Two-stage description of $^{56}Fe+p$ spallation reactions at 0.3-1.5GeV/A

Nikolaos G. Nicolis[1], G.A. Souliotis[2] and A. Bonasera[3]

[1]The University of Ioannina, Ioannina 45110, Greece
[2]University of Athens, Athens 15771, Greece
[3]Texas A&M University, College Station, U.S.A. and LNS INFN, Catania, Italy

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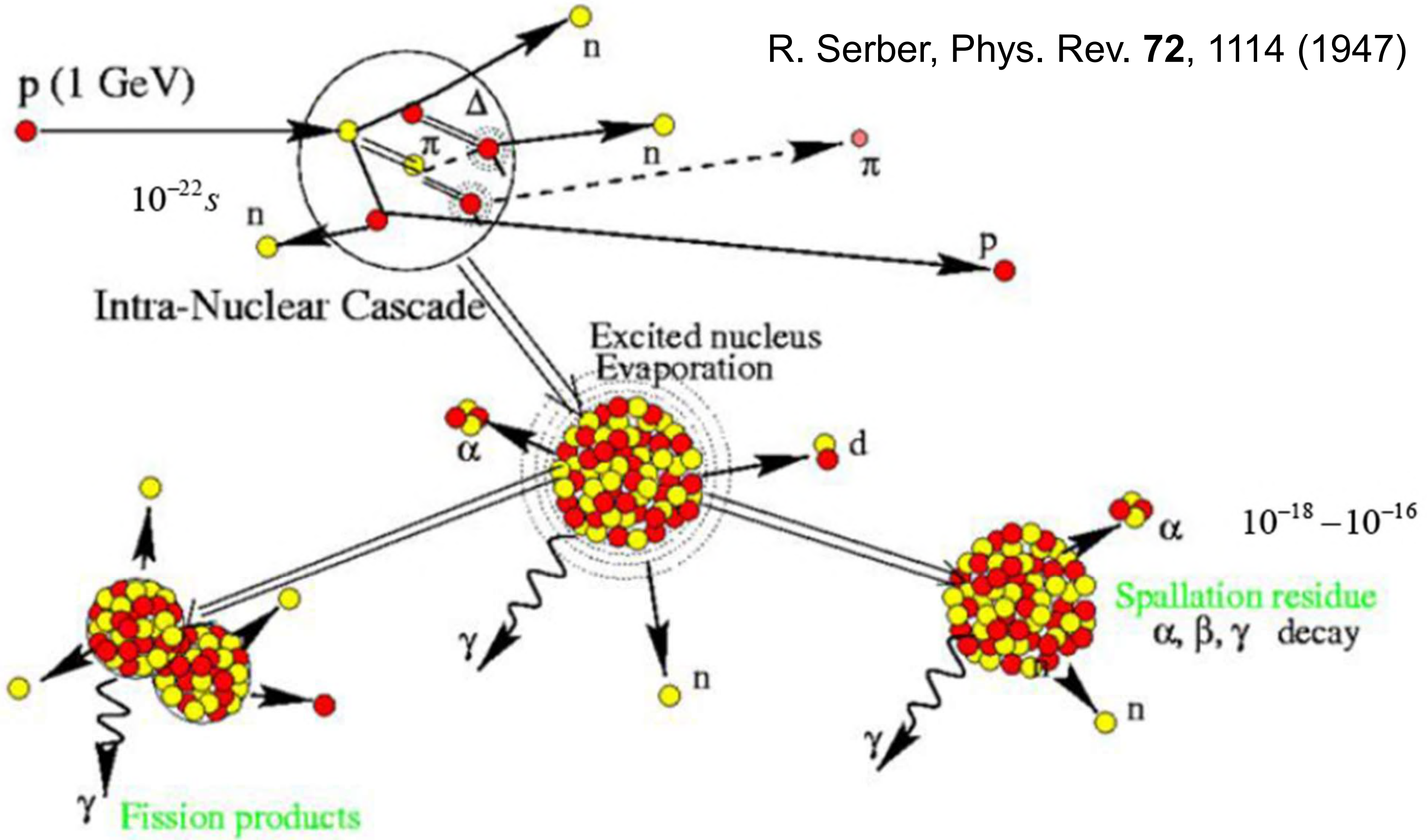
Motivation for studying spallation reactions in the mass A~50-60 region

- S.R. provide an environment for the development and testing high-energy nuclear reaction models (above 150-200 MeV)
- Production of isotopes of medical interest
- Interaction of cosmic rays with interstellar bodies (radiation damage)
- Radiation protection in space

