Production of hyper-nuclei in reactions induced by relativistic hadrons and heavy-ions.

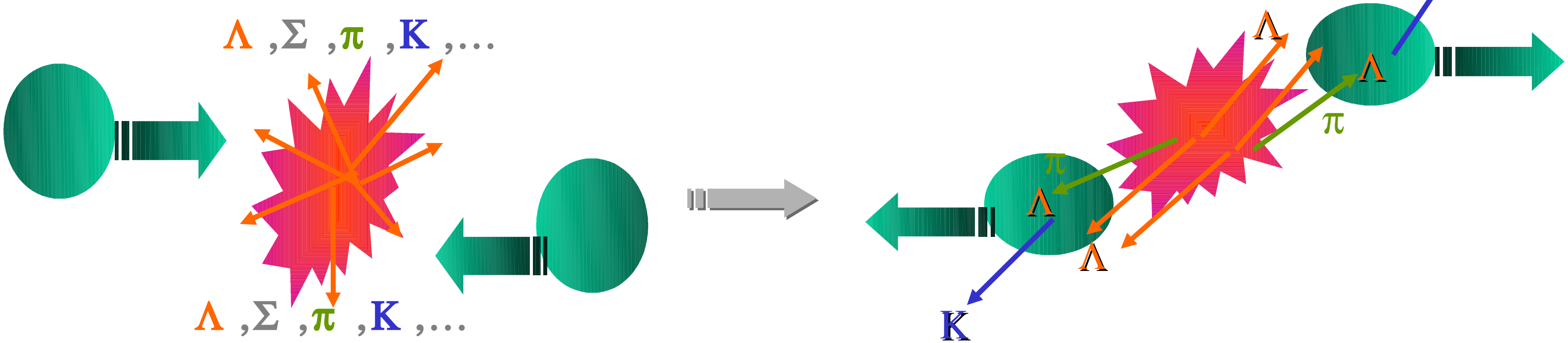
A.S.Botvina

Institute for Nuclear Research, RAS, Moscow, Russia
Frankfurt Institute for Advanced Studies, Frankfurt a.M., Germany

(in collaboration with K.K.Gudima and I.N.Mishustin)

SPHERE meeting
Prague, Czech Republic
September 4 – 6, 2010

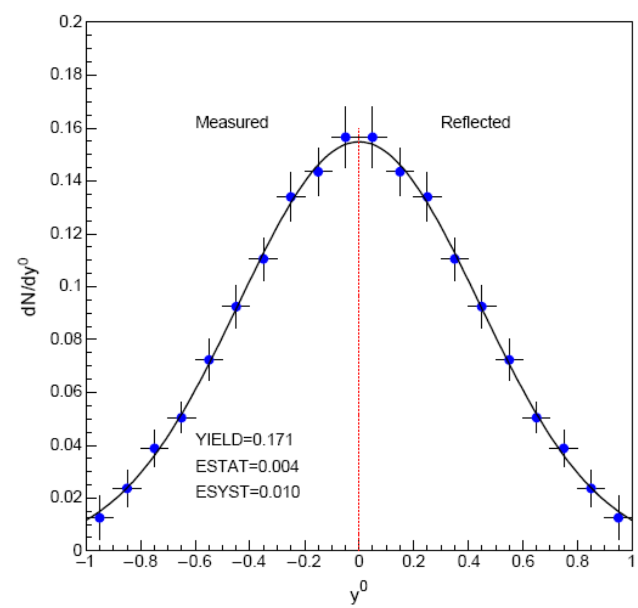
Relativistic Heavy-Ion collisions



- **Production of Hypermatter in Relativistic HIC**
  - Production of many hyperons by "participants",
  -Absorption of hyperons by excited "spectators"

X. Lopez / Progress in Particle and Nuclear Physics 53 (2004) 149–151

Reconstructed Λ rapidity distribution for central ($\sigma_{\text{geo}} = 350$ mb) Ni + Ni reactions at 1.93 A GeV.



Why hypernuclei ?

- Micro-laboratory with protons, neutrons, and hyperons
- YN & YY interaction can be investigated (strangeness sector of hadronic EoS)
- important for physics of neutron stars , "strange stars" , ...

  (F. Weber, Prog. Part. Nucl. Phys. **54** (2005) 193)

- Presently, info obtained mainly from nuclear structure studies
- Info on properties of strange baryons in neutron rich matter needed,

  we need exotic and multi-hypernuclei: ${}^{A}Z_{Y}$, ${}^{A}Z_{YY}$, ... ($Y=\Lambda ,\Sigma$)

- Formation of hypernuclei in high-energy reactions (p+A, A+A)
- **HypHI**: ${}^{6}Li+{}^{12}C$@SIS (in progress...), @FAIR (A+A@20AGeV)
- **J-PARC**: p+A@50GeV (in future...)
- **PANDA**: Antiproton-Nucleus (in future...)
- ...

Theoretical descriptions of strangeness production within transport codes

....

old models : *INC, QMD, BUU*	e.g., Z.Rudy, W.Casing et al., *Z. Phys. A351(1995)217*
GiBUU model: *(+SMM)*	Th.Gaitanos, H.Lenske, U.Mosel , *Phys.Lett. B663(2008)197,* *Phys.Lett. B675(2009)297*
INC approach: *(+QGSM+...)*	JINR version - K.K.Gudima et al., *Nucl. Phys. A400(1983)173, ...* *arXiv:0709.1736 [nucl-th]*

Main channels for production of strangeness in individual hadron- nucleon collisions: $BB \rightarrow BYK$, $B\pi \rightarrow YK$, ...

(like $p+n \rightarrow n+\Lambda+K^+$, and secondary meson interactions, like $\pi +p \rightarrow \Lambda+K^+$). Rescattering of hyperons is important for their capture by spectators. Expected decay of produced hyperons and hypernuclei: 1) mesonic $\Lambda \rightarrow \pi +N$; 2) in nuclear medium nonmesonic $\Lambda+N \rightarrow N+N$.

Λ-Hypernucleus formation in proton-nucleus reactions

Z.Rudy, W.Casing et al., *Z. Phys. A351(1995)217*

BUU approach (Λ-potential in matter ~ 30 MeV)

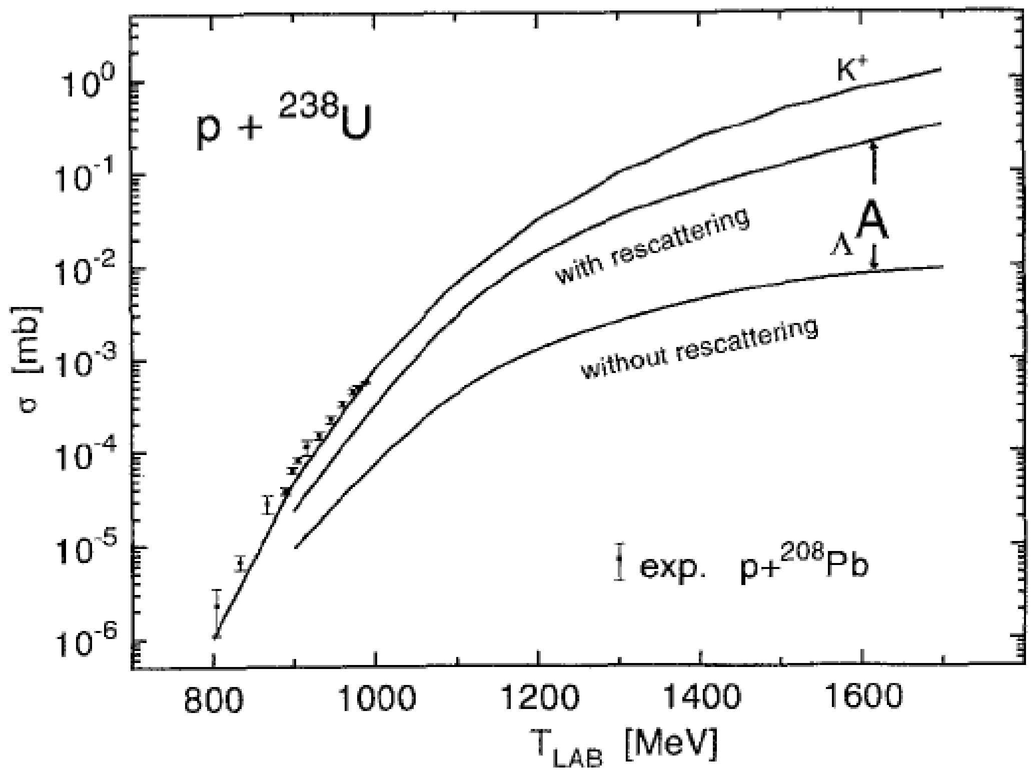


Fig. 5. The energy dependence of the $_{\Lambda}A$ production cross section for the cases with and without Λ hyperon-N rescattering. For relative orientation we also compare the calculated total K^+ cross section with the inclusive K^+ data from [30] for $p + {}^{208}$Pb

