Formation of hypernuclei in high energy reactions within a covariant transport model

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We investigate the formation of fragments with strangeness degrees of freedom in proton- and heavy-ion-induced reactions at high relativistic energies. The model used is a combination of a dynamical transport model and a statistical approach of fragment formation. We discuss in detail the applicability and limitations of such a hybrid model by comparing data on spectator fragmentation at relativistic SIS/GSI-energies. The theoretical results are analyzed in terms of spectator fragmentation with strangeness degrees of freedom such as the production of single-Λ – \(^{3,4,5}\)He hypernuclei. We provide theoretical estimates on the spectra and on inclusive cross sections of light hypernuclei, which could be helpful for future experiments on hypernuclear physics at the new GSI- and J-PARC-facilities.

Key words: BUU transport equation, statistical multifragmentation model, phase-space coalescence model, relativistic proton-nucleus collisions, relativistic heavy ion collisions, spectator fragmentation, Hypernuclei.
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1 Introduction

Hypernuclear physics opens the unique possibility to investigate the properties of the hyperon-nucleon (YN) and the hyperon-hyperon (YY) interaction (a historical overview can be found in Ref. [1]). Information on the strangeness sector of the hadronic equation of state is essential for nuclear astrophysics, e.g., for the properties of neutron stars [2], and in exploring exotic states of finite nuclei, e.g., neutron-rich strange nuclei and exotic di-baryonic systems [3].
Hypernuclear production in reactions between heavy nuclei was first theoretically proposed by Kerman and Weiss [4]. These authors found high energy reactions as the best possibility to create exotic finite nuclear systems with finite strangeness. Since then this field of research has been extended and attracted mainly theoretical interest, see, e.g., Refs. [5–7].

The experimental situation has so far been rather poor due to the short lifetime of hypernuclei [8], which impedes the detection of hypernuclei. However, the lifetime of hypernuclei seen in the laboratory is considerably enhanced in relativistic collisions due to relativistic effects. Hypernuclear production in proton-induced reactions has been experimentally studied also at COSY [9] and the comparison with theoretical predictions based on transport equations of the Boltzmann type has been successfully performed [10]. More recently, concrete experimental proposals with high energy heavy-ion and proton beams at GSI (Darmstadt, Germany) and J-PARC (Japan), respectively, have been suggested by T. Saito [11,12].

The production of hypernuclei by relativistic protons has been investigated before by non-relativistic transport theory [10] and fully quantum mechanically for coherent reactions [13]. In this Letter we use a covariant formulation of transport theory. The approach is first applied to the production of hypernuclei in relativistic heavy ion collisions, as planned at GSI and FAIR. Secondly, we also consider proton-induced reactions, but in the J-PARC energy regime of 50 GeV. The initial and intermediate non-equilibrium stages are described by covariant transport theory based on Quantum-Hadro-Dynamics (QHD) [14]. The formation of fragments in the exit channels is treated in the statistical multifragmentation model (SMM) [15], including different models of fragment formation (apart from evaporation/fission). The SMM has been found to account successfully for a large variety of observables in heavy ion induced fragmentation reactions, including mass spectra and momentum distributions. We thus continue our previous fragmentation studies [16] by including now as a new feature a coalescence scenario for the formation of (light) hypernuclei in dynamical transport simulations.

2 Theoretical description of reactions

The theoretical description of hadron-nucleus and heavy-ion reactions is based on the semiclassical kinetic theory of statistical mechanics [17]. The covariant extension of this equation is the relativistic Boltzmann-Uehling-Uhlenbeck (RBUU) equation [18]
\[
\left[ k^\mu \partial^\mu \left( k^\nu F_{\nu\mu} + M^* \partial^\mu M^* \right) \right] f(x, k^*) = \frac{1}{2(2\pi)^9} \times \int \frac{d^3 k_2}{E_{k_2}^*} \frac{d^3 k_3}{E_{k_3}^*} \frac{d^3 k_4}{E_{k_4}^*} W(k k_2 | k_3 k_4) \left[ f_{3\,4} f_{2\,4} - f_{2\,3} f_{3\,4} \right], (1)
\]

