Production and properties of hypernuclei in relativistic ion reactions

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Strangeness in neutron stars \( (\rho > 3 - 4 \rho_0) \)
Strange hadronic matter \((A \to \infty)\)

\( \Lambda\Lambda, \Xi \) hypernuclei

\( \Lambda, \Sigma \) hypernuclei

Proton-rich nuclei

Neutron-rich nuclei

3-dimensional nuclear chart
Qualitative picture of dynamical stage of the reaction leading to fragment production (e.g., UrQMD calculations)

Fragment formation is possible from both participants and spectator residues
UrQMD     PHSD       DCM      GiBUU

Production mechanisms of nuclear cluster species including anti-matter, hyper-matter in relativistic HI and hadron collisions:
- Production of all kind of particles (anti-, strange, charmed ones) in individual binary hadron collisions. Effects of nuclear medium can be included.
- Secondary interactions and rescattering of new-born particles are taken into account. (Looks as partial 'thermalization'.)
- Coalescence of all-possible baryons into composite (exotic, anti-, hyper-) nuclear species.
- Capture of produced baryons by big excited nuclear residues.

Statistical decay of excited nuclear species into new nuclei
- Multifragmentation into small nuclei (high excitations),
- Evaporation and fission of large nuclei (low excitations),
- (Fermi-) Break-up of small nuclei into lightest ones.
All transport modes predict similar picture: Hyperons can be produced at all rapidities, in participant and spectator kinematic regions.

Wide rapidity distribution of produced \( \Lambda \)!
Difference of fragment yields obtained in spectator region (very broad distribution) and in central collisions (exponential fall of yields with mass/charge): Indication on different fragment production mechanisms.

Also there is a fragment flow in central collisions (high kinetic energies per nucleon respective to c.m., of decaying system).

Long tradition of fragment measurements in high energy reactions:

**Fragment production in Au+Au collisions:**

ALADIN (GSI) + Multics/Miniball (MSU) experiments

(G.J.Kunde et al., PRL 74, 38 (1995))
Low/intermediate energies: hadron/lepton collisions with nuclei, the same mechanisms in peripheral relativistic ion collisions

Dynamical stage with particle emission and production of excited nuclear residues

Preequilibrium emission + equilibration

Statistical approach

N. Bohr (1936)
N. Bohr, J. Wheeler (1939)
V. Weisskopf (1937)

Starting 1980-th:

At high excitation energy $E^*>3-4$ MeV/nucl there is a simultaneous break-up into many fragments
Excitation energies of the nuclear spectator residuals

DCM: PRC95, 014902 (2017)

Masses of projectile residuals produced at dynamical stage (6b: H=0, 0.2b: H>0)

PRC84, 064904 (2011)
Multifragmentation in intermediate and high energy nuclear reactions

Experimentally established:
1) few stages of reactions leading to multifragmentation,
2) short time \( \sim 100 \text{fm/c} \) for primary fragment production,
3) freeze-out density is around \( 0.1 \rho_0 \),
4) high degree of equilibration at the freeze-out,
5) primary fragments are hot.
Statistical Multifragmentation Model (SMM)


Ensemble of nucleons and fragments in thermal equilibrium characterized by:
- neutron number \( N_0 \)
- proton number \( Z_0 \), \( N_0 + Z_0 = A_0 \)
- excitation energy \( E^* = E_0 - E_{CN} \)
- break-up volume \( V = (1 + \kappa) V_0 \)

All break-up channels are enumerated by the sets of fragment multiplicities or partitions, \( f = \{ N_{AZ} \} \)

Statistical distribution of probabilities: \( W_f \sim \exp \{ S_f (A_0, Z_0, E^*, V) \} \)

under conditions of baryon number (A), electric charge (Z) and energy (E*) conservation, including compound nucleus.
Two-stage multifragmentation of 1.4 GeV Kr, La, and Au

EOS collaboration: fragmentation of relativistic projectiles

FIG. 19. Caloric curves ($T_f$ vs $E_{th}^*/A$) for Kr, La, and Au. Points are experimental and curves are from SMM.

