On the coalescence phenomenology in heavy ion collisions

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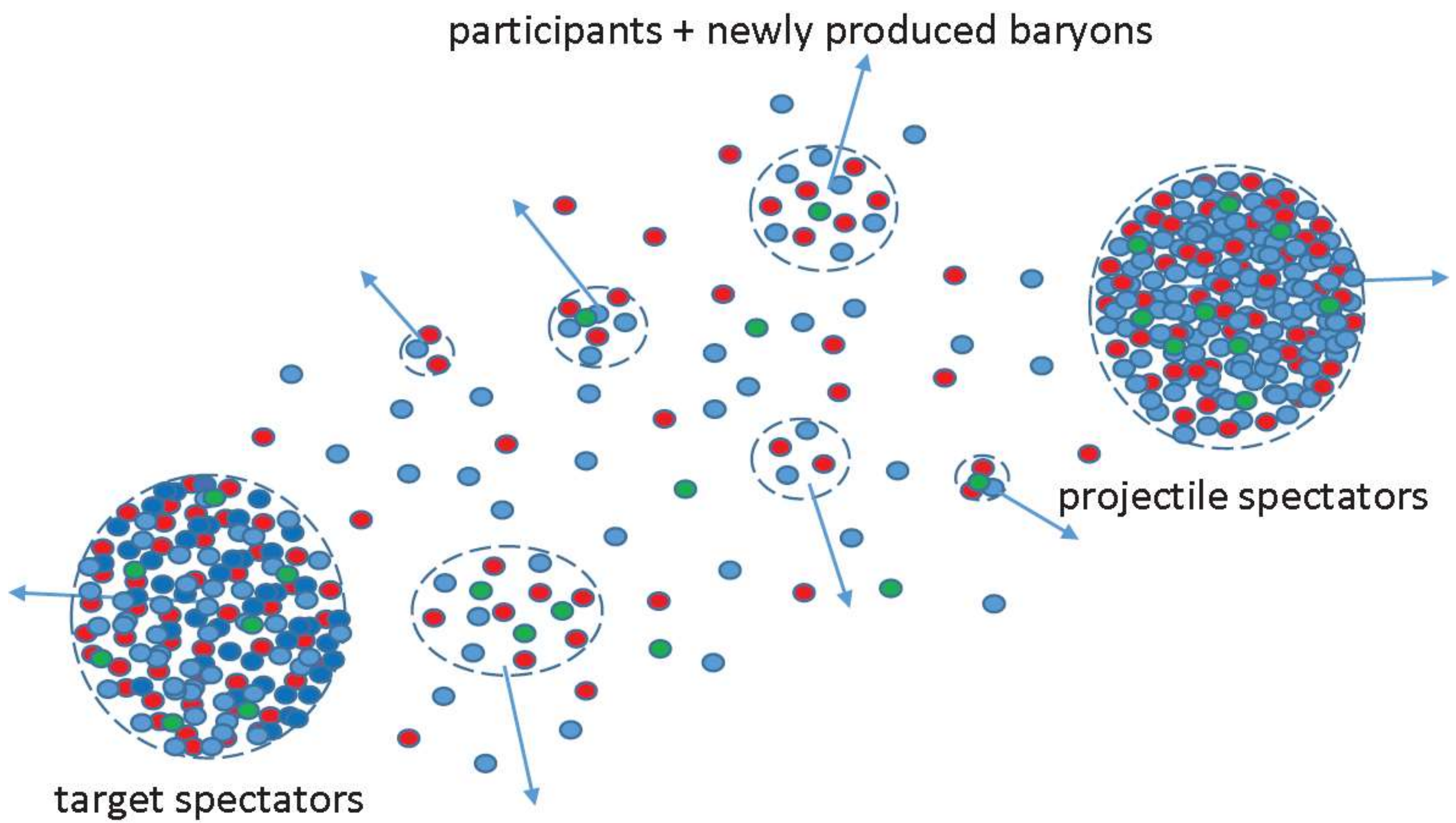

A schematic view of the coalescence of baryons in the mid-rapidity region after the collision of two nuclei is shown at relativistic energies.

The formation of baryon clusters from the dynamically produced baryons as a results of secondary interaction between them, when they are in the vicinity of each other.

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- It is known since the late 1970s that many different light complex nuclei can be produced in central nucleus-nucleus collisions [59].
- In particular, the process leading to hypernuclei is under study with the modern detectors [16, 17]. Usually it is associated with a coalescence-like mechanism, i.e., the complex particle are formed from the dynamically produced nucleons and other baryons, because of their attractive interaction.
- The coalescence model has demonstrated a good description of the data (by adjusting the coalescence parameter) from intermediate to very high collision energies [33, 35, 60].
- There were many other intensive investigations of the coalescence mechanism, e.g., see the latest Refs. [61–63].
- This supports the main idea that the baryons emerging after the initial dynamical stage are the main constituents of these nuclei.

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For the simulation of the dynamical stage we have applied the Dubna Cascade Model (DCM) [27].

By taking the produced hadrons as input we have used the coalescence of baryons (CB) models developed previously in Ref. [26].

This coalescence includes the proximity of baryons in the coordinate and velocity space.

The important velocity parameters V_c (in the units of the light velocity) gives the maximum velocity dierence for the baryons coalescing into a cluster. We believe that a large suggested parameter $V_c = 0.22c$ is realistic since it corresponds to the Fermi velocity in normal nuclei, and we employ it to demonstrate the effect more clearly.

The excitation energy of such coalescence clusters have been calculated within the CB model as the energies of the captured baryons respective to the center of mass of the cluster. For the secondary de-excitation of clusters the statistical Fermi-break-up (FB) model was adopted, which was generalized for hypernuclei [25].

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Yield per event of fragments formed from participant nucleons in the midrapidity region in 208Pb+208Pb collisions at projectile energies of 1 and 5 GeV per nucleon.

The dynamical stage and participant nucleons were calculated with DCM.

Top panel show mass yields of excited fragments as obtained with CB model for dierent coalescence parameters Vc = 0.1 and 0.22.

Middle and bottom panels denote mass yields of excited fragments with coalescence parameter Vc = 0.22 as for CB model and CB+FB after de-excitation of these fragments via Fermi-break-up (FB) process at energies 1 and 5 GeV per nucleon, respectively.

As a result of their following de-excitation the nuclei becomes smaller, and these distributions have a steep decrease with mass number A. Their isospin composition changes also, and the most bound nuclei survive.

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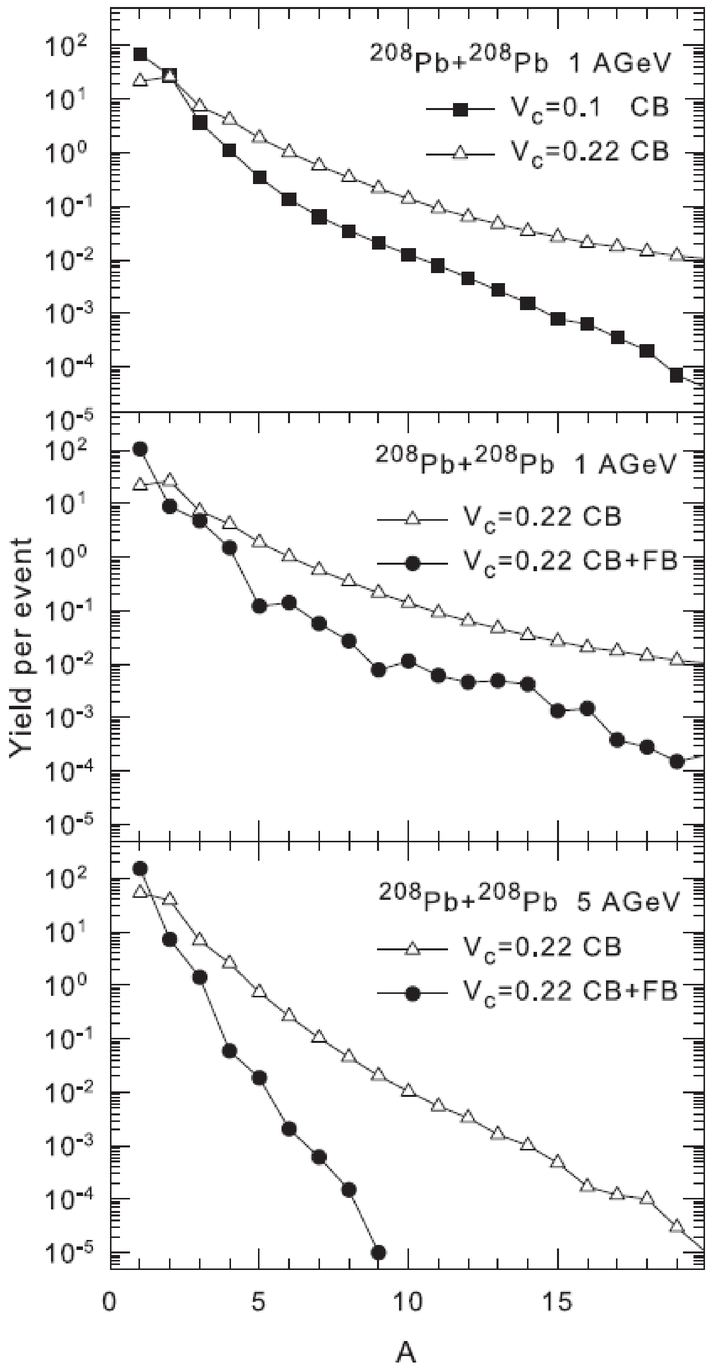

