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Proton induced spallation reactions investigated within the framework of BUU model

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Proton induced spallation reactions investigated within the framework of BUU model

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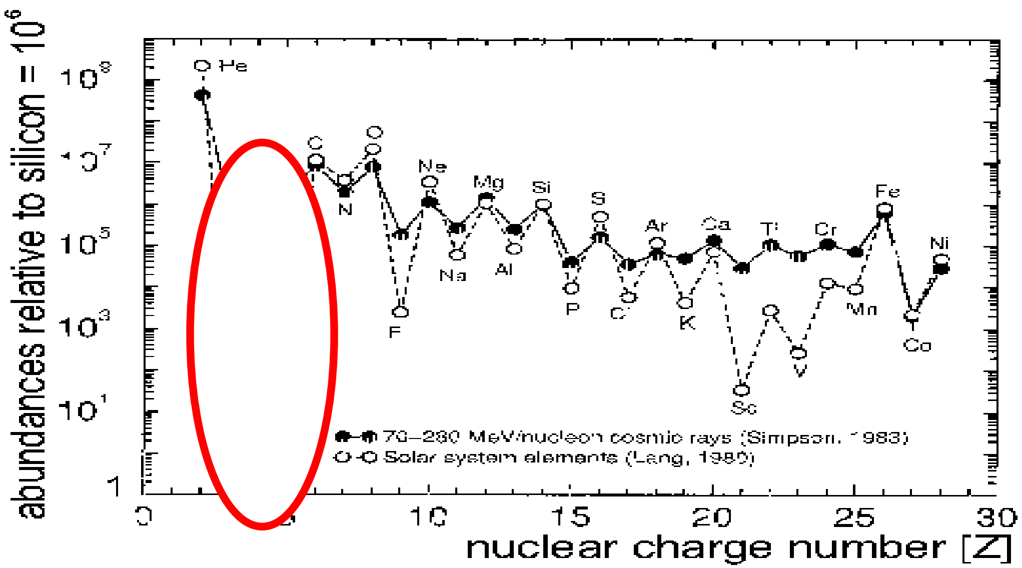
Outline:

- *Motivation*
- *Characteristics of the reactions*
- *BUU model description*
- *Model results - comparison with experimental data*
- *Conclusions*

Why are proton induced spallation reactions of interest?

- ***Knowledge of the reaction mechanism:***
- ***mechanism of spallation reaction is not well known***
- ***double differential cross sections of emitted particles in the reactions are necessary for testing, validation and developing of theoretical models***

- ***Applications:***
- *astrophysical aspects:*
- *comparison of cosmic ray elements and the solar system abundances*
- *Li, Be and B in cosmic rays are enriched by more than 6 orders of magnitude*

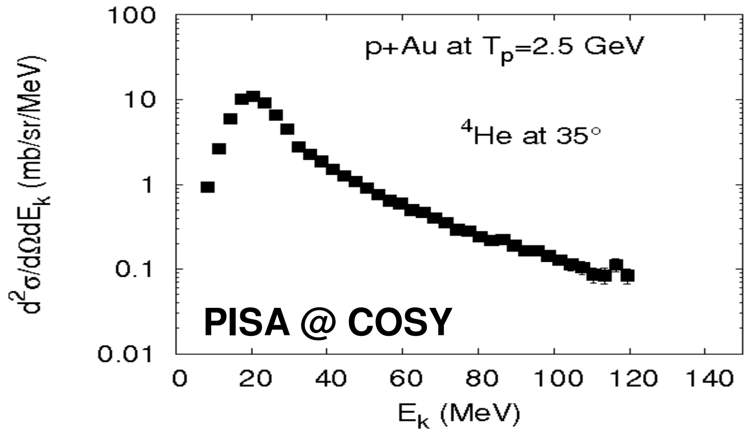


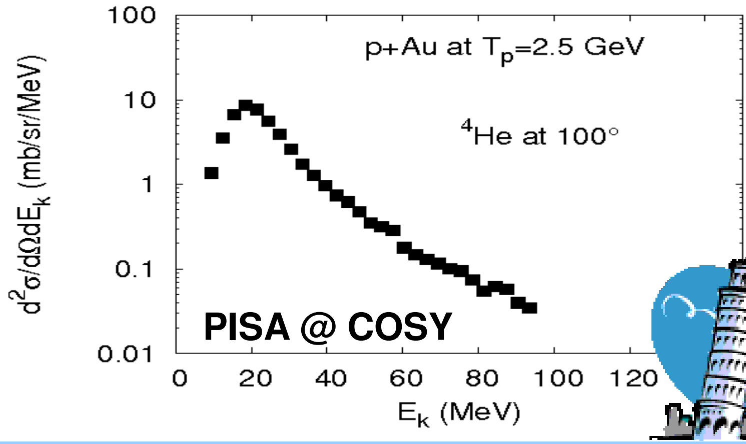
S. G. Mashnik*, On Solar System and Cosmic Rays Nucleosynthesis and Spallation Processes,* LANL, Report LA-UR-00-3658, (2000)

Experimental observations:

Study of the reactions possible due to development of accelerator technics
– the end of fourties –
accelerators provide projectiles with energies higher than 100 MeV

- ***2 – component spectra of emitted particles:***
  - *high energy part – dominant in forward angles,*
  - *isotropic low energy part*





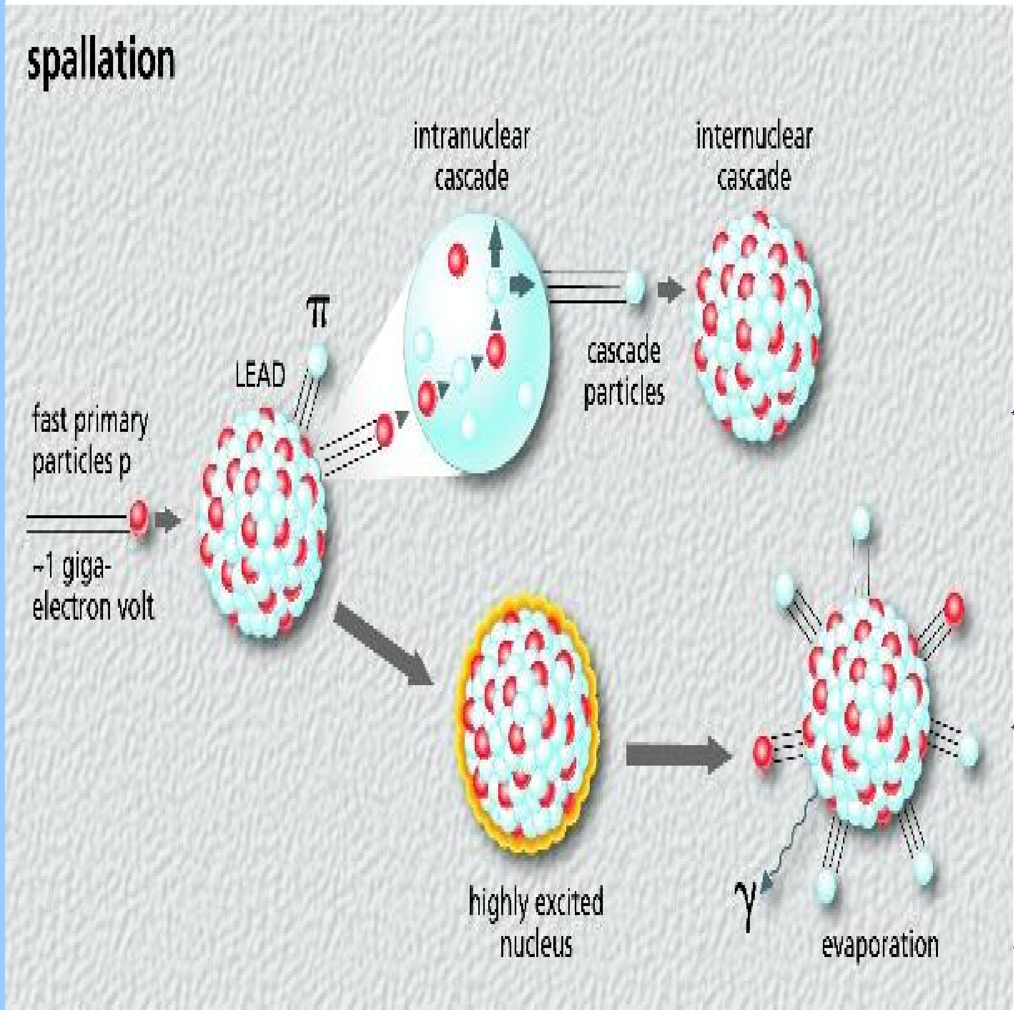
Based on experimental observations – general rules of spallation processes are established

Historically:

- **Metropolis** N. Metropolis et al., Phys. Rev. 110(1958)185
- **Dostrovsky** I. Dostrovsky et al., Phys. Rev. 111(1958)1658
- – *using the idea of* R. Serber, Phys. Rev. 72(1947)1114
- **Serber** *and* **Weisskopf** – V. Weisskopf, Phys. Rev. 52(1937)295
- *suggested description of spallation as two step process:*
- *energy deposition*
- *subsequent evaporation*

Such treatment of spallation reactions is used from that time up to now !

The Spallation Process:



- ***first (fast) stage:*** **Microscopic models**

- *high energy proton causes an **intra**-NC on a time scale ≈10^{-22}s*

- *highly non-equilibrated process, incoming proton deposits excitation energy and angular momentum*

- *high energy nucleons, pions and light ions are produced*

- *the result: excited residual nucleus in thermodynamical equilibrium with a few MeV/N of excitation energy*

- *emitted particles (n,p,π) can cause an **inter**-NC placing individual nuclei into excited states*

- ***second (slow) stage:*** **Statistical models**

- ***de-excitation by evaporating n, p, d, t, α, γ… on a time scale ≈ 10^{-18} 10^{-16}s***

Microscopic models:

- ***I**ntranuclear **C**ascade (**INC**)*
  – constant static potential

Bertini

Cugnon

Boudard

- ***B**oltzmann-**U**ehling-**U**hlenbeck (**BUU**)*
  – dynamically changing mean field

- ***Q**uantum **M**olecular **D**ynamics (**QMD**)*
  – two- and three- body potentials

Aichelin

Niita

Boltzmann-Uehling-Uhlenbeck (BUU) model:

*Based on **transport equation***

- *Originate in classical Boltzmann equation for one body phase – space distribution*

- *In 1933 – developed by **Uehling** and **Uhlenbeck**, by adding Pauli blocking factors*

A. E. Uehling and G. E. Uhlenbeck, Phys. Rev.43(1933)552

- *In 1984 – used first time to nuclear collision description, by **Bertsch***

G. F. Bertsch, et al., Phys. Rev. C, 29(1984)673

The transport equation:

$$\left\{\frac{\partial}{\partial t} + \left(\frac{\vec{p}_1}{m_1} + \frac{\partial U(\vec{r},\vec{p}_1,t)}{\partial \vec{p}_1}\right)\frac{\partial}{\partial \vec{r}} - \frac{\partial U(\vec{r},\vec{p}_1,t)}{\partial \vec{r}}\frac{\partial}{\partial \vec{p}_1}\right\} f(\vec{r},\vec{p}_1,t) =$$

$$\frac{4}{(2\pi)^3}\int d^3p_2\, d^3p_3\, d\Omega\, v_{12}\frac{d\sigma_{12}}{d\Omega}\delta^3(\vec{p}_1+\vec{p}_2-\vec{p}_3-\vec{p}_4)\cdot[f_3 f_4 \bar{f}_1 \bar{f}_2 - f_1 f_2 \bar{f}_3 \bar{f}_4]$$

- $f_i \equiv f(\vec{r},\vec{p}_i,t)$ – one-body phase-space distribution
- $\bar{f}_i \equiv 1 - f(\vec{r},\vec{p}_i,t)$ – Pauli blocking factors
- v_{12} – relative velocity of colliding particles 1 and 2
- Ω – angle between momenta of outgoing particles: $\vec{p}_3$ and $\vec{p}_4$
- $\frac{d\sigma_{12}}{d\Omega}$ – differential cross section of the reaction

- $U(\vec{r},\vec{p}_1,t)$ – mean-field potential, dynamically changing, calculated as a function of local density:

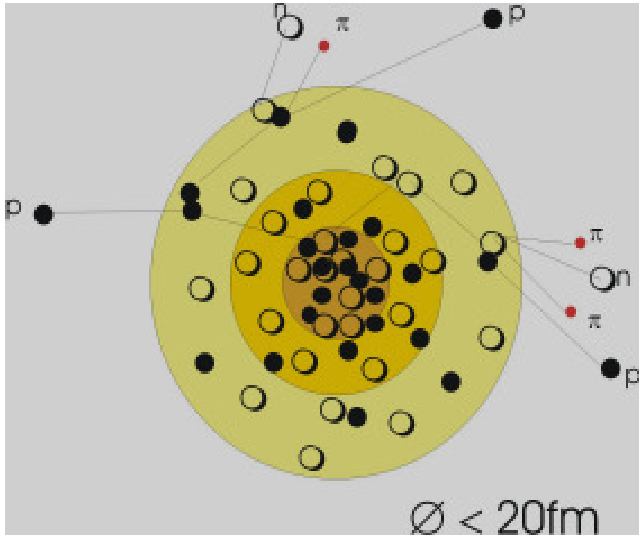
$$U(\vec{r}) = \frac{3}{4}t_0\rho(\vec{r}) + \frac{7}{8}t_3\rho(\vec{r})^{4/3} + V_0\int d^3\vec{r}'\frac{exp(-\mu|\vec{r}-\vec{r}'|)}{\mu|\vec{r}-\vec{r}'|}\rho(\vec{r}') + V_{Coul}$$

where:

t_0=-1124 MeV·fm^3; t_3=2037 MeV·fm^4; V_0=-378 MeV; μ=2.175 fm^{-1}.