FIG. 24. Second stage fragment charge distribution as a function of $Z/Z_{proj}$. Results are shown for three reduced multiplicity intervals for both data and SMM.
ALADIN data

GSI

multifragmentation of relativistic projectiles


H.Xi et al., Z.Phys. A359(1997)397

comparison with SMM (statistical multifragmentation model)

Statistical equilibrium has been reached in these reactions
Statistical (chemical) equilibrium is established at break-up of hot projectile residues! In the case of strangeness admixture we expect it too!

Very good description is obtained within Statistical Multifragmentation Model, including fragment charge yields, isotope yields, various fragment correlations.

Statistical (chemical) equilibrium is established at break-up of hot projectile residues! In the case of strangeness admixture we expect it too!
Dynamical+Statistical description of normal multifragmentation

ALADIN data
GSI

multifragmentation of relativistic projectiles


comparison with SMM (statistical multifragmentation model)

Statistical equilibrium has been reached in these reactions

Correlation characteristics are very important for verification of models!
Generalization of the statistical de-excitation model for nuclei with Lambda hyperons

In these reactions we expect analogy with

multifragmentation in intermediate and high energy nuclear reactions

+ nuclear matter with strangeness


production of hypermatter

At freeze-out : thermal and chemical equilibrium
Production of excited hyper-residues in peripheral collisions, decaying into hypernuclei (target/projectile rapidity region).

Λ-hyperon lifetime in very heavy hypernuclei produced in the $p+U$ interaction

The recoil shadow method for the detection of fission fragments has been used to investigate delayed fission of very heavy Λ hypernuclei produced in the $p+U$ interaction at the projectile energy of 1.5 GeV. From the measured distribution of delayed fission events in the shadow region and the calculated momenta of hypernuclei leaving the target the lifetime of the Λ hyperon in very heavy hypernuclei was determined to be $\tau = 2.40 \pm 0.60$ ps. The comparison of the number of delayed fission events with that of the prompt events leads to an estimation of the cross section for the production of Λ hypernuclei in $p+U$ collisions at 1.5 GeV of $\sigma_{H\nu} = 150^{+150}_{-80}$ μb. [S0556-2813(97)04506-8]

![Diagram](image)

H. Ohm et al., PRC 55 (1997) 3062

FIG. 1. Schematic presentation of the experimental setup. The thickness of the target holder is enhanced in the drawing to show the details. The real distances are given.
4.3.3. Evaporation from hot fragments

The successive particle emission from hot primary fragments with \( A > 16 \) is assumed to be their basic de-excitation mechanism. Due to the high excitation energy of these fragments, the standard Weisskopf evaporation scheme [2] was modified to take into account the heavier ejectiles up to \(^{18}\text{O}\), besides light particles (nucleons, \( d, t, \alpha \)), in ground and particle-stable excited states [81]. This corresponds to the excitation energies \( \epsilon^{(i)} \) of the ejectiles not higher than 7–8 MeV. By analogy with standard model the width for the emission of a particle \( j \) from the compound nucleus \((A, Z)\) is given by:

\[
\Gamma_j = \sum_{i=1}^{n} \left( \frac{E^*_{AZ} - B_j - \epsilon^{(i)}_j}{\pi^2 \hbar^3} \sigma_j(E) \frac{\rho_{A'Z'}(E_{AZ}^* - B_j - E)}{\rho_{AZ}(E_{AZ}^*)} \right) E \, dE
\]  

Here the sum is taken over the ground and all particle-stable excited states \( \epsilon^{(i)}_j (i = 0, 1, \ldots, n) \) of the fragment \( j \), \( g^{(i)}_j = (2s^{(i)}_j + 1) \) is the spin degeneracy factor of the \( i \)th excited state, \( \mu_j \) and \( B_j \) are corresponding reduced mass and separation energy, \( E_{AZ}^* \) is the excitation energy of the initial nucleus (55), \( E \) is the kinetic energy of an emitted particle in the centre-of-mass frame. In Eq. (60) \( \rho_{AZ} \) and \( \rho_{A'Z'} \) are the level densities of the initial \((A, Z)\) and final \((A', Z')\) compound nuclei. They are calculated using the Fermi-gas formula (41). The cross section \( \sigma_j(E) \) of the inverse reaction \((A', Z') + j = (A, Z)\) was calculated using the optical model with nucleus–nucleus potential from Ref. [117]. The evaporational process was simulated by the Monte Carlo method using the algorithm described in Ref. [118]. The conservation of energy and momentum was strictly controlled in each emission step.