Z.Rudy, W.Cassing et al., *Z.Phys. A351(1995)217*

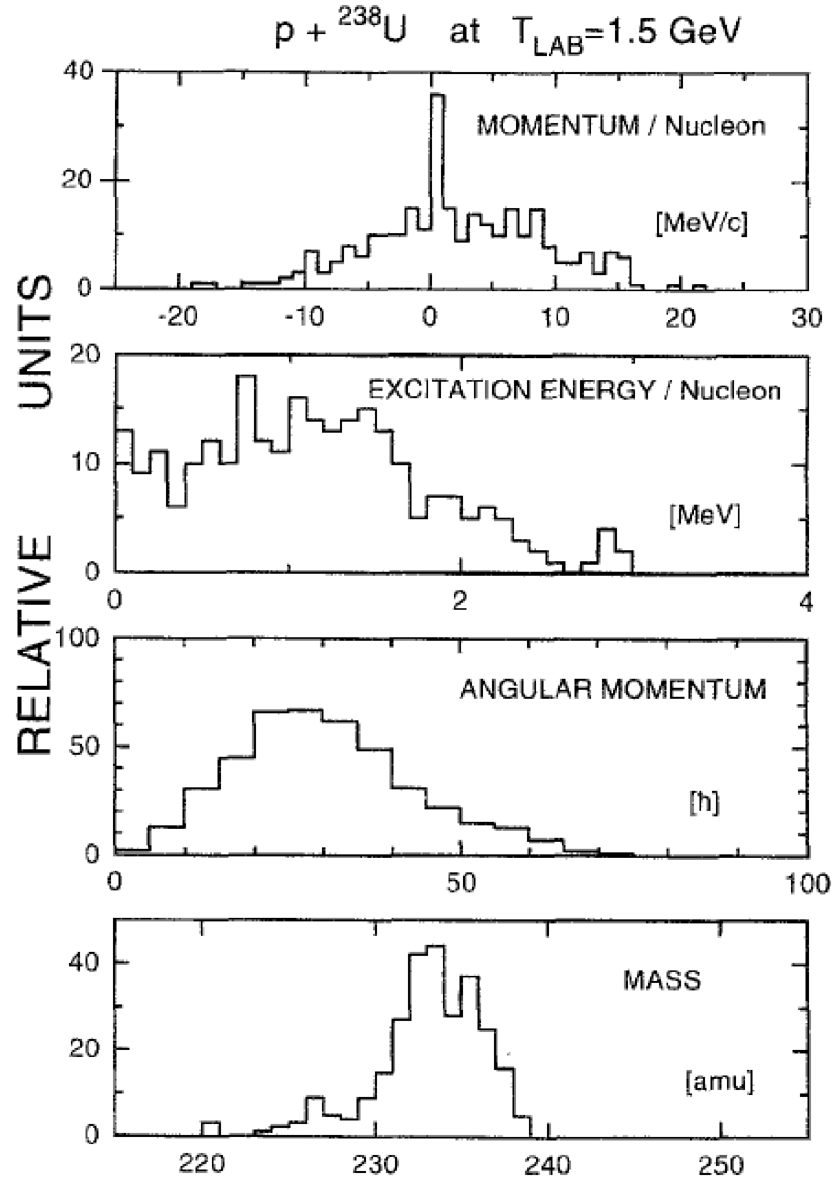


Fig. 7. Momentum, excitation energy, angular momentum and mass distribution of the created Λ-hypernuclei in $p + {}^{238}U$ at $T_{lab} = 1.5$ GeV

However, lifetime of these hypernuclei is too short ~200 p*s*, experimental identification using products of their decay is very difficult, because of background of other particles.

With heavy ion collisions E_{beam}>1.6AGeV
(since NN→ΛKN energy threshold ~ 1.6 GeV)
we can obtain

Relativistic Hypernuclei

Effective lifetime: longer by Lorentz factor γ
200 ps → 600 ps with γ=3 (2AGeV)
200 ps → 4 ns with γ=20 (20AGeV)

=> Detection of their decay products becomes feasible : target and hyper-fragment decay zones are separated in space, particle vertex methods can be used. At large γ direct separation of hypernuclei is possible.

Additional advantages of HI: Hypernuclei with multiple strangeness and exotic (e.g. neutron-rich) hypernuclei can be produced.

HypHi experimental program at GSI and FAIR

Modern BUU description of initial non-requilibrium stage of HI collisions leading to production of hypernuclei:

Relativistic transport equation of Boltzmann type: Gi BUU

Th. Gaitanos, H. Lenske, U.Mosel, Giessen group

http://gibuu.physik.uni-giessen.de/GiBUU/

Next stage: de-excitation of produced residuals - SMM
(including evaporation/fission, multifragmentation)

Formation of hyperfragments: coalescence in coordinate and momentum space

T.Gaitanos, H. Lenske, U. Mosel, PLB**675** (2009) 297

INC theoretical description of initial non-requilibrium stage of HI collisions leading to production of hypernuclei:

Intranuclear Cascade (INC) Model , JINR (Dubna) version

K. Gudima et al., (V. Toneev, N. Amelin, S. Mashnik, ...)

including Quar-Gluon String Model (QGSM) for description of
hadron interactions at high energies

Nucl. Phys. A**400** (1983)173, ... Sov. J. Nucl. Phys. **52**(1990)1722,...
Phys. At. Nucl. **57**(1994)628, ... arXiv:0709.1736 [nucl-th],...

The model is used in LAQGSM... codes (event generators), SHIELD,
MCNP6, MCHPX, MARS15 transport codes

Physical picture of INC: nucleons of projectile interact with nucleons of target, however, in peripheral collisions many nucleons (spectators) do not interact. All products of the interactions can also interact with nucleons and between themselves. The time-space evolution of all nucleons and produced particles is calculated with the Monte-Carlo method.

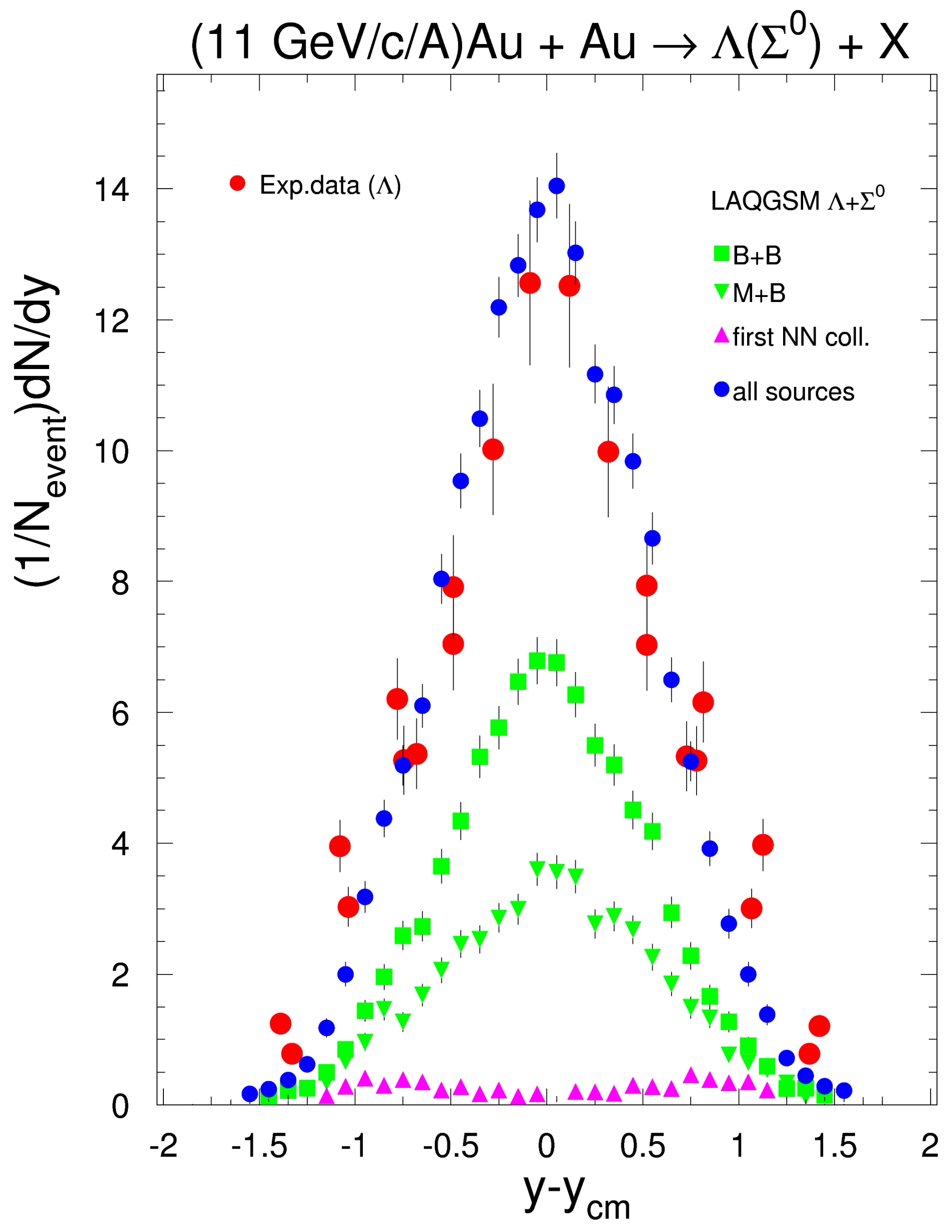
All strange particles: Kaons, Lambda, Sigma, Xi, Omega are included in INC

The residual nuclei produced during intranuclear cascade may capture produced Lambda hyperons if these hyperons are (a) inside nuclei and (b) their energy is lower than the hyperon potential in nuclear matter (~20-30 MeV). In the model a depletion of the potential with reduction of number of nucleons in nucleus is taken into account with two prescriptions: (1) average density of residue and (2) local density of spectator nucleons.

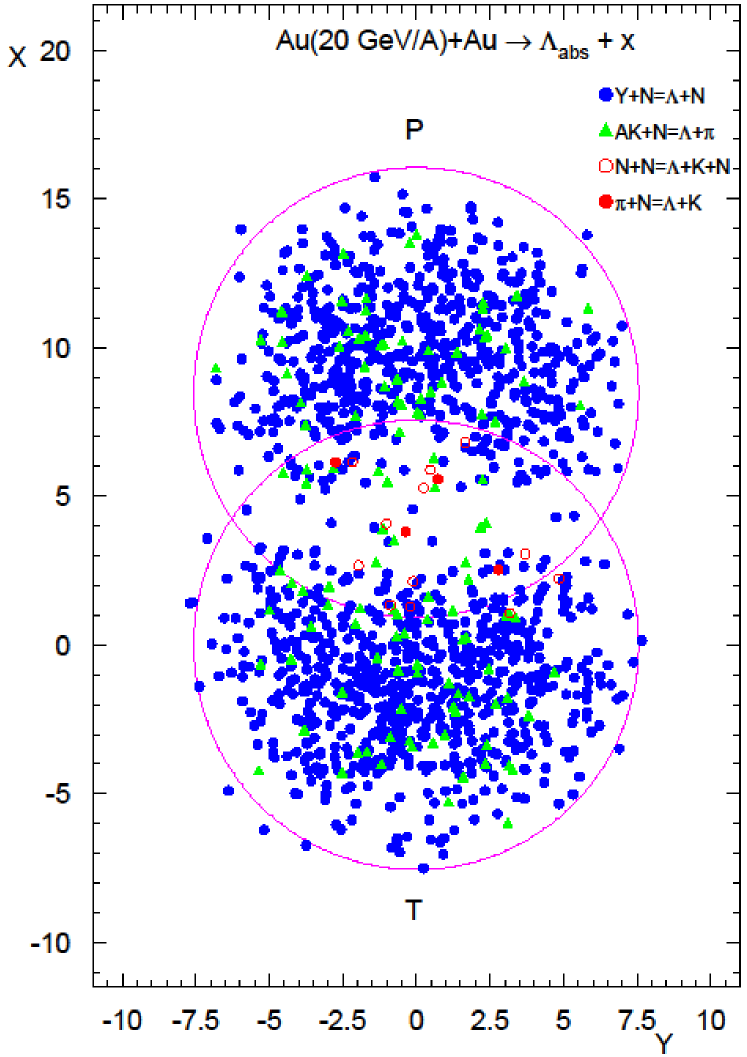
verification of hyperon production in INC (central collisions)

