Validation of spallation models

INNOVACYJNA GOSPODARKA
NARODOWA STRATEGIA SPÓJNOŚCI

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INTERNATIONAL PHD PROJECTS IN APPLIED NUCLEAR PHYSICS AND INNOVATIVE TECHNOLOGIES

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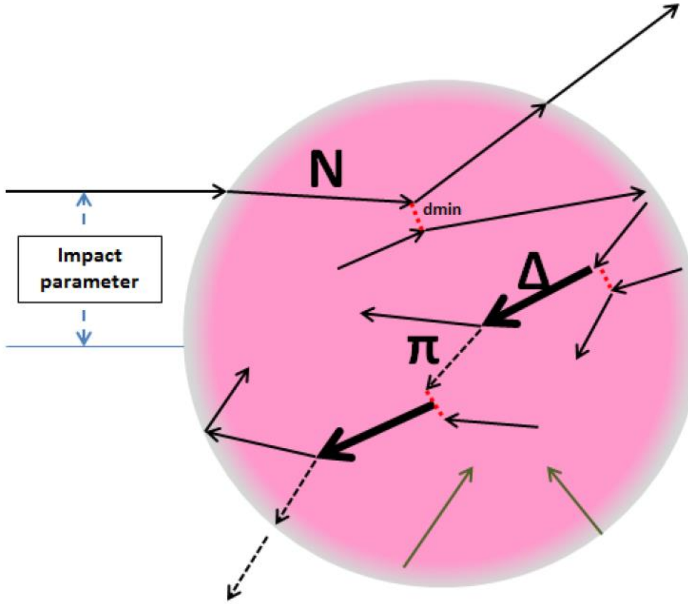
The definition of spallation reaction

The name „spallation" was invented by G. Seaborg:

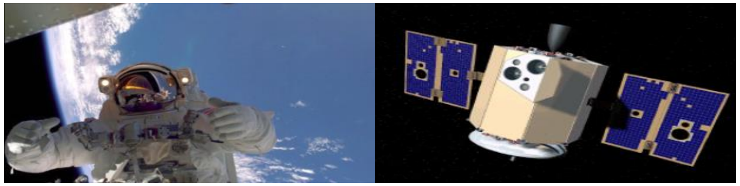
The incident proton knocks out several nucleons in a series of two-body collisions, leaving behind a highly excited heavy nucleus.

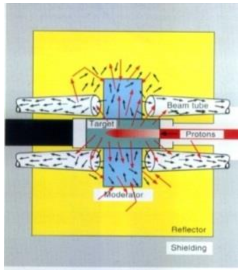


This nucleus decays by the evaporation of charged particles and neutrons, forming a continuous distribution of products ranging downward in A from the target mass number.

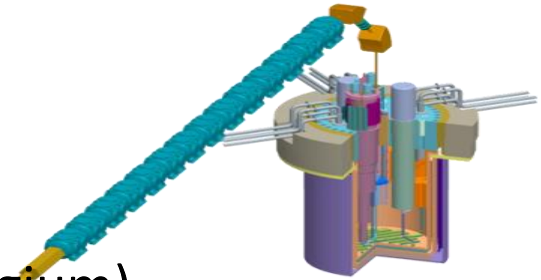
The spallation reactions are important because of:

- Radiation protection, damage to electronic circuits in space or near accelerators

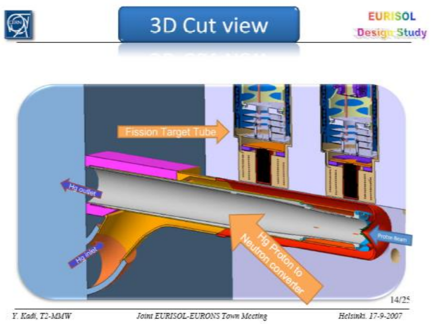




- Neutron sources for material science, condensed matter physics (SNS, JPARC, ESS)



- Accelerator-driven sub-critical reactors for nuclear waste transmutation (e.g. MYRRHA Belgium)



- Production of radioactive beams for fundamental nuclear physics studies (ISOLDE CERN, FRIB, EURISOL)

Many other applications…

Therefore, the realistic and reliable models which enable one to predict the cross sections are necessary.

