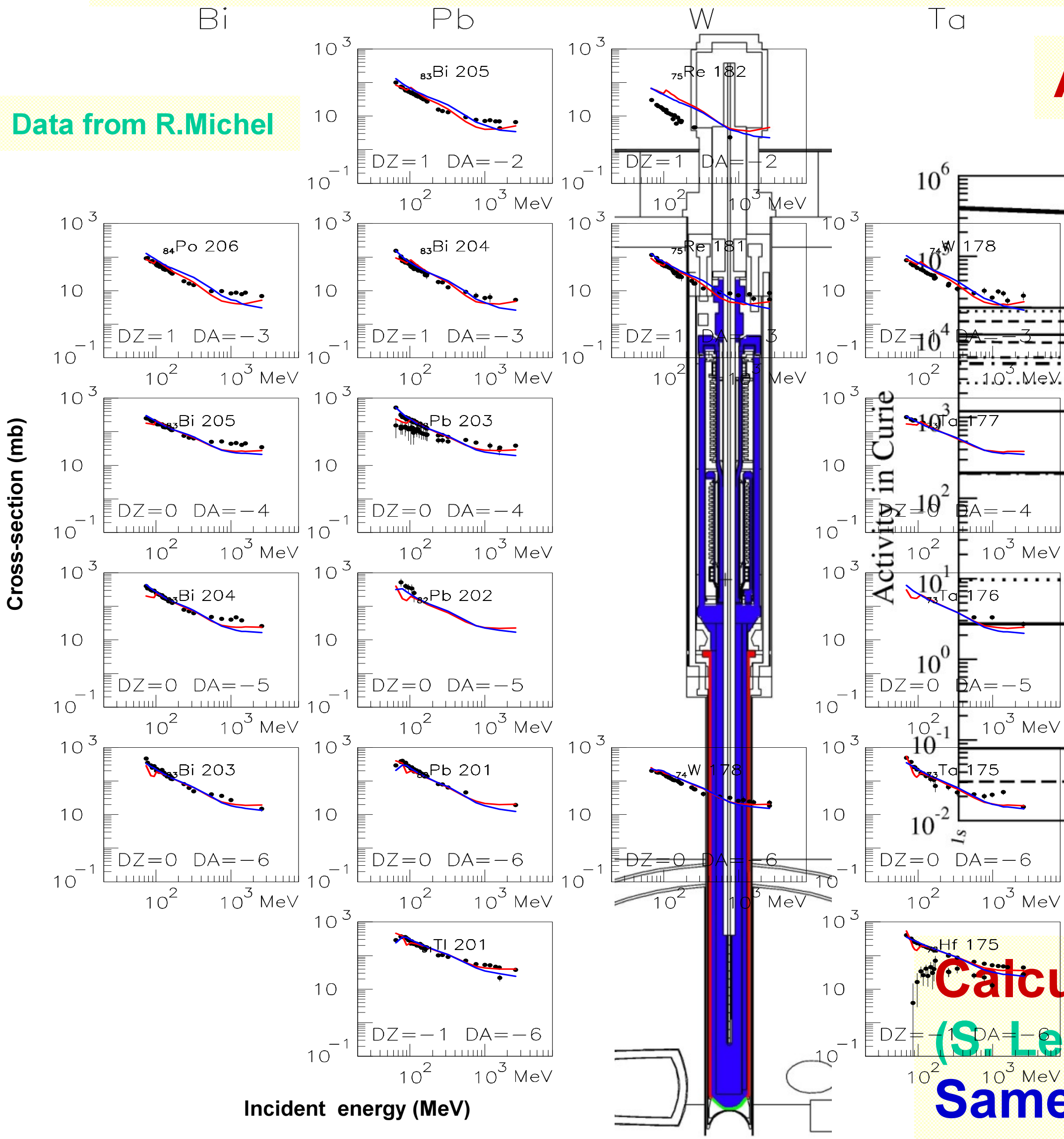
Data from Enqvist et al.

Data from Michel et al.

