1 A GeV ^{238}U on proton. Transition from fission to light evaporation residues. Data and calculation.

Paper:

"Light Nuclides Produced in the Proton-Induced Spallation of ^{238}U at 1 GeV"

accepted in Phys. Rev. C

Authors:

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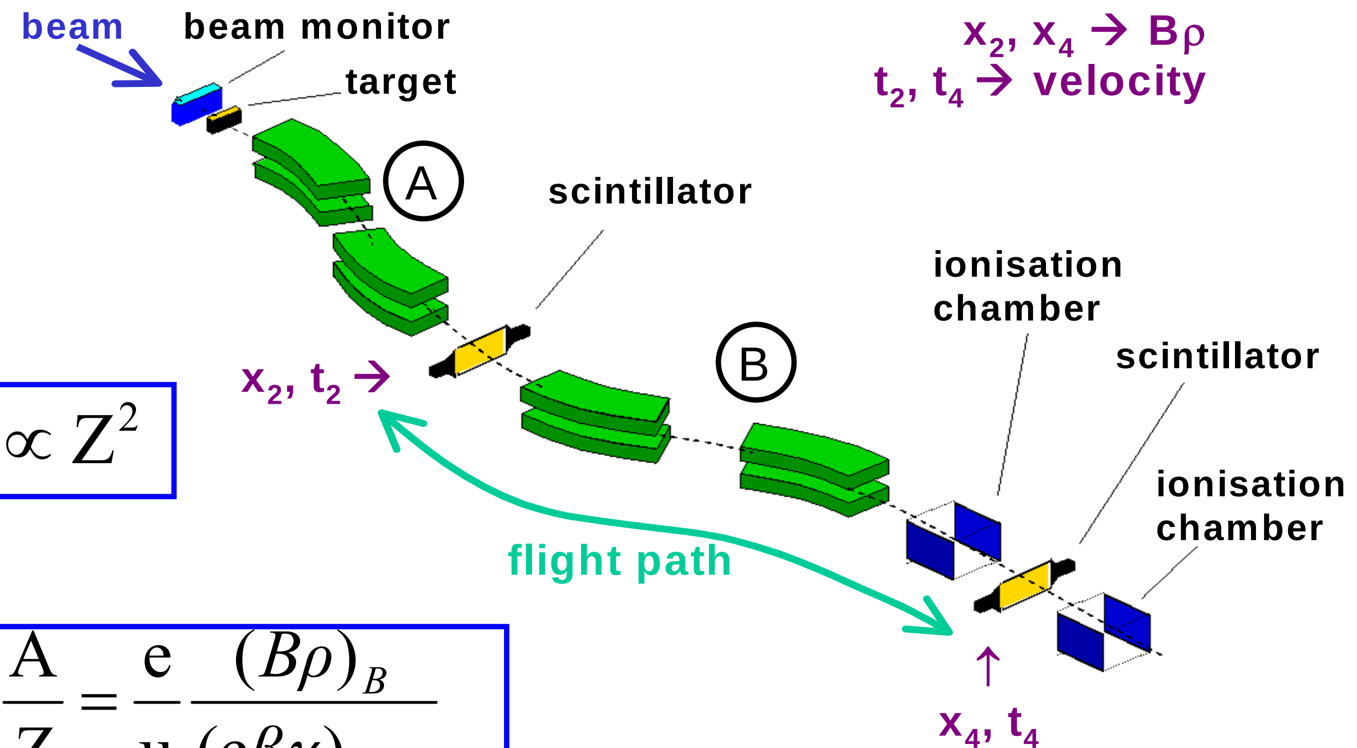
PART I:

DATA ANALYSIS

THE EXPERIMENTAL SET-UP for LIGHT RESIDUES

Analysis in the range:

$7 \leq Z \leq 37$



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

A/Z from time and position: $$\frac{A}{Z} = \frac{e}{u}\frac{(B\rho)_B}{(c\beta\gamma)_{TOF}}$$

velocity from magnetic rigidity: $$\beta\gamma c = \frac{e}{u + \delta u} \cdot \frac{Z}{A} \cdot (B\rho)_A$$

CHARGE RESOLUTION

$$\Delta E_{theory} \cong \frac{Z^2}{f(\upsilon)}$$

The MUSIC signals depended on two other additional factors:

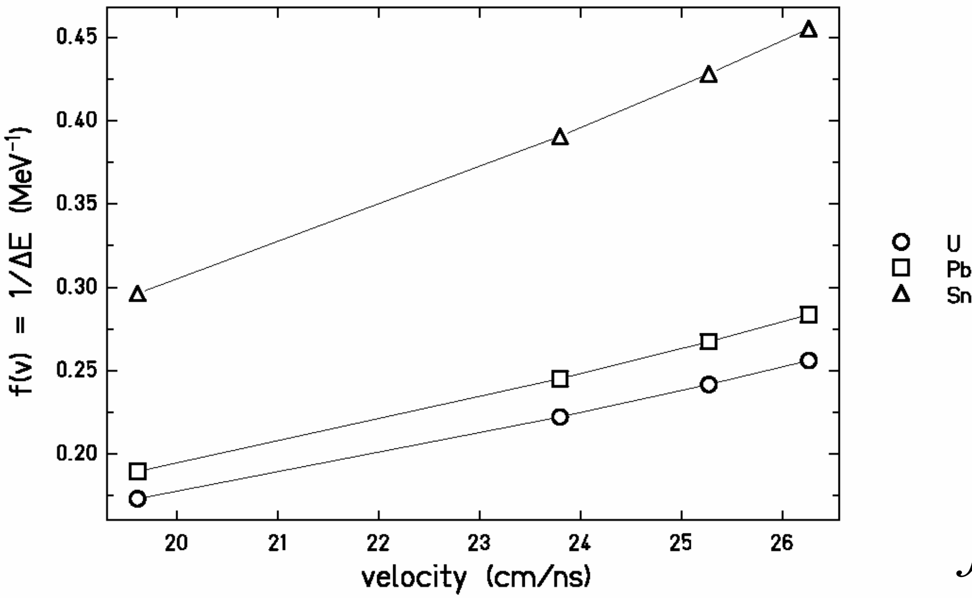
- on the distance of the ions from the anode, i.e. the x_4 position, due to a recombination effect, leading to a loss of free electrons in the gas
- on the density of the gas in the IC, which was observed to vary with the time at which ΔE was measured

$$\Delta E_{measured} \cong \frac{Z^2}{f(\upsilon)} \cdot p(t) \cdot g(x_4)$$

$$Z^2 \propto \Delta E_{measured} \cdot \frac{f(\upsilon)}{\mathrm{p}(t) \cdot \mathrm{g}(x_4)}$$

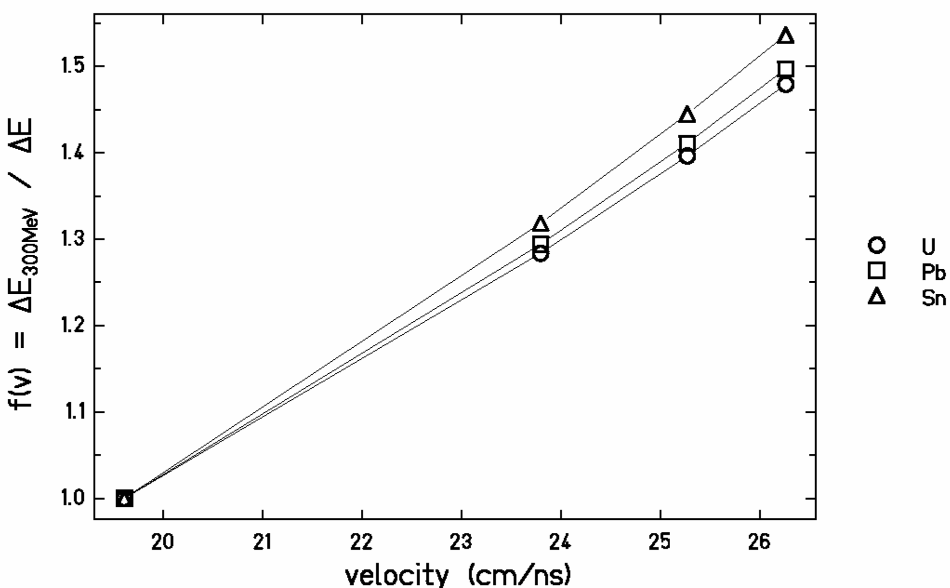
(we assumed that the variables υ, t, x_4, are separable)

CHARGE RESOLUTION



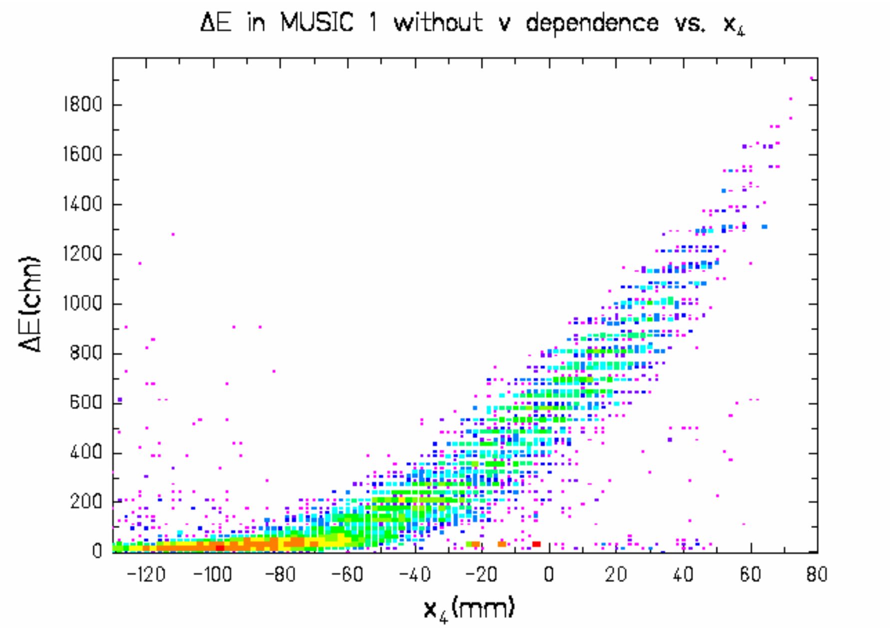
Correction for velocity dependence

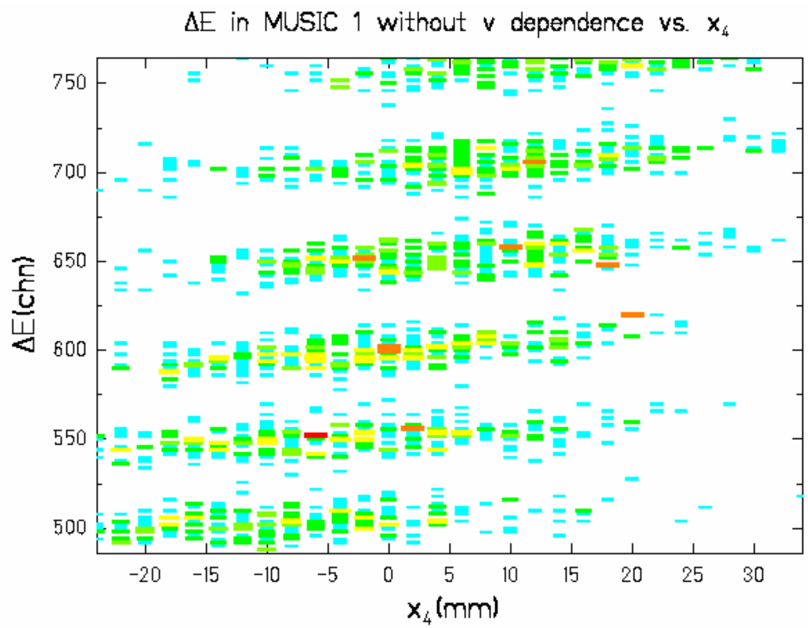
$$f(\upsilon) \propto \Delta E_{theory}^{300MeV} / \Delta E_{theory}$$



CHARGE RESOLUTION

Correction for position dependence





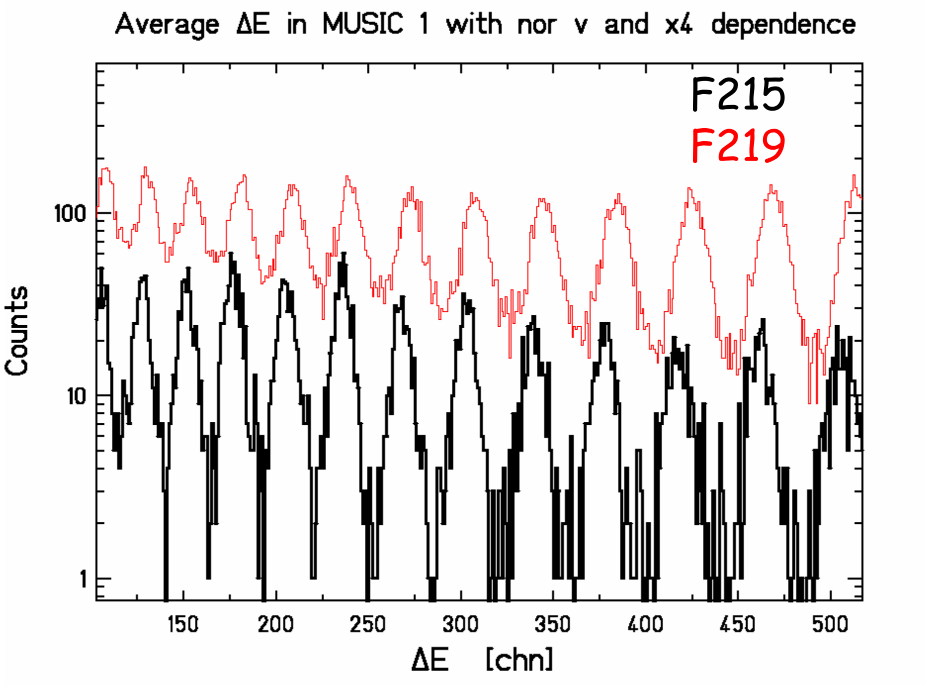
$$\Delta E_{corr} = \frac{\Delta E_{meas}}{g(x_4)} = \frac{\Delta E_{meas}}{e^{\lambda \cdot x_4}} = \Delta E_{meas} \cdot e^{-\lambda \cdot x_4}$$

$\lambda = 5 \cdot 10^{-4}$

The exponential dependence is due to the fact that the recombination of the electrons follows an *absorption law*, i.e. the number of electrons traversing a certain distance dx4 is reduced each time by the same percentage value.