for the \( f(x, k^*) \) 1-body phase space distribution function for the hadrons. In particular, nucleons, hyperons and all resonances up to a mass of 2 GeV, as well as mesons, e.g., pions, kaons, are explicitly propagated. In the collision term the short-hand notations \( f_i \equiv f(x, k_i^*) \) for the particle and \( \bar{f}_i \equiv (1 - f(x, k_i^*)) \) for the hole distributions are used, with the 4-momentum \( k^{*\mu} = (E^*, \vec{k}) \) where \( E^* \equiv \sqrt{M^2 + \vec{k}^2} \). The collision integral explicitly exhibits the final state Pauli-blocking while the in-medium scattering amplitude includes the Pauli-blocking of intermediate states. The collision term includes 21 mesons and 60 resonances. We note that all elastic and inelastic processes, such as resonance production and absorption with associated meson production, are included. In particular, inelastic processes with strangeness production are explicitly accounted for, e.g., \( BB \to BYK, B\pi \to YK, BK \to BK \) (with isospin exchange between \( K^0 \) and \( K^+ \)), which are important for the production of hyperons. An exact solution of the set of the coupled transport equations for the different hadrons is not possible. Therefore, the commonly used test-particle method for the Vlasov part is applied, whereas the collision integral is modeled in a parallel-ensemble Monte-Carlo algorithm. The baryonic mean-field is modeled within the non-linear Walecka model (mean-field approximation of the QHD) [14]. In the following calculations the \( NL2 \) parametrization of the non-linear Walecka model has been adopted, which gives reasonable values for the compression modulus (\( K = 210 \text{ MeV} \)) and the saturation properties of nuclear matter [18]. For the parameters of the collision integral see Ref. [19]. The numerical implementation for the solution of equation (1) is that of GiBUU [20].

The formation of hypernuclei depends on the way the fragmentation process between nucleons and, in particular, between nucleons and hyperons is accounted for in dynamical transport situations. It is well known, that the fragmentation process cannot be dynamically described within transport models of Boltzmann-type, since in such approaches only one-body phase-space densities are calculated and the dynamical phase-space evolution of physical fluctuations is neglected. In situations with long time scales for the fragmentation process, e.g. spectator dynamics in heavy-ion collision and dynamics in hadron-induced reactions, a statistical description of the fragmentation process is applicable, as has been shown in a previous work [16].

The statistical multifragmentation model (SMM) [15] has been widely applied to multiple fragment production. In its standard version [15], SMM does not account for strangeness degrees of freedom. Only recently it has been attempted to extend the statistical approach by including hyperons [21], how-
ever, this work is still in progress. We thus apply the SMM model only for the statistical decay of the excited nucleonic spectators. The formation of spectator hypernuclei is then modeled through a phase space coalescence between the fragments and the hyperons originating in the fireball. If hyperons are inside the (fragmenting) spectators and their velocities coincide with those of the fragments, they are supposed to form a hyperfragment. This is the basic idea of the coalescence model [22], which has been applied in the past to describing hypernuclei, see Refs. [5,6]. In those models one assumes that the hypernuclear production cross section factorizes into the cross section for hyperon production and that for the fragment production. Phase space coalescence effects are accounted for by a coalescence function, which enters into the hypernucleus cross section and can be determined within the density matrix formalism, as described in detail in Ref. [5]. From those studies the coalescence velocity $R$ can be also extracted. $R$ defines the radius in the velocity space, inside of which particles can form a (hyper)cluster. From those studies it turned out that the coalescence velocity is less or in the order of the Fermi-velocity, which agrees with phenomenological investigations of Ref. [7].

In this work, the coalescence velocity $R$ for the formation of hyperfragments is a phenomenological parameter, which should, in principle, be adjusted to empirical information. However, since there are no precise data on hypernuclear formation available yet, we have chosen $R$ such as to produce results as close as possible to predictions of the coalescence models of Refs. [6].

We have applied the transport model together with subsequent SMM and phase space coalescence calculations to $^{12}C + ^{12}C@2\ AGeV$ collisions in spectator fragmentation and to $p + ^{12}C@50\ GeV$ reactions. The reason for the choice of these colliding systems is that they will be experimentally investigated by the HypHI-collaboration at GSI and JPARC facilities, respectively. We thus present here for the first time estimates for such reactions from a dynamical model. However, before presenting the results on hypernuclei, a benchmark study is first discussed in the next section.

3 Benchmarks

According to the coalescence scenario [5] the production cross section of hypernuclei depends mainly on 3 parameters, the cross sections for strangeness and fragment production and the coalescence velocity. In this section we test the first two parameters from transport calculations and discuss the time evolution of spectator properties.