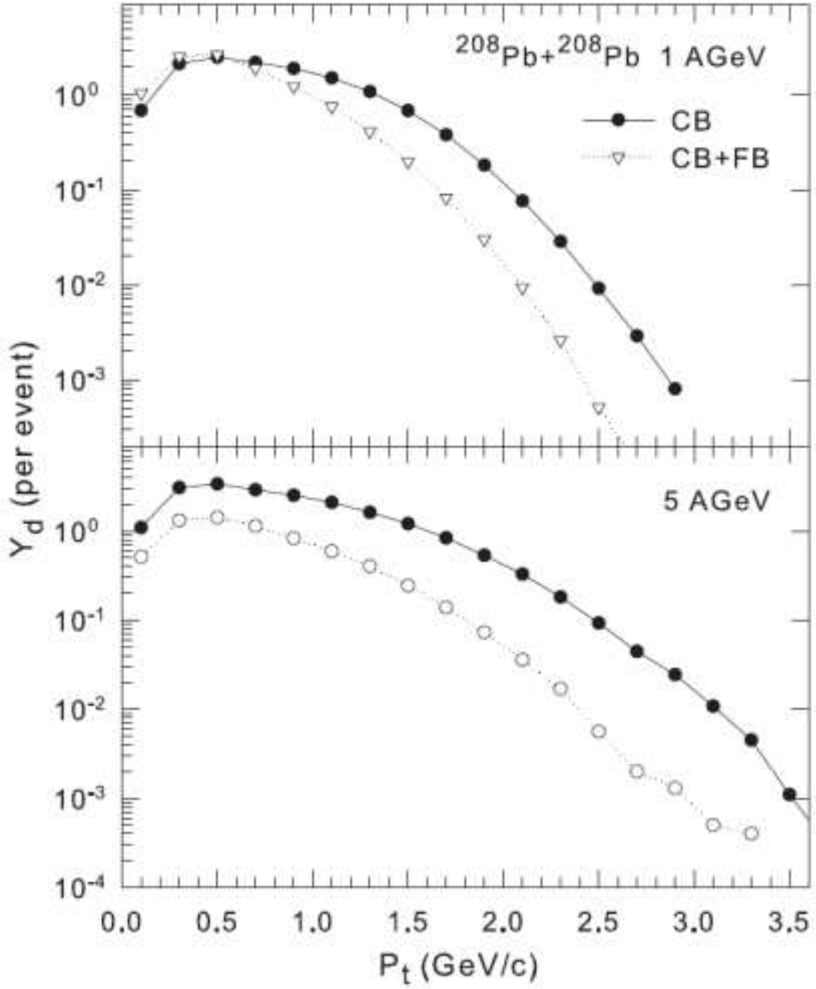

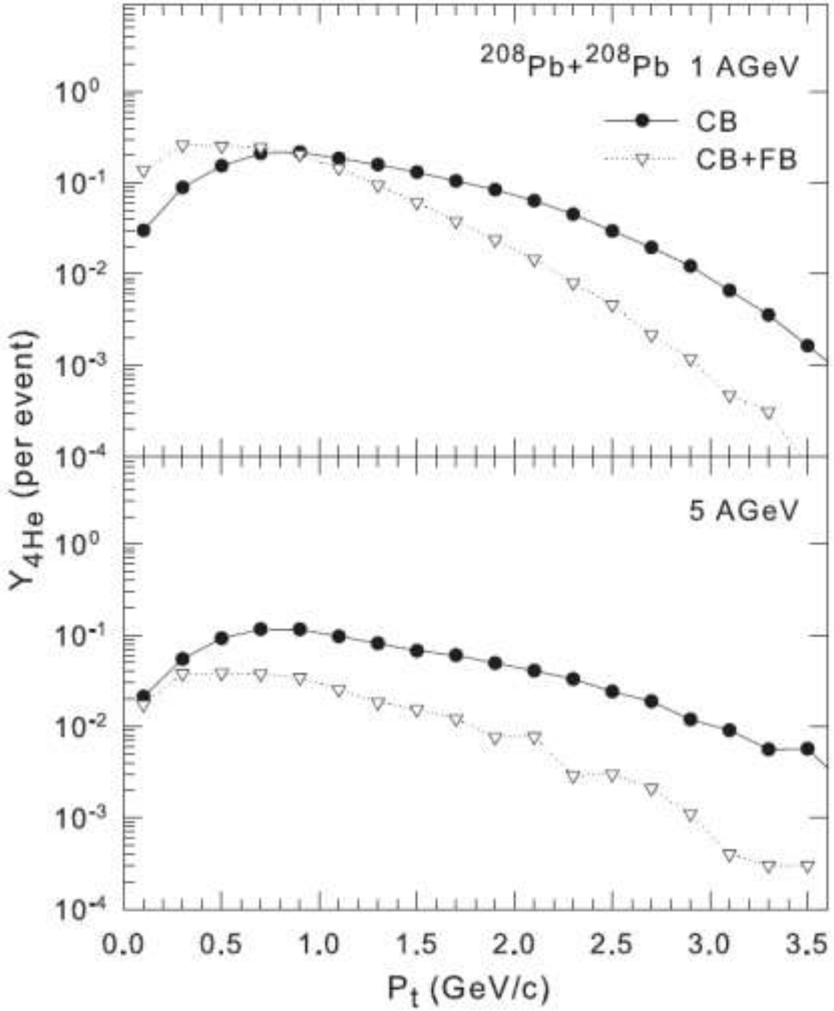

We present the transfer momenta distributions of deuteron and helium particles for coalescence parameter Vc = 0:22c after CB and CB+FB processes at 1 and 5 GeV per nucleon energies.

It can be seen that after de-excitation these momentum distributions become steeper and their maximums are shifted toward low energies. This is a consequence of the decay of the large primary fragments which are formed by coalescence from slow baryons. Namely this decay contributes mainly to the 2H and 4He yields.

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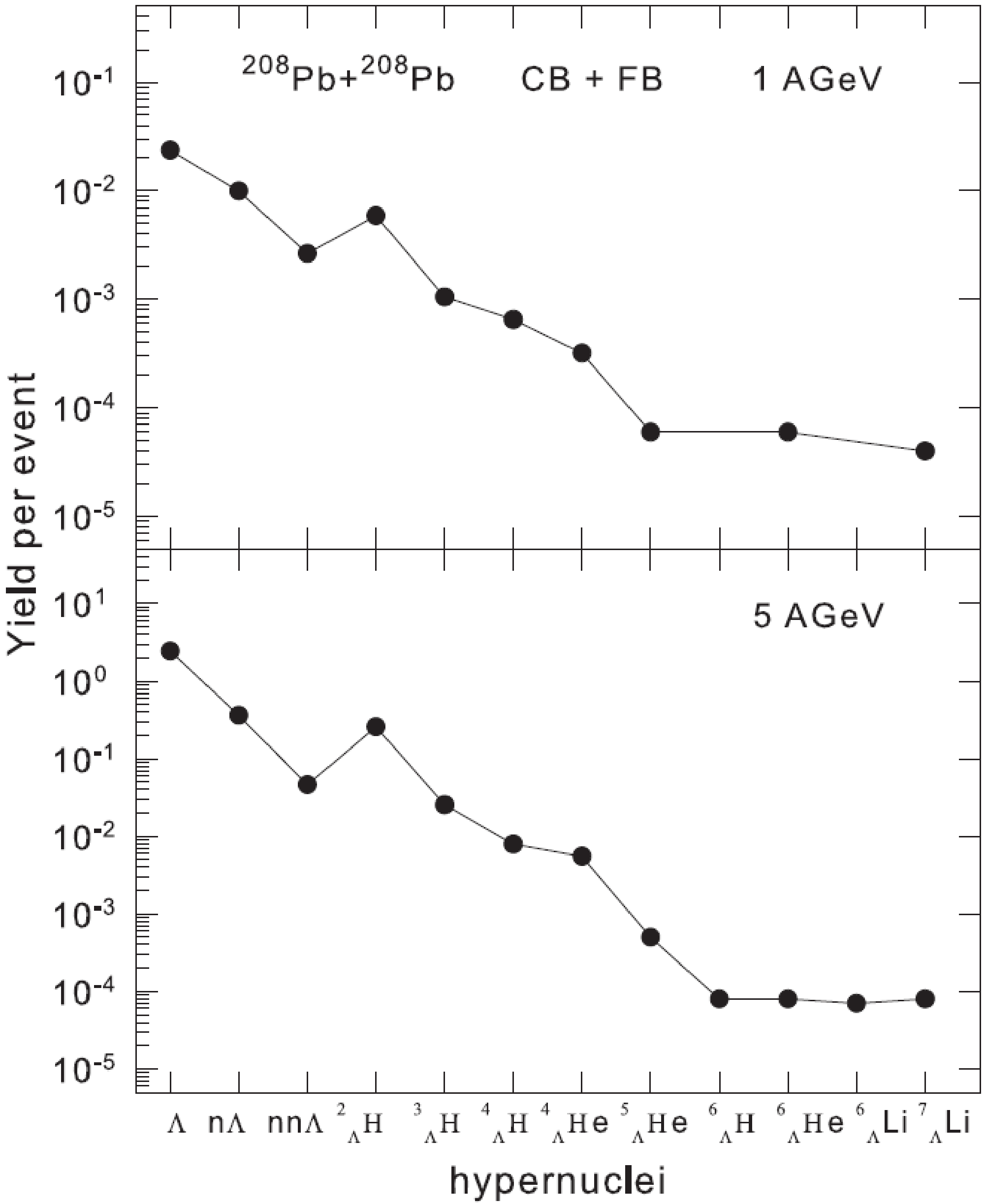
This kind of mechanism predicts a lot of hypernuclei after the secondary de-excitation, as demonstrated Figure.

In this case we can even assume and evaluate the production of exotic hypernuclei which widely discussed recently, in order to help experimenters in their investigation.

One can clearly see that the yield of lightest hypernuclei and hyperons have considerably increased when the collision energy becomes higher than the threshold one (i.e., more than 1.6 A GeV).

There is also the trend to the saturation of their yields. However, concerning relatively large hypernuclei (with mass number A > 5), the saturation comes already at low energies.

This is related to the increased internal excitations of primary big clusters and to decreasing their number at the highest colliding energy.



