united nations educational, scientific and cultural organization

international atomic energy agency

the
abdus salam
international centre for theoretical physics

SMR/1325-8

Workshop on

Nuclear Data for Science & Technology: Accelerator Driven Waste Incineration

10 - 21 September 2001

Miramare - Trieste, Italy

Comparison of high energy codes to experimental data

Sylvie Leray
DAPNIA/SPhN CEA/ Saclay
France

Comparison of high energy codes to experimental data

A large set of experimental data now available allows a detailed testing of the models

➥ comparison with widely used high-energy transport codes

- ✦ LAHET with Bertini, Isabel INC models and Dresner-Atchison evaporation-fission models
- ✦ TIERCE with INCL2-Dresner

➥ comparisons with models not implemented in high-energy transport codes

- ✦ INCL2-GEMINI
- ✦ INCL2-GSI

➥ comparisons with the new INCL4 model

Available high-energy experimental data

- **Neutrons**
  - ➥ multiplicity distributions
  - ➥ double-differential cross-sections
  - ➥ Thin and thick targets
- **Light charged particles**
  - ➥ multiplicities
  - ➥ differential cross-sections
- **Residual nuclides**
  - ➥ production yields
  - ➥ isotopic distributions
  - ➥ recoil velocities
- **Coincidence measurements**
  - ➥ light charged particles, fission fragments and low energy neutrons
    - ⇨ deeper insight of the reaction mechanisms

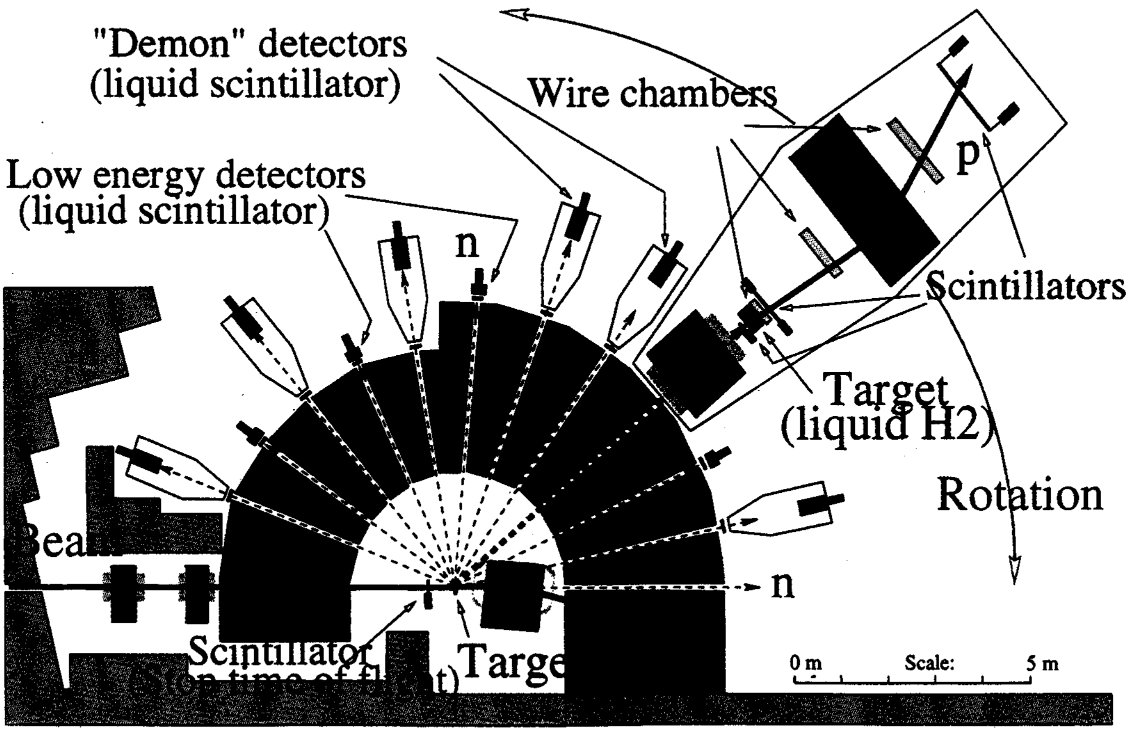
Neutron measurements at Saturne

Angle and energy spectrum measurements

- **Measurement of neutron production double-differential cross-sections at SATURNE**

Measurement method: (NIM A385 (1997) 339; 345)

- from 2 MeV to 400 MeV: time of flight between tagged incident proton and a neutron scintillator
- from 200 MeV to incident energy: $n-p$ conversion in a H_{2liq} target and a magnetic spectrometer
- Use of quasi-monokinetic neutron beams (break-up $d+Be$) for efficiency determination



Experimental setup

Neutron measurements at SATURNE

⇒ Thin targets

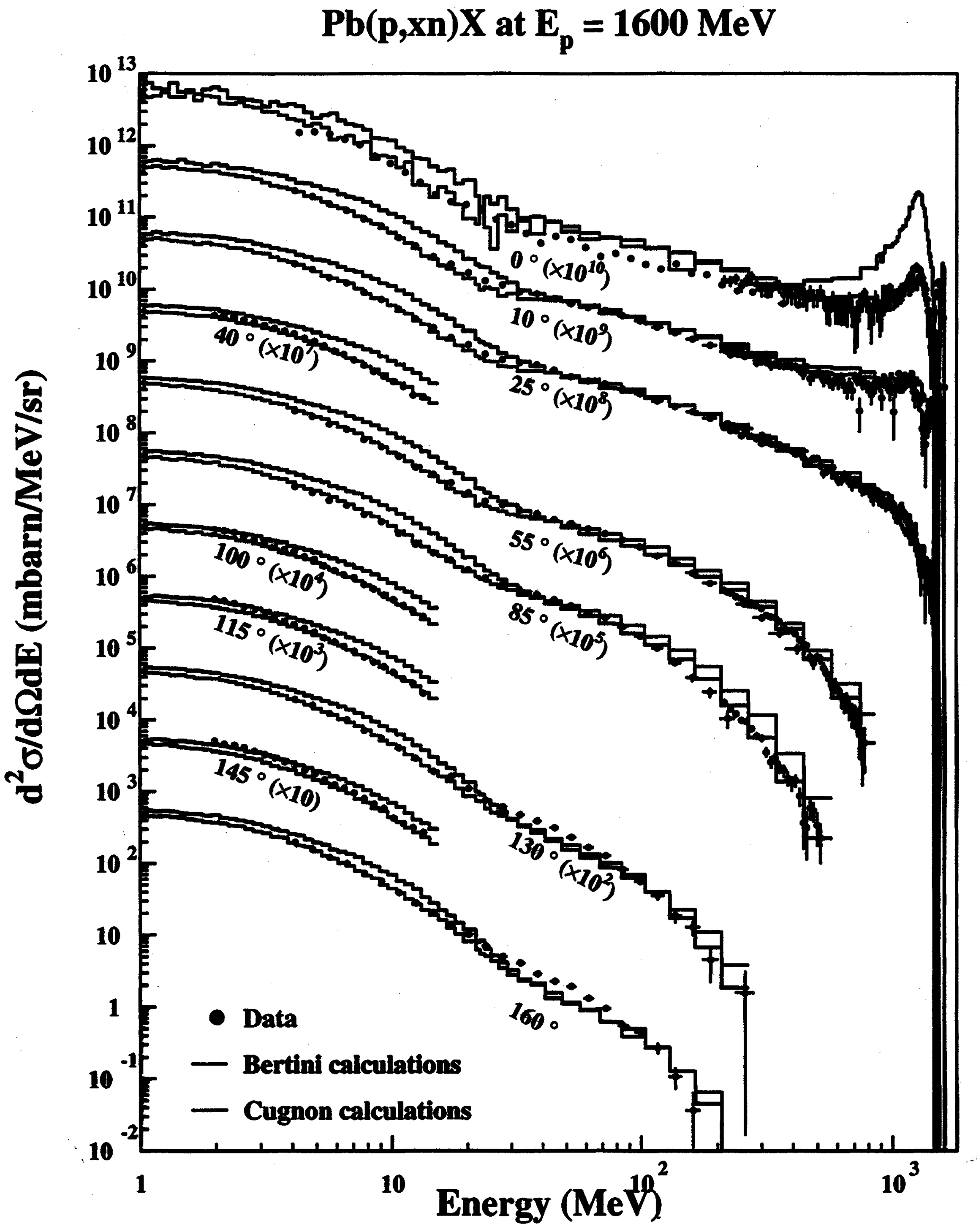
(coll. CEA-DAM, CEA-DSM, CNRS-IN2P3, Uppsala, Bruxelles)

- Measurement of energy-distributions at various angles from $0°$ to $160°$
- Protons and deuterons between 0.8 and 1.6 GeV on Al, Fe, Zr, W, Pb, Th

⇒ Thick targets

(coll. CEA-DAM, CEA-DSM, CNRS-IN2P3, Bruxelles)

- Measurement at various angles on targets of different diameters as a function of position in the target
- Protons and deuterons between 0.8 and 1.6 GeV on Al, Fe, W, Pb



X. Ledoux et al., PRL 82 (1999) 4412

Per reaction averaged neutron multiplicities and energy carried out by the emitted neutrons **obtained by integration of the double-differential cross-sections over the angular distribution and compared with calculations using** TIERCE code[1] **with Cugnon[2] or Bertini[3] INC model and** LAHET[4] **for a 2cm Pb target.**

Energy	M_n^{exp}	M_n^{Cug}	M_n^{Tie}	M_n^{Lah}	$E \times M_n^{exp}$	$E \times M_n^{Cug}$	$E \times M_n^{Tie}$	$E \times M_n^{Lah}$
E = 800 MeV σ_R = 1720 mb								
0 - 2 MeV		**4.9**	**6.1**	**5.6**		**4.8**	**6.2**	**5.7**
2 - 20 MeV	6.5 ± 1.0	**6.9**	**9.5**	**8.6**	38. ± 4.	**42.**	**55.**	**50.**
20 - E_{max}	1.9 ± 0.2	**2.2**	1.8	1.8	200. ± 20.	**211.**	**203.**	**202.**
TOTAL		**14.0**	**17.4**	**16.0**		**258.**	**264.**	**258.**
E = 1200 MeV σ_R = 1720 mb								
0 - 2 MeV		**5.8**	**6.9**	**6.3**		**5.8**	**7.0**	**6.5**
2 - 20 MeV	8.3 ± 1.0	**8.9**	**12.4**	**11.4**	52. ± 6.	**54.**	**78.**	**71.**
20 - E_{max}	2.7 ± 0.3	**2.8**	**2.4**	**2.4**	310. ± 31.	**309.**	**294.**	**299.**
TOTAL		**17.4**	**21.7**	**20.2**		**369.**	**379.**	**377.**
E = 1600 MeV σ_R = 1720 mb								
0 - 2 MeV		**6.0**	**7.4**	**6.8**		**6.0**	**7.5**	**7.0**
2 - 20 MeV	10.1 ± 1.4	**10.0**	**14.7**	**13.6**	65. ± 8.	**61.**	**97.**	**90.**
20 - E_{max}	3.4 ± 0.4	**3.1**	**3.1**	**3.1**	410. ± 40.	**422.**	**373.**	**389.**
TOTAL		**19.1**	**25.2**	**23.5**		**489.**	**478.**	**486.**

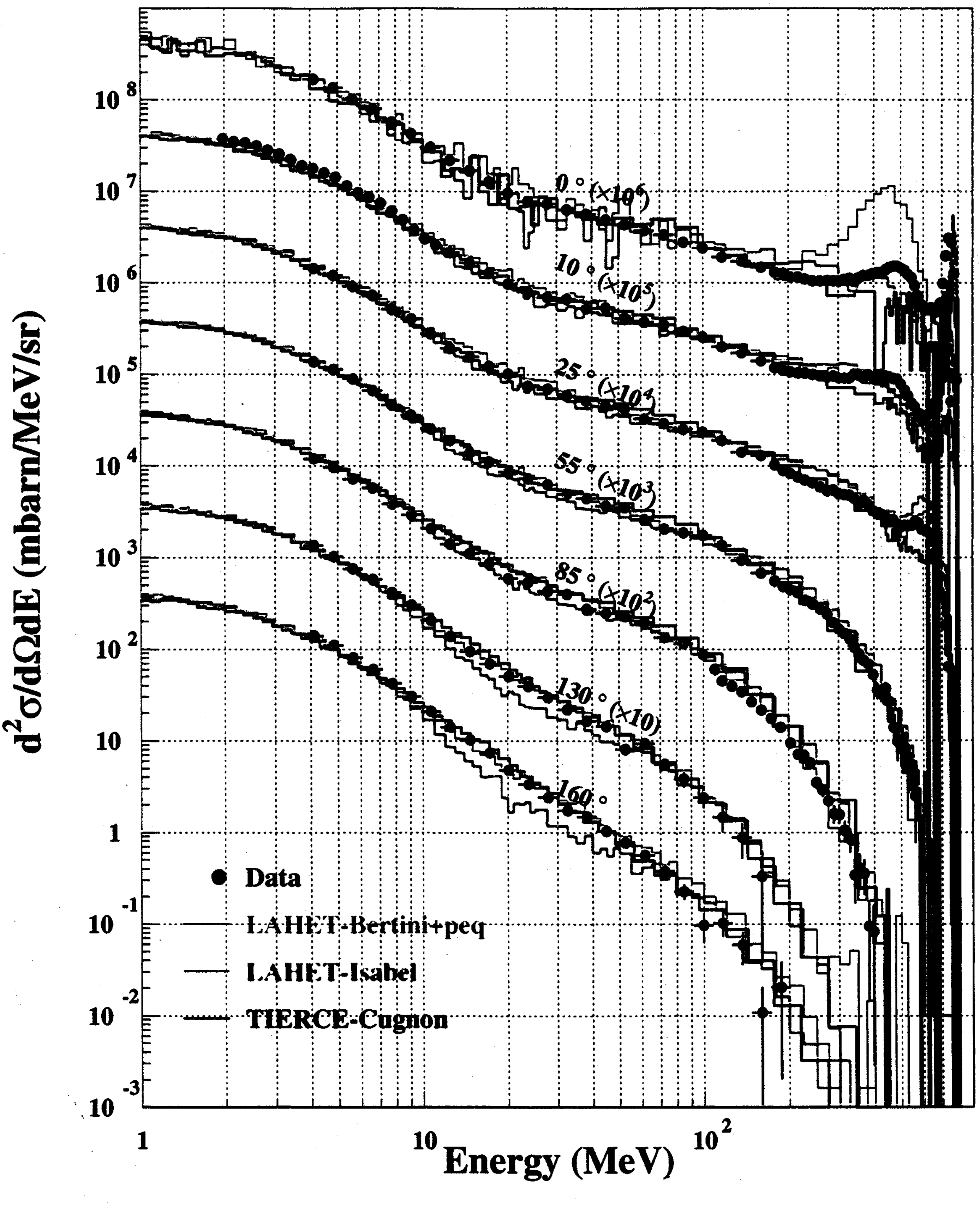
1) O. Bersillon, *2nd Int. Conf. on ADTT*, Kalmar, Suède, 3-7 Juin (1996).

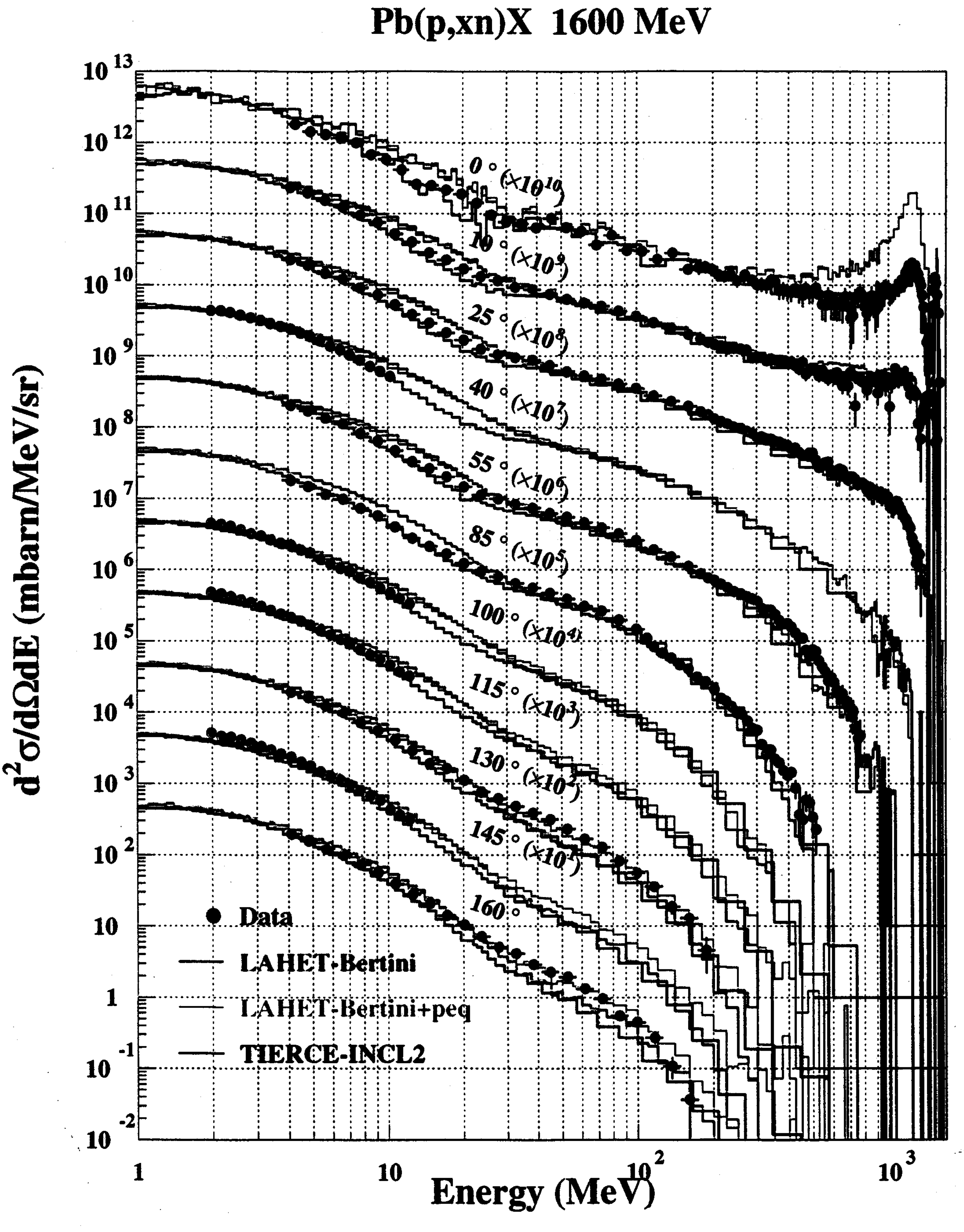
2) J.Cugnon, Nucl. Phys. A462 (1987) 751; J.Cugnon *et al.* Nucl. Phys. A620 (1997) 475.

