Evaluation of the hyperon binding energy via statistical production of hypernuclei

A.S. Botvina\textsuperscript{1,2}, M. Bleicher\textsuperscript{1}, N. Buyukcizmeci\textsuperscript{3}

\textsuperscript{1}Frankfurt Institute for Advanced Studies and ITP J.W. Goethe University, D-60438 Frankfurt am Main, Germany
\textsuperscript{2}Institute for Nuclear Research, Russian Academy of Sciences, 117312 Moscow, Russia
\textsuperscript{3}Department of Physics, Selcuk University, 42079 Campus, Konya, Turkey

E-mail: nihal@selcuk.edu.tr

Received: 29 November 2017

Abstract. In nuclear reactions of high energy one can simultaneously produce a lot of hypernuclei after the capture of hyperons by nuclear residues. We consider statistical disintegration of such hypernuclear systems and the connection of fragment production with the binding energies of hyperons. It is demonstrated that the hyperon binding energies can be effectively evaluated from the yields of different isotopes of hypernuclei. The double ratio method is suggested for this purpose. The advantage of this procedure is its universality and the possibility to involve many different isotopes. This method can also be applied for multi-strange nuclei, which binding energies were very difficult to measure in previous hypernuclear experiments.

PACS numbers: 25.75.-q, 21.80.+a, 25.70.Mn

Submitted to: \textit{J. Phys. G: Nucl. Phys.}

1. Introduction

A promising way to produce hypernuclei is to use the copious production of hyperons ($\Lambda, \Sigma, \Xi, \Omega$) in relativistic nuclear reactions with their subsequent capture by nuclei. Hypernuclei live significantly longer than the typical reaction times. Baryons with strangeness embedded in the nuclear environment allow for approaching the many-body aspect of the strong three-flavor interaction (i.e., including $u$, $d$, and $s$ quarks) at low energies. Also hypernuclei can serve as a tool to study the hyperon–nucleon and hyperon–hyperon interactions. The investigation of reactions leading to hypernuclei and the structure of hypernuclei is the progressing field of nuclear physics, since it provides complementary methods to improve traditional nuclear studies and open new horizons for studying particle physics and nuclear astrophysics (see, e.g., [1 3 2 4 5 6] and references therein).
Evaluation of the hyperon binding energy via statistical production of hypernuclei

We emphasize specially a possibility to form hypernuclei in the deep-inelastic reactions leading to fragmentation processes, as they were discovered long ago [7]. Many experimental collaborations STAR at RHIC [8], ALICE at LHC [9], CBM [10], HypHI, Super-FRS, R3B at FAIR [11, 12], BM@N, MPD at NICA [13] plan to investigate hypernuclei and their properties in reactions induced by relativistic hadrons and ions. The limits in isospin space, particle unstable states, multiple strange nuclei and precision lifetime measurements are unique topics of these fragmentation reactions. A capture of hyperons by large nuclear residues formed in peripheral collisions is also interesting since it provides a natural way to study large bulbs of hypermatter and its evolution, for example, the liquid-gas type phase transition. It was theoretically demonstrated [5, 14, 15, 16, 17, 18, 19, 20, 21] that in such a way it is possible to produce all kind of hypernuclei with a very broad isospin content. There were also experimental confirmations of such processes leading at least to single hypernuclei [22, 23, 11]. In addition, complex multi-hypernuclear systems incorporating more than two hyperons can be created in the energetic nucleus-nucleus collisions [16, 19]. This may be the only conceivable method to go beyond double hypernuclei, and obtain new experimental information on properties of multi-hyperon systems. In this Rapid Communication we demonstrate how the important knowledge on the hyperon binding energies, including in multi-strange nuclei, can be extracted from analysis of the relative yields of hypernuclei.

In high energy nucleus-nucleus and hadron-nucleus collisions the production of strangeness correlates with particle production, therefore, emission of many nucleons can accompany the production of hyperons. An initial nucleus can loose many nucleons, and, as known from normal nucleus interactions, these processes are leading to a high excitations of remaining residual nuclei, see e.g. Refs. [24, 25, 26]. In this case the capture of a produced hyperon will be also realized at the excited nuclei. As a result such deep-inelastic processes can form large hyper-residues with very broad distribution in mass and excitation energy. It was demonstrated in our previous works [17, 18, 19] that the yields of the hypernuclear residues in peripheral ion collisions will saturate with energies above 3–5 A GeV(in the laboratory frame).