The two stages of a proton-induced spallation reaction



Experimental data of interest for the present work

^{56}Fe + p @ 0.3, 0.5 0.75, 1.0 and 1.5 GeV/A

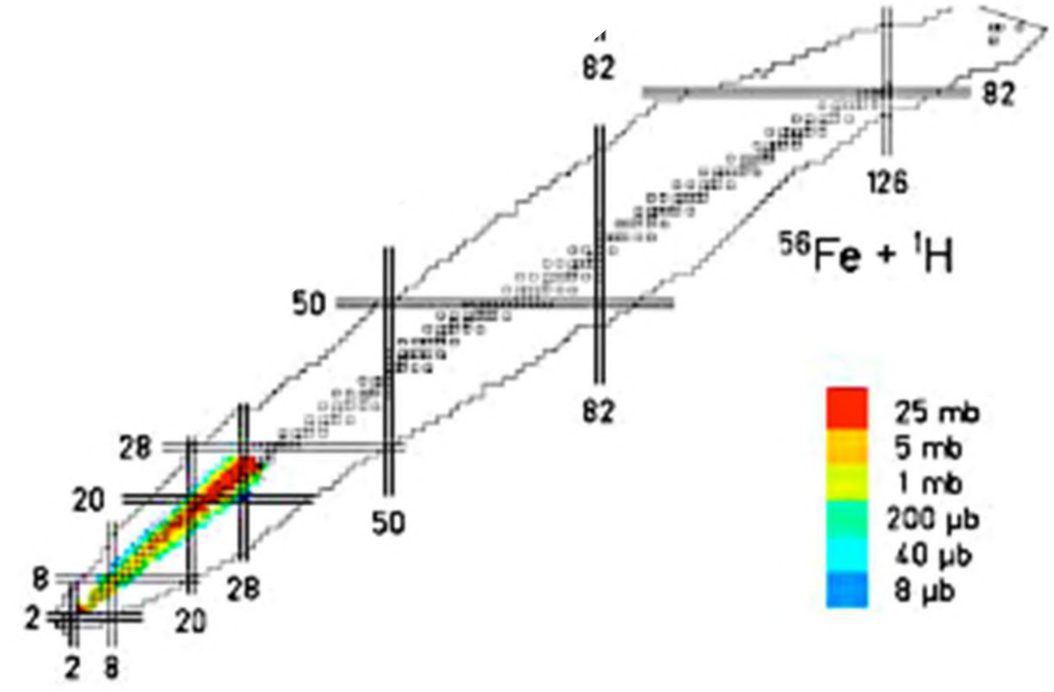


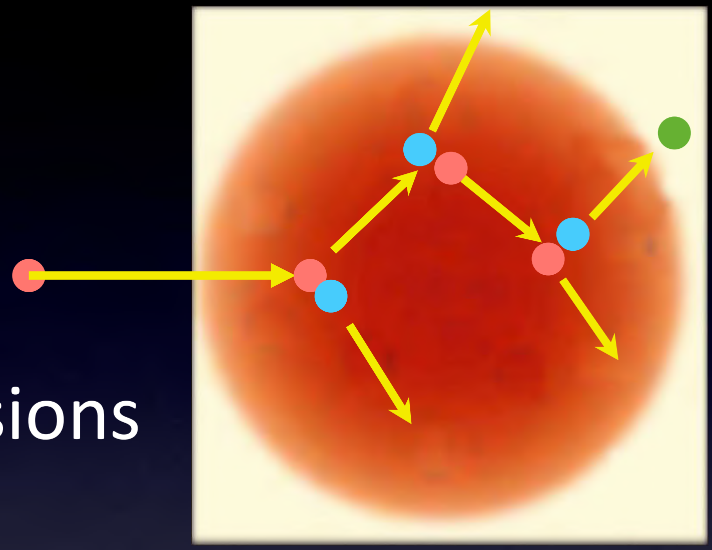
Figure 7. Overview on the nuclide production cross sections measured at the fragment separator for the four systems indicated at the energy of 1 *A* GeV on a chart of the nuclides. The colours indicate the production cross sections as defined in the colour scale.

Measured with the fragment separator (FRS) at GSI:

- A and Z-distributions.
- Isotopic distributions of s.r. and IMFs.
- Velocity distributions of spallation residues.

- P. Napolitani et al., PHYSICAL REVIEW C 70, 054607 (2004).
- C. Villagrasa-Canton et al., PHYSICAL REVIEW C 75, 044603 (2007).

The INC stage (ISABEL code)



- Continuous medium
- Diffuse nuclear surface
- Linear trajectories between collisions
- Free N-N cross sections
- Allows for inelastic N-N collisions
- Collision criterion based on the mean-free-path
- A Full Pauli blocking mechanism forbids nucleons from falling below the Fermi surface

Ref: Y. Yariv and Z. Fraenkel, Phys. Rev. C20, 2227 (1979); Phys. Rev. C24, 488 (1981)

The INC stage (The Constrained Molecular Dynamics (CoMD) model)

- Semi-classical
- Originally designed for reactions near and below the Fermi energy
- Nucleons are considered as Gaussian wave packets
- Phenomenological N-N interaction (Skyrme) and a surface term
- Angular momentum conservation
- Pauli principle is taken into account through an appropriate restriction in phase-space
- Recognition of fragment formation is made at each step of the time evolution

Ref: M.Papa, A.Bonasera et al., Phys. Rev. C64, 024612 (2001), M.Papa, G.Giuliani and A.Bonasera, J. Comp. Phys. 208, 403 (2005).

The code MECO (Multi-sequential Evaporation COde)

- The equilibrium decay of excited nuclei is described as a sequence of binary processes involving emission of fragments in their ground, excited bound and unbound states.
- Any number of user-defined channels may be considered.
- Emission of nucleons and fragments up to symmetric mass divisions is described in the framework of a generalized Weisskopf-Ewing evaporation formalism.
- Monte-Carlo code
- Description of low-spin, high-excitation energy reaction systems with an effective fissility below the Businaro-Galone point (x_{BG}=0.396 - ^{107}Pd).

Ref: N.G.Nicolis, Int. Jour. Mod. Phys. E 17 (2008) 1541-1556.

MECO run with 180 decay channels

Decay channels

γ (E1)	
n	1 g.s.
1-3H	1 g.s.
3,4He	2 g.s.
6-8Li	3 g.s. + 7 e.s.
7-10Be	3 g.s. + 7 e.s.
8-12B	4 g.s. + 17 e.s. + 2 c.s.
10-14C	5 g.s. + 21 e.s. + 4 c.s.
13-18N	5 g.s. + 12 e.s. + 2 c.s.
15-21O	4 g.s. + 16 e.s. + 5 c.s.
17-20F	5 g.s. + 25 e.s. + 5 c.s.
Ne	4 g.s. + 0 e.s. + 4 c.s.
Na	4 g.s. + 0 e.s. + 3 c.s.
23-25Mg	3 g.s. + 0 e.s. + 3 c.s.