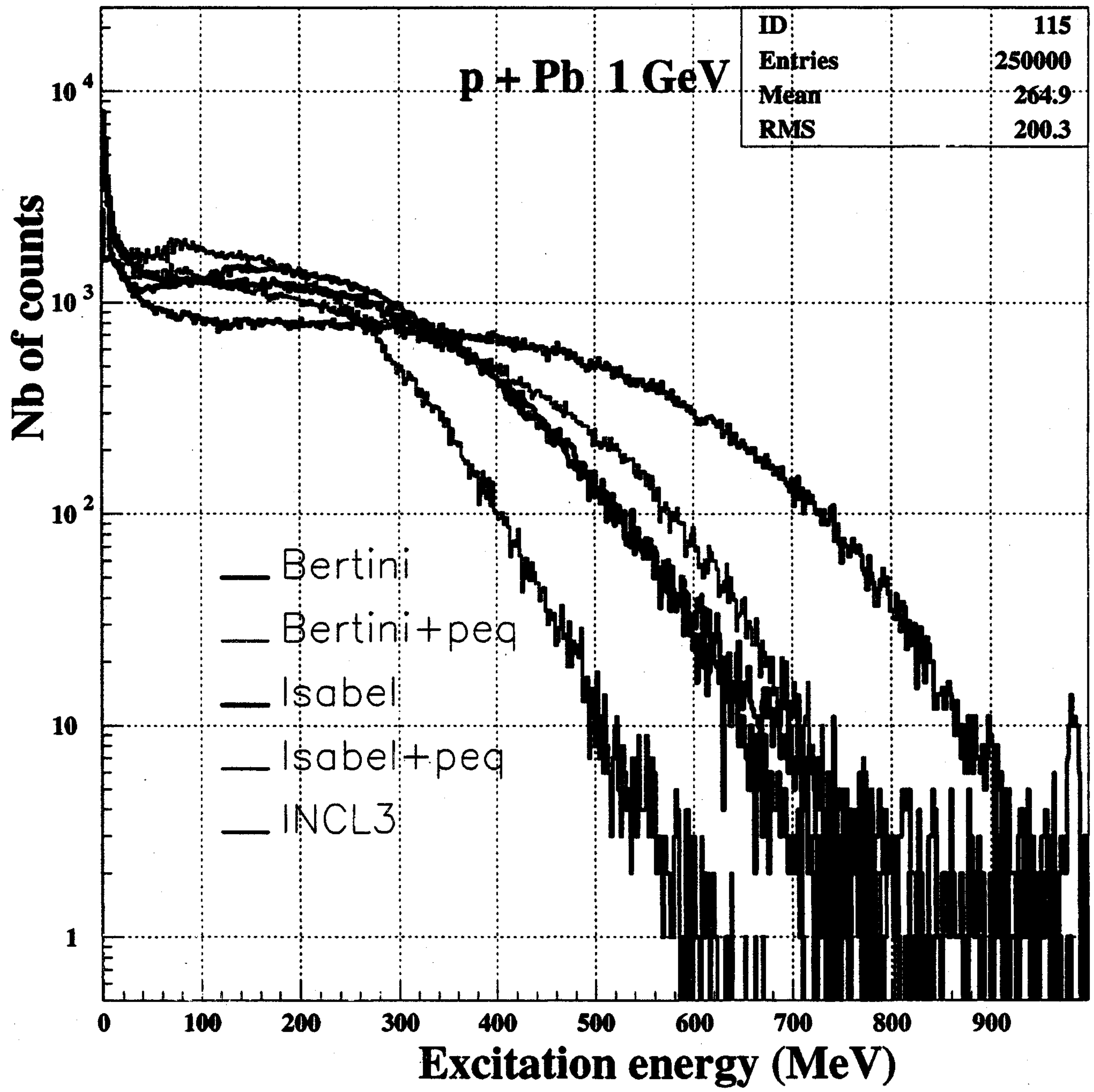
3) H. W. Bertini *et al.*, Phys. Rev. 131, 1801 (1963).

4) R.E.Prael *et al.*, *LAHET*™ Code System, Report LA-UR-89-3014, LANL 1989.

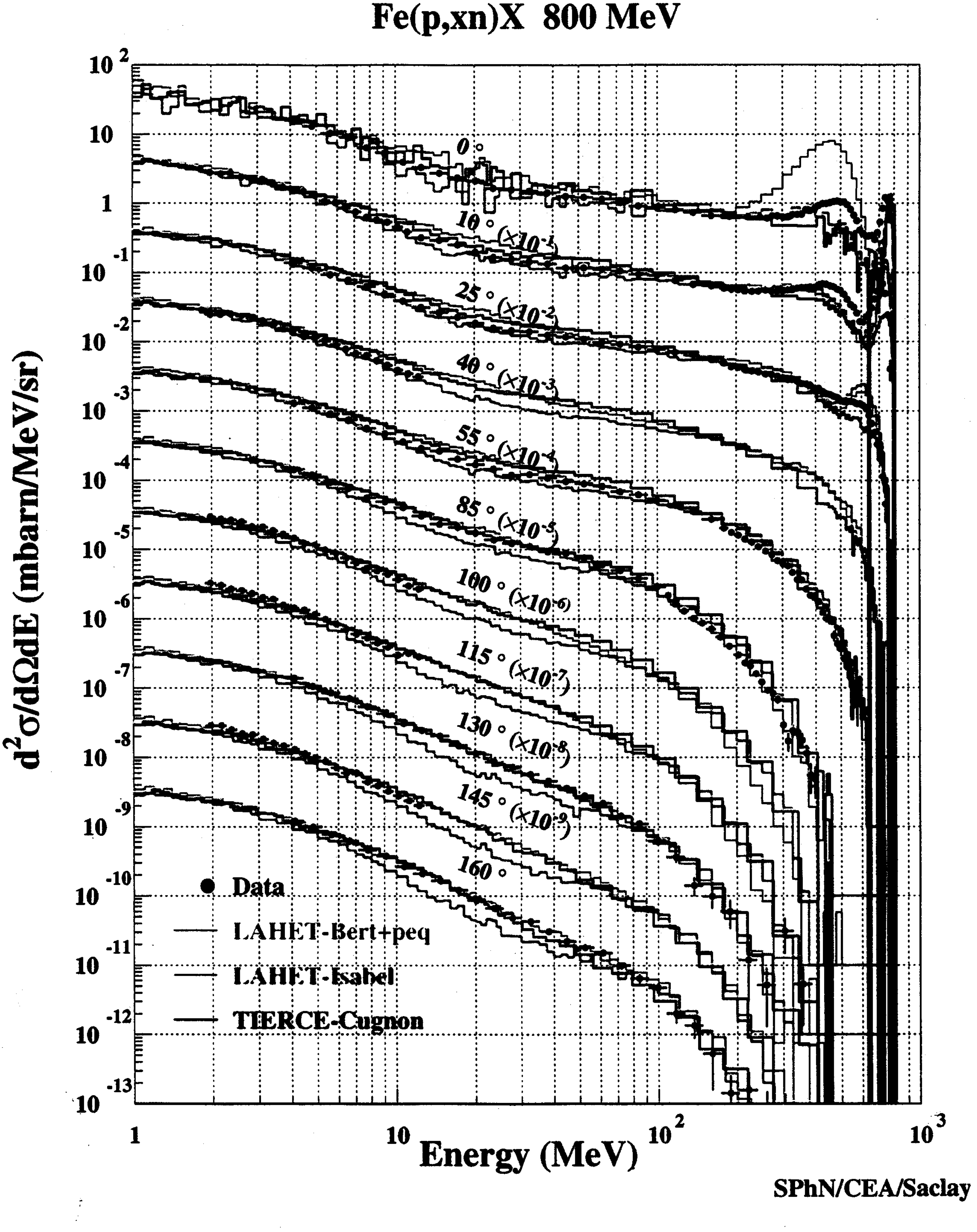
Pb(p,xn)X 800 MeV

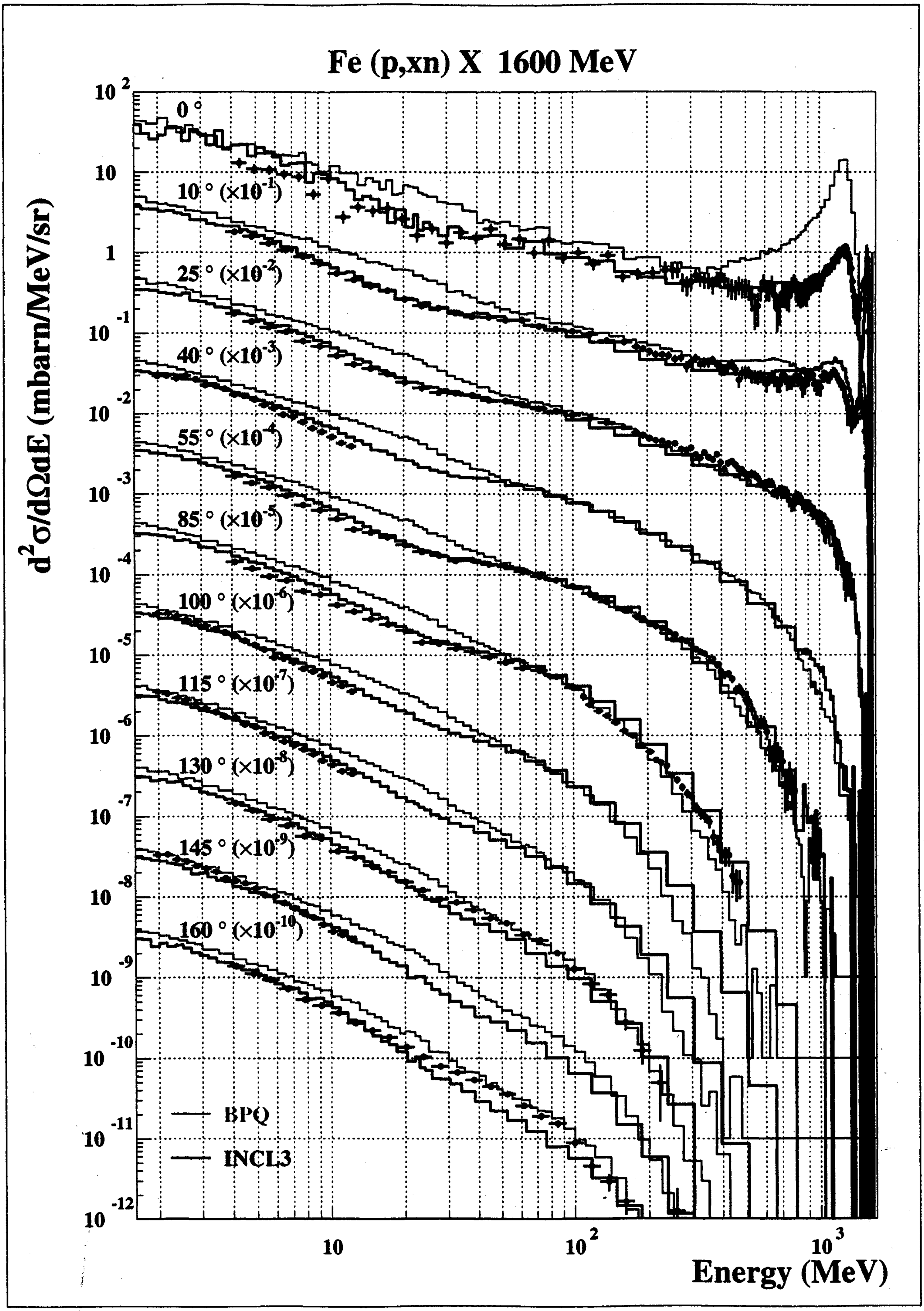



Pb(p,xn)X 1600 MeV
d²σ/dΩdE (mbarn/MeV/sr)
Energy (MeV)
0° (×10¹⁰)
10° (×10⁹)
25° (×10⁸)
40° (×10⁷)
55° (×10⁶)
85° (×10⁵)
100° (×10⁴)
115° (×10³)
130° (×10²)
145° (×10¹)
160°
Data
LAHET-Bertini
LAHET-Bertini+peq
TIERCE-INCL2



ID 115
Entries 250000
Mean 264.9
RMS 200.3
p + Pb 1 GeV
Nb of counts
Excitation energy (MeV)
Bertini
Bertini+peq
Isabel
Isabel+peq
INCL3


Fe(p,xn)X 800 MeV
d²σ/dΩdE (mbarn/MeV/sr)
Energy (MeV)
0 °
10 ° (×10⁻¹)
25 ° (×10⁻²)
40 ° (×10⁻³)
55 ° (×10⁻⁴)
85 ° (×10⁻⁵)
100 ° (×10⁻⁶)
115 ° (×10⁻⁷)
130 ° (×10⁻⁸)
145 ° (×10⁻⁹)
160 °
Data
LAHET-Bert+peq
LAHET-Isabel
TIERCE-Cugnon
SPhN/CEA/Saclay



Fe (p,xn) X 1600 MeV
d²σ/dΩdE (mbarn/MeV/sr)
0°
10° (×10⁻¹)
25° (×10⁻²)
40° (×10⁻³)
55° (×10⁻⁴)
85° (×10⁻⁵)
100° (×10⁻⁶)
115° (×10⁻⁷)
130° (×10⁻⁸)
145° (×10⁻⁹)
160° (×10⁻¹⁰)
BPQ
INCL3
Energy (MeV)

Neutron double-differential cross-sections

- Bertini
  - ➥ pathologic behaviour at 0°
  - ➥ largely over-predicts low energy neutron production ⇒ two high excitation energy
- Bertini + pre-equilibrium
  - ➥ good for Pb, especially at 800 MeV
  - ➥ over-predicts low and intermediate energy neutron production for Fe ⇒ still two high excitation energy for light nuclei
  - ➥ pre-equilibrium emission too much forward peaked
- Isabel (800 MeV only)
  - ➥ very good agreement for Pb except at backward angles
  - ➥ less good for Fe
- INCL2
  - ➥ very good overall agreement

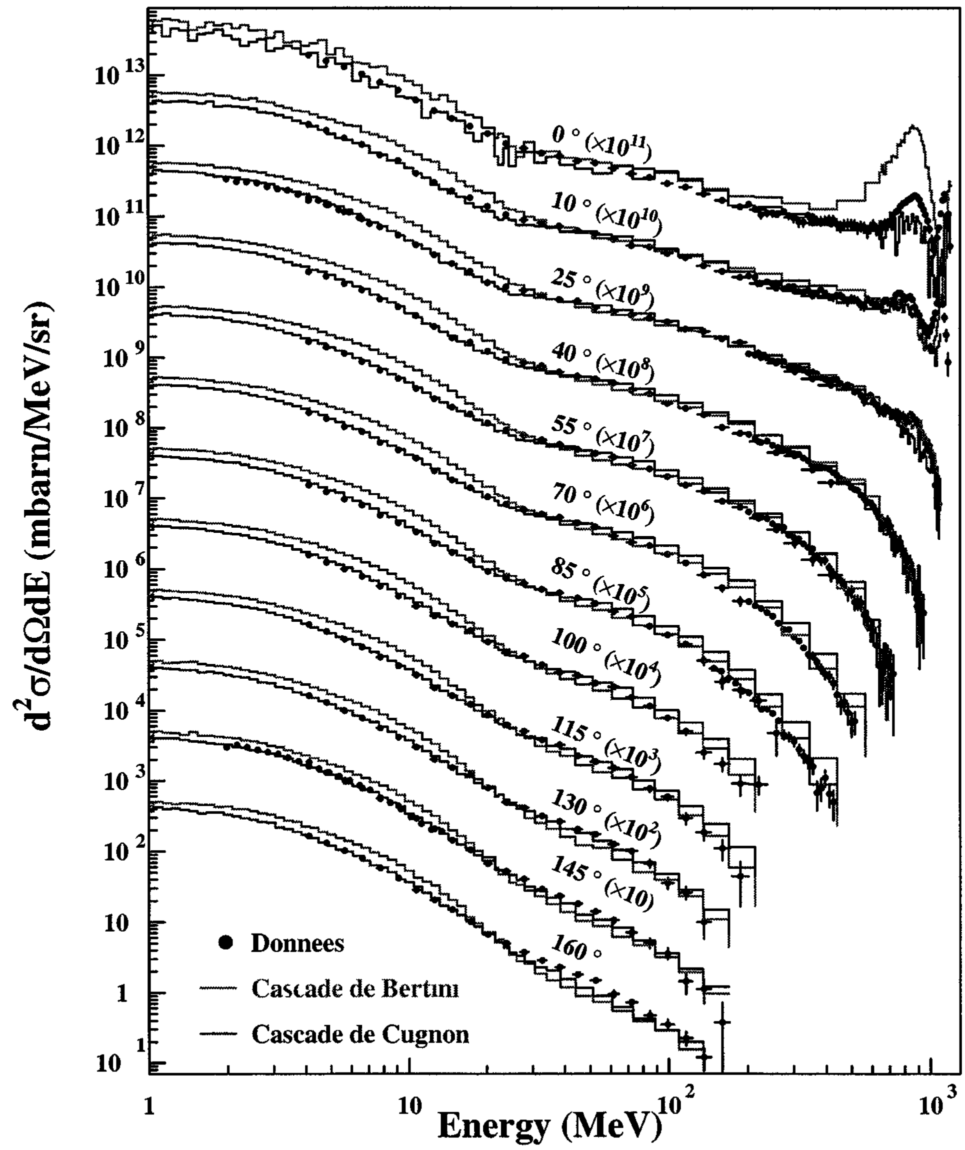
Neutron production double-differential cross-sections

collaboration CEA/DSM, CEA/DAM, IN2P3

⇒ Comparison of two different INC models inside the TIERCE HETC code

(same Dresner-Atchison evaporation-fission code)