experiment: S.Albergo et al., E896: PRL88(2002)062301

calculations of K.K.Gudima

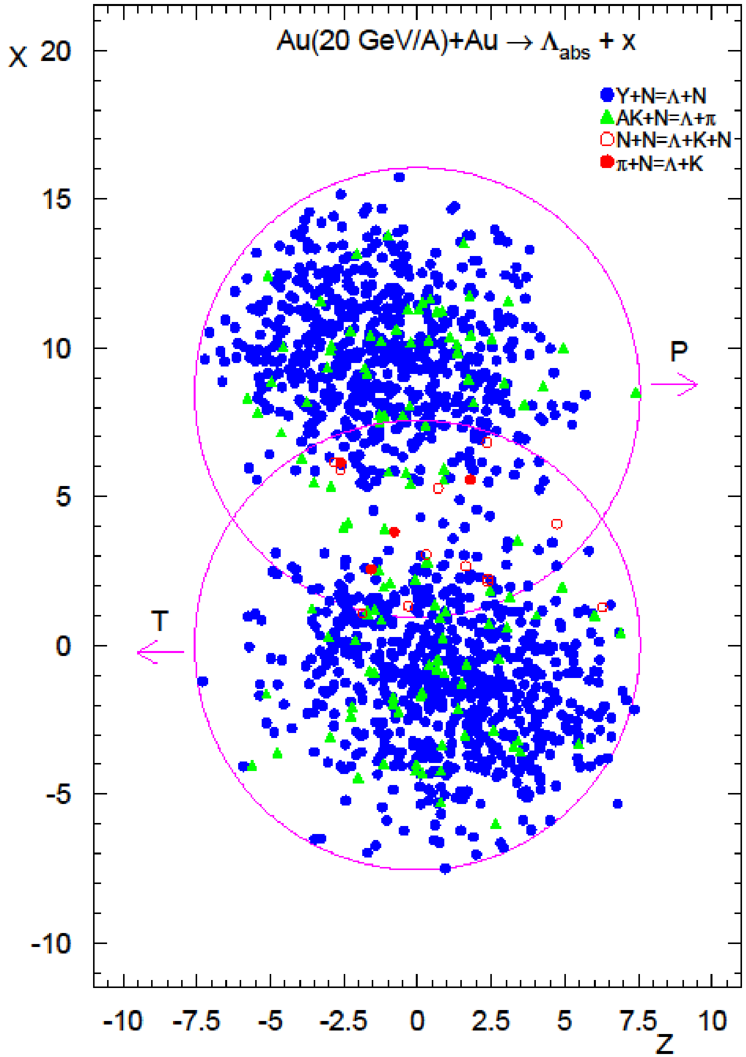


Absorption of Lambda hyperons inside residual nuclei after INC
(different processes leading to Lambda production are noted)



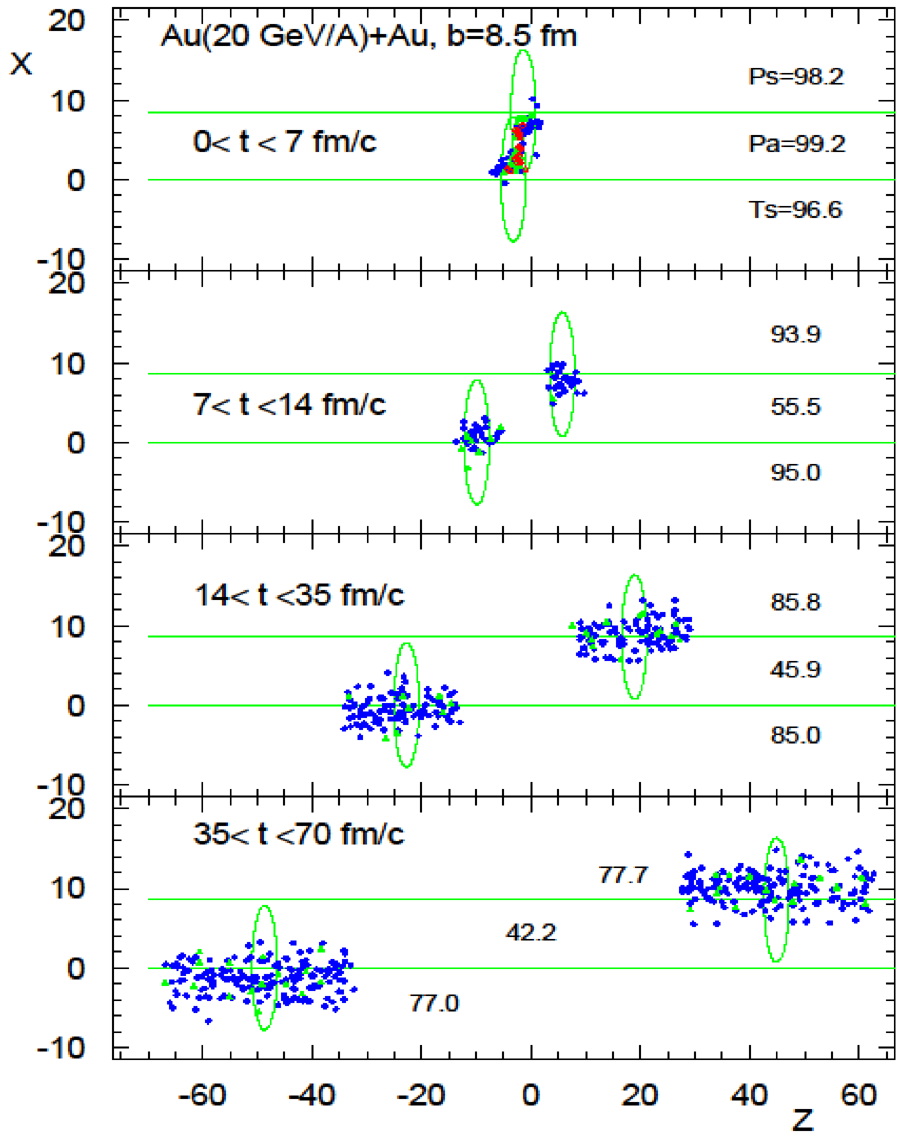
Perpendicular beam axis view

Absorption of Lambda hyperons inside residual nuclei after INC
(different processes leading to Lambda production are noted)

