Experimental cross sections and velocities of the light nuclides produced in the proton-induced fission of ^{238}U at 1 GeV

M. VALENTINA RICCIARDI[1]

K. -H. SCHMIDT[1], F. REJMUND[1], T. ENQVIST[1], P. ARMBRUSTER[1],
J. BENLLIURE[2],
M. BERNAS[3], B. MUSTAPHA[3], L. TASSAN-GOT[3],
C. STEPHAN[4], A. BOUDARD[4], S. LERAY[4], C. VOLANT[4],
S. CZAJKOWSKI[5], M. PRAVIKOFF[5]

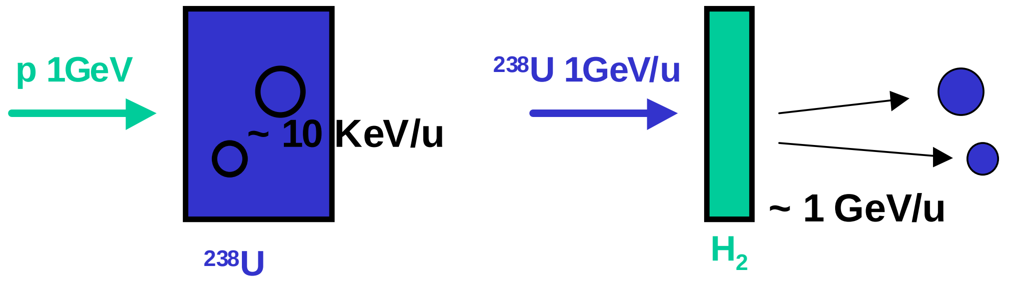
1 — GSI Darmstadt, Germany
2 — Universidad de Santiago de Compostela, Spain
3 — IPN Orsay, France
4 — DAPNIA / SPhN CEA /Saclay, France
5 — CEN Bordeaux, France

PART I:

EXPERIMENT AND RESULTS

THE EXPERIMENT: 1 A·GeV $^{238}U \rightarrow p$

direct kinematics **inverse kinematics**



Advantages of the inverse kinematics:

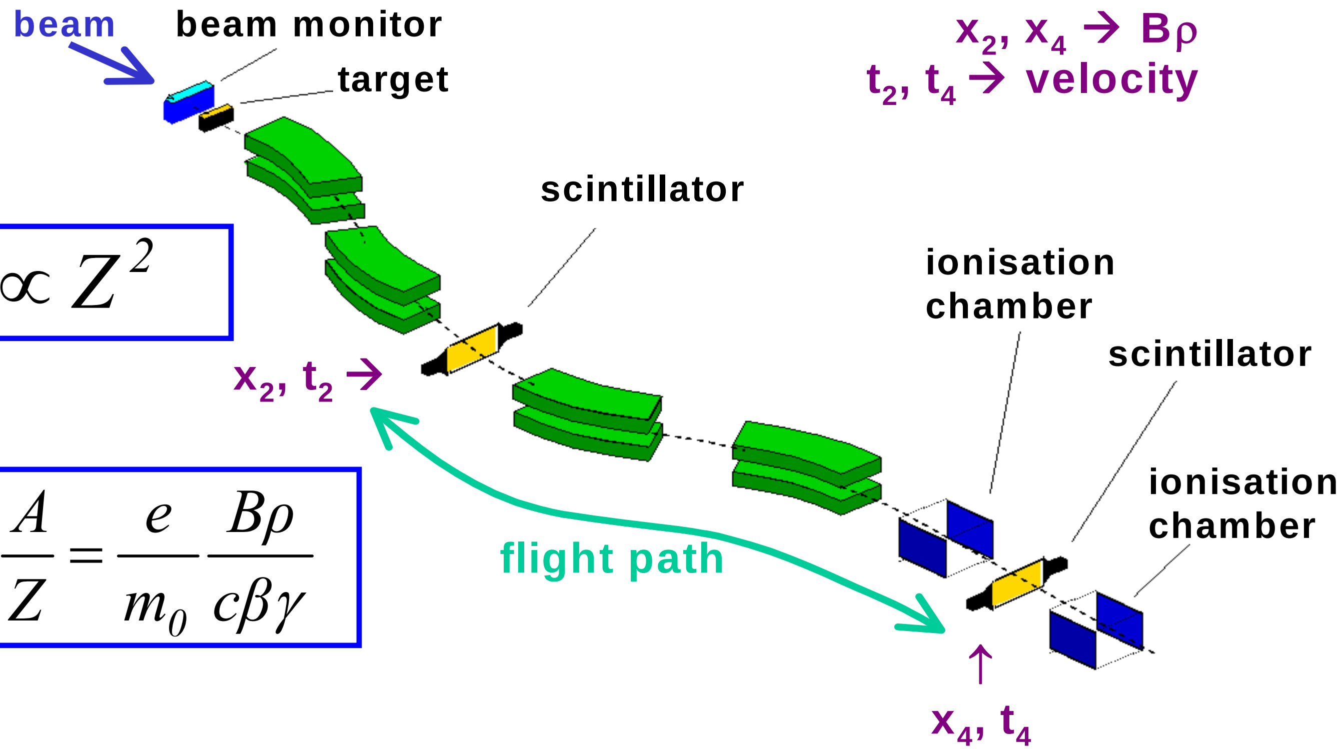
- complete identification
- knowledge of the kinematics

Disadvantage:

- I need a H_2 target

Background experiment ^{238}U on Ti

THE FRS AT GSI AND THE EXPERIMENTAL SET-UP for LIGHT RESIDUES



Z from IC: $\Delta E \propto Z^2$

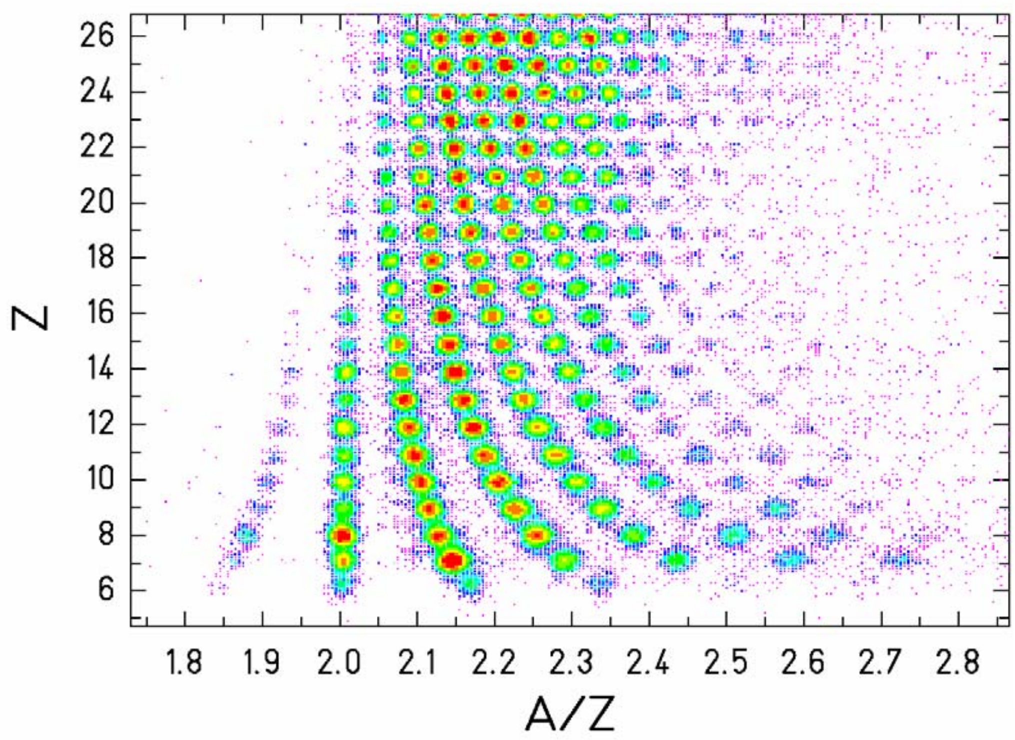
A/Z from time and position: $\frac{A}{Z} = \frac{e}{m_0} \frac{B\rho}{c\beta\gamma}$

Once mass and charge are identified (A, Z are integer numbers) the velocity is calculated from Bρ:

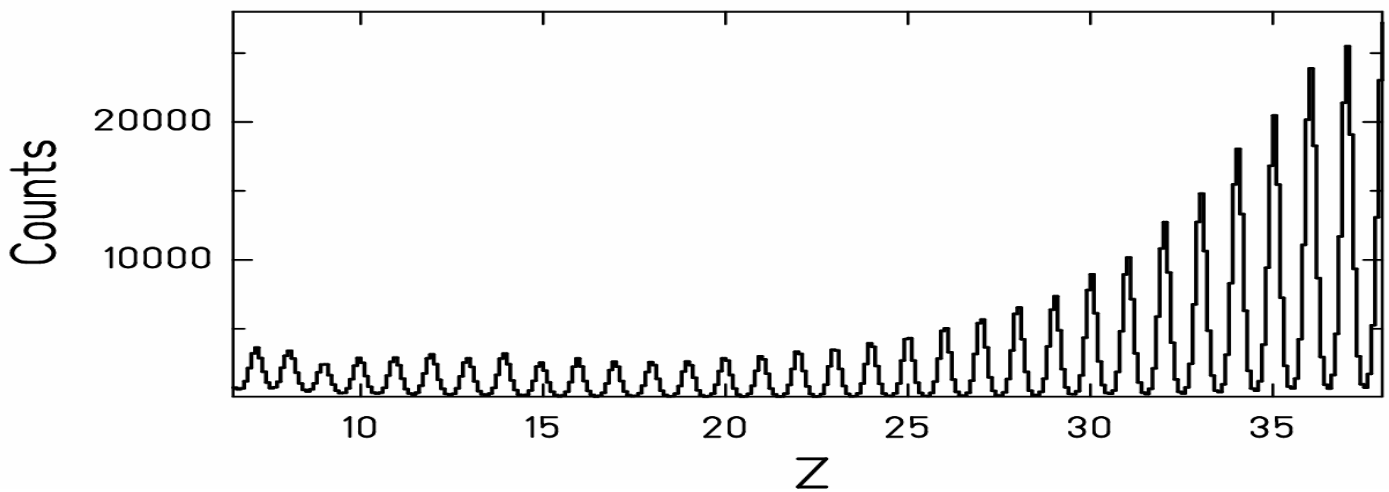
$$\beta\gamma c = \frac{e}{m_0} \cdot \frac{A}{Z} \cdot B\rho$$

very precise evaluation!

RESOLUTION

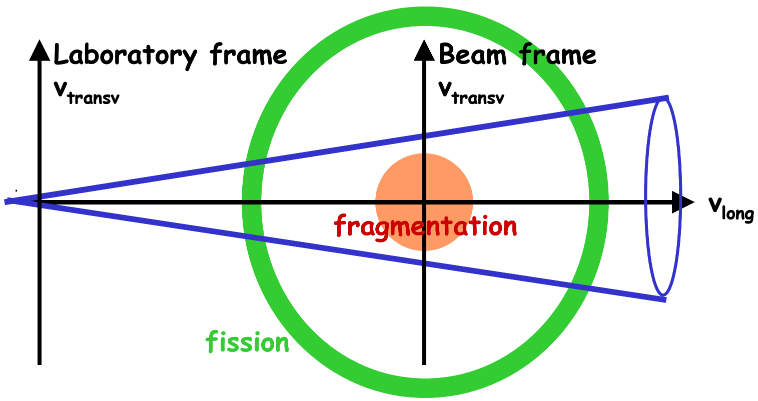


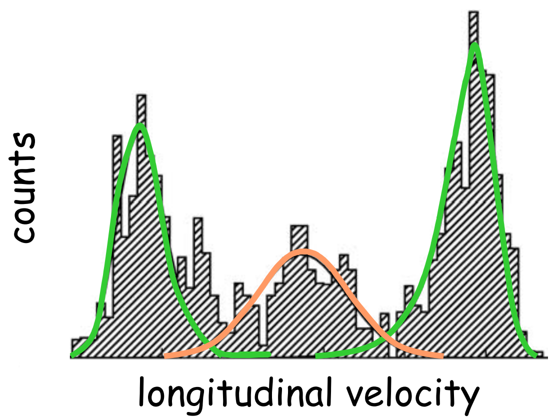
Z
A/Z
6
8
10
12
14
16
18
20
22
24
26
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8