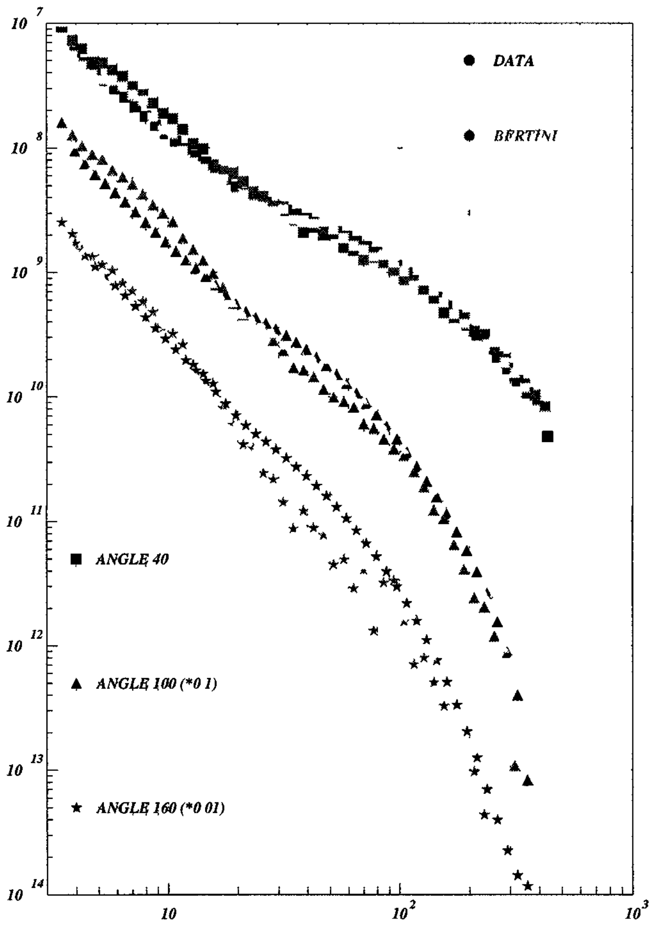
Pb(p,xn)X $E_p = 1200$ MeV



Neutron energy distribution measurements
Thick target results
collaboration CEA/DSM, CEA/DAM, IN2P3

⇒ Test of the transport part of the simulation codes

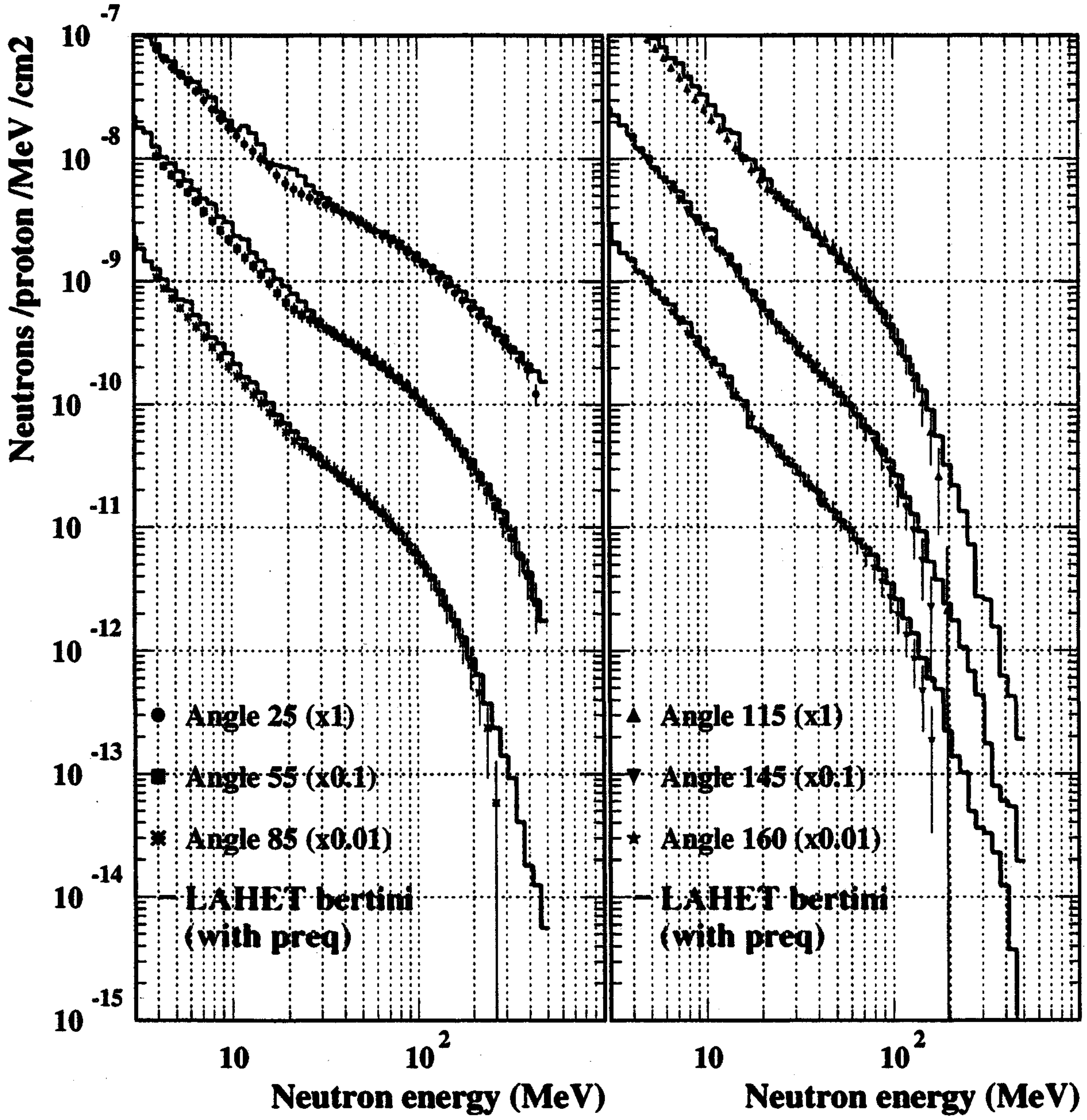
p(1 6GeV)+Pb , Diam=20cm, Long=105cm, pos=10cm



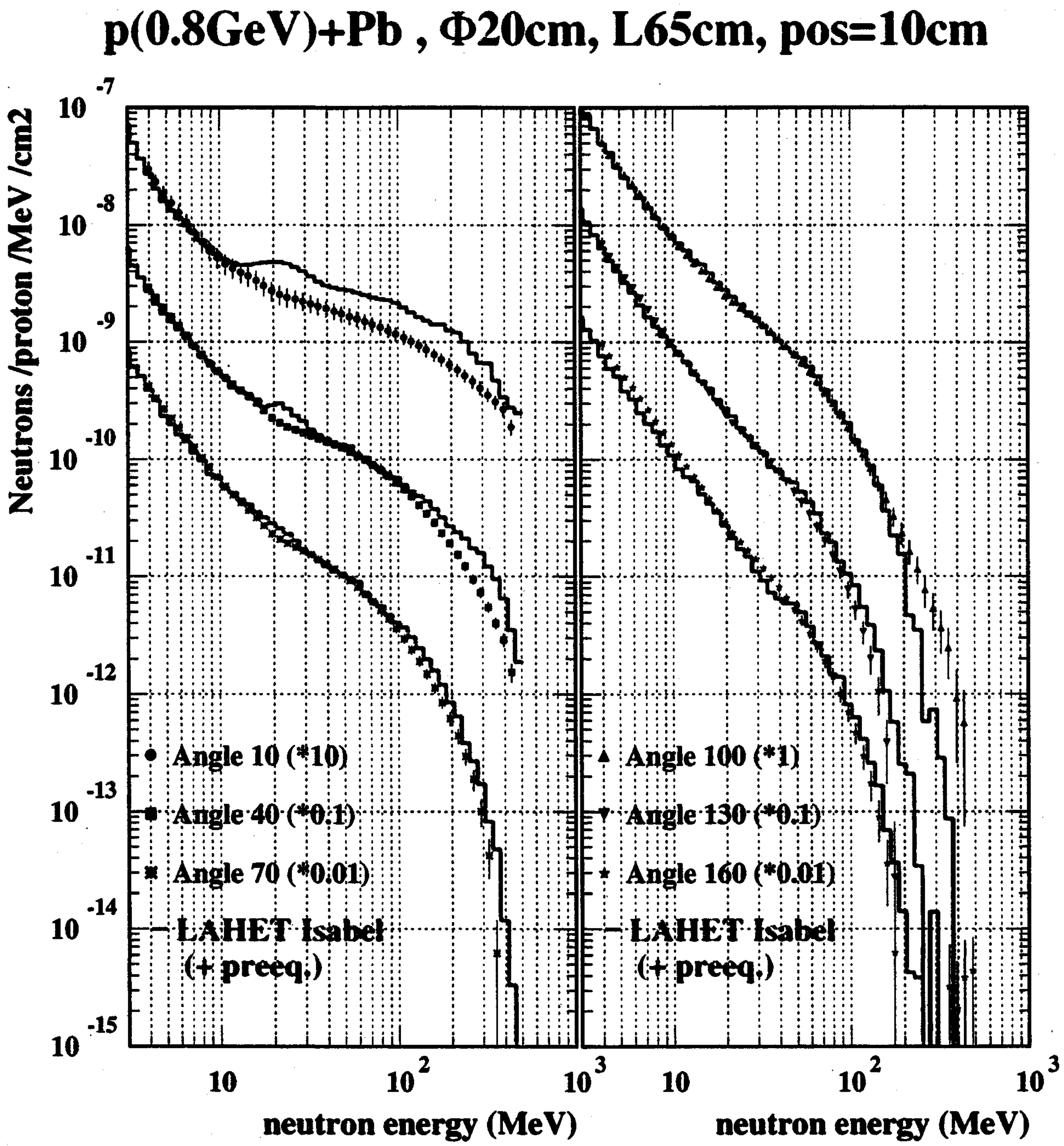
Total number of neutrons predicted by the TIERCE code :

	1200 MeV	1600 MeV
Bertini	28.6	43.7
Cugnon	23.6	34.8

p(1.6GeV)+Pb , Diam=10cm, Long=105cm, pos=10cm



C. Varignon, PhD Thesis, Caen 2000



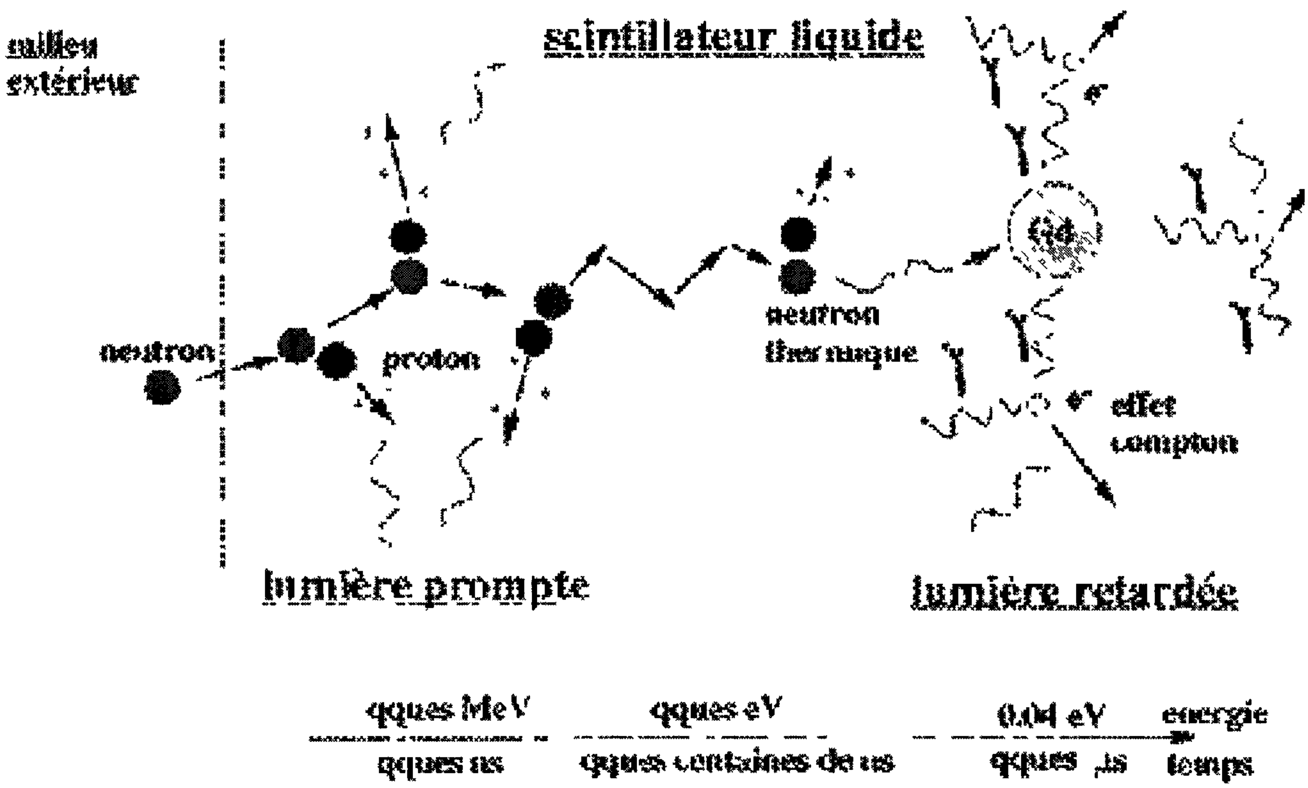
C. Varignon, PhD Thesis, Caen 2000

Neutron multiplicity distribution measurements with liquid scintillator neutron balls

NESSI (HMI-Berlin), ORION (GANIL)

Detection of low energy neutrons (below 20 MeV)

⇒ sensitivity to the amount of excitation energy at the end of the cascade stage

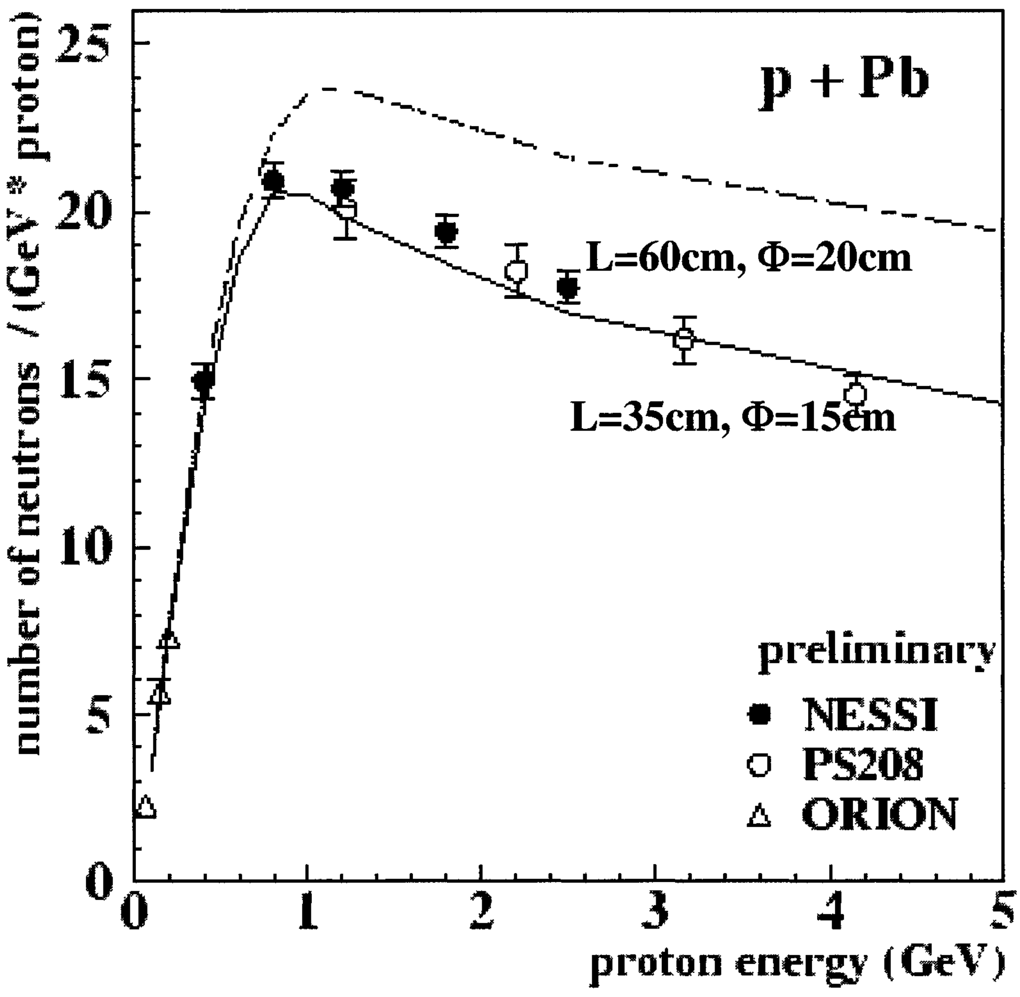


Neutron multiplicity measurements
Thick target results

collaboration NESSI (Berlin, Jülich, GANIL)

Data : Target Pb, length 35cm, diameter 15cm

Calculation: HERMES (Jülich)