CHARGE RESOLUTION

Correction for pressure dependence



$$p(t)_{\Delta E1} = -4.44 + 0.0479 \cdot (filenumber) - 1.05 \cdot 10^{-4} \cdot (filenumber)^2$$

MASS RESOLUTION

$$\frac{A}{Z} = \frac{\mathrm{e}}{\mathrm{u}} \frac{(B\rho)_B}{\beta_{TOF}\gamma_{TOF}\mathrm{c}}$$

The A/Z depends on two measured quantities:

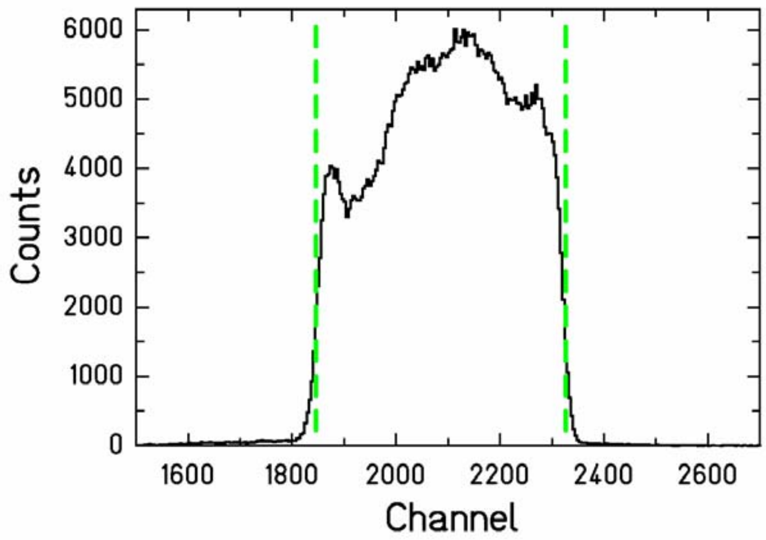
- the magnetic rigidity in the second stage $(B\rho)_B$
- the velocity from TOF

MASS RESOLUTION

The magnetic rigidity in the second stage $(B\rho)_B$

$$\Delta(B\rho)_{AB} = (B\rho)_A - (B\rho)_B \qquad (B\rho)_B = (B\rho)_{A0} \cdot \left(1 + \frac{x_2}{D_2}\right) - \Delta(B\rho)_{AB}$$

$\Delta(B\rho)_{AB}/(B\rho)_B$ from 0.2% to 1%



$$x_2(mm) = b_2 - a_2 \cdot SCI_2(channel)$$

MASS RESOLUTION

The velocity from ToF measurement

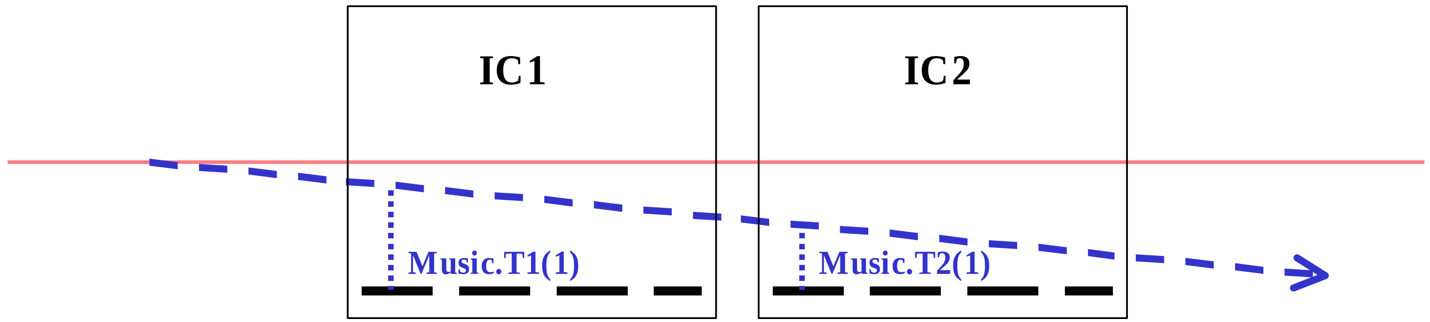
$$\upsilon_{TOF} = \frac{s}{ToF} = \frac{s_0 \cdot \left(1 + c_\alpha \alpha_x\right) + \Delta s}{T_0 - ToF^*} \qquad \text{with} \qquad \begin{cases} \Delta s = d_1 x_2 + d_2 x_2^2 \\ ToF^* = \dfrac{ToF_L^* \cdot \alpha_L + ToF_R^* \cdot \alpha_R}{2} \end{cases}$$

The flight path, s, differs from s_0 for two reasons:

- $(1+c_\alpha \alpha_x)$ = fragments acquire a transversal momentum → enter the 2nd section of FRS with different angles
- ΔS = fragments with different $B\rho$ enter the 2nd section of FRS with different x_2-positions → different paths along FRS

MASS RESOLUTION

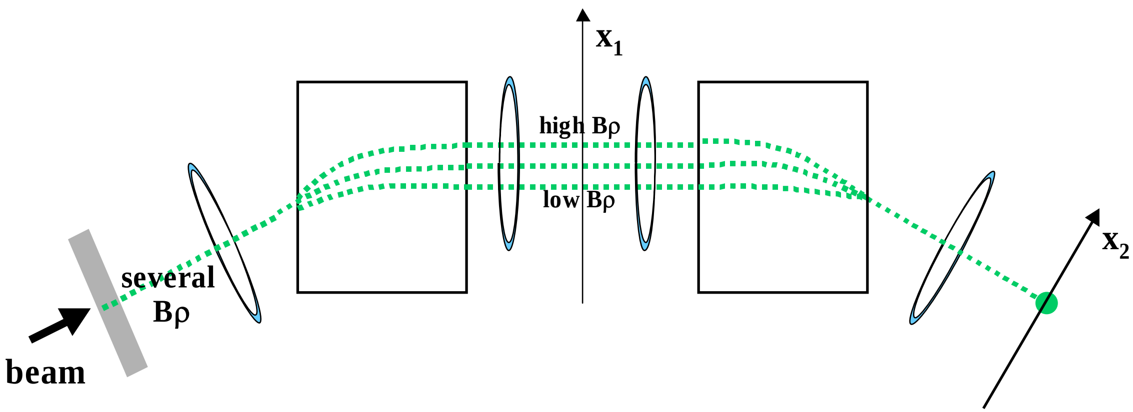
$(1+c_\alpha \alpha_x)$ = fragments acquire a transversal momentum → enter the 2nd section of FRS with different angles

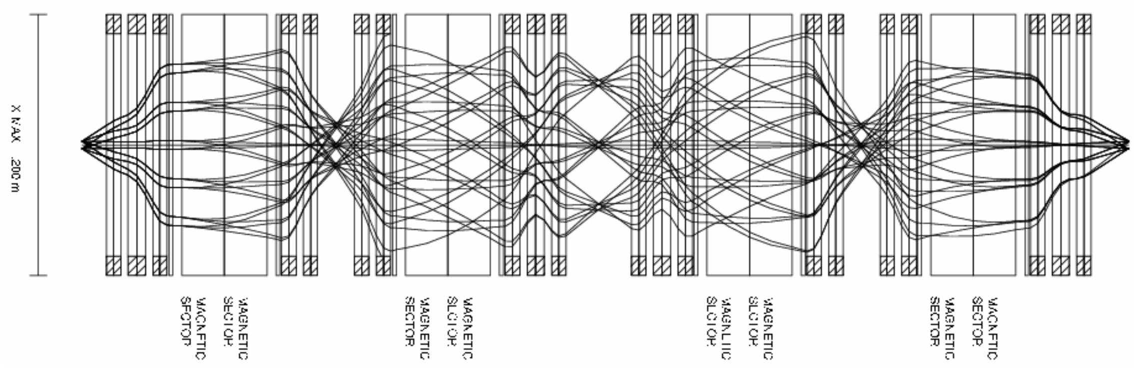


MASS RESOLUTION

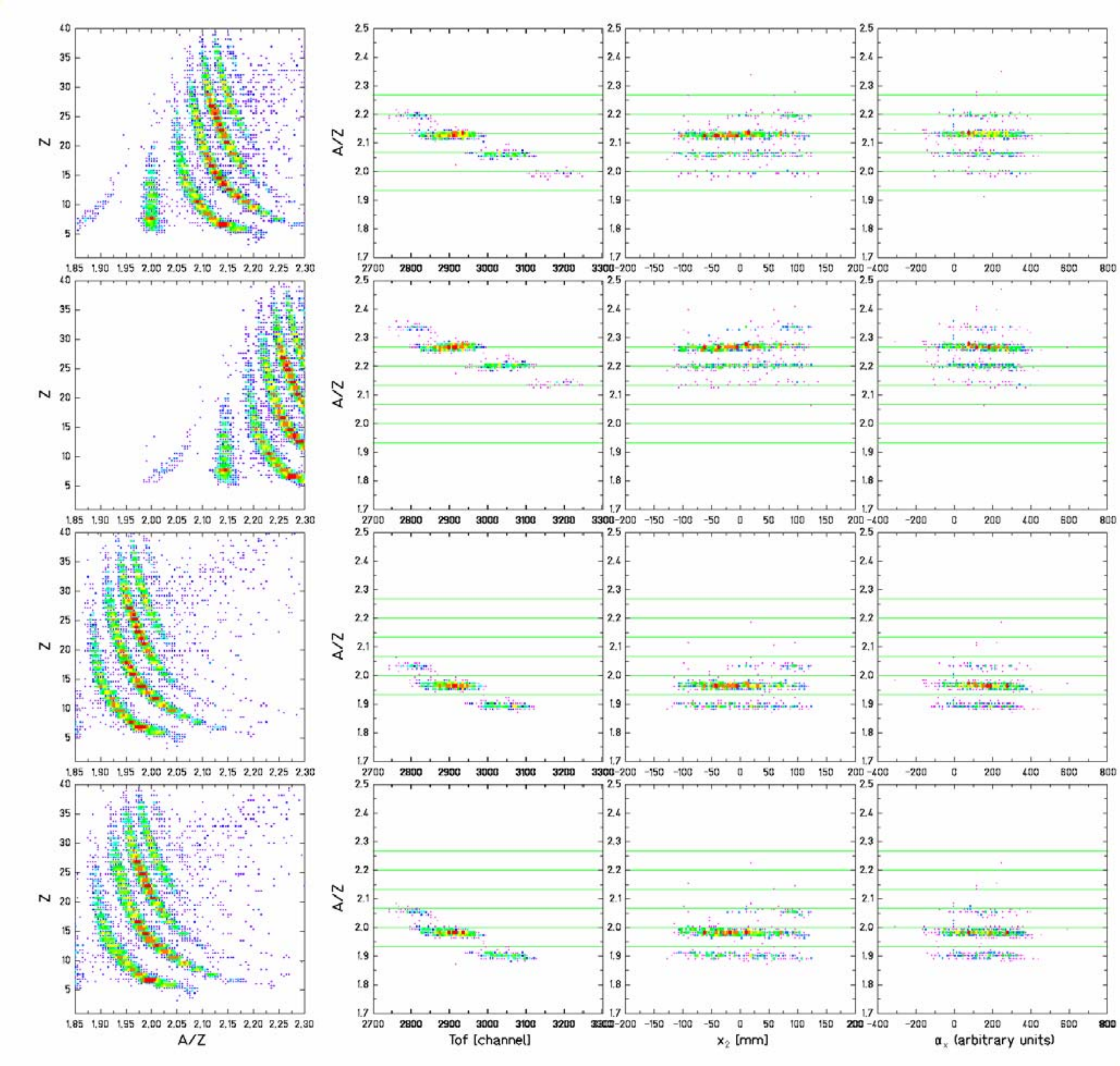
ΔS = fragments with different $B\rho$ enter the 2nd section of FRS with different x_2-positions → different paths along FRS