ISSUES

1. A thorough survey of scientific literature for the status of:

    - ***Representative data sets*** *and*
    - ***Theoretical codes*** *for modeling the reaction mechanism*

2. Compare selected data with model predictions

3. Conclusions concerning the possibility to improve the models

Search for representative data sets:

✓ Selection of different observables :

✓ **Inclusive –** total production cross sections
Isotopic σ(A/Z) , isobaric σ(Z)

✓ **Exclusive -** differential cross sections
angular and energy distributions dσ/dE dΩ

✓ **Different ejectiles :**
neutrons,
LCP ≡ light charged particles (p, d, t, 3He, 4He),
IMF ≡ intermediate mass fragments with A(LCP) < A < A(fission fragments)
heavy residua (target-like nuclei)

✓ for **28 combinations** of target masses (Al, Ni, Ag, Xe, Au, Pb) and beam projectile energy varying from 180 MeV – 3000 MeV

Selected data for <u>inclusive</u> observables

Different observables

Beam Energy (MeV)	Al	Xe	Au
180	Isobaric: σ (A) , angular and energy distribution		
500		Isotopic distribution σ (A|Z) Z=41 to Z=56	
1000 and 3000			Forward/Backward asymmetry

Selected data for differential cross section: n, LCP and IMF

ENERGY DEPENDENCE

Beam Energy (MeV)	Al	Ni	Ag	In	Au	Pb
5500			LCP/IMF			
3000	n			n		n
2500	LCP/IMF	LCP/IMF	LCP/IMF		LCP/IMF	
1900	LCP/IMF	LCP/IMF	LCP/IMF		LCP/IMF	
1500				n		
1200	n/LCP/IMF	LCP/IMF	LCP/IMF		LCP/IMF	n
590				n		
480			He/IMF			
256	n					n
200	He/IMF	Co(He/IMF)			He/IMF	
175		LCP/IMF				

MASS DEPENDENCE

Selection of models

✓ ***First stage model :*** **INCL4.6** - Intranuclear Cascade

✓ ***Models of the second stage:***

– **GEM2** (Generalized evaporation model)

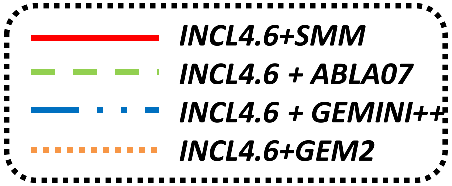
– **GEMINI++** (Sequential binary decay)
[*No simultaneoues multi-fragmentation*]