Level densities

- Composite Gilbert-Cameron formula

with

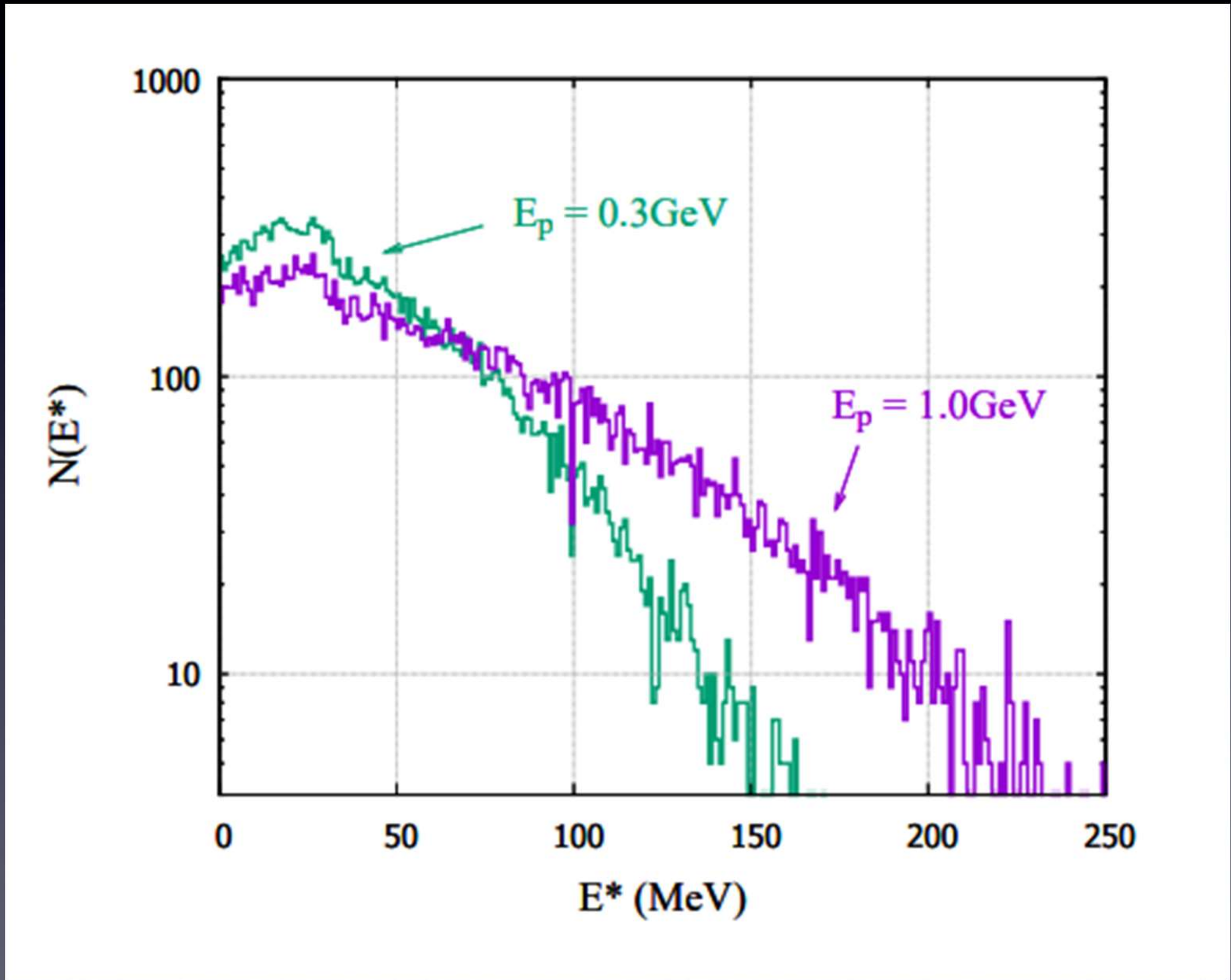
$$a = \frac{A}{k}\left[1 + Y\left(\frac{N-Z}{A}\right)^2\right]$$

where $k=10.5\,\mathrm{MeV}^{-1}$ and $Y=1.5$

Inverse cross sections

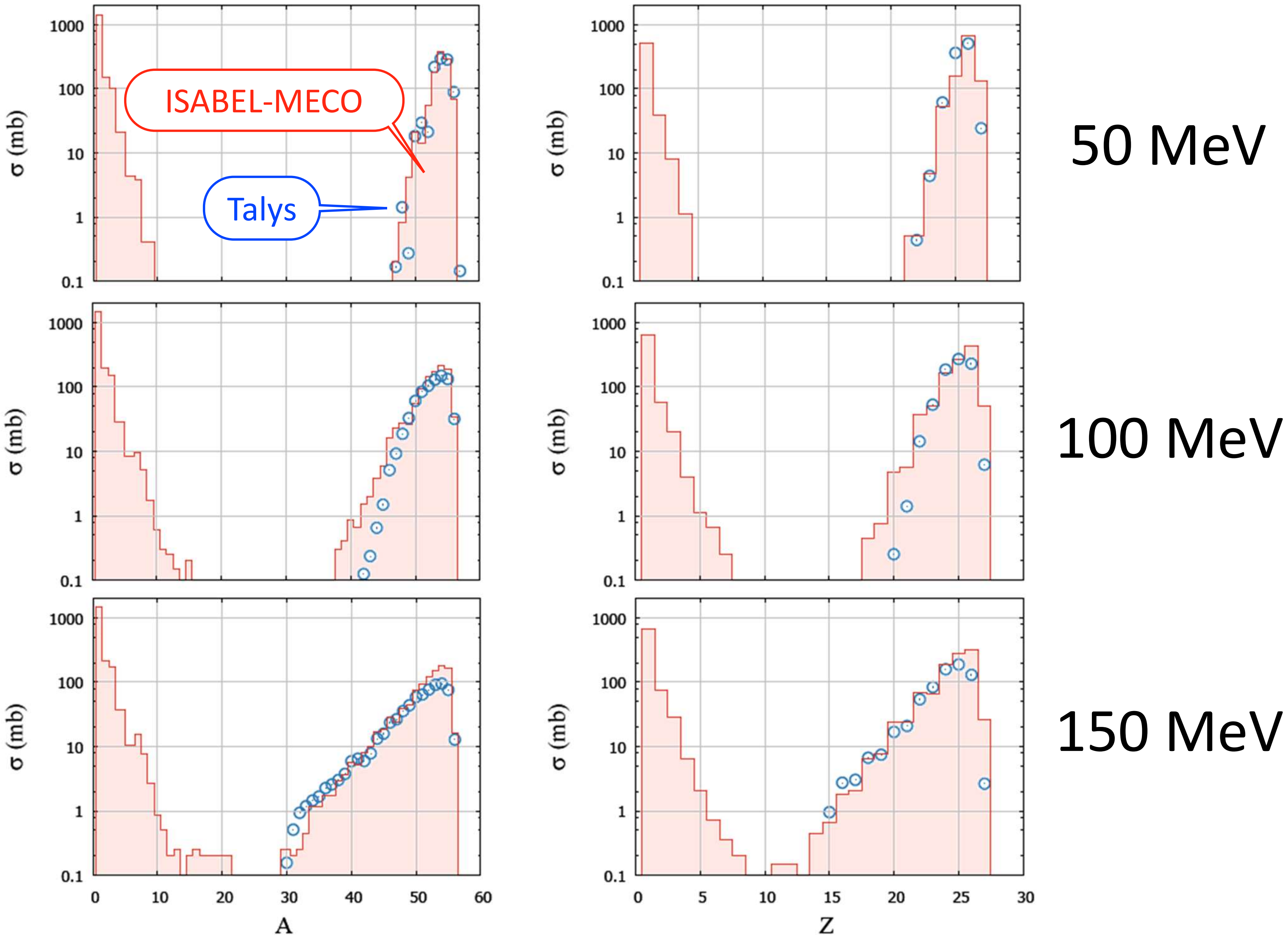
- O.M. for $A_F<4$
- B.P.M. for $A_F \geq 4$ with Christensen and Winther nuclear potential parameters