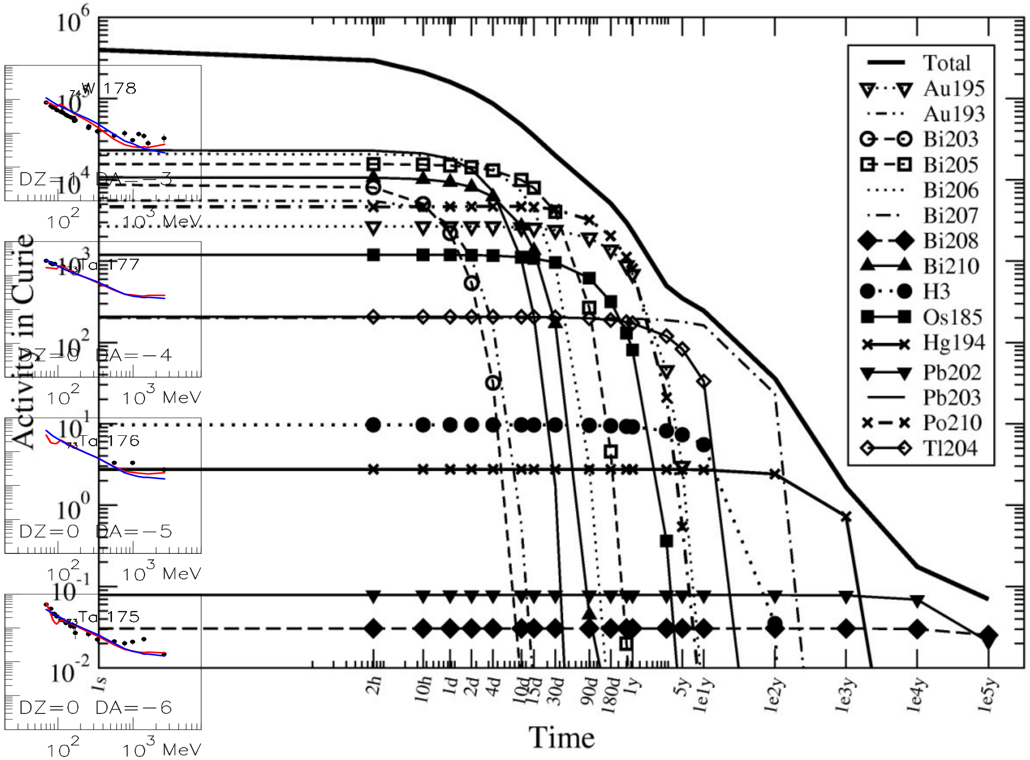


Residues close to the target

Data from R.Michel



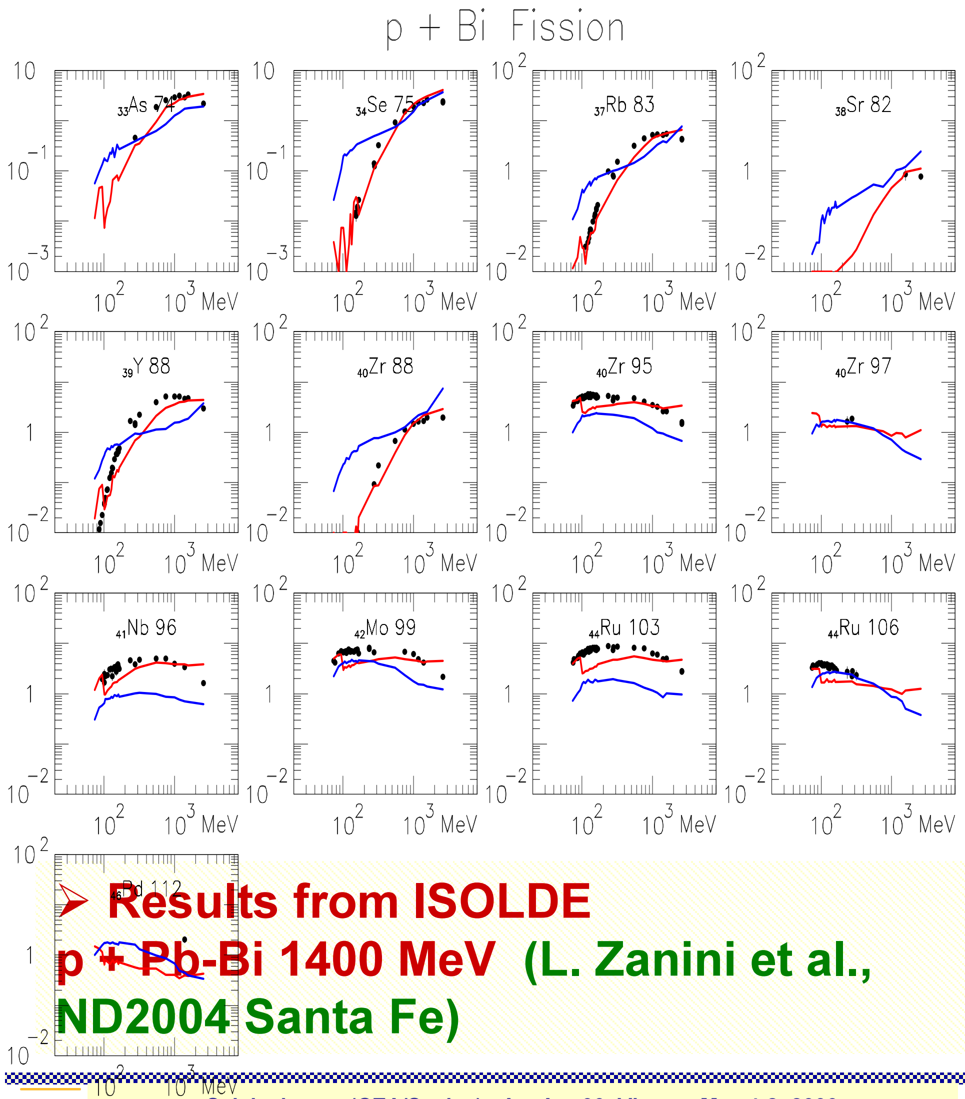
Activity in the MEGAPIE target



Calculation with INCL4/ABLA
(S. Lemaire et al., ND2007, Nice)
Same results with other models

Volatile isotope production

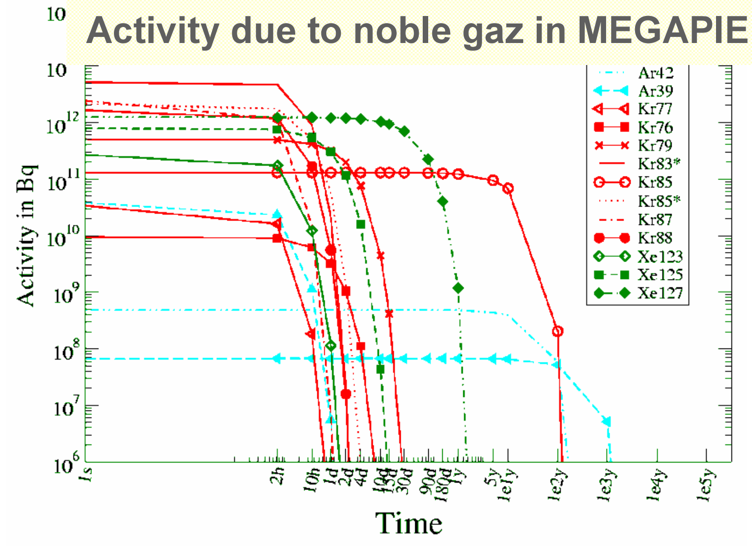
Data from Michel et al.

