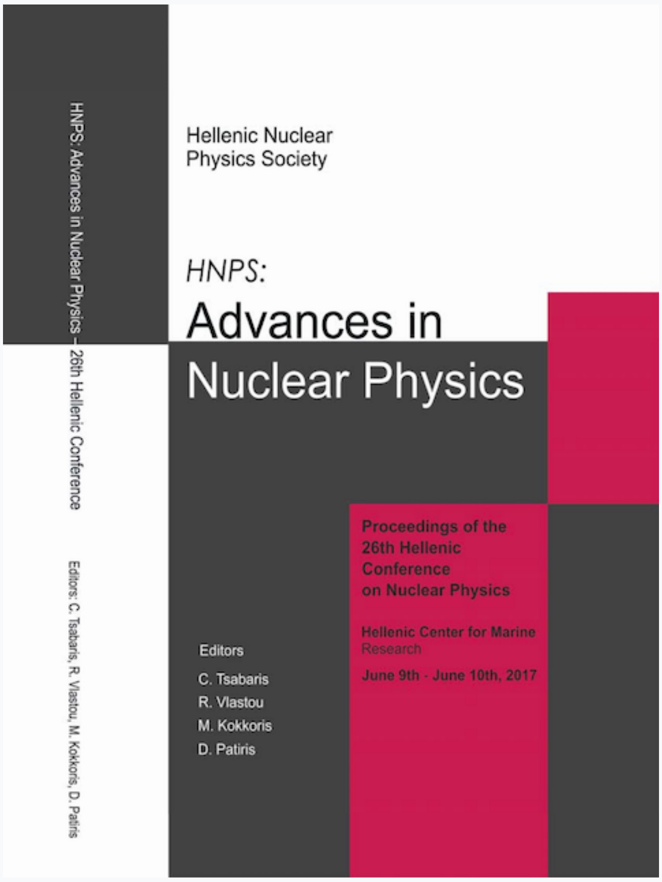
HNPS Advances in Nuclear Physics

Vol 25 (2017)

HNPS2017



Formation of fragments and hyperfragments in hadron-reduced reactions

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doi: 10.12681/hnps.1953

Formation of fragments and hyperfragments in hadron-induced reactions

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Abstract The formation of fragments and hyperfragments in hadron-induced reactions at intermediate relativistic energies is investigated. We use a combination of a covariant dynamical transport model (Giessen-Boltzmann-Uehling-Uhlenbeck, GiBUU) for the pre-equilibrium dynamics and a statistical approach (Statistical Multifragmentation Model, SMM) for the description of fragments. In particular, we discuss in detail the applicability and limitations of such a hybrid model by comparing data on fragmentation at low relativistic SIS/GSI-energies, before applying it to higher incident energies for studies on hypernuclei.

Keywords Nuclear Equation of State (EoS), nuclear reactions, hadron-induced reactions, fragmentation, hypernuclei

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INTRODUCTION

One of the main tasks of flavor nuclear physics is a realistic construction of nuclear forces between the octet-baryons. While empirical information for the nucleon-nucleon (NN) interaction is available with high accuracy experimental scattering data, empirical data involving the nuclear interaction with hyperons Y (Λ,Σ,Ξ,Ω) are still very sparse. Consequently, the parameters of the NN-interactions are very well determined at free space and at saturation density, while the parameters of the bare and also in-medium YN-interactions in the strangeness S= -1, -2 sectors are still under controversial debates, see for a recent review Ref. [1].

A precise knowledge of the nuclear interaction, not only between nucleons but also between all constituents of the baryon-octet involving hyperons, is indispensable for nuclear and hadron physics in general and, in particular, for nuclear astrophysics. The inner core of neutron stars, for instance, is supposed to consist of protons (and leptons due to charge neutrality), neutrons, and hyperons. Note that the existence of the heavy-mass Λ,Σ,Ξ,Ω-hyperons is in principle energetically allowed in the neutron star core due to the high densities.

Information on the NN- and on the YN-interactions in hadronic media can be achieved in nuclear reactions induced by heavy-ions or by hadronic beams. A prominent example is the PANDA-experiment at GSI proposing a two-step reaction method: at first, one uses antiproton-beams on nuclear targets to produce low-energetic cascade Ξ-particles, which they are used further as a secondary beam for secondary nuclear targets. The main idea here is the

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production of multi-strangeness hypernuclei. That is, the formation of fragments with more than one bound Λ-hyperons inside a nuclear or hadronic medium at finite density. In this way one would be able to explore the properties of hyperons in matter at densities around saturation and beyond.