Distributions of excitation energy
$^{56}Fe + p$ @ 0.3 and 1.5 GeV/A

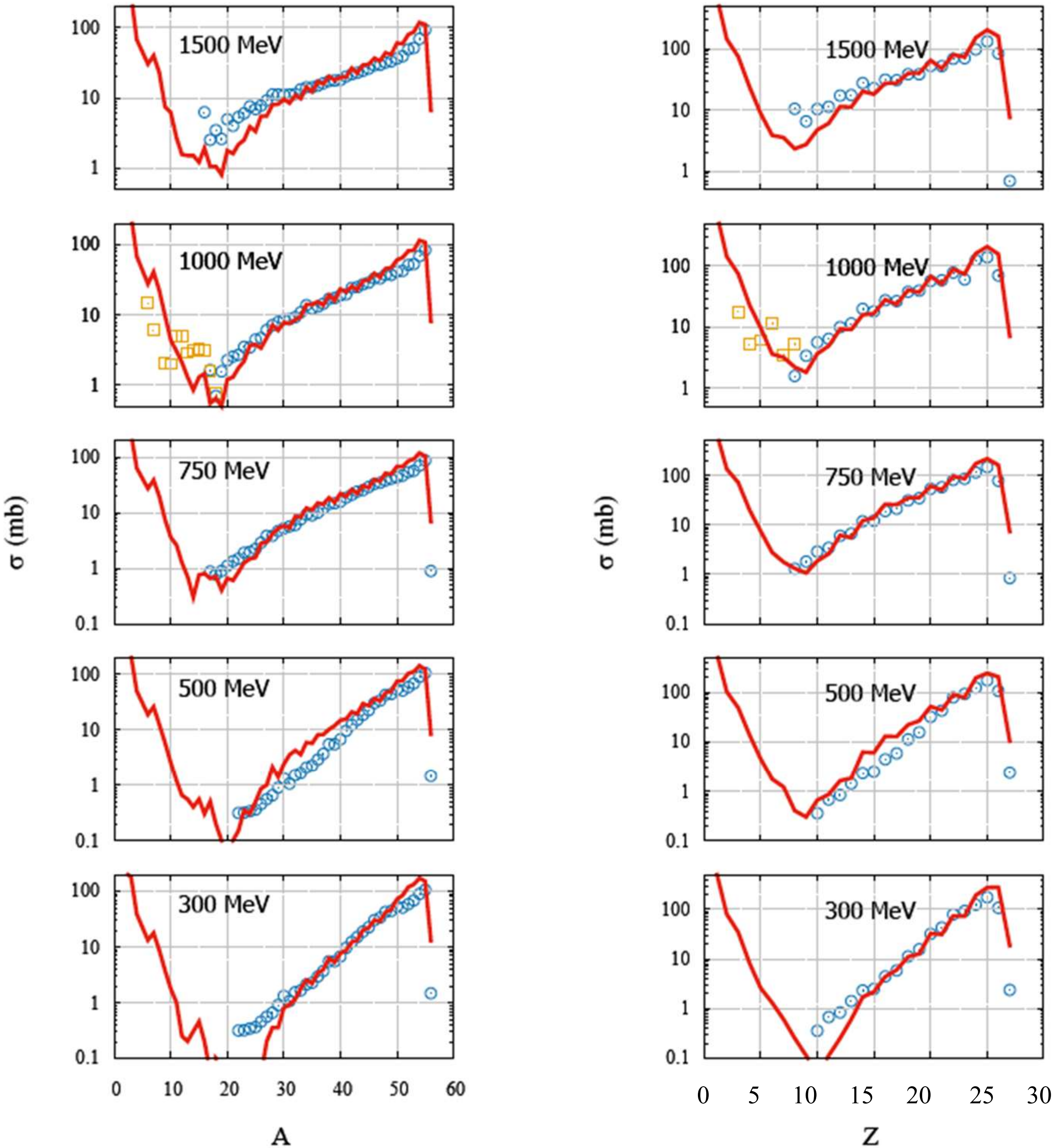


Based on 20000 ISABEL events

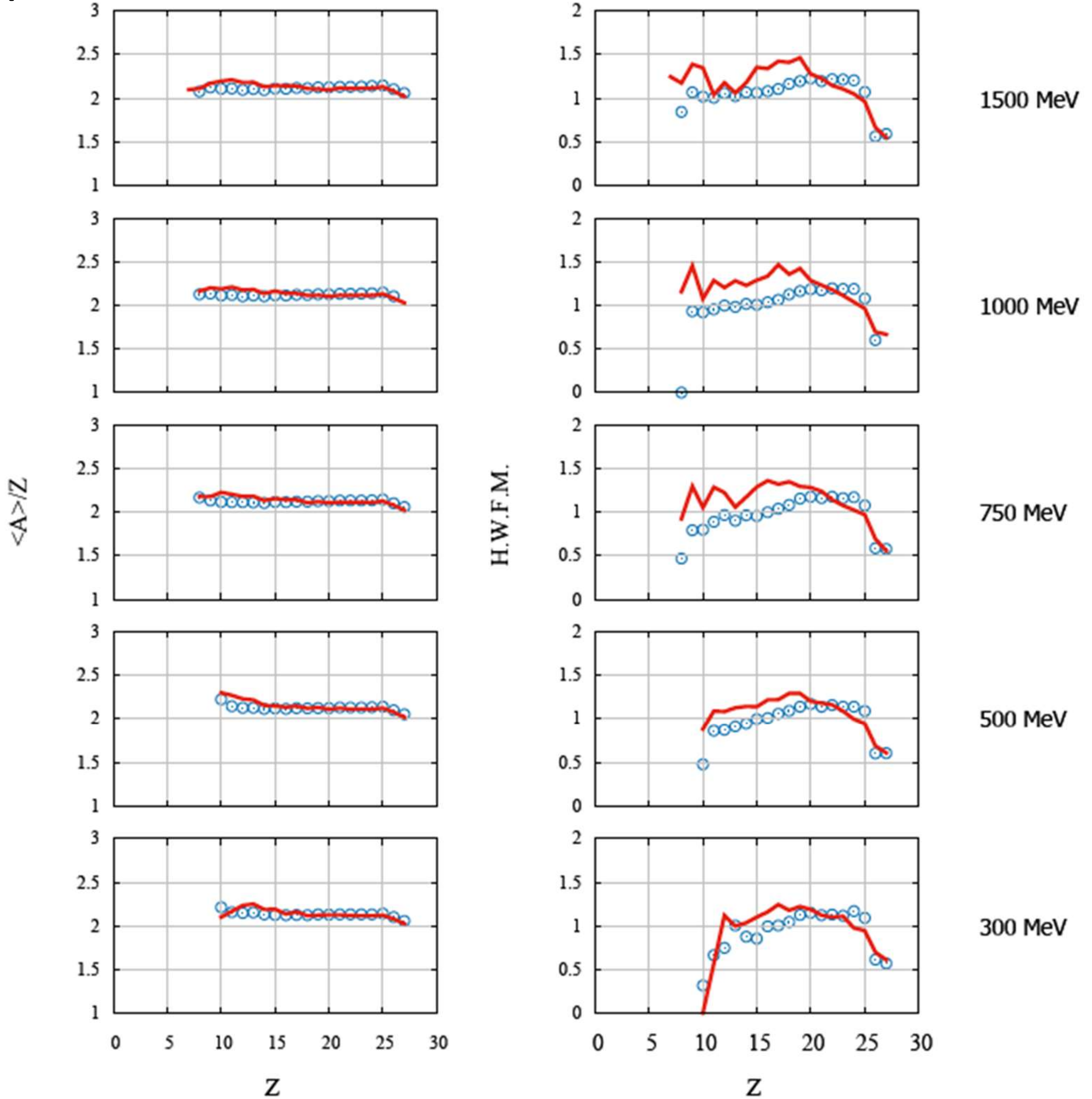
