Production of fragments with and without strangeness within a combined BUU+SMM approach

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Abstract

The formation of hypernuclei in hadron-induced reactions and in heavy-ion collisions within a combination of a covariant transport model and a statistical fragmentation approach is investigated. We study the applicability and limitations of such a hybrid approach by comparing fragmentation data in heavy-ion collisions and proton induced reactions. It turns out that the combined approach describes fairly well multiplicities and momentum spectra of fragments. We thus extend the model by including strangeness degrees of freedom in the fragmentation process, modeled by a phase-space coalescence method. We provide theoretical predictions on spectra and on inclusive cross sections of light hypernuclei for the future experiments on hypernuclear physics at the new GSI facility.

1 Introduction

Hypernuclear physics opens the unique opportunity to study the properties of the hyperon-nucleon and hyperon-hyperon interaction [1]. The theoretical production of light hypernuclei in reactions was originally proposed by Kerman and Weiss [2]. Since then this topic has been attracted again theoretical interest [3], motivated by the new FAIR facility at GSI, in which projects on hypernuclear physics are running or under planing [4, 5].

In this work the initial non-equilibrium stage of a reaction is described by a covariant transport theory of Boltzmann type (Giessen-BUU), while the fragmentation mechanism of the final channel is modeled by a purely statistical approach (Statistical Multifragmentation Model, SMM [6]). The first stage of a dynamical process is modeled by the BUU transport equation until the system approaches an intermediate equilibrated stage, which may be an excited configuration. The de-excitation of this configuration is then statistically treated by the SMM model, which contains different fragmentation mechanisms. We show that the combined approach reproduces fairly well fragment multiplicities and spectra in proton induced reactions and in spectator fragmentation in intermediate energy heavy-ion collisions. The model is then applied to higher energies by allowing the formation of fragments with strangeness degrees of freedom. Theoretical predictions on light single hypernuclei for specific reactions related to projects of the future FAIR facility are then discussed.
2 The hybrid GiBUU+SMM model

The standard theoretical approach in describing collisions induced by hadrons or heavy-ions is based on the semiclassical kinetic theory of statistical mechanics [7]. Here we use the covariant analogon of this equation known in the literature [8] as the Relativistic Boltzmann-Uehling-Uhlenbeck (RBUU) equation.

\[
\left[ k^\mu \partial_\mu + \left( k^\nu F_{\mu\nu} + M^* \partial^\mu x^\nu - k^\nu M^* \right) \partial_\mu \right] f(x, k^*) = \mathcal{I}_{\text{coll}} .
\]  

(1)

The transport equation (1) describes the space-time evolution of the 1-body phase space distribution function \( f(x, k^*) \) for the different types of hadrons (nucleons including their higher resonant excitations, pions, kaons, and other mesons). The numerical implementation of the transport equation (1), as realized the Giessen-group, is called the Giessen-BUU (GiBUU) equation [9]. Details on the approach and the model parameters can be found in [10, 11].

The fragmentation process, which is crucial for the production of hypernuclei, is not physically accounted by the transport equation. The standard approach in modeling fragmentation within transport studies is the phenomenological phase-space coalescence picture [13]. However, in situations with long time scales for the fragmentation process, as spectator fragmentation in heavy-ion collisions and dynamics in hadron-induced reactions, a statistical description is necessary. Here we apply the SMM model in describing the fragmentation of spectator matter in heavy-ion collisions or of residual nuclei in hadron-induced reactions. The physical condition of passing from the dynamical (BUU) to the statistical picture (SMM) is restricted to the existence of a pre-equilibrium excited configuration, determined by the anisotropy ratio of the local longitudinal and transverse pressure components. This is demonstrated in Fig. 1 for a proton-induced reaction. After the initial non-equilibrium phase, in which the proton beam penetrates the nucleus and excites it, the residual system achieves an equilibrated state at \( t \sim 75 \text{ fm/c} \), characterized by constant values of mass, charge number and excitation energy. Also

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Time evolution of a residual nucleus [12] in a central \( p + Fe@1 GeV \) reaction. Displayed are the average mass number (top-left), average charge number (top-right), excitation energy (bottom-left) and the anisotropy ratio (bottom-right) as function of time.}
\end{figure}
the anisotropy ratio approaches unity. However, the SMM approach does not account for strangeness degrees of freedom, thus we apply a phase-space coalescence algorithm for the formation of hyperfragments, in which the coalescence parameter in coordinate \( \text{and} \) in momentum space are fixed to results of analytical studies by Wakai et al. \cite{3}.

3 Fragmentation at low energies

It is convenient to study first the reliability of the combined approach by means of fragmentation observables at low incident energies, before applying it to the production of hypernuclei. The main quantities for the formation of hypernuclei are the cross sections of light fragment production and those of strangeness production.

Fig. 2 shows double differential kinetic energy spectra of emitted neutrons as extracted from the combined GiBUU+SMM model and from the experiment. The comparison with the data is very good. In particular, the theoretical transport calculations reproduce all the details of the entire process, e.g., the quasi-elastic peaks at forward polar angles at high kinetic energies, which is a dynamical effect, and the low energy spectra, as the result of the statistical decay of the residual nucleus. Total fragment cross sections are reproduced reasonable within the combined model, in particular, for isotopes produced in the spallation region (near the target mass) and for fission fragments, see Fig.3.