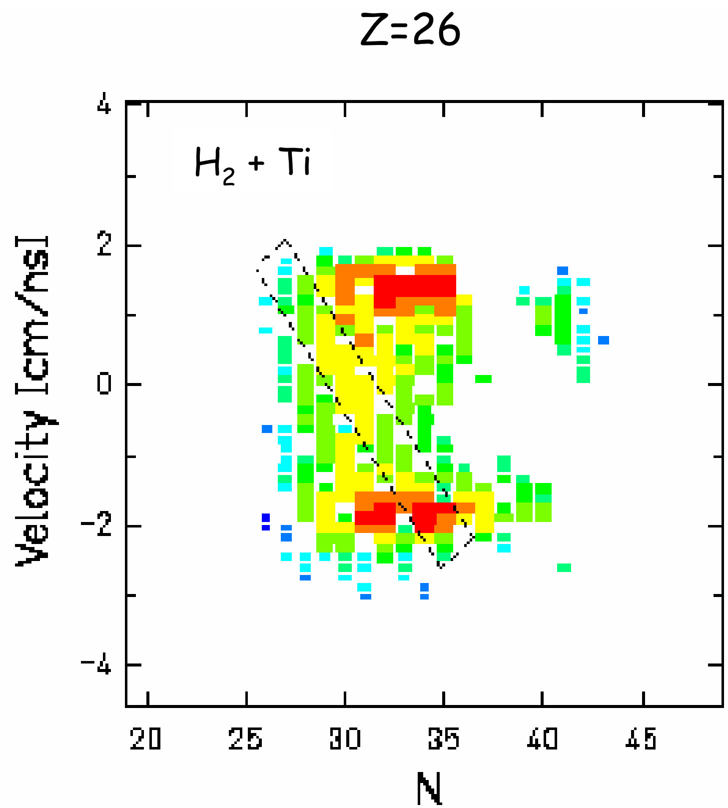


Counts
Z
10000
20000
10
15
20
25
30
35

DISCRIMINATION OF FISSION EVENTS

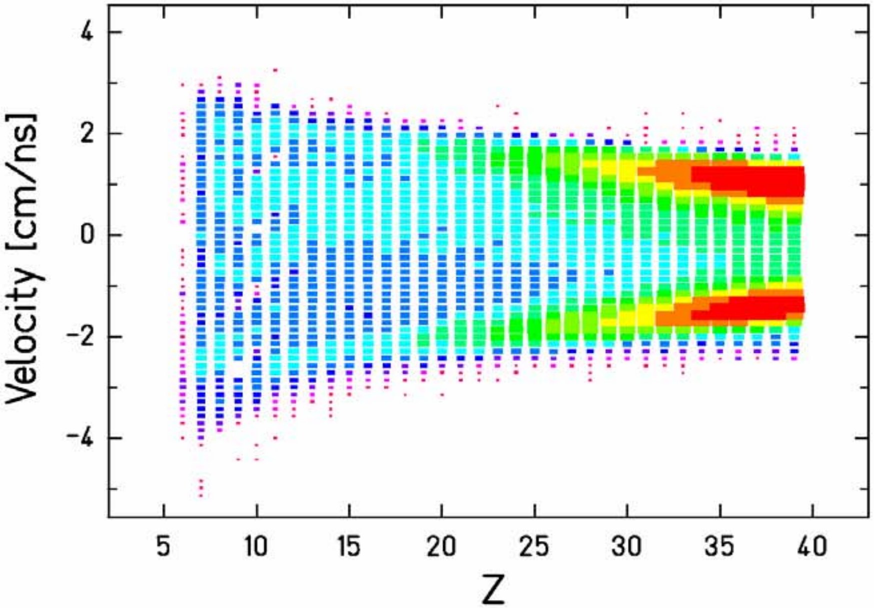




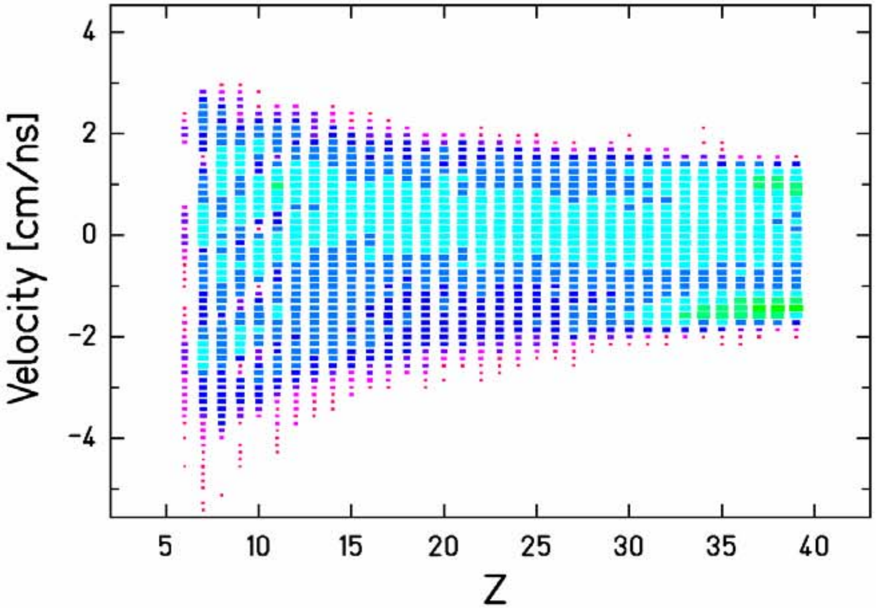


VELOCITY OF ALL RESIDUES

hydrogen+titanium

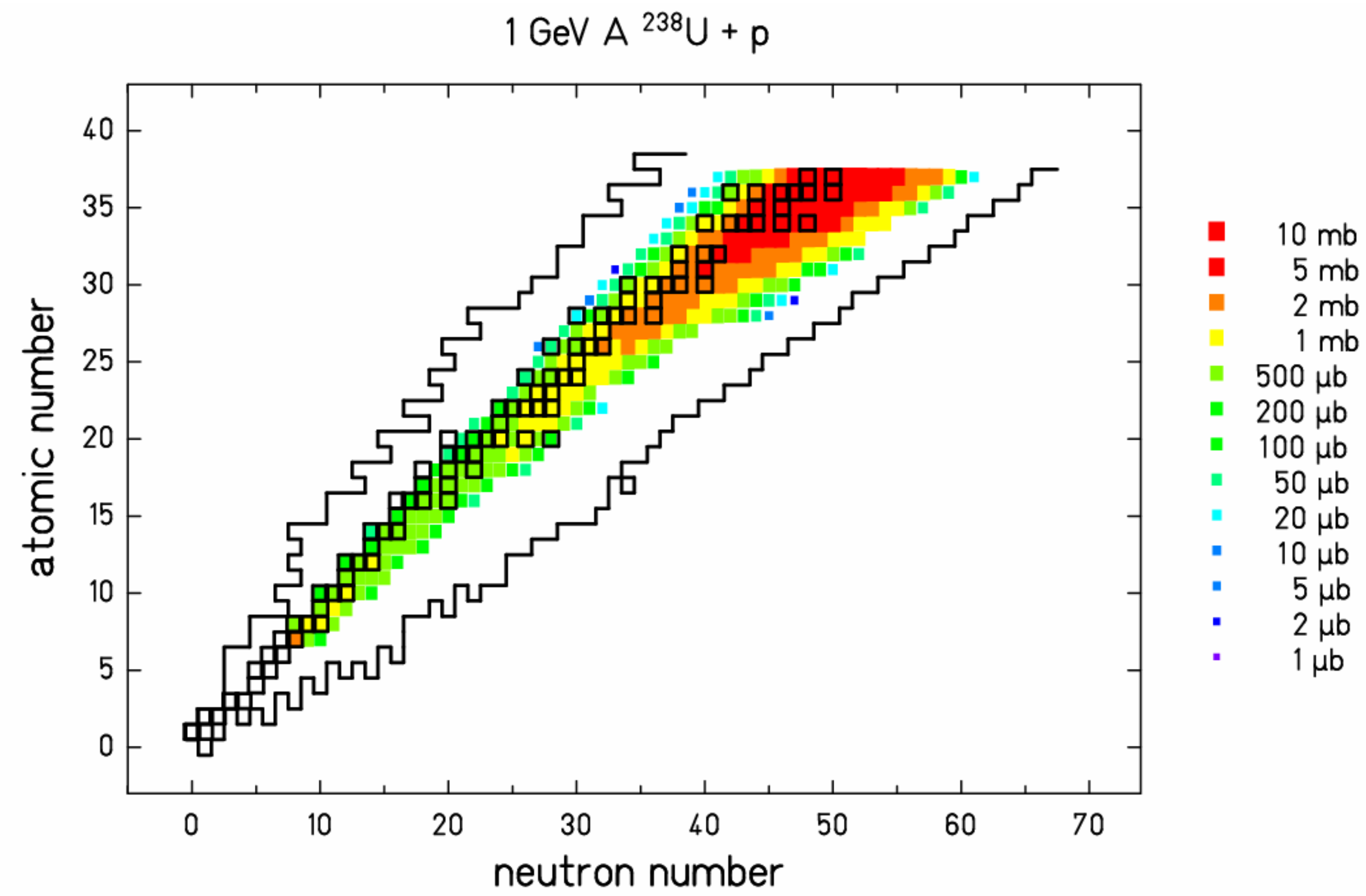


titanium alone



Evidence for a "binary" decay

CROSS SECTIONS OF THE LIGHT RESIDUES

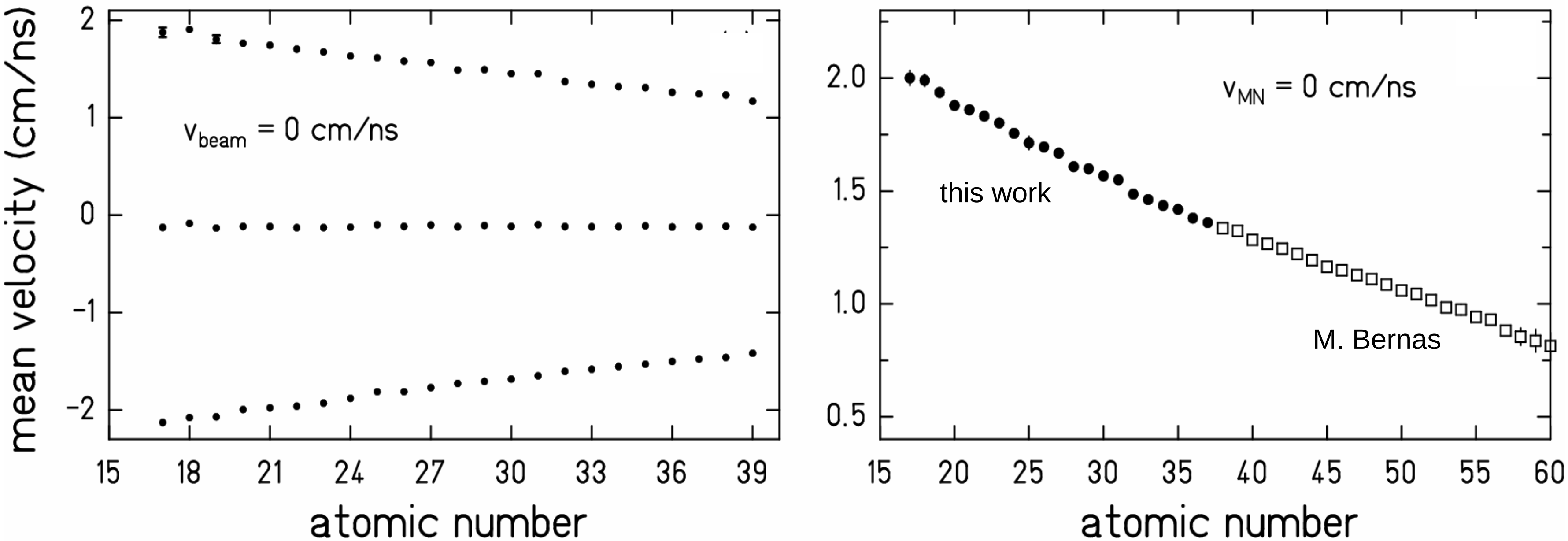


Data available at: http://www-w2k.gsi.de/charms/data.htm

PART II:

INTERPRETATION OF THE EXPERIMENTAL RESULTS

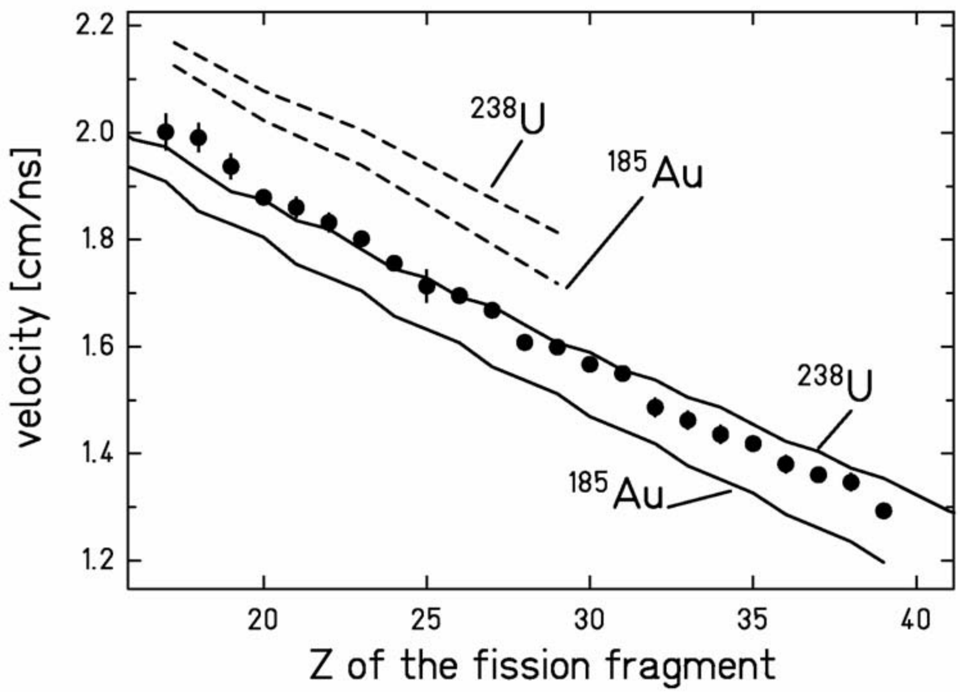
VELOCITY OF THE RESIDUES



We can interpret the counts in the two wings as very asymmetric fission products in proton-induced reactions on ^{238}U

TRANSITION FROM FISSION TO EVAPORATION

Velocity: from scission-point model towards asymmetric decay from undeformed nucleus



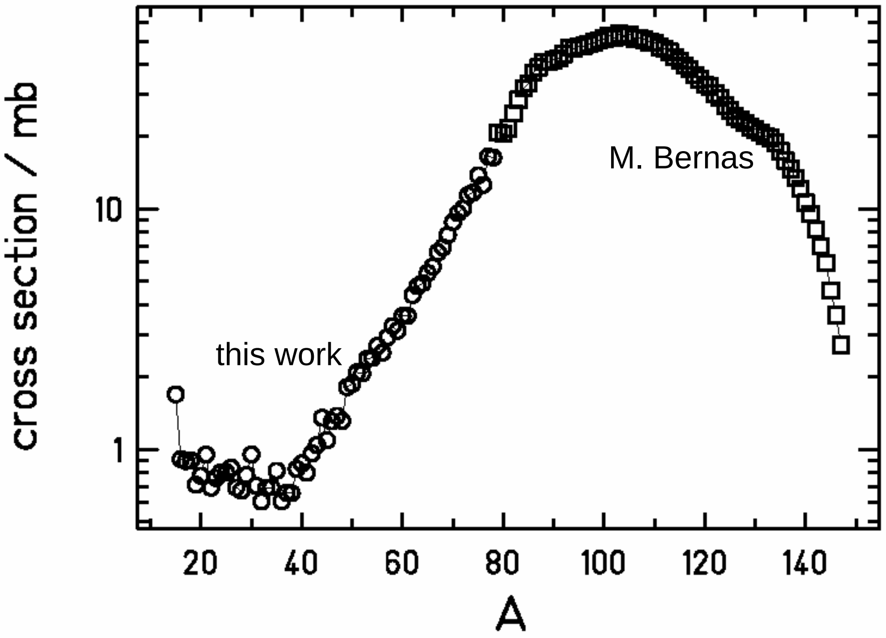
- Mean velocities in the frame of the fissioning nucleus

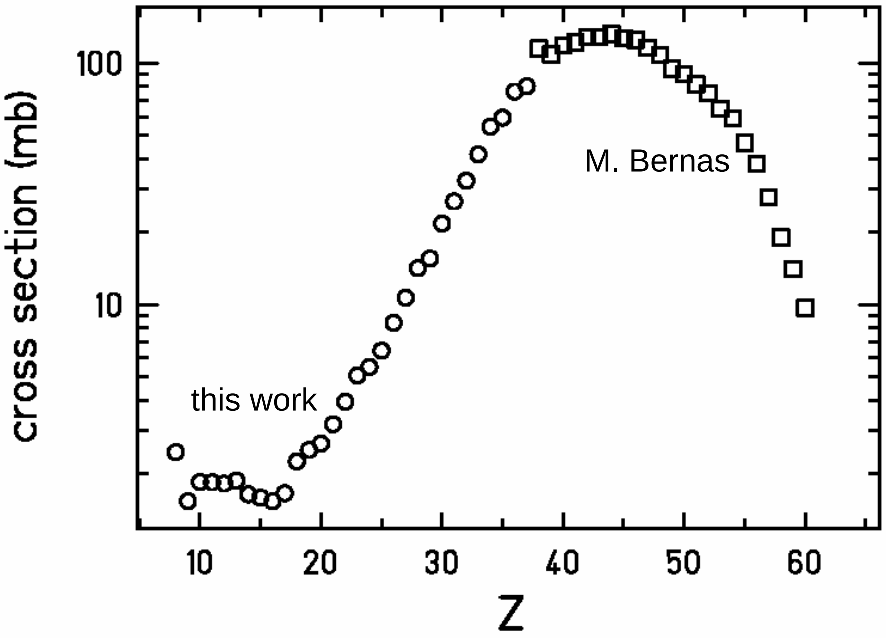
^{238}U, ^{185}Au = compound nuclei

—— scission-point model (deformed nuclei)

- - · Nucleus-nucleus fusion approach (undeformed nuclei)

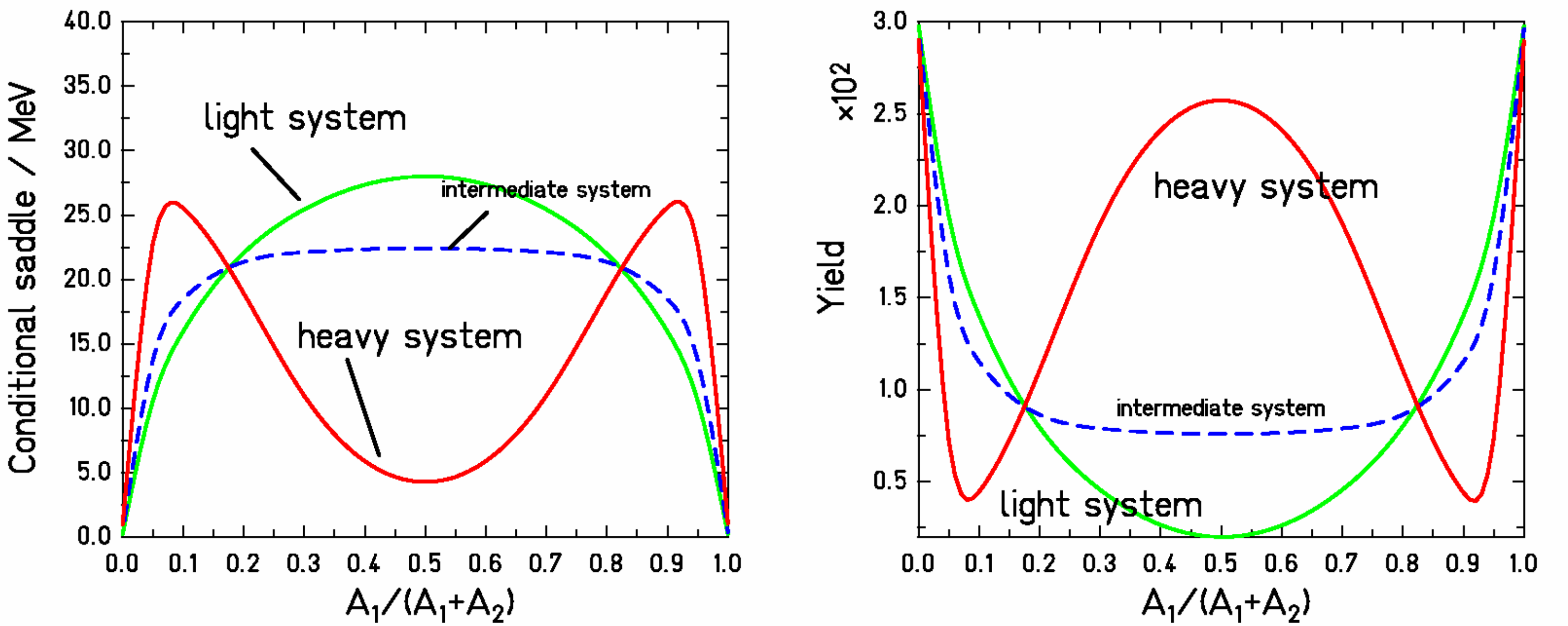
CROSS SECTIONS: MASS AND CHARGE DISTRIBUTIONS