Mass and charge distributions in p + ^{56}Fe reactions calculated with ISABEL-MECO and Talys_1.9



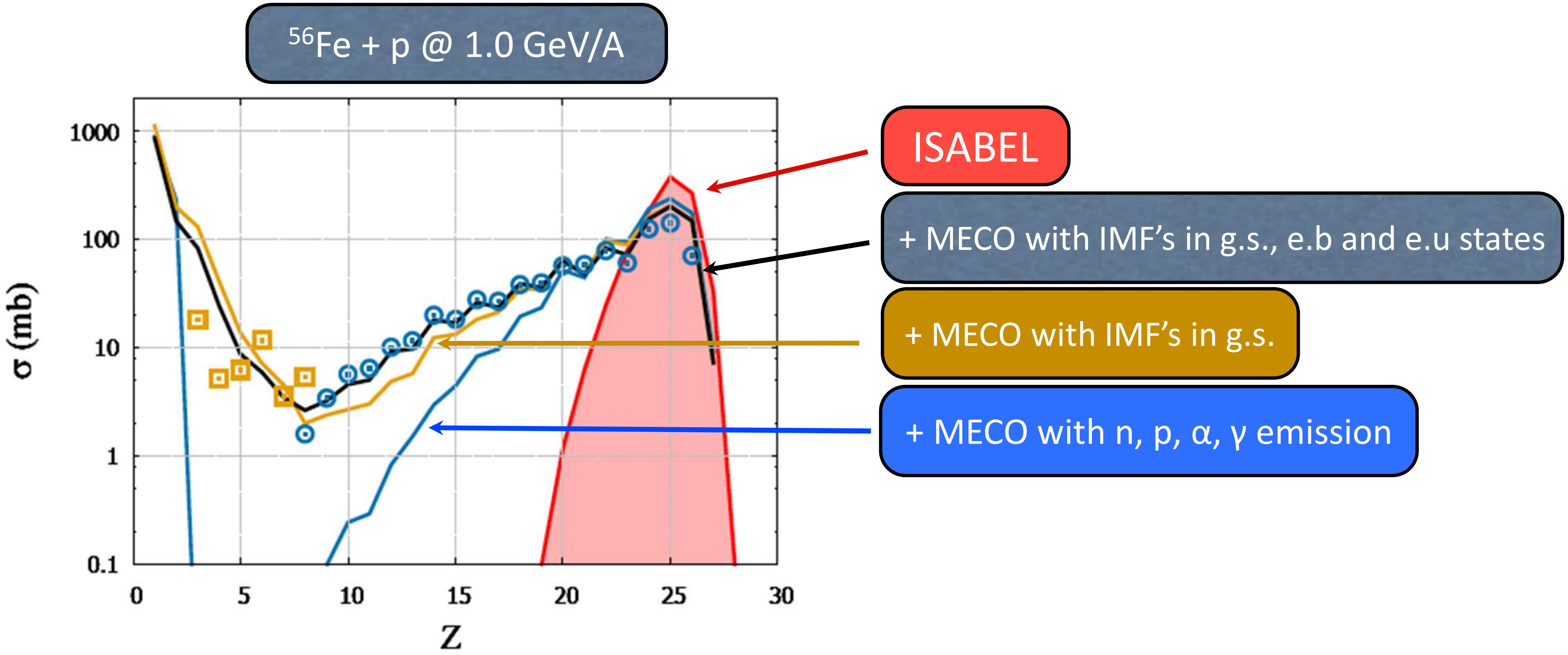
Mass and charge distributions in p + ^{56}Fe spallation reactions calculated with ISABEL-MECO