Boltzmann-Uehling-Uhlenbeck (BUU) model:

- *Classical Boltzmann transport equation complemented with Pauli blocking factors*
- *p + A collision is described as cascade of N + N collisions*
- *between collisions nucleons are moving in mean field being a function of nuclear density inside nucleus*



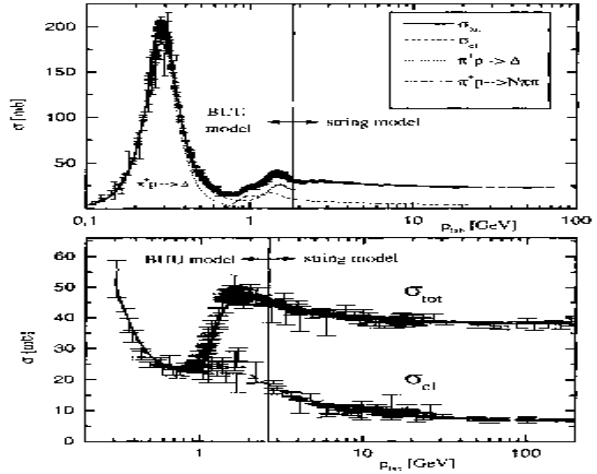
- *the equation is solved using Monte Carlo method, generating positions and momentum of particles in successive time steps*

K. Niita, W. Cassing and U. Mosel, Nucl. Phys. A 504(1989)391
G. F. Bertsch and S. Das Gupta, Phys. Rep. 160(1988)189

- *Interactions are based on elementary cross sections derived from empirical approximations of :*

- ***NN → NN (elastic)***
- ***NN → NR→ NπN***
- ***NN → RR → NπNπ***
- ***πN → πR → π Nπ***
- ***NR → NN (delta absorption)***
- ***πN → πN (elastic, charge exchange)***
- ***production and propagation of other baryons (Λ, Σ, Σ*, Ξ, Ω), corresponding antibaryons and mesons (K, η, η', ρ, ω, φ, K*, a1)***

R = Δ, N(1440),N(1535)



PDG, Phys. Rev. D 50(1994)1173

and other experimental informations !

J. Geiss, W. Cassing, C. Greiner, Nucl. Phys. A, 644(1998)107

- *Low energy limit:*
  - ***De-Broglie-wavelength λ** of cascade particles smaller than average distance of nucleons in nucleus (δ≈1.8fm) and mean free path length (**L**≈2 fm) in nuclear matter: **λ<<δ, λ<<L***

  → ***few hundred MeV***

- *High energy limit:*
  - *iimposed by implemented processes*

  → ***about 3.0 GeV***

λ=0.7 fm ↔ 1000 MeV

λ=2.7 fm ↔ 100 MeV

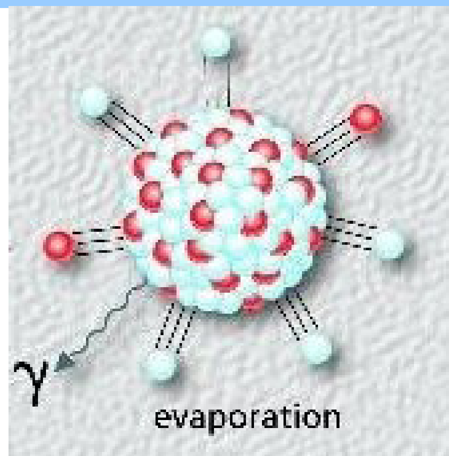
λ=9 fm ↔ 10 MeV

BUU + evaporation model:

Output *of BUU model*

defines

input *for evaporation model ("afterburner")*



Output of BUU model:

Properties of residual nucleus: **A, Z, E*, p, L**

evaluate by exploring the conservation of total energy, mass number, momentum and angular momentum:

$$< E_R^* > (t) = E_{tot} - \sum_{i=1}^{N_p(t)} \sqrt{p_i^2 + m_i^2} - M_R - E_C$$

$$< A_R > (t) = A_T + A_P - N_p(t)$$

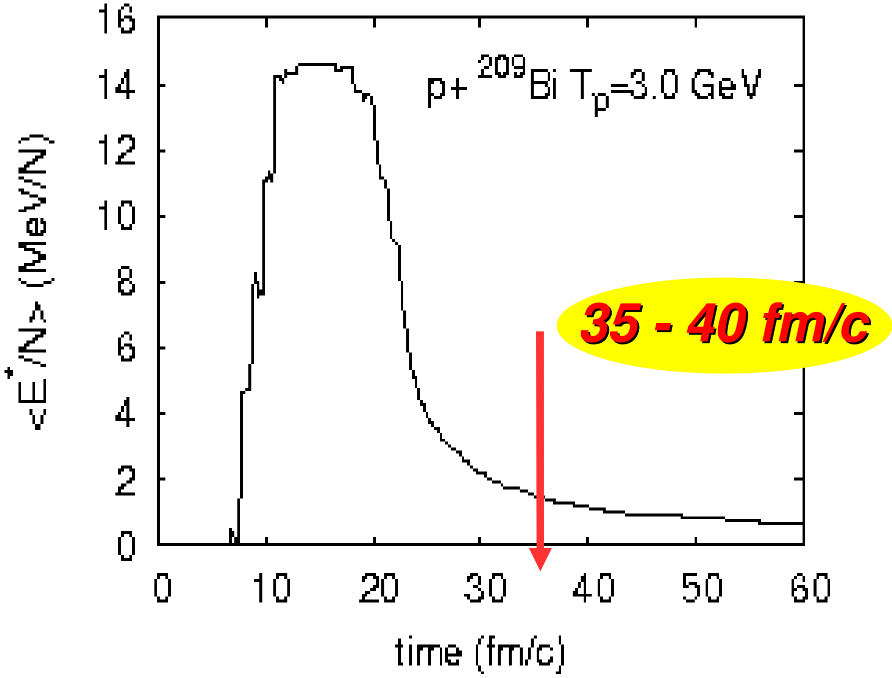
$$< \vec{p_R} > (t) = \vec{p_{tot}} - \sum_{i=1}^{N_p(t)} \vec{p_i}(t)$$

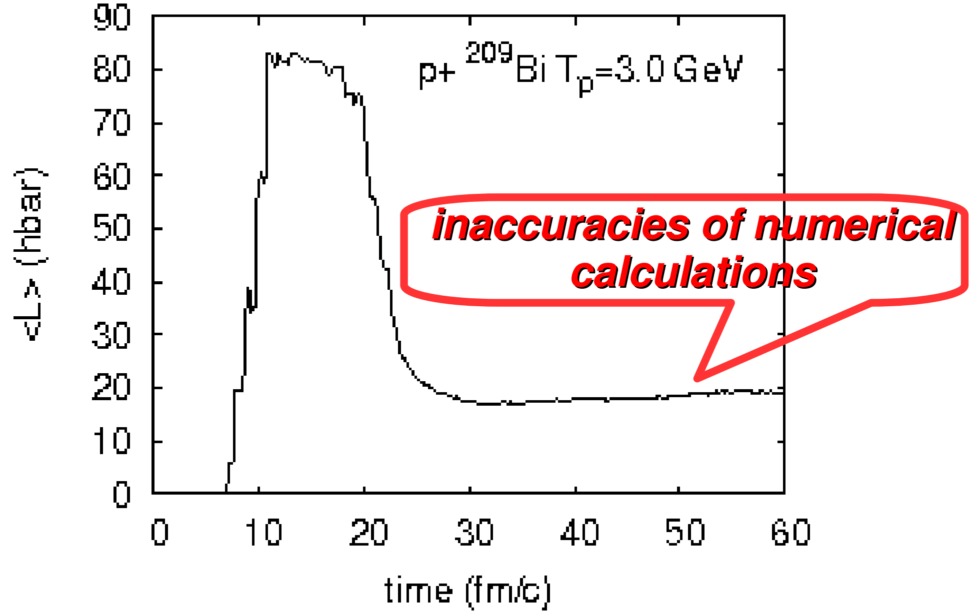
$$< L > (t) = L_{tot} - \sum_{i=1}^{N_p(t)} \vec{r_i}(t) \times \vec{p_i}(t)$$

where: $N_p(t)$ denotes the number of escaped particles, M_R is the mass of the residual nucleus, A_T is a mass of original target, $A_P = 1$ stands for incoming proton and E_C is the the energy of Coulomb interaction between the emitted particles and the residual nucleus.

Stopping time for the BUU model calculations:

- *Time evolution of the average values of properties of excited nucleus*
- *termination of the first stage indicated by stabilization of the values in time*



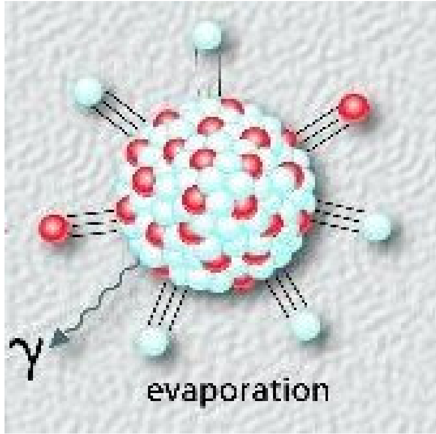


BUU + evaporation model:

Generalized Evaporation Model

GEM

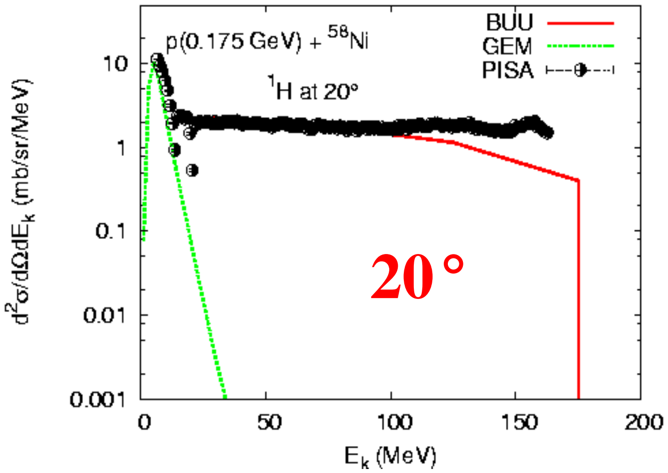
(evaporation in competition with fission)