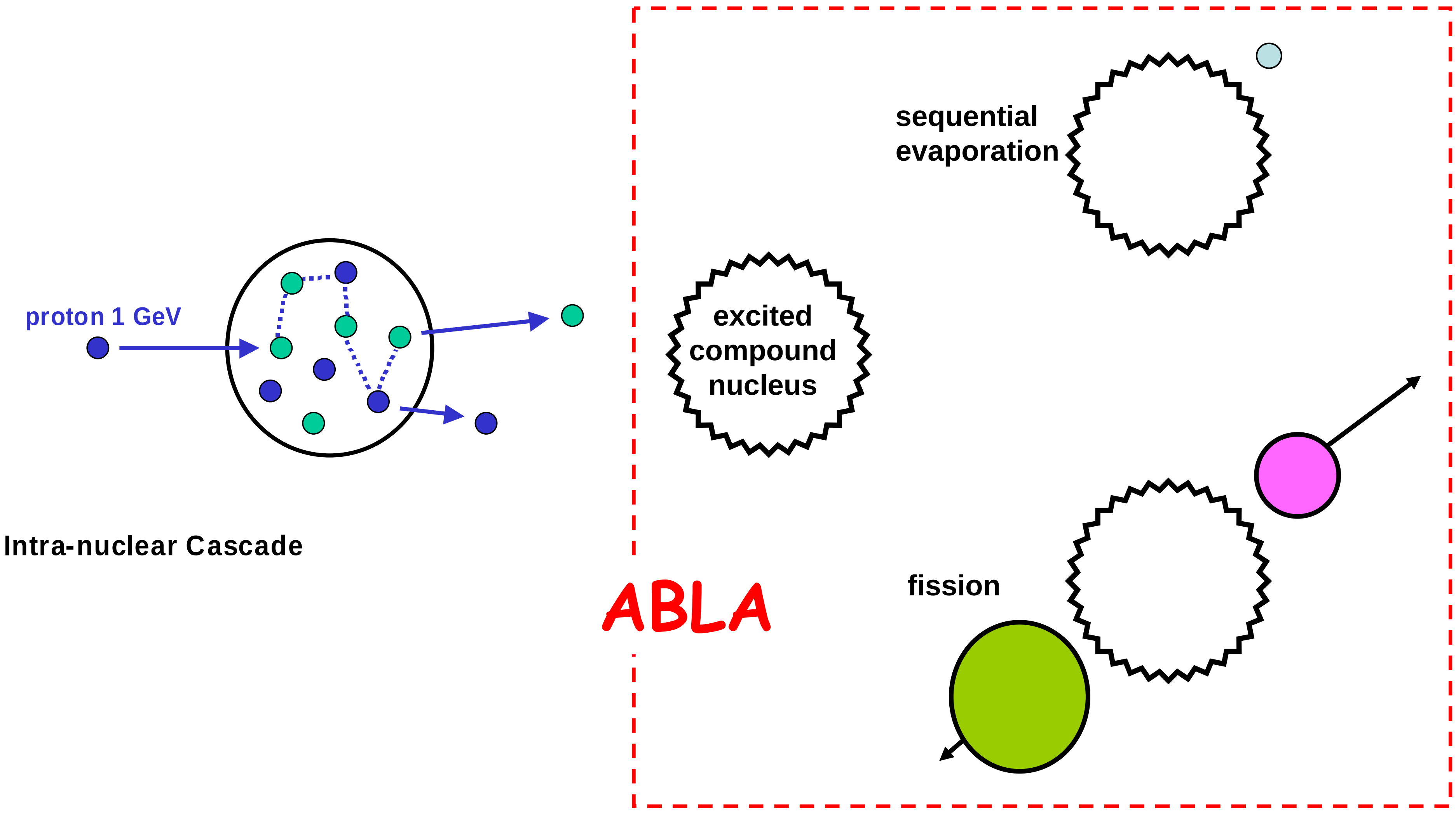


TRANSITION FROM FISSION TO EVAPORATION

Mass distribution: the statistical transition-state model



OUR STATISTICAL MODEL



THE FISSION MODEL:
THE FISSION PROBABILITIES

Fission decay width: transition-state method of Bohr and Wheeler

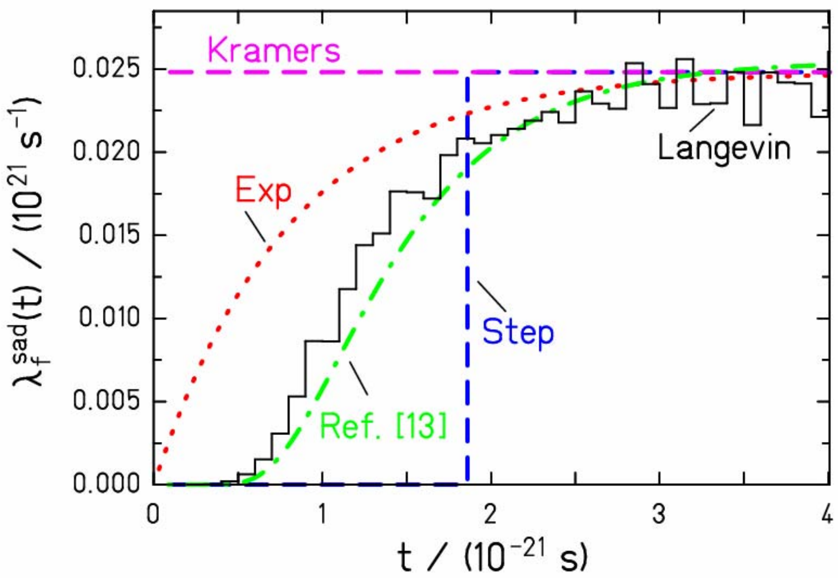
$$\Gamma_f^{BW} \approx T_f \frac{\rho_f(E - B_f)}{\rho_C(E)}$$

level density of the compound nucleus

level density of the transition states in the saddle-point configuration

The fission decay widths depend explicitly on time (dynamical evolution of the system along its path to fission)

(influence of nuclear viscosity)



B. Jurado, PhD thesis, Universidad de Santiago de Compostela, 2002.

THE FISSION MODEL:
THE FISSION-FRAGMENT PROPERTIES (SEMIEMPIRICAL)

J. Benlliure et al. / Nuclear Physics A 628 (1998) 458–478

The modeling of the potential for very asymmetric fission is missing

We use another approach...

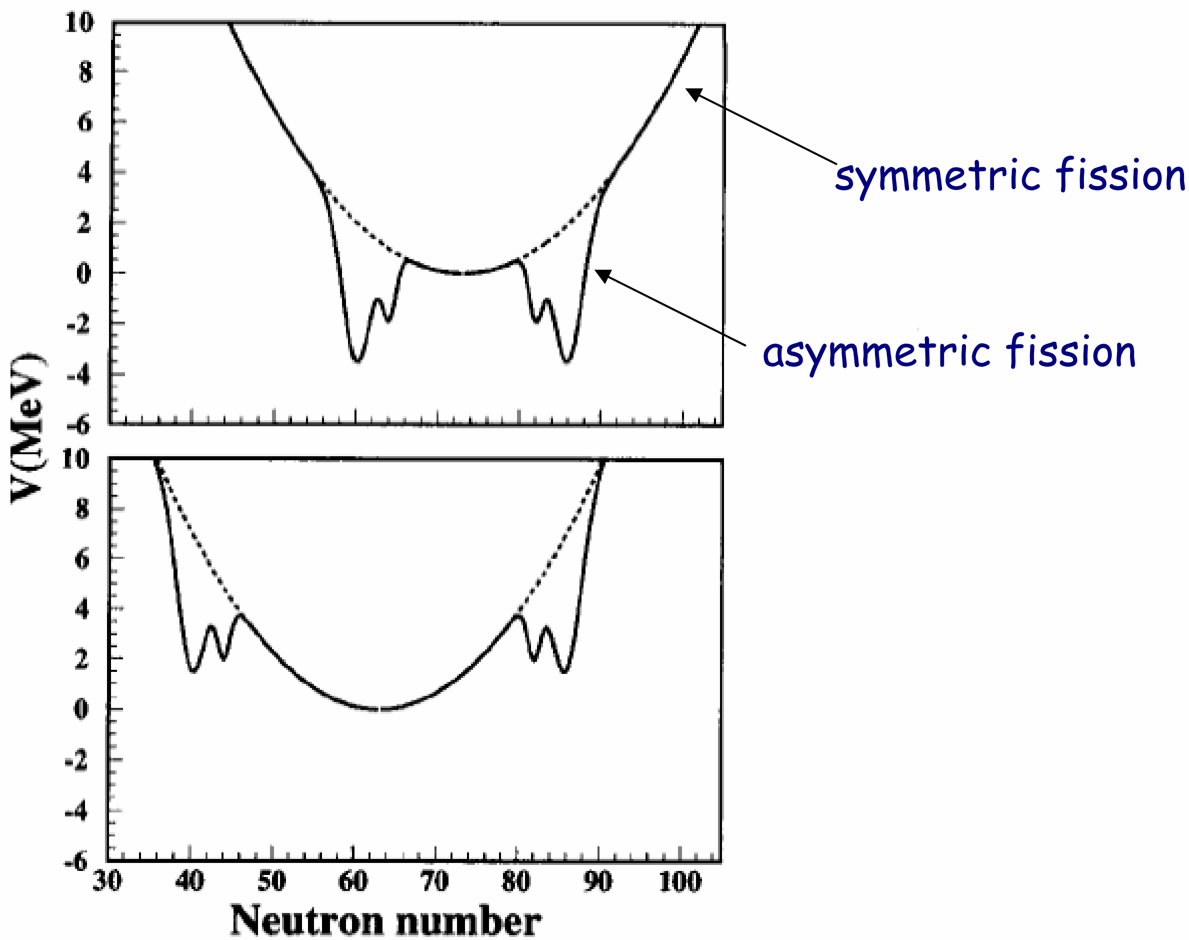


Fig. 1. Potential energy at the fission barrier for ^{238}U (upper part) and ^{208}Pb (lower part), as a function of mass asymmetry expressed by the neutron number of one of the preformed fragments.

THE VERY ASYMMETRIC FISSION: THE INTERMEDIATE-MASS FRAGMENT EMISSION

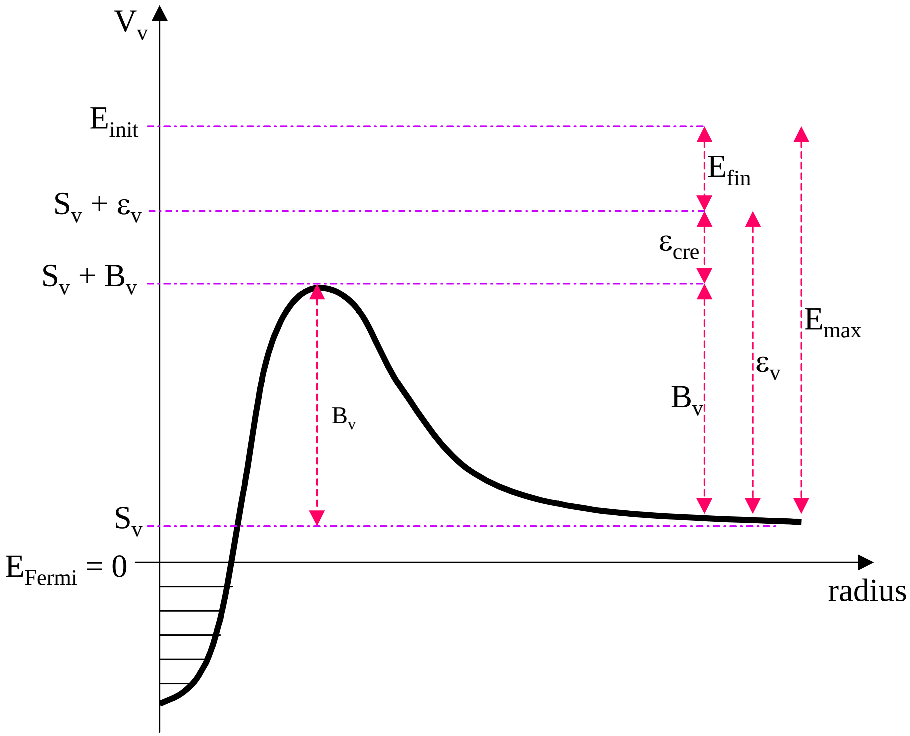
IMF decay width

$$\Gamma_{IMF} \approx \sigma_{inv} T_M^2 \frac{\rho_M(E - B_{IMF})}{\rho_C(E)}$$