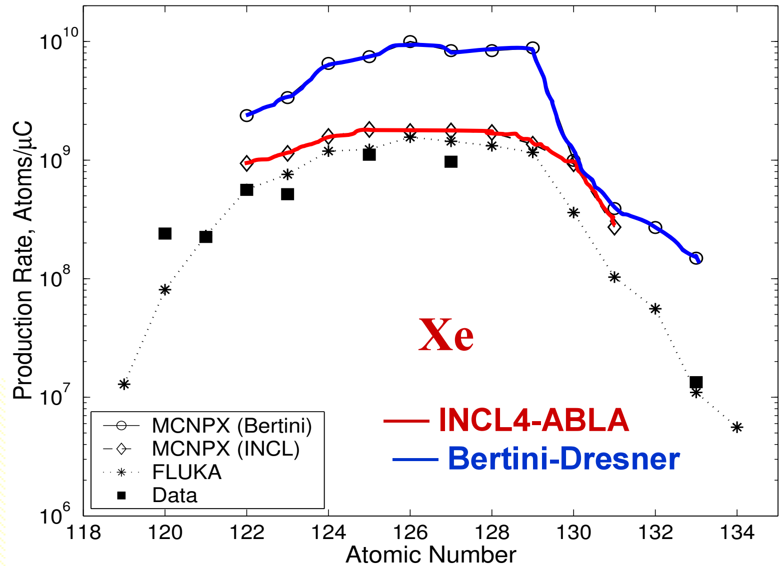


➢ **Results from ISOLDE**

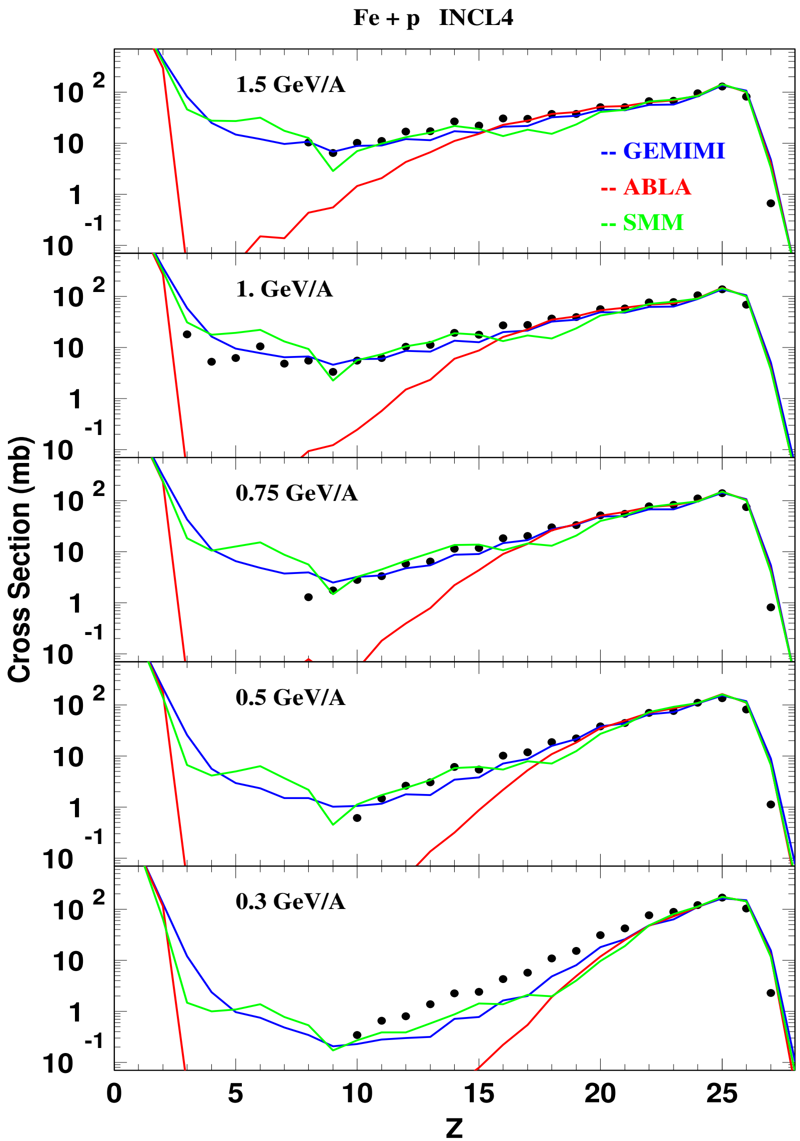
p + Pb-Bi 1400 MeV (L. Zanini et al., ND2004 Santa Fe)

Activity due to noble gaz in MEGAPIE





Residue production: light systems



FRS experiment (inclusive)
Fe + p :

impossibility to conclude on the mechanism producing IMFs and on the best model

Data : C.Villagrasa et al., PRC 75 (2007) 044603; Napolitani et al. PRC 70 (2004) 054607)

— **INCL4 + ABLA**

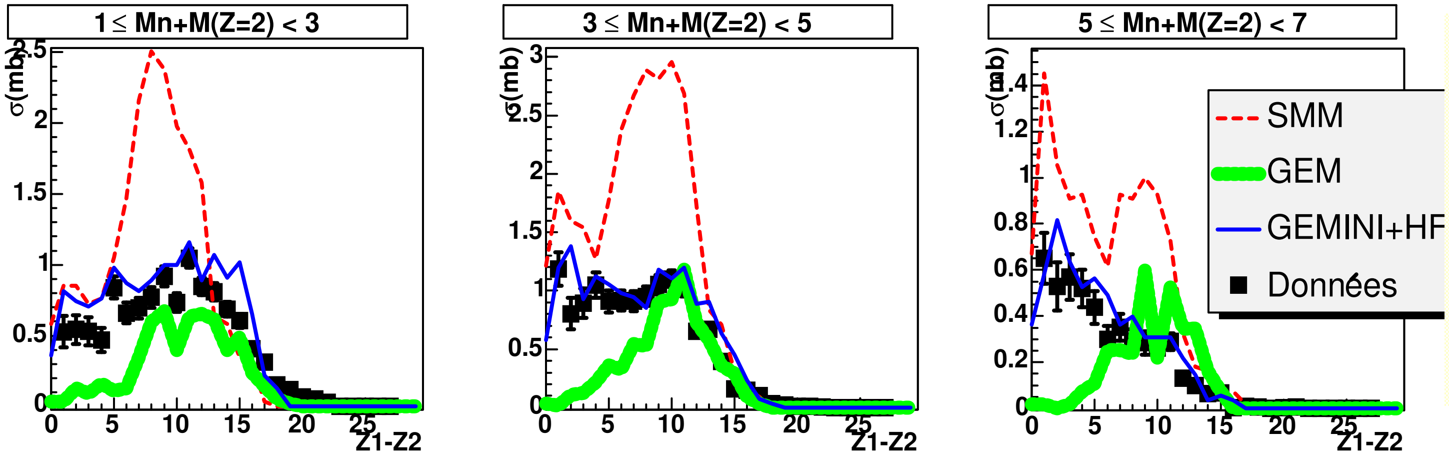
— **INCL4 + GEMINI (which includes an asymmetrical fission mode for light nuclei)** (Charity et al., NPA 483 (1988) 371)

— **INCL4 + SMM (multifragmentation model)** (A. Botvina et al., NPA 507, 649 (1990))

Importance of coincidence experiments:
Understanding of the mechanisms and constraints on the models

SPALADIN experiment Fe + p:

differences between the models (and mechanisms) when looking at the evolution of the de-excitation channels with excitation energy estimated from particle multiplicities (E. Le Gentil et al., PRL 100 (2008) 022701)