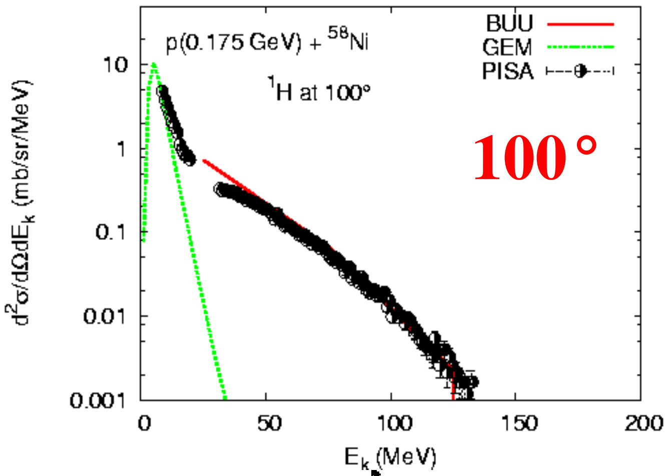


S. Furihata, Nucl. Inst. Meth. in Phys. Res. B 171(2000)251

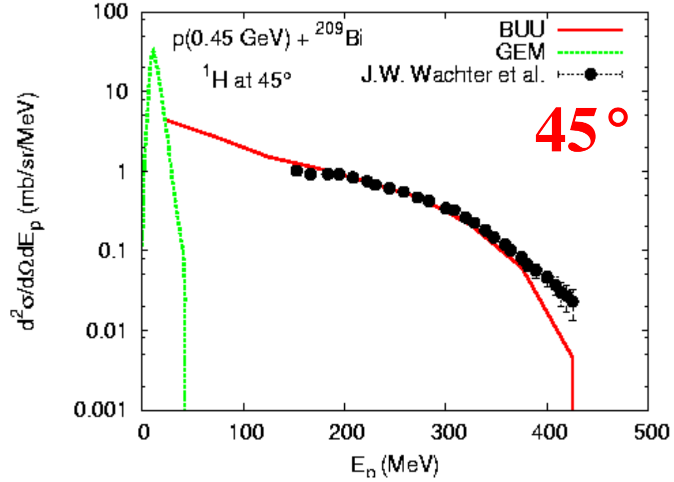
Results: ***proton spectra***

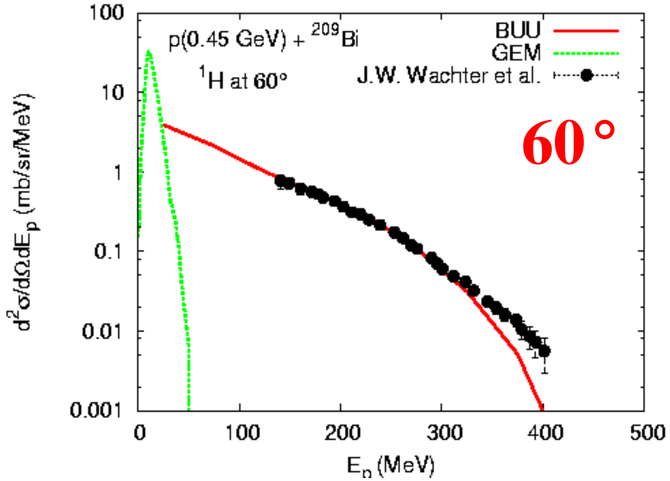
p + Ni @ 0.175 GeV





p + Bi @ 0.45 GeV



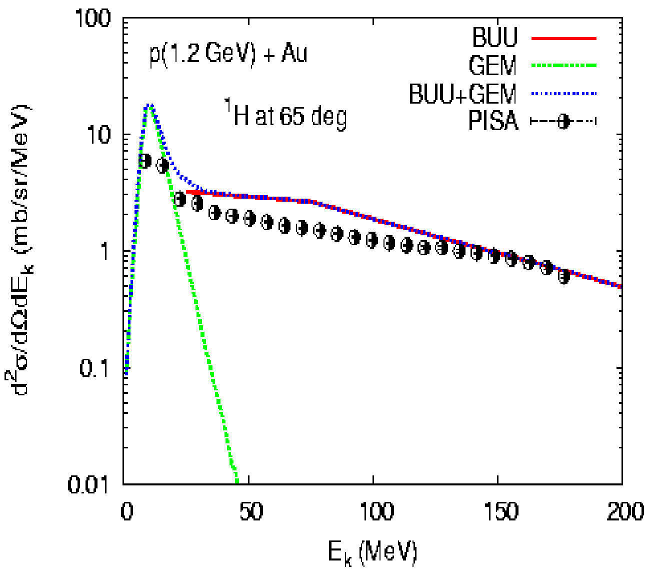


PISA @ COSY

J.W. Wachter et al., PRC 6(1972)1496

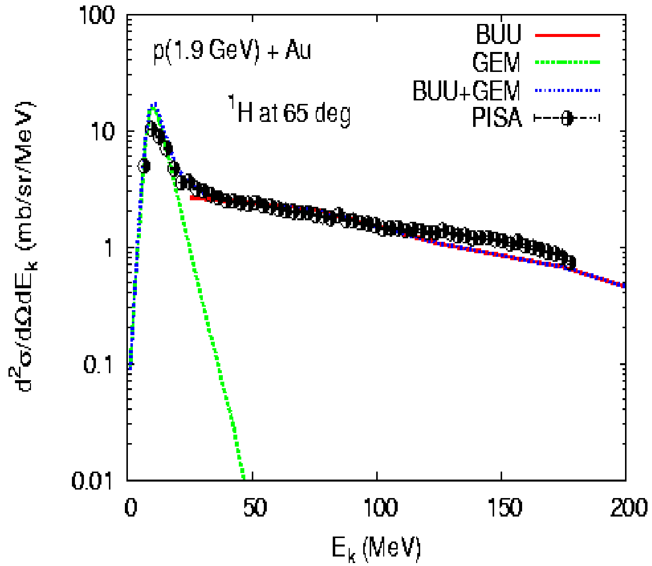
Results: ***proton spectra***

p + Au @ 1.2 GeV

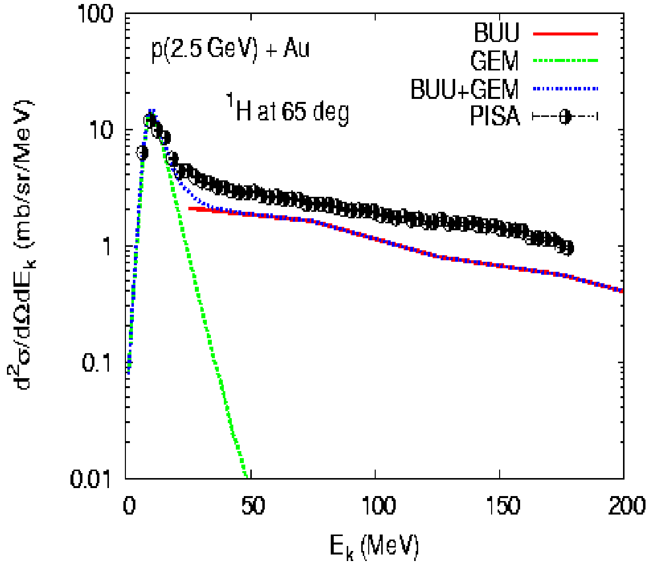


65°

p + Au @ 1.9 GeV



p + Au @ 2.5 GeV

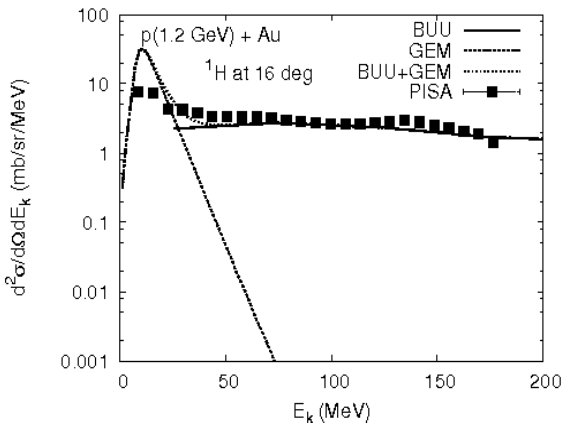


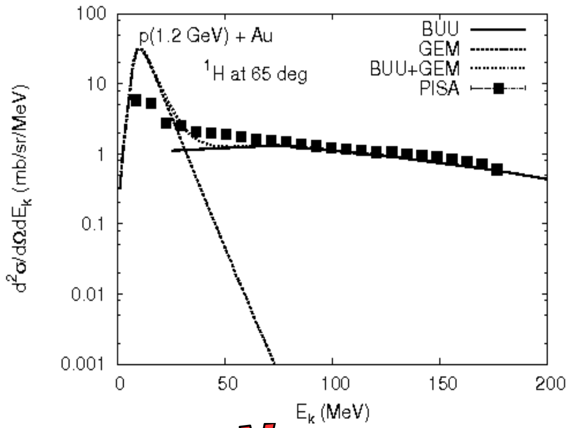
PISA @ COSY

R. Barna et al., NIM A 519 (2004) 610
A. Bubak et al., PRC 76 (2007) 014618

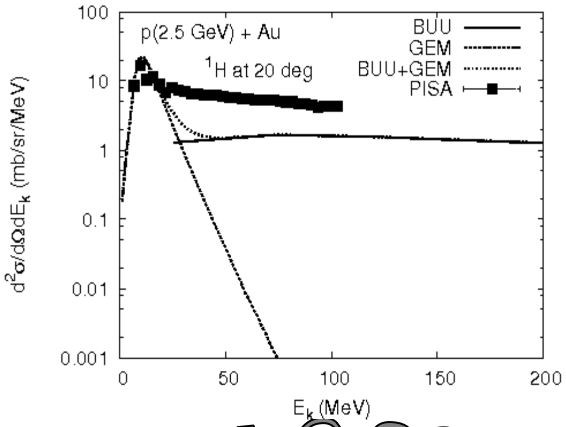
Results: proton spectra

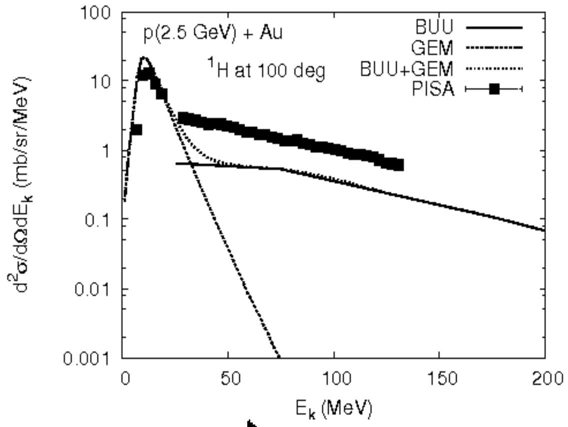
p + Au @ 1.2 GeV



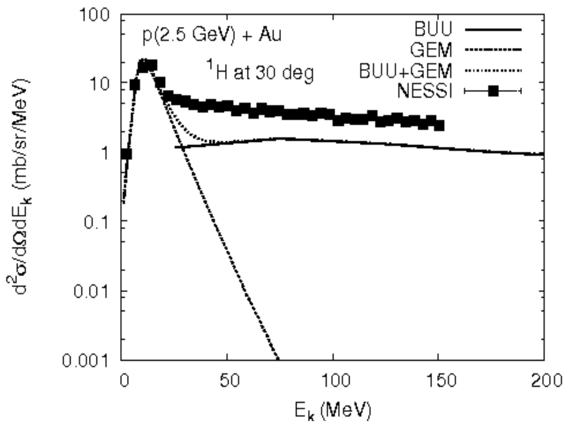


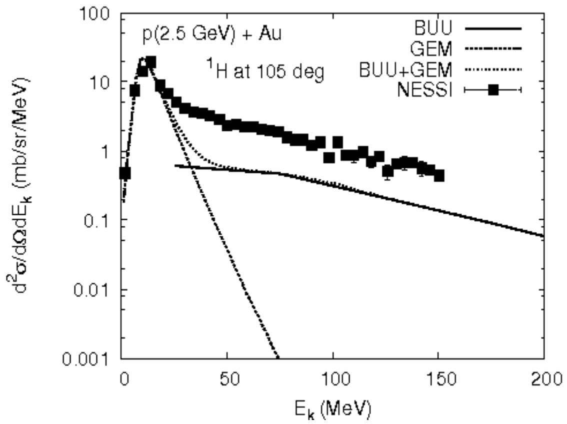
p + Au @ 2.5 GeV





p + Au @ 2.5 GeV





PISA @ COSY

R. Barna et al., NIM A 519 (2004) 610

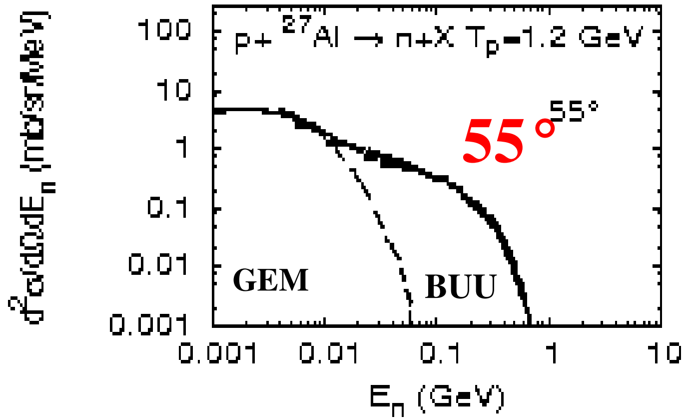
NESSI @ COSY

A. Letourneau et al., Nucl. Phys. A, 712(2002)133

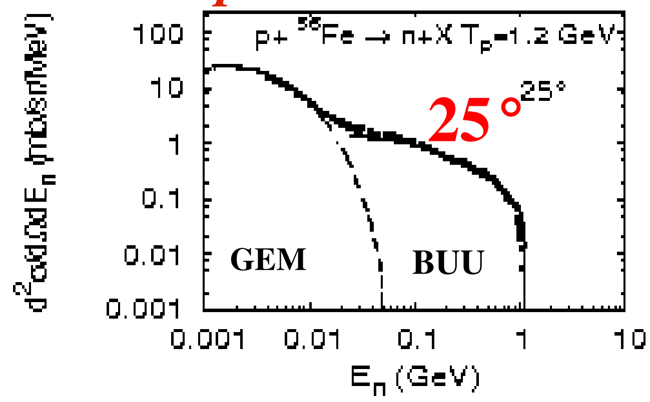
Results: neutron spectra

SATURNE (Saclay)