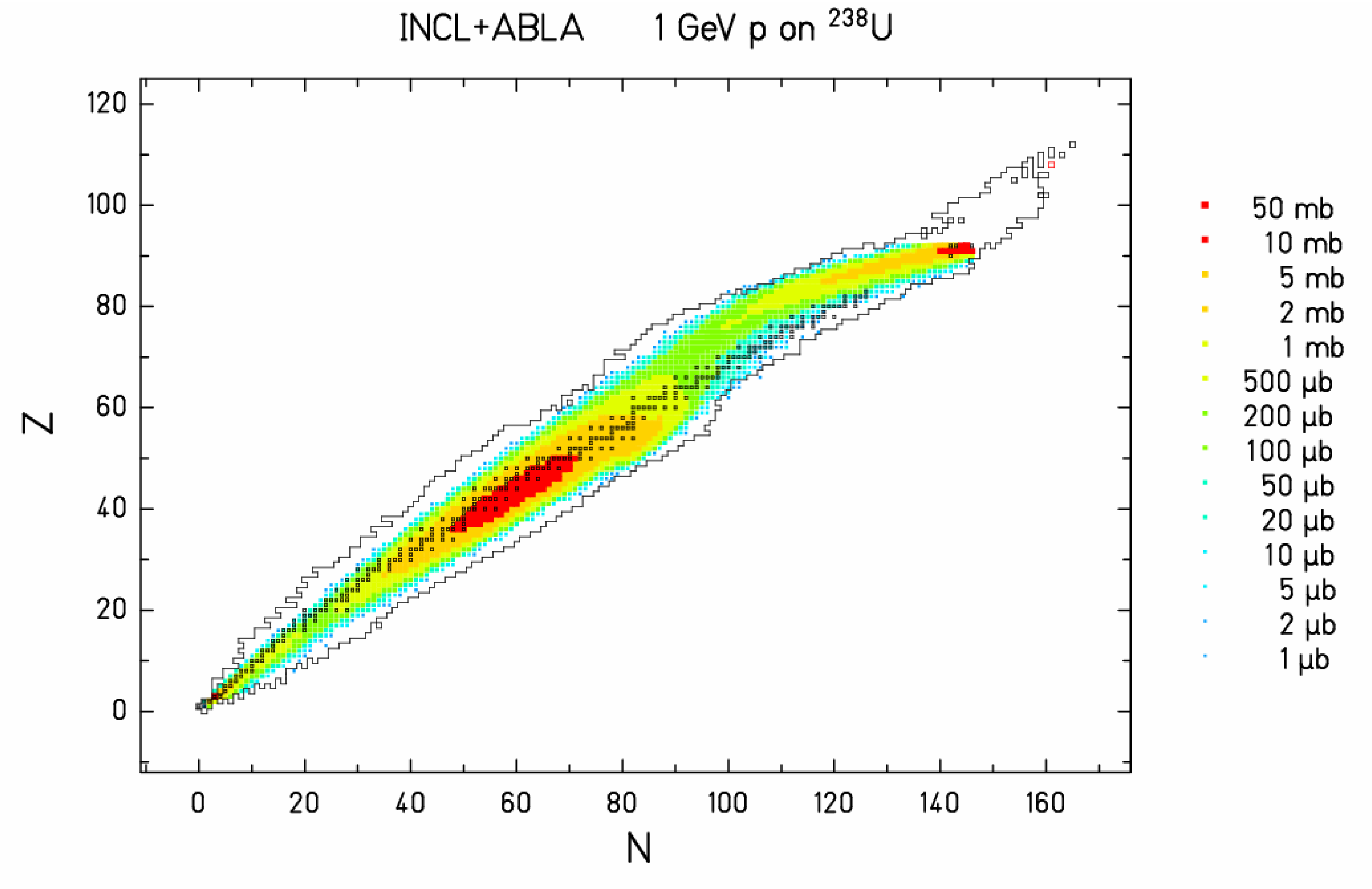
level density of the compound nucleus

level density of the mother nucleus at the barrier

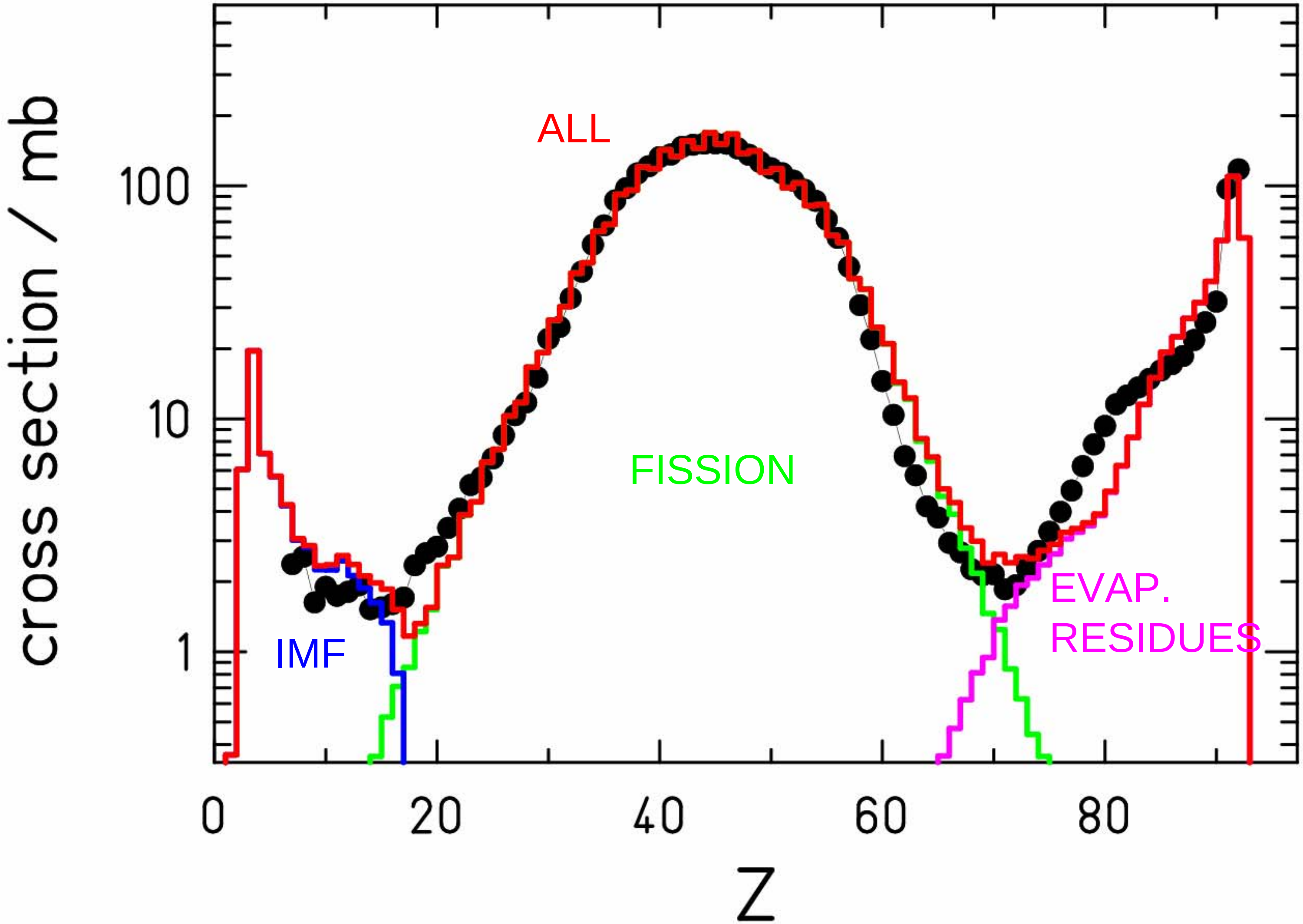
The barrier is calculated using the fusion nuclear potential of Bass