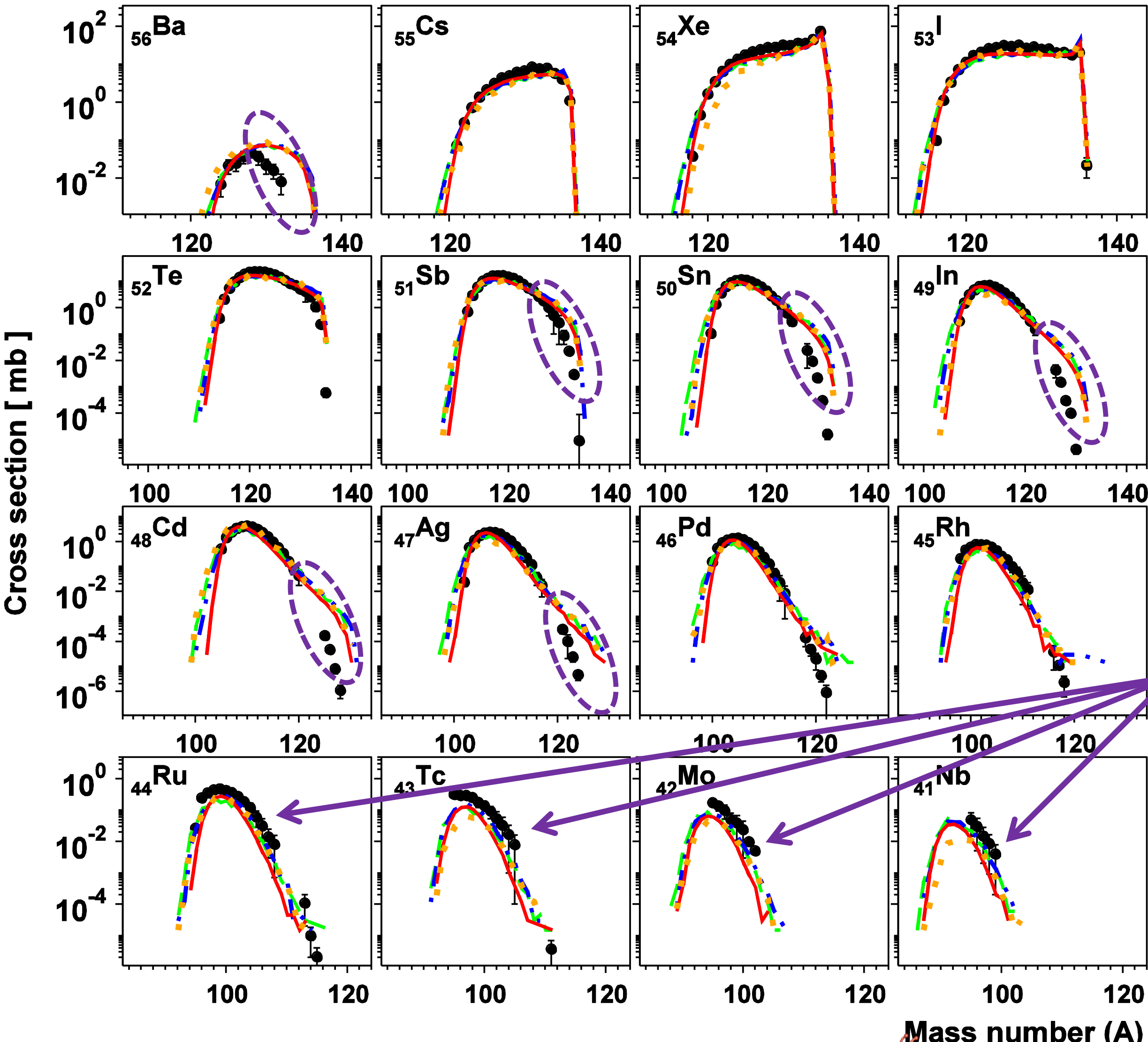
– **SMM** (Statistical multifragmentation model)

– **ABLA07** (Ablation model)

Qualitative comparison between model calculations and data (examples)

Isotopic distributions σ(A|Z) of residua in p(500MeV) + ^{136}Xe for 16 elements from Z=41 (Nb) to Z=56 (Ba)