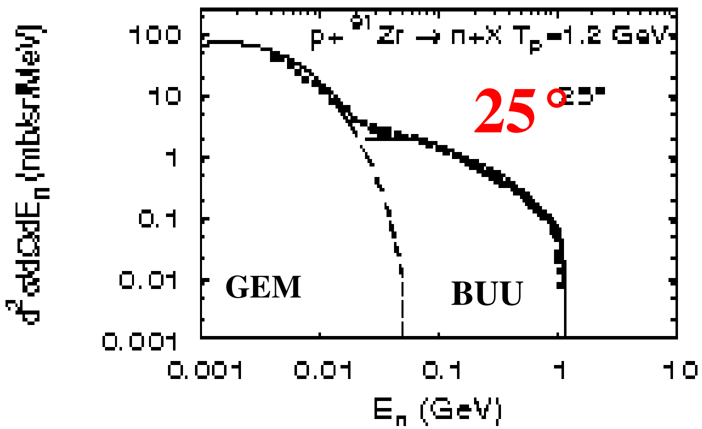
p + Al @ 1.2 GeV



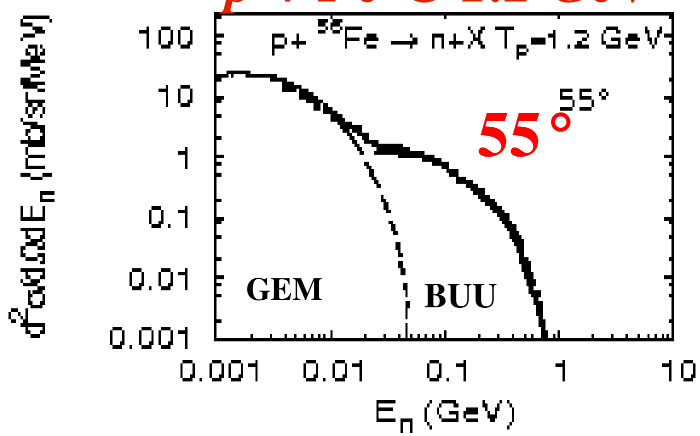
p + Fe @ 1.2 GeV



p + Zr @ 1.2 GeV



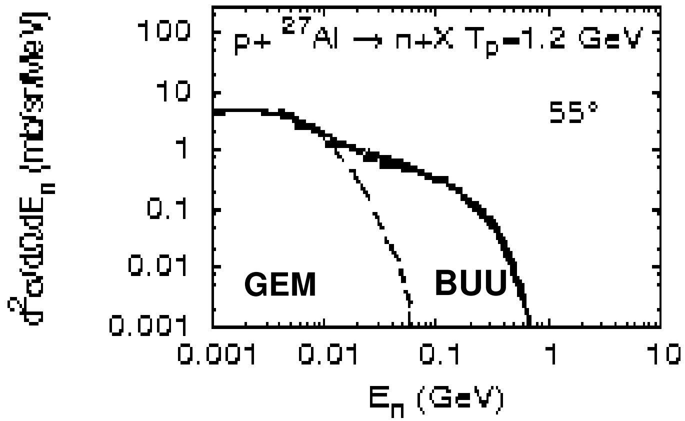
p + Fe @ 1.2 GeV

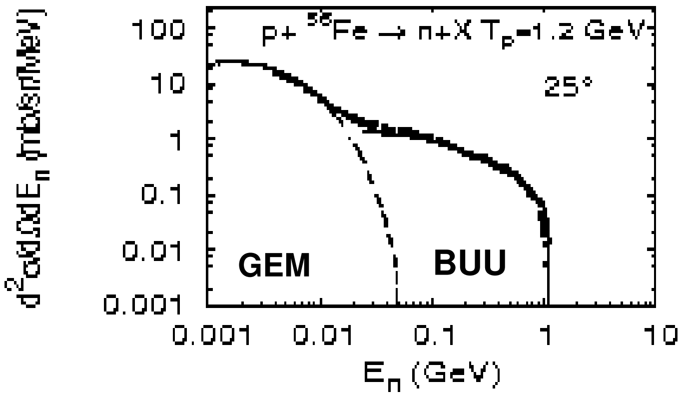


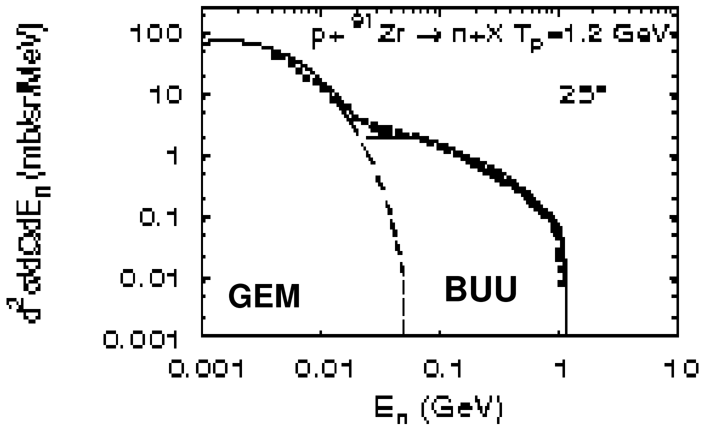
S. Leray et al., Phys. Rev. C, 65(2002)044621

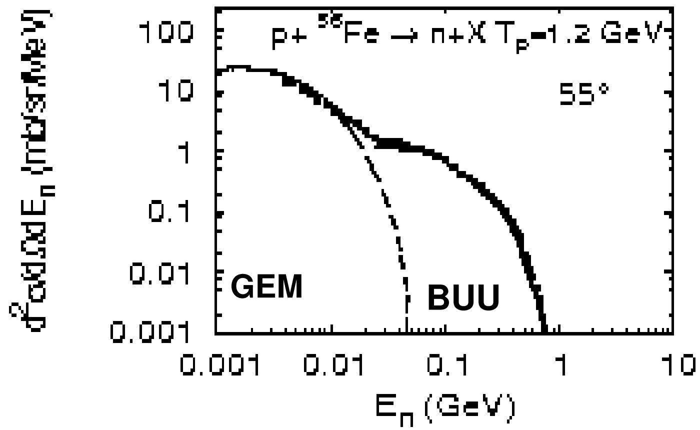
Results: neutron spectra

SATURNE (Saclay)







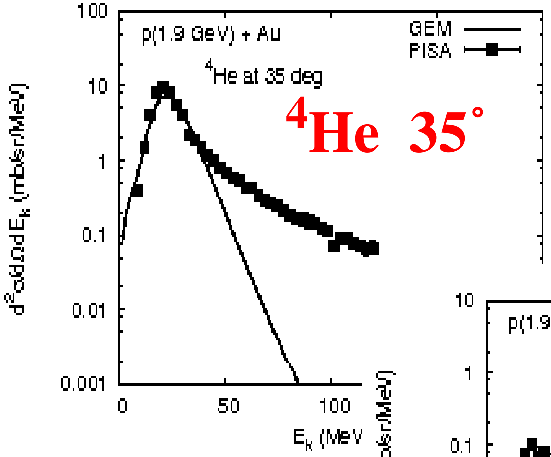


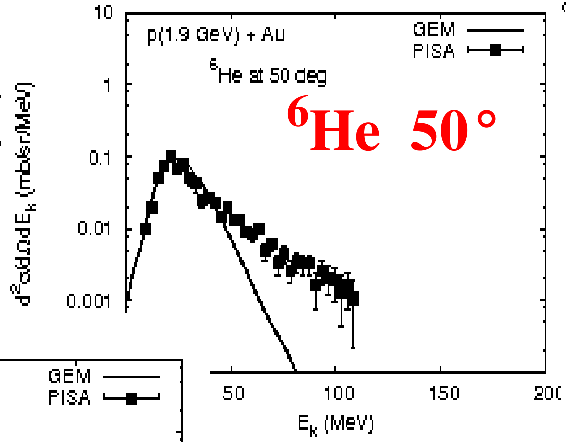
S. Leray et al., Phys. Rev. C, 65(2002)044621