In the more complex case of heavy-ion collisions the combined approach has been applied to spectator fragmentation only, since this system is well suited for theoretical and experimental studies of hypernuclei at higher energies (see below). As in the case of proton-induced reactions, the non-equilibrium dynamics of a heavy-ion collisions is modeled by the transport equation, until spectators achieve an equilibrated configuration characterized by a spherical local momentum distribution. Mass and charge number and excitation energy of spectators can be then determined, which serve as parameters for the statistical decay of excited spectators. Fig. 4 shows the centrality dependence of the average mass and excitation energy per nucleon of spectator matter. The theoretical predictions for these quanti-
ties quantitatively fit the experimental data, which is an important issue when applying the statistical multifragmentation model. More successful comparisons with data can be found in Ref. [11].

We conclude that the combination between the dynamical non-equilibrium transport model and the statistical fragmentation approach is a reliable tool to study the fragmentation process in reactions. It is therefore natural to extend it by including strangeness degrees of freedom in the fragmentation process, which is the topic of the next section.

4 Fragmentation at high energies (Hypernuclei)

The production of hypernuclei in high energy reactions induced by protons, antiprotons and heavy-ions belong to the major projects in hypernuclear physics proposed by the HypHI- and PANDA-collaborations at the new FAIR facility at GSI [4, 5]. As a first testing phase the HypHI collaboration will start in the next year with heavy-ion experiments induced by light $^{12}$C and $^7$Li nuclei, and in the RIKEN facility with high energy proton beams on light $^{12}$C targets. The reason of selecting collisions between light systems is the easier identification of hypernuclei via the weak decay of the hyperon into pions. In earlier theoretical studies cross sections of the order of only few microbarn ($\mu$b) were predicted [3], due to the low cross sections of strangeness production and the rare effects of secondary scattering, important in producing slow hyperons inside the spectator regions.

It is therefore natural to study these light systems again, in order to compare as a first step the results of our model with earlier theoretical and rare experimental predictions. The production of hypernuclei in spectator fragmentation has been theoretically modeled within a phenomenological coalescence prescription in coordinate and momentum space. The coalescence factors, which considerably influence the results, have been adjusted such to produce results as close as possible to earlier predictions of Refs. [3]. Fig. 5 shows inclusive rapidity distributions of different light fragments and the corresponding hyperfragments in spectator fragmentation. The estimated hyperfragment production is ca. 5 – 6 orders of magnitude less than that of fragment production in general. This effect was
expected due to two reasons: (a) the low values of strangeness production cross sections with 3, 4-body final states $BB \rightarrow BYK$, $BB \rightarrow BBK\overline{K}$, $B\overline{K} \rightarrow YB$ [17], which are important in producing slow hyperons, (b) and the small interaction spectator volume which prevents hyperon production inside the spectator matter in secondary processes, e.g., $B\pi \rightarrow YK$ and $B\overline{K} \rightarrow \pi Y$, and their elastic re-scattering. An integration over the projectile rapidity leads to total production cross sections of light hypernuclei $\sigma_{tot} = 2.2$, $4$, $1.4 \mu b$ for $^4\Lambda H$, $^4\Lambda He$ and $^5\Lambda H$ single hypernuclei, respectively, in spectator fragmentation. In particular, the contribution to hyperfragment formation from secondary pion-nucleon scattering inside the spectators is very moderate, e.g., $\sigma_{\pi N} = 0.3$, $0.2$, $0.03 \mu b$ for the formation of $^4\Lambda H$, $^4\Lambda He$ and $^5\Lambda H$, respectively. These results, which are consistent with earlier studies from Wakai et al. [3], lead to the conclusion that the major contribution to hypernuclear production originates from the capture of fireball hyperons during the passage stage of the spectators near the expanding fireball region.

In proton-induced reactions at much higher energies, e.g., $p+C@50 GeV$ (J-PARC) [18], the situation turns out to be different, as found in dynamical transport calculations. The major channels contributing to the formation of light hypernuclei are those with pion-baryon scattering. This seems obvious due to the very high total pion production cross section, in contrary to the $C + C@2 AGeV$ colliding system. The situation is summarized in Fig. 6, again in terms of the rapidity distribution. An interesting feature here is the appearance of two sources, a target at rest and a moving source. This dynamical break-up is due to small re-scattering effects inside the initial compound nucleus. A significant amount of the beam energy is thus transferred into only a few nucleons, which causes the pre-equilibrium break-up. The transport theoretical results predict high energetic light hypernuclei, which might be easily separated from the background and thus be experimentally accessible.
The investigation of hypernuclei in reactions, as they will be experimentally studied in the new FAIR facility at GSI, provides new insight on the still controversial hyperon-nucleon and hyperon-hyperon interaction. It has been thus obvious to explore this field from the theoretical point of view, as has been done here in terms of covariant transport dynamics.

We have theoretically explored the different mechanisms for hypernuclear production in heavy-ion and proton-induced reactions relevant to the future experiments at the new FAIR facility at GSI on hypernuclear physics, which have to be compared with experimental data, when they will be available.

Of particular interest will be the study of double-strange hypernuclei or generally from exotic multi-strange bound objects, e.g., $^4A_{\Lambda\Lambda}$, $^4A_{\Omega}$, which is an important issue in theoretical and experimental works to better understand the hyperon-hyperon force. This project, which will be one part of the proposals of the PANDA-collaboration, will be theoretically studied in antiproton-induced reactions. We conclude that the present theoretical work gives an appropriate basis for investigations on hypernuclear physics at the FAIR facility at GSI.

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Figure 6: Rapidity distributions of different particle types (as indicated) for the system \( p + ^{12}C@50\text{GeV} \).

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