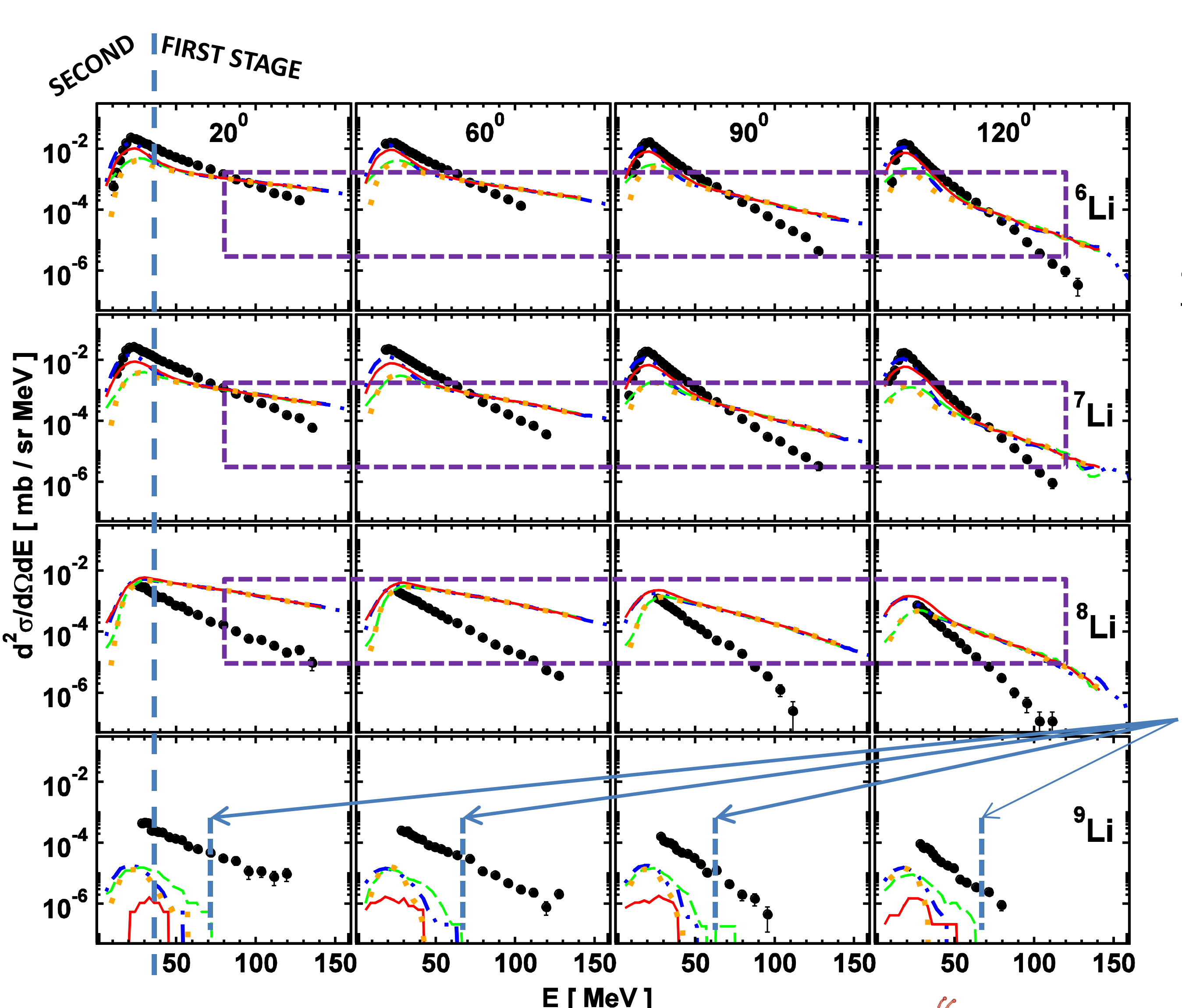
All models **are able to reproduce the shape** of isotopic distribution nearly for all elements,

however,

Systematic **overestimation** of σ for isotopes with heavier mass (for Ba - Ag) by all models.

σ for **all** isotopes of elements with small Z are **underestimated**

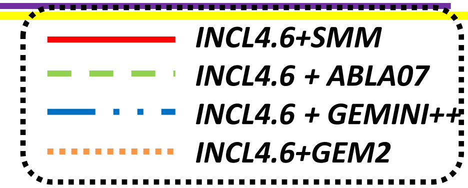
Emission of Li isotopes in p(480MeV)+Ag reaction