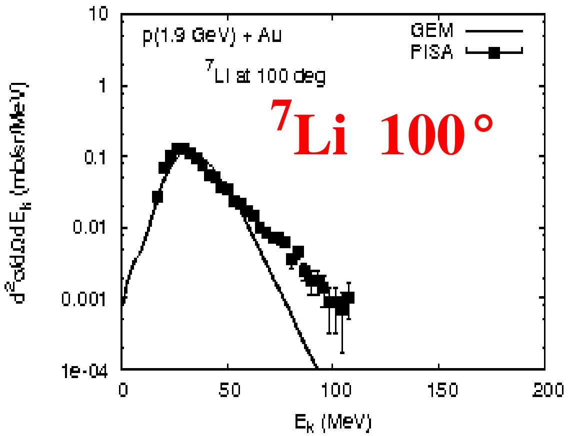
Results: other ejectiles

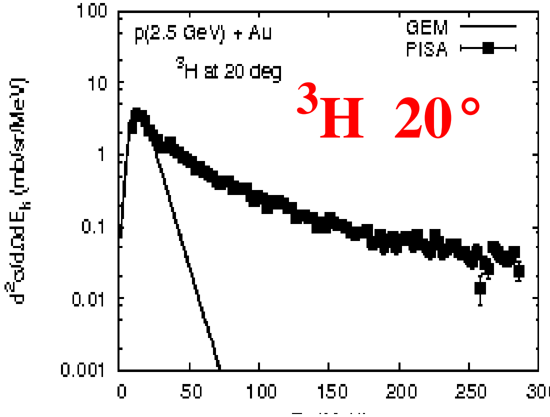
p + Au @ 1.9 GeV

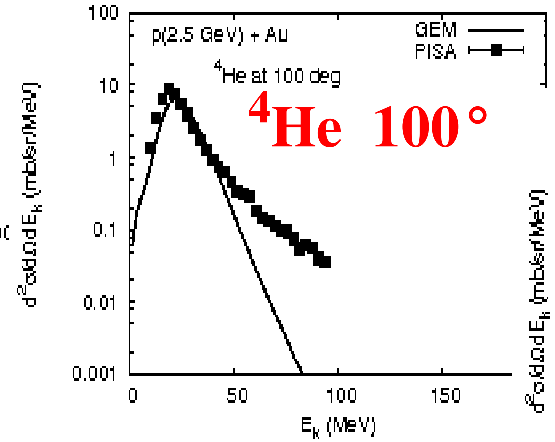
p + Au @ 2.5 GeV

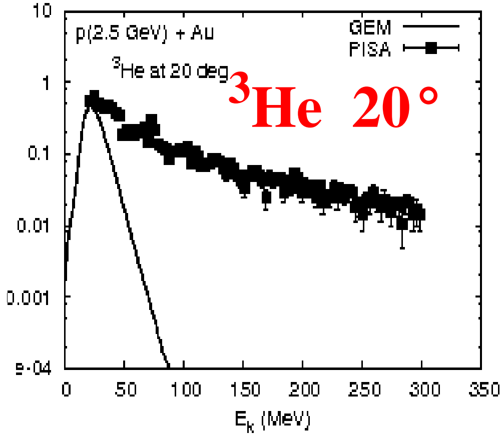


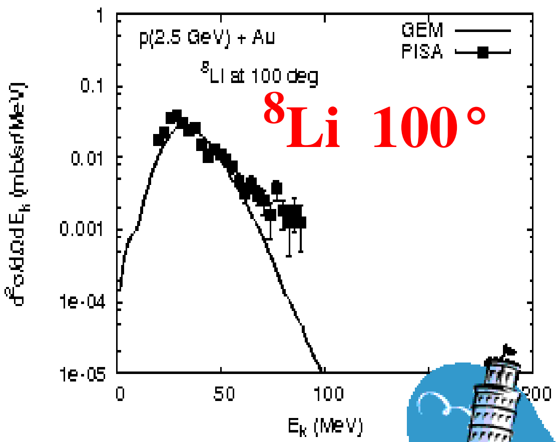








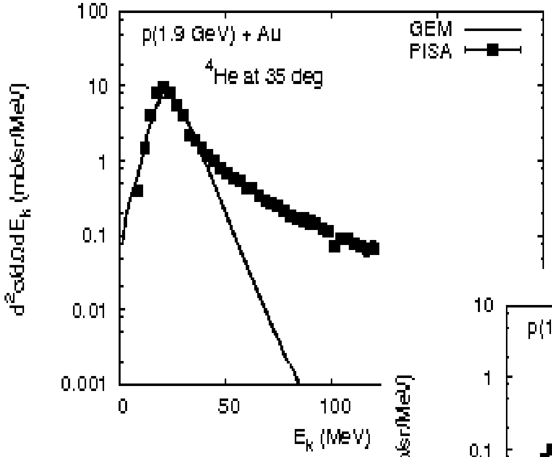


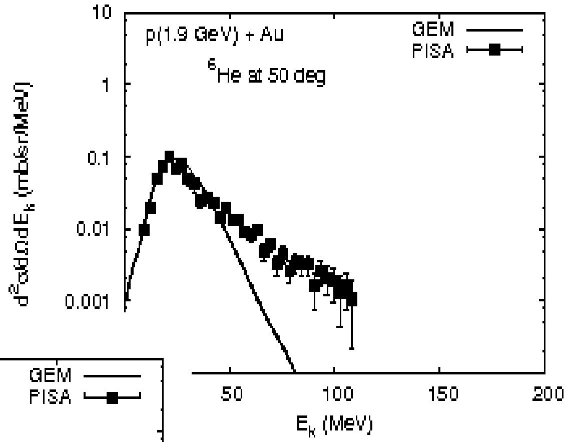


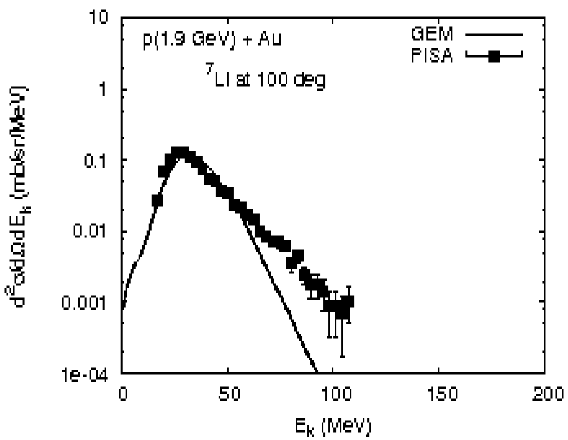
PISA @ COSY

Results: ***other ejectiles***

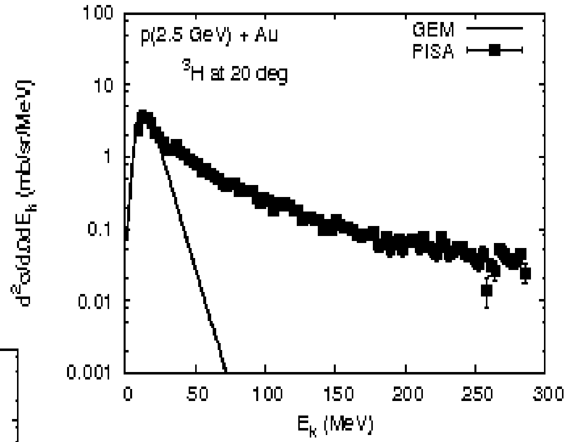
p + Au @ 1.9 GeV

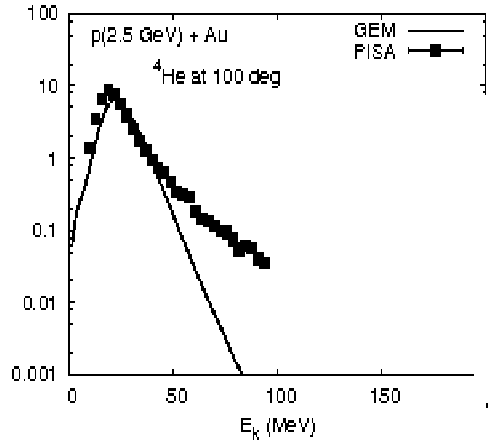


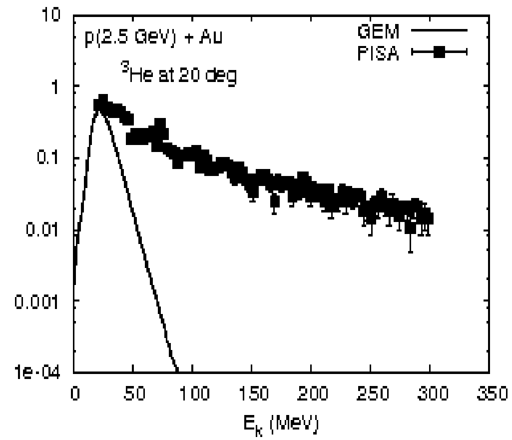


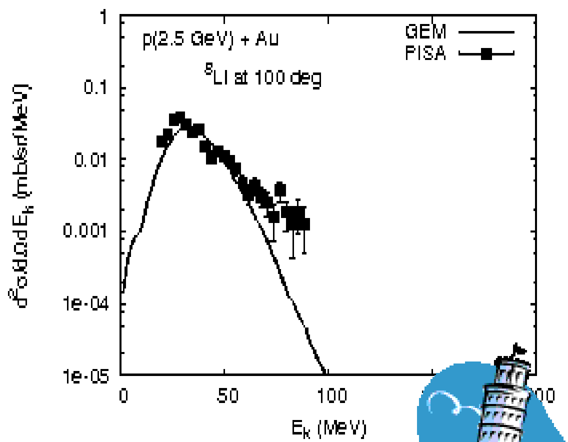


p + Au @ 2.5 GeV





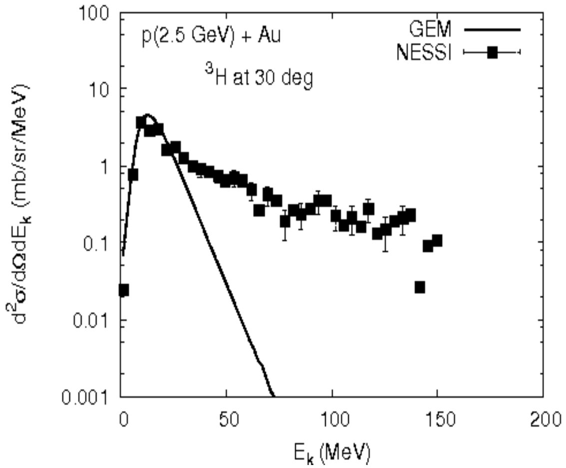




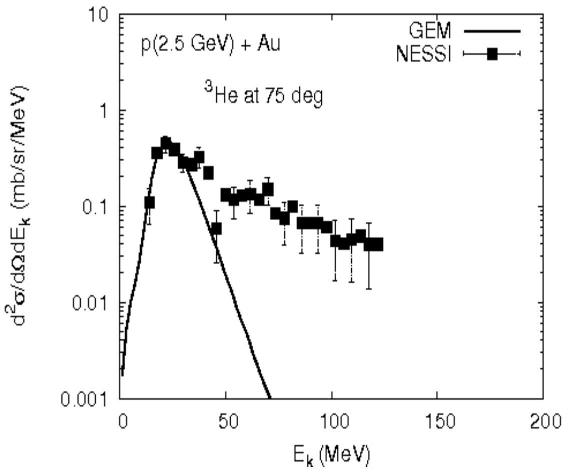
PISA @ COSY

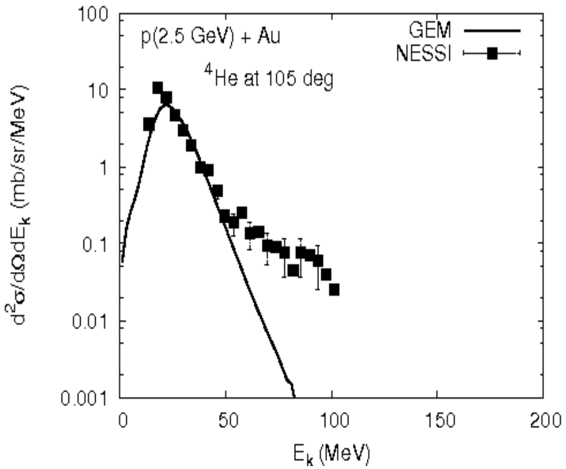
R. Barna et al., NIM A 519 (2004) 610

Results: other ejectiles



p + Au @ 2.5 GeV





NESSI @ COSY

A. Letourneau et al., Nucl. Phys. A, 712(2002)133

SOLUTION: TEST PARTICLE METHOD

Represent the one-body phase-space distribution by discretized test particles:

$$f(\vec{r},\vec{p},t) = \frac{1}{N} \sum_{i=1}^{N \cdot A(t)} \delta^3(\vec{r}-\vec{r}_i(t))\ \delta^3(\vec{p}-\vec{p}_i(t))$$

N – number of test particles
$A(t)$ – number of real particles at time t

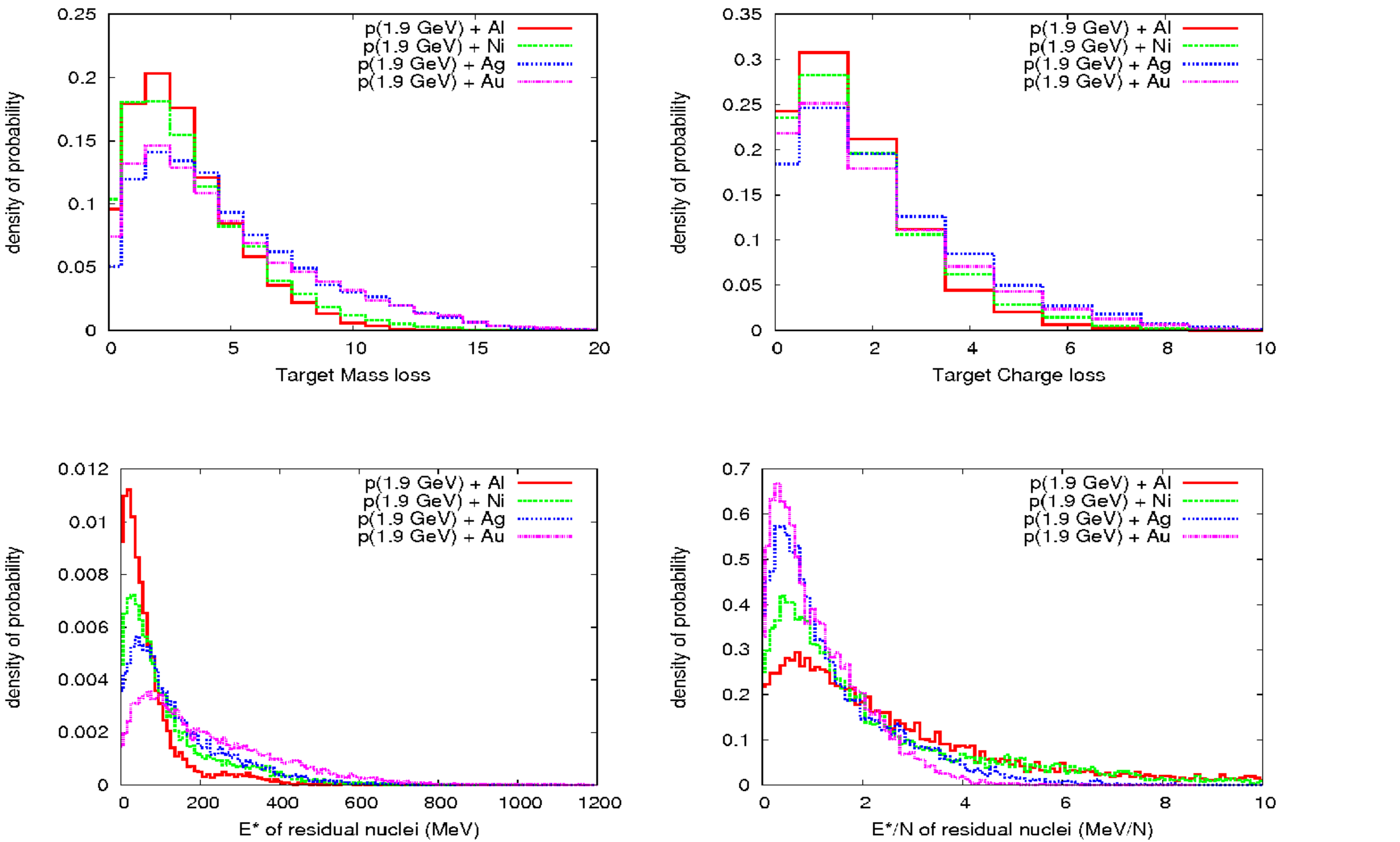
The test particles propagate between collisions according to classical Hamilton equations of motion:

$$\dot{\vec{p}}_i = -\frac{\partial U(\vec{r}_i,\vec{p}_i,t)}{\partial \vec{r}_i}$$

