Production of H and He isotopes in pA collision at a few GeV beam energy

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Theoretical efforts
on nuclear clusters

Low energies
(nuclear structure)

High and very high
energies
(heavy ion collisions)

Astrophysics

Theoretical efforts
on nuclear clusters

Low energies
(nuclear structure)

Reaction induced
by light projectile
(energies ~ GeV)
“nuclear spallation”

High and very high
energies
(heavy ion collisions)

Astrophysics

Mechanisms of nucleus disintegration at ~GeV range

- Old problem studied from many years;
- Due to complication of the nuclear system the consistent theory derived from first principles (still) not available;
- Various types of effective models used for data description and (qualitative) prediction of results;
- Experimentally studied in:
  - pA, NA → conglomerate of processes in general referred to as “spallation”;
  - heavy ion collisions (description mainly in “hydrodynamical” or “thermodynamical” language).

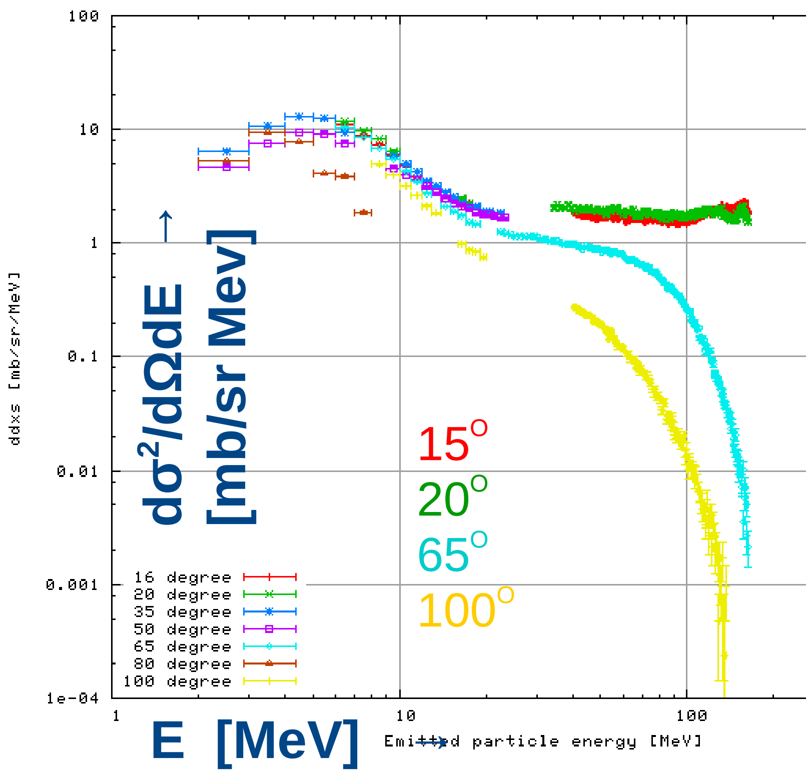
Advantages of reactions with light projectiles

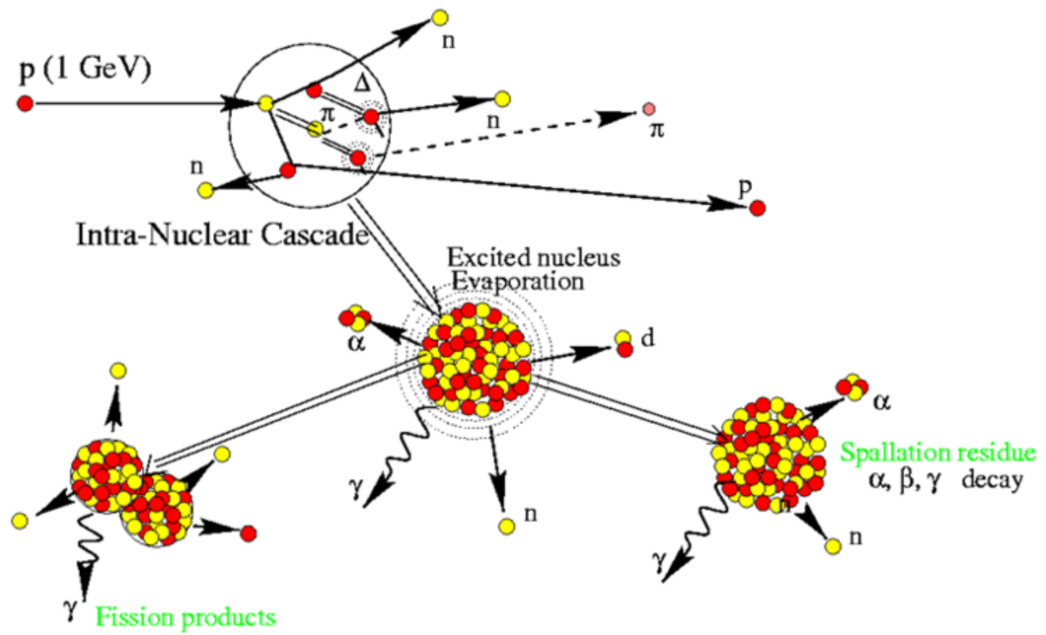
- only small modification of general parameters of nuclear ensemble (density, temperature, mass),
- introduction of only small amount of longitudinal and angular momentum,
- no (additional) deformation of bombarded nucleus,
- no collective motion,
- energy dissipation of introduced energy is not violent.

→ **Insight into:**

- hadronic interactions in medium,
- dynamics of energy dissipation in nuclear system,
- interplay of various mechanisms,
- **static/dynamic nuclear clustering - origin of high-energy composite particles.**

Observables - what can be learned





Measuring of the energy spectra at various angles permits to disentangle at least two components (processes ?) :

- at low energy - fast vanishing with the energy of product (assigned to evaporation),
- at higher energies - flat and extending up to kinematic limit (cascade + …),
- angular dependence for high energy part.

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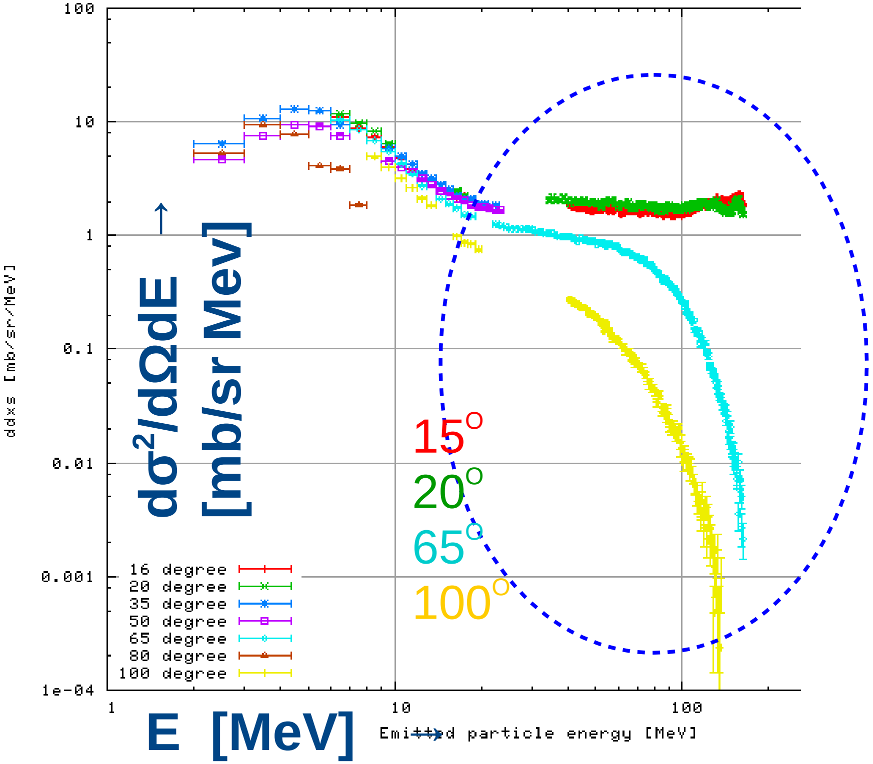

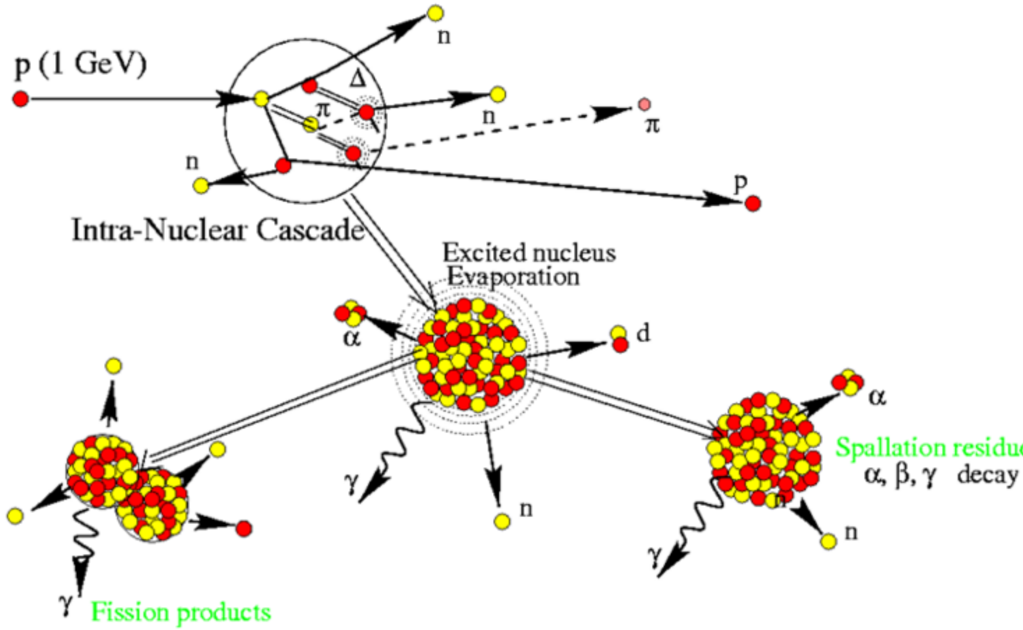

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PISA Experiment

PISA – Proton Induced SpAllation

Performed at internal beam of
Coller Synchrotron (COSY)
in FZ-Juelich, Germany.