The reactions of formation of excited nuclear residues in high-energy nucleus-nucleus and hadron-nucleus collisions were intensively studied in connection with fragmentation and multifragmentation processes. In particular, masses and excitation energies of the residues are known from experimental and theoretical works, e.g., Refs. [25, 19]. At high excitation energy the dominating decay mode is a multifragmentation process [24, 28, 27]. The hyperon interactions in a nucleus are similar to nuclear ones, and its potential is around 2/3 of the nucleon one. Therefore, we believe, that an addition of few hyperons to a multi-nucleon system can not change its disintegration behavior. According to the present understanding, multifragmentation is a relatively fast process, with a characteristic time around 100 fm/c, where, nevertheless, a high degree of equilibration (chemical equilibrium) is reached. This is a consequence of the strong interaction between baryons, which are in the vicinity of each other in the freeze-out volume.
The statistical models have demonstrated very good agreement in comparison with fragmentation and multifragmentation data \cite{24, 25, 27, 29}. It is naturally to extend the statistical approach for hypernuclear systems. The same numerical methods used previously for execution of the models can be extended. The statistical multifragmentation model (SMM), which was very successfully applied for description of normal multifragmentation processes, was generalized for hypernuclei in Ref. \cite{14}. The break-up channels are generated according to their statistical weight. The Grand Canonical approximations leads to the following average yields of individual fragments with the mass (baryon) number $A$, charge $Z$, and the $\Lambda$-hyperon number $H$:

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

$$\mu_{AZH} = A\mu + Z\nu + H\xi. \quad (1)$$

Here $T$ is the temperature, $F_{A,Z,H}$ is the internal free energies of these fragments, $V_f$ is the free volume available for the translation motion of the fragments, $g_{A,Z,H}$ is the spin degeneracy factor of species $(A, Z, H)$, $\lambda_T = \left(2\pi\hbar^2/m_N T\right)^{1/2}$ is the baryon thermal wavelength, $m_N$ is the average baryon mass. The chemical potentials $\mu$, $\nu$, and $\xi$ are responsible for the mass (baryon) number, charge, and strangeness conservation in the system, and they can be numerically found from the corresponding conservation laws. In this model the statistical ensemble includes all break-up channels composed of baryons and excited fragments. The primary fragments are formed in the freeze-out volume $V$. We use the excluded volume approximation $V = V_0 + V_f$, where $V_0 = A_0/\rho_0$ ($A_0$ is the total baryon number and $\rho_0 \approx 0.15$ fm$^{-3}$ is the normal nuclear density), and parametrize the free volume $V_f = \kappa V_0$, with $\kappa \approx 2$, as taken in description of experiments in Refs. \cite{25, 27, 29}.

### 2. Double ratio method for hypernuclei

The following model development depends on the physical processes which are the most adequate to the analyzed reactions. For example, nuclear clusters in the freeze-out volume can be described in the liquid-drop approximation: Light fragments are treated as elementary particles with corresponding spins and translational degrees of freedom ("nuclear gas"). Their binding energies were taken from experimental data \cite{1, 2, 24}. Large fragments are treated as heated liquid drops. In this way one can study the nuclear liquid-gas coexistence of hypermatter in the freeze-out volume. The internal free energies of these fragments are parametrized as the sum of the bulk ($F_B^B$), the surface ($F_S^S$), the symmetry ($F_{AZH}^{\text{sym}}$), the Coulomb ($F_{AZ}^C$), and the hyper energy ($F_{AH}^{\text{hyp}}$):

$$F_{A,Z,H} = F_B^B + F_S^S + F_{AZH}^{\text{sym}} + F_{AZ}^C + F_{AH}^{\text{hyp}}. \quad (2)$$

One can find in Refs. \cite{5, 14, 23} all details of this approach. In Ref. \cite{14} we have suggested that the hyper term $F_{AH}^{\text{hyp}}$ is determined only by the binding energy of hyperons with the following parametrization:

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

$$\quad (3)$$
where the binding of hypernuclei is proportional to the fraction of hyperons in matter \((H/A)\). As was demonstrated in Refs. [14, 5] this parametrization of the hyperon binding energy describes available experimental data quite well. It is important that two boundary physical effects are correctly reproduced: The binding energies of light hypernuclei (if a hyperon substitutes a neutron) can be lower than in normal nuclei, since the hyperon-nucleon potential is smaller than the nucleon-nucleon one. However, since the hyperon can take the lowest s-state, it can increase the nuclear binding energies, specially for large nuclei. Within the SMM approach we have performed an analysis of fragment and hyper-fragment production from excited hypernuclear systems. A transition from the compound hyper-nucleus to the multifragmentation regime was under investigation too [14, 5].