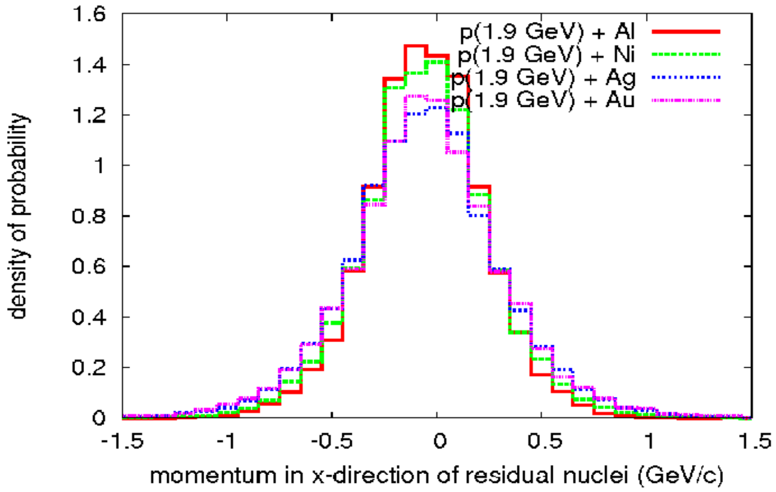
$$\dot{\vec{r}}_i = \vec{p}_i/\sqrt{m^2+p^2} + \frac{\partial U(\vec{r}_i,\vec{p}_i,t)}{\partial \vec{p}_i}$$

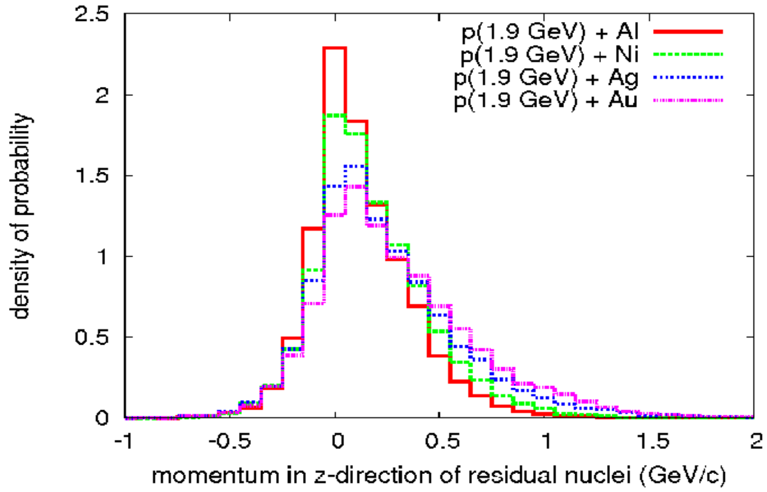
Literature:
K.Niita, W.Cassing, U.Mosel, Nucl.Phys.A 504(1989)391
G.F.Bertsch,S.Das Gupta, Phys.Rep. 160(1988)189
J.Geiss, W.Cassing, C.Greiner, Nucl.Phys.A 644(1998)107
⋮