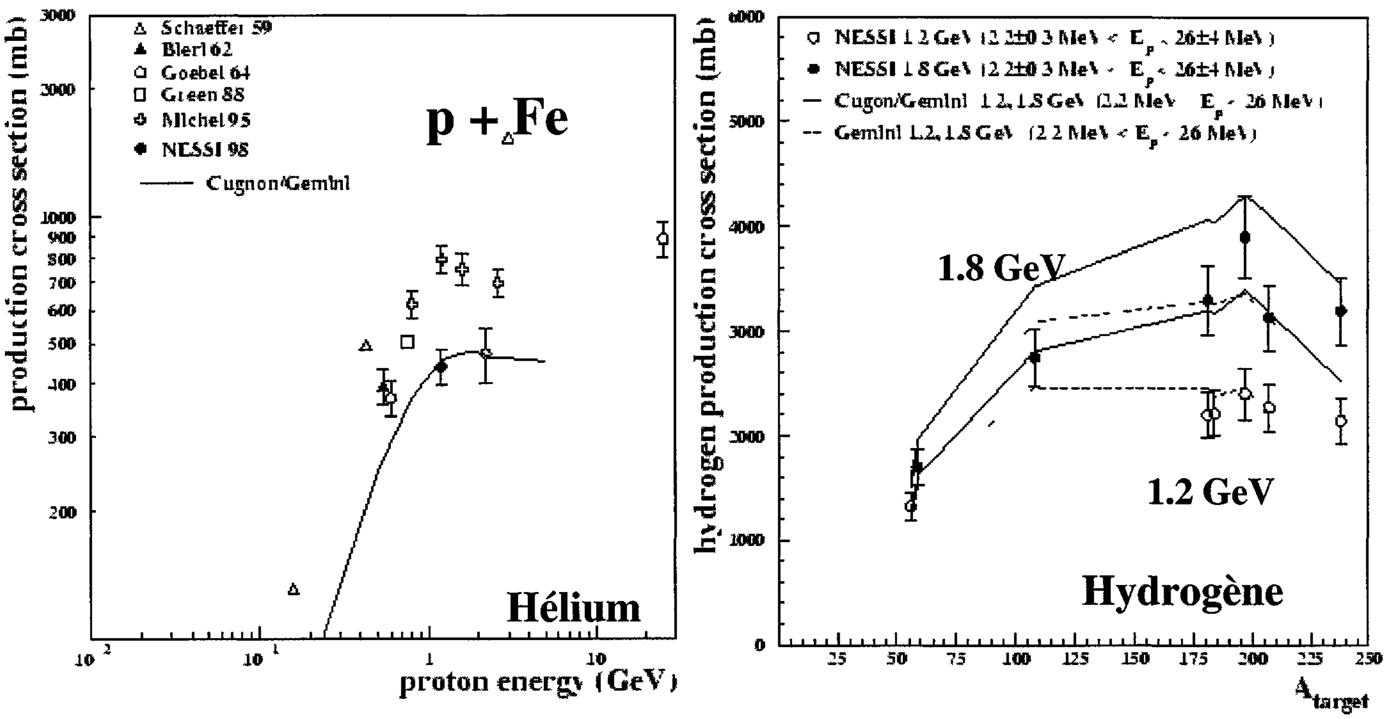


From Enke et al., 1998 Annual Report Bereich Festkörperphysik, HMI-Berlin

Measurements of hydrogen and helium production
Thin targets

collaboration NESSI (Berlin, Jülich, GANIL)

Calculations with the Cugnon model



From Enke et al., 1998 Annual Report Bereich Festkörperphysik, HMI-Berlin

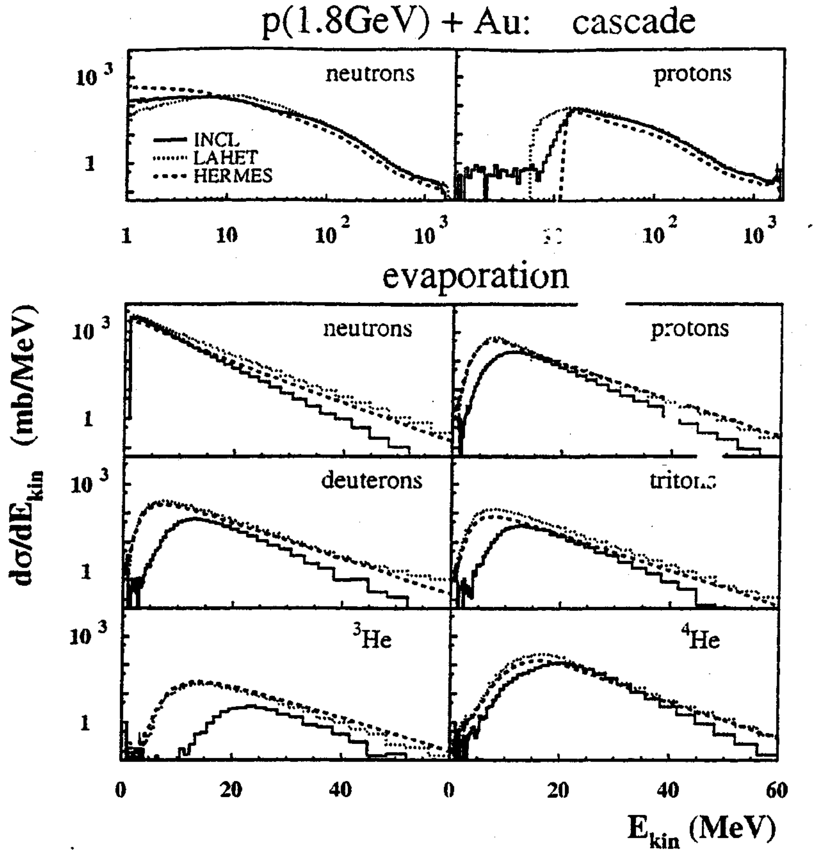


Fig. 15. Comparison of calculated particle energy spectra with the INCL (solid histogram) and LAHET-code (dotted histogram). The top two panels represent the nucleons emitted during the INC while the lower panels display the energy spectra of evaporated particles.

From Enke et al., NP A657 (1999) 317

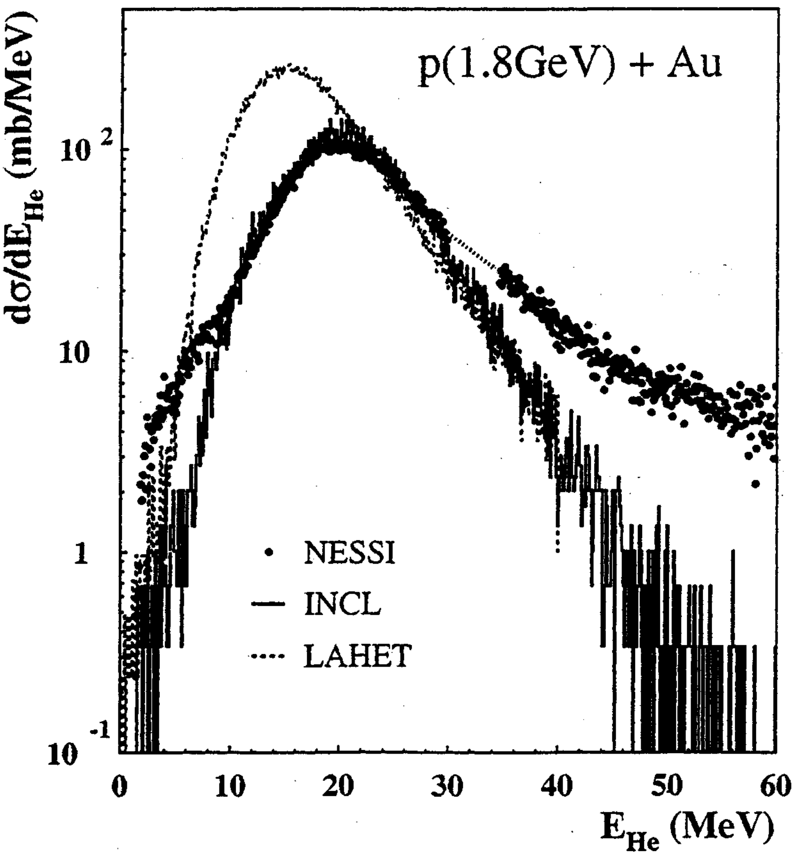
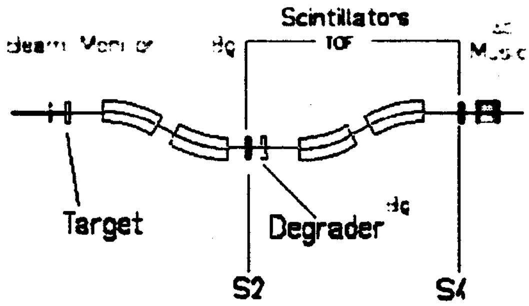


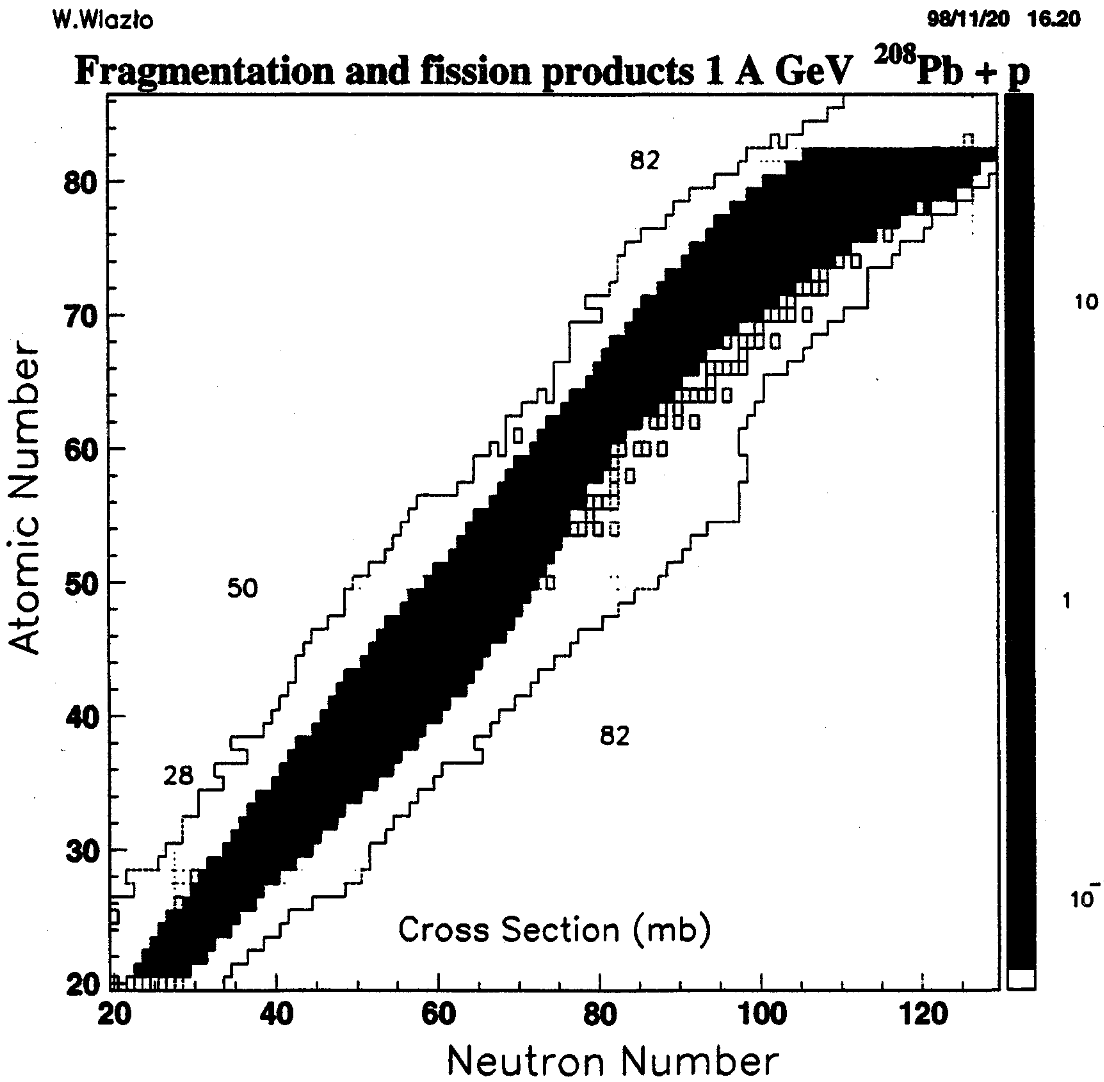
Fig. 16. Comparison of measured (solid circles) and calculated helium energy spectra with the INCL (solid histogram) and LAHET-code (dashed histogram). The experimental helium spectrum was integrated over $0 < \theta < 66^0$ and $114 < \theta < 180^0$, the **An target thickness was mg/cm^2**

RESIDUE MEASUREMENTS AT GSI

GOAL: Measurement of complete isotopic distribution of spallation residues using reverse kinematics



Collaboration: GSI Darmstadt, CEN Bordeaux, IPN Orsay, SPhN Saclay, Santiago Univ.



From W.Wlazlo et al., XXXVII Int. Winter Meeting on Nucl. Phys., Bormio, Jan. 1999, Italy

Spallation residue isotopic distribution measurements at GSI

(coll. GSI, Santiago Univ., CEA/DSM, IN2P3)

- ## Achieved experiments

➥ **Au + p 800 MeV/A**

Fragmentation: Rejmund et al., Nucl. Phys. A683 (2001) 540

Fission: Benlliure et al., Nucl. Phys. A683 (2001) 540

➥ **Pb + p 1 GeV/A**

Fragmentation : Wlazlo et al., Phys. Rev. Lett. 84 (2000) 5736

Fission: Enqvist et al., Nucl. Phys. A686 (2001) 481

➥ **Pb + d 1 GeV/A**

Enqvist et al., submitted to Nucl. Phys.