It is convenient to rewrite the above formulas in order to show separately the binding energy \(E_{bh}^A\) of one hyperon at the temperature \(T\) inside a hypernucleus with \(A, Z, H\):

\[
E_{bh}^A = F_{A,Z,H} - F_{A-1,Z,H-1}.
\]

(4)

Since \(\Lambda\)-hyperon is usually bound, this value is negative. Then the yield of hypernuclei with an additional \(\Lambda\) hyperon can be recursively written by using the former yields:

\[
Y_{A,Z,H} = Y_{A-1,Z,H-1} \cdot C_{A,Z,H} \cdot \exp \left[ \frac{1}{T} \left( E_{bh}^A - \mu - \xi \right) \right],
\]

(5)

where \(C_{A,Z,H} = (g_{A,Z,H}/g_{A-1,Z,H-1}) \cdot (A^{3/2}/(A-1)^{3/2})\) depends mainly on the ratio of the spin factors of \(A, Z, H\) and \(A - 1, Z, H - 1\) nuclei, and very weakly (especially for large nuclei) on \(A\). Since in the liquid-drop approximation we assume that the fragments with \(A > 4\) are excited and do populate many states (above the ground) according to the given temperature dependence of the free energy, then we take \(g_{A,Z,H} = 1\). Within SMM we can connect the relative yields of hypernuclei with the hyperon binding energies. It is interesting that in this formulation one can use other parametrizations to describe nuclei in the freeze-out. This statistical approach is quite universal, and only small corrections, like the table-known spins and energies, may be required for more extensive consideration.

We suggest the following receipt for obtaining information on the binding energies of hyperons inside nuclei. Let us take two hyper-nuclei with different masses, \((A_1, Z_1, H)\) and \((A_2, Z_2, H)\), together with nuclei which differ from them only by one \(\Lambda\) hyperon. When we consider the double ratio \((DR)\) of \(Y_{A_1,Z_1,H}/Y_{A_1-1,Z_1,H-1}\) to \(Y_{A_2,Z_2,H}/Y_{A_2-1,Z_2,H-1}\) we obtain from the above formulae

\[
DR_{A_1,A_2} = \frac{Y_{A_1,Z_1,H}/Y_{A_1-1,Z_1,H-1}}{Y_{A_2,Z_2,H}/Y_{A_2-1,Z_2,H-1}} = \alpha_{A_1,A_2} \exp \left[ \frac{1}{T} \left( \Delta E_{bh}^{A_1,A_2} \right) \right],
\]

(6)

where

\[
\Delta E_{bh}^{A_1,A_2} = E_{bh}^{A_1} - E_{bh}^{A_2},
\]

(7)

and the ratio of the \(C\)-coefficients we denote as

\[
\alpha_{A_1,A_2} = C_{A_1,Z_1,H}/C_{A_2,Z_2,H}.
\]

(8)
Evaluation of the hyperon binding energy via statistical production of hypernuclei

In central collisions of very high energy leading to production of lightest fragments, we can also model a more simple case when the (hyper-) fragments are assumed in the final states (i.e., cold ones) in the freeze-out volume. In such a way we avoid a sophisticated description of the hot fragments, and we consider fixed binding energies without a temperature dependence. Therefore, within this statistical approach \( F_{A,Z,H} \) will be only the binding energy of fragments \( (E_{A,Z,H}^b) \) and all above formulae remain without modifications but the trivial spin factors. We emphasize that the statistical and coalescence interpretation of the data leads to similar results in this case [30].

As one can see from eq. (6), the logarithm of the double ratio is directly proportional to the difference of the hyperon binding energies in \( A_1 \) and \( A_2 \) hypernuclei, \( \Delta E_{A_1 A_2}^{bh} \), divided by temperature. Therefore, we can finally rewrite the relation between the hypernuclei yield ratios and the hyperon binding energies as

\[
\Delta E_{A_1 A_2}^{bh} = T \cdot \left[ \ln(\alpha_{A_1 A_2}) - \ln(DR_{A_1 A_2}) \right].
\]

(9)