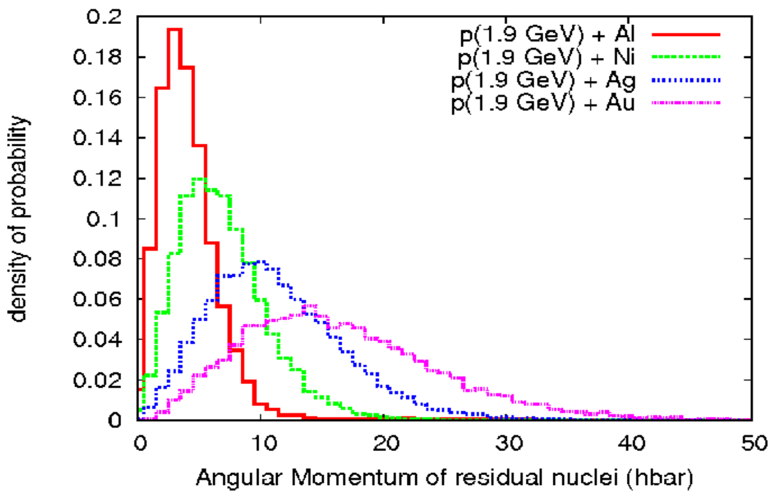
Properties of residual (hot) nuclei



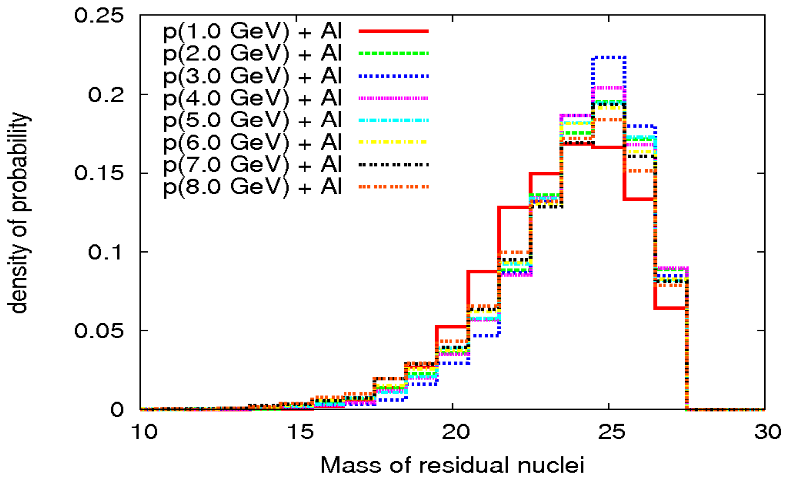
Properties of residual (hot) nuclei

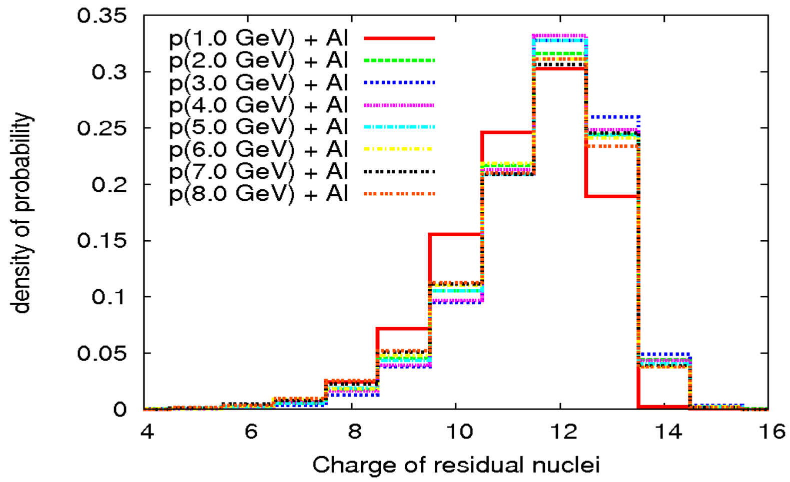


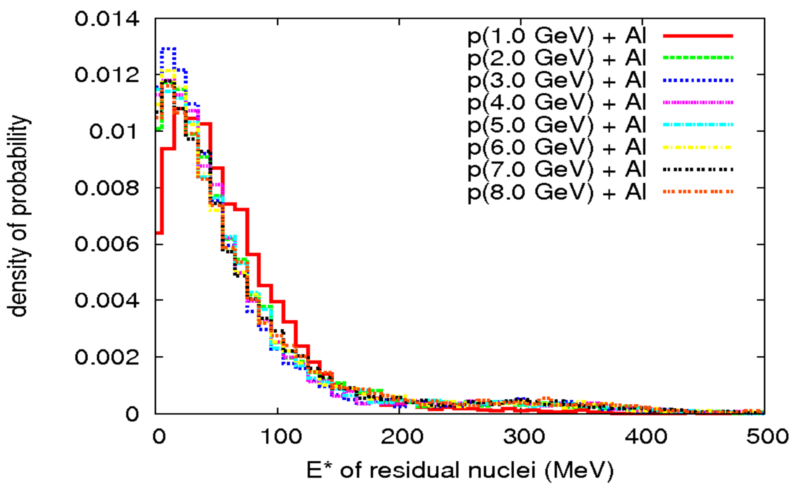


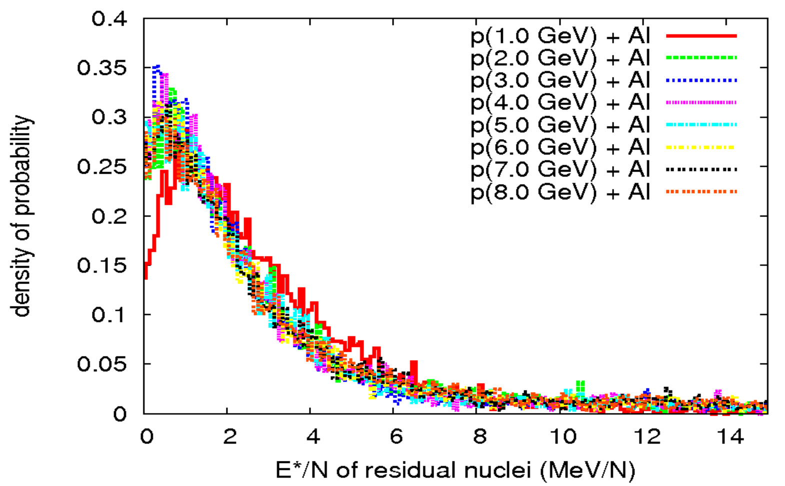


Properties of residual (hot) nuclei

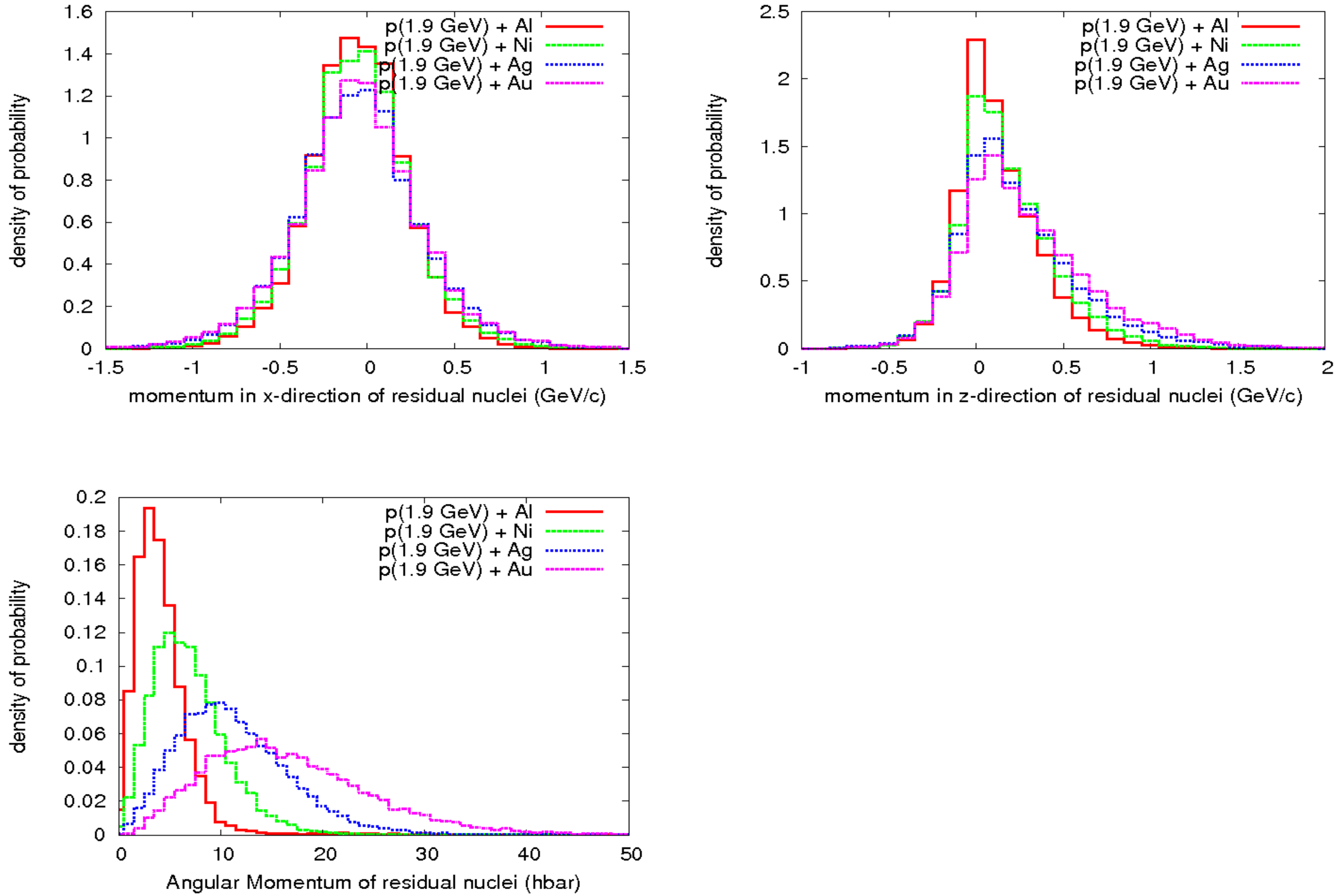


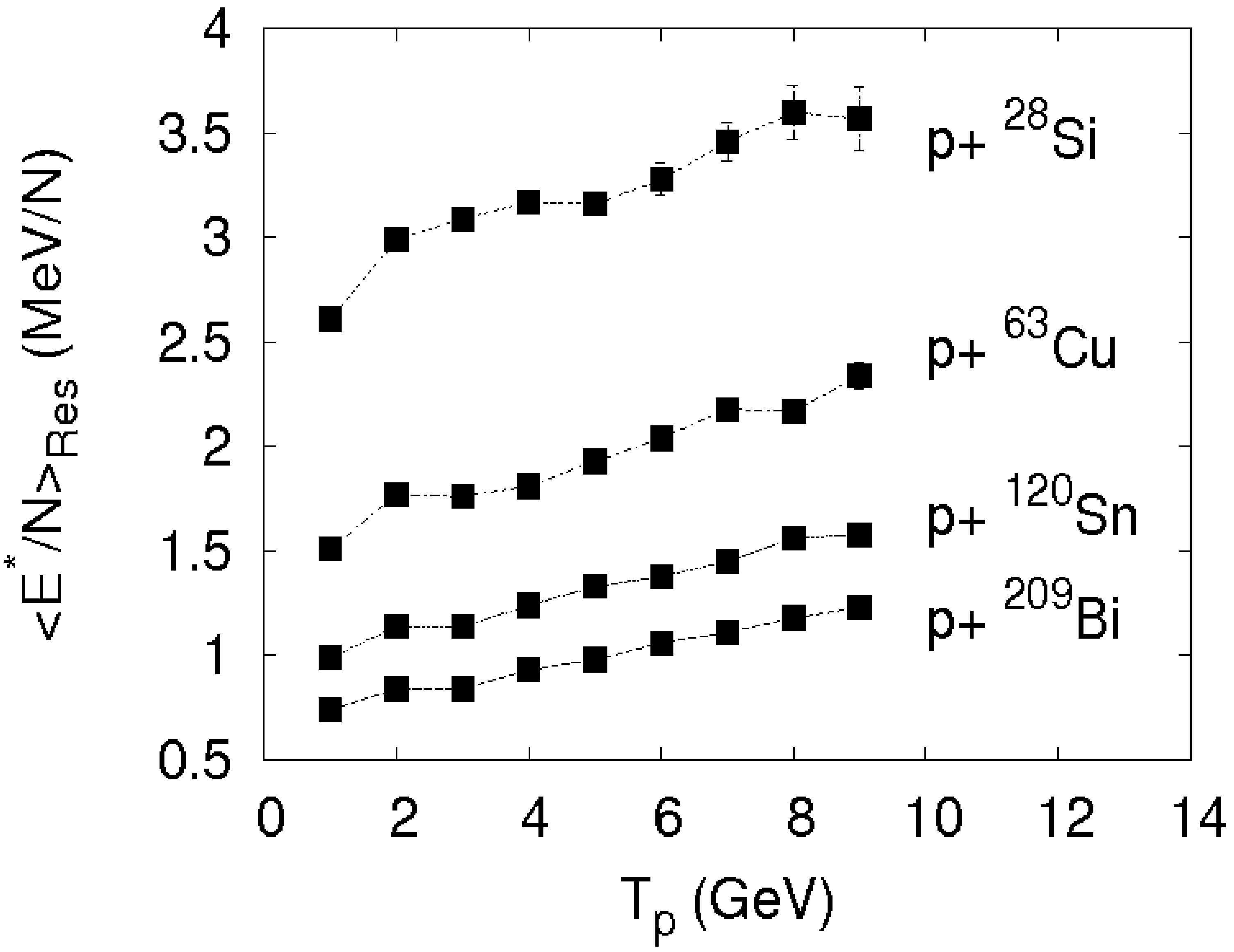




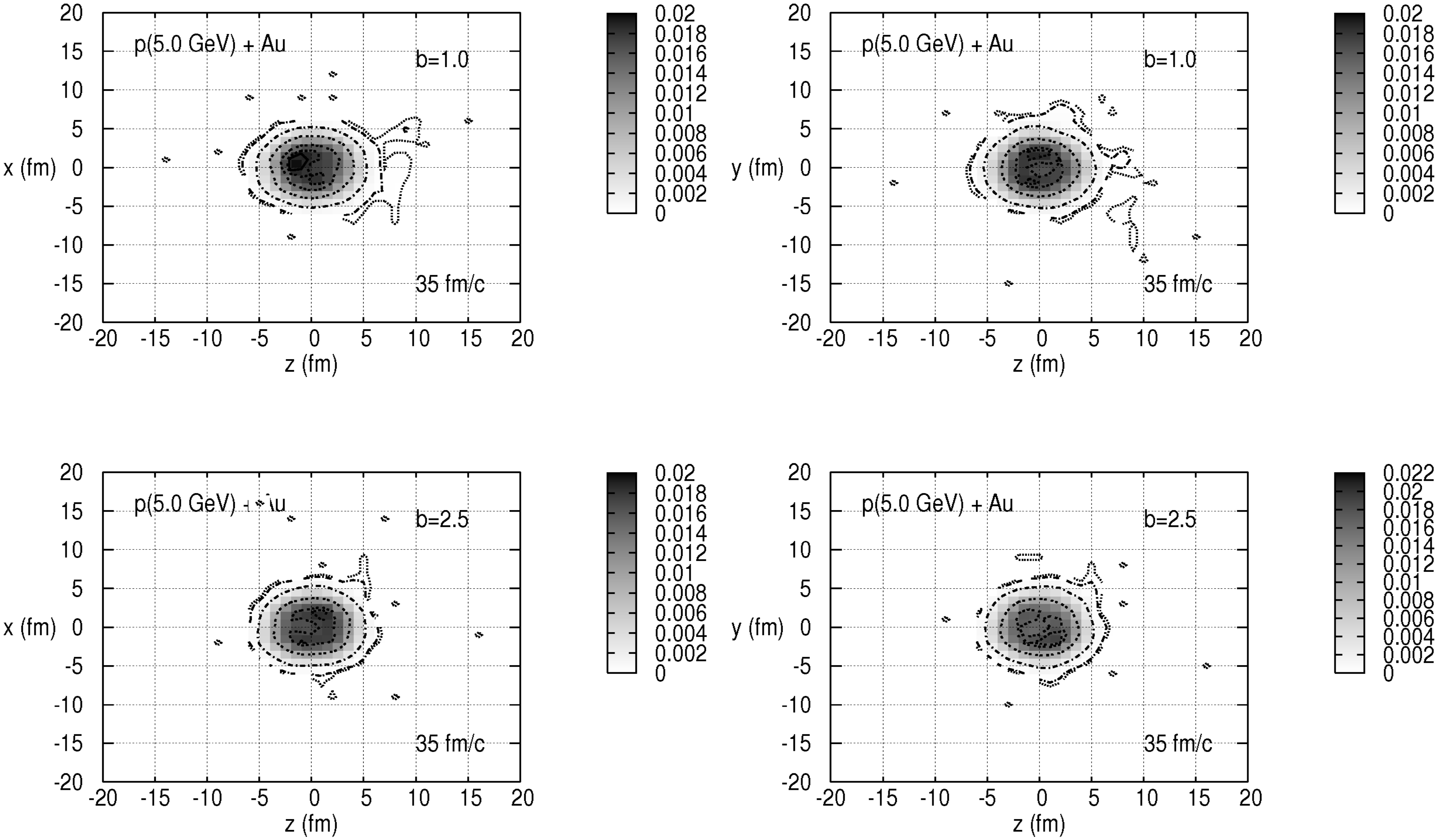


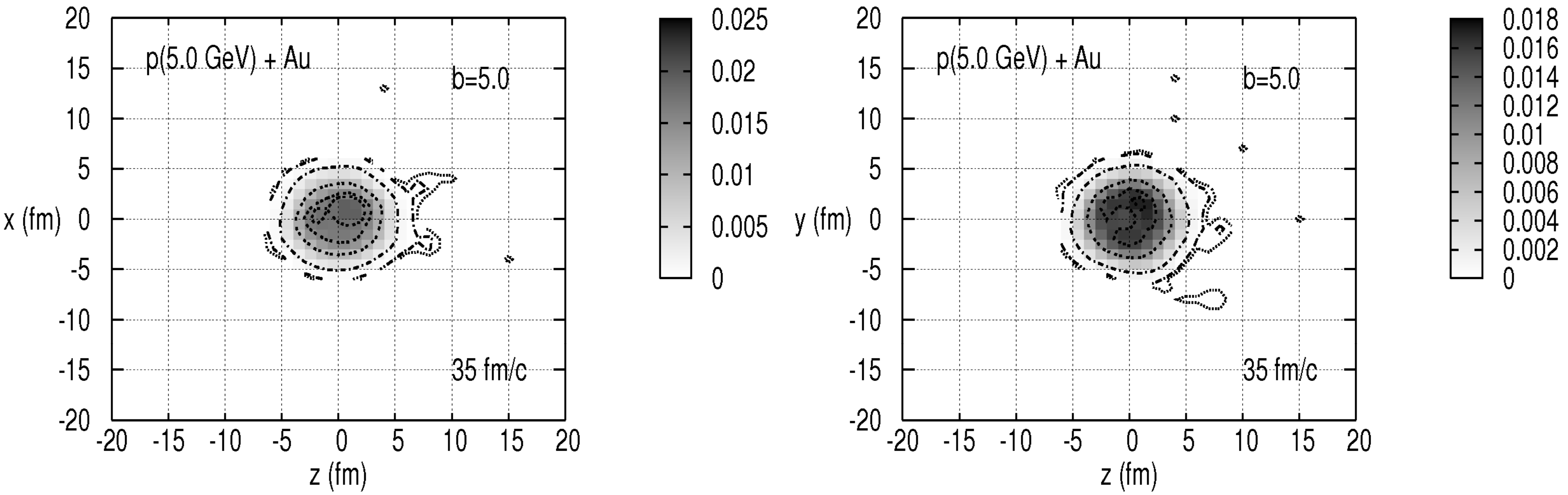
Properties of residual (hot) nuclei



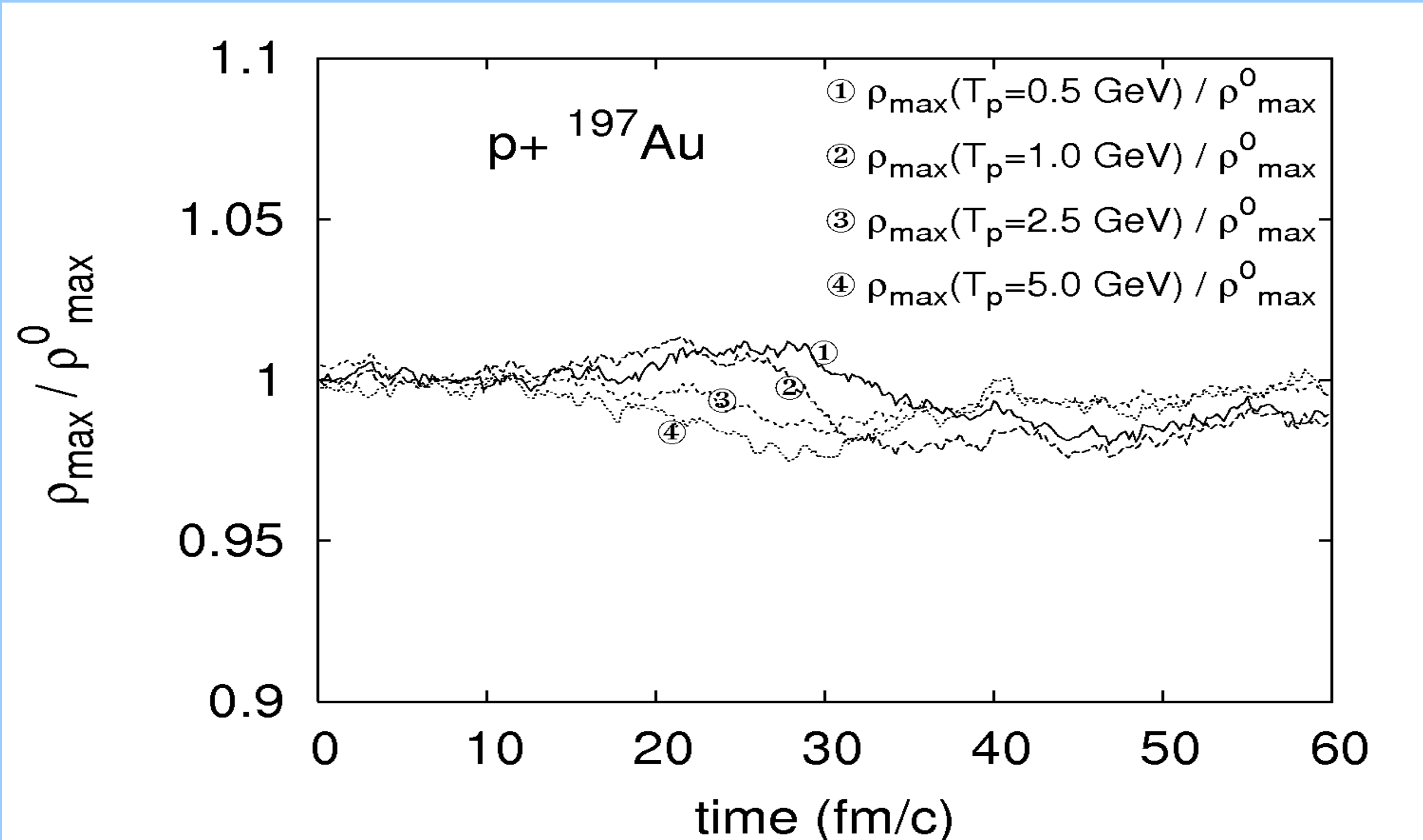


$<E^*/N>_{Res}$ (MeV/N)
4
3.5
3
2.5
2
1.5
1
0.5
0
2
4
6
8
10
12
14
T_p (GeV)
p+ ^{28}Si
p+ ^{63}Cu
p+ ^{120}Sn
p+ ^{209}Bi

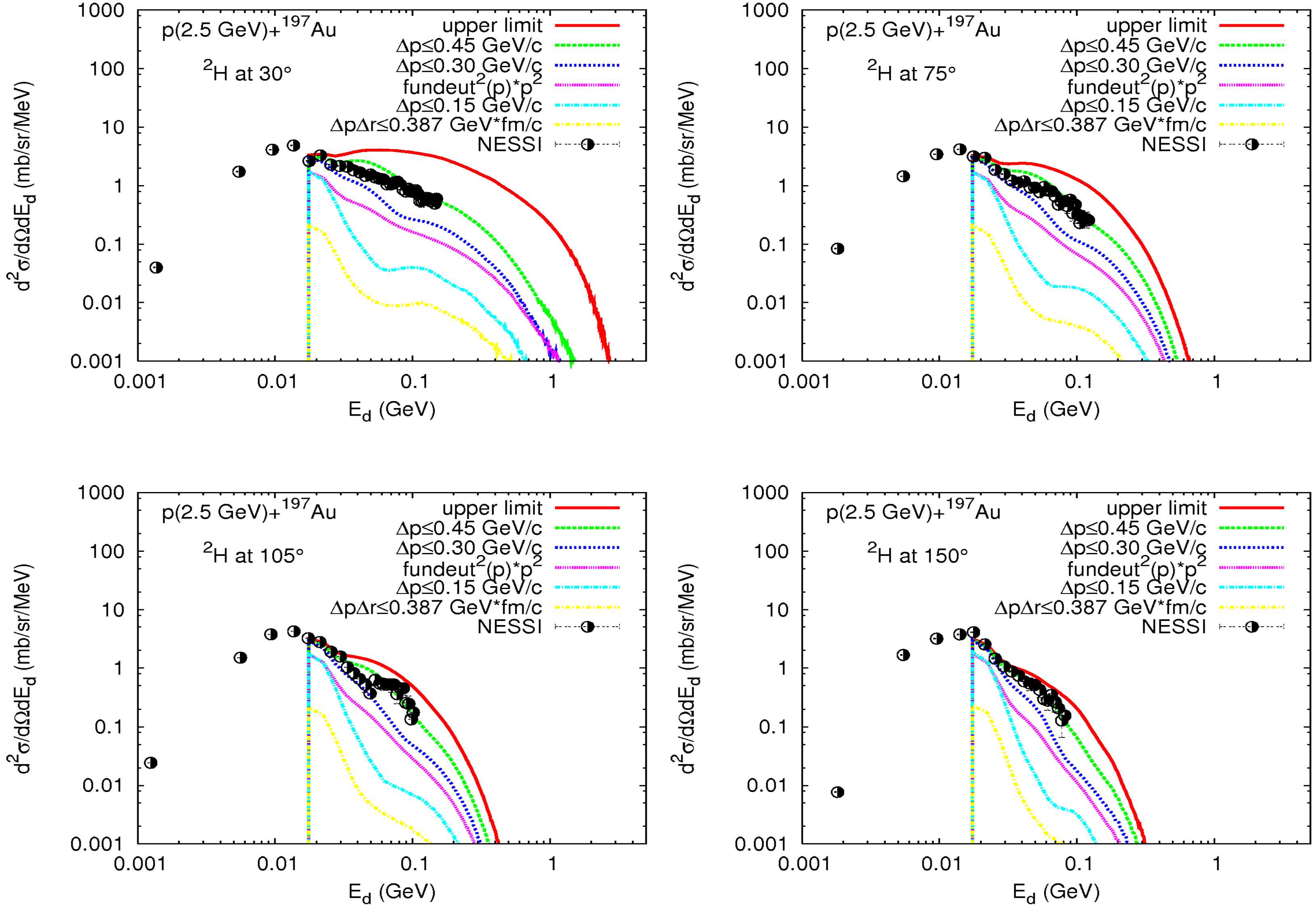

p(5.0 GeV) + Au
b=1.0
35 fm/c
x (fm)
z (fm)
y (fm)
b=2.5
p(5.0 GeV)
0.022
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0


p(5.0 GeV) + Au
b=5.0
35 fm/c
x (fm)
z (fm)
0.025
0.02