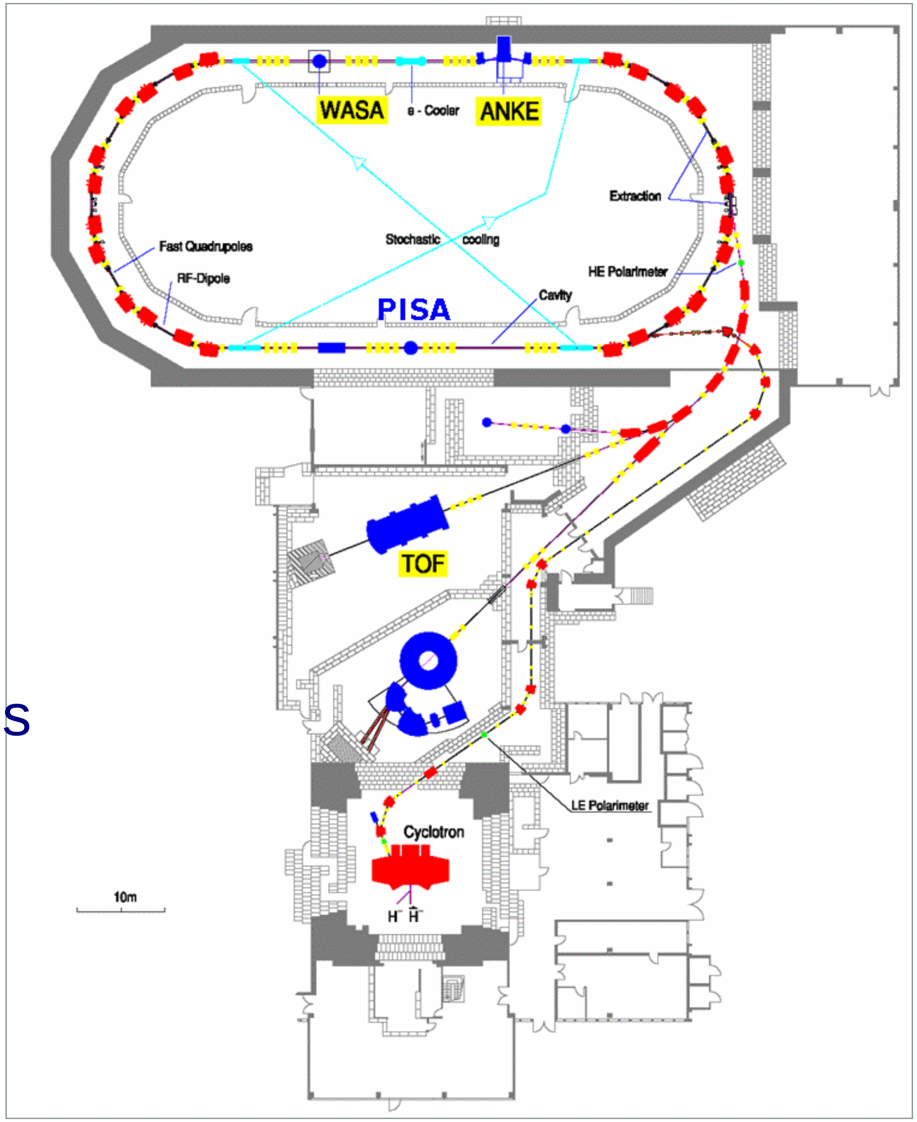
Proton beam
@ 175 MeV – 2.5 GeV

Targets: C, Al, Ni, Ag, Au

Particle detection at 8 emission angles

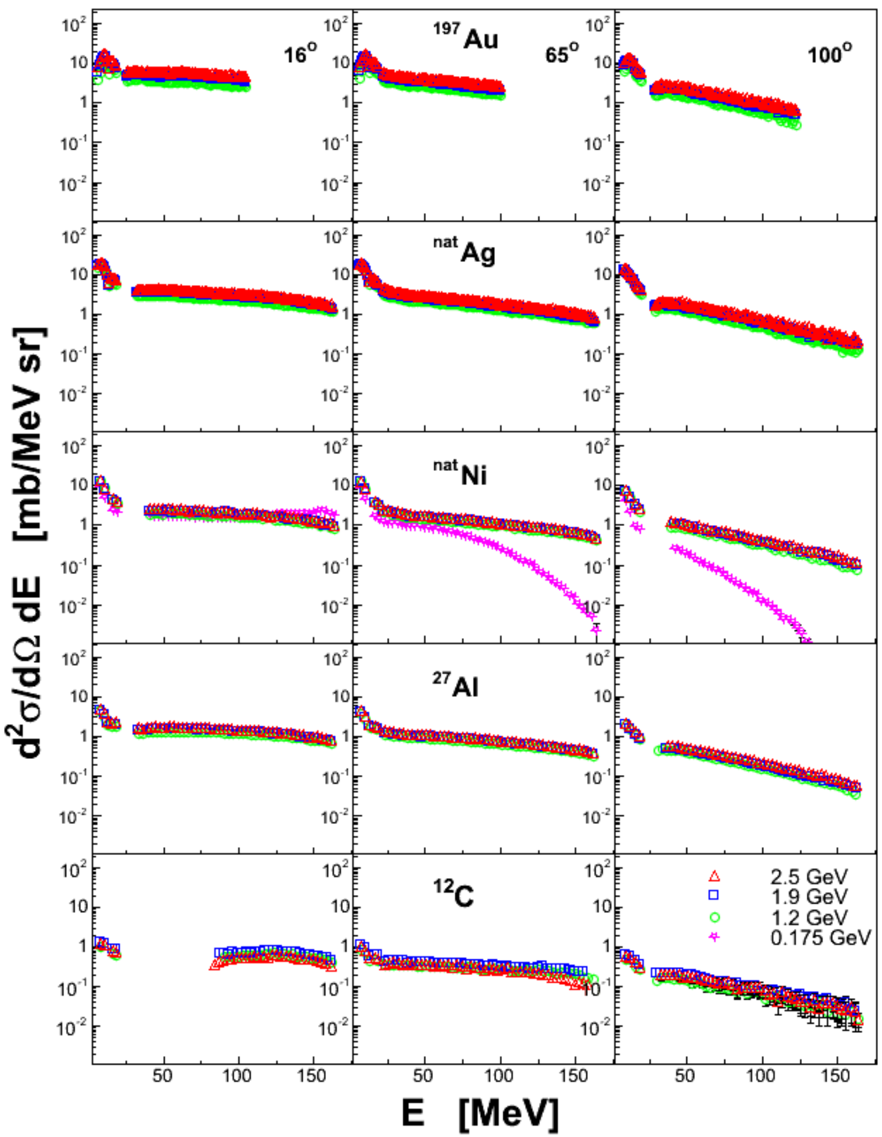
Thin targets – undistorted
information about mechanisms

PISA Collab., NIM A519(2004)610,
PISA Collab., NIM B226(2004)507
PISA Collab., NIM A(2006)733