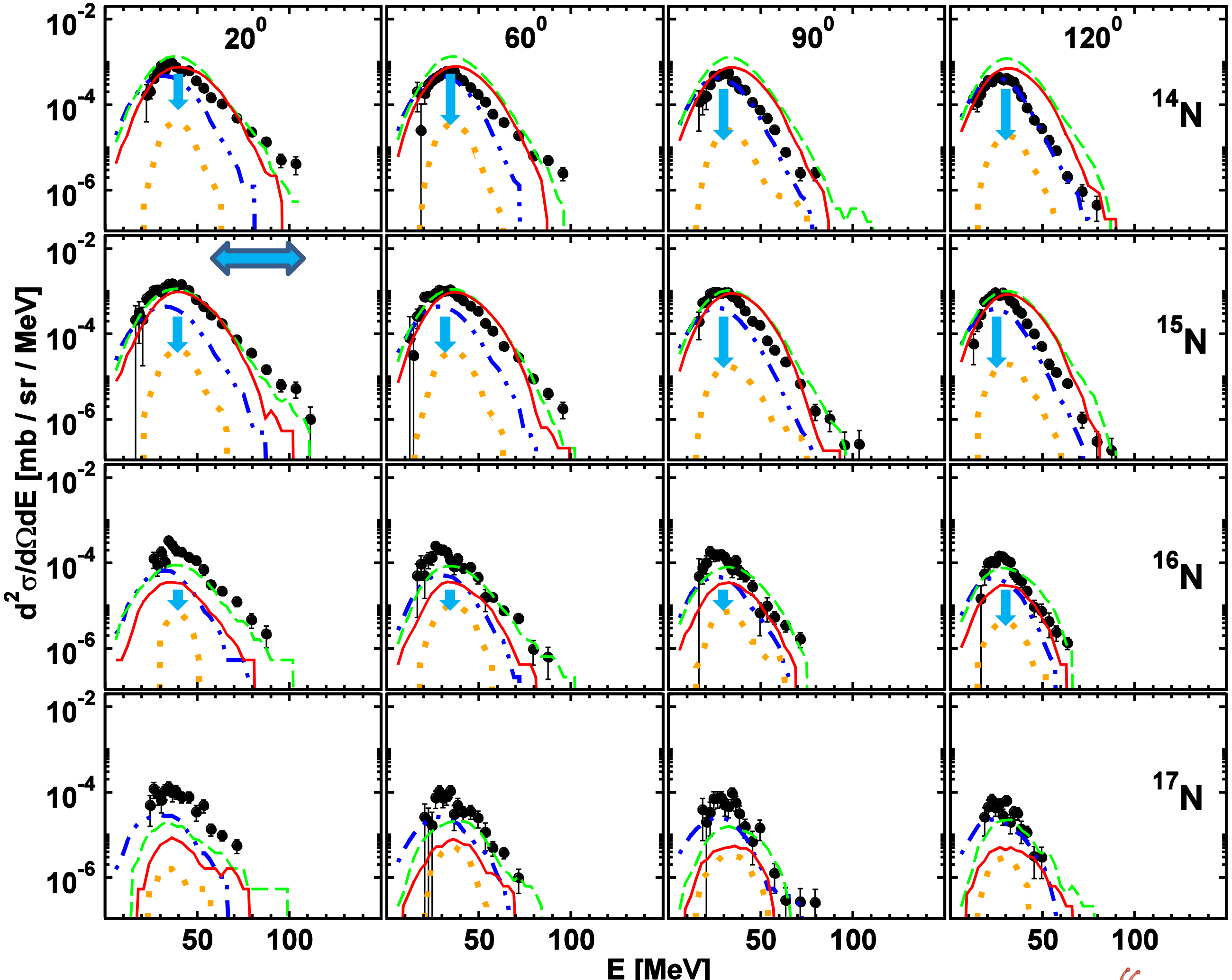
Slope of **high energy tail is TOO flat** for all isotopes of Li(6,7,8 : produced by coalescence model realized in INCL4.6)

There should be contribution from the first stage of the model for 9Li (coalescence restricted to A<9 in INCL4.6)

Emission of N isotopes in p(480MeV)+Ag reaction



Contributions only from second stage models



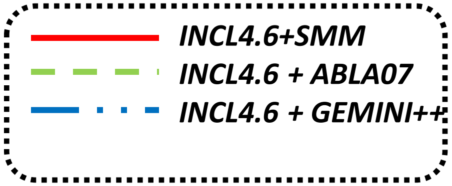
GEM2 (evaporation + fission) is always underestimating the data in comparison to other three models.