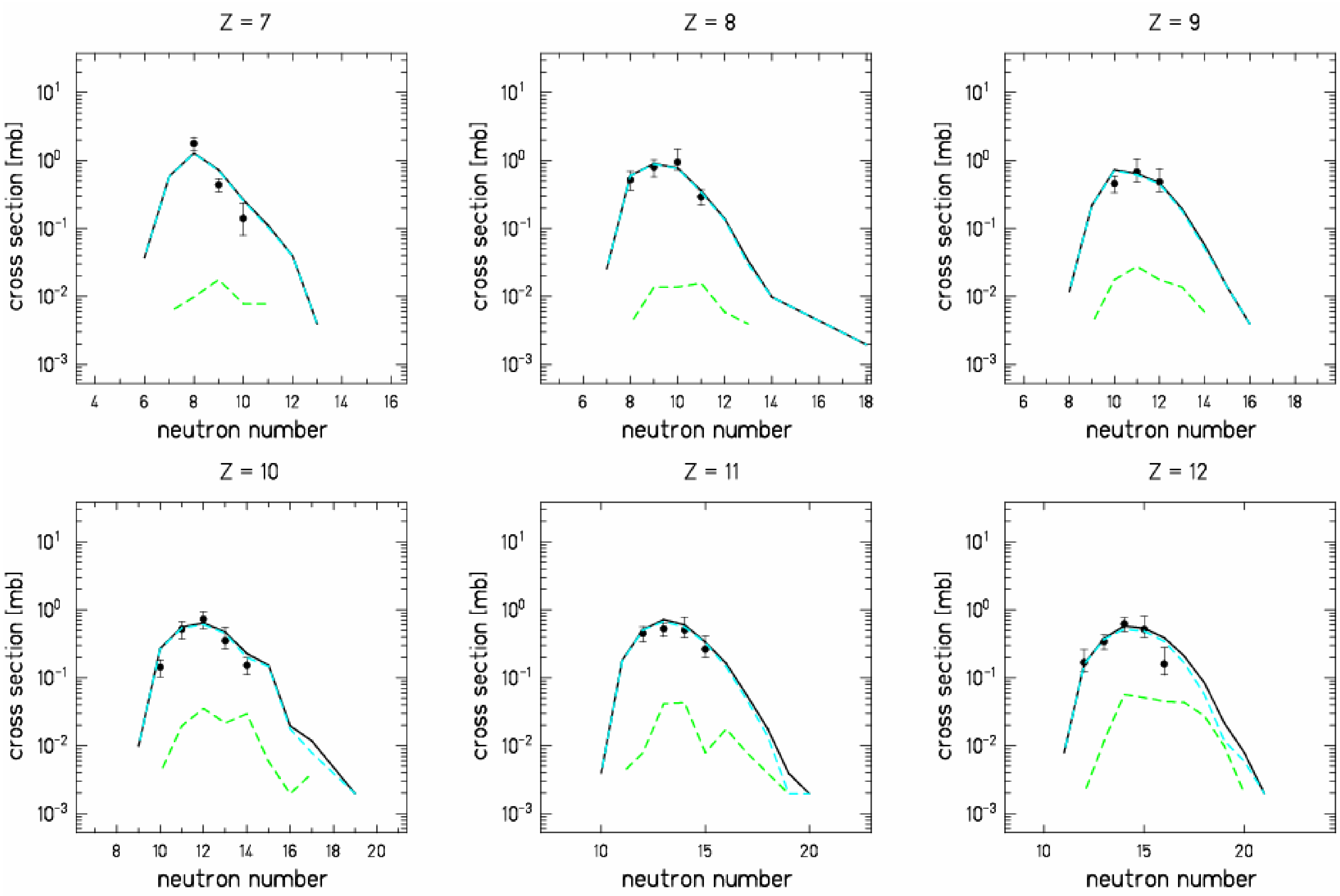
RESULT FOR 1 GeV p on ^{238}U



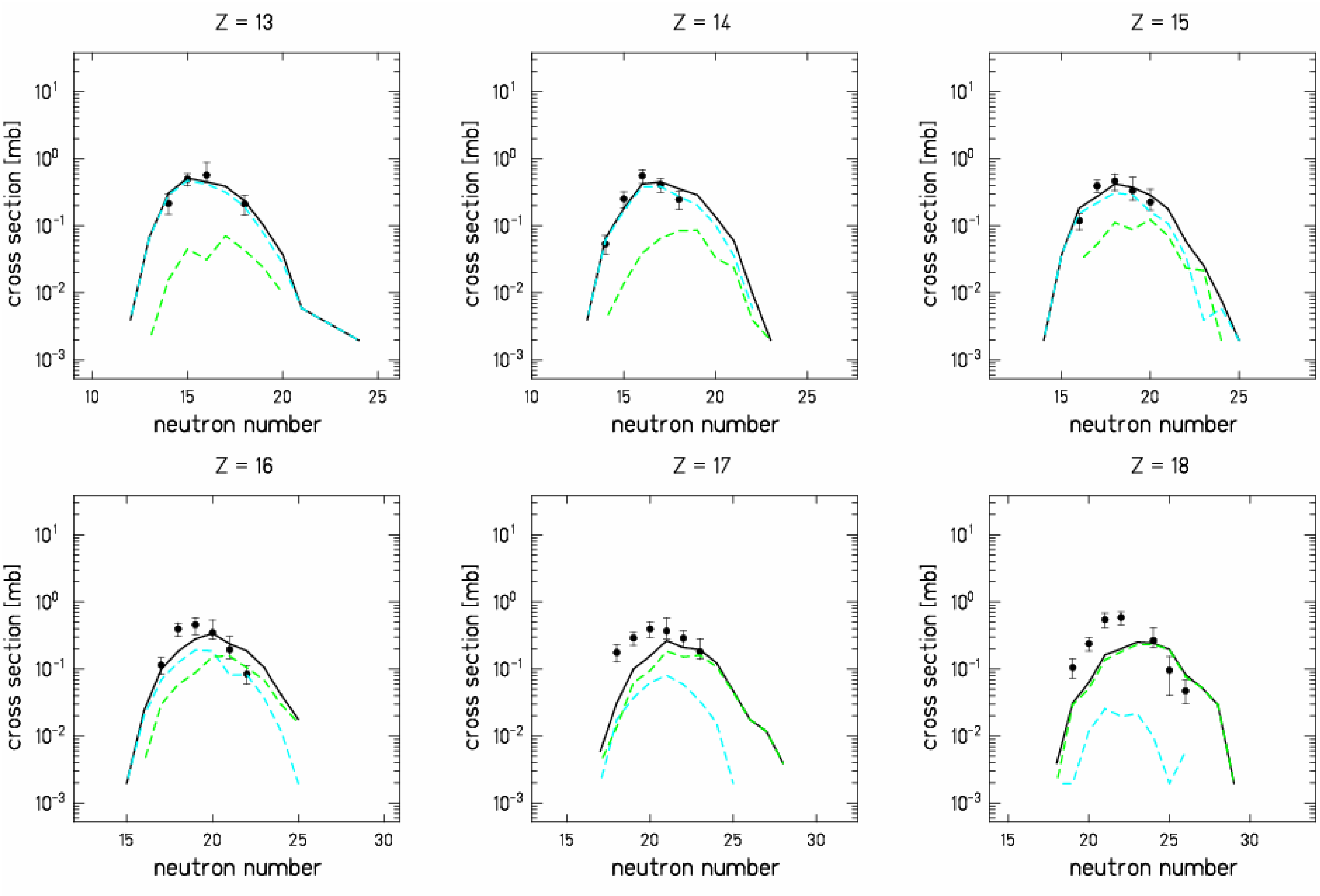
RESULT FOR 1 GeV p on ^{238}U



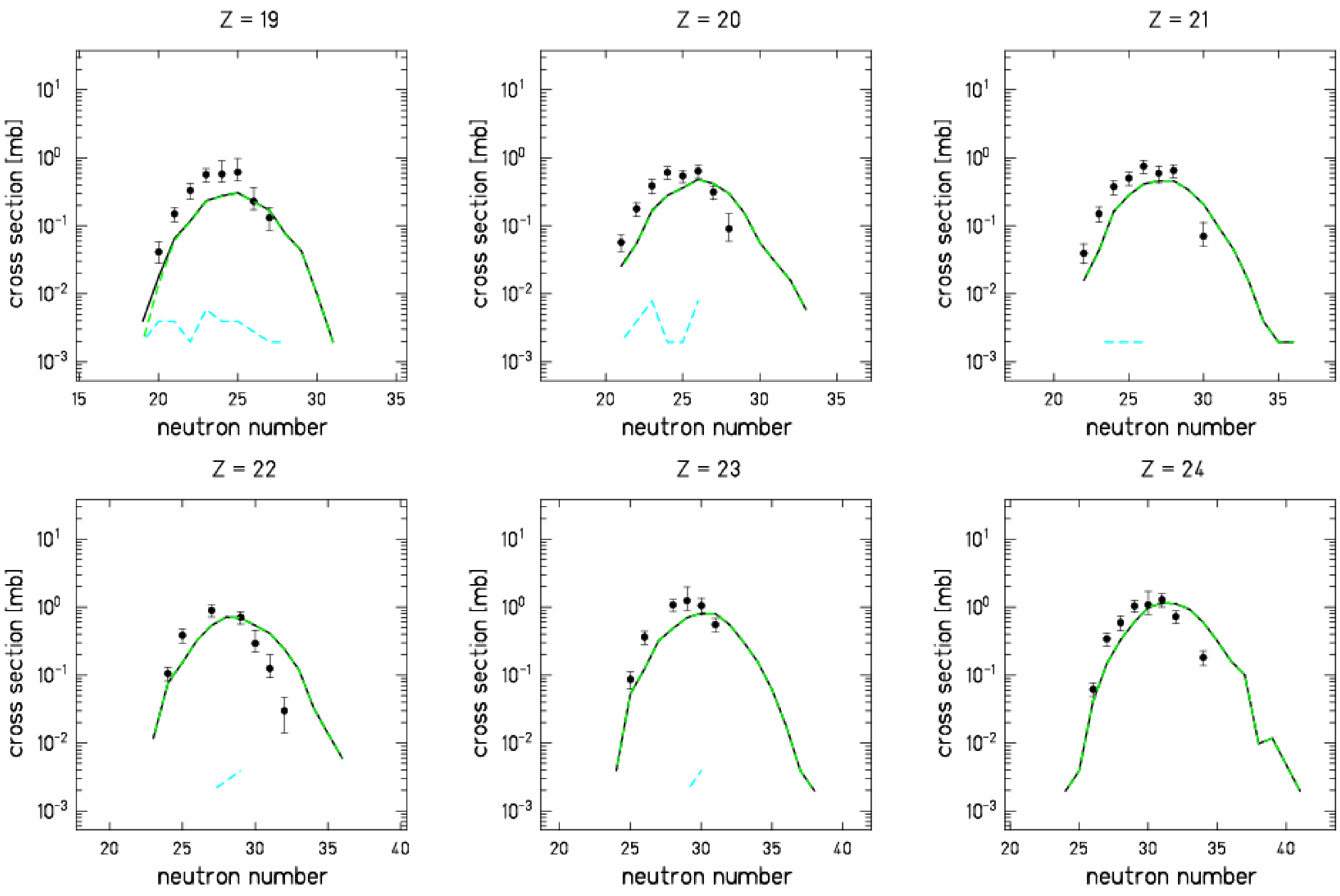
RESULT FOR 1 GeV p on ^{238}U



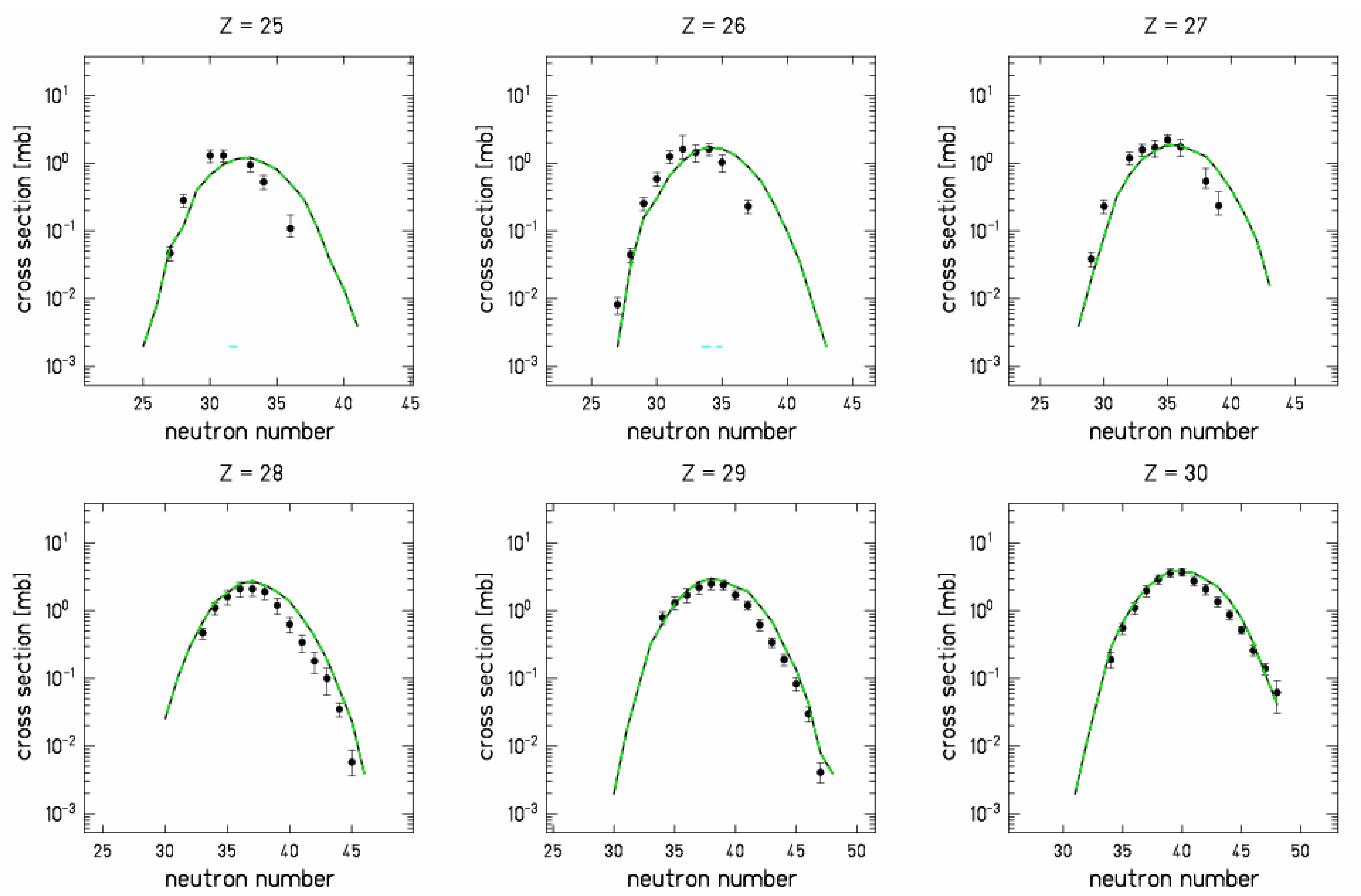
RESULT FOR 1 GeV p on ^{238}U



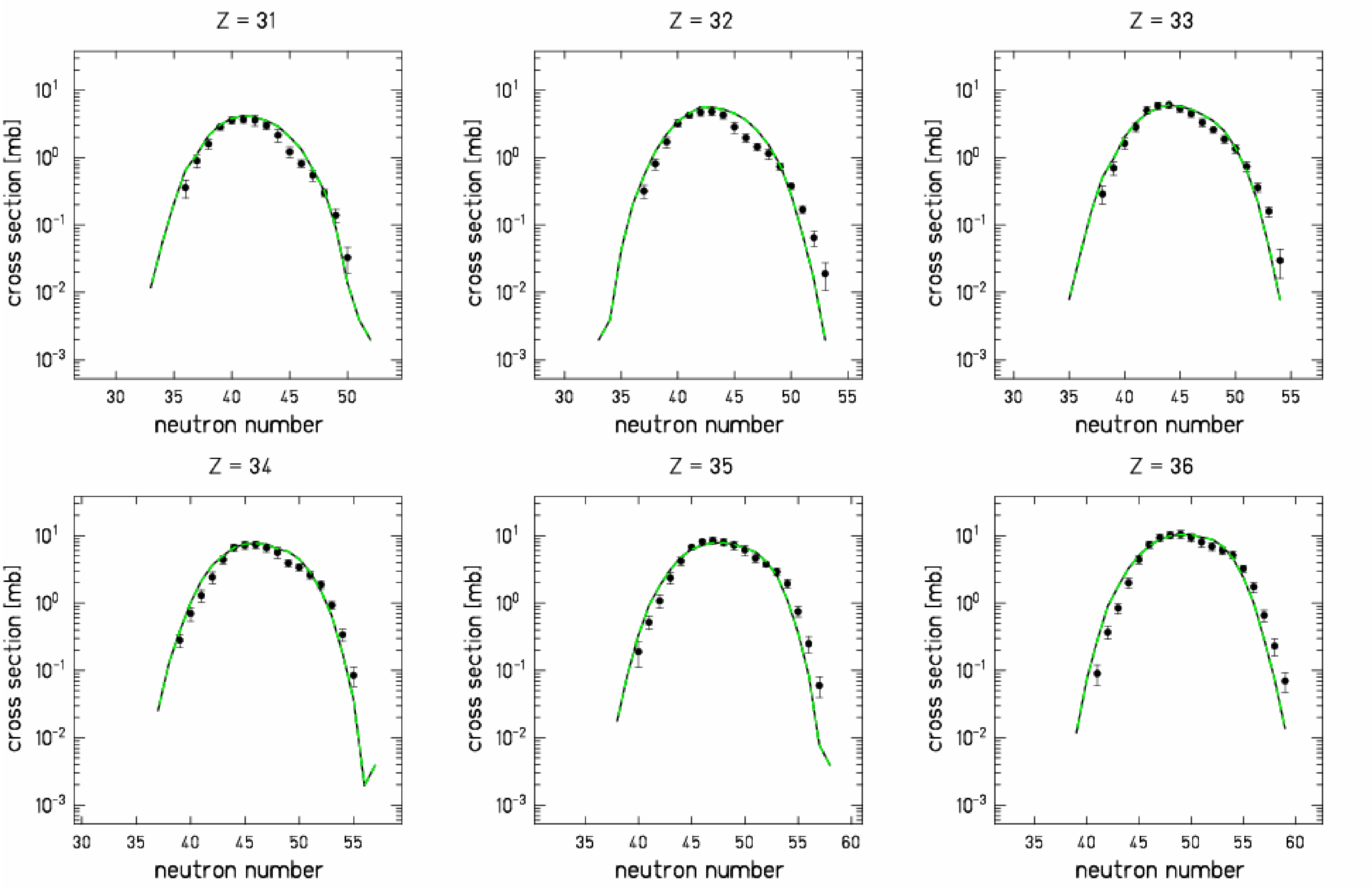
RESULT FOR 1 GeV p on ^{238}U



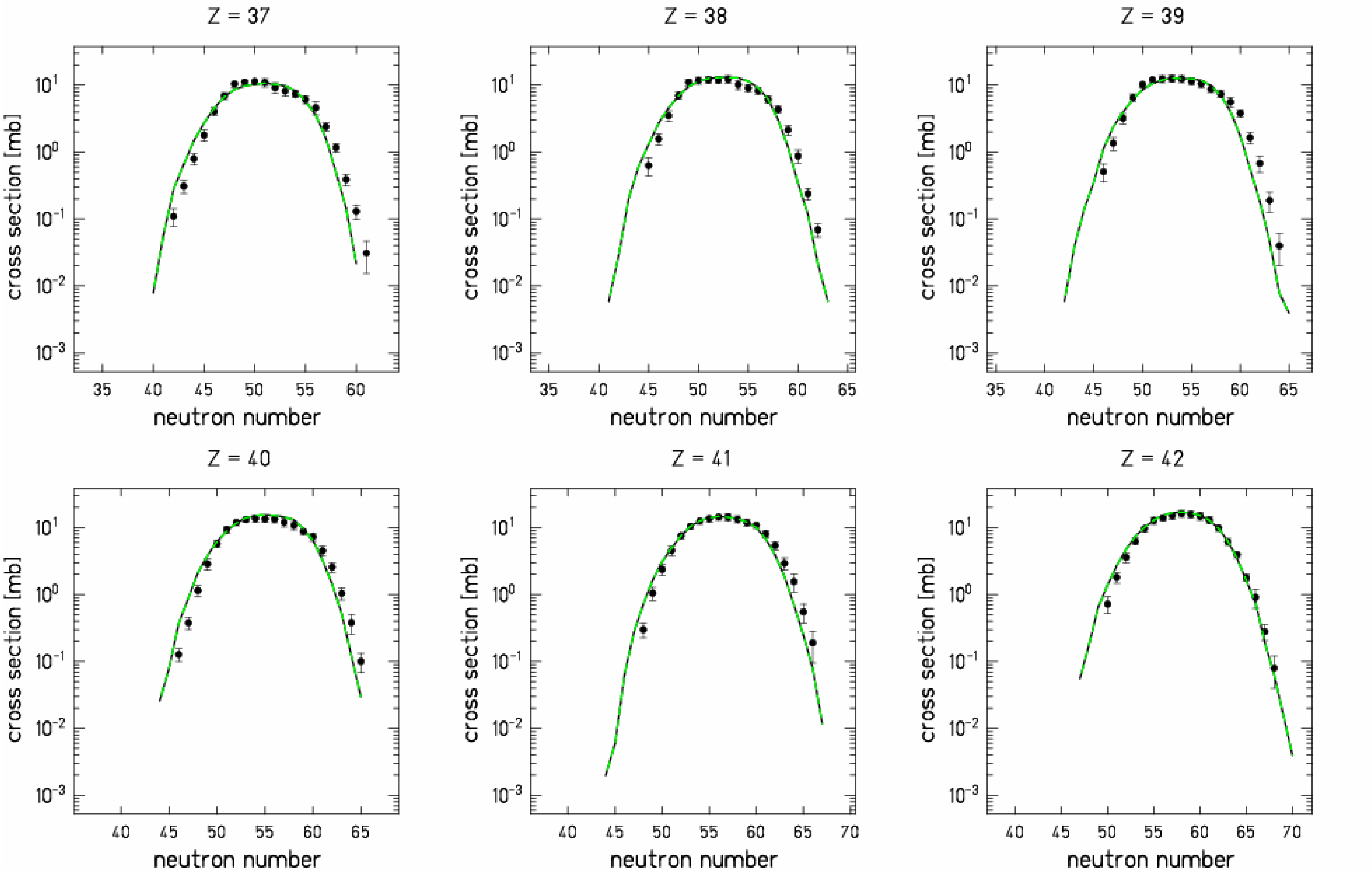
RESULT FOR 1 GeV p on ^{238}U



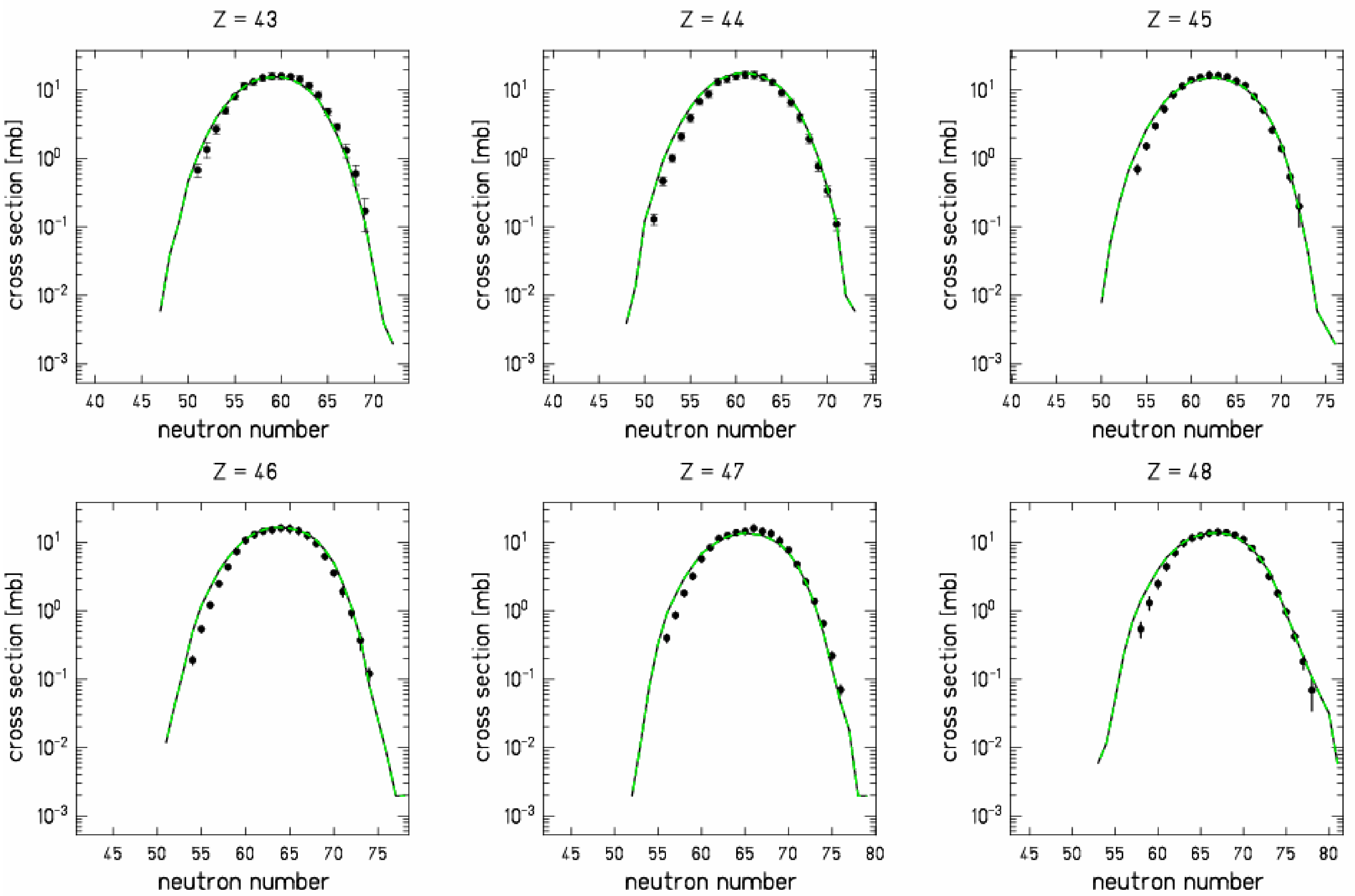
RESULT FOR 1 GeV p on ^{238}U



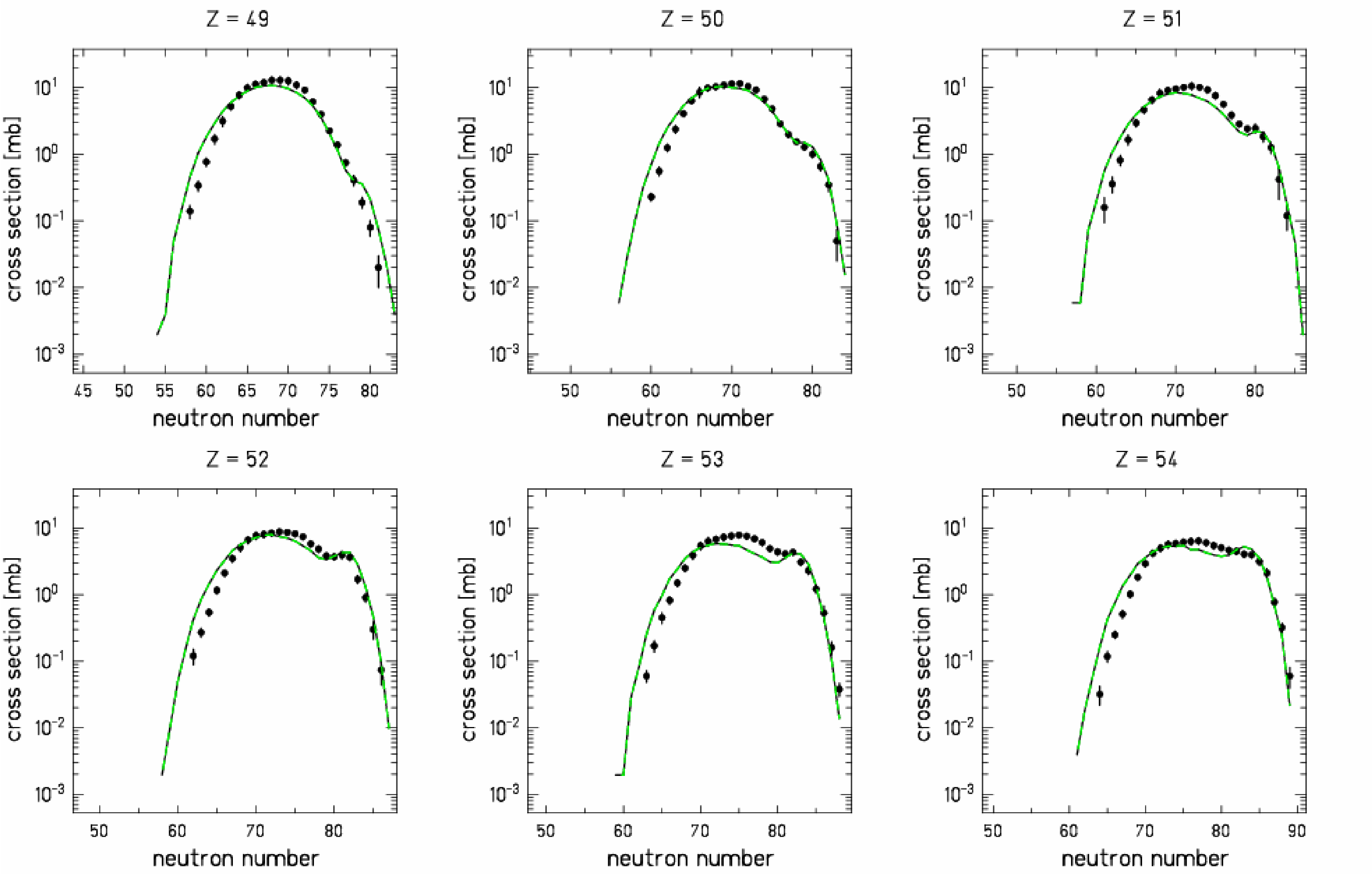
RESULT FOR 1 GeV p on ^{238}U



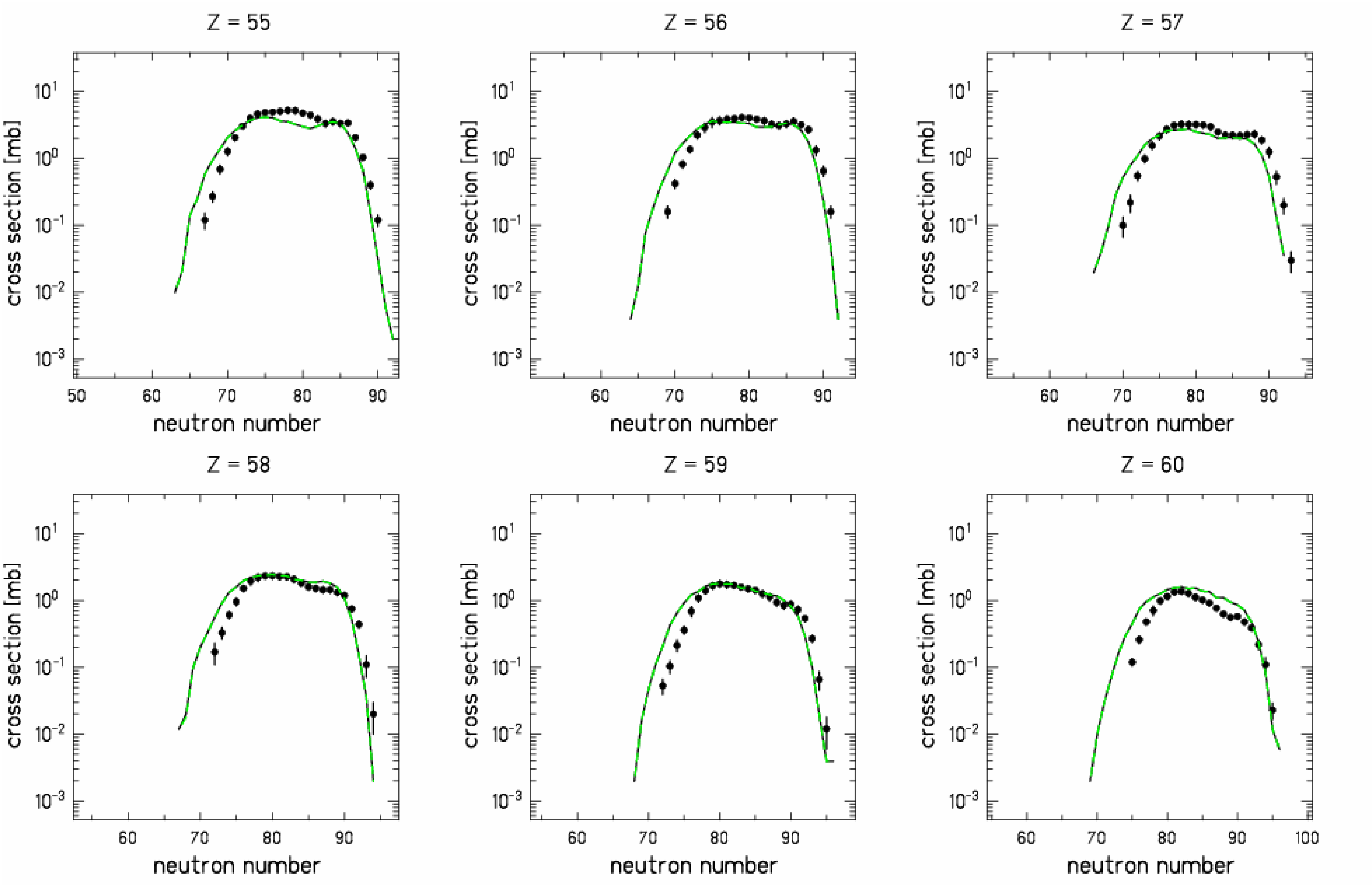
RESULT FOR 1 GeV p on ^{238}U



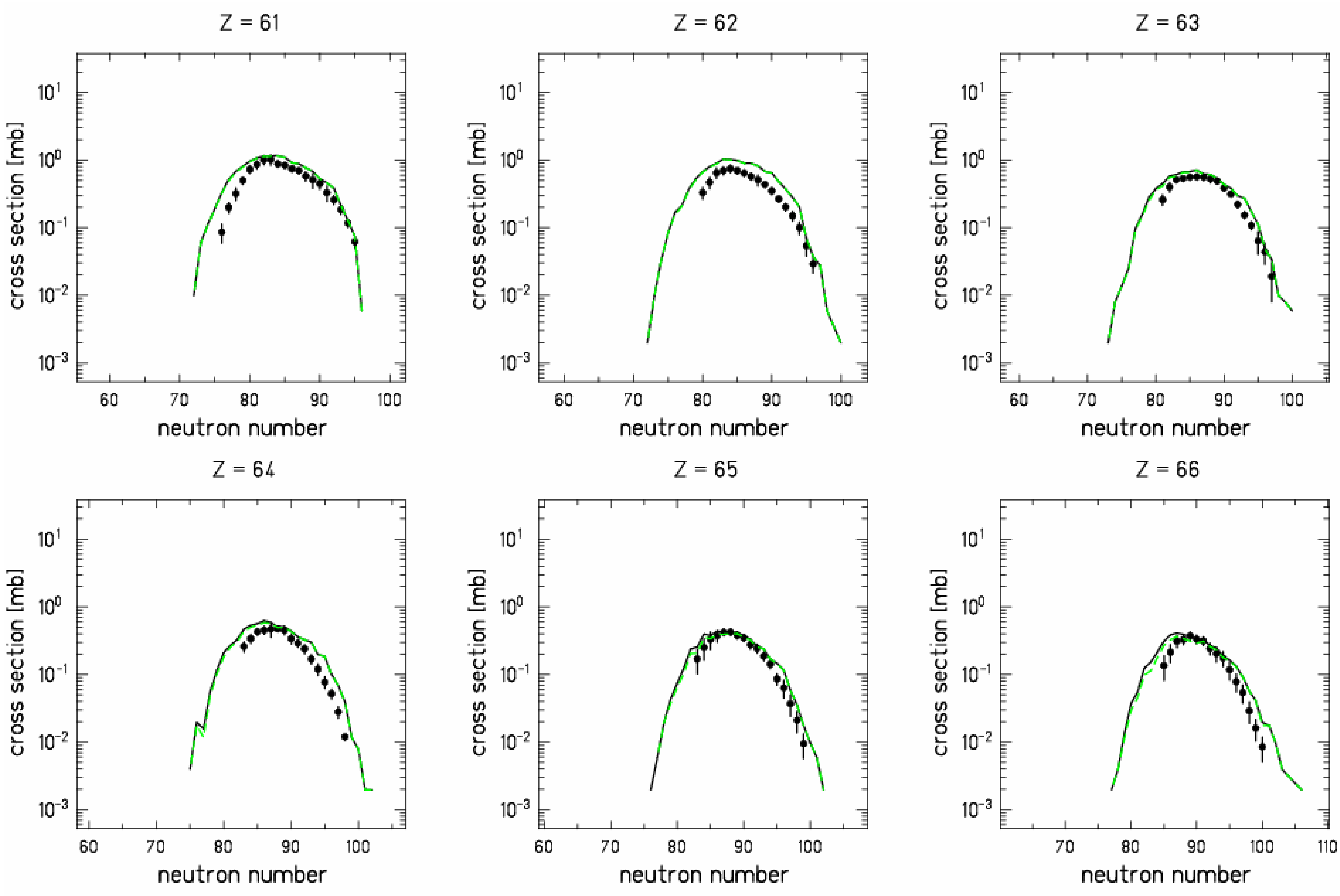
RESULT FOR 1 GeV p on ^{238}U



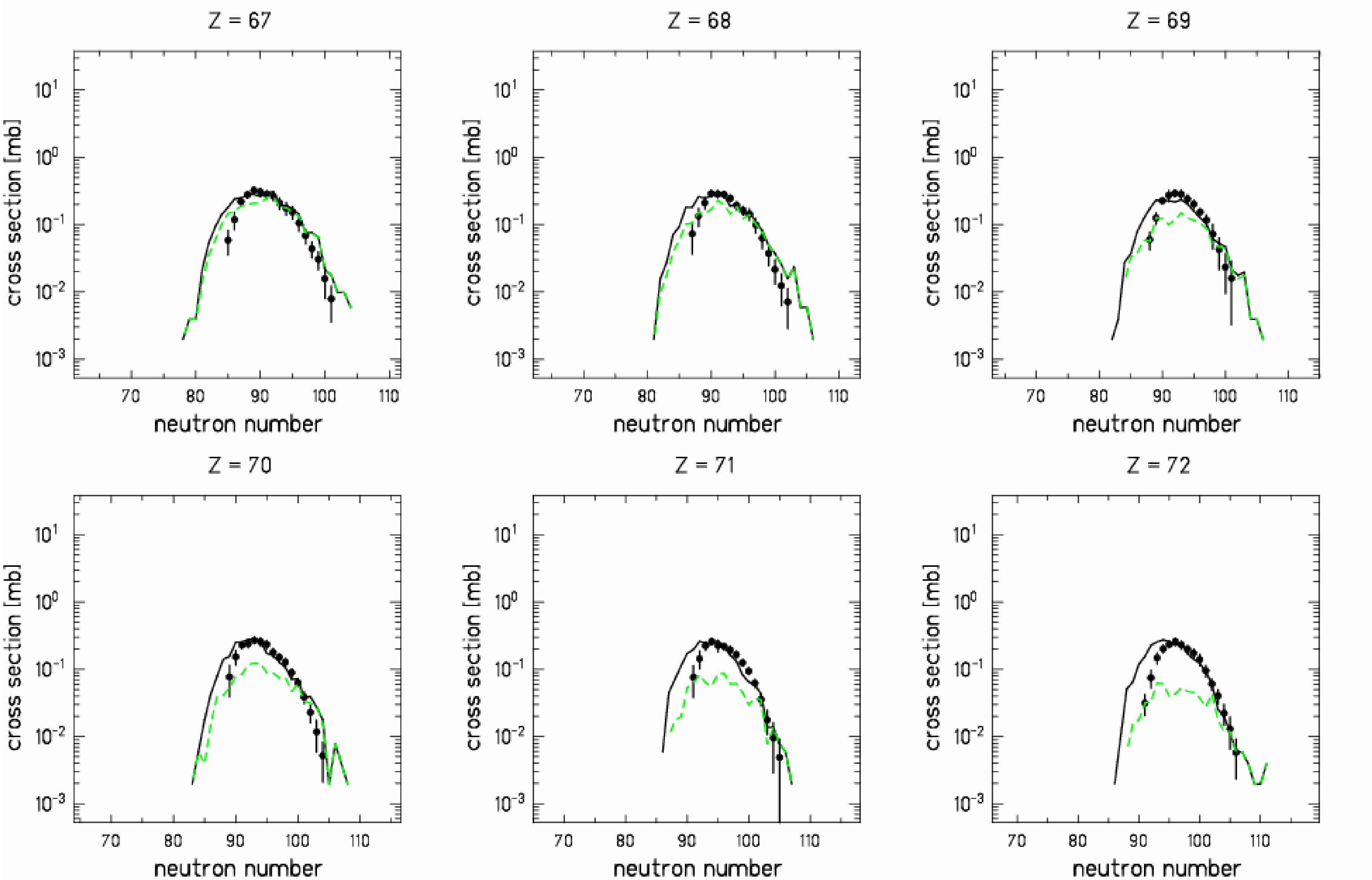
RESULT FOR 1 GeV p on ^{238}U



RESULT FOR 1 GeV p on ^{238}U



RESULT FOR 1 GeV p on ^{238}U



ADDITIONAL EFFECTS