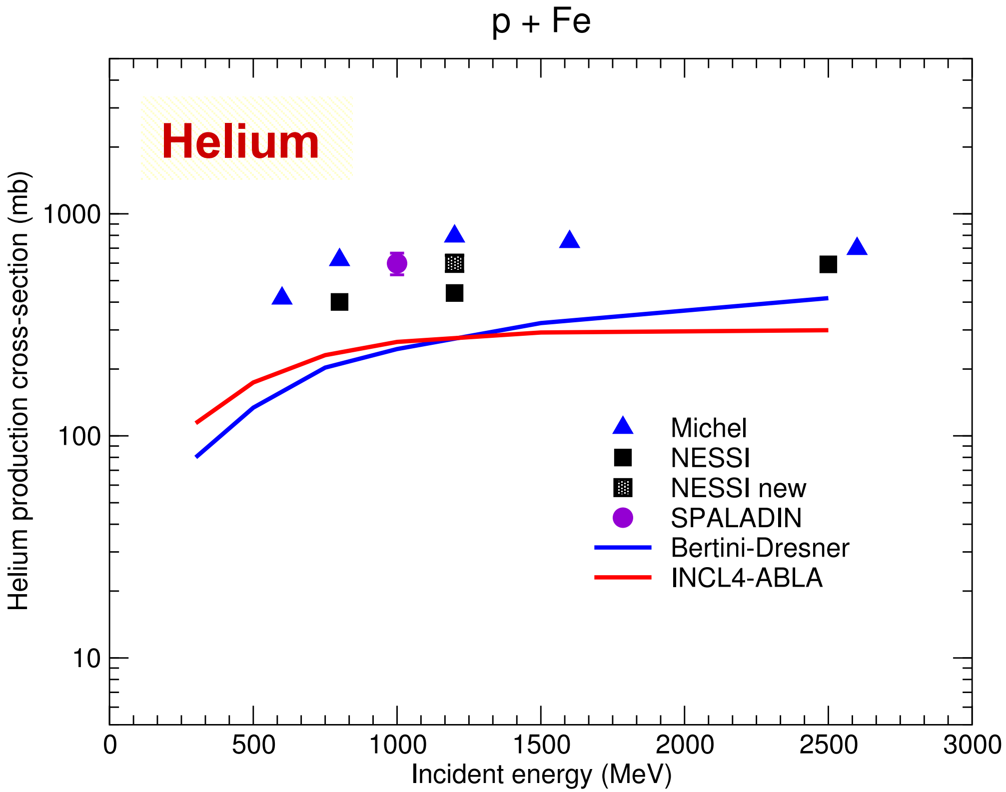
Z1-Z2 = Difference between the charges of the two heaviest fragments

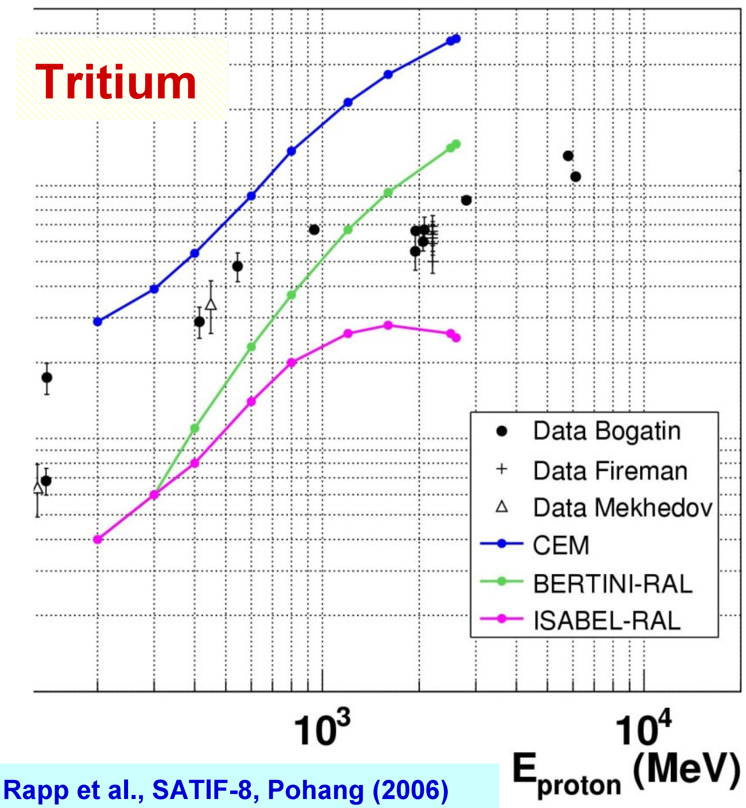
Mn+M(Z=2) = multiplicity of neutrons plus multiplicity of heliums

Events with 2 fragments (Z≥3) for different bins of particle multiplicity:

Difference between the charges of the two heaviest fragments

Gas production in Fe

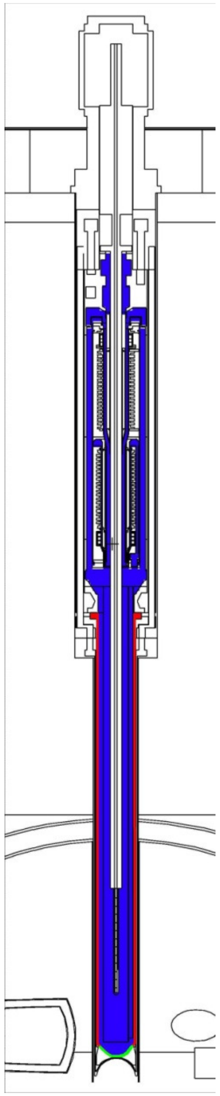




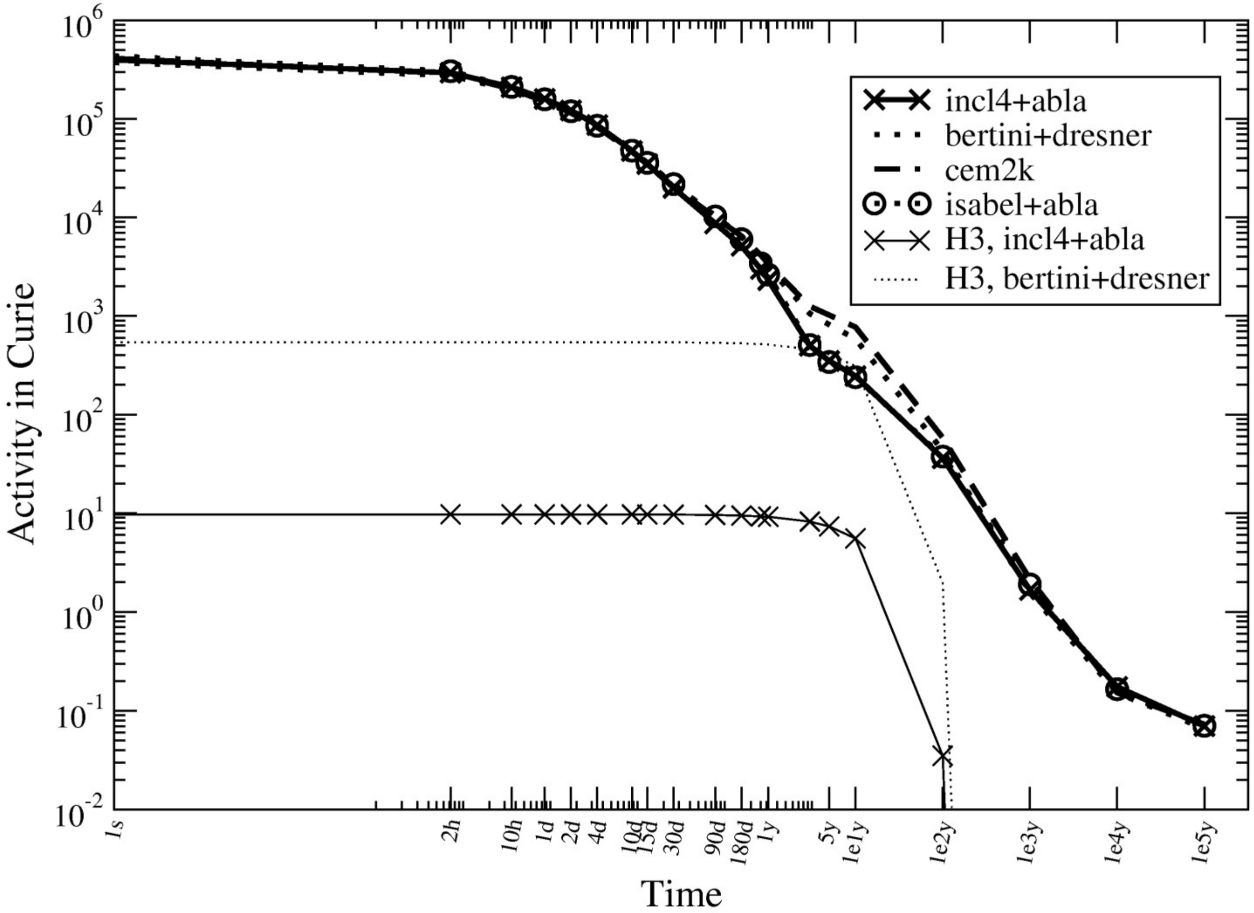
From Rapp et al., SATIF-8, Pohang (2006)

- **INCL4/ABLA does not produce tritium**
- **No good model for gas prediction in MCNPX**