Linear + quadratic term





A check for determining the good parameters

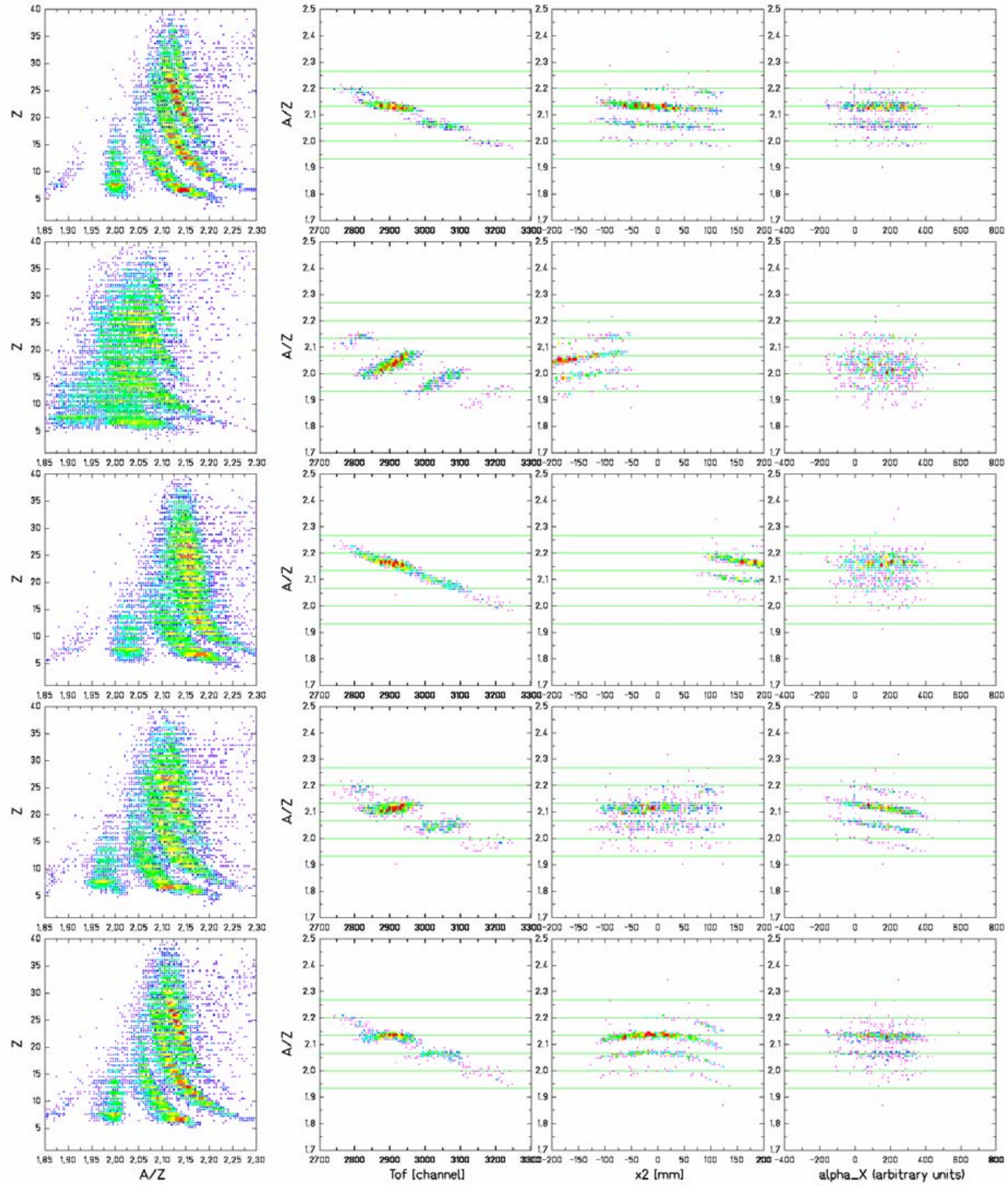


OK

wrong T_0

wrong s_0

wrong α_R



wrong D_2

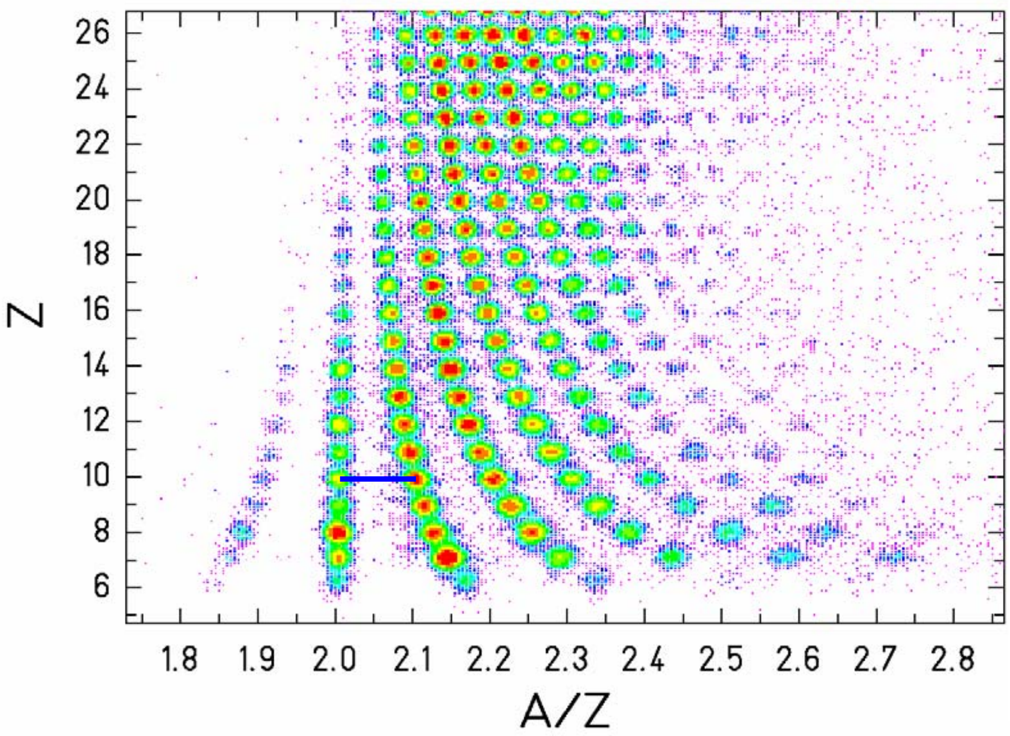
wrong a_2

wrong b_2

wrong c_α

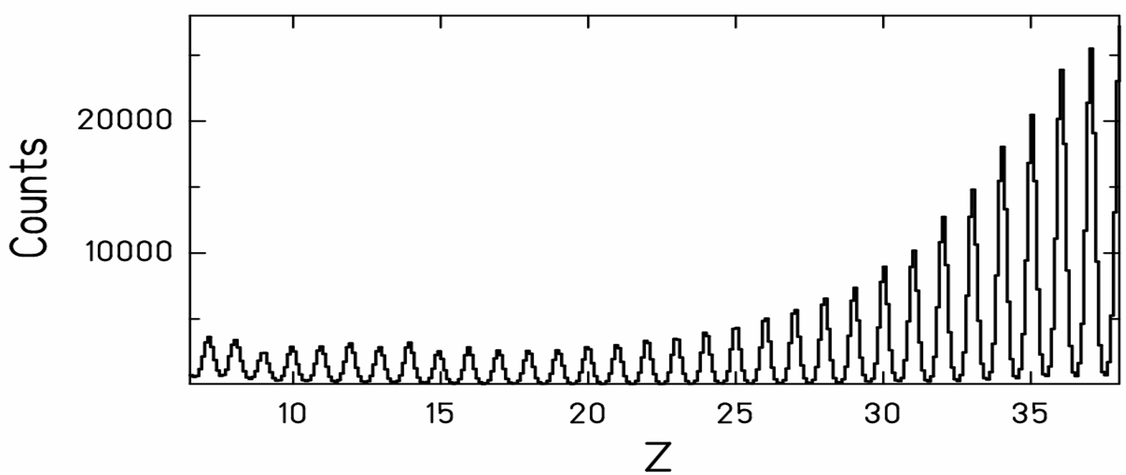
wrong d_2

RESOLUTION AND IDENTIFICATION

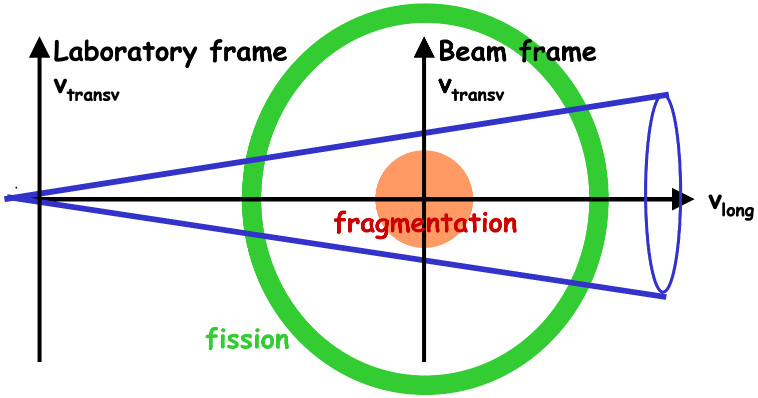


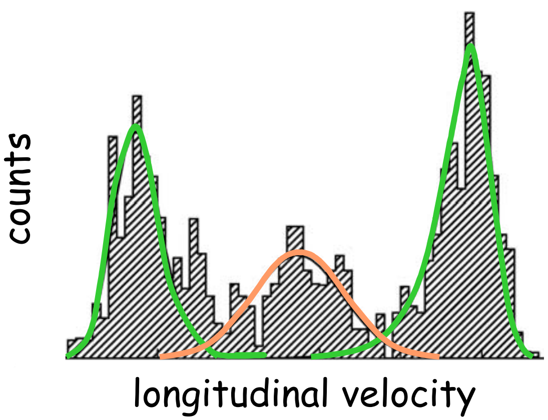
$$Z = \frac{-a_1 \pm \sqrt{a_1^2 - 4a_2(a_0 - \Delta E)}}{2a_2} + 4$$

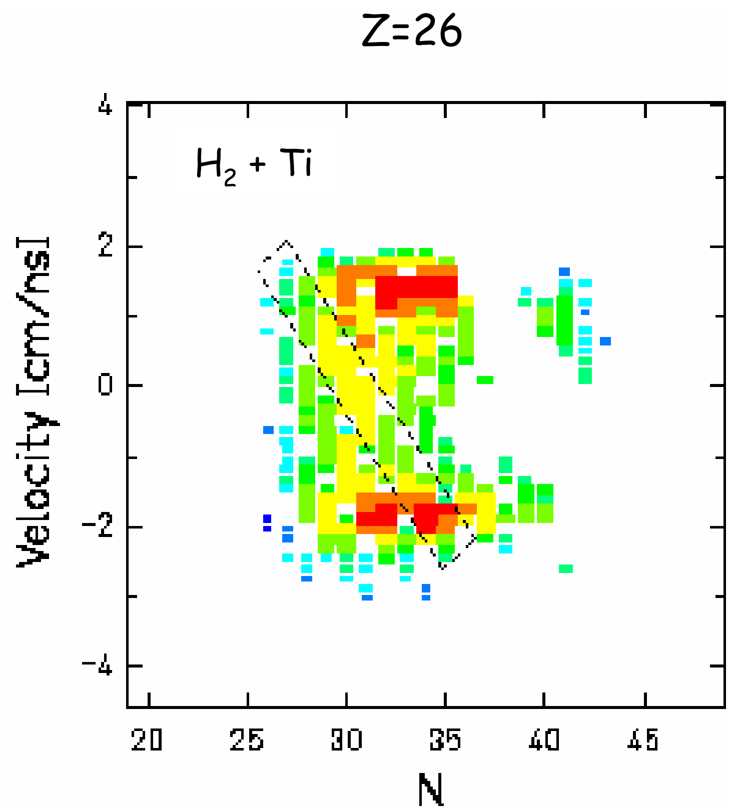
$$P = \frac{1}{((A+1)/Z) - (A/Z)} = Z$$



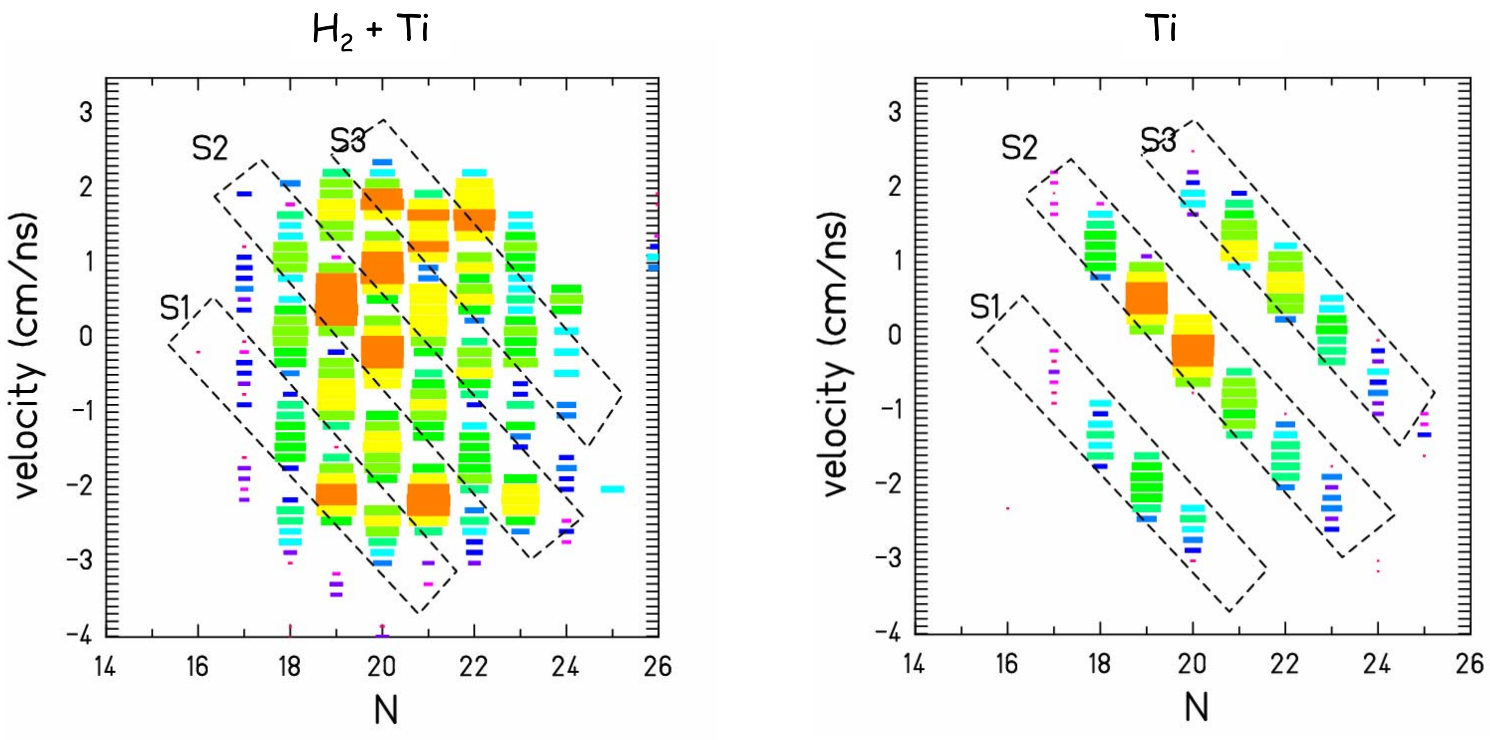
DETERMINATION OF THE VELOCITY







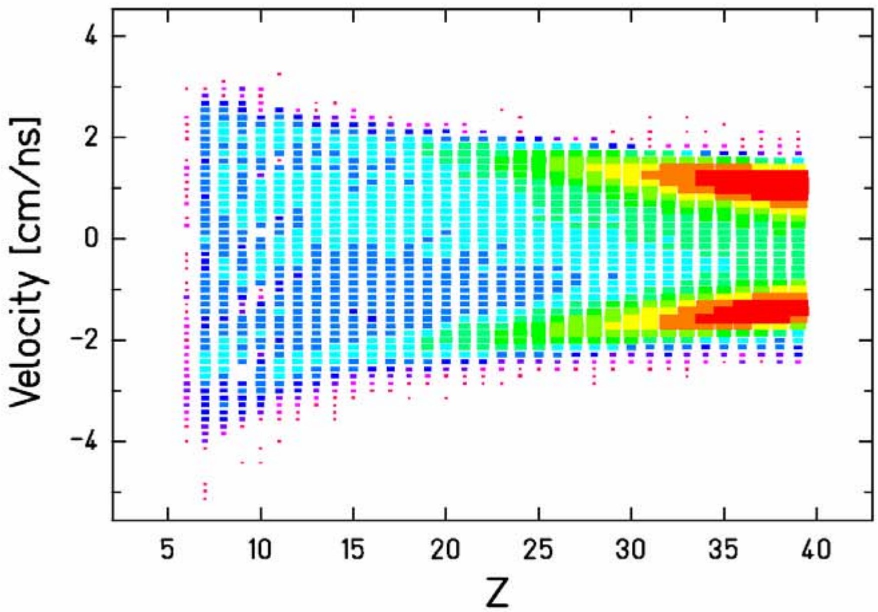
DETERMINATION OF THE VELOCITY



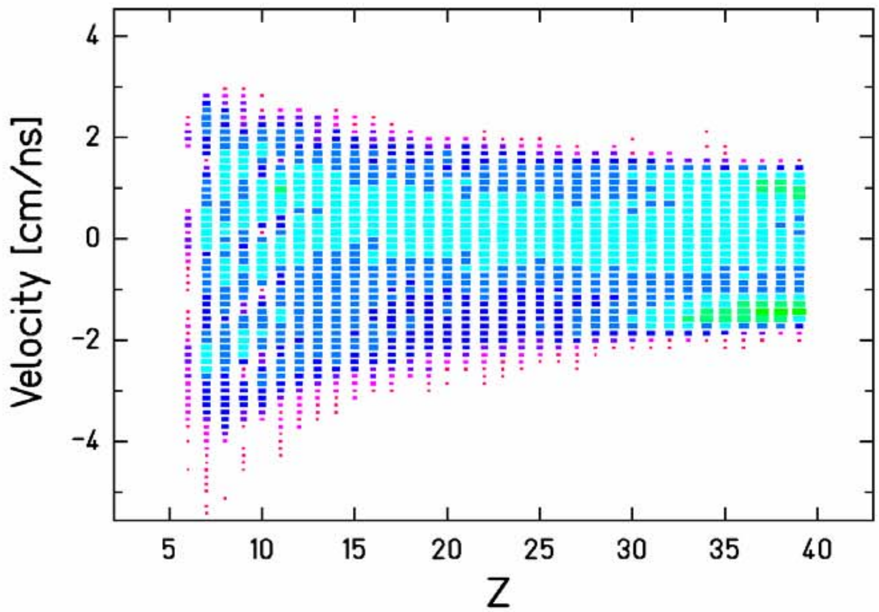
Too few settings for the dummy target!