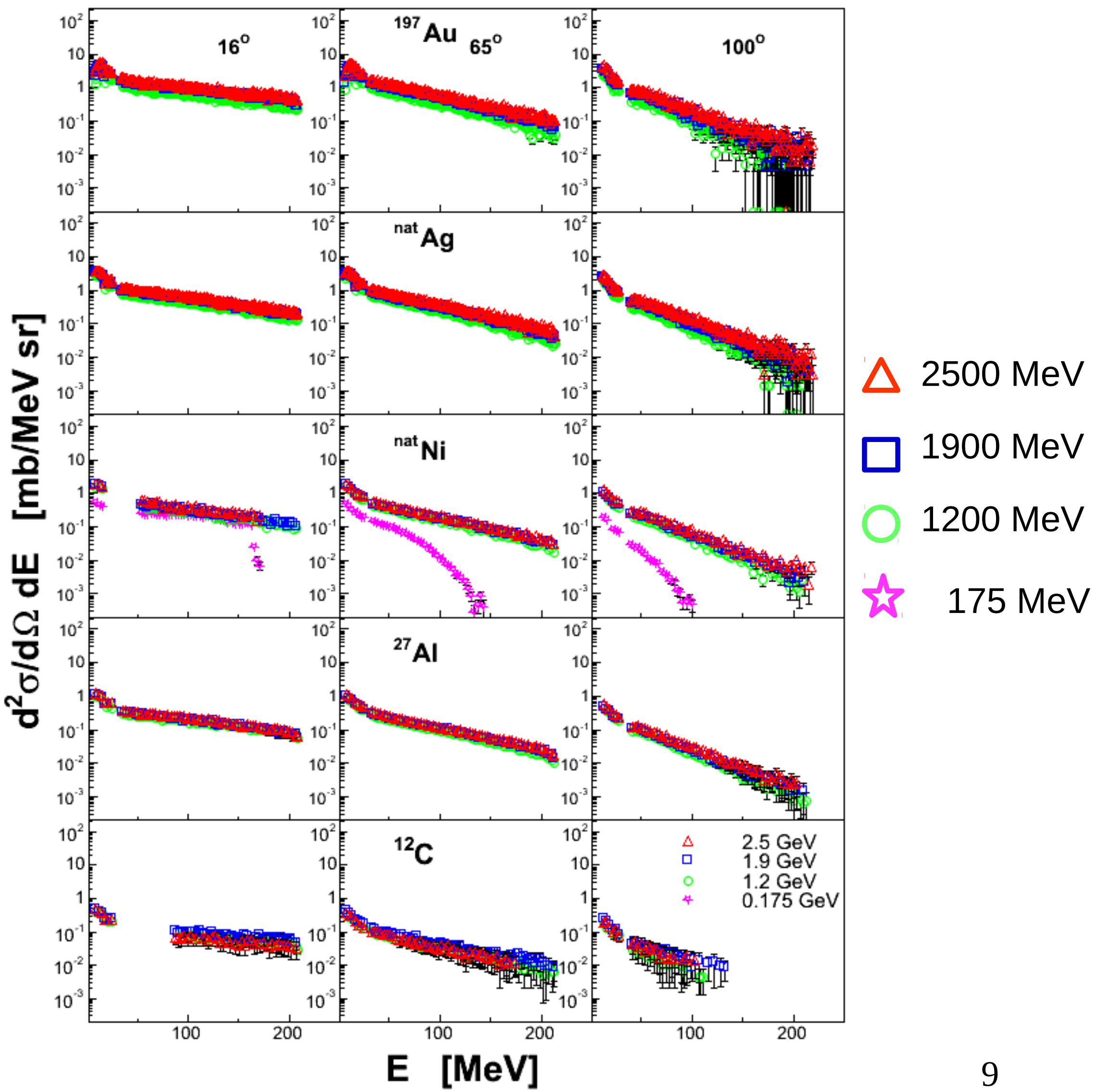


PISA – results for p and d

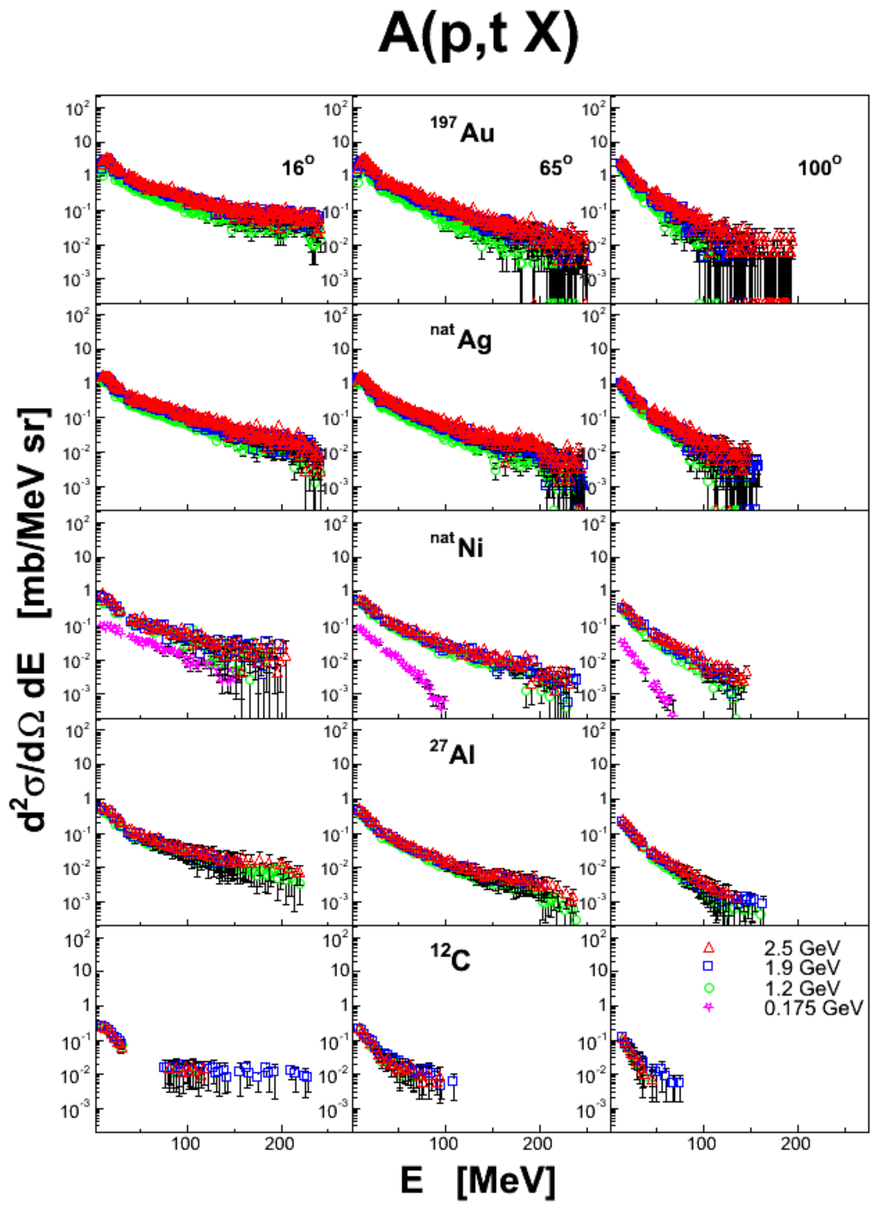
A(p,p X)

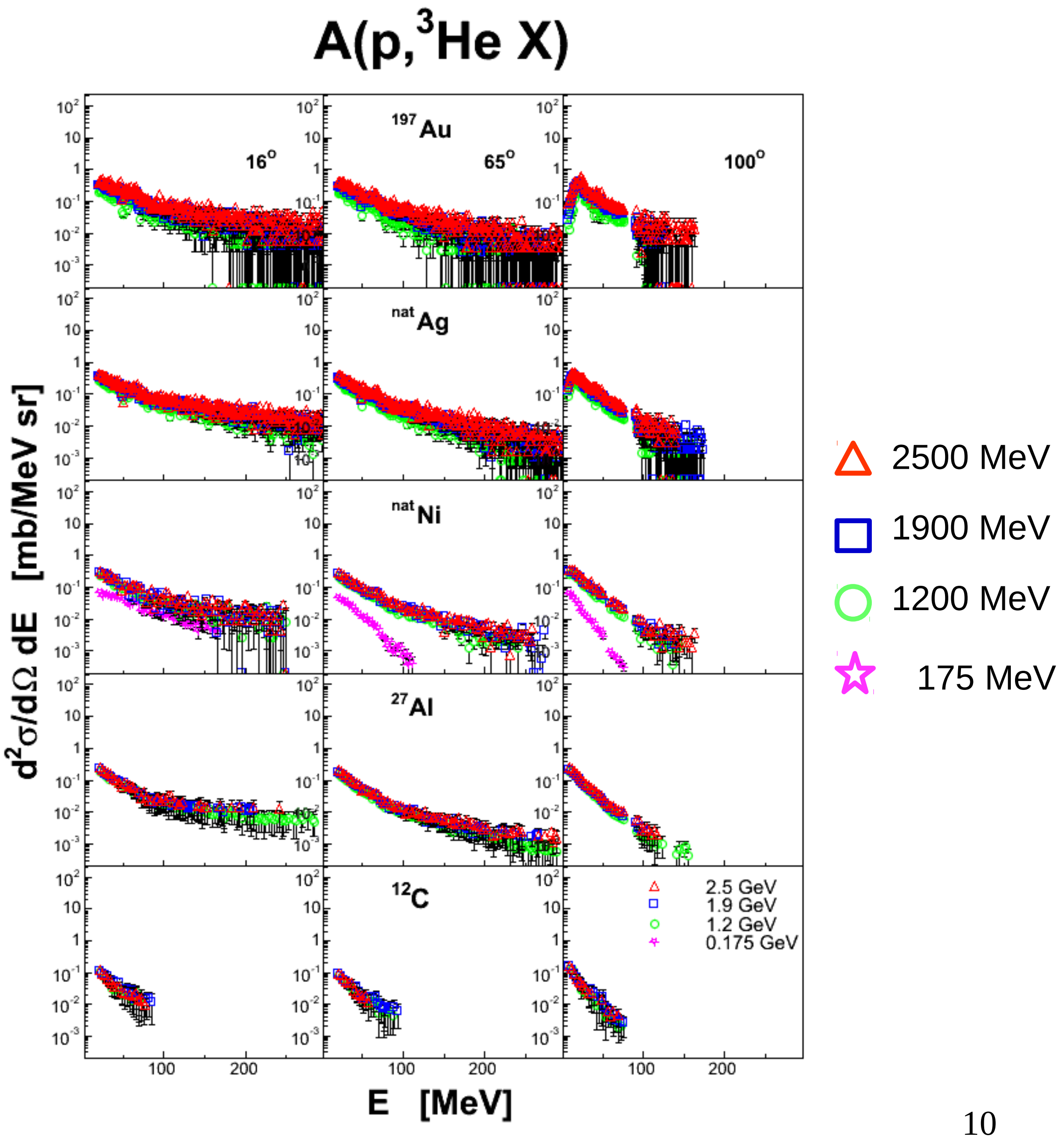


A(p,d X)