Tritium activity in the MEGAPIE target

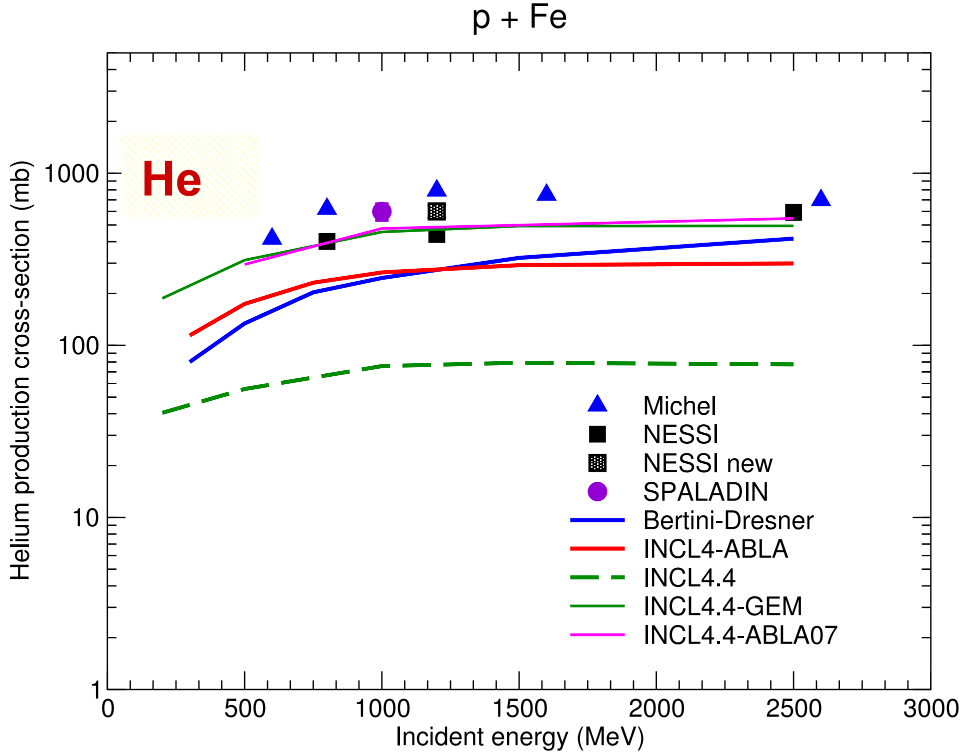


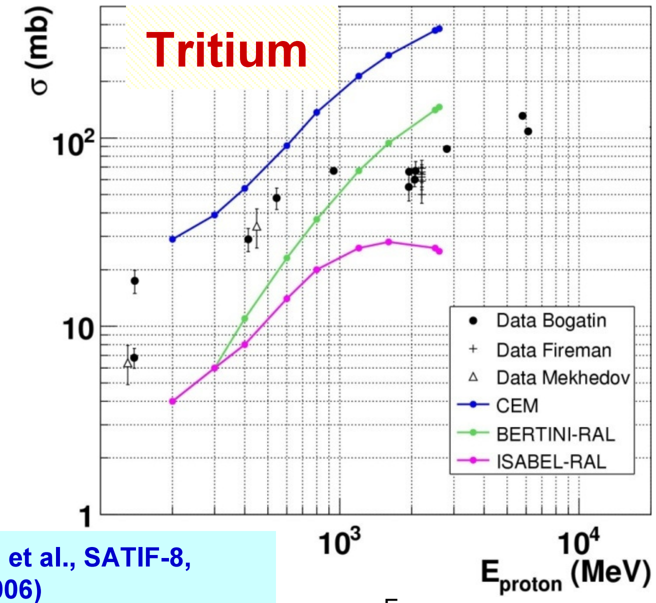
Total activity in the Pb-Bi



From S. Lemaire et al., ND2007

Gas production in Fe





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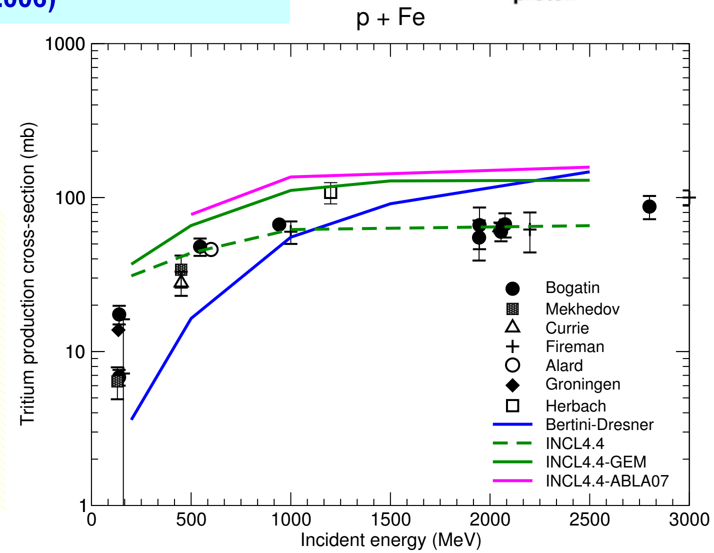
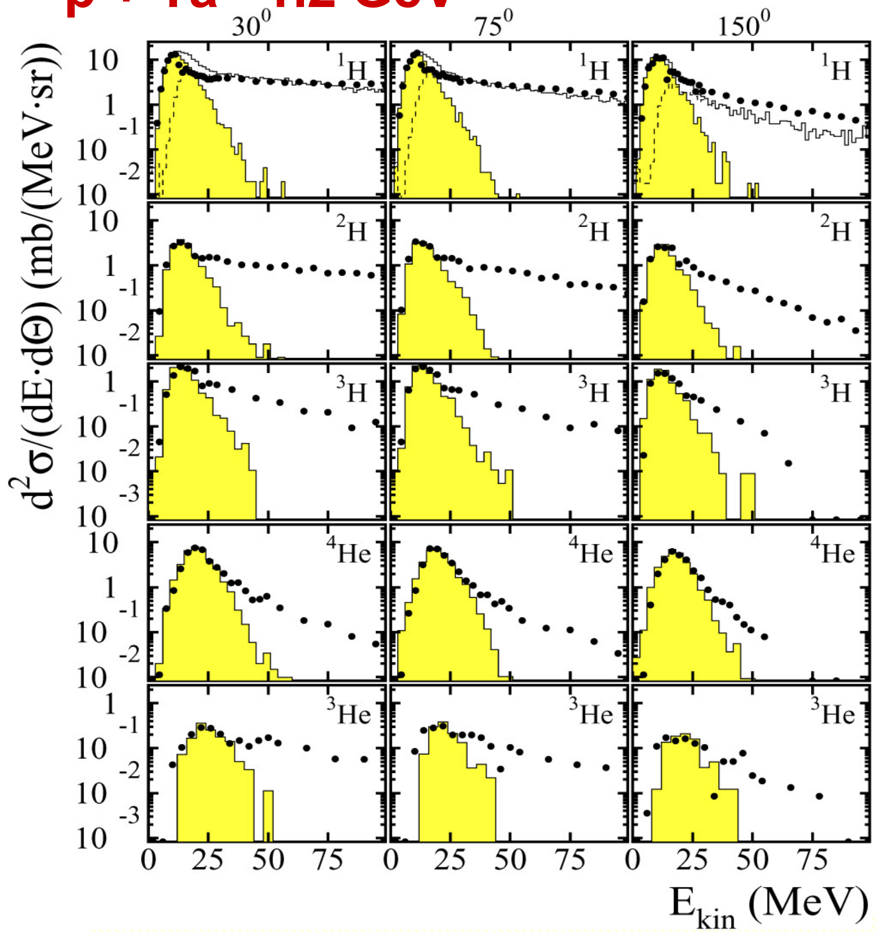
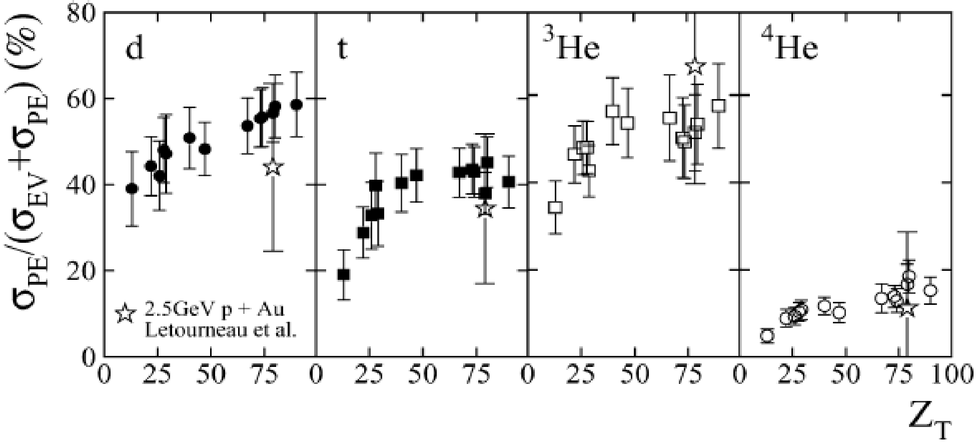


- **INCL4.4-ABLA07 now produces tritium**
- **situation improved compared to models presently in MCNPX**