In some cases we expect a large difference in hyperon binding energy in both nuclei. For example, according to the liquid-drop approach (see eq. (2)) it can be when the difference between \( A_1 \) and \( A_2 \) is essential (e.g., the mass number \( A_2 \) is much larger than \( A_1 \)). The influence of the pre-exponential \( \alpha \) coefficients is small and can be directly evaluated, depending on the selected hypernuclei. This opens a possibility for the explicit determination of the binding energy difference from experiments. In this case, it is necessary to measure some number of the hypernuclei in one reaction and select the corresponding pairs of hypernuclei. One has to identify such hypernuclei, for example, by the correlations, and with vertex [8, 9, 10, 11] or ‘shadow’ [22, 23] techniques. However, there is no need to measure very precisely the momenta of all particles produced in the reaction (including after the week decay of hypernuclei) to obtain their binding energy, as it must be done in processes of direct capture of hyperons in the ground and slightly excited states of the target nuclei (e.g., in missing mass experiments [2, 31]). Therefore, our procedure perfectly suits for investigation of hypernuclei in the high-energy deep-inelastic hadron and ion induced reactions.

Another interesting way for this study is to use the double ratios of yields with the same mass numbers for light and heavy pairs. This case is easy to illustrate for cold fragments. The so-called strangeness population factor \( S \) was introduced in Ref. [32] for interpretation of light hypernuclei production in relativistic heavy-ion collision (at momenta of 11.5 A GeV/c):

\[
S = \frac{Y_{3H/2}/Y_{3He}}{Y_{3H}/Y_P}.
\]

(10)

Generally, if we involve the pairs of nuclei which differ by one proton instead of \( \Lambda \)-hyperon, we can write the isobar double ratio:

\[
DR_{A_1 A_2}^I = \frac{Y_{A_1 Z_1 H}/Y_{A_1 Z_1 + 1 H - 1}}{Y_{A_2 Z_2 H}/Y_{A_2 Z_2 + 1 H - 1}} = \alpha_{A_1 A_2}^I \exp \left[ -\frac{1}{T} (\Delta E_{X}^{bh}) \right],
\]

(11)

where

\[
\alpha_{A_1 A_2}^I = \frac{g_{A_1 Z_1 H}/g_{A_1 Z_1 + 1 H - 1}}{g_{A_2 Z_2 H}/g_{A_2 Z_2 + 1 H - 1}}.
\]

(12)
and the binding energy difference between 4 fragments

$$\Delta E_{bh}^X = \left( E_{A_1,Z_1,H}^b - E_{A_2,Z_2,H}^b \right) - \left( E_{A_1,Z_1+1,H-1}^b - E_{A_2,Z_2+1,H-1}^b \right).$$  \hspace{1cm} (13)$$

The last expression (13) can not be factorized into the binding energies of normal nuclei with $A_1$ and $A_2$ and the part related only to the hyperon binding (as it was possible in formula (4)), since it includes also the difference of the hyperon binding in hyper-nuclei with $Z + 1$. Therefore, it requires complicated calculations of the coupled equations for extracting the hyperon binding. In addition, extra experimental isobar measurements will be necessary. Still, the convenient application of $DR^I$ can be found for single hypernuclei with $H = 1$, when for the pair nuclei (at $H - 1 = 0$ and $Z + 1$) there exist only normal nuclei with known binding energies. In this case one can rewrite the formula (12) as

$$\Delta E_{A_1,A_2}^{bh} = T \cdot \left[ \ln\left( a_{A_1,A_2}^I \right) - \ln( DR_{A_1,A_2}^I ) \right] + \Delta E_{A_1,A_2}^{GS}, \hspace{1cm} \text{(14)}$$

where $\Delta E_{A_1,A_2}^{GS}$ is the difference of the ground state binding energies of non-strange nuclei:

$$\Delta E_{A_1,A_2}^{GS} = \left( E_{A_1,Z_1+1}^b - E_{A_2,Z_2+1}^b \right) - \left( E_{A_1-1,Z_1}^b - E_{A_2-1,Z_2}^b \right).$$  \hspace{1cm} (15)$$

In the above mentioned example, as was obtained by AGS-E864 collaboration [32], $S = 0.36$ (with large error bars $\pm 0.26$) for the most central collisions and for fragments produced in the midrapidity region. The qualitative behavior of this factor with energy was also analyzed with dynamical models [33]. Since the binding energies of all nuclei in $S$-factor (10) are known from other experiments we can evaluate from formula (11) the temperature of the excited hyper-source leading to producing of these fragments and hypernuclei: The found chemical temperature is around $T \approx 5.5$ MeV. This is typical for the nuclear liquid-gas phase coexistence region under condition that all available baryons are produced in a dynamical way. It is also consistent with the chemical temperature and limited equilibration of non-strange fragments reported previously for central heavy ion collisions [30].