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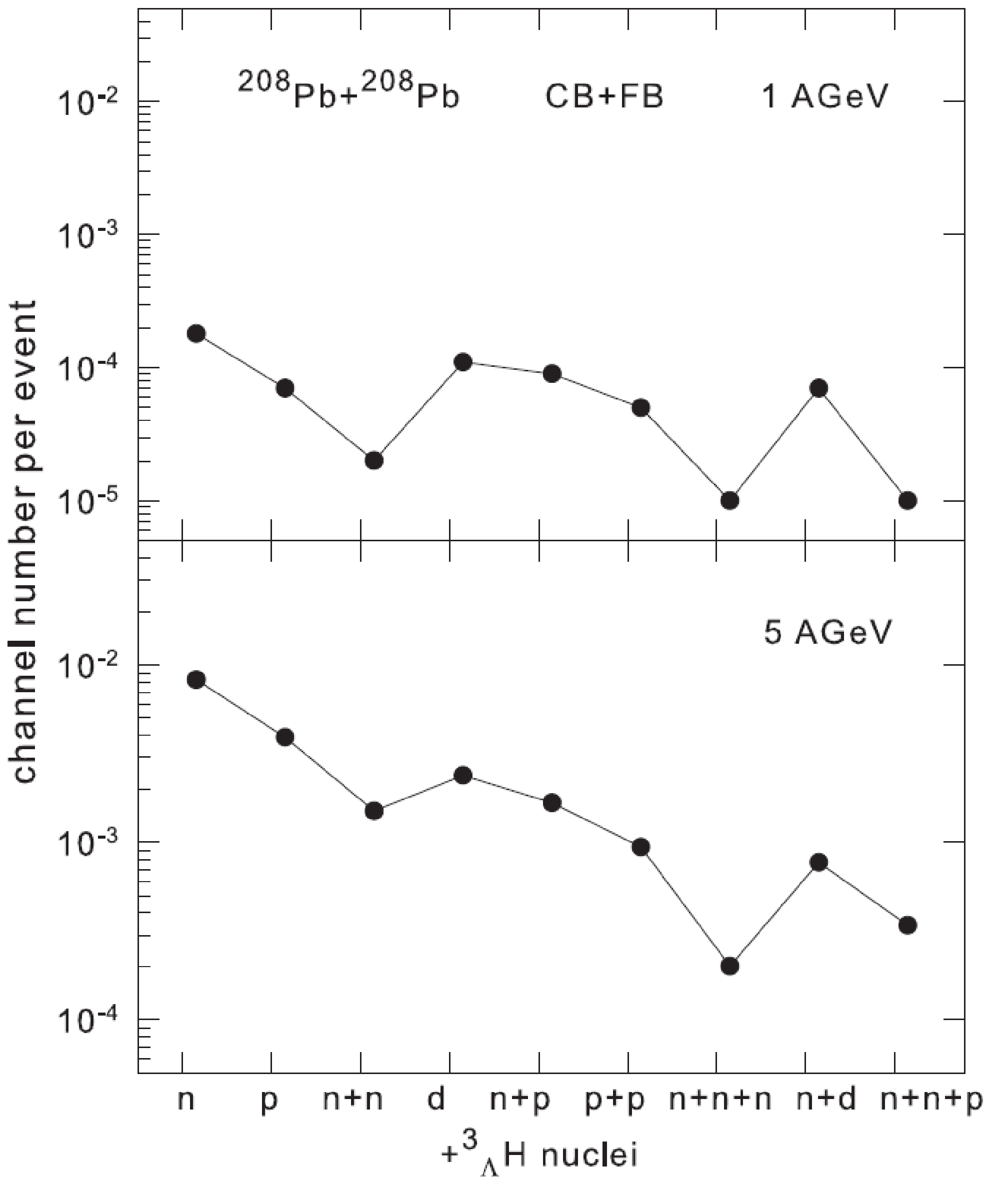
We show the correlated normal particle yields in the channels leading to the production of 3ΛH hypernucleus.

Measuring such yields would be the best prove of this process.The channels with the production of charged particles, like p+3H and d+3ΛH are especially interesting, since they can be easily detected by experiments.

In addition, the relative fraction of these channels is varying with the collision energy, and it can give the information about the sizes of hot hyperclusters.

On the other hand by measuring energies of the correlated particles we can extract information on the excited states in primary nite hyper fragments, and on hyperon interaction in the matter.

We believe the extension of the coalescence towards hot clusters and their de-excitation is the qualitatively new development, and it is consistent with the reaction processes known from the fragment formation study in peripheral collisions.



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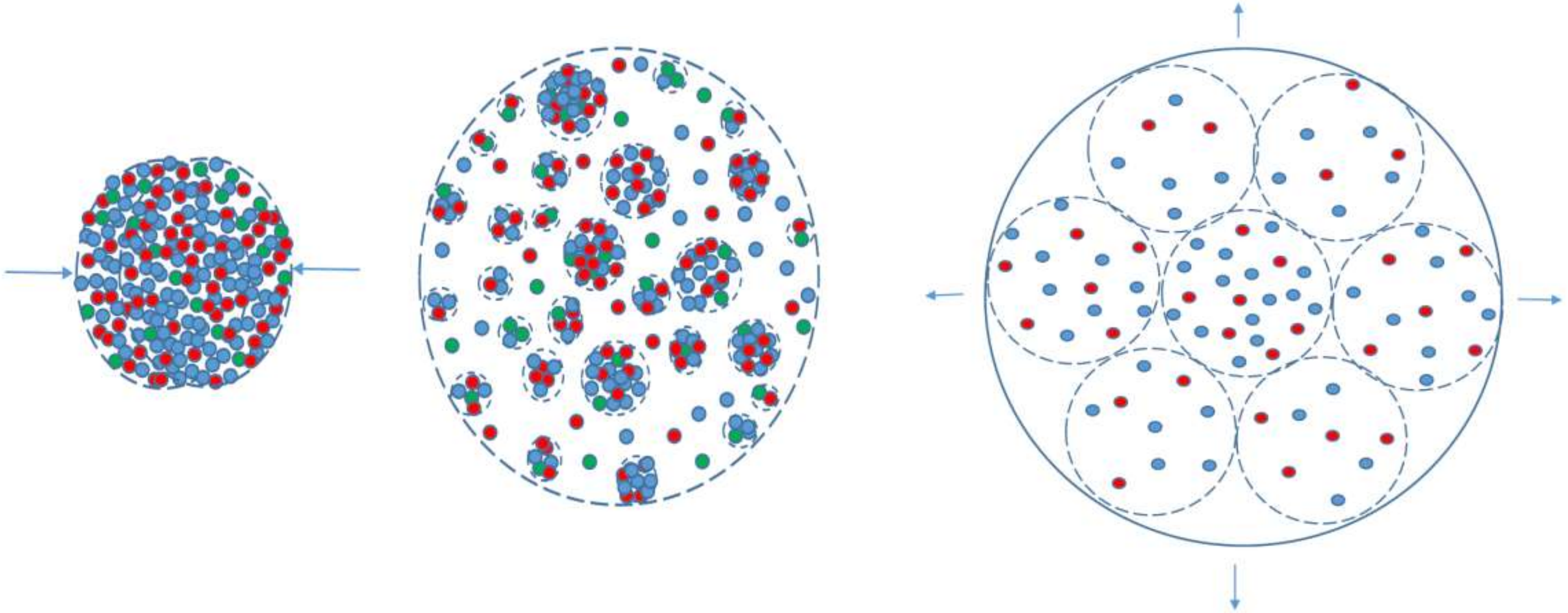


It is natural to use the transport models for the generation of baryon parameters (coordinates and momenta) after their dynamical production in relativistic nucleus collisions.

GENERATION 1 (G1):the Dubna Cascade model (DCM) which has demonstrated a good performance in description of many experimental data [2, 24, 27]. This model provides a defined time-end of the fast reaction stage and gives the corresponding parameters of baryons.

GENERATION 2 (G2):
We perform the isotropic generation of all baryons of the excited sources according the microcanonical momentum phase space distribution with the total momentum and energy conservation. It is assumed that all particles are in a large freeze-out volume (at subnuclear densities) where they can still interact to populate uniformly the phase space. Technically, it is done with the Monte-Carlo method applied previously in the SMM and Fermi-break-up model in the microcanonical way [16], and taking into account the relativistic effects according to the relativistic connection between momentum p, mass m, and kinetic energy of particles

$$\sum \sqrt{\vec{p}^2 + m^2} = E_0 + \sum m.$$

(where the sum is over all particles and all ingredients are taken in the energy units). The total energy available for kinetic motion of baryons E0 (we call it as the source energy) is the important parameter which can be adjusted to describe the energy introduced into the system after the dynamical stage.

Botvina, Buyukcizmeci, Bleicher, arXiv:2012.07679

GENERATION 3 (G3):

We assume the momentum generation similar to the explosive hydrodynamical process when all nucleons y out from the center of the system with the velocities exactly proportional to their coordinate distance to the center of mass. For this purpose, with the Monte-Carlo method, we place uniformly all nucleons inside the sphere with the Radius

$$F \cdot R_n \cdot A_0^{1/3}$$

without overlapping. Here A0 is the nucleon number, and Rn=1.2 fm is the nucleon radius. The size factor F=3 is assumed for the expanded freeze-out volume in which the nucleon can still strongly interact with each other. At the intermediate collision energies this volume corresponds approximately to the average expansion of the system after simulations with the transport models, when the baryon interaction rate drastically decreases. Finally, we attribute to each nucleon the velocity by taking into account the momentum and energy conservation for the relativistic case.

Obiovusly, the velocities and coordinates of baryons are strongly correlated with each other.