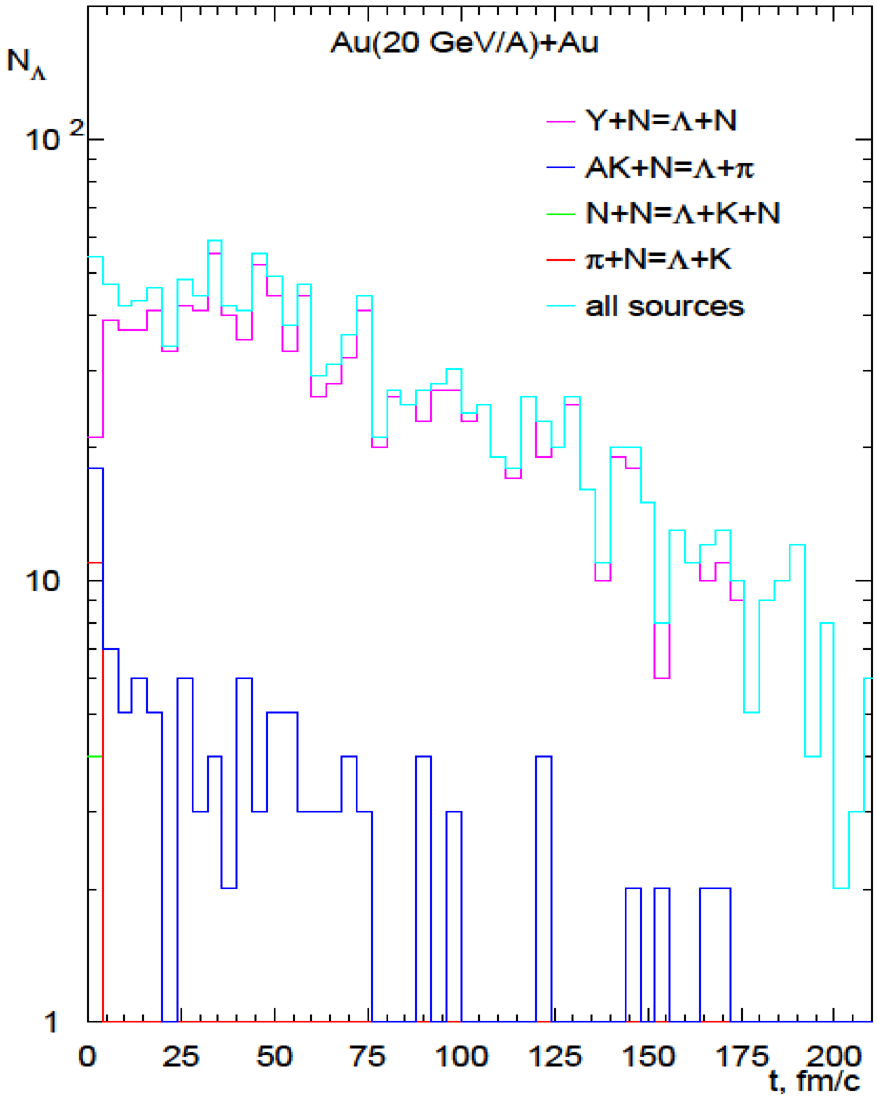


Along beam axis view

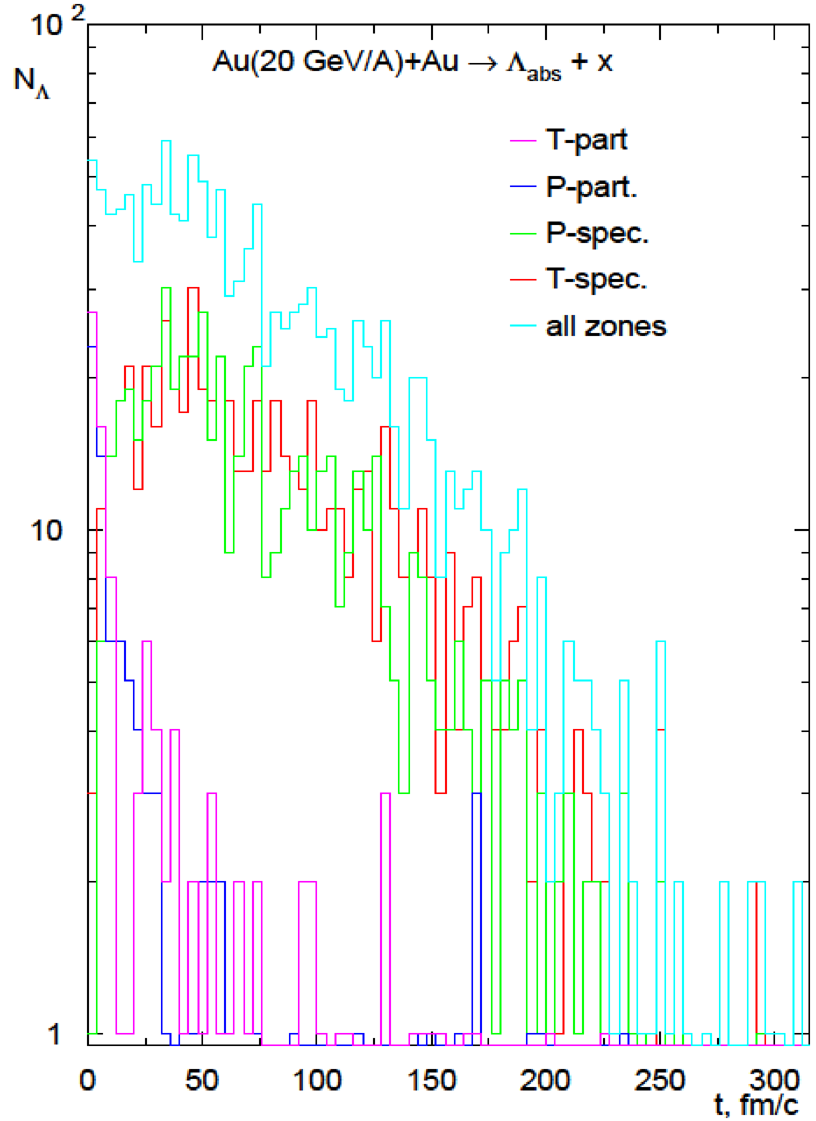
Absorption of Lambda hyperons inside residual nuclei after INC
(different times and coordinates of absorption are on panels)



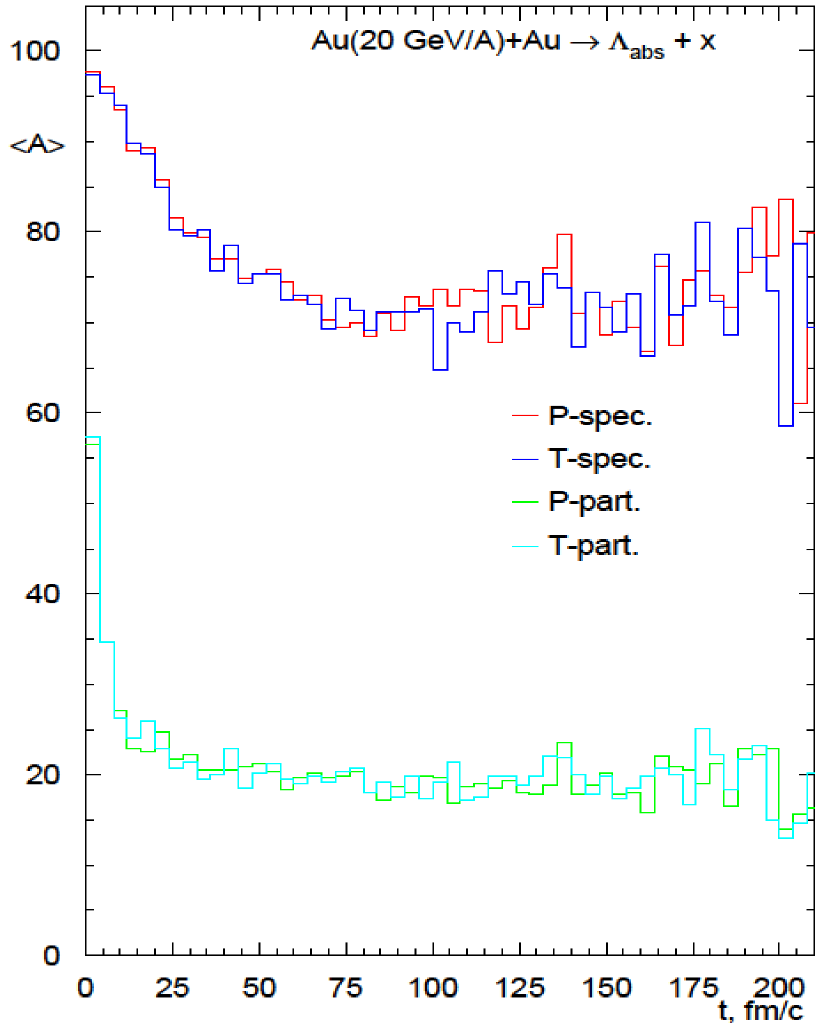
Sources of production of the absorbed Lambda (time evolution)



Zones of production of the absorbed Lambda (time evolution)

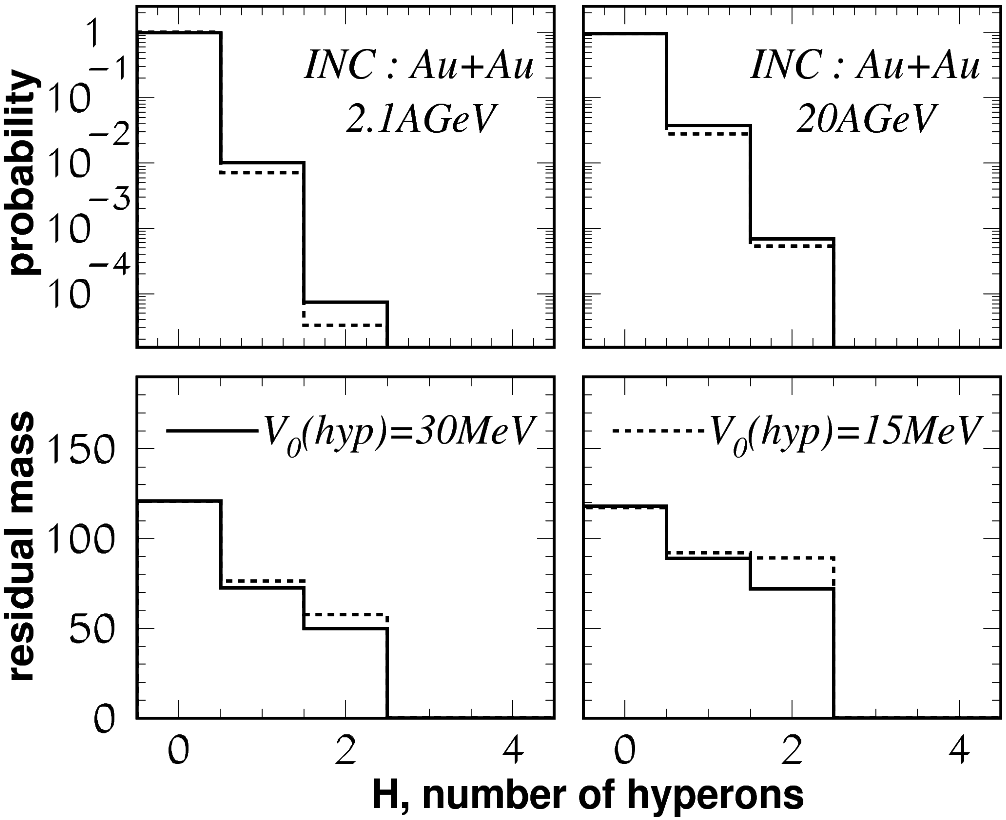


Time evolution of number of nucleons in the spectator and participant parts after Lambda absorption



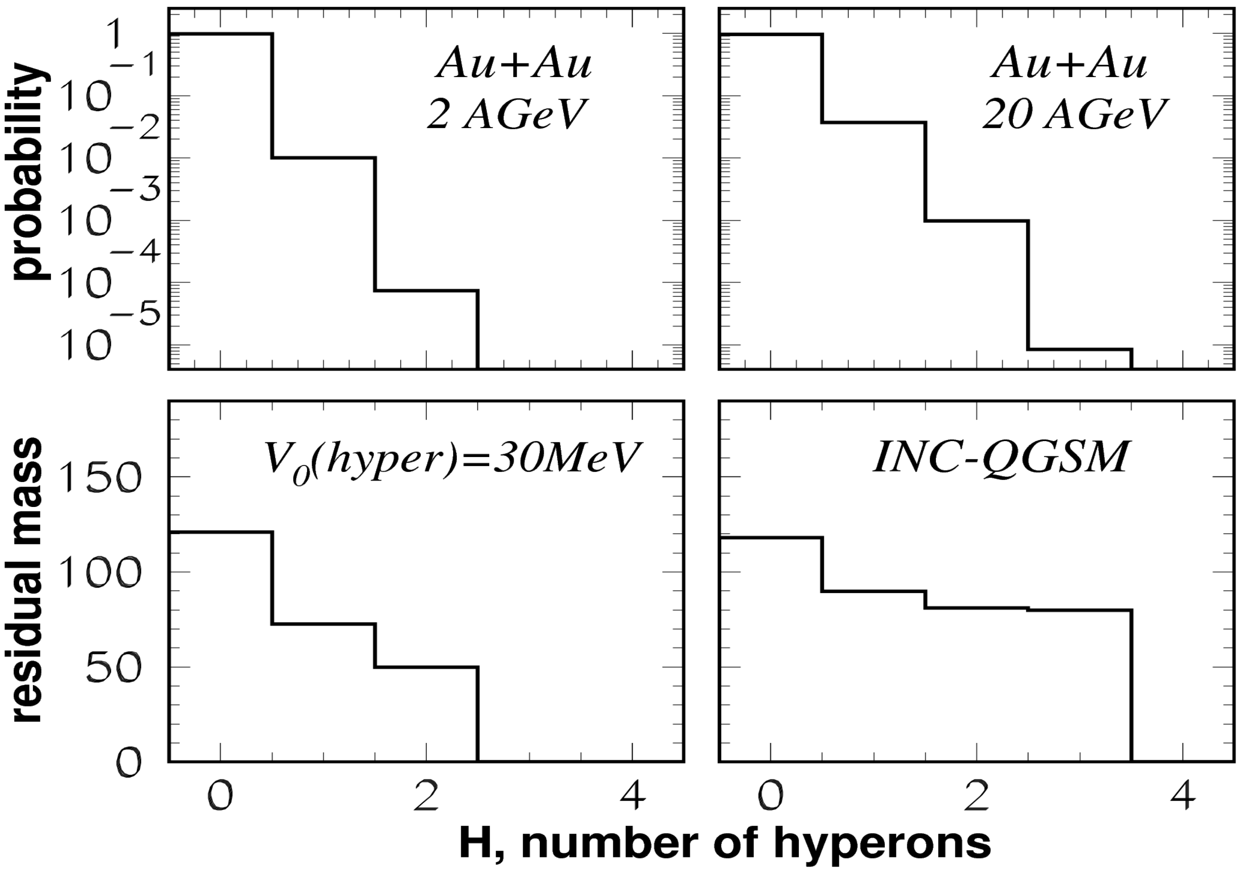
projectile residuals produced after intranuclear cascade

total yield of residuals with single hyperons ~1% , with double ones ~0.01%, at 2.1 GeV per nucleon, and considerably more at 20 GeV per nucleon