VELOCITY SPECTRA FOR ALL RESIDUES

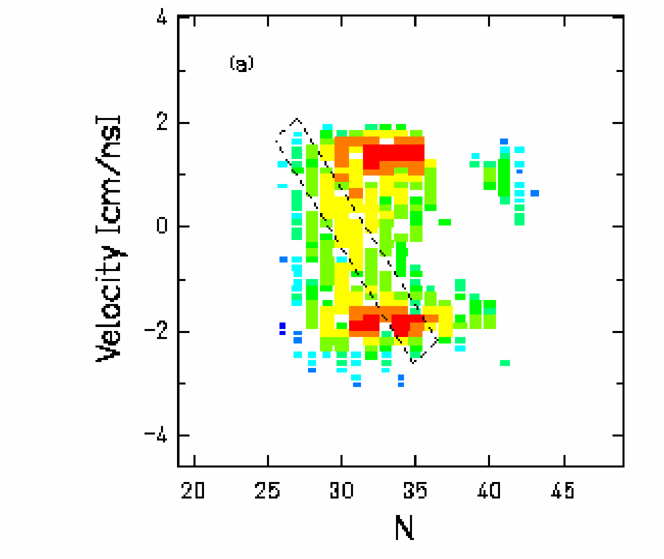
hydrogen+titanium

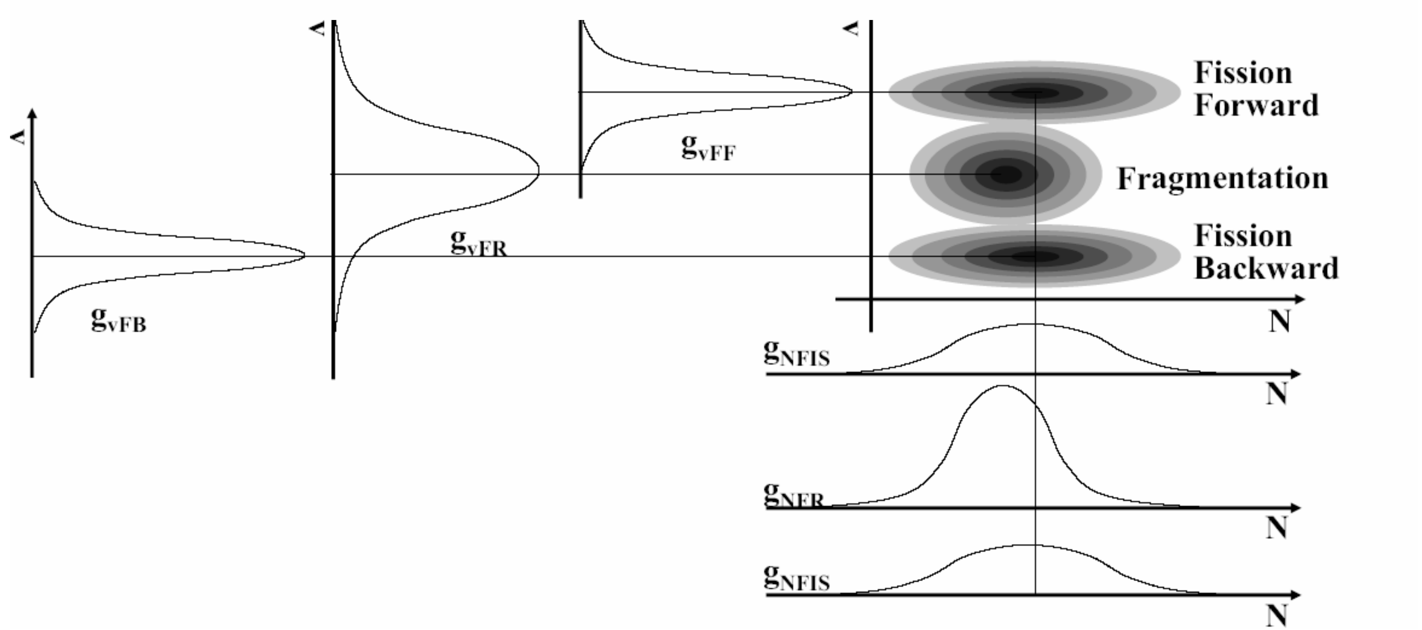


titanium alone

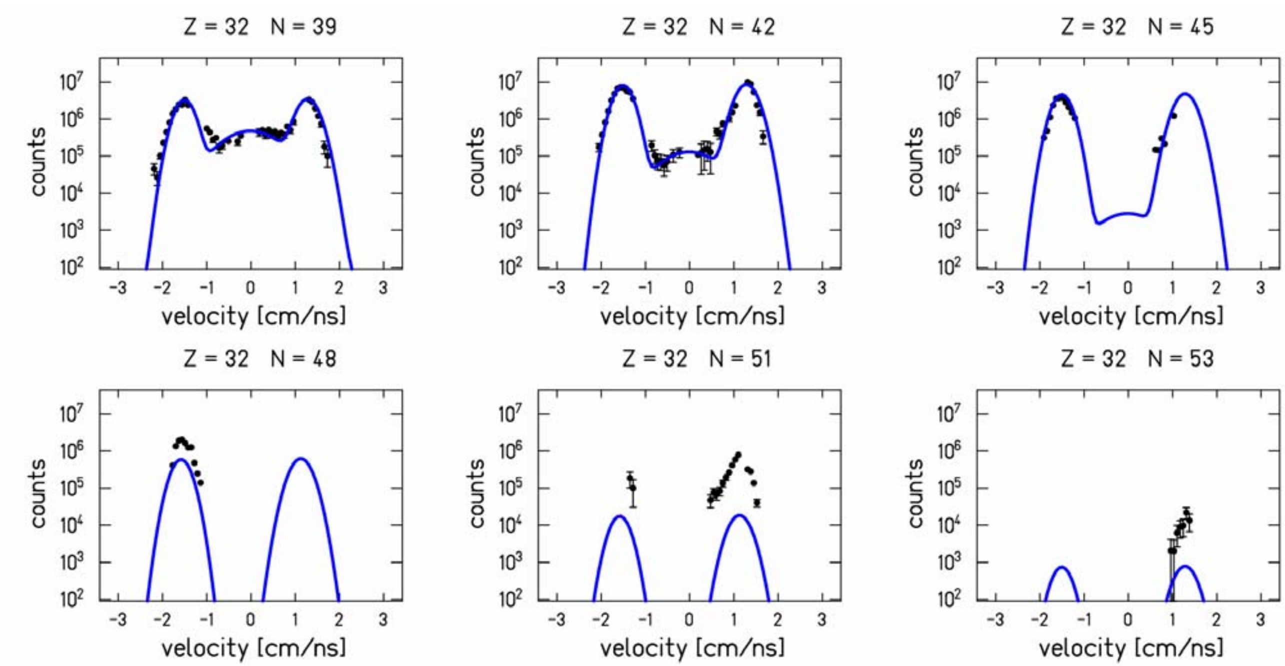


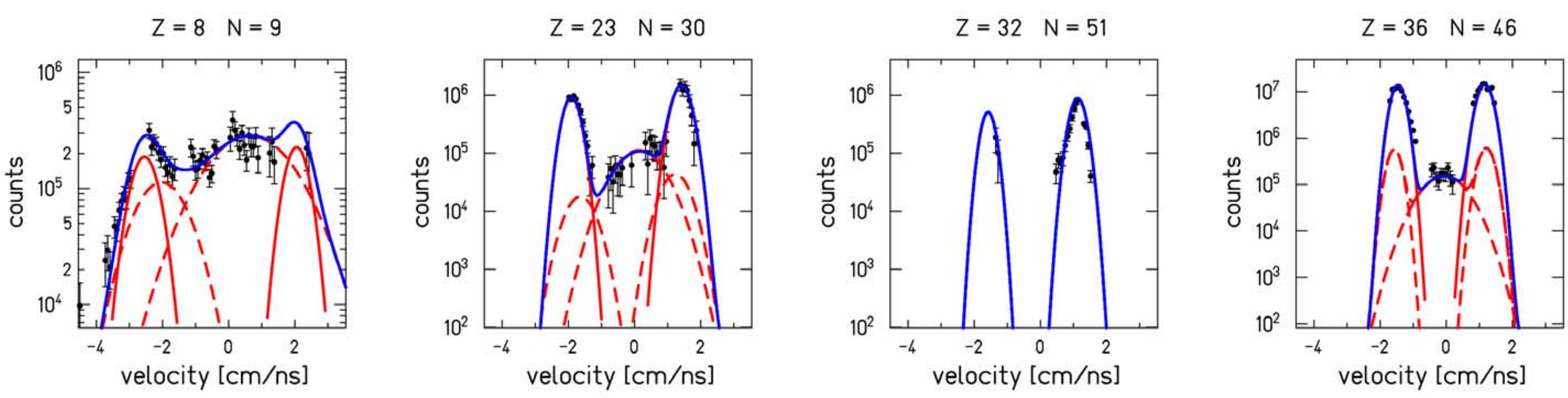
THE GLOBAL FIT





THE GLOBAL FIT AND THE INDIVIDUAL FIT

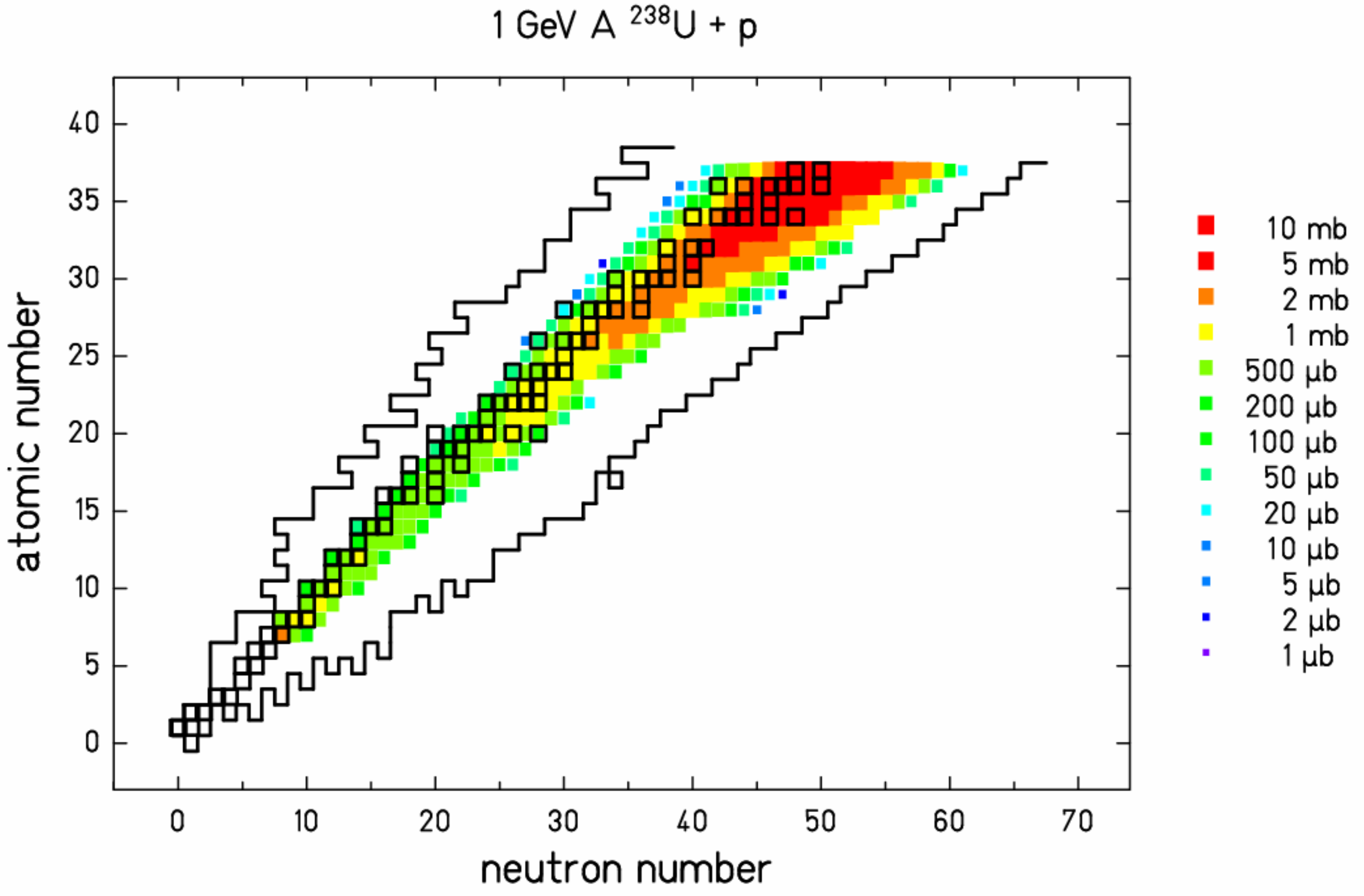




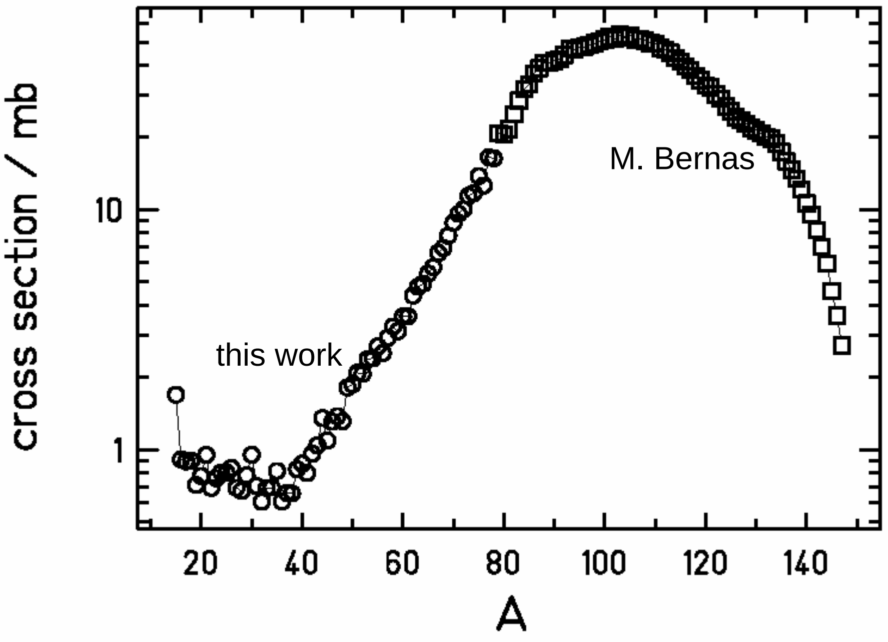
PART II:

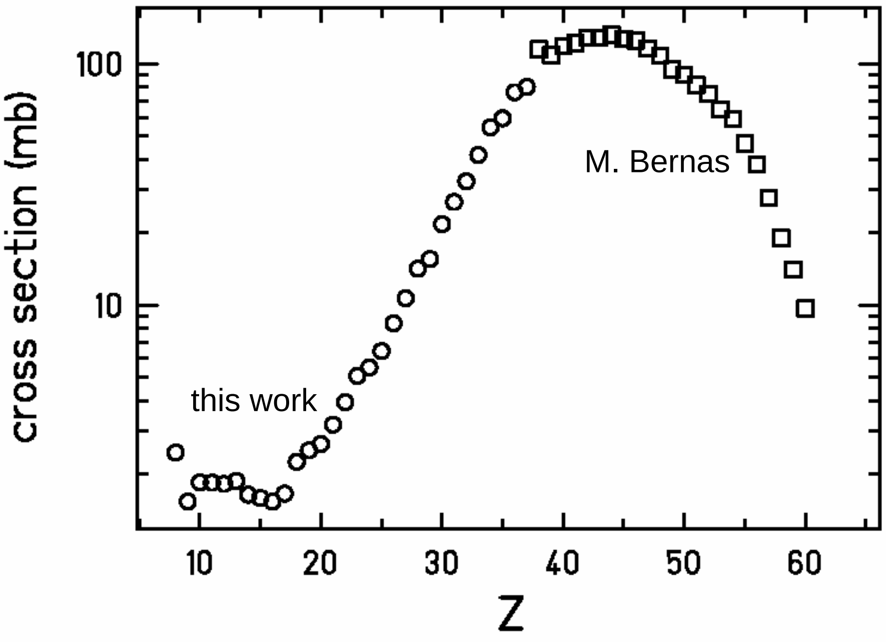
RESULTS

CROSS SECTIONS OF THE LIGHT RESIDUES



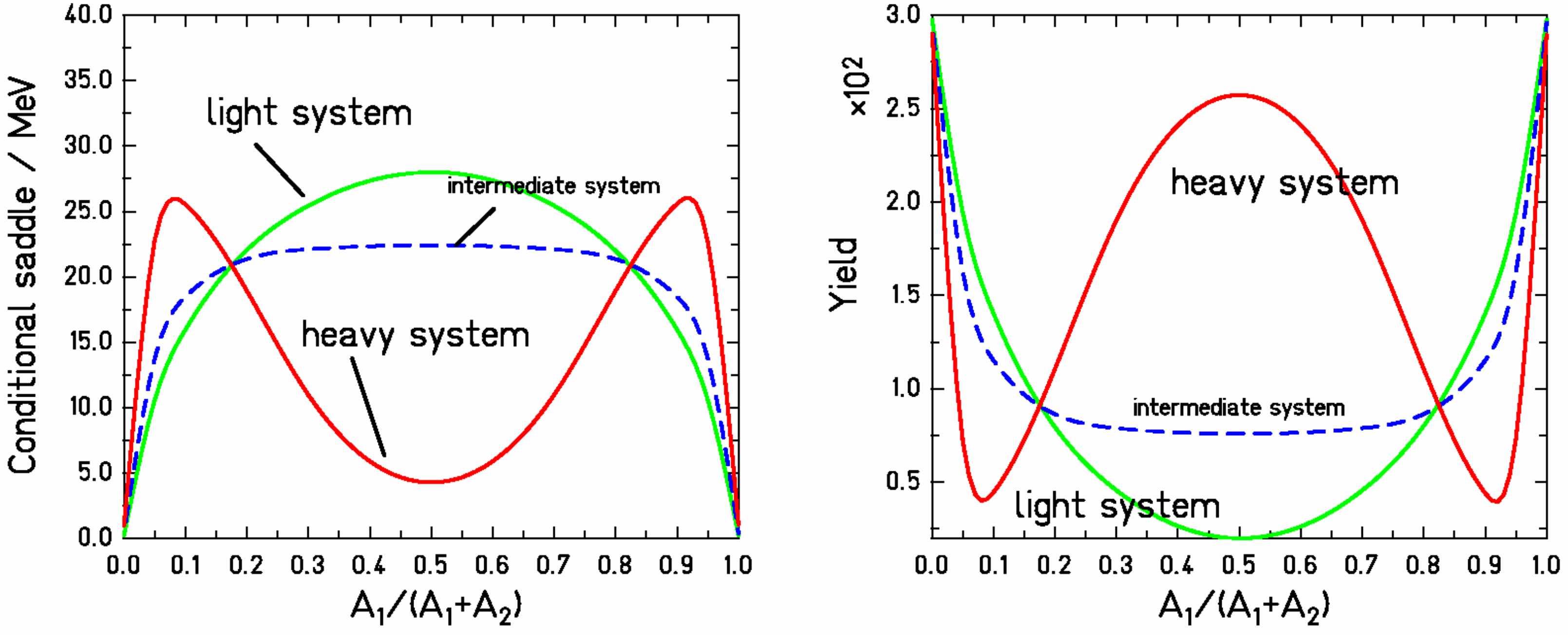
CROSS SECTIONS: MASS AND CHARGE DISTRIBUTIONS