The application of the combined GiBUU+SMM approach has been found to work very well in proton induced reactions in terms of cross sections of global
mass and charge distributions and, in particular, in terms of neutron number distributions of a wide selection of different isotopes [16]. However, in heavy-ion collisions (HIC) the situation is more complex with respect to that in proton-induced reactions. Depending on the centrality one has to clearly separate strongly interacting participant matter ("fireball") from less dynamically developed one ("spectators"). In a theoretical study this can be easily done just from the knowledge of suffered collisions for each particle. However, the experimental situation is less trivial, and several phase space limitations have to be imposed to separate spectators from fireball sources as precisely as possible. In the ALADIN experiment, which we will discuss in this section, a rapidity selection has been performed [23]. Particles with \( y \geq 0.75y_{proj} \) are assumed to belong to the spectator sources. In the theoretical calculations we have performed the same selection for consistency. In addition a density cut of \( \rho > \rho_{sat}/300 \) (with \( \rho_{sat} = 0.16 \text{ fm}^{-3} \) being the nuclear saturation density) has been applied in order to separate particles bound to spectators from emitted ones.

Fig. 1 shows the time evolution of the projectile-spectator in terms of its mass number, excitation energy and pressure and for particular centralities. The density \( \rho_{sp} \) and pressure \( P_{sp} \) have been extracted at the densest point of the spectator region. After its formation, the projectile source stabilizes after the freeze-out time of \( t_{fr} \sim 50 - 70 \text{ fm/c} \) as indicated by constant values of mass number and excitation energy. Furthermore, at \( t \sim t_{fr} \) the local pressure [24]
becomes negative and almost constant with time. Also the slope $dP_{sp}/d\rho_{sp}$ becomes negative after $t > 55, 65, 75 \text{ fm}/c$ for $b = 6, 8, 10 \text{ fm}$, respectively. This feature may indicate the onset of spinodal instabilities, assuming a constant temperature evolution in the center of the spectator. However, fragment formation cannot be described in transport theory. We, therefore, proceed as follows: The spectator matter reaches local equilibrium at $t \approx 40 \text{ fm}/c$, corresponding to momentum space isotropy, i.e., equality of longitudinal and transverse pressure components. Hence the dynamical evolution has come to an end. This slightly excited spectator configuration is then taken as the initial state for fragmentation which is treated as a statistical process according to the laws of thermodynamics as realized in the SMM approach. The physics discussed here is similar also for higher energies (see next section) and has been recently applied in describing spallation reactions [16].

The calculated parameters of the spectator source are shown in Fig. 2 and compared with data from the ALADIN collaboration [23]. The black bands in the theoretical calculations indicate the effects of moderate changes on mass and excitation energy at the time near the onset of equilibration. The comparison with the data is reasonable except for the very peripheral events, in which the average mass of spectator sources is theoretically underestimated. In this respect the ground state description for the initial nuclei within the GiBUU approach (or within any other transport model) becomes important. If the initial nuclear configuration is not a solution of the Hamiltonian underlying the transport model the early stage of the dynamical evolution include artificial density oscillations which may lead to spurious particle emission processes. Results for very peripheral reactions may be thus affected to some extent. An
Fig. 3. Left panel: Relation between the impact parameter and the observable $Z_{\text{bound}}$.
Right panel: Impact parameter dependence of the mean multiplicity of Intermediate-Mass-Fragments (IMF). Theoretical calculations (black band) are compared with data from the ALADIN collaboration [23] (open diamonds).

Improved initialization method in the spirit of a covariant density functional approach is under study [25].

Applying these parameters of the spectator source to the SMM model, we arrive at the results on spectator fragmentation, see Figs. 3. Here the relation between the impact parameter and the observable $Z_{\text{bound}} = \sum_{Z \geq 2} Z$ (with $Z$ being the charge) and the average number of intermediate mass fragments ($3 \leq Z \leq 30$) as function of the impact parameter are displayed. The observable $Z_{\text{bound}}$ is well reproduced for all centralities, but less so for the most peripheral ones (see discussion above). Interesting is the reasonable description of the IMF, even for peripheral collisions. This is an indication of stronger evaporation effects in the theoretical calculations; the underestimate in the mass distribution is compensated by the slightly higher values of the excitation energy in the theoretical calculations, see again Fig. 2.