We have studied this task by using a relativistic transport model for the pre-equilibrium description of the dynamical hadron-induced reactions and a statistical multifragmentation model for the fragment formation. In the following we show how the fragment formation can be incorporated within the relativistic transport and discuss the formation of multi-strangeness hypernuclei in relation to the YN-interactions.

THE HYBRID GIBUU+SMM MODEL

The theoretical description of dynamical processes such as heavy-ion collisions or hadron-induced reactions involves in principle the theoretical treatment of two steps. The pre-equilibrium stage, in which the dynamics takes place, and the freeze-out phase, where the initially excited system has reached a (local) equilibrium, thus, statistical methods do apply and can be used for the fragment formation. The pre-equilibrium stage is modeled successfully by relativistic transport of Boltzmann-type equations [2,3]. Here the entire dynamics is described, in which particle-trajectories evolve in phase-space due to the influence of nuclear and hadronic mean-field potentials and, furthermore, due to binary elastic and inelastic collisions. During this stage new baryons and mesons are produced, re-absorbed, re-scattered, and propagated in the appropriate mean-field gradients. Among others, protons, neutrons and hyperons are dynamically formed and survive until freeze-out.

This dynamical scenario is numerically realized within the Giessen-Boltzmann-Uheling-Uhlenbeck (GiBUU) transport model [3]. The freeze-out configuration in a hadron-induced reaction consists of an excited residual nuclear target, of emitted nucleons and other produced particles, and of hyperons. Depending on the system size and thus on rescattering, hyperons can escape out of the nucleus or can be captured inside the hadronic medium. This freeze-out configuration will undergo fragmentation, which is then modeled by the Statistical Multifragmentation Model (SMM) [4]. The SMM is a Monte Carlo prescription for the description of various "fragmentation channels", e.g., fission/evaporation/multifragmentation, where secondary de-excitation of primarily created fragments is taken into account.

The connection of the two approaches, the dynamical GiBUU and statistical SMM proceeds by calculating the relevant properties of the residual system from GiBUU. One of the most important quantities is the excitation energy of the residual nucleus, because it strongly affects the SMM results. In fact, the excitation energy appears in level densities in a highly non-linear way. Therefore, this quantity should be theoretically extracted as precise as possible. This task involves a numerical treatment of the GiBUU simulations with an energy conservation as precise as possible [3,5,6].

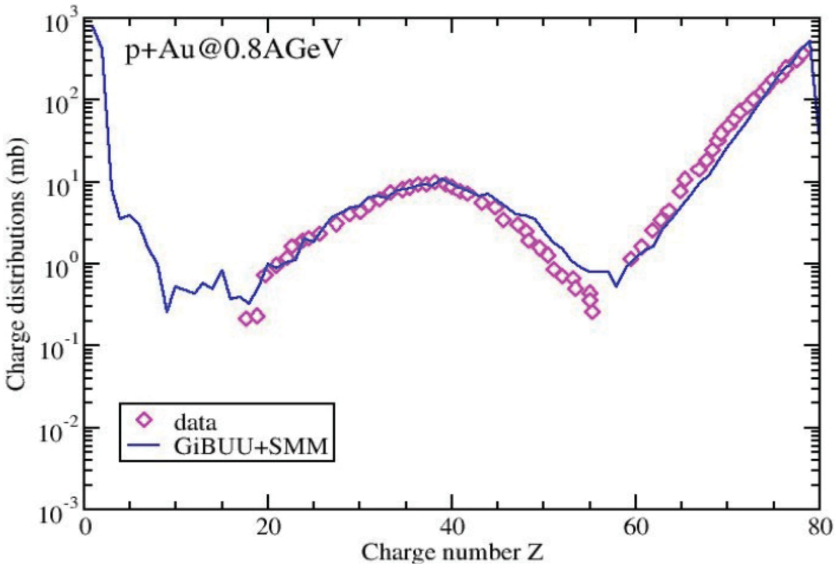

Fig. 1. Charge distributions for proton-induced reaction on Au-target at 0.8 GeV beam energy. The GiBUU+SMM calculations (solid curve) are compared with experimental data (open diamonds).