It is clear that the suggested double ratio approach can be applied to hypernuclei with any number of hyperons: Obviously, the equations (11) and (6) can be used for $H > 1$. One can reach a multi-strange residues in nuclear reactions with a quite large probability [19], and a very wide mass/isospin range will be available for examination. As a result, one can get direct experimental evidences for hyperon binding energies in double/triple hypernuclei and on influence of the isospin on hyperon interactions in multi-hyperon nuclear matter. Such a comprehensive analysis is possible within this approach, and it seems the only realistic way to address experimentally the hyperon binding in multi-strange nuclei. This is an important advantage over the standard hypernuclear measurements. Actually, the disintegration of hot hyper-residues suits in the best for this examination since all kind of normal and hyper-fragments can be formed within the same statistical process.

The connection between the relative hyperon binding energies $\Delta E_{A_1,A_2}^{bh}$ and its absolute values can be done straightforward: It should be sufficient to make
normalization to the binding energy of a known hypernuclei (e.g., $A_2$) obtained with other methods. However, even relative values are extremely important, when we pursue a goal to investigate the trends of the hyperon interaction in different nuclear surroundings, e.g., neutron-rich or neutron-poor ones. Novel conclusions can be obtained by comparing yields of neutron-rich and neutron-poor hypernuclei. The isospin influence on the hyperon interaction in matter (revealing in the hyperon binding energies) will be possible to extract directly in experiment by using the formula $\Delta E_{\text{bh}}^{A_1 A_2}$. Especially multi-strange nuclear systems would be interesting, since they can give info on evolution of the hyperon-hyperon interaction depending on strangeness. These measurements are important for many astrophysical sites, for example, for understanding the neutron star structure [34, 35].

We outline now other details which could be taken into account in the hypernuclear case. In order to find $\Delta E_{\text{bh}}^{A_1 A_2}$ in experiment within the double ratio approach, we should determine the temperature $T$ of the disintegrating hypernuclear system. This observable was also under intensive investigation recent years in connection with multi-fragment formation. There were suggested various methods: using kinetic energies of fragments, excited states population, and isotope thermometers [28, 36, 37]. Usually, all evaluations give the temperature around 4–6 MeV in the very broad range of the excitation energies (at $E^* > 2 – 3$ MeV per nucleon), providing so-called a plateau-like behavior of the caloric curve [24, 28]. The isotope thermometer method is the most promising, since it allows for involving a large number of normal measured isotopes in the same reactions which produce hypernuclei. The corresponding experimental and theoretical research were performed last years to investigate better the temperature and isospin dependence of the nuclear liquid-gas type phase transition [29, 37, 38, 39]. We believe that the great experience accumulated previously in this field gives a chance to find a reliable temperature of the hypernuclear residues.

In this case it would be instructive to select the reaction conditions leading to similar freeze-out states. The freeze-out restoration methods were extensively tested previously: In particular, the masses and excitation energies of the hypernuclear residues can be found with a sufficient precision [10, 11]. One can analyze the subsequent ranges of the excitation energy (from low to very high ones) to investigate the evolution of the hypernuclei with the temperature and the phase transition in hyper-matter. It is specially interesting to move into the neutron-rich domain of the nuclear chart, by selecting neutron-rich target or projectiles, in addition to sorting out the various excitations of the sources. As was previously established in multifragmentation studies, the selection of adequate reaction conditions can be experimentally verified.

We may expect that the primary fragments and hyper-fragments (specially, large ones) in the freeze-out volume could be excited, therefore, they should fastly decay after escaping the freeze-out. For low excited sources the fragment excitation energy should roughly correspond to the compound nucleus temperature. As was established in theory and multifragmentation experiments [12], the internal fragment excitations are around 2–3 MeV per nucleon for highly excited residue sources. The secondary de-excitation
Evaluation of the hyperon binding energy via statistical production of hypernuclei