So far it has been demonstrated that inclusive absolute yields are reproduced well in the hybrid GiBUU+SMM approach. However, a correct description of velocity distributions of statistically produced fragments is also crucial for their subsequent coalescence with hyperons. Fig. 4 shows fragment velocity distributions in the projectile frame in comparison with experimental data taken from [26]. The velocity distributions are described rather well on a quantitative level, in particular the width of the Gaussian-like fragment velocity distributions is well reproduced.

Similar studies on multifragmentation were performed within nuclear molecular dynamics and intranuclear cascade models. More extensive reviews can be found in Refs. [27] and [28]. Furthermore, we note that in the past similar hybrid approaches have been applied in dynamical situations. It turned out that
Fig. 4. Longitudinal velocity distributions in the projectile frame for \(^{136}\text{Xe} + \text{Pb}\) @1 AGeV reactions. Theoretical calculations (solid curves) are compared with experimental data (open diamonds) from [26].

momentum distributions are reproduced fairly well in heavy-ion collisions as well as in hadron- and pion-induced reactions, see, e.g., Ref. [15], which is an important issue before applying coalescence for the formation of hypernuclei.

For the formation of hypernuclei the production and propagation of strangeness degrees of freedom play also an important role. We have tested, that for the light \(C + C\)-system, which will be studied later, the production cross sections of \(K^+\) mesons are well reproduced (see Fig. 5), although the relativistic mean-field model gives a rather strong momentum dependence at these high energies. A more detailed discussion of strangeness production can be found in Ref. [19, 29].

We conclude that the combined GiBUU+SMM model describes inclusive multifragmentation observables at moderate relativistic energies and also strangeness production very well. Since strangeness production is also reproduced it is interesting to extend this model it to the description of hypernuclear formation in high energy heavy-ion collisions and proton-induced reactions. These topics will be discussed in the next two sections.

4 Hypernuclei Formation in heavy-ion collisions

The production of hypernuclei in energetic collisions between light nuclei is one of the major projects being investigated by the HypHI-collaboration at GSI. The reason for selecting very light systems is the easier identification of hypernuclei via the weak decay of the hyperon into pions. In earlier theoretical studies, see, e.g., Refs. [5–7], cross sections of the order of only a few microbarn (\(\mu b\)) were predicted, which can be easily understood: in collisions between very
light systems, such as $^{12}C + ^{12}C @ 2AGeV$, secondary re-scattering effects inside the spectator matter, important for producing low energetic hyperons, are rare processes due to the small interaction volume. The situation is different in collisions between heavy nuclei due to the high production rate of strangeness and many secondary scattering events.

The coalescence prescription (in coordinate and momentum space, see again section 2) for the formation of hypernuclei has been applied to the description of spectator fragmentation in $C + C @ 2AGeV$ collisions. The separation between spectator and participant matter has been adjusted by a rapidity criterion of $|y| > 0.7 y_{proj,targ}$. Inclusive rapidity spectra for different light fragments and hyperfragments from spectator matter are shown in Fig. 6. The estimated hyperfragment production is $\approx 5 - 6$ orders of magnitude less than that of fragment production in general. This is obvious, since the strangeness production cross sections from exclusive primary channels, i.e. primary $BB \rightarrow BYK$, $BB \rightarrow BBK\overline{K}$, and secondary ones ($B\pi \rightarrow Y K$ and $B\overline{K} \rightarrow \pi Y$, $B$ stands for a baryon and $Y$ for a hyperon) are very low (orders of few $\mu b$) [31]. Among the
different processes contributing to the formation of hypernuclei, $BB \rightarrow BY K$ and $\Lambda B \rightarrow \Lambda B$ and the secondary one $B\pi \rightarrow Y K$ give the major contribution to the formation of hypernuclei. Strangeness production channels with 3, 4-body final states are important in order to produce low energy hyperons that can be captured by spectator matter. The same argument also holds for secondary re-scattering via elastic hyperon-nucleon and pion-nucleon processes.