➥ **U + p, d 1 GeV/A**

fragmentation analysis completed, fission in progress

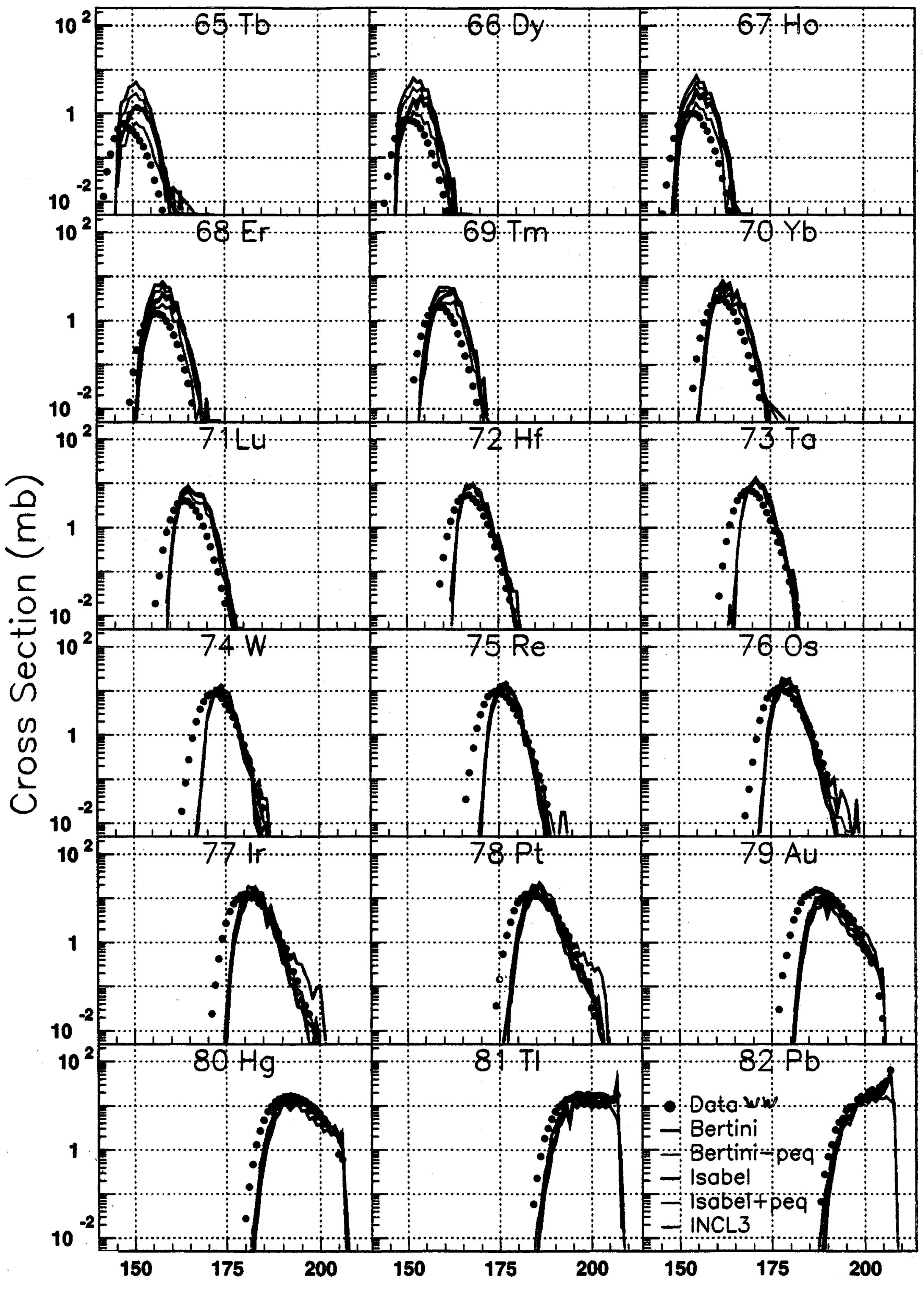
➥ **Pb + p, d 500 MeV/A**

analysis in progress

➥ **Fe + p, d several energies**

analysis in progress

1 GeV Pb+p, Dresner evapo

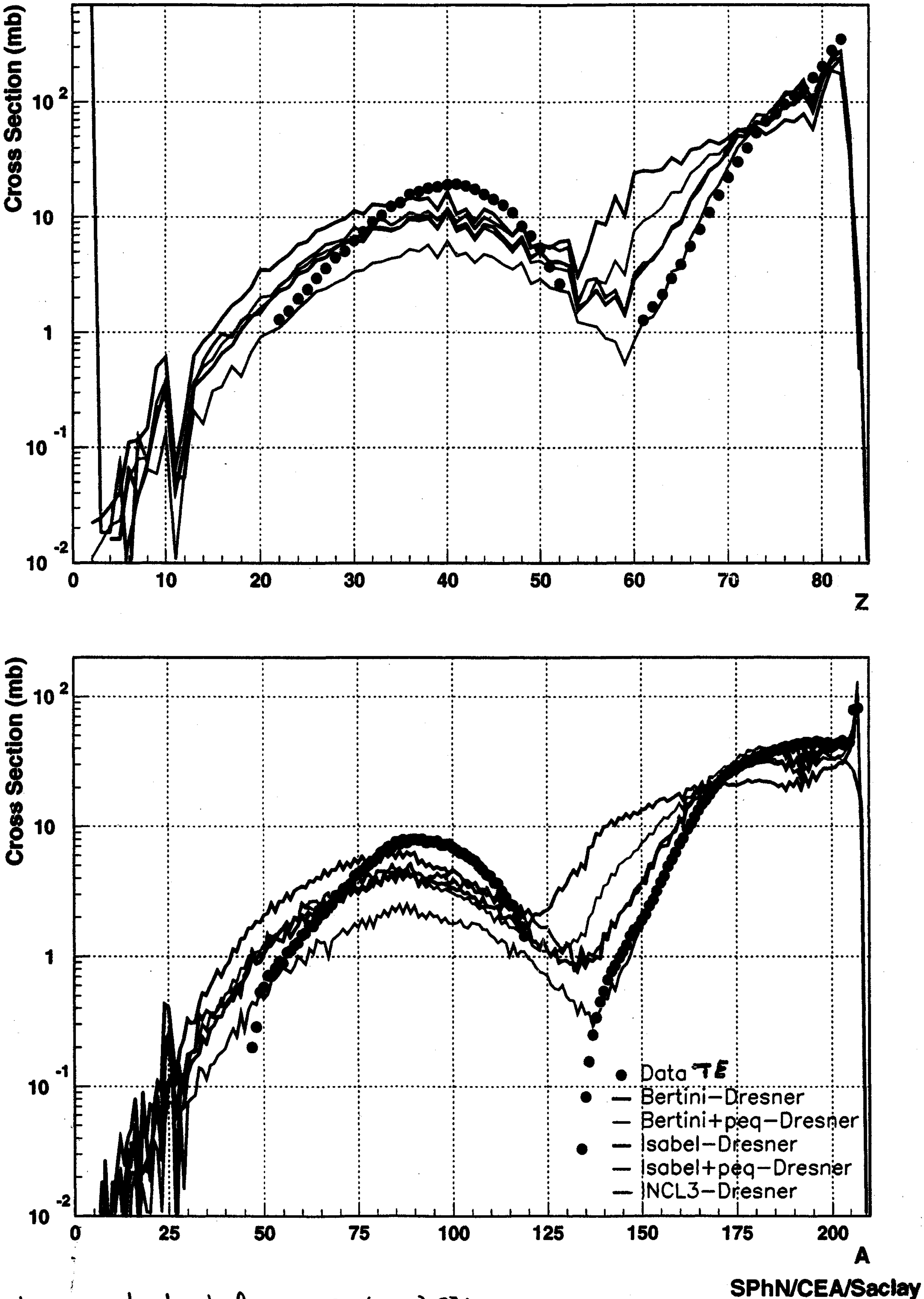


SPhN/CEA/Saclay

Data: W. Wlazlo et al., PRL 84 (2000) 5740

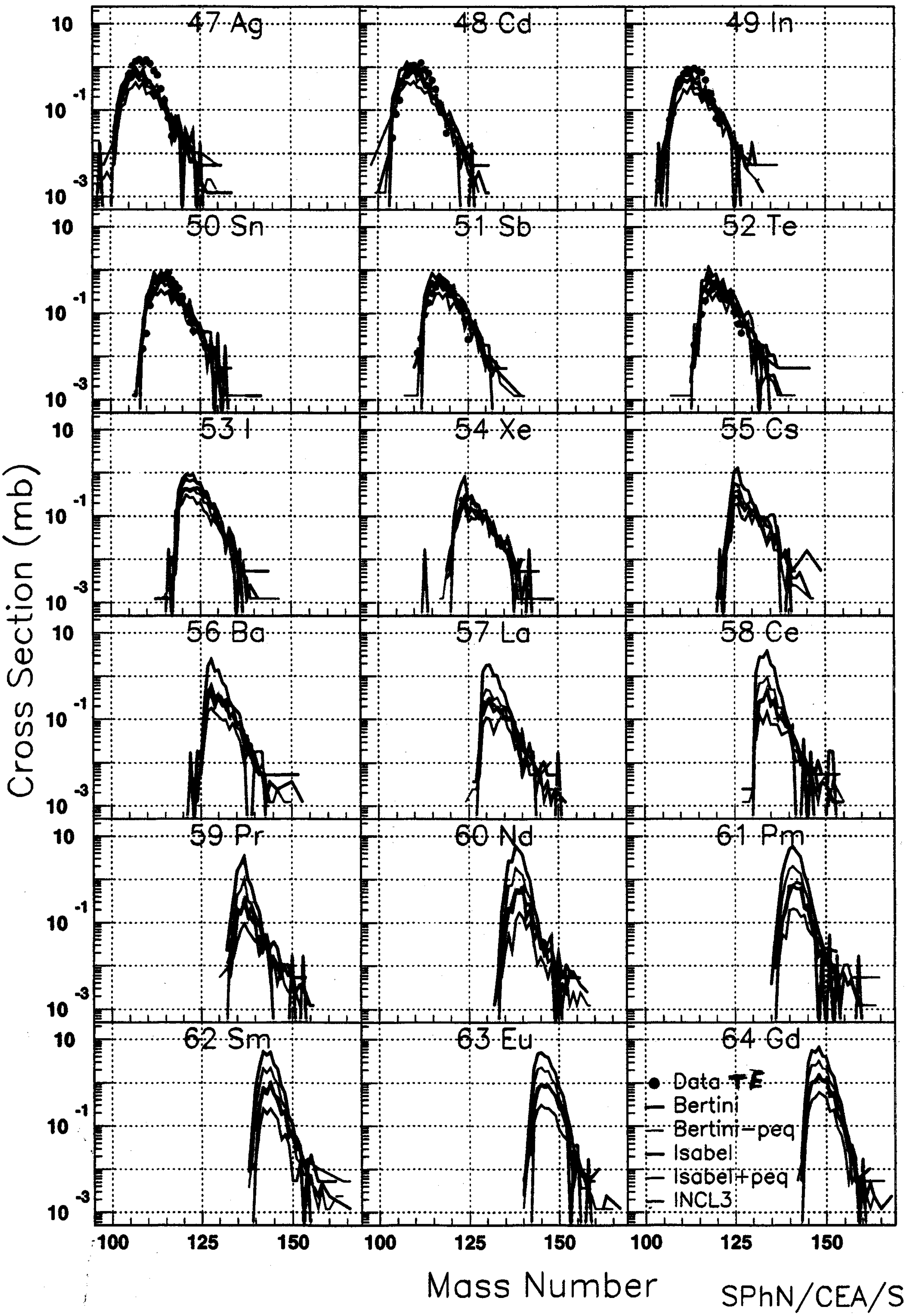
00/07/05 11.41

1 GeV Pb+p, Dresner evapo

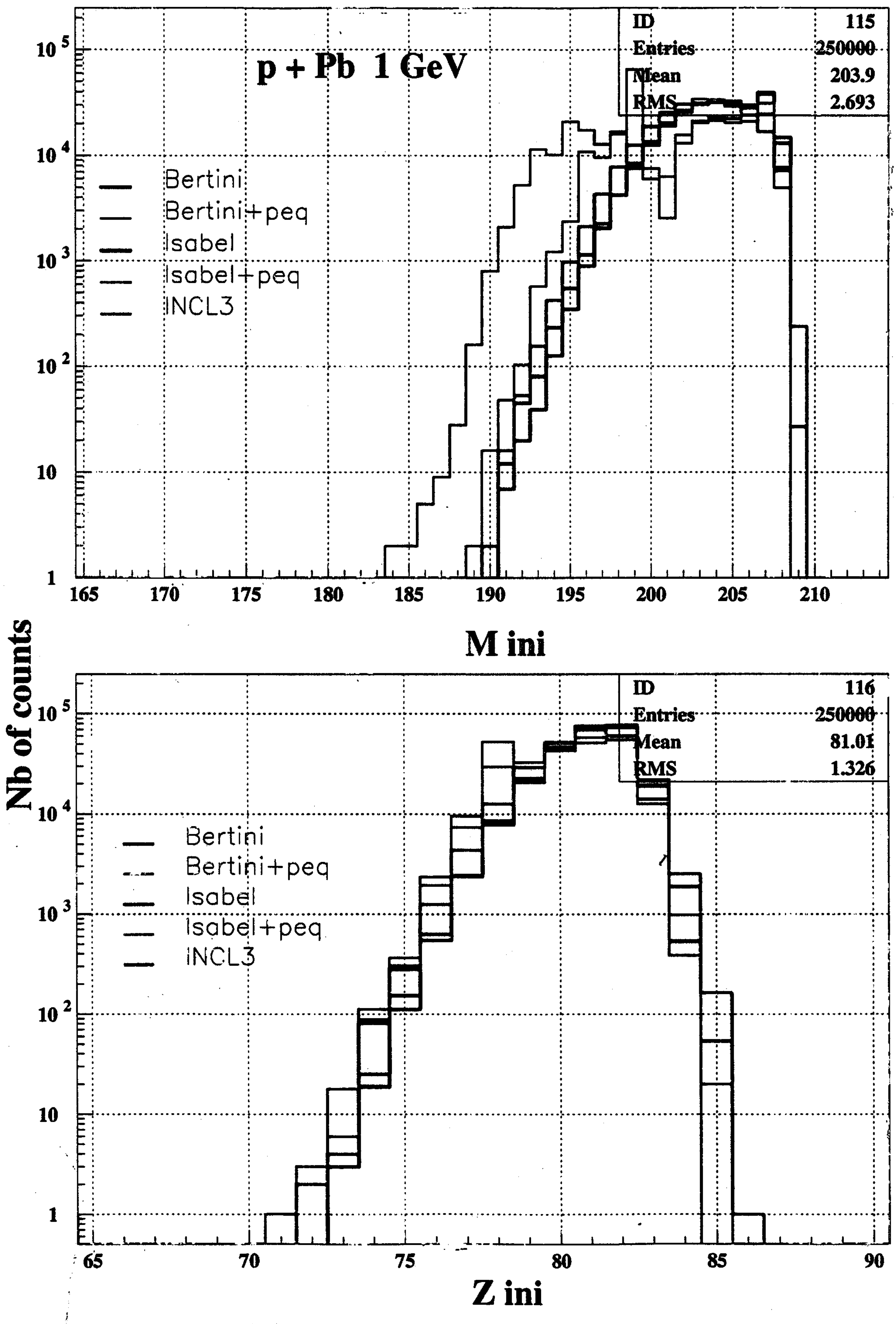


Data: W. Wlazlo et al., PRL 84 (2000) 5740
T. Enqvist et al., to appear in NP (2000)

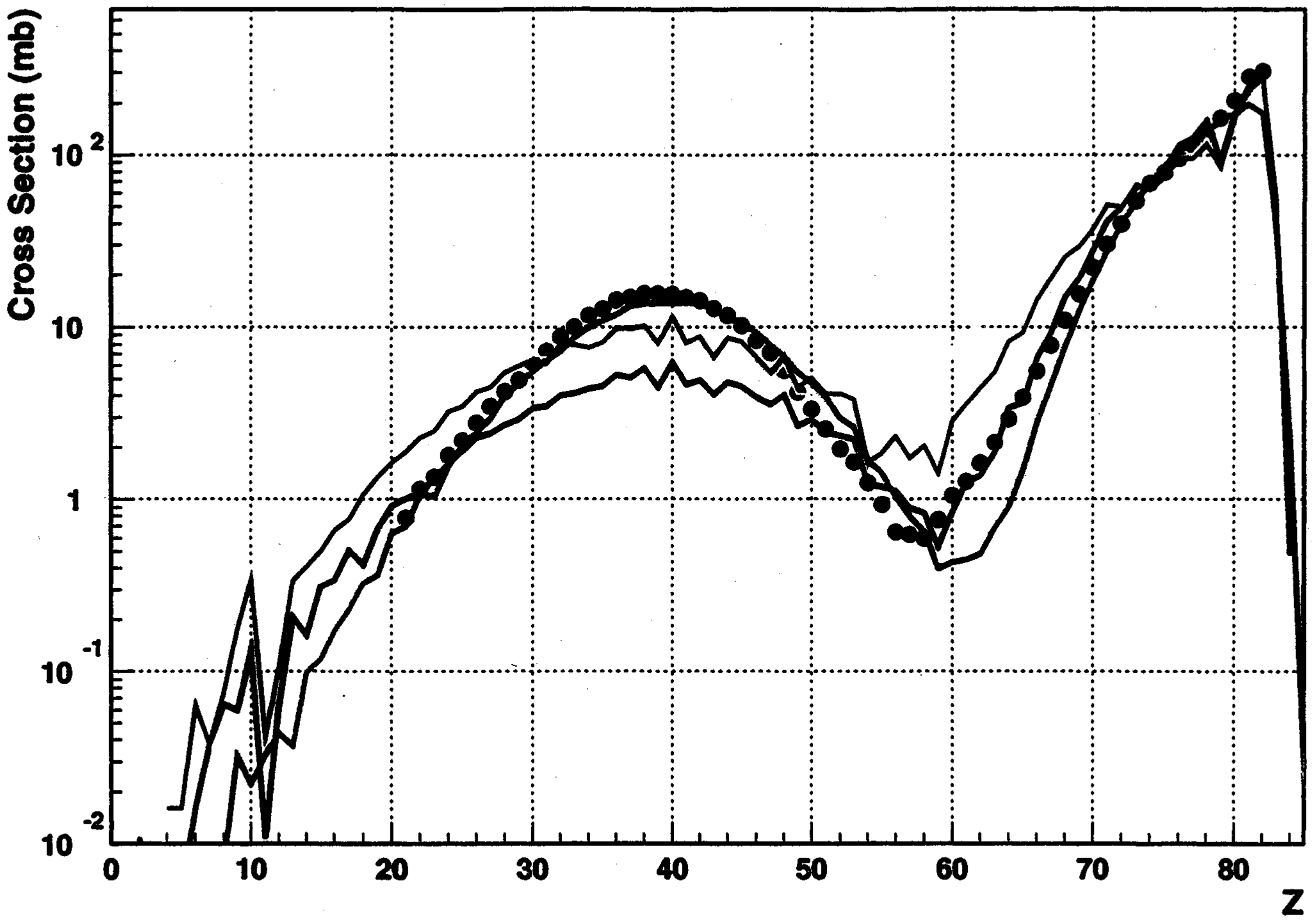
1 GeV Pb+p, Dresner evapo

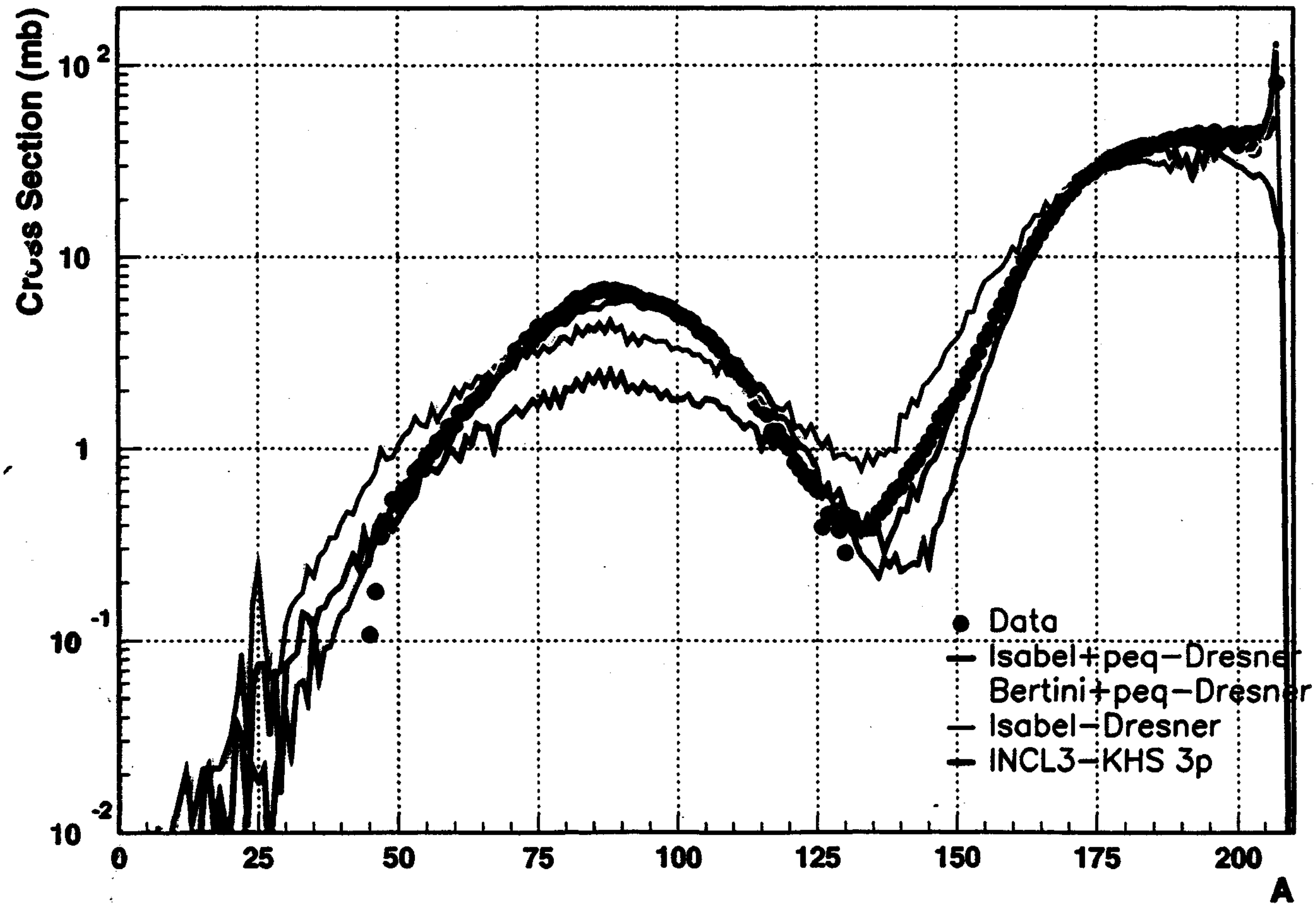


SPhN/CEA/Saclay


p + Pb 1 GeV
ID 115
Entries 250000
Mean 203.9
RMS 2.693
Bertini
Bertini+peq
Isabel
Isabel+peq
INCL3
M ini
Nb of counts
ID 116
Entries 250000
Mean 81.01
RMS 1.326
Bertini
Bertini+peq
Isabel
Isabel+peq
INCL3
Z ini