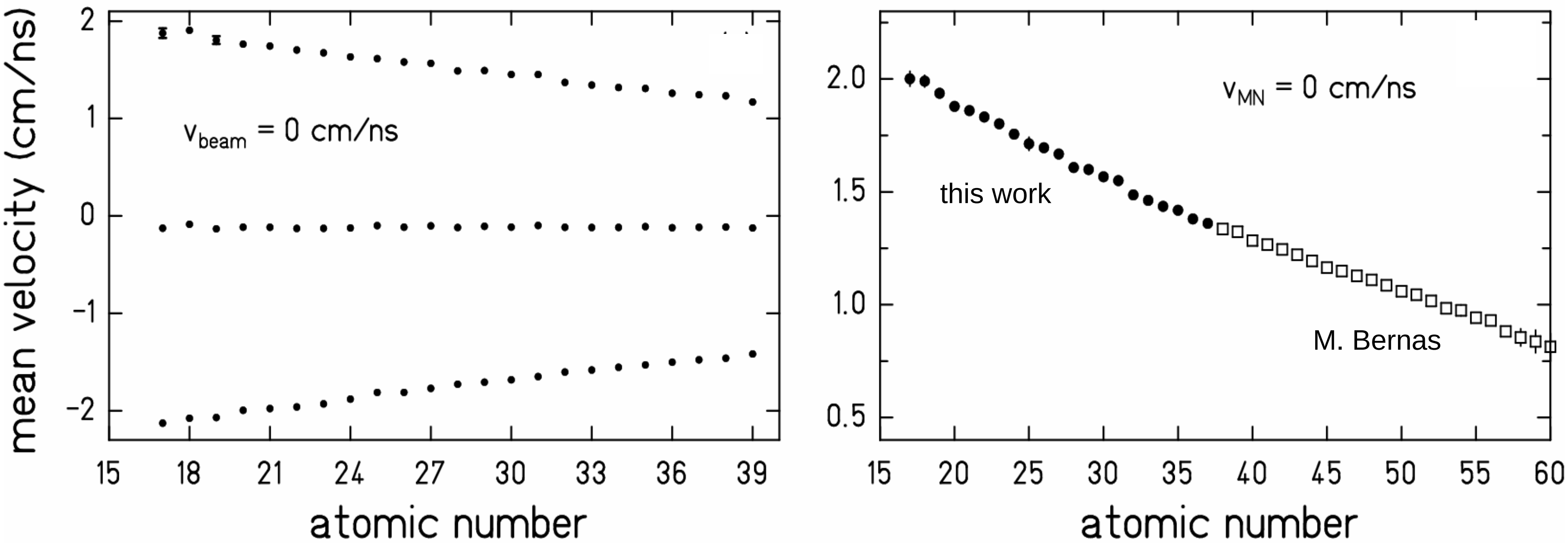


TRANSITION FROM FISSION TO EVAPORATION

Mass distribution: the statistical transition-state model



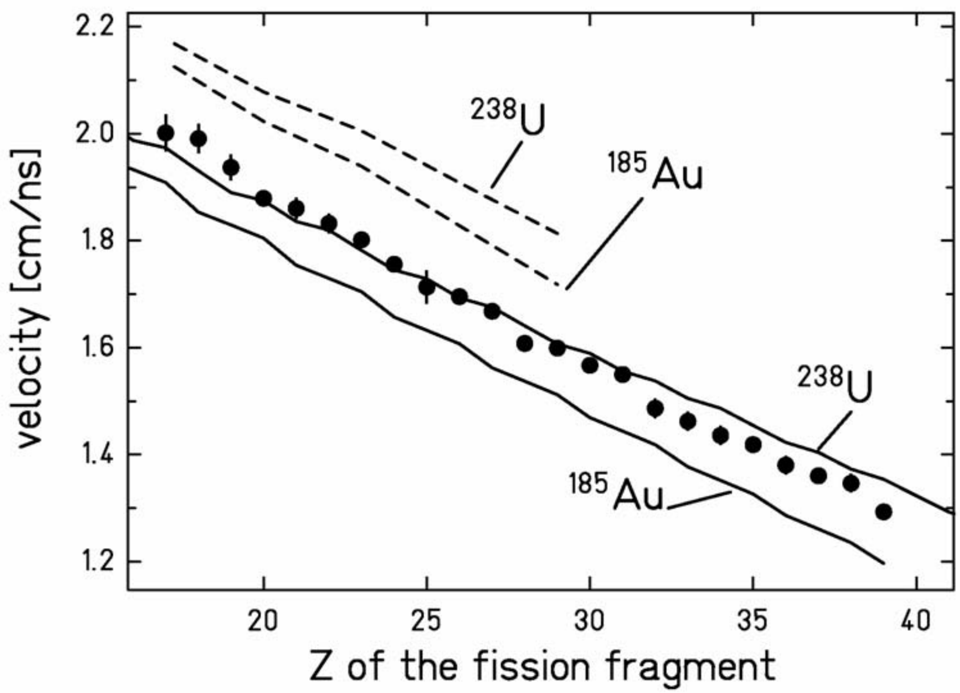
VELOCITY OF THE RESIDUES



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



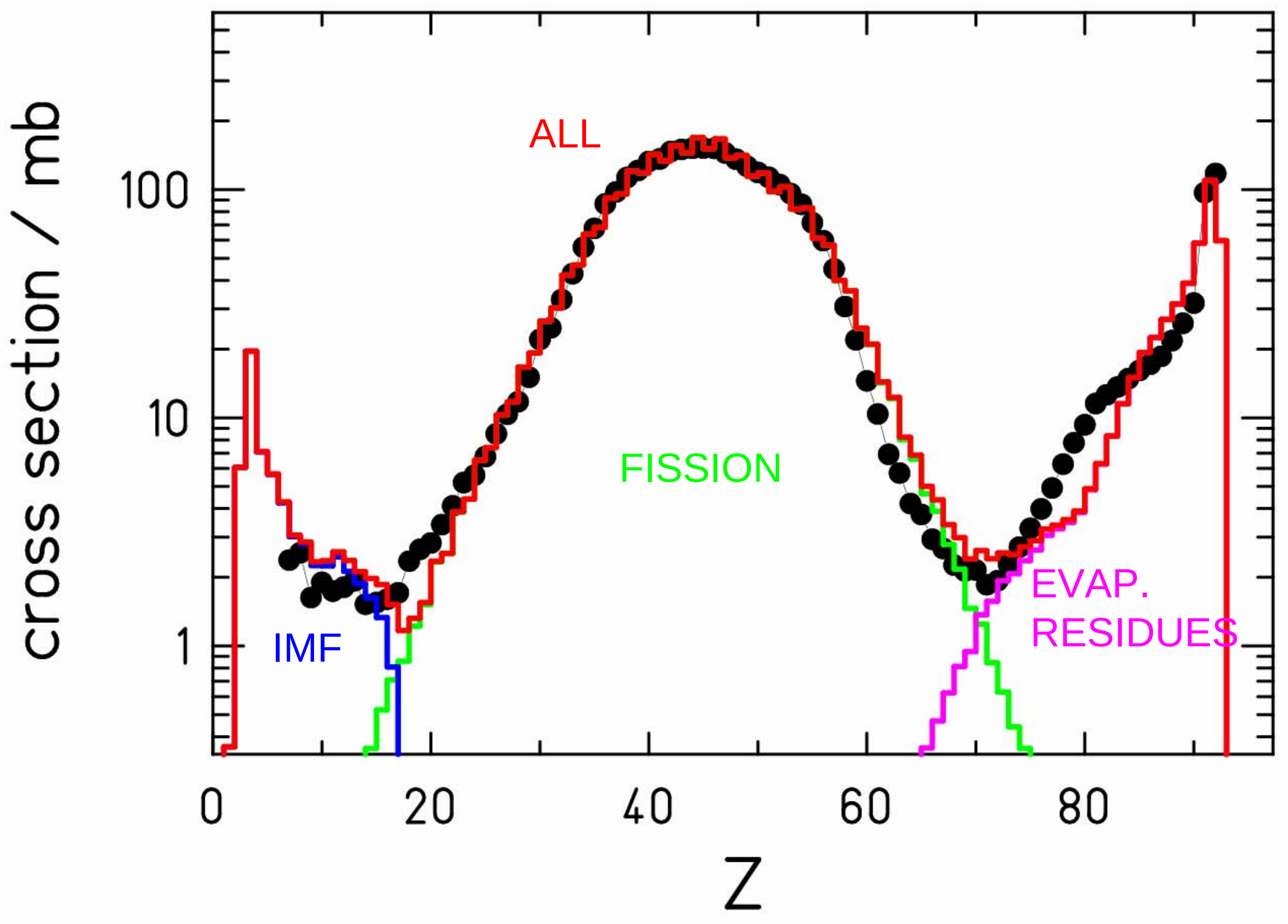
- Mean velocities in the frame of the fissioning nucleus

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

—— scission-point model (deformed nuclei)

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

RESULT FOR 1 GeV p on ^{238}U



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

The experimental data:

- Production cross-sections for every isotope + velocity distributions

The data analysis:

- Details available in my PhD Thesis

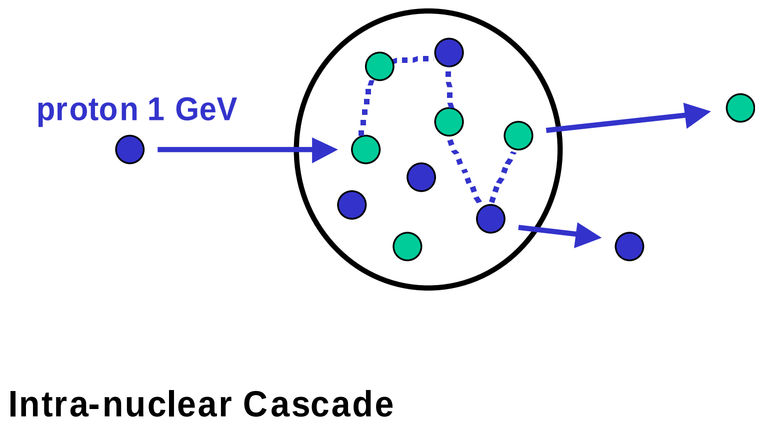
The physics:

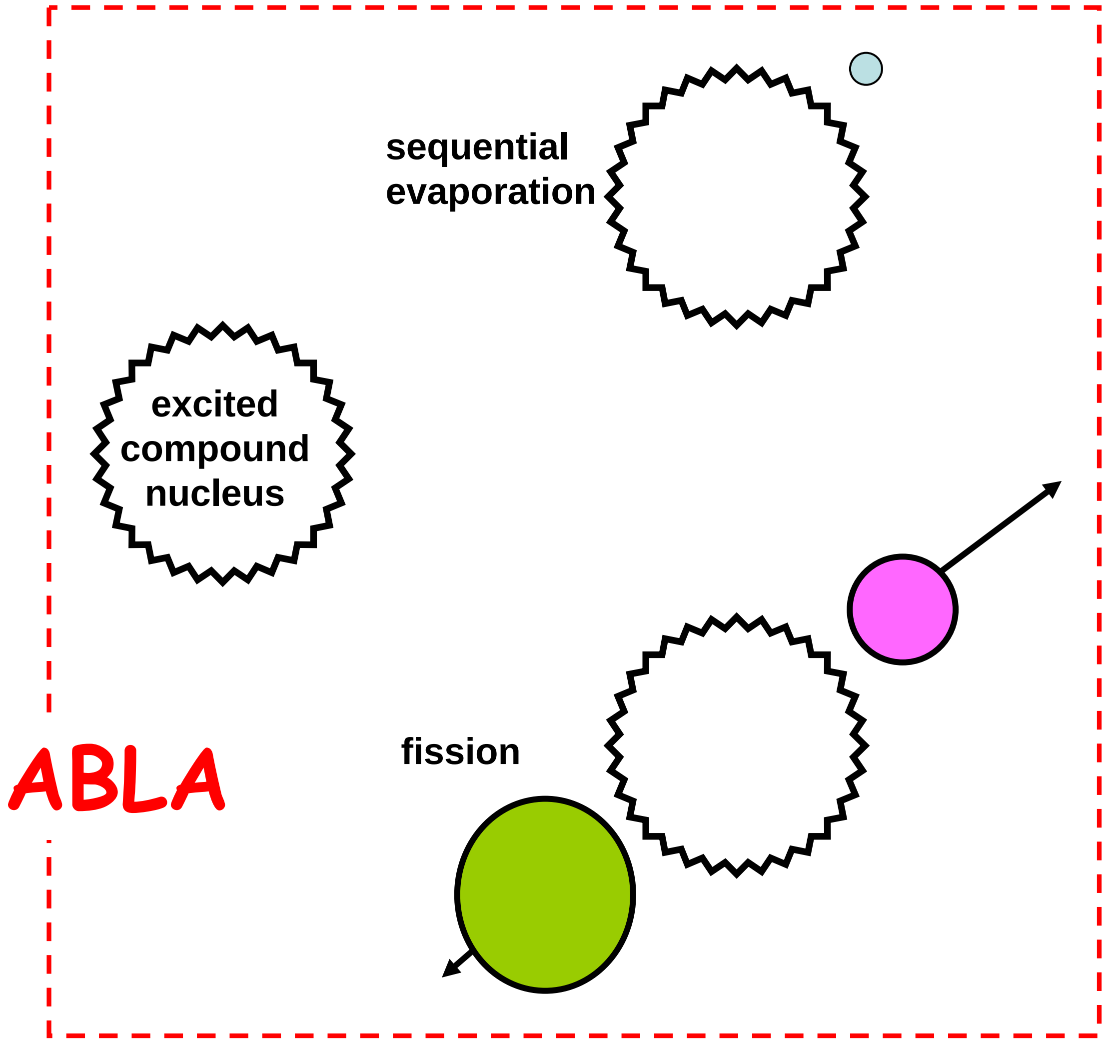
- Yields and velocities of light nuclides from 1 A·GeV ^{238}U + p indicate a transition from fission to evaporation
- The experimental data could be successfully reproduced by a statistical model, combining a fission approach with the evaporation of intermediate-mass fragments
- No indications for a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

The paper:

- accepted in Phys. Rev. C.

OUR STATISTICAL MODEL





THE FISSION MODEL: THE FISSION PROBABILITIES

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

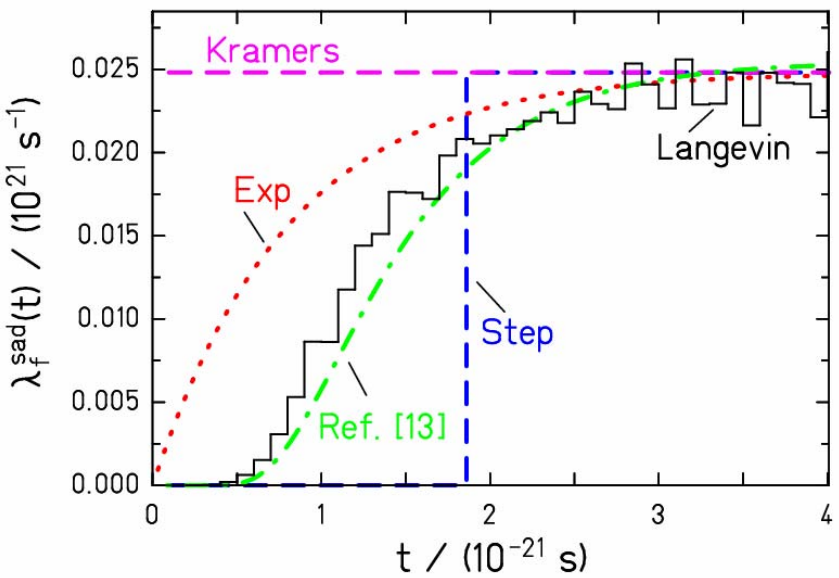
$$\Gamma_f^{BW} \approx T_f \frac{\rho_f(E-B_f)}{\rho_C(E)}$$

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)

The modeling of the potential for very asymmetric fission is missing

We use another approach...

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

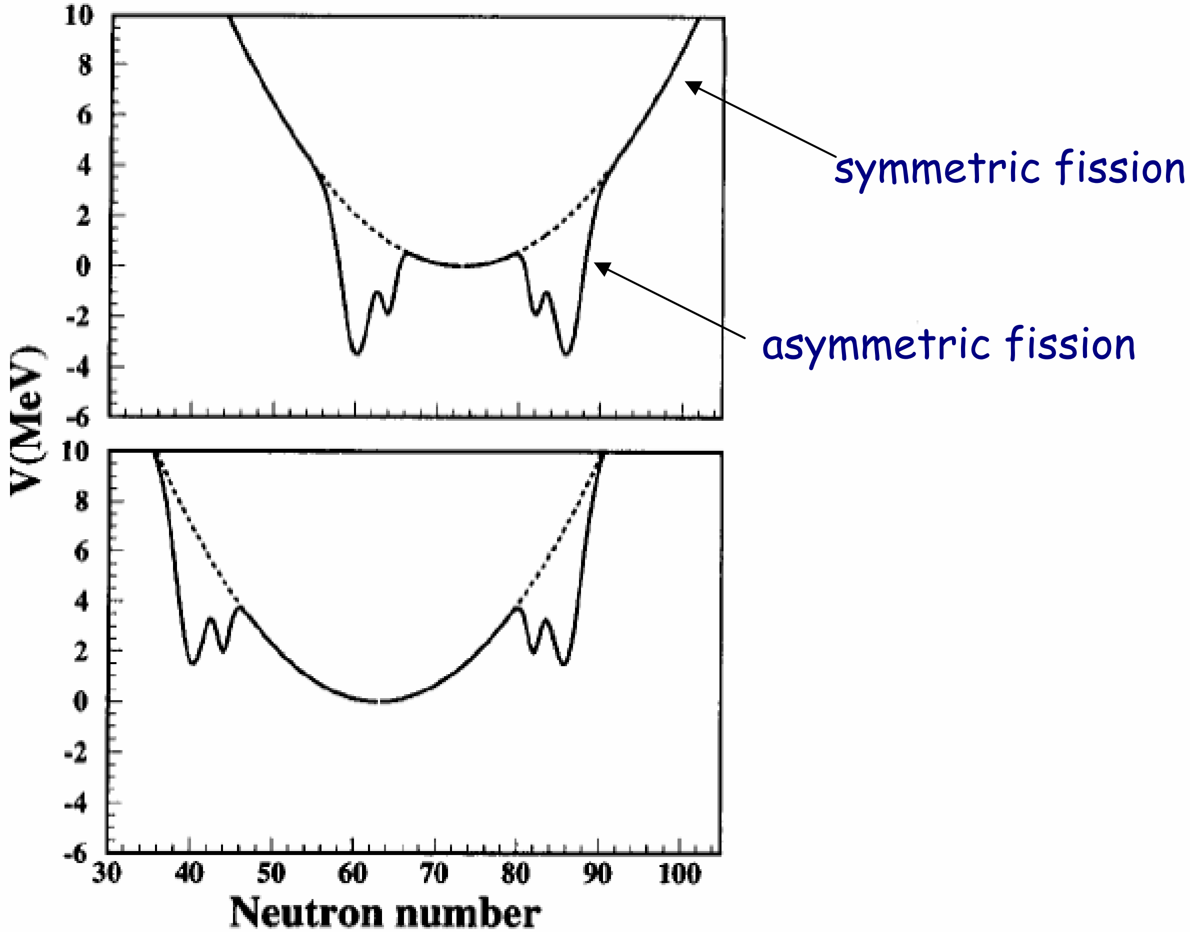


Fig. 1. Potential energy at the fission barrier for ^{238}U (upper part) and ^{208}Pb (lower part), as a function of mass asymmetry expressed by the neutron number of one of the preformed fragments.