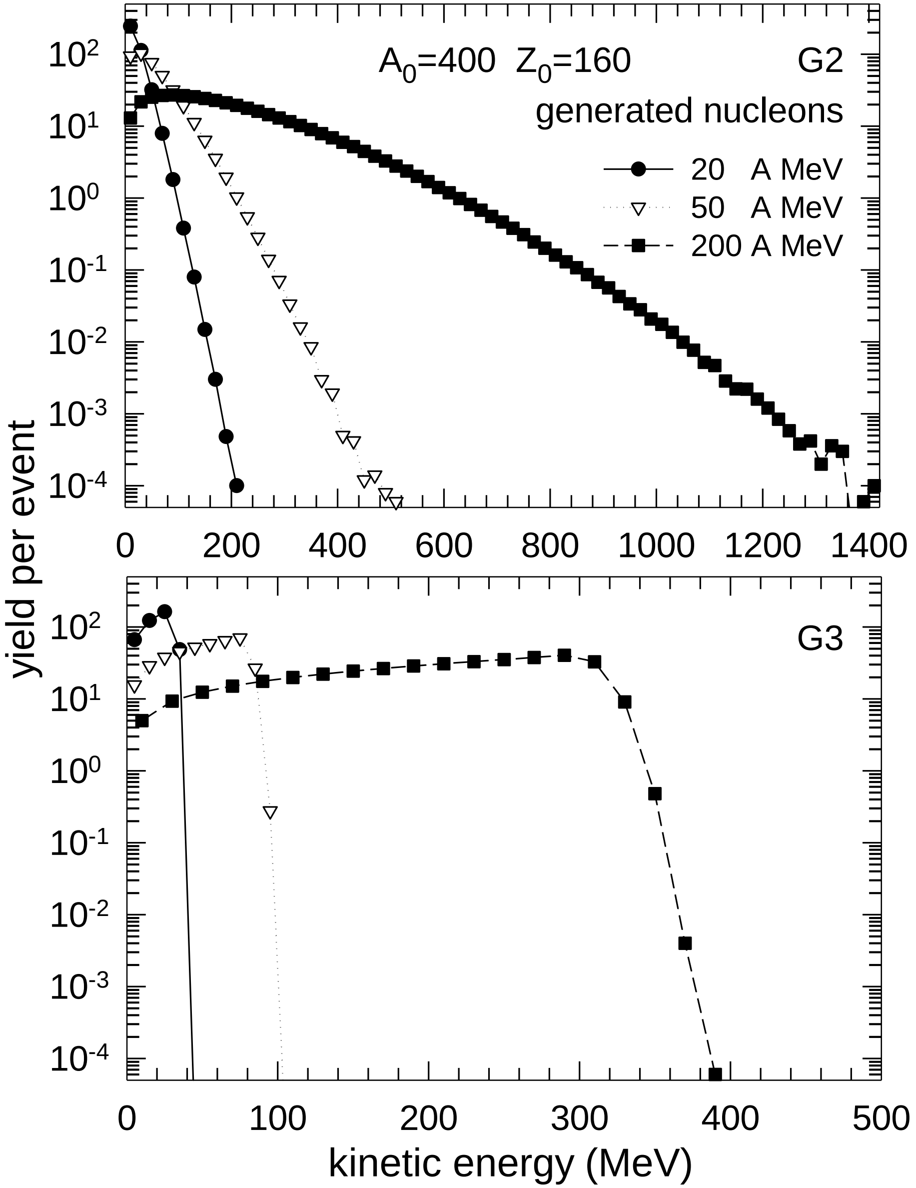
Botvina, Buyukcizmeci, Bleicher, arXiv:2012.07679

Energy spectra for initial nucleons of the hot expanding nuclear system according to the microcanonical phase space distribution - G2 (top panel), and according to the hydrodynamical-like explosion - G3 (bottom panel). The suggested total kinetic energies are 20, 50, and 200 MeV per nucleon. The nucleon source size and composition are shown in the top panel.

- This may characterize the hot systems produced at central collisions of heavy nuclei at laboratory energies around 100-1000 A MeV. As expected, the distributions are very broad. We have also checked that the size effect on the distributions is practically minimal, as it is following thermodynamical quantities in the one-particle approximation.

- In the bottom part we show the same distributions but for G3 generation. It is seen a qualitative dierence of the nucleon energy distributions after G2 and G3 generators.

- G3 provides a very compact distribution of nucleons according to their positions in the freeze-out volume. We think it is important to demonstrate how this difference will be manifested in the cluster production and the kinetic energy of clusters.



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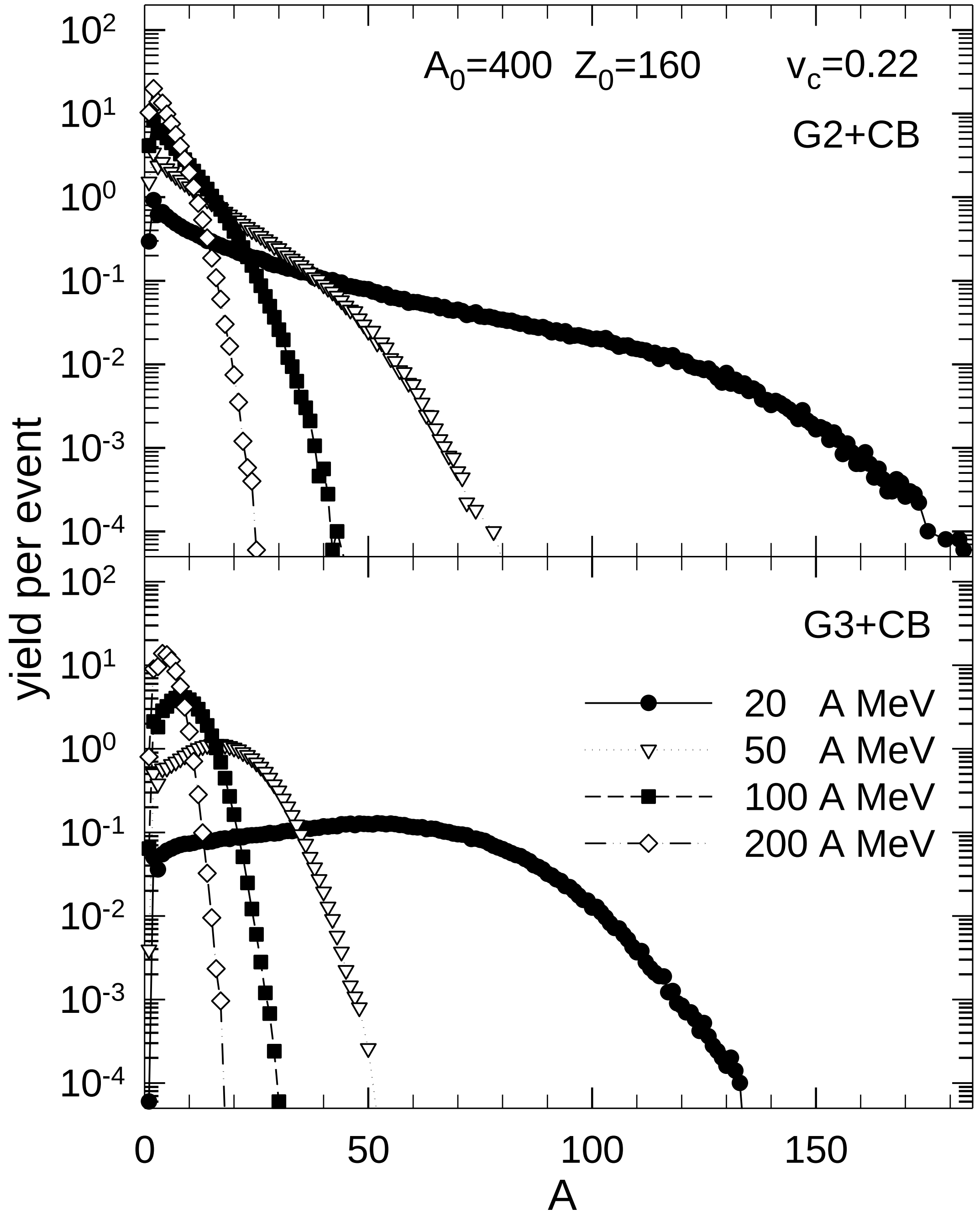
- We demonstrate the mass distributions in the biggest sources at the parameter vc=0.22 c for the wide range of E0.
- The yields of big clusters are larger at the low source energy, since the velocities of nucleons are smaller and closer to each other to form a cluster. However, there are a lot of intermediate mass clusters (with A> 10) even at high source energies. It is a consequence of the stochastic nature for production of such nucleons since they may appear in the phase space vicinity of other nucleons.

- Under the assumptions of G2 and G3 generators we simulate it by the Monte-Carlo method. The considered source energies correspond to nucleons originated from central heavy ion collisions with beam energies less than 1 A GeV.