Influences all 4 fragments entering the double ratio and the fragments should loose few nucleons. The investigation of similar nuclear decay processes of excited nuclei in normal multifragmentation reactions tell us that if the difference in mass between initial fragments is small then the mass difference between final products will be small too. Following this de-excitation the mass numbers will change and we expect a smooth transformation of $\Delta E_{bh}^{A_1A_2}$ versus the variation of mass difference $\Delta A = (A_2 - A_1)$: The new yields and mass numbers should be used for the final estimate. This effect can be investigated in the framework of the evaporation model for large ($A > 16$) hypernuclei developed in Ref. [43]. There was demonstrated that mostly neutrons and other light normal particles will be emitted from hot large hyper-fragments, since the hyperons have a larger binding energy. Such an effect should not change dramatically the general form of the $\Delta E_{bh}^{A_1A_2}$ dependence on $\Delta A$. For small ($A \leq 16$) hot hyper-fragments formed in the freeze-out volume the most adequate model is the Fermi-break-up [24], similar to the one for normal fragments. It was generalized for hypernuclei in Ref. [44]. The consequences of these secondary decay processes will be the subject of our future studies.

3. Conclusion

In conclusion, we should note that during last six decades there is permanent increasing the number of measured hypernuclei with their binding energies. However, the progress is very slow: Because of the special requirements on targets in hadron and lepton induced reactions, the traditional hypernuclear methods (e.g., the missing mass spectroscopy) can address only a small number of isotopes. Also the development of the detectors for measuring nearly all produced particles with their exact kinetic energies is very expensive and not always practical, that makes problems for a desirable acceleration of the studies.

The suggested double ratio method is related to deep inelastic reactions producing all kind of hypernuclei with sufficiently large cross-sections in the multifragmentation process. This is a typical case for relativistic ion-ion and hadron-ion collisions. Only the identification of hypernuclei is required, and, as demonstrated in recent ion experiments, there are effective ways to perform it. The experimental extraction of the difference in the hyperon binding energies between hypernuclei ($\Delta E_{bh}^{A_1A_2}$) is a novel and practical way to pursue hypernuclear studies. The advantage of this method over the traditional hypernuclear ones is that the exact determination of all produced particles parameters (with their decay products) is not necessary. Only relative measurements are necessary for this purpose, therefore, one can address similar weak-decay chains and their products, for example, with the vertex technique. The correlation the produced isotopes and particles is an adequate information for the double ratios.

Even more interesting and important that with this method one can also determine the difference of hyperon binding energies in double and multi-hypernuclei. This gives an access to hyperon-hyperon interactions and properties of multi-hyperon matter. It is very difficult to measure the hyperon binding energy for exotic (neutron-rich and
neutron-poor) nuclear species within traditional hypernuclear experiments. On the other hand, the hypernuclei with extreme isospin can be easily obtained in deep-inelastic reactions. Some of them may have the statistical disintegration origin and the suggested method opens an effective way for extension of the hypernuclear research.

We believe such kind of research would be possible at the new generation of ion accelerators of intermediate energies, as FAIR (Darmstadt), NICA (Dubna), and others. It is promising that new advanced experimental installations for the fragment detection will be available soon [45][46].

A.S. Botvina acknowledges the support of BMBF (Germany) N.B. acknowledges the Turkish Scientific and Technological Research Council of Turkey (TUBITAK) support under Project No. 114F328. M.B. and N.B. acknowledges that the work has been performed in the framework of COST Action CA15213 THOR. N.B. thanks the Frankfurt Institute for Advanced Studies (FIAS), J.W. Goethe University, for hospitality during the research visit.