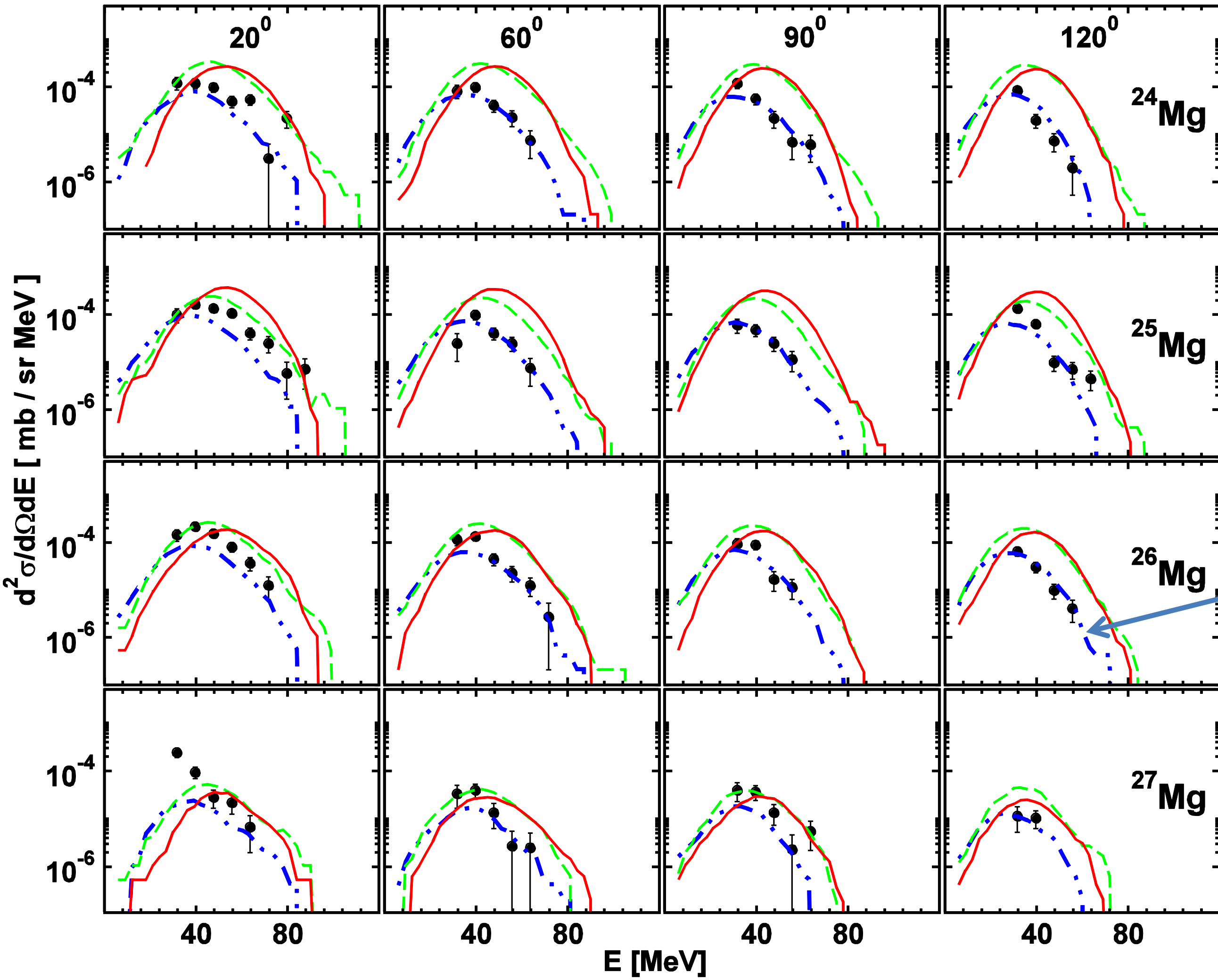
Other three models (ABLA07,SMM,GEMINI++) are competing for the better descriptions

Energy range of ejectiles is not the same for all models, moreover it is as broad as up to 100 MeV, which is beyond the scope of evaporation approach only (as in GEM2).