Centroid and width of isotopic distributions in p + ^{56}Fe spallation reactions calculated with ISABEL-MECO

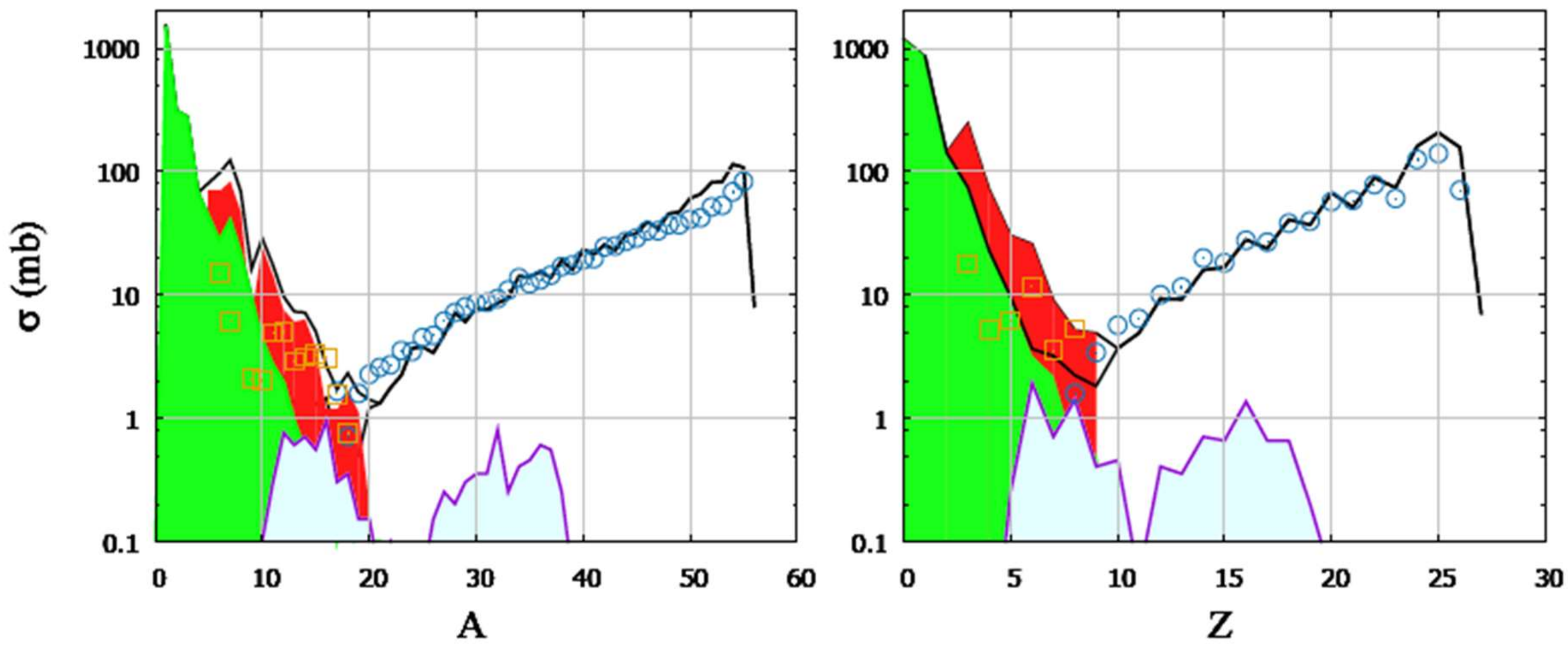


Necessity of considering heavy fragment emission in the equilibrium de-excitation