Light charged particle production

p + Ta 1.2 GeV

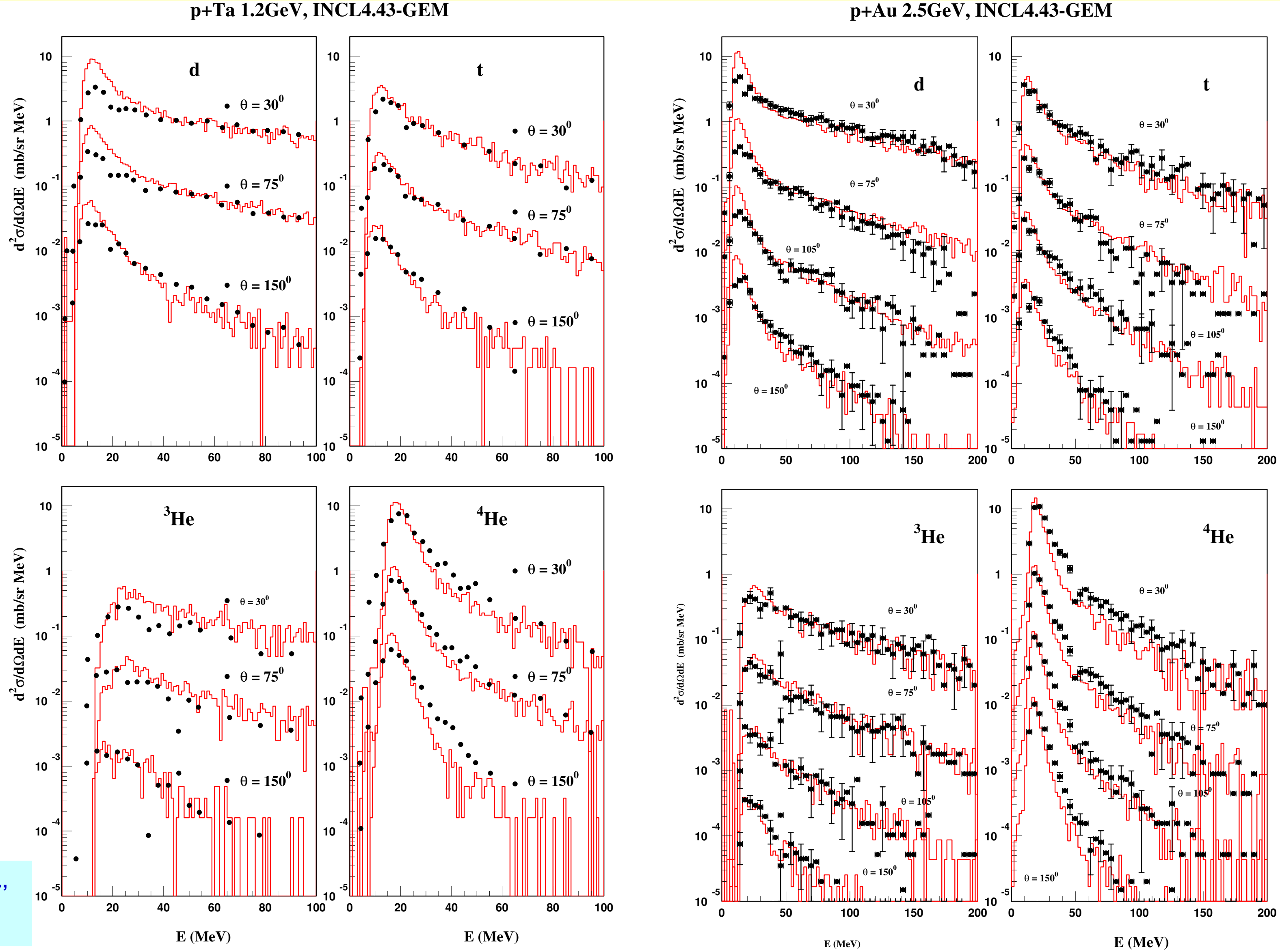




From Herbach et al., Nucl. Phys. A 765 (2006) 426

➥ important non-evaporative contribution in d, t, ^{3}He spectra

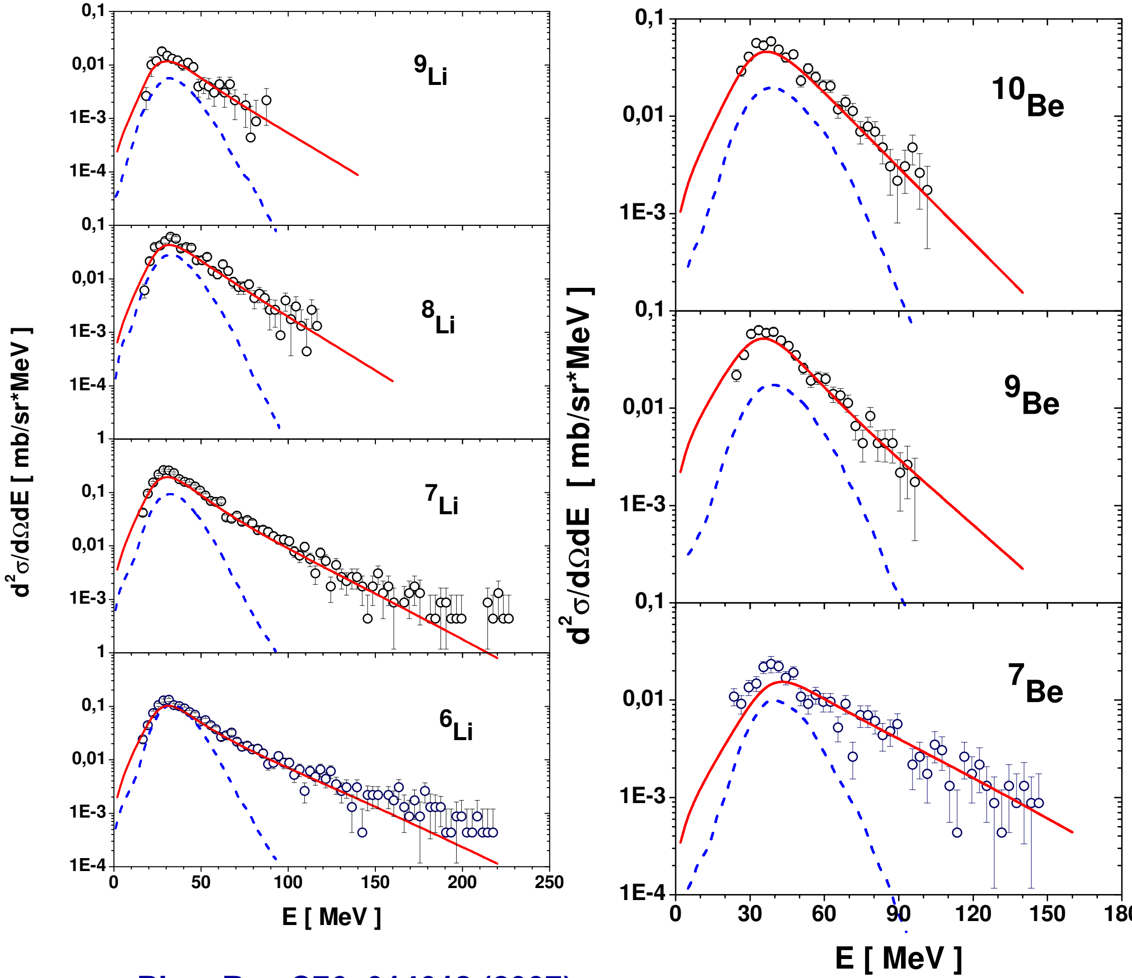
Cluster emission

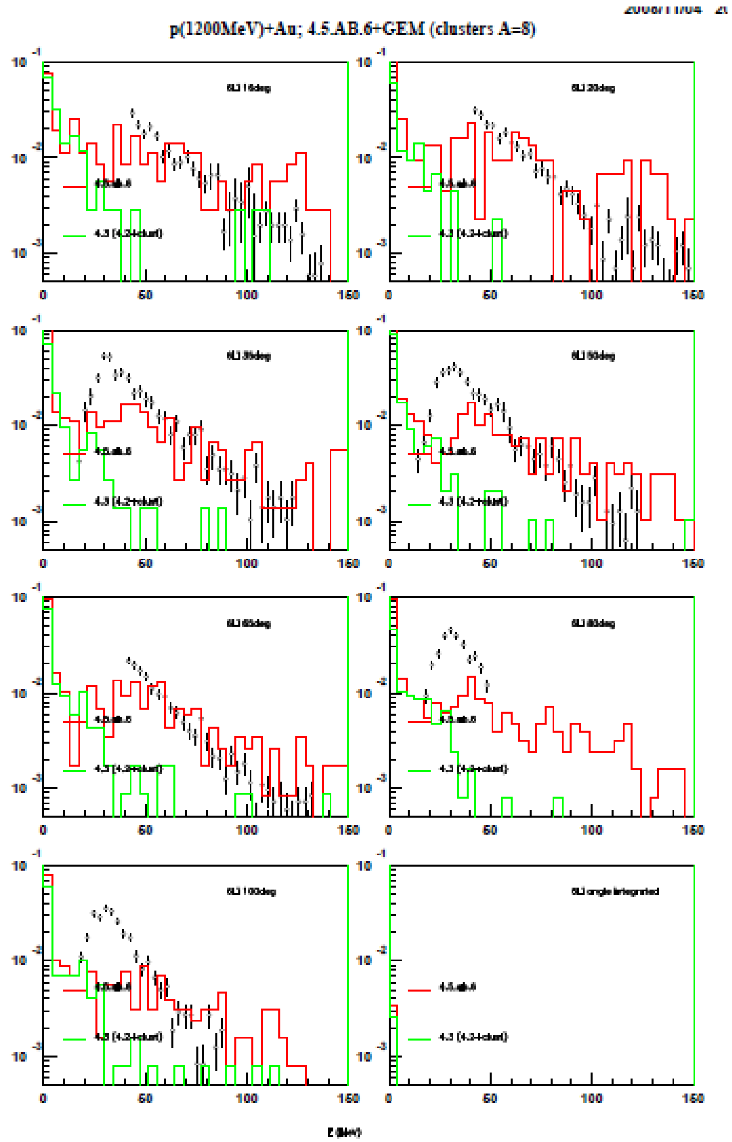


Data: Herbach et al., Nucl. Phys. A 765 (2006) 426

Intermediate mass fragment emission in INCL4

2.5 GeV p+Au   PISA@COSY





Phys.Rev.C76, 014618 (2007)

Benchmark of Spallation Models

Objectives

- **To assess the prediction capabilities of the spallation models used or that could be used in the future in high-energy transport codes**

- **To understand the reason for the success or deficiency of the models in the different mass and energy regions or for the different exit channels**

- **To reach a consensus, if possible, on some of the physics ingredients that should be used in the models.**

New FP7 project : ANDES (Accurate Nuclear Data for nuclear Energy Sustainability)

WP4 - High-energy model validation in the 150-600 MeV domain

General objectives:

- To identify remaining deficiencies and not understood features of the nuclear models used in high-energy transport codes between 150 and 600 MeV (ADS demo)
- to use/do a few specific experiments to solve the identified problems
- to further improve the models
- to do a few specific integral validation experiments
- to assess the uncertainty with which quantities related to high-energy reactions can be predicted