[Botvina, Buyukcizmeci, Bleicher, arXiv:2012.07679](https://arxiv.org/abs/2012.07679)

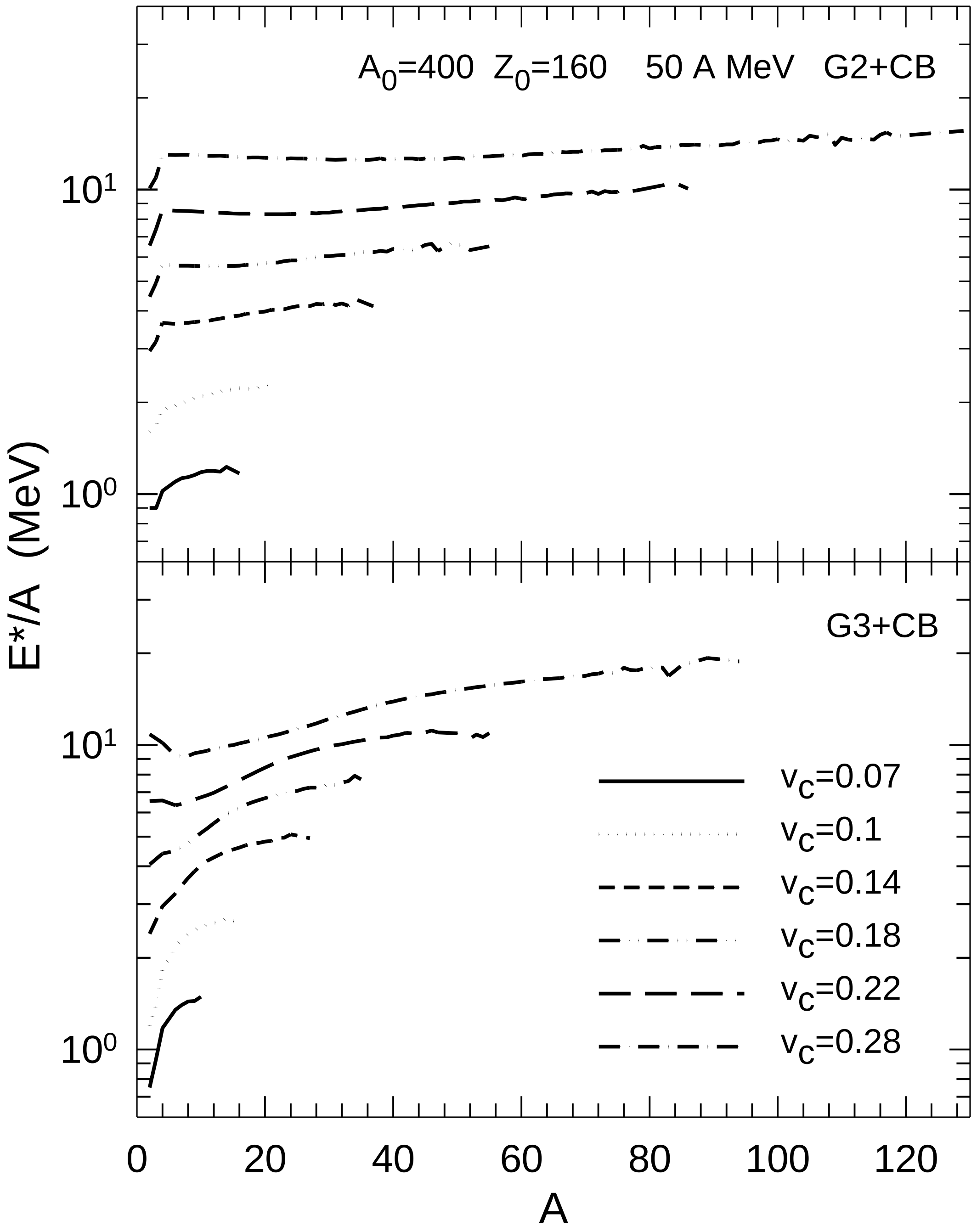
We present the average excitation energies of such clusters versus their mass number for the big systems A0=400, Z0=160, and E0=50 A MeV, with the coalescence parameters vc from 0.07, to 0.28 c.

One can see that the excitation energy per nucleon increases with this parameter. This is because more nucleons with large relative velocities are captured into the same cluster.

By comparing the panels of Figure, we see the effect of the source generator on these distributions:

The excitations are not very different, since they are determined by relative nucleon motions inside clusters.

Nevertheless the G3 provides a general increase of the excitation with the mass number since the large clusters are consisting of baryons having initially higher velocities.



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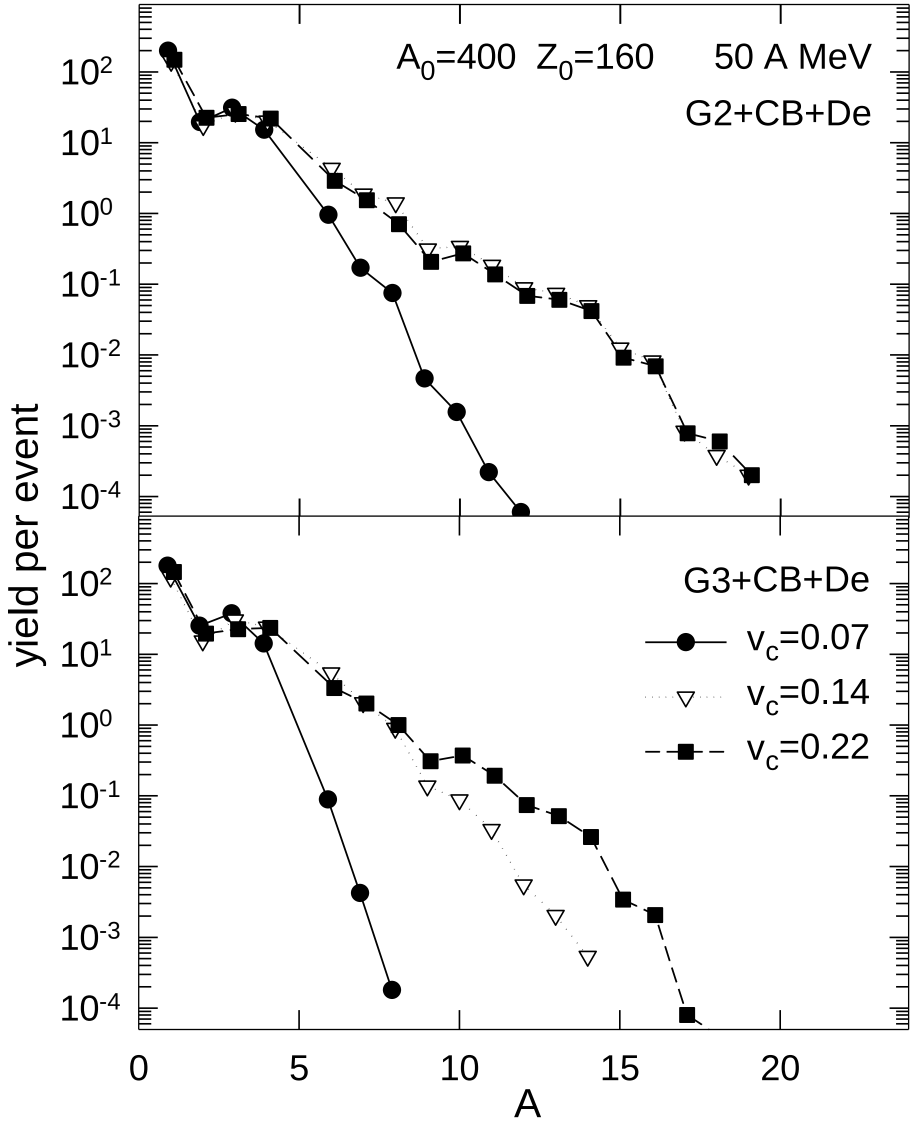
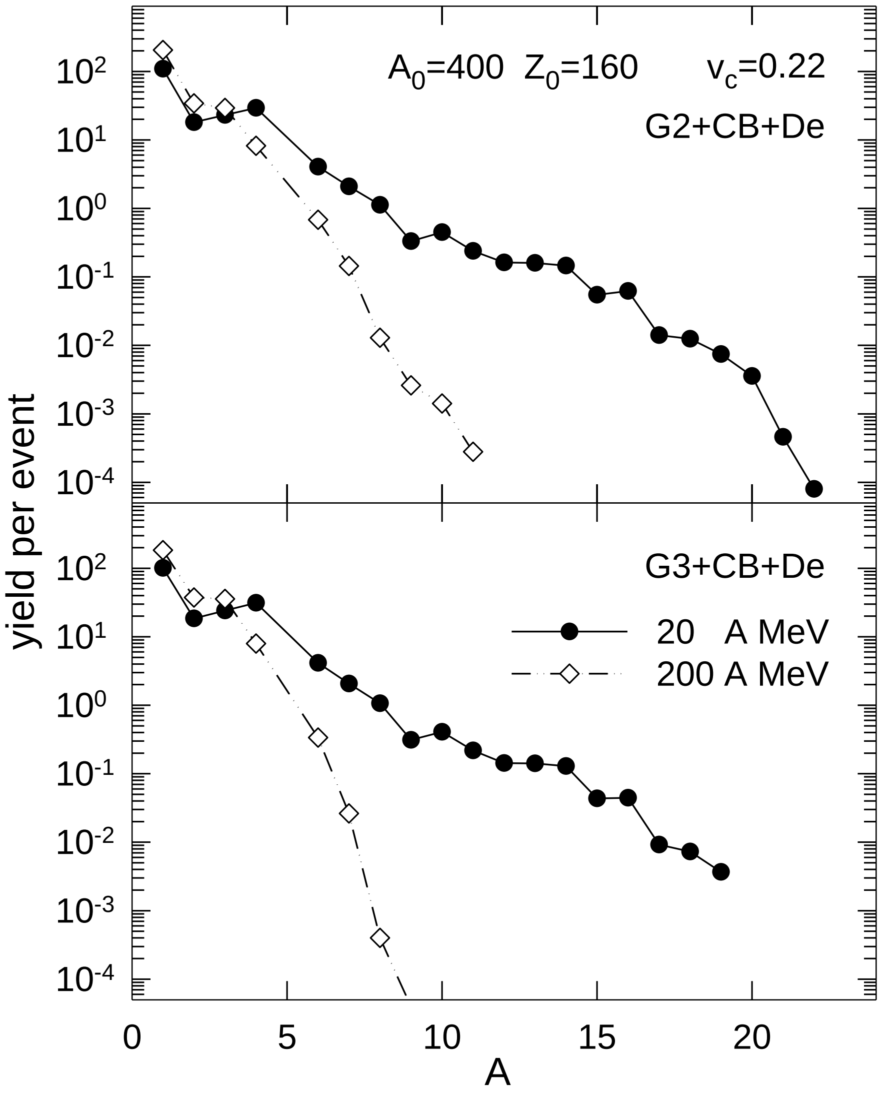
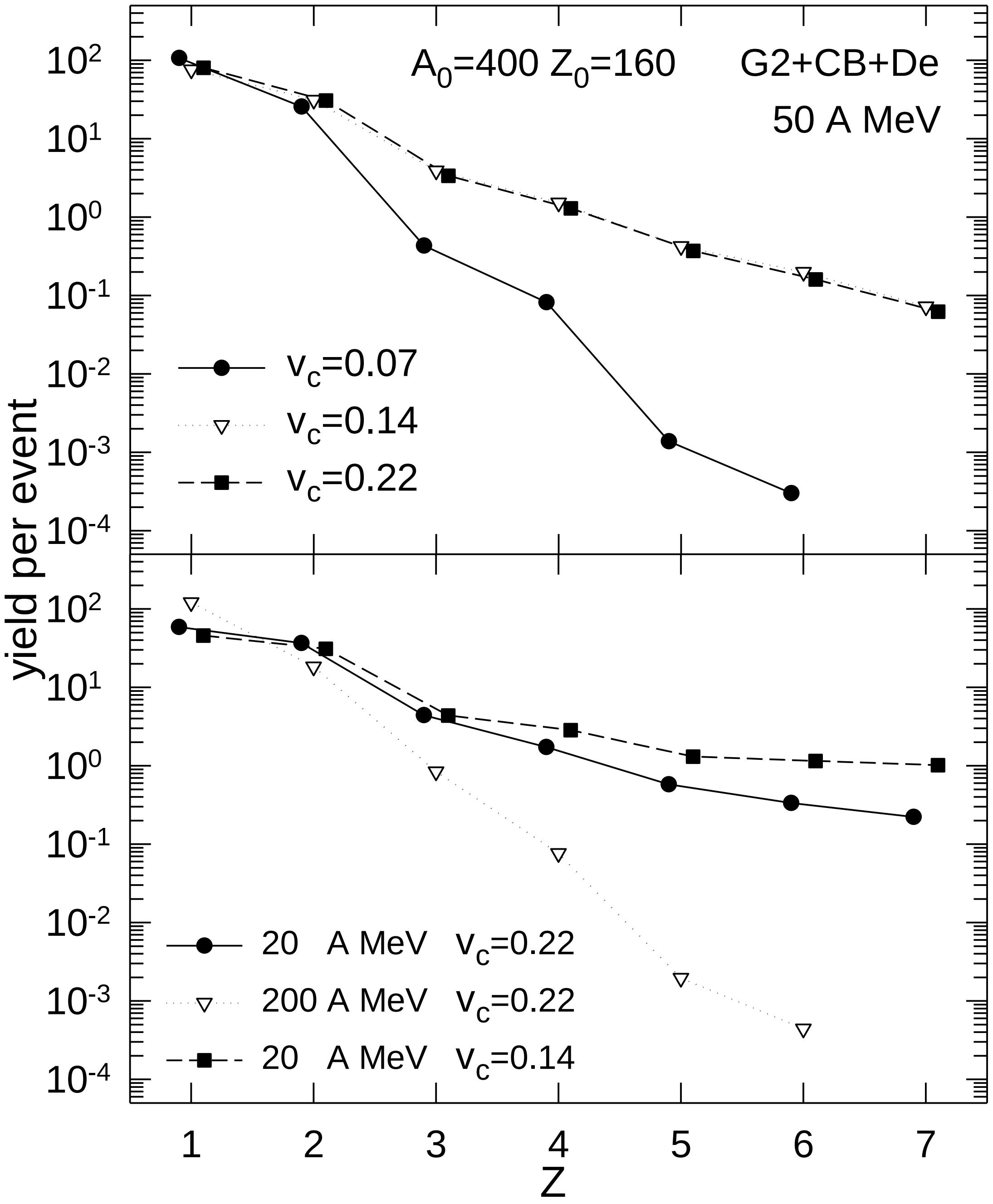