[1] H. Bando, T. Mottle, and J. Zofka, Int. J. Mod. Phys. A5, 4021 (1990).
[2] O. Hashimoto, H. Tamura, Prog. Part. Nucl. Phys. 57, 564 (2006).
[3] J. Schaffner, C.B. Dover, A. Gal, C. Greiner, and H. Stoecker, Phys. Rev. Lett. 71, 1328 (1993).
[4] Special issue on Progress in Strangeness Nuclear Physics, Edit. A. Gal, O Hashimoto and J. Pochodzalla, Nucl. Phys. A881, 1-338 (2012).
[5] N. Buyukcizmeci, A.S. Botvina, J. Pochodzalla, and M. Bleicher, Phys. Rev. C 88, 014611 (2013).
[6] T. Hell and W. Weise, Phys. Rev. C 90, 045801 (2014).
[7] M. Danyz and J. Pniewski, Philos. Mag. 44, 348 (1953).
[8] The STAR collaboration, Science 328, 58 (2010).
[9] B. Dönigus et al. (ALICE collaboration), Nucl. Phys. A904-905, 547c (2013).
[10] I. Vassiliev et al. (CBM collaboration), JPS Conf. Proc. 17, 092001 (2017).
[11] T.R. Saito et al. (HypHI collaboration), Nucl. Phys. A 881, 218 (2012).
[12] https://indico.gsi.de/event/superfrs3 (access to pdf files via timetable and key ’walldor’).
[13] Topical issue Exploring Strongly Interacting Matter at High Densities - NICA White Paper, Edt. D.Blaschke et al., Eur. Phys. J. A52, 211-267 (2016).
[14] A.S. Botvina and J. Pochodzalla, Phys. Rev. C 76, 024909 (2007).
[15] V. Topor Pop and S. Das Gupta, Phys. Rev. C 81, 054911 (2010).
[16] A.S. Botvina, K.K. Gudima, J. Steinheimer, M. Bleicher, I.N. Mishustin, Phys. Rev. C 84, 064904 (2011).
[17] A.S. Botvina, K.K. Gudima, J. Pochodzalla, Phys. Rev. C 88, 054605 (2013).
[18] A.S. Botvina et al., Phys. Lett. B 742, 7 (2015).
[19] A.S. Botvina, K.K. Gudima, J. Steinheimer, M. Bleicher, and J. Pochodzalla. Phys. Rev. C95, 014902 (2017)
[20] Z.Rudy, W.Cassing et al., Z. Phys. A 351, 217 (1995).
[21] Th. Gaitanos, H. Lenske, and U. Mosel, Phys. Lett. B 675, 297 (2009).
[22] T.A. Armstrong, J.P. Bocquet, G. Ericsson, T. Johansson, T. Krogulski, R.A. Lewis, F. Malek, M. Maurel, E. Monnand, J. Mougey, H. Nifenecker, J. Passaneau, P. Perrin, S. M. Polikanov, M. Rey-Campagnolle, C. Ristori, G.A. Smith, G. Tibell, Phys. Rev. C 47, 1957 (1993).
[23] H. Ohm, T. Hermes, W. Borgs, H.R. Koch, R. Maier, D. Prasuhn, H.J. Stein, O.W.B. Schult, K. Pysz, Z. Rudy, L. Jaraczyn, B. Kamys, P. Kulissa, A. Strzalkowski, W. Cassing, Y. Uozumi, I. Zychor, Phys. Rev. C 55, 3062 (1997).
[24] J.P. Bondorf, A.S. Botvina, A.S. Iljinov, I.N. Mishustin, and K. Sneppen, Phys. Rep. 257, 133 (1995).
[25] H. Xi et al., Z. Phys. A 359, 397 (1997).
Evaluation of the hyperon binding energy via statistical production of hypernuclei