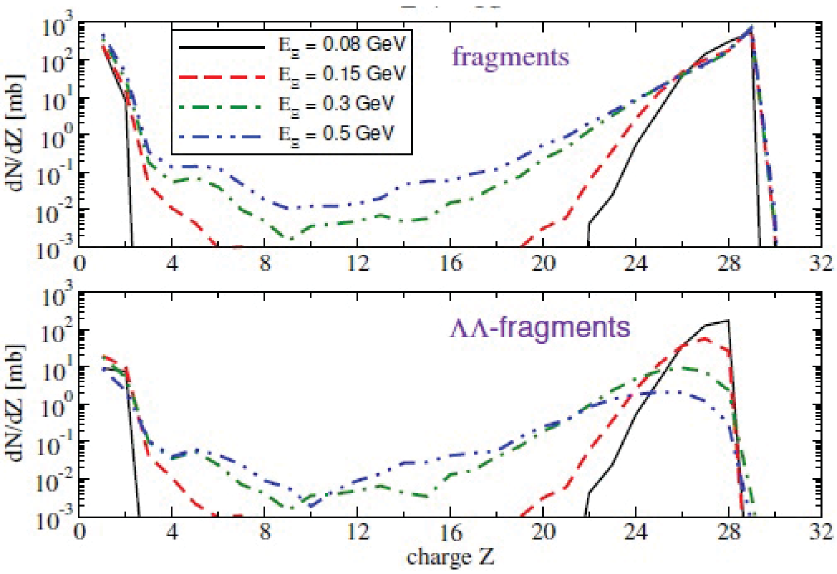

Fig. 2. Charge distributions of fragments (panel on the top) and double-Λ hyperfragments (panel on the bottom) for Ξ-induced reaction on Cu-target at different Ξ-beam energies, as indicated.

RESULTS AND DISCUSSION

We have studied hadron-induced reactions with the hybrid GiBUU+SMM approach [5,6,7]. At first, we have tested the reliability of the hybrid model in the simplest case, that is, in proton-induced reactions at intermediate relativistic energies, where a variety of fragmentation data exist. The pre-equilibrium dynamics was modeled by the GiBUU transport and the fragmentation process by the statistical SMM code. Fig. 1 shows an example of these benchmark transport calculations. In fact, the hybrid approach describes fairly well the experimental data on a logarithmic scale. In particular, the various fragmentation mechanisms appear in consistency with the experimental data. There are the evaporation peak close to the target charge and the fission wide peak close the half value of the target charge. The evaporation part originates from peripheral events with low excitation, while the fission peak (and the multifragmentation region) arises from rather central events with higher excitation energy. Note that not only absolute values (as shown in Fig. 1), but also kinetic energy spectra of fragments are described very well within the hybrid approach. This is important for the description of hyperfragments in terms of phase-space coalescence, where not only absolute yields, but also kinetic momenta are important. Having the fragments as the result of the hybrid GiBUU+SMM calculations, and also the produced hyperons from the GiBUU calculations, we have calculated the yields hypernuclei in reactions induced now not by protons, but by cascade Ξ-beams at energies as proposed by the PANDA experiment. The results are shown in Fig. 2 in terms of charge distributions of double-Λ hypernuclei (panel on the bottom) in comparison with the charge distributions of purely nucleonic fragments (panel on the top). The theoretical calculations predict a copious production of multi-strangeness hypersystems. This is a very important result indicating that the investigation of multi-strangeness in-medium interactions seems possible in reactions at PANDA. In fact, as discussed recently [8], the production yields of double-Λ hypernuclei are strongly affected by the underlying YN-interaction used. In particular, the production of multi-strangeness Ξ-hyperfragments is possible, depending again on the in-medium hyperon interaction to large extend.

CONCLUSIONS

In conclusion, hadron-induced in-medium nuclear reactions are a suitable tool to explore the still controversial strangeness sector of the nuclear EoS. This challenging task is crucial for a better understanding of flavor nuclear and hadronic physics with direct consequence for nuclear astrophysics. The forthcoming PANDA experiment will definitely contribute to better constrain the still unexplored strangeness valley of the nuclear EoS.

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