The transport results are summarized in table 1, in which the total inclusive hypernuclei production cross sections (first line) and the contributions originating from pion-nucleon scattering (inside the spectator matter) are shown. The transport calculations predict only moderate contributions to the total hyperfragment cross section from indirect coalescence through the $\pi B$-channel. We have investigated this point in more detail by applying the SMM model to different freeze-out times (not shown here) with the result of a rather early formation of hypernuclei. Thus, we conclude that hypernuclei are mainly formed due to the capture of fireball hyperons during the passage stage of the spectators near the expanding fireball region, with subsequent rescattering of hyperons with spectator matter, i.e. $\Lambda B \rightarrow \Lambda B$. This results was also confirmed by earlier model calculations from Wakai et al. [6], in which at low relativistic energies around $2 A GeV$ the coalescence between fragments and hyperons from $\pi B$ collisions is only of minor importance, which is obvious for collisions of light systems at low energies. In principle, antikaons $\bar{K}$ may also contribute to hypernuclear production. However, the formation of hypernuclei through antikaons has not been considered here due to their very low production cross
Table 2
Inclusive production cross sections for different types of hypernuclei (as indicated) for the system \( p + ^{12}C @ 50 \text{ GeV} \). The contribution from pion-nucleon scattering, i.e. \( \pi N \rightarrow Y K \), is shown separately.

| \( ^3\Lambda H \) | \( \sigma_{\text{tot}} [\mu b] \) | \( \sigma_{\text{pionic}} [\mu b] \) | \( ^\Lambda H \) | \( \sigma_{\text{tot}} [\mu b] \) | \( \sigma_{\text{pionic}} [\mu b] \) |
|----------------|----------|----------|----------------|----------|----------|
| \( ^3\Lambda H \) | 43       | 33       | \( ^3\Lambda He \) | 0.9      | 0.8      |
| \( ^3\Lambda H \) | 28       | 14       | \( ^3\Lambda He \) | 35       | 16       |
| \( ^3\Lambda H \) | 9.5      | 2.6      | \( ^3\Lambda He \) | 9.8      | 4.3      |
| \( ^6\Lambda H \) | 0.8      | 0.2      | \( ^6\Lambda He \) | 16       | 1.3      |

sections with very high threshold value, e.g. \( BB \rightarrow BBK \).

We conclude from our exploratory calculations, that hypernucleus formation in \( C + C @ 2AGeV \) reactions takes place with estimated production probabilities on a few \( \mu b \). To substantiate this result further theoretical extensions would be welcome. For example, a purely statistical treatment of excited fireball-like spectators including strangeness content seems possible [21].

5 Hypernuclear Formation in high energy \( p + ^{12}C \) reactions

The colliding system \( p + ^{12}C @ 50 \text{ GeV} \) will be investigated at the new J-PARC facility in Japan [12]. As in the case of low-energy proton induced reactions [16] and high energy heavy ion collisions (see previous section), we apply also here the same dynamical approach for the pre-equilibrium stage. We note that the string fragmentation model in terms of the PYTHIA high energy packages [32] is included in the transport simulations.

As an interesting feature here, transport simulations show a dynamical break-up of the excited residual nucleus into a remnant in the target rest frame and a moving source. Due to the small interaction region and thus small effect of re-scattering inside the initial compound system, the target nucleons which collide with the beam protons maintain their high momenta after the collision. This finally leads to a pre-equilibrium break up of the initial compound system into a moving source, which contains highly excited baryon and also anti-baryon states. This feature is shown in Fig. 7 in terms of the temporal evolution of the density profiles along the \( z \)-axis. This particular situation appears even in calculations without using any mean-field potential (cascade mode), as one would expect from moderate mean-field effects on the reaction.
dynamics at so high energies. This is not obvious due to the strong momentum dependence of the underlying relativistic mean-field model which linearly rises with energy, a well known feature of mean-field models of Walecka type [33]. In particular, the missing momentum dependence in the cascade calculations leads to a moderate density enhancement of the moving source due to the missing repulsion of the momentum dependent part of the mean-field. However, one should note this uncertainty of the momentum dependence of the mean-field at so high energies, in which there is no experimental information available, only moderately affects the yields of produced particles strange baryons and pions, in particular the differences between the cascade calculations and the full BUU calculations differ only by less than 5%. By considering inclusive reactions integrated over the entire centrality region the momentum dependent effect decreases. Therefore we do not expect considerable effects on the production of hypernuclei due to the uncertainty in the momentum dependence of the mean-field and continue the discussion on hypernuclei, which is the main topic of this work.

A clear separation between processes relevant for the formation of hypernuclei and others is a non-trivial task in reactions at very high relativistic energies. However, it is possible to give a rough picture using qualitative arguments. Relevant for the formation of hypernuclei are low energy hyperons, as in the case of heavy-ion collisions discussed in the previous section. Here processes with hyperon production in many-body final states are crucial as well as rescattering of initially produced pions with particles of the moving source. In
contrast to the situation of low-energy heavy-ion collisions the produced pion yields are now very high, i.e. a few $b$ (compared to the yields in the $mb$ region for other particles).