WP4 - High-energy model validation in the 150-600 MeV domain

Task 4.1: State-of-the-art of high-energy model predicting capability in the 150-600 MeV domain (CEA-Saclay, Univ. Liège, GSI Darmstadt, Univ. Santiago de Compostella)

Task 4.2: SPALADIN p+Pb at 500 MeV : measurement of the two fission fragments and light evaporation residues in coincidence with neutron and light charged particles (CEA-Saclay, GSI Darmstadt, Univ. Santiago de Compostella)

Task 4.3: Improving of the predicting capabilities of the simulation tools in the 150-600 MeV in order to reduce the uncertainties on key parameters of the demonstration facility spallation target (Univ. Liège, CEA-Saclay, GSI Darmstadt, CEA-Bruyères/NRG)

Task 4.4: Validation on the results from the post irradiation analysis of MEGAPIE samples (PSI Zürich, CEA-Saclay)

Task 4.5: Measurement of (n,n), (n,xn) and (n, lcp) at 175 MeV on Fe and Bi (Uppsala Univ., LPC Caen)

Conclusion

➢ **Specific features of spallation reactions: high energy particles, huge number of produced residues, high gas production**

➢ **Necessity of good physics models validated on good experimental data to be implemented in simulation codes**

⇨ **The benchmark of spallation models should allow**

- ➢ **to assess the predicting capabilities of the different available models**
- ➢ **to identify the best parameters/ingredients to be used in the models**

➢**Work still needed (model improvement and more constraining experiments) ⇨ ANDES FP7 project**