Evaporation from hypernuclei: nucleons, light particles, hyperons, light hypernuclei: New masses and assuming the level densities as in normal nuclei.
4.3.4. Nuclear fission

An important channel of de-excitation of heavy nuclei ($A > 200$) is fission. This process competes with particle emission. Following the Bohr–Wheeler statistical approach we assume that the partial width for the compound nucleus fission is proportional to the level density at the saddle point $\rho_{sp}(E)$ [1]:

$$
\Gamma_f = \frac{1}{2\pi \rho_{AZ}(E_{AZ}^*)} \int_{0}^{E_{AZ}^* - B_f} \rho_{sp}(E_{AZ}^* - B_f - E) \, dE,
$$

(61)

where $B_f$ is the height of the fission barrier which is determined by the Myers–Swiatecki prescription [120]. For approximation of $\rho_{sp}$ we used the results of the extensive analysis of nuclear fissility and $\Gamma_n/\Gamma_f$ branching ratios [121]. The influence of the shell structure on the level densities $\rho_{sp}$ and $\rho_{AZ}$ is disregarded since in the case of multifragmentation we are dealing with very high excitation energies $E^* > 30$–50 MeV when shell effects are expected to be washed out [122].

Fission of hypernuclei: New fission barriers including hyperon interaction (in the liquid-drop approach). It leads to increasing the barriers for $\sim 1$ MeV. The level densities at the saddle point are taken as in normal nuclei (first approximation).
Evaporation & Fission of hypernuclei

(depending on mass and excitation energy)


These processes recall normal fission and evaporation. However, producing exotic hyperfragments is possible (e.g. neutron rich ones) to investigate hyperon interactions in astrophysical conditions.


They have also observed a large correlation of i.e., may be considerable production of \( ^2H + \pi^- \) states
De-excitation of hot light hypernuclear systems


For light primary fragments (with $A \leq 16$) even a relatively small excitation energy may be comparable with their total binding energy. In this case we assume that the principal mechanism of de-excitation is the explosive decay of the excited nucleus into several smaller clusters (the secondary break-up). To describe this process we use the famous Fermi model [105]. It is analogous to the above-described statistical model, but all final-state fragments are assumed to be in their ground or low excited states. In this case the statistical weight of the channel containing $n$ particles with masses $m_i$ ($i = 1, \ldots, n$) in volume $V_f$ may be calculated in microcanonical approximation:

$$\Delta \Gamma_{f}^{\text{mic}} \propto \frac{S}{G} \left( \frac{V_f}{(2\pi \hbar)^{3}} \right)^{n-1} \left( \frac{\prod_{i=1}^{n} m_i}{m_0} \right)^{3/2} \left( \frac{2\pi}{\Gamma(\frac{3}{2}(n-1))} \right) \left( E_{\text{kin}} - U_f^C \right)^{(3/2)(n-5)/2}, \quad (58)$$

where $m_0 = \sum_{i=1}^{n} m_i$ is the mass of the decaying nucleus, $S = \prod_{i=1}^{n} (2s_i + 1)$ is the spin degeneracy factor ($s_i$ is the ith particle spin), $G = \prod_{j=1}^{k} n_j!$ is the particle identity factor ($n_j$ is the number of particles of kind $j$). $E_{\text{kin}}$ is the total kinetic energy of particles at infinity which is related to the prefragment excitation energy $E_{AZ}^*$ as

$$E_{\text{kin}} = E_{AZ}^* + m_0 c^2 - \sum_{i=1}^{n} m_i c^2. \quad (59)$$

$U_f^C$ is the Coulomb interaction energy between cold secondary fragments given by Eq. (49), $U_f^C$ and $V_f$ are attributed now to the secondary break-up configuration.