00/05/10 17.26



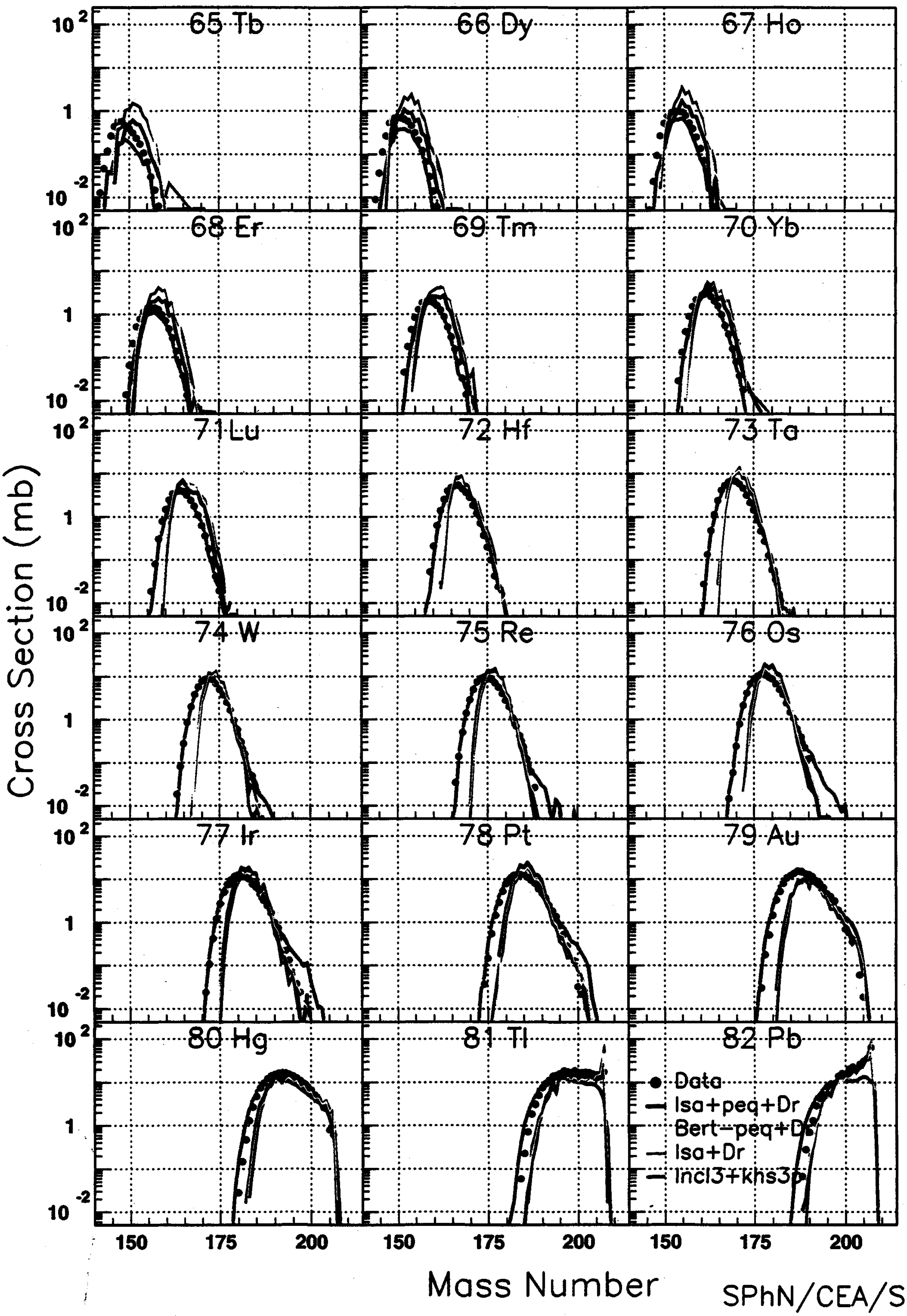


SPhN/CEA/Saclay

27

00/05/22 15.44

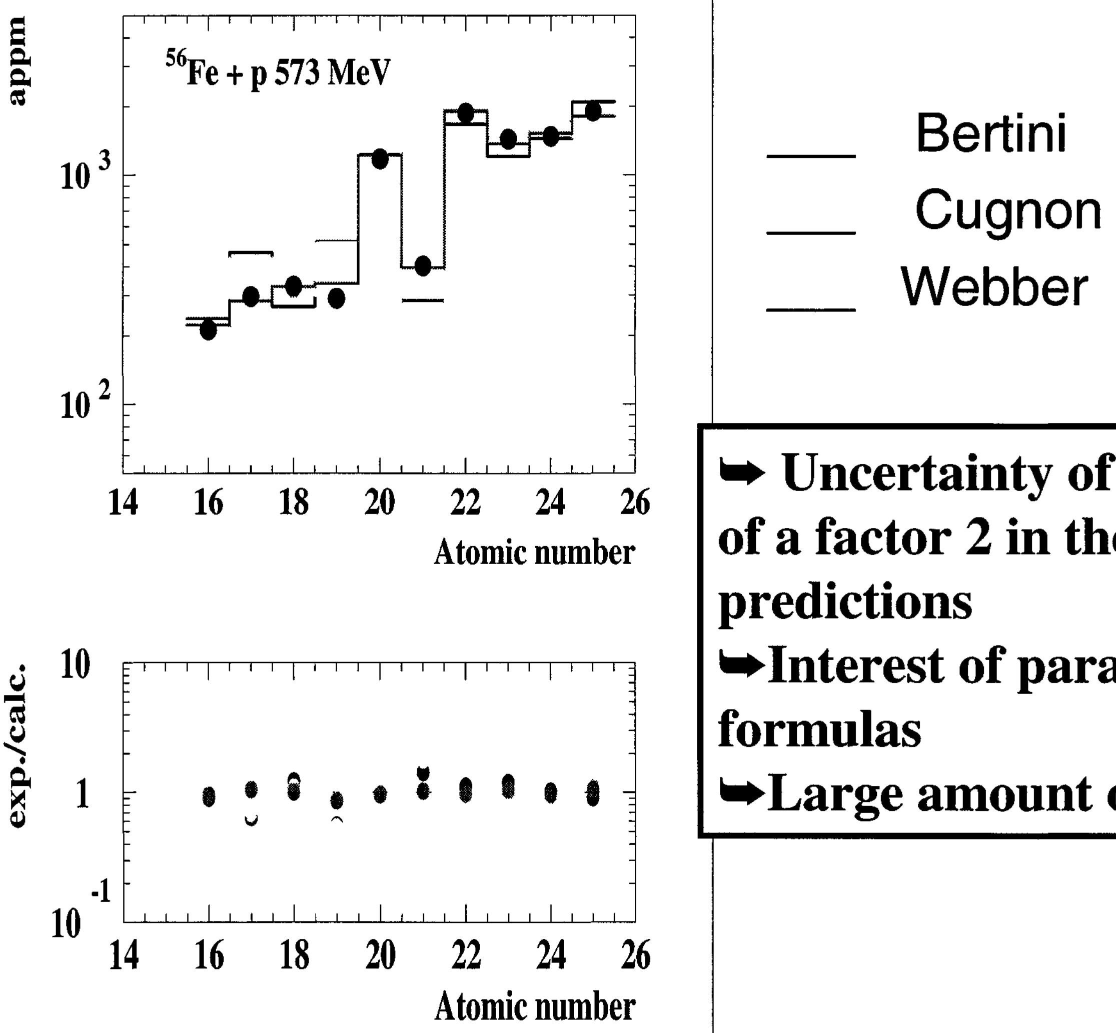
1 GeV Pb+p, Incl3+khs3p (V=45MeV, t0), LAHET-Bertini/Isabel



SPhN/CEA/Saclay

Impurety production in a Fe window

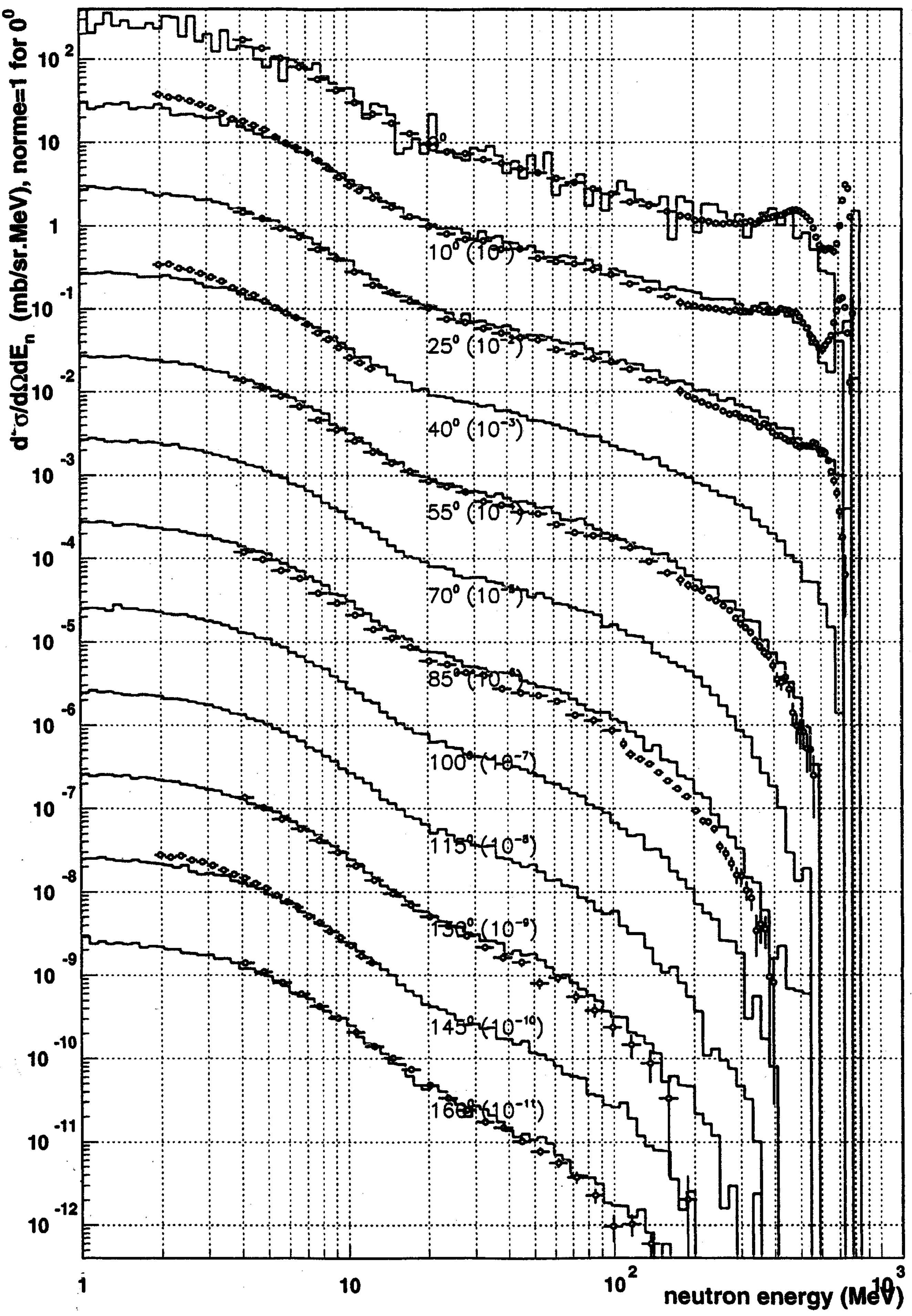
Data : Webber et al., Ap. J. 508 (1998) 940
Calculation: TIERCE, p + Fe, 77 μA/cm², 573 MeV, 1 year



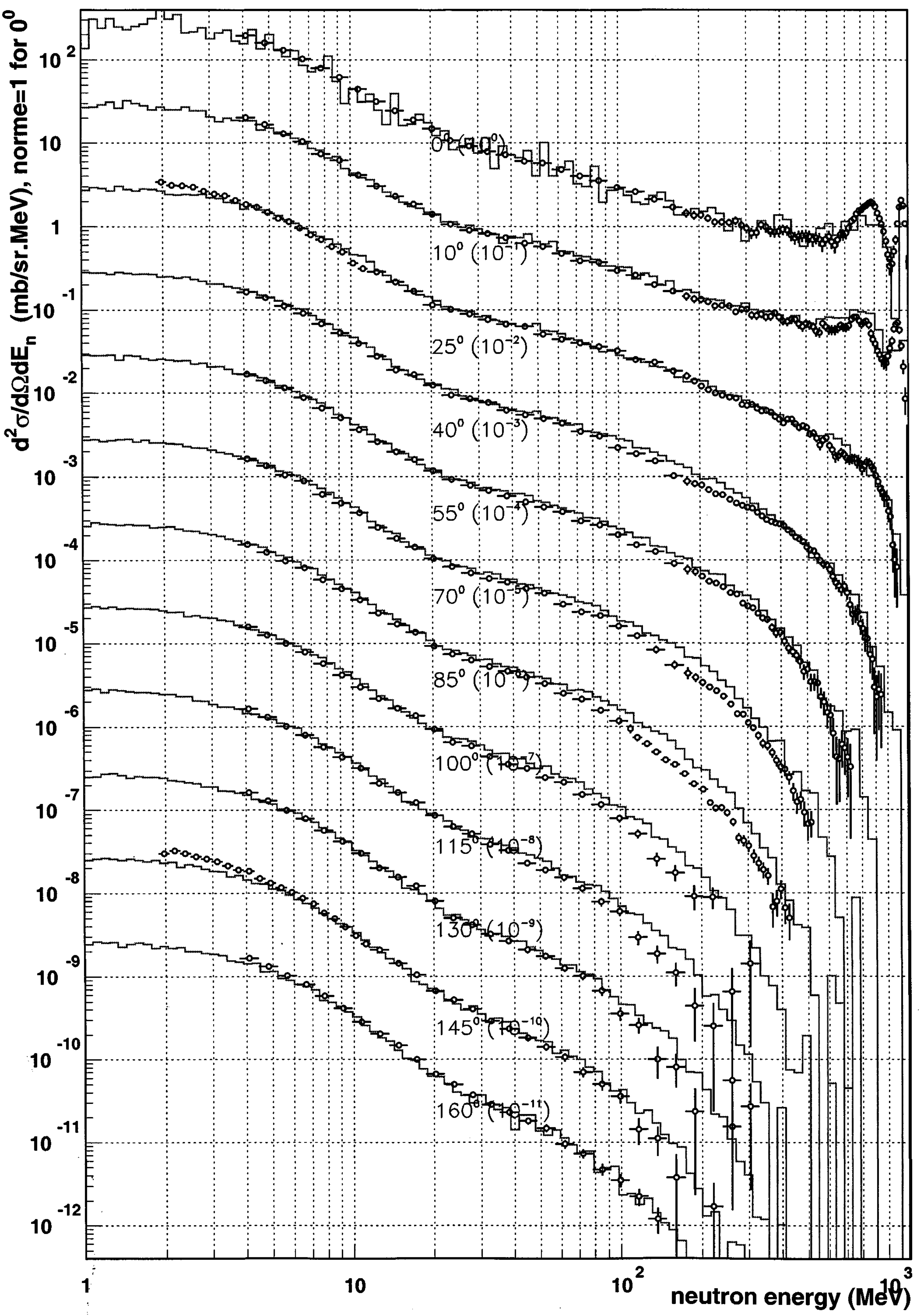
- ➥ **Uncertainty of the order of a factor 2 in the model predictions**
- ➥**Interest of parametric formulas**
- ➥**Large amount of S, Ca**