Yield of final cold fragments versus their mass number A after the coalescence and fragment de-excitation (CB+De) calculations at the source energy of 50 MeV per nucleon. Baryon generators, composition and sizes of sources, as well as coalescence parameters are shown in the panels.

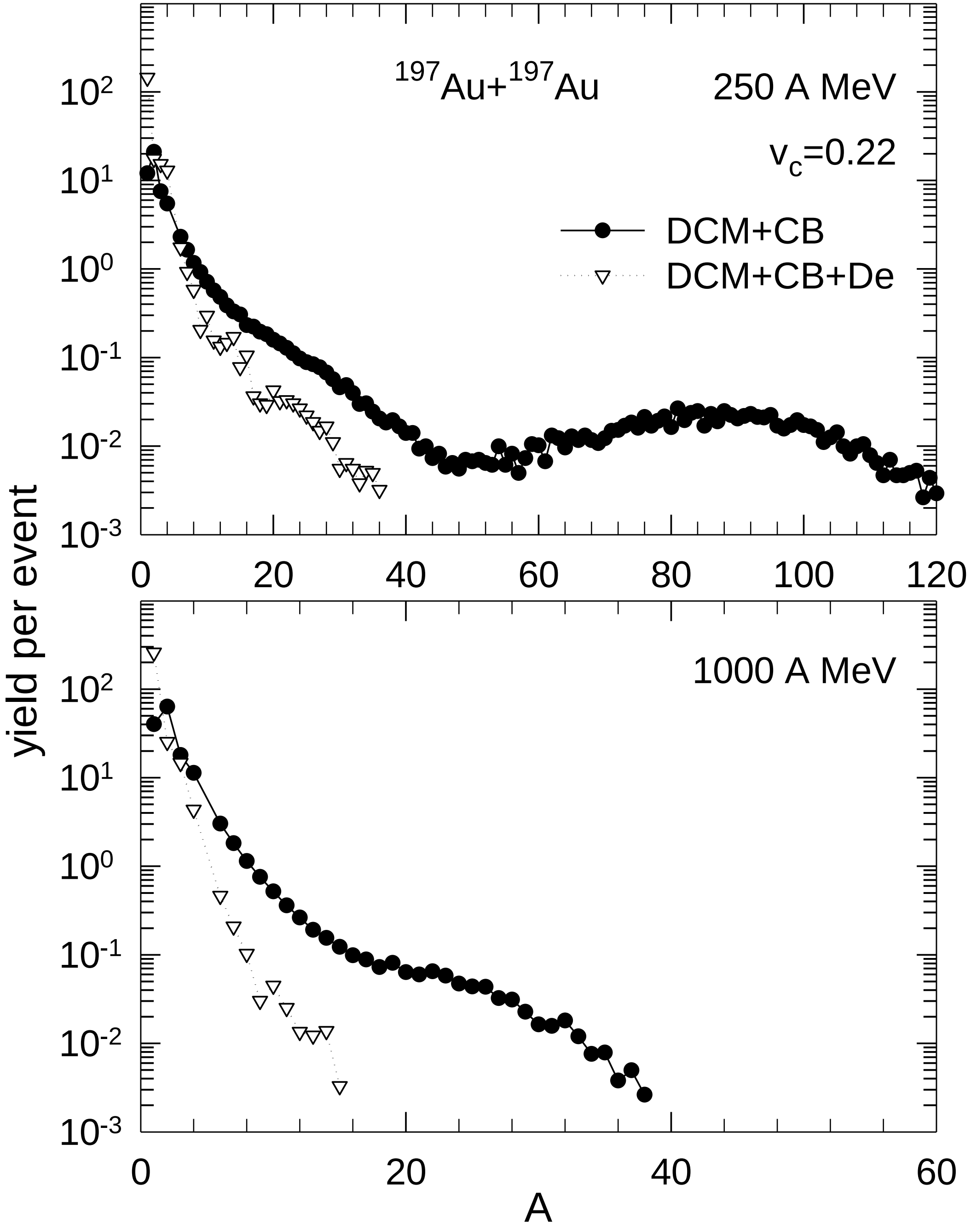
Botvina, Buyukcizmeci, Bleicher, arXiv:2012.07679

Charge yields of light and intermediate mass nuclei after the coalescence and de-excitation. The nucleon generator, source composition and energies, and coalescence parameters are indicated in the panels.



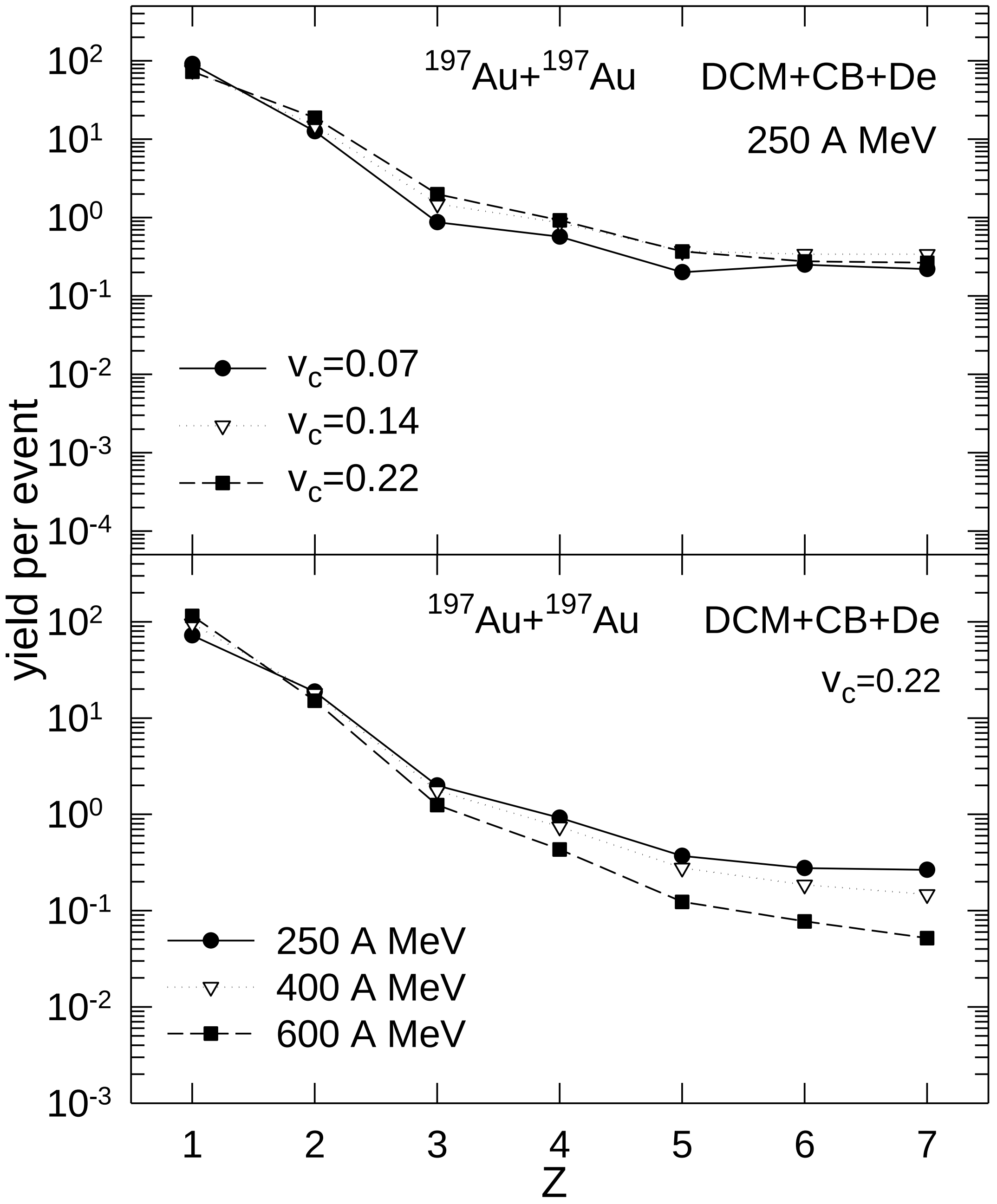
[Botvina, Buyukcizmeci, Bleicher, arXiv:2012.07679]