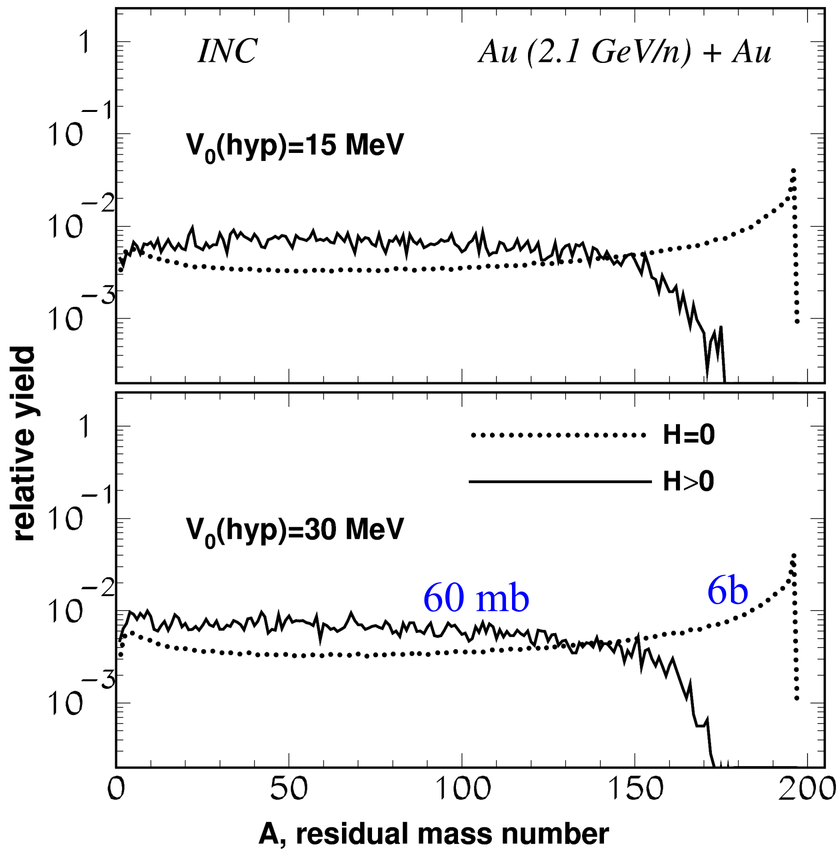
Approximation of average density of nuclei for the hyperon capture.

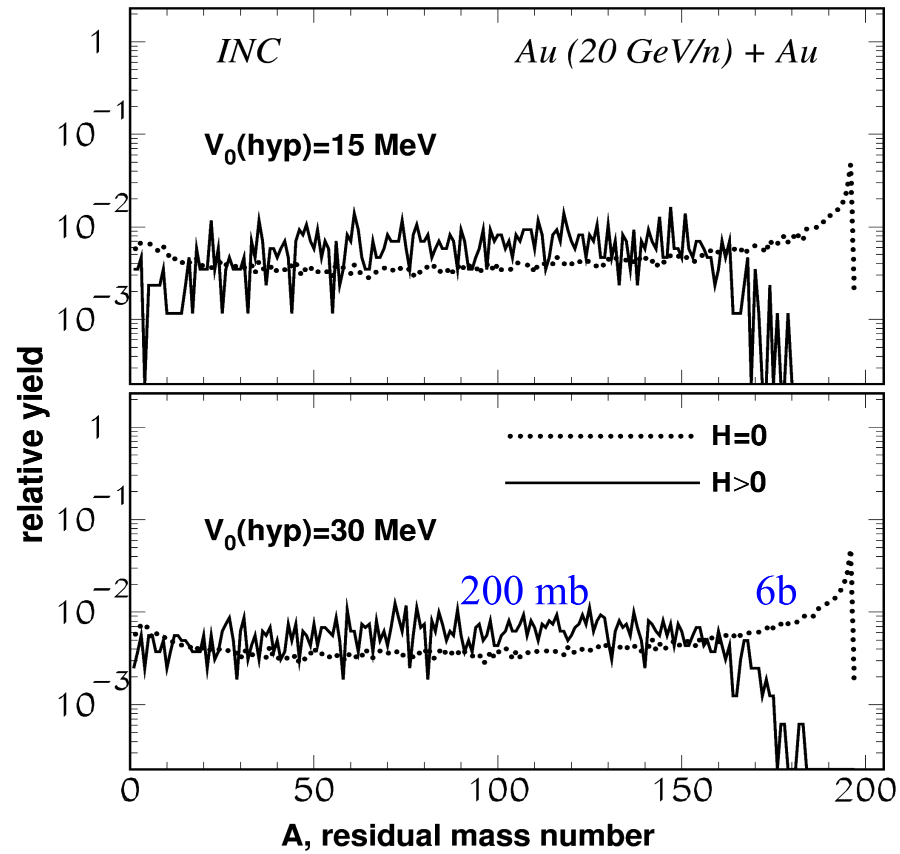
Approximation of local density of spectator nucleons for hyperon capture.



projectile residuals produced after intranuclear cascade

different hyper-residuals (with large cross-section) can be formed
(from studies of conventional matter: expected temperatures - up to 8-10 MeV)

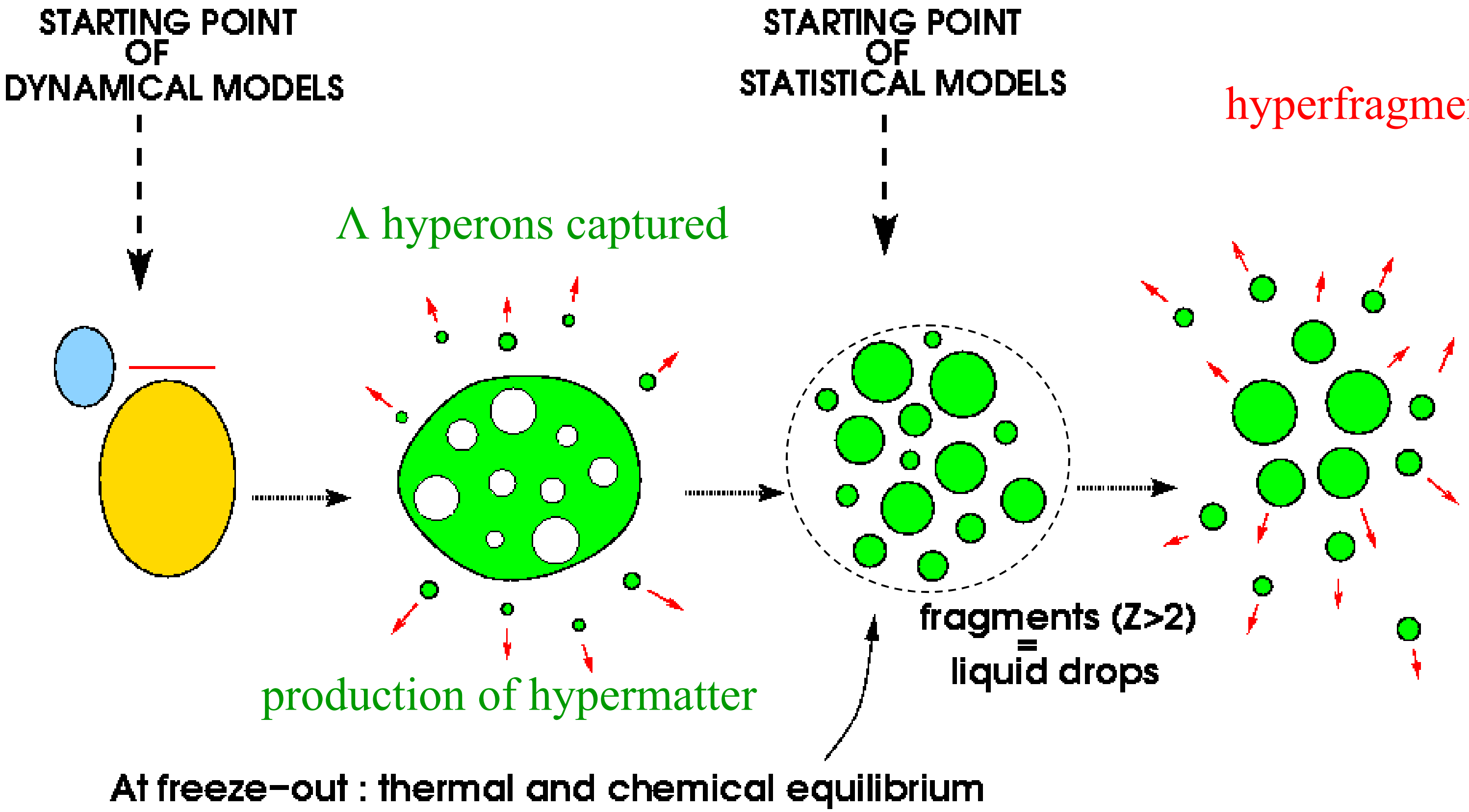




A.S.Botvina and J.Pochodzalla, Phys. Rev.C76 (2007) 024909

multifragmentation in intermediate and high energy nuclear reactions

+ nuclear matter with strangeness



Conclusions

Hot hypernuclear matter (density ≤ normal nuclear density) can be produced by capture of Λ hyperons in residual nuclei in peripheral nucleus-nucleus collisions of relativistic energies, and in hadron-nucleus reactions of high energy (E_p>2 GeV). The cross-section of the process may rich tens mb, as predicted by transport codes!

Disintegration of the residual matter (fragmentation and multifragmentation) at high excitation energy leads to production of hypernuclei. These nuclei can be studied experimentally and, in addition to the study of nuclear structure , bring info about hypermatter at subnuclear density.

An analysis of the hypermatter break-up via a statistical model gives thefollowing results:

-- general thermodynamical characteristics of the hyper-systems (with small admixture of strangeness) are similar to the ones of conventional matter;
-- production of large hypernuclei dominates at low excitation energies;
-- smooth transition to small hypernuclei with increasing excitation energy;
-- there is a sensitivity of yields of hypernuclei to their properties (mass formulae can be extracted from comparison with experiment) ;
-- there is a possibility to produce very exotic (e.g. neutron-rich) hypernuclei, which are not experimentally accessible within other reactions.

Production of hypernuclei in relativistic Heavy-Ion collisions is very promising !