THE VERY ASYMMETRIC FISSION: THE INTERMEDIATE-MASS FRAGMENT EMISSION

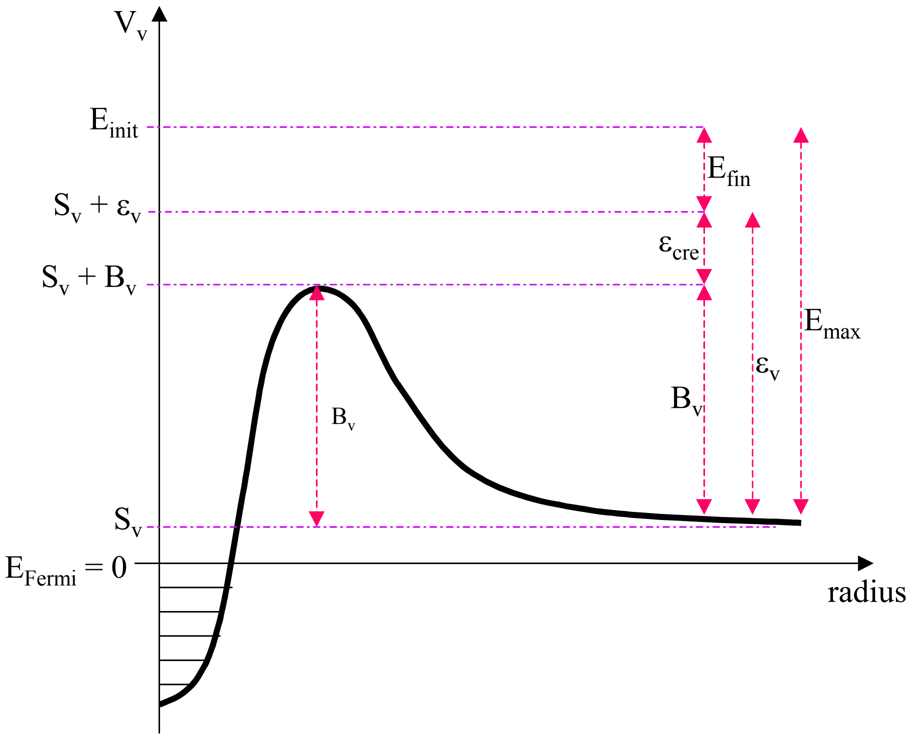
IMF decay width

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

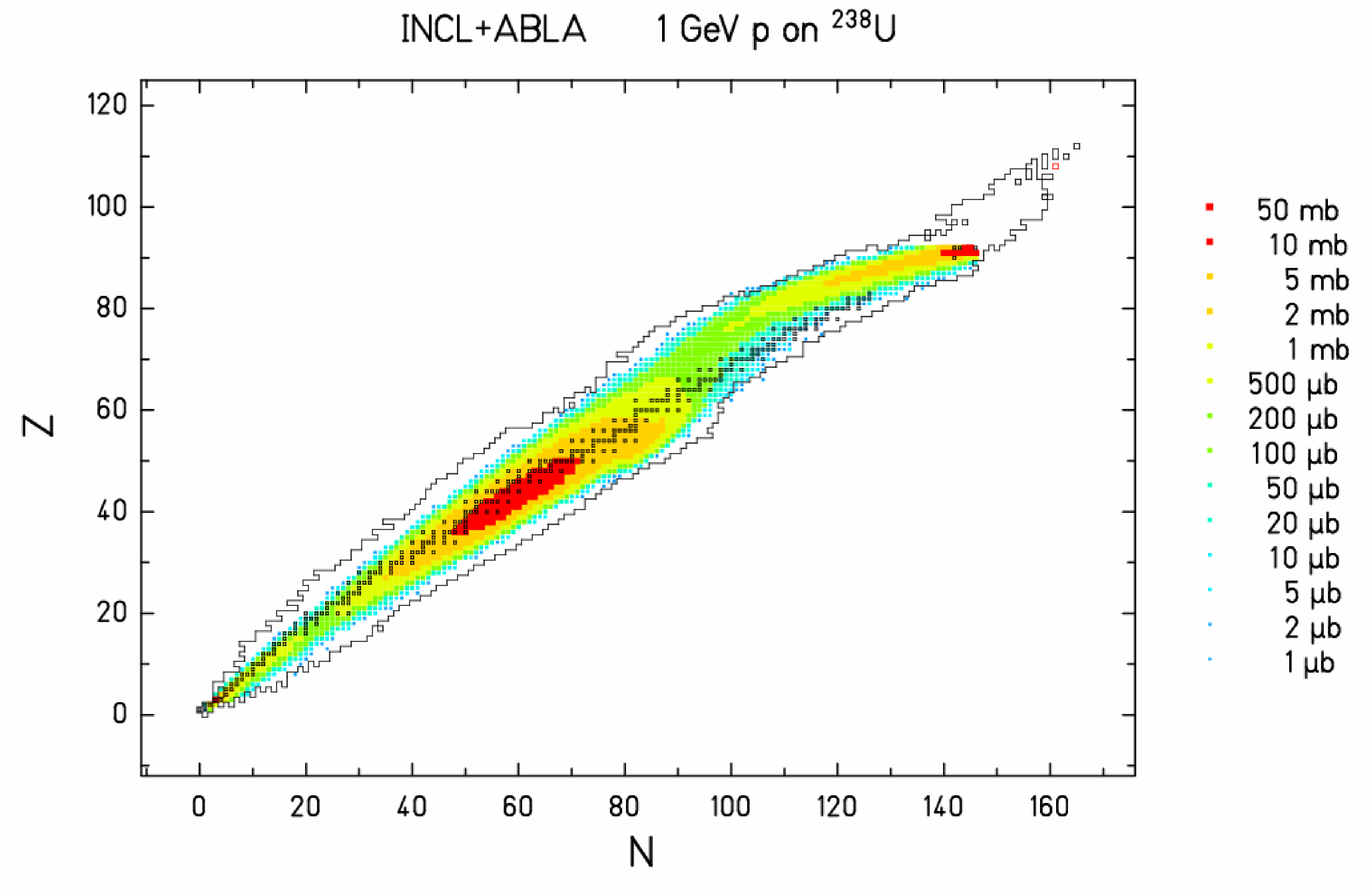
level density of the compound nucleus

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



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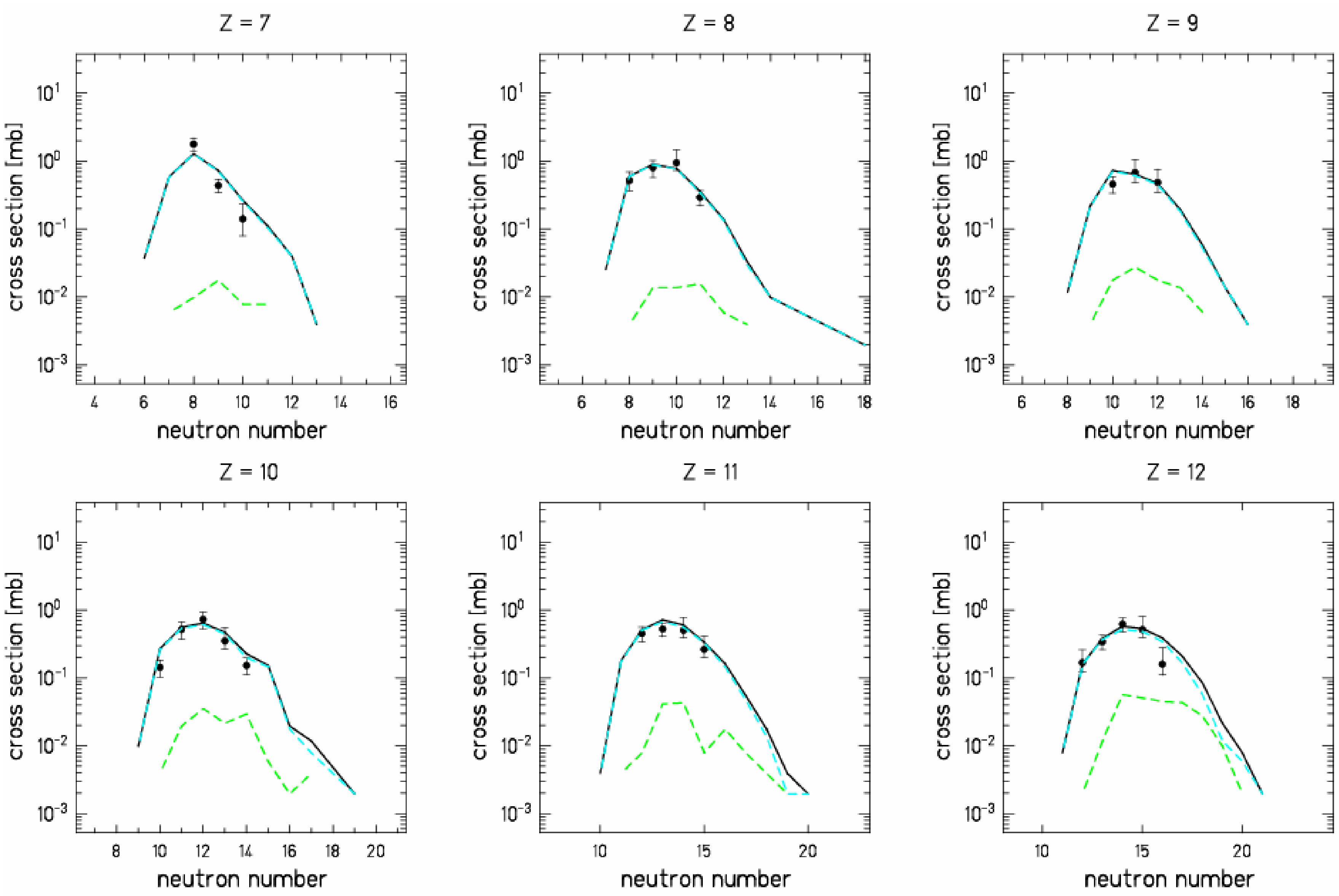
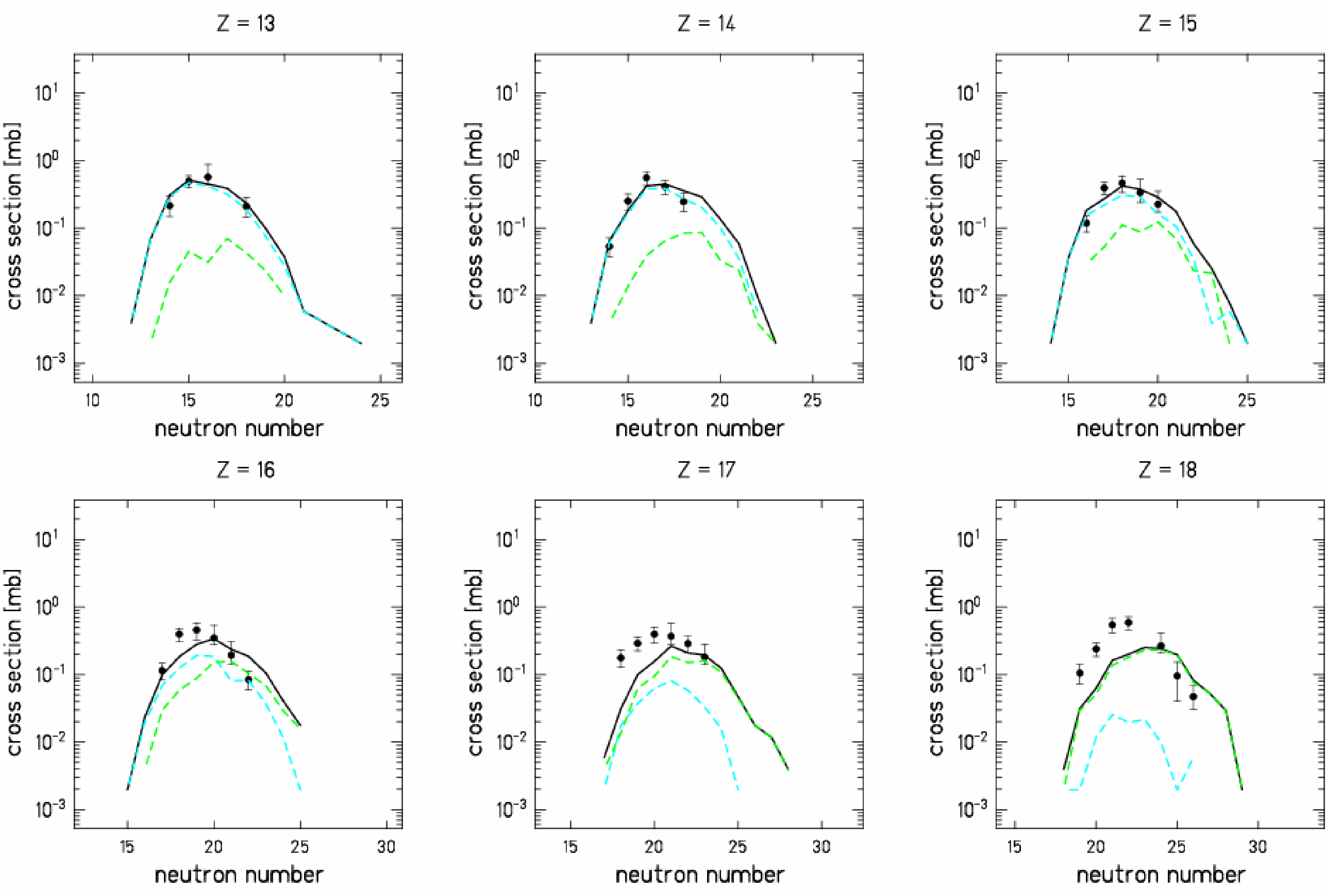