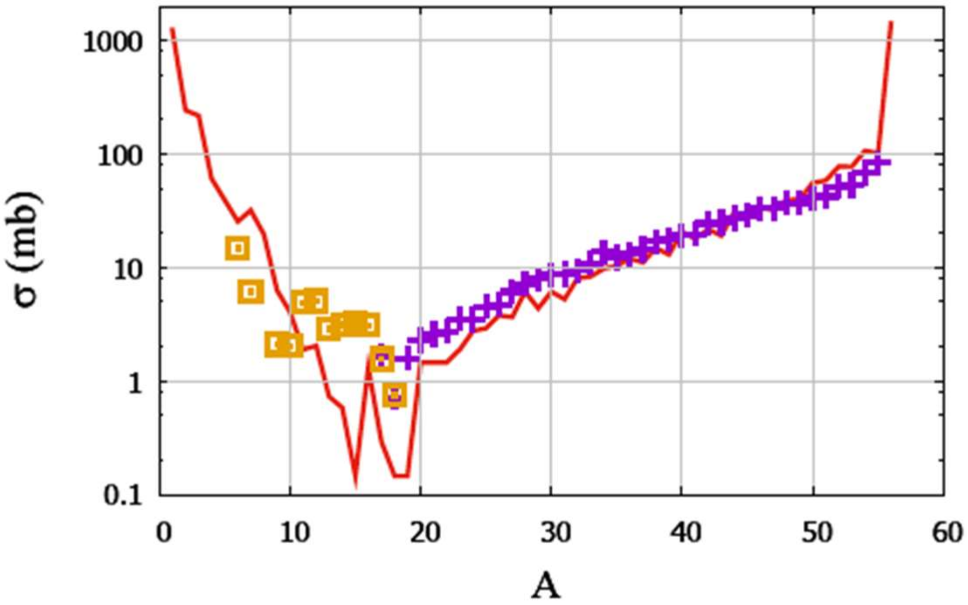


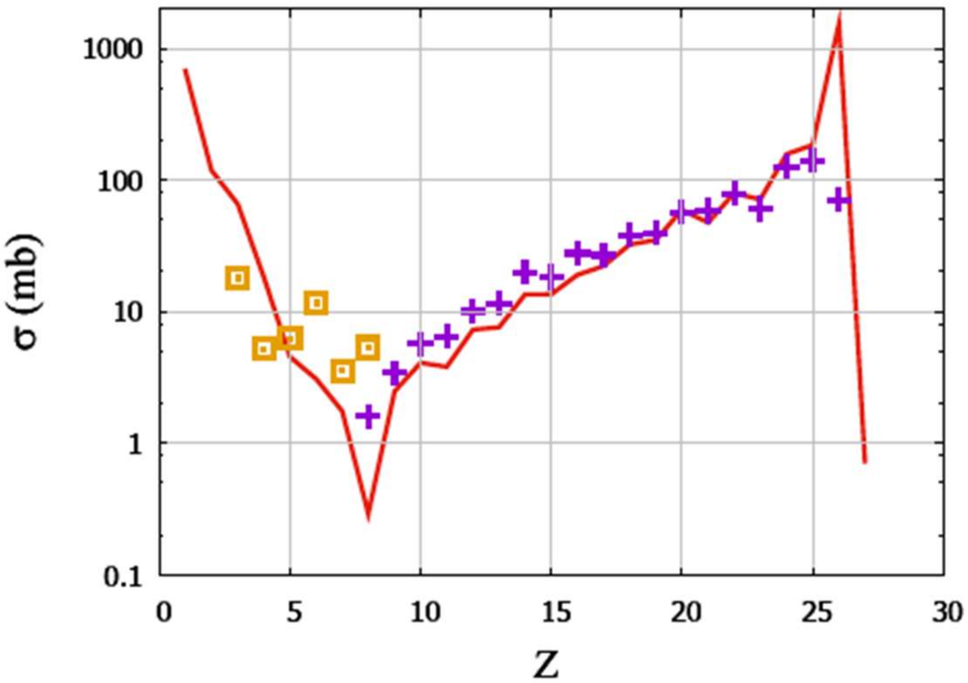
- The ISABEL distributions are structureless.
- The even-odd structure in the Z-distribution appears after the equilibrium decay stage.

Contributions to the A- and Z-distributions at 1GeV from fragment emission in the ground, excited-bound and binary decays



A preliminary calculation with CoMD-MECO at 1GeV

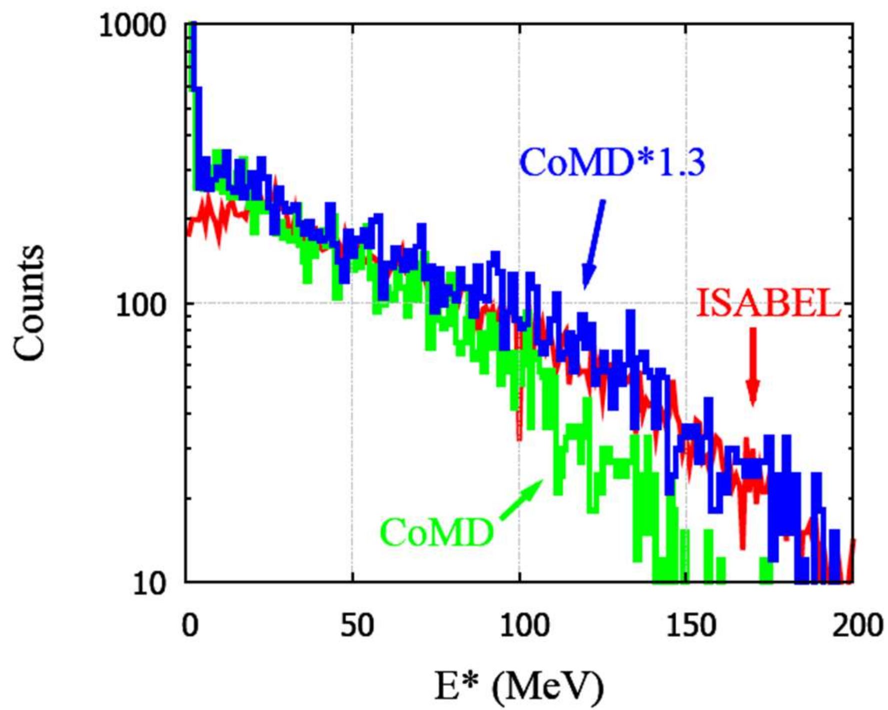




- Stringent test for CoMD, well above the bombarding energy range of its validity.

- Too many cold events (^{56}Fe)

- The E*-distribution of pre-fragments in CoMD does not extend to very high-energies as ISABEL does.



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Elusiveness of evidence for multifragmentation in 1-GeV proton-nucleus reactions