0.015
0.01
0.005
0
p(5.0 GeV) + Au
b=5.0
35 fm/c
y (fm)
z (fm)
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0

Properties of residual (hot) nuclei



”Coalescence”



BUU + evaporation

Momentum in z direction

(i.e. beam direction)

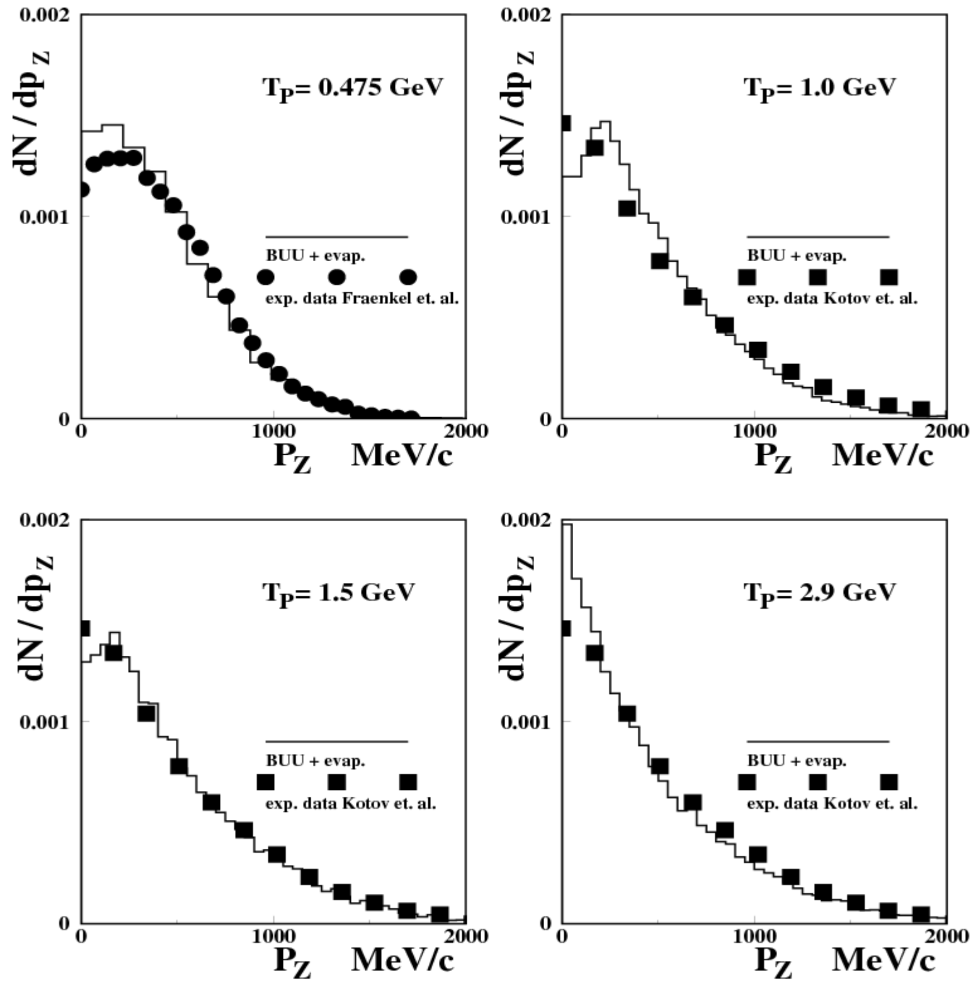
of residual nuclei

Fraenkel et al.

Phys. Rev. C41, 1050 (1990)

Kotov et al.

Sov. J. Nucl. Phys. 17, 498 (1974)



Conclusions:

- *Two – stage scenario of the proton induced spallation reactions (combined* ***BUU + GEM*** *model) gives good description of neutron and proton spectra*
- *In case of other ejectiles H, He, Li, ...*
  – only low energy part of spectrum is described
  – high energy part description needs implementation of coalescence processes into the first stage models
- *Proton induced spallation as rather non-invasive process*
- *Properties of residual nuclei depend weakly on proton impact energy, strongly on target mass*