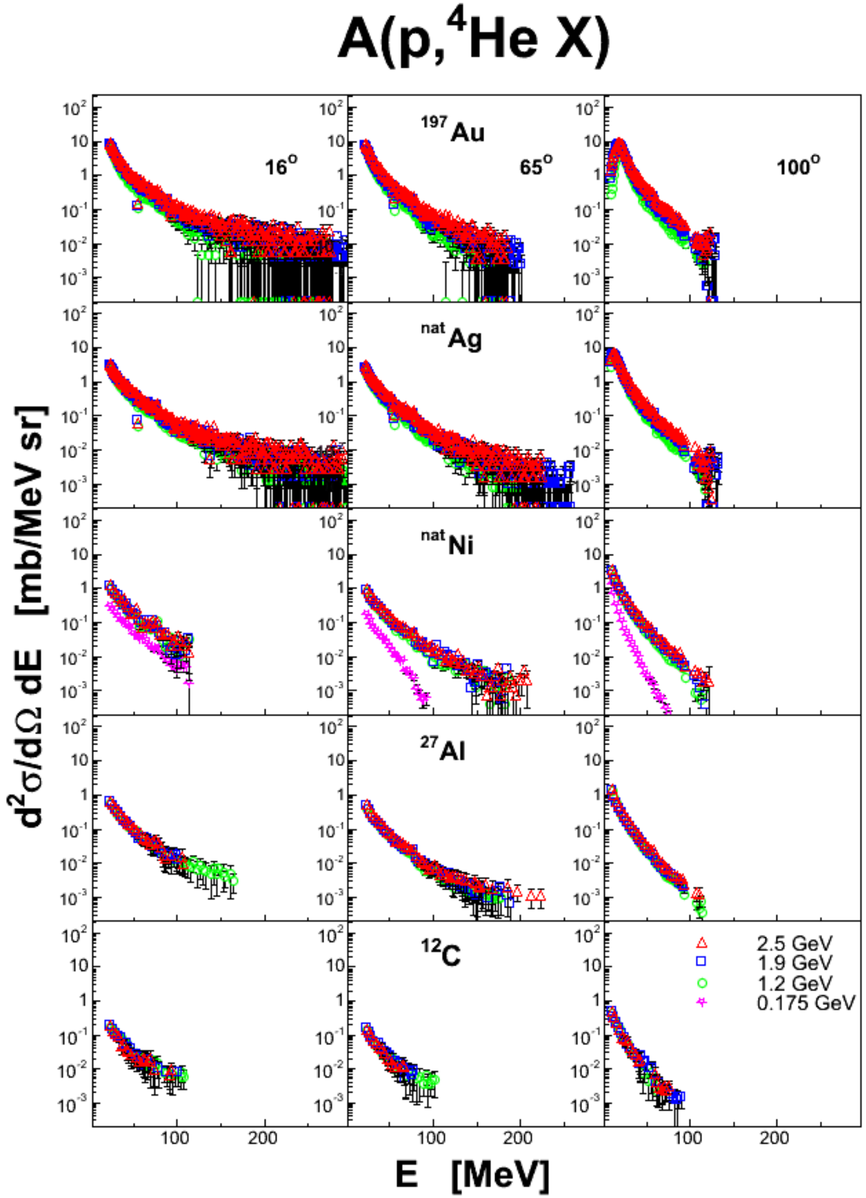


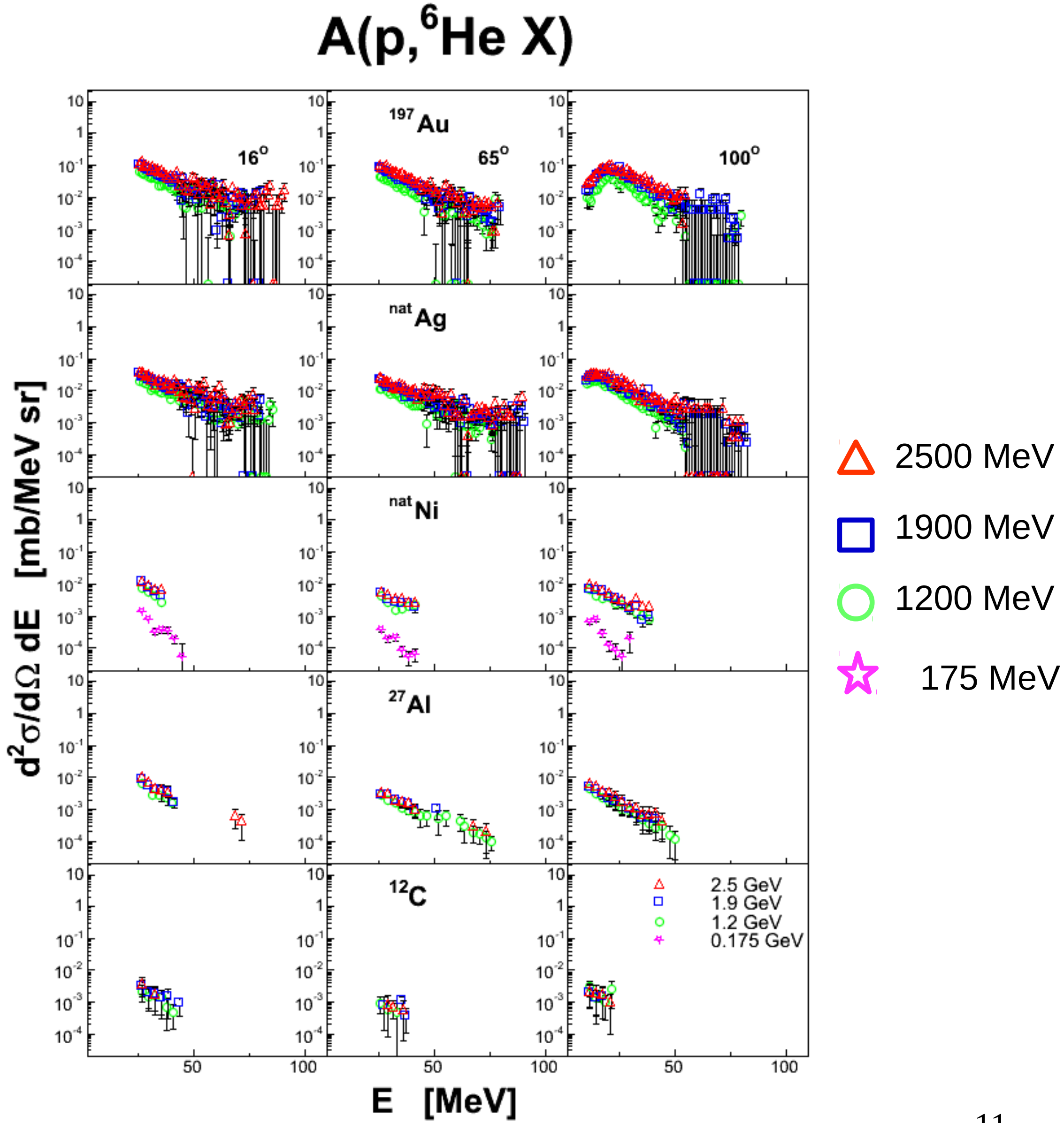
PISA – results for t and 3He





PISA – results for 4He and 6He





PISA – features of data

- The shapes of the spectra for individual ejectiles are almost the same for three highest bombarding energies of 2.5 GeV, 1.9 GeV and 1.2 GeV. Some differences are visible for lowest incident energy of 175 MeV;
- The angular dependence of distributions' shapes is monotonic;
- The magnitude of cross sections varies very little among bombarding energies of 2.5-, 1.9-vand 1.2 GeV;
- Even when the bombarding proton has only 175 MeV the yield of forward emitted protons and deuterons is similar as these for higher incident energies.
- At the low energies (< 50 MeV) the component with peak and steeply falling edge is visible. The peak position is stable. This component is independent of emission angle;
- A few times less abundant but extending over longer energy range component is observed at higher emission energies. It is less steep but anisotropic - the slope is rising with detection angle;
- The yield of particles of the second component decrease with the mass of ejectile and its emission angle;

PISA – available data

Double differential cross sections ($d^2\sigma/d\Omega dE$)
p + (**C, Al, Ni, Ag, Au**)
@ **0.175-, 1.2-, 1.9-, 2.5 GeV**.

Identified products:

od H do B (isotopes)
→ **Mg** (elements).

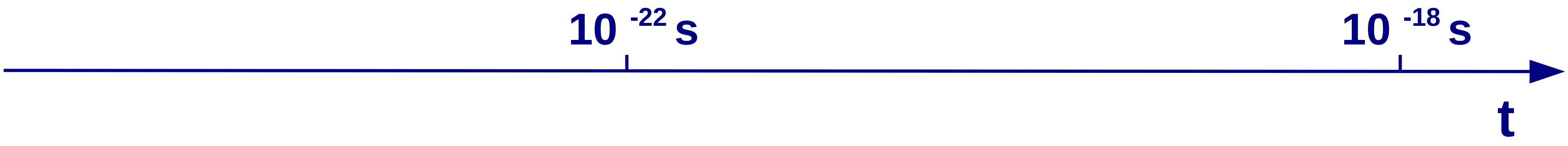
PISA Collab., PRC76(2007)014618
PISA Collab., PRC78(2008)024603
PISA Collab., PRC80(2009)054604
PISA Collab., PRC82(2010)034605
PISA Collab., PRC89(2014)054617

Accessible from
data base of International Atomic Energy Agency:

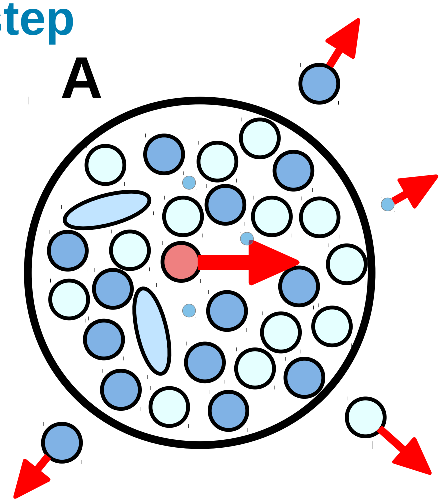
IAEA Benchmark of Spallation Models - Experimental Data,
https://www-nds.iaea.org/spallations/spal_exp.html

(plenty of experimental results from various experiments
given in the form of text files)

Traditional description: two step model

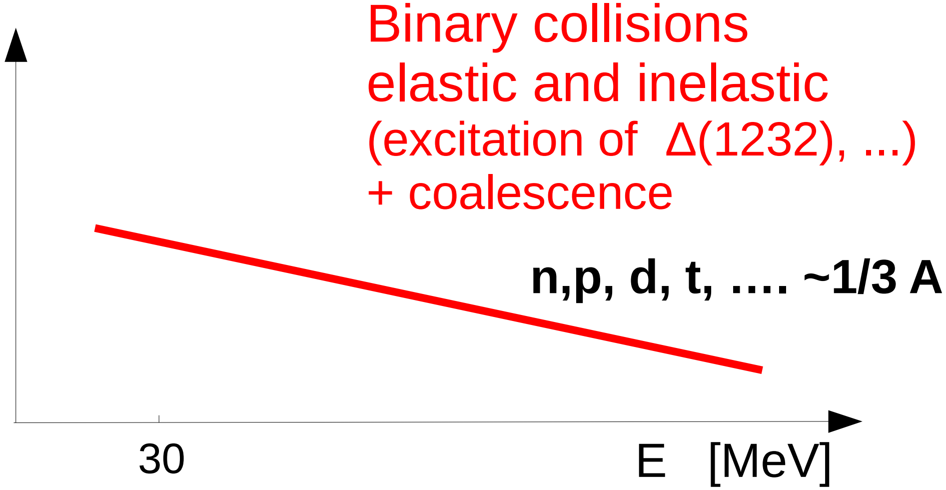


I step

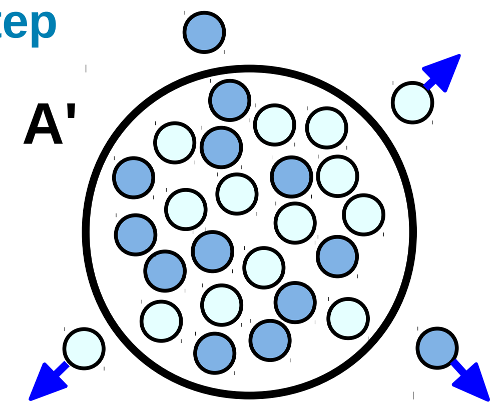


Intranuclear cascade

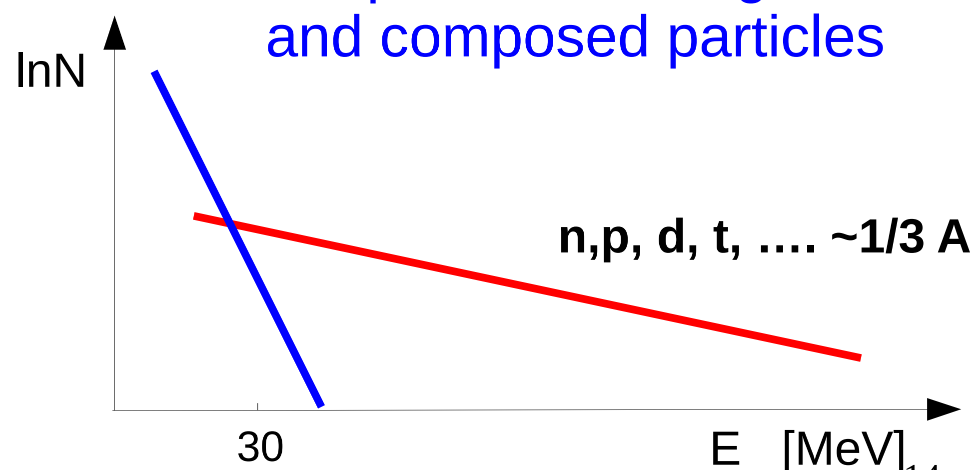
Binary collisions
elastic and inelastic
(excitation of Δ(1232), ...)
+ coalescence



II step



Evaporation of single
and composed particles



Traditional description: two step model

I step

Intranuclear cascade

Models of cascade, types:

- **Based on transport equation (BUU)**
  - mean field evolution during reaction,
  - lack of particles correlations – creation of composite particles excluded.
- **Based on quantum molecular dynamics (QMD)**
  - nucleons described with a probability functions,
  - density fluctuations and field modifications,
  - creation of composite object is possible.
- **Using simplified intranuclear cascade**
  - Fermi gas model,
  - constant nuclear potential,
  - nucleons – point objects.