1 — Thermal expansion of the nucleus

2 — Pre-formation factor

3 — Surface effects on the level density

4 — Deformation of the nucleus

For light systems → Thermal instabilities (break-up)

CONCLUSIONS

LIGHT NUCLIDES FROM 1 A·GeV ^{238}U + p

The experimental data:

- Formation cross-section for every isotope, along with its velocity distribution, could be measured at the FRS

The physics:

- Yields and velocities of light nuclides from 1 A·GeV ^{238}U + p indicate a transition from fission to evaporation
- The experimental data could be successfully reproduced by a statistical model, combining a fission approach with the evaporation of intermediate-mass fragments
- No indications for a multifragmentation-type of decay have been observed

Partial widths Γ_n and Γ_p for emission of neutrons and protons.

$$\Gamma_n = \frac{2mR^2 g}{{}^2\, 2\pi\rho\left(E - E_r^{gs}\right)} \int_0^{E-B_n} \varepsilon\rho\left(E - B_n - \varepsilon\right) \mathrm{d}\varepsilon$$

$$\Gamma_p = \frac{2mR^2 g}{{}^2\, 2\pi\rho\left(E - E_r^{gs}\right)}$$

$$\int_{\varepsilon_c}^{E-B_p} \varepsilon\left(1 - \frac{\varepsilon_c}{\varepsilon}\right)\rho\left(E - B_p - \varepsilon\right) d\varepsilon$$

(Approximation without considering tunneling.)

Γ_p is reduced by the Coulomb barrier ε_c.

Modelling the Width in A and N/Z of Fission-Product Isotopic Distributions

Approximated parabolic potential

$$U(\eta) = C_\eta \cdot (\eta - \eta_o)^2$$

Statistical population:

$$Y(\eta) \propto \exp\left\{2\sqrt{a(U_0 - U(\eta))}\right\} \quad \rightarrow$$

$$Y(\eta) \propto \exp\left\{-\frac{(\eta - \eta_0)^2}{2\sigma_\eta^2}\right\} \quad \textbf{with}$$

$$2\sigma_\eta^2 = \frac{T}{C_\eta}$$

U = **potential energy,**
η = **either A (mass split) or N/Z (polarisation),**
C_η = **stiffness of the potential,**
T = **nuclear temperature.**