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Multi-strangeness production in hadron induced reactions

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Abstract

We discuss in detail the formation and propagation of multi-strangeness particles in reactions induced by hadron beams relevant for the forthcoming experiments at FAIR. We focus the discussion on the production of the decuplet-particle Ω and study for the first time the production and propagation mechanism of this heavy hyperon inside hadronic environments. The transport calculations show the possibility of Ω-production in the forthcoming $\overline{\text{P}}$ANDA-experiment, which can be achieved with measurable probabilities using high-energy secondary Ξ-beams. We predict cross sections for Ω-production. The theoretical results are important in understanding the hyperon–nucleon and, in particular, the hyperon–hyperon interactions also in the high-strangeness sector. We emphasize the importance of our studies for the research plans at FAIR.

Keywords: $\overline{\text{P}}$ANDA; $\bar{p}$-induced reactions; Ξ-induced reactions; ΞN interactions; Ω-baryon

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1. Introduction

Hadronic reactions induced by heavy-ion and hadron beams build the central tool to look deeper inside the hadronic equation of state (EoS). Of particular interest is the strangeness sector

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of the EoS. Baryons with strangeness degree of freedom modify the nuclear EoS significantly at compressions beyond saturation [1–4]. Such effects show up already in ordinary matter (finite nuclei). Adding hyperons to a nucleus typically leads to a rearrangement of the whole system. Although hyperons are fermions, they do not underly the Pauli-exclusion principle with nucleons because strangeness makes them distinguishable. As a consequence one observes increased binding energies and even a slight shrinking of hypernuclei, corresponding to a larger saturation density [5].

Hyperons are also important for nuclear astrophysics. It is well known that the presence of hyperons in the cores of neutron stars may play important role in determining both bulk properties of neutron stars as well as various dynamical processes [6–8]. In particular, hyperons can be formed in the interior of neutron stars when the in-medium nucleon chemical potential is large enough to make the conversion of a nucleon into a hyperon energetically favorable. Actually, they can appear at densities of about 2–3 times the saturation density of nuclear matter. This conversion relieves the Fermi pressure exerted by the nucleons and makes the equation of state softer. It has been found that, the mentioned softness of the equation of state, leads to low values of maximum neutron star mass. This is in contradiction with a very recent accurate measurements of the masses, $M = 1.97 \pm 0.04 M_{\odot}$ (PSR J1614-2230 [9]) and $M = 2.01 \pm 0.04 M_{\odot}$ (PSR J0348+0432 [10]). This is the so called hyperon puzzle where while the presence of hyperons at high densities is predicted by the nuclear theory is not compatible with measured neutron star masses.

There are, mainly, three different approaches to study the hyperon formation in neutron star matter. The first one is based in the framework of the Brueckner–Hartree–Fock approach by using realistic nucleon–nucleon and hyperon–hyperon interactions [11–13]. The second method is based on Relativistic Mean Field Theory [14,15] and the third one on the construction of an effective equation of state by employing Skyrme-type interactions [16]. It has been suggested that the hyperon–hyperon repulsion and hyperonic three-body interactions effects may help to solve the hyperon puzzle problem [11]. Another recent review article on this still debated issue can be found in Ref. [17] (and further references therein).

The hyperon-puzzle is one of the most recent issues concerning the study of the static and dynamic properties of the neutron stars [17–19]. The solution of this problem may lead to a much better understanding of a complex phenomena in neutron star interior, such as the hyperon superfluidity and the hyperon bulk viscosity. All the mentioned effects are directly related with the neutron star cooling process, the glitches and the radiation of gravitation waves [20–24].

Heavy-ion collisions at intermediate relativistic energies of several GeV per particle supply information on the in-medium hadronic properties over a broad range in baryon density [25,26]. Heavy-ion reactions at energies around the strangeness production threshold have been studied theoretically and experimentally in the past [27,28]. One of the most important achievements was the conclusion of a soft nuclear EoS at densities $\rho_B \simeq (2\text{–}3)\rho_{sat}$, as a result from collective flow [25] and kaon production [27,29–31] studies. For further reading concerning the high density equation of state of symmetric matter and the symmetry energy of compressed matter we refer to Refs. [32–34]. Supplementary information on the in-medium properties of kaons have been reported also in Ref. [35]. Further investigations on strangeness and hypernuclear production in hadronic reactions have been recently started by several theoretical and experimental groups [36–39].

While intermediate-energy heavy-ion reactions give essential details of the highly compressed matter, the high production thresholds of heavier hyperons hinder their production. One the other hand, the main task of flavor nuclear physics consists in the construction of the in-medium