II step

Evaporation, fragmentation, fission

Statistical models:

- **Hauser-Feshbach formalism**
- **Weisskopf-Ewing formalism**
- **Statistical Multifragmentation**
- **Fermi decay**

(e.g. GEMINI, GEM2, ABLA, SMM)

In all models the Pauli blocking is respected.
For simulation of the interactions **the "vacuum" cross section for hadrons are used.**

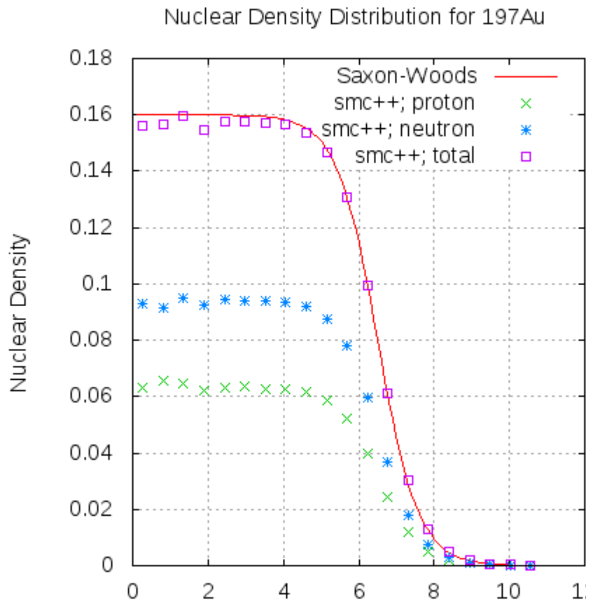
Intranuclear Cascade Model Liege (INCL)

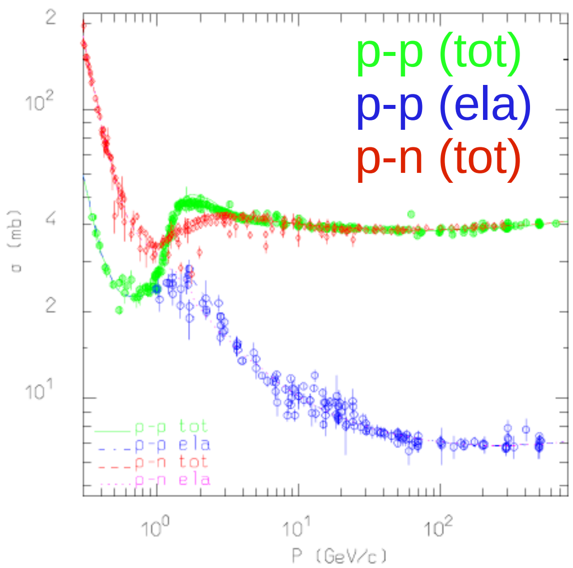
- nucleus as a Fermi Gas;
- constant nuclear potential;
- nuclear density – Saxon-Woods distribution;
- Pauli blocking;
- interactions:

$N\,N \rightarrow N\,N$ (elastic)
$N\,N \rightarrow N\,\Delta(1232)$
$\Delta(1232) \rightarrow \pi\,N$
$N\,\Delta(1232) \rightarrow N\,N$ (delta absorption)
$\pi\,N \rightarrow \pi\,N$ (elastic)
$\pi\,N \rightarrow \pi\,\Delta(1232)$

(parametrized cross sections for free particles)

- for particle emission the Coulmomb barrier is taken into account
- light composite particles - surface coalescence;

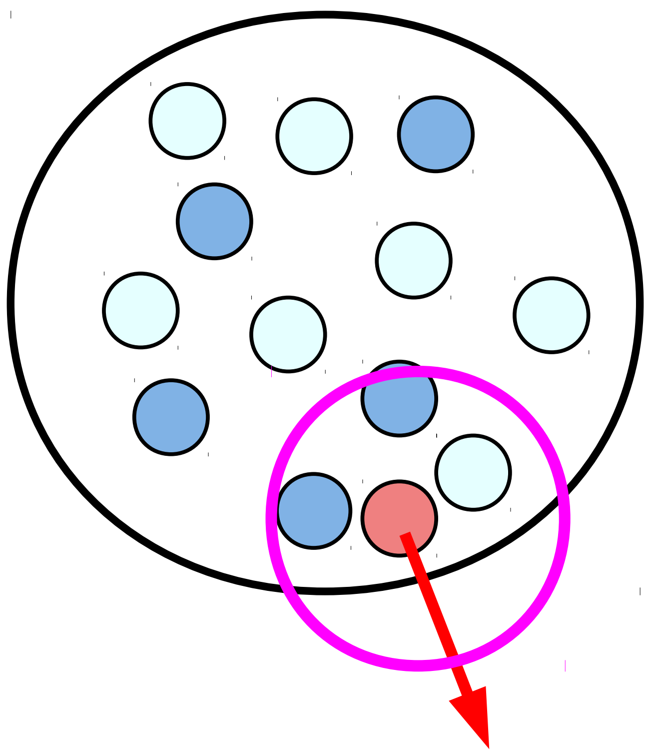




Hypothesis of surface coalescence

In INCL model only binary interaction are foreseen – no way to create the clusters.

In order to create the abundantly observed in experiment composite particles the mechanism of surface coalescence is assumed:



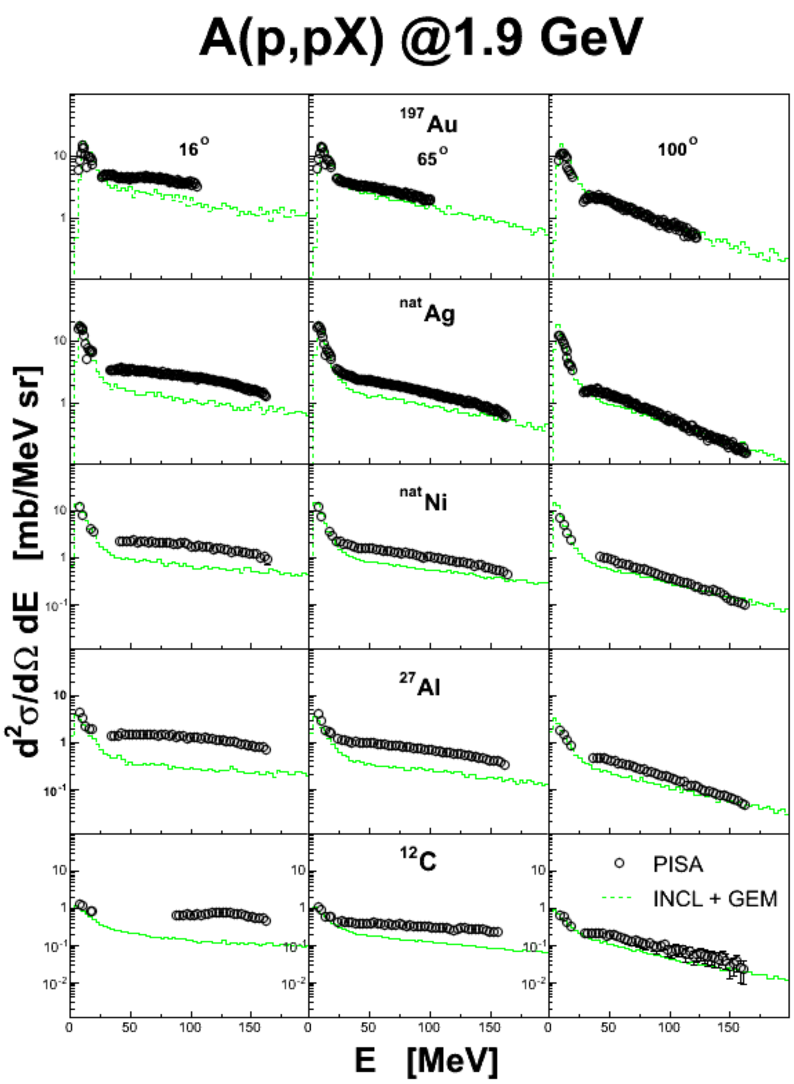
Assumption:

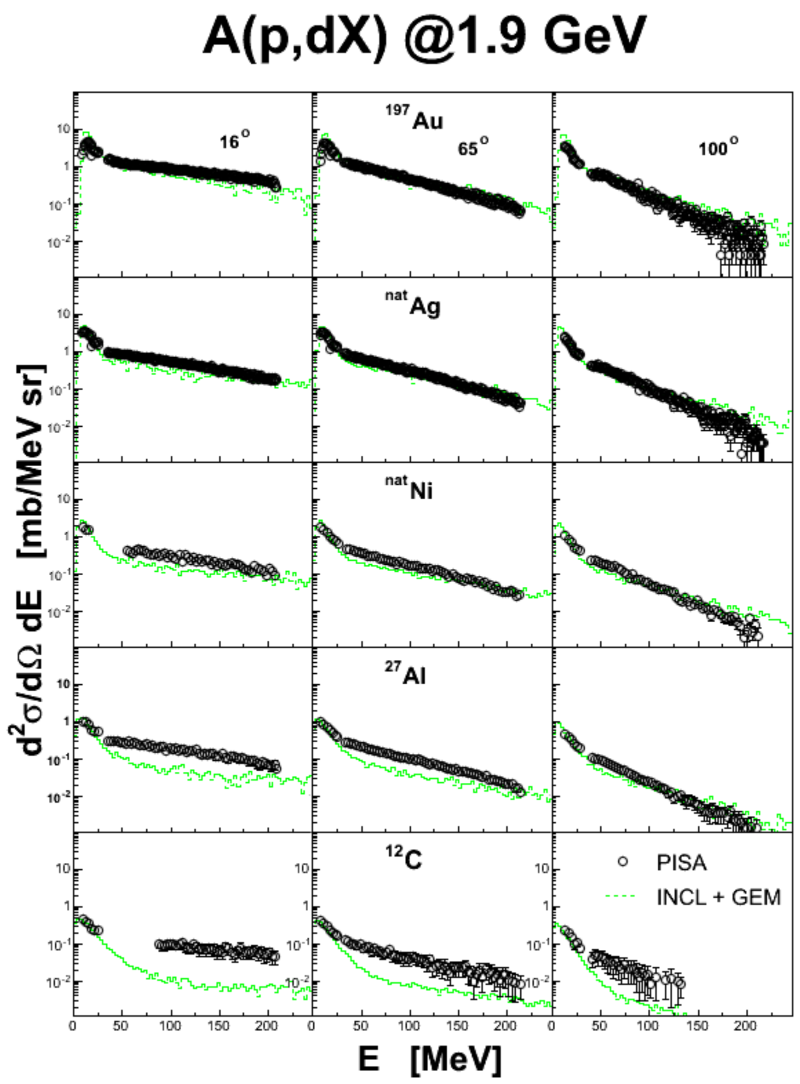
Emitted nucleon can sweep away others nucleons.