Statistical approach for fragmentation of hyper-matter

$$Y_{\rm AZH} = g_{\rm AZH} V_f \frac{A^{3/2}}{\lambda_T^3} \exp\left[-\frac{1}{T}\left(F_{AZH} - \mu_{AZH}\right)\right]$$

$$\mu_{AZH} = A\mu + Z\nu + H\xi$$

mean yield of fragments with mass number ***A***, charge ***Z***, and **Λ**-hyperon number ***H***

$$F_{AZH}(T,V) = F_A^B + F_A^S + F_{AZH}^{\rm sym} + F_{AZ}^C + F_{AH}^{\rm hyp}$$

$$F_A^B(T) = \left(-w_0 - \frac{T^2}{\varepsilon_0}\right) A \quad ,$$

liquid-drop description of fragments: bulk, surface, symmetry, Coulomb (as in Wigner-Seitz approximation), and hyper energy contributions

J.Bondorf et al., Phys. Rep. **257** (1995) 133

$$F_A^S(T) = \beta_0 \left(\frac{T_c^2 - T^2}{T_c^2 + T^2}\right)^{5/4} A^{2/3} \quad ,$$

$$F_{AZH}^{\rm sym} = \gamma \frac{(A - H - 2Z)^2}{A - H} \quad ,$$

parameters ≈ Bethe-Weizsäcker formula:

$w_0 = 16$ MeV, $\beta_0 = 18$ MeV, $T_c = 18$ MeV

$\gamma = 25$ MeV $\quad \varepsilon_0 \approx 16$ MeV

$$\sum_{AZH} AY_{\rm AZH} = A_0, \sum_{AZH} ZY_{\rm AZH} = Z_0, \sum_{AZH} HY_{\rm AZH} = H_0.$$

chemical potentials are from mass, charge and *H*yperon number conservations

$$F_{AH}^{\rm hyp} = E_{sam}^{\rm hyp} = H \cdot (-10.68 + 48.7/(A^{2/3})).$$

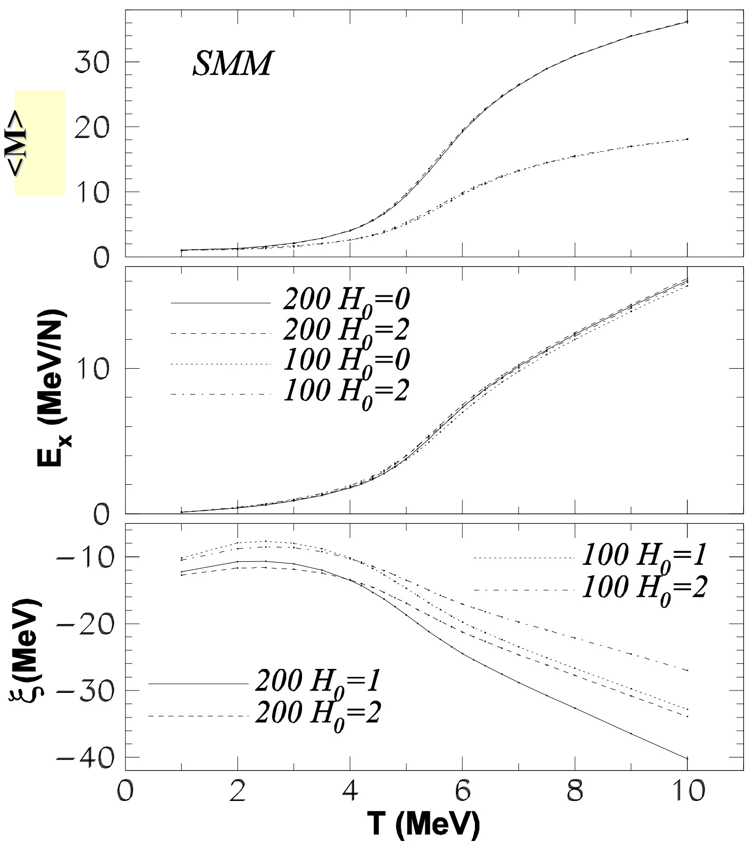
-- C.Samanta et al. J. Phys. G: 32 (2006) 363 (motivated: single **Λ** in potential well)

$$F_{AH}^{\rm hyp} = (H/A) \cdot (-10.68A + 21.27A^{2/3}).$$

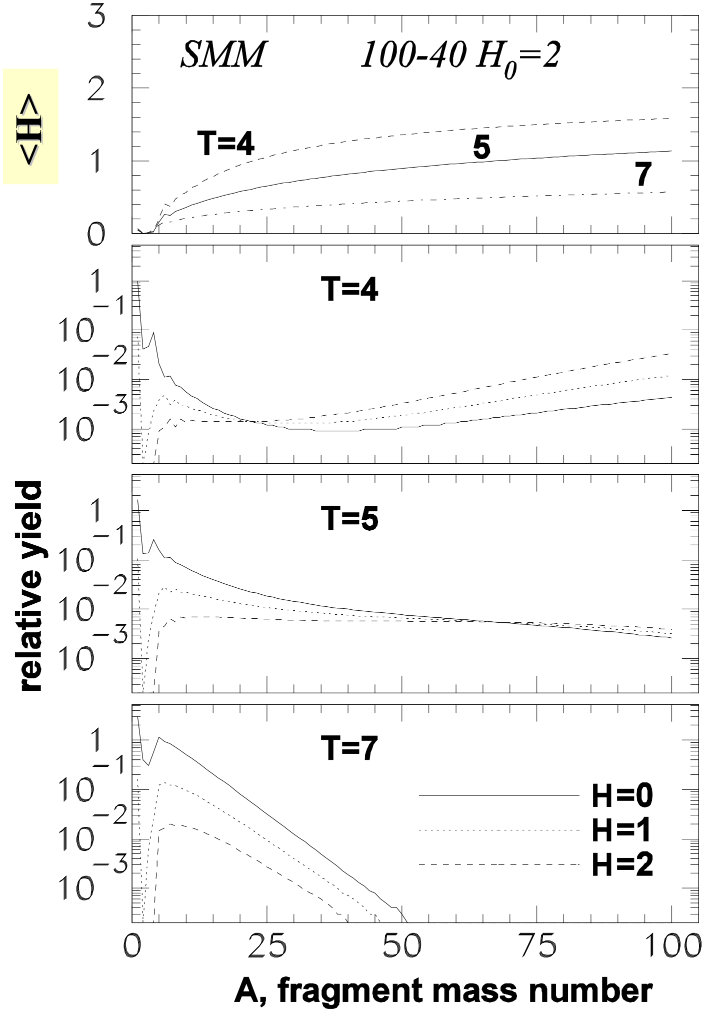
-- liquid-drop description of hyper-matter

Multifragmentation of sources with mass number A_0=100 (200), charge Z_0=40 (80), number of Λ hyperons H_0=0 (1, 2), and temperature T

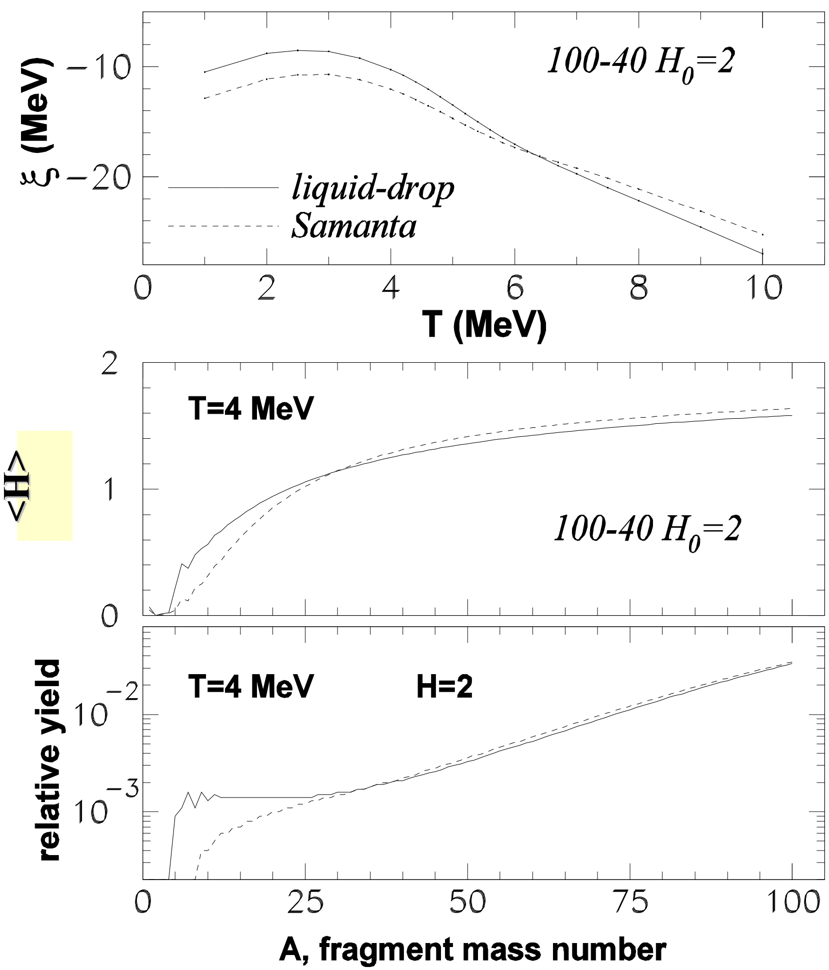
Mean multiplicity of produced fragments, caloric curve and 'hyper' chemical potential



Number of hyperons in fragments and yield of hyperfragments

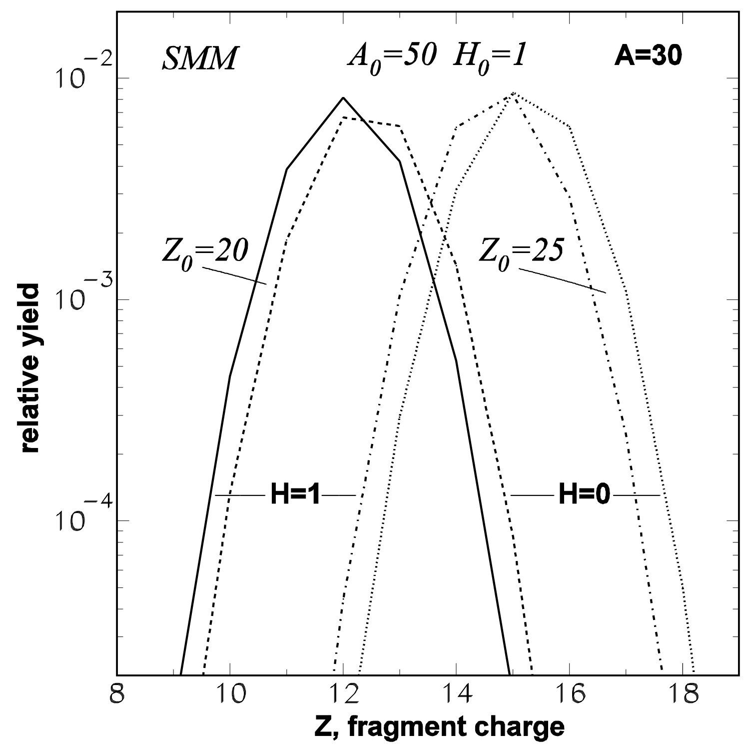


Chemical potentials, number of hyperons in produced fragments and their yields, in the cases of different ('C.Samanta et al.' and liquid-drop) hyper-terms in mass formulae for hypernuclei