Calculated distributions of coalescent clusters (after DCM and coalescence: DCM+CB) and nal nuclei (after de-excitation: DCM+CB+De) in mass number. Beam energies of central collisions of gold nuclei and the coalescence parameter are shown in the figure.



[Botvina, Buyukcizmeci, Bleicher, arXiv:2012.07679](https://arxiv.org/abs/2012.07679)

Charge yields of light and intermediate mass nuclei in central collisions of two gold nuclei obtained after DCM, coalescence, and de-excitation calculations. The beam energies and the coalescence parameters are indicated in the panels.



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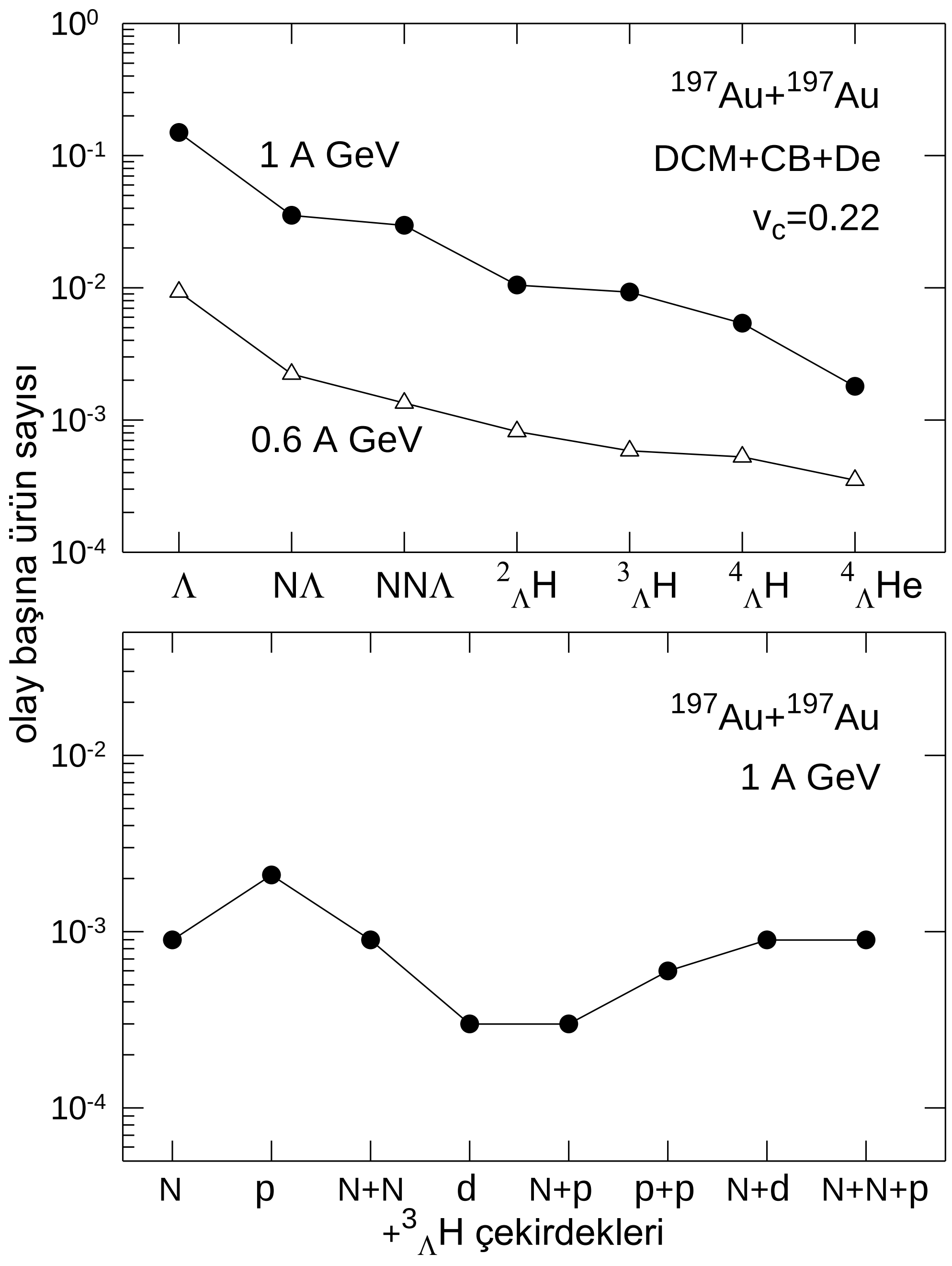
Yields of hypernuclei produced in central collisions of two gold nuclei after DCM, coalescence, and de-excitation calculations.

Top panel presents the full yields per event.

The yields of correlated particles (neutrons, proton, deutrons) in channels with the 3ΛH production are in the bottom panel.

The beam energies are indicated in the panels.



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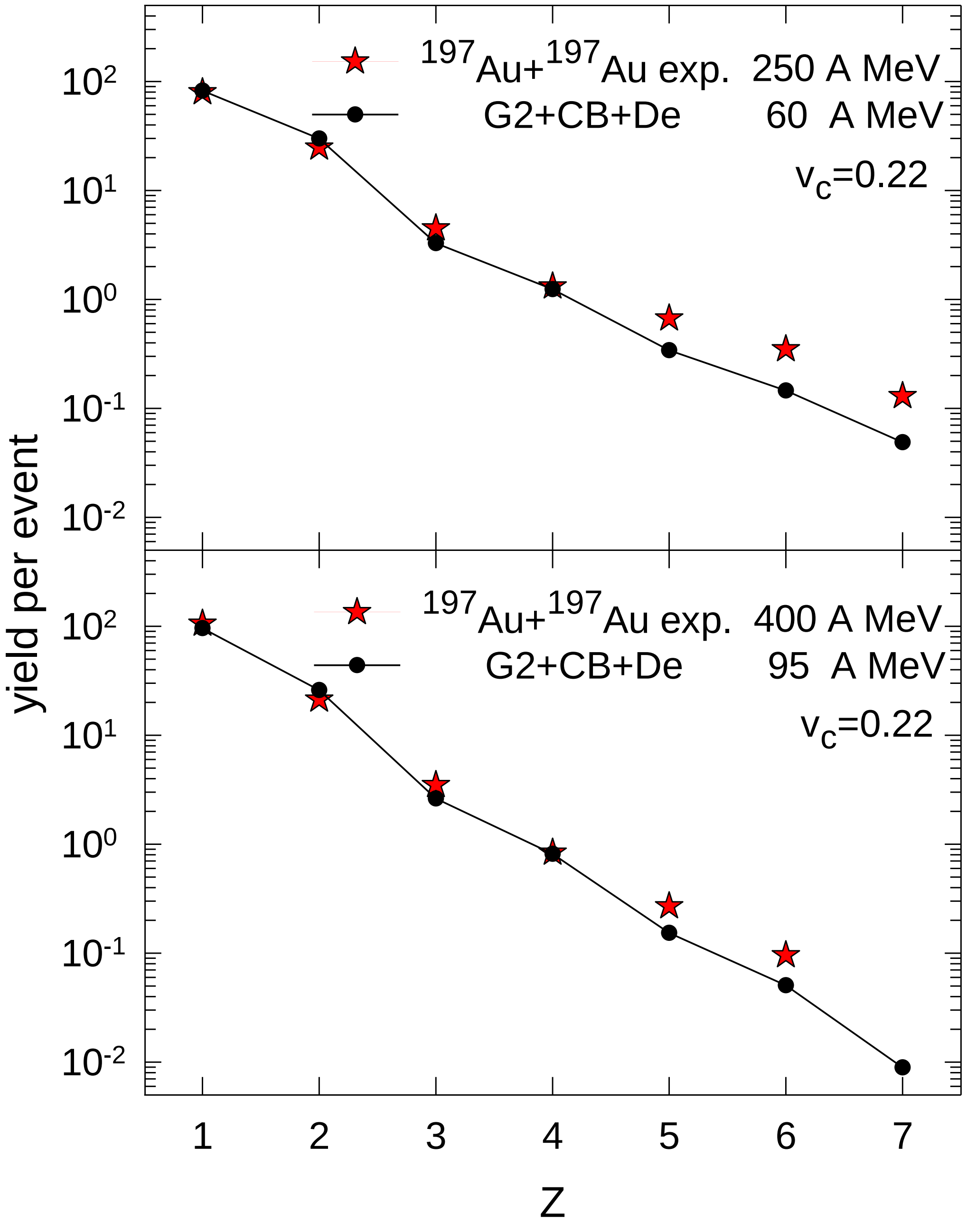
Yields of nuclei versus their charge Z.