[26] K. Turzo et al., Eur. Phys. J. A 21, 293 (2004).
[27] R.P. Scharenberg, B.K. Srivastava, S. Albergo, F. Bieser, F.P. Brady, Z. Caccia, D.A. Cebra, A.D. Chacon, J.L. Chance, Y. Choi, S. Costa, J.B. Elliott, M.L. Gilkes, J.A. Hauger, A.S. Hirsch, E.L. Hjort, A. Insolia, M. Justice, D. Keane, J.C. Kintner, V. Lindenstruth, M.A. Lisa, H.S. Matis, M. McMahan, C. McParland, W.F.J. Muller, D.L. Olson, M.D. Partlan, N.T. Porile, R. Potenza, G. Rai, J. Rasmussen, H.G. Ritter, J. Romanski, J.L. Romero, G.V. Russo, H. Sann, A. Scott, Y. Shao, T.J.M. Symons, M. Tincknell, C. Tuve, S. Wang, P. Warren, H.H. Wieman, T. Wienold, K. Wolf, Phys. Rev. C 64, 054602 (2001).
[28] J. Pochodzalla, Prog. Part. Nucl. Phys. 39, 443 (1997).
[29] R. Ogul et al., Phys. Rev. C 83, 024608 (2011).
[30] W. Neubert and A.S. Botvina, Eur. Phys. J. A 17, 559 (2003).
[31] A. Esser, S. Nagao, F. Schulz, P. Achenbach, C. AyerbeGayoso, R. Bohm, O. Borodina, D. Bosnar, V. Bozkurt, L. Debenjak, M.O. Distler, I. Friscic, Y. Fujii, T. Gogami, O. Hashimoto, S. Hirose, H. Kanda, M. Kaneta, E. Kim, Y. Kohl, J. Kusakka, A. Margaryan, H. Merkel, M. Mihoivilovic, U. Muller, S.N. Nakamura, J. Pochodzalla, C. Rappold, J. Reinhold, T.R. Saito, A. SanchezLorente, S. SanchezMajos, B.S. Schlomme, M. Schoth, C. Sfienti, S. Sirca, L. Tang, M. Thiel, K. Tsukada, A. Weber, K. Yoshida, Phys. Rev. Lett. 114, 232501 (2015).
[32] T.A. Armstrong, K.N. Barish, S. Batsouli, S.J. Bennett, M. Bertaina, A. Chikanian, S.D. Coe, T.M. Cormier, R. Davies C.B. Dover P. Fachini B. Fadem L.E. Finch N.K. George S.V. Greene P. Haridas J.C. Hill A.S. Hirsch R. Hoversten H.Z. Huang H. Jaradat B.C. Dover P. Fachini B. Fadem L.E. Finch N.K. George S.V. Greene P. Haridas J.C. Hill A.S. Hirsch R. Hoversten H.Z. Huang H. Jaradat B.S. Kumar T. Lajoie R.A. Lewis Q.Li B. Libby R.D. Majka T.E. Miller M.G. Munhoz J.L. Nagle I.A. Pless J.K. Pope N.T. Porile C.A. Pruneau M.S.Z. Rabin J.D. Reid A. Rimai A. Rose F.S. Rotondo J. Sandweiss R.P. Scharenberg A.J. Slaughter G.A. /M.L. Tincknell W.S. Toothacker G. VanBuren F.K. Wohl Z. Xu, Phys. Rev. C 70, 024902 (2004).
[33] J. Steinheimer et al., Phys. Lett. B 714, 85 (2012).
[34] J. Schaffner-Bielich, Nucl. Phys. A 804, 309 (2008).
[35] H. Togashi, E. Hiyama, Y. Yamamoto, M. Takano, Phys. Rev. C 93, 035808 (2016).
[36] J.P. Bondorf, A.S. Botvina, I.N. Mishustin, Phys. Rev. C 58, R27 (1998).
[37] A. Kelic, J.B. Natowitz, K.-H. Schmidt, Eur. Phys. J. A 30, 203 (2006).
[38] V.E. Viola et al., Nucl. Phys. A 681, 267c (2001).
[39] N. Buyukcizmeci et al. Eur. Phys. J. A 57, 57 (2005).
[40] L. Pienkowski, K. Kwiatkowski, T. Lefort, W.-c. Hsi, L. Beaulieu, V.E. Viola, A. Botvina, R.G. Korteling, R. Laforest, E. Ramakrishnan, D. Rowland, A. Huang, E. Winchester, S.J. Yennello, B. Back, S. Gushue, L.P. Reinsberg, Phys. Rev. C 65, 064606 (2002).
[41] S.N. Soisson et al. J. Phys. G: Nucl. Part. Phys. 39, 115104 (2012).
[42] S. Hudan, A. Chbihi, J.D. Frankland, A. Mignon, J.P. Wielaczko, G. Auger, N. Bellaize, B. Borderie, A. Botvina, R. Bougault, B. Bouriquet, A.M. Buta, J. Colin, D. Cussol, R. Dayras, D. Durand, E. Galichet, D. Guinet, B. Guiot, G. Lanzalone, P. Lautesse, F. Lavaud, J.F. Lecolley, R. LeGrain, N. LeNeindre, O. Lopez, L. Manduci, J. Marie, L. Nalpas, J. Normand, M. Parlog, P. Pawlowski, M. Pichon, E. Plagnol, M.F. Rivet, E. Rosato, R. Roy, J.C. Steckmeyer, G. Tabacaru, B. Tamain, A. vanLauwe, E. Vient, M. Vigilante, C. Volant, Phys. Rev. C 67, 064613 (2003).
[43] A.S. Botvina, N. Buyukcizmeci, A. Ergun, R. Ogul, M. Bleicher, J. Pochodzalla, Phys. Rev. C 94, 054615 (2016).
[44] A.S. Lorente, A.S. Botvina, and J. Pochodzalla, Phys. Lett. B 697, 222 (2011).
[45] Th. Aumann, Progr. Part. Nucl. Phys. 59, 3 (2007).
[46] H. Geissel et al., Nucl. Inst. Meth. Phys. Res. B 204, 71 (2003).