Emission of Mg isotopes in p(480MeV)+Ag reaction

Contributions only from second stage models

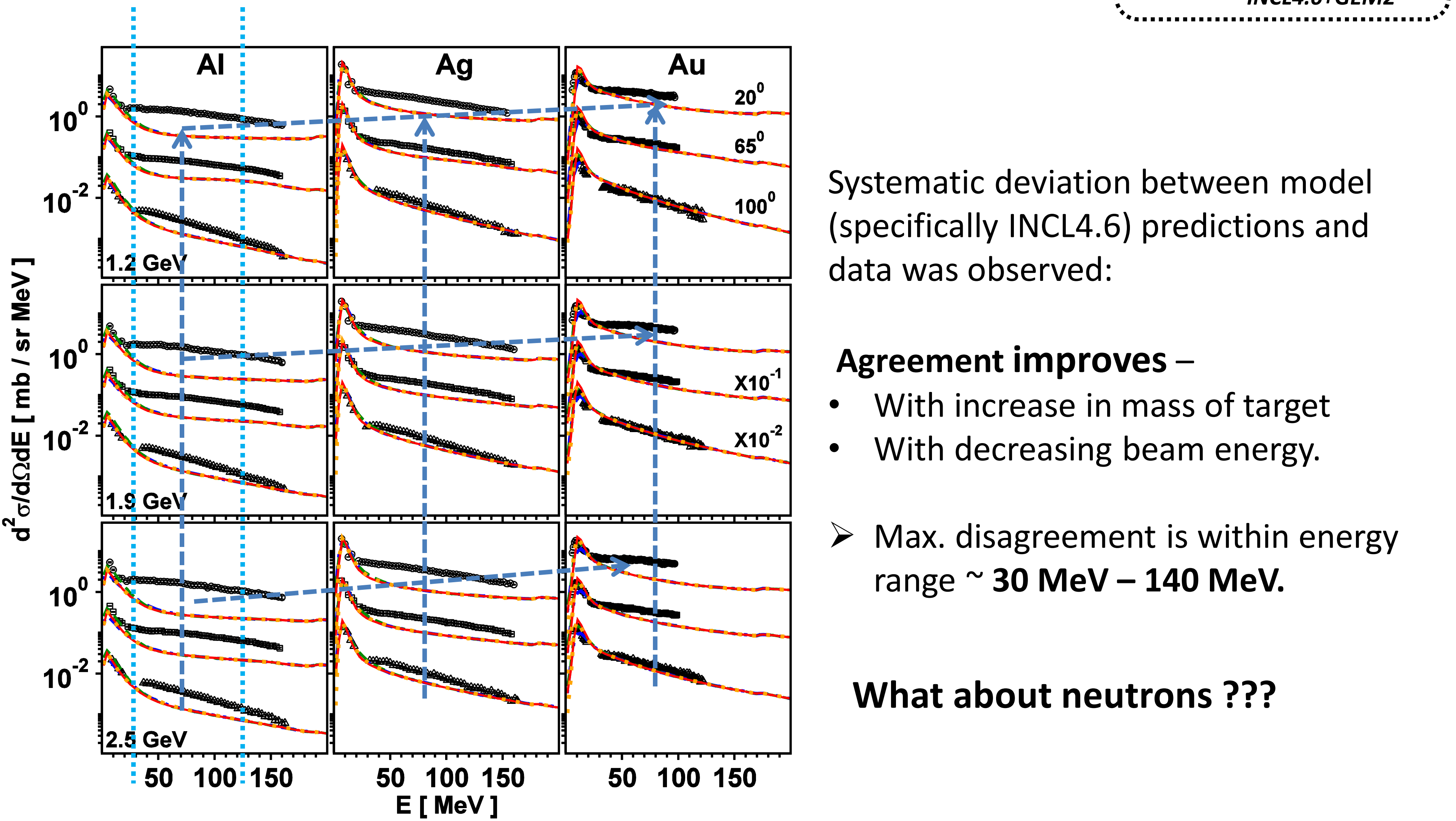




GEM2 contribution is not shown as it predicts very small cross sections with respect to other models.

GEMINI++ is clearly the best choice for the prediction of Mg isotopes for all angles.

Target mass and **beam energy** dependence for differential **Protons** production



Systematic deviation between model (specifically INCL4.6) predictions and data was observed:

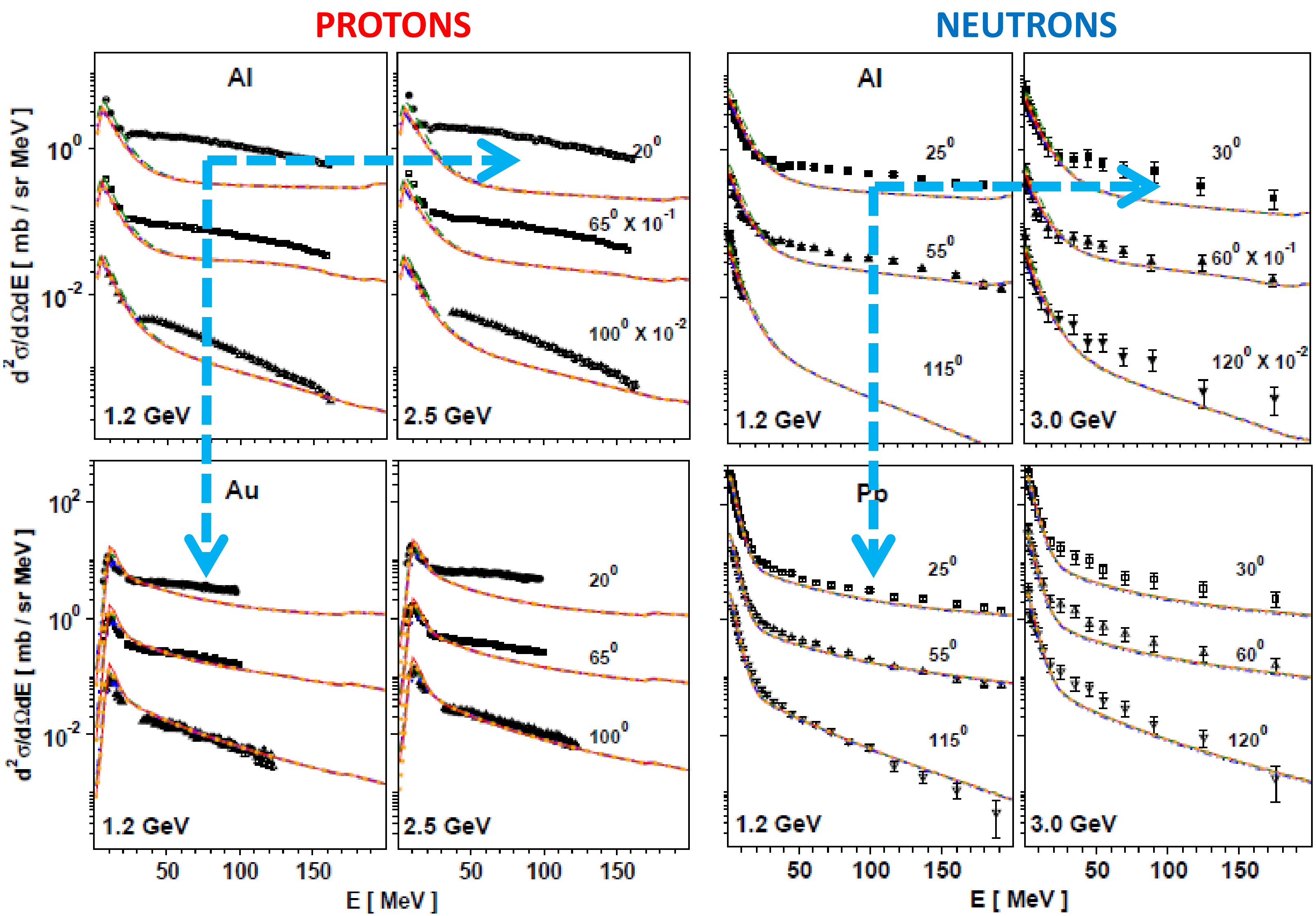
Agreement improves –

- With increase in mass of target
- With decreasing beam energy.

➢ Max. disagreement is within energy range ~ **30 MeV – 140 MeV.**

What about neutrons ???

Comparison between **Proton and Neutron** distributions



CONCLUSIONS

- The total isotopic cross sections
  - The high mass isotopes production is overestimated for elements close to the target
  - The high mass isotopes production is underestimated for the lightest elements observed

- The following systematic deviations are visible for differential cross sections
  - The high energy tail of the energy spectra for intermediate mass fragments has too small slope (first stage of the reaction – coalescence ?)
  - The contribution from the first stage (coalescence) is important also for A>8 at least up to A=12
  - The proton and neutron spectra are underestimated for energy range of nucleons from about 30 to 100 MeV. This effect is increasing with the proton beam energy and with decreasing of mass of the target.

SUMMARY

The present-day spallation models lead to better description of the data than the older ones, however

A need of some improvements is mandatory
(missing mechanism ???)

What are the candidates for the missing mechanism?

- Knock out of already present clusters from nucleus surface (evidence reported but no substantial information in literature)…

- Production of unstable clusters formed dynamically („fireball”) which may decay and contribute to emission of nucleons…