The red stars are the FOPI experiment [33, 34].

The parameters for the calculations including the nucleon generation in Au+Au source, coalescence and statistical de-excitation are shown in the panels.



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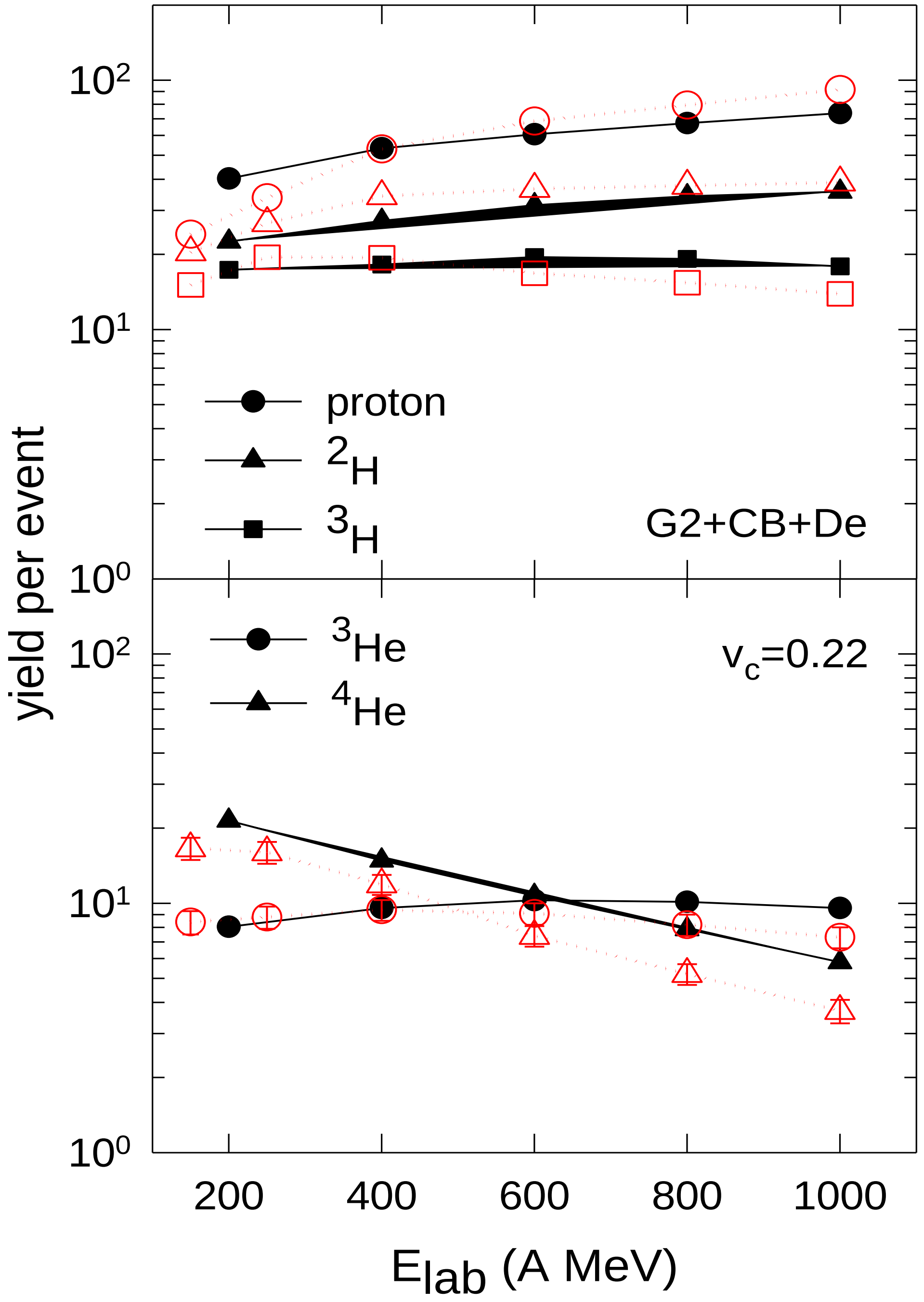
Yields of lightest nuclei as function of the beam energy in Au+Au collisions. Red symbols connected with the dashed lines are FOPI experimental data [34]. Black symbols connected with solid lines are our (G2+CB+De) calculations with the corresponding center of mass energies for Au+Au sources.



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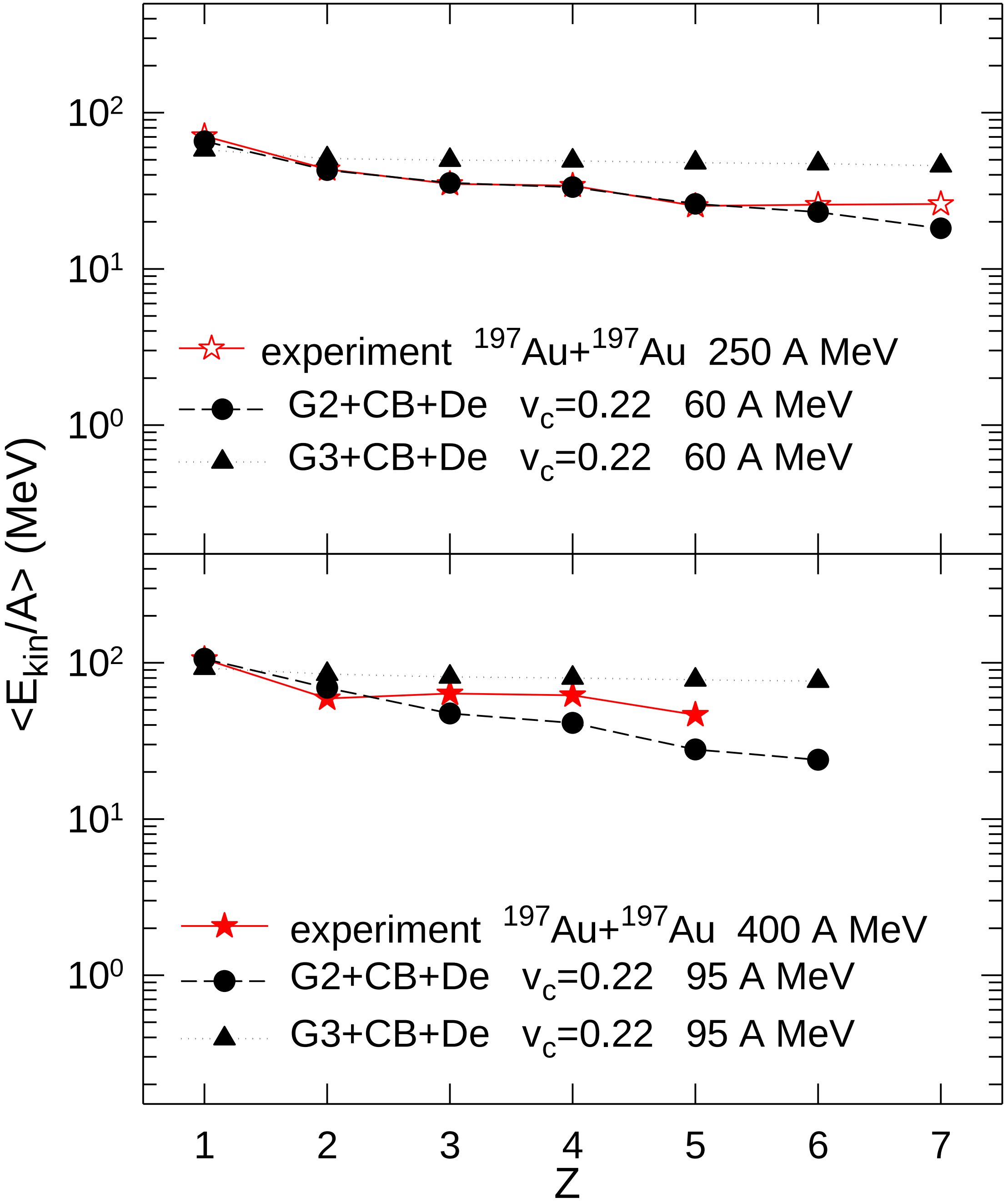
Mean kinetic energy (per nucleon) of charged nuclei for central 250 A MeV (top panel) and 400 A MeV (bottom panel) of Au+Au collisions. FOPI experimental data are in red color [34]. The parameters for our calculations (as in Fig. 21) are noted in the panels.



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Conclusions

- Central nucleus-nucleus collisions produce many new baryons and the nuclear clusters can be formed from these species. The phenomenological coalescence models were used extensively for description of light nuclei from these baryons in a very broad range of collision energies.
- We suggest that the coalescence nucleation process can be effectively considered as 1) the formation of low density baryon matter which can be subdivided into primary diluted clusters with the limited excitation energy, and 2) the following statistical decay of such clusters leading to the final cold nuclei production.
- We argue that the nuclei formation from the interacting baryons is a natural consequence of the nuclear interaction at subnuclear densities resulting in the nuclear liquid-gas type phase transition in finite systems.
- We can reasonably explain the recent FOPI data, however, we need new experimental data for verifying this approach.
- We investigate the regularities of this new kind of fragment production, for example, their yield, isospin, and kinetic energy characteristics.
- A generalization of such a clusterization mechanism for hypernuclear matter is suggested.
- The isotope yields and particle correlations should be adequate for studying these phenomena.

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