29

800 MeV p+Pb, INCL4 + KHSV3p

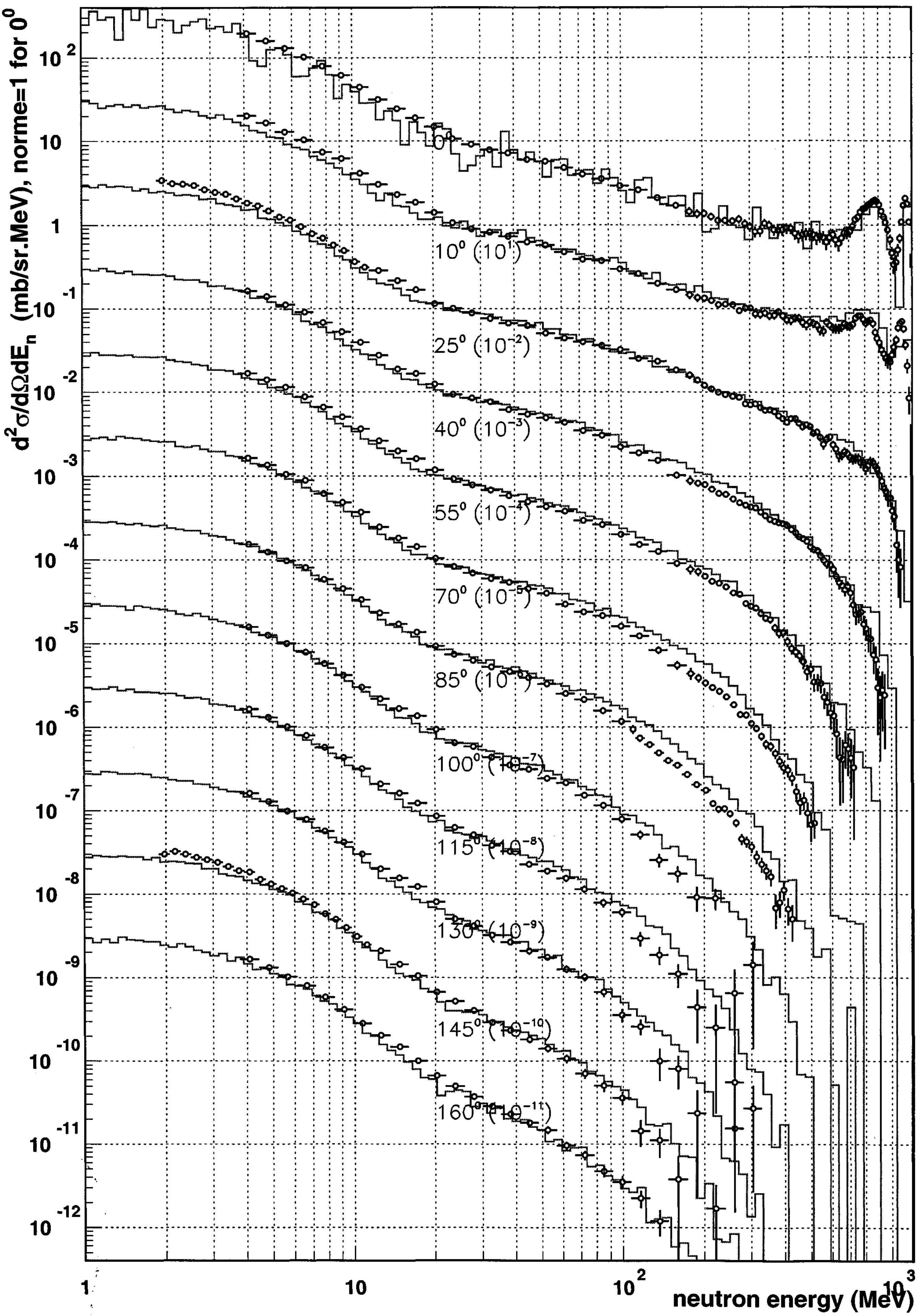


1200 MeV p+Pb, INCL4 + KHSV3p



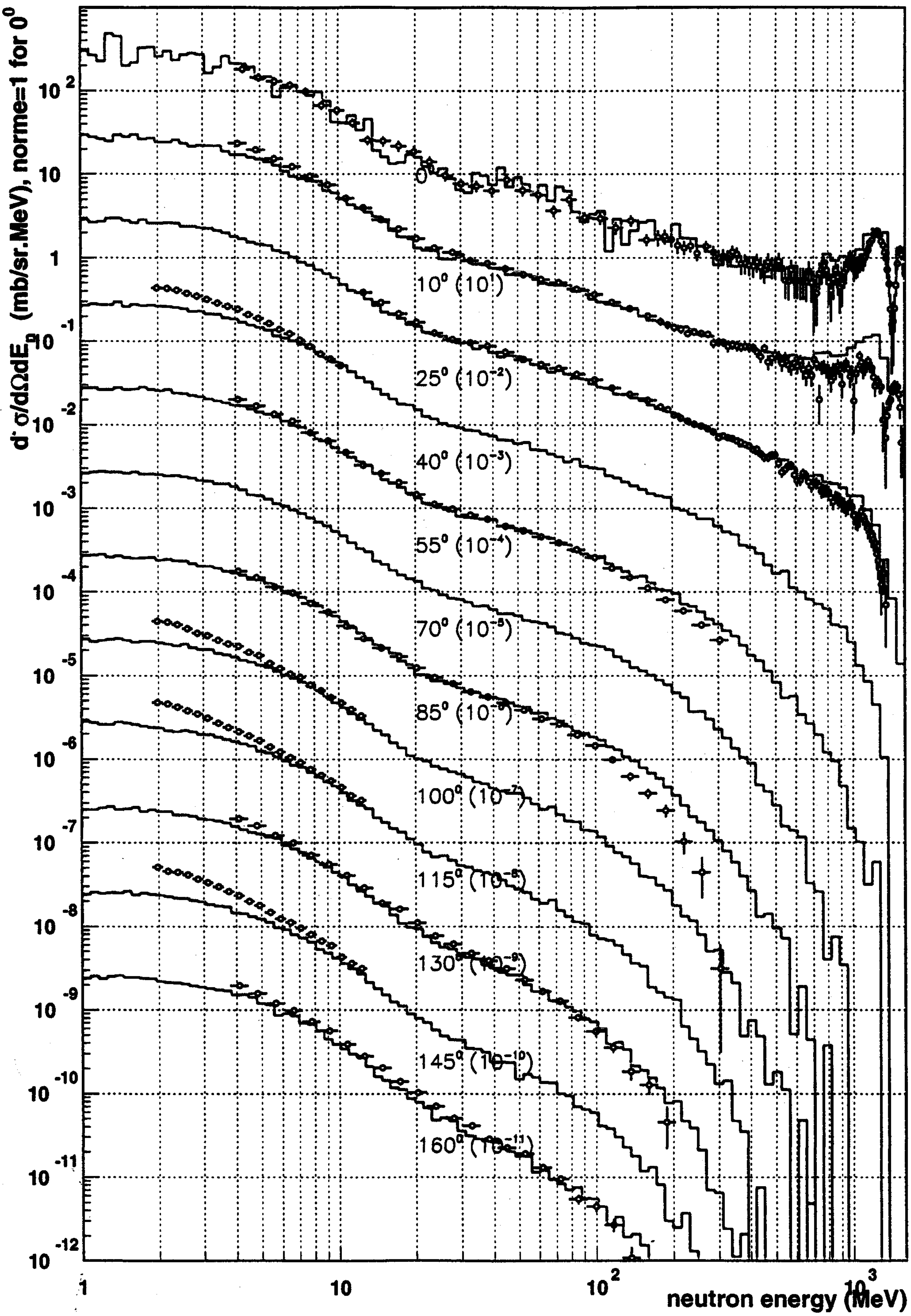
2001/07/16 13.16

1200 MeV p+Pb, INCL4 + Dresner

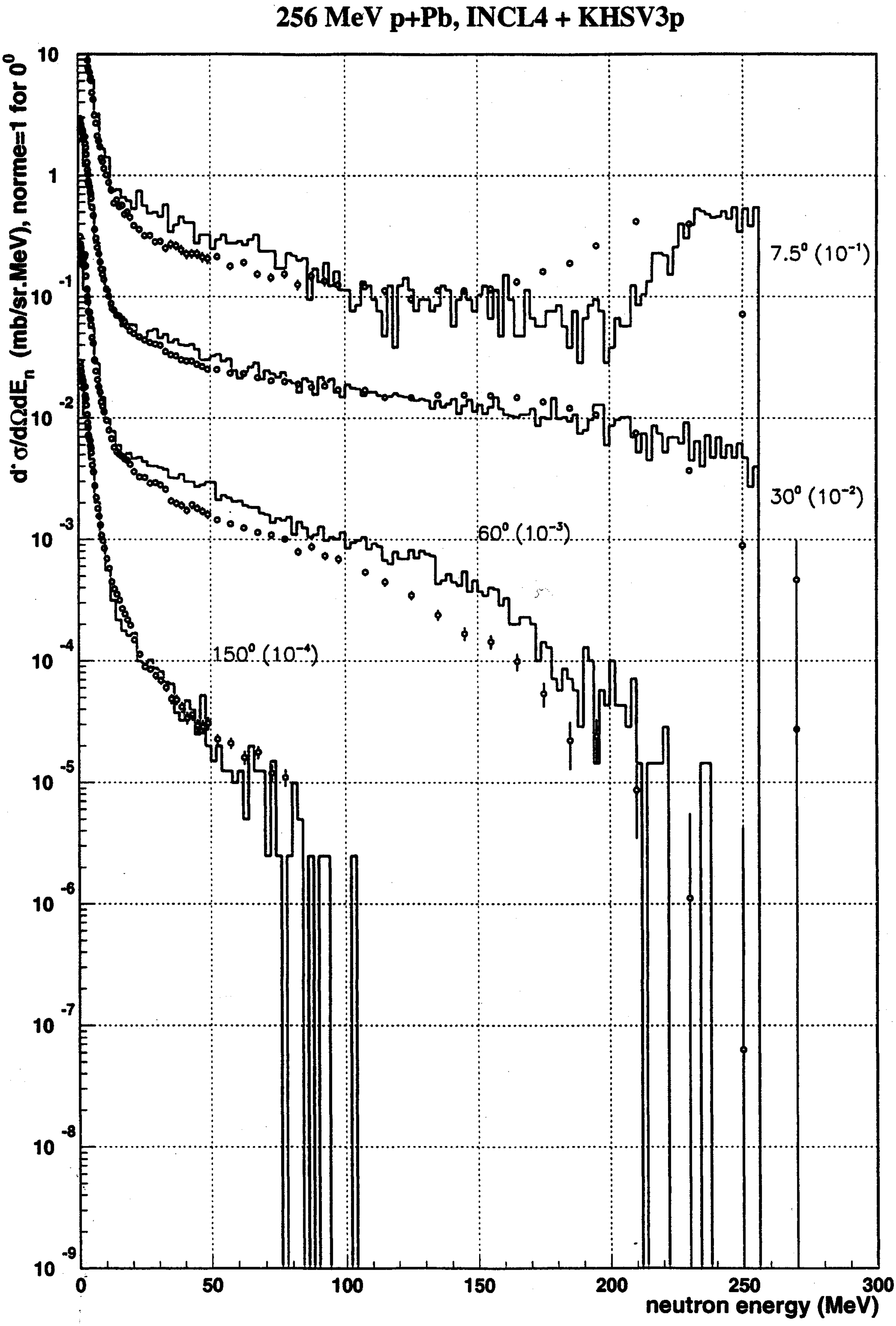


2001/07/11 13.25

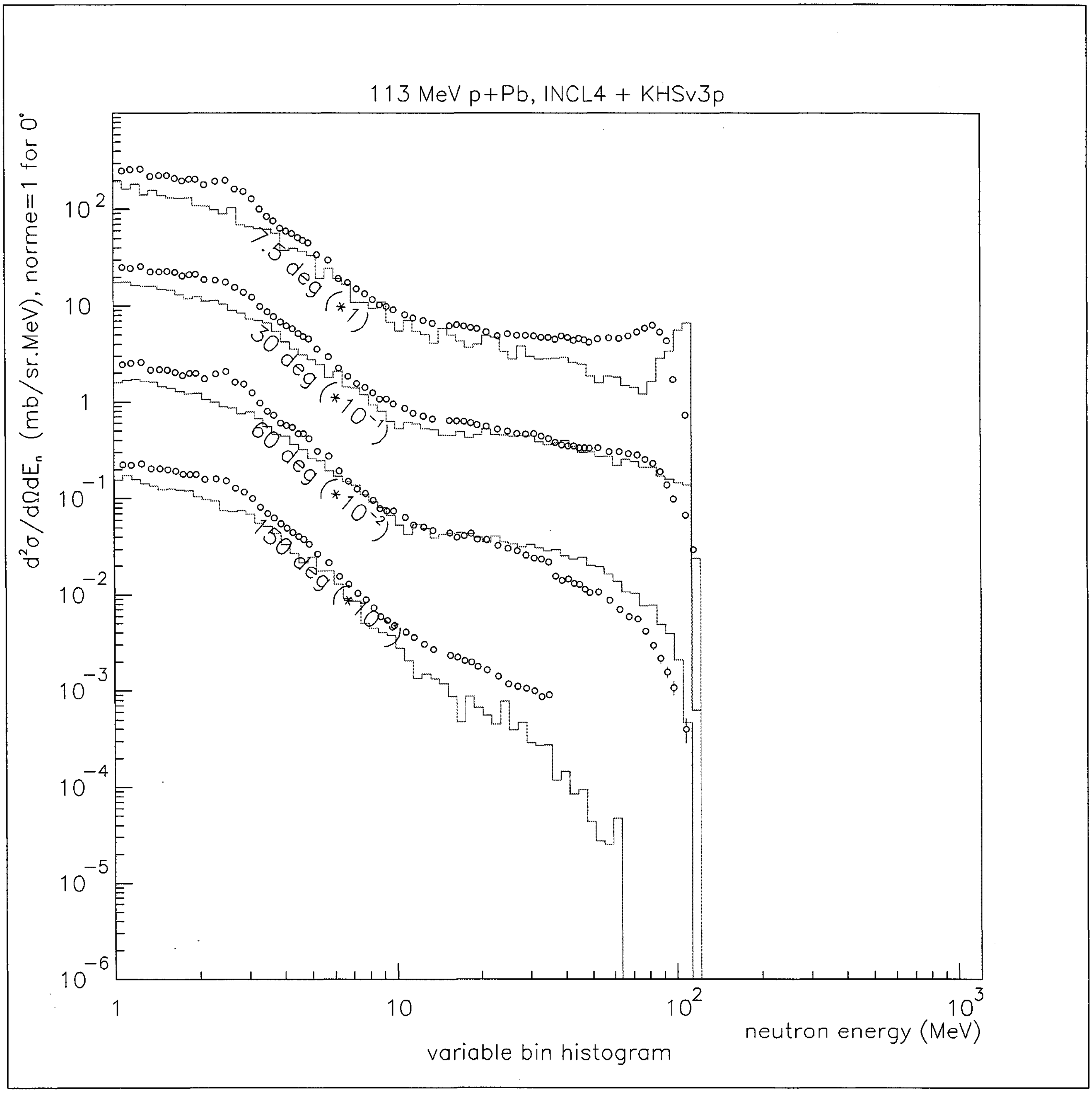
1600 MeV p+Pb, INCL4 + KHSV3p



2001/07/11 14.02



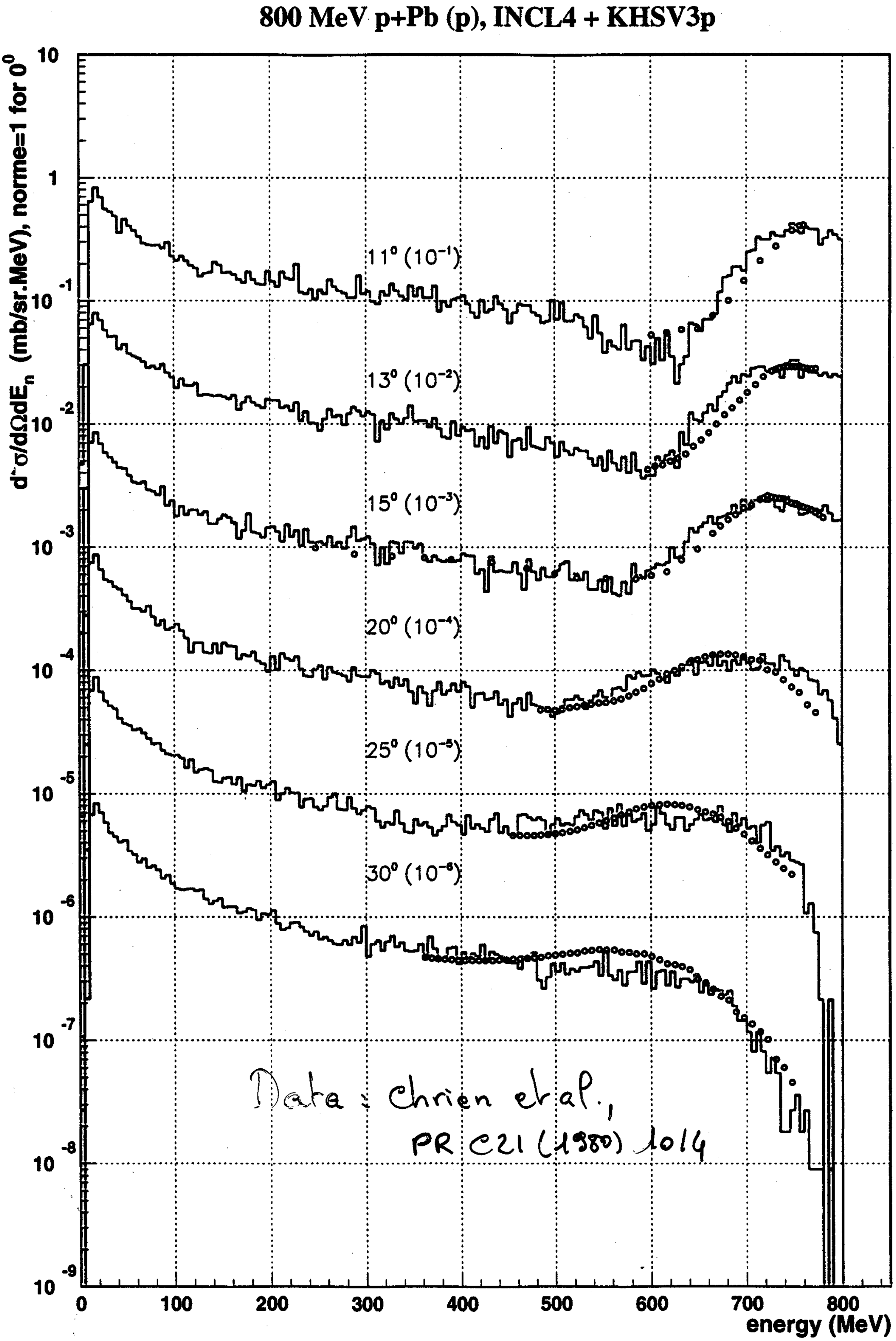
34



113 MeV p+Pb, INCL4 + KHSv3p
d²σ/dΩdEₙ (mb/sr.MeV), norme=1 for 0°
7.5 deg (*1)
30 deg (*10⁻¹)
60 deg (*10⁻²)
150 deg (*10⁻³)
neutron energy (MeV)
variable bin histogram