Conditions:

- they are all together sufficiently close in phase-space,
- they can form a stable particle.

Models – p and d





Data: PISA experiment (Kraków-Juelich); Model: INCL + GEM2

Common deficiencies of the “microscopic” models

- Composite particles are constructed with the use of surface coalescence (for A <= 8) – works satisfactory for targets of A ~ 100. For lighter nuclei disagreement with the data is significant.
- Models underestimate proton production for each target and energy (for lighter targets discrepancy is of factor 5 – 10)
- Strong underestimation of protons and problems with heavier products indicates that intranuclear cascade of pure binary interactions is not sufficient to describe actual physics of pA collision.

It is not possible to obtain the global improvement of the data description with the models by reasonable manipulations of the model parameters !

Common deficiencies of the "microscopic" models

- Too small energy/momentum transfer from projectile to the target;
- Too slow energy dissipation inside the target nucleus during cascade;
- Insufficient number of nucleons take part in cascade;
- Mean energy of cascade nucleons is too small – they can not be emitted;
- Emission of preequilibrium composite particles is insufficient for lighter targets;
- Coalescence permits "production" of only light nuclei.

What is missing ?

Common deficiencies of the "microscopic" models

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What is missing ?

Hypothesis: the dynamic clustering in nuclear medium takes place
- contribute to faster energy dissipation;
- enhances the single particle emission;
- is an intermediate process in production of observed composite particles.

Hypothesis of dynamic clustering in nuclear medium (DCNM)

Assumptions:

- density fluctuations may lead to creation of the <u>momentary</u> clusters (droplets ?) formed out of nucleons;
- such clusters “decay” in medium with the given probability (lifetime);
- nucleons in the cluster interact and exchange energy/momentum;
- clusters have chance to be emitted from the nucleus. Such aggregates contribute to production of real composite light particles (H, He).
- formation of momentary clusters competes with binary interactions between nucleons;
- “traditional” coalescence is not taken into account.

K. P., PRC91(2015)011602

Test by MC simulation

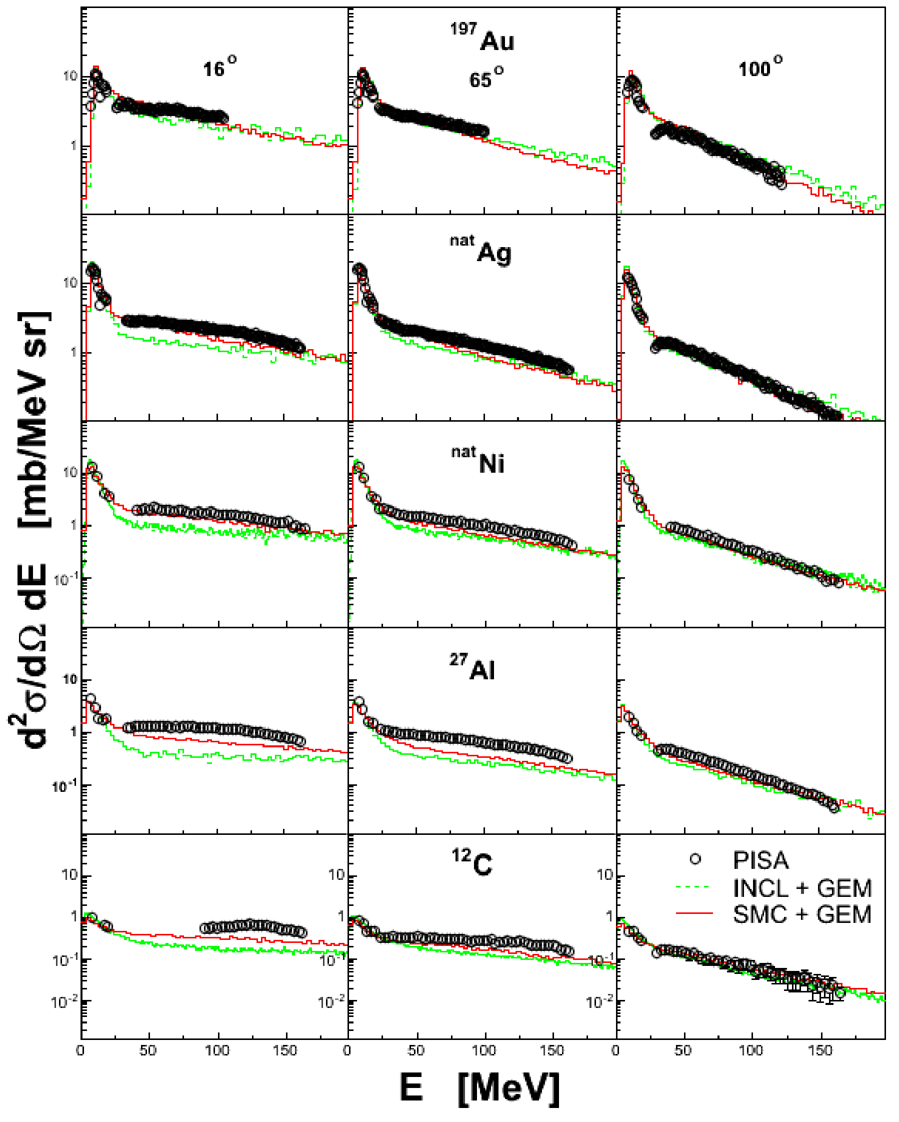
Implementation of idea of dynamical clusterization
into model of intranuclear cascade:

- all ideas and achievement of INCL are adapted;
- surface coalescence is disregarded;
- mechanism of DCNM as described above is introduced as a competition to binary interactions.

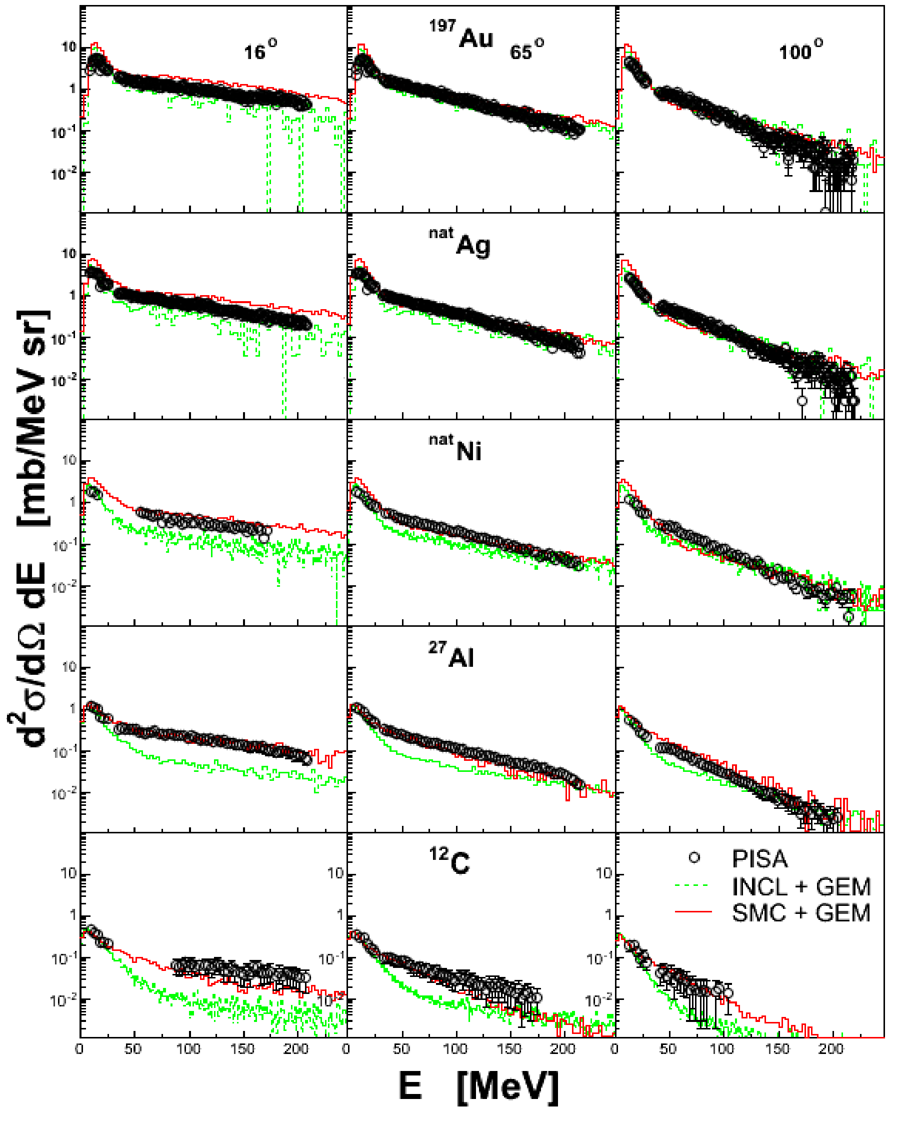
Spalation Model with Cascade++ (SMC++)