RESULT FOR 1 GeV p on ^{238}U



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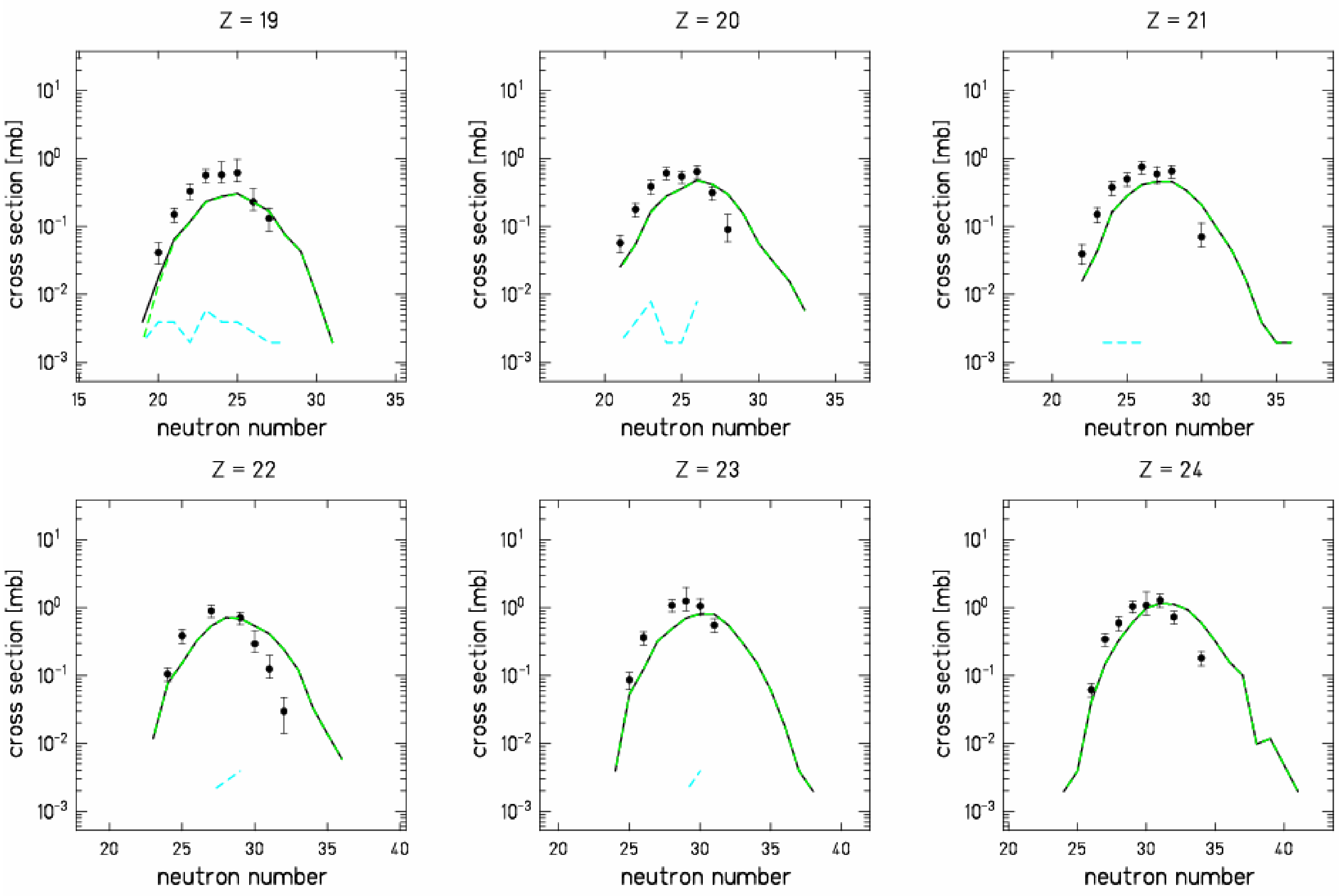
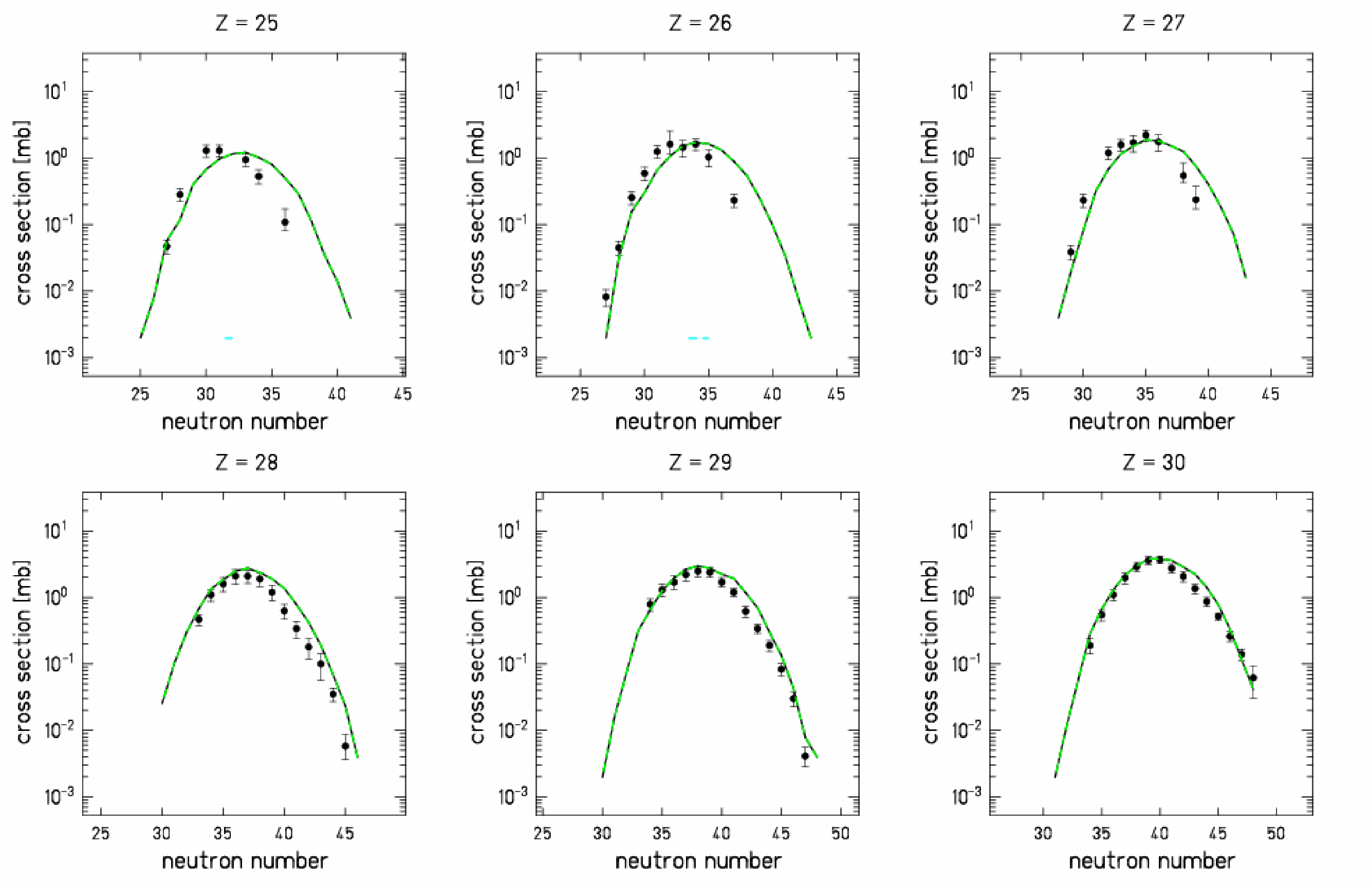
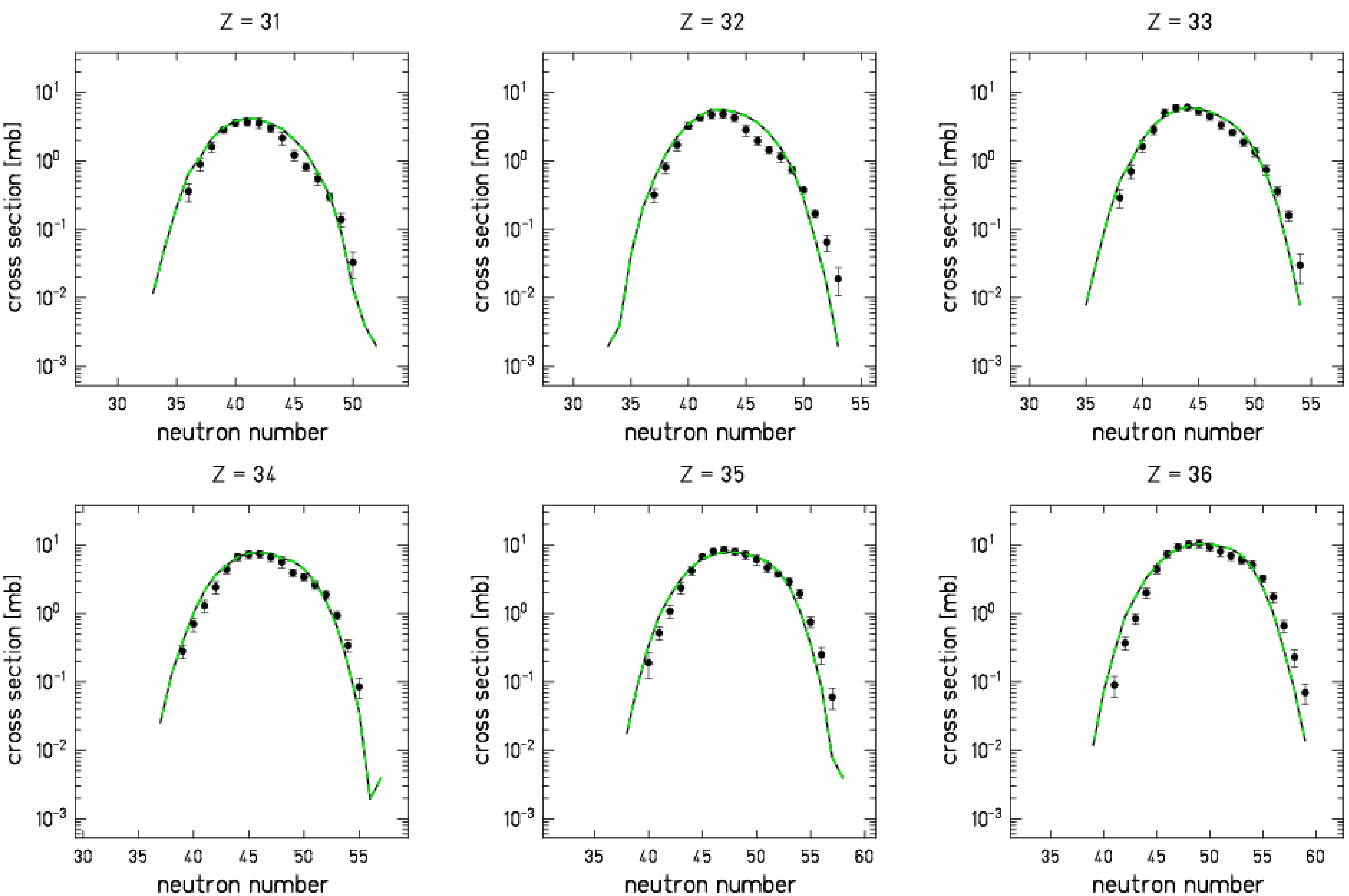