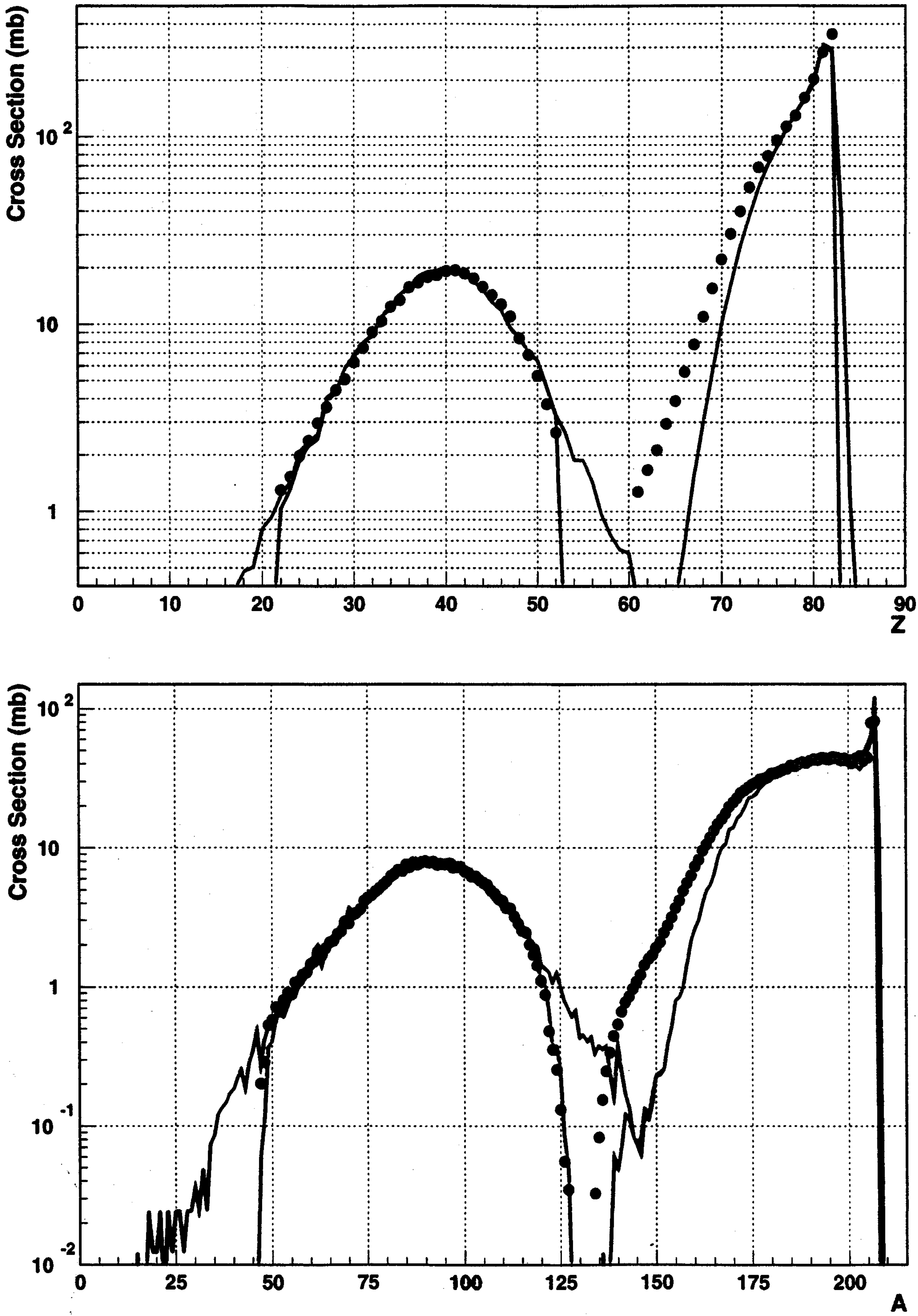
proton production

2001/07/10 16.45

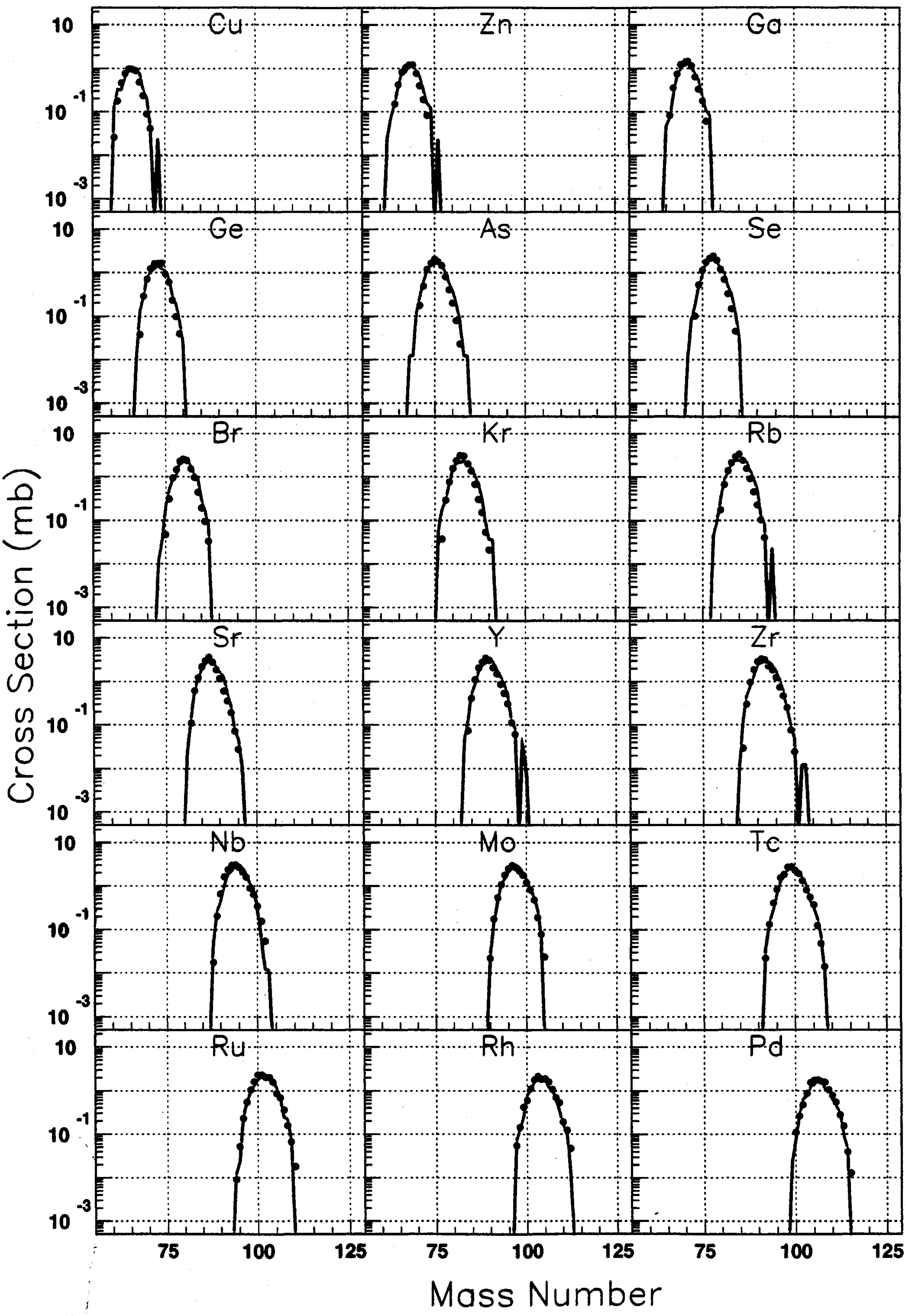


2001/07/10 09.36

1GeV Pb+p, cugn4 + KHS_V3p

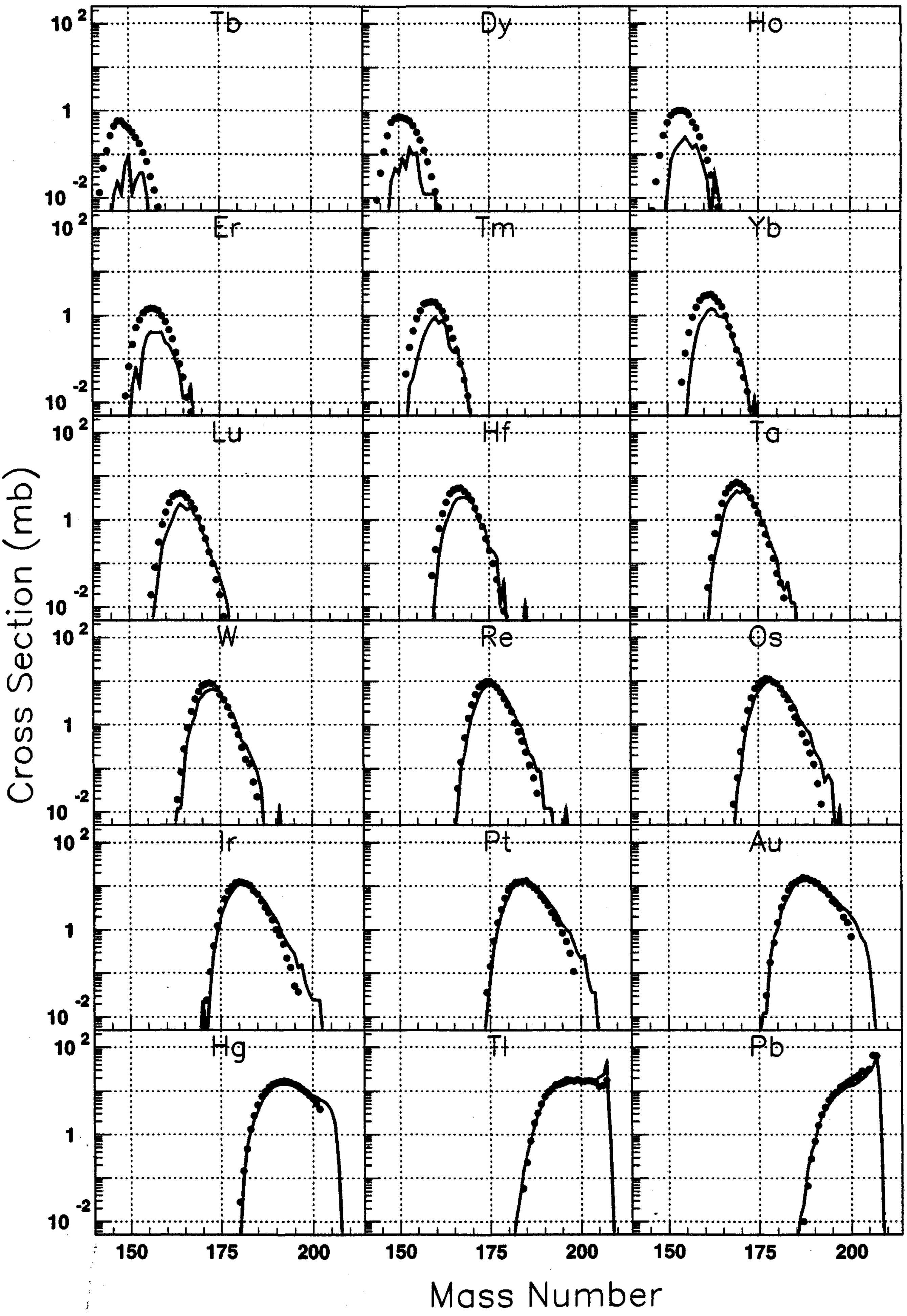


1GeV Pb+p, cugn4 + KHS_V3p



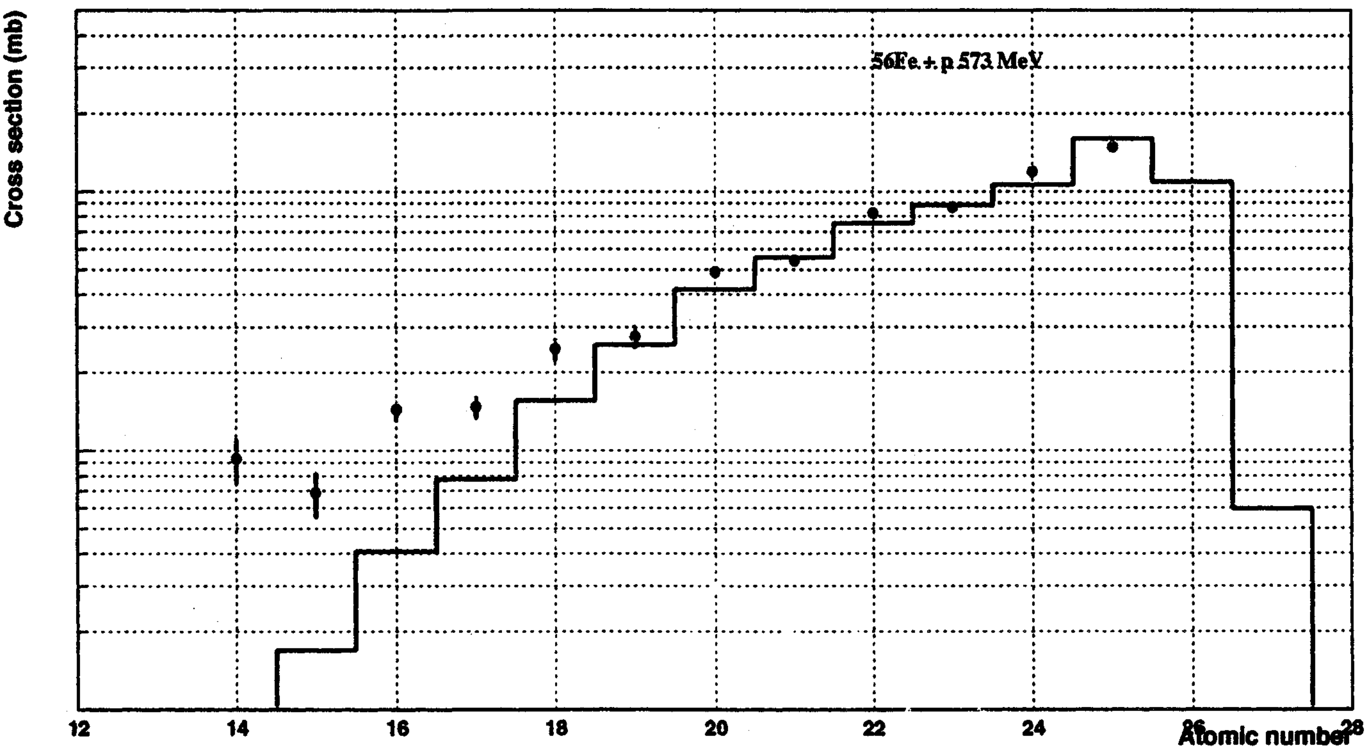
2001/07/10 09.36

1GeV Pb+p, cugn4 + KHS_V3p



39

573 MeV p+Fe INCL4 + KHSv3p



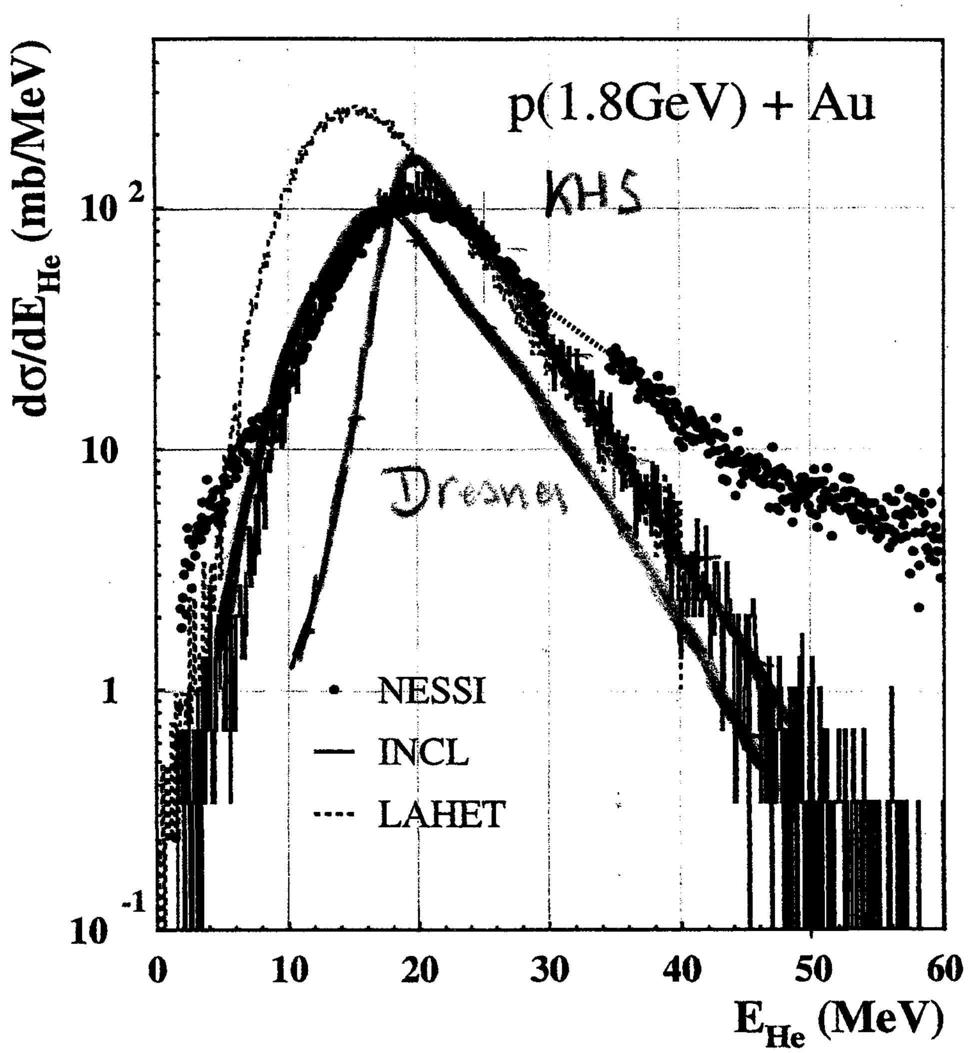


Fig. 16. Comparison of measured (solid circles) and calculated helium energy spectra with the INCL (solid histogram) and LAHET-code (dashed histogram). The experimental helium spectrum was integrated over $0 < \theta < 66^0$ and $114 < \theta < 180^0$, the Au target thickness was 8.7 mg/cm^2.

show large deviations in particular for heavy nuclei. We associate this discrepancy with (i) the mean excitation energy residing in the nuclei after the INC and (ii) different employed Coulomb barriers in the evaporation codes. Due to low statistics it was not possible in the present work to perform a detailed study of the various isotope ratios -frequently exploited as thermometers- as a function of dissipated excitation energies which, however, will be a challenge for future exclusive experiments.

5 Acknowledgments

Conclusions

- Large set of available high-energy data allowing the testing of nuclear models
- INC models
  - ➥ The widely used Bertini model ruled out (lead to too high excitation energies)
  - ➥ Isabel and Cugnon models seem to agree quite well with the data
  - ➥ Encouraging behaviour of the INCL4 version
- De-excitation models
  - ➥ Dresner-Atchison unable to reproduce isotopic distributions, fission, LCP emission
  - ➥ GSI model better for residues but deficiencies for LCP emission
- Perspectives
  - ➥ Improvements still needed to have a model reproducing all the bulk of data
  - ➥ Coincidence experiments will allow a deeper insight into the reactions mechanisms