Comparison: model with and w/o DCNM

A(p,pX) @1.2 GeV

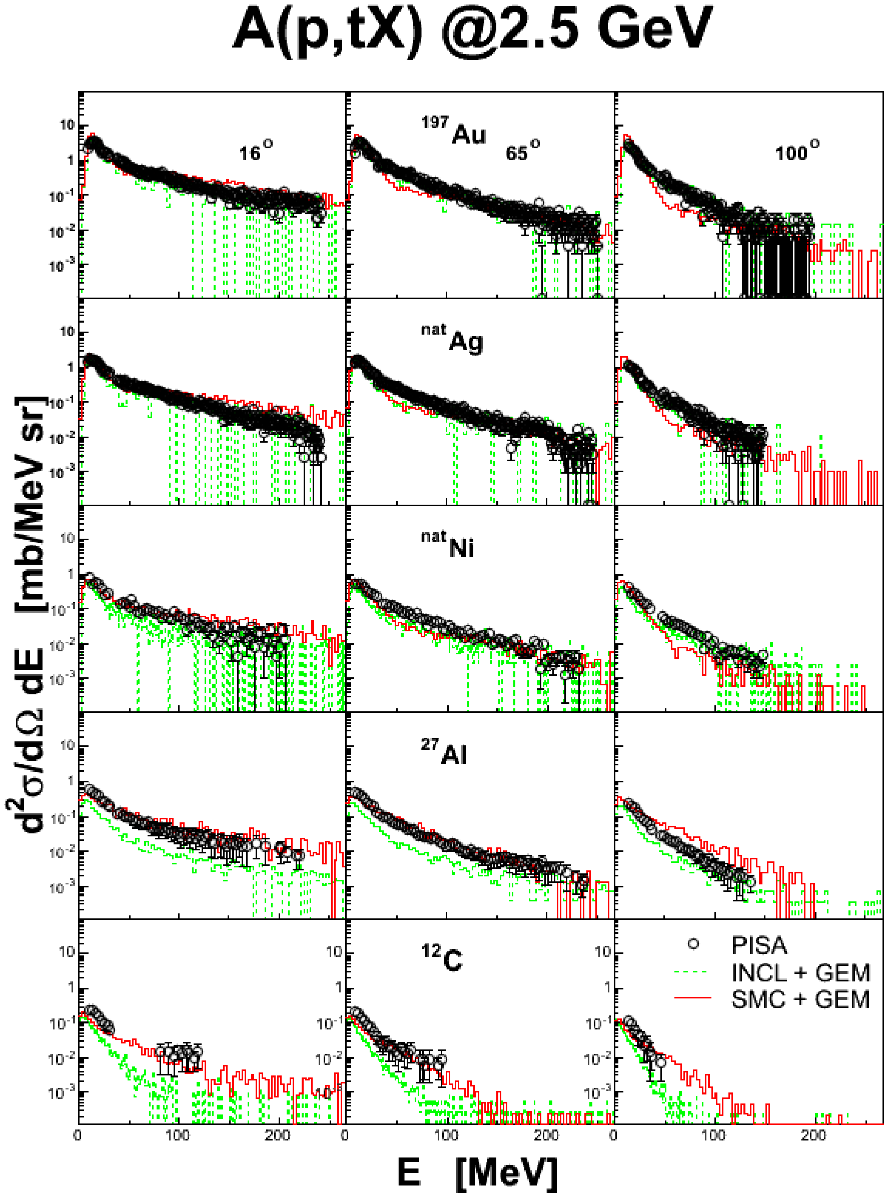


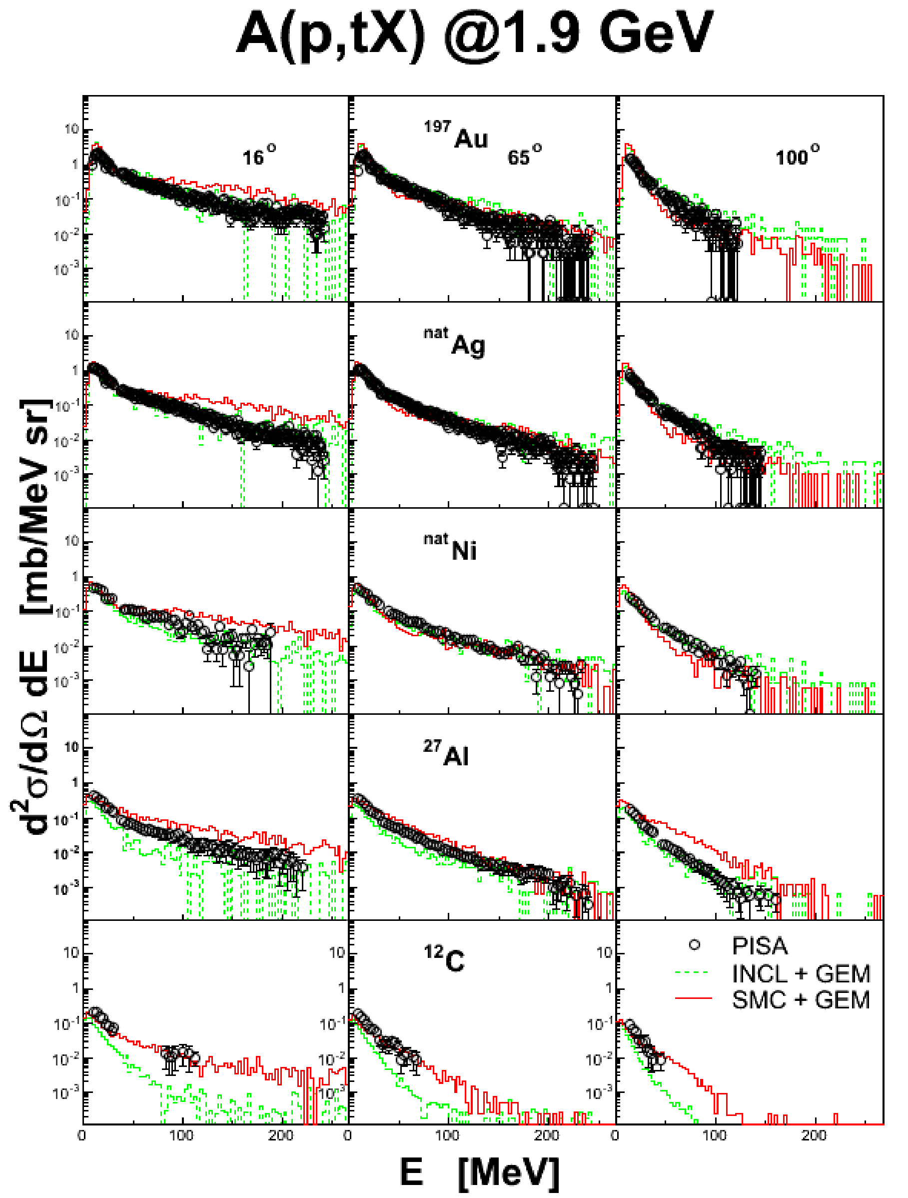
A(p,dX) @2.5 GeV



Data: PISA exp; Model: INCL(+coalescence); Model: Cascade+Dynamic Clustering

Comparison: model with and w/o DCNM





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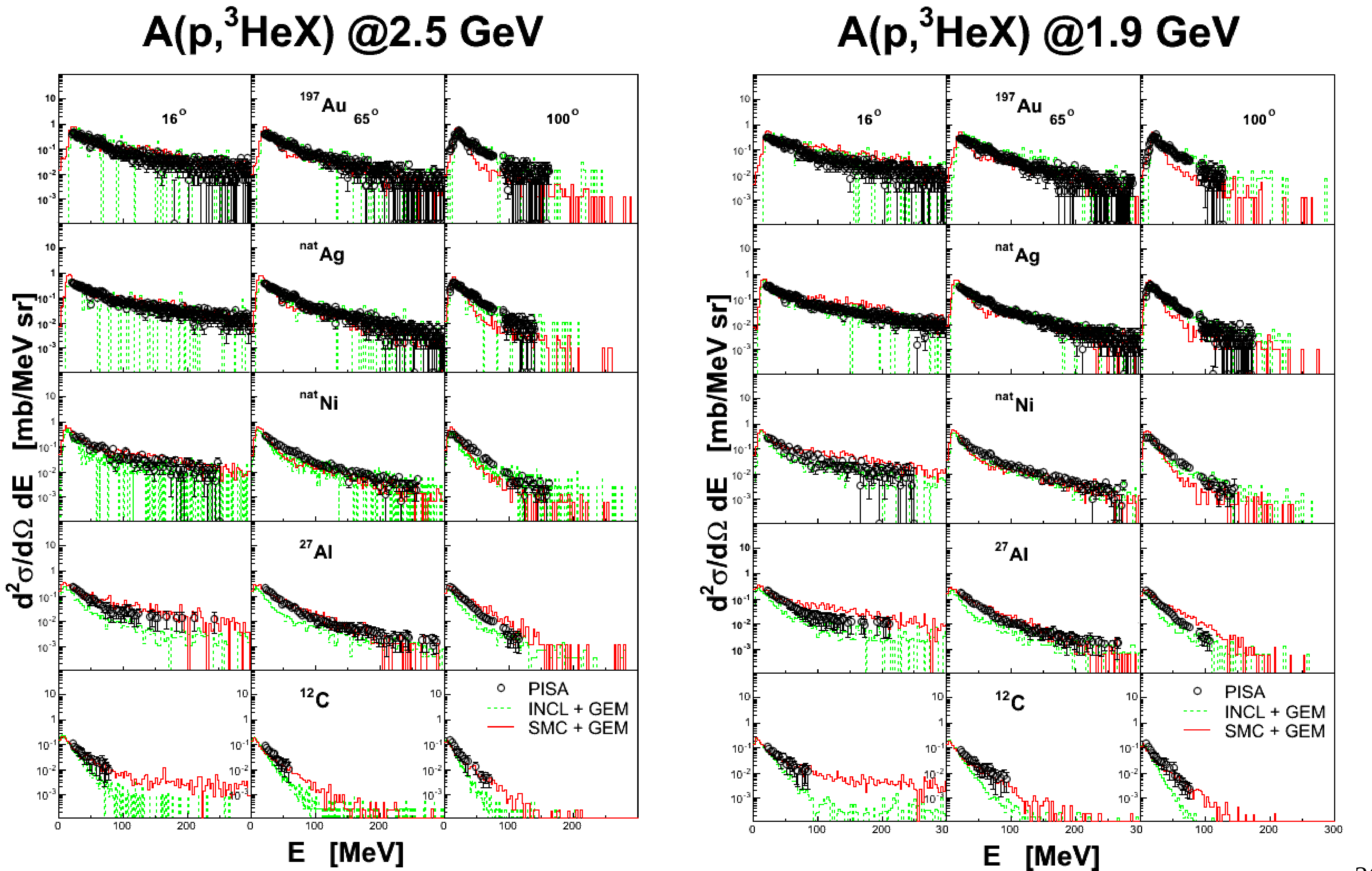