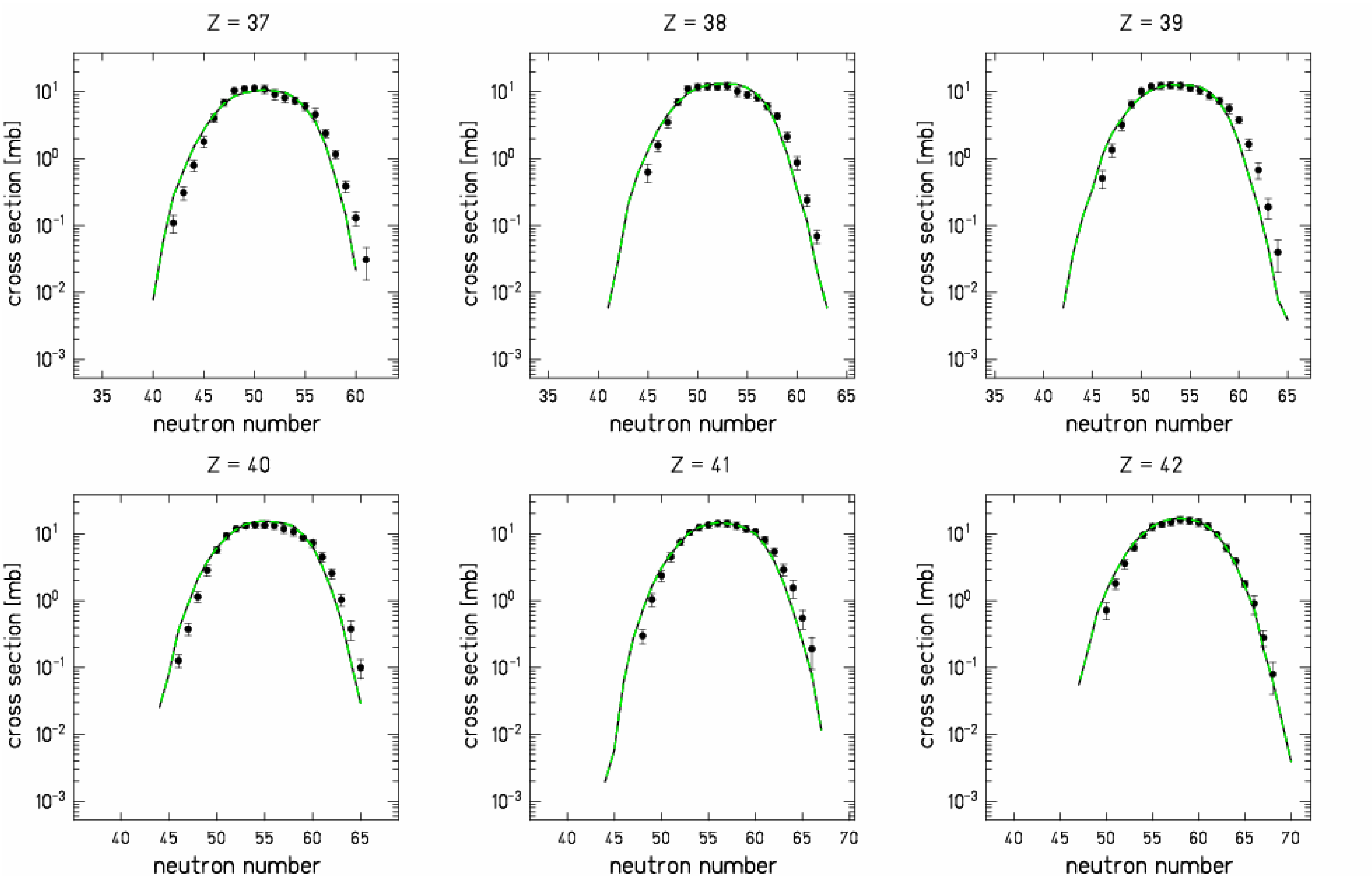
RESULT FOR 1 GeV p on ^{238}U



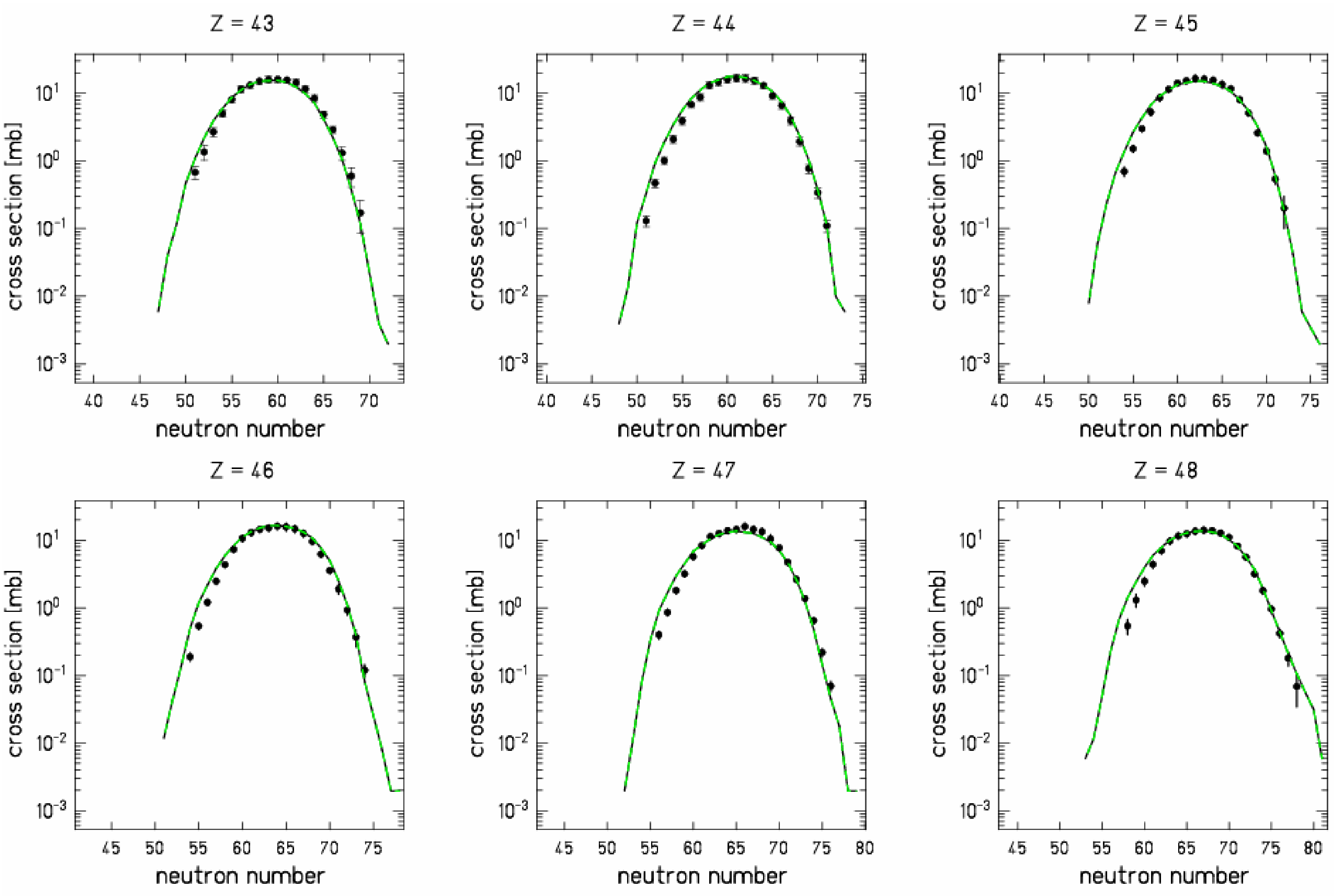
RESULT FOR 1 GeV p on ^{238}U



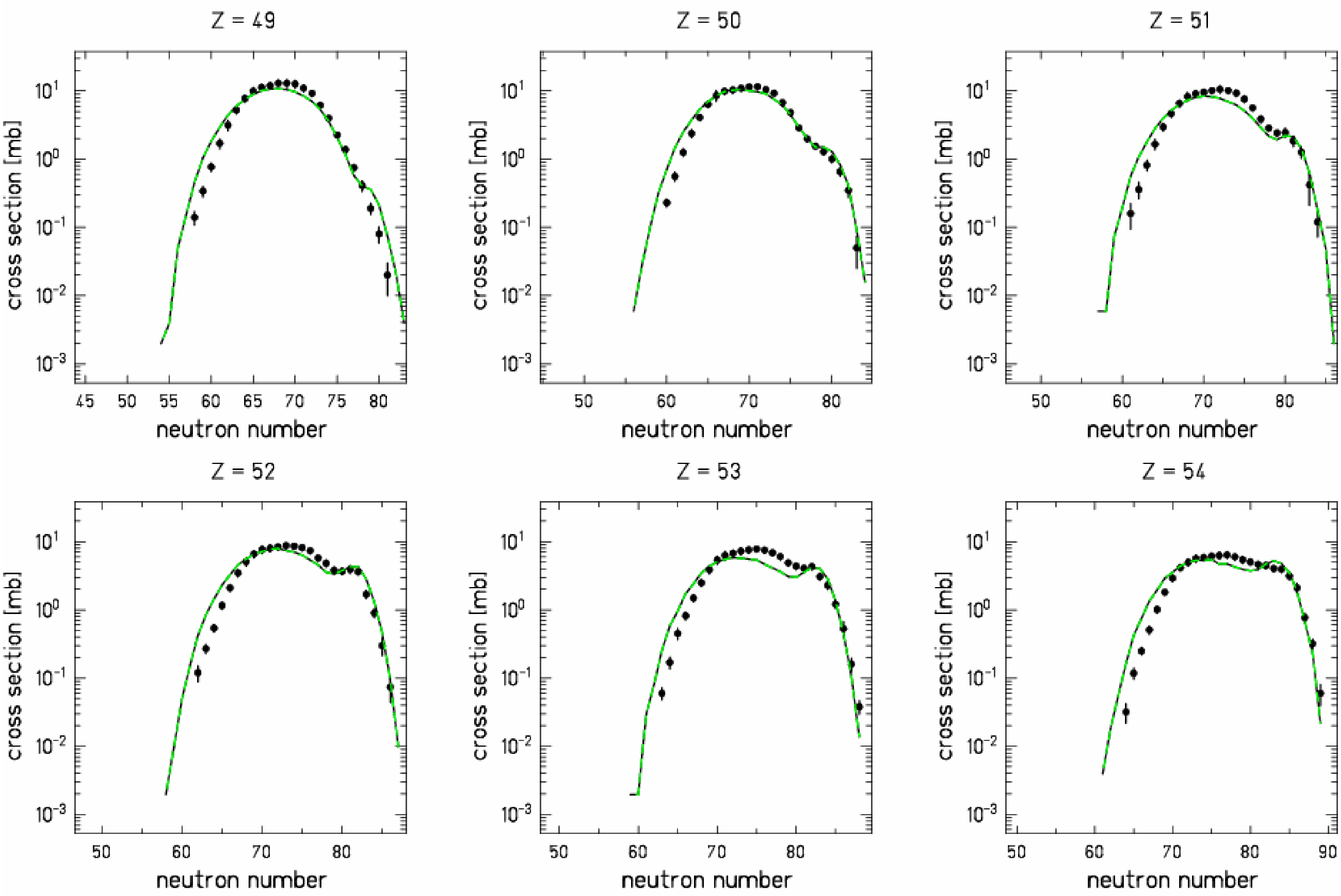
RESULT FOR 1 GeV p on ^{238}U



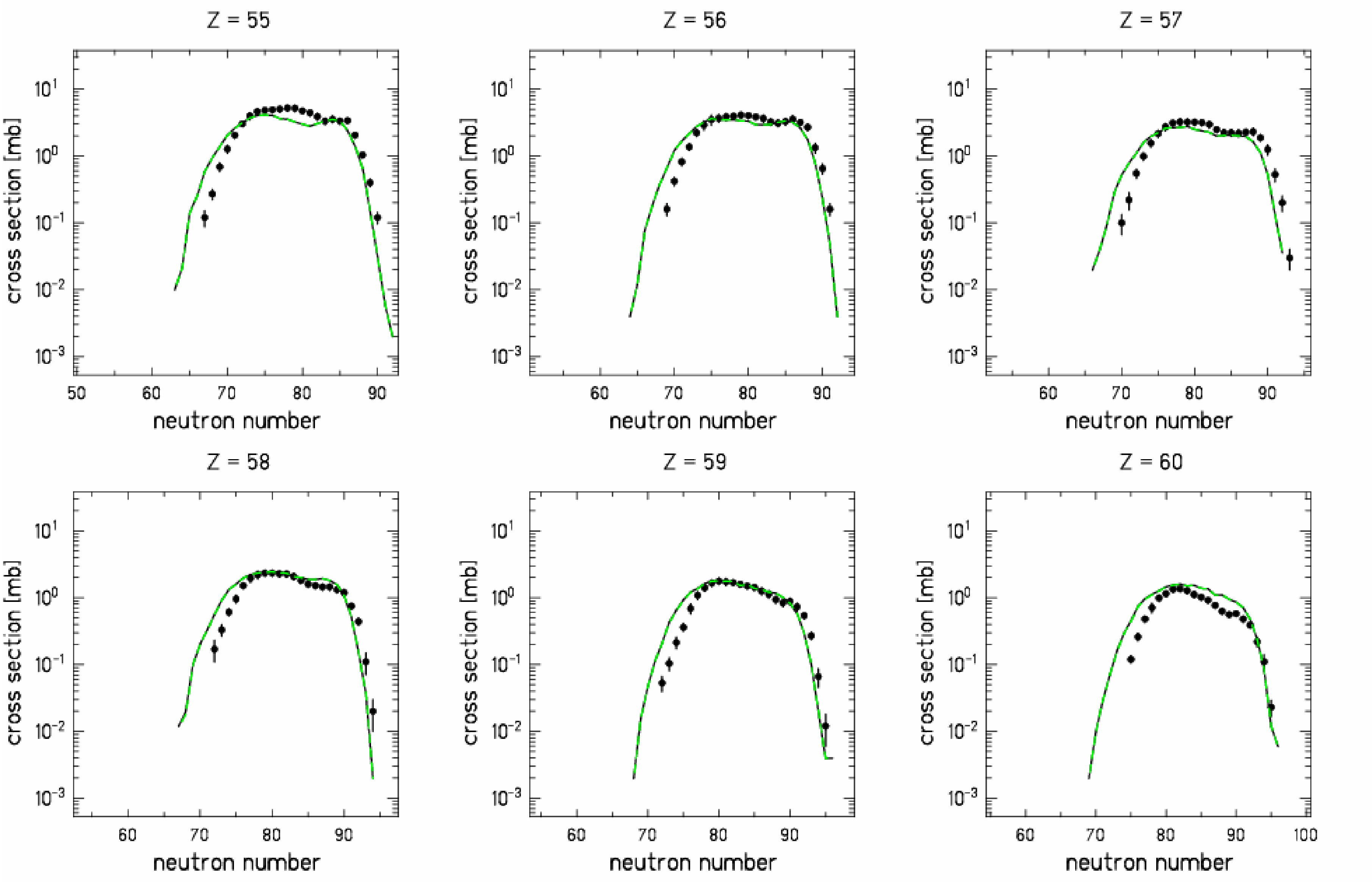
RESULT FOR 1 GeV p on ^{238}U



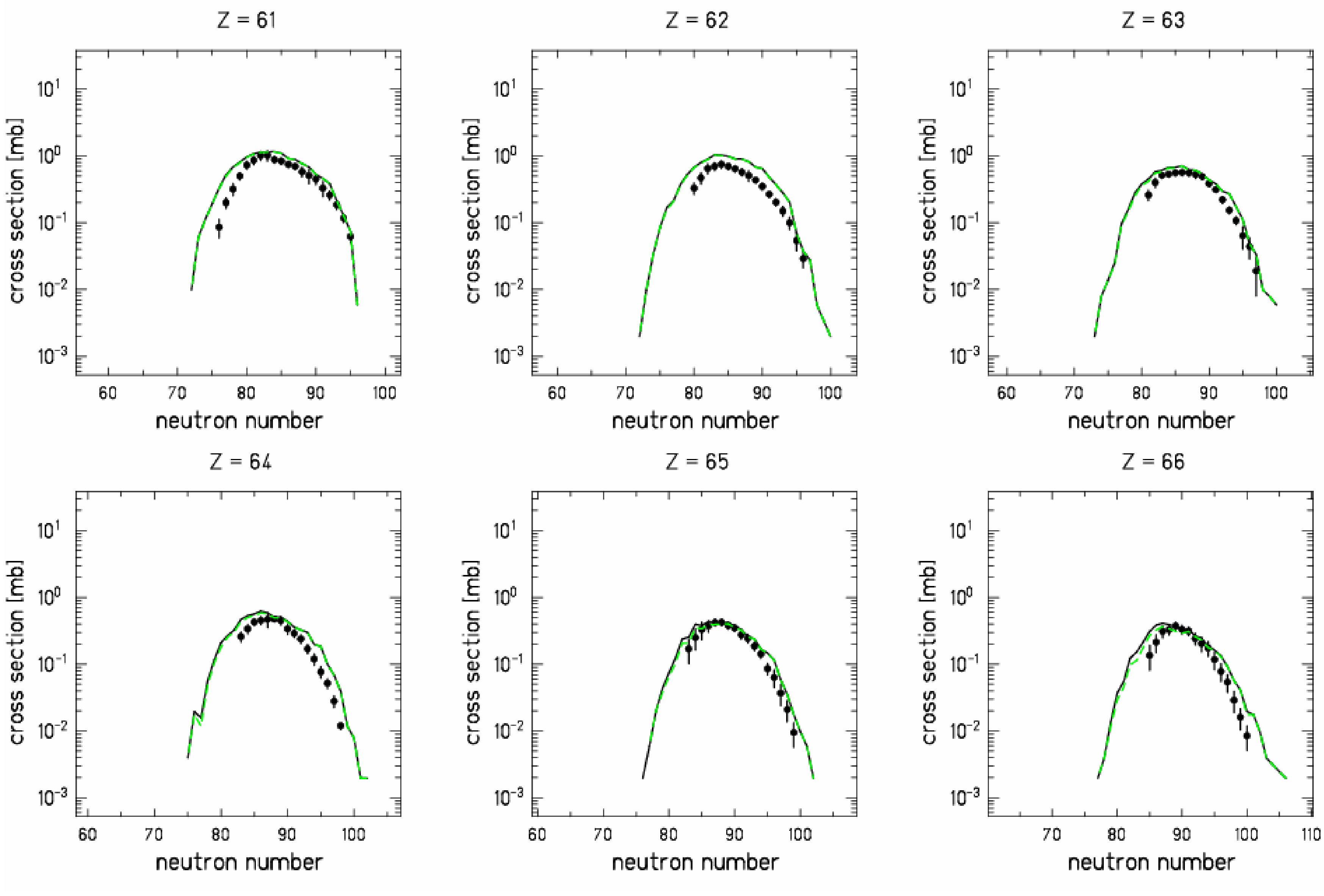
RESULT FOR 1 GeV p on ^{238}U



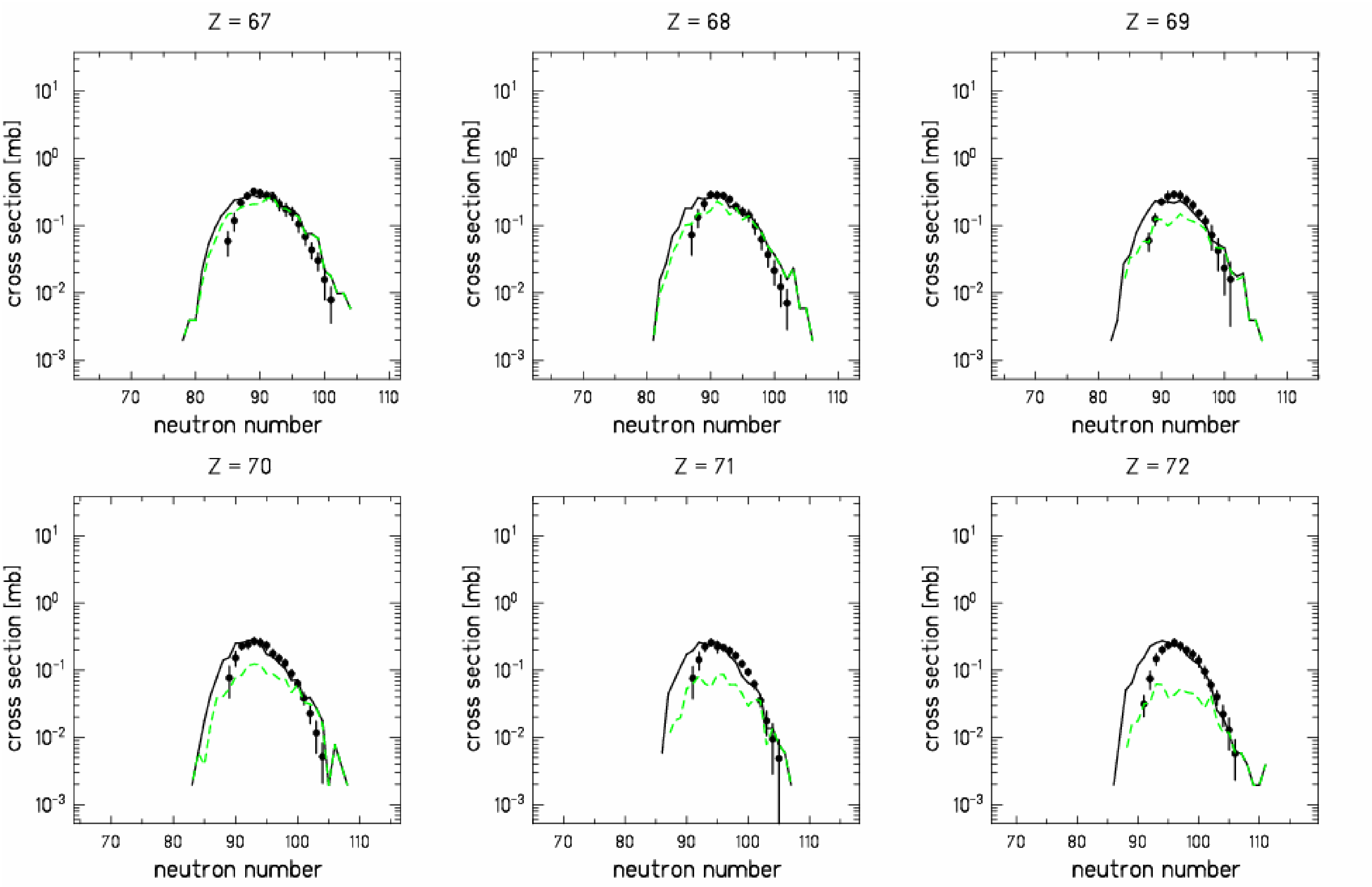
RESULT FOR 1 GeV p on ^{238}U



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)

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.**