Statistical multifragmentation calculations

Isotope distributions of normal and hyper fragments with **A**=30, produced for sources $\boldsymbol{A_0}$, $\boldsymbol{Z_0}$, $\boldsymbol{H_0}$ and **T**=5 MeV

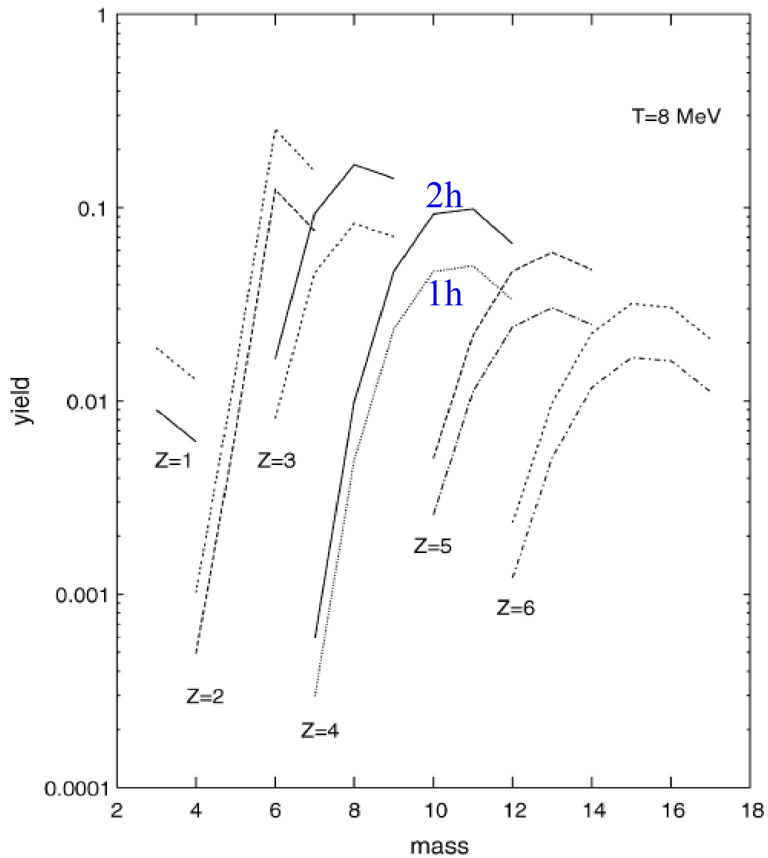


Canonical thermodynamical model: inclusion of hypernuclei

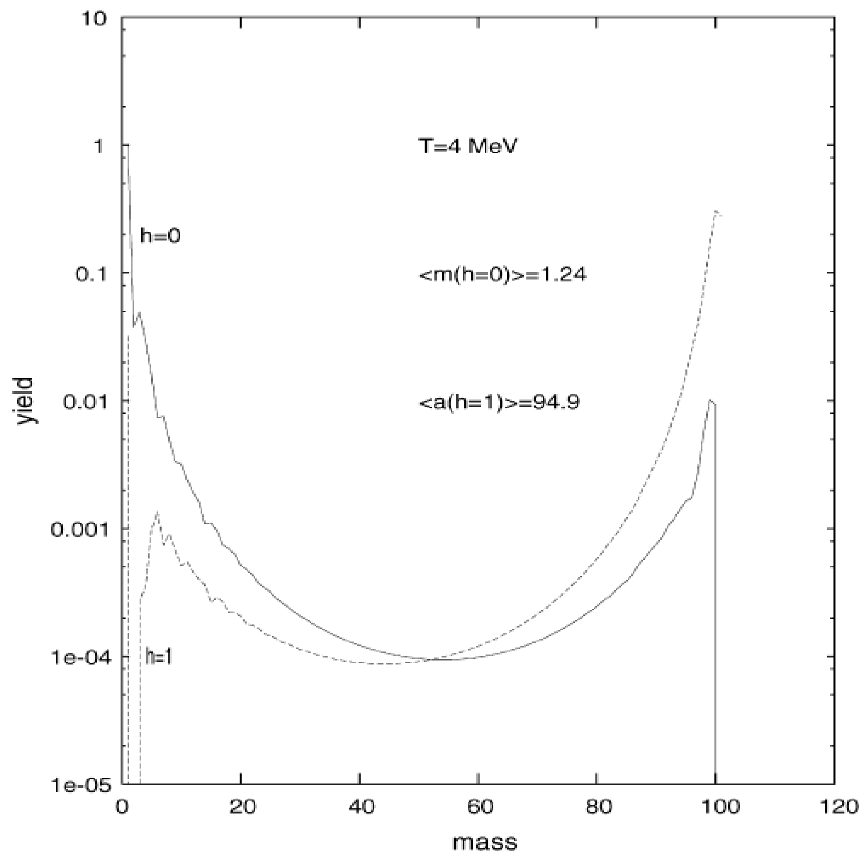
S. Das Gupta , *Nucl.Phys.* A 822 (2009) 41

Initial nuclear system: *A=100, Z=40* ; *H=1, 2* ; *T=4, 8* MeV
+ liquid-drop mass formula for hypernuclei