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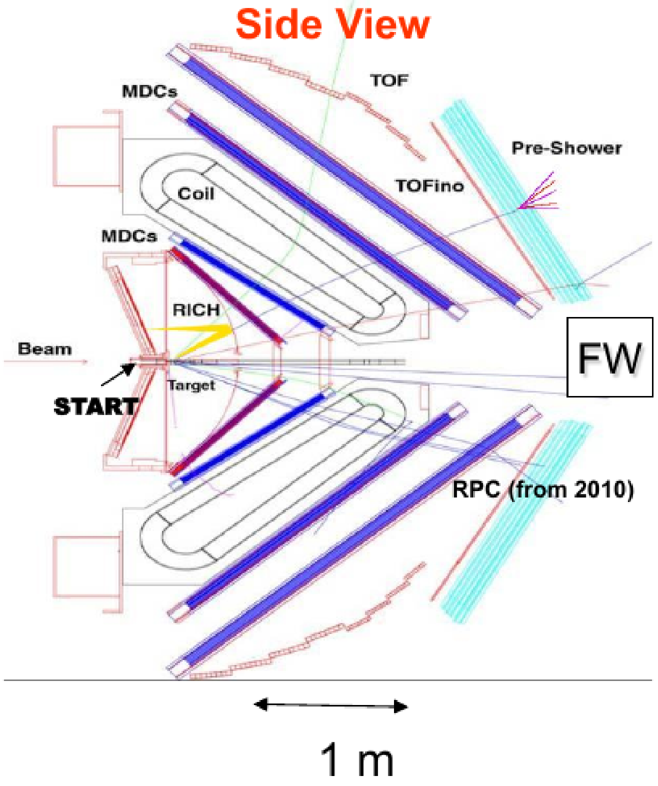
HADES – new data – new motivation

HADES - High Acceptance DiElectron Spectrometer

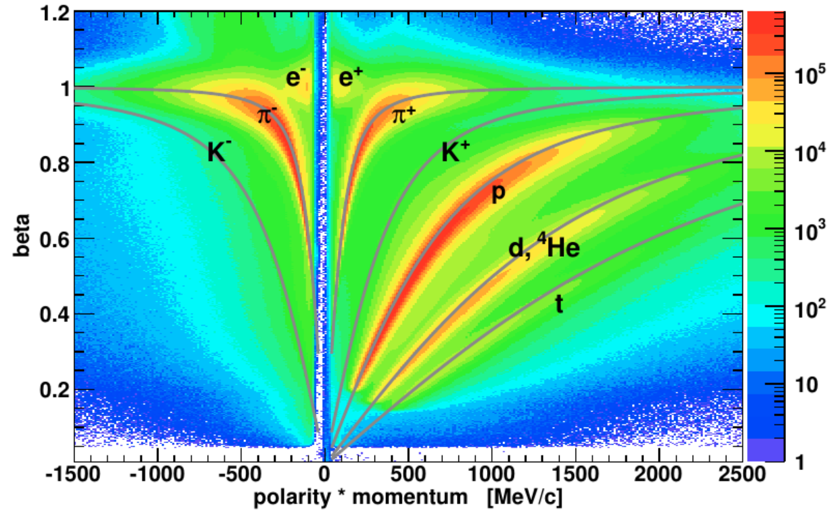
- Studies of QCD in low energy scale (excited and compressed nuclear matter);
- Investigation of hadron properties in nuclear medium (origin of hadron masses, …);
- Studies of disintegration mechanisms of target nuclei when bombarded by p and π in the HADES energy range.
  (investigations of in-medium effects in hadron interaction).



Nuclei in HADES

PID identification in HADES:

- MDC: dE/dx (ToT) vs. momentum
- TOF + TOFino
- $18^{O} < \theta < 85^{O}$
- 40 MeV < T < 2500 MeV



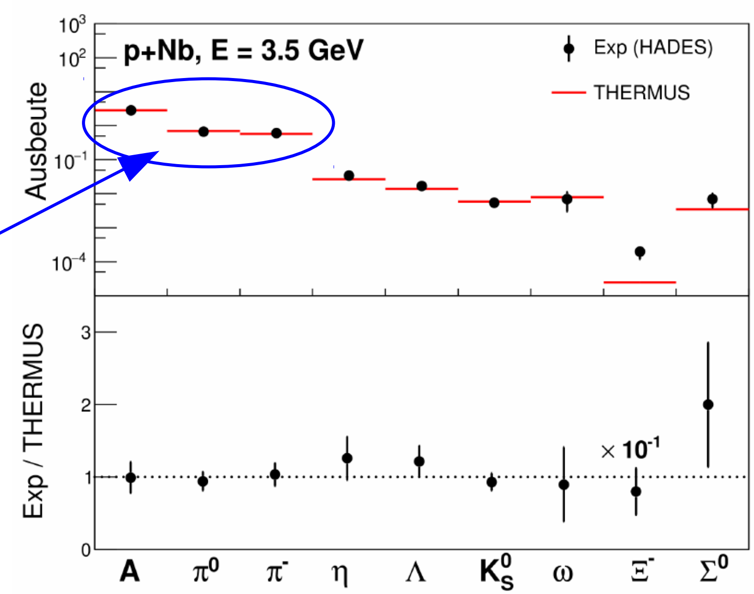
Statistical Hadronization Model THERMUS

Only total yields are taken into account

It confirms that in order to describe the general features of the nuclear system it can be approximated by a statistical ensemble.

Lets have a closer look

Could we perhaps learn something about mechanisms of target disintegration ?



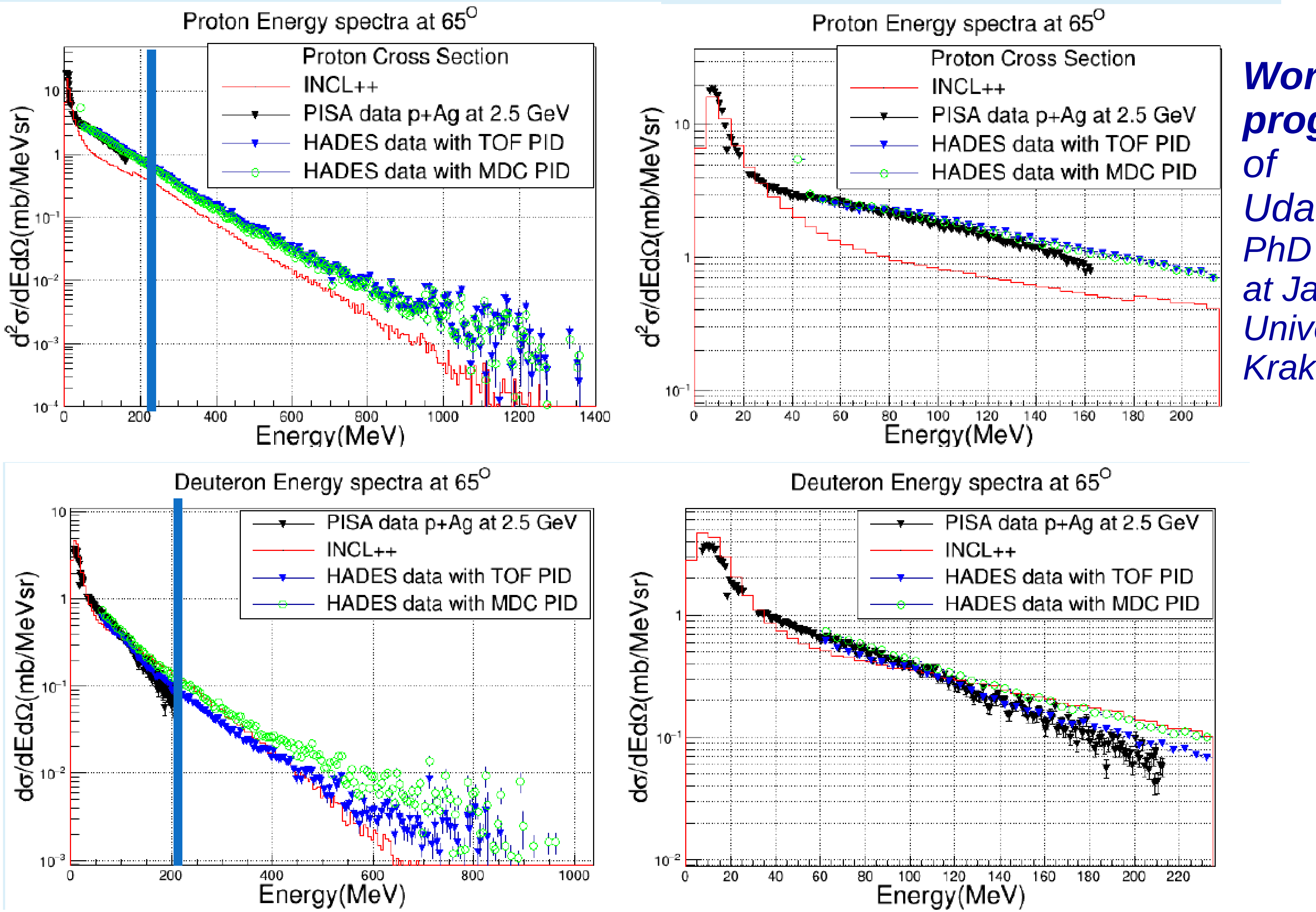
From theses of Manuel Lorentz and Tobias Kunz

Spallation @ HADES

Why nuclear product of HADES are interesting for studies of nuclei disintegration mechanism :

- light charged particles (p, d, t, 3He, 4He (?));
- detected in broad energy range (covering the high energy products originating from nuclear cascade (only lowest energy part of this distributions were measured in dedicated experiments yet);
- detected in forward angular range of interest;
- registered with high statistics and for large acceptance
  → hope for more exclusive observables ($d^4\sigma/d\Omega_1 d\Omega_2 dE_1 1dE_2$);
- associated with emitted pions (dominant carriers of energy/momentum in cascade);
- associated with detected mesons of smaller cross sections.

HADES peliminary (!) results; p+Nb @ 3.5 GeV



Work in progress *of Udai Singh, PhD student at Jagiellonian University Kraków*

Summary

- Good experimental data ($d^2\sigma/d\Omega dE$) for the proton and cluster production in p+A collisions, for broad range of incident energies, masses of targets, masses, energies and emission angles of products are available;
- New data for even broader energy range of products, and more exclusive ($d^4\sigma/d\Omega_1 d\Omega_2 dE_1 1dE_2$) will be soon provided by HADES Collaboration (for proton and pion projectiles);
- Contemporary numerical models of p+A reactions at ~GeV energy significantly underestimate the production of protons and have problems with correct reproduction of light composite particles. Heavier clusters are disregarded;
- Hypothesis of dynamic clustering of excited nuclear medium may improve the theoretical description of experimental data;
- Reactions with light projectiles at ~ GeV energy range might be an interesting field for theoretical investigation of the nature of nuclear clusters.