Davide Mancusi,[1,*] Alain Boudard,[2] Joseph Cugnon,[1] Jean-Christophe David,[2] Thomas Gorbinet,[2] and Sylvie Leray[2]
[1] *Fundamental Interactions in Physics and Astrophysics, University of Liège, allée du 6 août 17, bât. B5, B-4000 Liège 1, Belgium*
[2] *CEA, Centre de Saclay, IRFU/Service de Physique Nucléaire, F-91191 Gif-sur-Yvette, France*
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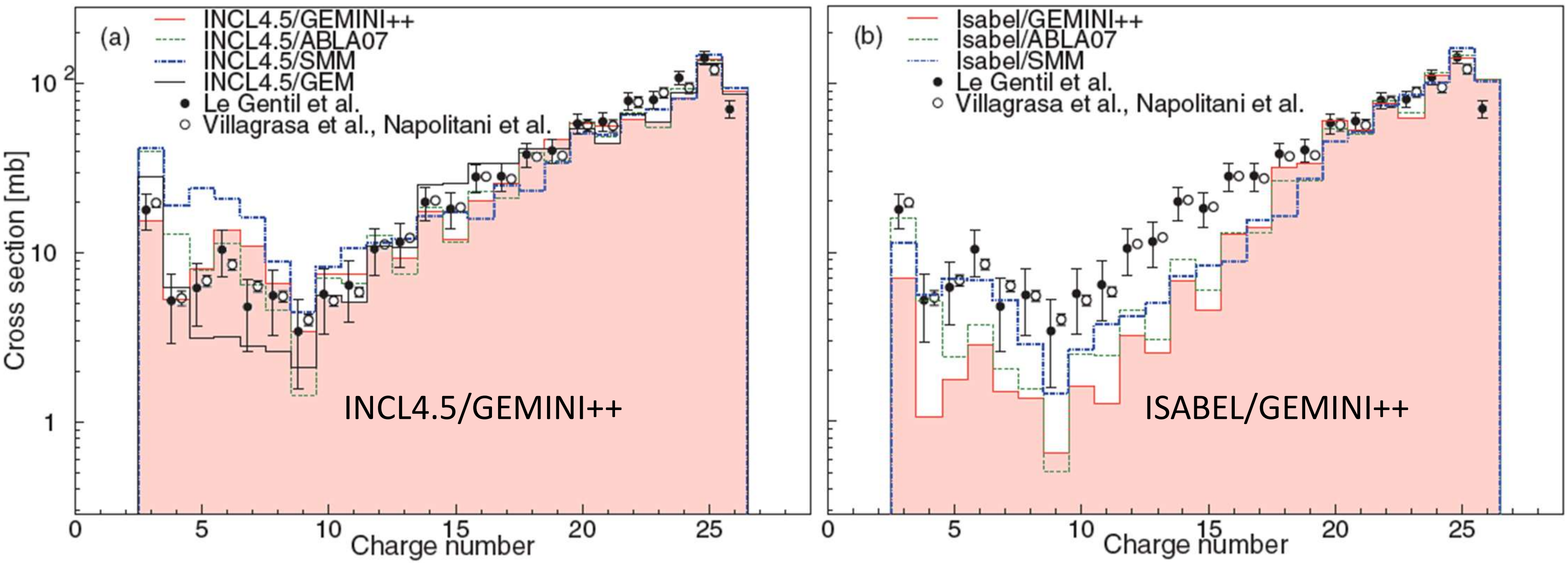
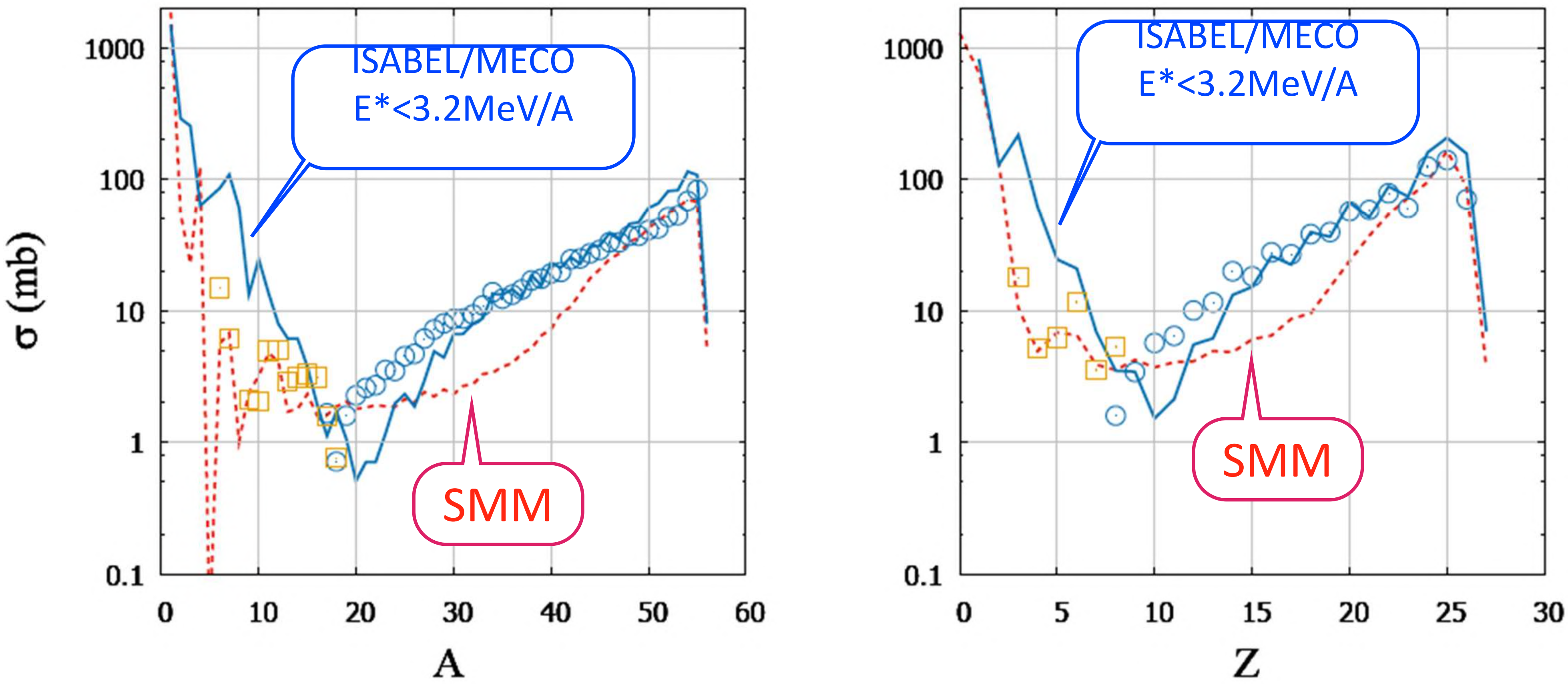


FIG. 2. (Color online) Inclusive residue-production cross sections for 1-GeV $p + {}^{56}Fe$, as a function of the nuclide charge. (a) Intranuclear cascade simulated by INCL4.5. (b) ISABEL. Experimental data from Refs. [6,7,9].

Multifragmentation ?

- We reject ISABEL/MECO events with E*>3.2MeV/A
- SMM calculation considering multifragmentation above E*=3MeV/A



- A proper mixture of multifragmentation events from SMM with events from ISABEL/MECO may fill in the gap at 19≤A≤30 and 9≤Z≤13

Summary

- Spallation products of ^{56}Fe+p reactions at 0.3-1.5 GeV/A were described as a two-stage process with the ISABEL INC followed by the the MECO sequential binary decay code.
- A good agreement with the experimental A- and Z- and isotopic distributions was obtained with an effective set of excitation-energy independent parameters for the equilibrium de-excitation.
- Consideration of the multi-fragmentation decay mode at the highest bombarding energies (1.0-1.5GeV) may require
  - An improved set of statistical decay parameters
  - Proper consideration of MF-decays
  - Comparisons with x-section and available velocity distribution data of emitted IMFs.
- Improvements in the calculation of the INC stage with the CoMD model should be considered.