Generalization of the Fermi-break-up model: new decay channels with hypernuclei were included; masses and spins of hypernuclei and their excited states were taken from available experimental data and theoretical calculations.
Statistical approach for fragmentation of hyper-matter

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

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

mean yield of fragments with mass number \(A\), charge \(Z\), and \(\Lambda\)-hyperon number \(H\)

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

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


\[ F_A^B(T) = \left(-w_0 - \frac{T^2}{\varepsilon_0}\right) A \]

parameters \(\approx\) Bethe-Weizsäcker formula:

\[ w_0 = 16 \text{ MeV}, \quad \beta_0 = 18 \text{ MeV}, \quad T_c = 18 \text{ MeV} \]

\[ \gamma = 25 \text{ MeV}, \quad \varepsilon_0 \approx 16 \text{ MeV} \]

\[ F_{AZH}^{sym} = \gamma \frac{(A - H - 2Z)^2}{A - H} \]

\[ \sum_{AZH} AY_{AZH} = A_0, \quad \sum_{AZH} ZY_{AZH} = Z_0, \quad \sum_{AZH} HY_{AZH} = H_0. \]

chemical potentials are from mass, charge and \(\Lambda\) hyperon number conservations

\[ F_{AH}^{hyp} = E_{s_{am}}^{hyp} = H \cdot (-10.68 + 48.7/(A^{2/3})). \]


(motivated: single \(\Lambda\) in potential well)

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

-- liquid-drop description of hyper-matter

Production of light hypernuclei in relativistic ion collisions

One can use exotic neutron-rich and neutron-poor projectiles, which are not possible to use as targets in traditional hyper-nuclear experiments, because of their short lifetime. Comparing yields of hypernuclei from various sources we can get info about their binding energies and properties of hyper-matter.

Abundant hyper-isotope production in multifragmentation (SMM)

Important features of these reactions: wide fragment/isotope distributions

Statistical regularities of fragment production can be employed to learn about fragments!

Yields of fragments:

\[ Y_{A,Z,H} = g_{A,Z,H} \cdot V_f \frac{A^{3/2}}{\lambda_T^3} \exp \left[ -\frac{1}{T} \left( F_{A,Z,H} - \mu_{A,Z,H} \right) \right], \]

\[ \mu_{A,Z,H} = A\mu + Z\nu + H\xi. \]
Statistical reaction models can be used not only for the production prediction:

Experimental yields of isotopes can be used for extracting properties of exotic cluster, e.g., the hyperon binding energies

Double ratio method:

\[ \Delta E_{bh} \quad \text{vs} \quad \Delta A \]


\[
\Delta E_{bh} = T \cdot \left[ \ln\left( \frac{g_{A_1}Z_{1,H}/g_{A_1-1,Z_{1,H-1}} \cdot (A_1^{3/2}/(A_1 - 1)^{3/2})}{g_{A_2}Z_{2,H}/g_{A_2-1,Z_{2,H-1}} \cdot (A_2^{3/2}/(A_2 - 1)^{3/2})} \right) - \ln\left( \frac{Y_{A_1,Z_{1,H}}/Y_{A_1-1,Z_{1,H-1}}}{Y_{A_2,Z_{2,H}}/Y_{A_2-1,Z_{2,H-1}}} \right) \right]
\]
Difference of fragment yields obtained in spectator region (very broad distribution) and in central collisions (exponential fall of yields with mass/charge): Indication on different fragment production mechanisms.

Also there is a fragment flow in central collisions (high kinetic energies per nucleon respective to c.m., of decaying system).
Formation of baryon clusters from the dynamically produced baryons as a result of secondary interaction between them, when they are in the vicinity of each other. Note: baryons in clusters can come to equilibrium and the clusters are excited respective to its ground state. This case is realized in Heavy-Ion collisions of medium/high energies.
A mechanism for production of novel fragments: Capture of produced baryons by other nucleons and by spectator residues (nuclear matter)

Phenomenological models:

Coalescence (condensation) of baryons into clusters: \( CB \)

momenta:

\[ |P_i - P_0| \leq P_c \]

coordinates:

\[ |X_i - X_0| \leq X_c \]

Capture in nuclear potential and coalescence are similar mechanisms

\( \text{Au(20AGeV)+Au: UrQMD&DCM: PRC84, 064904 (2011)} \)
Production of light nuclei in central collisions:


DCM versus experiment: coalescence mechanism

Hybrid approach at LHC energies: UrQMD+hydrodynamics+coalescence

It is not possible to produce big nuclei!

normal- and hyper-fragments; hyper-residues @ target/projectile rapidities
Because of secondary interactions the maximum of the fragments production is shifted from the midrapidity. Secondary products have relatively low kinetic energies, therefore, they can produce clusters and hypernuclei with higher probability.

for LHC @ 2.76 A TeV
Novel: coalescent fragments can be excited & undergo de-excitation
Comparison with FOPI experimental data on 3He and 4He production in central HI collisions. Preliminary.