Concerning the fragmentation mechanism the situation is similar to that of the previous section. As described in section 2, non-equilibrium dynamics is responsible for a de-excitation in terms of binary processes with multi-meson production, e.g., pions, and the achievement of thermal equilibrium for both systems, the remnant nuclei at rest and the moving source. We have checked in terms of the anisotropy ratio [16] that both systems approach thermal equilibrium at $t > (15 - 20) \text{ fm/c}$ (depending on centrality). Afterwards the SMM has been separately applied to fragmentation of both sources, i.e. the residual nuclei at rest and the moving source. In the later case the SMM model has been applied to moving sources consisting of 4 and more particles, otherwise a simple coalescence (in coordinate and momentum space) has been adopted.

The whole situation is illustrated in Fig. 8 in terms of the temporal evolution of the rapidity distributions of different particle types (fragments and hyperons), as indicated. First, a 2-component structure of the source can be clearly seen for the heaviest fragments. The rapidity spectra approach a freeze-out state after $t > 30 - 40 \text{ fm/c}$, in which the nucleonic content of the moving source is enhanced due to, e.g., resonance decays. The time behavior of the $\Lambda$-rapidity distribution demonstrates the features discussed above. In particular, some of the hyperons are produced inside the moving sources in the same rapidity region as that of the fragments. The role of initially produced pions will be also
of relevance for the hypernucleus formation (see below). These effects indicate a production of hypernuclei inside the moving sources.

Fig. 9 shows the inclusive rapidity spectra for $^3\text{He}$-isotopes, and the corresponding hypernuclei, respectively. The formation of hypernuclei takes mainly place inside the moving sources with energies per nucleon in the range of view $GeV$. Due to extremely high multiplicities of mesons, in particular pions, the pion-nucleon scattering contribution to the formation of hypernuclei is now the dominant process for the lightest hypernuclei, which it was not the case at the lower energies of the previous section. This result, which is again in line with earlier theoretical investigations [6], is demonstrated in table 2 for the total yields of different hypernuclei (first and third columns) and those yields originate only from pion-nucleon scattering. Thus, meson-nucleon rescattering should play an important role in the formation and propagation of hypernuclei in highly energetic proton-induced reactions. Other processes of similar type may also be of relevance, e.g., $\bar{K}N \rightarrow Y\pi$.

6 Conclusions and outlook

We have theoretically investigated the different mechanisms for hypernuclear production in reactions relevant to future experiments in hypernuclear physics. We have applied an extended GiBUU+SMM transport approach which accounts for the dynamical pre-equilibrium phase space evolution and also for the statistical decay of the asymptotically equilibrated spectator sources lead-
ing to spectator fragmentation. The formation of hyperfragments has been modeled within a phase space coalescence model.

The reasonable description of spectator fragmentation at intermediate energies and the fragmentation of residual nuclei in proton-induced reactions has served as the starting basis to extend the transport studies by accounting for fragments with strangeness degrees of freedom (hypernuclei).

We have applied the model to heavy-ion collisions at intermediate relativistic energies and to proton-induced reactions at very high incident energies by analyzing the transport calculations in terms of formation of light hypernuclei. We have estimated the production cross sections of light hypernuclei in such reactions by exploratory transport theoretical calculations.

This first transport theoretical study on hypernuclear production in reactions at low and high incident energies can be further extended. In particular, a future combination of our transport model with the recently developed statistical multifragmentation model including strangeness degrees of freedom would be a helpful tool. Furthermore, a detailed study on possible influences of the hadronic mean-field on hypernuclear formation may be important. Within a relativistic framework one can extend the present non-linear Walecka model to more general hadronic matter including strangeness degrees of freedom [34], which has been partially implemented and is being tested.

In summary, transport simulations predict significant production cross sections for highly energetic hypernuclei. The theoretical estimates may be useful for the future experiments at GSI and the J-PARC facility, since high energy hypernuclei can be easily separated from the background and detected. The production of hypernuclei with strangeness \( S = -2 \) may be also of major importance, e.g., \( \Xi \)- and double-\( \Lambda \)-hypernuclei. However, due to very low statistics these processes have not been studied in this Letter. We conclude that this work provides an appropriate theoretical basis for investigations on hypernuclear physics.

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