isotope distributions of hypernuclei

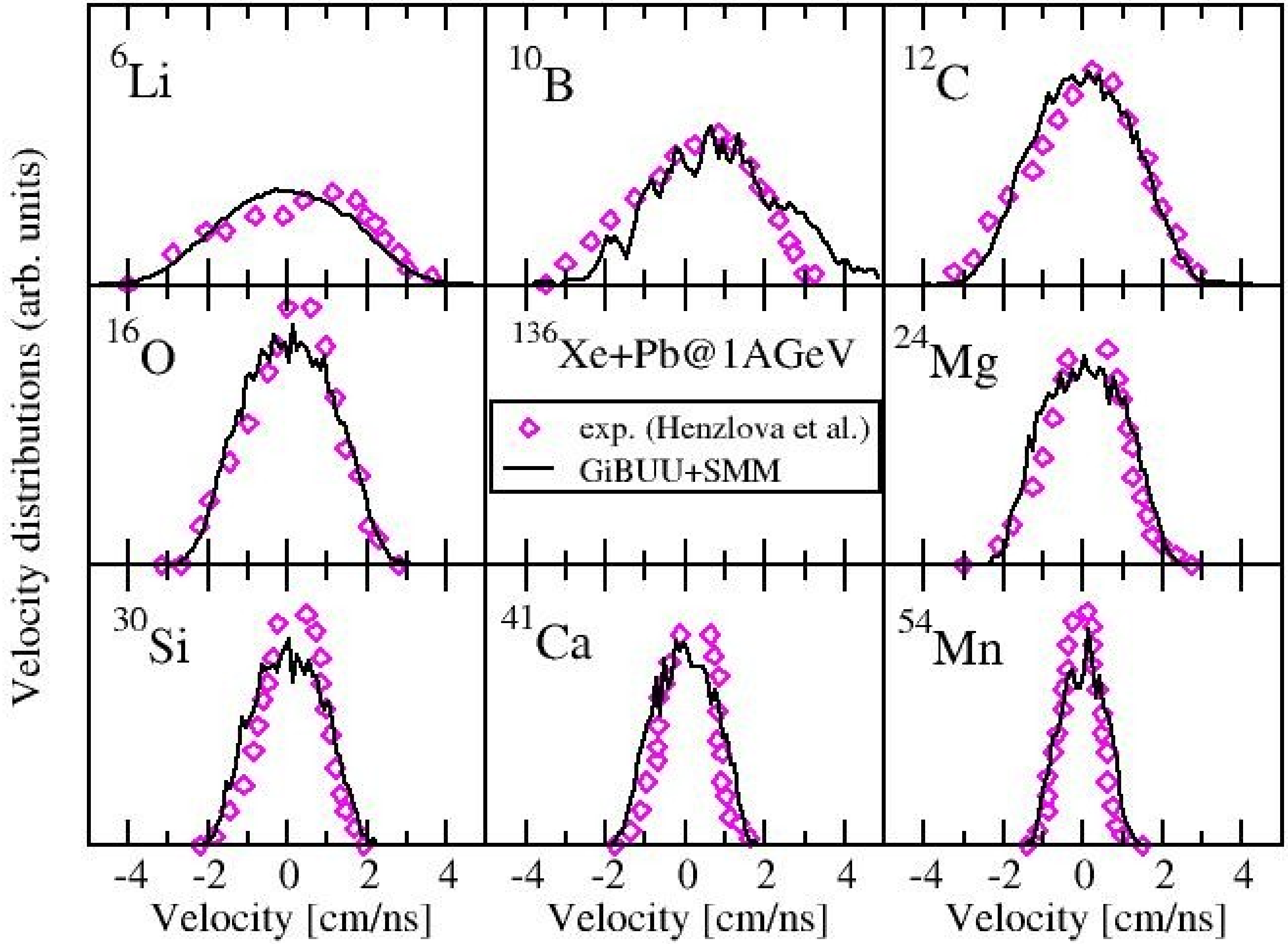


mass distributions



Verification of GiBUU+SMM approach in rapidity

FRS data: PR**C78** (08) 044616

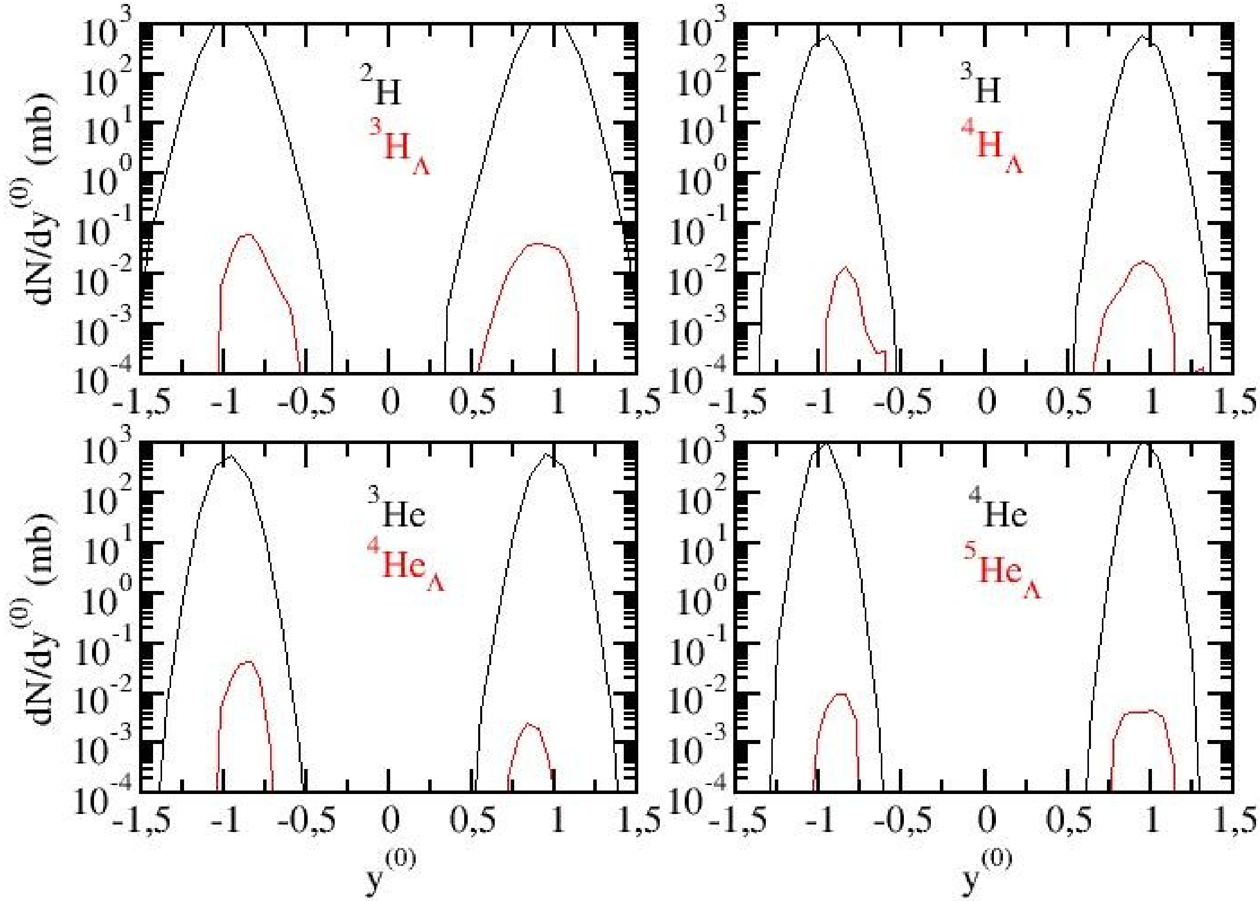


T.Gaitanos., H. Lenske, U. Mosel, PL**B675** (2009) 297.

Hypernuclei from spectator fragmentation…(HypHI@GSI(Phase-I), $^{12}C+^{12}C$@2AGeV)

Formation of hypernuclei from spectator fragmentation via **coalescence**

(condition: Y inside radius of fragmenting source+momentum coalescence)



Low total yields, ~1-3μ b, consistent with previous studies: M.Wakai, NPA547(92)89c

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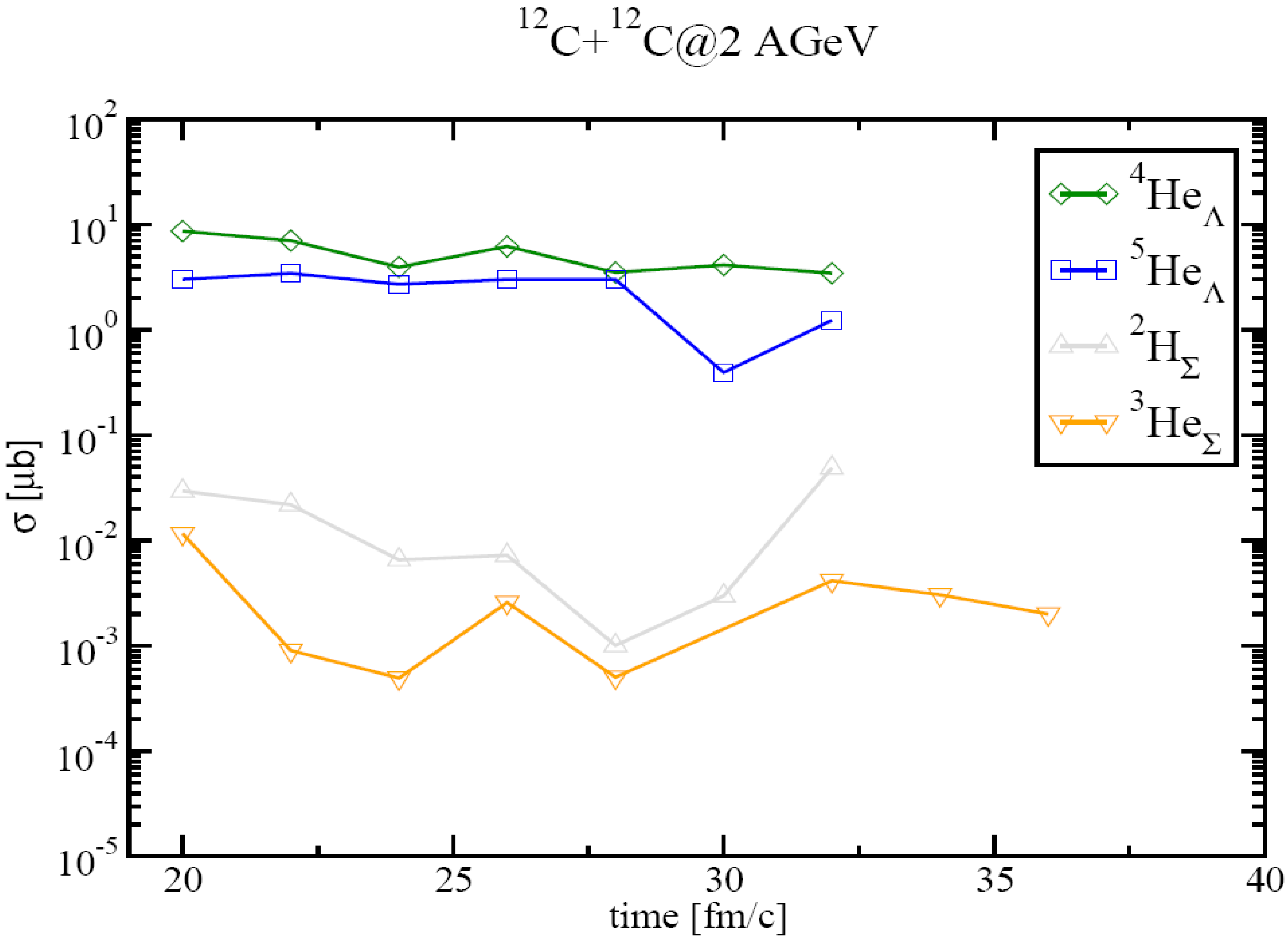
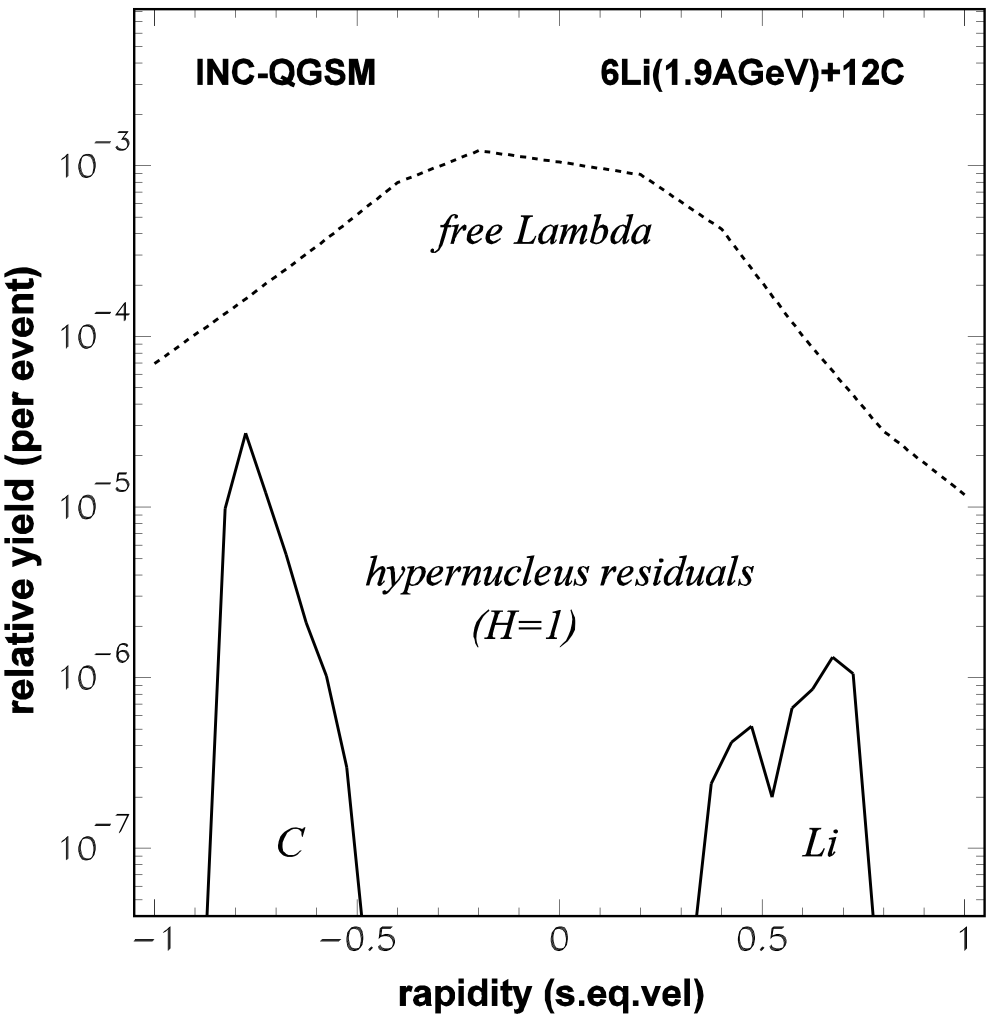
T.Gaitanos, GiBUU – hyperfragments are separated at early stages





INC-QGSM
6Li(1.9AGeV)+12C
free Lambda
hypernucleus residuals
(H=1)
C
Li
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
−1
−0.5
0
0.5
1
relative yield (per event)
rapidity (s.eq.vel)