Yields of these isotopes are modified essentially after the de-excitation processes. The main reason is the binding energy of the fragments inside the freeze-out volume.

Relative behavior of yields of 3He and 4He with energy is important confirmation of the coalescence and statistical mechanisms.
Conclusions

Collisions of relativistic ions are promising reactions to search for nuclear clusters, exotic clusters with very different isospin, including hypernuclei. These processes can be simulated within dynamical and statistical models.

Mechanisms of formation of hypernuclei in reactions: Strange baryons (Λ, Σ, Ξ, …) produced in particle collisions can be transported to the spectator residues and captured in nuclear matter. Another mechanism is the coalescence of baryons leading mostly to light clusters will be effective at all rapidities. The produced clusters are presumably excited and after their decay novel hypernuclei of all sizes (and isospin), including short-lived weakly-bound states, multi-strange nuclei can be produced.

Advantages over other reactions: there is no limit on sizes and isotope content of produced exotic nuclei; probability of their formation may be high; a large strangeness can be deposited in nuclei.

Properties of hypernuclei (hyperon binding) can be addressed in novel way! Correlations (unbound states) and lifetimes can be naturally studied. EOS and the symmetry energy of hypermatter at subnuclear density and hyperon interactions in exotic nuclear matter can be investigated.
Connection between coalescence and statistical models (Eur. Phys. J A17, 559 (2003)):

Coalescence mechanism:

\[ \frac{\text{d}^3\langle N_A \rangle}{\text{d}p_n^3} \simeq \left( \frac{4\pi}{3} p_0^3 \right)^{A-1} \left( \frac{\text{d}^3\langle N_1 \rangle}{\text{d}p_n^3} \right)^A \]

Assume initial Maxwell-Boltzmann distribution, then

\[ \langle N_A \rangle \simeq \left( \frac{4\pi}{3} p_0^3 \right)^{A-1} \frac{\langle N_1 \rangle^A}{(2\pi m_n T)^{3/2}(A-1) A^{3/2}}. \]

On the other hand, from thermal models one can obtain:

\[ \langle N_A \rangle = \langle N_1 \rangle^A \left( \frac{\lambda_T^3}{V} \right)^{A-1} A^{3/2} \exp \left( -\frac{B_A}{T_A} \right) \]

We get connection between coalescence parameter and fragment binding energy

\[ \frac{4\pi p_0^3 V}{3\hbar^3} \simeq \left( A^3 \cdot \exp \left( -\frac{B_A}{T_A} \right) \right)^{1/(A-1)} \]
FOPI data: fragment production in central HI collisions

Both coalescence and statistical descriptions are possible - EPJ A 17, 559 (2003). However, the statistical model requires flow and decreasing the source size with energy.
Discovery of a Strange nucleus: Hypernucleus

M. Danysz and J. Pniewski, Philos. Mag. 44 (1953) 348

First-hypernucleus was observed in a stack of photographic emulsions exposed to cosmic rays at about 26 km above the ground.

Incoming high energy proton from cosmic ray

colliding with a nucleus of the emulsion, breaks it in several fragments forming a star. **Multifragmentation!**

All nuclear fragments stop in the emulsion after a short path

From the first star, 21 Tracks $\Rightarrow 9\alpha + 11H + 1^{\Lambda}X$

The fragment $^{\Lambda}X$ disintegrates later, makes the bottom star. Time taken $\sim 10^{-12}$ sec (typical for weak decay)

This particular nuclear fragment, and the others obtained afterwards in similar conditions, were called **hyperfragments or hypernuclei**.
FIG. 4: (Color online) Influence of the secondary de-excitation on the difference of binding energies of hyperons in nuclei $\Delta E_{bh}$ as function of their mass number difference $\Delta A$, by taking single hypernuclei (which are same as in Fig. 2). The calculations of double ratio yields for primary hot nuclei shown for temperature 4 MeV (dashed line, color circle symbols). The triangles, squares, and stars are the calculations with modified double ratios after the secondary de-excitation (via nuclear evaporation) of primary nuclei at excitation energies of 1.5, 2.0, and 3.0 MeV/nucleon, respectively. The same color symbols show the evolution of the results corresponding to the nuclei